A new subseasonal atmospheric teleconnection bridging tropical deep convection over the western North Pacific and Antarctic weather

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Abstract
Previous studies indicate that convective heating variability of the western North Pacific summer monsoon (WNPSM) influences strongly weather and climate over East Asia. Based on daily reanalysis data and interpolated outgoing longwave radiation (OLR) data, this study demonstrates that the WNPSM convection can also cause severe weather events remotely over the Antarctic through the exciting of the Australia-South Pacific-Atlantic wave train (ASPA pattern). Surface air temperature (SAT) rises over the Ross Sea-Mawson-Dumont d’Urville Seas sector and over the Weddell Sea, while the SAT drops over the Amundsen–Bellingshausen Seas. Concurrently, sea ice concentration (SIC) is reduced over the Ross Sea and enhanced over the Amundsen–Bellingshausen Seas. The result suggests that the newly found ASPA pattern may serve as an important bridge linking the WNPSM convection and the weather over the Antarctic region.

The dynamics of ASPA’s formation and propagation are also investigated comprehensively. Day-to-day energy budget analysis suggests that after its initiation by WNPSM convection, the ASPA pattern is driven by the baroclinic energy conversion from the climatological flow and nonlinear term. The barotropic energy conversion from the climatological flow contributes to positive KE tendency before day +1 and negative KE tendency after day +1. It is therefore extremely important to improve the representations of the climatological-mean sea ice and jet stream, wave-mean flow interaction and wave-wave interaction in the mid- and high-latitudes of the Southern Hemisphere, as well as the convection over the WNPSM region of the Northern Hemisphere in numerical model for a better weather prediction for the Antarctic.

KEYWORDS
sea ice change, tropical forcing, tropic-Antarctic linkage

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1 | INTRODUCTION

The Indo-western Pacific Warm Pool, which is located in the tropics from the eastern Indian Ocean to western Pacific, is a place where sea surface temperature is highest in the global oceans. Over the Warm Pool, vigorous deep convection occurs frequently and tends to be organized by the Madden-Julian Oscillation (MJO) (Madden & Julian, 1971), the most dominant mode of subseasonal variability in the tropics. The MJO convective heating causes extreme weather/climate events locally and remotely through generation of Rossby wave trains. It has been found that the MJO convection has significant influence on the northern extratropics through modulation of the North Atlantic Oscillation (NAO) and Pacific/North American (PNA) pattern (Cassou, 2008; Mori & Watanabe, 2008; Riddle et al., 2013). Particularly, the global warming has caused significant increase of the MJO amplitude since 1981 due to the twofold expansion of the Warm Pool (Roxy et al., 2019) and an intensified MJO is found to play a role in Arctic amplification (Lee et al., 2011; Yoo et al., 2011) and East Antarctic cooling in boreal winter (Hsu et al., 2021), and Antarctic warming in austral winter (Yoo et al., 2012).

In addition to MJO convection, deep convection tends to be intensified significantly over the western North Pacific of the Warm Pool around the South China Sea/the Philippine Sea in boreal summer where the western North Pacific summer monsoon (WNPSM) prevails. The WNPSM convective heating has significant remote influence on the East Asian summer monsoon variability at various timescales from subseasonal to interannual timescales (Hirota & Takahashi, 2012; Hsu & Lin, 2007 and Kosaka et al., 2011, 2012, among others) through the exciting of a Rossby wave train, i.e. the Pacific-Japan pattern (Gong et al., 2018; Kosaka & Nakamura, 2006, 2010; Nitta, 1987; Sun et al., 2021; Wang et al., 2016; Zhu et al., 2020). At the same time, both observational and numerical studies indicate that the WNPSM diabatic heating can further affect Southern Hemisphere circulation responses at interannual timescale, leading to the establishment of an anomalous high over Australia (Liu & Wang, 2013), and a Rossby wave train propagating from the subtropical eastern Indian Ocean southeastward to the high-latitude South Pacific and then moving north-eastward into South America (Lin, 2009). It is also found that reduced tropical heating over the western North Pacific together with enhanced convective heating over central Pacific south of the equator are closely linked to the Pacific South American mode 2 (PSA 2) of period 40-day (Mo & Higgins, 1998).

It has not been addressed, however, whether and how the convective heating variability of the WNPSM affects remotely climate variability over the Antarctic in austral winter at subseasonal timescale, which is a dominant climate variability for the Antarctic. Here, we elucidate a physical mechanism linking the surface air temperature (SAT) and sea ice concentration (SIC) changes over the Antarctic to the WNPSM convective heating with periods of 7–30 day by analyzing observation data and model results.

