

Geophysical Research Letters[®]



RESEARCH LETTER

10.1029/2025GL119782

Remote Forcing of Super Typhoon Mawar on the 2023 Quebec Wildfires

Key Points:

- Super Typhoon Mawar remotely intensified North America blocking high by triggering a Rossby wave train
- Mawar contributed approximately 34%–55% to blocking amplification during the first three days of rapid development
- Intensified blocking high enhanced lightning and anomalous dry air, favoring Quebec's extreme wildfire initiation and maintenance

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Zhu, A., Xue, L., Wang, Z., Ding, K., Liu, Y., Lou, S., et al. (2026). Remote forcing of Super Typhoon Mawar on the 2023 Quebec wildfires. *Geophysical Research Letters*, 53, e2025GL119782. <https://doi.org/10.1029/2025GL119782>

Received 1 OCT 2025

Accepted 5 JAN 2026

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Abstract Typhoons and wildfires are major global climate and environmental hazards, yet their potential interactions remain poorly understood, particularly through remote atmospheric forcing. Taking the 2023 Quebec wildfires as an example, we investigate how a tropical cyclone can influence wildfire-favorable conditions. Observational analyses and Linear Baroclinic Model simulations reveal that western North Pacific Super Typhoon Mawar remotely intensified a North American blocking high by triggering a Rossby wave train, thereby driving dry lightning and anomalous dry air conditions that favored wildfire ignition and spread. Based on Weather Research and Forecasting model sensitivity experiments, we show that Mawar contributed $34 \pm 6\%$, $41 \pm 3\%$, and $55 \pm 5\%$ to the blocking's total amplification during the first three days of its rapid development, respectively. This findings highlight that western North Pacific typhoons can remotely modulate blocking highs to drive North American wildfire weather, advancing our understanding of remote typhoon-wildfire teleconnections.

Plain Language Summary Typhoons and wildfires are devastating disasters that threaten the environment and human society. While it well acknowledged that weather patterns influence these events, the connections between typhoons and wildfires across long distances remain poorly understood. This study investigates how Super Typhoon Mawar in the western North Pacific contributed to severe wildfires in Quebec, Canada, in early June 2023. We found that the typhoon triggered large-scale atmospheric waves that strengthened a long-lasting high-pressure system over Canada. The stronger high pressure created favorable conditions for wildfire ignition and spreading by increasing lightning activity and drying out the air. These findings reveal that typhoons can influence wildfire across continents, improving our understanding of how distant extreme weather events are linked globally. This finding could help improve wildfire prediction and risk assessment.

1. Introduction

Wildfires, as major natural disturbance agents, play an integral role in shaping ecosystems' composition and structure (Bowman et al., 2009). Meanwhile, they also have substantial impacts on climate systems, human health, and socioeconomic activities due to the release of large amounts of carbon dioxide, radiatively active aerosols, and other reactive gases (Bowman et al., 2009; Xu et al., 2023; Zhong et al., 2024). In recent decades, extreme wildfires have ravaged almost all the continents across the globe, such as Australia's 2019–2020 “Black Summer” (Abram et al., 2021), and large-scale Amazonian fires in South America during 2019–2020 (Kelley et al., 2021), and extensive boreal forest fires across Siberia (2020–2021; Zheng et al., 2023). Under the background of climate warming, the frequency of extreme wildfire events is projected to increase significantly (Abatzoglou et al., 2019; Gui et al., 2024; Jones et al., 2022). Therefore, conducting in-depth investigations on these extreme wildfires is of paramount importance for coping with climate warming and enhance disaster prevention and mitigation.

Atmospheric circulation is a fundamental controlling factor for wildfires, as it governs the transport and distribution of energy, moisture, and momentum (Cardil et al., 2023; Flannigan & Wotton, 2001; Hostetler

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et al., 2018). Positive anomalies in 500-hPa geopotential height are typically strongly correlated with burned area, particularly when they persist during atmospheric blocking events (Jain & Flannigan, 2021; Sharma et al., 2022). This is because such anomalies can lead to hotter and drier weather, which reduce biomass moisture, increase susceptibility to ignition, and thereby accelerate the rate of wildfire spread (Lubis et al., 2024; Yin et al., 2024; Zhao et al., 2022). Additionally, atmospheric circulation can also link typhoons and wildfires, forming compound remote extreme events on a large scale. For example, typhoons in the western Pacific can interact with mid-latitude flows to amplify high-pressure ridges over western North America, enhancing near surface winds through increased pressure gradients and thereby accelerating wildfire spread (Stuivenolt Allen et al., 2021). However, the pathways through which atmospheric circulation influence wildfires are diverse. Beyond the well-documented feature that typhoons intensify wildfires by accelerating near-surface wind, whether typhoon-induced fire-favoring circulation (i.e., anticyclonic system) exerts additional influences on wildfire ignition or spread remains uncertain and warrants investigation. Furthermore, existing studies on the remote impacts of typhoons on anticyclonic systems over fire-prone regions are predominantly qualitative, and quantitative assessments of these influences are still lacking.

