Modification of the wintertime Pacific–North American pattern related North American climate anomalies by the Asian–Bering–North American teleconnection

Bin Yu¹ · Hai Lin²

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Abstract

The Pacific–North American (PNA) pattern is closely related to North American climate. In this study, we demonstrate that the PNA associated anomalies of North American surface temperatures and temperature extremes are modified by the extratropical Asian–Bering–North American (ABNA) teleconnection. The temperature and temperature extreme anomalies in association with the combination of the PNA and ABNA patterns are most prominent over the Canadian Prairies, and can be approximated by a linear superposition of the circulation and temperature responses to the two patterns. The various temperature responses result from the corresponding atmospheric circulation anomalies, which are associated with sea surface temperature and precipitation anomalies in the tropical eastern-central Pacific and snow cover anomalies in the Siberian region. In particular, pronounced circulation anomalies are apparent over the Great Lakes/Hudson Bay, and around the Aleutian Islands with opposite sign for the in-phase PNA and ABNA combination. This induces anomalous temperature advection and precipitation, as well as the heating associated variations of vertical motion and clouds, leading to prominent surface temperature anomalies over the Canadian Prairies directly through the variation of the surface energy budget. For the out-of-phase PNA and ABNA combination, the anomalous circulation center tends to be situated along the west coast of North America. This induces weak circulation anomalies over north-central North America and brings weak thermal advection and precipitation anomalies there, leading to insignificant temperature anomalies over the Canadian Prairies. Both the ABNA and PNA can be skillfully predicted on the seasonal time scale, as well as their pattern related North American temperature anomalies. Hence it is important to consider both tropical and extratropical sources of predictability in improving North American climate prediction skill on seasonal to interannual time scales.

1 Introduction

The Pacific–North American (PNA, Wallace and Gutzler 1981) pattern is one of the most well-recognized and prominent atmospheric teleconnections in the wintertime extratropical Northern Hemisphere. The PNA is an internal mode of climate variability (e.g., Lau 1981; Straus and Shukla 2002), characterized by a wavetrain arcing from the Hawaiian Islands, through the North Pacific and Canada, and

then to the southeastern U.S. Its occurrence is significantly influenced by the tropical sea surface temperature (SST) anomaly, in particular that associated with the tropical El Niño–Southern Oscillation (ENSO) variability. The PNA pattern is closely related to North American climate. However, the PNA associated climate anomaly does not seem to be strongly modified by most major atmospheric circulation patterns. This is because the regions with climate anomalies related to those patterns, with different emphasis, are mostly distinct from the dominant PNA associated areas (e.g., Trenberth et al. 1998; Liu and Alexander 2007). For example, the West Pacific (WP) and North Pacific (NP) patterns are two pronounced teleconnections over the Pacific–North American sector in the boreal winter (Wallace and Gutzler 1981; Wallace and Blackmon 1983). Both of them consist primarily of a pair of north–south dipole centers of action in the western North Pacific, and are not strongly related to North American climate. The North Atlantic Oscillation (NAO,

✉ Bin Yu
Bin.Yu@canada.ca

¹ Climate Research Division, Environment and Climate Change Canada, 4905 Dufferin Street, Toronto, ON M3H 5T4, Canada

² Meteorological Research Division, Environment and Climate Change Canada, Dorval, Canada

e.g., Kushnir and Wallace 1989; Hurrell et al. 2003 and references therein) and more generally the Arctic Oscillation (AO, Thompson and Wallace 1998, 2000) are also situated adjacently to the PNA sector, but are strongly related to the climate over Eurasia and relatively weak to North America (e.g., Cohen et al. 2012). In addition, the PNA is distinct from the Tropical/Northern Hemisphere (TNH, Mo and Livezey 1986) pattern. Although both patterns affect the flow of marine air into North America, the PNA is primarily associated with surface temperature anomalies over western Canada and the extreme western U.S., accompanied by anomalies of opposite sign in the southern U.S., while the TNH is dominated by temperature anomalies over the western-central U.S. and central-eastern Canada.

Besides the PNA, other relationships of atmospheric circulation anomalies over the northern extratropics, including the circumglobal circulation anomaly (e.g., Branstator 2002; Ding et al. 2011; Teng and Branstator 2012; Lin and Wu 2011, 2012; Li and Ruan 2018) and circulation anomalies adjacent to North America (e.g., Wang et al. 2014, 2017; Yu and Zhang 2015; Kug et al. 2015; Harnik et al. 2016; Yu et al. 2016; Lyu and Yu 2017; L'Heureux et al. 2017; Liang et al. 2017), to North American climate have also been demonstrated. Among those, the extratropical Asian–Bering–North American (ABNA) teleconnection was constructed to directly relate the extratropical circulation anomalies to the wintertime surface temperature variability over North America by excluding the PNA pattern contribution (Yu et al. 2016). It reflects a zonally-elongated wave-train originating from North Asia and flowing downstream across the Bering Sea and Strait towards North America. The ABNA pattern is found to be associated with North American surface temperatures and temperature extremes to a large degree in all seasons, and explains higher proportion of surface temperature variances over North America compared to the PNA and NAO counterparts. The pattern is supported by synoptic-scale eddies in the upper troposphere, and forced by the snow cover anomalies over the Siberian region (Yu et al. 2017). In addition, the ABNA resembles the cold ocean–warm land (COWL, Wallace et al. 1996) pattern over North Asia and North America, with differences mainly over the oceans (Yu and Lin 2018). It also bears some resemblance to the zonal Wave3 pattern (Teng and Branstator 2012), especially the circulation anomalies over the North Pacific and North America, but with a zonal wave-number 2 like structure confined to the northern mid-high latitudes (cf. Fig. 11 in “Appendix A” with Fig. 1 in Teng and Branstator 2012). These findings highlight the importance of the extratropical atmospheric teleconnection and have strong implications for improving climate prediction over North America on seasonal to interannual time scales.

