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Surface-based temperature inversions in Alaska from a climate perspective

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ABSTRACT

Alaska surface-based temperature inversions were analyzed using radiosonde observations from Barrow, Fairbanks, McGrath, Anchorage, Kotzebue, Bethel and King Salmon, which represent different climate zones in Alaska. Inversion climatology, variability and links to the large-scale climate were investigated for the period of 1957–2008 when high quality radiosonde data are available.

Inversion parameters, such as depth, temperature difference, and frequency, have a long-term decreasing trend, which is not simply linear but displays multi-decadal variations. Inversion depth decreased from 1957 to the late 1980s and has been increasing since. The multi-decadal signal has been detected at all stations but is particularly dominant for Interior stations. The relationship between Alaska inversion and the Pacific Decadal Oscillation changes over time and was found to be stronger before 1989 than in recent years. Alaska inversions also demonstrate strikingly similar interannual variability, suggesting an important role of large-scale circulation.

1. Introduction

Physical controls of inversions are well documented and understood; Wexler (1936) and Bradley and Keimig (1992) found that temperature inversions are predominantly driven by a balance between radiative cooling and heat advection. In high latitude regions, in the presence of negative net radiation the surface cools to a temperature below that of the air above it. This decrease in surface temperature subsequently cools the atmosphere above it, creating a thermally induced inversion. Warm air advection above the inversion layer can concurrently create a strong thermal stratification between layers, resulting in extremely stable conditions.

Arctic temperature inversions have been studied for over a century. Brooks (1931) demonstrated the high frequency of occurrence of inversions using kite ascents over Siberia. Detailed studies made over a broad region of the Arctic during the *Maud* expedition offered scientists new information on the structure of inversions (Sverdrup, 1933). Wexler (1936) developed the idea of physical controls, which affect inversion formation in a negative net-radiation environment. Bilello (1966) investigated inversion characteristics such as frequency, base height, thickness, base temperature, and temperature gradient. Wendler (1975) demonstrated that low-level inversions were present more than 95% of the time in the winter (November–February) with maximum temperature differences of 20 °C in 200 m. Serreze et al. (1992) introduced the idea of the complexity of inversions, suggesting that inversions were not only affected by radiative cooling, but also by warm air advection, subsidence, radiative properties of ice crystals, surface melt, and topography. In general, increased (decreased) cloud cover leads to inversions with weaker (stronger) temperature gradients (Kankanala, 2007; Bourne, 2008). As cloud cover increases, downwelling longwave radiation is enhanced which causes surface warming and a weakening of the surface-based inversion. Hartmann and Wendler (2005a) examined the

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climatology of the wintertime surface-based inversion (SBI) and its importance for winter air quality in Fairbanks, Alaska. Strong winds can break up inversions, but in an orographically sheltered region such as Fairbanks that does not receive strong winds during winter months, pollutants move away from their sources fairly slowly, leading to unusually high pollution levels. In the wintertime in Fairbanks, surface wind speeds are generally less than 0.5 m s^{-1} (Kankanala, 2007), and previous research has suggested that strong inversions may persist with winds up to 1.5 m s^{-1} (Wendler and Nicpon, 1975).

The impact of inversions on air quality and their subsequent effect in society are a concern in high latitude communities. A better understanding of how SBIs are related to the large-scale climate can have direct societal benefits through improved seasonal predictability. The following topics present the research focus and highlight the unique contribution of this study with regard to the interannual variability of surface-based temperature inversions in Alaska:

- Document the seasonal evolution and climatology of SBI in Alaska for Barrow, Fairbanks, McGrath, Anchorage, Kotzebue, Bethel and King Salmon,
- Characterize the interannual variability and trends of inversion parameters such as inversion depth, inversion temperature difference, and temperature gradient for Alaska stations,
- Evaluate the relationship between Alaska inversions and the large-scale climate.

2. Data and methods

2.1. Data

Observational radiosonde data from the National Climatic Data Center (NCDC) are employed in this research. The NCDC's Integrated Global Radiosonde Archive (IGRA) consists of twice-daily, quality-controlled radiosonde and pilot balloon observations at more than 1500 globally distributed stations, seventeen of which are located in Alaska. Data for Alaskan stations is available beginning in 1948 with observations including pressure, temperature, geopotential height, dewpoint depression, wind direction, and wind speed (Durre et al., 2006). IGRA data is subject to quality assurance algorithms, which include but are not limited to checks for format problems, physically implausible values, climatological outliers, and temporal and spatial inconsistencies in temperature. Further details on the quality control process are available on-line (http://www.ncdc.noaa.gov/oa/climate/igra/index.php).

Radiosondes in Fairbanks have been launched at Fairbanks International Airport since 1951. According to Mahesh et al. (1997), temperatures recorded by radiosondes are subject to many sources of error. Vertical profiles collected before 1957 include measurements with considerable time lag and with long periods of no measurement, which can prevent the instrument from detecting smaller layers of atmosphere with negative lapse rates (Huovila and Tuominen, 1989). Therefore, data before 1957 was not used in order to minimize data inconsistencies, making the study period 1957–2008. The 0000 and 1200 UTC radiosondes are typically launched an hour or so earlier and the near surface temperatures are taken at 2300 and 1100 UTC. Also note that before the time zone change in 1983, the Fairbanks radiosondes were taken at 0200 and 1400 Alaska Standard Time. The analysis was also performed on several other stations in Alaska: Barrow, McGrath, Anchorage, Kotzebue, Bethel and King Salmon station data (Fig. 1). The stations represent five of the nine Alaska climate regions (see Fig. 1.23 in Shulski and Wendler, 2007): Arctic (Barrow), Interior (Fairbanks and McGrath), West Central (Bethel and Kotzebue), Bristol Bay (King Salmon) and Cook Inlet (Anchorage). Each station has unique climatological characteristics that are reflected in the inversion characteristics.

An additional concern arises as a result of urban development and human activities around the city of Fairbanks (Mölders and Olson, 2004). Magee et al. (1999) define the urban heat island as the temperature difference between a city and the same location if the city were not present. The presence of an urban heat island is of concern for surface-based temperature inversions because lower level temperatures will affect inversion structure and strength. Additionally, urban heat sources and the relatively low surface albedo when compared to that of snow may enhance the urban heat island effect (UHIE) in the boundary layer. One technique used to approximate the UHIE is to compare temperatures between the urban location in question, and a nearby location with similar orographic features. McGrath was used for this comparison since it is topographically similar to Fairbanks yet has not grown considerably in the past 50 years. The temperature difference between Fairbanks and McGrath was found to be negligible and UHIE adjustments for Fairbanks were not necessary.

2.2. Inversion detection algorithm and analysis methods

Because Arctic temperature inversion profiles often exhibit complicated vertical structures, they have been classified using various methods, which can affect the results. The algorithm used to detect inversions was based on the definition developed by Kahl (1990) and Serreze et al. (1992) which defined an inversion as a layer where temperature increases with altitude, including embedded layers with negative lapse rates, provided they are no more than 100 m in extent.

