Using Climate Divisions to Analyze Variations and Trends in Alaska Temperature and Precipitation

PETER A. BIENIEK AND JOHN E. WALSH

International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, Alaska

RICHARD L. THOMAN

Alaska Region, NOAA/National Weather Service, Fairbanks, Alaska

UMA S. BHATT

Department of Atmospheric Sciences, College of Natural Science and Mathematics, and Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska

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ABSTRACT

By extending the record of Alaskan divisional temperature and precipitation back in time, regional variations and trends of temperature and precipitation over 1920–2012 are documented. The use of the divisional framework highlights the greater spatial coherence of temperature variations relative to precipitation variations.

The divisional time series of temperature are characterized by large interannual variability superimposed upon low-frequency variability, as well as by an underlying trend. Low-frequency variability corresponding to the Pacific decadal oscillation (PDO) includes Alaska's generally warm period of the 1920s and 1930s, a cold period from the late 1940s through the mid-1970s, a warm period from the late 1970s through the early 2000s, and a cooler period in the most recent decade. An exception to the cooling of the past decade is the North Slope climate division, which has continued to warm. There has been a gradual upward trend of Alaskan temperatures relative to the PDO since 1920, resulting in a statewide average warming of about 1°C.

In contrast to temperature, variations of precipitation are less consistent across climate divisions and have much less multidecadal character. Thirty-year trends of both variables are highly sensitive to the choice of the subperiod within the overall 93-yr period. The trends also vary seasonally, with winter and spring contributing the most to the annual trends.

1. Introduction

The immense size and complex topography of Alaska results in various climate zones throughout the state (Searby 1968; Shulski and Wendler 2007). With the recent development of objectively based climate divisions for Alaska (Bieniek et al. 2012) it is now possible to better understand how climate trends and variability behave in different regions of the state. Without climate divisions, Alaska has lagged behind the divisionally based products and services available in the contiguous United States (CONUS), which has had climate divisions in varying forms since early in the twentieth century (Guttman and Quayle 1996). In this study, we employ the novel Alaska climate divisions (Fig. 1) in a historical retrospective analysis of regional climate trends and variability.

There is much interest in the changing climate of Alaska, especially owing to its high-latitude location that lends itself to enhanced trends and variability with polar amplification (Chapin et al. 2005; Bekryaev et al. 2010; Serreze and Barry 2011). Alaska has experienced increases in temperature over much of the last century, with relatively mixed trends in precipitation (ACIA 2005). The most recent report of the Intergovernmental Panel on Climate Change (IPCC 2014) shows trends in annual Alaskan temperature and precipitation in

Corresponding author address: Peter A. Bieniek, International Arctic Research Center, P.O. Box 757340, Fairbanks, AK 99775-7340.
E-mail: pbieniek@alaska.edu

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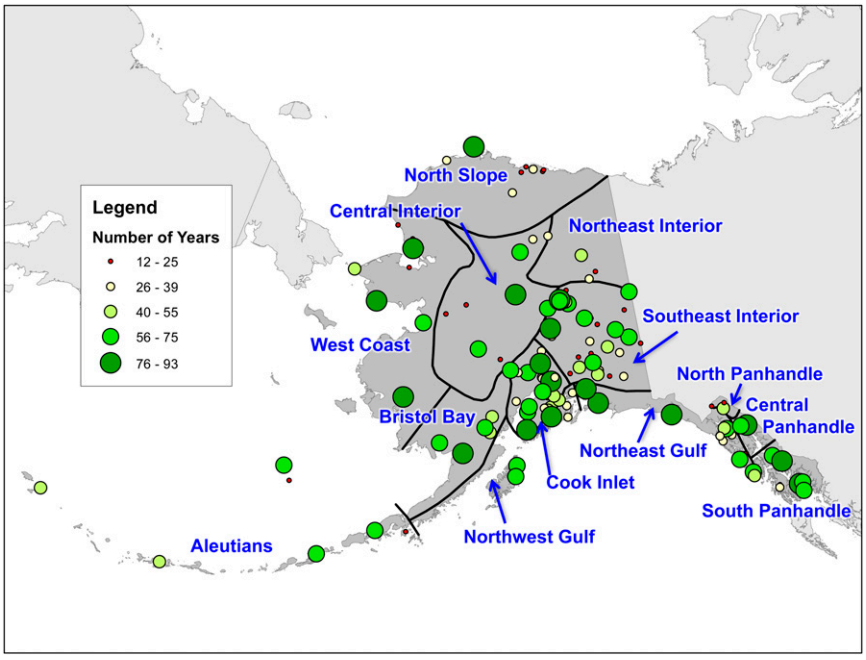

FIG. 1. Number of years between 1920 and 2012 with observations of temperature at weather stations within the GHCND database. Climate division boundaries and names are adapted from Bieniek et al. (2012). All of these stations were used to calculate divisional anomalies. Precipitation had a similar inventory and is not shown. Most divisions have at least one station with 76 or more years of observations.

a global context for different historical time slices using different data sources. For the longest time window, 1901–2012, all three major datasets used by the IPCC show warming over Alaska, typically about 1°C and slightly greater in the north than in the south [although substantial portions of Alaska are masked out as ''incomplete'' or ''missing'' in two of the analyses: the Hadley Centre/Climatic Research Unit (CRU) dataset, version 4 (HadCRUT4), and the National Climatic Data Center (NCDC) monthly land ocean surface temperature [MLOST, based largely on the Global Historical Climatology Network monthly dataset (GHCN-M) over Alaska]. When the MLOST trends are evaluated for 30-yr time slices (1911–40, 1951–80, and 1951–2012), warming is again apparent in each time slice although the trend is largest in 1911–40, especially in northern Alaska (IPCC 2014, Fig. 2.22). The current U.S. National Climate Assessment (NCA) (USGCRP 2013) presents only decadal means of annual temperatures averaged over the entire state of Alaska, again using the GHCN database. The national summary diagram in this assessment shows that Alaska's warmest three decades were the past three, which were preceded by three decades (1950s through 1970s) slightly cooler than the 1901–60 average, three decades (1920s through 1940s) slightly warmer than the 1901–60 average, and two slightly cooler decades (1900s and 1910s) (USGCRP 2013, Fig. 2.7). Neither the IPCC nor the NCA break down the trends by season.

The IPCC trends in annual precipitation from three datasets [CRU, GHCN, and Global Precipitation Climatology Centre (GPCC)] are generally missing or small, with little spatial coherence, over Alaska during two time slices, 1901–2010 and 1979–2010 (IPCC 2014, Fig. 2.29). Similarly, the decadal departures from the 1901–60 mean statewide average precipitation are small in the NCA, although the decadal statewide averages do show a small increase from the 1960s, which was the driest decade in the NCA depiction (USGCRP 2013, Fig. 2.12). Again, there is no seasonal breakdown of the trends by either the IPCC or the NCA.

Trends toward increased temperature have also been documented in diverse ways for Alaska over the last half of the twentieth century (Stafford et al. 2000; Wendler and Shulski 2009; Bone et al. 2010; Gil-Alana 2011; López-de-Lacalle 2011). Declines in temperature throughout much of Alaska since 2000 have also been documented following the warm decade of the 1990s (Wendler et al. 2012). These previous Alaska trend studies had to rely on individual stations for analysis with the regional representativeness of those stations not always clearly understood. Climate divisions help to

establish the regional representativeness of groups of stations at monthly and seasonal scales and allow for improved understanding of regional climate variability. They further permit the calculation of area-weighted statewide average values of monthly temperature and precipitation, which is important since interior and northern regions of the state are much larger than coastal regions and coastal regions often have more stations.

The importance of teleconnections, and their related influence on trends, in Alaska has been documented. The El Niño–Southern Oscillation (ENSO) has been shown to impact Alaska seasonal temperatures to varying degrees in all seasons with the positive phase of ENSO typically associated with warmer than average temperatures (Niebauer 1988; Barnston and He 1996; Hess et al. 2001; Papineau 2001; Bieniek et al. 2011). Related to ENSO, the Pacific decadal oscillation (PDO) (Mantua et al. 1997) has also been shown to impact the seasonal temperature with the positive phase of the PDO typically associated with warmer than average temperatures (Papineau 2001; Hartmann and Wendler 2005; Bourne et al. 2010). The PDO has further been attributed for the upward shift in seasonal/annual average temperature in the late 1970s throughout much of the state (Hartmann and Wendler 2005). Bieniek et al. (2012) demonstrated that many teleconnection indices, including ENSO and PDO, were significantly correlated with Alaska climate division time series, although the time series in their analysis was limited to 1977–2010. Since the PDO plays a vital role in driving the climate of Alaska, the role of the PDO with regard to the climate divisions will also be examined in this study.

The primary goal of this study is to further demonstrate the suitability of Alaska climate divisions for seasonal and annual analysis of historical climate variability and trends. Within this goal, we extend the analysis of Alaska climate variability to the longest time series allowable by the sparse station observation network and demonstrate that divisions are quite useful to this end. Finally, the value of having extended historical time series for evaluating trends and teleconnections is shown.

2. Data and methods

A major goal of this study was to determine divisional climate anomalies of temperature and precipitation in a similar fashion as for the CONUS (e.g., Fenimore et al. 2012). Daily meteorological station data for Alaska were obtained from the Global Historical Climatology Network–Daily (GHCND) database maintained by the National Climatic Data Center. The database includes numerous, quality controlled daily meteorological parameters observed from 1763 to present and integrates multiple data sources (Menne et al. 2012). All station data analysis in this study was ultimately based on the daily average temperature and accumulated precipitation from GHCND. Monthly mean temperature and accumulated precipitation were calculated for each month and only for those months with at least 15 days of observations. The GHCND inventory revealed approximately 740 stations falling within the state of Alaska with more than one year of recorded observations. To be included within this analysis stations must have at least 10 years of observations falling within the 1981–2010 normal period currently being used by the National Weather Service (NWS), with 163 stations ultimately meeting this criteria (see Fig. 1). The period of analysis was limited to 1920–2012 due to the relatively sparse number of observations earlier in the GHCND database for Alaska.

Each of the 163 stations was assigned to the division in which it was geographically located. All divisions had at least one station with 40 or more years of records with most having one or more stations with a nearly complete observational record (see Fig. 1). The three panhandle divisions, Northeast Gulf, Cook Inlet, and Southeast Interior, have the most numerous station observations as these divisions contain most of the population and roads in Alaska. The fewest number of stations were in the Northeast Interior division.

Monthly anomalies were calculated for all of the 163 GHCND stations based on the 1981–2010 climate normal period. An initial set of monthly mean divisional anomalies was calculated based on an average of all stations anomalies within that month for both temperature and precipitation. A simple averaging is desirable since the assumption of climate divisions is that all stations within a division should generally share anomalies of similar sign and magnitude at monthly and longer time scales. Inspection of the preliminary divisional anomalies revealed two major issues: large gaps in data in the Northeast Interior and North Panhandle climate divisions and increased variability in precipitation anomalies in the early portion of the records of the Aleutians and Central Panhandle climate divisions. Owing to large regional variation in precipitation anomalies, divisional precipitation was also expressed as a percentage of the 1981–2010 average for comparison. For simplicity, the anomalies will primarily be presented in this study since the fundamental variability was quite similar between the two.

