2021 North American heatwave amplified by climate-change-driven nonlinear interactions

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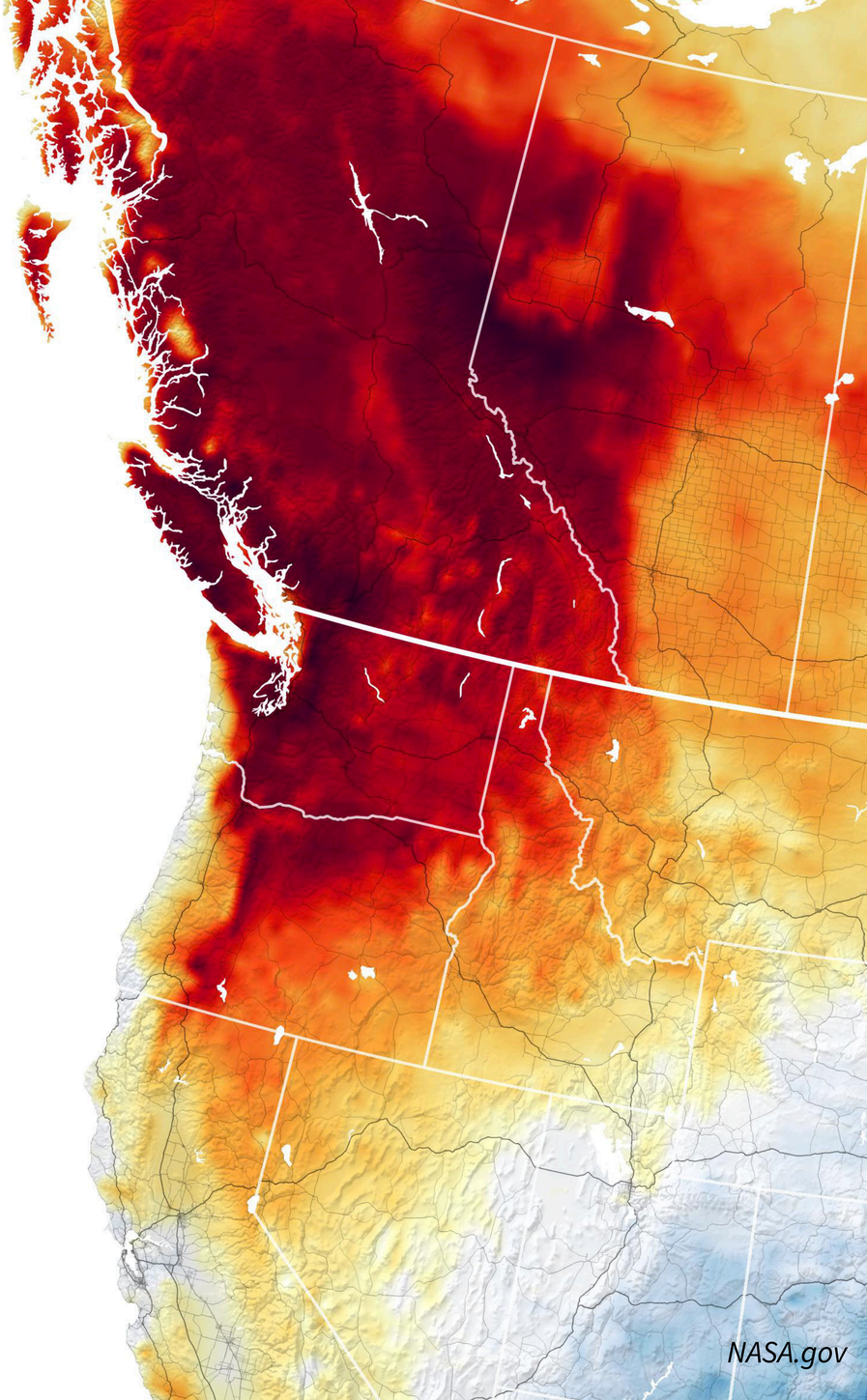
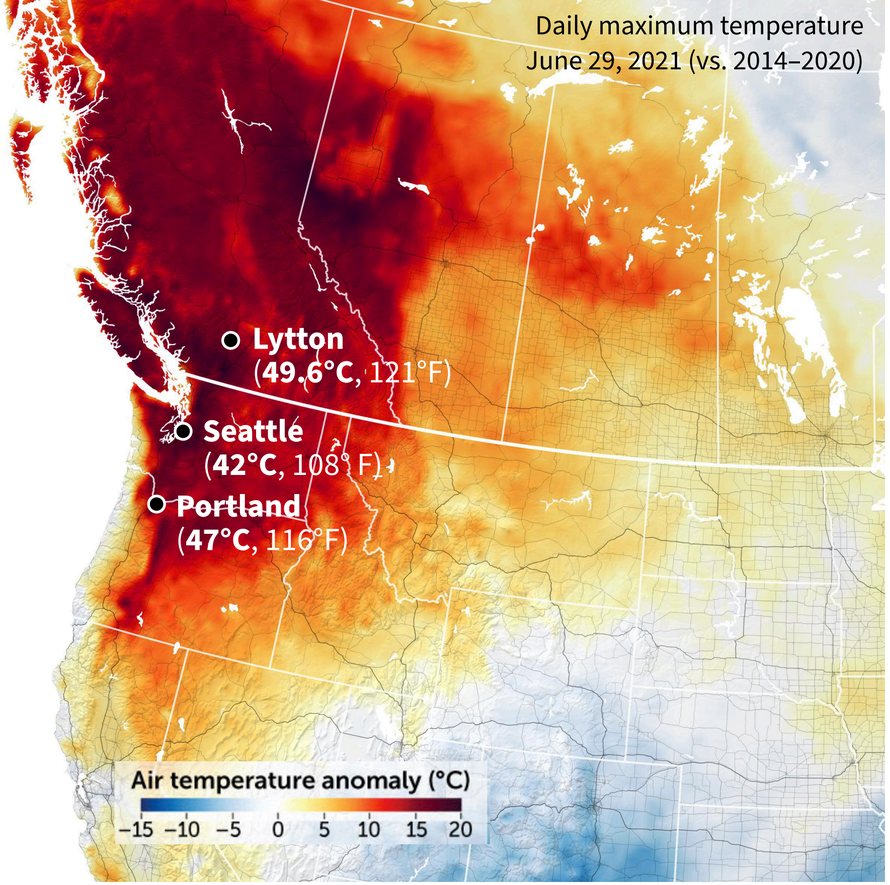
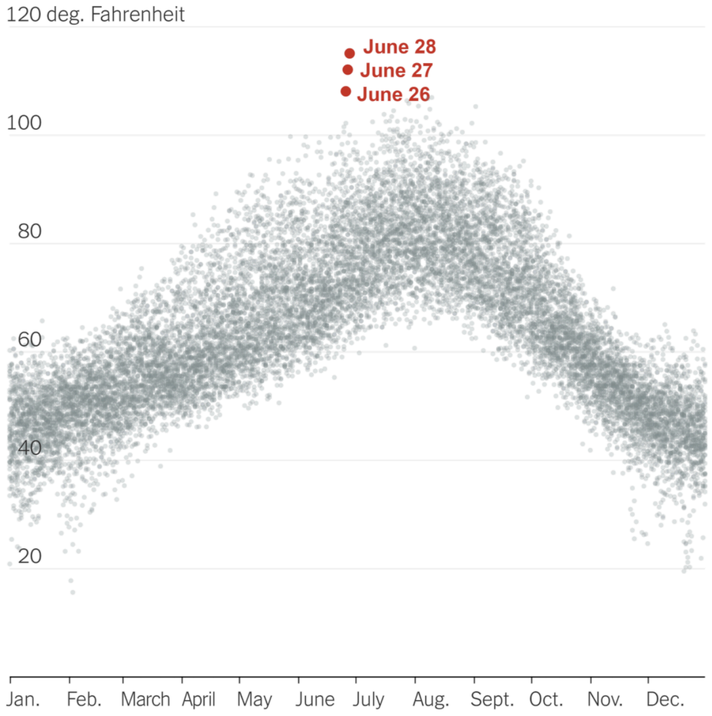




