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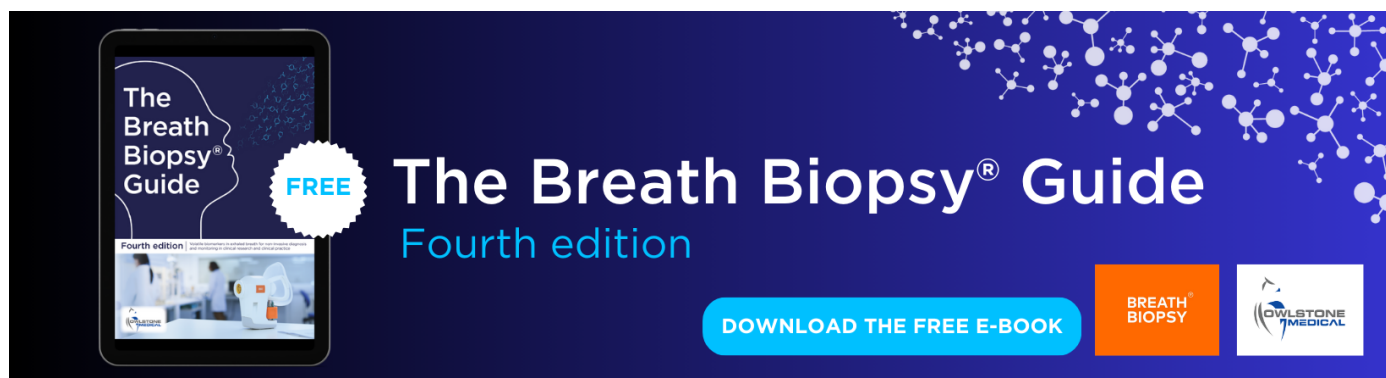
The zonal North Pacific Oscillation: a high-impact atmospheric teleconnection pattern influencing the North Pacific and North America

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The zonal North Pacific Oscillation: a high-impact atmospheric teleconnection pattern influencing the North Pacific and North America

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^{*} Author to whom any correspondence should be addressed.E-mail: bktan@pku.edu.cn**Keywords:** zonal North Pacific Oscillation, atmospheric teleconnection, subseasonal climate variabilitySupplementary material for this article is available [online](#)

Abstract

Based on unfiltered daily Japanese 55 year reanalysis covering the 60 winters in 1958–2018, a new teleconnection pattern called the zonal North Pacific Oscillation (ZNPO) pattern has been detected. The ZNPO pattern describes a mass oscillation in the troposphere between the eastern and western North Pacific, persisting for a week or so. It is shown that the ZNPO pattern is a high-impact teleconnection pattern that brings the wintertime North Pacific and North America severe weather and hydroclimate events. It may cause rapid surface air temperature drop or rise over the northern North Pacific and North America, remarkable sea ice concentration anomalies over the northeastern Bering Sea, and strong convective anomalies in the lower troposphere over the eastern and western midlatitude North Pacific. The ZNPO pattern arises from two westward-moving geopotential height disturbances over the North Pacific and North America and is driven mainly by baroclinic energy conversion and feedback forcing by transient eddies. The baroclinic energy conversion acts to overcome the available potential energy (APE) loss caused by the heat flux of transient eddies and at the same time acts as a major kinetic energy (KE) source to maintain the ZNPO pattern. The barotropic feedback forcing by transient eddies acts as a major KE source to drive the ZNPO pattern during the growing stage of the ZNPO pattern and as a major KE sink to heavily damp the ZNPO pattern during the decaying stage.

1. Introduction

For the Earth's turbulent atmosphere, the existence of the teleconnection patterns brings meteorologists hope for weather/climate prediction beyond one week or an even longer time period. The wintertime North Pacific is a place where the atmospheric teleconnection patterns, such as the Pacific/North American (PNA) pattern (Wallace and Gutzler 1981), the North Pacific Oscillation (NPO) pattern (Walker and Bliss 1932) or the western Pacific (WP) pattern (Horel 1981, Wallace and Gutzler 1981, Barnston and Livezey 1987, Linkin and Nigam 2008), and the eastern Pacific (EP) pattern (Athanasiadis *et al* 2010, Tan *et al* 2015), are mostly active and have been studied extensively for the past four decades or so. Early studies focused mainly on the internal dynamics of these teleconnection patterns and their relationship with the El Niño–Southern Oscillation (ENSO)-related

sea surface temperature (SST) anomalies over the tropics (Hoskins and Karoly 1981, Rogers 1981, Renwick and Wallace 1996, Mo *et al* 1998, Chu *et al* 2019, Sung *et al* 2019). These studies serve as a solid basis for improving climate prediction on seasonal and interannual timescales (Kumar *et al* 1996, Straus and Shukla 1997, Shukla *et al* 2000, Derome *et al* 2001). Recently, many studies concentrated on the PNA, WP and EP patterns on sub-seasonal timescale and their relationship to tropical convection, particularly Madden-Julian Oscillation (MJO)- and ENSO-associated deep convection (Feldstein 2002, Franzke and Feldstein 2005, Linkin and Nigam 2008, Mori and Watanabe 2008, Johnson and Feldstein 2010, Rivière 2010, Franzke *et al* 2011, Riddle *et al* 2013, Yuan *et al* 2015, Dai *et al* 2017, Dai and Tan 2019a, 2019b). Now, it is possible to predict PNA and WP pattern-associated weather by up to three to four weeks in advance (Younas and Tang 2013, Black *et al*

2017), which creates the hope for us to break through the one-week upper bound of state-of-the-art operational numerical models. Due to the importance of skillful subseasonal forecasts in decision-making in agriculture and food security, water and energy management, and disaster risk reduction, the improvement of skills and promotion of the utility of subseasonal weather and climate forecasts now becomes a main research task of governmental agencies and the scientific community (<https://www.wcrp-climate.org/s2s-overview>; www.cpc.ncep.noaa.gov/products/predictions/WK34).

This study will focus on teleconnection patterns over wintertime North Pacific on a subseasonal timescale. In view of the fact that all three known teleconnection patterns, the PNA, WP and EP patterns, take the form in the middle and upper troposphere of meridionally orientated wave trains across the Pacific jet and/or its exit region, this study, instead, will explore whether some teleconnection patterns exist in the form of zonally orientated wave trains along the Pacific jet and its downstream region. This kind of teleconnection pattern has been observed over Eurasia (such as the Scandinavian pattern, Barnston and Livezey 1987; the Eurasian Pattern, Wallace and Gutzler 1981; the Silk Road pattern, Lu *et al* 2002, Enomoto 2004; the British–Baikal Corridor pattern, Xu *et al* 2019), over the Asia–North America region (the Asia–North America teleconnection, Lau and Weng 2002, Zhu and Li 2016), or over the middle-latitude Northern Hemisphere (the Circumglobal teleconnection, Branstator 2002, Ding and Wang 2005). It turns out that a new teleconnection pattern called the ‘zonal North Pacific Oscillation’ (ZNPO) pattern does exist. The ZNPO pattern describes a mass oscillation in the troposphere between the eastern and western North Pacific and has a lifespan of a week or so. The spatial and temporal features of the ZNPO pattern and its climate impact are examined systematically. In particular, the formation, maintenance, and decay mechanisms of the ZNPO pattern are examined from the perspective of energetics.

2. Data and methodology

2.1. Data sets

This study uses daily (0000UTC) data from the Japanese 55 year Reanalysis (JRA-55) (Ebita *et al* 2011, Kobayashi *et al* 2015) for winters (December–February, DJF) from 1958 to 2018. The National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay *et al* 1996) has been used to study the ZNPO pattern-related circulations, while sea ice data from both the JRA-55 and European Center for Medium-Range Weather Forecasts interim daily reanalysis data set (ERA-Interim) have also been used to study the ZNPO pattern’s influence on sea ice cover over the North Pacific. The results are not sensitive

to the data sets, and in this manuscript, we report the results with JRA-55 reanalysis only. To examine the modulation of the ZNPO patterns by ENSO, we use the monthly (1958–2018) extended Reconstructed Sea Surface Temperature version 4 (ERSST.v4) data (Huang *et al* 2015, Liu *et al* 2015, Huang *et al* 2016). The ENSO phases are defined based on the ERSST.v4 ST anomalies in the Nino-3.4 region (5°N–5°S, 170°–120°W). For El Niño (La Niña) winters, the winter mean Nino-3.4 index must surpass the +0.5°C (−0.5°C) threshold. Based on this threshold, there are 21 El Niño winters, 19 La Niña winters and 20 ENSO-neutral winters in total, as shown in table S1 (available online at stacks.iop.org/ERL/16/074007/mmedia). This study also uses daily SST anomalies which are constructed from linear interpolation of the monthly ERSST.v4 data.

