

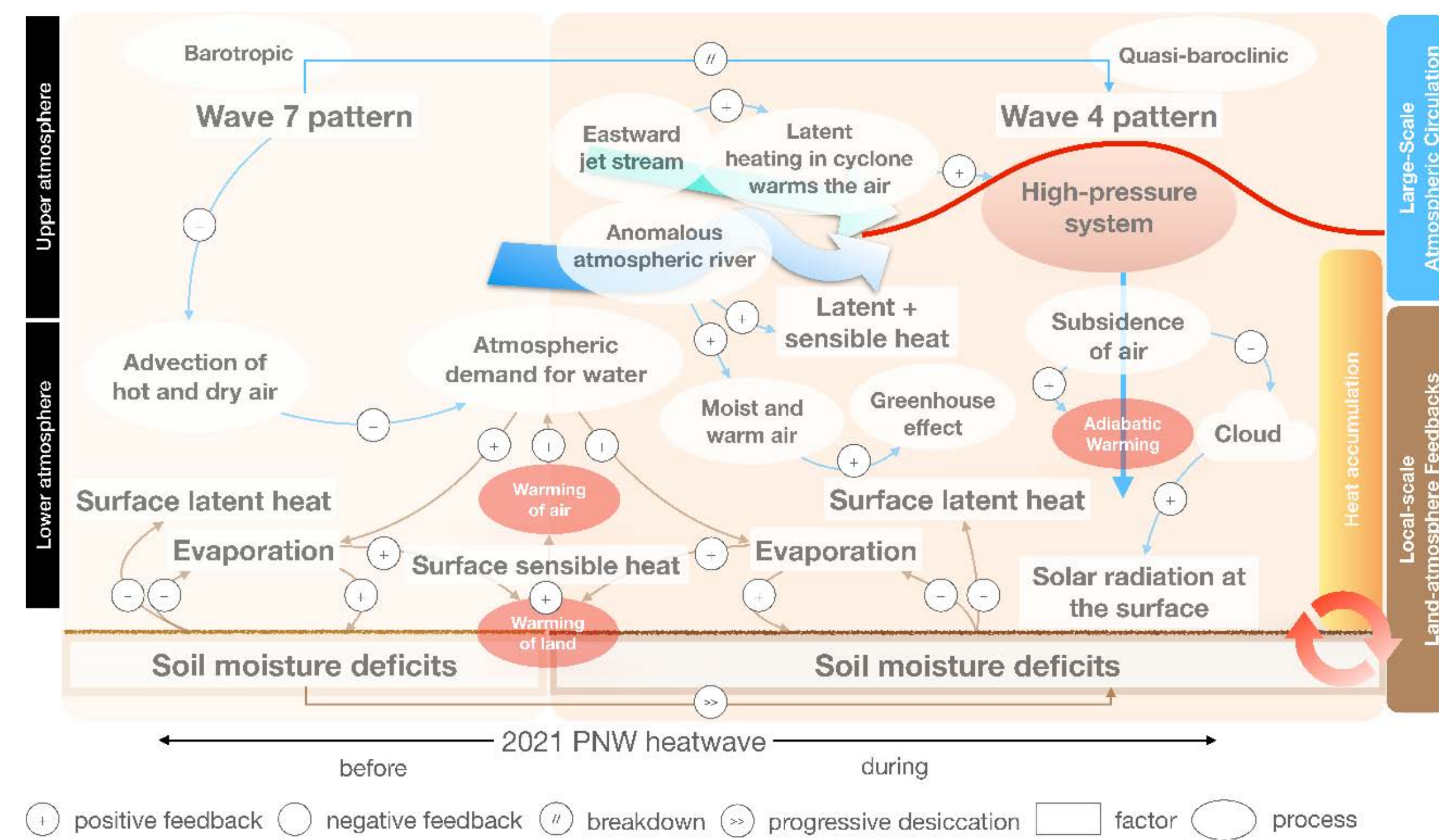
## 1. Revisit 2021 Pacific Northwest (PNW) "Heat Dome"

- Caused over 250 deaths in the U.S., and more than 400 in Canada.
- Caused at least \$8.9 billion USD in damages in the U.S.
- A *virtually impossible* event ( $> 4\sigma$ ) in the absence of human-caused warming.

