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7.2 ENSO AND NAO IMPACTS ON PLAINS WINTER SEASONS IN MODERN AND HISTORICAL PERIODS

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1. INTRODUCTION

Climatological teleconnection patterns, including the phase of the El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), are known predictors for variables such as seasonal temperature and precipitation and tropical cyclone activity. ENSO is known to affect synoptic patterns across the continental United States, particularly by its impact on the upper tropospheric jet stream position. Likewise, NAO is associated with changes in sea level pressure and upper-level jet strengths over the Atlantic Ocean, with upstream impacts affecting North American temperatures and precipitation distribution. While ENSO and NAO are two of many factors that influence global circulations, and by distillation may have a less distinguishable influence on the synoptic pattern, coherent signals can be uncovered in the synoptic environment, based on ENSO phase as well as the NAO, that influence temperatures and precipitation in the central United States.

Historically, ENSO variability has affected civilizations spanning the globe and the centuries (Fagan 1999). Dendroclimatological records support long-term variability in frequency and intensity of ENSO events, including the potential that modern ENSO events exhibit more variability than those earlier in the 300-year tree ring record (Stahle et al. 1998). Gergis et al. (2006) suggest that a single definition of ENSO may not suit the complexity of the phenomenon, and that the appropriate definition may depend on the application, and the study acknowledges limitations in the ability of paleoclimatological data to resolve the variance of ENSO cycles. Additionally, Sardeshmukh et al. (2000) indicate that the atmospheric response to ENSO phase is stronger but more variable during El Niño events than La Niña, which is critical considering that even a small shift in probabilities increases the likelihood of extreme anomalies.

The relationship between ENSO phase and weather impacts in the central United States, while not as thoroughly examined as impacts to the coastal margins, has been investigated in previous publications. Cook and Schaefer (2008) found a relationship between ENSO phase and winter (January through March) tornado activity in the southeast and south central United States, noting higher tornado probabilities during La Niña events near the Mississippi River valley, with higher tornado probabilities during El Niño events in the extreme coastal areas of the domain (Texas, Louisiana, North Carolina, and Florida), while the pattern during neutral winters was less spatially defined. Similarly, Mayes et al. (2007 and 2008) investigated the impact of ENSO phase on tornado activity in the north central United States, determining that the influence on tornado activity was dependent not only on the phase itself, but also whether the phase was antecedent (existing during the winter before) or developing during a given convective season. Activity was noted to be heightened from the central Plains to the Mississippi River valley during or following La Niña events, while tornado activity exhibited a tendency to be suppressed during or following an El Niño in the central Plains and Mississippi River valley while tending to be heightened in the northern Plains. Thus, both the Cook and Schaefer (2008) and Mayes et al. (2007 and 2008) studies indicate that the impacts of ENSO can indeed reach the central United States, impacting high-impact weather events such as convection that favors tornadoes.

The impacts of ENSO are more distinct during the cool season in the United States. Patten et al. (2003) investigated the relationship between ENSO phase and snowfall frequency across the United States for the period 1900-1997, investigating light, moderate, or heavy snowfall frequencies by ENSO phase. The continental United States was divided into subregions to allow regional conclusions; the Midwest area (encompassing Iowa, northern Illinois, southern Wisconsin, and southern Minnesota) and the Northern Plains (encompassing Nebraska, South Dakota, and North Dakota) behaved similarly to each other and generally in an opposite sense to the Northern Lakes region (encompassing northern Minnesota, northern Wisconsin, and the Upper Peninsula of Michigan). Compared to ENSO-neutral years, the Midwest and Northern Plains exhibited increased light snow frequency during El Niño events, with little signal for moderate or heavy snow frequency. The Northern Lakes region exhibited increased moderate snow frequency during La Niña events, as well as decreased frequencies of moderate and heavy snow during El Niño events, with little signal for light snow frequency. The gradient of snow frequency impacts from north to south in the central United States does raise the question of whether the changes are due to changes in precipitation

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amounts or temperatures. For several reasons, snowfall will not be included among the meteorological variables investigated in this study. First, snowfall records prior to 1900 are scarce at best, and no known snowfall measurement records exist that pre-date the mid-1880s. Second, snowfall measurement practices have varied through the period of record, which adds a lack of reliability to the record for climatological studies. Finally, the probability of snowfall in the north central United States is related strongly to the anomalies of both temperature and precipitation; thus, conclusions about snowfall probability can be inferred from conclusions about the combination of temperature and precipitation anomalies. Nonetheless, results from this study may compare to the Patten et al. (2003) study for the purpose of investigating consistency in ENSO signals.

The purpose of this study is to determine the impact, if any, of ENSO and NAO on wintertime precipitation and temperatures in the central United States, with a comparison of impacts during the “historical” (1879-1944) and “modern” (1945-2010) periods. It is expected that both ENSO and NAO impact both temperatures and precipitation in the central United States. The more pressing questions involve a more detailed investigation of those relationships, including the complicated interaction between the influence of ENSO and NAO, as well as a comparison of the modern and historical periods to determine if the influence of ENSO and NAO has changed. In particular, in addition to quantifying the relationship between both ENSO phase and NAO on wintertime temperatures and precipitation, this study will investigate two hypotheses. First, the study will investigate whether anomalies due to either ENSO or NAO will be substantially the same in 1879-1944 as 1945-2010; if so, then shorter and more recent periods of record could provide relevant information about historical periods. Second, the study will investigate, in the central US, the possibility that NAO affects temperatures more strongly and ENSO affects precipitation more strongly.

Data sets used in this study, as well as the methodology for investigating the relationships among oscillations and meteorological variables, are presented in section 2. Section 3 will provide preliminary results of the statistical analysis, as well as synoptic perspective on the statistical relationships. Finally, preliminary conclusions and options for future work will be presented in section 4.

2. DATA AND METHODOLOGY

2.1 Data sets

Temperature and precipitation data were collected through the Applied Climate Information System (ACIS; Hubbard et al. 2004), a combined data system utilized by the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center, NOAA National Weather Service (NWS), and the Regional Climate Centers, for 10 sites across the central United States: Bismarck, North Dakota (BIS), Dodge City, Kansas (DDC), Denver, Colorado (DEN), Duluth, Minnesota (DLH), Des Moines, Iowa (DSM), North Platte, Nebraska (LBF), Moline, Illinois (MLI), Madison, Wisconsin (MSN), Minneapolis/St. Paul, Minnesota (MSP), and Omaha, Nebraska (OMA). Sites were selected based on the presence of complete temperature and precipitation records from 1879 through 2010. Additional sites in the central United States exist that also follow this criteria and should be analyzed in future studies include Chicago, Illinois (CHI), Dubuque, Iowa (DBQ), and Milwaukee, Wisconsin (MKE). Sites that were excluded due to gaps in the data record that otherwise pre-dates 1879 include Cheyenne, Wyoming (CYS), La Crosse, Wisconsin (LSE), and St. Louis, Missouri (STL). Data for STL included complete temperature records but incomplete precipitation records; thus, the site may be used in the future in analyses involving only temperatures but was excluded from this investigation. All of the sites are considered “threaded” records, with station moves across the metropolitan areas collected into one continuous data record. Thus, an important caveat with the data is that each station may include multiple, though related, sites, with variations in site location and instrumentation through the period of record. While some conclusions may be drawn about the long-term record at these stations, they should be made with caution and supported by analysis of a homogenized data set.

