Temporal and Spatial Patterns of Hydroclimate Variability Related to the Pacific Decadal Oscillation in Michigan, USA

Todd Grote – Geosciences Program, School of Natural Sciences, Indiana University Southeast, New Albany, IN 47150; tdgrote@ius.edu
https://orcid.org/0000-0002-9824-6345

Zachary Suriano – Department of Earth, Environmental, and Atmospheric Sciences, Western Kentucky University, Bowling Green, KY 42101; zachary.suriano@wku.edu
https://orcid.org/0000-0001-7574-0191

Abstract

Teleconnections play an influential role in driving atmospheric circulation and hydroclimatic variability at regional and global scales. While hydroclimatic conditions are associated with the Pacific Decadal Oscillation (PDO) throughout North America, to date there has been limited study on the influence of the PDO on the hydroclimate of Michigan. Using statistical analyses, this study quantified the mean monthly streamflow, precipitation and temperature characteristics in climate divisions and selected stream gage stations in both the Upper and Lower Peninsulas of Michigan during the warm (+) and cool (-) phases of the PDO from 1967-2018. Streamflow is greater statewide during PDO+ phases compared to during PDO- phases, and most prominent from August through February. During the peak month of streamflow difference by PDO phase, November, there was a streamflow increase of nearly 26% during PDO+ phases compared to the long-term mean. Related, mean monthly precipitation increased (decreased) statewide from August through November during PDO+ (PDO-) phases, with decreased (increased) monthly precipitation from December through July. This study advances our understanding of the PDO's influence on hydroclimatic variability in Michigan, presenting novel results at intra-seasonal scales in this highly impactful and populated region.

Keywords: precipitation variability, streamflow variability, hydrology, hydroclimatology, Pacific Decadal Oscillation

This is an Accepted Manuscript version of the following article, accepted for publication in Physical Geography. Grote, Todd, and Zachary Suriano. 2024. "Temporal and Spatial Patterns of Hydroclimate Variability Related to the Pacific Decadal Oscillation in Michigan, USA." Physical Geography, April 26, 2023. doi:10.1080/02723646.2024.2315642. It is deposited under the terms of the Creative Commons Attribution-NonCommercial License (http://creativecommons.org/ licenses/by-nc/4.0/), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited."

Introduction

Ocean-atmosphere teleconnections play an influential role in driving atmospheric circulation patterns, thus in-turn surface weather systems, and hydroclimatic variability at regional and global scales. In North America, the Pacific Decadal Oscillation (PDO) is noted as a key forcing mechanism of hydroclimatological processes at regional scales, and has been the focus of much research. The PDO is a prominent mode of sea-surface temperature (SST) variability in the North Pacific Ocean that is often described in the context of the El Nino/Southern Oscillation (ENSO) due to their similar regional climate signatures. The PDO is characterized by having “warm” and “cool” phases that typically persist for 20-30 years compared to the typical ENSO phase length of 6-18 months (Mantua et al., 1997; Mantua and Hare, 2002; Neal et al., 2002). During the PDO warm phase, corresponding to positive values of the PDO index (PDO+), a pool of anomalously cool SSTs is observed in the central North Pacific, with anomalously warm SSTs along the west coast of North America. Anomalously low sea-level pressures are observed in the Aleutian Islands and across much of the North Pacific during warm PDO phases (Mantau et al., 1997). The cold PDO phase, with negative index values (PDO-), occurs during the opposite configurations, with warm SSTs in the central North Pacific and cool SSTs along the western North American coast. Recent research has revised this definition and indicated the PDO is not a single mode of climatic variability, but rather the embodiment of three separate processes related to ENSO manifestation in the Aleutian low, oceanic thermal inertia, and the Kuroshio-Oyashio system (Schneider & Cornuelle, 2005; Newman et al., 2016).

In North America, research on the hydroclimatic influences of the PDO include drought and soil moisture variability (McCabe et al., 2004; Tang et al., 2014; Assani et al., 2016a;

O'Mara et al., 2019; Suriano et al., 2020a), seasonal air temperature (Budikova, 2005; Birk et al., 2010; Whitfield et al., 2010), snow cover and snowpack dynamics (Sobolwski & Frei, 2007; Ge & Gong, 2009; Mudryk et al., 2014; Tamaddun et al., 2017; Welsh et al., 2019), snowfall totals and frequency (Hunter et al. 2006; Whitfield et al., 2010; Hartmann 2012; Kluver & Leathers, 2015a; Kluver & Leathers, 2015b; Suriano & Leathers, 2017a; Eck et al., 2019), precipitation and streamflow variability (Hamlet & Lettenmaier, 1999; Nigam et al., 1999; Neal et al., 2002; Tootle et al., 2005; Hodgkins, 2009; Hu & Huang, 2009; Khaliq et al., 2009; Whitfield et al., 2010; Giovannettone, 2021; Singh et al., 2021), and water levels of the Great Lakes (Ghanbari & Bravo, 2008; Assani et al., 2016a & b; Saber et al., 2023), among others. Most studies concerning the role of the PDO on the hydroclimatology of the United States have focused their efforts on western North America (United States and Canada), yet others indicate the PDO has a substantial influence on the hydroclimate of eastern North America, and the central U.S. specifically. While these efforts in the central U.S. document hydroclimatic conditions associated with the PDO, to date there has been little research into the role of the PDO on monthly streamflow, precipitation and temperature (i.e., hydroclimate) within Michigan specifically. Michigan represents a relatively unique environment, as expanded on below, with substantial hydroclimatic variability that warrants individualized study. To fill this gap, this paper explores temporal and spatial patterns revealing impacts of the PDO on monthly hydroclimate variability throughout the state, including streamflow, precipitation and temperature.

Michigan's Climate

Michigan lies within the heart of the Great Lakes Region and can be separated geographically into the Upper Peninsula and Lower Peninsula (UP and LP, respectively; Figure

1), each with distinctive land use-land cover mosaics (Harmon, 2009; Welsh et al., 2009). The influence of weather systems on Michigan's hydroclimatology is reflected by the position of longwave ridges and troughs across the continent, as well as the various air masses with differing origins that pass over the state (Isard et al., 2000; Shadbolt et al., 2006; Andresen & Winkler, 2009). Each system and air mass type can uniquely influence the spatiotemporal variability of streamflow and flooding potential through their impact on precipitation and air temperature. For example, mid-latitude cyclones originating on the leeside (east) of the Rocky Mountains near Alberta (Northwestern Canada) tend to be cold and in the Great Lakes region only produce light to moderate precipitation, because they are disconnected from moisture advection from the Gulf of Mexico. However, Alberta-born mid-latitude cyclones can produce heavy snowfalls due to lake effect airmass humidification from passage over the Great Lakes if they are not frozen over (ice covered) (Andresen & Winkler, 2009). In comparison, weather systems that originate to the lee of the Rocky Mountains in Colorado or in the southeast US tend to be warmer and humid, ingredients that may lead to heavy precipitation due to their ability to tap into moisture from the Gulf of Mexico (Isard et al., 2000; Andresen & Winkler, 2009).

Associated with the interannual frequencies of these common weather conditions, annual precipitation is greatest in the southwest LP with at least 95 cm/yr, while the least amount of precipitation is observed in the northeastern LP and extreme eastern UP, averaging 74-79 cm/yr (Table 1; Andresen & Winkler, 2009). Within the Great Lakes Basin as a whole, June through September are the wettest months (Johnston & Shmagin, 2008). Particularly to the lee of Lake Michigan and Lake Superior, a large proportion of annual precipitation is due to snowfall. The northern UP and the northwestern portion of the LP can receive greater than 550 cm of snowfall per year and is in stark contrast to the southeastern LP that generally receives approximately 90 cm of snow, on average (Table 1; Andresen & Winkler, 2009). The disparity in seasonal snowfall totals is greatly influenced by lake effect events that can deliver heavy snowfall (Scott & Huff, 1996; Andresen & Winkler, 2009). Braham and Dungey (1984) suggested that lake effect snow events may account for as much as 25-50% of the seasonal snowfall in western Michigan. Scott and Huff (1996) estimate that as much as 100% more precipitation falls downwind of Lake Superior during the winter than if the lake did not exist.

