Climate Divisions for Alaska Based on Objective Methods

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ABSTRACT

Alaska encompasses several climate types because of its vast size, high-latitude location, proximity to oceans, and complex topography. There is a great need to understand how climate varies regionally for climatic research and forecasting applications. Although climate-type zones have been established for Alaska on the basis of seasonal climatological mean behavior, there has been little attempt to construct climate divisions that identify regions with consistently homogeneous climatic variability. In this study, cluster analysis was applied to monthly-average temperature data from 1977 to 2010 at a robust set of weather stations to develop climate divisions for the state. Mean-adjusted Advanced Very High Resolution Radiometer surface temperature estimates were employed to fill in missing temperature data when possible. Thirteen climate divisions were identified on the basis of the cluster analysis and were subsequently refined using local expert knowledge. Divisional boundary lines were drawn that encompass the grouped stations by following major surrounding topographic boundaries. Correlation analysis between station and gridded downscaled temperature and precipitation data supported the division placement and boundaries. The new divisions north of the Alaska Range were the North Slope, West Coast, Central Interior, Northeast Interior, and Northwest Interior. Divisions south of the Alaska Range were Cook Inlet, Bristol Bay, Aleutians, Northeast Gulf, Northwest Gulf, North Panhandle, Central Panhandle, and South Panhandle. Correlations with various Pacific Ocean and Arctic climatic teleconnection indices showed numerous significant relationships between seasonal division average temperature and the Arctic Oscillation, Pacific–North American pattern, North Pacific index, and Pacific decadal oscillation.

1. Introduction

The climate of a geographic location is strongly linked to its latitude, elevation, and proximity to oceans. There has long been a great need to understand how the climate varies by region for climatic research and forecasting applications. Climate-classification techniques have often been employed to account for regional variability; the most well known being the Koeppen scheme (Koeppen 1923), which broadly classifies regions by their mean temperature and precipitation. The contiguous United States (CONUS) was first subdivided into broad climate regions in 1909 (Guttman and Quayle 1996). These regions were initially based solely on river drainage basins, but by as early as 1912 more-robust measures dividing the regions using mean temperature were employed (Guttman and Quayle 1996). The National Climatic Data Center (NCDC) currently maintains the set of official climate divisions for the United States.

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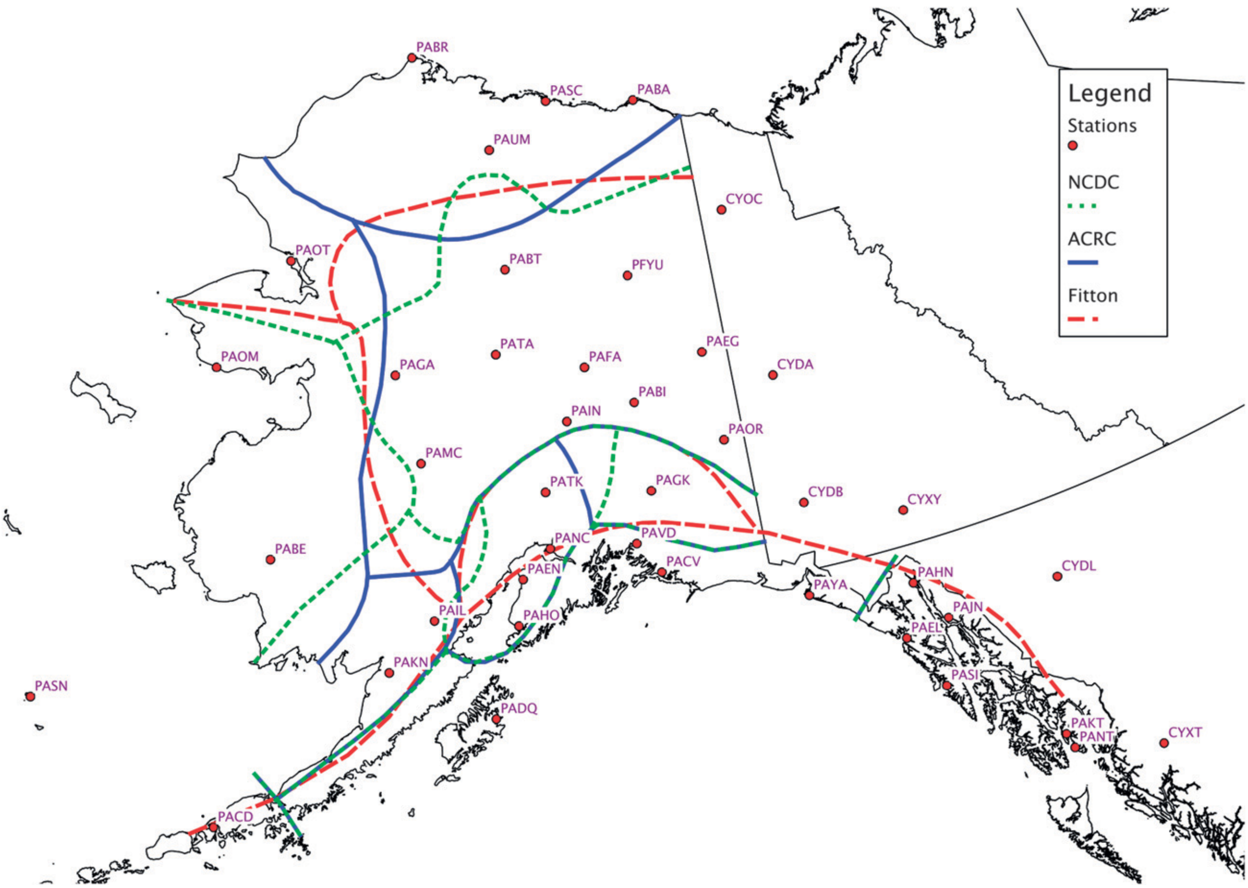

FIG. 1. Map of historical climate zones for Alaska. Fitton (1930) zones are outlined by red dashed lines, NCDC climate divisions are shown by green dashed lines, and the ACRC climate regions are delineated by solid blue lines, respectively. The stations used in the cluster analysis are shown by red dots with their airport codes (station list in Table 1). The climate zones have undergone only minor revisions since their inception and were drawn on the basis of mean station temperature and precipitation and/or by following major terrain features and river basins.

Because of Alaska's large geographical extent, complex terrain, and proximity to oceans and sea ice, its climate is highly regionalized. Zones of homogeneous climate type were first outlined in the 1920s by general examination of the mean temperature of the few weather observation stations available at the time (Fitton 1930; red dashed lines in Fig. 1). Although some of these initial boundaries intersected major terrain barriers, most notably the Brooks Range, Fitton (1930) noted the critical role of terrain boundaries in defining regional climate zones in Alaska. Later, a new set of boundaries was developed that was essentially based on drainage-basin regions (Searby 1968), and these boundaries are currently considered by NCDC to be the official climate divisions for Alaska (green dashed lines in Fig. 1; National Climatic Data Center 2002). The most recent update is by Shulski and Wendler (2007), who considered the NCDC climate divisions while updating the Alaska climate zones on the basis of annual mean temperature and precipitation (blue solid line in Fig. 1). Overall, 10–11 general climate zones have been traditionally identified, with disagreements as to the exact locations of the boundaries, some of which bisect major terrain barriers. Studies have also identified zones of similar surface characteristics (i.e., ecoregions) in Alaska (Gallant 1995; Simpson et al. 2007). Previous Alaska climate regions were all based on seasonal climatological means or annual means in temperature and precipitation. In this study, we employ cluster analysis on observed station temperature as an objective method to independently develop climate divisions for Alaska that are based on climatic variability and not on long-term seasonal climatological means, or ''climatologies.''