Anomalies for daily variables at each grid point are derived by removing the long-term mean seasonal cycle from the data. The long-term mean seasonal cycle is defined as the 60 winter mean value for each calendar day. Apart from the removal of the seasonal cycle, the data are not filtered in any other way in the analyses.

2.2. Composite analysis

To examine the formation features and associated climate impact of the ZNPO pattern, lagged-composite analysis is performed based on the ZNPO events of large amplitude. A positive (negative) ZNPO event is defined as when the ZNPO index reaches 1.0 (−1.0) standard deviations and subsequently stays above (below) that threshold for at least four consecutive days. The day of the peak ZNPO index is denoted as day 0. Taking the lifespan of the ZNPO pattern into consideration (about one week, see the next section), two ZNPO events of the same phase must be at least 15 days apart. Otherwise, the weaker event is discarded. Based on the above criteria, we obtain 73 positive and 79 negative ZNPO events in total from the 60 winters in 1958–2018.

2.3. Statistics

In most cases, the statistical significance of lagged-composites is assessed with a Monte Carlo simulation with 1000 randomly generated composites, while the Student’s *t*-test is used to evaluate the statistical significance for linear regressions with the number of effective degrees of freedom N_{eff} calculated by following Kosaka *et al* (2012), with the formula:

$$N_{\text{eff}} = \frac{N}{1 + 2 \sum_{\tau=1}^{\tau_{\text{max}}} \left(1 - \frac{\tau}{N}\right) [r_x(\tau) r_y(\tau)]}.$$

Here, N is the length of time series x and y , and r_x and r_y are the autocorrelation functions for x and y , respectively, with a lag of τ days. The maximum lag τ_{max} is set to be the maximum number that does not exceed $N/2$.

2.4. Budget analysis of energetics

To understand the dynamics of the formation and maintenance of the ZNPO pattern, day-to-day kinetic energy (KE) and available potential energy (APE) balances of the NPO pattern are analyzed. The KE equation used in this study takes the form:

$$\frac{\partial \text{KE}}{\partial t} = -\nabla \cdot \left(\overline{\overline{VKE}} \right) - \nabla \cdot \left(\overrightarrow{v'_l \varphi'_l} \right) + \text{CK}_{\text{EP}} + \text{CK}_{\text{B}} + \text{CK}_{\text{E}} + \text{CK}_{\text{F}}. \quad (1)$$

The term on the lhs of equation (1) is the KE tendency. The first two terms on the rhs of equation (1) are the horizontal convergence of the KE flux associated with the climatological-mean flow and geopotential height flux associated with ageostrophic flow, respectively. The terms CK_{EP} , CK_{B} , CK_{E} and CK_{F} are the KE-APE conversion, barotropic energy conversion, feedback forcing by transient eddies and damping by turbulent eddies, respectively.

The APE equation used is of the form:

$$\frac{\partial \text{APE}}{\partial t} = -\nabla \cdot \left(\overline{\overline{VAPE}} \right) + \text{CP}_{\text{B}} + \text{CP}_{\text{E}} - \text{CK}_{\text{EP}} + \text{CP}_{\text{Q}}. \quad (2)$$

The term on the lhs of equation (2) is the APE tendency. The first term on the rhs of equation (2) is the horizontal convergence of the APE flux associated with the climatological-mean flow. The terms CP_{B} , CP_{E} , $-\text{CK}_{\text{EP}}$ and CP_{Q} are the baroclinic energy conversion, APE gain due to transient eddy heat flux, KE-APE conversion with a minus sign and the APE generation by anomalous diabatic heating, respectively.

For KE (APE) conversion/generation terms, positive (negative) values indicate KE (APE) gain (loss) for the ZNPO pattern. The detail of the formula for each term in the KE and APE equations is given in the supplementary material.

3. Results

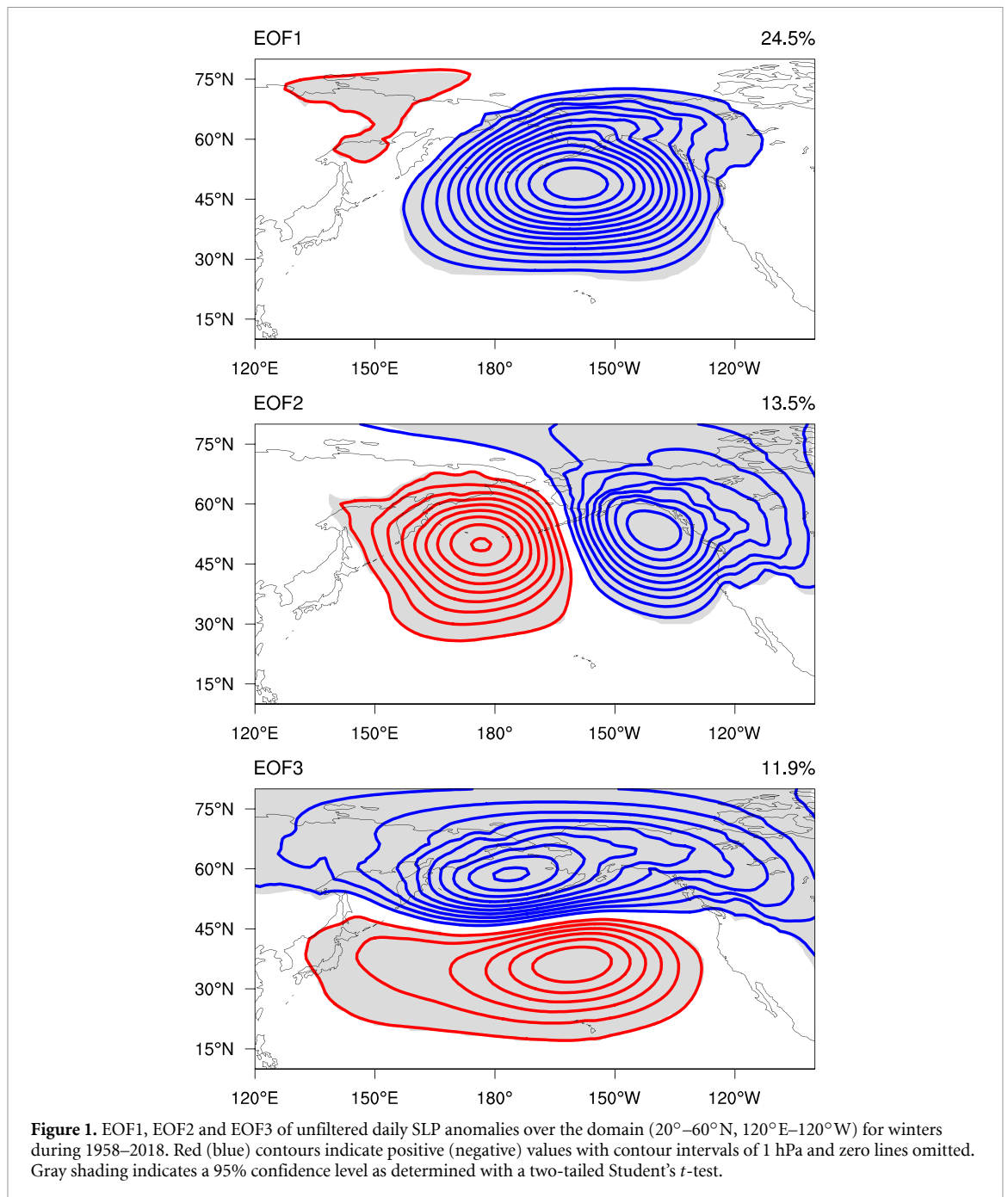
3.1. Definition and spatial-temporal features of the ZNPO pattern

To detect the wintertime (December to February) North Pacific teleconnection patterns on a sub-seasonal timescale, we apply Empirical Orthogonal Function (EOF) analysis to unfiltered daily Sea Level Pressure (SLP) anomalies over the domain (20° – 60° N, 120° E– 120° W). Shown in figure 1 are the first, second and third EOFs, which are well separated by the criterion by North *et al* (1982) and explain 24.5%, 13.5% and 11.9% of the total daily variance, respectively. The first EOF is a monopole centered south of the Aleutian Islands describing an intensity oscillation of the Aleutian Low. This is a surface feature of the well-known PNA pattern (Wallace and

Gutzler 1981). The third EOF is a meridional dipole describing an SLP oscillation between the northern and southern North Pacific, and is the NPO pattern (Walker and Bliss 1932) or surface feature of the WP pattern (Linkin and Nigam 2008). The second EOF of the daily SLP anomalies, shown in figure 1, is a zonal dipole with two extrema located over the eastern and western North Pacific, respectively. This EOF was previously unknown and is termed the ‘ZNPO’ pattern hereafter in the sense that it describes an SLP oscillation between the eastern and western North Pacific. This is in obvious contrast to the well-known NPO pattern that describes an SLP oscillation between the northern and southern North Pacific. In this study, the standardized daily principal components of the second EOF are defined as the ZNPO index, with the positive phase of the ZNPO pattern referring to a positive SLP anomaly over the western North Pacific.

