Impact of North America snow cover on tropical cyclogenesis over the western North Pacific

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Abstract
This study reveals a connection of summer–fall (JJASO) tropical cyclone (TC) genesis over the western North Pacific (WNP) to preceding boreal spring (MAM) North America snow cover (NASC). Sea surface temperature (SST) anomalies in the tropical central Pacific and subtropical eastern Pacific play a crucial role in relaying influence of the MAM NASC on the following JJASO WNP TC genesis frequency. The increased NASC leads to a decrease in upward sensible heat flux and the atmospheric cooling over the North America. The atmospheric cooling enhances the meridional thermal contrast and geopotential height gradient, which is favorable for the occurrence of lower-level westerly wind anomalies and positive precipitation anomalies over the tropical eastern Pacific. The lower-level northeasterly wind anomalies over the subtropical northeastern Pacific as a Gill-type atmospheric response to positive precipitation anomalies induce ocean surface cooling via the enhanced wind speed. A positive feedback between the northeasterly wind anomalies and negative SST anomalies leads to a westward extension of the easterly flows to the western Pacific. The easterly wind anomalies along with the negative specific humidity anomalies and negative lower-level vorticity anomalies, and enhanced vertical wind shear suppress the TC genesis over the WNP during JJASO.

1. Introduction
The western North Pacific (WNP) is the most active basin of tropical cyclone (TC) genesis, accounting for more than 30% of global TCs during 1981–2010 (Schreck et al 2014). Those TCs have large economic and social impacts over East and Southeast Asia (Emanuel 2005). Zhang et al (2009) showed that the TC intensity and destructiveness may increase under global warming. Thus, a better understanding of the WNP TC variability and its factors is of great importance to an improved seasonal prediction of the TC activity over the WNP and disaster prevention and mitigation of East and Southeast Asian countries.

Previous studies have indicated that the WNP TC activity is largely affected by sea surface temperature (SST) variations in different ocean basins on interannual time scale, such as the Pacific Ocean (Wang and Chan 2002, Chen and Tam 2010, Wu et al 2012, 2018, 2019, Zhang et al 2016, Cao et al 2018, Zhan et al 2019), the tropical Indian Ocean, and the tropical northern Atlantic Ocean (Du et al 2011, Zhan et al 2011, 2014, Ham et al 2013, Huo et al 2015, Cao et al 2016, Yu et al 2016, Liu and Chen 2018, Liu et al 2019, Wu et al 2020). Chen and Tam (2010) identified a positive correlation between the El Niño–Southern Oscillation (ENSO) Modoki and the WNP TC genesis frequency. The SST anomalies in the tropical Indian
Ocean and the tropical northern Atlantic Ocean influence the WNP TC genesis via an equatorial Kelvin wave response (Du et al. 2011, Zhan et al. 2011, Xie et al. 2016) and an Atlantic-Pacific teleconnection (Ham et al. 2013, Huo et al. 2015, Cao et al. 2016), respectively. Recently, Wang and Wang (2019) suggested that the two leading modes of subtropical high can integrate the trans-basin impact of SST over the Indian, Pacific, and Atlantic oceans on the TC genesis over the WNP.

Most of the previous studies mainly focused on the impacts on the WNP TC genesis of the tropical SST forcing in different ocean basins (e.g. Wang and Chan 2002, Chen and Tam 2010, Zhan et al. 2011, Ham et al. 2013, Cao et al. 2018). There are few studies about the extratropical forcings in the interannual variation of the WNP TC genesis. One extratropical forcing identified for the WNP TC genesis is snow over in the Tibetan Plateau, which is thought as the third pole of the world with the average elevation more than 4000 m (Wu et al. 2012a, 2012b). Previous studies have shown that the Tibetan Plateau can influence the global climate, such as the monsoon over East Asia (Luo and Yanai 1983, Fan et al. 1997, Wu and Zhang 1998, Yeh and Wu 1998, Hsu and Liu 2003, Zhao et al. 2007, Wu et al. 2012a, 2012b, You et al. 2020). In the boreal winter and spring, the Tibetan Plateau is covered by snow. Due to its high albedo, the snow cover may induce land–atmosphere heat exchange and thus modulate the thermodynamics of the atmosphere over the Tibetan Plateau (Wu et al. 2012a, 2012b, You et al. 2020).