Data from each station was obtained from the NCDC in ASCII format and were extracted for the winter months (November–March). The soundings were converted from geopotential to geometric height and were interpolated to 50 m height increments. The resulting monthly files contained twice-daily soundings (0 and 12 UTC) from 1957 to 2008 and included pressure, geometric height, and temperature. The data was then read into an algorithm detection program, which determined whether temperature was increasing or decreasing with height for each profile. If temperature was decreasing in the first two levels, the sounding was considered to not have a surface-based inversion. However, if the temperature in the first two levels was greater than the surface, the algorithm would check each subsequent layer moving upwards to verify that the temperature was increasing. If temperature decreases in a layer greater than 100 m, the top of the inversion is then defined as the warmest temperature above the surface including isothermal and cooling layers given they are less than 100 m in thickness. Once the top of the inversion was determined, the 0 and 12 UTC Surface Air Temperature (SAT), temperature difference across the inversion

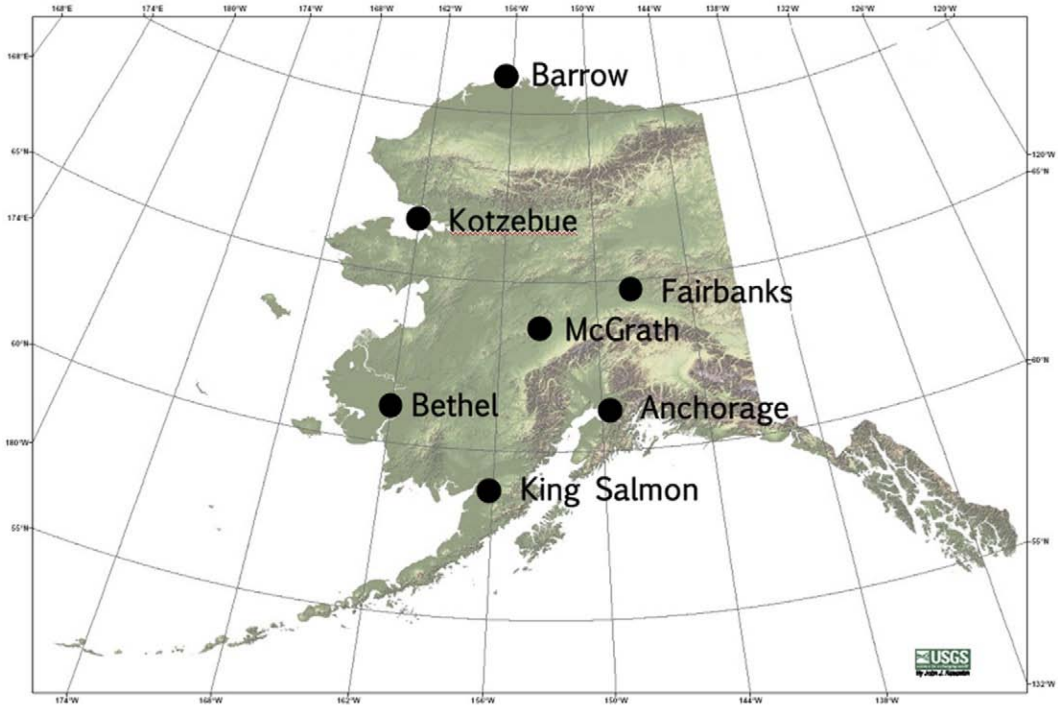

Fig. 1. Alaska radiosonde observation (RAOB) stations are identified on a topographic map (image modified from USGS and available on-line at http://rmmcweb.cr.usgs.gov/outreach/gps.html). The stations represent five of the nine Alaska climate regions (See Figure 1.23 in Shulski and Wendler, 2007): Arctic (Barrow), Interior (Fairbanks and McGrath), West Central (Bethel and Kotzebue), Bristol Bay (King Salmon) and Cook Inlet (Anchorage).

($T_{top}-$SAT), inversion depth ($Z_{top}-Z_{surface}$), and temperature gradient (dT/dz) were averaged, resulting in one value per day. Daily and monthly averaged inversion parameters were investigated.

Standard methods of climate analysis (e.g. correlations, linear trends) were applied to monthly average data over the 1957–2008 period to investigate trends, variability, and links to large-scale climate of SAT, inversion depth, temperature difference, and temperature gradient. Correlation analysis was performed on linearly detrended data and statistical significance at the 95% or greater level based on a *t*-test is identified by values shown in bold.

3. Results

3.1. Climatology of Fairbanks inversion parameters

During winter months inversions display marked seasonality, which is evident in the climatological (1957–2008 average) monthly vertical temperature profiles (Fig. 2). Warmer months (October and March) exhibit shallow surface-based inversions that cap below 100 m and above which temperature decreases with height during these warm months. Cooler months (November–February) have strong semi-permanent inversions that exhibit a more complicated structure with a shallow surface-based inversion and deeper elevated inversion aloft. When temperature profiles of cooler months are averaged over a long time period, the elevated portion of the inversion will cap around 1000–1500 m with 5–10 K temperature difference from the surface to the top of the inversion.

Climatological SAT decreases from October to January and begins to increase from February to March (Fig. 3a). Temperature difference across the inversion (air temperature at the top minus temperature at bottom) and inversion depth increase from October to January and then decrease as

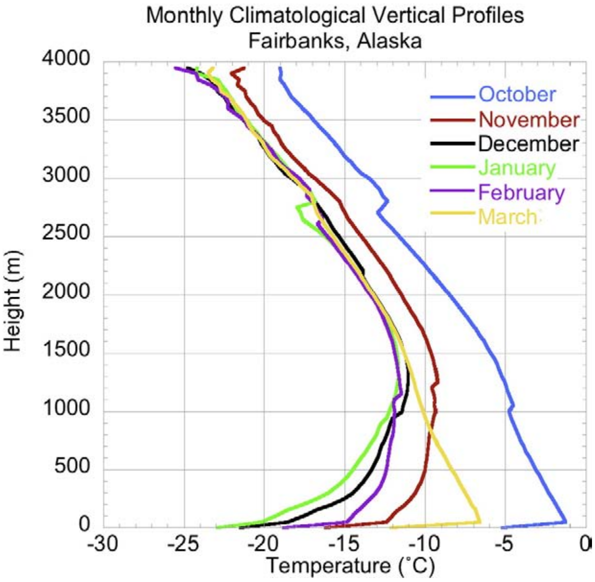

Fig. 2. Monthly average (1957–2008) vertical temperature profiles in °C for Fairbanks, Alaska from October to March.

