Impacts of two types of El-Niño on the winter North Pacific storm track

Minghao Yang, Chongyin Li, Yanke Tan, Xin Li and Xiong Chen

1 College of Meteorology and Oceanography, National University of Defense Technology, Nanjing 211101, People’s Republic of China
2 State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, People’s Republic of China
3 Department of Atmospheric and Oceanic Science & Institute of Atmospheric Sciences, Fudan University, Shanghai 200433, People’s Republic of China

E-mail: lcy@lasg.iap.ac.cn

Keywords: two types of El-Niño, winter North Pacific storm track, atmospheric baroclinicity, baroclinic energy conversion

Abstract

In the present study, the impacts of eastern Pacific (EP) and central Pacific El-Niño on the winter North Pacific storm track (WNPST) are investigated, and the possible reasons for the different responses of the WNPST to the two types of El-Niño are revealed. It is found that only EP El-Niño episodes have a distinct influence on the strength and movement of the WNPST. During EP El-Niño episodes, the WNPST is significantly enhanced and extended equatorward. The patterns of atmospheric baroclinicity anomalies are consistent during the two types of El-Niño. The enhancement and equatorward extension of the WNPST during EP El-Niño episodes can be attributed to anomalous baroclinic energy conversion. In addition, EP El-Niño episodes can also intensify the strength of the WNPST by warming the lower-tropospheric air upstream of the WNPST, which generates more synoptic-scale disturbances entering the WNPST.

1. Introduction

The North Pacific storm track (NPST) is one of the most active regions of bandpass filtered synoptic-scale disturbances in the Northern Hemisphere (Blackmon et al 1977) and is consistent with the tracks of surface cyclones and anticyclones in the middle latitudes (Wallace et al 1988, Penny et al 2013). As an important link to the tropical influence in mid-high latitudes (Held et al 1989, Chang et al 2002), synoptic-scale disturbances in the NPST occur frequently and propagate eastward (Charney 1947, Blackmon 1976, Zhao and Liang 2019), transporting abundant moisture, kinetic energy and heat poleward. As a result, NPST exerts large influence, especially in winter, on atmospheric circulation and climate variability (Jin 2010, Kug et al 2010, Luo et al 2016).

Previous studies have examined significant intraseasonal (Lau 1988, Nakamura and Sampe 2002), seasonal (Nakamura 1992, Lee et al 2011), interannual (Nakamura et al 2002, Harnik and Chang 2004, Lee et al 2010) and interdecadal (Chang et al 2002, Nakamura et al 2002, Lee et al 2012) variations in the NPST. The upper-tropospheric jet over the North Pacific and El Niño-Southern Oscillation (ENSO) prominently modulate the interannual variation in the NPST (Straus and Shukla 1997, Harnik and Chang 2004). During El-Niño episodes, the winter NPST (WNPST) and upper-tropospheric jet are intensified and moves southeastward due to the strengthened Hadley circulation over the East Pacific and vice versa during La-Niña episodes (Held et al 1989, Trenberth and Hurrell 1994, Chang et al 2002, Wang et al 2017).

In recent years, it has been widely accepted that El-Niño episodes can be divided into two types, canonical eastern Pacific (EP) El-Niño episodes and central Pacific (CP) El-Niño episodes (Kao and Yu 2009), according to the locations of the maximum sea surface temperature anomalies (Yu and Kao 2007, Ashok et al 2007, Wang et al 2019). Previous studies noted significant differences between the two types of El-Niño on the global climate (Ashok et al 2009, Kug et al 2009, Mo 2010, Wang et al 2014, Infanti and Kirtman 2016, Tan et al 2016). In terms of the storm track, Ashok et al (2009) reported that during CP El-Niño episodes, the strength of the austral winter storm
track (AWST) over Australia is weakened prominently due to anomalous blocking over Australia, while the AWST over South America is intensified. The researchers believed that the influences of CP El-Niño on the AWST in the Southern Hemisphere are distinctly different from and stronger than those of EP El-Niño (Ashok et al. 2007).