Further inspection of the height anomalies in the pressure-longitude cross-section along 50° N (figure 2(a)) indicates that the two Pacific centers of the ZNPO pattern are deep in the vertical direction, extending from the surface to the lower stratosphere. In addition to the two Pacific centers, the ZNPO pattern has a third center located over North America (figure 2(a)). Obviously, the North American center is weaker in intensity than the two Pacific centers and remains its main body at higher levels, not extending to the surface. One remarkable feature of the ZNPO pattern is the westward phase tilt of the three centers with height, with the most significant tilt being observed from the lower to middle troposphere (figure 2(a)). The phase of the western Pacific center also simultaneously tilts southwards in the troposphere (figure 2(b)), while the other two centers of the ZNPO pattern have no obvious phase tilt, neither northwards nor southwards (figures 2(c) and (d)). Westward and/or southward phase tilt of the ZNPO centers suggests a baroclinic energy conversion from the climatological mean flow to the ZNPO pattern, as will soon be seen. A similar situation also occurs with the winter WP pattern where the two centers of the WP pattern tilt in phase southwards and westwards with height, and the baroclinic energy conversion is a major APE source for the maintenance of the pattern (Tanaka *et al* 2016).

To determine the dominant timescale of the ZNPO pattern, a power spectrum analysis is applied to the ZNPO index shown in figure S1(a) of the supplementary material. From figure S1(a), it is clear that the spectrum reveals a prominent peak at the intraseasonal timescale at 2–20 days. This suggests that the ZNPO pattern mainly consists of both high-frequency eddies with periods of 2–10 days and low-frequency eddies of intermediate timescale with periods of 10–20 days. Previous studies indicate that teleconnection patterns of intermediate



timescale of 10–30 days usually take the form of zonally orientated wavetrains along preferred wave guides (Blackmon *et al* 1984). This is the case for the ZNPO pattern, the three centers of which also run zonally along the Pacific jet and its downstream region.

The autocorrelations of the ZNPO index indicate that the ZNPO pattern has an e-folding timescale of three days or so (figure S1(b)). This suggests that the ZNPO pattern has a lifespan of one week or so. In contrast, the autocorrelations of the time series of the EOF1 and EOF3 of SLP anomalies corresponding to figure 1 indicate that PNA and WP patterns have an e-folding timescale of five days, implying that the subseasonal PNA and WP patterns have a lifespan

of ten days, somewhat longer than that of the ZNPO pattern.

3.2. Evolutionary features

To see how the ZNPO pattern forms, we now examine the lagged-composites of anomalous 250 and 500 hPa geopotential height (Z250 and Z500), and anomalous sea-level pressure based on the ZNPO events (figure 3, contours). The arrows in figure 3 (left two columns) are the wave activity fluxes that indicate the direction of energy propagation of the wave train (Plumb 1985, Karoly *et al* 1989). Since only some minor asymmetries are observed between the positive and negative ZNPO patterns, we will mainly report the results for the positive ZNPO pattern.

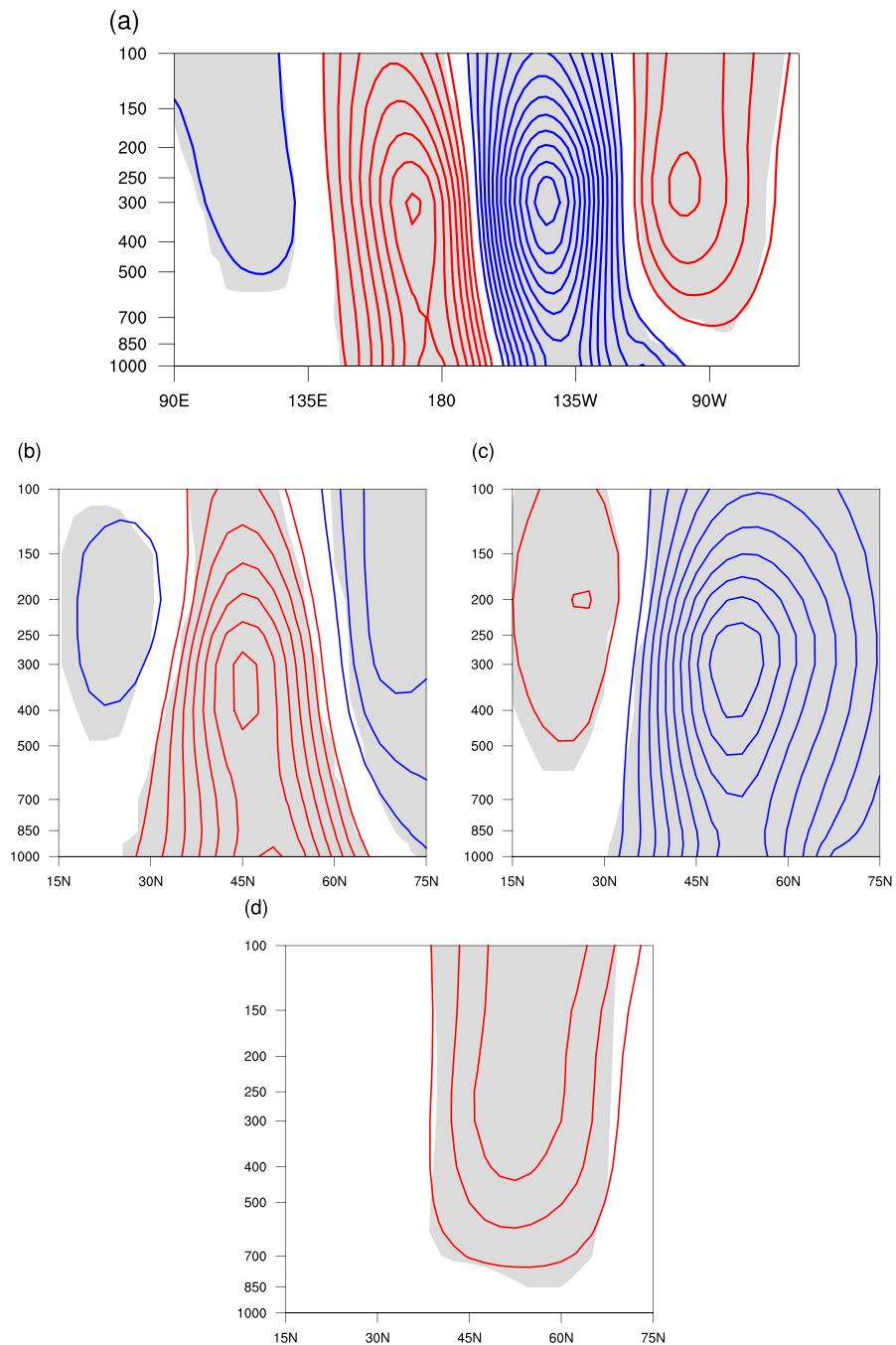
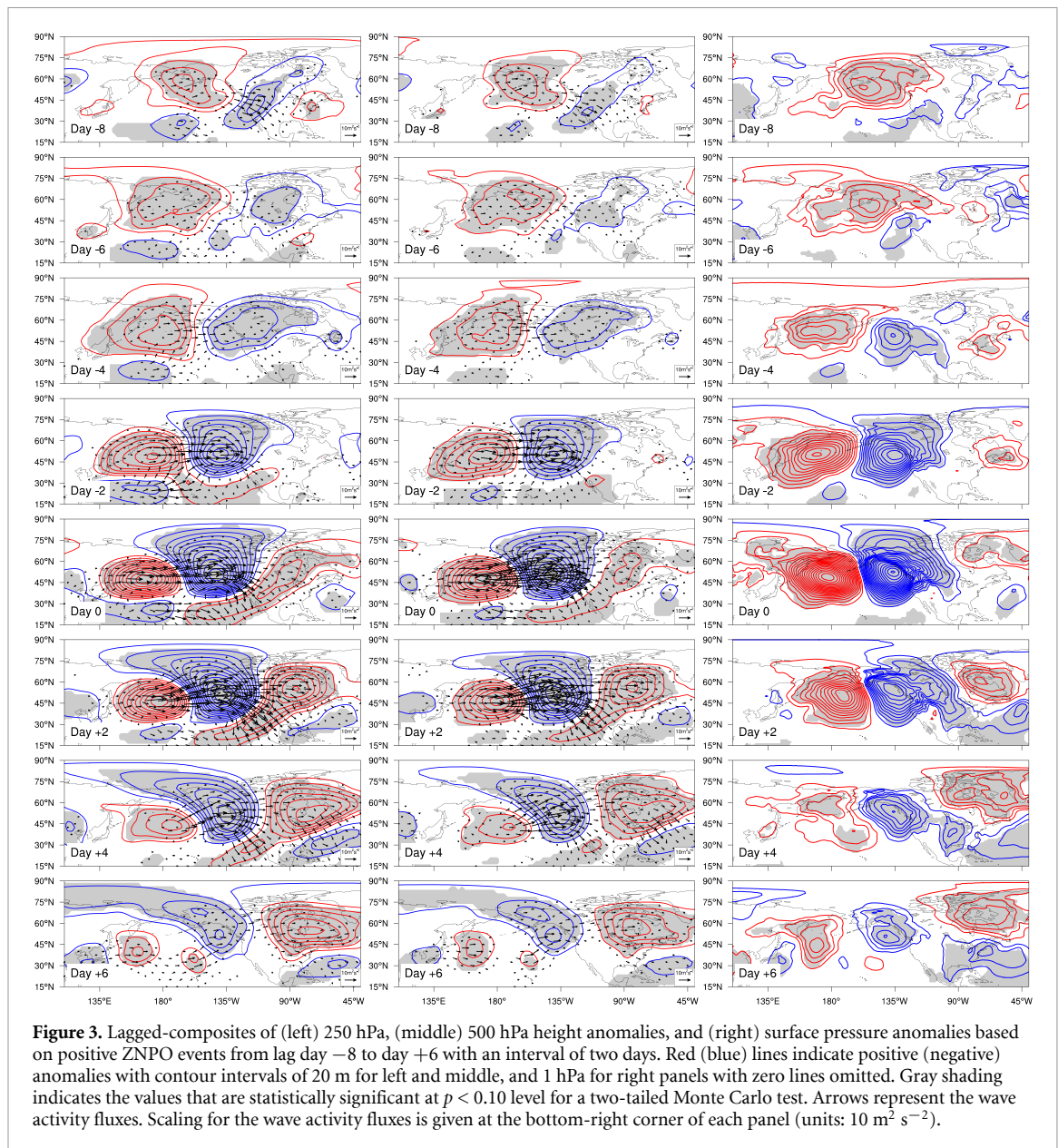