Michigan's Land Use-Land Cover (LULC)

The landscape of Michigan that we see is a direct result of Pleistocene glaciation and post-glacial erosional and depositional processes (Blewett et al., 2009). The geography of Michigan's soils is intimately linked to the glacial and bedrock geology of the state. Generally speaking, the southern portion of the LP is dominated by highly fertile Alfisols, whereas the northern LP and much of the UP are dominated by low quality, sandy Spodosols. In the southwestern portion of the LP, sandy, but highly-fertile Mollisols are common in areas of former tallgrass prairie (Schaetzl, 2009). Prior to Euro-American settlement, Michigan was primarily forest, estimated at approximately 96% (Dickmann, 2009), however settlement led to extensive land clearance and disturbance with the greatest impacts occurring in Michigan's LP where much of the landscape was transformed into agricultural fields. Widespread transformation of the southern LP from forest and prairie to agricultural land occurred between 1815 and 1860 (Lewis, 2009), influenced by the generally fertile soils of the region (Harman, 2009; Schaetzl, 2009). In the northern LP and UP, logging and mining severely altered the landscape (Dickmann, 2009; Harman, 2009; Welsh et al., 2009). Today, Michigan contains a patchwork of LULC from the mostly forested UP to extensive urbanization of the Detroit Metro

Area in the southeast. Nearly all water bodies within the state (e.g. streams, lakes, wetlands) have been impacted by human disturbance, with much of the impact occurring the LP (Table 2; Dahl, 1990; Comer, 2003; Wolfson, 2009; Harman, 2009).

The current LULC patterning of the state reflects socioeconomic conditions, underlying geology and soils of an area, historic LULC patterns and distribution of natural resources (Welsh et al., 2009). Forests now cover slightly more than half of the state with every county in the UP being > 75% forested or forested wetlands (Table 1; Dickmann, 2009). In contrast, the percentage forest cover in the LP ranges from > 75% in the northern counties to < 20% in some of the central and southern counties (Dickmann, 2009). A considerable amount of public land exists in the northern LP and throughout much of the UP due to the poor-quality soils (e.g. sandy Entisols) that blanket the landscape and create only marginal lands for agriculture or development, coupled with economic depression and droughts of the 1930s (Welsh et al., 2009).

Methodology

The USGS-HCDN consists of gaging stations with upstream drainage areas that are thought to be relatively free of anthropogenic disturbance (unimpaired) and therefore useful in climatological studies (Slack and Landwher, 1992; Lins, 2012). The USGS-HCDN 2009 database is part of the US Geological Survey (USGS) GAGES II database (Falcone, 2011). Using the GAGES II database, 12 streams specifically categorized as “Reference Streams” were selected for study, as they are thought to have only minimal human disturbance and little land cover change over the period of streamflow record, and also contain at least 20 years of continuous records with very few to no data gaps (Falcone, 2011). Several streams listed as Reference Streams were not used due to a short period of record, a fragmented streamflow record or the gage has been discontinued. Seven of the 12 selected stream gages are located in the extensively forested UP and 5 of the gages are located in the LP, primarily in the western half of the state (Figure 1) that frequently experiences lake effect snows (Meng & Ma, 2021). Monthly mean streamflow data were obtained from the USGS National Water Information System website (https://waterdata.usgs.gov) for each of the 12 selected gages over a period 1967-2018. While data exists for some gages before and after this period, the 52-year period was selected to balance maximizing the inclusion of as many gages as possible. Basin and gage attributes listed in the GAGES II database are shown in Table 1, along with average precipitation, snowfall percentage and temperature data obtained from Falcone (2011). LULC information as of 2009 for the stream basins are shown in Supplemental Table 1.

State Climate Division monthly total precipitation and mean temperature data were additionally obtained from the NOAA National Centers for Environmental Information website (Vose et al. 2014; https://www.ncdc.noaa/gov/) for the 52-year study period to match available streamflow data. Michigan consists of 10 climate divisions, with divisions 1 and 2 covering the UP, and divisions 3-10 covering the LP (Figure 1).

The long-term PDO dataset was obtained from the NOAA Physical Sciences Laboratory (https://www.psl.noaa.gov/data/climateindices/) and separated into PDO+ (warm) and PDO- (cool) phases respectively based on existing literature (Neal et al, 2002; Hodgkins, 2009; among others). PDO- phases were defined as 1967-1976 and 1999-2013, and PDO+ phases were defined as 1977-1998 and 2014-2018.

The monthly mean streamflow, precipitation and temperature datasets were linearly detrended to remove any potential long-term linear trends with time, and then binned into categories of PDO+ and PDO- phases based on the corresponding years noted above. To determine if the environmental variables (streamflow, precipitation and temperature) differed between PDO phases, a t-test was performed for each climate division and gaging station by month, as has been done in numerous other studies (e.g., Neal et al., 2002; Coleman & Rogers, 2003; Rogers & Coleman, 2004; Budikova, 2005). Statistical significance was based on an alpha value of 0.05. For environmental variables with significant differences by PDO phase, descriptive statistics are presented. In conducting the t-tests, Levene's test for equality (Levene 1960) was performed for each pairing of variable by PDO phase, where if Levene's Equality is statistically significant, the assumption of equal variances is violated and statistical significance of the t-test is based on calculations where equal variances are not assumed. In nearly all cases, and in all cases were t-tests yielded significant results, Levene's test resulted in equal variances in streamflow and precipitation monthly values being assumed. All statistical tests were conducted in IMB's SPSS software (v28.0).

Results

During PDO+ (PDO-) phases, the best temporally cohesive statewide signals are observed as increased (decreased) mean monthly streamflow from August through February, and increased (decreased) mean monthly precipitation from August through November (Figures 2 & 3). Mean monthly temperature was not found to exhibit statistically significant differences within any of the ten climate divisions by PDO phase (Supplemental Figure 1), and thus is not further discussed within the results.

Temporal and Spatial Patterns of Streamflow Variability

In general, streamflow is greater statewide during PDO+ phases compared to during PDO- phases (Figure 2; Table 2). This signal is most consistent from August through February (late summer through winter), with November being the peak month of differences between streamflow by PDO phase. Streamflow in November is significantly different, and larger, during PDO+ phases compared to PDO- phases for nearly the entire state (Table 2). Enhanced streamflow compared to the long-term mean in November during PDO+ phases ranges from over 177 cms in the Ford River to 6.3 cms in Augusta Creek, but are relative to baseline monthly streamflow of the respective streams (Figure 2). Represented as a percentage of average November streamflow, per station, the significant enhancements in streamflow during PDO+ phases, relative to PDO- phases, ranged between approximately 50% for Ford River and Trap Rock River, to just 1.5% for the Manistee River. In meteorological winter, significant streamflow differences by PDO phase are observed in three of the five LP streams with greater streamflow during PDO+ phases compared to PDO- phases, most prominently in December (Table 2; Figure 2).

In the UP, there are no significant differences observed between streamflow during PDO+ and PDO+ phases from March through July. However, within the LP, the enhanced streamflow signal during PDO+ phases compared PDO- phases continues into the meteorological spring months, including with the Sturgeon River (LP) were a March and April average 30.7 cms more streamflow is observed during PDO+ phases (Table 2), corresponding to approximately 11.2% of average streamflow.

Temporal and Spatial Patterns of Precipitation Variability

During PDO+ (PDO-) phases, increased (decreased) monthly precipitation occurs statewide from August through November, with decreased (increased) precipitation from December through July (Figure 3). During this 4-month period, climate divisions across the state average approximately 51.8 mm (SD: 71.6 mm) more precipitation during PDO+ phases than PDO- phases. This additional precipitation is approximately 16% of average August – November precipitation, but ranges between 9.3% in climate division 2 and 23.2% in climate division 7. Significant differences in precipitation by PDO phase were primarily observed in the late summer and early autumn months (Table 3). Mean August precipitation was significantly greater during PDO+ phases compared to PDO- phases for three climate divisions in the northeast LP and western UP, as was mean September precipitation in the central LP (Table 3). During Meteorological winter (December through February) and spring (March through May), precipitation is typically below (above) average during PDO+ (PDO-) phases, with approximately 12.9 mm less precipitation in southeast MI climate divisions in December, 10.6 mm less in the eastern UP in February, and some 41.9 mm less precipitation in central LP in May (Table 3; Figure 3).

During meteorological winter, a dipole signal in precipitation is apparent between PDO phases and with respect to the UP and northwestern LP lake-effect regions (Figure 3; Table 3). Particularly in December, outside of the primary lake-effect regions of both the UP and LP (climate divisions 4-10), below (above) average monthly precipitation is observed during PDO+ (PDO-) phases, including in the southeast climate divisions in December where approximately 12.9 mm less precipitation is observed during PDO+ phases. Within the main lake-effect regions (climate divisions 1-3), however, the relationships between PDO phase and monthly precipitation are not consistent throughout the winter months (Figure 3). In December, above (below) average precipitation is observed in the lake-effect regions during PDO+ (PDO-) phases. In February, the opposite is observed where below (above) average precipitation is observed during PDO+ (PDO-) phases, matching the rest of the state. Within climate division 2 of the UP specifically, precipitation is significantly greater in February during PDO- phases compared to PDO+, with approximately 10.6 mm more precipitation on average (Table 3). During late spring and early summer, precipitation is significantly less during PDO+ phases in the central and northeastern LP, meteorological spring, including some 20-23 mm less precipitation in central LP in May during PDO+ phases (Table 3).