There is a pressing need to define official climate divisions for Alaska. The past climate zones defined for Alaska were based on short records of sparse station data and were meant to provide climate-type zones; therefore, they do not necessarily coincide with regions of homogenous climatic variability. Climate-type zones give valuable information about the general characteristics of the average season, but they are not as useful for seasonal climatic forecasting and research applications because they do not give any information on year-to-year variability. There is now available a relatively long time length of station and remotely sensed data as well as robust objective methods to properly identify climate divisions for Alaska that fill this need.

Climate divisions have a wide variety of applications beyond simply identifying regions with similar climate types and variability. In the CONUS, studies have shown the influence of climatic teleconnection indices in each division (Wolter et al. 1999; Budikova 2005), which is highly valuable for seasonal climatic forecasting. The CONUS climate divisions are currently used as the zones for the seasonal climatic predictions made by the Climate Prediction Center (CPC). Climate divisions are also widely used for hydrological applications such as drought monitoring in the CONUS. As a result, climate divisions not only give useful information on the spatial extent of regional climatic variability in Alaska but can also be used in the evaluation of diverse climate-related problems.

A wide range of large-scale climatic teleconnections affects Alaska in all seasons. One of the strongest links is between winter temperatures and the El Niño–Southern Oscillation (ENSO) in which the positive phase of ENSO results in above-normal temperatures (Papineau 2001). ENSO has also been shown to influence spring temperatures and consequently river-ice breakup in interior Alaska (Bieniek et al. 2011). North Pacific Ocean teleconnections such as the North Pacific oscillation/west Pacific pattern (Linkin and Nigam 2008), shifts in the Pacific decadal oscillation (PDO; Hartmann and Wendler 2005), and other climatic indices (Bourne et al. 2010) have all been linked with the climate of Alaska in some way. Sea ice also plays an important role and has been linked with summer land temperatures and tundra vegetation along the Arctic and western Alaska coastlines (Bhatt et al. 2010). In all of these studies it is apparent that climatic teleconnections affect different parts of Alaska in diverse ways. Therefore, regions with relatively homogeneous climatic variability forced by a variety of different climatic teleconnections must exist for Alaska.

Cluster analysis is a method that is commonly used to group databases by the degree of similarity in variability and was first applied to the atmospheric sciences by Wolter (1987). Cluster analysis has been employed to determine climate zones in the CONUS on the basis of station data (Fovell and Fovell 1993) and has also been applied to diverse climates such as Turkey (Unal et al. 2003) and Saudi Arabia (Ahmed 1997). Cluster analysis has also been applied regionally in the United States to identify climate zones in the northern plains (Bunkers et al. 1996), the Northeast (DeGaetano 1996), and the Carolinas (Rhee et al. 2008). Wolter and Allured (2007) developed climate divisions for the CONUS using an approach that is based on cluster analysis (e.g., Fovell and Fovell 1993) but using a simplified method to process the data and correlation analysis for verification. In our study we will draw on elements from all of these studies to form an objective basis for climate divisions in Alaska. Our analysis relied heavily on objective methods, but Alaska's vast size and relatively sparse station network meant that local expert knowledge was necessary to refine the final division boundaries. Local expert knowledge has been demonstrated to benefit scientific understanding of weather systems in Samoa (Lefale 2010) as well as land-cover changes in South Africa (Chalmers and Fabricius 2007).

The novel aspects of this study include identifying regions of homogeneous climatic variability to develop climate divisions in Alaska on the basis of monthly station temperature, testing the division boundaries using gridded downscaled temperature and precipitation data, determining key seasonal climatic teleconnection linkages with temperature in each climate divisions, and using Advanced Very High Resolution Radiometer (AVHRR) surface air temperature to fill gaps in station temperature data.

2. Data and methods

a. Meteorological data

Meteorological data were obtained for stations throughout Alaska and neighboring Canada (Fig. 1). Monthly average temperature and accumulated precipitation were obtained from the NCDC, the Global Summary of the Day (GSOD) database at NCDC, Environment Canada (EC), the Alaska Climate Research Center (ACRC), and the National Weather Service (NWS). The location and source for each station are given in Table 1 (locations are plotted in Fig. 1). The overall goal for the selection of stations for the analysis was to maximize the spatial coverage while minimizing the amount of missing data. Stations were also selected to achieve a relatively even distribution of stations throughout the state to reduce analysis bias. This required selecting a single station from groups of stations that were in close proximity to each other and was especially important in the Anchorage area and southeastern Alaska. Few stations located at high-elevation locations had sufficient record length to be included in our analysis, and the underrepresentation of high-altitude locations is an ongoing concern in studies like this one. The period of analysis was selected to be 1977–2010 since evaluation of the station data inventories revealed that the data coverage is sparse prior to the mid-1970s. Canadian stations were included in the cluster

TABLE 1. List of stations with their airport code, data source, latitude/longitude, correlation with the nearest AVHRR pixel (Corr), percent missing temperature at the station over 1977–2010, and the percent of the missing replaced with mean-adjusted AVHRR when applicable. A three-letter code indicating the final division assigned to each station is shown in parentheses next to the station name. The climate division names are North Slope (NSP), Northeast Interior (NIN), Central Interior (CIN), Southeast Interior (SIN), West Coast (WCO), Bristol Bay (BBA), Aleutians (ALT), Northeast Gulf (NEG), Northwest Gulf (NWG), Cook Inlet (COI), North Panhandle (NPA), Central Panhandle (CPA), and South Panhandle (SPA). Canadian stations were not assigned to a climate division.

