Impact of Nonuniform Land Surface Warming on Summer Anomalous Extratropical Cyclone Activity Over East Asia

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Abstract As one of the typical midlatitude synoptic-scale disturbances, extratropical cyclones (ECs) can exert significant impacts on the atmospheric general circulation through its interaction with the time mean flow. Under the background of global warming, the Eurasian continent exhibits evident nonuniform warming, which has the potential to alter the atmospheric baroclinicity by changing the meridional temperature gradient and further affect the ECs activity. In this study, we investigated the possible connection between the land surface thermal anomaly over Eurasia and the summer ECs activity over East Asia together with relevant mechanisms. We found that the land surface warming (cooling) near 50⁰N of East Asia is associated with anomalous weak (strong) summer ECs activity over East Asia. Warm (cool) land surface usually reduces (increases) the meridional temperature gradient and further the atmospheric baroclinicity in the key area of cyclone activity, resulting in low (high) frequency of the extratropical cyclogenesis and weakened (intensified) ECs activity. The land surface warming (cooling) can also depress (benefit) the associated baroclinic conversion between the time mean effective potential energy and eddy effective potential energy, resulting in decrease (increase) in the eddy kinetic energy. As a result, the energy obtained by the synoptic-scale eddy from the time mean flow has been reduced (increased), which favors (hampers) the extratropical cyclogenesis, causing weak (strong) cyclone activity in the middle latitude of East Asia.

1. Introduction

Midlatitude disturbance is an important component of the East Asian summer monsoon (EASM) system (Tao & Chen, 1985). As one important type of synoptic-scale disturbances, extratropical cyclones (ECs) are regarded as important components of the atmospheric general circulation in the middle and high latitudes, playing a dominant role in the north-south exchange of energy. Anomalous activity of ECs can affect time mean flows and hence the EASM and climate (He et al., 2007; Huang, Chen, et al., 2003, Huang, Zhou, & Chen, 2003; Tao & Hu, 1994; Wu et al., 2003; Yin & Tao, 1997). Previous studies have paid much attention to both the climatology and variability of ECs in the Northern Hemisphere (Geng & Sugi, 2001; Lambert et al., 2002; Serreze et al., 1997). For instance, Ulbrich et al. (2009) and Zhang et al. (2012a) noted that two main centers of the ECs in the Northern Hemisphere appear in the North Atlantic and the North Pacific, and two other secondary active centers of cyclones are located in Asia and near the Mediterranean, respectively. The frequency, intensity, lifetime, and deepening rate of ECs all exhibit significant interannual and interdecadal variations. A number of studies indicate that the frequency and other statistics of the cyclones have changed evidently during recent decades. Cyclone activities in the North Atlantic, the North Pacific, and midlatitude regions have exhibited decadal weakening to various extents (Gulev et al., 2001; McCabe et al., 2001; Raible et al., 2008; Sickmöller et al., 2000; Wang et al., 2006; Zhang et al., 2012b). Many progresses have been made in studies of ECs in East Asia in recent years. For example, Zhang et al. (2012c) noted that ECs in East Asia originate primarily in three regions, that is, Mongolia, the region from the east coast of China to south of Japan, and western Siberia. ECs in northern East Asia exhibit distinct seasonal, interannual and interdecadal variations, and cyclones occur primarily in the region of 40–50⁰N, that is, the area of...
Mongolia (Lin & Yang, 1992; Wang & Guo, 2005; Wang & Wang, 2011; Wang, Jiang, et al., 2007, Wang, Zou, & Zhai, 2007; Yao et al., 2003).

The activities of ECs are usually closely related to the large-scale circulation and affected by the low-level jet and high-altitude troughs as well as the atmospheric teleconnections (Gulev et al., 2001; Lackmann, 2002; Strahl & Smith, 2001). The formation and development of ECs are affected by many factors, such as temperature and humidity advection, potential vorticity in the upper troposphere, low-level frontogenesis in the troposphere, diabatic heating, and latent heat release (Ahmadi-Givi et al., 2004; Beare, 2007; Martin & Otkin, 2004; Romero, 2008; Smith, 2000; Yoshida & Asuma, 2004). For a long time, the atmospheric baroclinic instability has been regarded as the main triggering mechanism of the midlatitude synoptic-scale weather system. Many studies indicate that the atmospheric baroclinicity is closely related to the activities of the ECs and storm tracks (Simmonds & Hoskins, 1978; Hoskins & Valdes, 1990; Lim & Simmonds, 2002, 2007). Simmonds & Hoskins (1978) suggested that synoptic-scale eddy activity in the storm track in the Northern Hemisphere could be explained by the development of the baroclinic waves. Hoskins & Valdes (1990) proposed the mechanisms of the formation and maintenance of winter storm tracks in the Northern Hemisphere based on the concept of atmospheric baroclinicity. Lim & Simmonds (2007) also investigated the impacts of variations in the tropospheric temperature on atmospheric baroclinicity, which is proposed to account for the variations and causes of winter ECs activity in the Southern Hemisphere. Lim & Simmonds (2002) studied the impact of atmospheric baroclinicity on the frequency of explosive cyclones, and their results indicate that the distribution of explosive cyclones in the Southern Hemisphere is closely related to the atmospheric baroclinicity. By comparing results from numerical experiments using dry and wet models, Hayashi & Golder (1981) pointed out that latent heat release can decrease the static stability of the atmosphere and favors the growth of baroclinic instability, which is conducive to the development of cyclones.

Previous studies indicate that in the context of global warming, land surface warming over Eurasia exhibits strong nonuniformity (Hansen et al., 2010, 2006; Xu, He, & Zhu, 2011; Xu, Zhu, & He, 2011; Zhou et al., 2015, 2016). It is found that significant summer land surface warming has been observed in the middle latitudes over East Asia, especially after the middle of the 1990s (Chen & Lu, 2014; Chen et al., 2017; Dong et al., 2016, 2017; Hong et al., 2017). Since part of the atmospheric baroclinicity originates from the meridional temperature gradient, nonuniform variations in the land surface thermal anomaly in Eurasia has the potential to affect the atmospheric baroclinicity via the changing meridional temperature gradient. Studies (Wang et al., 2009; Wu et al., 2010; Zhang et al., 2019) noted that the frequency of the EC activity evidently decreases after the early 1990s. Chen et al. (2017) pointed out that weakened EC activity after the early 1990s have the potential to influence the EASM via the synoptic-scale feedback, contributing to recent decadal weakening of EASM.