The relationship of the WNP TC genesis to the Tibetan Plateau snow cover was first found by Xie et al. (2005) and further confirmed by Zhan et al. (2016). Xie et al. (2005) found a negative correlation between the Tibetan Plateau snow cover in winter and WNP TC genesis in the following summer. Zhan et al. (2016) indicated that the relationship between snow cover over the Tibetan Plateau and TC genesis over the WNP was enhanced around 1994 and further explained that central Pacific SST anomalies plays a crucial role in this interdecadal change of the relationship. Recently, Han et al. (2021) found that the negative correlation between the Tibetan Plateau snow cover and WNP TC genesis remains after the central Pacific SST signals are removed. In addition, they showed that the Madden–Julian Oscillation (MJO) has an important contribution in modulating the relationship between the Tibetan Plateau snow cover and WNP TC genesis. However, few studies have examined the impacts of snow cover in other regions on the TC genesis over the WNP. Our analysis reveals an significant negative correlation of the TC genesis number over the WNP during the major TC season to the spring snow cover over North America. The goal of the present study is to investigate how the spring snow cover over North America makes a significant effect on the TC genesis over the WNP in the extended summer. The exploratory investigation is of much importance to improve the seasonal prediction of TC genesis over the WNP during the active TC season.

The rest of this paper is arranged as follows. Section 2 documents the data and methods used in the study. Section 3 discusses the impacts of the spring North America snow cover (NASC) on the interannual variation of the following summer-fall TC genesis over the WNP. The associated physical mechanisms including roles of large-scale circulation, land, and oceanic processes are investigated in section 4. The summary of our findings is provided in section 5.

2. Data and methods

The present study used the weekly Northern Hemisphere snow cover data of version 4, which were obtained from the National Snow and Ice Data Center (NSIDC) (Brodzik and Armstrong 2013). The original Equal-Area Scalable Earth Grid (EASE-Grid) snow cover fraction data has a 25 km spatial resolution and is available beginning from October 1966. The weekly snow cover is converted to regular monthly mean 1° × 1° grids. The present study mainly focuses on the snow cover during the boreal spring (March, April, and May, hereafter MAM).

The historical TC best-track data over the WNP in the present study were obtained from U.S. warning agencies, archived in the International Best Track Archive for Climate Stewardship (IBTrACS) v04r00 of the National Climate Data Center (Knapp et al. 2010). This TC track dataset contains the complete history of 6-hourly latitude and longitude and maximum one-minute sustained wind speed. The TC genesis is defined by the time when and location where tropical storm intensity (∼17 m s−1) is attained at the first time. The TC genesis over the WNP refer to those in the domain of 0°–30°N and 120°–180°E. The South China Sea is not included because there is an opposite interannual variation of large-scale circulation between the west and east of the Philippines (Chen et al. 1998). We mainly focus on the peak season of TC genesis, which is from June to October (hereafter JJASO) because it covers almost 70%–80% of total climatological TCs over the WNP. Therefore, the TC genesis frequency index is defined as the total TC genesis number during JJASO over the region of 0°–30°N and 120°–180°E from 1979 to 2017.

The global monthly mean SST data from 1979 to 2017 on a 2° × 2° grid were taken from the Extended Reconstructed Sea Surface Temperature (ERSST) version 5 data (Huang et al. 2017). The monthly mean precipitation was obtained from the Global Precipitation Climatology Project (GPCP) Precipitation data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at www.esrl.noaa.gov/psd/ (Adler et al. 2003). Conventional dynamic and thermodynamic variables...
including monthly mean lower-level and upper-level winds, humidity, temperature, geopotential height, vertical motion, and surface heat fluxes were derived from the ERA5 reanalysis dataset (Hersbach et al 2020). Those variables from GPCP and ERA5 have a horizontal resolution of 2.5° × 2.5°, beginning from 1979.

