Air-sea heat flux under the weather of winter cyclone in the Northwest Pacific during Western Pacific Jet Stream anomaly

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Abstract. The trajectories of the winter cyclone and the thermal field anomaly over the Northwest Pacific Ocean were studied with the atmospheric reanalysis data (from the NCEP/NCAR) and the SST’s observational data (from the Met Office Hadley Centre and the National Climatic Data Center of NOAA). The results showed that the thermal field would change as a response to the circulation shift (e.g. meridional motion of the WPJS). When the WPJS leaned to the north, SHF and LHF would be positive (negative) anomaly in the mid-high (low) latitude, while Qs and SST presented negative anomaly in the mid-high latitude. As a result, the dipole-pattern (+ -) of air temperature anomaly moved northward, which made the storm track leaned to the north. In the opposite, the storm track would lean to the south. On the other hand, if most of the cyclones in the whole winter changed the paths, the transport process of the heat flux, the kinetic energy and the vapor would be significantly different. As a result, there is discrepancy in storm-induced SHF anomaly, LHF anomaly, SST anomaly, and Qs anomaly, compared to other years. Finally, we found the storm-induced thermal field anomaly is comparable to the thermal field climate anomaly.

1. Introduction
In meteorology, a cyclone/anticyclone is a large scale air mass that rotates around a strong center of low/high atmospheric pressure. One of the major features in the winter of mid-latitude region is frequent cyclone activity, which is important to the earth system. In the energy budget, it brings the atmospheric heat, kinetic energy and fresh water from the mid-latitude to the high-latitude, and keeps the energy balance of the atmosphere \cite{1}. As an important role in the air-sea interaction study, cyclones always attract a lot of scientists’ attention. There are two ways to study the fluid dynamics: Euler’s method and Lagrange’s method. With Euler’s method, Blackman \cite{2} defined the storm track as the region where the cyclone appears frequently. Thus, there were two storm tracks during the winter in the Northern Hemisphere: mid-latitude of Pacific Ocean and Atlantic Ocean. Zhu and Sun \cite{3,4} analyzed daily reanalysis data over 16 years (1979-1994) and suggested there was inter-annual variation in the strength and the location of North Pacific storm track, which was related to the El Nino-Southern Oscillation. In the year of El Nino (La Nina), the North Pacific storm track moved southeastward (northwestward) \cite{5}. Han et al. \cite{6} found the North Pacific storm track anomaly was consistent from the upper layer to the lower layer. Ren et al. \cite{7,8} used Empirical Orthogonal Function (EOF) and Singular Value Decomposition (SVD) analysis to study the atmospheric transient eddies over the North Pacific, and discussed the relationship between the large scale air-sea couple patterns and the synoptic transient eddies.
Recently, more and more scientists paid attention to the air-sea interaction over the Pacific Ocean. Yang et al. [9, 10] found the Pacific Decadal Oscillation (PDO) was related to the precipitation of China and atmospheric circulation. Ren and Qian [11] analyzed how summer precipitation of Southeast China is influenced by latent heat flux (LHF) transport in the winter of South China Sea. With Lagrange method, Zhan et al. [12] explained there was significant and consistent relationship between the Pacific Ocean temperature and the extratropical cyclone of East Asia. Zhang et al. [13] pointed out that air-sea interaction in the Pacific region was strongest during the winter. However, they missed to notice the air-sea interaction under the winter storm.

As the observational technique and the numerical simulation developed, more and more scientists started to study the cyclone evolution with Lagrange method. Neiman and Shapiro [14] described the evolution of the atmosphere-ocean system through cyclone’s whole lifetime, with multiple datasets (from the ocean, the atmosphere and the land). Ren et al. [15] compared with the numerical results and the observations, and found which thermal fields gave contributions to the cyclone evolution. The scientists also suggested the winter cyclones would have meridional motion following the Aleutian Low.

For the scientists, some of them used Euler’s method to study the winter air-sea interaction in the North Pacific; while some of them used Lagrange’s method to explain how cyclone trajectory was influenced by the atmospheric circulation. However, they never studied the winter air-sea interaction in the North Pacific with Lagrange’s method. We would like to complete this goal and find the discrepancy with different methods to study the winter air-sea interaction. This paper is arranged as follows. In Section 2, we introduce the datasets and analysis methods. In Section 3, we analyze results with two different methods. In Section 4, we provide a summary and identify future research topics.

2. Datasets and methods
Dataset used in this study are (1) Monthly and Six hourly atmospheric reanalysis data from National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP/NCAR); (2) monthly sea surface temperature (SST) data from Met Office Hadley Centre; (3) daily SST data from the National Climatic Data Center of National Ocean and Atmosphere Administration (NOAA). Sea level pressure (SLP) we use is six hourly reanalysis data with a resolution of 2.5°×2.5°. For LHF, sensible heat flux (SHF) and specific humidity (Qs), we use both monthly and six hourly reanalysis data, which used Gaussian grid with grid number 192×94. The resolutions of monthly and daily SST data are 1°×1° and 0.25°×0.25°, respectively.

