

1     **The 2021 Pacific Northwest heat wave and associated**  
2     **blocking: meteorology and the role of an upstream**  
3     **cyclone as a diabatic source of wave activity**

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6             **Key Points:**

- 7             • A strong atmospheric blocking preceded the Pacific Northwest heat wave in late  
8             June 2021, setting up a heat-trapping stable stratification  
9             • An upstream cyclogenesis provided a critical diabatic source of wave activity flux,  
10            which converged downstream to create the block  
11            • When the upstream diabatic forcing is artificially reduced, the reconstructed block-  
12            ing weakens dramatically and shifts downstream

## Abstract

We investigate the meteorological and dynamical conditions that led to the extreme heat in the Pacific Northwest from late June to early July 2021. The extreme heat was preceded by an upper-level atmospheric blocking that snatched a warm pool of air from lower latitudes. A heat-trapping stable stratification ensued within the block, raising the surface temperatures significantly. An upper-tropospheric wave breaking and the concomitant surface cyclogenesis off the coast of Alaska initiated the block formation. The regional local wave activity budget reveals that a localized diabatic source associated with this storm critically contributed to the block by enhancing the zonal wave activity flux downstream, whose convergence over Canada drove the blocking. A simple model-based reconstruction predicts a 41 percent reduction in strength and a 10-degree eastward displacement of the block when the upstream diabatic source is reduced by just 30 percent.

## Plain Language Summary

From late June to early July 2021, an unprecedented heat wave enveloped the Pacific Northwest, causing over 1000 deaths. We investigate the meteorological condition and physical processes responsible for this event. Persistent meandering of the upper-level jet stream (blocking anticyclone) established a warm, stagnant column of air ('heat dome') over the Pacific Northwest, trapping heat near the surface. Somewhat counter-intuitively, the blocking anticyclone itself grew out of a cyclone that developed upstream (Gulf of Alaska) a few days prior, and the heat released during the formation of clouds in this storm played an essential role in fueling the blocking anticyclone (and heat wave) downstream. To the extent that blocking anticyclones in summer are fueled by condensation of moisture, we can expect them and associated heat waves to intensify as climate warms and the atmosphere contains more water vapor.

## 1 Introduction

The heat wave that enveloped the Pacific Northwest from late June through early July 2021 delivered unprecedented temperatures to the normally cool region — 108°F (42°C) in Seattle, 116°F (47°C) in Portland — and claimed over 1000 lives mostly in British Columbia (AON, 2021). One preliminary study puts it in a 1-in-1000 years event category (Philip et al., 2021). In the present study, we first provide an overview of the atmospheric conditions that led to the extreme heat event. As with most heat waves in the midlatitudes (Fang & Lu, 2020), this event was associated with an anomalous behavior of the jet stream (atmospheric blocking). We will show that the formation of an upper-level blocking preceded the extreme surface temperatures by 2-3 days, demonstrating a top-down thermodynamic control of blocking on the surface temperatures. We will then analyze the regional budget of local wave activity (LWA) (Huang & Nakamura, 2016, 2017, hereafter HN16 and HN17) to elucidate the dynamics behind the block formation. In particular, we will highlight the diabatic source of wave activity associated with an upstream cyclogenesis that contributed significantly to this unusually strong block. Our work complements previous trajectory-based studies (Pfahl et al., 2015; Steinfeld & Pfahl, 2019) to gain insight on the role of diabatic heating in blocking episodes. While the event lasted into July, we focus on the period leading up to the peak surface temperatures at the end of June. The demise and persistence of the event will be a topic of future study. The next section briefly describes the data and the wave activity diagnostic formalism. Section 3 summarizes the meteorological evolution during the event, followed by the wave activity diagnostic in Section 4. We conclude with a summary in Section 5.

## 2 Data and the wave activity diagnostic formalism

All data used in this study are derived from 6-hourly ERA5 reanalysis provided on 37 pressure levels with  $1^\circ \times 1^\circ$  horizontal resolution (Hersbach et al., 2020). The diagnostic framework follows the prescription of HN16 and HN17 (see also N. Nakamura & Huang, 2018; Valva & Nakamura, 2021, and Supporting Information of the present article). To quantify the jet stream’s meander and identify blocks we use LWA, which measures the meridional displacement of quasigeostrophic potential vorticity (QGPV),  $q$ , from a zonally symmetric reference state

$$A(\lambda, \phi, z, t) = -\frac{a}{\cos \phi} \int_0^{\Delta\phi} q_e(\lambda, \phi + \phi', z, t) \cos(\phi + \phi') d\phi', \quad (1)$$

where  $(\lambda, \phi, z, t)$  specifies longitude, latitude, pressure pseudoheight and time,  $a$  is planetary radius and  $q_e$  is the QGPV field relative to its reference state value at  $\phi$

$$q_e(\lambda, \phi + \phi', z, t) = q(\lambda, \phi + \phi', z, t) - q_{\text{REF}}(\phi, z, t). \quad (2)$$

The reference state  $q_{\text{REF}}$  is obtained by zonalizing the wavy QGPV field through an area preserving map (N. Nakamura & Solomon, 2010). In Eq. (1),  $\phi + \Delta\phi(\lambda, \phi, z, t)$  specifies the meridional location of the wavy QGPV contour whose value equals  $q_{\text{REF}}(\phi, z, t)$ , and  $\phi'$  is the displacement coordinate specific to, but independent of,  $\phi$ .

