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ABSTRACT

The wintertime Pacific–North American (PNA) teleconnection pattern has previously been shown to influence springtime snow conditions over portions of North America. This paper develops a more complete physical understanding of this linkage across the continent, using a recently released long-term, continental-scale gridded North American snow depth dataset and the 40-yr European Centre for Medium-Range Weather Forecasts Re-Analysis data. An empirical orthogonal function–based filtering process is used to identify and isolate the interannual snow depth variations associated with PNA. Then linear and partial correlations are employed to investigate the physical mechanisms that link winter PNA with spring snow depth. In the positive phase of PNA, the enhanced PNA pressure centers lead to warmer temperatures over northwestern North America and less precipitation at midlatitudes. The temperature and precipitation pathways act independently and in distinct geographical regions, and together they serve to reduce winter snow depth across much of North America. Winter anomalies in the snow depth field then tend to persist into spring. Dynamic mechanisms responsible for the PNA-influenced North American precipitation and temperature anomalies, involving moisture transport and cold air intrusions, are confirmed in this study and also extended to continental snow depth anomalies.

1. Introduction

Various prominent teleconnection patterns, such as El Niño–Southern Oscillation (ENSO), Pacific decadal oscillation (PDO), North Atlantic Oscillation (NAO), and Pacific–North American (PNA), are known to impact climate conditions over North America (NA), most notably during the Northern Hemisphere (NH) winter. These recurrent atmospheric circulation patterns are associated with variations in the intensity and location of the polar jet stream, the subtropical jet stream, or mid-latitude storm tracks. Through large-scale modulations of heat and moisture transport, these variations result in characteristic precipitation and temperature variations over parts of NA (Wallace and Gutzler 1981; Barnston and Livezey 1987; Leathers et al. 1991; Mantua et al. 1997; Curtis and Adler 2000; Sheridan 2003; Coleman and Rogers 2003; Haylock et al. 2007).

In mid- to high latitudes, precipitation and temperature anomalies can in turn influence snowpack accumulation and ablation, and thus snow depth (SND) on the land surface. Furthermore, the snowpack’s hydrologic storage capabilities introduce memory into the system, resulting in anomalies that can persist over weeks, months, or even seasons. An extensive body of literature describes the dynamic and thermodynamic drivers of snow cover variability over local regional scales (e.g., Namias 1960; Baker et al. 1992; Leathers and Robinson 1993; Brown 2000; Mote 2006). In particular regions within NA, various winter teleconnection patterns have been shown to influence snow cover variability (e.g., Cayan 1996; Hartley and Keables 1998; Serreze et al. 1998; Frei and Robinson 1999; Derksen et al. 2000; McCabe and Dettinger 2002; Jin et al. 2006; Mote 2006; Morin et al. 2008), although a dominant
climatic driver has yet to emerge. For example, PNA, ENSO, and PDO have all been found to affect spring snowpack in the western United States, while PNA, NAO, and east Pacific (EP) teleconnection patterns have been associated with snowfall signals over the eastern half of the United States. The reasons for this regional emphasis vary; they range from spatially constrained long-term datasets to an interest in societal issues, such as water supply in the western United States.

However, considering the broad scales of the climate phenomena that are often associated with some teleconnection patterns, the above-mentioned regional studies that focus only on parts of the United States may not portray their complete impact on North American snow. Early studies reported statistical relationships between North American snow cover extent and temperature across the entire United States during the winter season (Walsh et al. 1982; Gutzler and Rosen 1992; Leathers and Robinson 1993; Groisman et al. 1994). More recently, Sobolowski and Frei (2007) and Ge and Gong (2009) reported statistical relationships between various winter climate indices and continental-scale snowpack thickness. These studies suggest a broader-scale climate–snow relationship, but stop short of identifying climatic causal mechanisms responsible for such widespread snow cover anomalies. This paper contributes to this avenue of climate–snow research by comprehensively investigating the effect of the winter PNA teleconnection pattern on spring snowpack, over broad regions in NA.

SND is the snow cover parameter utilized in this paper, rather than the more extensively studied snow extent, that is, the presence or absence of snow. Ge and Gong (2008) showed that interannual SND and snow extent anomalies were not mutually consistent at regional/continental scales. Furthermore, Ge and Gong (2009) indicated that NA SND anomalies exhibited stronger and more robust statistical associations with large-scale climate indices relative to snow extent anomalies. More specifically, statistically significant zero-lag correlations between monthly average NA SND and PNA were found from November through April, and March and April average NA SND was significantly correlated with PNA in the preceding winter months. This result is consistent with previous findings of a winter PNA–1 April snow-water equivalent (SWE) relationship (Jin et al. 2006), but over a much larger spatial domain. Note that PNA is most influential during winter when the Aleutian center expands to cover a large portion of the North Pacific, and the dynamic forcing is most dominant (Leathers et al. 1991; Dominguez and Kumar 2005).