Multiple linear regressions were employed to fill the missing data in the Northeast Interior and North Panhandle divisions. The regression models were fit using

least squares regressions and the final best-fit models were determined by stepwise Akaike information criterion (AIC) model selection (Wilks 2006). The Northeast Interior has essentially no stations in the middle of the division in the final set, so it was determined that Fort Yukon (which is centrally located) should be added, in spite of not having sufficient data in the 1981–2010 period to calculate a mean, since it had a substantial observational record prior to the 1980s. The regression procedure was used to fill both monthly temperature and precipitation employing the surrounding first-order NWS weather stations. A single model was fit for temperature for all months while a separate model was fit for each month for precipitation. The overall correlations between the fitted and observed data were 0.98 and 0.85 for the temperature and precipitation, respectively, at Fort Yukon.

The North Panhandle division is the smallest in terms of total area and also has few stations (see Fig. 1). As a result, the division has gaps in the divisional temperature and precipitation anomalies before 1925 and during 1953–83 that were filled using a similar regression procedure to that used for Fort Yukon described in the previous paragraph. For the North Panhandle, however, all of the 12 other climate divisional anomalies were considered in the fitting procedure. Similarly, only a single regression model was needed for temperature, while monthly models were necessary for precipitation. For precipitation, the monthly temperature anomalies from the North Panhandle were also employed in the fitting. The overall correlations between the fitted/predicted and observed data were 0.96 and 0.80 for the temperature and precipitation, respectively.

Examination of the monthly divisional precipitation anomalies for the Aleutians and Central Panhandle divisions revealed higher amplitude variability in the early portion of their time series (Fig. 2); no other divisions displayed this phenomenon. Further investigation showed that the reduced number of stations early in the period was the culprit rather than a change in climate variability. Such issues with stations coming and going have been an ongoing problem with the creation of historical data and have typically been addressed through an adjustment of the variability (e.g., Brohan et al. 2006). We employed a straightforward standard deviation adjustment to the Aleutian and Central Panhandle monthly divisional precipitation anomalies. This was achieved by multiplying the time period with the enhanced variability by a correction factor:

$$\text{correction factor} = \frac{\sigma_{\text{full}}}{\sigma_{\text{fix}}},$$

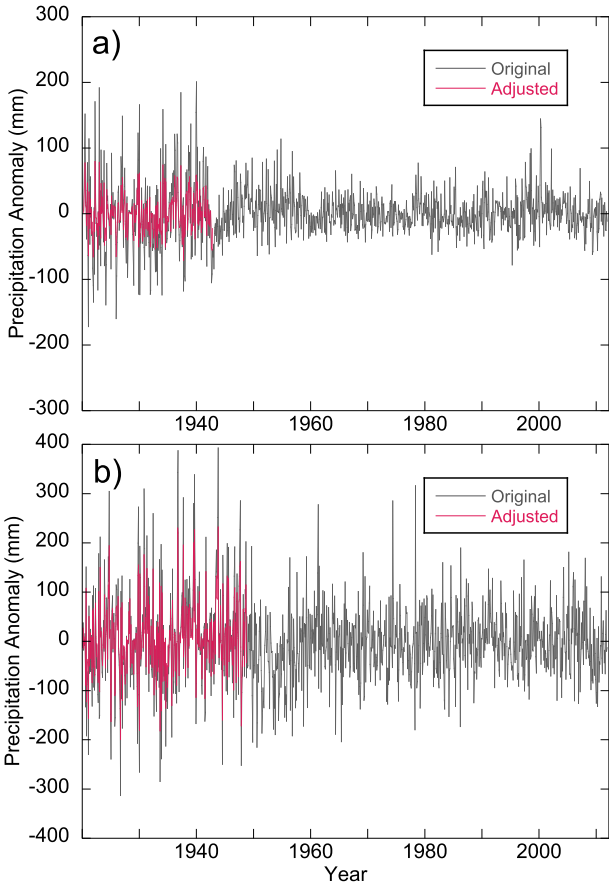

FIG. 2. Observed (gray) and adjusted (red) time series of monthly divisional precipitation anomalies for the (a) Aleutians and (b) Central Panhandle climate divisions. Enhanced variability results from relatively few stations early in the record and is damped by adjusting the time series with a standard deviation correction.

where σ_{fix} is the standard deviation of the period with enhanced variability to be adjusted and σ_{full} is the standard deviation of the remaining data. A correction factor was calculated for each month and applied to the corresponding data for that month. The final result of this correction is shown in Fig. 2.

Potential problems have been documented related to the use of climate-division-based anomalies for climate trend analysis in the CONUS (Keim et al. 2003, 2005; Allard and Keim 2007; Allard et al. 2009), so the sensitivity of station selection on the divisional anomalies was tested. The influence of each station on the divisional anomalies was carried out by removing all possible combinations of one, two, three, and so on stations and then recalculating the divisional anomalies based on the remaining stations. The normalized root-mean-square error (NRMSE) was then calculated (Wilks 2006) for all of the test cases and divisions. The maximum NRMSE for temperature and precipitation was 9% and 12%,

TABLE 1. Normalized rms error of station-based vs grid-based divisional annual temperature and precipitation anomalies.

	Temperature				Precipitation			
Division	1961–2009 Hill	1961–2009 CRU	1920–50 CRU	1920–2012 CRU	1961–2009 Hill	1961–2009 CRU	1920–1950 CRU	1920–2012 CRU
North Slope	0.08	0.08	0.10	0.08	0.20	0.14	0.18	0.15
West Coast	0.05	0.05	0.07	0.06	0.10	0.08	0.14	0.09
Central Interior	0.10	0.04	0.09	0.05	0.16	0.15	0.22	0.14
Northeast Interior	0.16	0.10	0.15	0.11	0.19	0.25	0.23	0.21
Southeast Interior	0.05	0.06	0.10	0.06	0.22	0.13	0.30	0.20
Cook Inlet	0.04	0.05	0.06	0.05	0.24	0.13	0.11	0.13
Bristol Bay	0.05	0.06	0.13	0.07	0.14	0.18	0.22	0.17
Northwest Gulf	0.07	0.11	0.12	0.10	0.11	0.18	0.22	0.16
Northeast Gulf	0.05	0.11	0.21	0.14	0.23	0.14	0.16	0.11
North Panhandle	0.12	0.09	0.16	0.11	0.36	0.23	0.32	0.20
Central Panhandle	0.13	0.11	0.28	0.17	0.48	0.16	0.18	0.16
South Panhandle	0.06	0.06	0.15	0.09	0.16	0.15	0.19	0.14
Aleutians	0.09	0.07	0.18	0.08	0.32	0.14	0.21	0.16

respectively. This analysis suggested that, while there is sensitivity to the selection of stations in the divisional anomalies, station selection impacts the anomalies by 10% at most, a smaller than expected value given the spatially and temporally sparse station network in Alaska.

The impact of using the sparse station network in Alaska for calculating divisional averages was further evaluated through comparison with gridded data. The gridded historical CRU time series (TS) version 3.21 monthly dataset [available 1901–2012 at 0.5° by 0.5° resolution, Mitchell and Jones (2005)] was obtained and monthly divisional average anomalies of temperature and precipitation were computed based on a 1981–2010 mean. In addition, the monthly gridded downscaled dataset developed by D. Hill (2013, personal communication) for Alaska (available on a 2-km grid) was obtained and divisional anomalies were calculated for temperature and precipitation for 1961–2009 following the same method as CRU. A comparison of the gridded versus station annual average divisional anomalies is shown by their NRMSE in Table 1. Overall, the NRMSE anomalies are lower for temperature (max is 0.28 for Central Panhandle) than for precipitation (max is 0.48 for Central Panhandle). This is expected as precipitation tends to be more localized than temperature and is also more difficult to measure. The highest NRMSE are with CRU in the early portion of the period (1920–50) for both temperature and precipitation, indicating some possible loss of accuracy in the earlier portion of the record. A major drawback within the gridding process is that, when stations are interpolated to the grid, stations across climate-type (i.e., climate division) boundaries will be mixed in the process. This accounts for some of the larger NRMSE values, especially those in the narrower coastal divisions where wetter coastal and drier interior stations are mixed in the interpolation. This is particularly noticeable in datasets such as CRU, which use fairly simple interpolation methods. Given the overall performance of the stations versus gridded data and the unique data issues in Alaska, little would be gained through a gridded approach to calculating divisional anomalies. For the purposes of this study, we will present the results of the GHCND-based division anomalies for simplicity and consistency with the divisional datasets in the CONUS.

3. Results

a. Time series and variability

The 1920–2012 time series of annual temperatures for the 13 Alaskan divisions, expressed as departures from the 1981–2010 divisional means, are shown in Fig. 3a. The divisional time series are characterized by large interannual variability superimposed upon low-frequency variability, as well as by an underlying trend, discussed in subsequent sections. The largest excursions from the mean temperatures are generally common to more than one division, pointing to a role of the large-scale circulation in driving interannual extremes. In the decades since about 1950, the largest annual departures from the means have often occurred in the North Slope division (blue in Fig. 3a). The low-frequency variations of the divisional temperatures have a multidecadal character, as a relatively warm period in the 1920s and 1930s was followed by a cold period from the late 1940s through the mid-1970s, a warm period from the late 1970s through the early 2000s, and a cooler period in the last decade.