The main draw for using LWA to quantify the waviness of the jet stream is that it possesses a relatively simple budget evaluable from data. In particular, the column budget of LWA is governed by (HN16, HN17)

$$\frac{\partial}{\partial t} \langle A \rangle \cos \phi = \underbrace{-\frac{1}{a \cos \phi} \frac{\partial \langle F_\lambda \rangle}{\partial \lambda}}_{\text{(I)}} - \underbrace{\frac{1}{a \cos \phi} \frac{\partial}{\partial \phi'} \langle F_{\phi'} \cos(\phi + \phi') \rangle}_{\text{(II)}} + \underbrace{\frac{f \cos \phi}{H} \left( \frac{v_e \theta_e}{\partial \theta / \partial z} \right)_{z=0}}_{\text{(III)}} + \underbrace{\langle \dot{A} \rangle \cos \phi}_{\text{(IV)}}, \quad (3)$$

where  $H$  is a constant scale height,  $f$  is the Coriolis parameter, and  $\langle \dots \rangle$  denotes density-weighted vertical average. Terms (I) and (II) on the RHS represent the zonal and meridional convergence of the column averaged wave activity flux. (See Supporting Information for the expressions for  $\langle F_\lambda \rangle$  and  $\langle F_{\phi'} \rangle$ .) Term (III) is the vertical wave activity flux at the base of the atmosphere, where the meridional velocity and potential temperature are partitioned as  $v_e = v$  and

$$\theta_e(\lambda, \phi + \phi', z, t) = \theta(\lambda, \phi + \phi', z, t) - \theta_{\text{REF}}(\phi, z, t). \quad (4)$$

Here  $\theta_{\text{REF}}$  is inverted hemispherically from  $q_{\text{REF}}$  (Supporting Information). Term (IV) is the nonadiabatic and non-quasigeostrophic sources-sinks. In practice, Term (IV) is evaluated as the residual of the budget. It is positive where there is net creation of QGPV anomalies (e.g. by convective transport of mass across isentropic surface, Madonna et al., 2014; Bueller & Pfahl, 2017) and negative where they are damped by mixing and friction (N. Nakamura & Zhu, 2010).

## 3 Meteorology

Figure 1 summarizes atmospheric conditions over the North Pacific/North American sector for 22-30 June 2021. Each row is a synopsis at 00 UTC (4 pm in the Pacific Northwest). On 22 June, the 250 hPa geopotential height and wind speed show an enhanced jet stream in the western Pacific around  $40^\circ\text{N}$  (column a). The jet is much weaker in the eastern Pacific, creating strong diffluence. The zonal variation of the jet speed is due partly to the zonally varying summertime sea surface temperatures (SSTs), which enforce relatively weak meridional temperature gradients in the eastern Pacific, both in the upper troposphere (450 hPa, columns b) and near surface (column c), leading to a

generally weaker jet stream aloft. A diffluent jet sets up a favorable condition for block formation in the eastern Pacific (e.g. N. Nakamura & Huang, 2018).

On 24 June the jet stream buckles, initiating anticyclonic wave breaking. A tongue of warm air intrudes northward at 450 hPa, forming a ‘warm conveyor belt’ (Madonna et al., 2014). As we will see later (Figs. 3e and 3f), this coincides with surface cyclogenesis off the coast of Alaska. By 26 June the jet stream develops a large meander and forms a quasi-stationary anticyclone over the Pacific Northwest with a signature of an omega block (Woollings et al., 2018, Fig. 1). The tongue of warm air at 450 hPa rolls up to become a part of the blocking anticyclone. Similar evolution is also observed during winter blocks over Europe (e.g. H. Nakamura, 1994, Fig. 1). The upper tropospheric ridge and the associated warm core remain stationary until 30 June and gradually move downstream afterward (not shown). The block matures between 26-27 June, when the peak 250 hPa geopotential height reaches well over 11000 m, which we found in the top 0.01 percentile of all June-August values at 49°N based on 1979-2021 ERA5 reanalysis.

