RESEARCH ARTICLE

Atmospheric response to the North Pacific hotspot in idealized simulations: Application to explosive and binary cyclogenesis

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Abstract
Marginal seas of the western North Pacific Ocean act as a hotspot in winter, warming the marine atmosphere. The atmospheric response to lower-level (below 700 hPa altitude) heating localized around this hotspot was studied using an idealized general circulation model with an assumed triangular hotspot. As simulated in previous studies, localized atmospheric heating over the mid-latitude hotspot enhances the westerly jet core, forming a stationary Rossby wave north of the core. This study found that the hotspot remotely influences the Rossby wave source (the sum of vortex stretching and vorticity advection caused by the divergent flow) and temperature deviations at upper levels (200–300 hPa). These results are qualitatively consistent with the winter climatology. The idealized experiment was applied to explosive and binary extratropical cyclones (pairs of surface cyclones located north and south of the main Japanese islands). The active area of transient eddies at lower levels splits into two in the hotspot, leading to regional explosive development and the formation of binary cyclones through an enhanced meridionally elongated trough. The hotspot is an essential factor driving the bifurcation of cyclone tracks into the southern and northern areas of Japan, leading to binary cyclones.

KEYWORDS
atmosphere, climate, dynamics, general circulation model, mid-latitude, synoptic

1 | INTRODUCTION

Atmospheric response to thermal heating in the tropics and extratropics exhibits stationary Rossby waves and their associated teleconnection patterns (e.g., Hoskins and Karoly, 1981; Held, 1983; Inatsu et al., 2002). Sea surface conditions such as oceanic fronts and temperature anomalies influence storm tracks (Inatsu and Hoskins, 2004; Brayshaw et al., 2008; Small et al., 2014) and general circulation (Peng et al., 1997; Peng and Whitaker, 1999; Kushnir et al., 2002). During the Northern Hemisphere winter, total sea-surface heat fluxes (i.e., the total of sensible, latent, and radiative fluxes at the sea surface) in the North Pacific and North Atlantic oceans are concentrated in currents along their western boundaries. The resulting large release of heat means that the area is a ‘hotspot’ in the climate system (e.g., Minobe et al., 2008; Nakamura et al., 2015). During
winter in East Asia, a hotspot forms in and around the Kuroshio and Tsushima warm currents, where the sea-surface heat flux is enhanced by cold airmasses over the warm sea surface. The sea-surface turbulent flux is considered as a heat source in the atmosphere over the hotspot. When the net longwave flux is greater than the net shortwave flux at the surface of warm marginal seas that have frequent widespread cloud cover, such as in the Sea of Japan in winter, the surface radiative flux should be also considered as the heat flux of the hotspot.

In several geophysical fluid dynamics studies (e.g., Kaspi and Schneider, 2011a, 2011b), the atmospheric response to the surface heat flux over a triangular hotspot has been investigated using an idealized general circulation model (GCM) in which the hotspot contributes to the contrast in mid-latitude winter temperatures and enhances the transient eddy kinetic energy over large areas corresponding to the North Pacific or North Atlantic basins. The present study focuses on the influence of the hotspot on extratropical cyclogenesis over the western boundary of the North Pacific with lower-level atmospheric heating over the hotspot.

In the vicinity of the North Pacific hotspot, binary extratropical cyclones are often seen in weather charts. In Japan, the binary cyclones appear at a rate of 15 per year (based on daily weather charts in Japan; Hirata and Kusaka, 2013). Some of the binary cyclones merge to form explosively developing systems leading to severe-weather events. The binary cyclone structures are associated with upper-level double jets (Ogura and Juang, 1990), the topography of Japan (Yamamoto, 2012), and sea-surface heat fluxes (Yamamoto, 2018; Yokoyama and Yamamoto, 2019). However, the formation of binary cyclones over marginal seas where explosive cyclones also occur frequently (e.g., Sanders and Gyakum, 1980; Yoshida and Asuma, 2004) remains poorly understood.

This study aims to provide a comprehensive understanding of marginal-sea-scale explosive and binary cyclogenesis over the western boundary of the North Pacific involving the atmospheric response to a stationary heating component localized over an idealized triangular hotspot (Section 2). The general circulation over the North Pacific Basin is reviewed (Section 3), and the atmospheric response to the hotspot is applied to explosive and binary cyclogenesis in the vicinity of the western boundary of the North Pacific Basin (Section 4).