In 2023, Canada experienced record-breaking wildfires, with the area burned exceeding seven times of the average during the past four decades, and forcing 232,000 people evacuations (Jain et al., 2024). Compared with other wildfires in Canada, the early June Quebec extreme wildfires attracted particular attention as the smoke plume reached the densely populated central and eastern United States, affecting over 100 million people and producing New York City's worst air quality in the last 50 years (Chen et al., 2025; Cooper et al., 2024; Wang et al., 2024). This extreme event was driven by hazardous fire weather conditions associated with a persistent blocking high over North America (Jain et al., 2024; Luo et al., 2025). Remarkably, Super Typhoon Mawar over the western North Pacific, one of the 2023s strongest tropical cyclones (WMO, 2024), reached its peak intensity on 26 May—merely 6–7 days prior to the outbreak of the Quebec fires. This near-synchronous occurrence constitutes a remote compound event, offering an ideal case for quantifying teleconnection pathways between typhoons and wildfires.

Here, we examine the teleconnection between Super Typhoon Mawar and the early June Quebec extreme wildfires using both observations and model experiments. In particular, we address two key questions: (a) How and to what extent did Mawar contribute to the blocking high over North America? (b) How did this circulation change create extreme fire weather conditions in Quebec? Our study is organized as follows: Section 2 describes the data, methods, and experimental designs; the main results are presented in Section 3; and our conclusions and discussions are provided in Section 4.

2. Materials and Methods

2.1. Fire Detections and Reanalysis Data

We use four wildfire-related data sets: Global Fire Emissions Database version 4.1s (GFED4.1s) for daily carbon emissions (van der Werf et al., 2017b), Fire INventory from NCAR version 2.5 (FINNV2.5) for daily burned area (Wiedinmyer et al., 2023), National Burned Area Composite (NBAC) for individual fire records (Skakun et al., 2024), and Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2) for daily aerosol optical depth (AOD) (Gelaro et al., 2017).

Atmospheric fields are obtained from the fifth generation European Center for Medium-Range Weather Forecasts reanalysis (ERA5) (Hersbach et al., 2020). Additional data sets include fire weather index (FWI) from the European Forest Fire Information System (Copernicus Climate Change Service, 2019), precipitation from Integrated Multi-satellite Retrievals for GPM (IMERG) (Huffman et al., 2020), Typhoon data are from the China Meteorological Administration (CMA) Tropical Cyclone Best Track (Lu et al., 2021). Anomalies for all variables are calculated relative to the 2011–2020 daily mean. Data set specifications are in Text S1 and S2 in Supporting Information S1.

2.2. Methodology

The propagation of quasi-stationary Rossby wave trains is described using the anomalous horizontal wave activity flux (WAF) proposed by Takaya and Nakamura (2001). The expression for the horizontal WAF in spherical coordinates is as follows:

$$\text{WAF} = \frac{p \cos \varphi}{2|U|} \left[\frac{U}{a^2 \cos \varphi} \left[\left(\frac{\partial \psi'}{\partial \lambda} \right)^2 - \psi' \frac{\partial^2 \psi'}{\partial \lambda^2} \right] + \frac{V}{a^2 \cos \varphi} \left[\frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial \varphi} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial \varphi} \right] \right] \\ \left[\frac{U}{a^2 \cos \varphi} \left[\frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial \varphi} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial \varphi} \right] + \frac{V}{a^2 \cos \varphi} \left[\left(\frac{\partial \psi'}{\partial \varphi} \right)^2 - \psi' \frac{\partial^2 \psi'}{\partial \varphi^2} \right] \right],$$

where U and V are the climatological seasonal means of the basic flow; ψ' is the stream function anomaly; a , φ , and λ represent the Earth's radius and the latitude and longitude; p is the pressure at 1,000 hPa.

To identify the dynamical origin of the wave train, the Rossby Wave Source (RWS) is calculated following Sardeshmukh and Hoskins (1988):

$$S = -\vec{v}_\chi \cdot \nabla \zeta_a - \zeta_a \nabla \cdot \vec{v}_\chi,$$

where $\vec{v}_\chi$ denotes the divergent wind and ζ_a is the absolute vorticity. The RWS comprises the vortex stretching term ($S1: -\zeta_a \nabla \cdot \vec{v}_\chi$) and the advection of vorticity by divergent wind ($S2: -\vec{v}_\chi \cdot \nabla \zeta_a$). The stretching term ($S1$) is dominant locally over the heating source, whereas the advection term ($S2$) is crucial for propagating the signal poleward, as it acts effectively upon the strong meridional vorticity gradients associated with the ambient jet stream.

The diabatic heating $Q1$ is calculated following Yanai et al. (1973):

$$Q1 = C_p \left[\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T + \left(\frac{p}{p_0} \right)^k \omega \frac{\partial \theta}{\partial p} \right]$$

where $Q1$ is diabatic heating, T is air temperature, $\mathbf{V}$ is horizontal wind vector, ω is vertical velocity, p is pressure, θ is potential temperature, $C_p = 1,004.64 \text{ J (K kg)}^{-1}$, $k = R/C_p$, $R = 287 \text{ J (K kg)}^{-1}$, and $p_0 = 1,000 \text{ hPa}$.

2.3. Model Experiments

To quantify Typhoon Mawar's contribution to downstream blocking development, we employ two complementary modeling approaches. We use a Linear Baroclinic Model (LBM; Watanabe & Jin, 2003) to confirm that Mawar's diabatic heating (Figure S1a in Supporting Information S1) can generate circulation anomaly patterns consistent with those observed in reanalysis data, thereby qualitatively identifying the Rossby wave propagation pathway triggered by Mawar.

