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Key Points:

- Anomalous Asian monsoon activity like that observed in late June 2021 can exert a cooling effect over the Pacific Northwest on average
- However, in the case of 2021, anomalous monsoon activity had a warming influence, contributing to the extreme Pacific Northwest heatwave
- Confusing the "*can it*" and "*did it*" questions could lead to contradictions on how the monsoon or other large-scale drivers affect extremes

Supporting Information:

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

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Impact of Asian Summer Monsoon on the 2021 Pacific Northwest Heatwave: Can It? Did It?

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Abstract This study examines the role of Asian summer monsoon in the unprecedented 2021 Pacific Northwest (PNW) heatwave. We address this by separating it into two relevant but independent questions: Can monsoon activity observed prior to the event impact PNW climate, and did it specifically impact the 2021 PNW heatwave? Based on observational diagnostics, numerical experiments, and subseasonal-to-seasonal (S2S) forecasts, our results consistently indicate although the monsoon activity can exert a cooling effect on the PNW, on average, it had a warming influence in the specific case of 2021 and thus contributed to the heatwave that summer. The contrasting answers to the *"can it"* and *"did it"* questions highlight how background flow and specific forcing pattern during the event can modulate—or even reverse—the expected impact. We advocate future work exploring the link between large-scale climatic drivers and extremes should be undertaken in an event-specific context to better understand these relationships.

Plain Language Summary The Pacific Northwest (PNW) experienced a record-breaking heatwave during the summer of 2021, resulting in significant adverse effects on both human society and ecosystems. A heavy rainfall band was observed stretching from south China to south of Japan 1 week prior to the heatwave, fueling the debate over whether the monsoon activity contributed to this event. Our study found that while the monsoon activity typically has a cooling effect on the PNW's climate, in this particular year, it had a warming effect and thus contributed to this specific heatwave. This unusual warming effect was driven by a stronger and more northward-shifted Pacific jet stream, which altered the extratropical response to the monsoon, resulting in an anticyclonic pattern over the PNW instead of the typical cyclonic response seen under average climatic conditions. Therefore, it is important to distinguish between the general question of whether monsoon *can* influence such events on average, and the specific question of whether it *did* in any specific case. We argue that when discussing the influence of large-scale climate drivers on extremes, it is crucial to clearly state whether the focus is on the general potential for influence or on the specific role in a particular event.

1. Introduction

The Asian summer monsoon, by releasing a vast amount of latent heat into the atmosphere, plays a crucial role in shaping circulation variability across the tropics and extratropics (Wang, 2006). This influence has been especially significant during periods when other large-scale climatic drivers, such as the El Niño-Southern Oscillation (ENSO), the Madden-Julian Oscillation (MJO), and the stratospheric polar vortex (SPV), have been weak or are absent in summer (Robertson & Vitart, 2019). A notable example of the monsoon's critical impact is its effect on North America (Lau & Weng, 2002; Zhu & Li, 2016). By exciting planetary waves that propagate across the Pacific (Hoskins & Karoly, 1981), the variability of the Asian summer monsoon can influence regional climate in North America, affecting the probability of extreme events such as heatwaves, storms, and droughts (Ding & Wang, 2005; Lopez et al., 2019; Yu et al., 2023).

Recently, several studies have reported that the Asian summer monsoon may have contributed to the unprecedented high-temperature event over North America at the end of June 2021 (Baier et al., 2023; Oertel et al., 2023), an event regarded as the most extraordinary heatwave on record (Leach et al., 2024; McKinnon & Simpson, 2022; Philip et al., 2022; Thompson et al., 2023). This heatwave (the PNW heatwave) exhibited an astonishing temperature deviation of 20°C above the climatological mean and surpassed previous temperature records by a remarkable 5°C. Consistent with the understanding of other historical extreme events, the PNW heatwave is thought to have resulted from an optimal combination of multiple factors (Mo et al., 2022; Neal et al., 2022; Overland, 2021; Schumacher et al., 2022; White et al., 2023), with the Asian summer monsoon playing a critical role (Lin et al., 2022; Qian et al., 2022). It is argued that, by exciting stationary Rossby wave that traverses the Pacific, the monsoon directly contributed to the build-up of atmospheric blocking over North America and thereby contributed to the heatwave. However, studies supporting the monsoon's influence reveal conflicting findings regarding the specific monsoon regions that drove the heatwave. For example, Lin et al. (2022) emphasized suppressed convection near the Philippines as a key driver of the heatwave. In contrast, Qian et al. (2022) identified enhanced convection south of Japan as the dominant factor, arguing that the convection center highlighted by Lin et al. (2022) does not contribute as a leading factor. Since anomalous Asian summer monsoon typically features spatially heterogeneous convective anomalies with multiple interacting centers, and all anomalous convection centers, regardless of their polarity, can affect the atmosphere, this divergence raises questions about whether the monsoon contributed to this event.