Check the full paper here



Why was it so extreme?  
How did it occur?  
What other factors were at play?



Schematic illustration of the confluence of antecedent and concurrent factors, including large-scale atmospheric circulation and local-scale land-atmosphere feedbacks, underlying the 2021 Pacific Northwest heatwave event.

## 2. Quasi-resonant Planetary Wave Amplification (QRA)

- Forced planetary-scale Rossby waves:** slow-moving, zonal wave numbers larger than 6 are normally weak.
- Free synoptic-scale Rossby waves:** fast-moving, high-amplitude.
- QRA conditions:
  - Free synoptic-scale Rossby waves become trapped within midlatitude waveguides.
  - Their quasi-stationary component, characterized by zonal wave numbers 6 to 8 can contribute to the persistence and formation of high-amplitude wave structures in forced large-scale Rossby waves due to quasi-resonance.
- For the quasi-stationary component of free synoptic-scale Rossby waves:

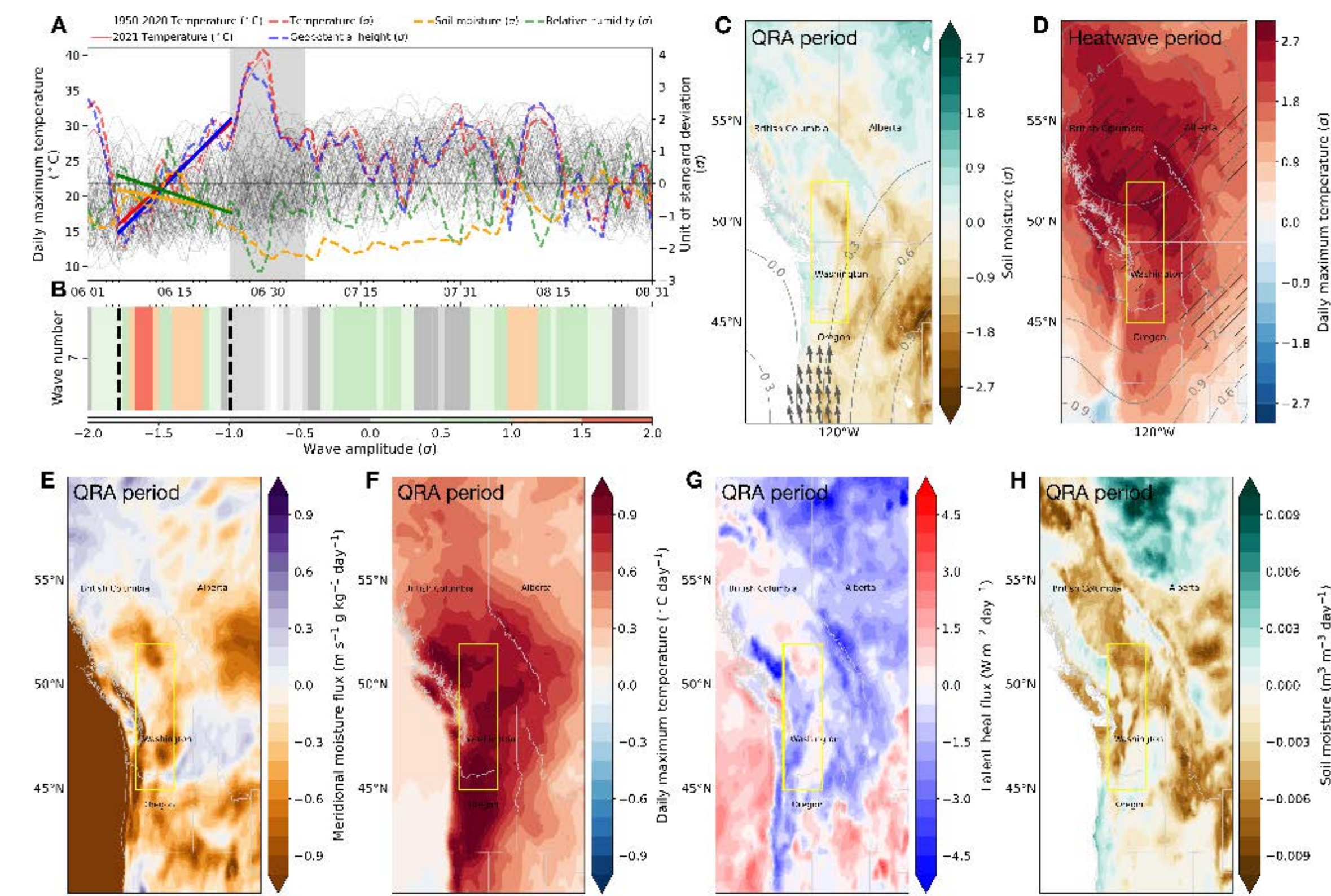
$$l^2 = f(\bar{u}, \varphi, k) = \frac{2\Omega \cos^3 \varphi}{a\bar{u}} - \frac{\cos^2 \varphi}{a^2 \bar{u}} \frac{d^2 \bar{u}}{d\varphi^2} - \frac{\sin \varphi \cos \varphi}{a^2 \bar{u}} \frac{d\bar{u}}{d\varphi} + \frac{1}{a^2} - \frac{k^2}{a^2}$$