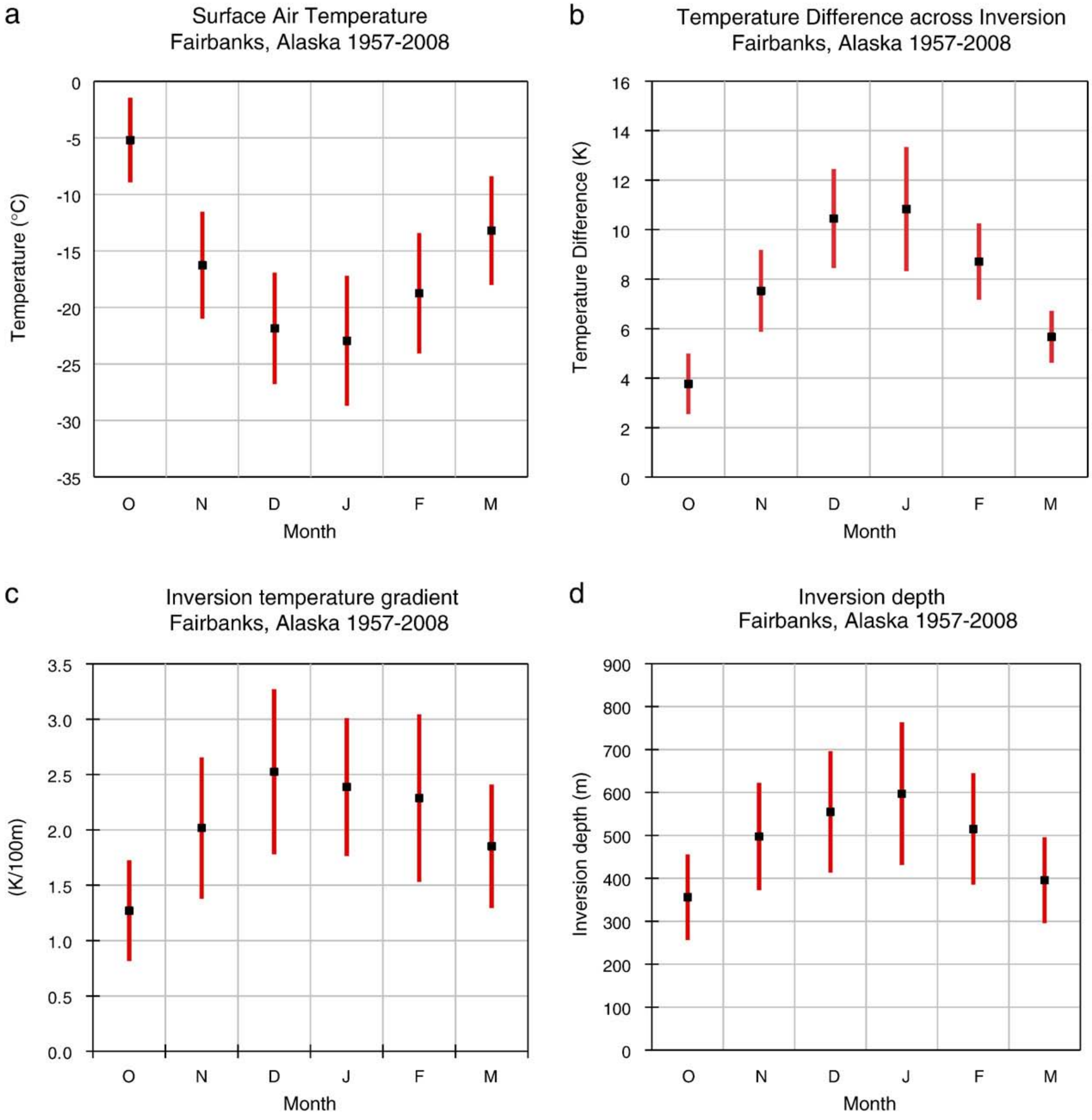

Fig. 3. Seasonal mean (black dot) and 1-sigma standard deviation (red line) over the period 1957–2008 of a) surface temperature, b) inversion temperature difference, c) inversion temperature gradient, and d) inversion depth in Fairbanks, AK.

spring approaches (Fig. 3b, d). Generally variability (standard deviation shown by vertical red lines in Fig. 3) of inversion characteristics is largest in the coldest months (Fig. 3). One exception is the inversion temperature gradient, which displays larger variability in December and February than January (Fig. 3c).

Inversion frequency displays diurnal and seasonal variation. The 1200 UTC profiles (Fig. 4, black line) are taken at 0300 Alaska Standard Time (AST) and display only a modest change with month, while the profiles at 0000 UTC (Fig. 4, red line) or 1500 AST demonstrate relatively larger seasonal variability. Impacted by the stronger diurnal cycle during the warmer months, the 0000 UTC inversion frequency is notably smaller than that at 0300 UTC during the warmer months. During cooler months such as December and January, the solar radiation deficit creates an environment where inversion frequency does not vary much with the diurnal cycle (Fig. 4). The asymmetry in the nighttime inversion frequency is a result of the progression of seasonal temperatures. In the beginning of the winter, climatological variables are

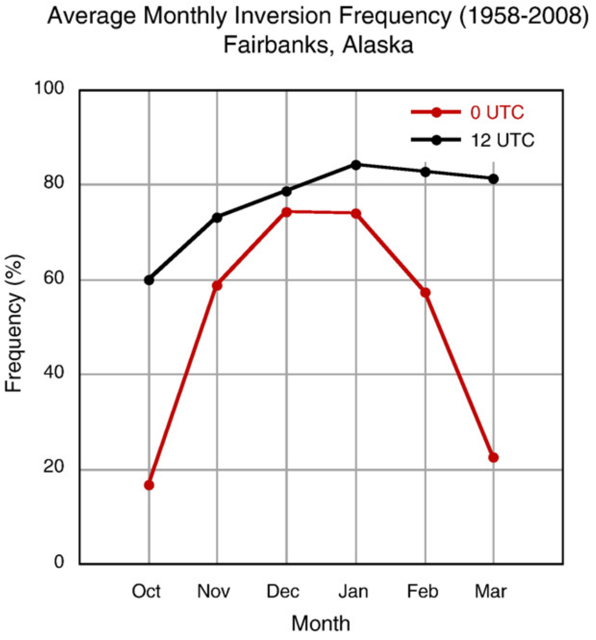

Fig. 4. Climatological wintertime surface-based inversion frequency in Fairbanks, AK. Long-term mean frequency of inversions is shown as a percentage of days of the month. Observations of inversion frequency are shown at 0000 UTC (1500 hours AST) and 1200 UTC (0300 hours AST).

emerging from warm summer conditions, making inversion frequency somewhat lower. Conversely, after the wintertime, the seasonal cycle is emerging from cooler temperatures, resulting in a higher inversion frequency. The land surface is generally cooler in spring as compared to autumn resulting to a higher spring inversion frequency.

Correlation analysis between SAT and inversion characteristics at Fairbanks showed that SATs were negatively correlated to inversion depth and temperature difference. Daily values of inversion depth (dz) and temperature difference (dT) are significantly correlated (greater than 95%) for Fairbanks during winter and are 0.69 (Oct), 0.62 (Nov), 0.64 (Dec), 0.78 (Jan), 0.41 (Feb), and 0.45 (Mar). When the surface is warm, inversions are shallow with a small temperature difference but when the surface is cool, inversions are deep with a larger temperature differences. This relationship is shown schematically in Fig. 5 and while it does not hold all of the time a large part of the variance is explained. This notion holds true for all stations in the study and makes physical sense because inversions develop from the surface due to longwave radiative loss.

3.2. Variability of Alaska inversion parameters

There is considerable interannual to multi-decadal variability in the time series of SAT anomalies at the seven Alaska stations (Fig. 6). SATs are typically below average from 1957 to the mid-1970s and during the 1990s while the 1980s and the last ten years are warmer than average for Barrow, Fairbanks, McGrath and Anchorage. Kotzebue, Bethel and King Salmon, display a similar pattern but with less warming in the last ten years. Temperature trend magnitudes over the 1957–2007 period are positive in December for all seven stations and vary from 0.44 in King Salmon to 1.1 K per decade for Fairbanks. January trends (in parenthesis on Fig. 6) from 1957 to 2008 are notably weaker and even negative for Kotzebue, Bethel, King Salmon and Barrow. Our Barrow results are consistent with a study by Stafford et al. (2000). Note that SAT trends are very sensitive to the period over which they are evaluated and removing one year from the January trend resulted in a change of trend sign for Bethel, King Salmon and Barrow. The sensitivity of trends to the chosen time period is of particular concern in the Arctic where large amplitude multi-decadal variability is present (Polyakov et al., 2002). SAT trends shown here are somewhat different than those of Shulski and Wendler (2007), which were taken over the 1947–2005 (see their Table 7.1). It is also noteworthy that there is a general tendency for anomalies to be of the same sign at the seven stations in Alaska during a given month, suggesting that climate anomalies are similar over a large area of the state.