In this manuscript, we present new evidence and insights into the role of the Asian summer monsoon in the 2021 PNW heatwave. We expand previous studies in three key ways. First, unlike earlier studies that focused solely on individual anomalous convection centers, we examine the holistic role of the monsoon by considering the spatial pattern of the monsoon system including all convection centers. Second, we employ a combination of observational diagnostics and model experiments of varying complexity to provide a comprehensive picture about the role of monsoon. Third, we further analyze using operational subseasonal-to-seasonal (S2S) forecast ensembles that accurately captured the event. In this way, the first two approaches address whether the Asian summer monsoon, as observed in 2021, *can* influence the PNW under climatological conditions (*can it?*), while the third enables a more direct assessment of the monsoon's role in the specific context of this event (*did it?*).

2. Data and Methods

Reanalysis data sets, including surface temperature (T2m), maximum surface temperature (Tmax), and atmospheric circulation variables, are from the 6-hourly Japanese 55-year Reanalysis (JRA-55) spanning 1981–2021 (Kobayashi et al., 2015), with daily means computed by aggregating the 6-hourly data. Precipitation data comprise the interpolated daily Outgoing Longwave Radiation (OLR) data (Liebmann & Smith, 1996) from the National Oceanic and Atmospheric Administration (NOAA), and NOAA's Climate Data Record (CDR) of the CPC Morphing Technique (CMORPH) High-Resolution Global Precipitation Estimates, Version 1 (Xie et al., 2017).

The Linear Baroclinic Model (LBM) and Community Atmosphere Model version 5 (CAM5) are used to isolate the impact of monsoon. Both models are forced with identical predefined diabatic heating anomalies associated with the Asian monsoon. The LBM (Watanabe & Kimoto, 2000) is a dry atmospheric general circulation model with T42 horizontal resolution (≈2.8°) and 20 sigma vertical layers. The prescribed basic state is set to the 1981–2020 summer climatology. The integration averaged from days 15–25 is examined when the atmospheric response is steady. The CAM5 (Neale et al., 2010) employs a more complex configuration at 1.9° × 2.5° horizontal resolution and 30 vertical levels. The underlying ocean is prescribed as the daily evolution of climatology. The control run is conducted over a period of 50 years, and the last 30 years are used to define the climatology. The sensitivity run is identical to the control run, except for the inclusion of diabatic heating prescribed exclusively in each June over 30 years, with the last 20 years, which effectively forms a 20-member ensemble, are used. The monsoon's impact is quantified as the difference between the sensitivity run and control run during 28 June–4 July, corresponding with the peak phase of 2021 PNW event.

The S2S ensemble forecasts (Vitart et al., 2017) from 10 operational centers initialized on either 17 or 18 June 2021, which is approximately 10 days prior to the heatwave onset, are analyzed. An ensemble sensitivity analysis