Thus, two questions are put forward: do the impacts of the two types of El-Niño on the WNPST have significant and robust differences like those in the Southern Hemisphere? If so, what is the reason for the differences between the two types of El-Niño? As a useful and practical tool, the energy budget diagnosis has widely been applied to investigate the storm track variations (Mak and Cai 2014, Lee et al. 2012, Wang et al. 2017, Ma and Zhang 2018, Zhao and Liang 2019). In addition, the variations of storm track intensity may also be attributed to the upstream seeding effect by the amount of baroclinic wave activity entering the storm track (Orlanski 2005, Lee et al. 2010, Penny et al. 2013). To answer these two questions, we investigate the impact of El-Niño on the WNPST again by distinguishing the EP El-Niño and the CP El-Niño to verify whether there exists a difference, and we attempt to find the possible reason by analyzing the role of atmospheric baroclinicity, the energy conversion and the upstream seeding effect.

2. Data and methods

The daily atmospheric data used in this research, including horizontal winds and air temperature, are provided by the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) global atmospheric reanalysis datasets (Kalnay et al. 1996) with a horizontal resolution of 2.5° × 2.5°. Monthly sea surface temperature (SST) data from the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) dataset (Rayner et al. 2003) with a horizontal resolution of 1° × 1° are utilized. The time span of the data used in this study is 1948 to 2018. The winter in the present study refers to the time period of December to February.

The Lanczos bandpass filter is used to isolate synoptic-scale (2.5–6-day) disturbances from the NCEP/NCAR daily data. The WNPST in the free atmosphere is characterized by the meridional eddy heat flux at 850 hPa (Nakamura et al. 2002, Gan and Wu 2015), the eddy kinetic energy at 500 hPa (Takahashi and Shirooka 2014, Afargan and Kaspi 2017) and the variance in meridional wind velocity at 300 hPa (Lee et al. 2010, Hoskins and Hodges 2019).

To distinguish the EP and CP El-Niño episodes, the method from Ham and Kug (2012) is adopted for simple calculation. Specifically, if the normalized winter mean Niño 3 (4) index is larger than its one standard deviation and the magnitude of the Niño 3 (4) index is larger than the Niño 4 (3) index, an episode is considered to be an (a) EP (CP) El-Niño. Based on this method, table 1 presents the El-Niño classification and the years of two types of El-Niño episodes from the HadISST dataset. In addition, we also use the Niño index in Ren and Jin (2011) to classify El-Niño episode to verify our results (not shown). It is found that the results are consistent.

3. Results

3.1. WNPST response to two types of El-Niño

Figure 1 shows the composite WNSPT anomalies related to the two types of El-Niño. From figure 1, we can find that the EP and CP El-Niño episodes have totally different impacts on the strength and movement of the WNPST. In the lower troposphere, a negative meridional eddy heat flux anomaly appears over southern Alaska in EP El-Niño years (figure 1(a)), while positive anomalies occur in the equatorward flank of the climatological mean. It is obvious that the peak area and southeastern part of the climatological eddy kinetic energy are prominently strengthened in the middle troposphere in EP El-Niño years (figure 1(b)), whereas the northern part over the Bering Sea is remarkably attenuated. In addition, the response of the meridional wind variance to the EP El-Niño case has a well-defined meridional asymmetric structure in the upper troposphere (figure 1(c)), with a robust positive anomaly emerging in the region south of 45°N, especially the southern climatology of the meridional wind variance, and some slightly negative anomalies occur in the poleward flank. The WNPST in the troposphere is uniformly significantly intensified and extends equatorward. However, except for the appearance of some significant positive anomalies in the two flanks of the climatological mean of the meridional wind variance in the upper troposphere (figure 1(f)), the responses of the WNPST to the CP El-Niño episodes fail the significance test, which indicates that the CP El-Niño has little influence on the strength and movement of the WNPST and is obviously different from the impact of EP El-Niño on the WNPST. To make the results more convincing, a more modern reanalysis dataset, ERA-Interim (Dee et al. 2011), is used to corroborate the

| Event         | Years selected in observations |
|---------------|-------------------------------|
| EP El-Niño    | 1958, 1966, 1973, 1983, 1987, 1992, 1998 and 2016 |
| CP El-Niño    | 1969, 1988, 1995, 2005, 2010 and 2015 |

Table 1. Years of the EP and CP El-Niño during 1948–2018 by using the standardized DJF Niño 3 and Niño 4 indices derived from the HadISST dataset. Years refer to January–February.
findings. The different impacts of two types of El-Niño on the WNPST can also be seen in the satellite era (Figures not shown). Considering the consistent variation in the tropospheric WNPST (figure 1), the WNPST is characterized by the meridional eddy heat flux for convenience in the following chapters.