Discussion

PDO Forcings of Streamflow and Precipitation Variability

Groundwater within Michigan and the broader Great Lakes region at large generates the majority of streamflow, accounting for approximately 70% of flow (Neff and Nicholas 2005). Exploring a sub-region of the UP, Kolka et al. (2010) concluded groundwater contribution to streamflow ranged from approximately 70% in June, to nearly 100% in August. This indicates groundwater recharge is an important process in understanding streamflow variations and external forcings in the region (Costa et al. 2021). Below, we discuss how the PDO, and other physical mechanisms, influence streamflow and groundwater recharge in the context of our results.

Previous research has established a link between the PDO and streamflow throughout the Great Lakes region, including Michigan (e.g., Barlow et al., 2001; Tootle et al., 2005), however neither of these studies took a monthly time-step approach as was performed here. Tootle et al. (2005) for example, utilized a long lead-time approach, with forecasting potential, to suggest that ocean-atmosphere teleconnections from the previous year may be a useful forecasting tool for the current streamflow year (annual water year). By analyzing the hydroclimatology at a monthly time scale, new insights can be gleaned.

From late summer into autumn, increased (decreased) streamflow appears to be responding, at least in part, to increased (decreased) precipitation during PDO+ (PDO-) years. This additional input of precipitation would logically increase the magnitude of runoff generated at the time of precipitation, as noted here in both the UP and the LP. For example, climate division 1 in the UP observed significantly enhanced precipitation during PDO+ phases during August, and in-turn roughly half of the streams in the UP observed enhanced streamflow during PDO+ phases. However, there are multiple climate divisions during this late summer to autumn period where enhanced streamflow is observed yet significant increases in precipitation are not. In these cases, it is suspected that enhanced streamflow is partially attributed to (a) the anomalously high, but not statistically significant, precipitation received during PDO+ phases and (b) the increase in groundwater recharge that occurred in the previous month(s) during enhanced precipitation. For much of the LP, approximately 20-25 mm of additional precipitation is received, on average, during PDO+ phases compared to PDO- phases, where results of the t-tests indicate alpha levels below 0.1. This cannot only directly increase streamflow through runoff, but through increases infiltration and groundwater recharge (e.g., Brouwer 2008) that then manifest as enhanced, but lagged, streamflow. This lagged response between enhanced precipitation and enhanced streamflow in late summer and early autumn during PDO+ phases is widely apparent in the UP and may be associated with the high percentage of wetlands in this region. A higher percentage of wetlands in the UP (see Supplemental Table 1) would slow the movement of water through the hydrologic system (e.g., Acreman and Holden, 2013), resulting in a delayed signal between precipitation, subsequent groundwater recharge, and an enhanced streamflow signal.

Additional research in the broader Great Lakes region has explored other hydroclimatological linkages with the PDO. Barlow et al. (2001) evaluated the role of various teleconnections on drought and moisture conditions across North America. They found the PDO was significantly associated with drought in the eastern Great Lakes and Northeast US regions, particularly during the 1960s drought of record (Barlow et al., 2001). The same physical mechanism was detected on the opposite end of the drought-excessive moisture spectrum by Assani et al. (2016a), where extreme wetness indices were positively correlated with the PDO in more northerly Great Lakes regions near the UP of Michigan, including during autumn. This is apparent within the autumn precipitation and streamflow results here, where PDO+ (PDO-) years experienced above (below) normal precipitation and streamflow totals. This is often attributed to variations in cyclone development at the end of the warm season and differences in moisture source regions. Recent research by Yang et al. (2023) indicates enhanced precipitation observed in summer is associated primarily with moisture originating in the Great Plains via enhanced low-level jets, compared to precipitation driven primarily by Great Lakes moisture in autumn via evapotranspiration recycling.

Examining cyclone activity in Canada, Wang et al. (2006) observes a dipole signal in the correlations of cyclone deepening rates and the PDO in southern Ontario along Lakes Erie, Huron and Superior between autumn and winter seasons. During autumn, a positive (negative) correlation between cyclone deepening and the PDO is present, where more (less) cyclones and thus more (less) precipitation is observed during PDO+ (PDO-) (Wang et al., 2006). The opposite is observed in winter, with negative correlations between cyclone deepening and the

PDO. While cyclone deepening is not a direct parallel to precipitation rates, they are logically associated; stronger cyclones typically result in heavier and/or more widespread precipitation.

Through the winter months, and in most cases including March, streamflow remains significantly above (below) average during PDO+ (PDO-), particularly in the LP. Here, precipitation enhancements from the PDO do not appear to be a primary driver of this increase, with the climate divisions in the LP not observing significantly differences in precipitation between PDO phases or observing significant decreases in precipitation during PDO+ phases in December such as in the southeast LP. Instead, the higher streamflow values during meteorological winter and early spring are likely a combination of snowmelt, groundwater contributions, and potential phase change (e.g., solid to liquid or vice versa) of precipitation.

Throughout the LP, snowmelt is common from December through March, where the snowpack is highly ephemeral, often accumulating and completely ablating multiple times during each cold season (Suriano and Leathers 2017b). Peak snowmelt frequency has been shown to peak in February in the southern LP and in March in the northern LP and UP, but variations in timing exist based on snowmelt magnitude, with larger events typically occurring earlier in the winter months (Suriano and Leathers 2017b). While all snowmelt does not runoff into streams, due to processes such as soil infiltration and evaporation, snowmelt and streamflow are inherently related with more snowmelt yielding more streamflow (e.g., Suriano et al. 2020b; Grote, 2021). Within the Great Lakes region, Ford et al. (2020) indicated that years with less and earlier snowmelt translated to lower and earlier peak flows and decreased net groundwater recharges, particularly in northern portions of the basin. Additionally, Ford et al. (2021) conclude that years with reduced snowpacks, associated with lesser snowfall from warmer atmospheric conditions, correlated with shifting winter streamflow and peak basin yields that were lower and earlier occurring by as much as three days. Yet, during those warmer years, there is increased infiltration and recharge during winter, associated with enhanced freeze/thaw effects (Motiee and McBean 2017) that would result in more streamflow in years with less snow.

The connections between snowfall in the Great Lakes region and the PDO are relatively well explored. Using multiple discriminant analysis, Kluver and Leathers (2015a) documented the phase of the PDO was significantly correlated to seasonal snowfall totals, with a negative correlation in northern Michigan and Wisconsin, inclusive of much of the LP. Using a different approach and examining snowfall event frequency, Kluver and Leathers (2015b) suggests the phase of the PDO is significantly negatively correlated to snowfall frequency in both the UP and LP of Michigan. For both research efforts (Kluver & Leathers. 2015a, 2015b), warm (cool) phased PDO yielded diminished (enhanced) snowfall totals or events. While different methodologies were used between these and our study, a decrease in snowfall when the PDO is positively phased (Kluver and Leathers 2015a,b) coupled with insignificant changes in total precipitation between PDO phases (this study) suggests the ratio of snow to total precipitation may be influenced by the PDO. The authors are not currently aware of a study that has investigated the potential influence of the PDO on this ratio, but observations within the Great Lakes region have indicated increased temperatures can alter these snow-precipitation ratios with warmer conditions yielding more rain in lieu of snow (e.g., Dong et al. 2020), including in the lake-effect belts (Wright et al. 2013; Vavrus et al. 2013).

Speaking specifically to the heavy lake-effect influenced climate divisions (1-3), the inverse signal of increased precipitation in December and decreased in February during PDO+ phases may be associated with lake-ice dynamics. By February, larger proportions of both Lake Michigan and Lake Superior are typically ice covered, inhibiting lake-effect development and reducing snowfall totals. Ghanbari et al. (2009) indicates the PDO is significantly correlated with lake-ice, where highly significant squared coherencies are observed (r = 0.75) between the PDO and ice-off date (Ghanbari & Bravo, 2008; Ghanbari et al., 2009). Wang et al. (2018) found a similar result, suggesting there is more lake-ice during PDO+ phases due to colder air and water temperatures, with less lake-ice during PDO- phases associated with warmer air and water temperatures. Such associations would result in less snowfall (or in general precipitation) later in the winter compared to earlier months during PDO+ years, aligning with our observed precipitation signals here.

During PDO+, a standard atmospheric response resembles that of a positively phased Pacific/North American Pattern (PNA; Leathers & Palecki, 1992), with mid-to-upper-level ridging in the western U.S. and enhanced troughing in the eastern U.S. (Rodionov & Assel, 2003). Such a pattern would favor mid-latitude cyclone formation along the east coast, subjecting Michigan to a more prominent regime of northwest flow, dampening winter precipitation outside of lake-effect regions and resulting in cooler temperatures as observed here. Rodionov and Assel (2003) note that this association is non-linear, as strong El Ninos can modify this pathway and inhibit trough development over the eastern U.S. and result in more mild and often abnormally wet winters in the Great Lakes region. Despite this, the lake-effect/non-lake-effect PDO signal is apparent within our precipitation results.