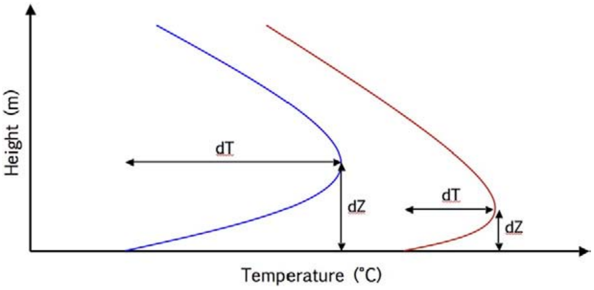

Fig. 5. Schematic showing the relationship between inversion depth and temperature difference. Surface-based temperature inversions in Alaska are largely a function of surface temperature. When surface temperatures are warm (cold), inversion depth and temperature difference is small (large).

December inversion depth anomalies, decadal trends and mean values are shown in Fig. 7, while January trends are shown in parentheses. Overall, inversion depth anomalies were positive until the late 1970s, negative during most of the 1980–90 period, and became more positive in the last 10 years (Fig. 7). Inversion depth in the early part of the record was between 800 and 1000 m at Interior stations but was between 400 and 600 m towards the end of the study period (not shown). Average inversion depths in Kotzebue, Anchorage, Bethel, and King Salmon were between 400 and 600 m in the early part of the record and have decreased to 300–500 m in recent years. The largest decreases in inversion depth have occurred in Barrow, which displays a similar multi-decadal variability as the other stations, but the depths have increased slowly since the late 1980s. The extreme inversion depths (>1000 m) in McGrath in 1961 and 1962 are consistent with the weather conditions during those winters, suggesting that they are correct. The low-frequency variability of inversion depth is strikingly similar at all the Alaska stations.

The mean inversion temperature difference ($T_{\text{top}} - T_{\text{bottom}}$) (not shown) displays large values early in the study period, decreasing until the late 1980s and subsequently increasing over the last 20 years. The December and January average

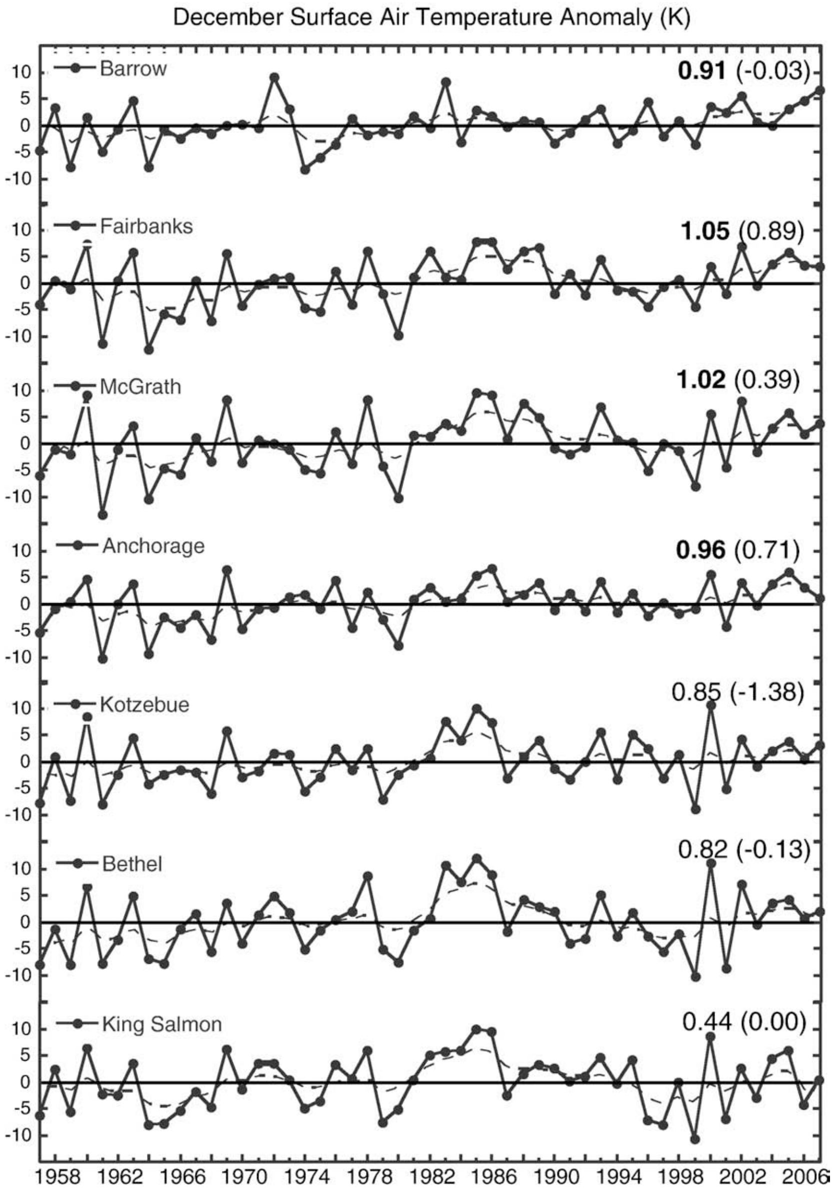

Fig. 6. Anomalies of SAT at stations in December. Numbers indicate linear trends in K per decade for December (January) from 1957 to 2007 (1957–2008). January trends are shown in parenthesis. The dashed line shows the 5-year running mean and bold trends are significant at the 95% or greater level.

inversion temperature differences are largest for McGrath, Fairbanks, Barrow, and Bethel at 11.1, 10.6, 7.2, and 6.5 K, respectively. The corresponding DJ mean climatological values for Anchorage, Kotzebue, and King Salmon are 4.2, 4.4, and 4.8 K, respectively. Anomalies of inversion temperature difference (Fig. 8) display above normal values until the mid-late 1970s, below average depths in the 1980s and generally weak anomalies during the past decade. The exception to this is Barrow, which displays a decrease over the entire record (e.g. December trend of −0.98 K per decade). All of the stations except Kotzebue have larger trends in January than December. Kotzebue displays the weakest trends of all the stations during both peak winter months.

On average, McGrath, Fairbanks, Bethel and Barrow have inversions that increase approximately 2 K per 100 m while Kotzebue has inversions that increase approximately 3 K per 100 m. Local topographic effects likely play a role in the strong temperature gradients in Fairbanks and McGrath, while different processes are key at other stations. The Canadian Arctic exhibits similar temperature gradient magnitudes of approximately 1.5 K per 100 m (Kahl et al., 1992) while the strongest inversions in Eurasia are found in Verkhoyansk in the Yana River Valley with temperature gradients averaging about 1.5 K per 100 m (Serreze et al., 1992).