Does the extratropical ABNA pattern modify the tropically related PNA associated anomalies of North American

climate? If so, how and why? What is the seasonal forecast skill of the ABNA compared to the PNA? Can the PNA and ABNA pattern related climate anomalies over North America be captured by dynamical seasonal forecasting systems? These issues are of fundamental importance to North American climate variability and prediction, and are addressed in this study. In the following section, we outline the data and methods employed in this study. We then examine the anomalies of North American surface temperature and temperature extremes in association with the combination of the PNA and ABNA patterns in Sect. 3. Section 4 presents physical diagnostics to help understand the generation and maintenance of North American temperature anomalies. Section 5 assesses the predictability of the PNA and ABNA patterns. Results are summarized and further discussed in Sect. 6.

2 Data and methodology

2.1 Data

The analysis is based on December–February (DJF) mean atmospheric variables extracted from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (NCEP hereafter, Kistler et al. 2001) over the period from 1951 to 2015. Here, years are in reference to the January dates. The fields we used involve monthly air temperature, precipitation, geopotential and wind velocities in the troposphere, and daily temperature and heat fluxes at the surface. The monthly variables are on the standard $2.5^\circ \times 2.5^\circ$ grid. The DJF mean surface skin temperature and heat fluxes are averaged from their daily values and interpolated from 192×94 Gaussian grids to standard $2.5^\circ \times 2.5^\circ$ grids. We also use the National Aeronautics and Space Administration Goddard Institute for Space Studies surface air temperature (GISTEMP, Hansen et al. 2010; surface temperature with 1200 km smoothing, <https://data.giss.nasa.gov/gistemp>) and the SST from the Met Office Hadley Centre, version 1 (HadISST1.1, Rayner et al. 2003) for the same 65 winters. In addition, the Climate Prediction Center (CPC) merged analysis of precipitation (CMAP, Xie and Arkin 1997) for the period 1980–2015 (36 DJFs) and the snow water equivalent (SWE) data (Mudryk et al. 2015) for the period 1981–2010 (30 DJFs) are employed. SWE depicts the hydrological feature of snow cover and represents the total amount of water available if the snowpack in an interest area were melted. The observation based GISTEMP, SST, precipitation and SWE are also interpolated to the standard $2.5^\circ \times 2.5^\circ$ grid. For North American surface temperature extremes, we use the temperature extreme indices from the HadEX2 dataset (Donat et al. 2013) with $2.5^\circ \times 3.75^\circ$ (latitude–longitude) grids from 1951

to 2010. The indices employed involve the warm extremes when daily maximum (minimum) temperature is greater than its 90th percentile termed TX90p (TN90p), and the cold extremes in which daily maximum (minimum) temperature is less than its 10th percentile TX10p (TN10p).

The PNA index, identified from the rotated empirical orthogonal function (REOF) analysis of monthly mean 500-hPa height anomalies over the northern extratropics, from 1951 to 2015 was downloaded from the CPC website (<http://www.cpc.ncep.noaa.gov/data/indices>). The ABNA index was calculated based on the NCEP reanalysis data. Specifically, the index was constructed by an additive combination of the three regionally averaged geopotential anomalies over the ABNA centers of action, using the normalized 500-hPa geopotential field after linearly removing the PNA pattern contribution (Yu et al. 2017).

We also analyze the hindcast data of the Canadian Seasonal to Interannual Prediction System (CanSIPS) to assess the seasonal forecast skill of the ABNA and its related surface temperature anomalies in comparison with those of the PNA. CanSIPS is the operational seasonal forecasting system at the Environment and Climate Change Canada (ECCC), which produces a 20-member ensemble 12-month forecasts using two coupled atmosphere–ocean–land climate models developed at the Canadian Centre for Climate Modelling and Analysis (CCCma) (Merryfield et al. 2013). The hindcast period covers the 30 years from 1981 to 2010. In this study, only the ensemble mean DJF forecasts are briefly examined.

2.2 Analysis methods

We perform composite analyses to characterize and compare the PNA and ABNA related North American climate anomalies, as well as the anomalies associated with the combination of the two patterns. Anomalies are computed relative to the 30-year climatology over 1981–2010. The composites are based on events during which the PNA and ABNA events exceed 0.5 standardized units. This generates 24 (21) positive (negative) PNA events and 26 (22) positive (negative) ABNA events, respectively, from 1951 to 2015. Considering the in-phase and out-of-phase combinations of the PNA and ABNA events, we obtain 11, 9, 7, and 7 cases for the +PNA + ABNA, +PNA – ABNA, –PNA + ABNA and –PNA – ABNA combinations, respectively, over the 65 DJFs (Table 1). This suggests that there are about one-fourth of winters that show the in-phase or out-of-phase combination. For the CMAP (SWE) data, we have 9 and 5 (8 and 4) cases over 1980–2015 (1981–2010) for the +PNA + ABNA and +PNA – ABNA combinations, respectively. Results from these two composites are compared to the corresponding PNA counterparts. The other two combinations (–PNA + ABNA and –PNA – ABNA) only involve a few

cases over the relatively short CMAP and SWE time periods and are not considered. In addition, statistical significance of the composite results is assessed based on Student's *t* tests, assuming one degree of freedom per year. The lag-one autocorrelation of the PNA and ABNA indices is pretty small, 0.03 and 0.05 for PNA and ABNA, respectively.