An additional limitation of this study is that temperature and precipitation trends were not normalized or removed. The retention of the trends in the data sets was intentional, as an important component of the comparison between the historical and modern periods is in fact that in some locations, significant trends exist. The effect of ENSO phase and NAO is modulated by those trends, and it is the combination of ENSO or NAO with trends that produces sensible weather impacts that may create an impact on human activities in the area. It does, however, limit the applicability of this study to others that intend to isolate the impact of either ENSO or NAO on wintertime temperatures and precipitation in the central United States.

Many data sets and methodologies exist to define ENSO, but few of these span both historical and modern periods. The Oceanic Niño Index (ONI) data set available from NOAA Climate Prediction Center (CPC) spans the period from 1950 to present. ONI is widely used in NOAA applications of ENSO studies, as well as in the operational definition of El Niño and La Niña utilized by CPC, which defines an El Niño (La Niña) episode by the presence of a sea surface temperature (SST) anomaly greater (less) than 0.5 °C (-0.5 °C) in the Niño3.4 region (Fig. 1) for five consecutive three-month-average periods (Kousky and Higgins 2004). Current CPC expertise (M. LeHeureux, personal communication) indicates that the requirement for five consecutive periods is somewhat arbitrary, and that shorter periods of anomalous SST can induce atmospheric responses characteristic of the cold or warm phases. CPC experts are developing monthly SST anomaly data for the Niño3.4 region based on Extended Reconstruction SST version 3b (ERSST.v3b) data (Smith et al. 2008), generating monthly anomaly data from 1871 through 2010; this data set has been provided via personal communication (M. LeHeureux) and will be applied here. CPC applied a least-squares fit to the data and calculated departures (anomalies) from that fit in order to de-trend the data set. That said, the data are unvetted and experimental, and particularly prior to 1950 when the data are less confident (Fig. 2), conclusions should be approached with due caution. The monthly SST anomalies were converted to three-month averages, with focus on the December-January-February (DJF) and January-February-March (JFM) periods as every episode from 1870 to present was noted to include SST anomalies above or below thresholds during at least one of those periods. Periods in which the three-month average SST anomaly was less than -0.5 °C were designated as La Niña events, and those with anomalies greater than 0.5 °C were designated as El Niño events, with neutral conditions designated for anomalies in between those thresholds. No requirement for duration of an episode was applied; most, but not all, of the events spanned both DJF and JFM.

As with ENSO, there is no single data set that defines NAO, and many analyses exist (Hurrell and Deser 2009). This study relies on data from the Climate Analysis Section of the National Center for Atmospheric Research (NCAR; available online at http://www.cgd.ucar.edu/cas/jhurrell/indices.html), spanning 1864 to the present (Fig. 3). In this data set, the NAO index is based on the difference in normalized sea level pressure (SLP) between Lisbon, Portugal, and Stykkisholmur/Reykjavik, Iceland. Hurrell normalized the SLP anomalies at each station by dividing the seasonal mean pressure by the standard deviation of the long-term mean (1864-1983). Normalization is used by Hurrell to avoid the series being dominated by the greater variability of the northern station. For the purposes of this study, the NAO index was considered to be "negative" when values were less than -0.5 and "positive" when values were greater than 0.5, a rather loose definition of the negative and positive phases that provides a robust sample size for positive and negative phases with relatively few "neutral" years.

Table 1 provides a categorization of each year from 1879-2010 by both ENSO phase and NAO index, as described above.

2.2 Methodology

The statistical technique used in this study was developed in partnership among NWS headquarters, CPC, and NWS staff in regional and field offices as a preliminary step in the introduction of a web tool that will allow NWS operational meteorologists to create analyses of the relationship between ENSO phase, or any other quantifiable oscillation, and a number of meteorological and user-input variables. Conditional climatologies can be combined with forecast probability of an ENSO phase to predict the probability of a given climatological variable occurring in the above, near, or below normal category given the ENSO phase that is forecast to occur. Much of the detail about the methodology is available online at: http://www.weather.gov/om/csd/pds/PCU4/Composites/CompInstructions.pdf

The statistical analysis employs a sampling technique based on the conditional probability of a given event occurring based on the ENSO phase or NAO index. The result is a conditional climatology of a given variable based on the ENSO phase or NAO index. The methodology incorporates a standardized method for developing climatologies of the given parameter for each ENSO phase (La Niña, neutral, and El Niño) or NAO index (negative, neutral, and positive) in comparison to the climatology of the period of record, as well as incorporating a test for statistical significance of the results to determine if deviations from the average climatology are significant relative to the null hypothesis that there is no relationship between ENSO phase or NAO index and each climatological variable.

In order to test for statistical significance, the compositing analysis methodology determines whether a significant ($\alpha = 0.10$) relationship exists between ENSO or NAO and the climatological variable. The probability of a given climatological variable occurring in the above, near, or below normal categories exactly x number of times, $P(x)$, within a given ENSO phase or NAO index is determined by comparison to a hypergeometric distribution. If the number of occurrences, x, falls within the lower 10% or upper 10% of the distribution, the event is deemed statistically significant, and the null hypothesis that the climatological variable occurred in the above, near, or below normal category during a given ENSO phase by chance is rejected.

In the application to wintertime average temperature and total precipitation used here, data were divided into terciles. Thus, an indication that there is an elevated probability for above normal temperatures, for example, translates to a statistically significant chance of temperatures in the highest third compared to the period of record climatological distribution. The average temperatures for DJF and JFM, and the total precipitation in DJF and JFM, were compared to the distribution of ENSO phase for DJF and JFM, respectively. The average temperature and total precipitation for DJF also were compared to the DJFM NAO index.

In addition to the statistical analyses, historical reconstructions were used to compare the average synoptic scale weather patterns during El Niño and La

Niña events for each of the two time periods, as well as during positive and negative phases of the NAO. Gridded historical data available through NOAA Earth Systems Research Laboratory (ESRL) were used to create composite synoptic plots (available online at http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/plot20thc.v2.pl). The data are from the Twentieth Century Reanalysis Project (Compo et al. 2011) version 2, which utilized synoptic pressure, sea surface temperature, and sea ice distribution to create a reanalysis that spans the period 1871 to 2008. The data do not have as fine of resolution as the NCEP/NCAR reanalysis (Kalnay et al. 1996), but the ability to create composite analyses prior to 1948 makes the Twentieth Century data the preferred choice, even though the latter dataset lacks input from 2009-2010. With 2009 as a La Niña year and 2010 as an El Niño year, each set of composites loses just one year; thus, the impact for this study was deemed to be negligible. Additionally, years in which the phase of ENSO was neutral in either DJF or JFM but categorized in the other season (underlined in Table 1) were omitted from the composites. Anomaly composites were examined in particular, due to the ease of seeing differences compared to looking at mean patterns. The NOAA ESRL web tool forces comparison of anomaly fields to a 1968-2006 mean, regardless of the years included in the composite analysis; this comparison is not customizable. Also, the color scales of each image are not customizable, and thus the color schemes for each image should be scrutinized for differences in contouring or shading intervals; these intervals also are not customizable. Finally, only 20 years can be input to the web tool for each composite; thus, the years in each phase were restricted if the phase did not occur in both DJF and JFM, to limit the number of years in each sample. Despite the limitations of the NOAA ESRL site, the availability of data for rapid analysis provides benefit in conducting first-level analyses of synoptic composites.

The combination of statistical relationships among the data sets and analyses of average synoptic patterns during different combinations of teleconnection patterns provides insight into the impact on wintertime temperatures and precipitation in the central United States.