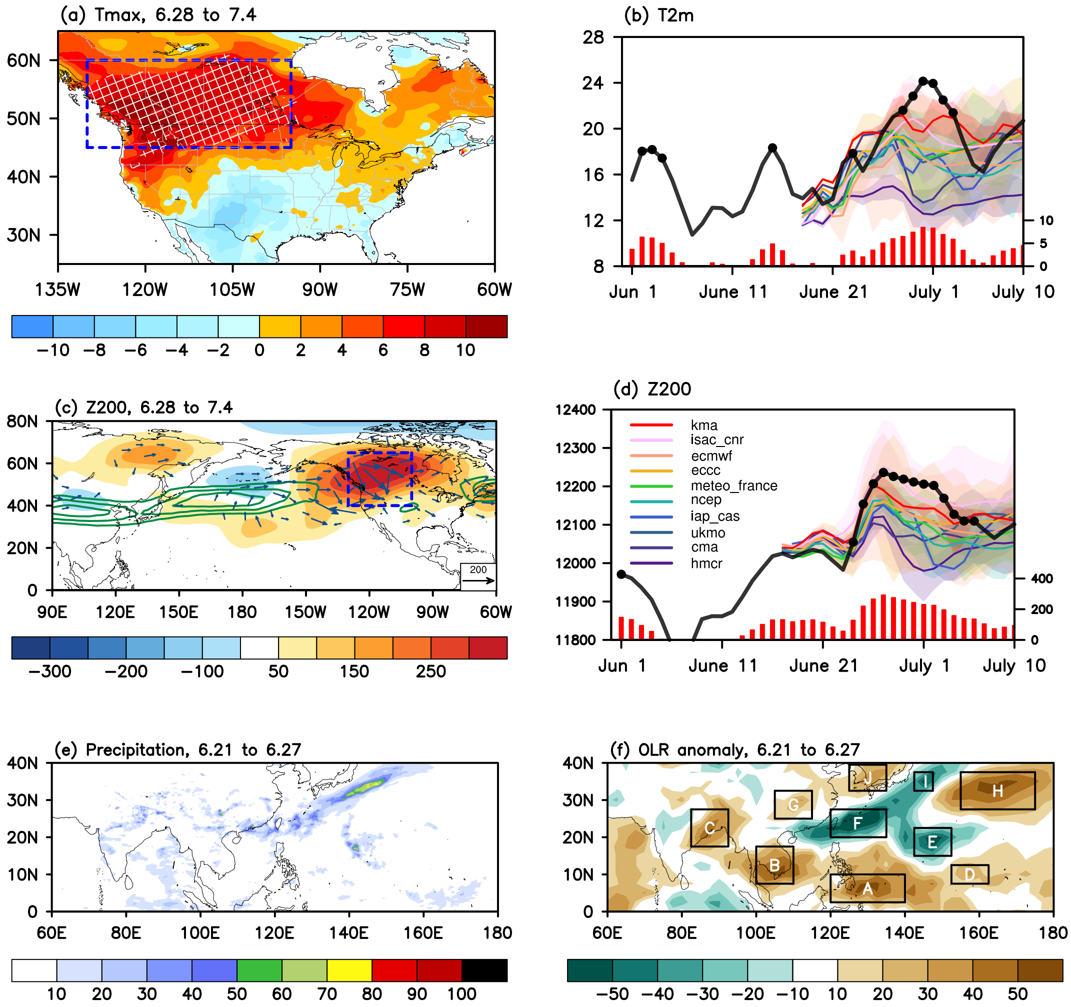

Figure 1. Characteristics of the 2021 PNW heatwave. (a) The maximum surface temperature (Tmax; °C) anomalies averaged during the peak stage of the heatwave. Hatching indicates where Tmax exceeded historical records. (b) The time evolution of daily mean surface temperature (T2m; °C) averaged over the region represented by the blue box in (a). The thick black line represents the observation, with dots indicating record-breaking values. The red bars depict the T2m anomalies and correspond to the right *y*-axis. Colored lines represent the multi-member mean of subseasonal-to-seasonal (S2S) predictions, where the shading represents the spread across members in each model. (c, d) Are same as (a, b), but for geopotential height at 200 hPa (Z200; gpm). In (c), green contours indicate the zonal wind speed (U200; m s^{-1}), with an interval of 10 m s^{-1} starting from 20 m s^{-1}. The vectors represent the horizontal wave activity flux (Takaya & Nakamura, 2001) (m^2 s^{-2}). (e) The precipitation (mm day^{-1}) averaged 1 week prior to the heatwave. (f) Is same as (e), but for the outgoing longwave radiation (OLR) anomalies. The labeled sub-boxes represent the anomalous convection centers within the Asian monsoon system examined in this study.

(ESA) (Torn & Hakim, 2008) is applied to assess the link between pre-event monsoon and subsequent blocking. By contrasting ensemble members with the strongest versus weakest predicted blocking, or strongest versus weakest predicted monsoon rainfall, we isolate differences among ensemble members to examine whether monsoon-driven heating affected the prediction of heatwave.

The statistical significance is evaluated by the two-tailed Student's *t* test. To quantify uncertainty in the estimates, we applied a bootstrap resampling method by randomly selecting 30 samples with replacement for 1,000 times (Wilks, 2011).

3. Results

3.1. Setting the Scene

The 2021 PNW heatwave primarily occurred in the southwest of Canada and northwest of the United States, with seven-day-averaged daily Tmax anomalies exceeding 10° (Figure 1a). The most pronounced Tmax anomalies were observed in proximity to the leeward slopes of the Coast Range and the northern part of the Cascade Range, highlighting the significant influence of regional topography in escalating the event (Loikith & Kalashnikov, 2023; Mass et al., 2024). The heatwave rapidly developed around June 20 and reached its peak between June 28 and July 4, with T2m continuously exceeding record-breaking values for nearly 1 week (Figure 1b). Above the PNW, a strong anticyclonic blocking event persisted in the upper troposphere (Figure 1c). The blocking was situated at the exit region of the Pacific jet stream, which is climatologically known as a favorable location for blocking (Nakamura & Huang, 2018). The blocking attained a record-breaking intensity (Figure 1d) but peaked several days earlier than the T2m. This indicates a top-down control (Bartusek et al., 2022; Hotz et al., 2024; Zhang & Boos, 2023). The blocking was linked to an upstream wave train propagating along the subtropical jet stream across the Pacific. The key focus of this study is to investigate whether this stationary wave pattern over the Pacific—and the blocking above the PNW—were forced by the Asian summer monsoon.