Therefore, the winter PNA–spring NA SND statistical relationship is used as a starting point for this study, with winter defined as November–February (NDJF) and spring defined as March–April (MA). Previous efforts to interpret the mechanisms behind these two teleconnection endpoints invoke atmospheric circulation changes and corresponding precipitation and temperature anomalies (Cayan 1996; Serreze et al. 1998; McCabe and Dettinger 2002; Jin et al. 2006). However, these studies, constrained to limited regions such as the western United States, did not quantitatively demonstrate the responsible pathways; hence, our current understanding is incomplete. Facilitated by a recently released SND dataset (see section 2a) and an empirical orthogonal function (EOF) filtering process (see section 2b), this paper will consider a broader region encompassing all of NA, and will explicitly investigate the teleconnection pathways and physical mechanisms involved. By refining our understanding of the winter PNA–spring SND teleconnection suggested in previous studies, we will gain insight into the climatic causes of snow cover variability over North America.

2. Data and methodology
   a. Datasets

1) GRIDDED NORTH AMERICAN SNOW DEPTH DATA

This study utilizes a long-term, continental-scale, gridded SND data product introduced by Dyer and Mote (2006, hereafter DM06). It provides daily 1° × 1° gridded values of SND from 1900 through 2000 over all of NA, derived from daily observations from about 7000 measurement stations in the United States and Canada. An inverse distance-weighted interpolation algorithm was applied at each grid cell using surrounding point measurements within a flexible search radius. However, the interpolation scheme did not take account of terrain variability, where SND is highly dependent on slope and altitude; thus, the data are less reliable in heterogeneous mountainous regions. Station locations frequently followed population patterns, resulting in observations that are often biased to lower elevations and lower latitudes. The lack of observations in data-sparse areas increases the spatial dependence on neighboring grids; for example, interior grid cells in far northern Canada have no nearby stations, so their values may be biased toward coastal stations and grid cells near Hudson Bay.

Another weakness of DM06 is that the SND time series are less reliable in early years, when very few stations in Canada were available and many stations were subject to frequent relocations. In particular, the gridded SND product prior to 1956 exhibits excessive
temporal variability and multiple years with erroneous spatial patterns; therefore, only the years 1956–2000 are used for this study. Ge and Gong (2008) conducted an independent quality review of the DM06 dataset by visually analyzing station distributions and corresponding SND fields. Station density remains low in the far northern regions of NA, even after 1956. Nevertheless, the DM06 dataset over this period captures the basic snow cover features for North America as a whole, consistent with other well-established datasets, for example, the National Oceanic and Atmospheric Administration (NOAA) visible satellite observations (Robinson 1999) and long-term reconstructions (Frei et al. 1999; Brown 2000). Furthermore, spatial SND features in northern NA compare well with SWE maps for the Canadian prairies derived using passive microwave data (Derksen et al. 2004).

Overall, the DM06 dataset used here offers extensive spatial coverage over all of NA, with a 45-yr-long duration, and fine spatial and temporal resolutions (daily 1° × 1° grids). Such a combination of features was not available in previous datasets used for SND–climate teleconnection studies, which had shorter temporal durations, more limited spatial domains, and/or irregularly spaced data points (e.g., Serreze et al. 1998; Brown 2000; Derksen et al. 2004). Therefore, the DM06 dataset allows for a more detailed and comprehensive analysis of the continental-scale SND response to climate patterns than has previously been possible. However, the local–regional features of this response must be interpreted carefully, bearing in mind local biases and uncertainty in mountainous and data-sparse regions.

2) PNA INDEX AND METEOROLOGICAL FIELDS

The PNA teleconnection pattern is a major contributor to winter climate variability over extratropical NA (Wallace and Gutzler 1981; Barnston and Livezey 1987; Leathers et al. 1991). The PNA index used in this study is obtained from the NOAA Climate Diagnostic Center (online at http://www.cpc.ncep.noaa.gov/data/teledoc/teleintro.shtml). It is computed by applying rotated principal component analysis on the Coordinated Data Analysis System (CDAS) monthly mean standardized 500-mb height in the 20°–90°N region between January 1950 and December 2000 (Barnston and Livezey 1987). The positive phase of the PNA pattern features anomalously strong Aleutian lows and high pressure over western NA, coinciding with an enhancement and eastward shift of the East Asian jet stream.