The corresponding time series for annual precipitation, shown in Fig. 3b, indicate that large departures from the divisional means are less spatially coherent

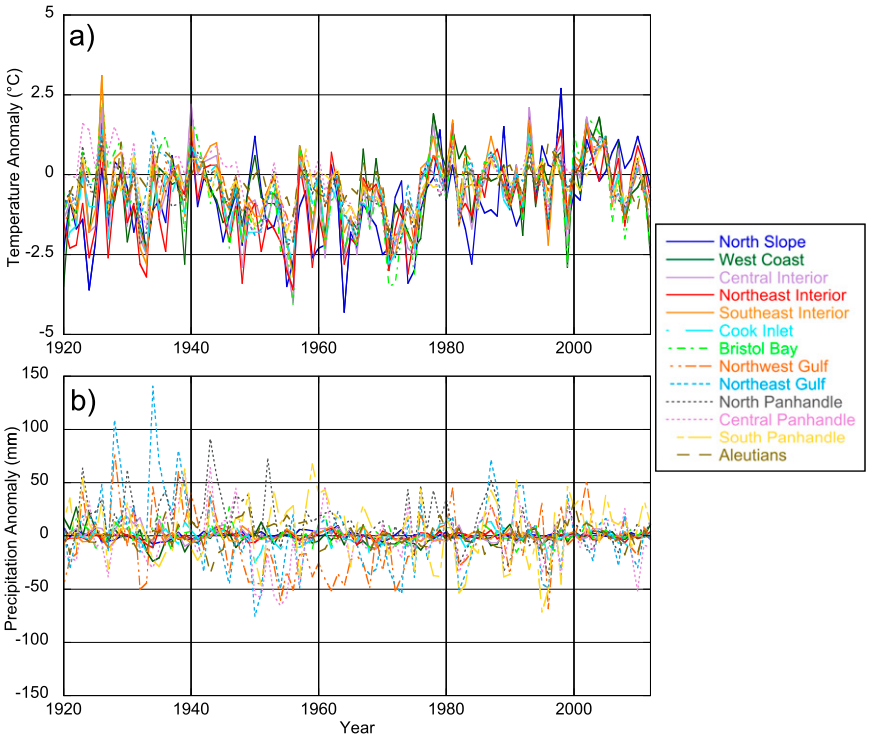

FIG. 3. Annual average divisional anomalies of (a) temperature and (b) precipitation for the 13 Alaska climate divisions. Temperature variability is similar among divisions though it is less coherent for precipitation.

than the large temperature excursions. Only one or two divisions generally experience large departures in any particular year, as one would expect from the more local nature of precipitation anomalies, especially in the warm months. Moreover, most of the large departures from the mean occur in the southern and southeastern divisions (dotted and dashed colored lines in Fig. 3b), where the mean precipitation amounts are larger (Bieniek et al. 2012, Fig. 6). Despite the more random distribution of the departures from mean precipitation, there is some tendency for extremely wet years during the earlier decades (the 1920s through the 1940s), dry years from the 1950s through the mid-1970s (especially in the Northwest Gulf division), and a more even distribution of wet and dry years from the late 1970s onward.

The low-frequency variations of the annual departures of temperature are more apparent in Fig. 4, which shows the 5-yr running average departures from the divisional means. Also shown in Fig. 4 is the 5-yr running mean of the Pacific decadal oscillation (PDO), which is the measure of the dominant mode of sea surface temperature variability in the North Pacific Ocean. All departures in Fig. 4 are relative to the means for 1981–2010. It is apparent that the temperature departures of all divisions track the PDO, although the North Slope division (blue line) becomes asynchronous with the PDO during the last few decades. In particular, the North Slope has been exceptionally warm relative to the PDO and to the other divisions over the past 5–10 years. As noted subsequently, this warming of the North Slope is strongest in autumn and coincides with the extreme summer retreat of sea ice north of Alaska in recent years (Stroeve et al. 2012).

The tracking of temperature anomalies with the PDO is generally apparent in the time series of most of the climate divisions, although there are occasional decadal excursions of the temperatures that have no counterpart in the PDO time series. The 1930s and 1980s are such examples. Temperatures in the 1980s may have been influenced for a few years by the El Chichón volcanic eruption in 1982, although the impacts on temperature are complicated by atmospheric circulation anomalies and by the occurrence of a large El Niño event at nearly the same time (Robock 1984). However, no such depression of Alaskan temperatures is apparent in Fig. 4 following the larger eruption of Mt. Pinatubo in 1991, and there were no known major eruptions preceding the downward excursion of the divisional temperatures in the 1930s. The depression of temperatures in the early 1980s may have been associated with the prevailing positive phase of the Arctic Oscillation, which is

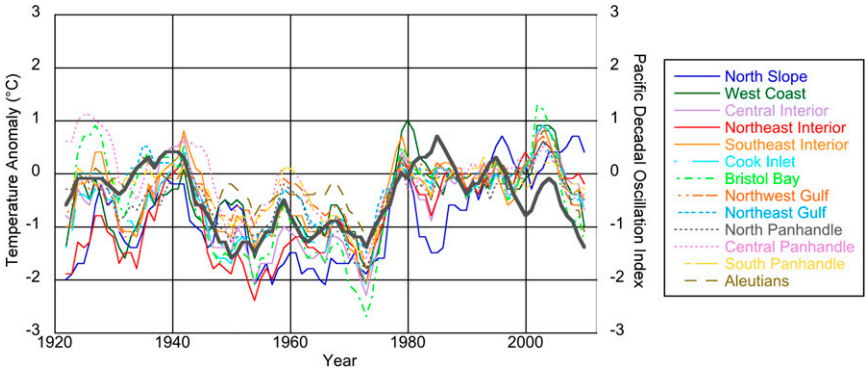

FIG. 4. Annual 5-yr running averaged divisional temperature anomalies for the 13 Alaska climate divisions. The Pacific decadal oscillation index (PDO) (http://jisao.washington.edu/pdo/) is shown in dark gray and has also been smoothed by 5-yr running average. The mean of the PDO has been adjusted to match the average mean of the 13 climate divisions for ease of comparison. Low-frequency variations of annual divisional temperature anomalies appear to follow that of the PDO.

associated with below-normal temperatures in Alaska. An impact of a volcanic eruption on the Arctic Oscillation remains a possibility, although further research and a larger sample of modern-day eruptions will be required to establish the robustness of such an association.

The correspondence between the PDO and Alaskan temperatures during the cold season has been noted by Hartmann and Wendler (2005), particularly with regard to Alaskan winter warming associated with the abrupt increase of the PDO in 1976–77. Figure 4 shows that this association extends to the annual mean temperatures. Closer examination of Fig. 4 shows that there has been a gradual upward trend of Alaskan temperatures relative to the PDO since 1920. This trend manifests itself in Fig. 4 as a clustering of the divisional temperatures below the PDO curve in the earliest decades (1920s and 1930s) and a clustering above the PDO curve in the most recent two decades. (The PDO trend over the 1920–2012 period is not statistically significant.) The underlying temperature trends are examined in greater detail in subsequent sections.

Figure 5 shows the 5-yr running mean departures from the divisional mean precipitation and percent of average precipitation. In comparison with the temperature time series in Fig. 4, the precipitation time series show much less multidecadal variability. As with the annual values in Fig. 3b, most of the excursions from the mean are limited to one or two stations at a time. Most of the colder (drier) divisions show little variation (solid lines in Fig. 5a), as would be expected from their much smaller means relative to the southern divisions. For the wetter divisions (southern regions, dashed lines), there is a slight tendency for a predominance of extreme wet years during the 1920s–1940s (the first warm period) and extreme dry years during the 1950s–1970s (the first cool period). From the late 1970s onward, there are both wet and dry periods during which several southern divisions show departures of the same sign. When annual precipitation is scaled to percentage of average (Fig. 5b), the variability of the drier interior divisions are enhanced relative to the wetter coastal divisions, which have greater magnitudes in anomalies. As a percentage, the North Slope displays the greatest precipitation variability overall with a dry period from the late 1920s to 1930s, a prominent wet period in the 1950s–1960s, followed by relatively reduced variability in recent decades (similar in the other divisions as well) and a wet 2000s.

The annual variations over the 1920–2012 period were spatially integrated into statewide averages by an area-weighting of the departures of the divisional values from their corresponding means. The statewide averages are shown in Fig. 6 as 5-yr running means. While the statewide temperatures in Fig. 6a reinforce the PDO-driven multidecadal variability discussed earlier, several other features of the time series are notable. First, the cooling of the past decade is readily apparent (despite the warming of the North Slope). Second, the most dramatic change in temperature occurred in the late 1970s when the PDO shift led to a warming from the lowest statewide average temperatures in the record to some of the warmest in the record. Finally, the warmest values of the entire record occurred in the early 2000s, prior to the recent cooling. This period of maximum temperatures is generally consistent with the Wendler and Shulski (2009) finding for a single station, Fairbanks, although the 5-yr running mean temperatures at Fairbanks were comparable in the 1980s and the late 1990s/early 2000s (Wendler and Shulski 2009). Finally, Fig. 6a places the

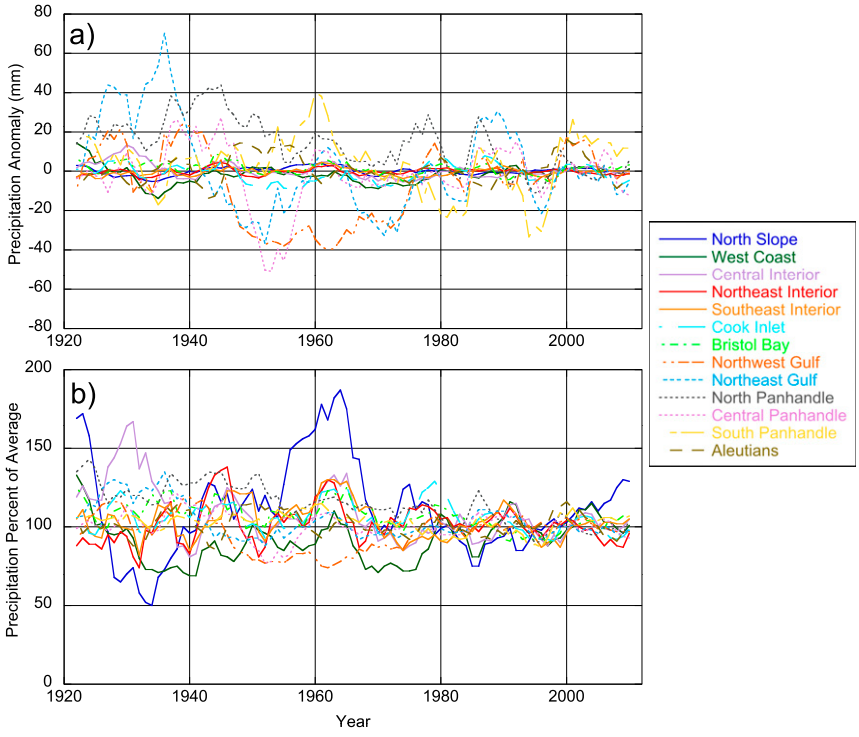

FIG. 5. Annual 5-yr running averaged divisional precipitation (a) anomalies and (b) percentage of average for the 13 Alaska climate divisions. Precipitation variability is smaller for climate divisions in northern Alaska than the southern coastal divisions while multidecadal variations are weaker for precipitation than temperature.

underlying trend into the context of the large multidecadal variability that characterizes Alaskan temperatures. The past 30 years have been warmer than the earlier warm period of the 1920s through the early 1940s, although the occasional peaks during the early warm period were comparable to the mean statewide temperature of the past 30 years. This finding is also consistent with that of Bekryaev et al. (2010) for the whole Arctic.

The statewide average precipitation departures (Fig. 6b) are characterized by large variability. The wettest period occurred in the 1920s, and the driest period in the 1970s. When displayed as a percent of average, statewide precipitation variability is generally subdued relative to the anomalies since the influence of the wetter coastal regions is further reduced (their influence already being reduced by the area weighting). The main difference from the anomalies is that the wettest period in terms of percent of average occurred in the 1960s instead of the 1920s. The shifted peak is likely due to the further enhanced influence of the North Slope division wet period in the 1960s (see Fig. 5b) when the precipitation variability is normalized to percent. No multidecadal periods are consistently wet or dry, as excursions of opposite sign occur during any such period. While the second half of the overall period is slightly drier than the first, there is no compelling indication in Fig. 6b of a trend in the statewide precipitation. There are suggestions of a 20-yr periodicity in the statewide precipitation anomalies in the post-1960 portions of the curves in Fig. 6b. This periodicity does not correspond with the longer cycle of the Pacific decadal oscillation. Moreover, the apparent periodicity breaks down in the decades prior to 1960. Without a known mechanism and also lacking robustness over time, this apparent cycle can only be noted here as a possible subject for further investigation.

