Solar cycle modulation of the Pacific–North American teleconnection influence on North American winter climate

Zhongfang Liu1,2, Kei Yoshimura2, Nikolaus H Buenning3 and Xiaogang He2

1 Key Laboratory of Water Resource and Environment, Tianjin Normal University, Tianjin, People’s Republic of China
2 Atmosphere and Ocean Research Institute, University of Tokyo, Kashiwa, Japan
3 Department of Earth Sciences, University of Southern California, Los Angeles, CA, USA

E-mail: liuzf406@gmail.com

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Abstract

We investigate the role of the 11-year solar cycle in modulating the Pacific–North American (PNA) influence on North American winter climate. The PNA appears to play an important conduit between solar forcing and surface climate. The low solar (LS) activity may induce an atmospheric circulation pattern that resembles the positive phase of the PNA, resulting in a significant warming over northwestern North America and significant dry conditions in the Pacific Northwest, Canadian Prairies and the Ohio-Tennessee-lower Mississippi River Valley. The solar-induced changes in surface climate share more than 67% and 14% of spatial variances in the PNA-induced temperature and precipitation changes for 1950–2010 and 1901–2010 periods, respectively. These distinct solar signatures in North American climate may contribute to deconvolving modern and past continental-scale climate changes and improve our ability to interpret paleoclimate records in the region.

Keywords: solar cycle, Pacific–North American, climate variability

1. Introduction

The Pacific–North American (PNA) teleconnection is the most prominent mode of low-frequency atmospheric variability in the Pacific–North American sector (Wallace and Gutzler 1981) and strongly affects winter temperatures and precipitation across North America (Leathers et al 1991). The PNA can be measured as an index derived from a linear combination of standardized 500-mb geopotential height anomalies (Wallace and Gutzler 1981). A positive PNA typically features a deepened Aleutian low over the North Pacific, expanded ridge over northwestern North America and deepened trough over the southeastern USA, which leads to positive temperature anomalies across northwestern North America and drier conditions in the Pacific Northwest and Ohio River Valley (Leathers et al 1991, Coleman and Rogers 2003). In contrast, a negative PNA corresponds to a weakened Aleutian low over the North Pacific and a dampened ridge–trough pattern over North America, leading to opposite temperature and precipitation anomalies over the same regions.

As a natural internal mode of atmospheric variability (Straus and Shukla 2002), the PNA can be affected by external forcings such as sea surface temperature (SST) and solar activity (Harzallah and Sadourny 1995, Ruzmaikin 1999). So far, much effort has been devoted to investigating the modulation of SST forcing associated with the El Niño Southern Oscillation (ENSO) on the PNA pattern (Straus and Shukla 2002, Yu and Zwiers 2007). Although there is still some debate about the role of SST forcing in triggering and/or amplifying the PNA variability (Trenberth and Hurrell 1994, Straus and Shukla 2002), most studies argue that the PNA
tends to be more positive in response to the warm ENSO phase (Renwick and Wallace 1996, Yu and Zwiers 2007). In contrast, very little work has been done relating the PNA variability to solar forcing. Ruzmaikin (1999) found an 11-year signal in the PNA variability based on spectrum analysis on the monthly PNA index and attributed it to the modulation of solar forcing on ENSO (White et al 1997). An investigation of solar cycle effects on modes of low-frequency circulation has also shown PNA-like geopotential height spatial variations (Huth et al 2006). Recent studies have further demonstrated that the solar peaks coincide with positive sea level pressure anomalies around the Aleutian Islands, resulting in a decrease in precipitation in the northwestern USA (van Loon et al 2007, van Loon and Meehl 2011). However, it is still not clear how the 11-year solar cycle forces changes in the PNA phase and thus temperature and precipitation in North America. In particular, the solar cycle may influence the teleconnection between ENSO variability and the phase of the PNA.

There is an increasing appreciation that the 11-year solar variability plays an important part in forcing climate variations by inducing atmospheric change (Gray et al 2010). Previous studies have focused more on the influence of the solar cycle on the North Atlantic Oscillation (NAO)/Arctic Oscillation (AO) patterns (Kodera 2002, Woollings et al 2010, Ineson et al 2011, van Loon et al 2012) and the Southern Annular Mode (SAM) (Kuroda and Shibata 2006, Kuroda et al 2007, Kuroda and Yamazaki 2010). For example, recent observations and simulations have demonstrated that the solar minimum tends to lead to the negative phase of both the NAO and AO (Woollings et al 2010, Ineson et al 2011, van Loon et al 2012) and lead to a weaker SAM signal (Kuroda and Yamazaki 2010) during the cool season. Yet, little emphasis has been placed on the relationships of the 11-year solar cycle with the PNA pattern and its influence on North American winter climate. Given the influence of the 11-year solar cycle on modes of low-frequency circulation variability, we speculate that the 11-year solar forcing may modulate PNA variability and thus affect North American winter climate. As such, we investigate the role of solar forcing in determining North American winter temperature and precipitation that are strongly related to the PNA and possible ENSO influence.