Figure 2. (a) Height-longitude cross-section regressions of height anomalies for 50°N against the ZNPO index. (b)–(d) Same as (a) but for height-latitude cross-section regressions of height anomalies for 180°E , 135°W and 90°W , respectively. Red (blue) contours indicate positive (negative) values with contour intervals of 1 hPa and 10 m, and zero lines omitted. Gray shading indicates a 95% confidence level as determined with a two-tailed Student's t -test.

As one can see, the ZNPO pattern arises from two weak westward moving height disturbances of opposite signs over the northern North Pacific and North America (figure 3, day -8 to day -6). The two disturbances observed in the whole troposphere with the Pacific center are considerably stronger than the North American center. Around day -4 , the two disturbances move to the western and eastern Pacific, respectively, and a perfect ZNPO pattern thus forms. The ZNPO pattern matures on day 0, and begins to decay afterwards with apparent downstream energy

dispersion. A new height anomaly forms over North America just downstream from the ZNPO pattern, and then another new height anomaly forms just downstream from the newly formed North American anomaly over the ocean near the southwestern US coast. The North American anomaly is huge, extending from northeastern North America southwestwards into the eastern tropical North Pacific, with its main body over northeastern North America reaching the surface. The North American anomaly may persist for more than a week. Together with the



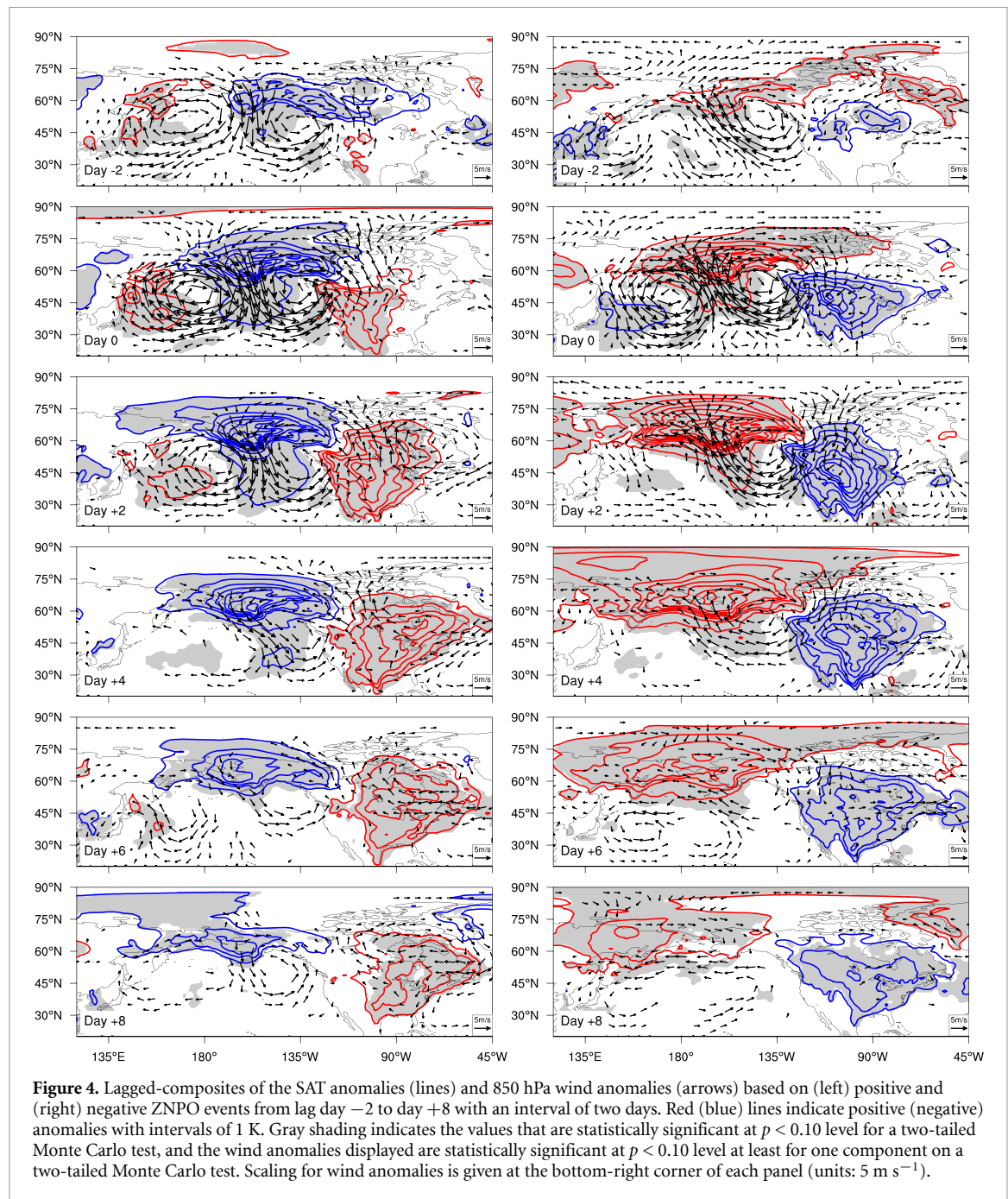
eastern Pacific center of the ZNPO pattern, the American anomaly brings severe weather episodes to North America, as will be seen below.

3.3. Weather and hydroclimate impacts

In the lower-tropospheric wind field over the North Pacific/North American sector, the ZNPO pattern manifests itself as a strong anomalous cyclone–anticyclone pair, as shown in figure 4. For a positive ZNPO pattern (figure 4 left), strong anomalous northerlies blow directly from the Arctic into the northern North Pacific, which causes a rapid surface air temperature (SAT) drop over the northern North Pacific and surrounding regions (figure 4 left, from days -2 to $+8$). Concurrently, strong southwesterlies bring warm air from the Pacific into the North American continent, causing a rapid SAT rise over North America. The strongest SAT anomalies occur on day $+2$ with the lowest SAT drop of near -9°C being

observed over the Bering Sea Strait and the largest SAT rise of about $+6^\circ \text{C}$ being observed over central North America. Clearly, the easterlies blowing from the Atlantic towards the North American continent also contribute to the SAT rise over North America (figure 4 left, days $+2$ to $+8$). The SAT anomalies for negative ZNPO events (figure 4 right) assume similar structure and evolutionary features as positive ZNPO events except with opposite sign. One significant difference is that the SAT anomaly over the northern North Pacific extends further westward and southward into northeastern Asia for negative rather than positive ZNPO events.