Monthly mean meteorological data fields, such as horizontal wind vectors, 700-hPa geopotential heights, air temperature, precipitation, and specific humidity, are obtained from the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) data server (online at http://data.ecmwf.int/data/d/era40_mnth/). The ERA-40 dataset contains monthly global analysis values interpolated to a regular 2.5° latitude × 2.5° longitude grid, from September 1957 to December 2000; therefore, we limit our analysis to 43-yr duration (hydrological year 1957/58–1999/2000) in this paper. The ERA-40 data fields of temperature and horizontal wind are considered to be highly reliable (Christensen et al. 2007). Trenberth and Guillemot (1995) and Serreze et al. (2005) evaluated the quality of the ECMWF moisture budget data, and diagnosed a problem involving excessive tropical oceanic precipitation and tropical troposphere humidity. However, these low-latitude biases do not affect the results presented in this paper that concern the snow-covered mid- and high-latitude regions only.

b. EOF filtering process

The statistical PNA–SND signal over NA could be obscured by local heterogeneities and weakened by other competing climatic influences on snow cover (Ge and Gong 2009). Here we employ an EOF filtering procedure to filter out SND variability unrelated to PNA. Our method, described in the following paragraphs, is similar to the method of Min et al. (2008).

First, a standard T-mode EOF analysis is performed on the MA SND data field: T-mode analysis includes temporal correlations in the matrix that is used in the eigenvector analysis. The snow-covered spatial domain is defined by including grid points with an average snow frequency of at least 50% over the study period (Ge and Gong 2008). For each month, snow frequency is computed as the percentage of snow-covered days in the month, and snow-covered days are defined as the days with SND larger than zero. The first five EOF spatial patterns are shown in Fig. 1: three of them exhibit a similar northwest–southeast orientation, although the specific locations differ. Table 1 indicates that when combined the five leading EOFs explain more than 45% of the total variance, but no single EOF dominates the total explained variance. Table 1 also presents the correlations between the principal component (PC) time series of the five leading EOFs versus the NDJF PNA index, along with the corresponding p value for a sample size of 43 yr (from NDJFMA 1957/58 to NDJFMA 1999/2000). Only PC1 exhibits a statistically significant correlation at the 95% confidence level. However, PC2 and PC3 have nonnegligible correlations that satisfy the 80% confidence level.

The similarities between some of the EOF patterns shown in Fig. 1 suggest that these modes of variability may not represent distinct physical phenomena.
Rather, the T-mode EOF procedure may be partitioning a broad signal into mathematically orthogonal components that are physically related; that is, different EOFs may all represent a portion of an overall NDJF PNA–MA SND relationship. Those EOF patterns with PC PNA correlation magnitudes larger than 0.1 (i.e., EOF1, EOF2, and EOF5) are considered to be PNA related. The 0.1 threshold is discussed in section 4.

To retain only the PNA-correlated portion of the SND signal, a linear mutiregression analysis is performed at each grid cell, with the MA SND time series as the predictand and the PC time series of the retained EOFs as the predictors. The resulting regressed MA SND data field is then used to compute the area-weighted average NA SND over all snow-covered grid cells, using the same 50% snow frequency threshold applied to the original SND data. The products of this EOF filtering procedure are 1) a spatial field with PNA-filtered SND at each grid cell, denoted as MA FSND<sub>PNA</sub>, and 2) a 43-yr time series of the filtered average NA SND, denoted as MA FSND<sub>PNA</sub>. This EOF filtering procedure retains the overall MA SND spatiotemporal variability associated with NDJF PNA by integrating specified EOF modes that exhibit PNA-type variability. The MA FSND<sub>PNA</sub> time series and MA FSND<sub>PNA</sub> field are used hereafter. This procedure is also applied to NDJF SND.

**FIG. 1.** Spatial patterns of the five leading EOFs of MA SND, presented as homogeneous correlations between the MA SND field and the PC time series of the leading EOFs. Statistically significant correlations at 95% confidence level ($r = 0.30$) or higher are shown.
c. Correlation analyses

Linear correlation is utilized to identify potential pathways linking NDJF PNA with MA SNDNA, by statistically associating the two ends of this pathway to the same intermediate meteorological and atmospheric circulation data fields. Partial correlation is also conducted in order to clarify the PNA–SND pathways, that is, by identifying the linked and causal effect of each component in the pathway. Partial correlation measures the linear relationship between two variables with the effect of a set of controlling variables removed. The partial correlation between $X$ and $Y$, with the effect of $Z$ removed, is given by $r_{XY|Z} = (r_{XY} - r_{XZ}r_{YZ})/\sqrt{(1 - r_{XZ}^2)(1 - r_{YZ}^2)}$. If there is no difference between $r_{XY|Z}$ and the original correlation $r_{XY}$, then the control variable $Z$ has no effect and $X$ is directly related to $Y$. If $r_{XY}$ is significant but $r_{XY|Z}$ is close to zero, then there is no direct link between $X$ and $Y$, and the significant $r_{XY}$ is simply due to the fact that both $X$ and $Y$ are related to $Z$ (Blalock 1961). In this case, $Z$ could act as either a common antecedent cause that independently drives variability in $X$ and $Y$, or as an intervening variable that responds to $X$ and subsequently drives $Y$ (or vice versa).