In this study, we investigated the possible relationship between variations in summer (June–July–August) land surface thermal anomaly over Eurasia and summer ECs activity in East Asia during 1979–2013 together with the relevant mechanisms, aiming to better understand how the variations in the land surface thermal anomaly in Eurasia affect EASM circulation system and climate in East Asia via ECs activities. The study was organized as follows. Section 2 describes the data and method. Section 3 presents the spatiotemporal variations of ECs in East Asia. Section 4 discusses the relationship between land surface thermal anomaly and ECs activity. Possible mechanisms are explored in section 5, and conclusion is drawn in section 6.

2. Data and Method

2.1. Data and Statistical Methods

The data used in this study are the European Centre for Medium-Range Weather Forecasts interim reanalysis data (Dee et al., 2011; http://apps.ecmwf.int/datasets/) with a horizontal resolution of 1.5° × 1.5° and 6-hr time interval, which covers 1979–2013. Meteorological variables used in this study include the geopotential height, horizontal and vertical wind velocities, temperature, sea surface pressure, and topography. Since the surface soil temperature can directly reflect the land surface thermal condition, we used the monthly average surface soil temperature (at depth of 0–7 cm) from European Centre for Medium-Range Weather Forecasts interim reanalysis to characterize the land surface thermal condition.
Statistical methods used in the current study include empirical orthogonal function (EOF) analysis, correlation, composite, and linear regression, and M-K test has been used in our analysis. Also, t test method was used to examine the statistical significance of the results.

2.2. Objective Identification and Tracking Algorithm for Cyclones

To acquire the statistics of the ECs, the objective identification and tracking algorithm for cyclones proposed by Murray & Simmonds (1991a, 1991b) and Simmonds & Keay (2000a, 2000b) was adopted. To quantitatively reflect the statistical feature of the EC activity, we define the number of cyclones generated in each 1.5 × 1.5 grid box as the cyclogenesis frequency by following Chen et al. (2017).

2.3. Equations of Energy Evolution and Diagnostics

Due to the midlatitude baroclinic meridional disturbances, the energy of midlatitude atmospheric motion can be converted from effective potential energy of time mean flow to eddy effective potential energy, which is then converted to eddy kinetic energy; the synoptic-scale eddy thereby obtains its energy from the time mean flow (Oort & Peixóto, 1974). To investigate the specific processes involved in the energy conversion, we referred to Chang & Orlanski (1993), Chen et al. (2013), Orlanski & Katzfey (1991), and Zhu & Sun (2001), and derived the equations of eddy effective potential energy and eddy kinetic energy based on the kinetic, thermodynamic, and hydrostatic equations:

\[
\frac{\partial \mathcal{A}_e}{\partial t} = -\nabla \cdot \mathbf{v} \mathcal{A}_e = \left( \mathbf{V} \cdot \nabla \mathcal{A}_e + \omega \cdot \frac{\partial \mathcal{A}_e}{\partial p} \right) - \frac{1}{r} \mathbf{T} \cdot \nabla \mathbf{T}_m + \frac{R}{\rho} \omega \cdot \mathbf{T} + \frac{Q}{r} \mathbf{T} 
\]

\[
\frac{\partial K_e}{\partial t} = -\nabla \cdot \mathbf{v} K_e = \left( \mathbf{V} \cdot \nabla K_e + \omega \cdot \frac{\partial K_e}{\partial p} \right) - \left( \mathbf{V} \cdot \nabla \mathbf{T}_m + \omega \cdot \frac{\partial \mathbf{T}_m}{\partial p} \right) - \mathbf{v} \cdot \mathbf{F} 
\]

where \( \mathcal{A}_e = \frac{1}{2} \left( \mathbf{u}^2 + \mathbf{v}^2 \right) \) is the eddy effective potential energy; \( K_e = \frac{1}{2} \left( \mathbf{u}_m^2 + \mathbf{v}_m^2 \right) \) is the eddy kinetic energy; \( r = \frac{1}{\rho} \frac{\partial \rho_0}{\partial p} \) is the static stability parameter; and \( \rho_0 \) and \( \beta_0 \) are the density and potential temperature at a reference surface, respectively. \( \mathbf{V} = \mathbf{u} \mathbf{i} + \mathbf{v} \mathbf{j} \) is the two-dimensional eddy horizontal wind vector; \( \omega \) is the eddy vertical velocity. Since the time mean flow is generally horizontal and nondivergent (i.e., \( \omega_m = 0 \)), \( \omega = \omega' \), and the vertical motion is all contributed by the eddy (Simmons & Hoskins, 1978). \( \mathbf{T}_m = \mathbf{u}_m \mathbf{i} + \mathbf{v}_m \mathbf{j} \) represents the time mean horizontal wind vector, \( T' \) is the eddy temperature, and \( \varphi' \) is the eddy portion of the geopotential height. According to equation (1), the change in eddy effective potential energy consists of the following energy conversion processes: The first term on the right side of equation (1) represents the advective transport of the eddy effective potential energy by the time mean flow; the second term represents the advective transport of eddy effective potential energy by the eddy flow; the third term represents the baroclinic conversion between time mean effective potential energy and eddy effective potential energy; and the fourth term represents the baroclinic conversion between the eddy effective potential energy and eddy kinetic energy. According to equation (2), the change in eddy kinetic energy consists of the following energy conversion processes: The first term on the right side of equation (2) represents the advective transport of eddy effective potential energy by the time mean flow; the second term represents the advective transport of eddy kinetic energy by the eddy flow; the third term represents the barotropic conversion between the time mean kinetic energy and eddy kinetic energy; the fourth term represents the frictional dissipation, the fifth term represents the divergence of the eddy nongeostrophic geopotential flux, and the sixth term represents the baroclinic conversion between the eddy effective potential energy and eddy kinetic energy.