The dipole-like SAT anomaly appears as the leading EOF of the daily SAT anomaly over the North Pacific/North American sector (figure 5(a)). The PNA pattern and ZNPO pattern are closely correlated with this dipole-like SAT anomaly, with the highest correlation of 0.45 being observed on day $+2$ for the



ZNPO pattern and of 0.35 on day $+4$ for the PNA pattern. This suggests that both PNA and ZNPO patterns make important contributions to the formation of the SAT dipole, while the contribution of the WP pattern is relatively weak (figure 5(b)). Lin (2015) once examined the subseasonal variability of SAT anomalies over North America and found that SAT anomalies over the North Pacific and North America take the form of a dipole, similar to ours. However, Lin (2015) attributed the formation of the SAT dipole only to the PNA pattern and failed to identify the contribution of the ZNPO pattern.

Concurrent with the variation of SAT over the northern North Pacific, a significant change in sea ice cover also occurs over the northeastern Bering Sea, as

shown in figure 6. An increase in sea ice cover occurs from day $+3$ to around day $+25$ for positive ZNPO pattern and a decrease in sea ice cover occurs from day $+3$ to day $+15$ for negative ZNPO pattern. It should be noted that a week longer persistence of sea ice cover anomaly for positive than negative ZNPO patterns may be due to the thermal inertia of the ice. Clearly, a significant sea ice cover anomaly over the Bering Sea occurs around day $+3$, while significant SAT anomaly occurs around day -2 , about five days earlier than the sea ice cover anomaly. This suggests that the sea ice cover change may be in response to the ZNPO-associated strong anomalous northerlies and cold/warm advection of air temperature by the strong anomalous northerlies (southerlies) (figure 4).

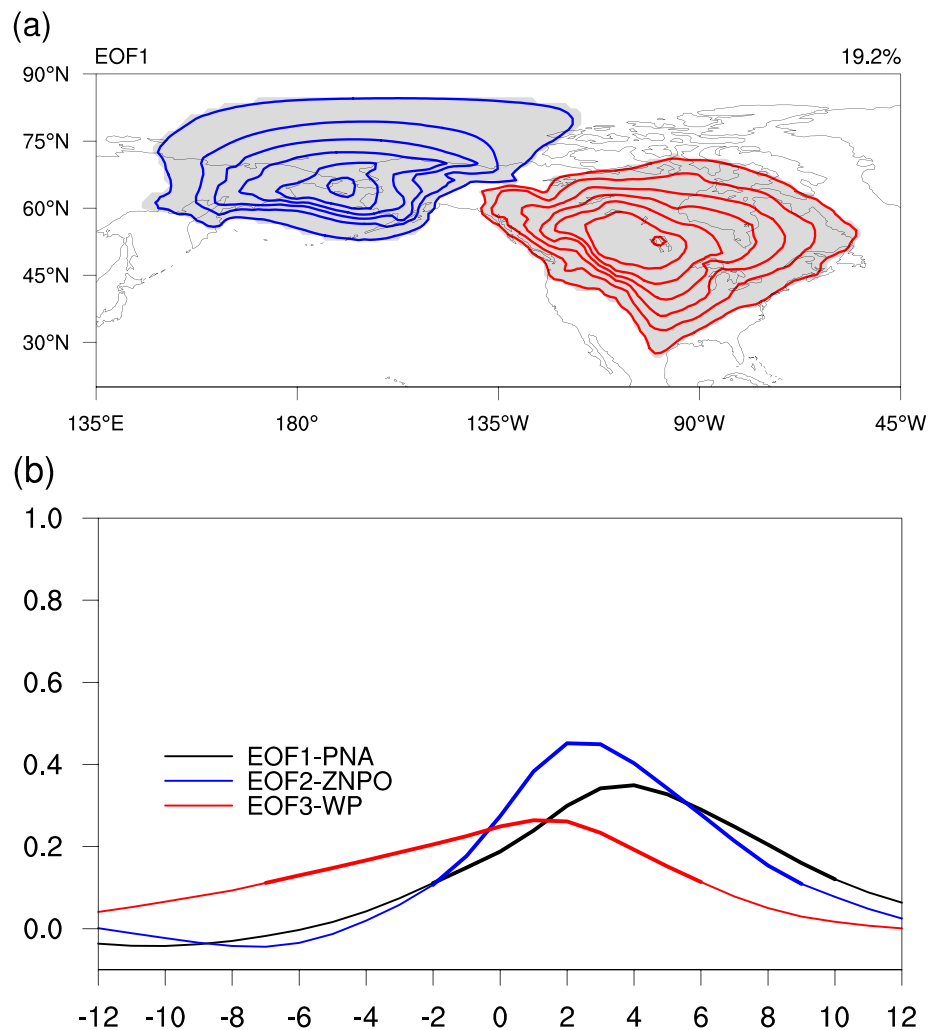
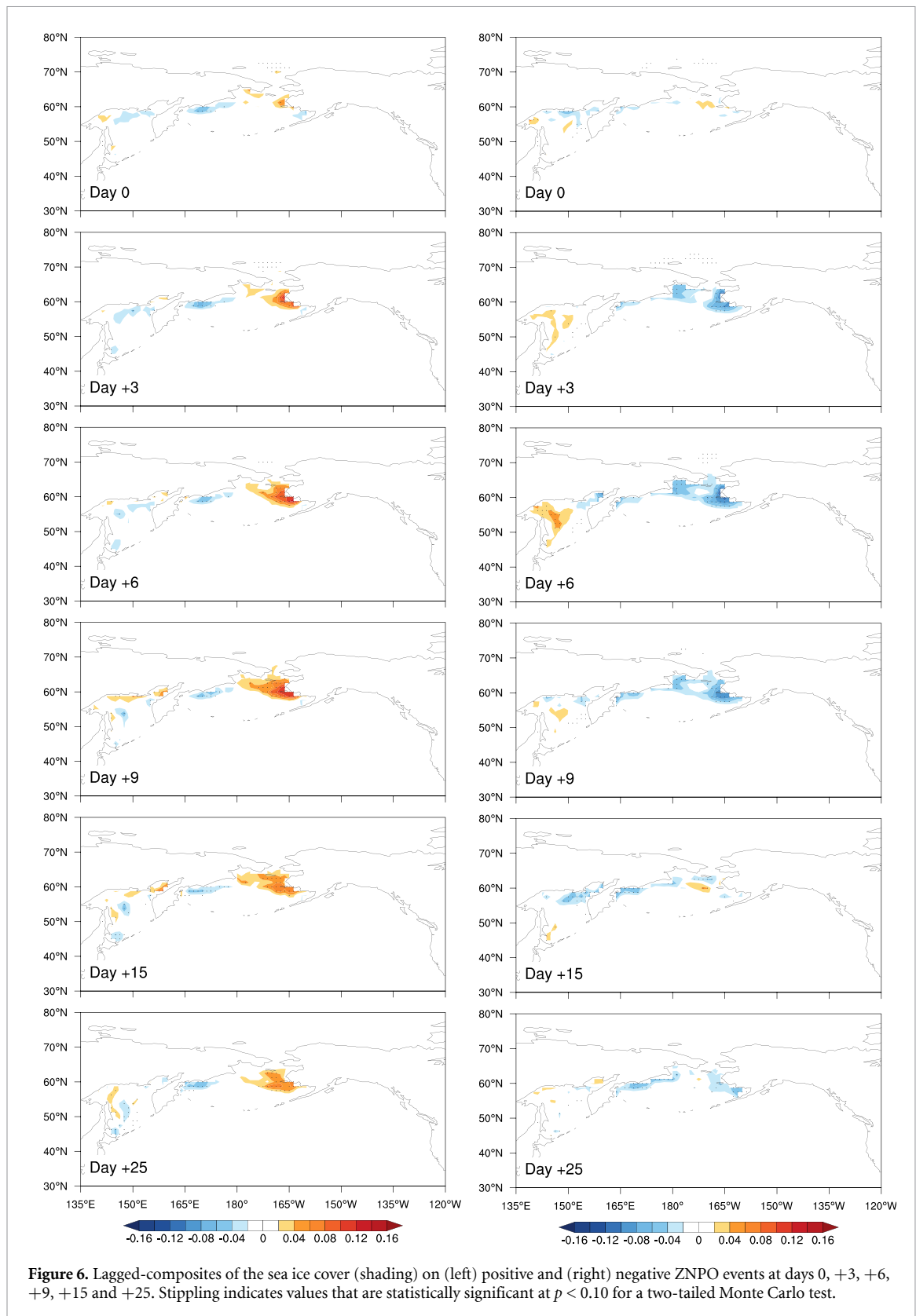


Figure 5. (a) EOF1 of unfiltered daily SAT anomalies over the domain (20°–75°N, 180°–45°W) for winters during 1959–2018. Red (blue) contours indicate positive (negative) values with contour intervals of 1 K and zero lines omitted. Gray shading indicates a 95% confidence level as determined with a two-tailed Student's *t*-test. (b) Lagged correlation between SAT-EOF1 and SLP EOFs and positive lags indicate SLP leading SAT. Bold lines indicate a 99% confidence level as determined with a two-tailed Student's *t*-test.

