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Diagnosis of Extended Cold-Season Temperature Anomalies in Alaska

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ABSTRACT

During the early winter of 2002 and late winter of 2007, the Alaskan sector of the North Pacific Ocean region experienced record-breaking temperature anomalies. The duration of these episodes was unusually long, with each lasting more than 1 month: 55 days for the warm anomaly of October–December 2002 and 37 days for the cold anomaly of February–March 2007. Temperature departures over each respective period were the largest for the continental climate of interior Alaska ($>10^{\circ}\text{C}$) and the smallest for the maritime regions of Alaska ($<4^{\circ}\text{C}$). Mean temperatures over the event periods in 2002 and 2007 easily ranked as the record warmest and coldest, respectively, for many surface observing stations. In addition, heating degree-day anomalies were on the order of 700 units for these periods. Atmospheric circulation patterns at the surface and upper levels for the circum-Arctic proved to be the driver for these persistent events. The 2002 warm anomaly was driven by enhanced southerly advection associated with an unusually strong Aleutian low and a positive Pacific decadal oscillation index, which resulted in a large area of anomalous temperatures in Alaska and northern Canada. The 2007 cold anomaly was driven by a weakening of the circulation pattern in the subpolar Pacific sector and a strengthening of the Siberian high, with the strongest temperature anomalies in Alaska and northwestern Canada.

1. Introduction

Large-scale atmospheric circulation patterns (Serreze and Barry 2005; Semenov 2007) and ocean conditions (Aagaard and Carmack 1989; Alexander et al. 2004) are known to strongly influence surface temperature patterns during winter at high latitudes. In particular, the strength and position of the semipermanent pressure features in the Northern Hemisphere are of high importance as they relate to airmass advection (Serreze et al. 1997; Papineau 2001; Hartmann and Wendler 2005). For the subpolar North Pacific Ocean region, the dominant cold-season feature is the Aleutian low

(Overland et al. 1999). In contrast, high pressure dominates the central Arctic with the Beaufort high in the Canadian Arctic, associated with the Beaufort gyre of the upper ocean (Proshutinsky et al. 2002) and the Siberian high in north-central Russia (Ding and Krishnamurti 1987). In addition, the region of Alaska and northwest Canada has been shown to be an area of anticyclogenesis (Bodurtha 1952). In geographical terms, Alaska lies at the intersection of these features. As such, the state can be divided synoptically with different features influencing different regions, or one particular feature can dominate depending on its relative position.

During the cold seasons, the variability in the strength and position of these semipermanent features translates into large temperature variability. As such, the standard deviation of mean monthly temperatures is high, with a winter aggregate mean of 5.1°C for Alaska's interior

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FIG. 1. Mean temperature departure from normal for the record cold event (20 Feb–25 Mar 2007).

FIG. 2. Mean temperature departure from normal for the record warm event (20 Oct–13 Dec 2002).

(Shulski and Wender 2007). Temperature anomalies normally last on the time scale of several days to a week, or the length of time for a synoptic pattern to move through the state.

Along with atmospheric circulation, another important factor for wintertime climatology at this latitude is the presence of a semipermanent temperature inversion at or near the surface (Wexler 1936; Wendler and Nicpon 1975; Kahl 1989; Overland and Guest 1991). Under a high pressure pattern with conditions of clear skies and calm winds, strong inversions develop that produce extreme differences in temperature with respect to elevation (Bowling 1986). Low-lying areas can be 15°C colder than surrounding areas of higher elevation. In addition, once this type of radiation-driven inversion is set up, it can be difficult to remove the cold air from localized topographic depressions. Even when a synoptic change takes place and warm air is advected into the area, leftover cold pools can remain for a period of time as they fail to be mixed out dynamically. This low-level inversion phenomenon strongly affects the microclimate of lowland areas, particularly for sheltered valleys of interior Alaska (Wendler and Jayaweera 1972).