Temperature gradient variations from November through March in Fairbanks display anomalies of the same

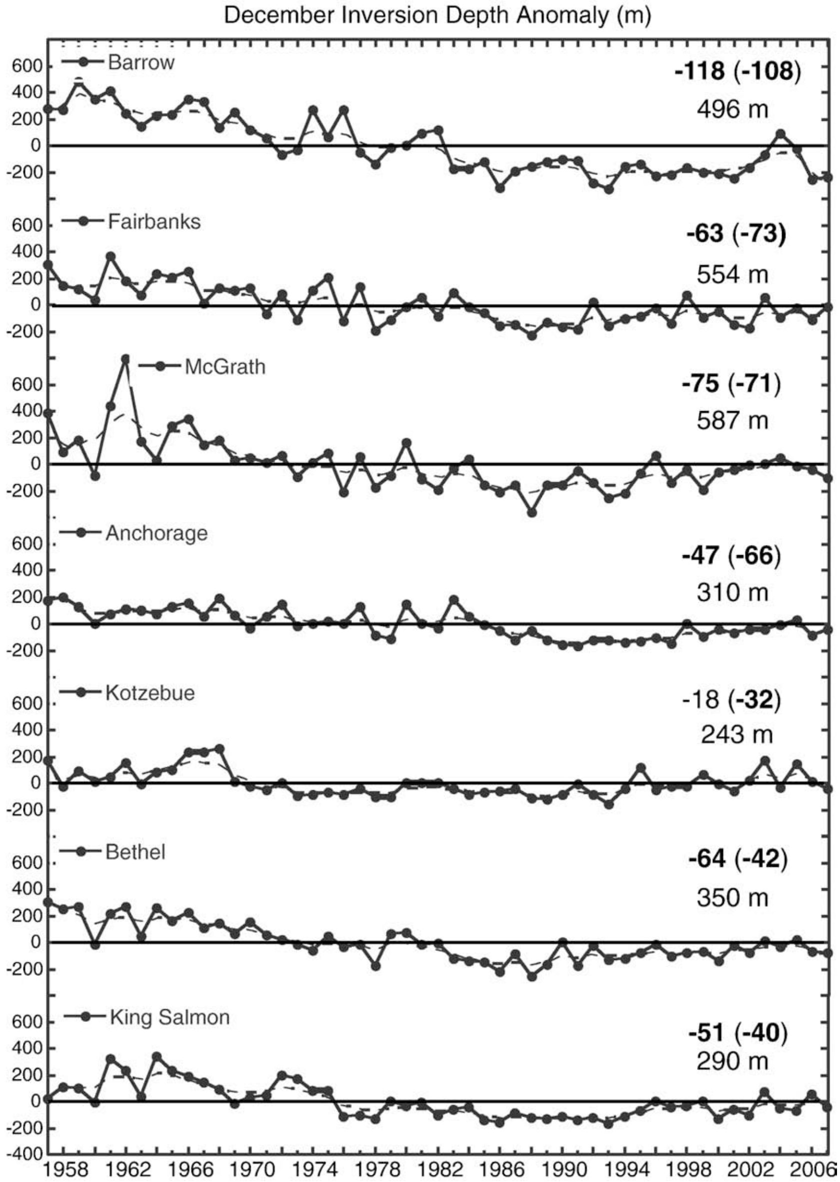

Fig. 7. Anomalies of inversion depth at stations in December. Numbers indicate linear trends in m per decade for December (January) from 1957 to 2007 (1957–2008). January trends are shown in parenthesis. Climatological mean station inversion depths are shown in m below trend values. The dashed line shows the 5-year running mean and bold trends are significant at the 95% or greater level.

sign within a winter season from 1957 to the mid-late 1970s and more intra-seasonal variability in the latter half of the record (Fig. 9). Understanding the mechanisms behind the persistence or lack of persistence within a season could be exploited for seasonal climate prediction. However, SAT anomalies for Fairbanks display greater variability within a winter than inversion temperature gradient, depth, or temperature difference. There is less persistence within a winter season for temperature anomalies than inversion parameters, suggesting that SAT variability is controlled less by the large-scale climate than the inversion parameters.

Before 1970, the temperature gradient at all stations in December (January) was near or slightly below the mean (Fig. 10). Temperature gradient is calculated by dividing inversion temperature difference by inversion depth, making it sensitive to changes in both variables. Inversion depths and temperature differences are large before 1970, resulting in small temperature gradient anomalies. Beginning in 1971, there is a period where gradient anomalies (Fig. 10) display large interannual variability. This feature is evident in all months (October–March) at each station. Trends are not presented for Fig. 10, since it is unclear whether they would be meaningful. Patterns of interannual variability in temperature gradient likely vary due to synoptic-scale forcing associated with modes of large-scale climate variability. Winter storms bring warm air and strong

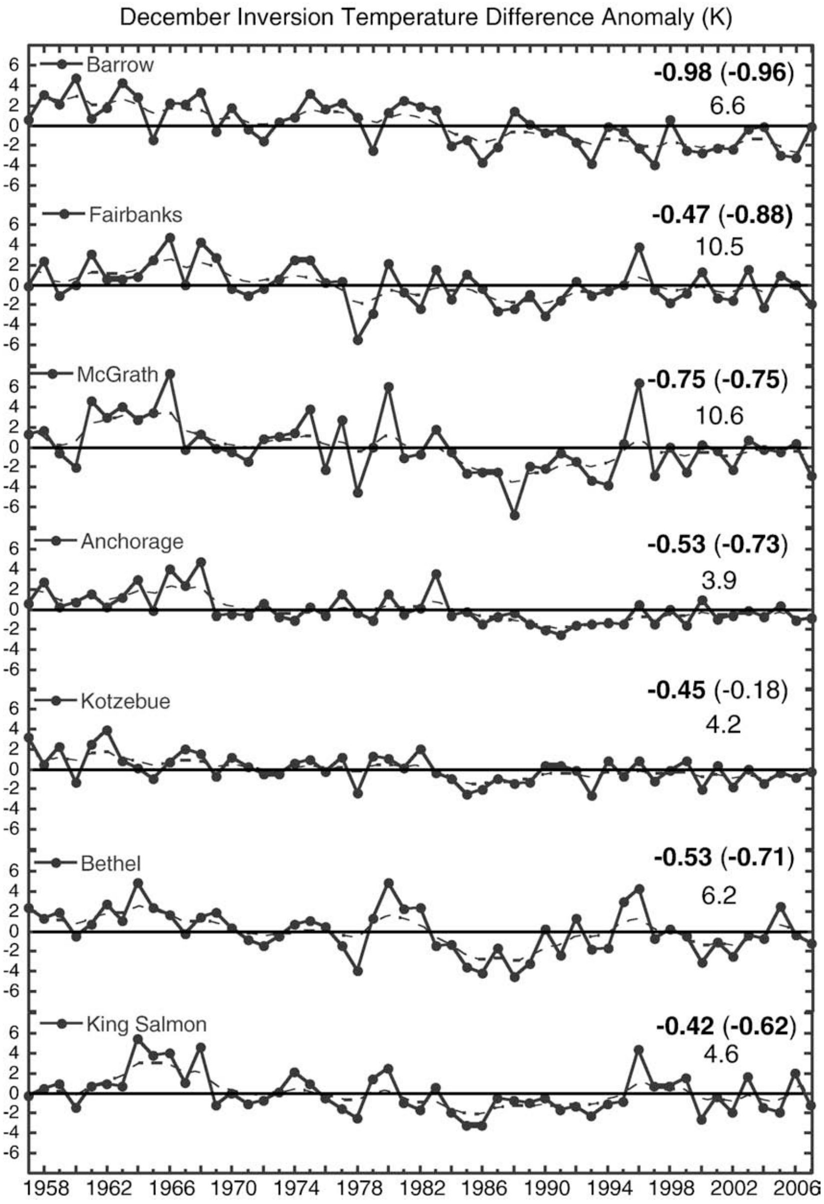

Fig. 8. Anomalies of inversion temperature difference at stations in December. Numbers indicate linear trends in K per decade for December (January) from 1957 to 2007 (1957–2008). January trends are shown in parenthesis. Climatological mean station inversion temperature differences are shown in K below trend values. The dashed line shows the 5-year running mean and bold trends are significant at the 95% or greater level.

winds that lead to mixing of boundary layer air that weakens inversions. A detailed analysis of available storm track data in relation to SBIs in Alaska was initiated but was beyond the scope of the current study.