Displayed in figure S2 is the regressed pattern of SST onto the daily ZNPO index. In addition to the weak SST anomalies over the eastern, western and tropical North Pacific, a long band of positive SST anomaly occurs over the central/eastern equatorial Pacific, implying a possible ZNPO-equatorial SST link. Further calculation indicates that the ZNPO pattern is correlated with ENSO (the Niño-3.4 index) on an interannual timescale ($r = 0.37$, calculated by taking a DJF average, significant at the $p < 0.01$ confidence level), and the frequency of occurrence of ZNPO events is significantly modulated by ENSO, as shown in table S1 of the supplementary material. Positive ZNPO events tend to occur more often during El Niño winters (1.57 events per winter), and less often during La Niña winters (0.95 events per winter), with respect to the climatology (1.22 events per winter), while negative ZNPO events tend to occur more often during ENSO-neutral winters (1.65 events per

winter) with respect to its climatology (1.32 events per winter).

At the same time, the ZNPO pattern-associated anomalous cyclone/anticyclone pair may also heavily influence the convective activity over the midlatitude North Pacific (figure 7). As indicated by the anomalous convective heating rates, the convective anomaly also takes the form of a dipole-like structure with its two extrema overlapped with the two centers of action of the ZNPO pattern (figure 7). The convection is significantly enhanced in the southern region of the anomalous cyclone, while it is significantly reduced in the southern region of the anomalous anticyclone. Further inspection shows that the anomalous convective heating rates are restricted to be mainly within the lower troposphere, with maximum convective heating rate anomalies occurring at around the 850 hPa level. This type of convection is termed 'shallow convection' (Minobe *et al* 2010),



which is frequently observed over the mid-latitude North Pacific during winter (Ling and Zhang 2013) and spring (Zhuge and Tan 2021).

Shown in figure S3 are the anomalous total column precipitation (including convective precipitation and large-scale condensation precipitation)

anomalies (shading) and total column water vapor flux anomaly (arrows). We observe that positive total column precipitation anomalies are observed over the eastern and western North Pacific, respectively, which are closely coupled to the ZNPO-associated anomalous total water vapor flux convergence over

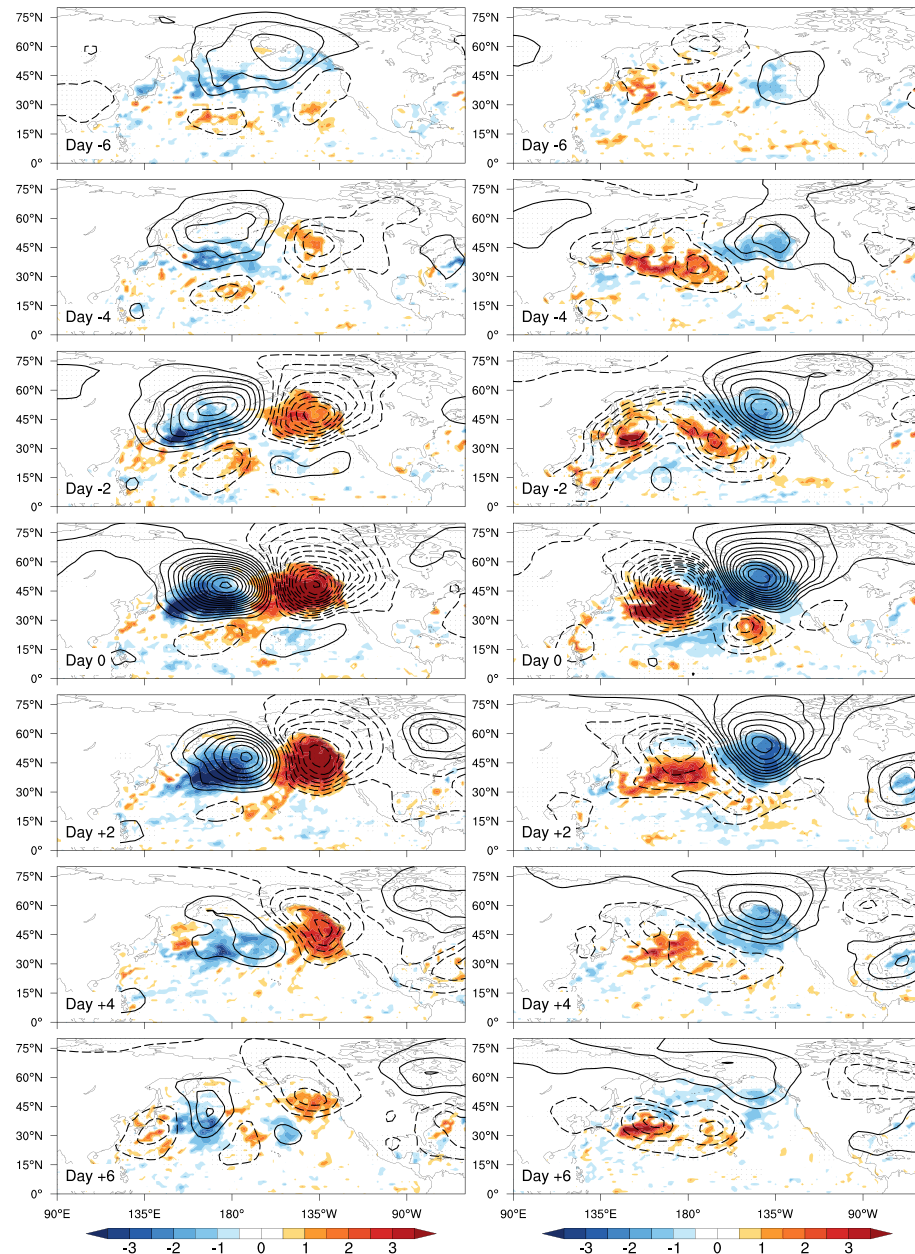


Figure 7. Lagged-composites of anomalous 850 hPa convective heating rate (shading, K d^{-1}) and eddy streamfunction (contour) for (left) positive and (right) negative ZNPO events from lag day -6 to day $+6$ with an interval of two days. Warming (cold) shadings indicate positive (negative) values. Solid (dashed) lines indicate positive (negative) anomalies with contour intervals of $10^6 \text{ m}^2 \text{ s}^{-2}$ and zero lines omitted. Stippling indicates eddy streamfunction anomalies that are statistically significant at $p < 0.10$ for a two-tailed Monte Carlo test. Only significant convective heating rate anomalies are plotted.

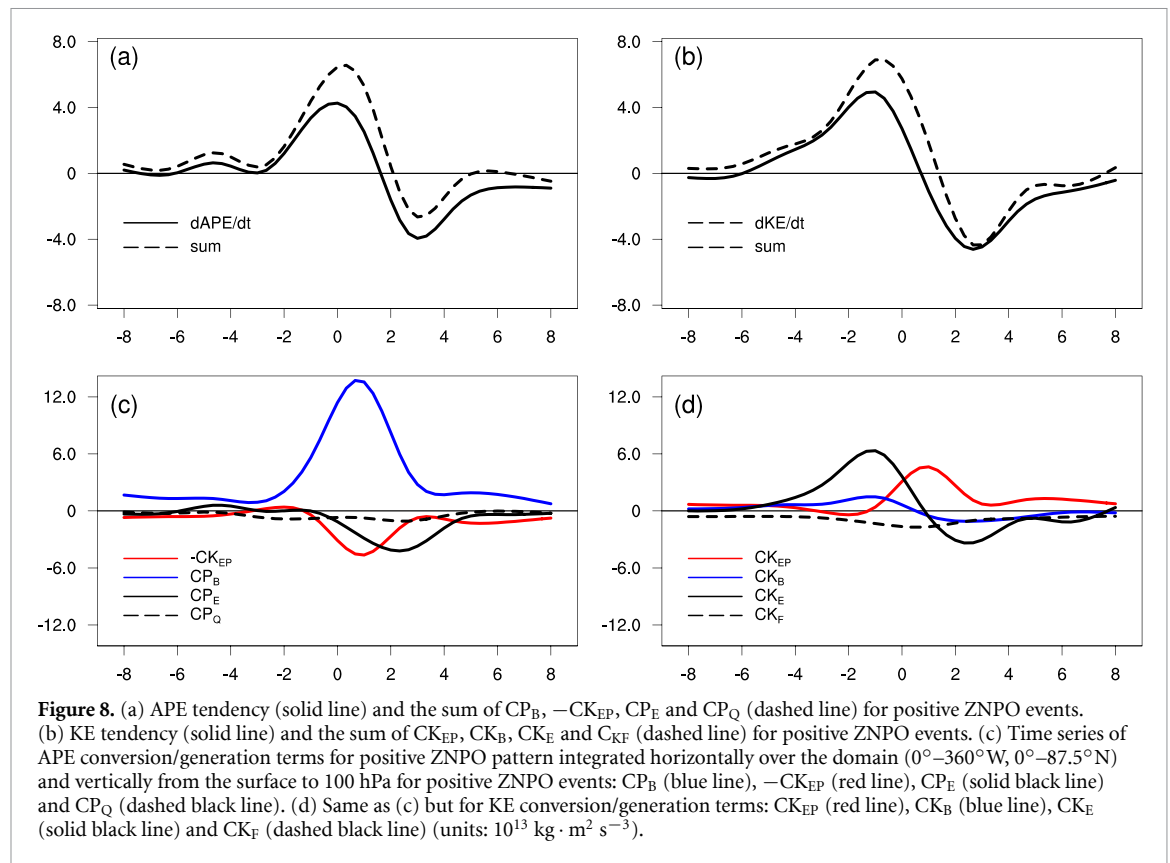
the regions. At the same time, negative total column precipitation of a large area is observed over the central North Pacific where an anomalous total water vapor flux divergence is observed.