Although periods of above- and below-normal temperatures lasting on the order of a week are common for high-latitude climate regions during the cold seasons, episodes during 2002 and 2007 of warm and cold anomalies, respectively, lasted more than 1 month. Both the extended cold period during the late winter of 2007 and the warm period in the early winter of 2002 were record breaking and were experienced by considerable portions of Alaska, most notably in the continental climate of the interior region. Mean temperature departures for the period from 20 February to 25 March 2007 were in the range from -8° to -13°C . The 2002 episode lasted

even longer, from about 20 October to 13 December, and resulted in temperature departures from $+7^{\circ}$ to $+12^{\circ}\text{C}$ for the 55-day period. Such extreme episodes pose special challenges to weather prediction, because not only are they highly anomalous climatologically but they are also consequential for humans and ecosystems affected by the events. For example, as discussed in section 4, heating costs during periods of anomalous temperatures can be much higher or lower than normal, affecting communities in which fuel costs are a major part of the economy. For these reasons, extended-duration anomalies such as those of 2002 and 2007 merit examination and discussion in terms of synoptic conditions and historical significance.

2. Anomaly review

Meteorological station data were obtained from the daily Summary of the Day climatological dataset [National

FIG. 3. Daily temperature departures from normal during the 2007 cold event for four locations across Alaska.

FIG. 4. Daily temperature departures from normal during the 2002 warm event for four locations across Alaska.

Climatic Data Center (NCDC)] for stations in Alaska. These data represent observations taken from the Automated Surface Observing System platforms, located mostly at airport and National Weather Service offices and from the cooperative observing network within the National Oceanic and Atmospheric Administration

(NOAA). The mean daily temperature was computed from the daily maximum and minimum for each station and was compared with the respective normal daily temperature, as published by NCDC. Gridded atmospheric data for the two events were obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset (Kalnay et al. 1996); these data included sea level pressure anomaly, surface air temperature anomaly, and 500-hPa geopotential heights. The normal period is defined in this study as the 30-yr period from 1971 to 2000.

The exact start and end of these two events were somewhat variable between locations. However, to define the onset and ending dates of the cold (2007) and warm (2002) anomalous events, daily temperature departures for the surface station data were compared with the respective standard deviations of mean daily temperature. The days in which the temperature departure was greater than 1 standard deviation from the mean were found for a subset of stations, which represent the different climate regions in Alaska (Barrow—polar, Fairbanks—continental, Anchorage—maritime/continental

FIG. 5. Sea level pressure anomalies (hPa) for the 2007 cold event (data source: NCEP–NCAR reanalysis, NOAA Earth System Research Laboratory).

FIG. 6. Surface air temperature anomalies ($^{\circ}\text{C}$) for the 2007 cold event (data source: NCEP–NCAR reanalysis, NOAA Earth System Research Laboratory).

transition, and Juneau—maritime). From this subset of stations, the average start and end dates for the two events were computed. The start and end dates for the 2007 cold event were 20 February and 25 March, and for the 2002 warm event the dates were 20 October and 13 December. Only stations with no more than 10% missing data over this period were included in the analysis, which yielded 80 stations for the 2002 event and 87 stations for the 2007 event. To place the events into historical context, the average temperatures for the two periods were ranked according to each station's respective period of record.

The temperature departures from normal for the 37-day period in 2007 show a clear regional pattern (Fig. 1). The strongest departures are found for the interior region, whereas the coastal areas from the far southern panhandle to the Arctic coast have weaker anomalies. Temperature departures for the continental climate of interior Alaska were in the range from -8° to -13°C (with an average of -10°C) for this entire episode—very significant for this long duration. In contrast, the departures for maritime regions were less than 4°C . Mean temperatures over the period were lowest for

locations in interior Alaska, ranging from around -19°C for areas of higher elevation (greater than 300 m) to around -25°C for valley bottom stations. This event ranks as the coldest on record for 56 of the 87 observing stations and is in the top 5 coldest for an additional 21 stations. Incidentally, the second coldest on record for many of these locations occurred during one particular year, 1972, when the February–March period was also unusually cold. The lowest observed temperatures statewide during this anomalous episode were reported at Chicken, Alaska ($64^{\circ}06'\text{N}$, $141^{\circ}55'\text{W}$, 549 m MSL) in the east-central interior with temperatures of -54°C on 24 February and -50°C on 3 March. Even though the elevation for this station is relatively high when compared with that of most interior valley locations (about 400 m higher), it is in a localized depression relative to the surrounding upland terrain and often records very low temperatures during cold periods.