The results presented thus far have been for annually averaged temperatures; the seasonal climate variability of the divisions will now be described. Figure 7 provides a seasonal breakdown of the time series of temperature and precipitation, expressed as 5-yr running averages as in Figs. 4 and 5. It is readily apparent from Figs. 7a–d that there is much greater variability in winter than in the other seasons. By contrast, the variance of the summer temperatures is the smallest of the four seasons. There are weak signatures in all seasons of the multidecadal temperature variability discussed above, although this variability tends to be obscured by shorter excursions. The North Slope deviation noted in the annual

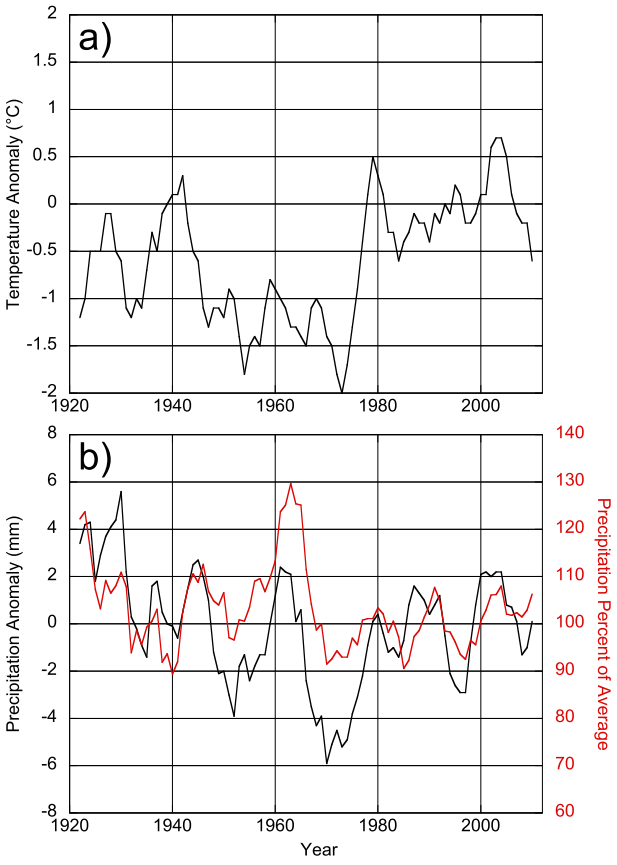

FIG. 6. Annual 5-yr running averaged statewide anomalies of (a) temperature and (b) precipitation with percent of average. Statewide values are based on an area-weighted (based on total geographic area of the divisions) average of the 13 annual divisional anomalies. Statewide temperatures also track PDO variability while precipitation displays little if any multidecadal variability.

temperatures is most apparent in the autumn and winter temperatures of the most recent decade. The North Slope division is also notable for its relatively cold autumn temperatures from the 1950s through the 1980s, although the magnitude of these negative anomalies may be enhanced by the effect of the recent autumn warming on the period-of-record mean used in calculating the departures.

The seasonal precipitation departures (Figs. 7e–h) are largest in winter and autumn, which are the seasons of greatest precipitation in most of the coastal divisions. The divisional departures are relatively small in summer, especially in the more recent decades. Notable features of the seasonal precipitation time series are the wet events in several coastal divisions during autumn over the first few decades, and the dry winters in several divisions from the 1950s through the 1970s. The past few decades have seen no negative winter departures as large as those of the 1950s–1970s.

b. Trends

The low-frequency variability discussed in the preceding section confounds the identification of trends in the time series of divisional temperature and precipitation. To highlight the variability of the trends within the 93-yr period of this study, we show in Fig. 8 the trends of the annual divisional temperatures and precipitation amounts for all 30-yr periods. The trends are plotted against the ending year of the 30-yr period. Outstanding features of Fig. 8a are that 1) the 30-yr trends of temperature are generally coherent across the divisions and 2) the 30-yr trends vary substantially, in magnitude and sign, over the 93-yr period of record. The temperature trends for most regions were negative for the 30-yr periods ending from 1955 through the late 1970s; all trends were positive for 30-yr periods from about 1980 through 2005, and the trends for the most recent period (30 years ending 2007–12) have been close to zero for all divisions except the North Slope, which has continued to warm. The divisions in which the trends have varied with the largest amplitude over time have been the North Slope and the Interior, consistent with the broader hemispheric pattern of polar amplification (Serreze and Francis 2006).

The 30-yr precipitation trends in Fig. 8b also vary with time, although only the southern and southeastern coastal divisions (dashed lines in Fig. 8) show trends with large amplitude. Most of the coastal divisions show negative precipitation trends for 30-yr periods ending between the 1950s and early 1970s, and positive trends over periods ending from the late 1970s to about 2000. An exception is the Southern Panhandle division, for which the trends are out of phase with the divisions to the north and west. Variations in prevailing storm tracks likely explain this discrepancy since synoptic-scale storms are the main source of precipitation in the coastal divisions. As was the case shown in Fig. 5, when annual precipitation is evaluated as a percentage of average, the relative magnitudes of the trends are altered (Fig. 8c), but signs remain the same. For precipitation percentage of average, the trends of the coastal divisions are reduced with the North Slope having the greatest trends in magnitude.

Figure 9 shows the seasonality of the temporally varying trends. It is apparent that the trends of annual temperature in Fig. 8 are determined primarily by the trends during winter; the springtime trends also contribute in some divisions. Figure 9 also highlights the amplification of the trend in the North Slope division, where the recent warming trend is strongest in autumn and spring. Figures 9e–h show that the negative trends of annual precipitation seen in Fig. 8 from the 1950s to the

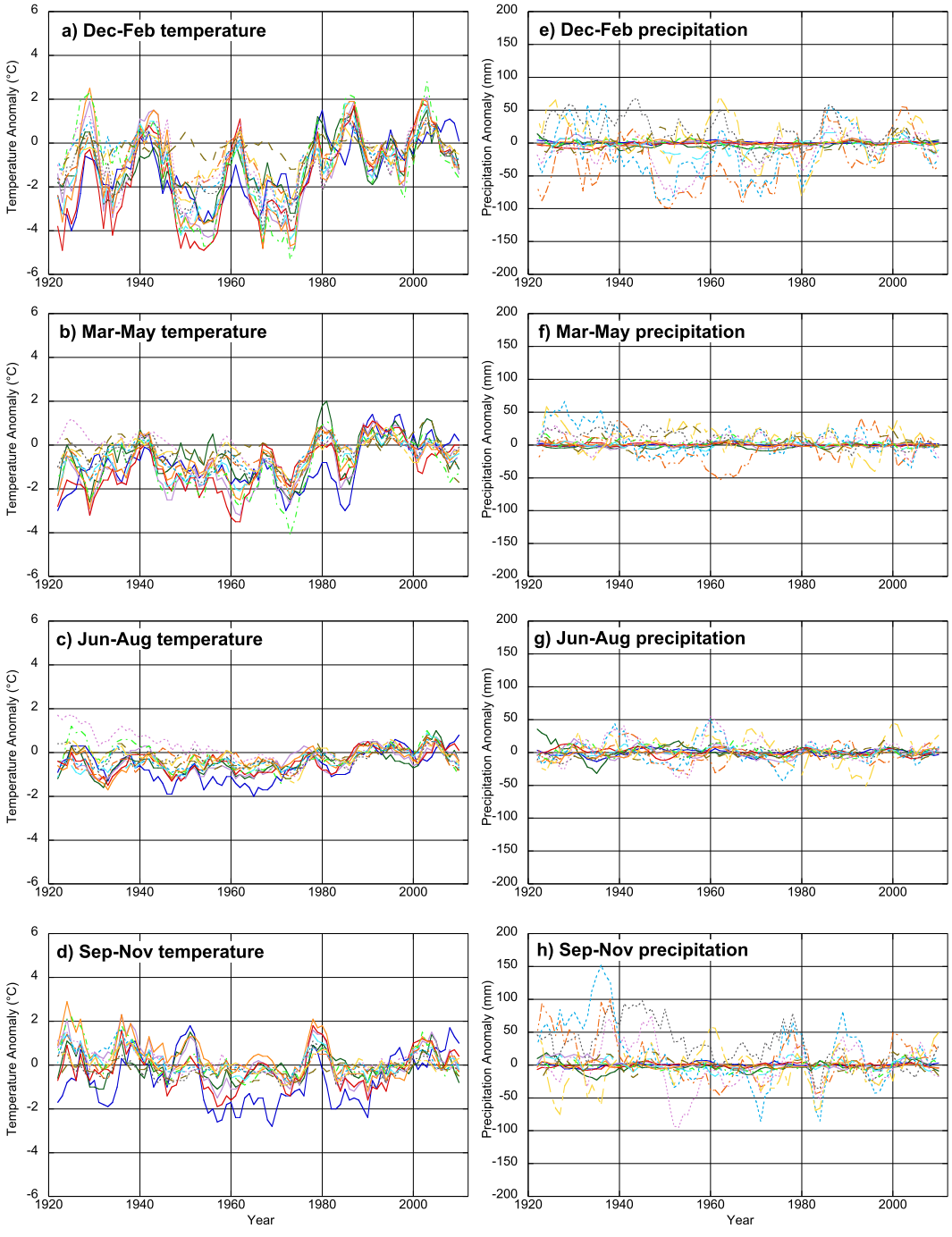

FIG. 7. Seasonal 5-yr running averaged divisional anomalies of (a)–(d) temperature and (e)–(h) precipitation anomalies for the 13 Alaska climate divisions. Seasons are December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON). See Fig. 4 or 5 for legend of line colors. Both temperature and precipitation variability also have seasonal differences.

1970s arise mainly from the trends in winter and spring, and in some divisions from the trends in autumn (Fig. 9h). The positive trends of annual precipitation from the 1970s onward are due mainly to trends in winter (Fig. 9e).

