A decadal abruption of midwinter storm tracks over North Pacific from 1951 to 2010

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ABSTRACT

Based on 60-year (1951–2010) reanalysis data of the National Oceanic and Atmospheric Administration and extended reconstructed sea surface temperatures, a detailed investigation was conducted to explore the midwinter storm track changes over the North Pacific. The root-mean-square (rms) of subweekly (2.5–6 days) transient of 300 hPa geopotential height field was calculated to represent the storm track. A decadal abruption occurred in 1982/1983, according to the Mann–Kendall test result. The first two Empirical Orthogonal Function (EOF) spatial patterns of the North Pacific storm track during P1 (1955–1982) and P2 (1983–2010) revealed opposite results: The EOF1 during P1 and the EOF2 during P2 revealed changes of intensity of the midwinter storm track in the North Pacific, whereas the EOF2 during P1 and the EOF1 during P2 exhibited a southward/northward shift of its central axis. In addition, pronounced differences in the thermal influence of the ocean on the storm track during P1 and P2 existed. A strong and sustained ENSO signal contributed to a storm track variation through the westerly jet from 1955 to 1982, as the storm track was observed to strengthen and shift equatorward during El Niño events. From 1983 to 2010, an apparent sea temperature frontal zone at approximately 40°N and the associated near-surface baroclinicity resulted in the organization of a prominent mid-latitude storm track throughout the depth of the troposphere.

1. Introduction

One of the primary features of middle and high latitude atmospheric circulation is transient variability. In the 1970s, Blackmon (1976) first defined a 2.5–6-day synoptic transient eddy region over the ocean as a ‘storm track.’ Since then, both observational research and theoretical study have revealed the importance of the storm track in the forecasting of cold air outbreaks at mid-latitude, its feedback to the time mean flow, and the momentum transport between the tropical and high-latitude atmosphere (Christoph, Ulbrich, and Speth 1997; Chang, Lee, and Swanson 2002; Chen et al. 2013; Zhu, Yuan, and Chen 2013; Gu et al. 2013).

Using a stationary wave model and an idealized global circulation model, Chang and Guo (2007) conducted experiments to determine that enhanced tropical heating forces a stronger and narrower Pacific jet and storm track. Orlanski (2005) used a high-resolution non-hydrostatic model with explicit convection to simulate the Pacific storm track (PST) and its sensitivity to tropical sea surface temperatures (SSTs) and natural variability. It is revealed that the storm track variability and its feedback to the quasi-stationary circulation were shown to depend on mid-Pacific baroclinicity, which is controlled by tropical SST and the strength of the upstream seeding. Chang, Lee, and Swanson (2002) summarized the relationship between the ENSO cycle and the large shifts in storm
track structure. On the interannual timescale, the PST shifts equatorward and downstream during the El Niño years, apparently in response to the local enhancement of the Hadley circulation over the eastern Pacific (Bjerknes 1966; Zhou and Wang 2008), while La Niña events mark opposite shifts. On the decadal timescale, Chang and Fu (2002) also observed that even if ENSO-like interdecadal variabilities are removed, the residual storm track data still exhibits significant interdecadal variability, which indicates that attributing all of these storm track structural changes to the direct tropical forcing is not appropriate.

Gan and Wu (2013) revealed that the mid-latitude warm (cold) SST anomalies in the preceding fall could remarkably reduce (enhance) the storm track activities in early winter through changes in the tropospheric baroclinicity. He, Deng, and Zhu (2009) determined that the anomalous sea ice area over the southwestern Sea of Okhotsk, together with the associated North Pacific SST anomaly (SSTA), can exert significant influence on the variability in the strength and extension (contraction) of the PST. However, the sea ice area anomalies over the northeastern Sea of Okhotsk and the associated North Pacific SSTA primarily affect the strength and South–North movement of the storm track.