For various PNA and ABNA composites, the anomalous horizontal temperature advection in the lower troposphere can be expressed as,

$$F_{adv} = -V \cdot \nabla \bar{T} = -u \frac{\partial \bar{T}}{\partial x} - v \frac{\partial \bar{T}}{\partial y}, \quad (1)$$

where $V(u, v)$ denotes the anomalous wind velocity including zonal and meridional components, based on various composites, and $\bar{T}$ the 65-DJF climatological mean temperature field.

The surface energy budget over land can be written as (e.g., Yu and Boer 2002; Zhang et al. 2011),

$$C_s \frac{\partial T_s}{\partial t} = R_s^d + R_s^u + R_l^d + R_l^u + LH + SH + Fg + Fm, \quad (2)$$

where C_s is the surface layer heat capacity, T_s the surface skin temperature, R_s^d (R_s^u) the surface downward (upward) shortwave radiation, R_l^d (R_l^u) the surface downward (upward) longwave radiation, LH (SH) the latent (sensible) heat flux at the surface, Fg the ground energy flux, and Fm the surface heat flux used for melt. All fluxes are defined to be positive downward to warm the surface. Also note that in a reanalysis output, especially that applying a simple data assimilation scheme as employed in the NCEP reanalysis, the energy budget equation is modified by a sizeable analysis term to keep the modelled atmosphere close to the observation (e.g., Yu and Zhang 2015). For the seasonal average, the left-hand side of Eq. (2) is much smaller than all flux terms and is not considered.

3 Anomalies of surface temperature and temperature extremes in association with the combination of the PNA and ABNA patterns

3.1 Surface air temperature

Figure 1 displays the composite results of surface air temperature (T_{2m}) anomalies over North America for positive and negative PNA and ABNA events. Positive PNA events are dominated by above-average temperatures over western Canada and the northwestern U.S., accompanied by below-average temperatures across the south-central and southeastern U.S., consistent with previous studies based on various datasets (e.g., Barlow et al. 2001; Higgins et al. 2002; Yu et al. 2007). By contrast, positive ABNA events feature

Fig. 1 North American T_{2m} anomalies for positive (left panels) and negative (right panels) PNA (upper) and ABNA (lower) events, based on the NCEP reanalysis from 1951 to 2015. Contour interval is $0.5\text{ }^{\circ}\text{C}$. Negative anomalies are cross-hatched. The positive (negative) anomalies that are significantly different from zero at the 5% level are red (blue) shaded

Table 1 Years of positive and negative PNA events during positive and negative ABNA events

	+ PNA	– PNA
+ ABNA	1953 1964 1983 1987 1992 1995 1998 2004 2006 2007 2012	1951 1952 1955 1956 1966 1989 1993
– ABNA	1963 1970 1977 1978 1986 2001 2003 2010 2015	1957 1959 1971 1972 1974 1979 2009

Years refer to the January dates

warm anomalies over the central-eastern parts of North America, especially prominent anomalies over the northern Great Plains extending eastward toward the Great Lakes in the U.S., accompanied by cold anomalies over Alaska and Mexico. T_{2m} anomalies in the negative composites are nearly mirror images of the positive composites, in terms of the spatial structure and amplitude, indicating the essential linearity of PNA and ABNA connections with North American surface temperatures. Results from events selected by the threshold of 1.0 standardized pattern index bear close resemblance to those seen in Fig. 1, but with stronger amplitudes for the centers of action, as would be expected (not shown).

We then concentrate on the temperature anomalies related to the combination of the two teleconnection patterns by analyzing the in-phase and out-of-phase combinations of the PNA and ABNA events (Table 1). T_{2m} anomalies are generally stronger for the in-phase combinations of PNA and ABNA events compared to the out-of-phase combinations, especially over Canada (Fig. 2). In the + PNA + ABNA composite, there is a band of intense T_{2m} anomalies extending northwestward from the Great Lakes to the Yukon Territory, with pronounced warm anomalies reaching about

$3.4\text{ }^{\circ}\text{C}$ over the Canadian Prairies. This is accompanied by weak cold anomalies over Mexico, western Alaska, and some patches in north Canada. Warm anomalies over the dominant center are significantly different from zero at the 5% level (shading in Fig. 2). By contrast, T_{2m} anomalies in the + PNA – ABNA composite are weak over the Canadian Prairies. Instead, pronounced warm anomalies in this composite are apparent over Alaska and northwest Canada, most of the Canadian Arctic Archipelago, and the west coast of North America, together with cold anomalies in the central-southeastern U.S. The anomalies for the – PNA – ABNA (– PNA + ABNA) composite generally resemble those for the + PNA + ABNA (+ PNA – ABNA) composite, but with opposite polarity and moderate differences mainly in the amplitude of T_{2m} anomalies.