Code	Name	Source	Lat °N	Lon °W	Corr	% Missing	% AVHRR
PANC	Anchorage (COI)	NCDC	61.17	150.02	0.92	0.25	
PANT	Annette (SPA)	NCDC	55.03	131.57	0.92	0.00	—
PABR	Barrow (NSP)	NCDC	71.28	156.77	0.98	5.81	100.00
PABA	Barter Island (NSP)	GSOD	70.13	143.58	0.97	18.18	100.00
PABE	Bethel (WCO)	NCDC	60.78	161.82	0.97	0.51	100.00
PABT	Bettles (CIN)	NCDC	66.9	151.50	0.98	0.25	100.00
PABI	Big Delta (SIN)	NCDC	63.98	145.72	0.98	0.00	
CYDB	Burwash	NWS	61.37	139.05	0.95	11.62	100.00
PACD	Cold Bay (ALT)	NCDC	55.22	162.72	0.82	0.00	—
PACV	Cordova (NEG)	NCDC	60.48	145.45	0.91	0.51	
CYDA	Dawson City	EC	64.04	139.13	0.97	10.35	100.00
CYDL	Dease Lake	EC	58.43	130.01	0.93	8.84	
PAEG	Eagle (SIN)	NWS	64.79	142.20	0.97	0.00	—
PAEL	Elfin Cove (NEG)	NCDC	58.18	136.33	0.82	1.77	
PAFA	Fairbanks (SIN)	ACRC	64.8	147.87	0.98	0.00	—
PFYU	Fort Yukon (NIN)	GSOD	66.57	145.25	0.98	7.07	64.29
PAGA	Galena (CIN)	NWS	64.73	156.93	0.98	12.12	81.25
PAGK	Gulkana (SIN)	NCDC	62.15	145.45	0.97	0.00	—
PAHN	Haines (NPA)	NCDC	59.23	135.50	0.88	5.30	
PAHO	Homer (COI)	NCDC	59.63	151.48	0.88	0.00	
PAIL	Iliamna (BBA)	NCDC	59.75	154.90	0.95	4.04	
PAJN	Juneau (CPA)	NCDC	58.35	134.55	0.89	2.27	
PAEN	Kenai (COI)	NCDC	60.57	151.23	0.94	0.00	
PAKT	Ketchikan (SPA)	NCDC	55.35	131.70	0.88	17.93	
PAKN	King Salmon (BBA)	NCDC	58.67	156.65	0.93	0.51	
PADQ	Kodiak (NWG)	NCDC	57.75	152.48	0.87	0.00	—
PAOT	Kotzebue (WCO)	NCDC	66.88	162.58	0.94	3.28	
PAMC	McGrath (CIN)	ACRC	62.95	155.60	0.97	0.00	—
PAIN	McKinley Park (SIN)	NWS	63.73	148.91	0.95	0.25	100.00
PAOM	Nome (WCO)	NCDC	64.5	165.43	0.96	1.01	
PAOR	Northway	NCDC	62.95	141.92	0.98	3.28	100.00
CYOC	Old Crow	EC	67.57	139.84	0.98	19.44	66.23
PASC	Prudhoe Bay (NSP)	NWS	70.32	148.71	0.98	32.07	100.00
PASI	Sitka (NEG)	NCDC	57.03	135.35	0.88	6.82	
PASN	St. Paul (ALT)	NCDC	57.15	170.22	0.81	0.00	—
PATK	Talkeetna (COI)	NCDC	62.32	150.08	0.96	0.51	100.00
PATA	Tanana (CIN)	NCDC	65.17	152.10	0.98	1.01	50.00
CYXT	Terrace	EC	54.47	128.58	0.89	0.25	
PAUM	Umiat (NSP)	NWS	69.37	152.14	0.98	31.57	98.40
PAVD	Valdez (NEG)	NCDC	61.12	146.35	0.90	0.00	—
CYXY	Whitehorse	EC	60.71	135.07	0.95	15.91	100.00
PAYA	Yakutat (NEG)	NCDC	59.5	139.67	0.82	0.00	—

analysis as a buffer to reduce the impact of the artificial boundary at the U.S.–Canadian border. The Canadian stations were not used beyond the cluster analysis nor assigned to climate divisions.

Satellite-based monthly land surface temperature from the AVHRR is available for the period of 1982–2010 on a 25-km square grid. The surface temperature data, from the infrared channel, were enhanced using an improved cloud-masking dataset and were calibrated using in situ surface air temperature (Comiso 2003). Although the AVHRR data have been calibrated using in situ data, they add an independent perspective to the analysis of station data and provide a source to fill in station-data gaps.

Gridded downscaled temperature and precipitation data for Alaska (Hill and Calos 2011, manuscript submitted to *J. Hydrol.*) were used to validate the climate division boundaries. These data were derived from station data that cover 1961–2009. The complete list of available stations was filtered on the basis of a minimum record length criterion, yielding 322 and 261 stations for temperature and precipitation, respectively. Monthly anomalies were created by comparing station data with a 1971–2000 climatic normal, obtained from the Parameter-Elevation Regressions on Independent Slopes Model (PRISM; Simpson et al. 2005). These scattered anomalies were then interpolated onto a 2 km × 2 km grid, using the splines-with-tension interpolation method. Last, synthesis of the anomaly and normal grids produced the gridded monthly precipitation and temperature fields.

Values of various climatic indices for the period of 1977–2010 were used in this analysis to identify possible seasonal large-scale climatic teleconnection linkages with temperature within each division. Indices of west Pacific pattern (WP), east Pacific/North Pacific pattern (EP/NP), and Pacific–North American (PNA) pattern were obtained from the CPC (online at http://www.cpc.ncep.noaa.gov/data/teledoc/pna.shtml). Also retrieved from CPC were the Arctic Oscillation (AO; online at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml), Southern Oscillation index (SOI), and Niño region 3.4 (Niño-3.4) sea surface temperature (SST) anomalies (online at http://www.cpc.ncep.noaa.gov/data/indices/). The North Pacific index (NPI; online at http://www.cgd.ucar.edu/cas/jhurrell/npindex.html) and the PDO (online at http://jisao.washington.edu/pdo/) were also used in this analysis.

b. *Analysis methods*

Our analysis followed this basic workflow: 1) the data were normalized, 2) cluster analysis was performed to group the stations, 3) the appropriate number of clusters was determined, 4) clustering-method results were compared to determine the optimal groupings, and 5) the final divisions were validated with correlation analysis and refined by manual inspection of regional climatic characteristics using the local expert knowledge of experienced weather forecasters. Station precipitation was unfortunately found to be too sparse to be suitable for cluster analysis, and therefore temperature alone was used. Precipitation data were used alongside temperature in the validation when possible, however.

Three clustering methods were selected to group the stations to identify regions with consistently homogeneous climatic anomalies: Ward's method, the average-linkage method, and the *k*-means method (Wilks 2006). Use of multiple methods allowed comparison of performance, because each method uses different clustering assumptions and thus has a unique bias. In this case, the results were similar among the three methods, allowing us to focus on Ward's method for simplicity. Ward's method looks for the minimum variance or error sum of squares (ESS) among potential groups of stations to find the appropriate cluster configuration at each iteration. The ESS, or minimum variance distance measure, is given as

$$W = \sum_{g=1}^{G} \sum_{i=1}^{n_g} \sum_{k=1}^{K} (x_{i,k} - \overline{x}_{g,k})^2, \qquad (1)$$

where $\overline{x}$ is the cluster mean, G is the number of clusters, n_g is the number of stations, and K is the number of time steps (Wilks 2006). In essence, the difference between each station and the cluster average to which it was joined is squared and then summed. To determine the optimal number of clusters, the ESS was visually checked for sudden jumps associated with a decreasing number of clusters. In other words, as the number of clusters decreases, the stations become increasing dissimilar to the clusters with which they are being joined. The results from all three methods were then compared to determine possible uncertainties or problems with the groupings of the stations.

In the ESS, relatively large station–cluster average differences would be amplified because the difference is squared and relatively large monthly and seasonal means would quickly dominate over the smaller magnitudes of climatic variability in the formation of clusters (Wilks 2006). As a conseqence, the data were processed prior to clustering since mean temperature and precipitation vary greatly by season and geographic location in Alaska. Although previous studies have used complex methods such as principal component analysis (e.g., Fovell and Fovell 1993), our study employed a simple method to normalize the data. Following the method of Wolter and Allured (2007), a 3-month moving mean was applied to the monthly station data. The resulting smoothed data were normalized by subtracting their corresponding 3-month average and dividing by the standard deviation. Normalizing by the individual 3-month period has the effect of equalizing the seasonal variance of the data. The smoothing also reduces the impact of isolated extreme monthly anomalies on the clustering results. Using a simplified method was preferred given the sparse number of stations available in Alaska.