We also perform realistic simulations using the Weather Research and Forecasting (WRF) model version 4.5.1 (Skamarock et al., 2021) to quantitatively assess atmospheric response evolution and timing. The model employs a three-domain, two-way nested configuration (Figure S1b in Supporting Information S1): D01 covers a quasi-global extent at 1° resolution, D02 covers the western North Pacific at 0.2° resolution, and D03 focuses on the typhoon core region at 0.04° resolution.

We conduct a control (CTRL) experiment with all physical processes active, and a sensitivity (NonTY) experiment with latent heating from microphysical processes disabled in D03. Five ensemble members are employed for each experiment. Since precipitation in D03 is predominantly typhoon-related during 24 May–4 June (Figure 1c), differences between the two experiments directly quantify Mawar's diabatic heating contribution to downstream circulation anomalies. Detailed configuration specifications for the models are provided in Text S3 in Supporting Information S1.

3. Results

3.1. Synoptic Background of the Extreme Wildfire and Its Possible Link With Typhoon Mawar

Canada has experienced increasing wildfire activity in the past decades. In early June 2023, exceptionally large wildfires raged across Quebec, forming extensive and thick smoke plumes with high AOD values over eastern North America (Figure 1a). These fires were reported to be triggered by lightning around 1–2 June (Boulanger