3. RESULTS

Despite not being located within a region traditionally impacted strongly by either ENSO or NAO, all ten sites across the central United States exhibited statistically significant relationships to both ENSO and NAO for temperatures and/or precipitation for at least one of the study periods. The relationships were spatially consistent, particularly when the results of the historical and modern periods were combined. While all results described here have passed at least a 90% confidence test, in many cases, the results are 95% or even >99% confident.

In figure 4, the positive and negative ENSO phases are displayed for the historical and modern periods. The upper Great Lakes area (DLH, MSP) and also LBF exhibited a tendency toward warmer temperatures during El Niño, while the High Plains area (DDC, DEN, LBF) tended toward warmer temperatures during La Niña. Meanwhile, the Mississippi River valley (DSM, MLI) exhibited a tendency toward cooler temperatures during El Niño, while the northern sites (BIS, DLH, MSP) tended to be cooler during La Niña. Only OMA exhibited no temperature tendencies during either phase and during either period. MSN was inconsistent between modern and historical periods during El Niño, exhibiting a cool signal during the historical period (more similar to MLI) but a warm tendency during the modern period (more similar to MSP). It also is notable that LBF exhibited a tendency toward warm temperatures associated with La Niña in the historical period and with El Niño during the modern period. Looking at precipitation, the Mississippi River valley area (MLI, MSN, MSP) exhibited a tendency toward drier conditions during El Niño, while the High and Central Plains (DDC, DEN, DSM, LBF, OMA) tended to be dry during a La Niña. The Central Plains (DSM, LBF) tended toward wetter conditions during an El Niño, while BIS alone exhibited a wet tendency during a La Niña. DLH was inconsistent between modern and historical periods during El Niño, exhibiting a dry signal during the historical period (similar to MSP) and a wet signal during the modern period. All 10 sites had some kind of significant precipitation signal related to ENSO, but overall, the impact of ENSO on precipitation was only slightly more pervasive than its impact on temperatures.

Figure 5 shows the positive and negative NAO phases for the historical modern periods. Looking at temperatures, most of the central sites (BIS, DEN, DSM, LBF, MLI, MSN, MSP, OMA) exhibited a tendency toward warmer temperatures during positive NAO, and no sites exhibited a cool tendency. Similarly, almost all sites (BIS, DDC, DEN, DSM, LBF, MLI, MSN, OMA) indicated a cool signal during negative NAO, and no sites indicated a warm signal. No sites had conflicting tendencies for temperatures related to NAO between the historical and modern periods. Regarding precipitation, a few central sites (DEN, DLH, OMA) exhibited a dry tendency during positive NAO. BIS carried a wet signal associated with positive NAO. DSM was inconsistent between modern and historical periods during positive NAO, exhibiting a dry signal (similar to OMA) during the historical period and a wet tendency during the modern period. A few sites in the center of the study area (DLH, DSM, MSP) had a wet signal during negative NAO. Overall, the impact of NAO on temperature was more widespread than its impact on precipitation.

The results from the historical and modern periods are combined in Figure 6 for easier visualization of the range of impacts of both ENSO and NAO across the study area. The combined results do exhibit spatial consistency, with few conflicting results between periods, perhaps allowing generalization of results to both periods for this data set. In particular, the results for negative NAO are remarkably widespread and consistent, with a dominant cold signal and a smaller wet signal. The results for positive NAO also are widespread and are nearly in symmetric opposition to the negative phase, with a prevailing warm signal and more localized dry signal (with the exception of wet BIS and inconsistent DSM). The signal for dry conditions during La Niña is pervasive across much of the area and also was consistent between modern and historical periods; additionally, the temperature tendency toward warmer conditions was spatially, if not temporally, consistent, with several sites exhibiting a warm signal in one period but not both. The signals during El Niño were the least spatially consistent across the area, though the eastern half of the study area did exhibit a consistent dry signal. The temperature signal appears banded, with a band of warm temperatures from western Nebraska northeast to northern Wisconsin, while a band of cool temperatures appears from southwest Kansas through eastern Iowa.

Analysis of the synoptic composites based on ENSO phase (available from NOAA ESRL) indicates that the prevailing upper-level jet stream pattern does support the expected patterns for both phases and in both the modern and historical periods (Figure 7). The least similar of these is the 300 hPa winds during El Niño in the historical period; rather than the jet being anomalously strong across the southern states, the strongest westerly anomalies are well offshore in the Pacific Ocean. The 500 hPa geopotential height anomalies are more consistent from historical to modern periods in both phases, with a tendency toward higher heights in the Northern Plains during El Niño, while higher heights tend to occur in the Southern Plains and Southeast during La Niña (Figure 8). The sea level pressure pattern is consistent with expectations in both periods and for both phases (Figure 9); during La Niña, an anomalously amplified pattern is in place, with troughing in the central United States; during El Niño, anomalously high heights are instead in place across the northern Plains. Like the 300 hPa wind analysis, the analysis of 2 m temperature is more consistent between periods for La Niña than for El Niño (Figure 10). In both periods, La Niña years exhibit anomalously warm temperatures focused on the Southern Plains to the East Coast, with a slight shift northward of those anomalies in the modern period compared to the historical period. During El Niño, warm anomalies are located in the Northwest, but the southward extent varies sharply from historical to modern periods. The modern period indicates a stronger tendency toward cooler temperatures in the Southern Plains and Southeast, while the historical period limited those cooler temperatures to Mexico and the Northeast. Overall, while the La Niña patterns have remained relatively consistent from the historical to the modern period, the El Niño patterns exhibit significant differences between the historical and modern periods, with a more robust signal across the southern United States in the modern period than in the historical period. This result may be consistent with the findings of Sardeshmukh et al. (2000) that El Niño tends to produce stronger but more variable atmospheric response than La Niña.

4. CONCLUSIONS AND FUTURE WORK

While there is consistency between the historical and modern periods regarding the impact of ENSO and NAO, the results do not overlap completely, and in a few cases, the tendencies have shifted between periods. There are a number of possible reasons for the differences, each of which likely is a study in itself. The results may be becoming overwhelmed by trends later in the modern period, with both temperature and precipitation trends apparent across the area, particularly since the mid-1970s. These trends may be affecting the statistical relationships between ENSO or NAO and meteorological variables that are highly trended. It is also possible that due to changes in prevailing weather patterns attributable to climate change, storm tracks have changed enough to shift the impact of either ENSO or NAO at a given point in those affected areas. In any case, the results prevent accepting Hypothesis 1, that the historical and modern periods would have essentially similar results, without further testing. Analysis of the synoptic composites supports a change in the prevailing pattern during El Niño, in particular, from the historical to the modern period. Future studies should address the trended data by performing statistical analyses with detrended temperature and precipitation data, and additional work would be required to create a comparative climatology of “storminess” between the historical and modern periods that could then be analyzed further for ENSO and NAO relationships.

Hypothesis 2, that NAO affects temperatures more strongly and ENSO affects precipitation more strongly, does appear to be at least partially supported by the results of this study. NAO indeed exerts a strong influence in the study area on temperatures that is spatially consistent as well as consistent between the historical and modern periods, particularly during negative NAO. The relative influence of the precipitation signal, where it does exist, compared to ENSO warrants further investigation utilizing principal component analysis or other rigorous means. In contrast to the hypothesis, though, ENSO does affect temperatures in addition to precipitation. Further site-specific analysis should be conducted to determine the direction of impact on temperature and precipitation when signals are in conflict, with the potential to determine whether results are widespread across the region. For example, noting that LBF tends toward warm conditions during El Niño but cold conditions during negative NAO, years when those influences are combined should be examined to determine whether the trends offset or one signal dominates the other. Likewise, MSP tends to be dry during El Niño and wet during negative NAO, and the years with those combined influences should be examined for signal interplay. Additionally, when signals resonate, such as the tendency toward colder than normal temperatures at DDC for both El Niño and negative NAO, further studies should determine whether the signal becomes particularly confident, as well determining whether those combinations provide a higher likelihood of reaching extremes.