Cluster analysis cannot operate with missing data, and therefore either gaps must be filled in or the entire record must be removed. AVHRR monthly average land surface temperature is available for Alaska from 1982 to 2010. Correlation analysis comparing the station temperature with the AVHRR pixel nearest the station revealed correlation coefficients greater than 0.9 at all stations north of the Alaska Range (Table 1), with lower values south of the mountains. Missing values were filled using AVHRR for many station temperature time series and were guided by the correlation coefficients and visual comparison between the station data and AVHRR data. Where AVHRR was used it was first bias corrected for the slight differences in monthly means. The AVHRR data were not suitable for filling missing station values in coastal areas south of the Alaska Range because the means were too dissimilar. This was likely due to interference from mixed ocean and land pixels, coupled with the complex topography and ground cover of the region. When AVHRR could not be used, missing periods were filled with the long-term monthly mean for that station. The percent of missing data filled with AVHRR at each station is shown in Table 1.

Correlation analysis was applied to the station temperature and precipitation data to validate the final divisional memberships. Division average temperature and precipitation values were calculated from the stations within each division. Annual and seasonal cross correlations were carried out between the individual stations and the division averages.

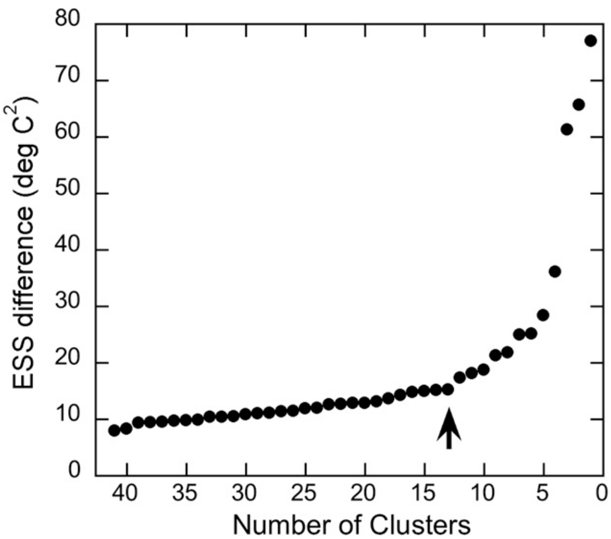

FIG. 2. ESS difference from step to step for the Ward's-method cluster analysis of station temperature for 1977–2010. An arrow marks where the optimal number of clusters was selected for our data (13 clusters).

3. Results

a. *Constructing the divisions*

Inspection of the ESS (Fig. 2) showed that the distance between clusters and their members began to increase relatively rapidly after 13 clusters. The result of Ward's method is shown in Fig. 3 for the 13-cluster solution (11 clusters were in Alaska, and 2 clusters were entirely in Canada). In this case, missing station data were filled using the mean-adjusted AVHRR land surface temperature when possible and others were filled using the long-term monthly mean. All three methods yielded consistent results when using a corresponding 13- or 14-cluster solution, but Ward's method is presented for simplicity. The clustering result served as a starting point for the analysis that is based on local expert knowledge that follows.

For comparison, cluster analysis was also carried out when the missing station temperature was exclusively filled with the long-term monthly means. The result (not shown) yielded a similar set of 13 clusters, as in Fig. 3, with minor differences. Therefore, although there was some sensitivity in the clustering results to how the missing data were filled, the overall number of clusters and general locations of the divisions did not appear to strongly influence the final outcome. This was expected because only those stations with minimal missing data were used in our analysis. Furthermore, despite the problems encountered with the southern coastal data, the AVHRR captures the variability in areas north of the Alaska Range and was found to be useful in filling gaps in station temperature.

The station data and AVHRR were also clustered in different configurations as an additional test. Cluster analysis conducted on the full gridded AVHRR surface temperature (not shown) revealed boundaries that broadly resembled the Alaska ecodivisions (Gallant 1995) when using Ward's method. It is not surprising that the AVHRR clusters resembled the ecodivisions, given that both are sensitive to surface characteristics (e.g., vegetation), many of which strongly influence or are influenced by the climate. Possibly because of AVHRR data-quality issues in the southern coastal regions, conflicting results among the different clustering methods indicated that the AVHRR could not be used alone to construct the divisions. In the data-sparse areas of northern Alaska, proxy "station" values were estimated from the AVHRR data and were added to the observed station dataset to test their usefulness. They did not appear to add useful information to the analysis, however, because they tended to cluster together.

The Climate Research Unit (CRU) "TS 3.0" (Mitchell and Jones 2005) and the North American Regional Reanalysis (NARR; Mesinger et al. 2006) gridded temperature and precipitation datasets were also evaluated as potential candidates for determining the climate divisions (not shown). Because the CRU data were interpolated using a simple method on a relatively sparse station network, the clusters unrealistically crossed major terrain boundaries such as the Brooks and Alaska Ranges. The

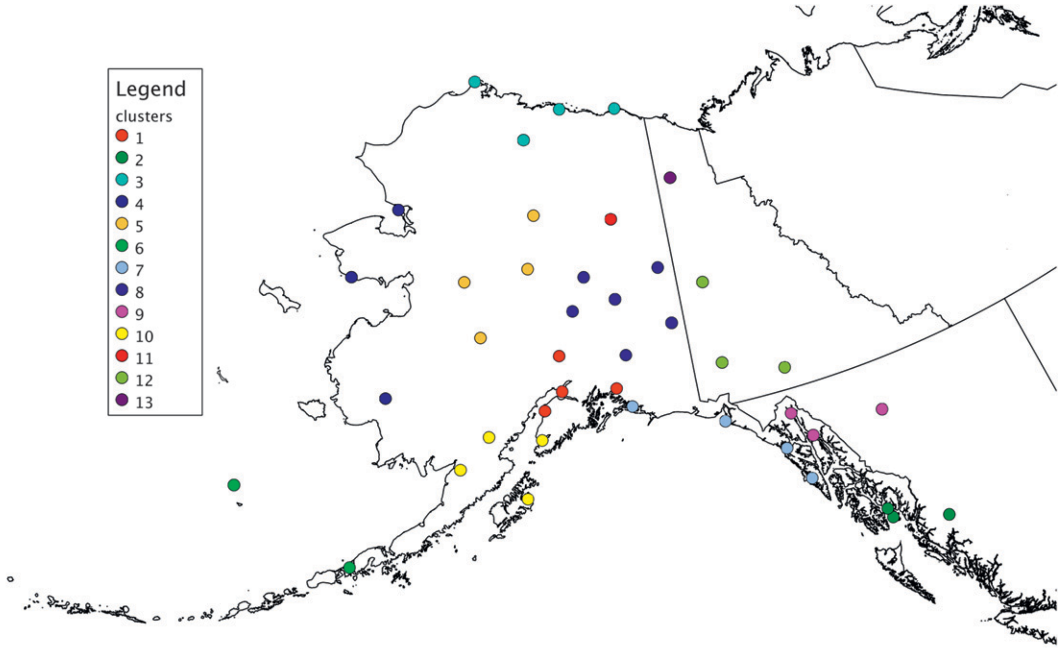

FIG. 3. The 13-cluster solution from the Ward's-method cluster analysis of station temperature. Dots are color coded by their cluster membership. There are 11 clusters in Alaska, with 2 entirely in Canada. The stations appear to group around major terrain features (terrain can be seen in Fig. 4, described below).