From April through July, the PDO does not widely influence the hydroclimatology of the state. The primary exception appears to be in the central LP where climate divisions 5 and 6 exhibited significantly lower precipitation in May during PDO+ phases, similar to the general pattern in winter. Likely due to the groundwater and wetland mechanisms noted above, the negative anomalies of precipitation do not appear to have a significant impact on streamflow.

During this April-July period, it is anticipated that other forcing mechanisms play more dominant roles in influencing precipitation and streamflow variability. Prior research has indicated a variety of other teleconnections, such as the North Atlantic Osciallation (NAO), the Pacific-North American Pattern (PNA), and the El Nino Southern Oscillation (ENSO) all influence the hydroclimatolgy of the Great Lakes basin (e.g., Fu and Steinschneider 2019; Saber et al. 2023). This includes the role teleconnections play in forcing the development, passage and frequency of specific synoptic-scale weather systems (e.g., Rohli et al. 2001; Isard et al. 2000; Lofgren and Bieniek 2008), the role of tropical moisture transport influencing precipitation (e.g., Steinschneider and Lall 2016), and the interactions between evapotranspiration and soil-water storage (Dong et al. 2020).

Temperature Variability

While the study did not detect any significant differences in temperature across the state between PDO phases (see supplemental data), broadly, air temperatures are anomalously cool (warm) during PDO+ (PDO-) phases across the state. This broad-scale and statistically insignificant association to the PDO is similar to research conducted in the Great Lakes basin evaluating lake ice cover forcings (Wang et al., 2018), lake water levels (Ghanbari and Bravo 2008), and studies evaluating the influence of the PDO on circulation in North America (Mills and Walsh, 2013).

Mills and Walsh (2013) evaluated surface air temperature anomalies across North America during PDO phases, identifying some of the same month-to-month directional variations in the broader Great Lakes region that were observed here. For most of Michigan, air temperatures during PDO+ phases were cooler than PDO- phases during November, January, and February, and warmer during December. The primary exception was in the extreme western UP where cooler air temperatures occurred in just November and January with warmer temperatures in December and February (Mills & Walsh, 2013). Just as with this study, many of the differences in air temperature by PDO phases were not statistically significant at the 90% confidence level (Mills & Walsh, 2013). The markedly lower impact of the PDO on air temperatures in Michigan detected here is similar to the conclusion drawn by Ghanbari and Bravo (2008) when evaluating the influences of lake water levels in the Great Lakes basin. Air temperature was not one of the variables identified to represent a coherent link between teleconnection indices and Great Lakes hydrology, compared other more hydrologic linkages (Ghanbari & Bravo 2008).

Limitations

While care was taken to ensure equal data coverage between all of the stream gages, hence the use of the 1967-2018 period of maximum overlap, there were a small number of missing monthly data points that result in slightly different sample sizes within the statistical analysis. This was deemed preferrable to using a longer study period that would have potentially captured more variability in the PDO, but would have resulting in each gaging station having a different period of record. For instance, by beginning analysis in 1947, we would have been able to include the entire span of the 1947-1976 PDO- period, but only 5 gaging stations would have had complete records back to this date. Preliminary exploration of varying the study period did not appear to substantially influence the overall conclusions drawn; with the methodological approach selected, there are robust statistical differences between streamflow values during PDO+ and PDO- phases.

Further, there is the potential for variability in the selection of specific years as PDO+ and PDO- phases to influence the results of the study. In line with previous research, we elected to use relatively large multi-year bins of PDO phases for analysis, compared to using short-duration phases (months to year) or filtering PDO phase to only strong signals based on a selected threshold. Particularly in the first 45 years of the PDO record used in this study, phases are well established within the literature (Neal et al, 2002; Hodgkins, 2009). The 2014-2018 period designated here as PDO+ aligns well with the long-term index, with the PDO index averaging + 0.34. With the study's analysis ending here as noted in the methodology, a PDO+ phase designation is warranted. It should be noted however that from 2019 through the present, the PDO has returned to a cool (PDO-) phases, suggesting the 2014-2018 warm period was either a short-duration phase, or an anomalous period within a much larger PDO- phase from 1999-present. We find the former to be sufficient grounds for inclusion as a PDO+ phase period for the purposes of this analysis.

Conclusions

This study advances our understanding of the PDO's influence on hydroclimatic variability in Michigan, presenting novel results at intra-seasonal scales in this highly impactful and populated region. Using statistical analyses, this study quantified the mean monthly streamflow, precipitation and temperature characteristics in climate divisions and stream gage stations in both the Upper and Lower Peninsulas of Michigan during the warm (+) and cool (-) phases of the PDO from 1967-2018. Analyses show that spatiotemporal variability in hydroclimatic features exists at monthly scales and can be differentiated by PDO phase. PDO+ (PDO-) phases produce statewide increased (decreased) streamflow from August through

February. In the peak month of streamflow differences, November, the enhancement of streamflow during PDO+ phases was nearly 26% of the respective long-term mean November flow at individual gaging stations statewide, on average. The streamflow anomalies observed during PDO phases temporally aligning well with precipitation anomalies by PDO phase during the late summer and autumn, and are likely more prominently associated PDO influences on snowmelt and recharged groundwater signals during the winter and spring.

Precipitation was increased (decreased) during PDO+ (PDO-) phases for Michigan from August through November, with regions in central and northeastern Michigan exhibiting the greatest significant differences between phases. This increased (decreased) precipitation would directly contribute to increased (decreased) streamflow within a specific month, but then also increase (decrease) groundwater recharge such that in subsequent months streamflow may continue to be increased (decreased) despite potentially differing precipitation signals. During winter and spring months, prior research has indicated that outside of lake-effect regions, PDO+ phases result in years with reduced snowfall across Michigan and the Great Lakes region (Kluver and Leathers 2015). When coupled with primarily insignificant differences in total precipitation seen here, this suggests the PDO may influence precipitation ratios of snow to rain in the region. More precipitation occurring as rain, instead of snow, as observed in other regions (e.g., Feng and Hu 2007), would directly lead to an increase in winter streamflow, even if total precipitation was neutral given the potential for rain to more easily runoff the land surface compared to snow.

Future research could consider the role of specific atmospheric weather patterns at finer temporal scales to potentially differentiate above or below average streamflow signals by PDO phase from high frequency but low intensity precipitation events, compared to low frequency but high intensity precipitation. This further could consider the role of the PDO in driving variations in snow-to-rain precipitation ratios as a mechanism of varying streamflow observed here.

References

Acreman, M.C., Holden, J. (2013) How wetlands affect floods. *Wetlands* 33: 359-373.

Andresen, J.A., Winkler, J.A. (2009) Weather and Climate. Chapter 19 in Michigan Geography and Geology, R.J. Schaetzl, D. Brandt, and J.T. Darden (eds). Pearson Custom Publishing, Boston, MA. ISBN: 0536987165.

Assani, A.A., Landry, R., Azouaoui, O., Massicotte, P., Gratton, D. (2016a) Comparison of the characteristics (Frequency and Timing) of drought and wetness indices of annual mean water levels in the five North American Great Lakes. *Water Resources Management.* 30(1): 359-373.

Assani, A.A., Azouaoui, O., Pothier-Champagne, A., Quessy, J-F. (2016b) Relationship Between Water Levels in the North American Great Lakes and Climate Indices. Chapter 2 in Lake Sciences and Climate Change, M.N. Rashed (ed.). *IntechOpen*, London, UK. ISBN: 978-953-51-5444-0.

Barlow, M., Nigam, S., Berbery, E.H. (2001) ENSO, Pacific decadal variability, and U.S. summertime precipitation, drought, and streamflow. *Journal of Climate* 14(9): 2105-2128.

Birk, K., Lupo, A.R., Guinan, P., Barbieri, C.E. (2010) The interannual variability of midwestern temperatures and precipitation as related to the ENSO and PDO. *Atmosfera* 23(2) 95-128.

Blewett, W.L., Schaetzl, R.J., Lusch, D.P. (2009) The physical landscape: A glacial legacy, in Schaetzl, R., Darden, J., and Brandt, D. (eds), Michigan Geology and Geography: Pearson Custom Publishing p 249-273

Bornhorst, T.J., Brandt, D. (2009) Michigan's earliest geology: The Precambrian, in Schaetzl, R., Darden, J., and Brandt, D. (eds), Michigan Geology and Geography: Pearson Custom Publishing p 24-39

Braham, R.R., Dungey, M.J. (1984) Quantitative estimates of the effect of Lake Michigan on snowfall. *Journal of Applied Meteorology and Climatology* 23(6) 940-949

Brouwers, M.H. (2008) A case study for assessing the hydrologic impacts of climate change at the watershed scale. Masters Thesis University of Waterloo. Accessed from https://uwspace.uwaterloo.ca/handle/10012/3514?show=full.