To better understand the dynamical cause of anomalous ECs activity, we focused our analysis on the following energy terms: the eddy effective potential energy \( \mathcal{A}_e = \frac{1}{2} \left( \mathbf{u}^2 + \mathbf{v}^2 \right) \), the eddy kinetic energy \( K_e = \frac{1}{2} \left( \mathbf{u}_m^2 + \mathbf{v}_m^2 \right) \), the baroclinic conversion between the time mean effective potential energy and eddy effective potential energy \( I(A_m, \mathcal{A}_e) = -\frac{1}{r} \mathbf{T} \cdot \nabla \mathbf{T}_m \), and the baroclinic conversion between the eddy effective potential energy and eddy kinetic energy.
2.4. Estimation of Maximum Eady Growth Rate

The atmospheric baroclinic instability has long been regarded as a main triggering mechanism of the mid-latitude synoptic-scale weather system. Studies suggest that the atmospheric baroclinicity is closely related to the activities of ECs and storm tracks (Hoskins & Valdes, 1990; Lim & Simmonds, 2002, 2007; Simmonds & Hoskins, 1978). As an effective index to measure the intensity of the atmospheric baroclinicity, the maximum Eady growth rate was calculated and used to explore the causal pathways and mechanisms by which the land surface thermal anomaly affects the midlatitude EC activity. The expression for the calculation of the maximum Eady growth rate is given as follows:

\[
\sigma_{BI} = 0.31 \frac{|U_z|}{N} = 0.31 \frac{M^2}{N} \tag{3}
\]

where \( f \) is the geostrophic parameter, \( U_z \) is the vertical wind shear, and \( N \) is the Brunt-Väisälä frequency. \( M \) is a measure of the meridional gradient of the potential temperature and can be estimated according to \( M^2 = -\frac{g}{\rho} \frac{\partial \theta}{\partial y} \); \( N \) is the static stability and is defined by \( N^2 = \frac{g}{\rho} \frac{\partial \theta}{\partial z} \). At a height of approximately 2 km above the atmospheric boundary layer, the meridional variation in \( \sigma_{BI} \) is dominated by the wind shear term \( M^2 \); and the impact of variations in \( N \) on \( \sigma_{BI} \) is important only in high-latitude regions (Hoskins et al., 1990; Simmons & Hoskins, 1980). Therefore, we selected the maximum Eady growth rate at 775 hPa for further analysis.

3. Spatiotemporal Variations of ECs in East Asia

It is noted that there is a distinct cyclogenesis area in the midlatitude region of East Asia, specifically in the area of Mongolia south to Lake Baikal (Figure 1a). According to the normalized standard deviation of the cyclogenesis frequency (Figure 1b), the region with large variability of the cyclone activity coincides with the region of high frequency of the cyclone activity. Figure 1c shows that the cyclogenesis frequency in the key area of cyclone activity is evidently decreasing.

We further performed an EOF analysis on the cyclogenesis frequency and found that the contribution of the first EOF leading mode to the total variance is 15.3%. Figure 2a shows the spatial distribution of the first EOF mode, and there is a distinct center of negative anomaly of the cyclogenesis frequency in the area of Mongolia south to Lake Baikal. Figure 2b shows the time coefficient corresponding to the first EOF mode, which exhibits a clear decadal change. Before the end of the 1980s, the time coefficient is generally negative, and there is a clear transition around 1990. After the early 1990s, the time coefficient is essentially positive. Since the

Figure 1. Geographic distributions of (a) climatology, (b) interannual variability (standard deviation), and (c) linear trend (year^{-1}) of summer (JJA) extratropical cyclogenesis frequency (number of cyclogenesis in each 1.5° × 1.5°grid) over East Asia for the period 1979–2013. The gray area represents the Tibetan Plateau (the same below), and the black dots in (c) indicate linear trends are statistically significant at the 0.05 level. JJA = June-July-August.
temporal field of the first mode has a significant increasing trend, by combining its spatial pattern, it is noted that the frequency of the extratropical cyclogenesis in the key area of cyclone activity over East Asia has been significantly decreased recently, which is consistent with the change in the frequency of the extratropical cyclogenesis shown in Figure 1c. To validate the reliability of the first EOF mode, we further calculated the correlation between the time series of the first EOF mode and the frequency of the extratropical cyclogenesis (Figure 2c). It shows that significant negative correlation (statistically significant at the 0.05 level) mainly locates in the key area of cyclone activity south to Lake Baikal. Figure 2d shows the geographic distribution of the regressed extratropical cyclogenesis frequency onto the time coefficient of the first EOF mode, and the key area of cyclone activity is featured by evidently negative anomaly (statistically significant at the 0.05 level). The above analysis indicates that the first EOF mode of the frequency of the extratropical cyclogenesis primarily reflects the variation in the frequency of the extratropical cyclogenesis in the key area of cyclone activity.

4. Relationship Between Land Surface Thermal Anomaly and EC Activity

Figure 3 shows the spatial distributions of the standard deviation and linear trend of summer surface soil temperature over East Asia. It can be seen that large interannual variability (Figure 3a) and evident warming (Figure 3b) in summer surface soil temperatures are mainly located in the midlatitude of East Asia, especially in the area south to Lake Baikal.