Following previous studies (Ashok et al 2003, Zhan et al 2019), the effect of one factor A was removed from the other factor B according to the method below:

\[ I_{RB} = I_B - r(I_B, I_A) \bar{O}_B \bar{I}_A, \]

where \( I_A \) stands for index A, \( \bar{I}_A \) denotes normalized \( I_A \), \( \bar{O}_B \) is the standard deviation of index B, \( r(I_B, I_A) \) denotes the correlation coefficient between index B and index A. As such, \( I_{RB} \) is the remainder of index B with the signal of index A removed.

The climatological monthly mean based on the time period from 1979 to 2017 is removed from the original data to obtain the monthly anomalies. The long-term trends of the snow cover index, SST index, TC genesis frequency index, and all other monthly mean variables are removed to avoid the interference of linear trend on the regression and correlation in the interannual variation, unless otherwise specified. Linear regression and correlation analyses are used in the present study to depict the relationship of interannual variation, unless otherwise specified. Linear regression and correlation analyses are used in the extended summer. The statistical significance of regression and correlation analyses is estimated based on the Student’s \( t \) test.

### 3. The relationship between NASC and WNP TC genesis

In this section, we present evidence for the relationship between the spring NASC and summer–fall WNP TC genesis. Before that, we first identify the key regions of snow cover in the globe which have a statistically significant correlation with the summer–fall TC genesis over the WNP. Then, we analyze the effect of the NASC anomalies in spring on the TC-related large-scale variables over the WNP. Those provide a basis to understand the influence of the NASC on the TC genesis over the WNP.

Figures 1(a) and (b) shows several regions with statistically significant correlation coefficient of MAM snow cover with the following JJASO WNP TC genesis frequency index. Based on the above correlation distribution, three key regions are selected to construct the snow cover indices. These are North America (35°–45°N, 120°–90°W), Tibetan Plateau (25°–40°N, 75°–115°E), and Eurasia (50°–60°N, 80°–115°E). The domains for the above three key regions are indicated by boxes in figures 1(a) and (b). Then, we calculated the correlation coefficients between snow cover indices in three key regions in the spring and the following summer–fall TC genesis over the WNP for the period 1979–2017. The correlation coefficients of MAM snow cover indices in North America, Tibetan Plateau, and Eurasia with the following JJASO WNP TC genesis are −0.45, −0.34, and −0.35. The three correlation coefficients are statistically significant at the 95% confidence level based on the Student’s \( t \) test. The first correlation coefficient is even statistically significant at the 99% confidence level. The significantly negative correlation between Tibetan Plateau snow cover and TC genesis over the entire WNP has been noted in previous studies (e.g. Xie et al 2005, Zhan et al 2016, Han et al 2021). The relationship between NASC and WNP TC genesis has not been examined yet. Thus, the present study investigates the impact of spring NASC on the summer–fall TC genesis over the WNP and the associated physical mechanisms.

In order to investigate whether the TC relationship with NASC is independent of Tibetan Plateau and Eurasia snow cover, a partial correlation analysis is performed to illustrate the contribution of Tibetan Plateau and Eurasia snow cover. When the Tibetan Plateau and Eurasia snow cover signals are removed from the MAM NASC index following the equation (1), the partial correlation coefficients between the NASC and TC genesis index are −0.39 and −0.37, respectively, which are still statistically significant at the 95% confidence level. The high correlations indicate that the impact of NASC on the WNP TC genesis is independent of Tibetan Plateau and Eurasia snow cover influences.