While significant work remains to investigate the relationships of both ENSO and NAO to winter weather in the central United States, the work begun with this study does provide a foundation for future studies. Preliminary results here support continued and rigorous investigation of temperature and precipitation trends during the winter months, emphasizing the interplay among ENSO, NAO, and trends due to climate change.

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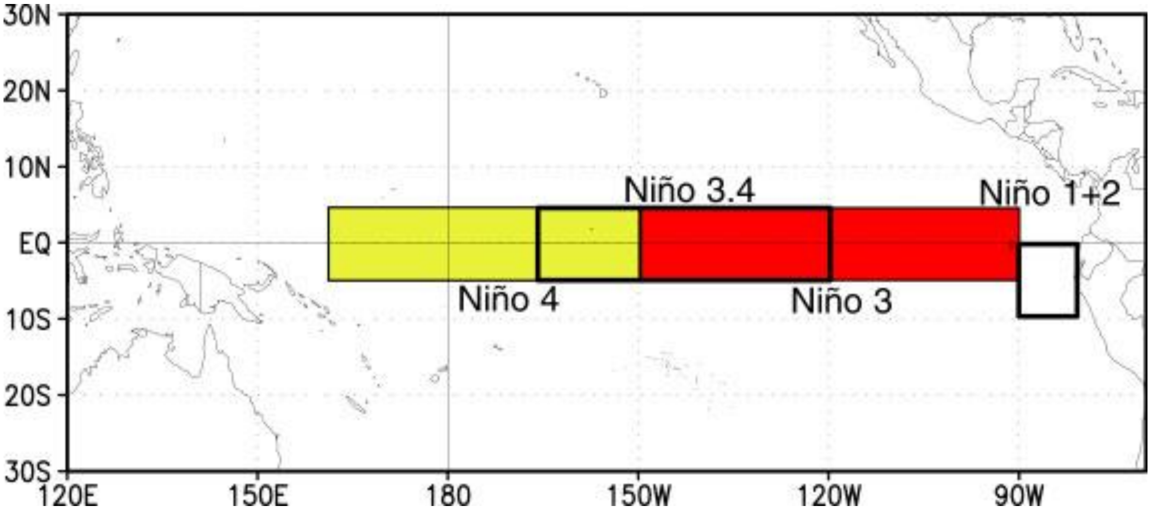


Figure 1. The four Niño regions utilized to define sea surface temperature anomalies in the equatorial Pacific Ocean. Available online at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/Niño_regions.shtml

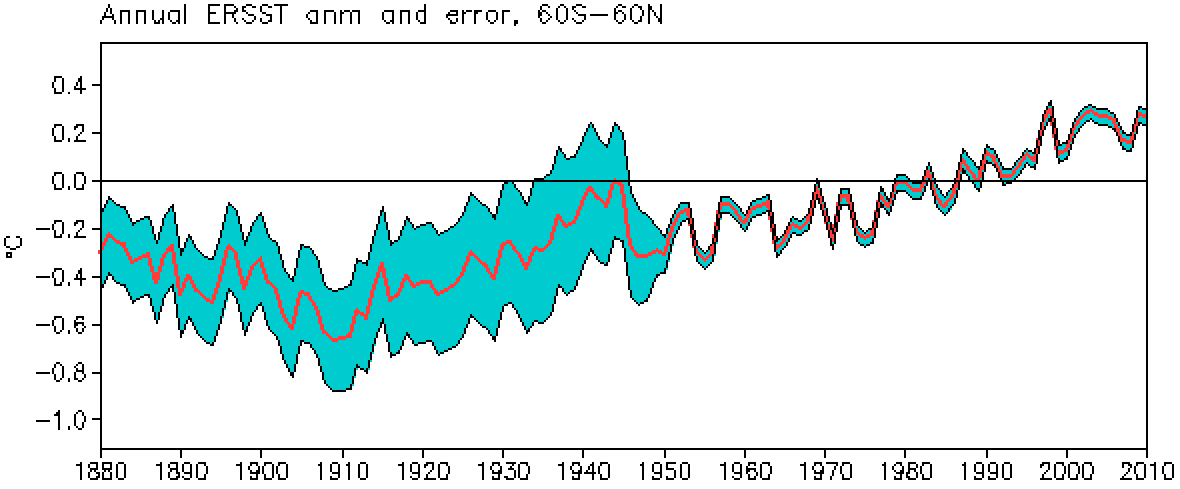


Figure 2. Annual ERSST.v3b anomaly from 1880-2010 from 60°S to 60°N (red solid line), with 95% confidence interval in light blue. Note that the confidence increase substantially from 1950 onward. Available online at http://www.ncdc.noaa.gov/oa/climate/research/sst/ersstv3.php

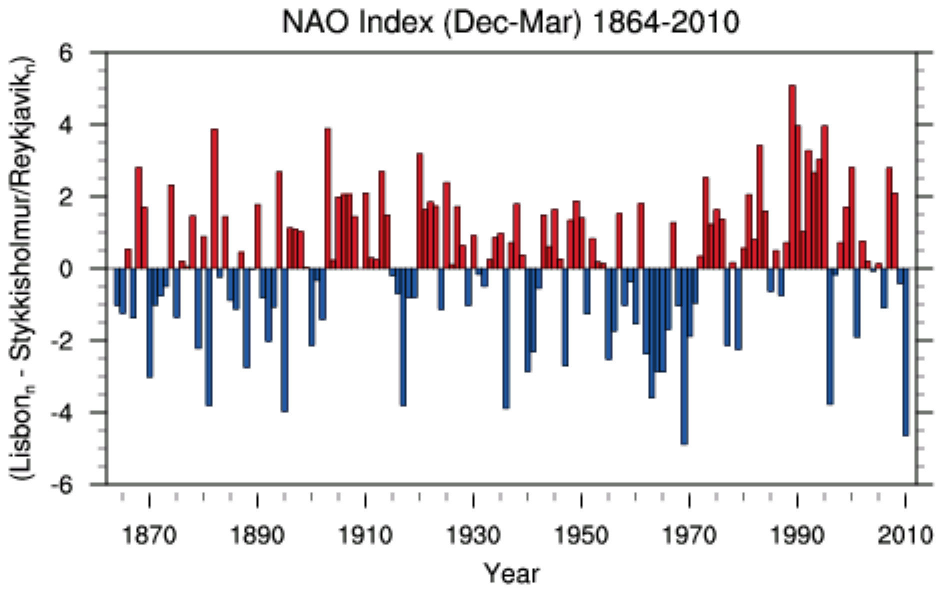
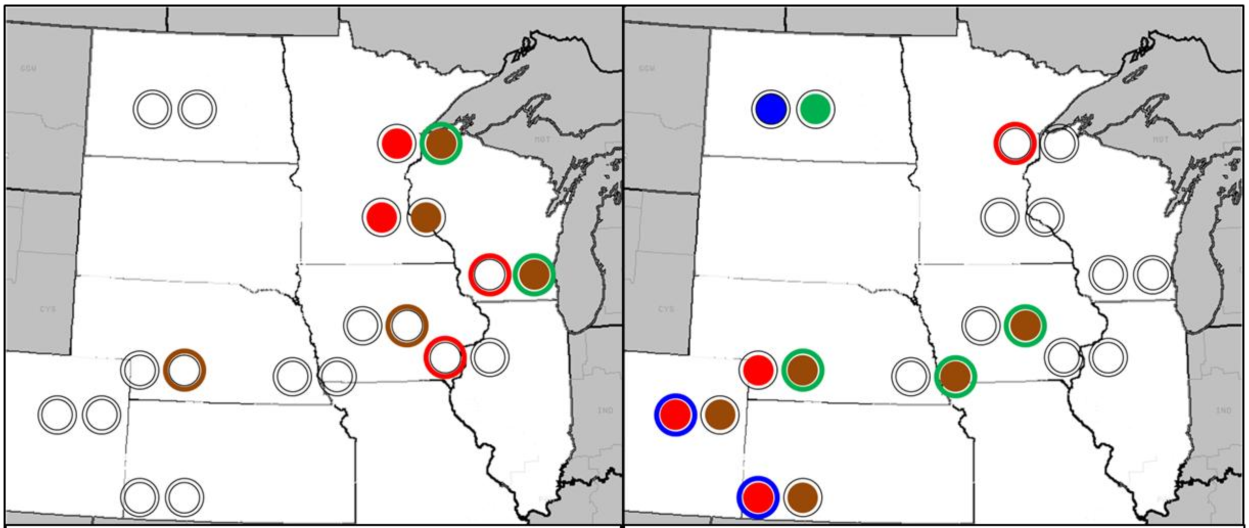