3.2. The role of atmospheric baroclinicity

Previous studies have documented that the WNPST is augmented and extended equatorward during El-Niño episodes without distinguishing different types (Held et al. 1989, Straus and Shukla 1997), and the anomalies in the WNPST and upper-tropospheric jet are consistent during El Niño events (Liu et al. 2014). To identify the role of atmospheric baroclinicity associated with the upper-tropospheric jet over the North Pacific, figure 2 shows the composite zonal wind anomaly at 300 hPa and the vertically integrated (from 925 to 700 hPa) maximum Eady growth rate (EGR) anomaly. According to the linear theory of baroclinic instability, EGR can be calculated by \( \sigma = 0.31N f \frac{\partial u}{\partial z} \) (Lindzen and Farrell 1980), where \( \sigma \) denotes EGR, \( N \) denotes the Brunt-Väisälä frequency, \( f \) denotes the Coriolis parameter, and \( \frac{\partial u}{\partial z} \) is the vertical shear of zonal wind. The EGR acts as a suitable indicator to measure the atmospheric baroclinicity, which is expected to feed synoptic-scale transient eddies to form a well-organized storm track (Hoskins and Valdes 1990, Nakamura et al. 2002, Kuwano-Yoshida and Minobe 2017). During EP El-Niño episodes, a robust positive upper-tropospheric zonal wind anomaly is slantly elongated from the Kuril Islands to the Hawaiian Islands and a remarkable negative anomaly arises over the northwest coast of North America (figure 2(a)). However, the sizable dipole anomalies of upper-tropospheric zonal wind are zonally oblong east of the date line during CP El-Niño episodes (figure 2(b)). In fact, we can find that there are no fundamental differences between the patterns of upper-tropospheric zonal wind responses to the two types of El-Niño. For the atmospheric baroclinicity represented by the EGR, a significant and robust negative EGR anomaly is located over southern Alaska during EP El-Niño episodes (figure 2(c)), which corresponds well to the negative WNPST anomaly (figure 1(a)). In addition, the prominent positive EGR anomalies near the Hawaiian Islands contribute to the enhancement and equatorward extension of the WNPST.

Figure 1. Maps showing (shading) the composite WNSPT anomalies during (a)–(c) EP and (d)–(f) CP El-Niño relative to the climatology. The WNSPT is represented by (a) and (d) the meridional eddy heat flux at 850 hPa, (b) and (e) the eddy kinetic energy at 500 hPa and (c) and (f) the variance of meridional wind velocity at 300 hPa. The black contours denote the climatological mean of WNPST during (a)–(c) EP and (d)–(f) CP El-Niño with the interval of (a) and (d) 1 K · m s\(^{-1}\), (b) and (e) 3 m\(^2\) s\(^{-2}\) and (c) and (f) 10 m\(^2\) s\(^{-2}\). The cross-hatched patterns denote the 95% confidence level by the Student’s \( t \) test.
The pattern of EGR anomalies during CP El-Niño episodes (figure 2(d)) is basically consistent with that during EP El-Niño episodes without fundamental differences due to the inherent connection between the EGR and upper-tropospheric zonal wind. However, the responses of the WNPST to the EP and CP El-Niño are totally different, indicating that the atmospheric baroclinicity anomaly is not the main reason for the different behaviours of the WNPST in response to the two types of El-Niño, and CP El-Niño cannot influence the WNPST by affecting the atmospheric baroclinicity just as EP El-Niño.

3.3. Barotropic and baroclinic energy conversion

To reveal the possible reasons for the different behaviours of the WNPST in response to EP and CP El-Niño, the eddy kinetic energy budget which is fundamental for the development of the WNPST (Lee et al 2011) is investigated in the present study. According to Mak and Cai (1989), Cai and Mak (1990), Cai et al (2007) and Ma and Zhang (2018), the barotropic energy conversion ($B_{TEC}$) and baroclinic energy conversion ($B_{CEC}$) can be expressed as follows:

$$B_{TEC} = \frac{\rho_0}{g} \left\{ \frac{1}{2} \left( \nabla^2 - \nabla^2 u \right) \left( \frac{\partial T}{\partial x} - \frac{\partial T}{\partial y} \right) \right.$$