Figure 1(c) shows the normalized time series of the MAM NASC index and the following JJASO WNP TC genesis frequency index with the linear trend removed. The NASC index and TC genesis index display a tendency of opposite sign anomalies. When the NASC anomalies are positive (negative), TC genesis number tends to decrease (increase) over the WNP.

The TC activity is modulated by large-scale dynamic and the thermodynamical factors (Gray 1968, 1979, McBride and Zehr 1981, Chia and Ropelewski 2002, Camargo et al 2007; Emanuel 2007, Nolan 2007, Cao et al 2014a, 2014b, 2020). We first compare the MAM NASC-related anomalies of atmospheric dynamic and thermodynamic variables during the study period. Figure 2 reveals following JJASO lower-level and upper-level wind anomalies regressed on the normalized MAM NASC index. Figure 3 displays anomalies of following JJASO precipitation, vertical p-velocity at 500 hPa, vertical wind shear between 200 hPa and 850 hPa, specific humidity at 700 hPa, stream function at 850 hPa, and velocity potential at 200 hPa regressed upon the MAM NASC index.

When the NASC anomalies are positive, lower-level easterly and westerly wind anomalies are
Figure 1. (a), (b) The correlation coefficient of snow cover in MAM with TC genesis number over the whole WNP during JJASO of the period 1979–2017 and (c) the normalized time series of the MAM NASC index (red dashed line) and the following JJASO TC genesis frequency index (black solid line). The purple boxes in (a) and (b) denote the domains with obvious negative correlation coefficients, which are located in North America, Tibetan Plateau, and Eurasia. The correlation coefficient between NASC and TC genesis frequency index is shown at the top right in (c).

Figure 2. Anomalies of the horizontal winds (m s$^{-1}$) at (a) 850 hPa and (b) 200 hPa during JJASO obtained as regression on the normalized MAM NASC index during the period 1979–2017. The red and blue shadings indicate that the anomalies in either direction are significantly at the 95% confidence levels, respectively. The wind vector scale is showed at the top right with unit m s$^{-1}$. The purple box denotes the region of the WNP TC index.

observed over the tropical and subtropical western Pacific, respectively (figure 2(a)). Meanwhile, southerly wind anomalies are found over the subtropical East Asia (figure 2(a)). Opposite wind anomalies are observed at upper level, with westerly wind anomalies in the tropical western Pacific along 110°–180°E and northeasterly anomalies in the subtropical Pacific between 120°–130°E and 150°–160°E (figure 2(b)). Negative anomalies of precipitation and 700-hPa specific humidity, and positive anomalies of 500-hPa vertical p-velocity and vertical wind shear between 200 hPa and 850 hPa are located to east of 140°E when the NASC anomalies are positive (figures 3(a)–(d)). Meantime, there are positive anomalies of stream...
function at 850 hPa and velocity potential at 200 hPa over the entire WNP (figures 3(e) and (f)). Those anomalies imply a weakened lower-level vorticity, suppressed convection and upward motion, and enhanced upper-level convergence, drier air in the middle level, and larger vertical wind shear over most of the WNP. These conditions are unfavorable for TC genesis over the WNP. Therefore, MAM NASC anomalies impose a strong impact on the interannual variation of TC genesis frequency over the entire WNP in the following JJASO during the period 1979–2017.

In order to consolidate the contributions of environmental large-scale variables to TC genesis over the WNP, the genesis potential index (GPI) from Murakami and Wang (2010) is used and calculated as follows:

\[
\text{GPI} = A \times B \times C \times D \times E, \tag{2}
\]

where \(A = 10^5 \eta^{3/2}/2\), \(B = (1 + 0.1 V_{\text{shear}})^{-2}\), \(C = \left(\frac{H}{50}\right)^{3/2}\), \(D = \left(\frac{V_{\text{pot}}}{700}\right)^{1/3}\), \(E = (1 - \omega/0.1)^{-1}\), \(\eta\) is the 850-hPa absolute vorticity in s\(^{-1}\), \(V_{\text{shear}}\) is the magnitude of the vertical wind vector difference between 200 hPa and 850 hPa in m s\(^{-1}\), \(H\) is the 700-hPa relative humidity in %, \(V_{\text{pot}}\) is the potential intensity in m s\(^{-1}\) and \(\omega\) is the 500-hPa vertical pressure velocity in Pa s\(^{-1}\). The detailed definition of PI could be found in Bister and Emanuel (2002). Significantly negative GPI anomalies are observed over most of the WNP, particularly to the east of 140°E (figure 4), which is consistent with the results based on individual variables in figures 2 and 3.