3.2. Can It?

One week prior to the heatwave, the Asian monsoon exhibited complex convective anomalies. While precipitation was dominated by a prominent northeast-southwest Meiyu rainband stretching from the South China Sea to Japan (Figure 1e), anomalous OLR revealed a mosaic of both enhanced and suppressed convective centers across the monsoon domain (Figure 1f). This spatial complexity sparked the debate over which monsoon system component triggered the downstream heatwave. For example, Lin et al. (2022) highlighted the suppressed convection centers A and B, while Qian et al. (2022) underscored the role of convection centers F and I in driving the heatwave. However, focusing solely on individual convective centers as a representation of monsoon activity might risk oversimplifying the monsoon's interconnected impacts. To reconcile these discrepancies, we adopt a holistic definition of the Asian summer monsoon that integrates all convective centers shown in Figure 1f, and explore their combined impacts.

First, we analyze their overall impact by assessing observational data sets. A monsoon index is constructed based on the pattern correlation of OLR anomalies during June 21–27 in 2021 (Figure 1f and Figure S1 in Supporting Information S1). We then perform regression against the 1-week average field from June 28–July 4 to examine the delayed impact of this particular convection pattern. The 1-week interval for regression is based on the consideration that it takes approximately 1 week for an excited Rossby wave to propagate across the Pacific. However, the results remain largely insensitive to reasonable variations in the choice of interval. The regression analysis is conducted for the period 1981–2020, in which we deliberately exclude the year 2021 to reveal a clean statistical relationship. The regressed Z200 onto the monsoon index reveals a wave-like structure in the middle-to-high latitudes. Although an anomalous anticyclone persists over the exit of the Pacific jet stream, it is located further upstream around Alaska (Figure 2a) and does not coincide with the center of the blocking in this event. Instead, an anomalous cyclone persists above North America, which correspondingly results in a significant negative T2m response over the PNW. This suggests that a convective pattern like that observed in late June 2021 can, on average, support a cyclonic response and a cooling effect over the PNW.

We further conduct numerical experiments using the LBM and CAM5 to study the monsoon's impact. Realistic diabatic heating anomalies associated with the convection in late June 2021 (Figure 1f) are prescribed in the models. The diabatic heating for the experiments is obtained by applying the thermodynamic equation to the 6-hourly reanalysis data set (Figures S2 and S3 in Supporting Information S1). Figure 2 suggests both models show very similar Z200 responses to the observed diabatic forcing with a cyclonic response over North America (Figure 2). Notably, the atmospheric response shows remarkable similarity over the region extending from the exit of the Pacific jet stream to the North America, with pattern correlation to Figure 2a reaching 0.59 for LBM and 0.75 for CAM5 over [30°N–60°N, 150°W–60°W]. This suggests the potential role of the jet stream in anchoring the pattern (e.g., Simmons et al., 1983). Although the basic state in CAM5 is less realistic compared to that used to drive the LBM experiments (green contours), the wave-like response in CAM5 is more similar to observations than in LBM, suggesting nonlinear processes, such as eddy feedback, are important in shaping the response. Corresponding to the cyclonic circulation response, both models show negative T2m anomalies over the