2. Data and methods

Gridded monthly geopotential height data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data set (Kalnay et al 1996), as well as temperature and precipitation data from Climatic Research Unit (Mitchell and Jones 2005) are used in this study. The CRU TS 3.1 dataset covers the global land surface (excluding Antarctica) with 0.5° by 0.5° grid cells, spanning a period from 1901 to 2010, and is constructed through interpolation of instrumental measurements. Winter means are calculated by averaging the monthly means of December through February (DJF), obtaining 109 complete winters, of which 61 winters from 1950 to 2010 overlap with the PNA record.

| HS winter | PNA index | ENSO state | LS winter | PNA index | ENSO state |
|-----------|-----------|------------|-----------|-----------|------------|
| 1950      | −1.69     | C          | 1953      | 0.86      |            |
| 1956      | −1.48     | C          | 1954      | 0.00      |            |
| 1959      | −0.25     |            | 1955      | −0.62     |            |
| 1960      | 0.37      |            | 1977      | 1.43      |            |
| 1967      | −0.08     |            | 1985      | −0.16     |            |
| 1968      | −0.22     | C          | 1986      | 0.96      |            |
| 1969      | −1.50     |            | 1987      | 1.01 W    |            |
| 1970      | 1.14      |            | 1996      | 0.20      |            |
| 1971      | −0.69     | C          | 1997      | −0.01     |            |
| 1972      | −1.45     |            | 2006      | 0.57      |            |
| 1979      | −1.08     |            | 2007      | 0.83      |            |
| 1980      | 0.36      |            | 2008      | 0.11      |            |
| 1989      | −0.38     | C          | 2009      | −0.58     |            |
| 1990      | −0.44     |            | 2010      | 0.72 W    |            |
| 1991      | 0.14      |            |           |           |            |
| 1999      | −0.02     | C          |           |           |            |
| 2000      | 0.17      |            |           |           |            |
| 2001      | 0.86      |            |           |           |            |
| 2002      | 0.22      |            |           |           |            |

We use winter season mean values of the PNA index (figure 1(b), Climate Prediction Center; available at www.cpc.ncep.noaa.gov) to identify winters characterized by strong positive or negative PNA patterns. Selecting winters lying outside of a threshold value of ±0.5 standard deviations (σ), we identified 19 positive and 15 negative PNA winters. The cold tongue index (CTI, Deser and Wallace 1990) (available at http://jisao.washington.edu/enso/), defined as the difference between SST anomalies averaged over 6°N–6°S, 180°–90°W and the global mean SST, is used as a measure of ENSO variability (figure 1(c)). Here winters with the normalized CTI > 1σ and < −1σ are defined as warm and cold ENSO events, respectively (Calvo and Marsh 2011).

There are several different indices used to measure solar variability (Gray et al 2010, Lockwood et al 2010a,b). Here, we use the monthly sunspot number during the 1900–2010 period (National Geophysical Data, NOAA) to characterize solar variability. We define high and low solar activity winters according to terciles of sunspot number throughout the study period: winters above the upper and below the lower tercile are referred to as high solar (HS) and low solar (LS) winters, respectively (figure 1(a) and table 1, Woollings et al 2010, Ineson et al 2011). Because changes in observed winter atmospheric circulation can be masked by large volcanic eruptions (Robock 2000), our analysis also excludes the winters (first two winters following each eruption) with major volcanic eruptions (13 eruptions between 1900 and 2010, see Robock and Mao 1995, Esper et al 2013) in either the Northern Hemisphere or tropics during the HS and LS winters (figure 1(a)).

To assess the influence of solar activity on the PNA, we explore composite differences of 500-mb geopotential height, temperature and precipitation fields between LS and
Figure 1. Time series of winter (DJF) sunspot numbers (SSN) (a), PNA index (b) and ENSO index (c). Long dashed lines in (a) show the terciles over the 1900–2010 period. Winters with sunspot numbers above the upper tercile represent high solar (HS, red circle) winters, and those below the lower tercile represent low solar (LS, blue circle) winters. The crosses represent the winters with major volcanic eruptions in either the Northern Hemisphere or tropics. The pink line represents the PNA time series after $11 \pm 0.5$ year band-pass filtering (a second-order Butterworth band-pass filter is used here). Short dashed lines in (c) show $\pm 1$ standard deviation from mean value.