To investigate the possible linkage between the land surface thermal anomaly and the anomalous ECs activity, we defined (90–120°E, 40–50°N) as the key area of cyclone activity, which shows high frequency and significant variability of ECs activity. We calculated the regional average frequency of ECs over the key area of
Cyclone activity and derived its normalized time series as $I_{\text{cyclone}}$ to represent the intensity of ECs activity over this region. High $I_{\text{cyclone}}$ represents more frequent cyclogenesis frequency and intensified cyclone activity. On the contrary, low $I_{\text{cyclone}}$ shows that the frequency of extratropical cyclogenesis is relatively low and the cyclone activity is relatively weak. Figure 4a shows the time series of $I_{\text{cyclone}}$ during the period of 1979–2013, which shows a clear decadal decrease in the frequency of the extratropical cyclogenesis in

Figure 3. Geographic distributions of (a) standard deviation (K) and (b) linear trend (K/year) of summers (JJA) surface soil temperature (STL1) over East Asia for the period 1979–2013, in which the black dots in (b) indicate linear trends are statistically significant at the 0.05 level. JJA = June-July-August.

Figure 4. (a) Normalized time series $I_{\text{cyclone}}$ (bars) of the regional mean cyclogenesis frequency over the midlatitude cyclogenesis center (40–50°N, 90–120°E) during 1979–2013, (b) normalized time series $I_{\text{STL1}}$ (bars) of the regional mean STL1 over the key region (50–60°N, 90–120°E), (c) correlation coefficients between $I_{\text{cyclone}}$ and the simultaneous STL1. (d) Regression of the simultaneous cyclogenesis frequency onto $I_{\text{STL1}}$. The dashed line and solid line in (a) and (b) represent linear trend and 11-year moving average, respectively. The black dots in (c) and (d) indicate correlation and regression are statistically significant at the 0.05 level. JJA = June-July-August.
the midlatitude region of East Asia. The frequency of the ECs is relatively high in the 1980s and rapidly declined around 1990. After 1990, the cyclone activity in this region is generally weakened. The variation in $I_{\text{cyclone}}$ is very similar to the temporal field of the first EOF mode of the extratropical cyclogenesis frequency discussed before, with a correlation coefficient of $-0.696$, passing the $t$ test at the 99% confidence level. This also supports our results presented above that the first EOF mode of the extratropical cyclogenesis frequency can primarily reflect the variation in the extratropical cyclogenesis frequency in the key area of cyclone activity over East Asia.

To better understand the variation of the land surface thermal anomaly related to anomalous cyclone activity, we further calculated the correlation between $I_{\text{cyclone}}$ and summer surface soil temperature. Results are shown in Figure 4c. North of 50°N, there is a distinct region with negative correlation between the cyclogenesis frequency and summer surface soil temperature, which passes the $t$ test at the 95% confidence level. We extracted the surface soil temperature in this key region (90–120°E, 50–60°N) to acquire the regional average and define the normalized time series as $I_{\text{STL1}}$. As shown in Figure 4b, there is a clear decadal variation in $I_{\text{STL1}}$, which is generally negative before 1990 and positive afterward. This trend is essentially opposite to the variation of $I_{\text{cyclone}}$. The correlation coefficient between $I_{\text{STL1}}$ and $I_{\text{cyclone}}$ is $-0.674$ and passes the $t$ test at the 99% confidence level. We further conducted a regression analysis of $I_{\text{STL1}}$ and the frequency of the extratropical cyclogenesis in East Asia. Figure 4d shows that the key area of cyclone activity is a distinct center of negative anomaly, passing the $t$ test at the 95% confidence level. This indicates that there is a key region (90–120°E, 50–60°N) north of 50°N where the land surface thermal anomaly affects the anomalous EC activity in the midlatitude of East Asia. When summer surface soil temperature in the key region increases, the frequency of the extratropical cyclogenesis in the midlatitude region of East Asia declines, and the EC activity is relatively weak. In contrast, the decrease in summer surface soil temperature is always accompanied by an increase in the extratropical cyclogenesis frequency and relatively strong cyclone activity.

5. Possible Mechanism Accounting for the Impacts of Land Surface Thermal Anomaly on ECs

5.1. Atmospheric Baroclinic Instability and Anomalous Cyclone Activity

Since the atmospheric baroclinicity is mainly resulted from the meridional temperature gradient, we also calculated the meridional gradient of the surface soil temperatures to explore the possible mechanism whereby the land surface thermal anomaly affects the atmospheric baroclinicity and thus affects ECs activity. Figures 5a and 5b show the climatologic distribution of the maximum Eady growth rate at 775 hPa and the meridional gradient of the surface soil temperature (anomalous values due to the impact of the terrain over the Tibetan Plateau are treated as missing values), respectively. Figure 5a shows that the Mongolian area south to Lake Baikal is the region with the greatest atmospheric baroclinicity and the greatest meridional gradient in the surface soil temperature, corresponding to the region with highest frequency of the extratropical cyclogenesis shown in Figure 1a. This region also exhibits the largest maximum Eady growth rate at 775 hPa and the largest interannual variation in the meridional gradient of the surface soil temperature (not shown). Results above indicate that the atmospheric baroclinicity, meridional gradient in surface soil temperature, and cyclogenesis frequency are closely related. The region of high atmospheric baroclinicity corresponds to that with large meridional gradient of the surface soil temperature and strong cyclone activity.

Figures 5c and 5d show the normalized time series of $I_{\text{Eady}}$ and $I_{\text{gradT}}$, that is, the regional averaged maximum Eady growth rate at 775 hPa and the meridional gradient of the surface soil temperature over the key area of cyclone activity (90–120°E, 40–50°N). They both exhibit similar variation and clear decadal variations. Both $I_{\text{Eady}}$ and $I_{\text{gradT}}$ are generally positive before the end of the 1990s. After the early 1990s, they are basically negative and remain relatively weak, followed by a slight enhancement after 2008. By combining $I_{\text{cyclone}}$ and $I_{\text{STL1}}$ in Figures 4a and 4b, we noted consistent variations of $I_{\text{cyclone}}$, $I_{\text{STL1}}$, $I_{\text{Eady}}$, and $I_{\text{gradT}}$. Table 1 shows the correlation coefficients among them, and it is noted that the correlation coefficient between every two of them is statistically significant at the 0.05 level, indicating close linkages among these variables.