3. Results

a. Observed NDJF PNA–MA SND teleconnection

The MA time series of average SND over snow-covered grid cells, derived from the unfiltered DM06 dataset (hereafter MA SNDNA), is significantly correlated with the NDJF PNA index ($r = -0.48$, $p = 0.001$; see Table 1). Figure 2a presents a linear correlation map between the unfiltered MA SND field and the NDJF PNA index. Only statistically significant correlations at the 95% confidence level ($r = 0.30$) or higher are shown. A somewhat narrow northwest–southeast negative correlation band is seen over central-western NA, which is generally consistent with the monthly lagged PNA–SND correlation fields presented in Ge and Gong (2009). Note that this

![Fig. 2. (a) Linear correlations between the NDJF PNA index and the unfiltered MA SND field, and (b) linear correlations between the NDJF PNA index and the MA SND–PNA field. Statistically significant correlations at the 95% confidence level ($r = 0.30$) or higher are shown.](image-url)
correlation band extends northward into regions that have previously been overlooked because of the unavailability of data. For example, the widely used Brown (2000) gridded snow depth data are constrained to south of approximately 55°N latitude. Nevertheless, the spatial extent shown in Fig. 2a is modest relative to the generally recognized broad influence of winter PNA on NA climate (Wallace and Gutzler 1981; Barnston and Livezey 1987; Leathers et al. 1991), in part due to the competing climate influences and/or local factors that obscure the PNA signal (Ge and Gong 2009).

After the EOF filtering procedure is applied, the linear correlation between NDJF PNA and MA $\text{FSND}_{\text{PNA}}$ is $-0.63$ ($p = 5.8 \times 10^{-6}$), which is stronger than the correlations between NDJF PNA and any individual MA SND PCs, and also the unfiltered MA $\text{SND}_{\text{NA}}$ time series (Table 1). Furthermore, Fig. 2b shows a broad region in which the MA $\text{FSND}_{\text{PNA}}$ field is significantly correlated with the NDJF PNA index, stretching across all of NA from Alaska to Quebec, Canada. Figure 2b exhibits stronger and broader signals than the correlations between NDJF PNA and the original MA SND field (Fig. 2a). Hence, the EOF filtering procedure successfully retains and aggregates only the EOF components of MA SND that are associated with the PNA, and yields a considerably stronger teleconnection between NDJF PNA and MA SND. Note that this signal does not extend to the far northern portions of Canada, where limited station data compromise the gridded SND product.

A hypothesized mechanistic pathway between the endpoints of the NDJF PNA–MA SND teleconnection is illustrated in Fig. 3, drawn from established literature. Circulation variations across the eastern Pacific and North America associated with anomalous NDJF PNA conditions have been shown to produce temperature and precipitation anomalies over certain regions of North America (e.g., Barnston and Livezey 1987; Leathers et al. 1991; Coleman and Rogers 2003). We hypothesize that both the temperature and precipitation anomalies influence NDJF SND, yielding broad SND variations across much of the continent. We further hypothesize that the NDJF SND anomalies persist into the spring and result in MA SND variations that are driven by NDJF PNA anomalies. Some aspects of this pathway have already been established, for example, Leathers et al. (1991) demonstrated PNA-driven precipitation and temperature anomalies over the United States. Here we extend the analysis to consider MA SND variations, and we expand the analysis over a broader region, including both the United States and Canada. We also investigate the regional distinctions between the temperature and precipitation mechanisms. The steps that comprise this hypothesized pathway are individually evaluated, because they relate to both the NDJF PNA and MA SND endpoints.

b. Role of NDJF geopotential heights, precipitation, temperature, and snowpack

Intermediate NDJF parameter fields (precipitation, temperature, 700-hPa geopotential heights, and $\text{FSND}_{\text{PNA}}$) are linearly correlated with the two teleconnection endpoints—NDJF PNA and MA $\text{FSND}_{\text{PNA}}$—in Fig. 4. Correlations between NDJF PNA and NDJF 700-hPa geopotential heights (Fig. 4a) suggest deeper-than-normal troughs over the North Pacific and southeastern NA, and a higher-than-normal ridge over northwestern NA. Figure 4a forms a typical PNA anomaly pattern described by Barnston and Livezey (1987). Figure 4b plots the correlation map between MA $\text{FSND}_{\text{PNA}}$ and NDJF

![Fig. 3. Hypothesized mechanistic pathway linking winter PNA to spring snow depth anomalies.](image-url)
700-hPa heights. It also exhibits the PNA spatial pattern, but with the signs reversed from those of Fig. 4a.