The primary message of Figs. 8 and 9 is that trends of Alaskan temperature and precipitation are strongly dependent on the time frame chosen for analysis. This reality has important implications for assessments of

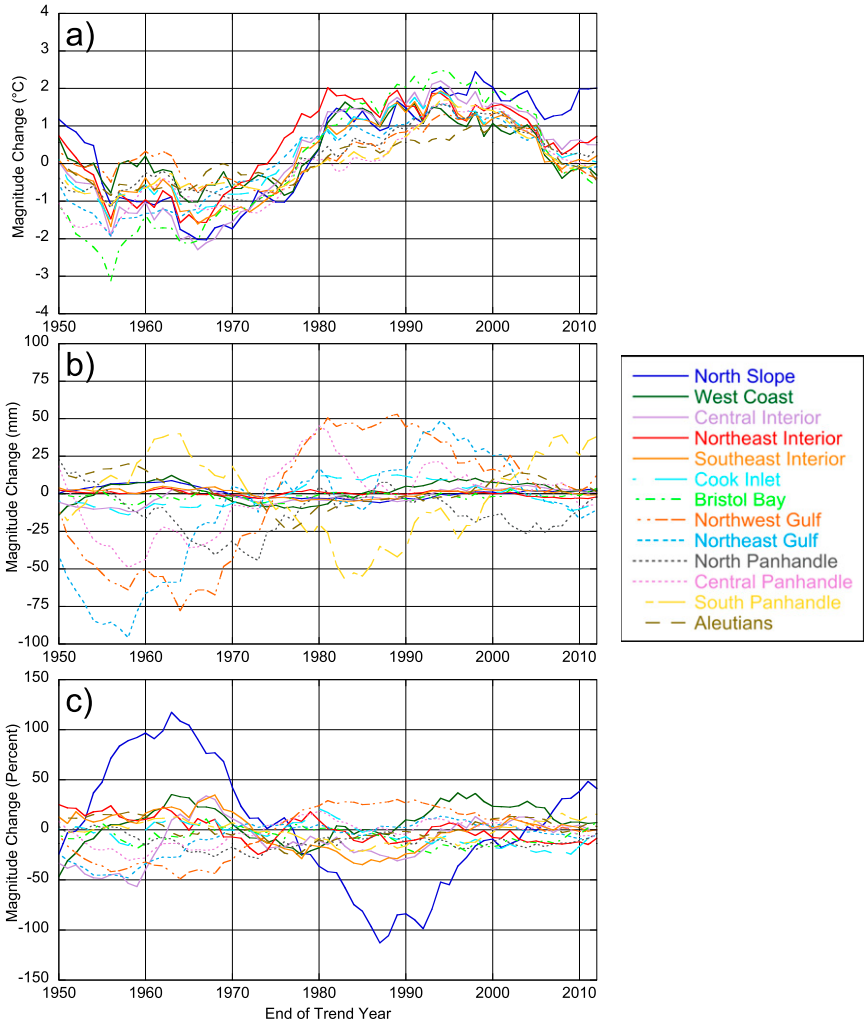

FIG. 8. Annual 30-yr running magnitude change (trend coefficient times number of years) of divisional anomalies of (a) temperature and (b) precipitation and (c) precipitation percent of average for the 13 Alaska climate divisions. The ending year of each 30-yr period is indicated on the plots. Trends in temperature are similar among divisions, while they are more varied for precipitation.

impacts associated with trends, and it has motivated a closer look in this study. In Fig. 10, the divisional trends are mapped for the entire period of record (1920–2012) and for three nonoverlapping subperiods, each of about 30-yr duration: 1921–50, 1951–80, and 1981–2012. It should be noted that the trends for each period are computed using linear least squares regression, and the changes plotted in Fig. 10 are the slopes [°C (yr)$^{-1}$] multiplied by the number of years in the period or subperiod. Because the 30-yr regression lines are discontinuous at the subperiod boundaries, the change over the entire 93-yr period is not equal to the sum of the changes in the three subperiods.

When the trends are evaluated over the entire period of record (Fig. 10a), a polar-amplified warming dominates Alaska. Only the small Central Panhandle division shows a cooling. The warming is largest in two northern regions, the North Slope (1.6°C) and the Northeast Interior (1.8°C). The overall pattern is consistent with a combination of polar amplification and the tendency for temperature variations to have greater magnitudes in inland than in coastal areas. While this pattern is consistent with expectations in a warming world, the trend maps for the three 30-yr subperiods are very different. The 1921–50 and 1981–2012 subperiods are characterized by cooling over most of the southern divisions and by a near-zero trend in the statewide average temperature (numbers in upper right of each panel). Only the North Slope and Northeast Interior show warming greater than 0.2°C in these two subperiods. By

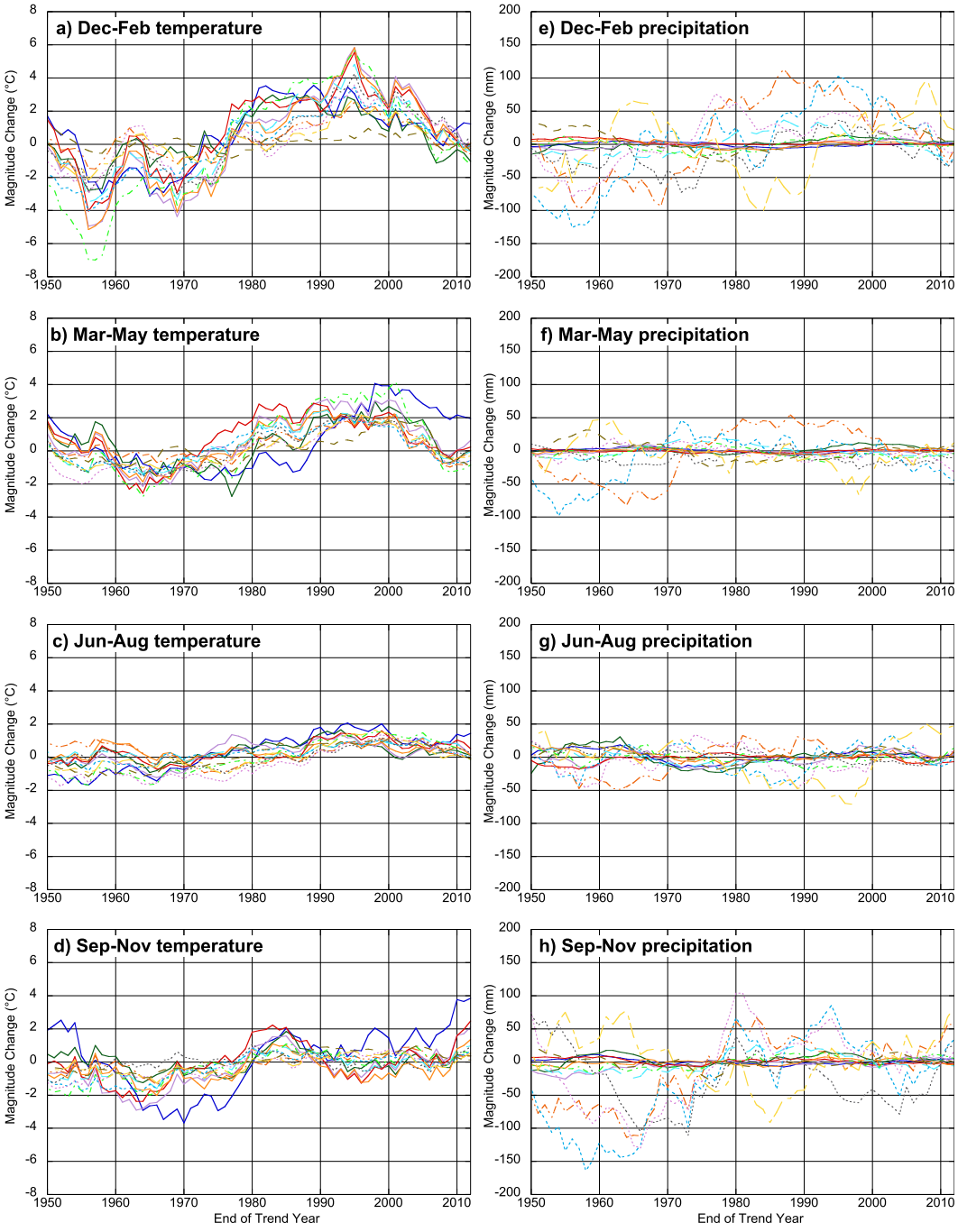

FIG. 9. Seasonal 30-yr running trends expressed as magnitude change (trend coefficient times number of years) of divisional anomalies of (a)–(d) temperature and (e)–(h) precipitation for DJF, MAM, JJA, and SON. The ending year of each 30-yr trend period marks the location of the point on the plots. See Fig. 8 for legend of line colors. The greatest trends in temperature are during the winter. The trends are less coherent for precipitation; largest trends overall occur in fall and winter.

contrast, the period 1951–80, which includes the rapid shift from a negative to a positive PDO noted earlier, shows warming over nearly the entire state. The spatial patterns for the 1951–80 subperiod and the overall 93-yr period are quite similar. Given the history of the PDO (Fig. 4), it is apparent that 30-yr trends over nearly all of Alaska's climate divisions are largely driven by the PDO, perhaps in combination with other large-scale

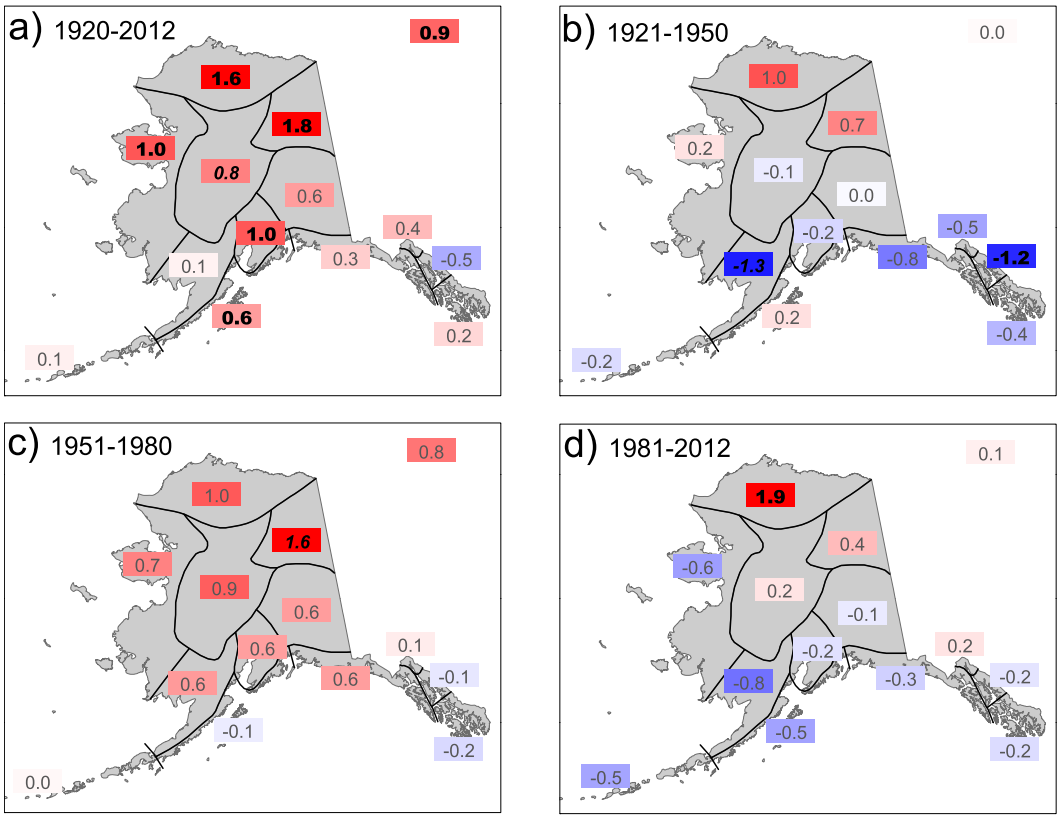

FIG. 10. Total change (trend coefficient times number of years) of annual divisional and statewide average temperature anomalies for (a) 1920–2012, (b) 1921–50, (c) 1951–80, and (d) 1981–2012 (°C). The statewide trend is shown in the upper right corner. Shading of box depends on the size of the trend. Trends significant at the 95% (90%) level are shown in boldface (italic). The full period had the most significant warming with mixed trends in the subperiods. There has been significant warming in the Arctic division over the most recent 30 years.

modes of ocean–atmosphere variability. The only exception is the North Slope, which has shown the greatest warming (1.0°C or larger) in every subperiod.