## 2 | MODEL AND METHOD

We applied the model of Held and Suarez (1994) to the global Weather Research and Forecasting (WRF) model (global WRF, the Held–Suarez test case ‘heldsuarez’ of the Advanced Research WRF model, version 3.9.1.1) using a finite-difference method (Skamarock and Klemp, 2008). This model is often used as an idealized, dry GCM (e.g., Dias Pinto and Mitchell, 2014; Lu and Yamamoto, 2020). General circulation is driven by the Newtonian-cooling relaxation to a reference temperature and the flow is dissipated by Rayleigh friction at sigma levels of \( \sigma = 1.0–0.7 \). Here, the Held–Suarez experiment is referred to as the control experiment (CNTL). In this experiment, the Held–Suarez forcing option was chosen as longwave radiation in the idealized model, avoiding the use of physical parametrizations of microphysics, shortwave radiation, and the surface layer. The two-dimensional Smagorinsky first-order closure of the model constant \( Cs = 0.25 \) was applied (Dias Pinto and Mitchell, 2014; Lu and Yamamoto, 2020). We focused on synoptic eddies simulated in the global WRF model with a 128° longitude \( \times 64° \) latitude horizontal grid and 32 vertical sigma layers. Because zonal wavenumbers 1–10 are predominant in the experiment of Held and Suarez (1994), a horizontal resolution of \( \sim 2.8° \) was applied in the CNTL case. To investigate the atmospheric response to lower-level heating over the western boundary of the North Pacific, diabatic heating by the total surface heat flux from the sea-surface hotspot was simplified as an atmospheric heating rate over the idealized triangular area. In the triangular heating experiment (TRIA), a total flux, \( Q_s \), of 500 W m\(^{-2}\) was assumed in the idealized hotspot, with a linear flux decrease in the log \( P \) coordinate (altitude scale) to simplify the estimation of the heating rate (0.486 K hr\(^{-1}\)), as follows:

\[
\left( \frac{dT}{dt} \right)_{\text{dia}} = -\frac{1}{\rho_s C_P H_s \ln \sigma_{\text{top}}} Q_s, \tag{1}
\]

for a triangular prism region (25°–45°N, 120°–140°E with \( \sigma_{\text{top}} = P/P_s = 0.7 \) (\( P \approx 700 \) hPa and \( -H_s \ln \sigma_{\text{top}} \approx 3 \) km; Figure 1a,b). Here, \( P \) is pressure (Pa), \( P_s \) is standard surface pressure (Pa), \( \rho_s \) is surface density (kg m\(^{-3}\)), \( C_P \) is specific heat at constant pressure (J K\(^{-1}\) kg\(^{-1}\)), and \( H_s \) is scale height (m). The triangular heating region mimics the shape of Asian shorelines and adjacent western boundary currents. The magnitude of the heat flux was assumed to be similar to that observed by Kaspi and Schneider (2011a). Rather than altering the vertical profile of the flux in the prism, the top of the atmospheric heating (\( \sigma_{\text{top}} \)) was changed in the sensitivity experiments (Table S1). Simulations began from a motionless state (0000 UTC, Day 0) and ran for 5 years. The data output at 6-hr intervals were analysed for the 4 years from 0000 UTC Day 365 to Day 1825; the spin-up and time-average periods were somewhat longer at 200 and 1,000 days, respectively, in Held and Suarez (1994).
A measure of the baroclinicity at low levels is provided by the Eady growth rate, $\sigma_E$, at 900 hPa defined by:

$$\sigma_E = 0.31 \frac{|f|}{|du_h/dz|/N},$$

where $f$ is the Coriolis parameter, $u_h$ is horizontal flow, and $N$ is the buoyancy frequency. Here, to avoid the problem of missing data that often occurs below 950 hPa altitude in the vertical differentiation in Equation (2), 900 hPa was chosen as the level for the analysis of the Eady growth rate near the surface. The local deepening rate (LDR; Kuwano-Yoshida, 2014) was used to investigate explosive cyclones, defined as:

$$\text{LDR} = \frac{\text{SLP}(t + 12\text{hr}) - \text{SLP}(t - 12\text{hr})}{24} \frac{\sin 60^\circ}{\sin \phi},$$

where SLP is sea-level pressure, $t$ is time (hr), and $\phi$ is the latitude of the grid point.

The Rossby wave source was calculated from the time mean of the quantity $S$,

$$S = -\zeta_a D - \mathbf{v}_x \cdot \nabla \zeta_a,$$

where $\zeta_a$ is absolute vorticity, $\mathbf{v}_x$ is the divergent component obtained from the velocity potential, and $D$ is horizontal divergence.