NARR precipitation data appeared to cluster around an artificial north–south boundary centered along the longitude of Fairbanks, Alaska. Whereas the NARR precipitation data were problematic, the NARR temperature clusters appeared to be much more physically realistic, but an optimal number of clusters on the basis of the ESS could not be identified. The cluster analyses of the NARR and CRU gridded datasets were unsuitable in themselves for determining the climate divisions, but their 13-cluster solutions were broadly similar to the locations of the divisions that are based on the station data and appear to support our findings.

On the basis of the clustering result of the Alaska stations in Fig. 3, preliminary climate-division boundaries were drawn by visually identifying major terrain features that surrounded the groups of stations. Given the spatial distribution of the clusters of stations, major terrain features appeared to be natural barriers between regions. Local expert knowledge from experienced NWS forecasters was then used to improve and refine the division boundaries (Fig. 4). At this step it was decided that Juneau and Haines, Alaska, should be grouped independently from each other to form North and Central Panhandle divisions, respectively, because of their seasonal climatic differences. Annette and Ketchikan, Alaska, remained grouped together in the South Panhandle division. In southwestern Alaska, two divisions were created, encompassing areas along and inland from Bristol Bay and the south-central coast including Kodiak Island in Alaska (Northwest Gulf), that are also based on seasonal differences in climate. Having these two divisions divided was also consistent with the historical climate-type regions in Fig. 1, which were divided by the Aleutian Range, a formidable mountain barrier. The reasons for deviating from the cluster results will be discussed further when the climatic characteristics of the individual divisions are presented in section 3c.

b. Sensitivity analysis

Cross correlation of station data with the division averages (not shown) yielded no case in which a station was correlated higher with a different division for annual temperature and precipitation. Even when evaluated seasonally (not shown), very few stations had a higher correlation with another division average than their own. The few cases of stations correlating higher with another division tended to occur in the southern coastal areas. There were no cases in which the correlation was consistently higher with another division throughout multiple seasons that might have warranted changing the station to another division.

To validate the division lines, the station division average temperature and precipitation were correlated with the 2-km downscaled temperature and precipitation data for the entire state. The division membership of each point

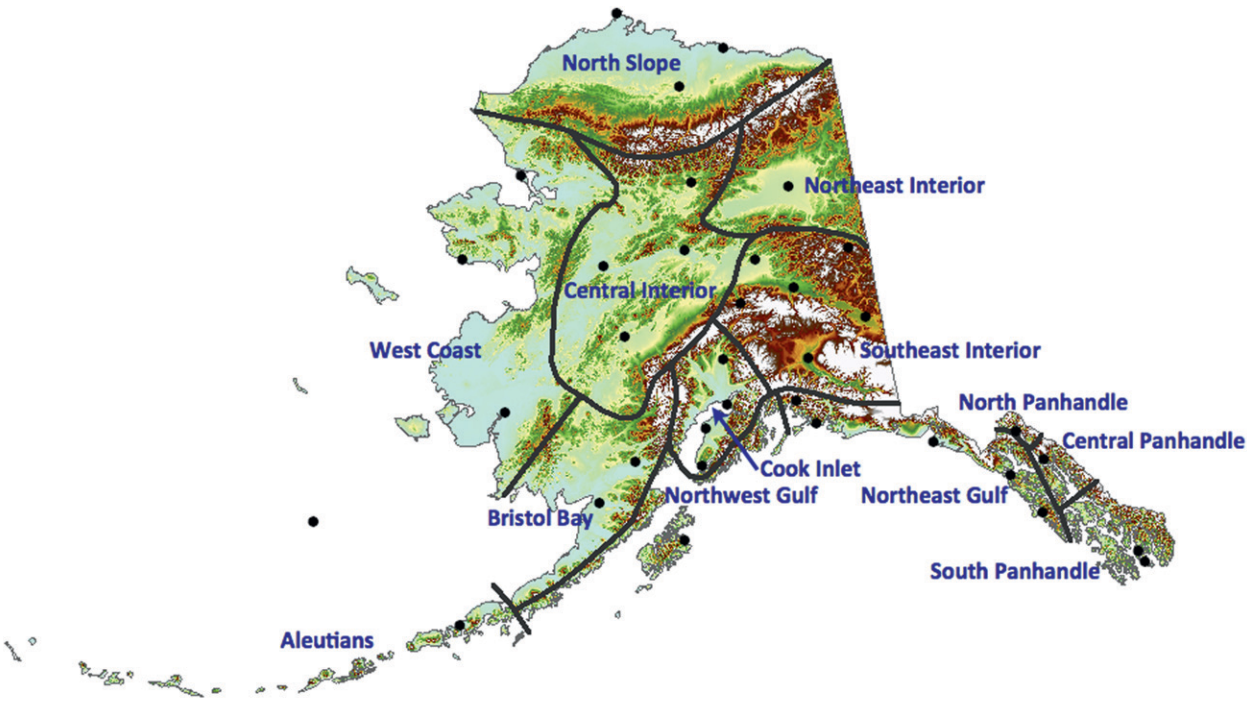

FIG. 4. Climate-division boundaries are shown over Alaska topography with the division names. Black dots indicate the locations of the Alaska stations used in the cluster analysis. Local expert knowledge from experienced weather forecasters in Alaska was employed to draw the final lines.

in the downscaled data was identified on the basis of our lines. The time series for each grid point was then correlated with all 13 division averages for both temperature and precipitation. Each time that a point had a higher correlation with a division other than its own, the sum for that point was increased by 1. In the ideal case every point should have a count of zero, implying that it was best correlated with its own division. For both temperature and precipitation there were only a few areas with higher correlation with division average time series other than their own (Fig. 5). Most areas with elevated counts were located in the Northeast Interior division, which was based on a single station (Fort Yukon, Alaska). The highest counts, and subsequently the highest uncertainty, occurred with precipitation (Fig. 5b), with the highest counts along the boundary between the Southeast Interior and Northeast Gulf divisions. With the exception of the Northeast Interior, every division was regularly correlated best with the division average temperature and precipitation from the stations assigned to that division. Overall, the positions of the division boundaries appear to be very reasonable by this validation method.

c. Characteristics of the divisions

The long-term monthly average temperature and precipitation for each station and the average for all stations within each division are shown in Fig. 6. The overall climate regimes of the individual stations within any division were generally consistent in seasonality and magnitude. The divisions with the highest precipitation amounts are along the southern coastal areas of Alaska, where the annual temperature ranges also tend to be the smallest in the state. The most-extreme temperature ranges occur in the interior where precipitation amounts are also the lowest in the state. Most divisions have the highest precipitation amounts in late summer or autumn.