4. Potential physical mechanisms

The previous section presented evidence for a connection of the JJASO WNP TC genesis frequency and associated dynamic and thermodynamic factors with the MAM NASC anomalies. This section investigates the possible mechanisms responsible for the remote connection between the NASC and WNP TC genesis. We perform a linear regression analysis of temperature, precipitation, specific humidity, vertical p-velocity, geopotential, surface heat flux, lower-level circulation and the SST during MAM
Figure 4. Anomalies of the GPI during JJASO obtained as regression on the normalized MAM NASC index during the period 1979–2017. The red and blue shadings indicate that the anomalies are significantly at the 95% confidence levels, respectively.

and JJASO with the spring NASC index. Note that positive and negative surface heat flux anomalies in figures 5 and 6 denote downward and upward, respectively.

According to previous studies, increased Tibetan Plateau snow cover in prior winter leads to the weakening of the South Asian and East Asian monsoons during the following summer (Fan et al 1997, Chen et al 2000, Zhang and Tao 2001, Souma and Wang 2010, You et al 2020). The effect of the winter Tibetan Plateau snow cover is through the modulation of the thermal contrast between the land and ocean. More snow cover over the Tibetan Plateau during the prior winter increases surface albedo and reduces heating, which reduces the thermal contrast between the land and ocean and thus leads to a weakened Asian summer monsoon (Souma and Wang 2010).

We present in figure 5 the temperature at 2 m and 500 hPa, surface sensible heat flux and geopotential height at 850 hPa regressed on the spring NASC index. Negative surface and middle-level tropospheric temperature anomalies are seen over North America in MAM when the spring NASC anomalies are positive (figures 5(a) and (e)), and those temperature anomalies tend to persist to the following JJASO though the magnitude of temperature anomalies becomes smaller (figures 5(b) and (f)). Negative surface temperature anomalies result in sensible heat flux from the atmosphere to the land surface (figures 5(c) and (d)). As such, the increased snow cover reduces the tropospheric temperature through changes of surface sensible heat flux. Those processes are consistent with those over the Tibetan Plateau (Zhang and Tao 2001, Xie et al 2005, Souma and Wang 2010, Zhan et al 2016, You et al 2020, Han et al 2021). Negative and positive 850-hPa geopotential height anomalies are observed in MAM over North America and tropical central Pacific, respectively, when the NASC anomalies are high (figure 5(g)). These contrasting geopotential height anomalies tend to persist into JJASO (figure 5(h)).

The tropospheric cooling enhances the meridional thermal contrast, particularly over North America and tropical central-eastern Pacific (figures 6(c) and (d)) as climatological mean air temperature decreases with the latitude (figures 6(a) and (b)). The increased thermal contrast and associated increase in zonal gradient of geopotential height are favorable for the formation of westerly wind anomalies over the tropical eastern Pacific (figures 7(a)–(f)). Those dynamic and thermodynamic anomalies are favorable for the intensification of precipitation anomalies in the tropical eastern Pacific during the MAM and following JJASO (figures 7(g) and (h)).