Budikova, D. (2005) Impact of the Pacific Decadal Oscillation on relationships between temperature and the Arctic Oscillation in the USA in winter. *Climate Research* 29 199-208

Coleman, J., Rogers, J. (2003) Ohio River valley winter moisture conditions associated with the Pacific-North American teleconnection pattern. *Journal of Climate* 16(6) 969-981.

Comer, P. (2003) Michigan's vegetation circa 1800. Michigan Department of Natural Resources, Michigan Natural Features Inventory, Lansing, MI.

Costa, D., Zhang, H., Levison, J. (2021) Impacts of climate change on groundwater in the Great Lakes basin: A review. *Journal of Great Lakes Research* 47(6): 1613-1625

Dahl, T.E. (1990) Wetland losses in the United States 1780 to 1980s. Us Department of the Interior, US Fish and Wildlife Service, Washington DC.

Dickmann, D.I. (2009) Forests and Forestry from a Historical Perspective. Chapter 40 in Michigan Geography and Geology, R.J. Schaetzl, D. Brandt, and J.T. Darden (eds). Pearson Custom Publishing, Boston, MA. ISBN: 0536987165.

Dong, B., Lenters, J.D., Hu, Q., Kucharik, C.J., Wang, T.J., Soylu, M.E., Mykleby, P.M. (2020) Decadal-scale changes in the seasonal surface water balance of the central United States from 1984-2007. *Journal of Hydrometeorology*. 21(9) 1905-1927.

Eck, M.A., Perry, L.B., Soule, P.T., Sugg, J.W., Miller, D.K. (2019) Winter climate variability in the southern Appalachian Mountains, 1910-2017. *International Journal of Climatology* 39(1) 206-217.

Falcone, J.A. (2011) Geospatial attributes of gages for evaluating streamflow. Available at: https://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml.

Ford, C.M., Kendall, A.D., Hyndman, D.W. (2020) Effects of shifting snowmelt regimes on the hydrology of non-alpine temperate landscapes. *Journal of Hydrology*. 590: 125517.

Ford, C.M., Kendall, A.D., Hyndman, D.W. (2021) Snowpacks decrease and streamflows shift across eastern US as winters warm. *Science of the Total Environment*. 793: 148183.

Fu, W., Steinschneider, S. (2019) A diagnostic-predictive assessment of winter precipitation over the Laurentian Great Lakes: Effects of ENSO and other teleconnections. *Journal of Hydrometeorology* 20(1): 117-137.

Ge, Y., Gong, G. (2009) North American snow depth and climate teleconnection patterns. *Journal of Climate* 22(2): 217-233.

Ghanbari, R.N., Bravo, H.R. (2008) Coherence between atmospheric teleconnections, Great Lakes water levels, and regional climate. *Advances in Water Resources* 31(10): 1284-1298.

Ghanbari, R.N., Bravo, H.R., Magnuson, J.J., Hyzer, W.G., Benson, B.J. (2009) Coherence between lake ice cover, local climate, and teleconnections (Lake Mendota, Wisconsin). *Journal of Hydrology* 374(3-4): 282-293

Giovannettone, J. (2021) Assessing the relationship between low-frequency oscillations of global hydroclimate indices and long-term precipitation throughout the United States. *Journal of Applied Meteorology and Climatology* 60(1): 87-101.

Grote, T. (2021). A synoptic climatology of rain-on-snow flooding in Mid-Atlantic Region using NCEP/NCAR Re-Analysis compositing. Physical Geography v. 42:5, p. 452-471.

Hamlet, A.F., Lettenmaier, D.P. (1999) Columbia River Streamflow Forecasting Based on ENSO and PDO Climate Signals. *Journal of Water Resources Planning and Management* 125: 333-341.

Harman, J.R. (2009) Plant Geography. Chapter 21 in Michigan Geography and Geology, R.J. Schaetzl, D. Brandt, and J.T. Darden (eds). Pearson Custom Publishing, Boston, MA. ISBN: 0536987165.

Hartmann, H. (2012) Neural network based seasonal predictions of lake-effect snowfall. *Atmosphere-Ocean* 50(1) 31-41

Hodgkins, G.A., Dudley, R.W., Aichele, S.S. (2007) Historical changes in precipitation and streamflow in the U.S. Great Lakes Basin, 1915-2004. *National Water Availability and Use Program, USGS*. Report 2007-5118. https://pubs.usgs.gov/sir/2007/5118/pdf/SIR2007-5118.pdf

Hodgkins, G.A. (2009) Streamflow changes in Alaska between the cool phase (1947-1976) and the warm phase (1977-2006) of the Pacific Decadal Oscillation: The influence of glaciers. *Water Resources Research* 45(6) 1-5

Hu, Z.Z., Huang, B.H. (2009) Interferential impact of ENSO and PDO on dry and wet conditions in the US Great Plains. *Journal of Climate* 22(22): 6047-6065.

Hunter, T., Tootle, G., Piechota, T. (2006) Oceanic-atmospheric variability and western US snowfall. *Geophysical Research Letters* 33(13): L13706.

Isard, S.A., Angel, J.R., VanKyke, G.T. (2000) Zones of origin for Great Lakes cyclones in North America, 1899-1996. *Monthly Weather Review* 128(2) 474-485.

Johnston, C.A., Shmagin, B.A. (2008) Regionalization, seasonality, and ternds of streamflow in the US Great lakes basin. *Journal of Hydrology* 362(1) 69-8

Khaliq, M.N., Ouarda, T., Gachon, P. (2009) Identification of temporal trends in annual and seasonal low flows occurring in Canadian rivers: The effect of short- and long- term persistence. *Journal of Hydrology* 369, 183-197.

Kluver, D., Leathers, D.J. (2015a) Winter snowfall prediction in the United States using multiple discriminant analysis. *International Journal of Climatology* 35(8): 2003-2018.

Kluver, D., Leathers, D.J. (2015b) Regionalization of snowfall frequency and trends over the contiguous United States. *International Journal of Climatology* 35: 4348-4358

Kolka, R.K., Giardina, C.P., McClure, J.D., Mayer, A., Jurgensen, M.F. (2010) Partitioning hydrologic contributions to an 'old-growth' riparian area in the Huron Mountains of Michigan, USA. *Ecohydrology* 3(3): 315-324.

Leathers, D.J., Palecki, M.A. (1992) The Pacific/North American teleconnection pattern and United States climate

Levene, H. (1960) *In Contributions to Probability and Statistics*: Essays in Honor of Harold Hotelling. I. Olkin et al. eds. Stanford University Press. pp. 278-292.

Lewis, K.E. (2009) The Settlement Experience. Chapter 27 in Michigan Geography and Geology, R.J. Schaetzl, D. Brandt, and J.T. Darden (eds). Pearson Custom Publishing, Boston, MA. ISBN: 0536987165.

Lins, H. F. (2012) *USGS Hydro-Climatic Data Network 2009 (HCDN–2009)*. Fact Sheet 2012–3047. U.S. Geological Survey, Washington, D. C..

Lofgren, B.M., Bieniek, P. (2008) Large-scale 700 hPa height patterns associated with cyclone passage and strong winds on Lake Erie. *Journal of Great Lakes Research* 34(1): 36-53.

Mantua, N.J., Hare, S.R. (2002) The Pacific Decadal Oscillation. *Journal of Oceanography* 58: 35-44.

Mantau, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., Francis, R.C. (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* 78(6) 1069-1080.

McCabe, G.J., Palecki, M.A., Betancourt, J.L. (2004) Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. *PNAS* 101(12): 4136-4141.

Meng, L., Ma, Y. (2021) On the relationship of lake-effect snowfall and teleconnections in the Lower Peninsula of Michigan, USA. *Journal of Great Lakes Research* 47(1): 134-144

Mills, C.M., Walsh, J.E. (2013) Seasonal variation and spatial patterns of atmospheric component of the Pacific Decadal Oscillation. *Journal of Climate* 26(5) 1575-1594.

Motiee, H, McBean, E. (2017) Assessment of Climate Change Impacts on Groundwater Recharge for Different Soil Types-Guelph Region in Grand River Basin Canada. *ECOPERSIA*, 5 (2): 1731-1744

Mudryk, L.R., Kushner, P.J., Derksen, C. (2014) Interpreting observed northern hemisphere snow trends with large ensembles of climate simulations. *Climate Dynamics* 43(1-2): 345-359.

Neal, E.G., Walter, M.T., Coffeen, C. (2002) Linking the pacific decadal oscillation to seasonal stream discharge patterns in Southeast Alaska. *Journal of Hydrology* 263: 188-197.

Neff, B.P., Nicholas, J.R. (2004) Uncertainty in the Great Lakes water balance: Scientific Investigations Report 2004-5100. US Geological Survey. pp. 42.