Similar composite results are seen from the NCEP and GISTEMP datasets, while the anomalous patterns in GISTEMP are smoother than the NCEP counterparts owing to a 1200 km spatial smoothing applied to the GISTEMP data. In addition, the temperature anomalies in association with the combinations of the PNA and ABNA events (Fig. 2) bear close resemblance to the corresponding sums of T_{2m} anomalies associated with the individual PNA and ABNA events (Fig. 1), in terms of the spatial distribution and amplitude of the action centers (not shown). This implies a linear additivity of temperature responses to the two teleconnection patterns as an approximation. This may be expected since PNA and ABNA are uncorrelated with each other by construction. The lead-lag correlation between the two indices (with the lag time within 6 months) is also found to be lower than 0.2, in-significant at the 5% level (not shown). The differences of temperature anomalies seen in the four composites and the consistency of the results obtained from the two different datasets demonstrate a robust modification of the PNA associated surface temperature anomalies over North America by the ABNA teleconnection.

Fig. 2 North American T_{2m} anomalies for positive PNA events during positive (1st row) and negative (2nd row) ABNA events, and for negative PNA events during positive (3rd row) and negative (4th row) ABNA events. Contour interval is 0.5°C . Negative anomalies are cross-hatched. The positive (negative) anomalies that are significantly different from zero at the 5% level are red (blue) shaded. Results are based on the NCEP reanalysis (left column) and the GISTEMP analysis (right column)

3.2 Temperature extremes

The anomalous temperature extreme patterns in association with the PNA and ABNA events bear some resemblance to the corresponding mean surface temperature patterns (not shown, but see Yu et al. 2017 based on 31 DJFs from 1980 to 2010). Thus the PNA associated temperature extreme anomalies are also modified by the ABNA pattern. The anomaly patterns of warm days (TX90p) and warm nights (TN90p) for the combined effect of PNA and ABNA are similar (Fig. 3, two left columns), with differences mainly in amplitude of the anomalies. In particular, TX90p and TN90p anomalies that are significantly different from zero at the 5% level are evident over the Canadian Prairies for the in-phase combinations of the PNA and ABNA events, with increased anomalies for the +PNA +ABNA composite and reduced ones for the −PNA −ABNA composite. By contrast, the TX90p and TN90p anomalies are statistically insignificant over the Canadian Prairie region for the out-of-phase combinations. Instead, significantly increased warm days and warm nights are apparent over Alaska, northwest Canada and most of the Canadian Arctic

Archipelago, along with reductions over the southeastern U.S. for the +PNA −ABNA composite, while significantly decreased TX90p and TN90p are evident over western Canada and the northwestern U.S. for the −PNA +ABNA composite.

The composite patterns of cold days (TX10p) and cold nights (TN10p) also share similarities (Fig. 3, two right columns) and resemble the patterns of warm days and warm nights, but with opposite signs. TX10p and TN10p depict reduced cooling anomalies over most parts of North America with significant reductions extending northwestward from the southeastern U.S. to Alaska for the +PNA +ABNA composite, and exhibit increased anomalies over most parts of North America with statistically significant increase mainly over southern Canada for the −PNA −ABNA composite. The composite patterns of cold days and cold nights for the out-of-phase combinations of the PNA and ABNA events reveal insignificant anomalies over the Canadian Prairies and somewhat resemble the corresponding patterns for the warm days and warm nights, but with opposite signs.

Fig. 3 North American climate extreme anomalies for positive PNA events during positive (1st row) and negative (2nd row) ABNA events, and for negative PNA events during positive (3rd row) and negative (4th row) ABNA events. Contour interval is 1.0%. Negative anomalies are cross-hatched. The positive (negative) anomalies

that are significantly different from zero at the 5% level are red (blue) shaded. Anomalies of percentages of warm days (TX90p), warm nights (TN90p), cold days (TX10p), and cold nights (TN10p) are shown from the left to the right columns

4 Physical diagnostics of the combined anomalies

To aid in understanding the generation and maintenance of North American surface temperature anomalies, we examine the anomalies of atmospheric circulation and thermal advection, SST, precipitation, SWE, and surface energy budget for various PNA and ABNA combinations.

4.1 Anomalous atmospheric circulation and temperature advection

The PNA pattern consists of height anomalies in the vicinity of Hawaii and over the North American intermountain region, as well as anomalies of opposite sign located south of the Aleutian Islands and the southeastern U.S. (Fig. 11 in “Appendix A”). The ABNA pattern is dominated by circulation anomalies in the northern extratropics, with height anomalies over north-central Asia and north-central North America, accompanied by anomalies of opposite sign over the Bering Sea and Strait region (Fig. 11). The combined height anomalies tend to show a linear superposition of the anomalies associated with the two patterns. When the PNA and the ABNA operate in phase, the geopotential anomalies at 500-hPa (Φ_{500}) over the PNA sector

are dominated by a pair of significant anomaly centers located south of the Aleutian Islands and over the central-eastern parts of North America with opposite sign (Fig. 4). The anomalous circulation would influence the temperature field by advection and/or adiabatic processes (e.g., Wallace et al. 1996; Gong et al. 2017). The anomalous circulation in the +PNA +ABNA composite, in particular the negative geopotential anomalies around the Aleutian Islands and positive anomalies over the Great Lakes and the Hudson Bay region, induces warm advection at 850-hPa over western-central Canada and the northwestern U.S., especially the Canadian Prairies, and cold advection over northeastern Canada and the southern U.S. (F_{adv850} , Fig. 5). Basically opposite F_{adv850} anomalies are seen in the -PNA -ABNA composite. In addition, the lower-troposphere temperature advection is dominated by its meridional wind related component (not shown), except the comparable contributions from both the anomalous zonal and meridional wind related advection components over the Canadian Prairies in the -PNA -ABNA composite. The temperature advection pattern bears some resemblance to the pattern of surface temperature anomalies, in particular for the prominent T_{2m} anomalies described above (Fig. 2), confirming the relationship between the anomalous circulation and surface temperatures.