It is noteworthy that an anomalous lower-level cyclone is induced over the tropical eastern Pacific to west of 90°W via a Gill-type atmospheric response (Matsuno 1966, Gill 1980) (figures 6(e) and (f)). The accompanying northeasterly wind anomalies result in upward latent heat anomalies (figures 6(g) and (h)). The persistence of anomalies into the summer–fall (figures 6(f) and 7(h)) may be related to a positive feedback between precipitation and the atmospheric circulation. That is, the atmospheric cyclonic circulation is favorable for the precipitation enhancement, which could result in the positive latent heat anomalies and thus contribute to the persistence of lower-level cyclonic circulation anomalies. Note that there is an anomalous lower-level cyclone located over North America in MAM (figure 6(e)), which may be the reason for the increased snow cover over North America.

The northeasterly wind anomalies over the tropical eastern Pacific enhance wind speed and induce local SST cooling (figure 8(a)) due to increased upward surface latent heat flux (figure 6(g)). The westerly wind anomalies on the southern side of the
anomalous lower-level cyclone lead to the increase of SST in the equatorial eastern Pacific (figure 8(a)) through reducing upwelling. These positive SST anomalies may have a minor contribution to the development of lower-level anomalous cyclonic circulation due to the relatively weak magnitude and low background SST in the eastern equatorial Pacific compared to the precipitation anomalies, particularly in JJASO (figure 8(b)). The surface cooling over the tropical northeastern Pacific in turn induces lower-level anticyclonic circulation anomalies over the central Pacific via a Gill-type atmospheric response (Matsuno 1966, Gill 1980, Wang et al 2000, Ham et al 2013). The positive air–sea feedback intensifies the surface cooling in the central Pacific and the easterly wind anomalies over the tropical western Pacific (Wang et al 2000, Ham et al 2013, Cao et al 2016, Li et al 2017). Thus, negative SST anomalies develop with a westward extension to the equatorial central Pacific and easterly wind anomalies extend to the western–central Pacific in JJASO through the above mentioned positive air–sea feedback mechanism (figure 8(b)).

Figure 9 presents the temporal evolution of monthly 850-hPa zonal wind anomalies averaged in 0°–15°N and SST anomalies averaged in 10°S–10°N regressed upon the normalized spring NASC index from March to November. Only the anomalies with at least 90% confidence level are shown here. Significantly negative SST anomalies begin to appear in March in the tropical central Pacific and significant easterly wind anomalies occur with one month
delay over the tropical western Pacific. In the following summer–fall, the negative SST anomalies and easterly wind anomalies intensify and maintain via the local air–sea interaction. This indicates that the central Pacific SST anomalies may be a bridge connecting the NASC and WNP TC genesis. Previous studies have indicated that ENSO Modoki SST anomalies play an important role in the interannual variation of TC genesis over the entire WNP (Chen and Tam 2010, Cao et al 2018, Liu et al 2019). Cao et al (2018) have detected a strengthened influence of the central Pacific SST anomalies on the TC genesis number during summer–fall over the whole WNP since early 1990s. This is attributed to the expansion of the central Pacific SST anomalies along with the conjunct contribution of SST anomalies in other ocean basins. Note that ENSO Modoki SST variation has its own cycle with long-lasting anomalies in the tropical Pacific. We perform a partial correlation analysis to examine whether those SST anomalies are important for the influence of the NASC. Our analysis reveals that the relationship between MAM
Figure 7. Same as in figure 5, except for (a), (b) specific humidity averaged between 950 hPa and 500 hPa (g kg$^{-1}$), (c), (d) divergent wind at 850 hPa (m s$^{-1}$), (e), (f) vertical p-velocity at 500 hPa (10$^{-2}$ Pa s$^{-1}$) and (g), (h) precipitation (mm day$^{-1}$). The purple boxes denote the domains with obvious anomalies of precipitation.

NASC and preceding DJF and MAM SST anomalies is not significant in the tropical Pacific (figure not shown).