3. Results

3.1. Changes in the PNA for LS and HS winters

Figure 2 shows the circulation pattern differences between the composites of LS and HS winters (LS minus HS) at lags 0, 1 and 2 years in the Northern Hemisphere. In the current winters (at lag 0 year), the composite difference of 500-mb geopotential heights in the Pacific and North American sectors projects a clear quadrupolar structure, with centers over the tropical Pacific Ocean (close to Hawaii), the Aleutian Islands, western North America and southeastern United States (figure 2(a)), revealing a PNA-like circulation pattern in the region. Compared to HS winters, 500-mb heights in LS winters significantly ($p < 0.1$) increase over the tropical Pacific ($>10$ m) and northwestern North America ($>20$ m), and significantly ($p < 0.1$) decrease over the Aleutian Islands ($<−30$ m) and the southeastern United States ($<−20$ m) (figure 2(a)). Such a spatial configuration is indicative of the positive phase of the conventional PNA pattern. In subsequent winters (at lags 1 and 2 years), however, a clear decline in the PNA signal is apparent, though the difference in 500-mb heights in individual centers is significant (figures 2(a)–(c)). The contrast between HS and LS is evident also in the PNA index with no lag. The probability density function of the PNA index for HS and LS shows that negative PNA events (PNA index $<−0.5$) are more strongly linked to HS and positive PNA events (PNA index $>0.5$) frequently occur during LS (figure 3). Quantifying the change in the PNA index between LS and HS winters yields a difference of 0.70, with mean values of 0.38 for LS winters and $−0.32$ for HS winters. A two-sample $t$-test shows that they are significantly different at the $p < 0.01$ level ($T = −2.67, df = 31$). Whereas, the changes in the PNA index between LS and HS winters are 0.15 for lag 1 year and $−0.03$ for lag 2 years, respectively, and both are not statistically significant ($p > 0.1$). Given the fact that the PNA response to solar forcing is only significant for the current winter (lag = 0 year), subsequent analysis is only limited to the winters at lag 0 year.
3.2. Changes in temperature and precipitation for LS and HS winters

The changes in temperature for LS and HS winters are well defined, especially in northwestern North America (figures 4(a) and (c)). A statistically significant warming (>1°C) signal is found across the northwestern USA, central Canada and Alaska during LS winter compared to HS winter, whereas the southeastern continent tends to be slightly cooler (<−0.5°C). The changes in temperature between LS and HS winters bear a clear resemblance to that caused by the positive and negative PNA patterns (positive minus negative) (figure 4(e)). A spatial correlation between solar- and PNA-associated temperature changes indicates that the solar forcing has 77% (p < 0.0001) shared variance with PNA-induced temperature changes during the period of 1950–2010. The 1901–2010 period exhibits a slightly stronger spatial correlation (R² = 82%, p < 0.0001) (figure 5(a)). Although there are some differences in the magnitude (i.e., smaller differences for LS and HS winters in figures 4(a), (c) and 5(a)), likely due to the contrasting effects of external forcing and internal climate dynamics, the similarities may suggest that the solar forcing is affecting North American winter temperature through its influence on the PNA pattern (figures 1 and 2).

Precipitation also exhibits a substantial difference between LS and HS winters in some regions, comparable to PNA-induced precipitation difference (figures 4(b), (d) and (f)). Significant dry conditions (<−5 mm/month) are observed in the Pacific Northwest, Canadian Prairies, central Alaska and the Ohio-Tennessee-lower Mississippi River valley during LS winters compared to HS winters, with significant wet conditions (>5 mm/month) in the south coast of Alaska, Yukon and the southeastern coasts of the United States. The solar-associated precipitation differences have some similarity to those induced by the PNA in both magnitude and spatial pattern. Spatially, they have 31% and 38% (p < 0.0001) shared variance for the 1950–2010 and the 1901–2010 periods, respectively (figure 5(b)). The disagreements between the PNA- and solar-associated precipitation differences occur mostly in the Labrador, Great Lakes and Northern Plains regions (figures 4(b), (d) and (f)). In contrast to temperature, lower shared variances for precipitation are probably due to the weaker influence of the PNA on precipitation (Leathers et al 1991).