The anomalous circulation associated with NDJF PNA in turn generates anomalous precipitation and temperature over the NA continent. NDJF PNA and NDJF precipitation are negatively correlated over a band near 45°N that stretches across much of NA (Fig. 4c), while MA FSND\textsubscript{PNA} and NDJF precipitation show positive correlations over the same area (Fig. 4d). NDJF PNA is positively (negatively) correlated with NDJF temperature over northwestern (southeastern) NA (Fig. 4e), while MA FSND\textsubscript{PNA} and NDJF temperature correlations show an exactly opposite pattern (Fig. 4f). Note that the temperature relationships over southeastern NA are not directly relevant to this study because this region is generally south of the MA snow line, although the opposing relationships to the teleconnection endpoints are consistent with our premise. The winter NA precipitation and temperature response to winter PNA (Figs. 4c,e) has been well established (e.g., Barnston and Livezey 1987; Leathers et al. 1991; Coleman and Rogers 2003). Meanwhile, Figs. 4d,f suggest a translation from these PNA-driven winter climate anomalies to spring SND variation that is physically expected, that is, warmer (cooler) temperatures and less (more) precipitation are usually associated with shallower (thicker) MA SND.

In Figs. 4g,h, there are similar broad regions north of the snow line where NDJF FSND\textsubscript{PNA} is negatively associated with NDJF PNA and positively correlated with MA FSND\textsubscript{PNA}. Figure 4h is consistent with the intuitive notion that deeper winter snow takes longer to fully ablate and thus will lead to above-normal SND in the following spring season. Figures 4c,e,g suggest that PNA-driven NDJF precipitation and temperature anomalies produce physically consistent NDJF SND anomalies; that is, both warmer temperature and less precipitation in positive PNA years induce shallower-than-normal NDJF SND. The spatial extent of the NDJF FSND\textsubscript{PNA} anomaly in Figs. 4g,h encompasses the separate precipitation and temperature anomaly regions in Figs. 4c-f. Thus, the teleconnection between NDJF PNA and MA FSND\textsubscript{PNA} (Fig. 2b) appears to be the result of a physically based NDJF PNA–NDJF SND relationship and the temporal persistence of snow from winter to spring. Note that in Figs. 4g,h isolated areas of opposite-signed NDJF FSND\textsubscript{PNA} correlations appear.
in particular, near Hudson Bay. This may be an artifact of the sparse station data in the DM06 dataset for these areas, and a resulting bias toward coastal Hudson Bay stations. Such an interpretation highlights the strengths and weaknesses of the continental-scale DM06 dataset, and the care that must be taken when using it.

The similar correlation patterns (of opposite sign) shared by NDJF PNA and MA FSNDPNA indicate that the positive winter PNA index and below-normal spring SND coincide with an intensified PNA-style pressure system, reduced NDJF precipitation near 45°N, higher temperatures in northwestern NA, and shallower NDJF SND over most of NA. Figure 4 reveals the essential components that connect NDJF PNA with MA SND, consistent with the mechanistic pathway hypothesized in Fig. 3.

Figures 5a,b show that NDJF FSNDPNA is positively correlated with NDJF precipitation over midlatitude NA, and negatively (positively) correlated with NDJF temperature over northwestern (southeastern) NA. These correlation patterns using NDJF FSNDPNA resemble Figs. 4d,f using MA FSNDPNA. Similarly, Table 1 indicates that the linear correlation between NDJF PNA and NDJF FSNDPNA is strong and statistically significant ($r = -0.84, p = 1.2 \times 10^{-16}$) much as for MA FSNDPNA. This supports the premise that the statistical relationship between NDJF precipitation–temperature and MA SND is the result of a physical relationship between NDJF precipitation–temperature and NDJF SND, and subsequent persistence of NDJF SND anomalies into MA.