Fig. 4 Anomalies of the extra-tropical Φ_{500} for positive PNA events during positive (1st row) and negative (2nd row) ABNA events, and for negative PNA events during positive (3rd row) and negative (4th row) ABNA events. Contour interval is $100 \text{ m}^2 \text{ s}^{-2}$. Negative anomalies are cross-hatched. The positive (negative) anomalies that are significantly different from zero at the 5% level are red (blue) shaded

When the PNA and the ABNA are out of phase, by contrast, the anomalous circulation center over North America tends to shift westward and the Φ_{500} anomalies are weaker over north-central North America compared to those associated with the in-phase combination of the PNA and ABNA events (Fig. 4). Hence there are warm (cold) F_{adv850} over Alaska and northwest Canada, and cold (warm) advection over the central-southeastern parts of North America in the +PNA – BNA (–PNA + ABNA) composite, while the anomalous F_{adv850} is relatively weak over the Canadian Prairies (Fig. 5). The advection is dominated by its meridional wind related component, and also supports the pronounced temperature anomalies in these two composites.

4.2 Anomalous SST, precipitation and SWE

The PNA associated SST anomalies exhibit an ENSO-like pattern (e.g., Trenberth et al. 1998; Yu et al. 2007; Lin et al. 2017). The positive phase of the PNA pattern is associated with above-average SSTs in the tropical eastern-central Pacific and below-average SSTs in the midlatitude North Pacific (Fig. 12 in “Appendix A”). The ABNA associated SST anomaly is dominated by a horseshoe-shaped structure in the North Pacific, which is largely driven by the anomalous atmospheric circulation (Yu et al. 2017). The positive phase of the ABNA pattern is related to above-average SSTs in the midlatitude North Pacific surrounded

by below-average SSTs in the northeastern and subtropical North Pacific, and accompanied by weak above-average SSTs in the equatorial eastern Pacific (Fig. 12). Hence when the PNA and the ABNA operate in phase, SST tends to be dominated by anomalies in the tropical eastern-central Pacific (Fig. 6), which may act as a forcing source for the combined pattern influence on North American climate. The SST anomalies are weak in the midlatitude North Pacific for the +PNA + ABNA composite, owing to the cancellation of opposite SST anomalies there in association with the +PNA and +ABNA patterns. While this is not the case for the –PNA–ABNA composite, which reveals SST anomalies weighted towards the negative PNA associated counterpart in the midlatitude North Pacific (cf. Fig. 6 with Fig. 12). This indicates that the SST anomalies in the positive and negative phases of the individual PNA and ABNA events are not mirror images, especially for the ABNA associated SST anomalies. Relatively strong SST anomalies are also apparent in the Indian Ocean (Fig. 6), likely due to the inter-annual SST relationship between the tropical Pacific and Indian oceans. By contrast, SST is dominated by anomalies in the midlatitude North Pacific when the PNA and the ABNA are out of phase, a reinforcement of the similar SST patterns there in association with the two circulation patterns (Fig. 12). Strong wind anomalies in the North Pacific are well collocated with the action centers of SST anomalies (not shown), implying that the anomalous circulation

Fig. 5 Anomalies of North American horizontal temperature advection (contours $0.3\text{ }^{\circ}\text{C day}^{-1}$) and winds (arrows in m s^{-1} with a scale shown at the lower right, anomalies less than 0.1 m s^{-1} in both directions are omitted) at 850 hPa for positive PNA events during positive (1st row) and negative (2nd row) ABNA events, and for negative PNA events during positive (3rd row) and negative (4th row) ABNA events. The positive (negative) anomalies are light red (blue) shaded

largely drives the SST in the midlatitude North Pacific, consistent with previous studies (e.g., Cayan 1992; Kushnir et al. 2002).

The PNA associated precipitation anomalies bear some resemblance to the ENSO related counterpart in the tropical eastern Pacific, while the anomalies in the western Pacific are much weaker compared to that of ENSO (e.g., Wallace et al. 1998). In addition, significant precipitation anomalies are also evident in the North Pacific (Fig. 13 in “Appendix B”, lower panel). This indicates that the major PNA associated heating lies in the eastern Pacific, consistent with Yu (2007) in examining the PNA related diabatic heating anomalies. Similar to the SST anomalies, precipitation is dominated by marked anomalies in the tropics for the in-phase combinations of PNA and ABNA events, but less significant anomalies in the equatorial central-eastern Pacific and pronounced ones in the subtropical-midlatitude North Pacific for the out-of-phase combinations (Fig. 7).