$l$ : meridional wave number;  $\bar{u}$ : zonal mean zonal wind;  $\varphi$ : latitude;  $k$ : zonal wave number.

- Turning point (TP):** wave energy reflected back where  $l = 0$ . No energy loss towards equator or poles.
- Waveguide:** two TP are observed. Waves with zonal wave number  $k \approx 6 - 8$  can be trapped within a midlatitude waveguide.
- Presence of *double-jet*.

## 3. Preconditioning: QRA + land-atmosphere feedbacks

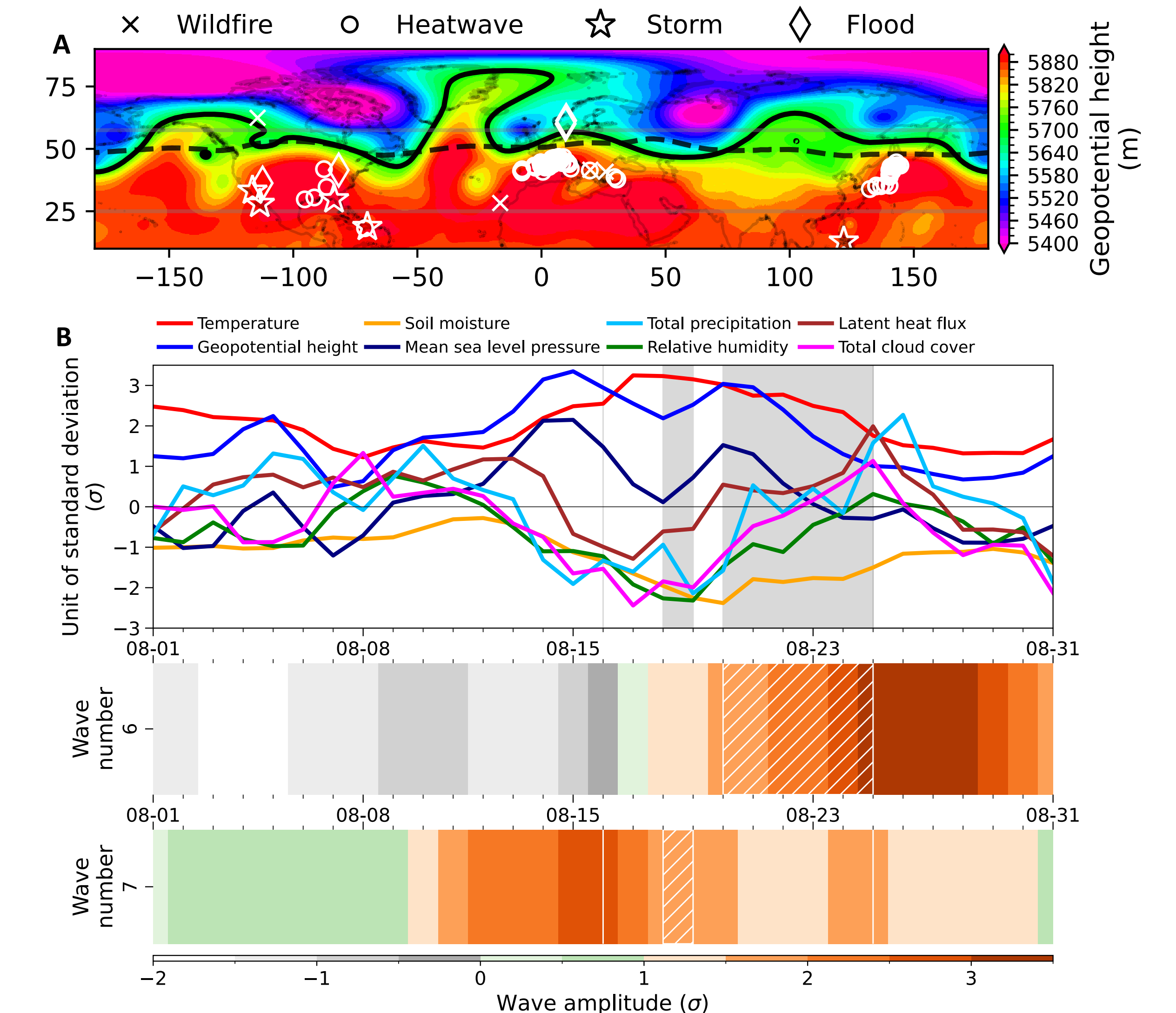
- An anomalously high-amplitude resonant planetary **wave 7 pattern** is detected about two weeks before the onset of the heatwave.
- QRA favored drying** via anomalous **advection of dry, warm air** into the region under anomalous southerly continental flow.
- The **interplay between extended QRA circulation state and local land-atmosphere coupling** leads to a steady ramp up in temperature via decreased *evaporative cooling* and *latent heat flux* and increased *surface sensible heat flux*.
- The **progressive built-up of heat** sets the stage for an unprecedented heatwave wherein an **upper-level high-pressure system** remains in place thereafter.