During the extended warm period in the early winter of 2002, mean temperatures for the 55-day period were in the range from -12° to -4°C , with characteristic differences based on latitude and elevation. Temperature

FIG. 7. The 500-hPa geopotential heights (m) for the 2007 cold event (data source: NCEP–NCAR reanalysis, NOAA Earth System Research Laboratory).

departures for the entire episode were in the range from $+7^{\circ}$ to $+12^{\circ}\text{C}$ (Fig. 2). The mean temperature ranks as warmest on record for an astonishing 73 out of the 80 observing stations. In addition, this period ranks in the top 5 warmest on record for the remaining 7 stations. Some of the new records set during this event were impressive. For example, the mean temperature over the 55-day period of -2.7°C in Big Delta, Alaska (145 km southeast of Fairbanks), breaks the previous record warmest at this location, set in 1957, by a staggering 4.4°C . In contrast somewhat to the 2007 cold event, the warm anomaly was more widespread (as can be seen from a comparison of Figs. 1 and 2) and a greater number of stations set new records (73 vs 56).

A look at the time series of daily temperature anomalies shows the consistent nature of both events. Stations chosen here (Barrow, Fairbanks, Anchorage, Juneau) represent a north–south transect through Alaska. Aside from only a few cases, temperature departures remained negative for the 44-day period in 2007 (Fig. 3). The strongest anomalies overall are seen for Fairbanks, with the weakest for Barrow in this event. The same analysis for the 2002 event similarly reveals the consistency over

time, with only a few breaks in the pattern (Fig. 4). In fact, Fairbanks had no negative departures in the mean daily temperature throughout the entire 55-day period. The daily departures were the strongest for Fairbanks and the weakest for Juneau—a result to be expected for locations in a continental and maritime climate, respectively. Also shown with the daily temperature departures during this event is a relative weakening of the anomaly during mid-November. All four locations show a respite from the strong departures for a period of several days, which suggests intrusion of a regional-scale feature in the circulation pattern.

3. Temperature-anomaly diagnosis

a. Synoptics

Specific atmospheric circulation patterns are known to produce warm and cold wintertime temperature anomalies for Alaska and other high-latitude areas and are primarily related to anomalies of the semipermanent features in the pressure pattern. From the NCEP–NCAR reanalysis, the composite sea level pressure

FIG. 8. Sea level pressure anomalies (hPa) for the 2002 warm event (data source: NCEP–NCAR reanalysis, NOAA Earth System Research Laboratory).

anomaly for the 44-day period in 2007 shows a large positive anomaly of more than 12 hPa in the region of the Aleutian low (Fig. 5). This weakening in the pressure field results in less advection of the relatively warm midlatitude air mass into Alaska. Just to the east and centered on the Alaska Panhandle is a region of lower-than-normal sea level pressure in the range of 4–8 hPa. In the North Atlantic Ocean, the area of the Icelandic low shows a broad pattern of negative anomalies (>4 hPa), although not as strong as the anomaly pattern in the North Pacific. This dipole in the pressure patterns resulted in a weakening of the subpolar circulation in the Pacific sector and a strengthening in the Atlantic sector. Large surface temperature anomalies in the reanalysis data are shown for Alaska and western Canada, with the strongest departures of 10°C or more in east-central interior Alaska and central Yukon Territory (Fig. 6). Other notable temperature anomalies are the abnormal warmth (anomalies from $+2^{\circ}$ to $+6^{\circ}\text{C}$) over eastern Siberia and broad areas of positive anomalies in the subpolar North Atlantic and Barents Sea region. However, the most prominent anomalies in the Northern Hemisphere are those over Alaska and the Yukon. The

Alaskan anomalies are in agreement with surface station climatological data for this region (see Fig. 1). Furthermore, the extended cold period during 2007 was marked by a deep upper-level trough pattern and the persistence of cold upper-level lows tracking southward into Alaska from the high Arctic (Fig. 7). The 500-hPa trough in Fig. 7 is displaced eastward from its normal position while the adjacent ridge over far eastern Siberia is highly anomalous. The 44-day average geopotential height anomalies over the western Bering Sea exceed $+150$ m.