In addition, below-normal (above-normal) precipitation is accompanied by above-average (below-average) Φ_{500} anomalies over western-central Canada and the northern U.S. for the +PNA +ABNA (−PNA −ABNA) composite (cf. Fig. 7 with Fig. 4). The co-location of above-normal (below-normal) temperatures and below-normal (above-normal) precipitation may be a consequence of positive (negative) height anomalies. The similar relationship can be seen over the southeastern U.S. for the out-of-phase combinations of PNA and ABNA events. The precipitation anomalies from the NCEP reanalysis have been confirmed by analyzing the CMAP data for the +PNA +ABNA and +PNA −ABNA composites. The main features as described above are also seen in the CMAP result (Fig. 13). The differences between the two datasets mainly appear in amplitude of the precipitation anomalies, in particular, relatively stronger anomalies along the equator in the CMAP result compared to the NCEP reanalysis.

Figure 8 displays the snow water equivalent anomalies in association with the PNA pattern, and the PNA and ABNA combinations. The PNA associated anomalies show SWE decrease over Siberia, most of Canada and the U.S. However, the anomalies are generally not statistically significant at the 5% level, except those over southwestern Canada. By contrast, pronounced SWE decrease (increase) is apparent over southern Siberia with a north-westward extension toward the West Siberian plain for the +PNA +ABNA (+PNA −ABNA) composite. Opposite SWE anomalies are also seen over the southeastern U.S. between the two composite patterns. The regions over North Asia and the southeastern U.S. are two with pronounced SWE variations in association with the ABNA pattern (Yu et al. 2017). Significant SWE anomalies are also evident over the Central Siberian Plateau for the +PNA −ABNA composite. The spatial correlations of the SWE anomalies between the +PNA +ABNA and +PNA −ABNA composites are -0.53 over the northern extratropical land of Fig. 8 and -0.65 over the land within ($0\text{--}180^{\circ}\text{E}$, $20\text{--}80^{\circ}\text{N}$). This further suggests the modification of the PNA associated SWE anomalies by the ABNA events, especially over the Eurasian region. The spatial correlations of the SWE anomalies over the northern extratropical land are 0.77 between the +PNA −ABNA and +PNA composites and -0.26 between the +PNA +ABNA and +PNA composites, indicating the SWE anomalies are structurally similar in the +PNA −ABNA and +PNA composites. As documented in our previous study, the snow-temperature interaction tends to influence the variation of local surface temperatures over North Asia and North America via changes in the surface energy balance, while SWE anomalies over the Siberian region also act as a forcing source for the ABNA atmospheric teleconnection (Yu et al. 2017).

Overall, there are pronounced SST and precipitation anomalies in the tropical eastern-central Pacific and marked

Fig. 6 As in Fig. 4, but for the tropical and northern mid-latitude SST anomalies. Contour interval is $0.2\text{ }^{\circ}\text{C}$

Fig. 7 As in Fig. 4, but for the tropical and northern mid-latitude precipitation anomalies. Contour interval is 0.5 mm day^{-1}

Fig. 8 SWE anomalies over the northern extratropical lands for positive PNA events during positive (top) and negative (middle) ABNA events, and for positive PNA events (bottom). Contour interval is 0.5 cm. Negative anomalies are cross-hatched. The positive (negative) anomalies that are significantly different from zero at the 5% level are red (blue) shaded

SWE anomalies over southern Siberia when PNA and ABNA operate in phase. These may act as forcing sources for the corresponding circulation anomalies, originated from the tropics and upstream from North Asia, which impact North American temperatures. By contrast, when the PNA and the ABNA are out of phase, pronounced SWE anomalies are still evident over the Siberian region. However, the tropical heating anomalies are weak, and the SST anomalies are largely driven by the anomalous atmospheric circulation in the midlatitude North Pacific.

4.3 Anomalous surface energy budget

The anomalies of surface energy budget over North America for the combined PNA and ABNA composites are analyzed. Table 2 lists the spatial standard deviations of surface temperature T_s and various components in the surface energy

balance ($X = \langle X \rangle + X^+$ with the angular braces representing the spatial average over the North American land of Fig. 9), as well as the spatial correlations and covariances between anomalies in surface temperature and energy balance terms. T_s anomalies over North America are nearly identical to the surface air temperature T_{2m} anomalies (Fig. 2), including the spatial structure and amplitude of the action centers (not shown). Broadly similar features of heat flux contributions to surface temperature anomalies are obtained in the four composites.

The energy budget is dominated by surface longwave downward (Rl^d) and upward (Rl^u) radiation anomalies in all the composites (Fig. 9), which is seen in the comparison of both the spatial standard deviations of various energy budget components and the spatial covariances between anomalies in temperature and energy budget terms (Table 2). The Rl^d (Rl^u) anomalies are highly and positively (negatively)

Table 2 Spatial standard deviation ($\langle X^2 \rangle^{1/2}$), covariances ($\langle T_s^+, X^+ \rangle$), and correlations ($r(T_s^+, X^+)$) of the anomalies of surface temperature ($^{\circ}\text{C}$) and the surface energy budget components (W m^{-2}) for different PNA and ABNA combined composites calculated over the North American (20–80°N, 170–50°W) land