(A) Evolution of anomalies (dashed colored lines) measured in units of standard deviations ( $\sigma$ ) from the climatological mean of the preceding decades (1950–2020). The trend lines, when the wave-7 pattern persists, are indicated by thick colored lines. (B) The detected QRA period for wave 7. (C-D) Spatial patterns of anomalies during the QRA/heatwave period. (E-H) Trends in anomalies during the QRA period. The yellow box indicates the PNW region.

## 4. Concurrent Extremes in Summer 2023

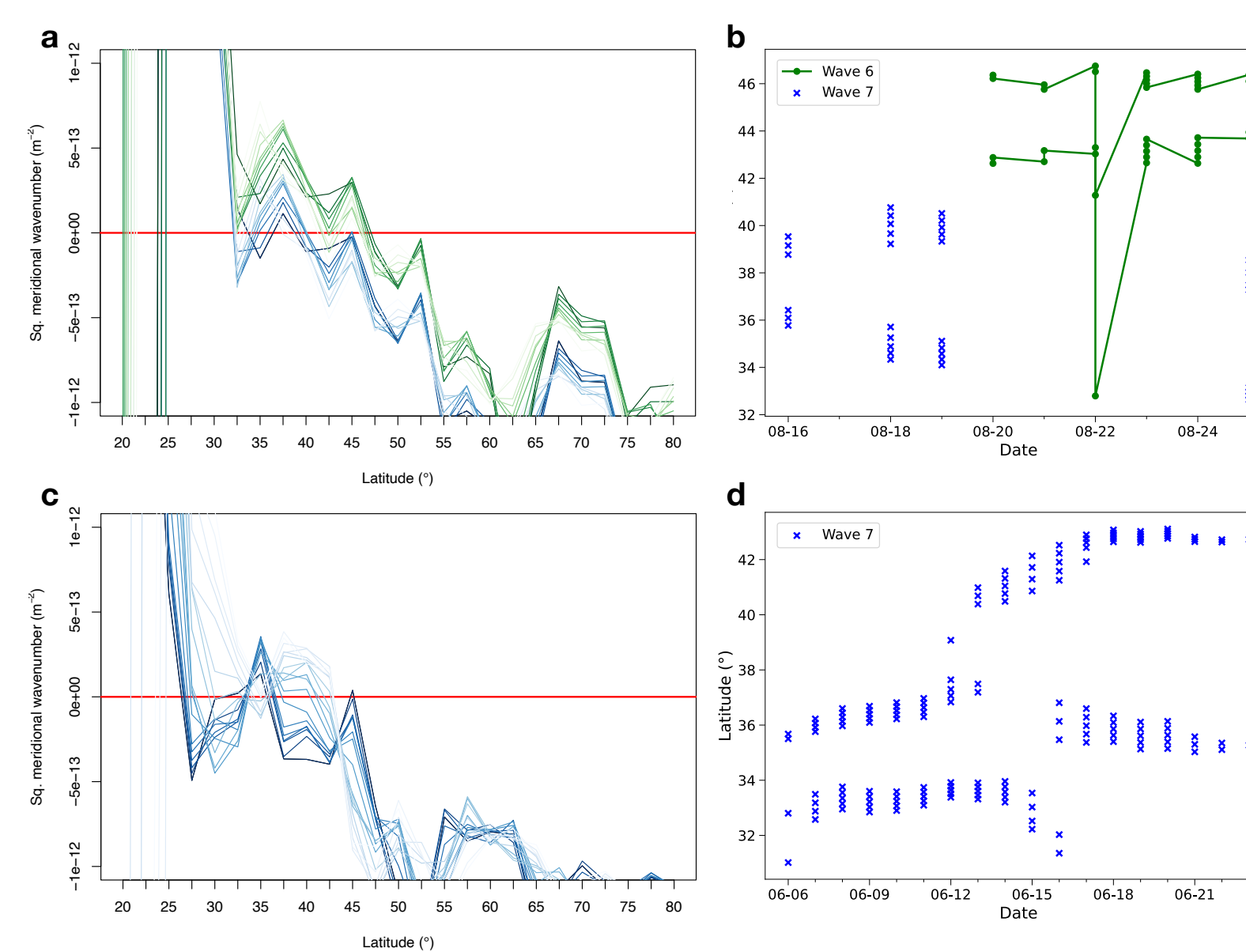
- A simultaneous occurrence of extreme events, preferentially located in the southern U.S., the Mediterranean region, and Japan where **high-pressure systems** prevail.
- A series of resonant planetary wave configurations is identified throughout August 2023, primarily characterized by **zonal wave numbers 6 and 7**.



(A) Concurrent extreme events observed from August 16–25, 2023, over the Northern Hemisphere. The isopleth of 5700 m is highlighted with a solid black line for 2023 and a dashed black line for the historical mean of 1950–2022. (B) Evolution of anomalies and associated wave circulation pattern. The period of wave resonance is hatched in white.

## 5. Waveguide Propagation

- The turning latitude **shifts poleward** after episodes of rainfall.
- In the concurrent extremes in summer 2023 case (a-b): during the dominance of wave 6.