To address the intraseasonal variability of the trends, Fig. 11 shows the trends in Fig. 10 broken down into calendar months. For the entire 1920–2012 period (top panel), the polar-amplified warming is apparent in most months except for August, October, and November. October and November stand out as months with cooling over much of the state. The calendar months with the strongest warming are December, April, and May. The first 30-yr subperiod displays a mix of warming and cooling, consistent with the statewide trend of 0.0 in the annual mean temperature (Fig. 10b). Cooling is most widespread in November, December, and August, while March is the only month in which warming dominates most of the state. The second 30-yr subperiod, 1951–80, indeed shows a predominance of warming, although the warming across divisions and calendar months is not as widespread as in the full period, 1920–2012. There is substantial cooling in June and December, especially in the Panhandle divisions, although these divisions are much smaller in area than the Interior regions that show the stronger warming. Finally, the most recent subperiod, 1981–2012, is characterized by a mixed pattern of calendar months with warming and cooling, although the former predominates. Months with substantial cooling over large areas (including the Interior divisions) are January, March, and December. The combination of calendar months with warming and cooling undoubtedly contributes to the small overall trends for the period (including the statewide net change of 0.1°C) seen in Fig. 10d.

Figure 12, the precipitation counterpart of Fig. 10, shows the divisional precipitation changes for the entire 93-yr period (Fig. 12a) and for the three 30-yr subperiods (Figs. 12b–d). Consistent with the 30-yr running trends in Fig. 8, the trends of precipitation are much more heterogeneous in space and time than the trends of temperature. As indicated by the area-weighted statewide average changes (numbers in upper right of the panels), there is a net drying over the 93-yr period and

1920-2012	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
North Slope	1.9	**3.8**	***2.0***	1.4	**2.1**	**1.2**	**1.2**	0.9	**1.5**	0.6	0.2	***2.0***
West Coast	1.0	2.3	1.5	0.4	**1.8**	0.6	**1.8**	0.7	0.8	-0.5	0.2	2.1
Central Interior	-0.3	1.0	1.4	**3.1**	**2.0**	**0.9**	**1.2**	0.2	0.5	-1.7	-1.6	2.6
Northeast Interior	1.8	2.0	0.5	**4.2**	**2.9**	**1.2**	**1.1**	0.6	**1.5**	0.0	-0.1	**5.6**
Southeast Interior	0.4	0.4	0.8	**2.6**	**1.4**	***0.8***	**1.4**	0.3	0.3	**-2.0**	-1.9	2.6
Cook Inlet	1.8	0.8	1.4	**1.6**	**1.7**	**1.0**	**1.3**	**0.9**	***0.7***	-0.7	-1.1	**2.8**
Bristol Bay	-0.7	0.2	1.1	1.1	**1.4**	-0.6	0.0	-0.1	0.2	***-1.4***	-1.0	1.1
Northwest Gulf	1.5	0.3	0.5	**1.1**	**1.4**	0.5	**0.7**	**0.8**	0.4	-0.4	-1.1	**1.9**
Northeast Gulf	0.2	0.4	0.4	**1.0**	**1.5**	***0.6***	**0.6**	***0.5***	-0.3	-0.5	***-1.4***	0.8
North Panhandle	0.8	1.1	0.5	**1.1**	0.4	-0.2	-0.2	0.3	0.2	0.5	-0.9	1.5
Central Panhandle	0.8	1.1	0.0	-0.4	**-1.0**	**-1.7**	**-1.5**	**-1.1**	**-0.7**	-0.2	-1.3	0.3
South Panhandle	0.9	1.1	0.4	***0.7***	0.3	-0.2	0.1	0.0	0.1	-0.3	-0.7	0.6
Aleutians	-0.7	0.8	-0.7	-0.1	0.4	0.5	0.0	-0.2	0.1	***0.5***	0.3	0.8
Statewide	0.7	1.5	1.2	**1.8**	**1.8**	**0.7**	**1.1**	0.4	0.7	-0.8	-0.8	***2.4***

1921-1950	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
North Slope	2.0	2.6	***2.9***	2.3	0.4	**-2.1**	-1.0	-1.1	0.7	2.7	2.0	0.4
West Coast	-0.3	3.1	-1.1	2.7	0.7	-0.3	1.2	-1.4	0.3	1.1	-1.4	-2.9
Central Interior	0.4	0.9	1.6	0.2	-0.6	-0.3	***1.3***	-1.4	0.5	0.2	-3.5	-1.2
Northeast Interior	3.5	0.9	2.5	1.2	0.6	-0.2	0.5	-1.1	0.9	0.3	-1.5	0.6
Southeast Interior	1.5	-0.1	1.9	0.7	0.3	0.0	0.8	-1.3	0.9	-0.8	-3.4	-0.5
Cook Inlet	0.6	0.6	0.1	0.2	0.0	-0.2	0.4	-0.2	0.4	-0.6	-3.2	-0.7
Bristol Bay	-2.1	-0.7	-0.3	0.8	0.4	***-1.6***	-0.3	-0.6	-0.1	-1.5	***-4.1***	**-5.2**
Northwest Gulf	2.0	0.4	0.1	0.8	0.2	0.4	0.5	1.0	0.7	-0.1	***-2.4***	-1.2
Northeast Gulf	-1.2	-2.0	-0.1	-0.1	0.9	0.1	-0.4	-0.8	-0.3	-0.8	***-2.7***	-2.1
North Panhandle	1.3	-1.9	1.1	-0.5	-0.1	0.0	-0.7	-0.8	0.4	-1.3	-3.0	-1.1
Central Panhandle	0.1	-2.4	0.1	-1.3	**-1.1**	-0.6	***-1.5***	**-1.8**	-0.5	-0.9	***-3.0***	-1.9
South Panhandle	-1.4	-0.7	0.1	-0.3	0.5	-0.9	-0.7	**-1.3**	0.3	-0.6	-0.8	0.0
Aleutians	-0.2	***2.0***	-1.4	0.4	0.1	-0.3	***-0.9***	-0.7	-0.7	-0.4	-0.6	-0.3
Statewide	0.6	1.1	0.9	1.1	0.3	-0.6	0.4	-1.1	0.4	0.4	-1.9	-1.4

1951-1980	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
North Slope	***4.2***	3.5	0.4	-2.4	-0.2	1.0	0.3	1.1	1.2	-0.5	1.8	1.4
West Coast	3.9	0.8	0.9	-1.0	-0.2	-1.2	***1.4***	**1.7**	1.1	0.6	0.0	1.6
Central Interior	1.1	0.5	1.6	1.0	1.4	-0.4	**1.5**	**1.9**	1.5	1.1	0.1	0.1
Northeast Interior	5.0	-0.4	2.3	2.4	**2.7**	-0.2	0.3	0.9	***1.8***	2.6	0.8	1.7
Southeast Interior	1.6	0.3	2.1	1.1	0.7	-0.2	0.6	0.7	0.8	1.2	-0.4	-0.9
Cook Inlet	0.9	1.2	2.6	0.6	0.1	-0.6	0.2	0.6	0.7	1.3	0.0	-0.7
Bristol Bay	2.5	0.4	2.3	0.5	-0.1	-1.2	-0.1	0.4	0.7	0.4	0.0	1.5
Northwest Gulf	0.4	-0.5	1.0	0.3	-0.2	-0.5	-0.4	-0.3	-0.2	0.3	-0.5	-0.7
Northeast Gulf	0.4	0.7	**2.1**	***1.2***	0.4	0.1	0.3	0.7	0.5	1.0	0.1	-0.4
North Panhandle	0.0	0.0	1.7	1.0	-0.2	-0.7	***-1.0***	0.3	0.5	***1.6***	0.1	-1.5
Central Panhandle	0.1	-0.3	1.2	0.4	-0.4	-1.2	**-1.5**	0.4	0.3	0.9	-0.5	-1.5
South Panhandle	-0.9	0.3	1.0	0.4	-1.0	-0.2	-0.9	0.1	-0.1	0.3	-0.5	-1.2
Aleutians	0.3	-1.1	-0.3	0.0	-0.1	0.6	0.3	-0.1	0.1	-0.2	0.0	0.8
Statewide	2.5	0.8	1.5	0.2	0.5	-0.4	0.7	1.1	1.1	0.8	0.3	0.6

1981-2012	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
North Slope	-1.1	2.1	-0.5	***3.6***	1.8	1.0	**1.7**	***2.2***	***2.3***	**4.8**	***4.7***	1.2
West Coast	-4.1	1.1	**-3.7**	1.3	0.3	0.2	-0.2	0.4	1.2	1.2	-1.2	-1.6
Central Interior	-4.8	3.2	**-4.3**	2.5	1.8	0.6	0.0	0.8	1.7	3.3	0.4	-1.9
Northeast Interior	-4.8	2.1	**-3.8**	1.8	1.7	0.9	0.7	1.2	1.8	2.6	2.3	-0.2
Southeast Interior	-4.4	2.4	***-4.0***	2.0	0.8	0.6	-0.1	0.5	1.0	2.0	0.3	-1.5
Cook Inlet	-3.6	1.6	**-3.1**	1.2	0.7	0.4	0.2	0.5	1.0	2.0	-0.2	-1.5
Bristol Bay	**-6.3**	4.3	**-6.3**	1.5	0.5	0.1	-0.5	0.1	0.7	***2.7***	-1.5	-3.9
Northwest Gulf	-2.6	1.1	**-3.2**	0.0	0.0	0.0	-0.4	-0.1	0.3	1.0	-0.3	-1.8
Northeast Gulf	-1.5	0.3	**-2.2**	-0.1	-0.2	0.0	-0.2	0.1	0.3	0.5	0.7	-0.2
North Panhandle	-1.1	0.7	-1.6	0.8	0.3	0.4	0.2	0.2	0.6	0.8	0.6	0.3
Central Panhandle	-1.0	0.3	**-2.4**	0.0	0.1	0.2	-0.5	0.0	0.2	0.2	0.8	0.2
South Panhandle	-1.1	0.0	**-1.5**	0.0	0.0	0.2	-0.5	0.0	0.3	0.2	0.6	0.0
Aleutians	-1.1	0.8	***-2.6***	-0.6	-0.5	-0.2	-0.4	0.1	0.4	0.3	-0.3	-0.8
Statewide	-3.8	2.2	**-3.4**	1.9	1.0	0.5	0.2	0.8	1.3	***2.5***	0.7	-1.1

-2.0 -1.0 0.0 1.0 2.0 °C

FIG. 11. Trend magnitudes (trend coefficient times number of years) of monthly divisional and statewide average temperature (°C). The magnitudes of the trends are shaded. Trends significant at the 95% (90%) level are in boldface (italicized).