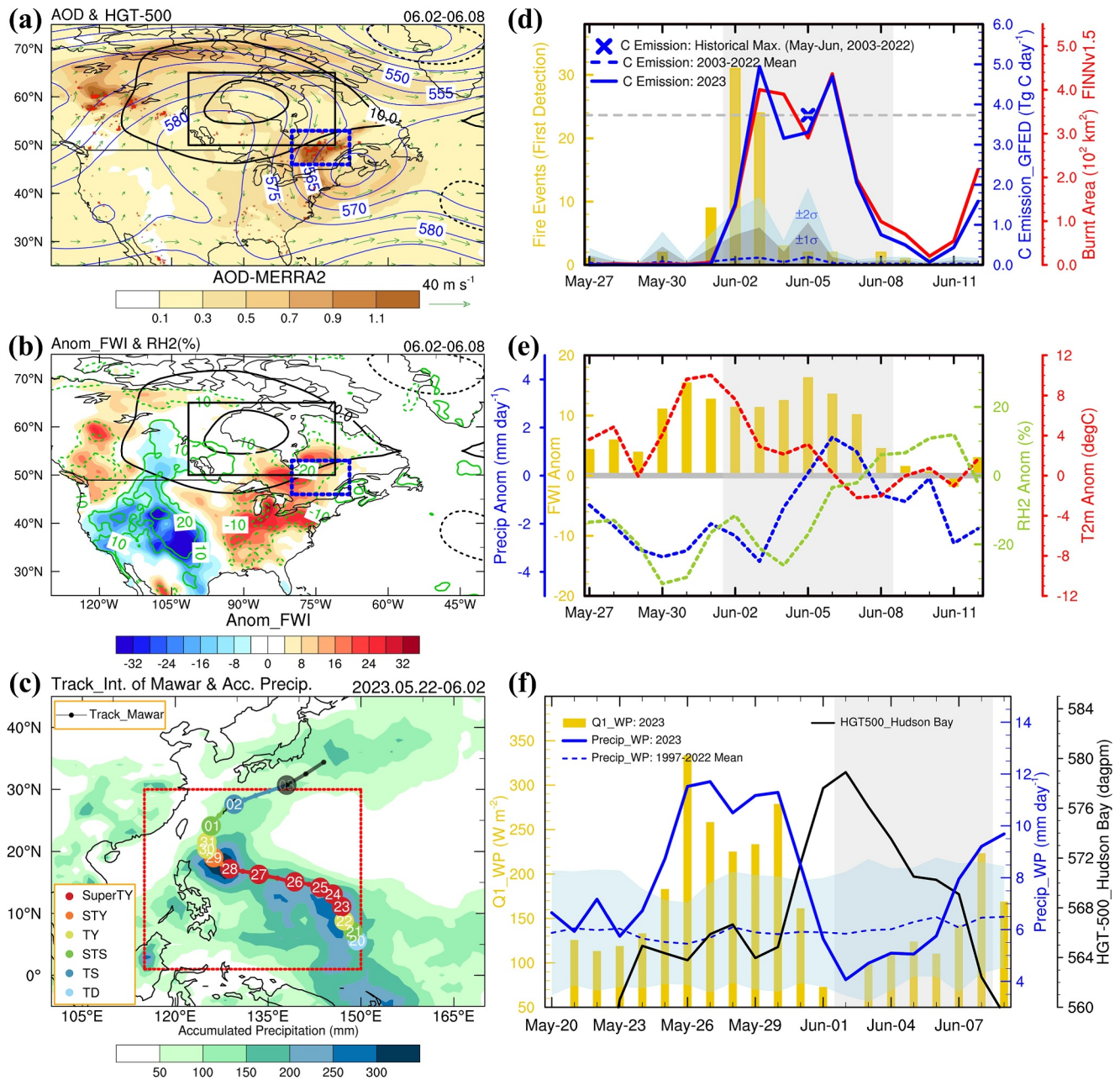


Figure 1. Characteristics of the Quebec wildfire and associated weather conditions. (a) Mean 500-hPa geopotential height (HGT-500, blue contours; dagpm), anomaly (black contours), and wind vectors overlaid with AOD (shading) for 2–8 June 2023. Red dots denote carbon emissions greater than $0.1 \text{ g C m}^{-2} \text{ day}^{-1}$. Boxes outline the Hudson Bay blocking (black; 100° – 70° W, 50° – 65° N) and primary Quebec fire (blue; 80° – 68° W, 46° – 53° N) regions. (b) As in (a) but for fire weather index (FWI) (shading), relative humidity (RH2) (green contours), and HGT-500 anomaly. (c) Track of Super Typhoon Mawar (colors indicate intensity; numbers denote dates) and accumulated precipitation (shading) from 20 May to 3 June 2023. Intensity categories include Tropical Depression, Tropical Storm, Severe Tropical Storm, Typhoon, Strong Typhoon (STY), and Super Typhoon (SuperTY). (d) Daily fire activity in the Quebec region (blue box in a), showing carbon emissions (blue line), burned area (red line), and newly detected fire events (bars). Blue dashed line and shading indicate the climatological range (mean $\pm 1\sigma/2\sigma$) of carbon emissions. (e) As in (d) but for the anomalies of FWI (yellow bars), precipitation (blue line), RH2 (green line), and T2m (red line). (f) Daily time series of column-integrated diabatic heating (Q1, yellow bars) and precipitation (blue line) over the typhoon region (red box in c) and HGT-500 (black line) over the Hudson Bay region (black box in a). Blue dashed line and shading represent the 1997–2022 climatological mean precipitation and the $\pm 1\sigma$ ranges over the typhoon region, respectively.

et al., 2024), and developed rapidly with exceptional intensity (Figure 1d). During this extreme wildfire event, burned area hit a record high of over $400 \text{ km}^2 \text{ day}^{-1}$. Accordingly, daily fire carbon emissions exceeded $4.0 \text{ Tg C day}^{-1}$ on 3 and 6 June, exceeding the previous historical maximum of $3.7 \text{ Tg C day}^{-1}$ recorded on 5 June 2005.

This intense fire activity was fueled by anomalous weather conditions, including high air temperature, low humidity, and fierce wind. Spatially, the fire hotspots were concentrated in southeastern Canada with significantly positive FWI anomalies (Figure 1b). Temporally, these conditions evolved in a distinct pattern (Figure 1e, Figure S2 in Supporting Information S1). The pre-ignition phase featured extreme heat and dryness, with significant anomalies in 2-m temperature (T2m), 2-m relative humidity (RH2), and vapor pressure deficit (VPD). As the fire intensified, temperature anomalies moderated, but the atmosphere became even drier. Wind speed anomalies were initially minimal, but a distinct positive anomaly emerged around June 6, favoring fire spread and persistence. The fires were subsequently suppressed after 6–7 June due to the arrival of precipitation and increased humidity.

The evolution of regional fire-weather conditions was driven by a persistent Omega blocking pattern anchored over Hudson Bay (Figure 1a). During the pre-ignition phase (28–30 May), a weak anticyclonic anomaly over central Canada suppressed precipitation and created widespread warm and dry anomalies across eastern North America (Figures S3a, S3e, S3i in Supporting Information S1). On 31 May, the geopotential height anomaly over Hudson Bay intensified abruptly, further exacerbating these conditions in the Quebec fire region (Figure 1f, Figure S4 in Supporting Information S1). The intensifying ridge also displaced mid-level moisture southward into Quebec (Figure S4a–S4d in Supporting Information S1), where it overlapped with a pre-existing hot (Figure S4i–S4l in Supporting Information S1), unstable lower troposphere (Figures S4e–S4h in Supporting Information S1). These conditions were conducive to dry lightning (Kalashnikov et al., 2022; Rorig & Ferguson, 1999), which ignited the wildfires on 1–2 June (Figure S5 in Supporting Information S1). When the blocking high got fully established on 3–5 June, strong northerly winds advected dry continental air while large-scale subsidence transported upper-tropospheric dryness downward (Figures S6 in Supporting Information S1), causing a extreme FWI and accelerating fire spread. From 6 June onward, a mid-latitude cyclone developed southeast of the blocking high, bringing precipitation over Quebec (Figure S3d in Supporting Information S1).

The formation of the Omega block was likely facilitated by Super Typhoon Mawar in the western North Pacific. Mawar intensified into a super typhoon on 23 May and produced exceptional precipitation (approximately two standard deviations above climatology) over the warm pool region during its mature phase (26–29 May), with column-integrated diabatic heating ($Q1$) exceeding 200 W m^{-2} (Figures 1c–1f and Figure S7 in Supporting Information S1). Such tropical diabatic heating can excite a poleward-propagating Rossby wave trains that amplified downstream blocking ridges (Lin et al., 2022). Notably, the Hudson Bay blocking anomaly peaked around 1–2 June, lagging the precipitation and $Q1$ maximums by approximately 6–7 days (Figure 1f). This lag matches the characteristic timescale of trans-Pacific Rossby wave propagation (Hoskins & Karoly, 1981), suggesting a potential link between Mawar's diabatic forcing and the extreme fire over Quebec.