2 | DATA AND METHODOLOGY

Daily (0000UTC) geopotential heights, air temperature, horizontal winds, 2-m air temperature and diabatic heating rate used in this study are taken from the Japanese 55-year Reanalysis (JRA-55) (Ebita et al., 2011; Kobayashi et al., 2015) covering 40 austral winters (June–August) from 1979 to 2018. Daily sea ice data from both JRA-55 and European Center for Medium-Range Weather Forecasts interim daily reanalysis data set (ERA-interim) have also been used in this study. The results are not sensitive to the data sets, so we show the results based on ERA-interim data only. Daily interpolated outgoing longwave radiation (OLR) data is provided by the National Oceanic and Atmospheric Administration (Liebmann & Smith, 1996). To obtain the anomalies, the seasonal cycles for all the variables are removed from the raw data. Here, the seasonal cycles are defined as the means of the variables of each calendar day from 1979 to 2018. Apart from the removal of the seasonal cycle, the data are not filtered in any other way in the analyzes.

Both OLR and convective heating rate are used to describe the tropical convection. In order to capture the co-variability between the tropical convection and Southern Hemisphere circulation response, a singular vector decomposition (SVD) analysis is performed with the OLR field over the western North Pacific (110°E–150°E, 10°N–30°N) and 850-hPa geopotential height field (Z850) over the whole Southern Hemisphere (0°–80°S, 0°–360°E). Before the SVD analysis, both the OLR anomalies and Z850 anomalies are weighted by the square root of cosine of latitudes and locally divided by their standard deviations.

To reveal the structures and evolutional features of the convection and associated circulations, linear correlation and regression will be performed. The statistical significance for linear correlation and regression is estimated with the Student’s t-test with the number of effective degrees of freedom $N_{df}$ calculated with the following formula:

$$
N_{df} = \frac{N}{1 + \sum_{i=1}^{r_{max}} (1 - \pi_{i}) [r_{x}(\tau) r_{y}(\tau)]}
$$

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 $\tau$ days. The maximum lag $\tau_{\text{max}}$ is set to be the maximum number that does not exceed $N/2$ (Kosaka et al., 2012).

FIGURE 1 (a) Regression patterns of 850-hPa geopotential height anomalies onto the ASPAI (contour) and OLR anomalies onto the OLRI (shading, unit: W/m$^2$), respectively. Red (blue) contours indicate positive (negative) values with an interval of 10 gpm (zero lines omitted). Letters A–D denote the main anomalous centers of the ASPA pattern. (b) Autocorrelations (left ordinate) of ASPAI (black line) and OLRI (red line) and cross-correlation (right ordinate) between ASPAI and OLRI (blue line, negative days indicating OLR leads the ASPA pattern). Shown in (c) and (d) are the mean power spectra of the ASPAI and OLRI for the period 1979–2018, respectively. Thick segments in (b) denote statistically significant values at the 95% confidence level based on a Student’s $t$ test. Red line in (c) and (d) denotes the Markov red noise spectrum, while the blue line represents the 95% confidence level.

To reveal the mechanisms of the circulation response to the tropical convection, day-to-day budget analysis of kinetic energy (KE) and available potential energy (APE)
3 | RESULTS

3.1 | Spatial and temporal characteristics of the convection and circulation response

Figure 1a shows the leading pair of SVD mode with the OLR pattern (shading) and the 850-hPa geopotential height pattern (contours), which explains 47.8% of the total squared covariance. The OLR field assumes a monopole over the western North Pacific extending from the South China Sea eastward into the Philippines Sea (Figure 1a, shading), which represents anomalous deep convection with the maximum convective heating rate observed at 400 hPa (Figure S1). The 850-hPa circulation response to the convection is a wavenumber-3 pattern extending from the midlatitude South Pacific south of Australia southeastward into the high-latitude South Pacific and then turning into the midlatitude South Atlantic (Australia-South Pacific-South Atlantic pattern, Figure 2).
ASPA pattern hereafter) (Figure 1a), which resembles highly the wave pattern as an interannual variability in Lin (2009). ASPA pattern also resembles the PSA 2 of period of 40-day in structure (Mo & Higgins, 1998) except that the Pacific centers are located at higher latitudes for ASPA pattern. Vertically, ASPA pattern is a deep system with its four anomalous centers (Centers A to D) extending from the surface vertically into lower stratosphere with the maximum amplitude at the upper troposphere (Figure S2).