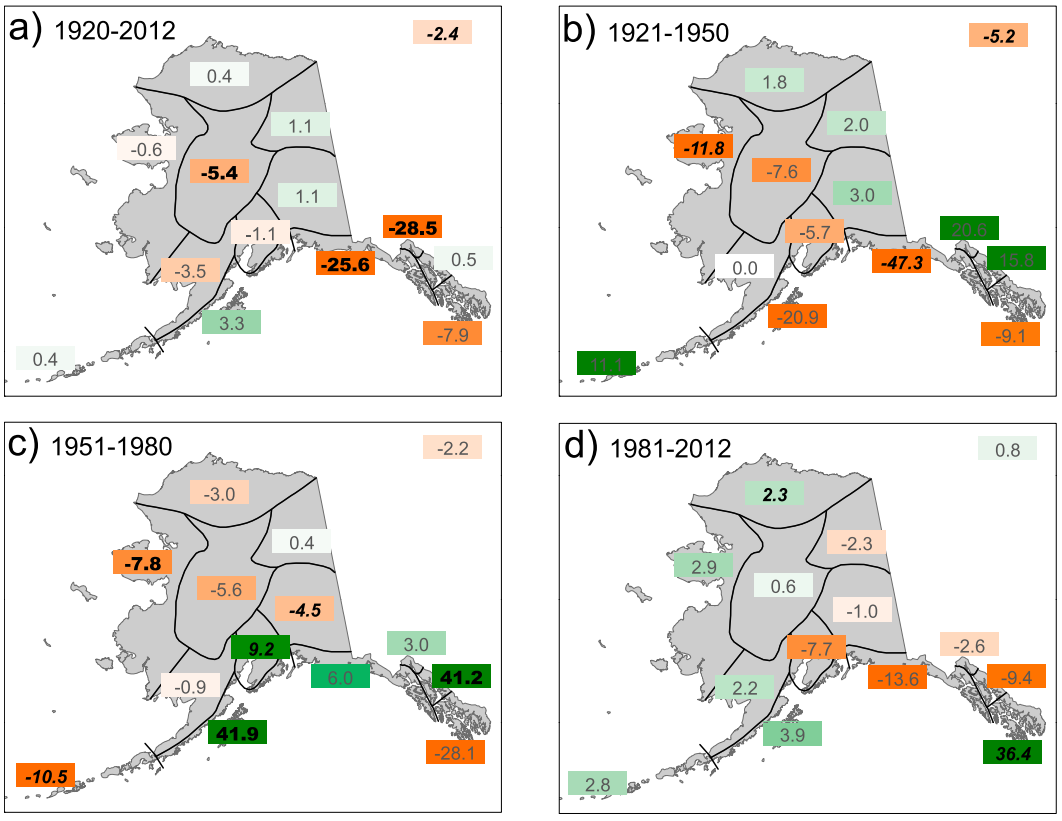

FIG. 12. Total change (trend coefficient times number of years) of annual divisional and statewide average precipitation anomalies for (a) 1920–2012, (b) 1921–50, (c) 1951–80, and (d) 1981–2012 (mm). The statewide trend is shown in the upper right corner. Shading of box depends on the size of the trend. Trends significant at the 95% (90%) level are shown in boldface (italic). The precipitation trends are of mixed sign over the full period and three subperiods.

the first two 30-yr subperiods. However, these net changes are small residuals of largely offsetting divisional changes. The regions with the strongest indications of drying over the full (1920–2012) record are the Panhandle divisions in the Southeast and the Central Interior divisions. The strongest indications of increasing wetness are in the southern (coastal) divisions during the two most recent 30-yr subperiods. In general, the southern and southeastern coastal divisions show the greatest temporal variability in their changes, and the Interior divisions are characterized by small changes of precipitation, consistent with the 30-yr running trends in Fig. 8b.

The depiction of the precipitation changes by calendar month (Fig. 13) confirms the heterogeneity of the precipitation changes. While the largest changes tend to occur in the cold seasons and in the coastal divisions, there is little cohesiveness in the signs of the changes. There are hints of summer/autumn wetting and winter/spring drying in the trends of the Panhandle divisions during the first 30-yr period (1921–50), but overall there is little evidence of systematic changes across calendar months, across the different time periods, or across the different portions of the state. This absence of coherent trends of precipitation is consistent with the trends of annual and decadal precipitation in the global and national assessments summarized in section 1.

Finally, Fig. 14 shows the divisional and statewide temperature and precipitation changes on a seasonal and annual basis over the period 1949–2012. This time period was chosen to permit comparisons with the corresponding tabular depiction of trends at 19 first-order observing stations by the Alaska Climate Research Center (ACRC 2013; http://climate.gi.alaska.edu/ClimTrends/Change/TempChange.html) as well as the Alaskan statewide time series shown by Wendler et al. (2012). This time period has the advantage that it includes nearly three decades before the 1976/77 PDO shift from the ''Alaska cold'' phase to the ''Alaska warm'' phase, as well as approximately a decade after the shift back to the Alaska cold phase. Figure 14a shows statewide warming that is strongest in winter (3.7°C) and weakest in autumn (0.4°C). Consistent with the results in Figs. 9 and 11, the

1920-2012	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
North Slope	-0.4	-0.4	-0.8	1.5	2.3	1.5	-3.3	5.1	**7.3**	-2.1	-1.2	-2.0
West Coast	-9.4	-2.1	-1.7	4.4	**7.9**	**10.0**	-14.8	-20.1	-14.2	7.9	**16.2**	***7.8***
Central Interior	-7.9	***-7.9***	**-10.8**	2.2	1.7	7.9	-7.2	-12.5	**-22.3**	***-11.3***	0.0	2.1
Northeast Interior	**15.2**	-1.1	-3.3	***3.3***	-2.9	-2.9	-8.5	-4.7	-0.3	**8.6**	0.0	**7.3**
Southeast Interior	-7.9	1.3	**-9.4**	1.1	-2.7	**14.2**	***15.8***	-2.7	-5.4	-4.0	5.4	**8.6**
Cook Inlet	-10.4	-2.5	-8.1	4.5	5.8	4.2	-4.6	-3.4	-0.3	-13.9	3.2	10.8
Bristol Bay	-5.3	**-14.9**	**-17.5**	-6.2	-5.1	12.1	-0.1	-11.8	0.3	**-23.3**	**29.2**	-0.4
Northwest Gulf	***69.1***	14.0	-3.0	4.6	12.5	-0.4	-2.5	-2.4	29.5	***-84.8***	-42.2	***72.2***
Northeast Gulf	4.2	-40.2	-21.8	***-39.9***	-35.7	23.1	***-44.7***	-5.5	41.9	**-125.9**	**-118.2**	52.0
North Panhandle	**-72.5**	-27.9	-29.4	**-42.3**	-9.6	4.9	-2.0	***23.8***	3.0	**-89.6**	**-109.5**	-16.0
Central Panhandle	**66.0**	-14.7	8.9	***-25.5***	***-31.6***	3.7	4.8	-11.9	***64.7***	-26.6	-48.4	17.3
South Panhandle	0.1	-39.5	-6.8	-41.6	-6.5	12.7	1.5	-17.7	**95.4**	0.1	-55.2	-39.2
Aleutians	13.2	-10.5	5.7	-11.1	-13.2	-7.0	***13.5***	3.1	5.7	-13.3	7.2	16.8
Statewide	-1.3	-5.8	***-7.0***	-1.4	-0.4	**7.5**	-5.2	-8.0	-1.1	**-11.8**	-2.1	7.0

1921-1950	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
North Slope	-3.1	-0.4	**-4.8**	3.1	0.7	6.5	-10.9	**29.5**	**15.7**	-8.4	-0.5	**-5.7**
West Coast	***-32.6***	1.5	-12.5	-2.4	10.4	-13.6	-22.2	-21.9	***-39.0***	5.8	6.1	***-15.6***
Central Interior	-7.6	-7.4	-11.9	-0.8	-4.8	4.3	**-37.2**	28.0	**-37.3**	-12.1	-3.5	-1.3
Northeast Interior	**10.7**	0.5	6.2	3.6	-0.3	-3.7	-18.5	-6.2	-4.6	***14.2***	4.5	**15.7**
Southeast Interior	8.6	-1.1	-14.9	11.1	-8.2	5.3	18.1	26.8	-15.9	-8.7	6.0	***12.5***
Cook Inlet	9.8	-25.6	-11.7	**-27.9**	9.7	**28.1**	5.1	10.4	-18.4	-15.3	-21.9	-10.5
Bristol Bay	-9.1	-11.1	-1.7	-15.1	-6.3	20.9	0.7	36.5	-7.1	-24.7	8.1	14.3
Northwest Gulf	63.1	-6.4	-11.8	-69.2	44.4	0.1	1.1	34.4	46.9	***-180.7***	-93.2	-40.6
Northeast Gulf	-13.6	**-164.5**	-66.1	**-104.5**	-18.7	47.6	-22.8	-4.4	94.1	-101.7	-149.0	-64.4
North Panhandle	37.3	-36.3	19.4	-29.0	***29.0***	-8.5	32.3	33.4	***89.6***	100.2	24.7	-75.0
Central Panhandle	47.3	**-76.7**	-21.6	-27.6	17.0	20.7	32.4	29.0	84.1	69.4	37.8	-25.9
South Panhandle	2.1	***-114.1***	-43.7	28.2	-51.3	60.0	50.1	27.0	105.8	45.4	-114.7	-104.1
Aleutians	20.4	***32.8***	-16.4	-7.4	6.1	***-22.3***	3.9	***25.2***	27.6	3.9	42.5	37.9
Statewide	-4.2	***-12.8***	***-11.6***	-7.0	-0.4	5.7	-11.3	14.6	-6.7	-12.4	-9.6	-7.1