The time series of inversion frequency (averaged December and January) (Fig. 11) displays a decrease from 1957 to the late 1980s/early 1990s and a slight increase in the last 10–20 years for Fairbanks, McGrath, Bethel, and King Salmon. This is consistent with the patterns of low-frequency variability found in SAT and the inversion parameters. The Barrow time series stands out as different and displays a secular decrease in inversion frequency (decrease of 5.3% per decade). The inversion frequency in Kotzebue, Bethel and King Salmon is characterized by multi-decadal variability and has decreased by 2, 2.7, and 3.1% per decade, respectively. Inversion frequencies in Anchorage have decreased by 1.4% per decade, while Fairbanks and McGrath have stayed relatively constant with trends of −0.6 and −0.2% per decade, respectively.

3.3. Alaska inversions and large-scale climate

The relationship between Alaska inversion parameters and indices of large-scale climate was investigated through a correlation analysis with the North Pacific Index (NPI), Pacific

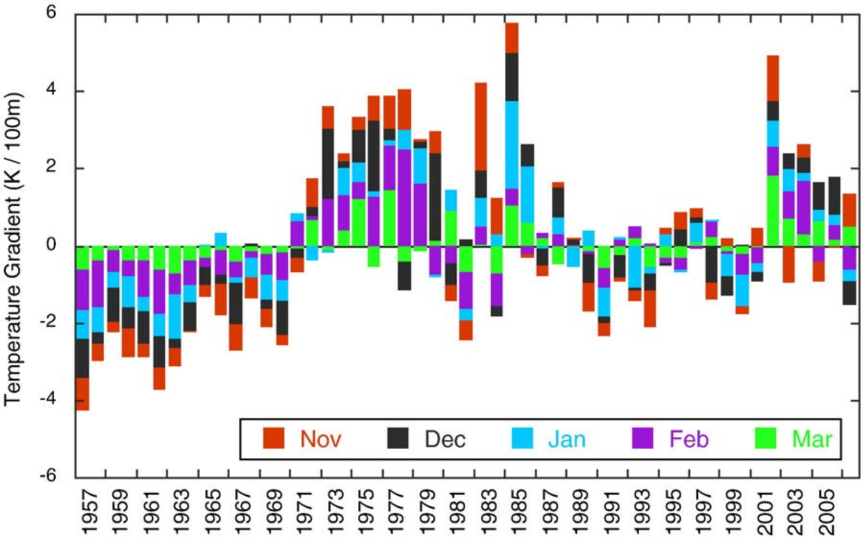

Fig. 9. Interannual and intra-seasonal variability of temperature gradient anomalies in K $(100\ \mathrm{m})^{-1}$ for Fairbanks. Note that the value for the year refers to November and December (e.g. 1972 is Nov–Dec 1972 and Jan–Mar 1973).

Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO).

The North Pacific Index (NPI) is an area-weighted sea level pressure (SLP) that provides a measure of strength of the wintertime Aleutian Low (Trenberth and Hurrell, 1994). The NPI was compared with SAT and inversion depth in Fairbanks (Fig. 12a) during the winter months (Nov–Feb). SAT is negatively correlated to the NPI index (−0.56), consistent with the notion that the positive phase of the NPI which is accompanied by a weaker Aleutian low, reduced southerly advection, and cooler than average SATs in Alaska. The inversion depth and temperature difference are weakly correlated with the NPI index (0.16 and 0.15 — not statistically significant). Applying a five-year smoothing on the time series results in stronger correlations of the NPI with SAT (−0.77), with inversion depth (0.40), and with inversion temperature difference (0.45). Fig. 12a indicates that while interannual variations may differ the low-frequency multi-decadal variations are very similar between the Fairbanks inversion parameters and the NPI.

The PDO, defined as the first Empirical Orthogonal Function (EOF) of North Pacific monthly sea surface temperature poleward of 20 N (Mantua et al., 1997), is correlated with wintertime (December–January) Fairbanks inversion depth and temperature difference (−0.36 and −0.22, respectively) over the entire observation period (1957–2008). The correlation between the wintertime (November–February) PDO and Fairbanks SAT is 0.50. From 1957 to 1989, the correlation between the PDO and the inversion parameters is even higher (−0.64 with depth and −0.58 with temperature difference). The remaining period from 1990 to 2007 shows no statistically significant relationship between the PDO and inversion depth and temperature difference (Table 1). Time series of the PDO with Fairbanks SAT and inversion depth are shown in Fig. 12b. Using smoothed (5 year running mean) time series results in stronger correlations of the PDO over the full record with SAT (0.78), with inversion depth (−0.62), and with inversion temperature difference (−0.67). This is not contradictory to the change in correlation with time but can be viewed as follows. The low-frequency variability of the PDO influences Fairbanks inversions over the entire record but interannual variations of the PDO (unsmoothed correlations) exerted a stronger influence on Fairbanks inversions from 1957 to 1989 (Table 1). Hare and Mantua (2000) document a second shift in the PDO in 1989 evident in components of the North Pacific ecosystem. In addition, Bond et al. (2003) use EOF analysis of ocean sea surface temperatures (SST) to show that since 1989 the prevalent SST anomaly pattern in the North Pacific has changed. In sum, the PDO and NPI are two forms of large-scale Pacific climate variability that influence the low-frequency variability of inversion parameters in Alaska.

According to Papineau (2001), synoptic-scale forcing resulting from large-scale climate oscillations has a considerable effect on temperature anomalies over Alaska. SAT changes that occur as a result of synoptic-scale flow are inhibited by the development of strong, stable inversions. Additionally, warm anomalies are primarily a function of advection, therefore temperatures during warm anomalies oscillate in phase with changes in the synoptic-scale flow. For this reason, it is important to determine the effect other modes of natural climate variability have on inversion characteristics in Alaska.

The North Atlantic Oscillation (NAO) index is the normalized SLP difference between Iceland and the Azores (Hurrell, 1995), where the positive phase is characterized by an above average meridional pressure in the Atlantic and more intense storms penetrating into the Arctic (Zhang et al., 2004). Correlations between the NAO and Alaska surface inversion parameters are weak (not shown). While, interannual variations are not coherent, the general low-frequency tendencies between the NAO and inversion parameters in Fairbanks compare favorably (Fig. 12c). Applying a five-year smoothing to the time series results in significant correlations of the NAO with SAT (0.42), with inversion depth (−0.87), and with inversion temperature difference (−0.82) and is consistent with the visual impression gained from Fig. 12c.