Figure 6a shows the correlation between $I_{\text{Eady}}$ and the surface soil temperature. It is evident that there is a region of significant negative anomaly north of 50°N, corresponding to the key region where the surface soil temperature affects the key area of cyclone activity as mentioned in section 4. Similarly, as shown in
Figure 6b, the maximum Eady growth rate at 775 hPa from the regression of $I_{STL1}$ displays a distinct negative anomaly in the key area of cyclone activity, which indicates that when $I_{STL1}$ is relatively high, the maximum Eady growth rate at 775 hPa in the key area of cyclone activity in East Asia exhibits a significant negative anomaly. The meridional gradient in the surface soil temperature displays a similar relationship with $I_{STL1}$. Results from the correlation and regression analysis are very similar to those of the maximum Eady growth rate at 775 hPa (not shown).

We designated the years when $I_{STL1}$ is greater than 0.8 and less than −0.8 as years of anomalous warming and cooling in the middle latitude land surface of East Asia, respectively. Anomalous warming years include

![Table 1](image)

*Correlations are statistically significant at the 0.05 level.
1994, 2000, 2001, 2002, 2005, 2007, 2008, and 2011. And anomalous cooling years are 1981, 1982, 1983, 1984, 1987, 1988, and 1989. Then we performed composite analysis of the cyclogenesis frequency and the maximum Eady growth rate by calculating the difference between anomalous warming and cooling years.

Figure 6c shows the differences in the cyclogenesis frequency between warming and cooling years. It is found that a distinct negative anomaly (statistically significant at the 0.05 level) locates over regions south to Lake Baikal. Figure 6d shows the differences in the maximum Eady growth rate at 775 hPa. It is noted that the key area of cyclone activity exhibits a distinct negative anomaly corresponding to the weakening of the atmospheric baroclinicity. The differences between the meridional gradient in surface soil temperature display a spatial pattern similar to that of the maximum Eady growth rate, and the positive anomaly is also centered in the key area of the ECs (not shown). To eliminate the impact of the decadal variations, we performed a detrending of the original data and then carried out regression and composite analysis (Figure 7). As can be seen in Figure 7, the detrended results support a similar conclusion. The analysis above indicates that the mechanism whereby the land surface thermal anomaly affects the cyclone activity is as follows: Land surface warming in the middle latitude over East Asia tends to decrease the meridional gradient of surface soil temperature in the key area of cyclone activity, which further reduces the atmospheric baroclinicity, resulting in decreased cyclogenesis frequency and weakened cyclone activity.
5.2. Energy Conversion and Anomalous Cyclone Activity

To further analyze the mechanism by which the land surface thermal anomalies affect the midlatitude ECs activity, we diagnosed the specific processes of the energy conversion based on the equations of eddy effective potential energy and eddy kinetic energy.

Figure 7. Same as in Figure 6, except the linear trends have been removed. JJA = June-July-August.

Figure 8. Normalized time series of regional averaged $I(A_m, A_e)$, $A_e$, $I(A_e, K_e)$ and $K_e$ at 775 hPa during 1979–2013 over the midlatitude cyclogenesis center (40–50°N, 90–120°E). JJA = June-July-August.
We calculated the main energy conversion terms related to the atmospheric baroclinicity in the lower atmosphere (~775 hPa) by equations (1) and (2), including eddy effective potential energy $A_e$, eddy kinetic energy $K_e$, baroclinic conversion term from time mean effective potential energy to eddy effective potential energy $I(A_m, A_e)$, and the baroclinic conversion term from eddy effective potential energy to eddy kinetic energy $I(A_e, K_e)$. We further calculated the normalized regional averaged time series of the four energy terms over the midlatitude ECs key region, which was shown in Figure 8.

### Table 2

| Regional averaged terms | Baroclinic conversion term from time mean effective potential energy to eddy effective potential energy $I(A_m, A_e)$ | Eddy effective potential energy $A_e$ | Baroclinic conversion term between the eddy effective potential energy and the eddy kinetic energy $I(A_e, K_e)$ | Eddy kinetic energy $K_e$ |
|-------------------------|-------------------------------------------------|-----------------|-------------------------------------------------|-----------------|
| $I(A_m, A_e)$           | 1                                               | 0.720*          | 0.567*                                           | 0.587*          |
| $A_e$                   | 1                                               | 0.779*          | 0.442*                                           | 0.338*          |
| $I(A_e, K_e)$           | 1                                               | 0.338*          | 1                                               |                 |
| $K_e$                   |                                                  |                 |                                                  | 1               |

*Correlations are statistically significant at the 0.05 level.

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![Figure 9](https://example.com/figure9.png)

**Figure 9.** Composite differences (strong I$_{QY1}$ minus weak I$_{QY1}$ years) in (a) 775 hPa $I(A_m, A_e)$ in square meters per cubic second, (b) $A_e$ in square meters per square second, (c) $I(A_e, K_e)$ in square meters per cubic second, and (d) $K_e$ in square meters per square second, in which the black dots are statistically significant at the 0.05 level. JJA = June-July-August.
Since the effective potential energy is directly related to the atmospheric baroclinicity, whereas the eddy kinetic energy is mainly originated from the baroclinic conversion term between the eddy effective potential energy and the eddy kinetic energy, we calculated the correlation between \( I(A_{e}, K_{e}) \), and the normalized time series of regional average \( I(A_{e}, K_{e}) \) in the key area of cyclone activity. The correlation coefficient between them is 0.347 (statistically significant at the 0.05 level), indicating that the variation in the atmospheric baroclinicity exerts an important effect on the energy conversion between the time mean flow and the eddy disturbance. Figure 8 also shows consistent variations among \( A_{e}, K_{e}, I(A_{m}, A_{e}), \) and \( I(A_{e}, K_{e}) \). From Table 2, it is noted that the correlation coefficients between every two series are all statistically significant at the 0.05 level, which indicates that the variation in the atmospheric baroclinicity can affect the baroclinic conversion term between the time mean effective potential energy and the eddy effective potential energy, thereby altering the eddy effective potential energy. The variation in eddy effective potential energy will further affect the baroclinic conversion term between the eddy effective potential energy and eddy kinetic energy, and thereby alter the eddy kinetic energy, resulting in anomalous ECs.