Figure 3. NAO index for December through March from 1864-2010, as determined by the sea level pressure difference between Lisbon, Portugal, and Stykkisholmur/Reykjavik, Iceland. Positive NAO phases are shaded red, and negative NAO phases are shaded blue. Available online at http://www.cgd.ucar.edu/cas/jhurrell/nao.stat.winter.html

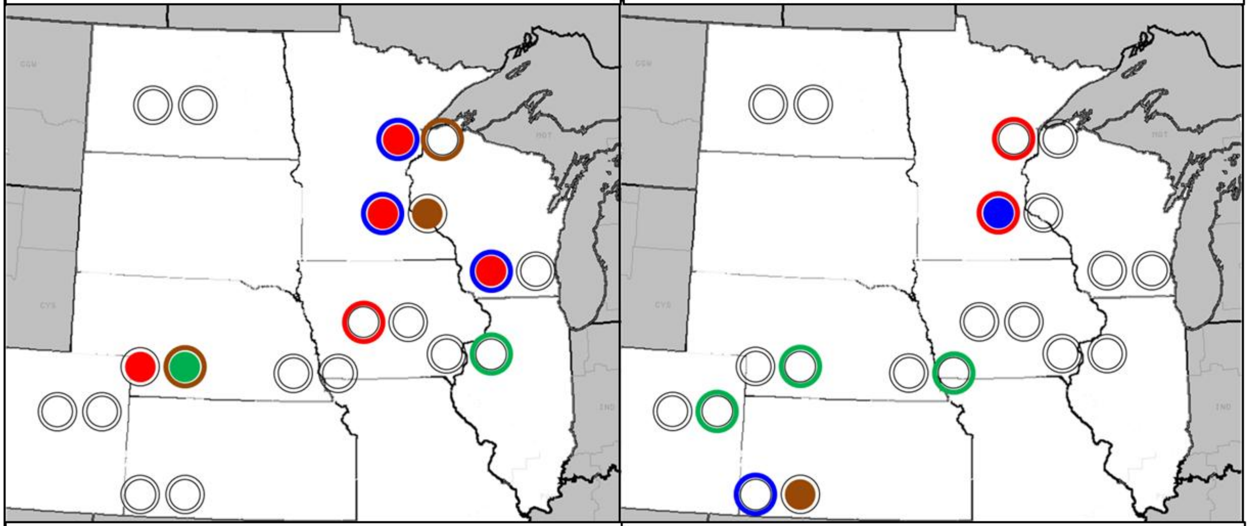
	ENSO +	**ENSO N**	**ENSO -**
NAO +	1896, 1897, 1903, 1905, 1906, 1914, 1920, 1930, 1952, 1973, 1980, 1983, 1988, 1992, 1995, 1998, 2007	1882, 1884, 1898, 1907, 1908, 1913, 1922, 1927, 1928, 1935, 1937, 1944, 1948, 1949, 1957, 1961, 1967, 1981, 1982, 1984, 1986, 1990, 1991, 1993, 1994, 2002	1880, 1890, 1894, 1910, 1921, 1923, 1925, 1934, 1938, 1943, 1945, 1950, 1974, 1975, 1976, 1989, 1999, 2000, 2008
NAO N	1889, 1912, 1915, 1926, 1931, 1953, 1954, 1959, 1978, 2003, 2005	1883, 1899, 1901, 1933, 1946, 1997, 2004	1887, 1904, 1909, 1911, 1939, 1972, 2009
NAO -	1881, 1885, 1888, 1900, 1919, 1924, 1940, 1941, 1942, 1958, 1964, 1966, 1969, 1970, 1977, 1987, 2010	1879, 1886, 1891, 1892, 1895, 1902, 1929, 1936, 1947, 1960, 1962, 1979	1893, 1916, 1917, 1918, 1932, 1951, 1955, 1956, 1963, 1965, 1968, 1971, 1985, 1996, 2001, 2006

Table 1. Categorization of each year from 1879-2010 by both ENSO phase and NAO index. Underlined years are those in which the ENSO phase was neutral during either the DJF or JFM season and was of the categorized ENSO phase during the other season.