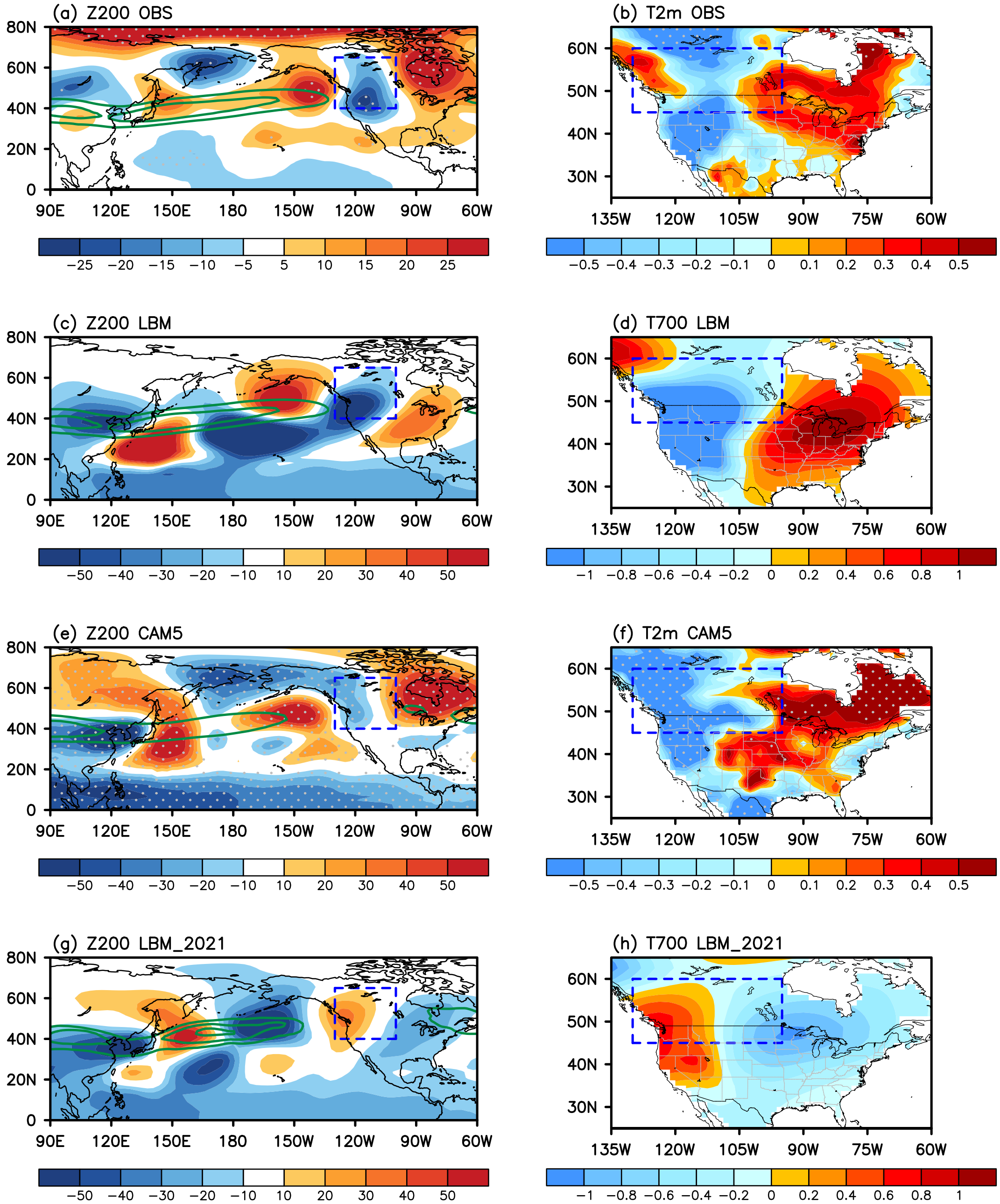

Figure 2. Climate response to the anomalous Asian summer monsoon activity 1 week before the heatwave. (a) The regressed anomalies of Z200 (gpm) and (b) T2m (°C) based on the constructed monsoon index. (c) The response of Z200 and (d) temperature at 700 hPa (T700; K) to the prescribed diabatic heating associated with the monsoon in LBM. (e, f) Are the same as (c, d) but for the Z200 and T2m response in CAM5, respectively. (g, h) LBM experiments as in (c, d), but using June 2021 conditions as the basic flow. The blue boxes in the left panel and right panel are the same as the blue boxes in Figures 1c and 1d. Green contours represent the zonal wind speed (U200; m s^{-1}) with an interval of 8 m s^{-1} starting from 24 m s^{-1}. Gray dots for the observational regression and CAM5 experiments indicate values exceeding 95% significance level.

PNW. The consistency and high degree of similarity across different methods confirm that the combined impact of anomalous convective activity observed in late June 2021 can, on average, decrease the occurrence probability of a heatwave.

To further shed light on discrepancies in previous studies like Lin et al. (2022) and Qian et al. (2022), we repeat the above analysis for each individual convection centers shown in Figure 1f. The monsoon index is defined as the