Figure 9 presents composite results of \( A_{e}, K_{e}, I(A_{m}, A_{e}), \) and \( I(A_{e}, K_{e}) \) between warming and cooling land surface years. It can be seen that a significantly negative anomaly of the eddy effective potential energy appears in the key area of cyclone activity, which also coincides with the negative anomaly center of the eddy kinetic energy. The negative baroclinic conversion term \( I(A_{m}, A_{e}) \) indicates that the eddy effective potential energy is converted to the time mean effective potential energy in this region. Negative \( I(A_{e}, K_{e}) \) is mainly found in the upper reach of the energy center, while positive \( I(A_{e}, K_{e}) \) happens in its downstream, which indicates that the baroclinic conversion term \( I(A_{e}, K_{e}) \) represents the transport of the energy from the upper reach to the lower reach. Such a situation favors the enhancement of energy and development of the synoptic-scale eddy in the lower reach area. To eliminate the impact of the decadal variations, we also performed regression and composite analysis after removing the linear trends and acquired a consistent conclusion (not shown here).

It is concluded that the possible physical mechanism whereby the land surface thermal anomalies affect the anomalous cyclone activity was shown in Figure 10 and is as follows: The land surface thermal anomalies, especially the uniform land surface warming, can weaken the atmospheric baroclinicity in the middle and lower troposphere, which reduces the conversion of the time mean kinetic energy to the eddy kinetic energy via mediating effect of eddy effective potential energy, and thus weaken the cyclone activity. During years with evident land surface warming around Lake Baikal (over regions north of 50°N), decreased meridional gradient of the surface soil temperature in the key area of cyclone activity will decrease the atmospheric baroclinicity and the associated baroclinic conversion between the time mean effective potential energy and the eddy effective potential energy, which can result in a negative anomaly in the eddy effective potential energy. Meanwhile, the baroclinic conversions between the eddy effective potential energy and the eddy kinetic energy also exhibit negative anomalies, which hamper the energy transfer from the time mean flow to the synoptic-scale eddy, thereby leading to a negative anomaly in the frequency of the extratropical cyclogenesis and weak cyclone activity.

Figure 10. Schematics on mechanisms in which summer nonuniform land surface warming affects summer extratropical cyclones of East Asia.
6. Conclusions and Discussion

By analyzing the variations of summer ECs activities and land surface thermal anomalies in the midlatitude of East Asia, we found that there is a distinct summer cyclogenesis area in the midlatitude of East Asia, located near Mongolia south to Lake Baikal, which is also characterized by large interannual variability of ECs. The frequency of summer cyclogenesis in this area exhibits a significant decadal weakening during 1979–2013, which is relatively high before the 1990s, but evidently decreases after 1990. The surface soil temperature in the midlatitude of East Asia exhibits persistent warming, which is most significant near 50°N and north to Lake Baikal. There is a key region (90°–120°E, 50°–60°N) north of 50°N that affects anomalous ECs. Recent warming of land surface in this key region is closely related to the decreased frequency of summer extratropical cyclogenesis and weak ECs activity.

Further analysis suggests that the land surface warming near 50°N of East Asia is associated with anomalous weak summer ECs over East Asia. Warming land surface usually reduces the meridional temperature gradient and further the atmospheric baroclinicity in the key area of cyclone activity, resulting in low frequency of the extratropical cyclogenesis and weakened ECs activity. The land surface warming can also depress the associated baroclinic conversion term between the time mean effective potential energy and eddy effective potential energy, resulting in decrease in the eddy kinetic energy increases. As a result, the energy obtained by the synoptic-scale eddy from the time mean flow has been reduced, which favors the extratropical cyclogenesis causing weakened ECs. For cooling land surface case, contrary situation happens and the ECs activity tends to be intensified.

Previous studies indicate that the ECs can be affected by many factors, including eddy advection, temperature advection, latent heat release, friction, radiation, and terrain. The generation and development of ECs are also closely related to the large-scale circulation; the subtropical high, the 500 hPa height field at middle and high latitudes, the temperature field, and the sea surface temperatures in the upper and lower reaches can also affect the ECs. In the current study, from the perspective of land surface thermal anomaly, we applied the statistical analysis methods to confirm that there is a close relationship between the land surface thermal anomaly and cyclone activity in the midlatitude region of East Asia. The variation in land surface thermal anomaly was found to exert an important effect on the anomalous cyclone activity, and the relevant physical mechanisms were preliminarily proposed, which need further examination via numerical experiments. In addition, the detailed physical mechanisms and energy conversion processes involved deserve further investigation since internal dynamic processes of the atmosphere are very complex.

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References

Ahmadi Givi, F., Graig, G., & Plant, R. (2004). The dynamics of a midlatitude cyclone with very strong latent-heat release. *Quarterly Journal of the Royal Meteorological Society, 130*(956), 295–323. https://doi.org/10.1002/qj.2226

Beare, R. J. (2007). Boundary layer mechanisms in extratropical cyclones. *Quarterly Journal of the Royal Meteorological Society, 133*(623), 503–515. https://doi.org/10.1002/qj.30

Chang, E. K., & Orlanski, I. (1993). On the dynamics of a storm track. *Journal of the Atmospheric Sciences, 50*(7), 999–1015. https://doi.org/10.1175/1520-0469(1993)050<0999:ODOSAT>2.0.CO;2

Chen, H., Teng, F., Zhang, W., & Liao, H. (2017). Impacts of anomalous midlatitude cyclone activity over East Asia during summer on the decadal mode of East Asian summer monsoon and its possible mechanism. *Journal of Climate, 30*(2), 739–753. https://doi.org/10.1175/JCLI-D-16-0155.1

Chen, W., & Lu, R. (2014). A decadal shift of summer surface air temperature over northeast Asia around the mid-1990s. *Advances in Atmospheric Sciences, 31*(4), 735–742. https://doi.org/10.1007/s00376-013-3154-4