In 1992, Nakamura discovered the midwinter suppression phenomenon in which the strength of the midwinter PST in January is weaker than that in autumn or early spring. This suppression occurs despite the fact that the low-level baroclinicity and the intensity of the jet stream are strongest in midwinter. He also noted that the baroclinic wave activity over the Pacific Ocean is positively correlated with the strength of the upper-tropospheric jet for wind speeds up to 45 m s$^{-1}$ (Nakamura 1992). Nakamura and Sampe (2002) further explained the possible effect of the westerly jet on the storm track midwinter suppression. As the East Asian winter monsoon intensifies, eddies with subweekly periods propagating through the mid-latitude tropopause into the storm track tend to be trapped in the jet core, which is 1,000 km from the surface baroclinic zone. The trapping weakens the interaction between the upper-level eddies and baroclinic zone, thus contributing to the midwinter minimum in the eddy activity. An energy analysis (Chen, Zhu, and Yuan 2013) showed in midwinter, with large decreases in the baroclinic energy conversion and barotropic energy conversion, a remarkable net loss in the eddy kinetic energy might lead directly to the midwinter suppression of the North PST.

Thus far, many studies have revealed the interdecadal variations in winter (November–December–January) and midwinter (January) PST. Chang and Fu (2002, 2003) examined the interdecadal changes over 1949–1999 and found there was a remarkable transition during the early 1970s from a weak state prior to 1972/73 to a strong state subsequently. Lee et al. (2012) achieved a consistent conclusion and pointed out that midwinter PST underwent decadal change from a weak regime in the early 1980s to a strong regime in the late 1980s. But the main reason dominating the peaks and valleys at each stage have not yet to be discussed. Therefore, in our study, the temporal and spatial variability of the midwinter storm track over the North Pacific was explored using the Empirical Orthogonal Function (EOF) method. A significant decadal abrupton was observed in approximately 1982/1983, and changes in the thermal influence of the ocean and associated atmospheric circulation are discussed. This paper has certain innovations and provides a basic reference for further study of the midwinter storm track characteristics.

2. Data and methods

2.1. Data

Sixty-year (1951–2010) atmospheric variables, including zonal wind velocity, geopotential height, and air temperature, were obtained from NOAA at a horizontal resolution of 2.5° × 2.5° (Kalnay et al. 1996). SST data were extracted from the Met Office Hadley Centre Sea Ice and Sea Surface Temperature version 1 (HadISST1) data-set with a 1° spatial resolution (Rayner et al. 2003).

2.2. Definition of storm track

A storm track is defined as a region where the subweekly transient disturbance is the most intensive over the oceans. In the Eulerian method, Blackmon (1976) showed that the bandpass-filtered (2.5–6 days) root-mean-square (rms) of geopotential height for the Northern Hemisphere (NH) correspond significantly with the locations of maximum synoptic-scale cyclone activity. Therefore, in this study, we identified the storm tracks as the rms of subweekly transient of the 300 hPa geopotential height. Subweekly (2.5–6 days) transient fluctuations were derived from the daily 300 hPa geopotential height on the basis of the Butterworth bandpass filter. Then we calculated the Standard Deviation month by month to represent the storm track.

2.3. Eddy growth rate (baroclinicity)

As the synoptic scale disturbance is closely related to the mid-latitude atmospheric baroclinicity, we used the Eddy growth rate index ($\sigma$) (Lindzen and Farrell 1980) given by:

$$\sigma_{BI} = 0.31 \times f \times \frac{\partial |\mathbf{V}|/\partial z}{N}$$

where $BI$ means baroclinic instability, $f$ is the Coriolis parameter, $\mathbf{V}$ is the horizontal wind speed, $z$ is the vertical depth, and $N$ represents the static stability.
where \( \Omega \) is the self-rotating angular velocity of the earth, \( \phi \) is latitude, \( g \) is the gravity parameter, and \( \theta \) represents the potential temperature.