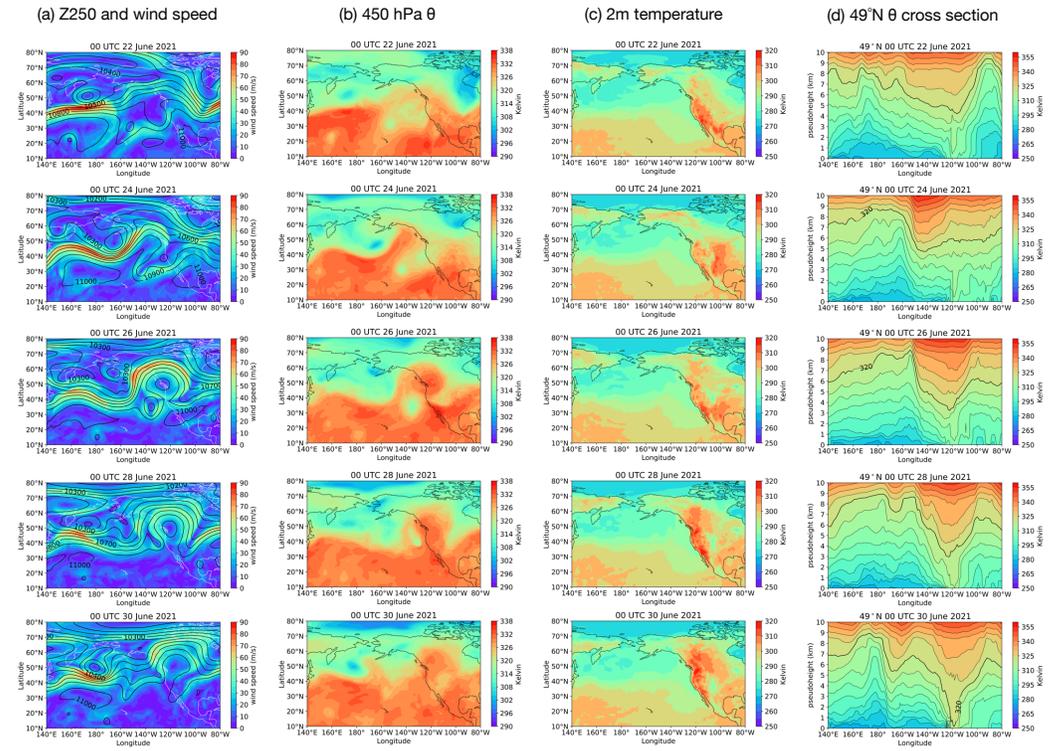
Until 26 June, 2-m temperature (column c) shows hotspots mostly in the southern part of western North America, where the land surfaces are dry. The peak temperatures gradually shift northward thereafter, and by 30 June they align with the location of the block. The highest surface temperatures in the region were reported between 28 June and 1 July (AON, 2021). Therefore, there appears a 2-3 day lag between the maturation of the block and the occurrence of the peak surface temperatures. Column d of Fig. 1 shows vertical cross sections of potential temperature at 49°N during the same period. They capture the emergence of an upper-level warm core associated with the block around 120°W 24-26 June. Subsequently the isentropes in the region move down, as highlighted by the 320 K contour, creating a vertically coherent ‘heat dome.’

Figure 2 samples vertical potential temperature profiles at 119°W 49°N (east of Vancouver, BC), approximately at the center of the block, for 24-30 June. All profiles are sampled at 4 pm local time. On 24 June (before blocking), potential temperature is well mixed in the convective boundary layer up to  $z = 4$  km (dotted curve). The arrival of the block on 26 June significantly raises potential temperature above 3 km (dashed curve). The overlying warm air caps the convective boundary layer at a lower altitude, effectively decreasing its heat capacity. As a result, daytime heating from the ground raises the temperature of the boundary layer by 12 K in 4 days until it deepens again, while the profile in the free troposphere remains nearly steady (dot-dashed and solid curves). This analysis strongly suggests that the extreme heat at surface was a thermodynamic response of the lower troposphere to an anomalously stable stratification aloft set up by the block and heating from below. In comparison, horizontal advection of temperature is deemed weak in the center of the block.

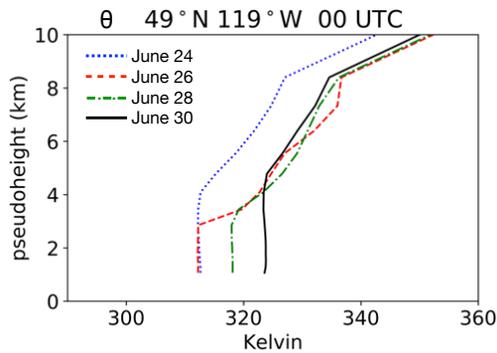
Column b of Fig. 1 suggests that the warm air above the boundary layer of the block originates from lower latitudes in the upstream. However, it is unclear how much of that warmth is attributable to latent heating. Previous studies based on trajectory analyses suggest that air parcels experience substantial latent heating in the warm conveyor belt of an extratropical cyclone (Madonna et al., 2014; Methven, 2015) and some of them end up in a blocking anticyclone downstream (Pfahl et al., 2015; Steinfeld & Pfahl, 2019). These studies also show that latent heating produces a significant amount of negative QGPV anomaly in the upper troposphere, an essential ingredient for blocking anticyclones. In the next section we examine the regional LWA budget and identify key processes that formed the block, including an upstream diabatic source of wave activity.