Chen, Y., Zhu, W., & Yuan, K. (2013). An energy analysis of midwinter suppression of the North Pacific storm track (in Chinese). *Transactions of Atmospheric Sciences, 36*(6), 725–733. https://doi.org/10.3969/j.issn.1067-1733.2013.06.009

Dee, D. P., Uppala, S. M., Simmons, A., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society, 137*(656), 553–597. https://doi.org/10.1002/qj.828

Deng, X., & Sun, Z. (1994). Characteristics of temporal evolution of northern storm tracks (in Chinese). *Journal of Nanjing Institute of Meteorology, 17*(2), 165–170. https://doi.org/10.13878/j.cnki.dqxxbs.1994.02.006

Dong, B., Sutton, R. T., Chen, W., Liu, X., Lu, R., & Sun, Y. (2016). Abrupt summer warming and changes in temperature extremes over northeast Asia since the mid-1990s: Drivers and physical processes. *Advances in Atmospheric Sciences, 33*(9), 1005–1023. https://doi.org/10.1007/s00376-016-5247-3

Geng, Q., & Sugi, M. (2001). Variability of the North Atlantic cyclone activity in winter analyzed from NCEP–NCAR reanalysis data. *Journal of Climate, 14*(18), 3865–3873. https://doi.org/10.1175/1520-0442 (2001)014<3865:VNANN>2.0.CO;2

Gulev, S., Zolina, O., & Grigoriev, S. (2001). Extratropical cyclogenesis variability in the Northern Hemisphere winter from the NCEP/NCAR reanalysis data. *Climate Dynamics, 17*(10), 795–809. https://doi.org/10.1007/s003820010045

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Hansen, J., Ruedy, R., Sato, M., & Lo, K. (2010). Global surface temperature change. Reviews of Geophysics, 48, RG4004. https://doi.org/10.1029/2010RG000345

Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D. W., & Medina-Elizade, M. (2006). Global temperature change. Proceedings of the National Academy of Sciences, 103(9), 14,288–14,293. https://doi.org/10.1073/pnas.0606291103

Hayashi, Y., & Golder, D. (1981). The effects of condensational heating on midlatitude transient waves in their mature stage: Control experiments with a GFDL general circulation model. Journal of the Atmospheric Sciences, 38(11), 2532–2549. https://doi.org/10.1175/1520-0469(1981)038<2532:TECOCH>2.0.CO;2

He, J., Ju, W., Zeng, Z., & Jin, Q. (2007). A review of recent advances in research on Asian monsoon in China. Advances in Atmospheric Sciences, 24(6), 972–992. https://doi.org/10.1007/s00376-007-9072-2

Hong, X., Lu, R., & Li, S. (2017). Amplified summer warming in Europe–West Asia and Northeast Asia after the mid-1990s. Environmental Research Letters, 12(9), 094007. https://doi.org/10.1088/1748-9326/aa7909

Hoskins, B. J., & Valdes, P. J. (1990). On the existence of storm-tracks. Journal of the Atmospheric Sciences, 47(15), 1854–1864. https://doi.org/10.1175/1520-0469(1990)047<1854:OTEST>2.0.CO;2

Huang, R., Chen, W., Ding, Y., & Li, C. (2003). Studies on the monsoon dynamics and the interaction between monsoon and ENSO cycle (in Chinese). Advances in Atmospheric Sciences, 20(1), 55–69. https://doi.org/10.1007/BF03342050

Lambert, S., Sheng, J., & Boyle, J. (2002). Winter cyclone frequencies in thirteen models participating in the Atmospheric Model Intercomparison Project (AMIP). Climate Dynamics, 18(1), 1–16. https://doi.org/10.1007/s00382-001-0206-8

Lim, E.-P., & Simmonds, I. (2002). Explosive cyclone development in the Southern Hemisphere and a comparison with Northern Hemisphere events. Monthly Weather Review, 130(9), 2188–2209. https://doi.org/10.1175/1520-0493(2002)130<2188:ECDES>2.0.CO;2

Lin, M., & Yang, K. (1992). The analysis of the weather of cyclones in the northern part of China (in Chinese). Meteorological Monthly, 18(5), 20–26.

Martin, J. E., & Otkin, J. A. (2004). The rapid growth and decay of an extratropical cyclone over the central Pacific Ocean. Weather and Forecasting, 19(2), 358–376. https://doi.org/10.1175/1520-0434(2004)019<0358:TRGADO>2.0.CO;2

McCabe, G. J., Clark, M. P., & Serreze, M. C. (2001). Trends in Northern Hemisphere surface cyclone frequency and intensity. Journal of Climate, 14(12), 2763–2768. https://doi.org/10.1175/1520-0442(2001)014<2763:TINHSC>2.0.CO;2

Murray, R., & Simmonds, I. (1991b). A numerical scheme for tracking cyclone centres from digital data. Part II: Application to January and July general circulation model simulations. Australian Meteorological Magazine, 39(3), 167–180.

Murray, R. J., & Simmonds, I. H. (1991a). A numerical scheme for tracking cyclone centres from digital data. Part I: Development and operation of the scheme. Australian Meteorological Magazine, 39(3), 155–166.