	X^+	T_s	Rs^d	Rs^u	Rl^d	Rl^u	LH	SH
+ PNA	$\langle X^2 \rangle^{1/2}$	1.09	0.93	1.49	4.13	4.10	1.36	2.27
+ ABNA	$\langle T_s^+, X^+ \rangle$	1.19	-0.02	-0.02	4.23	-4.43	-0.06	0.48
	$r(T_s^+, X^+)$	1.00	-0.02	-0.01	0.94	-0.99	-0.04	0.19
+ PNA	$\langle X^2 \rangle^{1/2}$	1.74	1.58	2.17	6.67	6.65	2.06	2.82
- ABNA	$\langle T_s^+, X^+ \rangle$	3.03	-0.67	1.05	11.18	-11.51	-0.83	1.31
	$r(T_s^+, X^+)$	1.00	-0.24	0.27	0.96	-0.99	-0.23	0.27
- PNA	$\langle X^2 \rangle^{1/2}$	1.15	1.47	1.51	4.60	4.13	1.86	3.20
+ ABNA	$\langle T_s^+, X^+ \rangle$	1.32	-0.43	0.45	4.62	-4.67	-0.01	-0.49
	$r(T_s^+, X^+)$	1.00	-0.25	0.26	0.88	-0.99	-0.01	-0.13
- PNA	$\langle X^2 \rangle^{1/2}$	1.15	1.27	1.66	4.09	4.44	1.72	2.58
- ABNA	$\langle T_s^+, X^+ \rangle$	1.32	-0.32	0.35	4.16	-5.04	0.03	0.68
	$r(T_s^+, X^+)$	1.00	-0.22	0.18	0.89	-0.99	0.02	0.22

Fig. 9 North American surface anomalies of downward longwave radiation RI^d (left column), upward longwave radiation RI^u (middle column), and sensible heat flux SH (right column) for positive PNA events during positive (1st row) and negative (2nd row) ABNA events, and for negative PNA events during positive (3rd row) and

negative (4th row) ABNA events. Contour interval is 2.0 W m^{-2} . Negative anomalies are cross-hatched. The positive (negative) anomalies that are significantly different from zero at the 5% level are red (blue) shaded

correlated with T_s anomalies (cf. Figs. 2 and 9; Table 2), reflecting that the longwave radiation anomalies are structurally very similar to the temperature anomalies. The result further suggests that the downwelling longwave radiation tends to support and maintain the North American temperature anomalies while the outgoing longwave radiation damps the temperature anomalies, following the Planck feedback mechanism (e.g., Peixoto and Oort 1992). Apparently, the longwave radiation anomalies are due to both the anomalous lower-troposphere thermal advection (Fig. 5) and precipitation anomalies over North America (Fig. 7), as well as the heating associated variations of vertical motion and clouds. The result is also consistent with those documented by Zhang et al. (2011) in investigating ENSO related U.S. surface temperatures and by Gong et al. (2017) in studying Arctic surface temperature anomalies. In addition, the surface shortwave radiation (Rs^d and Rs^u) anomalies for the composites are much weaker compared to the longwave anomalies, and only weakly correlated with the surface temperature anomalies (Table 2).

The anomalous surface turbulent heat flux is dominated by the sensible heat flux (SH) anomalies, which show higher

spatial standard deviation and covariance with T_s anomalies than those of the latent heat flux (LH). The SH anomalies partially support the North American surface temperature anomalies (Fig. 9), especially for the in-phase combination of the PNA and ABNA events (Table 2). In addition, the anomalies of the ground heat flux F_g and flux F_m are small and negligible (not shown). Thus the surface net radiative anomalies are compensated by the surface turbulent heat flux anomalies for all the composites, as would be expected.

5 Predictability of the PNA and ABNA patterns

To assess the seasonal forecast skill of the ABNA pattern and its associated surface temperature anomalies in comparison with those of the PNA, we analyze the CanSIPS hindcast data. The CanSIPS predicted PNA and ABNA indices are obtained by projecting the forecast DJF ensemble mean Φ_{500} anomaly onto the PNA and ABNA spatial patterns, respectively. For forecasts initialized at 00Z December 1 (lead=0), the correlation skill of the ABNA is 0.57 over the 30-year

Fig. 10 North American T_{2m} anomalies regressed upon the normalized PNA (left) and ABNA (right) indices using the CanSIPS hindcast data from 1981 to 2010. Contour interval is 0.6 °C. Negative

anomalies are cross-hatched. The positive (negative) anomalies that are significantly correlated with the pattern index at the 5% level are red (blue) shaded

hindcast period, which is similar to that of the PNA (0.56) and is statistically significant at the 1% level. This indicates that both the ABNA and PNA patterns can be skillfully predicted at the seasonal time scale. We then examine the PNA and ABNA pattern related North American temperature anomalies in the hindcast. North American T_{2m} anomalies regressed upon the normalized PNA and ABNA indices over the hindcast period (Fig. 10) depict similar features as seen in the NCEP reanalysis (Fig. 1), although the prominent temperature anomalies in association with the ABNA shift slightly eastwards in CanSIPS compared to the NCEP. As both the ABNA and PNA can be skillfully predicted, as well as the well simulated pattern related temperature anomalies over North America, it can be expected that the pattern associated North American surface temperatures can be predicted as well.

For forecasts of lead = 1 month, i.e., those initialized at 00Z November 1, however, the DJF PNA index maintains a high correlation skill of 0.59, but the DJF ABNA index skill (0.11) is not statistically significant. This also indicates that the PNA is associated with tropical ENSO related forcing, which has a longer predictability, while the ABNA likely has an extratropical origin.