$$\left. - u \nabla u \left( \frac{\partial \theta}{\partial x} + \frac{\partial \theta}{\partial y} \right) \right\} \quad (1)$$

$$B_{CEC1} = C_2 \left( u T \frac{\partial T}{\partial x} + v T \frac{\partial T}{\partial y} \right) \quad (2)$$

$$B_{CEC2} = C_1 \left( \omega' T' \right) \quad (3)$$

where $u$, $v$ and $\omega$ denote three-dimensional wind, $\rho_0$ represents 1000 hPa, $g$ refers to the gravity acceleration, $T$ denotes air temperature, $\theta$ represents the 95% confidence level by the Student’s $t$ test.

Figure 2. Maps showing (contour) the climatological mean and (shading) the composite anomalies of (a) and (b) the zonal wind at 300 hPa and (c) and (d) the vertically integrated (from 925 to 700 hPa) maximum EGR related to the (a) and (c) EP and (b) and (d) CP El-Niño. The contour intervals are (a) and (b) 10 m s$^{-1}$ and (c) and (d) 3 $\cdot$ 10$^{-4}$ s$^{-1}$. The cross-hatched patterns denote the 95% confidence level by the Student’s $t$ test.

The pattern of EGR anomalies during CP El-Niño episodes (figure 2(d)) is basically consistent with that during EP El-Niño episodes without fundamental differences due to the inherent connection between the EGR and upper-tropospheric zonal wind. However, the responses of the WNPST to the EP and CP El-Niño are totally different, indicating that the atmospheric baroclinicity anomaly is not the main reason for the different behaviours of the WNPST in response to the two types of El-Niño, and CP El-Niño cannot influence the WNPST by affecting the atmospheric baroclinicity just as EP El-Niño.

3.3. Barotropic and baroclinic energy conversion

To reveal the possible reasons for the different behaviours of the WNPST in response to EP and CP El-Niño, the eddy kinetic energy budget which is fundamental for the development of the WNPST (Lee et al 2011) is investigated in the present study. According to Mak and Cai (1989), Cai and Mak (1990), Cai et al (2007) and Ma and Zhang (2018), the barotropic energy conversion ($B_{TEC}$) and baroclinic energy conversion ($B_{CEC}$) can be expressed as follows:

$$B_{TEC} = \frac{\rho_0}{g} \left\{ \frac{1}{2} \left( \nabla^2 - \nabla^2 u \right) \left( \frac{\partial T}{\partial x} - \frac{\partial T}{\partial y} \right) \right.$$

$$\left. - u \nabla u \left( \frac{\partial \theta}{\partial x} + \frac{\partial \theta}{\partial y} \right) \right\} \quad (1)$$

$$B_{CEC1} = C_2 \left( u T \frac{\partial T}{\partial x} + v T \frac{\partial T}{\partial y} \right) \quad (2)$$

$$B_{CEC2} = C_1 \left( \omega' T' \right) \quad (3)$$

where $u$, $v$ and $\omega$ denote three-dimensional wind, $\rho_0$ represents 1000 hPa, $g$ refers to the gravity acceleration, $T$ denotes air temperature, $\theta$ represents the 95% confidence level by the Student’s $t$ test. Noteworthy negative $B_{TEC}$ anomalies occur near the Hawaiian Islands (figure 3(a)), resulting in an anomalous $B_{TEC}$ from eddy kinetic energy to the mean kinetic energy of basic flow. Thus, the anomalous $B_{TEC}$ during EP El-Niño episodes attenuates the strength of the southeastern WNPST and is not beneficial to the equatorward extension. Significantly and robustly positive $B_{CEC1}$ anomalies zonally elongated over the North Pacific (figure 3(b)) provide a favourable condition for $B_{CEC2}$ by converting the mean available potential energy to the eddy available potential energy. Figure 3(c) shows that prominently positive $B_{CEC2}$ anomalies appearing at the southern flank of the WNPST directly enhance the strength of the WNPST; in addition, prominently negative $B_{CEC2}$ anomalies arising over the west coast of North
America weaken the strength of the WNPST, which is conducive to the equatorward and eastward movement of the WNPST. Although the impacts of $B_{TEC}$ and $B_{CEC2}$ on the strength of the WNPST near the Hawaiian Islands are opposite, the magnitude of the $B_{CEC2}$ anomaly is larger than that of $B_{TEC}$, resulting in the southward extension of the WNPST during EP El-Niño episodes. However, the $B_{TEC}$ and $B_{CEC}$ anomalies are not significant in the CP El-Niño episodes (figures 3(d)–(f)), indicating that the barotropic and baroclinic energy conversion may be an important way that the two types of El-Niño modulate the WNPST.