During the warm period of 2002, the Aleutian low showed a broad area of negative SLP anomalies of more than 12 hPa (Fig. 8). The Icelandic low during the 2002 event showed positive anomalies over the Barents Sea region, well to the east of Iceland. These positive anomalies extend across much of northern Asia. The strong negative anomalies in the North Pacific are striking given that it is over a 2-month time period. The enhanced Aleutian low translates into greater advection of warmer air into Alaska and significantly affects surface temperatures. As can be seen from Fig. 9, temperature anomalies occur not only for Alaska, but for much of western Canada, the Canadian high Arctic, Greenland, and the

FIG. 9. Surface air temperature anomalies ($^{\circ}\text{C}$) for the 2002 warm event. (data source: NCEP–NCAR reanalysis, NOAA Earth System Research Laboratory).

central Arctic. Similar to the 2007 event, the strongest anomalies for Alaska are in the continental climate of the interior. The positive temperature anomalies in the eastern Canadian region, especially Baffin Bay, appear to be associated with a late formation of sea ice in this region. Of interest is that the 2002 minimum sea ice coverage, reached in mid-September 2002, set a new record for the least sea ice on record in the Arctic. [That record has since been broken several times; cf. Stroeve et al. (2007).] The atmospheric circulation was clearly the primary driver of the excessive warmth over interior Alaska and the Yukon during October–December (OND) 2002, but the presence of extensive open water and the delayed freeze-up of the Arctic coastal waters may have contributed to the positive temperature anomalies north of Alaska in Fig. 9.

In contrast to the 2007 cold event, the 2002 warm event was characterized by a deep trough over the western Bering region and a ridge to the east of Alaska (Fig. 10). The trough was part of a wavenumber-3 pattern, with other troughs over eastern Canada and north-central Asia. The location of the Bering trough favors the tracking of storms into southern and southeastern

Alaska. Because OND is a cyclonically active period, the poleward heat transport by extratropical cyclones contributed to the abnormal warmth over northwestern North America.

b. Teleconnections

The cool seasons are often the time of year during which climate signals have their most prominent impact on synoptic characteristics in Alaska. Since the two periods studied here involve regional-scale patterns that persisted over an unusually long time period, a likely cause might be found in the presence of a strong ocean–atmosphere signal. The phases of ENSO, the Pacific decadal oscillation (PDO), and the Arctic Oscillation (AO) patterns were investigated to check for possible linkages to the anomalous periods.

For the period July 2006–February 2007, ENSO was in the warm phase and thereafter was in a neutral phase until the autumn. Therefore there was no strong ENSO forcing that occurred during the majority of this cold episode. The PDO, operating on a decadal time scale that has been predominantly positive (warm phase) since the mid-1970s, was neutral for January and February, and

FIG. 10. The 500-hPa geopotential heights (m) for the 2002 warm event. (data source: NCEP-NCAR reanalysis, NOAA Earth System Research Laboratory).

for March it was weakly negative (cool phase) with a PDO index of -0.4 (see online at <http://jisao.washington.edu/pdo/PDO.latest>). The transition to a cool phase in March agrees with the temperature departures experienced during 2007 because the cool phase is associated with northerly atmospheric circulation over Alaska and cold anomalies in the Gulf of Alaska and eastern equatorial Pacific. The AO showed monthly changes for the 2007 period, with a positive index (warm phase) for January, negative (cool phase) for February, and a return to positive for March. The relatively weak sea level pressure anomalies over the Atlantic sector in Fig. 5 are consistent with this month-to-month vacillation of the AO index.

For the 2002 warm event, ENSO was in a warm phase beginning in April and continuing through March of the following year. The intensity peaked in OND, with a mean index of $+1.4$ for the 3 months (Niño-3.4). The PDO was in a positive phase from August of 2002 through October of 2004, with especially large PDO index values of $+1.5$ and $+2.1$ in November and December, respectively, of 2002, favoring a circulation pattern of increased southerly flow into Alaska that

brought warmer-than-normal conditions (intensified Aleutian low). The AO was strongly negative for OND of 2002 (-1.5), consistent with the positive anomalies of sea level pressure in the subarctic North Atlantic and in northern Eurasia (Fig. 8). Because the AO shows a weak negative correlation with temperatures over Alaska (Serreze and Barry 2005, their Fig. 11.12), the AO may be regarded as a contributing factor to the abnormal warmth of late 2002 in Alaska. However, the North Pacific circulation anomaly pattern was clearly the more immediate driver.

4. Discussion and conclusions

Although cold-season temperature variability is normally large for high-latitude locations, the episodes of 2002 and 2007 are noteworthy because of their respective duration and magnitude. In a historical context, both events are clearly outliers and record breaking in nearly a century of data (for some long-term observing stations). One important consideration is that these events have an impact on society, such as through the viability of outdoor activities and through energy demands.