3.3. Possible ENSO modulation of solar influence

Although the patterns of PNA, temperature and precipitation fields show some substantial changes in response to solar forcing, the solar influence may be confounded by the simultaneous occurrence of ENSO events in the Pacific sector. Previous studies have indicated a possible link between the solar cycle and the ENSO phase, suggesting a strong La Niña-like pattern during HS winters (van Loon et al 2007, Meehl et al 2008), albeit with a large uncertainty (Haam and Tung 2012, Roy and Haigh 2012). Thus, the positive (negative) PNA pattern during

![Figure 2](image-url) Composite differences of 500-mb geopotential height (m) between LS and HS winters (LS minus HS). (a)–(c) show the differences at lags 0, 1 and 2 years. The areas enclosed by the gray line show the field significant above the p < 0.1 level.

![Figure 3](image-url) Probability density function of the PNA index during HS (a) and LS winters (b).
Figure 4. Composite differences in winter surface climate for LS minus HS ((a)–(d)) and positive PNA minus negative PNA ((e) and (f)). Panels (a) and (c) show temperature (°C) for the 1950–2010 and 1901–2010 periods, respectively. Panels (b) and (d) show precipitation (mm/month) for the 1950–2010 and 1901–2010 periods, respectively. Panels (e) and (f) show PNA-induced temperature and precipitation differences for the 1950–2010 period. The areas enclosed by the gray line show the field significant above the $p < 0.1$ level.

LS (HS) winters may partially be due to the influence of the solar-driven warm (cold) ENSO events in the Pacific sector. To isolate the PNA response to solar change without the influence of ENSO variations, we remove all warm (cold) ENSO winters from LS (HS) winters (table 1) and then re-calculate the composite differences of 500-mb geopotential height, surface air temperature and precipitation for the two groups.

Figure 6 shows the isolated response of 500-mb geopotential height to solar variability. The quadrupolar structure is still clear in the Pacific and North American sectors, of which three regions exhibit statistically significant ($p < 0.1$) difference between LS and HS winters (the center of the southeastern USA is not significant). Compared to figure 2(a), the changes over the Pacific and southeastern USA centers tend to decrease in both magnitude and spatial extent, whereas the center over northwestern North America is significantly strengthened. When ENSO years are removed the occurrence of PNA events is similar to the case that includes ENSO year (figure 3), though with a slightly weakened signal (figure 7). A direct comparison of the change in the PNA index gives a difference of 0.53, with mean values of $−0.23$ in HS and $0.30$ in LS winters, respectively. Although the change in the PNA index slightly decreases compared to the solar influence that includes ENSO winters, it is still significant at the $p < 0.05$ level ($T = −1.74$, $df = 21$). This weakening response of the PNA to solar variability may suggest that solar-induced changes to the ENSO phase can contribute to some of the changes in the PNA.
Given this weakened response of the PNA to solar forcing, the contrast in horizontal circulations (difference in meridional circulation) will therefore decline, which should provoke a reduction of temperature and precipitation differences between LS and HS winters. Figure 8 shows the composite differences in spatial temperature and precipitation fields for LS and HS winters that only include non-ENSO winters. Clearly, though the change in temperature over northwestern North America to a large extent mimics that caused by the PNA shift, same as what is shown in figure 4, the southeast does not show the same trend (figures 8(a), (c) and (e)). A point-wise comparison between ‘pure solar’ and ‘pure PNA’ yields 67% and 71% ($p < 0.001$) shared variances in temperature for the 1950–2010 and 1901–2010 periods, respectively (figure 9(a)), revealing a reduction of about 10% in shared variance compared to solar influence that includes the ENSO events.

The change in precipitation response to ‘pure solar’ forcing also bears some resemblance to that induced by ‘pure PNA’ (figures 8(b), (d) and (f)). This is clear for certain regions: for example, significant dry conditions for LS and positive PNA winters are co-located in the Canadian Prairies and Ohio-Tennessee-lower Mississippi River Valley where the PNA/precipitation correlation is strongest (Leathers et al 1991). The relationship does not hold up in Mexico and southwestern Texas, where dry conditions during LS winters versus wet conditions for positive PNA winters. Overall, the change in precipitation due to ‘pure solar’ describes 14% and 17% ($p < 0.0001$) of variances of the ‘pure PNA’ precipitation differences for the 1950–2010 and 1901–2010 periods.
periods, respectively (figure 9(b)), decreased by a factor of 2.2 compared to those that include ENSO years (figure 5(b)).