3.4. The lower-level temperature upstream of the WNPST

It is widely accepted that EP and CP El-Niño episodes can excite significantly different extratropical teleconnection patterns (Ashok et al, 2009, Kug et al 2009, Mo 2010, Wang et al 2014, Infanti and Kirtman 2016, Tan et al 2016, Chen et al 2019). Considering that the extratropical atmospheric circulations associated with El-Niño have impacts on the strength and movement of the WNPST on an interannual time scale, the EP and CP El-Niño may exert influences on the WNPST by affecting certain extratropical climate systems via atmospheric teleconnections. Lee et al (2010) well documented that anomalous lower-atmospheric heating at the upstream of the WNPST can cause a strengthened seeding effect by an anomalous heat process with a decrease in low-level static stability. The augmented upstream seeding effect generates more baroclinic disturbances and synopticscale transient eddies entering the storm track (Orlanski 2005, Lee et al 2010, Penny et al 2013), thus favouring the development of the WNPST.

Figure 3. Maps showing (contour; unit: W m$^{-2}$) the climatological mean and (shading) the composite anomalies of the 850 hPa (a) and (d) $B_{TEC}$, (b) and (e) $B_{CEC1}$ and (c) and (f) $B_{CEC2}$ related to the (a)–(c) EP and (d)–(f) CP El-Niño. The cross-hatched patterns denote the 95% confidence level by the Student’s t test.

Figure 4. The regression map of (shading; unit: °C) anomalous winter air temperature at 850 hPa on the strength index of the WNPST. The black contours denote the climatology of WNPST (unit: K·m s$^{-1}$). The cross-hatched patterns denote the 95% confidence level by the Student’s t test.
Based on the strength index of the WNPST (Yang et al. 2020), which sets a threshold that is the median of the WNPST amplitudes of all of the grids within a domain of (25°–65°N, 130°E–120°W) and then the mean of the values greater than the threshold in all the grids is defined as the strength index of the WNPST, the temperature anomalies at 850 hPa associated with the strength of the WNPST are found to be distinctly positive upstream of the WNPST (figure 4), which is accompanied by an enhanced seeding effect producing more intense storm track eddies (Orlanski 2005).

The lower-level anomalous anticyclone related to the El-Niño over the Northwest Pacific, especially the southerly on the western side, links the East Asian climate and El-Niño episodes (Zhang et al. 1996, Chen et al. 2019). Figure 5(a) shows that the anomalous anticyclone related to EP El-Niño guides remarkably warm air to move northward over the Kuroshio, which tends to heat the lower-level atmosphere upstream of the WNPST. However, the anomalous southerly during CP El-Niño episodes (figure 5(b)) is not as robust and significant as that during the EP El-Niño episodes due to the far westward anomalous anticyclone related to the westward sinking side of the Walker circulation excited by the CP El-Niño.

The lower-tropospheric prominently positive temperature anomalies over the Northwest Pacific are associated with the EP El-Niño (figure 5(c)). However, there are no significant temperature anomalies over the Northwest Pacific during the CP El-Niño episodes (figure 5(d)), indicating that the CP El-Niño cannot affect the WNPST by influencing the lower-level temperature upstream of the WNPST through the seeding effect.

4. Summary and discussion

In the present study, based on the NCEP/NCAR reanalysis and HadISST dataset, we investigate the impacts of the EP and CP El-Niño on the WNPST and explore the role of baroclinicity and the possible reasons for the different responses of the WNPST to the two types of El-Niño.

EP and CP El-Niño episodes have totally different impacts on the strength and movement of the WNPST. During the EP El-Niño episodes, the WNPST in the troposphere tends to become significantly enhanced and extend equatorward. However, there is no prominent change in the strength and movement of the WNPST during the CP El-Niño episodes. The anomalous atmospheric baroclinicity related to the upper-tropospheric jet over the North Pacific is found to provide favourable conditions for the enhancement and equatorward extension of the WNPST during both types of El-Niño, which means that the atmospheric baroclinicity cannot explain the behaviour of the WNPST during the CP El-Niño episodes.