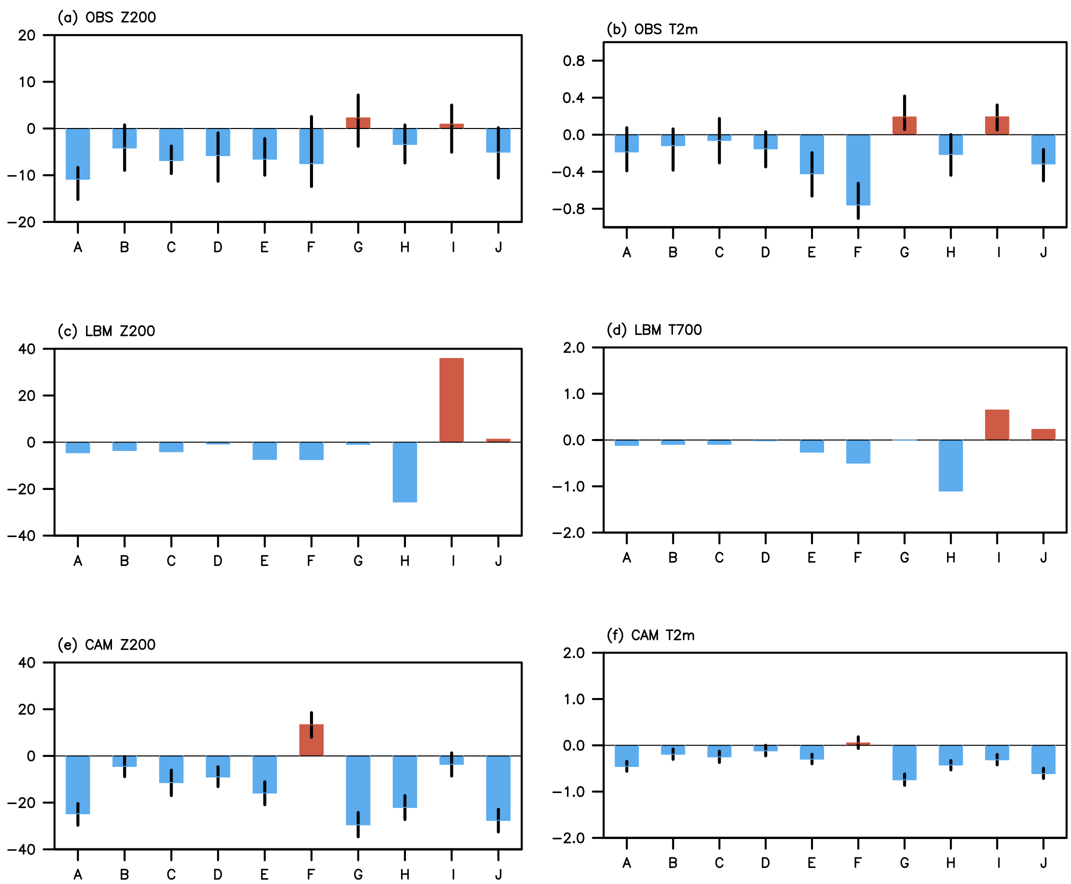

Figure 3. Climate response over the PNW to individual convection centers within the Asian summer monsoon system. (a) The averaged anomalies of regressed Z200 and (b) T2m upon the monsoon indices for each sub-region (denoted by letters A to J). (c, d) Are the same as (a, b), but for the Z200 and T700 in LBM experiments. (e, f) Are the same as (c, d), but for the Z200 and T2m in CAM5 experiments. The averaging regions for Z200 and temperature are indicated by the blue boxes in the left and right panels of Figure 2, respectively. The black bars represent the 5% to 95% uncertainty range.

standardized average of the OLR anomalies for each sub-region. To remain consistent with the 2021 event, the monsoon index and the prescribed diabatic forcing retain the same sign as in 2021 (Figure 1f). Figure 3 summarizes the Z200 and T2m response over the PNW. The corresponding spatial responses to each individual centers are shown in Figures S4–S9 in Supporting Information S1. It is clear that most convection centers exert a cooling influence on the region, though a subset produces warming response. For example, for regions A and B, which were highlighted by Lin et al. (2022), all approaches consistently indicate a cooling effect over the PNW. In contrast, for regions F and I, which were highlighted by Qian et al. (2022), their individual effects are more uncertain, as different approaches show divergent signs of impact. This suggests that, compared to their combined impacts, the impact of individual convection centers is more uncertain, being more influenced by internal variability and sensitive to the specific approach used. Nevertheless, Figure 3 generally supports that anomalous monsoon activities in 2021 can contribute to a cooling over the PNW, on average, thereby decreasing the probability of a heatwave occurrence.

3.3. Did It?

The results so far generally demonstrate a robust cooling impact of the monsoon on the PNW, on average, across a range of large-scale atmospheric environments. However, the forced response in any specific state (or year) may differ from this average perspective. To investigate the specific role of the monsoon in this 2021 heatwave, we use the S2S ensemble forecasts for further analysis.