In section 3a the Bristol Bay stations were separated from Kodiak and Homer, Alaska. Bristol Bay then became its own division (Fig. 6k), Homer was added to the Cook Inlet division (Fig. 6f), and Kodiak became part of the Northwest Gulf division (Fig. 6m). When comparing the seasonal climates of the individual stations with their divisions (Figs. 6k,f,m), it can be seen that the Bristol Bay stations tend to have different seasonalities in precipitation and temperature than do Kodiak and Homer. This was a case in which, while these stations tended to share the same year-to-year climatic anomalies, differences in their seasonal climate regimes suggest they would best be grouped separately. This distribution of the stations was also consistent with the historical climate-type regions (see Fig. 1). A similar situation occurred when Haines and Juneau were grouped together with

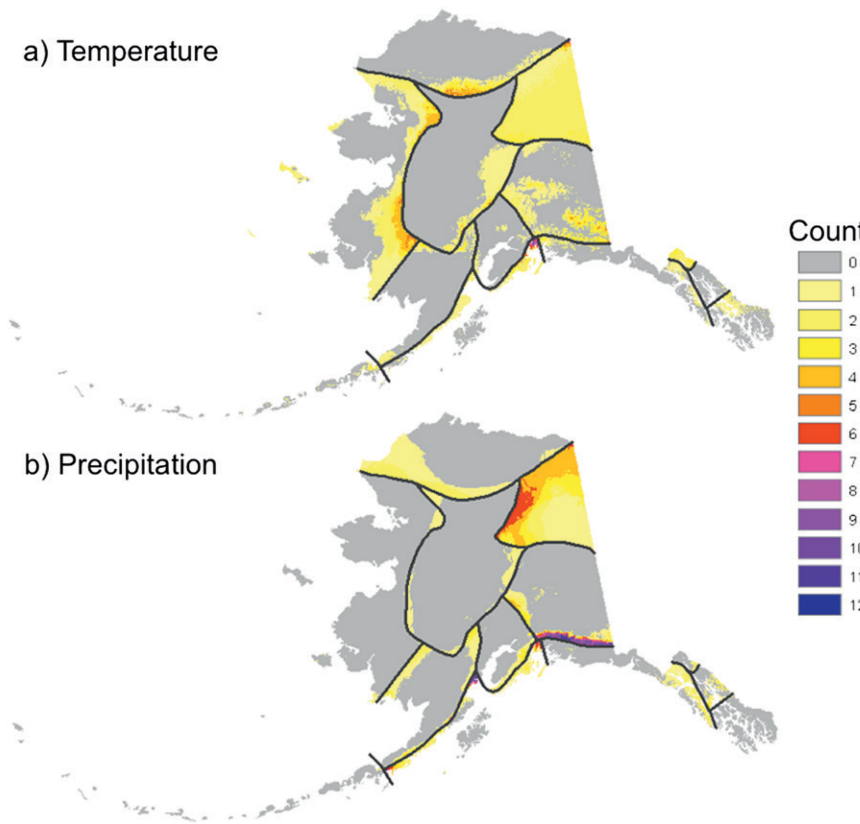

FIG. 5. Each division average time series from station data was correlated with every grid point of the Hill and Calos (2011, manuscript submitted to *J. Hydrol.*) dataset. This plot displays the number of times each grid point had a higher correlation with a division average time series other than its own division. This is shown for (a) temperature and (b) precipitation. Most areas have counts of zero and therefore correlate best with their own division average time series, demonstrating that the climate-division boundaries drawn with the aid of local expert knowledge were robust.

Dease Lake in Canada by the cluster analysis. Haines (North Panhandle; Fig. 6h) tends to get less precipitation than Juneau (Central Panhandle; Fig. 6j) from late spring through summer. Haines is also rain shadowed by the coastal mountains and therefore tends to be less cloudy than Juneau. The geographical and seasonal characteristics of each climate division are described next.

The North Slope division is shown as cluster 3 in Fig. 3 and includes the stations at Barrow, Umiat, Barter Island, and Prudhoe Bay. This division is the northernmost in Alaska and encompasses the Arctic tundra portion of Alaska north of the Brooks Range. The division is bounded by the Arctic Ocean on the north and west and the Brooks Range on the south. The Arctic Ocean is covered by sea ice in winter but has variable sea ice in summer. The climate of the region (Fig. 6a) is among the driest, with a maximum precipitation of less than 5 cm in the wettest summer month, and has seasonal average temperatures ranging from below −25°C in winter to above 10°C in summer.

The Central Interior division is shown as cluster 5 in Fig. 3 and includes the stations at Bettles, Tanana, Galena, and McGrath, Alaska. The region is bounded by the Brooks Range to the north and the Alaska Range to the south. It is relatively far from ocean influences and has a continental climate (Fig. 6b) with relatively low precipitation when compared with the coastal regions.

The Northeast Interior division is shown as cluster 11 in Fig. 3 and includes the station at Fort Yukon. Because this division is far from the ocean, it has a very continental climate with the largest seasonal mean temperature range in Alaska (Fig. 6c). This region is bounded to the north by the Brooks Range and to the south and west by the Yukon–Tanana uplands. Precipitation here is among the lowest in the state.

The Southeast Interior division is shown as cluster 8 in Fig. 3 and includes the stations at Fairbanks, McKinley

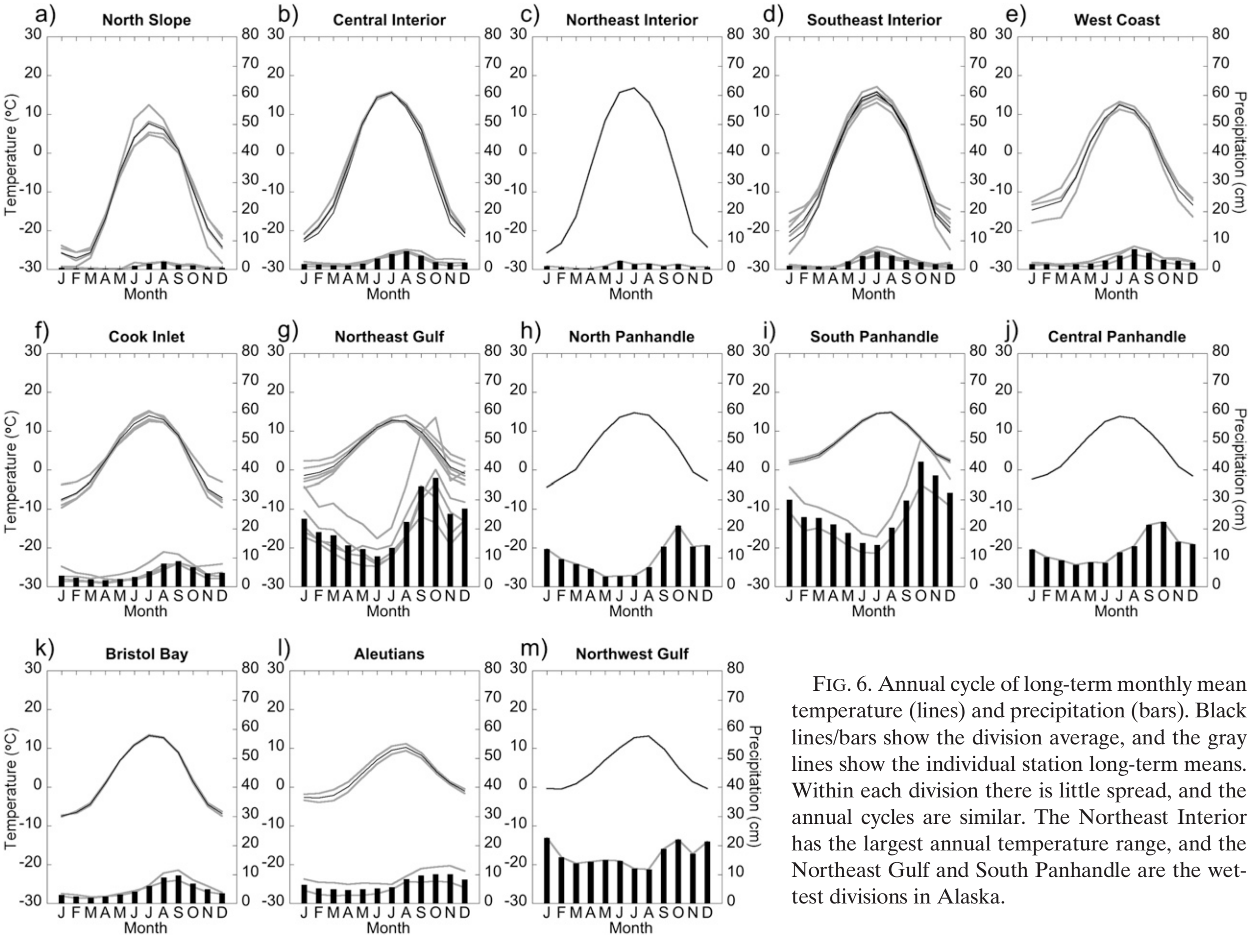

FIG. 6. Annual cycle of long-term monthly mean temperature (lines) and precipitation (bars). Black lines/bars show the division average, and the gray lines show the individual station long-term means. Within each division there is little spread, and the annual cycles are similar. The Northeast Interior has the largest annual temperature range, and the Northeast Gulf and South Panhandle are the wettest divisions in Alaska.