FIG. 11. RMSE for the observed and MOS maximum and minimum daily temperature at Fairbanks, shown as the aggregate mean over (top) the 2002 warm event and (bottom) the 2007 cold event.

Heating degree-day (HDD) totals for these events represent an indication of the direct weather impact to humans. HDDs are calculated as the difference in mean daily temperature from a base temperature (18°C used here), accumulated over a given time interval.

A clear negative impact of the 2007 cold event was greater energy needs with significantly higher-than-normal HDD. For Barrow, Fairbanks, Anchorage, and Juneau, Alaska, the HDD departures from normal for the 37-day period were 161, 647, 408, and 240, respectively. With rural Alaska limited to airplane and boat traffic for distribution of goods and services, local energy supplies must be able to last through the winter, until the warm-season delivery time for fuel. In addition, energy costs remain high and present a significant economic impact—in particular, for the many rural communities not on the road system. For the warm event of 2002, energy needs were very different as the 55-day HDD totals were well below normal. Departures were -517 , -946 , -758 , and -327 for Barrow, Fairbanks, Anchorage, and Juneau, respectively. These HDD anomalies are greater than for 2007 and are in agreement with the more widespread and larger-magnitude temperature anomalies for this event. The economic impact of lower

FIG. 12. Daily maximum and minimum temperature bias ($^{\circ}\text{C}$) between the observed and MOS values at Fairbanks, shown as the aggregate mean over (top) the 2002 warm event and (bottom) the 2007 cold event.

energy demands would of course be a positive one for consumers in this case. A negative impact, however, was the freezing-rain events that occurred in interior Alaska in November of 2002. These events are rare for this time of the year and produced hazardous road conditions that lasted well into the winter.

As noted in section 3b, the teleconnection patterns are in general agreement with the temperature departure patterns one would expect given the various atmospheric circulation forcings. We can also consider how the weather forecasts performed during these extended episodes. The model output statistics (MOS) are one of the products typically used as guidance for routine operational forecasts within the National Weather Service. As the name implies, MOS utilizes statistical methods to determine predicted variables from a numerical model (Glahn and Lowry 1972). MOS products are available for a variety of weather variables, including daily maximum and minimum temperature, and are currently produced every 12 h.

In a systematic comparison of MOS and observed daily maximum and minimum temperatures during the

two events, there are some consistent findings. One predominant feature found for both the warm- and cold-anomaly periods was that the temperature bias and error increase over the forecast period from 12 to 192 h (Figs. 11, 12). The temperature bias increasing over time shows a tendency for MOS to gravitate toward climatological means as the forecast hour increases. This tendency is exacerbated by the seasonal trends. Day length is significantly changing over the course of these long-lasting events (decreasing for the 2002 event and increasing for the 2007 event). The temperature “climatology” is drifting with the season accordingly—a cooling trend in early winter 2002 and a warming trend in late winter 2007.

In addition, there were noteworthy differences in the prediction accuracy of maximum versus minimum temperature. The bias was consistently greater for the minimum temperature than for the maximum. This difference is thought to be a result of complex near-surface boundary conditions that strongly determine the local temperature pattern and occur on a subgrid-scale level that cannot be resolved by the models. For the 2007 event, the difference in prediction accuracy of maximum and minimum temperature was more pronounced. Factors such as increasing daylight hours for this time of year and frequent clear skies lead to strong radiational cooling at night, daytime mixing of the boundary layer, and a high diurnal temperature range. For the 2002 event, day length was decreasing throughout the period and warm-air advection at the synoptic scale along with frequent cloud cover tended to reduce the longwave energy loss at the surface and keep the diurnal temperature range relatively low.

In summary, the extended anomaly periods of 2002 and 2007 represent two unique case studies because of their large spatial extent and long duration. These events clearly stand out in the historical record for many of the observing stations. Both cases were driven by synoptic-scale circulation pattern anomalies at the surface and upper levels in conjunction with corresponding teleconnection regimes. Comparison of observed and modeled temperatures shows that these anomalous periods were difficult to forecast using a routine model product. These extreme events were not only of climatological significance—there were also societal implications because of their spatial and temporal extent.

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