Figures 6a,b plot the partial correlations between MA FSNDPNA and the NDJF precipitation and temperature fields after removing the influence of NDJF FSNDPNA. The partial correlations are weak and scattered, in comparison to Figs. 4d,f, where NDJF FSNDPNA is not removed. This indicates that NDJF SND is an intervening variable that is responsible for the relationship between NDJF precipitation/temperature and MA FSNDPNA. Thus, the mechanistic pathway between winter precipitation/temperature anomalies and spring SND consists of an initial winter SND response that then persists into spring SND.

c. Distinct temperature and precipitation pathways for NDJF SND

Figures 5a,b show that NDJF precipitation and temperature are two possible factors that could impact NDJF SND. To identify the individual roles of winter precipitation and temperature, Figs. 6c,d plot the partial correlations between NDJF FSNDPNA and NDJF precipitation after removing the influence of NDJF temperature, and the partial correlations between NDJF FSNDPNA and NDJF temperature after removing the
influence of NDJF precipitation. The signals in Figs. 6c,d are effectively the same as in Figs. 5a,b without the other factor removed. In other words, the PNA-driven NDJF precipitation and temperature anomalies appear to occur independently of each other and to contribute independently to NDJF SND anomalies.

The results thus far suggest that there are two distinct mechanistic pathways by which NDJF PNA anomalies can influence MA SND. The temperature pathway affects a broad region over northwest NA, while the precipitation affects more southerly regions across NA, near 45°N. The geographically different and statistically distinct temperature and precipitation response regions each affect NDJF SND, and subsequently MA SND, so that the PNA-influenced MA SND region is broad and encompasses both the temperature- and
precipitation-influenced regions. Next, the underlying physical mechanisms of the two pathways, that is, moisture budgets and airmass intrusions, are considered in more detail.

1) TEMPERATURE PATHWAY

During positive PNA years, the enhanced ridge spanning most of northwestern NA is known to impact the nature of airmass advection into the region. Sheridan (2003) applied spatial synoptic classification (SSC) analyses to examine the frequency of different weather types associated with winter PNA. Winter PNA was found to be negatively correlated with the occurrence of dry polar (DP) air masses over Alaska, western Canada, and the northwestern United States. The decrease of DP air was compensated by an increase of dry moderate (DM), moist polar (MP), and moist moderate (MM) air masses that are considerably warmer than DP air, and increased temperatures in the affected areas. Grundstein (2003) followed a similar approach to study SWE variability over the U.S. northern Great Plains. High SWE years were characterized by substantially greater intrusion of the coldest and driest air masses (DP), and low SWE years have a greater frequency of more moderate air masses (DM and MM). The geographic regions affected by these studies are consistent with the temperature anomaly regions in Figs. 4e,f. Thus, the enhanced NA ridge associated with positive PNA anomalies reduces the frequency of occurrence of Arctic air intrusions, which increases temperatures under the ridge.

Figure 5b shows that PNA-driven NDJF temperature and NDJF SND\textsubscript{PNA} are negatively correlated over a broad region in northwestern NA. A negative temperature–SND relationship is typically expected to occur where air and snowpack temperatures are near freezing, so that warming can induce phase changes and snowmelt. However, for the high-latitude region shown in Fig. 5b, NDJF temperatures (air and snowpack) are consistently well below freezing, so that the specific processes by which positive PNA-driven warming reduces SND are less clear. One possibility is that warming reduces SND via densification of the solid-phase snowpack. Because the density of newly fallen snow tends to increase with air temperature, precipitation events may yield a shallower snowpack if temperatures are higher. When an existing snowpack receives more energy from warmer overlying air, constructive metamorphism may be enhanced via increased sublimation from the upper snowpack convex surfaces, water vapor transport within the snowpack, and condensation onto lower snowpack concave surfaces (Dingman 2002). Furthermore, positive temperature anomalies can reduce the cold content of the snowpack, raising its temperature and facilitating later melting when air temperature increases above freezing. Hence, the high-latitude winter temperature–SND relationship shown in Fig. 5b is physically plausible.

2) PRECIPITATION PATHWAY

The moisture transport field is calculated using a vertically integrated equation for the conservation of water vapor (Trenberth 1991),

\[
\mathbf{M} = M_x \mathbf{x} + M_y \mathbf{y} = \int_0^{T_D} \mathbf{q} v \, dP,
\]

where \(\mathbf{M}\) is the two-dimensional horizontal moisture transport vector (kg m\(^{-1}\) s\(^{-1}\)), \(M_x\) and \(M_y\) are zonal and meridional components of \(\mathbf{M}\), \(\mathbf{x}\) and \(\mathbf{y}\) are unit vectors directed positively east and north, \(q\) is the specific humidity (g kg\(^{-1}\)), \(v\) is the horizontal wind vector (m s\(^{-1}\)), \(P\) is pressure level (hPa), \(P_S\) denotes surface pressure (hPa), and \(g\) represents gravity (m s\(^{-2}\)).