3.2. Diagnosis Analysis of Typhoon Mawar's Role in Fire Weather

To elucidate the dynamic linkage between Typhoon Mawar and the fire-related blocking pattern over North America, we diagnosed the evolution of the RWS and WAF. During the early intensification stage (23–25 May), the dynamic interaction between Mawar and the mid-latitude circulation remained largely decoupled (Figure 2a). Because the typhoon was located south of 15°N where the Coriolis parameter (f) is relatively small, the stretching term ($S1$) generated only a weak negative anomaly near the core (Figure S8a in Supporting Information S1). Furthermore, despite the presence of upper-level divergent outflow, the advection term ($S2$) contributed negligible RWS to the subtropical jet region due to the long meridional distance and the weak vorticity gradient in the intervening latitudes (Figures S8e in Supporting Information S1). Consistent with this decoupling, WAF vectors showed no coherent wave propagation from the typhoon region toward the jet (Figure 2f).

A robust tropical-extratropical teleconnection emerged as Mawar intensified and moved north of 15°N (26–28 May). Due to the increase in planetary vorticity, the $S1$ term generated a pronounced dipole structure: a negative core driven by strong upper-level divergence, surrounded by a positive ring associated with compensating subsidence (Figure S8b in Supporting Information S1). More importantly, the strengthened poleward outflow began to impinge upon the southern flank of the westerly jet. By advecting low-vorticity air across the strong

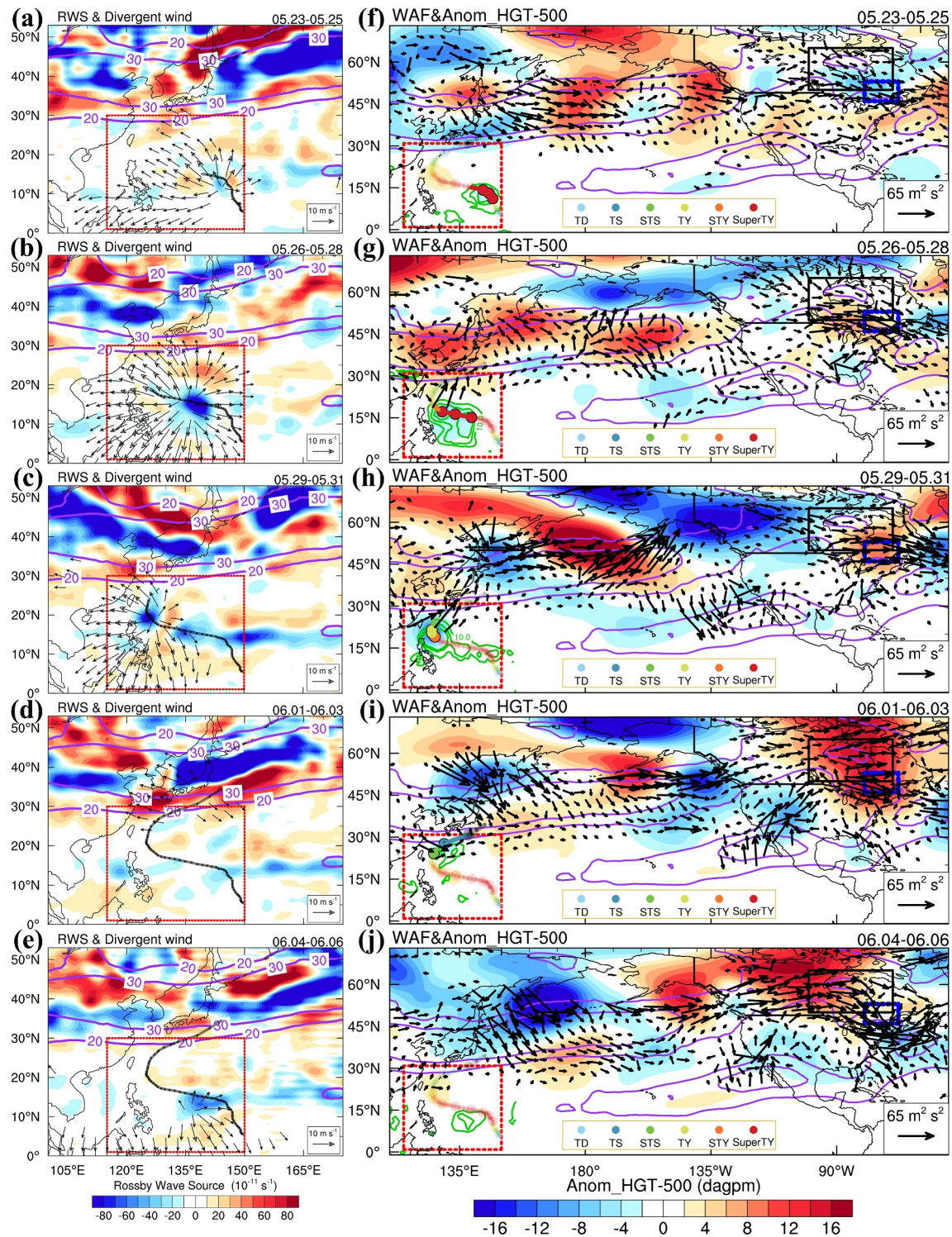


Figure 2. Evolution of tropical forcing and downstream Rossby wave propagation associated with Typhoon Mawar (23 May–6 June 2023). Left column (a–e): Three-day mean 200-hPa divergent wind (vectors; values $>5 \text{ m s}^{-1}$ only) and Rossby wave source (shading). Right column (f–j): Three-day mean HGT-500 anomaly (shading) and wave activity flux (vectors), with precipitation (green contours; mm day^{-1}). Purple contours represent 250-hPa jet stream (at 20 and 30 m s^{-1}). Black lines (left column) and colored circles (right column) indicate Typhoon Mawar's position.

meridional vorticity gradient, the $S2$ term generated a significant positive RWS anomaly north of the typhoon (Figure S8f in Supporting Information S1). This combination yielded a distinct negative-positive dipole oriented toward the jet entrance (Figure 2b), providing an effective source for Rossby wave generation. Consequently, WAF vectors emerged from the western Pacific and propagated northeastward (Figure 2g), marking the injection of wave energy into the jet waveguide.