The obvious differences of $B_{\text{TEC}}$ and $B_{\text{CEC}}$ are found between the EP and CP El-Niño episodes. The patterns of prominently anomalous $B_{\text{CEC}}$, including $B_{\text{CEC1}}$ and $B_{\text{CEC2}}$, are basically consistent with that of the WNPST during the EP El-Niño episodes. However, the $B_{\text{TEC}}$ and $B_{\text{CEC}}$ anomalies are not significant in the CP El-Niño episodes. In addition, the significantly anomalous southerlies related to the anomalous anticyclone over the Northwest Pacific induced by the EP El-Niño tend to warm the lower troposphere upstream of the WNPST, resulting in the intensified strength of the WNPST.
It should be noted that the links between baroclinicity, baroclinic conversion and storm track amplitudes are quite complex (Chang et al. 2002). In addition, apart from the dry mechanism, such as the aforementioned EGR and energy conversion, the WNPST is also impacted by the moisture effects (Chang et al. 2002, Lee et al. 2011), including the latent heat release associated with meridional moisture flux and large-scale condensation and the moist baroclinic instability associated with diabatic conversion, which is sometimes more important than the dry mechanism (Ma et al. 2017; Kuwano-Yoshida and Minobe 2017). The mismatched patterns between the EGR anomalies and WNPST anomalies may be attributed to the moisture effect.

The contrast of the influences of the two types of El-Niño on the wintertime storm tracks in the Northern Hemisphere and Southern Hemisphere is notable. In addition, corresponding to the two types of El-Niño, the impacts of the two types of La-Niña on the WNPST are investigated (not shown), revealing the similar but opposite results with a significant damping effect of EP La-Niña, instead of CP La-Niña, on the WNPST. In the present study, the asymmetry in the impacts of the two types of El-Niño on the WNPST is only documented through reanalysis data; however, the sample sizes of two types of El-Niño events are limited. Therefore, climate model data with longer time series, such as the Coupled Model Intercomparison Project 6 (CMIP6), is needed to further investigate and verify this issue. In addition, whether two types of El-Niño can affect the WNPST through ocean processes remains to be further studied. Furthermore, a recent study shown that CP El-Niño can be divided into different types (Wang et al. 2018). The influence of different types of CP El-Niño on the WNPST is an interesting and leading-edge issue we will focus on next.

Acknowledgments

This research was jointly supported by the National Natural Science Foundation of China (41490642, 4160501 and 41520104008), Research Project of the National University of Defense Technology (ZK20-45) and the ‘Double First-Class’ construction guidance project of the National University of Defense Technology (ZXB1GB02). The authors would like to thank three anonymous reviewers, Professor Sir Brian Hoskins and Akira Kuwano-Yoshida for their helpful and crucial comments. The first author thanks Professor Lifeng Zhang for the useful discussion and constructive comments in the course ‘Atmospheric Dynamics and Numerical Simulation’. The NCEP/NCAR reanalysis dataset was obtained online (https://www.esrl.noaa.gov/psd/data/gridded/reanalysis/). The HadISST SST was obtained online (https://www.metoffice.gov.uk/hadobs/index.html).

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://www.esrl.noaa.gov/psd/data/gridded/reanalysis/.

ORCID iDs

Minghao Yang Ⓞ https://orcid.org/0000-0003-1298-2307
Xiong Chen Ⓞ https://orcid.org/0000-0003-0067-8420