We used 30-year mean National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis 1 data (Kalnay et al., 1996) as climatological normals in discussing the validity of idealized-model results.
The general circulation over the North Pacific Basin is reviewed here to confirm the validity of our idealized-model experiment. Figure 1c,d (contours) indicates the longitudinally averaged general circulation over 120°E–120°W in the TRIA. The lower-level heating over the hotspot weakens Hadley circulation (0–30°N) and strengthens Ferrel circulation (30–60°N) in the Northern Hemisphere, relative to the Southern Hemisphere (Figure 1c). The westerly jet in the Northern Hemisphere becomes slower than that in the Southern Hemisphere (Figure 1d), associated with the weakened Hadley circulation in the Northern Hemisphere. Compared with the CNTL, the zonal wind speeds in the TRIA weaken on the equatorward flank of the westerly jet (blue shading, Figure 1d) and Ferrel circulation (negative contours, Figure 1c) is reduced over the hotspot (red shading, Figure 1c). In contrast, on the poleward flank of the jet, the Ferrel circulation induced by the poleward eddy heat flux is enhanced north of the hotspot (~50°N), where the horizontal temperature gradient is regionally strong. A westerly jet core of >30 m·s⁻¹ at 300 hPa forms east of the northern vertex of the triangular heating area (black contour, Figure 2a), as shown previously (Kaspi and Schneider, 2011a, 2011b).

We found that temporally averaged warm deviations (positive temperature deviations from the zonal mean; red and orange shading, Figure 2a) occur in the jet core and to its north, which was not observed in the CNTL (Figure S1a). The warm area extends along the jet core and advects along the northward flow of the stationary Rossby wave. The deviation pattern is similar to that observed in NCEP/NCAR Reanalysis 1 data (Kalnay et al., 1996) over the North Pacific Basin at 300 hPa (Figure 2b), although the amplitude is small because of the lack of ocean-continent contrast in the idealized experiment.

The temporally averaged geopotential height (GPH) deviation from the zonal mean has a dipole structure across the jet core. The existence of the dipole, comprising negative and positive GPH deviations, implies that changes in atmospheric heating over the East Asian marginal sea could potentially modulate the Western Pacific teleconnection pattern if the heating varied interannually over the hotspot (Takano et al., 2008; Hirose et al., 2009). Positive GPH deviations at about 50°N, 150°W are associated partly with the negatively intensified Rossby wave source (RWS) at 200 hPa (Figure 2c) via the enhanced divergence of Ferrel circulation around 60°N, which differs from the CNTL (Figure S1b). The negative RWS over the North Pacific (Shimizu and Cavalcanti, 2011; Park et al., 2018) is induced by upper-level divergence associated with the eddy-driven indirect circulation, which is regionally enhanced (Figure 1c) due to the hotspot. Park et al., 2018)
et al. (2018) discussed the modification of the RWS through horizontal divergence of regional meridional circulation in the nonstationary relationship between El Nino-southern oscillation and the Western Pacific teleconnection. In contrast, the present work suggests a stationary relationship between the oceanic hotspot and the upper-level RWS owing to storm-track (eddy)-driven meridional circulation.

4 | APPLICATION TO EXPLOSIVE AND BINARY CYCLOGENESIS

Here we focus on regionally heated lower atmospheric levels and their relationship with explosive and binary cyclones at sea-surface level. The horizontal structures in the TRIA (Figure 3) are quite different from the zonally uniform structures that are apparent in the absence of the hotspot (CNTL case, Figure S2). The Eady growth rate, $\sigma_E$, at 900 hPa is enhanced in and around the triangular heating area (Figure 3a), with the horizontal temperature gradient being intensified in the vertical shear of horizontal wind (on the hypotenuse of the triangle in Figure S3a,c). The regionally high Eady growth rate is associated with the high incidence of explosive deepening, with $LDR > 1$ hPa hr$^{-1}$ (Figure 3b). The high-incidence area is similar to that of the high frequency with which the growth rate of the central pressure reaches its maximum (130–180°E and 30–50°N; Iwao et al., 2012). The frequency and mean LDR of the explosive deepening are high east of the northern vertex of the triangular heating area. Atmospheric heating over the hotspot thus regionally enhances the intensity and frequency of explosive cyclones.

Transient eddy activity was calculated from the time-mean magnitude of the deviation of the relative vorticity, $\zeta$, from the time-average for 10 days (Figure 3c) to detect binary cyclones with lifetimes of only a few days passing over the main Japanese islands (Yamamoto, 2012, 2018; Yokoyama and Yamamoto, 2019). In regions of high Eady growth rate, the activity of transient eddies is high at 950 hPa (Figure 3c). This active area near the surface is more concentrated in the hotspot than on the storm track in the troposphere (Kaspi and Schneider, 2011a, 2011b). The eddy activity east of the triangular heating area (black curve around 45°N, Figure 4a) is 40% greater than that without heating (black curve around 45°S, Figure 4a). The lower-level short-period vorticity increases in the zonal area of 140°E–130°W (Figure 3c) and upper-level vorticity is enhanced in the zonal jet core (Figure S3b), indicating that coupling between lower- and higher-level eddies is important around the northern vertex of the triangle (Figure S4b).