#### 4 Regional wave activity budget

Here we apply the LWA diagnostic outlined in Section 2 for the formative stage of the block. To visualize the increase in LWA associated with the block, we integrate Eq.



**Figure 1.** Circulation and temperature over North Pacific and North America 22-30 June 2021. Rows are, from top to bottom, 22, 24, 26, 28, 30 June at 00 UTC. Column a: 250 hPa geopotential height (contours in meters) and wind speed. Column b: 450 hPa potential temperature. Column c: 2-m temperature. Column d: vertical cross sections of potential temperature at 49°N (contour interval = 5 K). The vertical axis is pressure pseudoheight with  $H = 8$  km (450 hPa = 6.4 km). Data source: ERA5 (Figs. 1-4).



**Figure 2.** Vertical profiles of potential temperature at 119°W 49°N. The vertical axis is pressure pseudoheight with  $H = 8$  km. Only values above the ground are shown. Dotted-blue: June 24. Dashed-red: June 26, Dot-dashed-green: June 28. Solid-black: June 30. All profiles are sampled at 00 UTC (4 pm local).

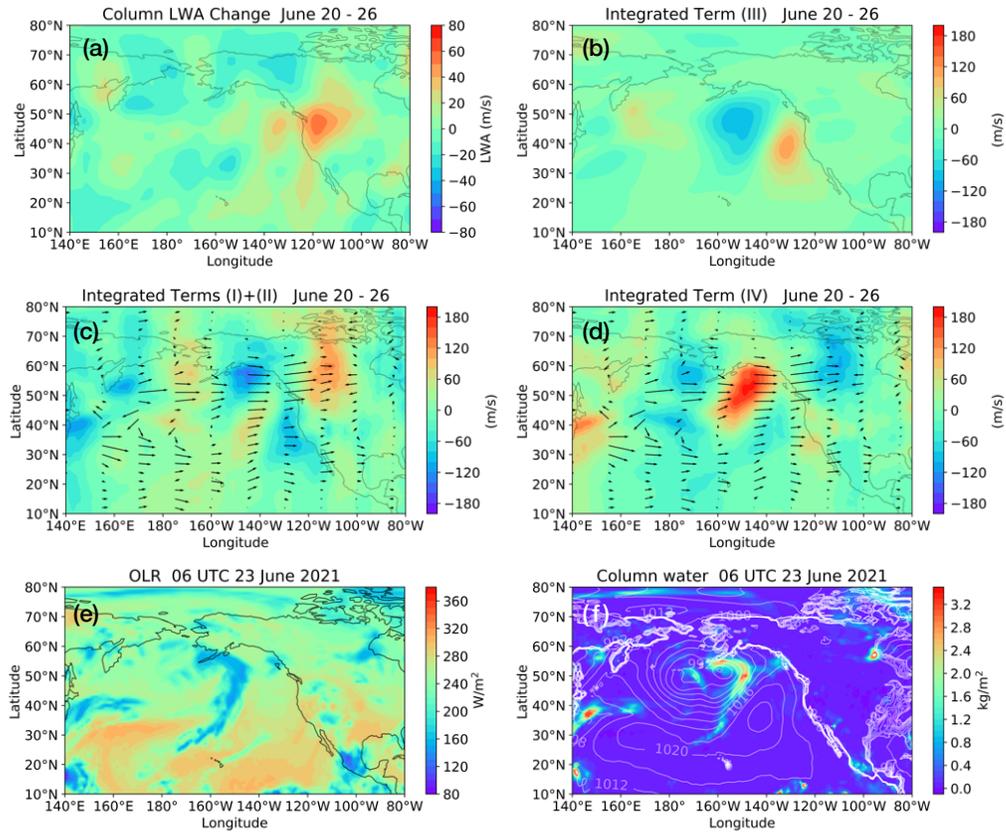
151 (3) from 20 to 26 June 00 UTC and diagnose the budget term-by-term. Figure 3a shows  
 152 a map of the LHS, i.e., the change in column LWA from 20 to 26 June. The largest in-  
 153 crease centers around the Pacific Northwest, roughly the location of the blocking anti-  
 154 cyclone (Fig. 1 column a). The other maps show the time integrals of Term (III) (Fig.  
 155 3b), Terms (I)+(II) (Fig. 3c) and Term (IV) (Fig. 3d). The sum of Figs. 3b, 3c and 3d  
 156 equals Fig. 3a (note a different color scale for Fig. 3a). Figure 3c and 3d also overlay  
 157 the change in the 6-day average horizontal wave activity flux vector,  $(\langle F_\lambda \rangle, \langle F_\phi \rangle)$ , from  
 158 the previous 6-day period (14-20 June).