3. Results

3.1. Climatological distribution and Mann–Kendall test

Figure 1(a) shows the 60-year climatology of the January storm track (the rms of the subweekly transient 300 hPa geopotential height field) over the North Pacific Ocean averaged from 1951 to 2010. The storm track shows a zonal distribution at mid-latitude, with the axis located at 40–45°N, 160°E–160°W. The maximum intensity exceeds 60 gpm in the central zone. To analyze the intensity changes of the storm track, a new storm track index (STI) was defined as a regional average of storm track values over 34–48°N, 150°E–150°W.

$$ f = 2 \times \Omega \times \sin \phi $$

$$ N^2 = \frac{g \times \theta \times \partial \theta}{\theta \times \partial z} $$

A non-parameter Mann–Kendall test method was applied to analyze the trend and abruptness of STI during the 60 years. As shown in Figure 1(b), there has been a rising trend of the storm track strength since 1980, as the UF is greater than 0 from this year and reached 1.98 in 2007. The intersection of UF and UB illustrates that an abrupt decadal change occurred in 1982/1983 (at a significance level of 0.05). To further explore its changing mechanism, we divided our research scope into two periods: P1 (1955–1982) and P2 (1983–2010) due to this abruptness.

3.2. EOF results

The EOF method was used to analyze the main storm track modes in the North Pacific for the two periods. During P1, the explained variances of the first two EOF (EOF1 and EOF2) eigenvectors are 18% and 17%, respectively. Similarly, the variances occupied 17% and 15% in P2. This result implies that multiple modes coexisted in the storm track changes in January, due to the transient characteristics of the storm track. More specifically, the EOF results in the two periods revealed a significant difference. The first
spatial pattern during P1 (Figure 2(a)) presented a peak in the heartland, indicating a general increase in the storm track intensity over the central axis. The EOF2 during P1 (Figure 2(b)) exhibited a northwest (−)–southeast (+) dipole form distributed on both sides of the climatological storm track axis, reflecting the southeastward/northwestward
4. Correlations of the storm track with the Pacific SST

As mentioned in Section 3.1, we divided the STI into 2 stages: P1 (1955–1982) and P2 (1983–2010), according to the Mann–Kendall test result. To explore the potential connection between the storm track strength in January and the SST over the Pacific, correlations of the preceding and simultaneous Pacific SST with the STI were calculated separately in P1 and P2.

Figure 3 shows that the correlations between STI and contemporaneous SST during P1 exceed 0.5 over the equatorial central and eastern Pacific, which indicates an intense El Niño event. Similarly, the correlations between STI and the Pacific SST anomalies which lead storm track by
one to six months were also calculated. The results are provided in Figure A1 in the Appendix. This result implies that following a strong sustained (at least seven months) signal of El Niño, the central storm track intensity was enhanced. In addition, a significant negative correlation coefficient (CC) existed over the Okhotsk Sea and the Western Bering Sea (Figure 3(a)), which suggests that the cooler Okhotsk and western Bering SST might also contribute to the reinforced storm track in January.

During P2, a clear dipole form is presented in Figure 3(b). A significant negative CC between STI and Pacific SST was largely distributed over the Okhotsk Sea and Bering Sea areas, reaching −0.5 in the central regions. On its south side, a smaller significant positive CC occurred in the central Pacific Ocean. This result could suggest that as the Okhotsk and Bering SST decreased and the central Pacific SST increased, the meridional SST gradient between them was enhanced, forming a tight oceanic frontal zone at approximately 40°N (Sampe et al. 2010). Further explanation will be provided in the next section based on the observations.

Although a similar significant negative correlation was discovered over the Okhotsk and Bering seas during two periods, pronounced differences in the thermal influence of the ocean on mid-latitude storm track exist. A strong and sustained ENSO signal plays a dominant role in the storm track variation during 1955–1982, while the SST frontal zone in P2 might lead to the formation and maintenance of the storm track.

5. Atmospheric circulation related to the storm track variations

The question arose as to how different SST regions in P1 and P2 have a different influence on the storm track intensity. To answer this question, the atmospheric circulation over the North Pacific was investigated.