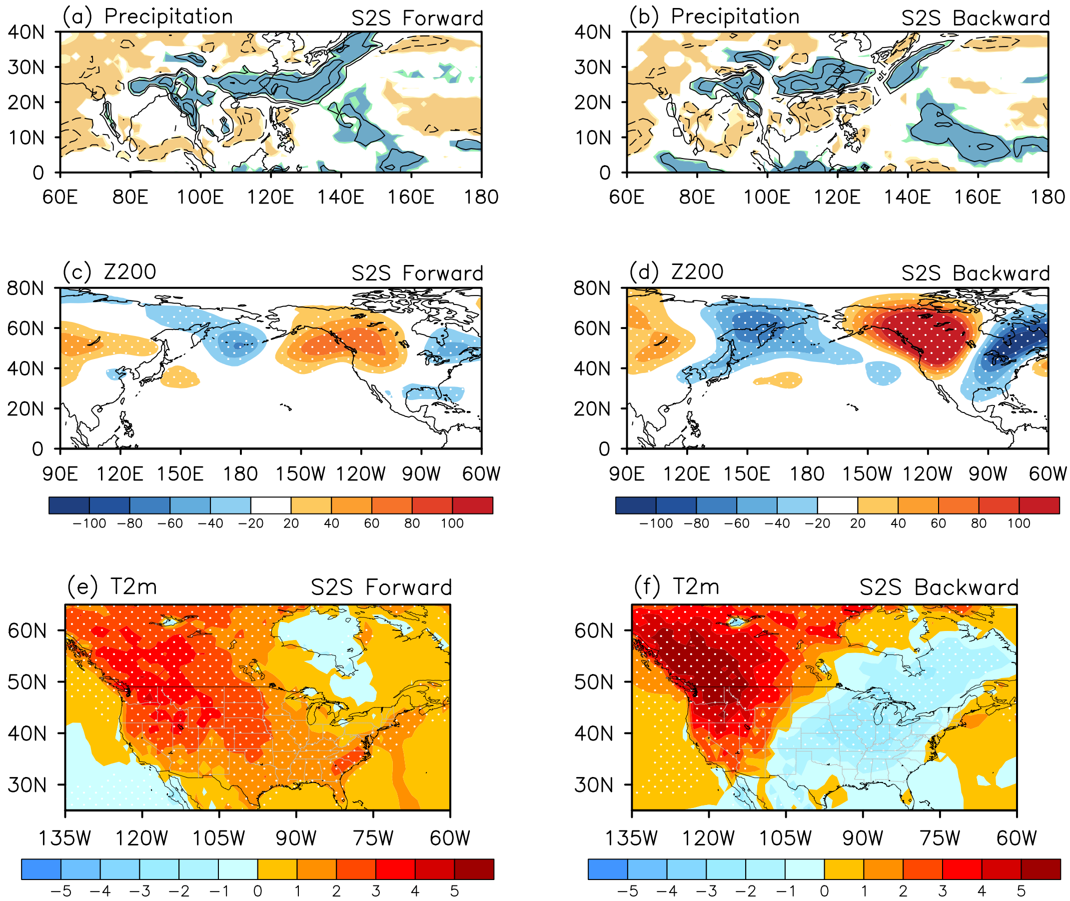

Figure 4. Linkage of the Asian monsoon precipitation and heatwave prediction in S2S ensemble forecasts. (a) Predicted differences of precipitation (mm day^{-1}) during 21–27 June, (c) Eddy Z200 during 28 June–4 July, and (e) T2m during 28 June–4 July between the upper and lower one-third members in terms of monsoon precipitation intensity during 21–27 June. (b, d, f) Are the same as (a, c, e), but for the ensemble differences based on the blocking intensity during 28 June–4 July. The shadings for precipitation and dots for Z200 and T2m indicate results that exceed the 95% significance level.

Figures 1b and 1d show the S2S forecasts issued approximately 10 days before the event. The S2S forecasts demonstrate reasonable skill in capturing the heatwave. Although they generally underestimate the T2m intensity during the peak stage of the heatwave, possibly due to missing local physical processes and feedbacks (e.g., soil moisture feedback), they do realistically capture the intensity of the blocking, which is the primary focus of this study, thereby increasing confidence in the S2S-based results. Here, we adopt a two-way perspective in the ESA: in the forward perspective, we select the ensemble members based on the forecasted monsoon precipitation during 21–27 June and then examine the differences in predicted blocking between the top and bottom thirds of the members 1 week later. Since all S2S forecast members significantly underestimate the rainfall intensity (not shown), those members are selected based on the monsoon precipitation intensity averaged over [0°–40°N, 60°E–180°]. For the backward perspective, we select the ensemble members based on the forecasted PNW blocking during 28 June–4 July and examine differences in monsoon precipitation 1 week earlier. Those members are selected based on the eddy Z200 averaged over [45°N–60°N, 130°W–100°W] (blue box in Figure 1a).

Figure 4 presents the differences among ensemble members across all S2S models, which include 192 members in total. The differences for each individual S2S model are shown in Figures S10–S15 in Supporting Information S1. In the forward perspective, where ensemble members are selected based on their accuracy in simulating pre-event monsoon rainfall, the precipitation field shows a difference that is very similar to the anomalous precipitation field during that period (Figure 1f vs. Figure 4a), indicating the selection criteria effectively identifies members that represent the observed rainfall characteristics. In addition, the predicted blocking is also more intense in members with more accurate monsoon rainfall simulation (Figure 4c), which in turn leads to forecasts of a more intense heatwave (Figure 4e). In the backward perspective, where ensemble members are selected based on the intensity of predicted blocking (Figures 4d and 4f), the pre-event monsoon rainfall in members with stronger blocking more closely resembles the observed rainfall (Figure 4a), with rainfall differences enhanced along a southwest–northeast band stretching from South China to south of Japan. In other words, both the forward and backward perspective analyses consistently suggest a positive linkage between the Asian monsoon and the heatwave. Although the analysis might only indicate a statistical relation rather than a causal influence, the accurate S2S prediction of the blocking and the consistent findings from both perspectives increase confidence that the monsoon likely played a positive role in this event.