Park, Big Delta, Eagle, Northway, and Gulkana, Alaska. This region is bounded to the north by the Yukon–Tanana uplands and to the south by the Chugach Mountains, which block southerly maritime influence. The seasonal ranges in temperature (Fig. 6d) are similar to those of the Central and Northeast Interior divisions and can be characterized as continental. This division has a summer maximum in precipitation.

The West Coast division is shown as cluster 4 in Fig. 3 and includes the stations at Kotzebue, Nome, and Bethel, Alaska. This division is bounded to the west by the Bering and Chukchi Seas, to the east by the Kuskokwim Mountains, and to the north by the Brooks Range. The seasonal temperature range (Fig. 6e) is more moderate than that of the interior divisions. Precipitation is higher than that of the interior divisions but is much lower than for the southeastern coastal regions of Alaska, and this division has a summer maximum similar to that of the interior.

The Cook Inlet division is shown as cluster 1 and part of 10 in Fig. 3 and includes the stations at Talkeetna, Anchorage, Kenai, and Homer, Alaska. This is a coastal division that straddles Cook Inlet and is bounded by the Alaska Range and the Chugach Mountains. The seasonal temperature range (Fig. 6f) is maritime with precipitation seasonality that is similar to (although less in amount) that of the interior divisions and the West Coast division.

The Northeast Gulf division is shown as cluster 7 and part of 1 in Fig. 3 and includes the stations at Valdez, Cordova, Yakutat, Elfin Cove, and Sitka, Alaska. This division is situated along the northeastern Gulf of Alaska with the Chugach Mountains to the north. It has a relatively small annual temperature range (Fig. 6g) and receives among the highest seasonal average precipitation, with maximum values in autumn.

The North Panhandle division is shown as cluster 9 in Fig. 3 and contains the station at Haines. This division is in the interior of the southeastern Panhandle of Alaska and is bounded on all sides by mountains. The annual temperature range (Fig. 6h) is also moderate like that of its neighboring division, Northeast Gulf. It receives less precipitation in all seasons than does the Northeast Gulf division, however. This region has its maximum precipitation in the autumn.

The South Panhandle division is shown as cluster 2 in Fig. 3 and contains the stations at Ketchikan and Annette. This division includes the southernmost coastal areas of Alaska and is bounded to the east by the Coast Mountains. Average monthly temperatures (Fig. 6i) have small variability throughout the year, and average precipitation is among the highest in the state, with the maximum occurring in the autumn.

The Central Panhandle division is shown as cluster 9 in Fig. 3 and includes the station at Juneau. This division is located in the interior of southeastern Alaska, with mountains to the east and west. Monthly average temperatures (Fig. 6j) are moderate, and this division receives less precipitation than do the Northeast Gulf and South Panhandle on average.

The Bristol Bay division is shown as cluster 10 in Fig. 3 and includes the stations at Iliamna and King Salmon, Alaska. This division is located along the southwestern coast of Alaska along Bristol Bay and extends north to the Kuskokwim Mountains and east and south to the Aleutian Range. Monthly average temperatures (Fig. 6k) are relatively moderate. Precipitation values are much lower than in the Northwest Gulf division and are maximum during late summer.

The Aleutians division is shown as cluster 12 in Fig. 3 and includes the stations at Cold Bay and St. Paul. This division included the entire Aleutian Island chain and St. Paul Island. This division is bounded by the Pacific Ocean to the south and Bering Sea to the north. Monthly average temperatures (Fig. 6l) have the smallest range of any of the divisions and have relatively low precipitation when compared with the Northeast Gulf and Northwest Gulf divisions. Maximum precipitation occurs from late summer through autumn.

The Northwest Gulf division is shown as the southern portion of cluster 10 in Fig. 3 and includes the station at Kodiak. This division, located along the northwestern part of the Gulf of Alaska, includes Kodiak Island, coastal areas south of the Aleutian Range on the Alaska Peninsula, and the southernmost portion of the Kenai Peninsula. Monthly average temperatures (Fig. 6m) are moderate and precipitation amounts are lower than in the Panhandle divisions, with the maximum generally occurring in late autumn and winter.

d. Teleconnections

An example of the usefulness of these climate divisions can be found when the division average temperatures were correlated with climatic indices. A set of climatic teleconnection indices from the Pacific/Arctic region were correlated, after being linearly detrended, with each division average temperature to demonstrate the individual links with the large-scale climate in each season for 1977–2010. Table 2 shows the teleconnection indices that were significantly correlated with the division average temperatures each season at the 95% or greater level on the basis of a *t* test.

Many of the climate divisions were significantly correlated with the AO throughout much of the year. The AO (Thompson and Wallace 1998) is a leading mode of Northern Hemisphere sea level pressure variability and effects the large-scale circulation. Table 2 shows that the AO is significantly negatively correlated with temperature, or the negative phase results in warm temperature anomalies, in multiple climate divisions in each season. Note that most of Eurasia and the continental United States are colder than normal during the negative phase of the AO (see graphical analysis online at http://jisao.washington.edu/analyses0500/tempprecipao.1deg.gif).

ENSO has been shown to be a key driver in the climate of Alaska (Papineau 2001; Bieniek et al. 2011). Evaluation of tropical Pacific, or ENSO-related, climatic indices showed a substantial and widespread relationship, with significant correlations occurring in each division in at least one season of the year. The ENSO-specific indices evaluated were the SOI and the Niño-3.4 SST anomaly. The PNA was also evaluated and is a natural mode of atmospheric variability that extends into the Alaska region (Wallace and Gutzler 1981). The PNA has been shown to be linked with ENSO (Horel and Wallace 1981) as well as purely midlatitude processes (Dole 1983). Of the ENSO-related indices, the PNA had by far the most significant correlations. This result indicates that the PNA may be the primary pathway for the linkage between ENSO and the seasonal average temperature in most of the climate divisions. In all cases the PNA was positively correlated with temperature, which means that the positive phase of the PNA (which corresponds to the positive phase of ENSO) tends to result in above-average temperatures in those divisions for which the correlations were significant. Of interest is that the only time that ENSO had an opposite sign relationship from the rest of the divisions was for the North Slope division in winter (Table 2), for which there was a positive correlation with the SOI. Our findings are in general agreement with the aforementioned studies.