In this paper, the region we studied is 20°N~70°N, 120°E~240°W over the Northwest Pacific. The winter season is defined as December and the following January, February and March. And the climate mean is defined as average of winter during 1958 to 2007. The climate anomaly means difference from climate mean.

The cyclone’s trajectory showed the location of the cyclone center, which is defined as the minimum of the SLP. For the cyclone evolution history, we have four criterions to define the initial stage of the cyclone: (1) the SLP of the cyclone center is lower than 1010 hPa, (2) there are more than two closed contours, (3) the cyclone center is in the region of 25°N-50°N, 100°E-180°E, (4) the cyclone center is not on the continent. The mature stage of the cyclone is defined as when the SLP arrive the smallest value through cyclone’s whole lifetime. When the closed contours decreased to no more than 2, or the cyclone center arrive the continent, we think the cyclone is dead. When the seasonal mean of the winter Western Pacific Jet Stream (WPJS) leans northward, we define it a JMN year. When the seasonal mean of the winter WPJS leans south ward, we define it a JMS year.
3. Results

3.1. The trajectories of the winter storm

Ren and Zhang [16] used Euler’s method to study the WPJS during the winter. With EOF analysis, they found there were 3 modes of WPJS anomaly. The first mode represents the strength of the Western Wind above the Pacific Ocean, which is related to ENSO. The second mode explains the strength anomaly of the WPJS. And the third mode shows the meridional motion of the WPJS.

In this study, we focus on the third mode. We employ Lagrange’s method study the cyclone with the assumption that storm track would move following the WPJS. In the third mode, there are 11 years that the absolute value of the principal component (PC) is larger than 1.1 (not shown), and they are selected as the object of the study. In the winter of 1959, 1960, 1987, 1998 and 2000, the WPJS leaned northward, while in the winter of 1961, 1962, 1967, 1980, 1990 and 1995, the WPJS leaned southward.

![Figure 1](image-url)

**Figure 1.** The trajectories of the winter cyclones in a (a) JMN or (b) JMS year. The frequencies of the winter cyclones appear in a (c) JMN or (d) JMS year. (e) The averaged location of winter storm track in each year is presented as × (+) in a JMN (JMS) year. And the averaged location of winter storm track in all JMN (JMS) years is presented as ⊕ (Ⅲ).

With Lagrange’s method, we traced all winter cyclones in the 11 years (figure 1a, b). Consider the trajectories of different cyclones may be the same, and lead to being ignored in trajectory figure; we analyzed the frequencies of the winter cyclones appear in the whole region. In a JMN year (PC is positive); the winter cyclones are more likely to appear to the north of 50°N (figure 1c). As annual mean of the trajectories, the averaged storm track in winter is located to the north of 46.5°N in each JMN year (figure 1e), and the averaged location of storm track in all JMN years is 174.91°E, 47.71°N. In the opposite, in a JMS year (PC is negative); the winter cyclones are more likely to appear to the south of 50°N (figure 1d). As annual mean of the trajectories, the averaged storm track in winter is located to the south of 46.5°N in each JMS year (figure 1e), and the averaged location of storm track
in all JMS years is 172.37°E, 45.34°N. The results showed the storm track did move following the WPJS in the meridional direction.

3.2. Climate anomaly of the thermal field
In JMN years, the seasonal averaged SHF and LHF were positive anomaly near the coast of Northwest Pacific; where it could reach up to more than 20 $\text{wm}^{-2}$. The maximum of the anomaly were found in the mid-latitude. In JMS years, the seasonal averaged SHF and LHF were negative anomaly in the mid-high latitude. It reached -10 $\text{wm}^{-2}$ and -30 $\text{wm}^{-2}$ at Northeast of Japan and Bering Strait, respectively. The seasonal averaged SHF and LHF were positive anomaly to the south of Japan, where it could reach up to more than 20 $\text{wm}^{-2}$.

![Figure 2](image_url)

**Figure 2.** SHF climate anomaly in (a) JMN and (b) JMS years are presented; also there is (c) difference between (a) and (b); LHF climate anomaly in (d) JMN and (e) JMS years are presented; also there is (f) difference between (d) and jet (e). Unit: $\text{wm}^{-2}$.