159 Except over the eastern Pacific, Term (III) is small (Fig. 3b). The dipole pattern  
 160 in the eastern Pacific reflects the fact that in this region the perturbation potential tem-  
 161 perature  $\theta_e$  [Eq. (4)] is everywhere negative near the surface because of low SSTs. There-  
 162 fore the Term (III) in Eq. (3) will be negative where the wind is southerly ( $v_e > 0$ ) and  
 163 positive where it is northerly ( $v_e < 0$ ). The dipole pattern arises from a persistent an-  
 164 ticyclonic circulation in this region during the period.

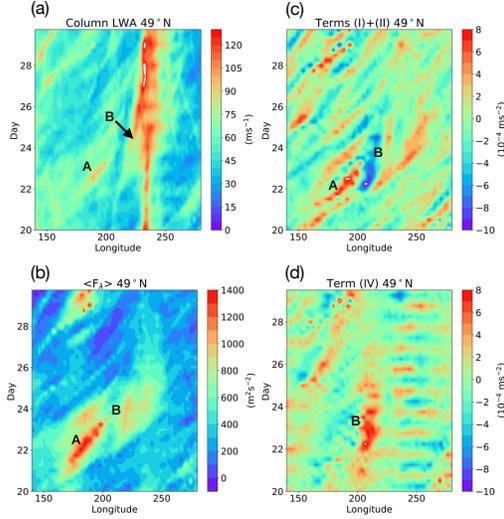
165 The block-related change in LWA is largely due to Terms (I) and (IV). Contribu-  
 166 tions from Term (II) prove also weak in the regions of interest, so the signal in Fig. 3c  
 167 largely comes from Term (I). Figure 3c shows predominantly positive values (i.e. wave  
 168 activity flux is convergent) over the western Canada. There are large negative values (di-  
 169 vergence) off the coast of Alaska, and also broadly off the west coast of North America.  
 170 The convergence of wave activity flux over Canada is compensated to a large degree by  
 171 negative values of Term (IV) (Fig. 3d), presumably from dissipation of wave activity due  
 172 to mixing and friction. Then there are very large positive values of Term (IV) off the coast  
 173 of Alaska, which more than compensate the negative values of Terms (I), (II), (III) com-  
 174 bined in the same region. This is believed to be the effect of latent heating associated  
 175 with a cyclone that formed in this region 23-24 June. Figures 3e and 3f show, respec-  
 176 tively, the outgoing longwave radiation (OLR) at the top of the atmosphere and column  
 177 water (excluding vapor) overlaid with sea level pressure for 23 June. Both the minimum  
 178 OLR and the maximum column water depict tall, comma-shaped clouds associated with  
 179 a cyclone, in good agreement with the location of the local maximum in Term (IV) (Fig.  
 180 3d) and the warm conveyor belt (Fig. 1 column b, second panel).

181 Figures 3c and 3d also show enhanced eastward wave activity fluxes over the Pa-  
 182 cific during this period. The enhancement is particularly pronounced in 45-60°N, and  
 183 east of the Gulf of Alaska. All this suggests that latent heating off the coast of Alaska  
 184 was a significant source of wave activity flux downstream, which then converged over the  
 185 western Canada to form a block. Although the location of the block is somewhat south  
 186 of the peak of flux convergence, the observed LWA budget at the center of the block still  
 187 fits the above description: at 118°W 49°N, the 6-day change in column LWA is 54.1 ms<sup>-1</sup>,  
 188 and contributions from Terms (I)-(IV) are 102.2, -10.2, 1.0, -38.9 ms<sup>-1</sup>, respectively. There-  
 189 fore about 40 percent of flux convergence is compensated by frictional loss to produce  
 190 the observed LWA change.

191 The process of block maturation is further elucidated in the Hovmöller diagrams  
 192 of column LWA (Fig. 4a), zonal LWA flux (Fig. 4b), flux convergence [Terms (I)+(II),  
 193 Fig. 4c] and residual [Term (IV), Fig. 4d] at 49°N. Column LWA has a quasistationary  
 194 maximum around 235°E (125°W). This reflects waviness in low-altitude QGPV arising  
 195 from large land-sea thermal contrast across the coastline. However, LWA increases sig-  
 196 nificantly toward the end of June as the block forms (Fig. 4a). Prior to this, there is a  
 197 broad enhancement of eastward wave activity flux in the upstream (Fig. 4b). The en-  
 198 hancement entails two distinct stages, labeled A and B. Stage A is characterized by a  
 199 strong, but migratory maximum in flux with a corresponding flux convergence (Fig. 4c).  
 200 Since the convergence is short-lived at a given location, it does not increase LWA sig-  
 201 nificantly (Fig. 4a). Here the increased flux simply reflects an enhanced jet speed (top  
 202 left panel of Fig. 1). Stage B, on the other hand, is initiated by a local diabatic source  
 203 that spans 22-24 June between 200-220°E (140-160°W, Fig. 4d). This coincides with a