3.4. Energetics

To better understand the growth of and mechanisms that maintain the ZNPO pattern, the day-to-day APE and KE balances of the ZNPO pattern are analyzed. To this end, the tendency of APE (KE) and each of the APE (KE) conversion/generation terms are estimated using the composited anomalies, similar to Tanaka *et al* (2016). Then, they are integrated horizontally

over the domain (0° – 360°W , 0° – 87.5°N) and vertically from the surface to 100 hPa. Since the asymmetry between positive and negative ZNPO events is only minor, here we report the results for positive ZNPO events only.

Figures 8(a) and (b) indicate that the sum of the APE (KE) conversion terms is overall consistent with APE (KE) tendency, suggesting that the energy budgets can reasonably capture the essential dynamics governing the evolution of the ZNPO pattern. For the APE conversion/generation (figure 8(c)), the baroclinic energy conversion from the climatological mean flow (CP_B , blue line), is always positive and acts



as the APE source. From days -8 to -2 , the CP_B term remains a relatively weak value, then increases sharply and peaks on day $+1$. It then decreases rapidly till day $+3$, and then remains a relatively weak positive value again till day $+8$. This implies that the most efficient baroclinic energy conversion takes place for the period from day -2 to day $+3$. This is the key period when the ZNPO pattern becomes strongest in its lifespan. The APE-KE conversion term ($-CK_{EP}$, red line) varies with time in a similar way to CP_B , but with opposite sign and considerably smaller value. This suggests that part of CP_B converts into KE through the rising of warm air and sinking of cool air to drive the ZNPO pattern. The APE generation by total transient eddies (CP_E , solid black line) is basically weak except for the period from day 0 to day $+5$ when CP_E is negative and large in value. This suggests that APE conversion by transient eddies acts as an APE sink to heavily damp the ZNPO pattern after the ZNPO pattern matures. Apparently, the APE generation by diabatic heating (CP_Q , dashed black line) is negative and weak, implying that the diabatic heating, contributed mainly by convective heating and large-scale condensation, acts as a weak APE sink.

For KE conversion/generation (figure 8(d)), the most efficient KE conversion from APE conversion (CK_{EP} , red line) takes place for the period from day -1 to day $+3$. This suggests that the CK_{EP} term acts as an important KE source to maintain the ZNPO pattern for this period of time. Clearly, the feedback forcing by transient eddies (CK_E , black line) acts as a

major KE source to support the rapid growth of the ZNPO pattern before day $+1$, and acts as a major KE sink to heavily damp the ZNPO pattern after day $+1$. As one can see, the barotropic conversion (CK_B , blue line) contributes only weak positive KE before day $+1$ and weak negative KE after day $+1$. As expected, the friction term (CK_F , dashed black line) always acts as a KE sink to damp the ZNPO pattern.

It turns out that strong positive and negative CP_B maxima occur mainly in the middle and lower troposphere from day -2 to day $+4$ along the background Pacific jet and downstream region where the baroclinicity is strongest in the lifespan of the ZNPO pattern. The positive and negative CP_B centers occur alternatively in the form of a wavetrain with the positive centers dominating the negative ones (figure S4). In addition, strong CK_E occurs over the midlatitude North Pacific, mainly in the upper and middle troposphere (figure S5). Apparently, positive CK_E maxima dominate the negative CK_E maxima before day $+1$, and the reverse is true after day $+1$.

4. Discussion

In this study, a new atmospheric teleconnection pattern, the ZNPO pattern, is detected based on reanalysis data. The ZNPO pattern describes a large-scale mass oscillation in the troposphere between the eastern and western North Pacific and a strong large-scale SAT oscillation between the northern North Pacific and North America, which persist for about eight

days. This SAT oscillation, as a leading EOF mode of daily SAT anomalies, brings severe weather episodes to the northern North Pacific and North America, with maximum SAT drop reaching as low as -9°C and maximum SAT rise as high as $+6^{\circ}\text{C}$. The ZNPO pattern can also significantly influence the sea ice cover over the Bering Sea. The sea ice cover is significantly increased over the northeastern Bering Sea for positive ZNPO pattern, and the reverse is true for negative ZNPO pattern. In addition, the convective activity is obviously influenced by the ZNPO pattern. Convection is enhanced over the western North Pacific and reduced over the eastern North Pacific for positive ZNPO pattern, and the reverse is true for negative ZNPO pattern. This suggests that the ZNPO pattern is one of the most important atmospheric teleconnection patterns one should take into account when making weather and hydroclimate predictions for the North Pacific and North America.

The energetics analysis indicates that the ZNPO pattern is an internal atmospheric mode arising from two disturbances over the northern North Pacific and North America and driven mainly by the baroclinic energy conversion from the climatological mean flow and barotropic feedback forcing of the transient eddies. The baroclinic energy conversion acts to overcome APE loss caused by the heat flux of transient eddies and acts as a major KE source to maintain the ZNPO pattern. The feedback forcing by transient eddies acts as a major KE source to support the rapid growth and development of the ZNPO pattern and a major KE sink to heavily damp the ZNPO pattern during the decaying stage of the ZNPO pattern. This suggests that to better describe the ZNPO pattern for a numerical model, the background flow, wave-mean flow interaction and interaction between high- and low-frequency eddies should be accurately described first.

This study also indicates that the ZNPO pattern also appears in spring, summer and autumn as the second EOF of unfiltered daily SLP anomalies over the North Pacific (figure S6). In addition, the ZNPO pattern can also appear as the third EOF of monthly mean SLP anomalies for winter, spring, summer and autumn (figure S7) or as the third EOF of winter- or spring-mean SLP anomalies or second EOF of autumn-mean SLP anomalies, but is absent for summer-mean SLP anomalies (figure S8). This suggests that the ZNPO pattern occurs as sub-seasonal, seasonal or interannual variability over the North Pacific. The spatial and temporal features and underlying dynamics of the ZNPO pattern at different timescales and different seasons are topics of great scientific interest for future studies. In particular, this study indicates that ENSO significantly influences the frequency of occurrence of positive ZNPO events. However, the mechanism of ENSO modulation remains unclear and deserves further study.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

B T conceived the study. A Z performed the data analysis and designed the figures. Both authors wrote the manuscript.

Conflict of interest

The authors declare that they have no competing interests.

Data and materials availability

All the data sets used in this study are publically available. The JRA-55 reanalysis data are obtained from <https://rda.ucar.edu/datasets/ds628.0/>. The ERA-interim reanalysis data were obtained from www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim. The NOAA ERSST.v4 data were obtained from <https://psl.noaa.gov/data/gridded/data.noaa.ersst.v4.html>.