Newman, M., Alexander, M.A., Ault, T.R., Cobb, K.M., Deser, C., Di Lorenzo, E., Mantua, N.J., Miller, A.J., Minobe, S., Nakamura, H., Schneider, N., Vimont, D.J., Phillips, A.S., Scott, J.D., Smith, C.A. (2016) The Pacific Decadal Oscillation, Revisited. *Journal of Climate* 29: 4399-4427.

Nigam, S., Barlow, M., Berbery, E.H. (1999) Analysis links Pacific Decadal variability to drought and streamflow in United States. *EOS* 80(51) 1-8

O'Mara, N.A., Cheung, A.H., Kelly, C.S., Sandwick, S., Herbert, T.D., Russell, J.M., Abella-Gutierrez, J., Dee, S.G., Swarzenski, P.W., Herguera, J.C. (2019) Subtropical Pacific Ocean temperature fluctuations in the common era: multidecadal variability and its relationship with Southwestern North American megadroughts. *Geophysical Research Letters* 46(24): 14662-14673.

Rodionov, S., Assel, R.A. (2003) Winter severity in the Great Lakes region: a tale of two oscillations. *Climate Research* 24: 19-31.

Rogers, J., Coleman, J. (2004) Ohio winter precipitation and streamflow associations to pacific atmospheric and oceanic teleconnection patterns. *Ohio Journal of Science* 104: 51-59.

Rohli, R.V., Vega, A.J., Binkley, M.R., Britton, S.D., Heckman, H.E., Jenkins, J.M., Ono, Y., Sheeler, D.E. (2001) Synoptic circulation and stream discharge in the Great Lakes basin, USA. *Applied Geography*. 21(4): 369-385.

Saber, A., Cheng, V.Y.S., Arhonditsis, G.B. (2023) Evidence for increasing influence of atmospheric teleconnections on water levels in the Great Lakes. *Journal of Hydrology* 616. https://doi.org/10.1016/j.jhydrol.2022.128655

Schaetzl, R.J. (2009) Soils. Chapter 20 in Michigan Geography and Geology, R.J. Schaetzl, D. Brandt, and J.T. Darden (eds). Pearson Custom Publishing, Boston, MA. ISBN: 0536987165.

Schneider, N.S., Cornuelle, B.D. (2005) The forcing of the Pacific Decadal Oscillation. *Journal of Climate* 18: 4355-4373.

Scott, R.W., Huff, F.A. (1996) Impacts of the Great Lakes on regional climate conditions. *Journal of Great Lakes Research* 22(4) 845-863

Shadbolt, R.P., Eleanor, A.W., Messina, J.P., Winkler, J.A. (2006) Source regions of lower-tropospheric airflow trajectories for the lower peninsula of Michigan: A 40-year air mass climatology. *Journal of Geophysical Research* 111: D21117.

Singh, S., Abebe, A., Srivastava, P., Chaubey, I. (2021). Effect of ENSO modulation by decadal and multi-decadal climatic oscillations on contiguous United States streamflows. *Journal of Hydrology: Regional Studies* 36. https://doi.org/10.1016/j.ejrh.2021.100876

Slack, J. R. and L.M. Landwher (1992) *Hydro-Climate Data Network (HCDN): A U. S. Geological Survey Stream Flow Data Set for the United States for the Study of Climate Variations, 1874-1988*. Open-File Report 92-129. U. S. Geological Survey, Washington, D. C.

Sobolowski, S., Frei, A. (2007) Lagged relationships between North American snow mass and atmospheric teleconnections indices. *International Journal of Climatology* 27(2) 221-231.

Steinschneider, S. Lall, U. (2016) Spatiotemporal structure of precipitation related to tropical moisture exports over the eastern United States and its relation to climate teleconnections. *Journal of Hydrometeorology*. 17(3) 897-913.

Suriano, Z.J., Leathers, D.J. (2017a) Synoptic climatology of lake-effect snowfall conditions in the eastern Great Lakes region. *International Journal of Climatology* 37, 4377-4389

Suriano, Z.J., Leathers, D.J. (2017b) Spatiotemporal variability of Great lakes basin snow cover ablation events. *Hydrological Processes,* 31: 4229-4237

Suriano, Z.J., Leathers, D.J., Benjamin, A.E. (2020a) Regionalization of Northeast U.S. moisture conditions: Analysis of synoptic-scale atmospheric drivers. *Climate Research* 79, 193-206

Suriano, Z.J., Henderson, G.R., Leathers, D.J. (2020b) Discharge responses associated with rapid snow cover ablation events in the Susquehanna and Wabash River basins. *Physical Geography* 41: 70-82.

Tamaddun, K.A., Kalra, A., Bernardez, M., Ahmad, S. (2017) Multi-scale correlation between the western US snow water equivalent and ENSO/PDO using wavelet analyses. *Water Resources Management* 31(9): 275-2759.

Tang, C.L., Chen, D., Crosby, B.T., Piechota, T.C., Wheaton, J.M. (2014) Is the PDO or AMO the climate driver of soil moisture in the Salmon River Basin, Idaho? *Global and Planetary Change* 120: 16-23.

Tootle, G.A., Piechota, T.C., Singh, A. (2005) Coupled ocean-atmospheric variability and U.S. streamflow. *Water Resources Research* 41(12): W12408.

Vavrus, S., Notaro, M., Zarrin, A. (2013) The role of ice cover in heavy lake-effect snowstorms over the Great Lakes basin as simulated by RegCM4. *Monthly Weather Review*. 141(1): 148-165.

Vose, R.S., Applequist, S., Squires, M., Durre, I., Menne, M.J., Williams, C.N., Fenimore, C., Gleason, , Arndt, D. (2014) NOAA Monthly U.S. Climate Divisional Database (NClim). Monthly. NOAA National Climatic Data Center. Doi: 10.7289/V5M32STR. Accessed July 10, 2023

Wang, J.Y., Whitfield, P.H., Cannon, A.J., (2006) Influence of Pacific climate patterns on low-flows in British Columbia and Yukon, Canada. *Canadian Water Resources Journal* 31(1):25-40.

Wang, J., Kessler, J., Bai, X.Z., Clites, A., Lofgren, B., Assuncao, A., Bratton, J., Chu, P., Leshevich, G. (2018) Decadal variability of Great Lakes ice cover in response to AMO and PDO, 1963-2017. *Journal of Climate* 31(18): 7249-7268.

Welsh, B., Brown, D., Messina, J. (2009) Land-Use and Land-Cover. Chapter 29 in Michigan Geography and Geology, R.J. Schaetzl, D. Brandt, and J.T. Darden (eds). Pearson Custom Publishing, Boston, MA. ISBN: 0536987165.

Welsh, C., Smith, D.J., Coulthard, B. (2019) Tree-ring records unveil long-term influence of the Pacific Decadal Oscillation on snowpack dynamics in the Stikine River basin, northern British Columbia. *Hydrological Processes* 33(5): 720-736.

Whitfield, P.H., Moore, R.D., Fleming, S.W., Zawadzki, A. (2010) Pacific Decadal Oscillation and hydroclimatology of Western Canada – review and prospects. *Canadian Water Resources Journal* 35(1):1-28.

Wolfson, L. (2009) Surface Water Resources. Chapter 15 in Michigan Geography and Geology, R.J. Schaetzl, D. Brandt, and J.T. Darden (eds). Pearson Custom Publishing, Boston, MA. ISBN: 0536987165.

Wright, D.M. Posselt, D.J., Steiner, A.L. (2013) Sensitivity of lake-effect snowfall to lake ice cover and temperature in the Great Lakes region. *Monthly Weather Review* 141(2): 670-689.

Yang, Z., Qian, Y., Xue, P., Wang, J., Chakraborty, T.C., Pringle, W.J., Li, J., Chen, X. (2023) Moisture sources of precipitation in the Great Lakes region: Climatology and recent changes. *Geophysical Research Letters* 50, e2022GL100682.

Table Captions

Table 1: USGS stream gaging station drainage area, location (latitude and longitude) and climatological averages as of 2009. Data from Falcone (2011).

Table 2: Stream gages exhibiting statistically significant monthly streamflow differences between PDO+ and PDO- phases after detrending based on a T-test, 1967-2018. Streamflow values are in cubic meters per second and are represented here as anomalies from individual gages' long-term linear fit. Negative values in the Mean Difference column indicate increased (decreased) streamflow during PDO+ (PDO-) phases. Gages in the UP shaded in light gray.

Table 3: Climate Divisions exhibiting statistically significant monthly precipitation differences between PDO+ and PDO- phases after detrending based on a T-test, 1967-2018. Precipitation values are in mm and are represented here as anomalies from individual divisions' long-term linear fit. Negative values in the Mean Difference column indicate increased (decreased) precipitation during PDO+ (PDO-) phases. Divisions in the UP are shaded in light gray.

Supplemental Table 1: USGS stream gaging station upstream drainage basin land-use/land-cover as of 2009. Data from Falcone (2011).