In the North Pacific, several teleconnection indices were correlated with the division average temperatures. The NPI, a measure of the strength of the Aleutian low (Trenberth and Hurrell 1994), was negatively correlated with multiple divisions and was correlated in all seasons. A negative correlation indicates that when the Aleutian low was stronger temperatures were warmer in Alaska. This is intuitive, because a stronger Aleutian low will tend to advect warm air and moisture from the Pacific Ocean into Alaska. Also positively correlated with the

TABLE 2. Correlations significant at the 95%-or-greater level between climatic indices and division average station temperature for each season.

Division	Index	Dec–Feb	Mar–May	Jun–Aug	Sep–Nov
North Slope	PNA				0.39
	EP/NP	0.53	0.51		
	WP			0.50	
	AO				−0.37
	SOI	0.40			
Central Interior	PNA	0.53	0.38	0.45	0.44
	EP/NP		0.39	0.46	
	WP			0.41	
	AO	−0.54		−0.34	−0.38
	SOI			−0.36	
	NPI	−0.47	−0.60	−0.54	−0.44
	PDO	0.45			0.35
Northeast Interior	PNA		0.38		
	EP/NP			0.44	
	WP			0.59	
	Niño-3.4				0.41
	NPI		−0.48		
Southeast Interior	PNA	0.70	0.54	0.35	0.53
	EP/NP			0.44	
	WP			0.50	
	AO	−0.45	−0.38		−0.39
	SOI			−0.34	
	NPI	−0.59	−0.62	−0.37	−0.59
	PDO	0.52			0.43
West Coast	PNA			0.46	
	EP/NP		0.54	0.41	0.41
	AO			−0.49	−0.36
	Niño-3.4		0.40		
	NPI		−0.61	−0.59	
	PDO				0.40
Cook Inlet	PNA	0.64	0.62		0.57
	EP/NP				0.37
	AO	−0.53	−0.46		
	Niño-3.4	0.37			
	NPI	−0.60	−0.75	−0.38	−0.66
	PDO	0.60	0.52	0.43	0.48
Northeast Gulf	PNA	0.82	0.65		0.60
	EP/NP		0.35		0.36
	AO	−0.42	−0.39		
	SOI	−0.39			
	Niño-3.4	0.44			
	NPI	−0.73	−0.72		−0.64
	PDO	0.60	0.54	0.41	0.40
North Panhandle	PNA	0.74	0.39		0.47
	EP/NP			0.41	
	SOI			−0.43	
	Niño-3.4			0.37	
	NPI	−0.62			−0.52
	PDO	0.46		0.45	0.38

TABLE 2. (*Continued*)

Division	Index	Dec–Feb	Mar–May	Jun–Aug	Sep–Nov
South Panhandle	PNA	0.77	0.62		0.43
	EP/NP			0.49	
	WP			0.39	
	SOI	−0.54	−0.40		
	Niño-3.4	0.54	0.40	0.36	
	NPI	−0.68	−0.67		−0.46
	PDO	0.63	0.66	0.14	0.46
Central Panhandle	PNA	0.80	0.65		0.37
	EP/NP			0.41	
	WP			0.45	
	SOI	−0.34			
	Niño-3.4	0.37			
	NPI	−0.67	−0.60		−0.53
	PDO	0.48	0.40		
Bristol Bay	PNA	0.39	0.47		
	EP/NP		0.52		0.44
	AO	−0.50	−0.37		
	Niño-3.4		0.36		
	NPI	−0.37	−0.75		−0.48
	PDO	0.46	0.47		0.41
Aleutians	EP/NP		0.51		0.49
	AO	−0.50			
	NPI		−0.37		
	PDO	0.41		0.37	
Northwest Gulf	PNA	0.46	0.38		0.39
	EP/NP		0.52		0.45
	AO	−0.65	−0.40		
	Niño-3.4		0.35		
	NPI	−0.51	−0.62		−0.59
	PDO	0.67	0.44	0.38	0.52

divisions were the EP/NP and WP circulation indices, which are primarily winter modes of variability in the tropospheric circulation over the North Pacific (Barnston and Livezey 1987). The EP/NP has widespread correlations throughout the year, but the WP was limited to the summer, which is perplexing because the WP is entirely a winter phenomenon.

The PDO is a leading mode of variability of the North Pacific SSTs (Mantua et al. 1997). In every case the PDO had positive and significant correlations, meaning that the positive phase resulted in warmer temperatures. In winter and autumn (Table 2), the PDO was correlated with divisions in the interior and southern coastal regions. In spring and summer, the PDO was related only to divisions along the south-central coast and the Aleutians. The PDO was never significantly correlated with the North Slope division. These correlation results are consistent with the findings of Papineau (2001), Hartmann and Wendler (2005), and Bourne et al. (2010).

The correlations of Pacific and Arctic climatic teleconnections with the division average temperatures revealed several relationships. One is that the NPI, AO, PNA, and PDO all had a strong influence on the variability of temperatures in all seasons throughout Alaska. No divisions, however, had consistently the same relationships with the same set of teleconnection indices. The exact mechanisms for these correlations are beyond the scope of this paper and are a fruitful area for future investigation.

4. Conclusions

A combination of objective analysis and local expert knowledge identified 13 regions of homogeneous climatic variability, or climate divisions, for Alaska on the basis of observed station temperature. The cluster analysis was limited to temperature because precipitation data were too sparse for the cluster analysis. The available station precipitation correlated well within each division in the validation, however. Analysis of alternate gridded datasets, although not useful in determining the divisions on their own, tended to support the final clustering of the stations. The AVHRR was also shown to be invaluable in filling gaps in the station data north of the Alaska Range. Because of the vast geographical extent of Alaska and the relatively sparse station network, drawing the division boundaries relied heavily on following the major terrain features surrounding the grouped stations. A broad cross-correlation analysis using both station temperature and precipitation also supported the groupings of the stations. The lines of the division boundaries could not be drawn completely objectively, but correlation analysis using the division averages and downscaled gridded temperature and precipitation supported the final placement of the division boundaries.

Evaluation of the climates of the divisions revealed that the stations in each division have similar annual cycles in temperature and precipitation. Our divisions were determined using cluster analysis, and the similar climatic cycles also served to support our division choices. An evaluation of a diverse set of teleconnection indices with the division average temperature showed possible links between multiple indexes throughout the Arctic and Pacific regions. The most prevalent significantly correlated indices were the AO, PNA, NPI, and PDO, which all had significant correlations in all seasons. There were also numerous instances of connection with the EP/NP throughout the year and the WP in summer. The relative importance of, and interactions among, the various indices in controlling temperature in each division are highly relevant for seasonal climatic prediction and are areas of potential future work.

There are a few major differences between the new climate divisions (Fig. 4) and original historical climate zones (Fig. 1). There were several new divisions identified through our analysis in both the interior and the Panhandle of Alaska. Because our analysis was focused on identifying regions of homogenous variability and not homogeneous climate type, differences between the climate divisions and the historical zones were expected. Novel to this analysis, the exact climate divisions' boundaries were also evaluated. Although there is still some uncertainty in the final boundaries, our analysis has confirmed that boundaries following terrain are very reasonable.

The practical value of these Alaska climate divisions is high across disciplines. An example of this can be seen when comparing Fig. 4 with a map of Alaska native languages (Krauss et al. 2011). Although there are differences between the exact locations of the lines, many of the language families have similarly located regions as the climate divisions, especially for the Yupik and Athabascan languages. The numerous potential relationships with other disciplines are also an area for future research related to climate divisions.

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