4. Conclusions and discussion

Our results have shown the influence of the 11-year solar cycle on the PNA-associated atmospheric circulation pattern and winter surface climate in North America. We found a significant positive PNA pattern during LS winters compared to HS winters. Unlike the NAO response at lags of around 2 year (Scaife et al 2013), however, the PNA response decreases fairly in the subsequent two winters and is not significant. We also found that the PNA response to solar forcing can be clearly enhanced by the simultaneous occurrence of ENSO events due to the solar influence on ENSO. When this influence is removed, the PNA response tends to be slightly weak but still significant at the $p < 0.05$ level. This is also the case for temperature and precipitation, with a significant warming in northwestern North America and drier conditions in the Canadian Prairies and Ohio-Tennessee-lower Mississippi River Valley for LH winters compared to HS winters.

Winter temperature and precipitation across North America can strongly be affected by the PNA pattern (figures 4(e), (f), 8(e) and (f), Leathers et al 1991). Given the spatial co-variability between PNA- and solar-associated differences of temperature and precipitation, we suggest that the solar forcing may be affecting surface climate (especially temperature) variability through its modulation of the PNA pattern. This assertion appears to be supported by the co-variability between the (filtered) PNA and 11-year solar activity (figure 1).

Previous observations and simulations of the effects of solar variability on the Earth’s atmosphere have suggested that
large variations in the solar ultraviolet radiation could significantly affect heating and ozone chemistry in the stratosphere, which modifies tropospheric circulation and thus affects surface climate through the so-called ‘top-down’ mechanism (Kodera and Kuroda 2002, Gray et al 2010, Lockwood et al 2010b, 2011). Another mechanism named ‘bottom-up’ is said to magnify the response of a small solar forcing anomaly by air–sea coupling and complement the ‘top-down’ mechanism (van Loon et al 2007, Meehl et al 2009). The circulation response to solar forcing shown here suggests that LS induces an enhanced ridge–trough pattern over the North American continent (figures 2(a) and 6), resembling the positive phase of the PNA. The enhanced ridge in the northwest brings tropical/subtropical air masses from the Pacific into northwestern North America (figure 10), resulting in a significant warming in the region (figures 8(a), (c) and (e)). At the same time, a northward shift of the polar jet associated with this enhanced ridge also leads to significant dry conditions across northwestern Canada (figures 8(b), (d) and (f), Leathers et al 1991). In contrast, the deepened trough over the southeastern United States is associated with a southward displacement of the polar jet, allowing cold Arctic air to move southward into the southeast (figure 10), causing a slight cooling in the region and drier conditions in the Ohio-Tennessee-lower Mississippi River Valley (figure 8). The opposite is true for HS that yields a negative phase of the PNA.

While our results show that solar forcing is clearly important for the PNA-like circulation influence on surface climate in North America, there remain some uncertainties. These include three aspects. One lies in some spatial discrepancies between solar- and PNA-driven changes in surface climate variables. For example, significant changes in temperature associated with PNA shifts in the southeast are not observed or exhibits a converse trend to solar forcing when ENSO years are excluded (figures 8(a), (c) and (e)). Secondly, there exist some differences in the magnitude of the solar- and PNA-associated temperature changes. For example, the solar-induced temperature change is about a factor of 2 smaller than that induced by the PNA in the northern region of the continent (figures 8(a), (c) and (e) and 9(a)). Thirdly, there are fewer regions with significant changes in precipitation for LS and HS winters when compared to the PNA influence (figures 8(b), (d) and (f)).

In consideration of these uncertainties, future research efforts should aim to understand the PNA/solar forcing relationship through longer-term observations or performing model experiments.

A framework for understanding the solar modulation of the PNA pattern and surface climate in North America has some implications for the detection and attribution of modern and past climatic changes in the region. Previous studies have suggested that systematic climate oscillations at different time scales in North America relate to changes in solar forcing (Minobe 1997, Hu et al 2003, Asmerom et al 2007). Based on our present findings, we speculate that the PNA may play a critical conduit between solar forcing and surface climate. Recently discovered robust PNA signals in modern isotopes in precipitation (Birks and Edwards 2009, Liu et al 2011, 2012, 2013) and paleo-proxies (e.g., Moore et al 2002, Trouet and Taylor 2010, Hubeny et al 2011) have indicated that the PNA pattern influences hydroclimate variability across North America by modulating mid-tropospheric atmospheric circulation.
patterns and storm tracks. Thus, an improved understanding of PNA/solar forcing relationship will represent a step toward constraining the role of solar activity in determining modern and past changes in circulation patterns, temperature, moisture, and precipitation across North America.

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