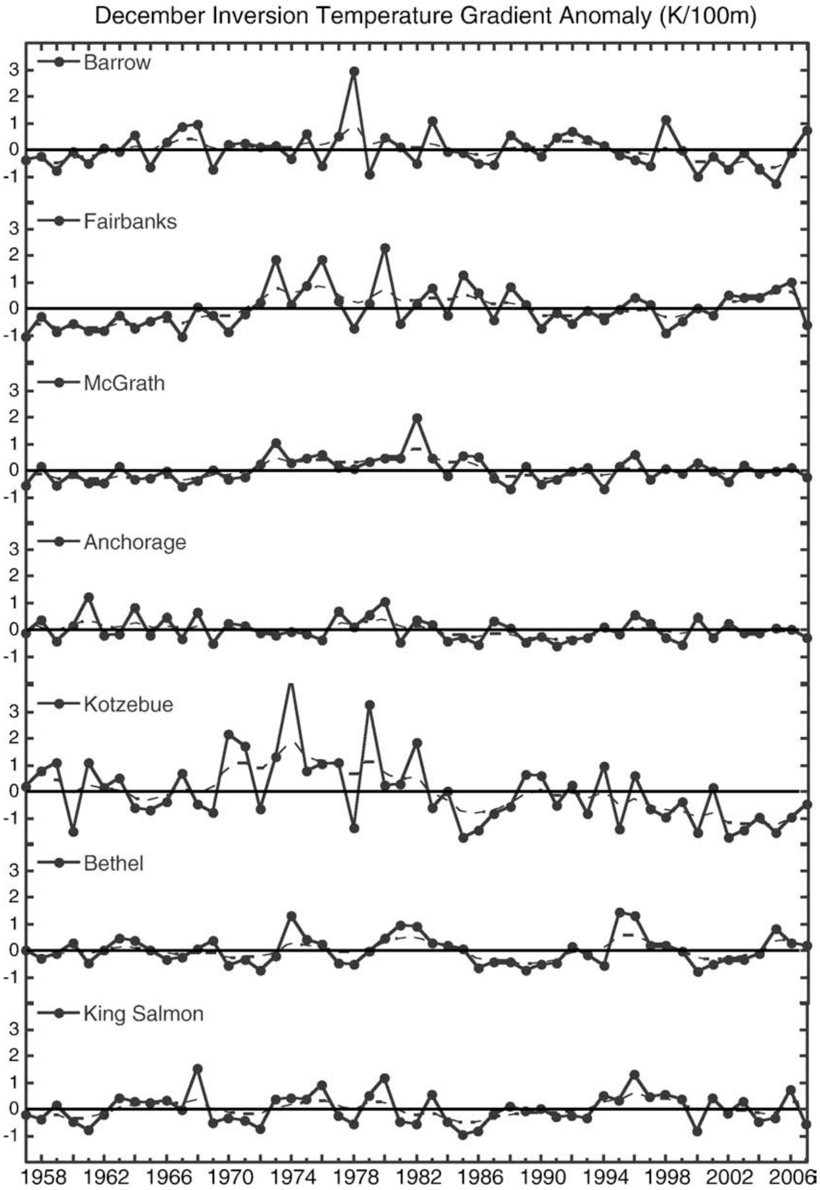

Fig. 10. Anomalies of temperature gradient in K $(100\ \mathrm{m})^{-1}$ at study stations in December from 1957 to 2007. The dashed line shows the 5-year running mean.

The smoothed correlations suggest that during the positive phase of the NAO, Alaska SATs are warmer, inversion depths are shallower, and inversion temperature differences are weaker than normal. In sum, the NAO is not correlated at interannual time scales but is correlated at decadal and longer time scales with inversion parameters in Alaska.

4. Summary and conclusions

The primary goal of this work was to document the climatology, characterize trends and variability, and explore links to large-scale climate variability of observed wintertime (November–March) surface-based temperature inversions for the Alaska stations of Barrow, Fairbanks, McGrath, Anchorage, Kotzebue, Bethel and King Salmon from 1957 to 2008.

The key findings are summarized as follows:

- There is a relationship between surface air temperature (SAT), inversion temperature difference and inversion depth. When SATs are warm (cold), inversion depth and inversion temperature difference are small (large) (Fig. 5).
- The Alaska stations display similar interannual variability for SAT and inversion parameters, suggesting an important role of large-scale circulation in Alaska.
- The analysis of trends in inversion parameters is not straightforward because the time series display clear multi-decadal variability, making trend values sensitive to

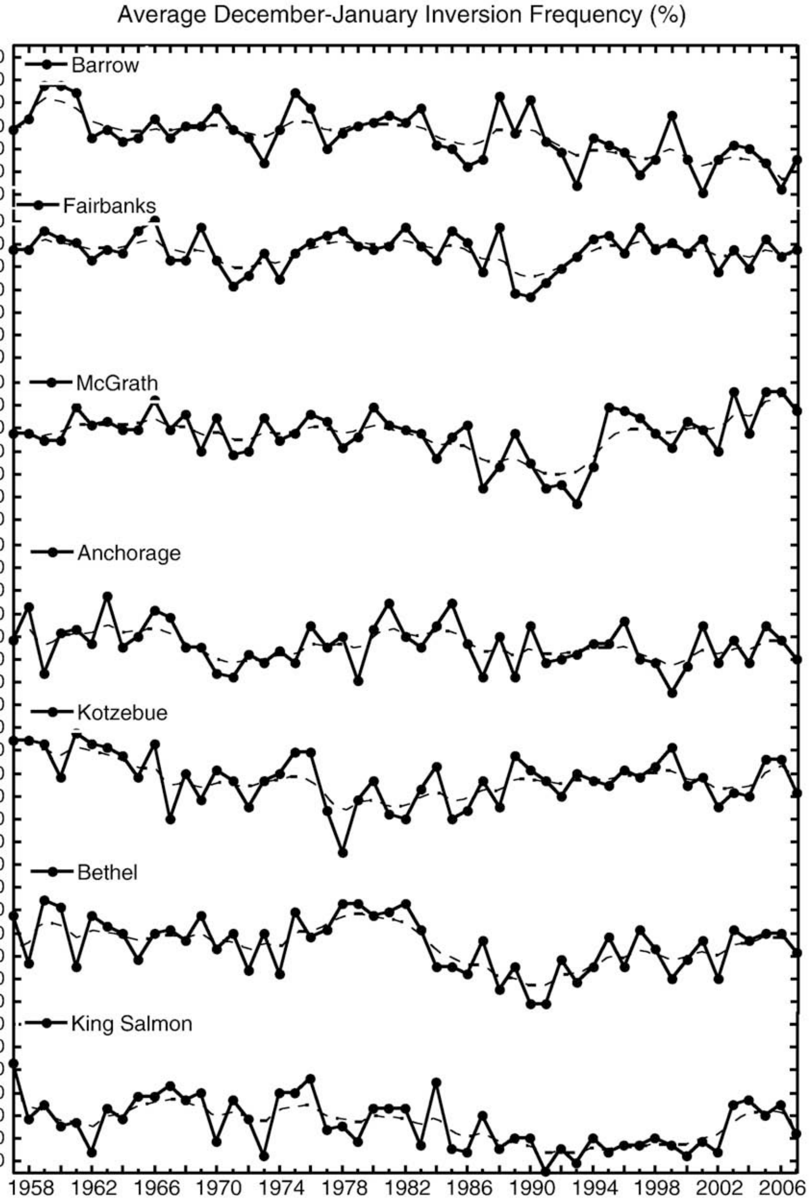

Fig. 11. Averaged December and January inversion frequency in percent from 1957 to 2007. The dashed line shows the 5-year running mean.

choice of analysis period. Inversion depth and temperature difference at all Alaska stations decrease from 1957 to the late 1980s and have increased since about 1990 (Figs. 6–8).

- SATs at all Alaska stations show warming during December. Interior stations (Fairbanks and McGrath) and Anchorage have warmed during January, while the other stations show cooling trends (Fig. 6). The low-frequency variability displayed in SAT is different from that of inversion parameters and is consistent with the work of Hartmann and Wendler (2005b), showing an abrupt temperature increase in 1976.
- The frequency of inversions has decreased over the study period at all stations but only Barrow displays a linear decrease of 5.3% per decade over the study period. The pattern of decreasing frequency until about 1989 and then an increase is evident for Fairbanks, McGrath, King Salmon and Bethel but not at the other stations (Fig. 11).
- Inversion parameters are most strongly correlated to the large-scale climate (NPI, PDO and NAO) at decadal and longer time scales.