4. Conclusion and Discussion

We have analyzed the impact of the Asian summer monsoon on the 2021 PNW heatwave based on observational diagnostics, model experiments, and operational S2S forecast analysis. We find that despite the fact that individual convective anomalies can either exert a warming or cooling impact on the PNW, the combined impact of anomalous monsoon activity with a pattern like that in late June 2021 can, on average, exert a robust cooling impact on the PNW and reduce the likelihood of events similar to the 2021 PNW heatwave. However, despite this, for this specific event, it appears the Asian summer monsoon activity contributed positively to the event and amplified the heatwave.

At first glance, it may seem odd that there are opposing results for the role of the monsoon from the observational and model experiments compared to the S2S forecast analysis. However, these discrepancies highlight the importance of the subtle difference between the "*can it*" and "*did it*" questions, as also highlighted by previous studies, such as Barnes and Screen (2015) and Henderson et al. (2018). Finding no response or not the response one was looking for in a *"can it"* type approach does not mean it *did not*. Equally, if the *"can it"* question had been a *yes*, that does not necessarily mean it *did*. The key resolving factor is that in June 2021, the Pacific jet stream was strengthened and shifted poleward (Figure S16 in Supporting Information S1), making it a more conducive waveguide to transmit the monsoon's impact on the PNW. We repeated our LBM experiments using the actual June 2021 state instead of the 1981–2020 summer climatology, and the atmospheric response was reversed in this time, yielding a warming effect over the PNW (Figures 2g and 2h). Furthermore, repeating experiments for each individual convection center under the June 2021 state (cf. Figure 3) consistently showed a predominantly positive PNW response (Figures S17–S19 in Supporting Information S1), contrasting with the mostly negative responses under the climatological state. Therefore, the specific state of the background flow fundamentally modulated the extratropical response to monsoon forcing, explaining these conflicting results between the "*can it*" and "*did it*" framings. In this way, the apparently contradictory results by Lin et al. (2022) and Qian et al. (2022) are not actually contradictory: while they may differ in terms of how localized convective anomalies *can* influence the PNW on average, both studies—and ours—suggest that the Asian monsoon *was* a contributing factor to the 2021 PNW heatwave.

Our results here have broader implications for studies linking large-scale climatic drivers to specific extreme events. The research question—whether it is *"can it"* or *"did it"*—should be clearly defined in advance. Given the near-infinite range of possible background states, the *"can it"* question could become inherently more difficult to answer, while the *"did it"* framing offers a more useful and well-posed approach. To address the *"did it"* question effectively, analyses must evaluate the specific climatic driver within the context of the event, accounting for both the forcing and the background flow. The importance of background flow has been demonstrated here. For the forcing, since real-world climatic drivers often exhibit spatial patterns that diverge from the theoretical canonical patterns, analyses should focus on the actual spatial pattern of the driver. In fact, the anomalous monsoon activity in late June 2021 had a complex structure that bore little resemblance to historical patterns (Figure 1f and Figure S20 in Supporting Information S1), using a canonical pattern to study its specific role in the 2021 event could lead to misleading conclusions. In addition, the impact of any climatic driver could be significantly obscured by internal variability and sensitive to the specific approaches used. Different methodologies may yield conflicting conclusions about the role of a driver (Figure 3). Robust conclusion thus demands cross-validation through multiple methodologies to constrain uncertainties.

Data Availability Statement

The JRA-55 data is available in Kobayashi et al. (2015) and can be acquired from https://rda.ucar.edu/datasets/ds628.0. The interpolated OLR data is available in Liebmann and Smith (1996) and can be acquired from https://www.ncei.noaa.gov/data/outgoing-longwave-radiation-daily/access/. The CMORPH precipitation data set is available in Xie et al. (2017) and can be acquired from https://www.ncei.noaa.gov/data/cmorph-high-resolution-global-precipitation-estimates/access/. The S2S database is available in Vitart et al. (2017) and can be acquired at https://apps.ecmwf.int/datasets/data/s2s. All data analysis and visualizations were performed using the NCAR Command Language (NCL) (http://dx.doi.org/10.5065/D6WD3XH5) and can be acquired from https://www.ncl.ucar.edu/.

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