**Figure 3.** (a) Map of the LHS of Eq. (3) integrated from 20 to 26 June 2021 00 UTC. (b) Same as (a) but for Term (III). (c) Same as (b) but for Terms (I)+(II). (d) Same as (c) but for Term (IV). Arrows in (c) and (d) indicate the change in the 6-day average  $\langle F_\lambda \rangle, \langle F_{\phi'} \rangle$  from the previous 6 days (14-20 June). The longest arrow is  $40 \text{ m}^2\text{s}^{-2}$ . For (a)-(d), a 10 degree running mean is applied in longitude to suppress noise. Note the different color scale for (a). (e) Outgoing longwave radiation at the top of the atmosphere at 06 UTC 23 June 2021. (f) Same as (e) but for column water (excluding vapor) and sea level pressure (in hPa).



**Figure 4.** (a) Hovmöller diagram of column LWA at 49°N for 20-30 June 2021 00 UTC. (b) Same as (a) but for the column mean zonal wave activity flux  $\langle F_\lambda \rangle$ . (c) Same as (b) but for Terms (I)+(II) in Eq. (3). (d) Same as (c) but for Term (IV). A 10 degree running mean is applied in longitude for (c) and (d). The regularly spaced zonal striping in 225-270°E in (d) reflects the diurnal cycle in land-surface heating. See text for details.

204 strong flux divergence and a weak but persistent convergence immediately downstream  
 205 (Fig. 4c). LWA that exits the region of divergence accumulates in the region of conver-  
 206 gence, evidenced in Fig. 4a as a track of LWA emerges east of 200°E and eventually merges  
 207 with the existing maximum at the Pacific Northwest. LWA achieves a peak intensity af-  
 208 ter the merger, 27-28 June.

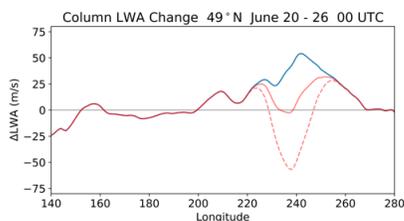
209 To quantify the effect of the upstream diabatic source of wave activity on the down-  
 210 stream blocking, we integrate Eq. (3) at  $\phi = 49^\circ\text{N}$  with a modified forcing. To this end,  
 211 we first diagnose the zonal transport velocity  $C(\lambda, t)$  and the diabatic forcing coefficient  
 212  $\gamma(\lambda, t)$  for 20-26 June from the observed  $\langle F_\lambda \rangle$ ,  $\langle A \rangle$ ,  $\langle \dot{A} \rangle$ , using the following relations:

$$213 \quad \langle F_\lambda \rangle = C \langle A \rangle \cos \phi, \quad \langle \dot{A} \rangle = \gamma \langle A \rangle, \quad \phi = 49^\circ\text{N}. \quad (5)$$

214 We then modify  $\gamma$  such that any positive value in 200-220°E is decreased by 30 percent  
 215 during 22-24 June. The change,  $\Delta\gamma(\lambda, t)$ , represents an artificial reduction of diabatic  
 216 forcing in the region of cyclogenesis. Assuming that  $C$ , Terms (II) and (III) will not change,  
 217 we may estimate the downstream influence of the perturbed forcing by rewriting Eq. (3)  
 218 for the LWA perturbation (see Supporting Information):

$$219 \quad \frac{\partial}{\partial t} \Delta \langle A \rangle = -\frac{1}{a \cos \phi} \frac{\partial (C \Delta \langle A \rangle)}{\partial \lambda} + (\gamma + \Delta\gamma) \Delta \langle A \rangle + \langle A \rangle \Delta\gamma, \quad \phi = 49^\circ\text{N}. \quad (6)$$

220 We integrate Eq. (6) between 20-26 June from a zero initial condition. ( $C$ ,  $\gamma$  and  $\Delta\gamma$   
 221 are interpolated in time and we also add a small numerical diffusion.) The blue curve  
 222 in Fig. 5 shows the observed change in column LWA between 20 and 26 June. The solid  
 223 red curve is the predicted change for the same period with the modified forcing. The peak  
 224 value is reduced by 41 percent and its location is displaced 10 degrees eastward (from  
 225  $54.1 \text{ ms}^{-1}$  at  $242^\circ\text{E}$  to  $31.8 \text{ ms}^{-1}$  at  $252^\circ\text{E}$ ). When positive  $\gamma$  in 200-220°E is completely  
 226 suppressed during 22-24 June, the change in LWA over the Pacific Northwest turns vastly  
 227 negative (red dashed curve): instead of forming a block, the jet stream would become  
 228 much less wavy.