References

Afargan H and Kaspi Y 2017 A midwinter minimum in North Atlantic storm track intensity in years of a strong jet Geophys. Res. Lett. 44 12511–8
Ashok K, Nakamura H and Yamagata T 2007 Impacts of ENSO and Indian Ocean dipole events on the Southern Hemisphere storm-track activity during austral winter J. Clim. 20 3147–63
Ashok K, Tam C-Y and Lee W-J 2009 ENSO Modoki impact on the Southern Hemisphere storm track activity during extended austral winter Geophys. Res. Lett. 36 L12705
Blackmon M L 1976 A climatological spectral study of the 500 mb geopotential height of the Northern Hemisphere J. Atmos. Sci. 33 1607–23
Blackmon M L, Wallace J M, Lau N-C and Mullen S L 1977 An observational study of the Northern hemisphere wintertime circulation J. Atmos. Sci. 34 1040–53
Cai M and Mak M 1990 On the basic dynamics of regional cyclogenesis J. Atmos. Sci. 47 1417–42
Cai M, Yang S, Den Dool H M and Kousky V E 2007 Dynamical implications of the orientation of atmospheric eddies: a local energetics perspective Tellus Ser. A 59 127–40
Chang E K M, Lee S and Swanson K L 2002 Storm track dynamics and Indian Ocean dipole events on the Southern Hemisphere storm-track activity during austral winter J. Clim. 15 2163–83
Charney J G 1947 The dynamics of long waves in a baroclinic westerly current J. Meteorol. 4 136–62
Chen W, Wang L, Feng J, Wen Z P, Ma T J, Yang X Q and Wang C H 2019 Recent progress in studies of the variabilities and mechanisms of the East Asian monsoon in a changing climate Adv. Atmos. Sci. 36 887–901
Dee D P et al 2011 The ERA-Interim reanalysis: configuration and performance of the data assimilation system Q. J. R. Meteorol. Soc. 137 553–97
Gan B and Wu L 2015 Feedbacks of sea surface temperature to wintertime storm tracks in the North Atlantic J. Clim. 28 306–23
Ham Y-G and Kug J-S 2012 How well do current climate models simulate two types of El Niño? Clim. Dyn. 39 383–98
Harnik N and Chang E K M 2004 The effects of variations in jet width on the growth of baroclinic waves: implications for midwinter Pacific storm track variability J. Atmos. Sci. 61 23–40
Held I M, Lyons S W and Nigam S 1989 Transients and the extratropical response to El Niño J. Atmos. Sci. 46 163–74
Hoskins B J and Hodges K I 2011 The annual cycle of northern hemisphere storm tracks. Part I: seasons J. Clim. 24 1607–23
Hoskins B J and Valdes P J 1990 On the existence of storm-tracks J. Atmos. Sci. 47 1854–64
Infanti J M and Kirtman B 2016 North American rainfall and temperature prediction response to the diversity of ENSO Clim. Dyn. 46 3007–23
Jin F 2010 Eddy-induced instability for low-frequency variability J. Atmos. Sci. 67 1947–64
Kalnay E et al 1996 NCEP/NCAR 40-year reanalysis project Bull. Am. Meteorol. Soc. 77 437–72