Figure Captions

Figure 1: The geographic distribution of state climate divisions and selected USGS gaging stations used in this study. Inset map shows Michigan in the heart of the Great Lakes region of North America.

Figure 2: Monthly streamflow anomalies, in cm/s, from the long-term monthly mean between PDO+ (gray) and PDO- (black) phases for each of USGS gaging station: (a) Ford River, (b) Manistique River, (c) middle branch Escanaba River, (d) Sturgeon River at Hahma Junction, (e) Sturgeon River at Sidnaw, (f) Tahquemenon River, (g) Trap Rock River, (h) Augusta Creek, (i) Manistee River, (j) Per Marquette River, (k) Sturgeon River in LP, and (l) White River.

Figure 3: Monthly precipitation anomalies, in mm, from the long-term monthly mean between PDO+ and PDO- phases for each of ten Michigan Climate Divisions. Positive values (warm tones) indicate less precipitation during PDO+ phases and more precipitation during PDO- phases. Negative values (cool tones) indicate more precipitation during PDO+ phases and less precipitation during PDO- phases.

Supplemental Figure 1. Monthly temperature anomalies, in °C, from the long-term monthly mean between PDO+ (gray) and PDO- (black) phases for of the ten Michigan Climate Divisions: (a) Climate Division (CD) 1, (b) CD2, (c) CD3, (d) CD4, (e) CD5, (f) CD6, (g) CD7, (h) CD8, (i) CD9, and (j) CD10.

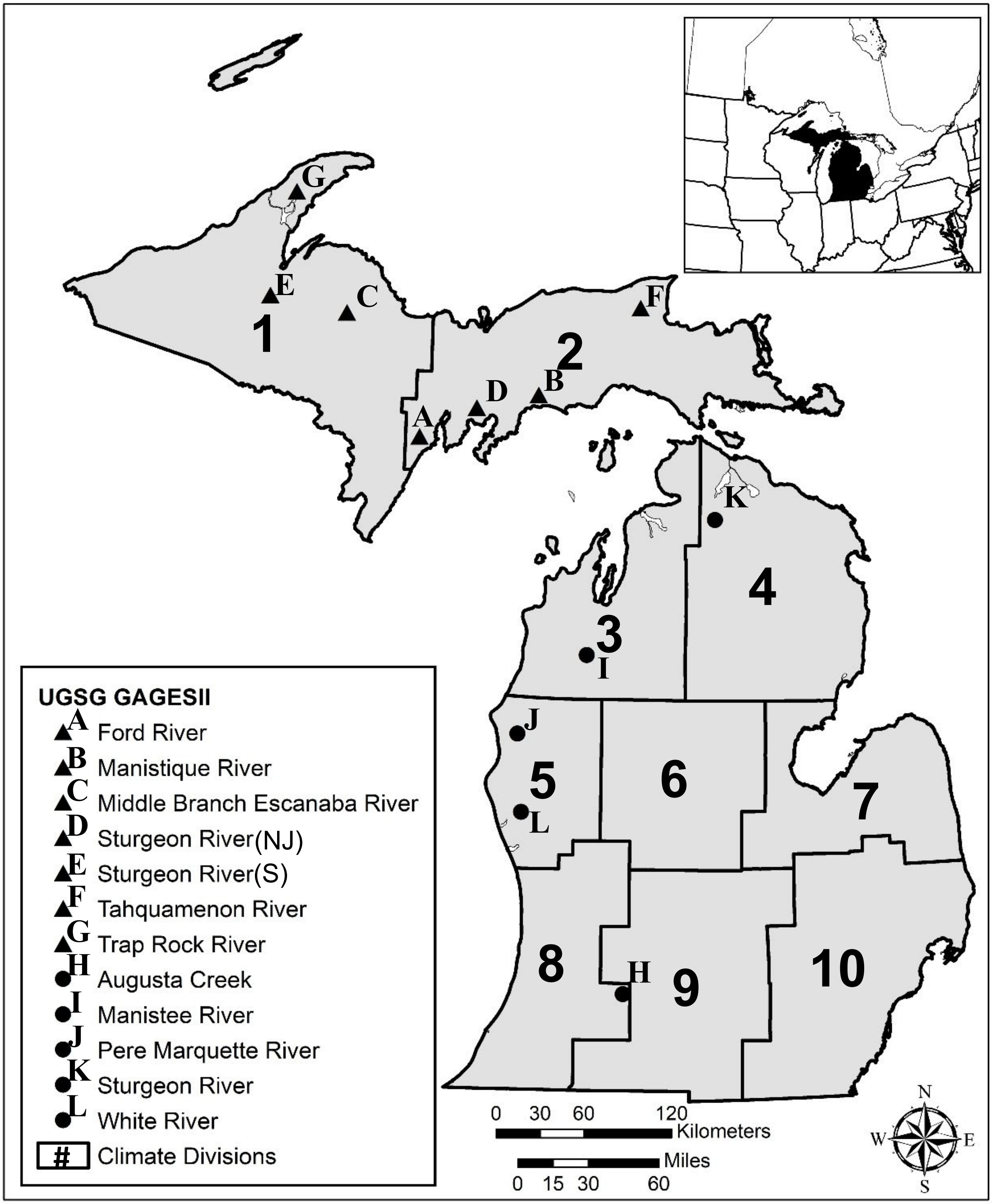

G
E
C
F
1
2
D
B
A
K
4
3
I
J
5
6
7
L
8
H
9
10
UGSG GAGESII
A Ford River
B Manistique River
C Middle Branch Escanaba River
D Sturgeon River(NJ)
E Sturgeon River(S)
F Tahquamenon River
G Trap Rock River
H Augusta Creek
I Manistee River
J Pere Marquette River
K Sturgeon River
L White River
Climate Divisions
0 30 60 120
Kilometers
Miles
0 15 30 60
N
W
E
S