A partial correlation analysis is performed to illustrate the role of the central Pacific SST anomalies during JJASO in the connection between NASC and WNP TC genesis number variation. Following previous studies (Ashok et al 2007, Kao and Yu 2009), the ENSO Modoki index (EMI for brevity) is defined as $\text{EMI} = \text{SSTA}_C - 0.5 \times \text{SSTA}_E - 0.5 \times \text{SSTA}_W$, where SSTA$_C$, SSTA$_E$, and SSTA$_W$ represent the SST anomalies averaged in the regions of (165$^\circ$E–140$^\circ$W and 10$^\circ$S–10$^\circ$N), (110$^\circ$W–70$^\circ$W and 15$^\circ$S–5$^\circ$N), and (125$^\circ$E–145$^\circ$E and 10$^\circ$S–20$^\circ$N), respectively. When the central Pacific SST signal represented by the EMI index is removed from the NASC index following the equation (1), the partial correlation coefficient between the NASC and TC genesis index drops to $-0.16$. The large drop of the correlation coefficient indicates a significant role of the ENSO Modoki as a bridge in the impact of NASC on the JJASO WNP TC genesis.

In addition to central Pacific SST anomalies, figure 8 shows that obvious SST anomalies also
Figure 8. Anomalies of horizontal winds at 850 hPa (m s$^{-1}$) and SST ($^\circ$C) during (a) MAM and (b) JJASO obtained as regression on the normalized MAM NASC index during the period 1979–2017. Only the anomalies with at least 90% confidence level are shown. The red box indicates the domain of NASC. The blue boxes indicate the domains of the central Pacific (160°E–170°W and 10°S–10°N) and subtropical eastern Pacific (160°W–130°W and 10°N–25°N).

appear in the subtropical eastern Pacific (figure 8(b)). Previous studies have indicated that the Pacific Meridional Mode (PMM), which features an anomalous meridional SST gradient over the subtropical and tropical eastern Pacific (Chiang and Vimont 2004, Zhang et al 2016, 2020, Gao et al 2018, Wu et al 2021), plays a role in the interannual variability of the WNP TC genesis. Zhang et al (2016) suggested that the negative PMM can sustain an anticyclonic circulation and thus suppress the TC genesis over the WNP. To examine the role of the PMM in the connection between the NASC and WNP TC genesis, we perform a partial correlation analysis using the PMM index derived from the singular value decomposition analysis of anomalous monthly SST and surface wind data, which were downloaded from the website at www.aos.wisc.edu/~dvimont/MModes/PMM.html. When the PMM signal is removed from the NASC index, the partial correlation coefficient between the NASC and TC genesis index drops to $-0.23$. This indicates that the PMM is also a bridge in the connection between the NASC and WNP TC genesis.

Local SST indices were also defined for the central Pacific (160°E–170°W and 10°S–10°N) and subtropical eastern Pacific (160°W–130°W and 10°N–25°N) as shown in blue boxes of figure 8(b). When SST signals in JJASO in both the central Pacific and subtropical eastern Pacific are removed from the MAM NASC index, the partial correlation coefficient between the MAM NASC and JJASO TC genesis index drops to $-0.13$. This confirms that SST signals in both the central Pacific and subtropical eastern Pacific play a role in the linkage between the NASC and WNP TC genesis. The changes in the partial correlation coefficients suggest that the contribution from the central Pacific SST may be larger than the subtropical eastern Pacific SST. Zhang et al (2020) found a dominant role of the SST variation in the central Pacific in the TC genesis over the WNP compared to the simultaneous
Figure 9. Longitude–time cross section of anomalies of the (a) 850-hPa zonal winds (m s\(^{-1}\)) averaged in 0°–10°N and (b) SST (°C) averaged in 10°S–10°N obtained as regression on the normalized MAM NASC index from March to November during the period 1979–2017. The red and blue shadings in (a) and (b) indicate anomalies that are statistically significant at the 90% confidence levels. Contour intervals for 850-hPa zonal winds and SST are 0.2 m s\(^{-1}\) and 0.1°C, respectively.