a. ENSO +, 1879-1944

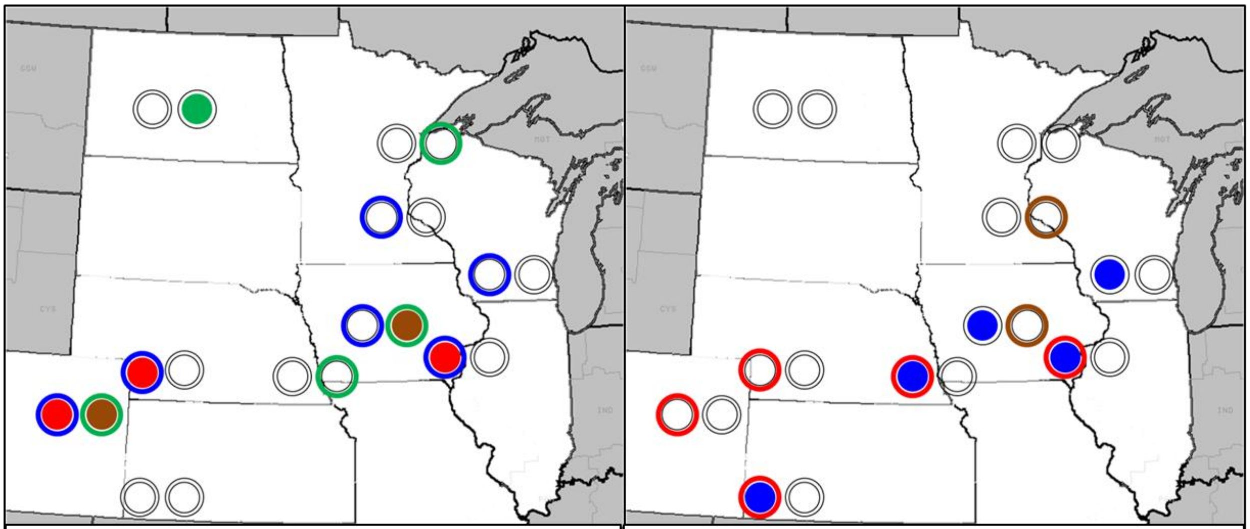
b. ENSO -, 1879-1944



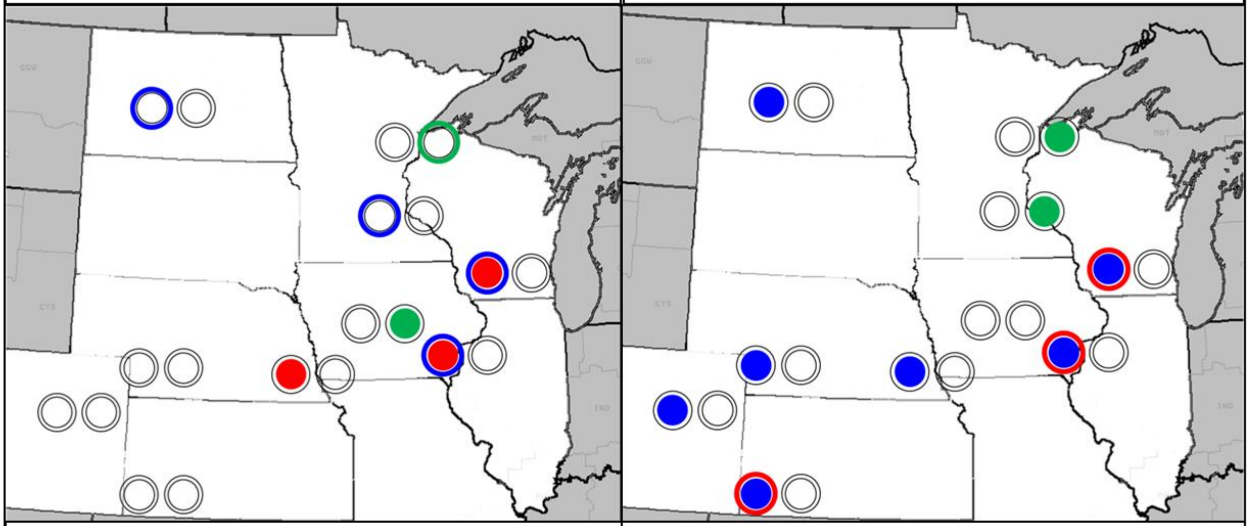
c. ENSO +, 1945-2010

d. ENSO -, 1945-2010

Figure 4. Temperature and precipitation tendencies during positive and negative ENSO phases for historical and modern periods. Filled-in circles represent a significantly higher tendency, while empty circles represent a significantly lower tendency. Blue indicates cold, red indicates warm, brown indicates dry, and green indicates wet. (For example, a solid blue circle surrounded by a red ring indicates both a signal toward suppressed potential for above normal temperatures and heightened potential for below normal temperatures.)

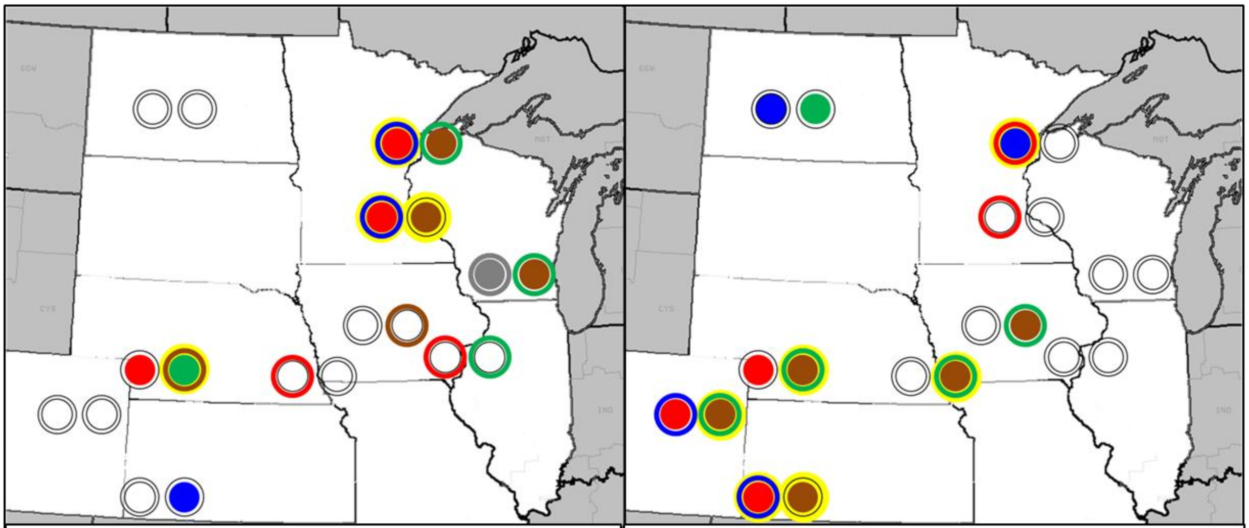


a. NAO +, 1879-1944 **b. NAO -, 1879-1944**



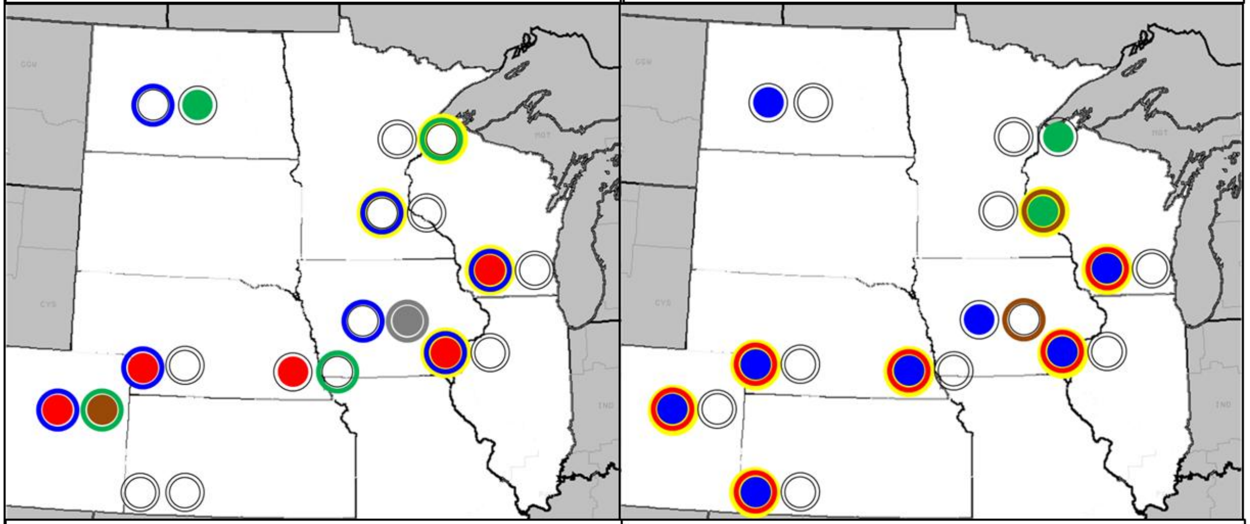
c. NAO +, 1945-2010 **d. NAO -, 1945-2010**

Figure 5. As in Figure 4, but for NAO.



a. ENSO +, 1879-2010

b. ENSO -, 1879-2010



c. NAO +, 1879-2010

d. NAO -, 1879-2010

Figure 6. Temperature and precipitation tendencies during positive and negative ENSO and NAO phases for the combined historical and modern periods. In addition to color coding noted in Figure 4, gray circles indicate conflicting signals between periods. Yellow highlighting indicates sites with consistent signals in both periods.