Figure 1

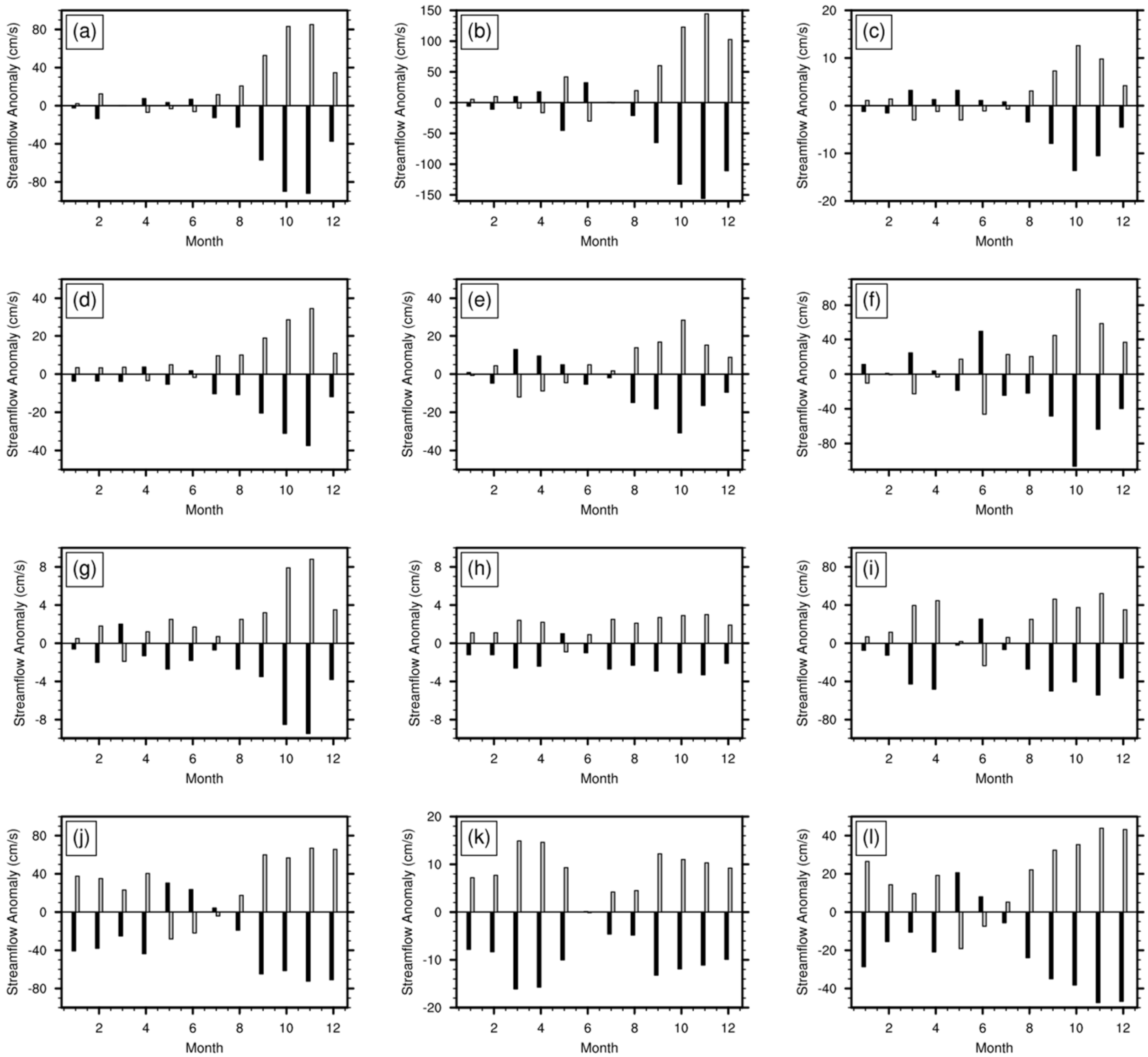
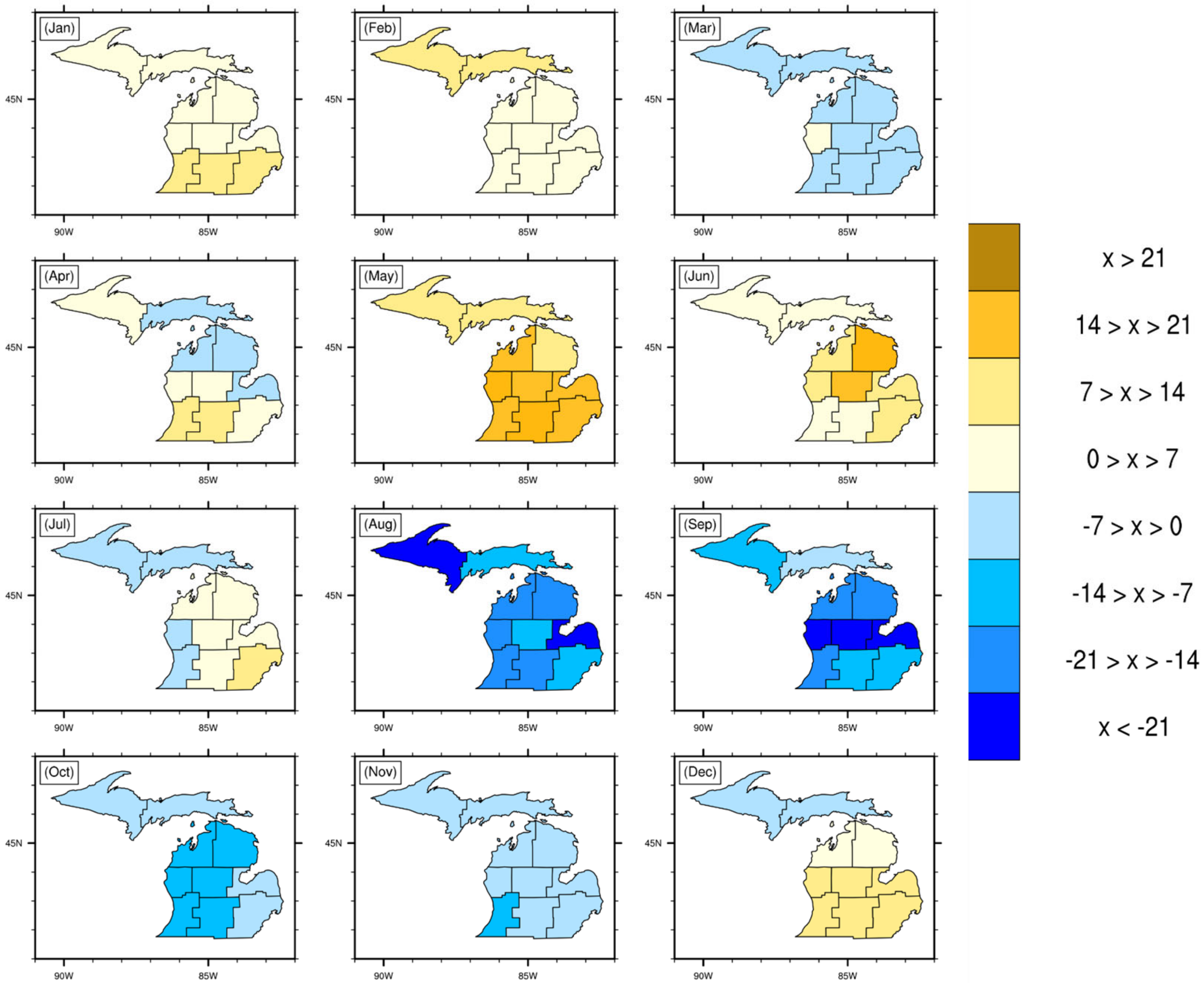
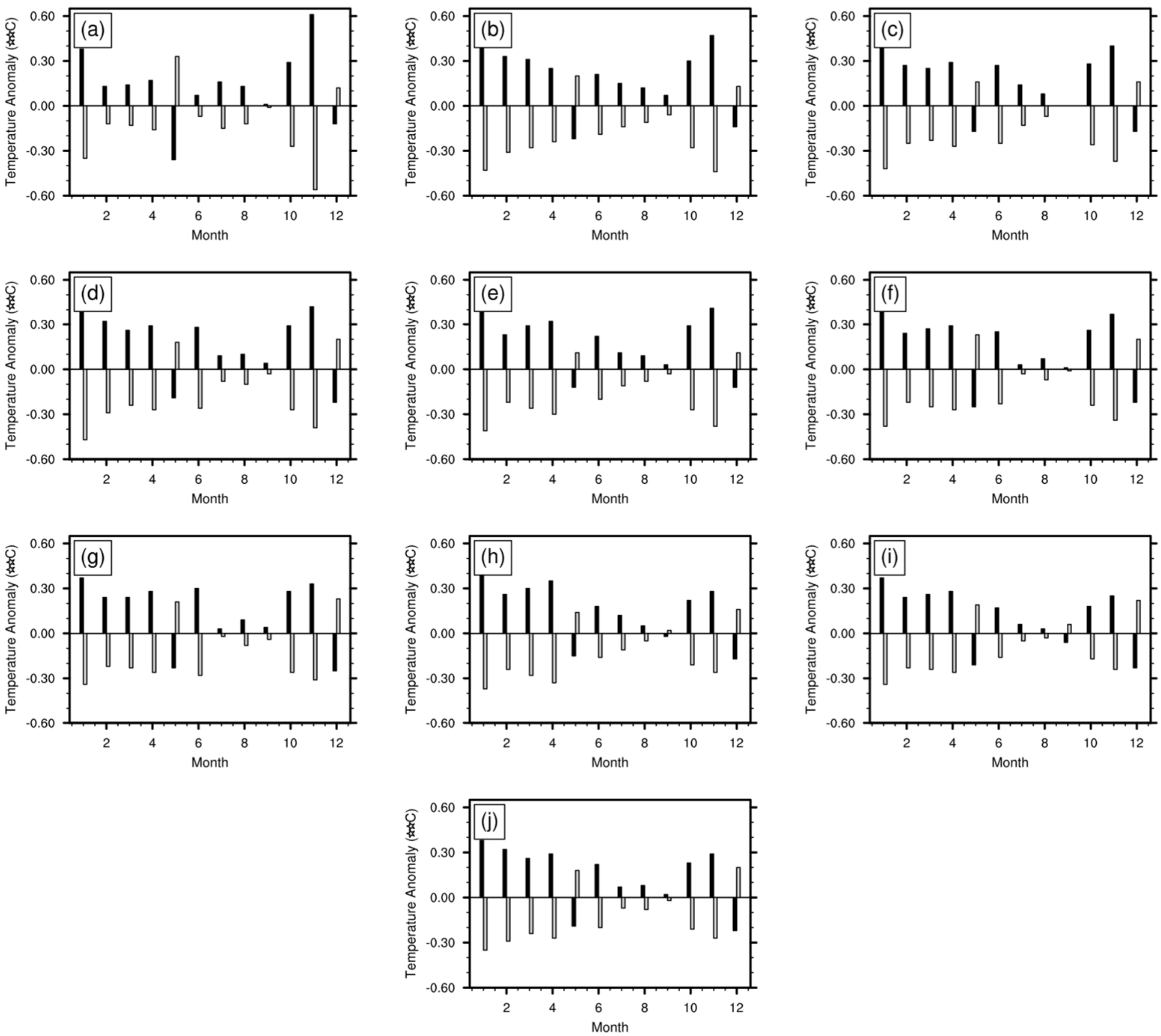


Figure 2



(Jan)
(Feb)
(Mar)
(Apr)
(May)
(Jun)
(Jul)
(Aug)
(Sep)
(Oct)
(Nov)
(Dec)
45N
90W
85W
x > 21
14 > x > 21
7 > x > 14
0 > x > 7
-7 > x > 0
-14 > x > -7
-21 > x > -14
x < -21

Figure 3



Supplemental Figure 1