5. Summary

Previous statistical analyses have investigated the modulation of TC genesis frequency during the summer–fall over the WNP by the snow cover over the Tibetan Plateau during the prior winter and spring (e.g. Xie et al 2005, Zhan et al 2016, Han et al 2021). The present study shows observational evidence that there is a negative correlation between MAM NASC and JJASO TC genesis over the WNP. When the snow cover over the North America is higher (lower) during MAM, the TC genesis number decreases (increases) over the entire WNP during the following JJASO.

A diagnosis of large-scale environmental factors is performed to show the contributions of the NASC to the TC genesis over the WNP. When the snow cover anomalies over North America are positive, significant anomalies in the lower-level stream function, upper-level velocity potential, mid-level vertical p-velocity, and precipitation are observed over the entire WNP. In addition, significant anomalies in the vertical wind shear and mid-level humidity are detected east of 140°E. Those anomalies are unfavorable for the TC genesis over the WNP. In the contrast, when the snow cover anomalies over North America are negative, these anomalies change sign and TC genesis number increases over the entire WNP.

A possible mechanism to connect NASC in the prior spring and WNP TC genesis frequency in the following summer-fall is proposed based on the regression analysis. The remote connection between NASC and WNP TC genesis is associated with the SST anomalies in the tropical central Pacific and subtropical eastern Pacific induced by NASC variation, which is shown schematically in figure 10. The increased snow cover over North America results in the atmospheric cooling by reducing upward sensible heat flux. The persistent cooling over North America modulates the zonal gradient of geopotential height and leads to lower-level westerly wind anomalies over the tropical central–eastern Pacific. Westerly anomalies induce anomalous convergence, ascending motion, and positive specific humidity and thus positive precipitation anomalies over the tropical eastern Pacific, which in turn lead to the formation of an anomalous lower-level cyclone through a Gill-type atmospheric response. Note that the positive SST anomalies induced by the westerly anomalies may also have a minor contribution to the formation of an anomalous cyclone. The northeasterly flows on the northwest side of anomalous cyclone induces ocean surface cooling through enhanced wind speed over the tropical northeastern Pacific. The northeasterly wind anomalies and negative SST anomalies extend southwestward to the tropical central Pacific through a positive feedback and...
Figure 10. Schematic diagrams showing the configuration how the NASC anomalies lead to the (a) increase and (b) decrease of TC genesis over the WNP. CP SST+ and CP SST- (EP SST+ and EP SST-) indicate the positive and negative SST anomalies over the central (eastern) Pacific, respectively. PRE+ and PRE- indicate the positive and negative precipitation anomalies in the tropical region between North America and South America, respectively. Cold and warm indicate the cold and warm temperature anomalies. Red and cyan vectors indicate the cyclonic and anticyclonic circulations.

the easterly flows form over the western Pacific in the following JJASO. The easterly anomalies along with other large-scale environmental factors suppress the TC genesis over the western Pacific during JJASO (figure 10(a)).

When the snow cover is reduced over North America, the chain of processes with opposite anomalies enhances the TC genesis number over the WNP (figure 10(b)). It is noteworthy that when the ENSO Modoki signal is removed from the NASC index, the partial correlation coefficient between the NASC and TC genesis index drops to $-0.16$, which means that ENSO Modoki plays an important role as a bridge in the impact of NASC on the WNP TC genesis.

The negative correlation between MAM NASC and JJASO TC genesis over the WNP may be helpful to improve seasonal prediction of the TC genesis over the entire WNP. Meantime, we note that the results from the present study are obtained from statistical analyses. In the future work, a series of snow cover anomaly forced experiments should be further carried out to validate the proposed processes.

Data availability statement

The data that support the findings of this study are openly available.

The IBTrACS data were obtained from www.ncdc.noaa.gov/ibtracs/index.php. The ERA5 data set was obtained from https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-layers?tab=form. The GPCP was obtained from www.esrl.noaa.gov/psd/. The PMM index was downloaded from the website at www.aos.wisc.edu/~dvimont/MModes/PMM.html.

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