P Publishing

Environ. Res. Lett. 15 (2020) 094062

M Yang et al
Kao H and Yu J 2009 Contrasting eastern-Pacific and central-Pacific types of ENSO J. Clim. 22 615–32
Kug J, Jin F, Park J, Ren H and Kang I 2010 A general rule for synoptic-eddy feedback onto low-frequency flow Clim. Dyn. 35 1011–26
Kug J-S, Jin F and An I 2009 Two types of El Niño events: cold tongue El Niño and warm pool El Niño J. Clim. 22 1499–515
Kuwano-Yoshida A and Minobe S 2017 Storm-track response to SST fronts in the northwestern Pacific region in an AGCM J. Clim. 30 1081–102
Lau N-C 1988 Variability of the observed midlatitude storm tracks in relation to low-frequency changes in the circulation pattern J. Atmos. Sci. 45 2718–43
Lee S, Lee J, Wang B, Jin F, Lee W and Ha K 2011 A comparison of climatological subseasonal variations in the wintertime storm track activity between the North Pacific and Atlantic: local energetics and moisture effect Clim. Dyn. 37 2453–69
Lee S-S, Lee J-Y, Wang B, Ha K-J, Heo K-Y, Jin -F-F, Straus D M and Shukla J 2012 Interdecadal changes in the storm track activity over the North Pacific and North Atlantic Clim. Dyn. 39 313–27
Lee Y, Lim G and Kug J 2010 Influence of the East Asian winter monsoon on the storm track activity over the North Pacific J. Geophys. Res. 115 1566–7
Lindzen R S and Farrell B 1980 A simple approximate result for the maximum growth rate of baroclinic instabilities J. Atmos. Sci. 37 1648–54
Liu C J, Ren X J and Yang X Q 2014 Mean flow-storm track relationship and Rossby wave breaking in two types of El Niño Adv. Atmos. Sci. 31 197–210
Luo D, Xiao Y, Yao Y, Dai A, Simmonds I and Franzke C 2016 The impact of Ural blocking on winter warm Arctic-cold Eurasian anomalies. Part I: blocking-induced amplification J. Clim. 29 3925–47
Ma X, Chang P, Saravanan R, Montuoro R, Nakamura H, Wu D, Lin X and Wu L 2017 Importance of resolving Kuroshio front and eddy influence in simulating the North Pacific storm track J. Clim. 30 1861–80
Ma X and Zhang Y 2018 Interannual variability of the North Pacific winter storm track and its relationship with extratropical atmospheric circulation Clim. Dyn. 51 3685–98
Mak M and Cai M 1989 Local barotropic instability J. Atmos. Sci. 46 3289–311
Mo K C 2010 Interdecadal modulation of the impact of ENSO on precipitation and temperature over the United States J. Clim. 23 3639–56
Nakamura H 1992 Midwinter suppression of baroclinic wave activity in the Pacific J. Atmos. Sci. 49 1629–42
Nakamura H, Izumi T and Sampe T 2002 Interannual and decadal modulations recently observed in the Pacific stormtrack activity and East Asian winter monsoon J. Clim. 15 1855–74
Nakamura H and Sampe T 2002 Trapping of synoptic-scale disturbances into the North-Pacific subtropical jet core in midwinter Geophys. Res. Lett. 29 8–1
Orlanski I 2005 A new look at the pacific storm track variability: sensitivity to tropical SSTs and to upstream seeding J. Atmos. Sci. 62 1367–90
Penny S M, Battisti D S and Roe G H 2013 Examining mechanisms of variability within the Pacific Storm Track: upstream Seeding and Jet-Core Strength J. Clim. 26 5242–59
Rayner N A, Parker D E, Horton C K, Alexander L V, Rowell D P, Kent E C and Kaplan A 2003 Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century J. Geophys. Res. 108 4407
Ren H-L and Jin -F-F 2011 Niño indices for two types of ENSO Geophys. Res. Lett. 38 L04704
Straus D M and Shukla J 1997 Variations of midlatitude transient dynamics associated with ENSO J. Atmos. Sci. 54 777–90
Takahashi C and Shirooka R 2014 Storm track activity over the North Pacific associated with the Madden-Julian Oscillation under ENSO conditions during boreal winter J. Geophys. Res. Atmos. 119 10663–83
Tan W, Wang X, Wang W, Wang C and Zuo J 2016 Different responses of sea surface temperature in the South China sea to various El Niño events during boreal Autumn J. Clim. 29 1127–42
Trenberth K E and Hurrell J W 1994 Decadal atmosphere ocean variations in the Pacific Clim. Dyn. 9 303–19
Wallace J M, Lim G and Blackmon M L 1988 Relationship between cyclone tracks, anticyclone tracks and baroclinic waveguides J. Atmos. Sci. 45 439–62
Wang J, Kim H and Chang E K M 2017 Changes in Northern Hemisphere winter storm tracks under the background of Arctic amplification J. Clim. 30 3705–24
Wang X, Chen M, Wang C, Ye S-W and Tan W 2019 Evaluation of performance of CMIP5 models in simulating the North Pacific Oscillation and El Niño Modoki Clim. Dyn. 52 1383–94
Wang X, Tan W and Wang C 2018 A new index for identifying different types of El Niño Modoki events Clim. Dyn. 50 2753–65
Wang X, Zhou W, Li C and Wang D 2014 Comparison of the impact of two types of El Niño on tropical cyclone genesis over the South China Sea Int. J. Climatol. 34 2651–60
Yang M, Tan Y, Li X, Chen X, Zhang C and Yu P 2020 Influence of cumulus convection schemes on winter North Pacific storm tracks in the regional climate model RegCM4.5 Int. J. Climatol. 40 1294–305
Yu J-Y and Kao H-Y 2007 Decadal changes of ENSO persistence barrier in SST and ocean heat content indices: 1958–2001 J. Geophys. Res. 112 L04
Zhang R H, Sumi A and Kimoto M 1996 Impact of El Niño on the regional climate model RegCM4.5 Int. J. Climatol. 34 2651–60
Zhao Y and Liang X 2019 Causes and underlying dynamic processes of the mid-winter suppression in the North Pacific storm track Sci. China Earth Sci. 62 872–90