Following this onset, a coherent quasi-stationary Rossby wave train propagated downstream along the North Pacific jet (29–31 May). The wave packet manifested as an alternating “trough-ridge-trough” pattern, characterized by a cyclonic anomaly over the Kuril Islands ($\sim 150^\circ\text{E}$, 50°N), an anticyclonic anomaly south of the Aleutians, and a cyclonic anomaly in the Gulf of Alaska (Figure 2h). Although Mawar began to recurve and weaken, its continued proximity to the jet allowed the $S2$ term to maintain a continuous supply of wave energy (Figure 2c, Figure S8g in Supporting Information S1). The WAF clearly depicts the dispersion of wave energy along the great circle path, extending from the typhoon region across the North Pacific to the North American continent.

By 1–3 June, the convergence of downstream wave energy flux amplified the ridge over Hudson Bay, establishing the peak blocking pattern (Figure 2i). Subsequently (4–6 June), as the upstream energy supply diminished with the dissipation of Mawar and its merger into the mean flow, the blocking high weakened and retrograded (Figure 2j). These diagnostic results provide strong observational evidence that the extreme fire weather in Quebec was dynamically linked to Typhoon Mawar through a teleconnection mechanism, wherein the typhoon acted as an active RWS to trigger and sustain a trans-Pacific Rossby wave train.

3.3. Quantifying Typhoon Mawar's Contribution Through Numerical Experiments

To verify the physical mechanism, we employed the LBM model with prescribed thermal forcing. The background states were derived from ERA5 reanalysis averaged over 15 May–14 June 2023. A Mawar-like heating profile (centered at 134°E , 16.5°N ; maximum heating rate of $6\text{--}7\text{ K day}^{-1}$) was imposed to mimic the typhoon's deep convection. The simulated steady-state response (Figure 3a) successfully reproduces the poleward-propagating wave train that matches the observed “trough-ridge-trough” pattern across the North Pacific. Notably, it captures a strong anticyclonic anomaly over northeastern North America that closely resembles the Hudson Bay blocking center observed during early June (Figures 2h and 2i). This agreement confirms that the linear Rossby wave dispersion, excited by the typhoon's diabatic heating, is dynamically sufficient to produce the downstream blocking pattern.

To quantitatively understand the contributions from the Typhoon Mawar, we performed two numerical experiments using the WRF model. One is the CTRL experiment that successfully reproduces the observed circulation evolution, maintaining pattern correlation coefficients exceeding 0.9 for 500-hPa geopotential height over the North Pacific–North America sector from 24 May to 4 June (Figure S9 in Supporting Information S1). Details of the validation against observations are provided in Table S2 in Supporting Information S1. To isolate Mawar's diabatic forcing, we conducted a sensitivity experiment (NonTY) that uses the exact same model configuration as CTRL but excludes the latent heating associated with the typhoon. Figure 3b shows the circulation response (CTRL minus NonTY) averaged over 29 May–2 June. Unlike the LBM's linear response to prescribed forcing, the WRF simulated difference field incorporates fully nonlinear processes, including moist thermodynamics, radiative processes, surface energy exchanges, and the complex interactions between the typhoon outflow and the westerly jet. Despite this added complexity, the response exhibits a robust wave-train structure consistent with both the LBM solution and observations, further supporting the teleconnection mechanism.

The quantitative assessment of Mawar's role, mainly focus on 24 May–2 June, as the simulation approaches the intrinsic limit of deterministic predictability. The CTRL simulation successfully captured the rapid amplification of the blocking high starting May 30 (Figure 3c, Figure S10h in Supporting Information S1), during which 500-hPa geopotential heights over the Hudson Bay region increased sharply, while the NonTY run exhibited a much weaker response. The typhoon-induced anomalies (CTRL minus NonTY) over this region reached 1.8 ± 0.3 , 4.4 ± 0.3 , and 5.8 ± 0.55 dagpm (mean $\pm$ inter-member standard deviation), corresponding to approximately 0.26 ± 0.04 , 0.62 ± 0.04 , and 0.79 ± 0.07 standard deviations of the local daily climatological variability derived from ERA5. To quantify Mawar's contribution to the blocking development, we calculated the ratio of these typhoon-induced anomalies to the total geopotential height growth in the CTRL run relative to the 30 May baseline. The results indicate that the typhoon accounted for approximately $34 \pm 6\%$, $41 \pm 3\%$, and $55 \pm 5\%$ of the