The standardized expansion coefficients of SVD1 from Z850 and OLR will be used as the ASPA index (ASPAI) and OLR index (OLRI), respectively. The power spectrum analysis of the daily ASPAI and OLRI (Figure 1c,d) indicates that ASPA pattern and OLR anomaly have dominant periods of 7-day to 30-day. The autocorrelations of the daily OLR index and ASPA index (red and black lines, Figure 1b) give the e-folding timescales of 5-day and 6-day for the OLR and ASPA pattern, respectively. This suggests that the convection anomaly and ASPA pattern have lifespans of 10-day to 2-week or so. The cross-correlation of the daily OLR index and ASPA index (blue line, Figure 1b) indicates that the OLR anomaly and ASPA pattern are significantly correlated from day −10 to day +7 with the peak correlation value of 0.26 observed at day −1 (negative lag days indicating the convection leads the height anomalies). This suggests that the convective anomaly may serve as a source to excite ASPA pattern.

It should be noted that the ASPA OLR anomaly studied here differs from the MJO OLR anomaly: The ASPA OLR anomaly is a stationary monopole over the tropical western North Pacific extending from the South China Sea eastward into the Philippine Sea, while the MJO OLR anomaly is an eastward-moving dipole with its two extremes located over the eastern Indian Ocean and western North Pacific, respectively. The ASPA OLR anomaly also differs from the boreal summer intraseasonal oscillation (BSISO) OLR anomaly: The BSISO OLR anomaly assumes a similar structure as the MJO OLR anomaly with an eastward and northward movement (e.g., Kikuchi, 2021; Wang & Xie, 1997).

### 3.2 Formation and energetics features of ASPA pattern

Lagged regressions of the 250-hPa streamfunction anomalies against ASPA index (Figure 2, red and blue contours) indicate that ASPA pattern arises from a dipole-like disturbance straddling Australia (day −10), as the wave activity fluxes indicated (Takaya & Nakamura, 2001). The dipole may be induced by the energy transported along the upper-level climatological northerly winds across the equator from the convection over the western North Pacific as illustrated numerically by Liu and Wang (2013) and Lin (2009). New anomalous centers of alternative signs form one after another as the energy dispersion downstream along the southern branch of the westerly jet (Figure S3), and the full ASPA pattern establishes around day −6. Afterwards, ASPA pattern further intensifies and matures at day 0. Then, it begins to decay (days +2 to +8). Clearly, as an energy source of ASPA pattern, the enhanced convection over the western North Pacific (blue shadings, Figure 2) occurs as early as day-10 and persists till around day +6.

To understand the mechanisms for the ASPA pattern development and maintenance in the Southern Hemisphere westerlies, day-to-day APE and KE budgets for ASPA pattern are estimated, in a way similar to Tanaka et al. (2016) and Zhuge and Tan (2021a, 2021b). As indicated in Figure 3a, the baroclinic energy conversion from the climatological flow (CPb, solid black line) acts as the only APE source to overcome the thermal damping...
caused by turbulence, transient eddies, and diabatic heating. At the same time, small part of APE gained by CPΒ converts through KE-APE conversion term (CKEP, red line) into KE of ASPA pattern (Figure 3b, black line). Actually, the strongest baroclinic energy conversion occurs in the lower troposphere (Figure S5) and distributes along the high latitudes over South Pacific and South Atlantic near the Antarctica (Figure S6), where the southern branch of the climatological June–July–August jet (Figure S3) forms due to the strong thermal contrast along the climatological sea-ice edge. Obviously as indicated in Figure 3b, the nonlinear term (CKN, solid blue line) acts as a dominant KE source during the whole lifespan of the ASPA pattern. The barotropic energy conversion (CKΒ, solid black line) contributes to positive KE tendency before day +1, and negative KE tendency after day +1, indicating an energy conversion from the ASPA pattern to the background flow. The KE-APE conversion term (CKEP, red line) contributes weak positive KE tendency before day −1 and substantial positive KE tendency after day −1. Both the divergence term of the ageostrophic geopotential height flux (dashed red line) and the turbulent friction term (dashed blue line) always contribute negative KE tendency equally to damp the ASPA pattern.

Obviously, the two nonlinear terms including transient eddy feedback, CKN and CPΕ, contribute positively and negatively for the formation and maintenance of the ASPA pattern, respectively. This result is basically consistent with the finding of Lau and Nath (1991) and Tanaka et al. (2016) for some other types of low-frequency variability.