6 Conclusions and discussion

This study analyzes the modification of the PNA pattern associated North American surface temperature and temperature extreme anomalies by the ABNA teleconnection using the NCEP reanalysis and observation-based datasets. To aid in unraveling the generation and maintenance of the surface temperature anomalies over North America, we diagnose the anomalous atmospheric circulation and thermal advection, the potential forcing source of circulation anomalies including SST, precipitation and SWE, and

the anomalous surface energy budget for various PNA and ABNA combinations. In addition, we assess the seasonal forecast skill and surface temperature anomalies related to the ABNA pattern in comparison with those of the PNA pattern using the CanSIPS hindcast data. The main findings from this study are as follows:

1. The ABNA pattern modifies the PNA related anomalies of North American surface temperatures and temperature extremes. In particular, North American surface temperature and temperature extremes change significantly over the Canadian Prairies with the in-phase combination of the PNA and ABNA events, but not with the out-of-phase combination. The combined anomalies can be approximated by a linear additivity of temperature anomalies related to the two individual patterns. There are about one-fourth of winters over the period 1951–2015 that show the in-phase or out-of-phase influence of the PNA and ABNA combinations.
2. When the PNA and the ABNA operate in phase, there are pronounced SST and precipitation anomalies in the tropical eastern-central Pacific and snow cover anomalies in southern Siberia, which may act as forcing sources of the anomalous atmospheric circulation, leading to North American surface temperature anomalies. In particular, pronounced circulation anomalies over the Aleutian Islands and anomalies of opposite sign over the Great Lakes and the Hudson Bay region are apparent in the in-phase combination. This induces anomalous temperature advection in the lower troposphere, which is dominated by its meridional wind related component, and supports the prominent temperature anomalies over North America. When the PNA and the ABNA are out of phase, pronounced snow cover anomalies are still evident over the Siberian region. However, the tropical heating anomalies are weak, and SST anomalies are

largely driven by the anomalous atmospheric circulation in the midlatitude North Pacific. The anomalous circulation center over North America tends to shift westward compared to that with the in-phase combination. Hence the circulation anomalies are weak over north-central North America, which induce weak thermal advection and insignificant temperature anomalies over the Canadian Prairies.

3. The surface energy balance is dominated by surface longwave radiation anomalies for all the composites considered. Over North America, there is more (less) surface downward longwave radiation when the atmosphere is warm (cold), as a result of the anomalous atmosphere imposed by thermal advection and precipitation anomalies. This is offset by the corresponding outgoing longwave radiation increase (decrease) at the surface.
4. Both the ABNA and PNA patterns can be skillfully predicted at the seasonal time scale, as well as their pattern related North American surface temperature anomalies.

In this analysis, we examine the anomalies of North American surface temperatures and temperature extremes in association with the combination of the PNA and ABNA patterns, and examine the maintenance of the mean temperature anomalies. Similar anomalous temperature patterns, in particular the dominant centers of action, in the four composites are also clearly evident in the twentieth Century Reanalysis (20CR, Compo et al. 2011) and GISTEMP datasets from 1901 to 1950 and from 1901 to 2010 (not shown). This increase confidence in the results reported here based on the period from 1951 to 2015. In addition, the combined anomalies appeared to be dominated slightly more by those coming from the PNA, especially over the anomalous center of action. This suggests that the PNA is stronger in some sense than the ABNA, but the ABNA's contribution is still sufficient for it to modify the PNA influence.

In terms of the extreme temperature, previous attribution studies suggested that changes in temperature extremes can result from regional circulation pattern changes and regional- and global-scale thermodynamic changes (e.g., Dole et al. 2011; Barnes 2013; Horton et al. 2015). The

temperature extreme anomaly may also be related to high frequency climate activities, such as cyclone/anticyclone tracks and blocking activity (e.g., Favre and Gershunov 2006; Chang et al. 2016; Sillmann et al. 2017). The generation and maintenance of the temperature extreme anomalies in association with the atmospheric pattern remain to be explored. Moreover, Lin (2015) and Ma et al. (2018) recently found that the East Asian winter monsoon affects the convection and precipitation patterns over the tropical central and/or western Pacific by cold air outbreaks, which modulate the generation of Rossby wavetrains related to ENSO, leading to subseasonal–seasonal temperature anomalies over North America. This suggests another pathway in linking North Asian and North American climate, different from the direct connection through the anomalous atmospheric circulation in the extratropics (Lin and Wu 2011; Yu et al. 2017; Yu and Lin 2018). The tropical-extratropical interaction on different time scales and its influence on North American climate merit further investigation.

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Appendix A: PNA and ABNA associated Φ_{500} and SST anomalies

Anomalies of the northern extratropical Φ_{500} (Fig. 11) and the tropical and northern mid-latitude SST (Fig. 12) for positive and negative PNA events and positive and negative ABNA events are shown herein.

Fig. 11 As in Fig. 4, but for positive and negative PNA events and positive and negative ABNA events from the top to the bottom

Fig. 12 As in Fig. 6, but for positive and negative PNA events and positive and negative ABNA events from the top to the bottom

Appendix B: CMAP based precipitation anomalies for the PNA and ABNA combinations

The CMAP based precipitation anomalies for positive PNA events, and positive PNA events during positive and negative ABNA events (Fig. 13) are shown herein.

Fig. 13 Anomalies of the tropical and northern mid-latitude precipitation for positive PNA events during positive (top) and negative (middle) ABNA events, and for positive PNA events (bottom), based on the CMAP data. Contour interval is 0.5 mm day^{-1} . Negative anomalies are cross-hatched. The positive (negative) anomalies that are significantly different from zero at the 5% level are red (blue) shaded

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