The predominant large-scale moisture transports for NA winter are 1) southwesterly moisture flux from the Pacific Ocean between 35° and 60°N, and 2) southerly moist subtropical air from the Gulf of Mexico (Hirschboeck 1991; Dominguez and Kumar 2005). Figures 7a,c show correlation maps between NDJF PNA and the zonal and meridional components of NDJF moisture transport, respectively. For positive PNA, zonal moisture transport shifts southward over the Pacific and eastern NA, in response to Aleutian and southeast NA trough strengthening (Fig. 4a). Meanwhile, meridional transport is enhanced on either side of the strengthened western NA ridge (Fig. 7c), that is, with stronger (weaker) southerly moist flow over the Pacific coast (central plains) of NA. Overall, positive PNA anomalies reduce zonal moisture flow in favor of meridional moist flow, resulting in the reduced transport of moisture into NA. The intensified Aleutian trough and northwestern NA ridge will block the westerly moisture transport from the North Pacific to western NA. Meanwhile, the increased meridionality of the 700-hPa heights induces Arctic air intrusion over central and eastern NA and impedes moisture transport from the Gulf of Mexico.

The divergence of the vertically integrated atmospheric moisture flux \((\mathbf{v} \cdot qv)\) is an indicator of precipitation likelihood for monthly or longer time averages (Trenberth and Guillemot 1995). Moisture divergence can be decomposed into two components—one that depends on the mass divergence when \(q\) is large \((q \mathbf{V} \cdot \mathbf{v})\), and another that depends on the horizontal advection by wind across the \(q\) gradient \((\mathbf{v} \cdot \mathbf{V}q)\). The magnitude of \(\mathbf{v} \cdot \mathbf{V}q\) is generally more influential because of the ocean–continent moisture contrast, and it is considered here. Positive (negative) \(\mathbf{v} \cdot \mathbf{V}q\) indicates that the wind is in the
opposite (same) direction of the humidity gradient, that is, wind blows from dry (wet) to wet (dry) region, so the precipitation likelihood is low (high). Figure 7e presents the correlations between NDJF PNA and the NDJF \( v/C_1 \) \( q \) field and shows a positive divergence band over midlatitudes, which is consistent with the reduced precipitation indicated in Fig. 4c.

These PNA-related moisture transport mechanisms are consistent with the existing literature. Dominguez and Kumar (2005) performed a complex EOF analysis on \( M \) to identify the dominant modes of moisture flux variability over NA. Their first mode of variability resembles Figs. 7a,c, which suggests that PNA substantially influences moisture flux. Coleman and Rogers (2003) studied the inverse relationship between PNA and Ohio River Valley winter precipitation, and they detected that moisture flux divergence extends north from the Gulf Mexico during dry positive PNA winters. Sheridan (2003) demonstrated that the frequency of oceanic moist tropic (MT) weather over eastern NA is diminished significantly (i.e., less moisture arrives from the Gulf of Mexico) resulting from polar intrusions when PNA is positive. Moreover, Rogers and Raphael (1992) and Lin and Derome (1997) found that during winters with a positive PNA pattern, eddy activity was reduced over the North Pacific Ocean because of a smaller contribution from large-scale seasonal mean flow and a southward shift of high-frequency baroclinic wave activity. All of these factors will lead to reduced precipitation in positive PNA years. For negative PNA the opposite occurs, that is, moist air from Pacific Ocean and the Gulf of Mexico reaches relatively cool NA midlatitudes, the water vapor cools and condenses, and winter precipitation increases.

FIG. 7. Linear correlations between (a),(c), and (e) NDJF PNA and (b),(d), and (f) NDJF FSND\( _{PNA} \) vs NDJF zonal and meridional components of the NDJF moisture transport vector \( (M_x \text{ and } M_y) \) and the divergence caused by the horizontal advection across the \( q \) gradient (\( v \cdot Vq \)). Statistically significant correlations at 95% confidence level (\( r = 0.30 \)) or higher are shown.
Figures 7b,d,f show moisture budget correlation fields for NDJF FSNDPNA instead of NDJF PNA. Correlations between NDJF FSNDPNA and NDJF $M_s$ and $M_v$ (Figs. 7b,d) resemble the NDJF PNA influence on the moisture transport components (Figs. 7a,c) but with opposite signs. Similarly, the correlations between NDJF FSNDPNA and NDJF $v \cdot V_q$ (Fig. 7f) share the same pattern as that for NDJF PNA (Fig. 7e), but with a convergence band instead of a divergence band. Spatial patterns in either column of Fig. 7 are essentially identical, but with reversed signs, which indicates that the moisture flux mechanisms linking the NDJF PNA to NDJF precipitation also extend to NDJF SND. Therefore, Fig. 7 supports the precipitation pathway linking NDJF PNA to MA FSNDPNA, illustrated in Figs. 4c,d.