The eddy-activity area at 950 hPa bifurcates over the hotspot to ~30°N and ~50°N, at 128°E (red curve, Figure 4a). Additional experiments (Table S1) were undertaken to assess the sensitivity of the eddy bifurcation to hotspot area and intensity. Although there were differences in eddy activity between the experiments, the sensitivity study confirmed the split of the active region of extratropical cyclones over the hotspot (Figure S5).
The two maxima in transient eddy activity were also formed in an experiment with horizontal resolution twice that of the TRIA (Figure S6), suggesting that lower-level heating localized over the hotspot is essential in driving bifurcation of the area of eddy activity to the north and south of the Japanese main islands, as observed in climatological studies (e.g., Adachi and Kimura, 2007).

A meridional trough forms over the triangular heating area in the TRIA (Figure 3c) but not in the CNTL case, suggesting that such a trough is likely to develop over the hotspot. SLP decreases with increasing latitude, and baroclinic eddies are often formed in the northern region (>40°N) in the CNTL case (Figure 4b). Therefore, binary cyclones do not form in the absence of the hotspot. In contrast, low SLP often appears in the heating region (25–45°N) in the time–latitude cross-section of the TRIA (Figure 4c). When southern lows (low SLP in the triangular heating area) develop, the trough elongates northward into the active area of the northern lows at 45–60°N.

The northern surface cyclone couples with the upper-level eddies in the trough (Figure S4b), similar to East Asian cyclogenesis associated with upper-level shortwave troughs over the Sea of Japan and/or the Sea of Okhotsk (Yoshida and Asuma, 2004; Kuwano-Yoshida and Asuma, 2008). In contrast, the southern cyclone develops below the 700 hPa altitude (Figure S4a), consistent with the southern shallow low in the early stage of binary cyclogenesis (Yamamoto, 2018; Yokoyama and Yamamoto, 2019). Southern vortices developed at and confined within lower levels are not observed in the absence of the hotspot (CNTL case; Figure S4c).
Binary cyclones appeared at 0000 UTC on Day 390 (Figure 4d) when a meridionally elongated trough developed in the heating area. After this, these two cyclones merged into a fully developed cyclone. The development and merging of binary cyclones were often observed in previous case studies of explosive binary cyclones over marginal seas with high surface heat flux around Japan (Yamamoto, 2018; Yokoyama and Yamamoto, 2019). Such a binary cyclone development is not seen in the absence of the hotspot (CNTL).

5 | CONCLUSIONS

Lower-level heating over the western-boundary hotspot of the North Pacific Ocean weakens the Hadley circulation and enhances eddy-driven Ferrel circulation over the North Pacific Basin (Figure 1c), compared with those in the Southern Hemisphere. In the schematics of Figure 5, the localized heating (grey triangle area) forces stationary Rossby waves (‘L’ and ‘H’) and modifies transient eddy activity (red area). As was simulated in previous studies with assumed triangular hotspots, the zonal jet core (black arrow) and the transient wave activity (thick red line below the jet core) are enhanced east of the heating area over the marginal seas (e.g., Kaspi and Schneider, 2011a, 2011b). The present work reveals the following atmospheric responses to the triangular hotspot:

- The lower-level heating localized over the hotspot remotely produces a 300-hPa warm deviation (orange area in Figure 5a; advected by the enhanced jet and the stationary Rossby waves’ geostrophic flow) and enhances a 200-hPa RWS (purple area in Figure 5a) via the modified Ferrel circulation over the North Pacific Basin. This is qualitatively consistent with the winter climatology.
- The hotspot increases the incidence of explosive deepening and deepening rate of explosive cyclones, which are associated with intensified Eady growth rate in and around the heating area (purple area in Figure 5b) where binary extratropical cyclones are generated through the bifurcation into two regions of wave activity and the development of a meridionally elongated trough.

The small hotspot modifies the upper-level dynamics of the jet core, warm deviation pattern, and RWS over the North Pacific Basin and the lower-level dynamics of explosive and binary cyclogenesis over East Asian marginal seas. Although the model used here was simplified, the idealized experiment demonstrates that the hotspot over the marginal sea forms both explosive and binary cyclones. The hotspot is essential in driving the bifurcation of the cyclone track to southern and northern areas of Japan, leading to binary cyclones. The main Japanese islands thus do not necessarily cause the bifurcation of the cyclone into southern and northern tracks.

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CONFLICT OF INTEREST
The author declares no potential conflict of interest.

DATA AVAILABILITY STATEMENT
The data presented in this article were stored in the figshare repository (https://doi.org/10.6084/m9.figshare.13340483.v1).

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