Oort, A. H., & Peixoto, J. P. (1974). The annual cycle of the energetics of the atmosphere on a planetary scale. Journal of Geophysical Research, 79(18), 2705–2719. https://doi.org/10.1029/JC079i018p02705

Orlanski, I., & Katzfey, J. (1991). The life cycle of a cyclone wave in the Southern Hemisphere. Part I: Eddy energy budget. Journal of the Atmospheric Sciences, 48(17), 1972–1998. https://doi.org/10.1175/1520-0469(1991)048<1972:TICWVT>2.0.CO;2

Raible, C., Della-Marta, P., Schwierz, C., Wernli, H., & Blender, R. (2008). Northern Hemisphere extratropical cyclones: A comparison of detection and tracking methods and different reanalyses. Monthly Weather Review, 136(3), 880–897. https://doi.org/10.1175/2007MWR2143.1

Romero, R. (2008). A methodology for quantifying the impacts and interactions of potential-vorticity anomalies in extratropical cyclones. Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography, 134(631), 385–402. https://doi.org/10.1002/qj.219

Serreze, M. C., Carse, F., Barry, R. G., & Rogers, J. C. (1997). Icelandic low cyclone activity: Climatological features, linkages with the NAO, and relationships with recent changes in the Northern Hemisphere circulation. Journal of Climate, 10(3), 453–464. https://doi.org/10.1175/1520-0442(1997)010<0453:ILCACA>2.0.CO;2

Sickmüller, M., Blender, R., & Fraedrich, K. (2000). Observed winter cyclone tracks in the Northern Hemisphere in re-analysed ECMWF data. Quarterly Journal of the Royal Meteorological Society, 126(563), 591–620. https://doi.org/10.1002/qj.47921656311

Simmonds, I., & Keay, K. (2000a). Variability of Southern Hemisphere extratropical cyclone behavior, 1958–97. Journal of Climate, 13(3), 550–561. https://doi.org/10.1175/1520-0442(2000)013<0550:VOSHEC>2.0.CO;2

Simmonds, I., & Keay, K. (2000b). Mean Southern Hemisphere extratropical cyclone behavior in the 40-year NCEP–NCAR reanalysis. Journal of Climate, 13(5), 873–885. https://doi.org/10.1175/1520-0442(2000)013<0873:MSHIEB>2.0.CO;2

Simmons, A. J., & Hoskins, B. J. (1978). The life cycles of some nonlinear baroclinic waves. Journal of the Atmospheric Sciences, 35(3), 414–432. https://doi.org/10.1175/1520-0469(1978)035<0414:TLCBSN>2.0.CO;2

Simmons, A. J., & Hoskins, B. J. (1980). Barotropic Influences on the Growth and Decay of Nonlinear Baroclinic Waves. Journal of the Atmospheric Sciences, 37(8), 1679–1684. https://doi.org/10.1175/1520-0469(1980)037<1679:BIGADO>2.0.CO;2

Smith, P. J. (2000). The importance of the horizontal distribution of eddy energy during extratropical cyclone development. Monthly Weather Review, 128(10), 3693–3694. https://doi.org/10.1175/1520-0493(2000)128<3693:TIOED>2.0.CO;2

Strahl, J. L., & Smith, P. J. (2001). A diagnostic study of an explosively developing extratropical cyclone and an associated 500-hPa trough merger. Monthly Weather Review, 129(9), 2310–2328. https://doi.org/10.1175/1520-0493(2001)129<2310:ADSECE>2.0.CO;2

Tao, S., & Chen, L. (1985). The East Asian summer monsoon. Proceedings of International Conference on Monsoon in the Far East, Tokyo, Nov. 5–8, 1985.

Tao, Z., & Hu, A. (1994). The blocking high and transient disturbances in Mei-yu period of 1991 (in Chinese). Acta Meteorologica Sinica, 52(2), 231–234. https://doi.org/10.11666/qxbh1994.029

Ulbrich, U., Leckebusch, G., & Pinto, J. G. (2009). Extra-tropical cyclones in the present and future climate: A review. Theoretical and Applied Climatology, 96(1–2), 117–131. https://doi.org/10.1007/s00704-008-0083-8

Wang, X., Jiang, Z., Zhai, P., Fan, X., & Lu, T. (2007). Study on climatic characteristics and variation of Mongolia cyclone (in Chinese). Meteorological and Environmental Sciences, 30(1), 35–38. https://dx.doi.org/10.3989/jissn.1673-7148.2007.01.008

Wang, X., Zhai, P., & Wang, C. (2009). Variations in extratropical cyclone activity in northern East Asia. Advances in Atmospheric Sciences, 26(3), 471–479. https://doi.org/10.1007/s00376-009-0471-8.
Wang, X., Zou, X., & Zhai, P. (2007). Researches on extratropical cyclone variability in the Northern Hemisphere (in Chinese). Advances in Climate Change Research, 3(04), 532–544. https://doi.org/10.1016/S1674-2137(07)60053-5

Yin, L., & Tao, X. (1997). Role of the standing and the transient eddies in atmospheric water cycle in the Asian monsoon region (in Chinese). Acta Meteorologica Sinica, 55(5), 532–544. https://doi.org/10.1016/S1674-2137(07)60053-5

Zhang, Y., Ding, Y., & Li, Q. (2012a). Interdecadal variations of extratropical cyclone activities and storm tracks in Northern Hemisphere (in Chinese). Chinese Journal of Atmospheric Sciences, 36(5), 912–926. https://doi.org/10.3969/j.issn.1006-9895.2012.11158

Zhang, Y., Ding, Y., & Li, Q. (2012b). Cyclogenesis frequency changes of extratropical cyclones in the Northern Hemisphere and East Asia revealed by ERA40 reanalysis data (in Chinese). Meteorological Monthly, 38(6), 646–656.

Zhang, Y., Ding, Y., & Li, Q. (2012c). A climatology of extratropical cyclones over East Asia during 1958–2001. Acta Meteorologica Sinica, 69(3), 261–277. https://doi.org/10.1007/s13351-012-0301-2

Zhao, L., Chen, H., & Dai, Y. (2015). Stronger warming amplification over drier ecoregions observed since 1979. Environmental Research Letters, 10(6), 064012. https://doi.org/10.1088/1748-9326/10/6/064012

Zhao, L., Chen, H., Hua, W., Dai, Y., & Wei, N. (2016). Mechanisms for stronger warming over drier ecoregions observed since 1979. Climate Dynamics, 47(10), 2955–2974. https://doi.org/10.1007/s00382-016-3007-9

Zhu, W., & Sun, Z. (2001). Effects of eddy ageostrophic geopotential fluxes on the maintenance of storm tracks (in Chinese). Chinese Journal of Atmospheric Sciences, 25(1), 71–78.