Compared with SHF (figure 2c) and LHF (figure 2f) climate anomaly between JMN and JMS years, there was considerable discrepancy when the WPJS moved in the meridional direction. The discrepancy of LHF climate anomaly was larger in the mid-latitude, which was positive anomaly and could reach up to more than 40 $\text{wm}^{-2}$, while the discrepancy of SHF climate anomaly here was only 20 $\text{wm}^{-2}$. However, in the subtropical region, the discrepancy of SHF climate anomaly was more significant, which was negative anomaly and could reach up to lower than -30 $\text{wm}^{-2}$. As a climate feature, when the SHF and LHF climate anomaly were positive (negative) in the mid-latitude (subtropical) region, a lot of heat was released (lost) in the mid-latitude (subtropical) region, and warmed (cooled) the atmosphere. As a result, the dipole pattern (+-) of the 2-m air temperature anomaly moved northward from lower latitude (not shown); which led to the storm track moving northward, vice versa.

Contrary to SHF and LHF, the seasonal averaged $Q_s$ (figure 3a) and SST (figure 3b) were positive (negative) anomaly in the subtropical (mid-latitude) region in a JMN year, and negative (positive) anomaly in the subtropical (mid-latitude) region in a JMS year (figure 3c, d). The absolute value of
anomaly in both of the mid-latitude and subtropical region reached up to 0.5 (°C or g/kg). In the subtropical region, the seasonal averaged Qs anomaly could reach up to 1 g/kg. There were also considerable discrepancies of Qs (figure 3e) and SST (figure 3f) climate anomaly between the JMN and JMS years. When the seasonal averaged Qs and SST were negative (positive) anomaly in the mid-latitude (subtropical) region, the storm track moved northward, vice versa.

The SHF is determined by the wind speed, SST and 2-m air temperature. Compared with the climate anomaly pattern, we figured SST is the principle factor to SHF anomaly, as their climate anomaly patterns (figure 2e and figure 3b) were nearly the same but with opposite sign. For the LHF, it is determined by the Qs, SST, wind speed, and 2-m air temperature, we found it was more likely to be a result influenced by several factors instead of a single factor.

Figure 3. Qs climate anomaly in (a) JMN and (b) JMS years are presented, and there is (c) difference between (a) and (b); unit: g/kg. SST climate anomaly in (d) JMN and (e) JMS years are presented; also there is (f) difference between (d) and (e), unit: °C.

3.3. The thermal field anomaly induced by cyclone activities
In the previous section, we confirmed the storm track would move in the meridional direction as a result of the atmosphere-ocean system anomaly. In this section, we would study the relationship between cyclone and thermal field with Lagrange’s method. By calculating the average of the thermal field at the mature stage of all the cyclones in JMN and JMS years separately, we would analyze the thermal field anomaly when there is cyclone anomaly during the whole winter. (Note: Because the AVHRR SST data began at January 1981, thus, the SST was analyzed with two JMN and JMS years. However, we found the results still proved what we assumed.)

In this section, the mature stage anomaly (MSA) is defined as mean discrepancy between the JMN and JMS years at the mature stage of all cyclones. The MSA of SHF (figure 4a) and LHF (figure 4b) were positive (negative) at mid-latitude (subtropical) region. We found the distribution of SHF and LHF’s MSA were similar to the climate anomaly discrepancy between JMN and JMS years but with different magnitude, and the sign of SHF and LHF’s MSA was even more uniformed along the same latitude. The MSA of the Qs (figure 4c) and the SST (figure 4d) were also similar to the climate
anomaly discrepancy between the JMN and JMS years; only the absolute value was even larger in the MSA. Compare with figure 4 a, b, c, d and figure 2c, f, figure 3c, f, we found the pattern of the thermal fields’ MSA were similar to their climate anomaly discrepancy between the JMN and JMS years, which proved the distribution of thermal fields at cyclones’ mature stage could present the thermal fields’ climate status.

Figure 4. Calculate the mean of the thermal field at mature stage of all cyclones in JMN and JMS years, the differences are shown as (a) SHF, (b) LHF, unit: $wm^{-2}$, (c) $Qs$, unit: $g/kg$, and (d) SST, unit: $°c$.

4. Summary and discussions
In this study, we analyzed the climatic and synoptic thermal field, such as SHF, LHF, $Qs$, and SST, and we can conclude as followed.

(1) The thermal field of the atmosphere-ocean system would be influenced by the effect of large scale circulation anomaly, which also changed the location of storm track. When the SHF and LHF climate anomaly were positive (negative) in the mid-high latitude (low latitude) and the SST climate anomaly was negative (positive) in the mid-high latitude (low latitude), which resulted in the dipole pattern of the air temperature moving northward. Thus, the storm track moved northward, vice versa.

(2) When most of the cyclones in the whole winter changed the paths, the heat flux, momentum and vapor transport would be influenced, and the thermal field anomaly appears. We found the thermal field anomaly induced by cyclone activities is comparable to the climate anomaly, which confirmed we had the same conclusion in two different scale studies.

In the future, we would like to answer these questions. (1) What is the mechanism of cyclone-induced thermal field anomaly? (2) How does synoptic system (e.g. Subtropical High) change the thermal field in atmosphere and ocean? (3) Would the storm track move in other directions besides in the meridional direction?

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