- In the 2021 PNW "heat dome" case (c-d): in the southwestern portion of the domain from June 13 to 15.



Detection of mid-latitude waveguides that trap synoptic-scale quasi-stationary free waves. (a, c) Squared meridional wave number used to determine the latitudinal positions of the two TPs. (b, d) Evolution of the latitudinal positions of the TPs for zonal wave number 6 (comprising 5.8, 5.9, 6.0, 6.1, and 6.2) and 7 (comprising 6.8, 6.9, 7.0, 7.1, and 7.2). (a-b) correspond to the August 2023 case, while (c-d) pertain to the 2021 Pacific Northwest "heat dome" case.

## 6. Take-home Message

- In the 2021 PNW "heat dome" case, we reveal **how QRA events may affect antecedent atmospheric condition** (in this case, through land-surface processes), introducing an additional, though *indirect*, mechanism through which QRA impacts extreme heat events.
- In the concurrent extremes in summer 2023 case, we show the synchronized interplay of jet-trapped heat domes and advected diabatic heating that enhances the persistence and strength of circulation anomalies.
- In both cases, the influx of **warm and moist air** from lower latitudes **shifts the mid-latitude waveguide northward**, significantly affecting regions within these longitudinal bands.
- Our findings hold the potential for more skillful predictions of *low-probability yet impactful* weather extremes that can have devastating consequences.