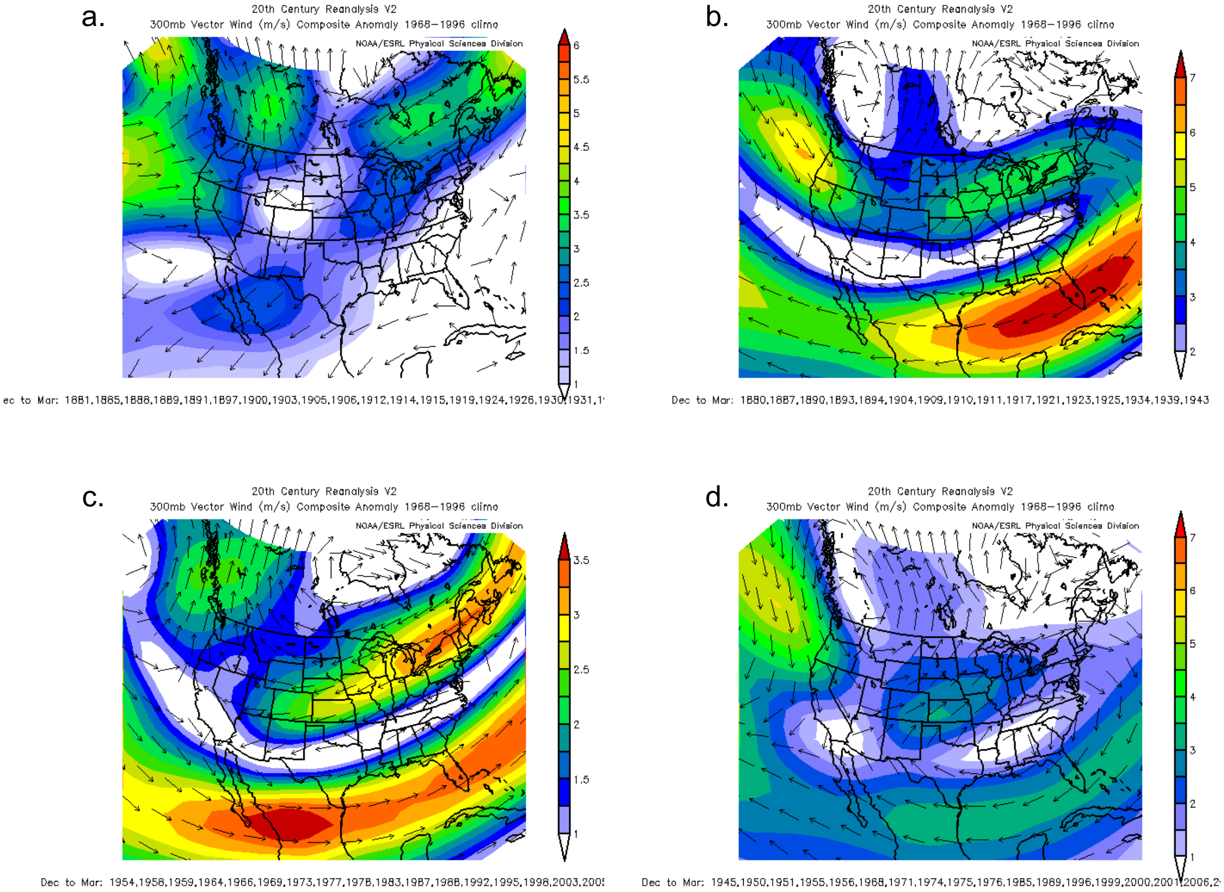


Figure 7. 300 hPa vector wind anomalies, relative to a 1968-2006 base period, for (a) historical El Niño, (b) historical La Niña, (c) modern El Niño, and (d) modern La Niña.

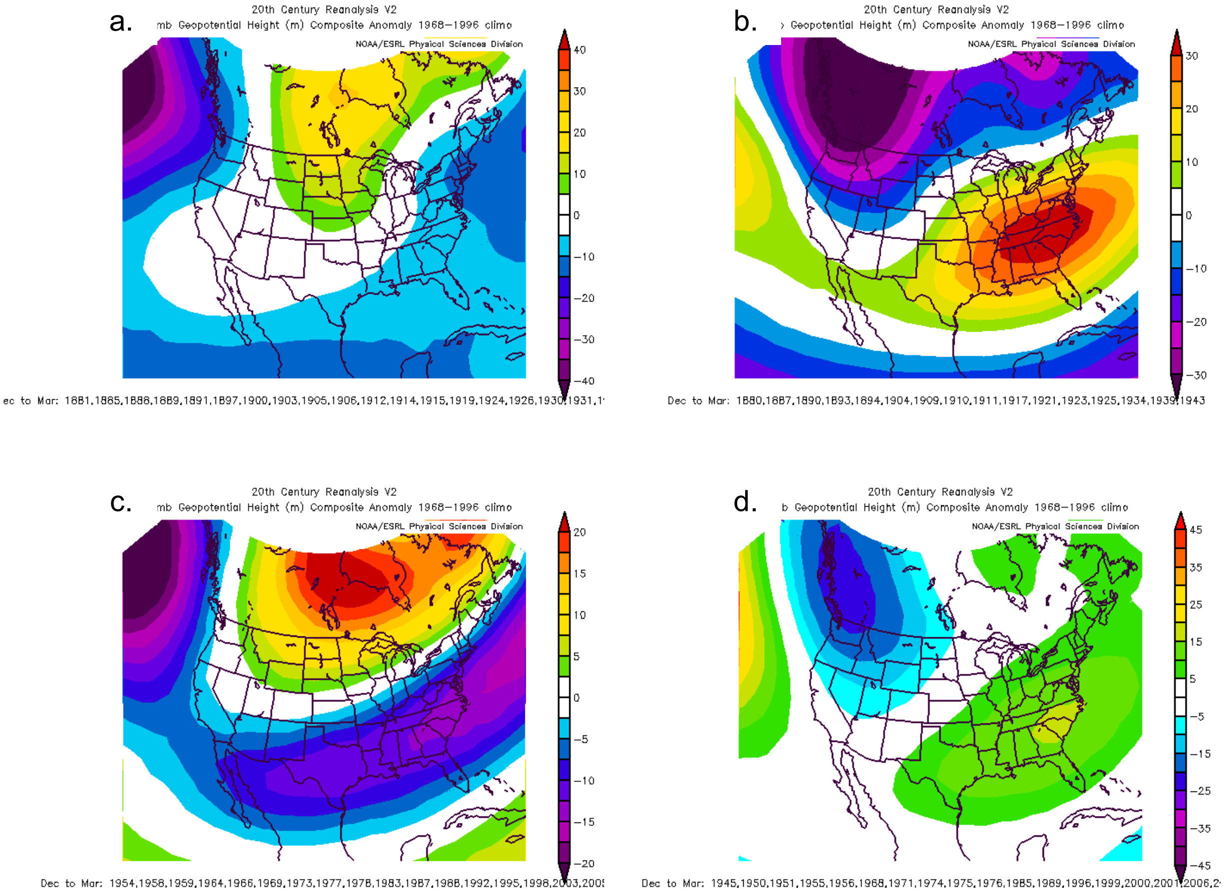


Figure 8. As in figure 7, but for 500 hPa geopotential height anomalies.