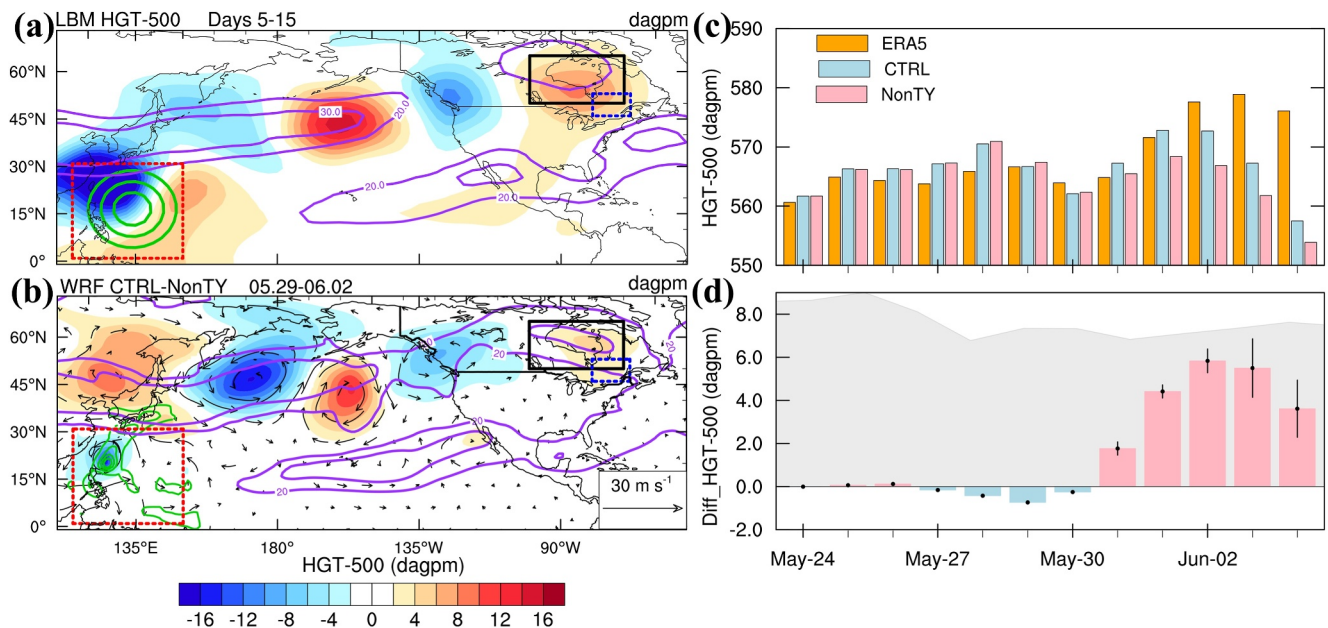


Figure 3. Simulated atmospheric response to Typhoon Mawar and its contribution to the downstream blocking. (a) Linear Baroclinic Model-simulated HGT-500 response (shading) at days 5–15 to a prescribed Mawar-like heat source (green contours; K day^{-1}). (b) Weather Research and Forecasting (WRF)-simulated HGT-500 (shading) and wind fields (vectors) response to the typhoon (CTRL minus NonTY) averaged from 29 May to 2 June. Purple contours in (a) and (b) denote the background 250-hPa jet stream. (c) Time series of HGT-500 in the Hudson Bay region (black box in b) from ERA5 (orange) and from WRF simulations with (CTRL; blue) and without (NonTY; pink) the typhoon. (d) Difference in HGT-500 averaged over the Hudson Bay region. Error bars indicate the inter-member standard deviation range. The gray shading in (d) indicates the daily standard deviation from ERA5 (1991–2020).

total blocking amplification on these three days, respectively. These findings demonstrate that remote forcing from Typhoon Mawar played a substantial and amplifying role in establishing the extreme blocking pattern associated with the Quebec wildfires. Quantitatively, the typhoon-induced blocking resulted in a near-surface warming of approximately $2\text{--}3^{\circ}\text{C}$, a reduction in RH2 of about 6%–9%, an elevated VPD of $\sim 1\text{--}2$ hPa, and suppressed precipitation during the fire outbreak period (Figure S11 in Supporting Information S1). These findings confirm that Mawar not only intensified the downstream blocking but also directly exacerbated the near-surface meteorological conditions conducive to extreme wildfire.

4. Conclusions and Discussions

Using observational analyses and numerical simulations, this study reveals how Super Typhoon Mawar remotely modulated the Quebec extreme wildfires in early June 2023. As summarized in Figure 4, Mawar triggered a trans-Pacific Rossby wave train that intensified the North American blocking high. This amplified blocking pattern enhanced lightning activity and promoted anomalous air dryness favorable for wildfire ignition and sustained burning across Quebec.

Crucially, this study highlights that a tropical cyclone can remotely modulate midlatitude wildfire conditions specifically during its pre-recurvature tropical phase. This distinguishes our findings from previous work focusing on recurving or transitioning cyclones that directly interact with the midlatitude jet (Archambault et al., 2013; Stuivenolt Allen et al., 2021). During this tropical stage, Mawar functioned as a powerful tropical heat source, generating upper-level divergent outflow that induced an effective RWS (Sardeshmukh & Hoskins, 1988). The extended propagation pathway from the deep tropics resulted in a 6–7-day lag between peak heating and downstream blocking, which was longer than the ~ 4 -day timescale typical of recurving systems. Moreover, while prior studies emphasized wind-driven fire enhancement (Stuivenolt Allen et al., 2021), our results show that the remotely forced blocking partly shaped thermodynamic conditions conducive to dry-lightning ignition, revealing a distinct teleconnection pathway linking tropical cyclones to wildfire initiation.