1951-1980	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
North Slope	-4.0	-4.4	-3.2	-3.0	1.1	11.8	-14.5	-10.4	1.0	-7.6	1.8	-4.0
West Coast	-6.0	**-13.2**	-8.0	1.5	***-8.8***	**21.9**	-5.1	**-71.3**	-19.5	6.3	8.6	0.7
Central Interior	-6.5	**-14.6**	-3.2	3.9	0.5	9.7	-6.6	**-50.0**	-23.9	6.9	12.2	3.8
Northeast Interior	1.7	-2.5	-4.1	4.3	-5.6	8.0	-7.8	3.4	-2.9	**10.2**	-2.2	1.4
Southeast Interior	-6.9	***-8.7***	-1.7	1.7	-0.3	-3.4	-0.4	-12.3	***-19.9***	1.3	2.4	-5.0
Cook Inlet	18.4	17.1	***19.5***	***22.3***	5.4	12.6	-10.0	***-36.2***	13.4	27.7	0.7	19.3
Bristol Bay	**-25.7**	-18.7	-9.2	11.6	14.1	19.4	12.3	-20.1	-13.5	20.7	-0.3	-1.1
Northwest Gulf	***78.3***	70.3	11.4	***46.1***	***79.0***	25.7	-5.8	34.2	83.5	***97.4***	-6.8	-10.9
Northeast Gulf	8.5	-11.0	24.0	11.4	5.0	12.3	-8.7	-89.1	25.2	***151.8***	-34.9	-22.1
North Panhandle	***-74.1***	-13.3	20.6	-20.5	-6.0	14.5	***20.1***	11.6	-6.8	116.3	-15.9	-11.3
Central Panhandle	**107.6**	12.2	12.6	11.4	-31.4	26.0	51.6	-9.2	68.5	**162.8**	59.7	23.3
South Panhandle	-64.4	-47.7	-24.3	-24.9	19.0	-10.3	24.4	-75.6	12.8	-12.0	-48.6	-85.4
Aleutians	-19.9	-20.8	***-25.8***	11.5	**-39.8**	-18.7	-1.9	-14.3	4.9	-23.3	14.3	8.1
Statewide	-3.6	-7.9	-2.5	4.6	1.5	***11.2***	-4.0	**-33.6**	-7.1	**15.8**	2.3	-2.3

1981-2012	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
North Slope	0.2	2.3	1.7	0.1	**3.8**	2.8	4.2	-2.3	1.9	***5.5***	**7.4**	**3.9**
West Coast	-0.6	10.2	1.0	0.4	-1.2	2.6	11.6	5.6	-12.8	2.4	5.0	2.5
Central Interior	-0.8	1.2	-5.4	-0.5	-3.1	12.4	-5.8	-0.5	-7.5	4.7	14.0	-0.4
Northeast Interior	5.0	0.6	3.0	-1.0	-2.7	-7.4	-8.9	-9.3	-0.2	-6.4	-1.5	-2.9
Southeast Interior	-0.4	0.2	1.2	0.5	1.5	3.7	-2.3	-1.7	-1.5	***-9.3***	-1.2	-4.1
Cook Inlet	***-42.3***	13.2	-13.8	4.3	-9.5	-3.5	5.7	-11.5	-23.5	-3.5	10.7	-22.8
Bristol Bay	-18.6	3.1	-12.5	4.5	-10.6	11.4	23.5	-1.0	5.7	7.9	13.1	-1.8
Northwest Gulf	***-132.0***	89.7	-29.3	22.6	2.0	-39.5	***52.0***	-25.4	21.7	96.6	61.6	-57.1
Northeast Gulf	-67.0	-20.4	-29.1	-50.4	-38.5	-45.2	30.2	-27.1	29.0	1.2	48.8	9.1
North Panhandle	-44.0	-53.1	5.5	-26.1	-9.1	-3.0	-5.3	9.2	20.6	-0.9	52.1	19.7
Central Panhandle	-33.0	-32.4	-5.8	-18.1	**-58.5**	-6.1	34.8	-12.7	46.1	-48.7	11.8	21.4
South Panhandle	30.0	-12.6	45.3	-24.1	-1.4	13.2	60.2	64.0	***133.6***	59.7	23.0	62.8
Aleutians	-1.3	1.8	-1.6	17.6	5.3	8.7	10.6	-12.2	-6.5	28.4	-11.3	1.5
Statewide	-9.6	4.3	-2.9	-1.4	-3.7	1.3	7.5	-1.8	1.0	5.0	10.5	-0.5

-40.0 -20.0 0.0 20.0 40.0 mm

FIG. 13. Trend magnitudes (trend coefficient times number of years) of monthly divisional and statewide average precipitation (mm). The magnitudes of the trends are shaded. Trends significant at the 95% (90%) level are shown in boldface (italicized).

a) 1949-2012 Total change in temperature (°C)

	DJF	MAM	JJA	SON	Annual
North Slope	**3.9**	**2.2**	**2.1**	1.7	**2.4**
West Coast	**2.6**	1.1	**1.2**	0.0	**1.1**
Central Interior	**4.3**	**2.5**	**1.2**	0.4	**2.0**
Northeast Interior	**4.9**	**2.6**	**1.3**	1.1	**2.4**
Southeast Interior	**4.1**	**1.6**	**0.7**	-0.4	**1.5**
Cook Inlet	**4.0**	**1.9**	**0.9**	0.3	**1.7**
Bristol Bay	**4.2**	**2.2**	**0.8**	0.4	**1.8**
Northwest Gulf	**1.7**	**1.2**	0.4	0.2	**0.8**
Northeast Gulf	**2.9**	**1.5**	**0.9**	0.5	**1.4**
North Panhandle	**3.3**	**1.5**	0.4	0.2	**1.3**
Central Panhandle	**2.9**	**0.9**	0.2	0.4	**1.0**
South Panhandle	**2.1**	**1.2**	**0.7**	0.2	**1.0**
Aleutians	0.1	0.3	**0.8**	**0.8**	0.4
Statewide	**3.7**	**1.9**	**1.2**	0.4	**1.7**

b) 1949-2012 Total change in mean accumulated precip (mm)

	DJF	MAM	JJA	SON	Annual
North Slope	-1.9	-0.8	-2.3	-1.2	-1.7
West Coast	**6.8**	3.3	-2.4	5.1	3.6
Central Interior	-0.3	-0.8	4.1	2.3	1.4
Northeast Interior	1.7	-0.6	0.5	0.0	0.5
Southeast Interior	-3.9	-1.0	0.8	0.7	-0.8
Cook Inlet	**18.2**	1.5	-2.0	13.8	**7.5**
Bristol Bay	-2.0	**-8.3**	-2.3	14.0	0.6
Northwest Gulf	**105.7**	**37.4**	***24.9***	43.8	**51.5**
Northeast Gulf	**65.6**	-11.7	-3.8	32.6	19.5
North Panhandle	-9.3	**-21.6**	-6.2	***-42.6***	**-19.7**
Central Panhandle	**56.3**	***-18.5***	5.4	**58.9**	**24.6**
South Panhandle	-0.8	-30.4	-9.1	9.3	-8.0
Aleutians	-6.3	**-17.2**	-1.6	-2.9	-7.0
Statewide	**7.2**	-1.1	0.2	6.2	**3.1**

FIG. 14. Trend magnitudes (trend coefficient times number of years) of seasonal/annual divisional and statewide average temperature (°C) and precipitation (mm) anomalies for 1949–2012. The magnitudes of the trends in (a) and (b) have equivalent shading to Figs. 11 and 13, respectively. Trends significant at the 95% (90%) level are shown in boldface (italicized).

divisions with the strongest warming are the North Slope, the Northeast Interior, and the Central Interior. The divisions with the weakest warming (<1.0°C) are the Aleutians and the Northwest Gulf. This geographical pattern matches closely the station-derived trends from the ACRC (2013), which shows that the Interior stations have experienced the strongest warming over 1949–2012. The change of annual mean temperature in Fig. 14a is 1.7°C, which agrees very well with the 1.6°C average for the 19 stations (ACRC 2013). The area-weighted statewide anomalies from the division data provide slightly enhanced trends relative to ACRC (2013) since the impact of the lower variability of the coastal stations is reduced. This is true since the interior divisions, while larger in geographic extent than those on the coasts, have fewer stations. We conclude that the divisional representation captures the patterns of temperature change deduced from the network of first-order stations in Alaska, while

enabling extensions of the information on temperature variations to the entire state and to longer time periods.

In keeping with our parallel examination of the divisional data on precipitation, Fig. 14b shows the changes of precipitation over the 1949–2012 period. In agreement with the results summarized earlier, the outstanding feature of Fig. 14b is the geographical and seasonal heterogeneity. There are indications of increases of precipitation in the southern coastal divisions in autumn and winter, as well as decreases in spring. However there are exceptions to these changes (e.g., the North Panhandle in autumn and winter and the Northwest Gulf in spring). Moreover, the statewide increases during autumn and winter do not have strong support in Fig. 13. Hence, any conclusions about trends of precipitation during 1949–2012 are open to question.

4. Conclusions

By extending the record of Alaskan divisional temperature and precipitation back to 1920, we have been able to document the variations and trends of two key climate variables, temperature and precipitation. Our analysis spans the entire state over a longer time period than in previous evaluations of Alaskan statewide climate variations. The use of the divisional framework highlights the greater spatial coherence of temperature variations relative to precipitation variations, and it allows us to show how variations and trends vary spatially within the state.

The divisional time series of temperature are characterized by large interannual variability superimposed upon low-frequency variability, as well as by an underlying trend. Much of the low-frequency variability corresponds to the Pacific decadal oscillation, a major mode of ocean–atmosphere variability in the North Pacific. The PDO association is manifested in the relatively warm period of the 1920s and 1930s, a cold period from the late 1940s through the mid-1970s, a warm period from the late 1970s through the early 2000s, and a cooler period in the most recent decade. An exception to the cooling of the past decade is the North Slope climate division, which has continued to warm, especially during autumn and winter when the impacts of extreme summer ice retreats have contributed to the warming. There has been a gradual upward trend of Alaskan temperatures relative to the PDO since 1920, resulting in a statewide average warming of about 1°C.

In contrast to temperature, relatively large variations of precipitation are generally limited to one or two climate divisions and have much less multidecadal character. On the basis of the area-weighted statewide average precipitation values, the wettest period occurred in the 1920s and the driest period in the 1970s.

In view of the multidecadal variations in the temperature record, it is not surprising that trends of the divisional temperatures and precipitation are strongly dependent on the time frame of the trend evaluation. In particular, trends over the 30-yr time period used for climatic normal vary widely from negative to positive during the 93-yr period examined here. The divisional trends were also shown to vary strongly by season over both 30-yr and the full 90-yr time frames. Moreover, trends for individual calendar months are sometimes of opposite sign than the seasonal trend, as seen by the recent (1981–2012) cooling during March and warming during April and May. Another example is the February warming bracketed by cooling in January and March for the 1981–2012 period. Even during the full time period (1920–2012), October and November show cooling despite the overall net warming during this period.

The combination of multidecadal variability and an underlying trend of temperature raise interesting possibilities for future decades. The cooling over the recent decade reduced the warming trends evaluated for the post-1920 and post-1949 time frames. However, to the extent that the cooling is a decadal-to-multidecadal manifestation of the PDO, the contribution of low-frequency variability to the temperature trend will eventually reverse, quite possibly in the next decade or two. At that time, an enhancement of the positive trend, perhaps accompanied by new maxima, could well be the scenario that unfolds in Alaska. If the past is a guide, the enhanced warming would be greatest in the Interior and North Slope divisions, which show greater multidecadal variability than the coastal and southern divisions.

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