Time series analysis of wintertime inversions indicates that SATs are negatively correlated to the inversion parameters. When SATs are warm (cold), inversion depths are shallow (deep) and inversion temperature differences are small (large). This relationship implies that recent warming of SATs in Alaska could create shallower inversions, which has implications for regional air quality management. Inversions trap pollutants in the lowest layer of the atmosphere causing threats to human

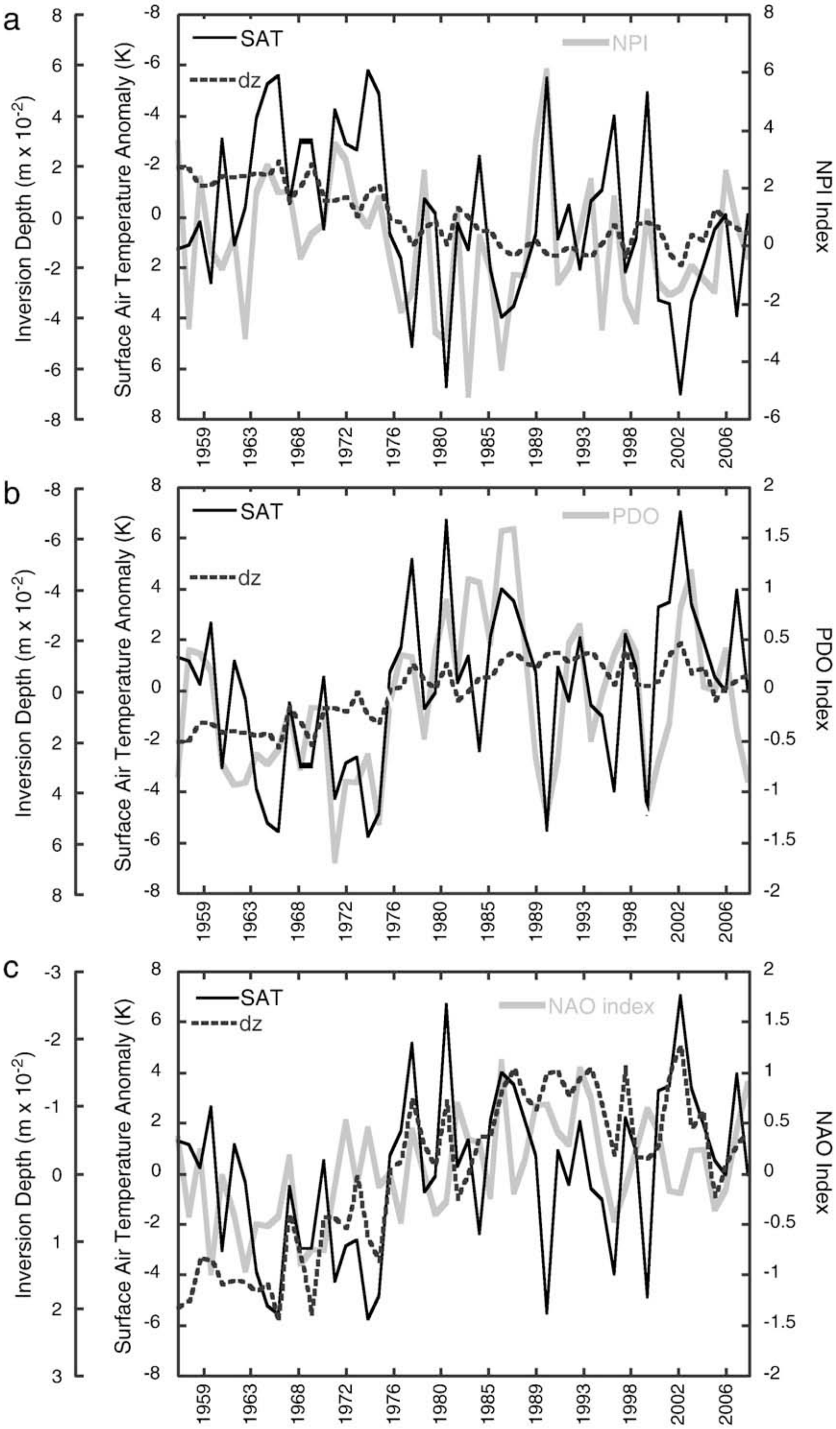

Fig. 12. November–February averages of Fairbanks SAT (K) and inversion depth (m x 10^{-2}) plotted with the a) NPI, b) PDO, and c) NAO climate indices. Note that SAT (a) and inversion depth (b and c) legends are reversed.

health and safety. Warmer climate and growing populations in the Arctic raise new challenges for air quality management.

Interannual variability of inversion parameters over Alaska is influenced by synoptic-scale flow patterns. For example, cold anomalies last longer and are more frequent in the Interior than warm anomalies. According to Papineau (2001), strong inversions over the Interior limit the response of temperature to changes in synoptic-scale flow. Therefore, warm anomalies in this region are caused by synoptic-scale patterns while cold anomalies are a result of local conditions such as radiative cooling of the boundary layer and orographic blocking by the Alaska and Brooks Ranges.

Table 1
Correlations between the PDO and Alaska station surface temperature (T), inversion depth (dz), inversion temperature difference (dT), and inversion temperature gradient (dT/dz) for the early (1957–1989) and later (1990–2007) periods.

	SAT	dz	dT	dT/dz
Detrended correlation to PDO from 1957 to 1989 in DJ				
Anchorage	**0.60**	−0.02	−0.08	−0.34
Barrow	0.33	0.08	**−0.37**	**−0.48**
McGrath	**0.46**	**−0.37**	−0.15	0.14
Fairbanks	**0.50**	−0.22	−0.17	−0.07
Kotzebue	**0.47**	−0.13	**−0.42**	−0.34
King Salmon	**0.53**	**−0.58**	**−0.53**	**−0.39**
Bethel	0.31	−0.03	−0.09	−0.08
Detrended correlation to PDO from 1990 to 2007 in DJ				
Anchorage	0.29	0.17	0.28	**0.53**
Barrow	0.38	−0.22	−0.06	0.29
McGrath	***0.41***	0.31	0.12	−0.03
Fairbanks	0.26	−0.06	0.16	**0.57**
Kotzebue	0.26	0.13	−0.09	−0.06
King Salmon	0.26	0.03	−0.07	−0.11
Bethel	0.30	0.27	0.18	0.24

Bold (italic) values indicate significance at the 95% (90%) level or greater.

Changes in storm tracks associated with the large-scale climate were not linked to the variations of inversion parameters and should be further investigated.

In addition to the effect of synoptic flow, trends and variability in inversions observed in Alaska appear to be associated to large-scale multi-decadal variability, not only in the Pacific but also in the Atlantic. Recent work by Zhao and Moore (2009) suggests that Atlantic and Pacific multi-decadal variability are linked which is consistent with the correlations between Alaska inversion parameters and the NAO at low-frequencies. The relationship between local Alaska climate variables and multi-decadal variability, particularly associated with the PDO, appears to change with time. The changing relationship at multi-decadal time scales between the NAO and North Atlantic SSTs has been demonstrated by Polyakova et al. (2006). Understanding the causes behind such phenomena is important for making advances in seasonal and longer time scale climate predictability.

As society turns to climate projects to prepare for the future, an analysis of Global Climate Model (GCM) simulations suggests that the coarse scale of a GCM does not adequately capture inversion profiles or resolve their vertical structure at the study stations. Dynamical downscaling of GCM simulations using a high-resolution regional model improves the overall average inversion profiles, and better captures the fine structure of the vertical temperature profile. Dynamically downscaled climate variables for Alaska can provide useful information for stakeholders at higher resolution than GCMs and biases can be corrected (Zhang et al., 2007).

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