Strong El Niño and La Niña years were selected separately due to the great influence of the ENSO cycle on the storm track during 1954–1981. On the basis of the Oceanic Niño Index (ONI) data from NOAA, years with ONI values greater than 0.5 and lasting for at least five months were regarded as El Niño years; those with ONI values smaller than −0.5 and lasting for a minimum of five months were considered La Niña years. Therefore, we selected nine strong El Niño years and eight La Niña years.

The rms of subweekly transient 300 hPa geopotential height field was averaged over the El Niño and La Niña years. Moreover, the synthetic difference field was also determined. The storm track shifted equatorward in El Niño events, with the central intensity exceeding 65 gpm (Figure 4(a)). In La Niña years, the strength was 55 gpm in the central zone and the axis marked an opposite shift (Figure 4(b)). The difference field (Figure 4(c)) showed the same result: the storm track was remarkably strengthened during El Niño years and moved equatorward. Meanwhile, the synthetic difference field of 200 hPa westerly jet shown in Figure 4(d) illustrates a coordinated variation in correspondence with the storm track changes. The westerly jet in the upper troposphere was conspicuously strengthened over the 20–40°N and shifted equatorward in El Niño years. A strong and sustained ENSO signal contributed to the storm track variation through the westerly jet during 1955–1982.

According to Chang, Lee, and Swanson (2002), the westerly stream intensifies in El Niño years, primarily due to the local enhancement of the Hadley circulation over the eastern Pacific. In addition, coordinated activities between the westerly jet and the storm track have been proven by several studies (Nakamura 1992; Zhu and Sun 2000a; Harnik and Chang 2004; Han, Ren, and Yang 2007; Ren, Yang, and Chu 2010; Huang and Liu 2011). In general, the storm track intensifies in accordance with the reinforced westerly jet and is normally located on the downstream and equatorward side of the jet axis.

More specifically, Nakamura and Sampe (2002) proposed that the subtropical jet and polar front jet play different roles in storm track changes. As the subtropical jet develops in some winters, the subweekly eddies tend to be trapped in the jet core, thus acting against the eddy amplification. However, Sampe et al. (2010) also proved that a polar front jet is formed and maintained, which is consistent with a SST front and meridional momentum transport (E–P flux) from eddies. An additional detailed mechanism is needed to explain the consistent changes of the westerly jet and storm track during the ENSO cycle in the future.

Based on the correlation results in Section 4, an apparent sea temperature frontal zone forms at approximately 40°N during 1983–2010. The meridional SST gradient averaged between 150°E and 150°W was calculated each year in P2. The strong and weak oceanic front years were selected separately due to the meridional SST gradient averaged from 36 to 44°N. Therefore, we obtained eight strong oceanic front years and six weak front years. The meridional SST gradients and the baroclinicity (eddy growth rate) fields throughout the troposphere were averaged over the strong and weak front years separately. The synthetic difference field of the storm track was also obtained.

Figure 5(a) illustrates that the peak gradient arrived up to 1.2 °C at approximately 40°N in the strong front years, which is in accordance with the north (+)–south (–) dipole form on the correlation map. Correspondingly, a vigorous near-surface baroclinicity was reinforced above the sharp SST front at approximately 37°N (Figure 5(c)).
Figure 4. (a) The storm track averaged over eight El Niño years during P1. (b) The storm track averaged over nine La Niña years. (c) The difference between El Niño and La Niña years during P1. (d) The 200 hPa westerly jet difference between El Niño and La Niña years during P1. The shaded regions show the 90% significance level.
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higher than surface air temperature (SAT), while at its poleward flank, SAT is higher than SST. In correspondence, this results in a peak of surface SHF at the equatorward flank of the front and a sharp decrease of SHF poleward across it. The sharp decline in heat supply leads to the development of near-surface baroclinicity. Therefore, the strong near-surface baroclinicity associated with the SST front enhances baroclinic eddy growth as a whole, leading to the organization of a prominent mid-latitude storm track throughout the depth of the troposphere.

Meanwhile, the synthetic difference field of the storm track (Figure 5(e)) exhibited a strengthening trend along the oceanic frontal zone, with an equatorward shift of the core axis.