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References

- Athanasiadis P J, Wallace J M and Wettstein J J 2010 Patterns of wintertime jet stream variability and their relation to the storm tracks *J. Atmos. Sci.* **67** 1361–81
- Barnston A G and Livezey R E 1987 Classification, seasonality and persistence of low-frequency atmospheric circulation patterns *Mon. Weather Rev.* **115** 1083–126
- Black J, Johnson N C, Baxter S, Feldstein S B, Harnos D S and L'Heureux M L 2017 The predictors and forecast skill of Northern Hemisphere teleconnection patterns for lead times of 3–4 weeks *Mon. Weather Rev.* **145** 2855–77
- Blackmon M L, Lee Y H, Wallace J M and Hsu H H 1984 Time variation of 500 mb height fluctuations with long, intermediate and short time scales as deduced from lag-correlation statistics *J. Atmos. Sci.* **41** 981–91

- Branstator G 2002 Circumglobal teleconnections, the jet stream waveguide, and the North Atlantic Oscillation *J. Clim.* **15** 1893–910
- Chu J E, Timmermann A and Lee J Y 2019 North American April tornado occurrences linked to global sea surface temperature anomalies *Sci. Adv.* **5** eaaw9950
- Dai Y, Feldstein S B, Tan B and Lee S 2017 Formation mechanisms of the Pacific–North American teleconnection with and without its canonical tropical convection pattern *J. Clim.* **30** 3139–55
- Dai Y and Tan B 2019a Two types of the western Pacific pattern, their climate impacts, and the ENSO modulations *J. Clim.* **32** 823–41
- Dai Y and Tan B 2019b On the role of the eastern Pacific teleconnection in ENSO impacts on wintertime weather over East Asia and North America *J. Clim.* **32** 1217–34
- Derome J, Brunet G, Plante A, Gagnon N, Boer G J, Zwiers F W, Lambert S J, Sheng J and Ritchie H 2001 Seasonal predictions based on two dynamical models *Atmos.–Ocean* **39** 485–501
- Ding Q and Wang B 2005 Circumglobal teleconnection in the Northern Hemisphere summer *J. Clim.* **18** 3483–505
- Ebita A *et al* 2011 The Japanese 55 year reanalysis 'JRA-55': an interim report *Sci. Online Lett. Atmos.* **7** 149–52
- Enomoto T 2004 Interannual variability of the Bonin high associated with the propagation of Rossby waves along the Asian jet *J. Meteorol. Soc. Jpn.* **82** 1019–34
- Feldstein S B 2002 Fundamental mechanisms of the growth and decay of the PNA teleconnection pattern *Q. J. R. Meteorol. Soc.* **128** 775–96
- Franzke C and Feldstein S B 2005 The continuum and dynamics of Northern Hemisphere teleconnection patterns *J. Atmos. Sci.* **62** 3250–67
- Franzke C, Feldstein S B and Lee S 2011 Synoptic analysis of the Pacific–North American teleconnection pattern *Q. J. R. Meteorol. Soc.* **137** 329–46
- Horel J D 1981 A rotated principal component analysis of the interannual variability of the Northern Hemisphere 500 mb height field *Mon. Weather Rev.* **109** 2080–92
- Hoskins B J and Karoly D J 1981 The steady linear response of a spherical atmosphere to thermal and orographic forcing *J. Atmos. Sci.* **38** 1179–96
- Huang B *et al* 2015 Extended Reconstructed Sea Surface Temperature version 4 (ERSST.v4). Part I: upgrades and intercomparisons *J. Clim.* **28** 911–30
- Huang B, Thorne P W, Smith T M, Liu W, Lawrimore J, Banzon V F, Zhang H-M, Peterson T C and Menne M 2016 Further exploring and quantifying uncertainties for Extended Reconstructed Sea Surface Temperature (ERSST) version 4 (v4) *J. Clim.* **29** 3119–42
- Johnson N C and Feldstein S B 2010 The continuum of North Pacific sea level pressure patterns: intraseasonal, interannual, and interdecadal variability *J. Clim.* **23** 851–67
- Kalnay E *et al* 1996 The NCEP/NCAR 40 year reanalysis project *Bull. Am. Meteorol. Soc.* **77** 437–71
- Karoly D J, Plumb R A and Ting M 1989 Examples of the horizontal propagation of quasi-stationary waves *J. Atmos. Sci.* **46** 2802–11
- Kobayashi S *et al* 2015 The JRA-55 reanalysis: general specifications and basic characteristics *J. Meteorol. Soc. Jpn.* **93** 5–48
- Kosaka Y, Chowdary J S, Xie S P, Min Y M and Lee J Y 2012 Limitations of seasonal predictability for summer climate over East Asia and the northwestern Pacific *J. Clim.* **25** 7574–89
- Kumar A, Hoelling M, Ji M, Leetmaa A and Sardeshmukh P 1996 Assessing a GCM's suitability for making seasonal predictions *J. Clim.* **9** 115–29
- Lau K-M and Weng H 2002 Recurrent teleconnection patterns linking summertime precipitation variability over East Asia and North America *J. Meteorol. Soc. Jpn.* **80** 1309–24
- Lin H 2015 Subseasonal variability of North American wintertime surface air temperature *Clim. Dyn.* **45** 1137–55
- Ling J and Zhang C 2013 Diabatic heating profiles in recent global reanalysis *J. Clim.* **26** 3307–25
- Linkin M E and Nigam S 2008 The North Pacific Oscillation–west Pacific teleconnection pattern: mature-phase structure and winter impacts *J. Clim.* **21** 1979–97
- Liu W, Huang B, Thorne P W, Banzon V F, Zhang H-M, Freeman E, Lawrimore J, Peterson T C, Smith T M and Woodruff S D 2015 Extended Reconstructed Sea Surface Temperature version 4 (ERSST.v4). Part II: parametric and structural uncertainty estimations *J. Clim.* **28** 931–51
- Lu R, Oh J and Kim B-J 2002 A teleconnection pattern in upper-level meridional wind over the North African and Eurasian continent in summer *Tellus A* **54** 44–55
- Minobe S, Miyashita M, Kuwano-Yoshida A, Tokinaga H and Xie S-P 2010 Atmospheric response to the Gulf Stream: seasonal variations *J. Clim.* **23** 3699–719
- Mo K C, Fyfe J and Derome J 1998 Phase-locked and asymmetric correlations of the wintertime atmospheric patterns with the ENSO *Atmos.–Ocean* **36** 213–39
- Mori M and Watanabe M 2008 The growth and triggering mechanisms of the PNA: a MJO–PNA coherence *J. Meteorol. Soc. Jpn.* **86** 213–36
- North G R, Bell T L, Cahalan R F and Moeng F J 1982 Sampling errors in the estimation of empirical orthogonal functions *Mon. Weather Rev.* **110** 699–706
- Plumb R A 1985 On the three-dimensional propagation of stationary waves *J. Atmos. Sci.* **42** 217–29
- Renwick J A and Wallace J M 1996 Relationships between North Pacific wintertime blocking, El Niño, and the PNA pattern *Mon. Weather Rev.* **124** 2071–6
- Riddle E E, Stoner M B, Johnson N C, L'Heureux M L, Collins D C and Feldstein S B 2013 The impact of the MJO on clusters of wintertime circulation anomalies over the North American region *Clim. Dyn.* **40** 1749–66
- Rivière G 2010 Role of Rossby wave breaking in the west Pacific teleconnection *Geophys. Res. Lett.* **37** L11802
- Rogers J C 1981 The North Pacific Oscillation *J. Climatol.* **1** 39–57
- Shukla J *et al* 2000 Dynamical seasonal prediction *Bull. Am. Meteorol. Soc.* **81** 2593–606
- Straus D M and Shukla J 1997 Variations of midlatitude transient dynamics associated with ENSO *J. Atmos. Sci.* **54** 777–90
- Sung M K, Jang H Y, Kim B M, Yeh S W, Choi Y S and Yoo C 2019 Tropical influence on the North Pacific Oscillation drives winter extremes in North America *Nat. Clim. Change* **9** 413–8
- Tan B, Yuan J, Dai Y, Feldstein S B and Lee S 2015 The linkage between the eastern Pacific teleconnection pattern and convective heating over the tropical western Pacific *J. Clim.* **28** 5783–94
- Tanaka S, Nishii K and Nakamura H 2016 Vertical structure and energetics of the western Pacific teleconnection pattern *J. Clim.* **29** 6597–616
- Walker G T and Bliss E W 1932 World weather V *Mem. R. Meteorol. Soc.* **4** 53–84
- Wallace J M and Gutzler D S 1981 Teleconnections in the geopotential height field during the Northern Hemisphere winter *Mon. Weather Rev.* **109** 784–812
- Xu P, Wang L and Chen W 2019 The British–Baikal corridor: a teleconnection pattern along the summertime polar front jet over Eurasia *J. Clim.* **32** 877–96
- Younas W and Tang Y 2013 PNA predictability at various time scales *J. Clim.* **26** 9090–114
- Yuan J, Tan B, Feldstein S B and Lee S 2015 Wintertime North Pacific teleconnection patterns: seasonal and interannual variability *J. Clim.* **28** 8247–63
- Zhu Z and Li T 2016 A new paradigm for continental U.S. summer rainfall variability: Asia–North America teleconnection *J. Clim.* **29** 7313–27
- Zhugue A and Tan B 2021 The springtime Western Pacific pattern: its formation and maintenance mechanisms and climate impacts *J. Clim.* **34** 4913–36