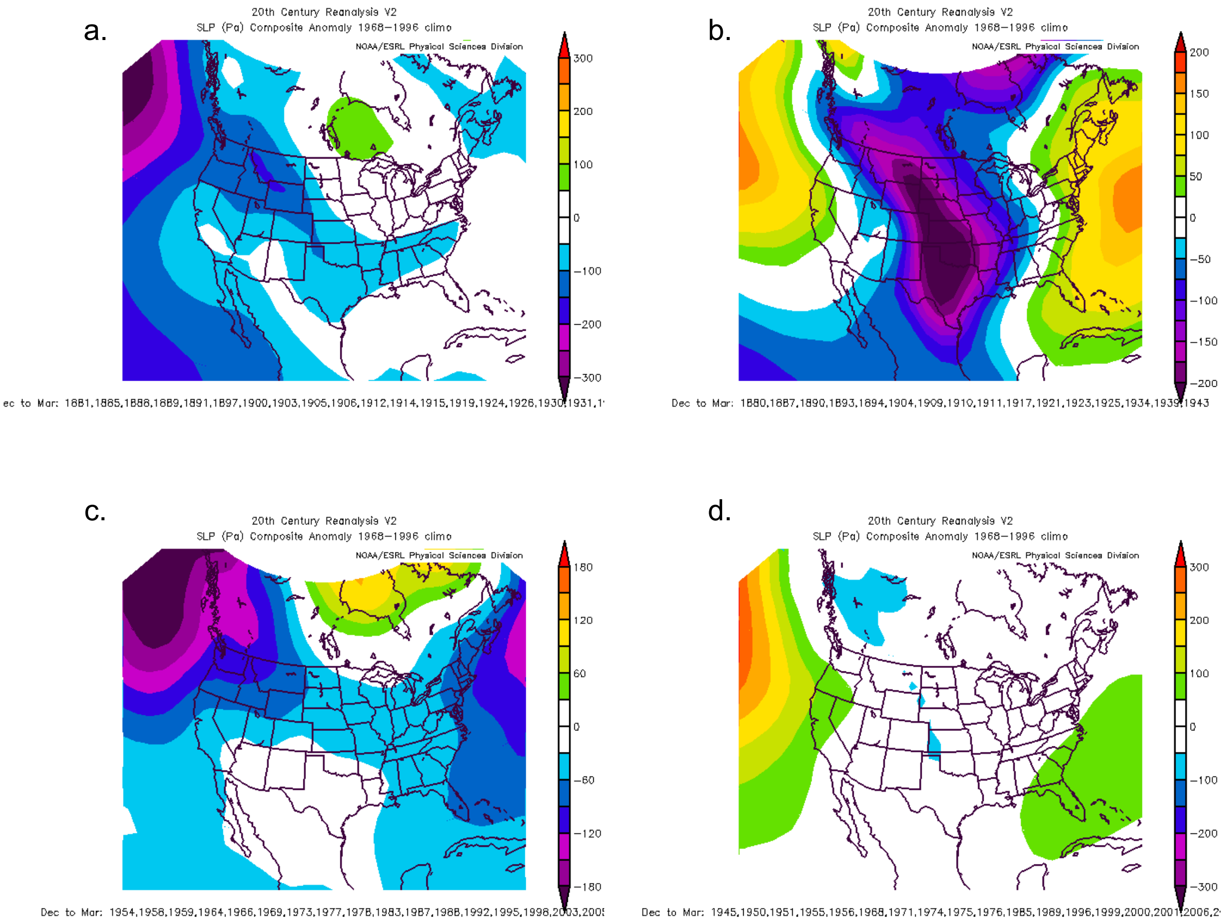


Figure 9. As in figure 7, but for sea level pressure anomalies.

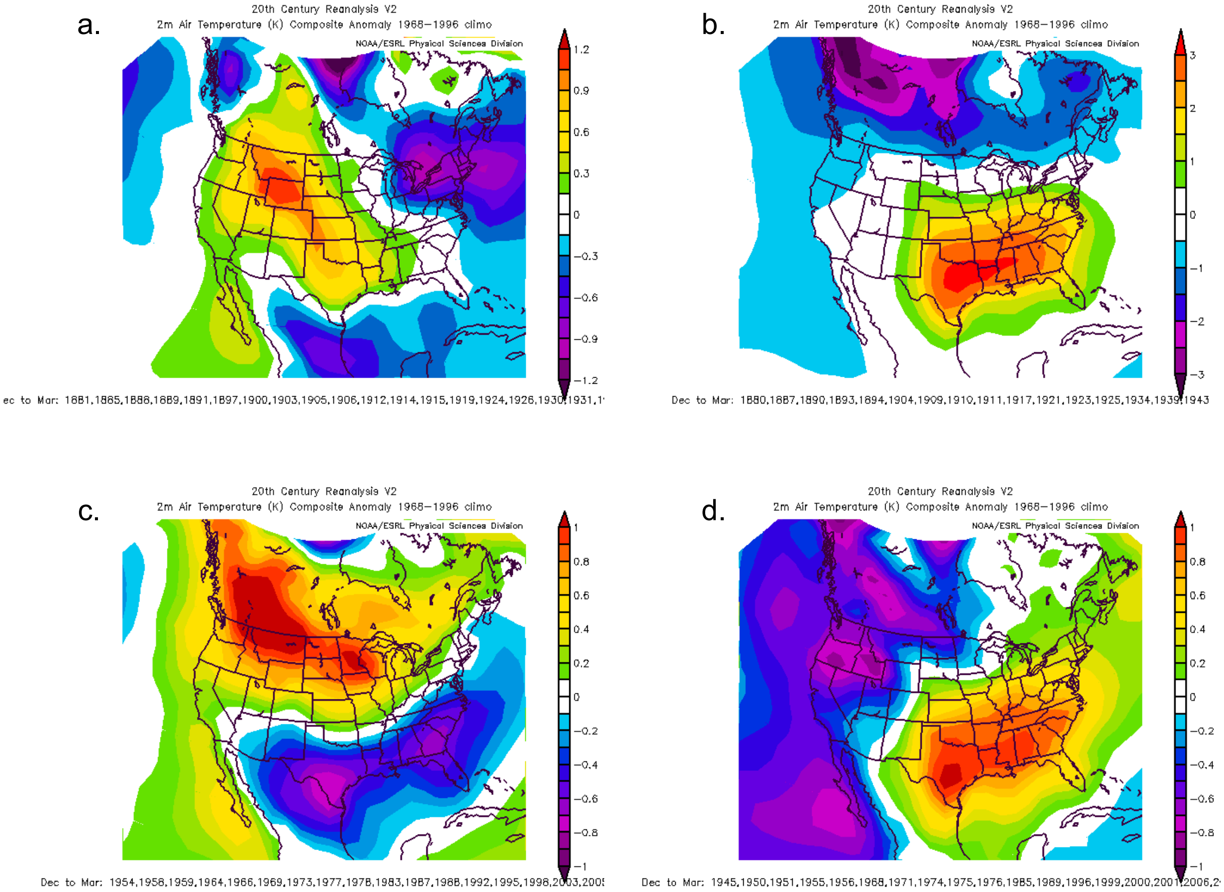


Figure 10. As in figure 7, but for 2 m temperature anomalies.