The mechanism of the mid-latitude SST front affecting the storm track was explained clearly by Zhu and Sun (2000b), Nakamura et al. (2004) and Sampe et al. (2010). The tight SST gradient maintains the near-surface baroclinicity through the surface sensible heat flux (SHF). Specifically, at the equatorward flank of the frontal zone, the SST is higher than surface air temperature (SAT), while at its poleward flank, SAT is higher than SST. In correspondence, this results in a peak of surface SHF at the equatorward flank of the front and a sharp decrease of SHF poleward across it. The sharp decline in heat supply leads to the development of near-surface baroclinicity. Therefore, the strong near-surface baroclinicity associated with the SST front enhances baroclinic eddy growth as a whole, leading to the organization of a prominent mid-latitude storm track throughout the depth of the troposphere.

Figure 5. (a) SST gradient averaged over eight strong front years during P2. (b) Same as (a) but for six weak front years. (c) Baroclinicity throughout the troposphere averaged over eight strong front years during P2. (d) Same as (c) but for six weak front years. (e) Storm track difference between strong and weak front years during P2. The shaded regions show the 90% significance level.
6. Conclusions and remaining questions

In this study, a decadal abrupt change of a midwinter storm track over the North Pacific was discovered. According to the Mann–Kendall test result, the storm track intensified from 1980 to 2010, and the significant abruption occurred in 1982/1983. To further explore its changing mechanism, we divided the storm track into two periods: P1 (1955–1982) and P2 (1983–2010).

The EOF results in the two periods revealed a significant difference. EOF1 of the midwinter storm track in P1 and EOF2 of P2 both indicated changes of intensity in the North Pacific, whereas EOF2 of P1 and EOF1 of P2 exhibited a southward/northward shift of the central axis. Although the first two spatial patterns are presented in opposite results and their explained variances are less significant than the large-scale circulation field due to the highly nonlinear and stochastic processes of transient activities, the two distinctive features of the storm track have been clearly revealed. Therefore, these two characteristics were primarily discussed in this paper.

The correlations between the leading and coincident Pacific SST and STI in P1 and P2 indicate that pronounced differences in the thermal influence of the ocean on the storm track exist. A strong and sustained ENSO signal played a dominant role in storm track variation during 1955–1982. The westerly stream intensified during El Niño events in response to the local reinforcement of the Hadley circulation over the eastern Pacific. Generally, the storm track intensified in accordance with the enhancement of the westerly jet and was located at the downstream and equatorward side of the jet core. We could infer that a strong and sustained ENSO signal contributes to storm track variation through the westerly jet.

From 1983 to 2010, an apparent sea temperature frontal zone formed between the Okhotsk Sea and the central Pacific, maintaining the near-surface baroclinicity through surface SHF. Across-frontal differential sensible heat supply from the ocean retained an intense near-surface baroclinicity, as is observed along the oceanic frontal zone. Therefore, the strong near-surface baroclinicity associated with the SST front enhanced the baroclinic eddy growth as a whole, leading to the organization of a prominent mid-latitude storm track throughout the depth of the troposphere.

Why the storm track activity in P2 is stronger than in P1 along with the sustained ENSO signal disappearing during P2? Combining the conclusion of Lee et al. (2012), we could infer that the remarkable meridional SST gradient during P2, which is located over storm track entrance area, could intensify the storm track directly through the enhancement of local baroclinic eddy growth. While the strong tropical heating in P1 could only influence the mid-latitude storm track indirectly through enhancement of Hadley circulation and westerly jet. In addition, some recent discoveries indicate that the subtropical jet and polar front jet play different roles in storm track changes. Therefore, further studies are needed to reveal the disappearance of ENSO signal during P2 and the mechanism of how ENSO affects the storm track.

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Figure A1. The correlation between the January storm track and the Pacific SST that lead storm track by (a) six months, (b) five months, (c) four months, (d) three months, (e) two months, and (f) one month from 1955 to 1982.