3.3 | SAT and SIC responses

In the lower tropospheric wind field, ASPA pattern manifests itself as a strong anomalous cyclone-anticyclone pair (vectors, Figure 4a). Strong anomalous northerlies (southerlies) associated the cyclone-anticyclone pair bring the
Antarctic region significant warm (cold) SAT anomalies (shadings, Figure 4a). The SAT rises over Mawson-Dumont d’Urville Seas to Ross Sea and Weddell Sea with peak SAT anomaly above 3°C. The SAT drops over the Amundsen–Bellingshausen Seas, with maximum drop as low as ~4°C. The SAT anomalies may persist for over 2 weeks with the peak values observed at day 0. Particularly from day 0 on, the SAT anomaly over the Ross Sea-Mawson-Dumont d’Urville Seas extends further westward into the eastern Antarctic, which persists more than 1 week. Concurrently, significant SIC changes also occur in the marginal region of the climatological mean SIC of the Ross Sea and the Amundsen–Bellingshausen Seas (Figure 4b). SIC is reduced in the Ross Sea and enhanced in the Amundsen–Bellingshausen Seas, with weak reduction being observed in the Weddell Sea (not pass the significant confidence level). The SIC anomalies occur after day 0 and persist over 2 weeks.

**DISCUSSION**

For a recent decade, the linkage between the MJO convection and climate variability over the Antarctic has received much attention as we mentioned previously in the introduction section. At the same time, the impact of tropical SST anomalies over the central tropical Pacific and eastern tropical Pacific on climate changes over the Antarctic has also received an increasing attention (Ding et al., 2011, 2012; Lee & Feldstein, 2013). These studies deal with mainly the Antarctic climate trends for recently three decades or so. The linkage of climate variability at subseasonal timescale between the tropics and Antarctic, however, is less studied (Lee & Seo, 2019). In this study, we revealed a new subseasonal pathway through which the WNPSM convection brings about the Antarctic anomalous weather events during austral winter through the exciting of ASPA pattern. First, the WNPSM...
convection induces a dipole disturbance straddling Australia, and then the ASPA pattern develops from the dipole along the southern branch of the climatological jet as a result of the wave energy dispersion and further amplifies with the energy supply from the baroclinic energy conversion, nonlinear term, and barotropic energy conversion. This strong circulation anomaly brings the Antarctic anomalous weather events, as illustrated by Figure 5.

It should be noted that the ASPA SAT pattern here (Figure 4a) highly resembles the leading EOF mode of daily SAT anomalies (EOF1-SAT) over the Antarctic (Figure S7) with the temporal correlation of 0.55 between the ASPA index and the time series of EOF1-SAT being observed at day $-1$ (Figure S7). This suggests that ASPA pattern makes important contribution to the leading mode of subseasonal SAT variability over the Antarctic (the EOF1-SAT). Further analysis indicates that ASPA pattern also contributes to the second mode of subseasonal SIC variability over the Antarctic (the EOF2-SIC) (Figure S8). The temporal correlation of 0.288 between ASPA index and the time series of EOF2-SIC being observed at day $-8$.

It should also be noted that the circulation anomaly responsible for the EOF1-SAT highly resembles the ASPA pattern in structure over the Southern Pacific and South America (Figure S9). Apparently, this wave-like circulation pattern arises from the streamfunction anomaly over the midlatitude Indian Ocean rather than the dipole disturbance straddling Australia. This suggests that both local internal atmospheric process in the midlatitude Southern Hemisphere and remote convective activity over the western North Pacific in the Northern Hemisphere can exert influences on the SAT changes over the Antarctic, which should be taken fully into consideration for making extended and seamless forecasts and numerical modeling of subseasonal climate variability over the Antarctic. To obtain a better weather prediction over the Antarctic, it is therefore extremely important to improve the representations of the climatological-mean sea ice and jet stream, wave-mean flow interaction and wave-wave interaction in the mid- and high-latitudes of the Southern Hemisphere, as well as the convection over the WNPSM region of the Northern Hemisphere in numerical model. Furthermore, Liu et al. (2020) found that the WNPSM precipitation assumes significant seasonal changes. In early summer the WNPSM precipitation is weak, and it becomes strong during Meiyu season and late summer. Whether or not the seasonal variation of the WNPSM exerts significant influence on the ASPA pattern is an interesting topic for future study.

**AUTHOR CONTRIBUTIONS**

**Yuexiang Sun**: Data curation; formal analysis; investigation; methodology; software; validation; visualization; writing – original draft; writing – review and editing.

**Benkui Tan**: Conceptualization; funding acquisition; project administration; resources; supervision; visualization; writing – original draft; writing – review and editing.

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**CONFLICT OF INTEREST**

The authors declare no potential conflict of interest.

**DATA AVAILABILITY STATEMENT**

The JRA-55 reanalysis data used in this study were obtained from https://rda.ucar.edu/datasets/ds628.0/. OLR data used in this study were obtained from https://psl.noaa.gov/data/gridded/data.interp_OLR.html. The ERA-interim reanalysis data were obtained from https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-interim.

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