The simulated typhoon-related blocking high was positioned west of the wildfire region, consistent with climatological findings linking high-pressure anomalies to lightning-ignited fires in eastern Canada (Jain &

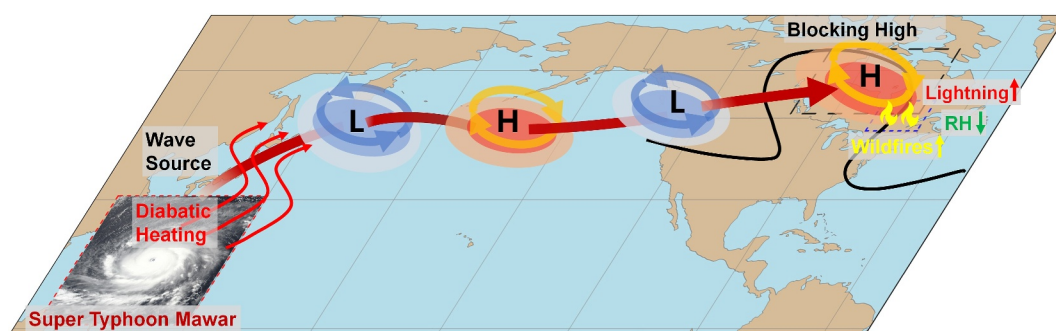


Figure 4. Schematic of the remote forcing mechanism linking Super Typhoon Mawar to the 2023 Quebec wildfires. The typhoon triggered a trans-Pacific Rossby wave train that intensified the North American blocking high, enhancing lightning potential and atmospheric aridity favorable for wildfire initiation and maintenance.

Flannigan, 2021; Skinner et al., 2002; Zhao et al., 2022). This consistency suggests that the influence of the typhoon-related blocking was not coincidental. Nevertheless additional cases and longer-term analyses are needed to further validation. Meanwhile, our quantitative attribution is subject to inherent model limitations. The 12-day simulation period, required to link these remote phenomena, exceeds typical limits of deterministic predictability in the mid-latitudes (Zhang et al., 2019), restricting our quantification to the blocking development phase rather than its full lifecycle. Moreover, the 1° resolution cannot adequately resolve diabatic heating processes outside the typhoon core, which are critical for blocking establishment and Rossby wave breaking (De Luca et al., 2024). This likely contributes to the underestimated blocking intensity after day 10 and the associated RMSE in surface variables (T2m, RH2 and precipitation), hindering a precise diagnosis of dry lightning probability attributable to the typhoon-induced anomalies. Future research employing very-high-resolution idealized climate models that explicitly resolve convection and isolate mechanisms (De Luca et al., 2024; Reed et al., 2025), or hybrid physics-AI models with extended forecast skill, may allow more accurate quantification of the typhoon's influence throughout the entire blocking lifecycle and provide improved assessments of downstream wildfire impacts.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study..

Data Availability Statement

The daily global fire carbon emissions from GFED4.1s (van der Werf et al., 2017a) are accessible through <https://globalfiredata.org/related.html/>. FINNV2.5 (Wiedinmyer & Emmons, 2022) daily burned area data are available at https://www.acom.ucar.edu/acresp/MODELING/finn_emis_txt/. The NBAC individual fire records (Canadian Forest Service, 2024) are archived at <https://cwfis.cfs.nrcan.gc.ca/downloads/nbac/>. The MERRA-2 aerosol reanalysis data (Global Modeling and Assimilation Office, 2015) are available at https://disc.gsfc.nasa.gov/datasets/M2I3NXGAS_5.12.4/summary. IMERG Final Precipitation data (Huffman et al., 2024) are available at <https://gdex.ucar.edu/datasets/d734000/>. The ERA5 meteorological (Copernicus Climate Change Service, 2023a, 2023b) and FWI data (Copernicus Climate Change Service, 2019) are available at <https://cds.climate.copernicus.eu/datasets> and <https://doi.org/10.24381/cds.0e89c522>, respectively. The daily lightning data from gridded World Global Lightning Climatology (Kaplan, 2024) is available at <https://zenodo.org/records/10725446>. Typhoon track and intensity data from the CMA Tropical Cyclone Best Track Dataset (China Meteorological Administration, 2024) are available at <https://tcdata.typhoon.org.cn/en/zjljsjj.html>. The source codes of the LBM (Watanabe & Jin, 2024) and WRF (University Corporation for Atmospheric Research, 2024) are available at <https://ccsr.aori.u-tokyo.ac.jp/~lbm/sub/lbm.html> and https://www2.mmm.ucar.edu/wrf/users/download/get_source.html, respectively. All the data used in the manuscript are available via Zhu (2025) (<https://doi.org/10.5281/zenodo.17234923>).

Acknowledgments

This work was supported by the National Natural Science Foundation of China (42325506), Guangxi Science and Technology Program (No. AB24010074), and the New Cornerstone Science Foundation through the XPLOER PRIZE. We are grateful to the High Performance Computing Center (HPCC) of Nanjing University for doing the numerical calculations in this paper on its blade cluster system.

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