4. Summary and discussion

The PNA teleconnection pattern has previously been observed to affect climate and hydrology in broad regions over NA, most notably during winter. Studies of the winter PNA influence on spring NA snow cover have focused on limited regions in the contiguous United States, but neglected broad areas in northern NA, in part because of the scarcity of continental-scale snow depth data. The recently released DM06 SND dataset helps overcome this data constraint, and it is utilized here to develop a more complete understanding of winter PNA–spring SND teleconnection pathways over NA.

An EOF filtering process is used to isolate PNA-related SND signals, allowing us to identify the statistical teleconnection. Linear and partial correlations are utilized to identify two distinct mechanistic pathways that link winter PNA with spring SND. During the positive PNA years, the North Pacific and/or Gulf of Mexico (northwestern NA) exhibit negative (positive) geopotential height anomalies, establishing an enhanced meridional circulation pattern across NA. The enhanced ridge over northwestern NA prevents cold Arctic air from intruding, and thus the temperature increases in this region. In the meantime, the meridionality reduces the westerly moisture flux from the Pacific Ocean and southerly moist subtropical air intrusions from the Gulf of Mexico, increasing water vapor divergence and decreasing precipitation over midlatitudes. The temperature and precipitation pathways act independently over distinct geographical regions, so that the PNA-influenced winter SND region encompasses both the temperature and precipitation response areas. Finally, the winter SND anomalies persist over time and translate to the anomalous spring SND.

Additional complementary statistical analyses are also performed to confirm the robustness of the results. A known limitation of EOF analysis is that it only detects mathematical orthogonal patterns, while physically distinct variability patterns may not necessarily be orthogonal. Therefore, a rotated EOF (REOF) analysis is also conducted in an effort to produce more physically meaningful patterns. However, the results (not shown) are basically unchanged, that is, separate REOF modes share similar features and appear to comprise a spatially broad relationship with NDJF PNA that is effectively accumulated by the EOF filtering procedure.

Certain features of the analysis were selected somewhat subjectively. For example, the definition of winter and spring months is based on results from Ge and Gong (2009), rather than using standard boreal seasons. Also, the 0.1 correlation threshold for retaining EOF modes in the filtering procedure was arbitrarily selected. Therefore, the statistical analyses presented in section 3 were repeated with different season definitions [e.g., December–February (DJF)/MA and January–March/April (JFM/A)] and combinations of retained EOF/REOF modes in the filtering procedure. A qualitative assessment showed that the results are generally insensitive to these procedural variations. The NDJF/MA seasons and the $|r| > 0.1$ criterion are presented in this paper because together they yield the clearest PNA–SND signal.

It should be noted that the linear correlations and partial correlations employed cannot detect the existence of any nonlinear relationships. Scatterplots (not shown) of correlated time series were studied at various grid cells spanning different geographic regions and correlation magnitudes, but no clear indication of nonlinear relationships was found. Rank correlations and composite analyses were also conducted to complement the linear correlation and partial correlation results. The results (not shown) from these two methods are consistent with the results presented in section 3, but are not stronger than the linear correlation signals. These complementary analyses confirm the robustness of the results obtained from simple linear and partial correlations.

Of course, the PNA teleconnection pattern only accounts for a portion of the observed snow depth variability over North America. The remaining variability may result from other climatic teleconnections or simply local-scale snow depth heterogeneities that blur any climatic signal. Furthermore, the filtered SND field is a mathematical construct, whose retained EOF modes may not exclusively represent PNA-related SND variability. For example, PNA has been shown to be correlated with other climate indices, such as PDO and ENSO (Mantua et al. 1997; Straus and Shukla 2002), so SND variability related to these other phenomena may be retained by the filtering procedure. Despite this
limitation, our results indicate that the filtered SND field effectively removes many confounding factors and thus is better able to discern PNA-related SND variability. The structured winter PNA and spring snow depth relationship that emerges here is stronger, broader, and more robust than any previously reported snow–climate signal over North America.

Moreover, this paper provides a physically based explanation for this climatic cause of spring SND anomalies over NA involving two distinct pathways emerging from established winter PNA anomalies. Recognition of the physical mechanisms that connect this major climate teleconnection mode with NA SND will be beneficial to a more fundamental understanding of the snow feedbacks associated with climate variability and change, incorporating both SND and the well-studied snow extent variability. Improved knowledge on the snow–climate relationships will have far-reaching societal benefits for water resource management, hazard mitigation, climate prediction, and climate model evaluation.

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REFERENCES