**Figure 5.** Blue: observed change in column LWA between 20 and 26 June 2021 00 UTC at 49°N. Solid-red: reconstructed change in column LWA with 70 percent of positive diabatic forcing in 200-220°E during 22-24 June. Dashed-red: Same as solid-red but with positive diabatic forcing completely suppressed in 200-220°E during 22-24 June.

## 5 Conclusions

We have identified the chain of events that led to the Pacific Northwest heat wave in late June - early July 2021: (i) cyclogenesis and associated wave breaking over the Gulf of Alaska (23-24 June), (ii) formation of a blocking anticyclone over the Pacific Northwest (24-27 June), and (iii) subsequent heating of surface (27-30 June). Our study suggests strong causal links between them: latent heating within the cyclone created an anomalous wave activity flux, which seeded the blocking anticyclone in the immediate downstream; and the stable stratification within the block suppressed convection and raised surface temperature. Other factors such as soil moisture deficit (Whan et al., 2015) and the foehn effect (Elvidge & Renfrew, 2016) may be important but are outside the scope of this work.

The absorption of incident wave activity flux from upstream has long been recognized as formation and maintenance mechanisms of blocks (Shutts, 1983; Mullen, 1987; H. Nakamura & Wallace, 1993; Luo, 2005; Yamazaki & Itoh, 2013; N. Nakamura & Huang, 2018), and the role of upstream cyclogenesis has also been reported for winter blocks (Colucci, 1985). These mechanisms are still at play in the 2021 event, but this event was unique in that the impact of latent heating over the upstream ocean manifested both dynamically and thermodynamically over a dry land in the downstream, where the small heat capacity of both ground and the block-capped boundary layer contributed to an unusual summertime heat event. Our result complements previous studies that suggest the influence of upstream latent heating on blocking based on trajectory analyses (Pfahl et al., 2015; Steinfeld & Pfahl, 2019). The LWA-based approach is particularly suited for the attribution of dynamical sources that contribute to the formation of a block.

The present analysis alone is insufficient to quantify the influence of climate change on the extreme events like this. However, to the extent that latent heating contributes to the strength of summer blocks and associated extreme heat, the severity of similar events will likely increase as the atmosphere warms and is loaded with more water vapor. Since the eastern North Pacific/Gulf of Alaska is a favorable location for block formation (Woollings et al., 2018), the risk for extreme heat in the Pacific Northwest will likely follow suit.

## 6 Open Research

ERA5 reanalysis data may be downloaded from <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview>. The python code to compute LWA is found here: [https://github.com/csyhuang/hn2016\\_falwa](https://github.com/csyhuang/hn2016_falwa).

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## References

- AON. (2021). *Global catastrophe recap september 2021*. Retrieved from <http://thoughtleadership.aon.com/Documents/20210012-analytics-if-september-global-recap.pdf>
- Bueler, D., & Pfahl, S. (2017). Potential vorticity diagnostics to quantify effects of latent heating in extratropical cyclones. part i: Methodology. *Journal of the Atmospheric Sciences*, *74*, 3567-3590. doi: 10.1175/jas-d-17-0041.1
- Colucci, S. J. (1985). Explosive cyclogenesis and large-scale circulation changes - implications for atmospheric blocking. *Journal of the Atmospheric Sciences*, *42*, 2701-2717. doi: 10.1175/1520-0469(1985)042<2701:ecalsc>2.0.co;2
- Elvidge, A. D., & Renfrew, I. A. (2016). The causes of foehn warming in the lee of mountains. *Bulletin of the American Meteorological Society*, *97*, 455-466. doi: 10.1175/bams-d-14-00194.1
- Fang, B., & Lu, M. (2020). Heatwave and blocking in the northeastern asia: Occurrence, variability, and association. *Journal of Geophysical Research-Atmospheres*, *125*(6), e2019JD031627. doi: 10.1029/2019jd031627
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horanyi, A., Munoz-Sabater, J., ... Thepaut, J. N. (2020). The era5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999-2049. doi: 10.1002/qj.3803
- Huang, C. S. Y., & Nakamura, N. (2016). Local finite-amplitude wave activity as a diagnostic of anomalous weather events. *Journal of the Atmospheric Sciences*, *73*(1), 211-229. doi: 10.1175/JAS-D-15-0194.1
- Huang, C. S. Y., & Nakamura, N. (2017). Local wave activity budgets of the wintertime northern hemisphere: Implication for the pacific and atlantic storm tracks. *Geophysical Research Letters*, *44*, 5673-5682. doi: 10.1002/2017GL073760
- Luo, D.-H. (2005). Barotropic envelope rossby soliton model for block-eddy interaction. part i: Effect of topography. *Journal of the Atmospheric Sciences*, *62*, 5-21. doi: 10.1175/1186.1
- Madonna, E., Wernli, H., Joos, H., & Martius, O. (2014). Warm conveyor belts in the era-interim dataset (1979-2010). part i: Climatology and potential vorticity evolution. *Journal of Climate*, *27*, 3-26. doi: 10.1175/jcli-d-12-00720.1
- Methven, J. (2015). Potential vorticity in warm conveyor belt outflow. *Quarterly Journal of the Royal Meteorological Society*, *141*, 1065-1071. doi: 10.1002/qj.2393
- Mullen, S. L. (1987). Transient eddy forcing of blocking flows. *Journal of the Atmospheric Sciences*, *44*, 3-22. doi: 10.1175/1520-0469(1987)044<0003:tefobf>2.0.co;2
- Nakamura, H. (1994). Rotational evolution of potential vorticity associated with a strong blocking flow configuration over europe. *Geophysical Research Letters*, *21*, 2003-2006. doi: 10.1029/94GL01614
- Nakamura, H., & Wallace, J. M. (1993). Synoptic behavior of baroclinic eddies during the blocking onset. *Monthly weather Review*, *121*, 1892-1903. doi: 10.1175/1520-0493(1993)121<1892:sboded>2.0.co;2
- Nakamura, N., & Huang, C. S. Y. (2018). Atmospheric blocking as a traffic jam in the jet stream. *Science*, *361*(6397), 42-47. doi: 10.1126/science.aat0721
- Nakamura, N., & Solomon, A. (2010). Finite-amplitude wave activity and mean flow adjustments in the atmospheric general circulation. part i: Quasigeostrophic theory and analysis. *Journal of the Atmospheric Sciences*, *67*, 3967-3983. doi: 10.1175/2010jas3503.1

- 316 Nakamura, N., & Zhu, D. (2010). Finite-amplitude wave activity and diffusive flux  
317 of potential vorticity in eddy-mean flow interaction. *Journal of the Atmo-*  
318 *spheric Sciences*, *67*, 2701-2716. doi: 10.1175/2010jas3432.1
- 319 Pfahl, S., Schwierz, C., Croci-Maspoli, M., Grams, C. M., & Wernli, H. (2015).  
320 Importance of latent heat release in ascending air streams for atmospheric  
321 blocking. *Nature Geoscience*, *8*, 610–614. doi: 10.1038/ngeo2487
- 322 Philip, S. Y., Kew, S. F., van Oldenborgh, G. J., Anslow, F. S., Seneviratne,  
323 S. I., Vautard, R., . . . Otto, F. E. L. (2021). Rapid attribution analy-  
324 sis of the extraordinary heatwave on the pacific coast of the us and canada  
325 june 2021. *Earth System Dynamics Discussions*, *2021*, 1–34. Retrieved  
326 from <https://esd.copernicus.org/preprints/esd-2021-90/> doi:  
327 10.5194/esd-2021-90
- 328 Shutts, G. J. (1983). The propagation of eddies in diffluent jetstreams: Eddy vortic-  
329 ity forcing of blocking flow fields. *Quarterly Journal of the Royal Meteorologi-*  
330 *cal Society*, *109*, 737-761. doi: 10.1002/qj.49710946204
- 331 Steinfeld, D., & Pfahl, S. (2019). The role of latent heating in atmospheric block-  
332 ing dynamics: a global climatology. *Climate Dynamics*, *53*, 6159–6180. doi: 10  
333 .1007/s00382-019-04919-6
- 334 Valva, C., & Nakamura, N. (2021). What controls the probability distribution of  
335 local wave activity in the midlatitudes? *Journal of Geophysical Research - At-*  
336 *mospheres*, *126*, WOS:000683523400017. doi: 10.1029/2020jd034501
- 337 Whan, K., Zscheischler, J., Orth, R., Shongwe, M., Rahimi, M., Asare, E. O., &  
338 Seneviratne, S. I. (2015). Impact of soil moisture on extreme maximum  
339 temperatures in europe. *Weather and Climate Extremes*, *9*, 57-67. doi:  
340 10.1016/j.wace.2015.05.001
- 341 Woollings, T., Barriopedro, D., Methven, J., Son, S. W., Martius, O., Harvey, B.,  
342 et al. (2018). Blocking and its response to climate change. *Current Climate*  
343 *Change Reports*, *4*(3), 287–300. doi: 10.1007/s40641-018-0108-z
- 344 Yamazaki, A., & Itoh, H. (2013). Vortex-vortex interactions for the maintenance of  
345 blocking. part i: The selective absorption mechanism and a case study. *Journal*  
346 *of the Atmospheric Sciences*, *70*, 725-742. doi: 10.1175/jas-d-11-0295.1