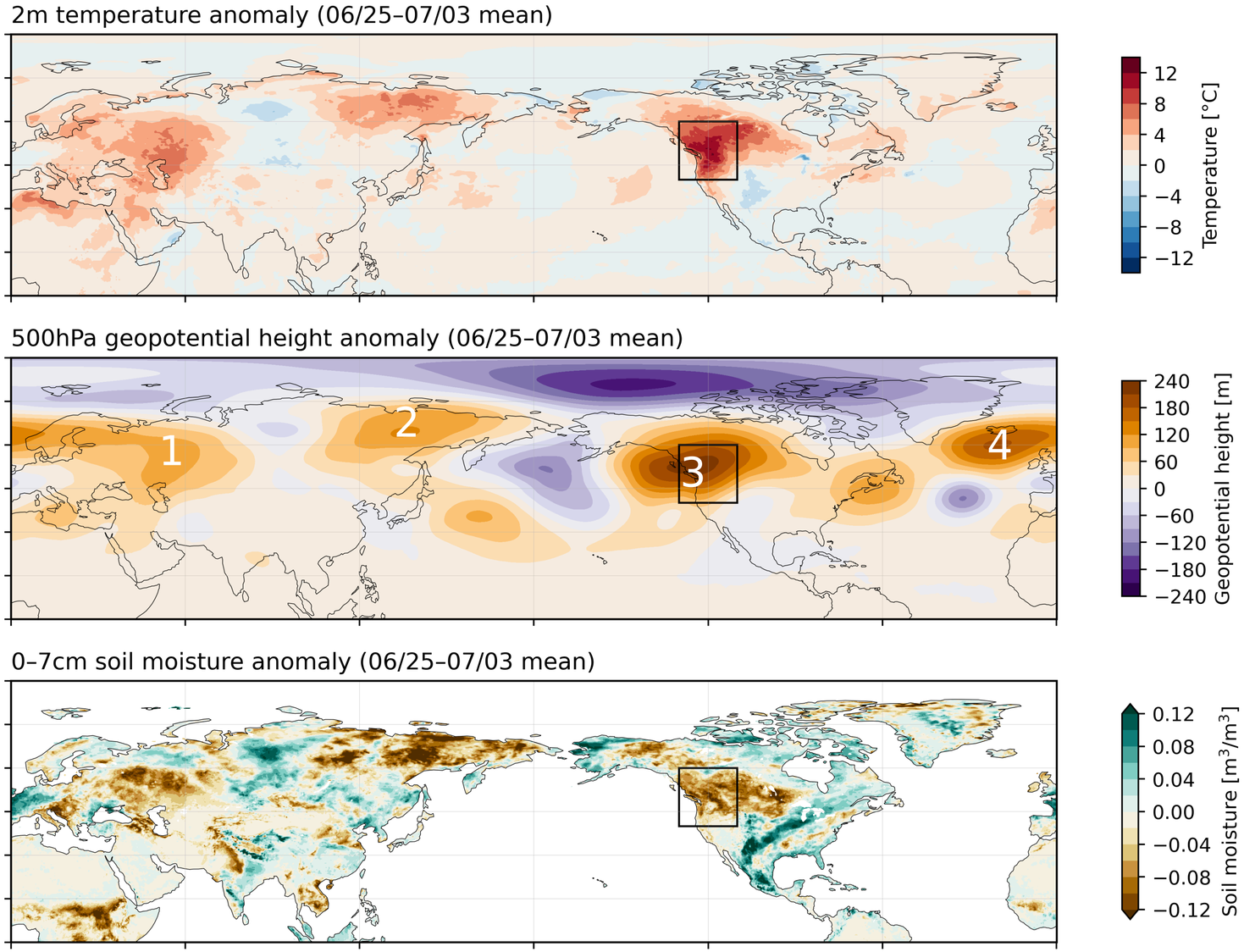


NASA, Getty Images, New York Times, AP Photo

- Record-shattering heat
  - Canada saw highest temperature ever in North America outside desert S.W.
- Compounding factors & repercussions
  - Low air conditioning access
  - High social vulnerability, outdoor agricultural worker populations
  - Likely >1,000 heat-related deaths
  - Wildfires *(e.g., New York City's worst air quality in 15 years)*
  - Drought *(>95% of U.S. PNW in drought preceding heatwave)*

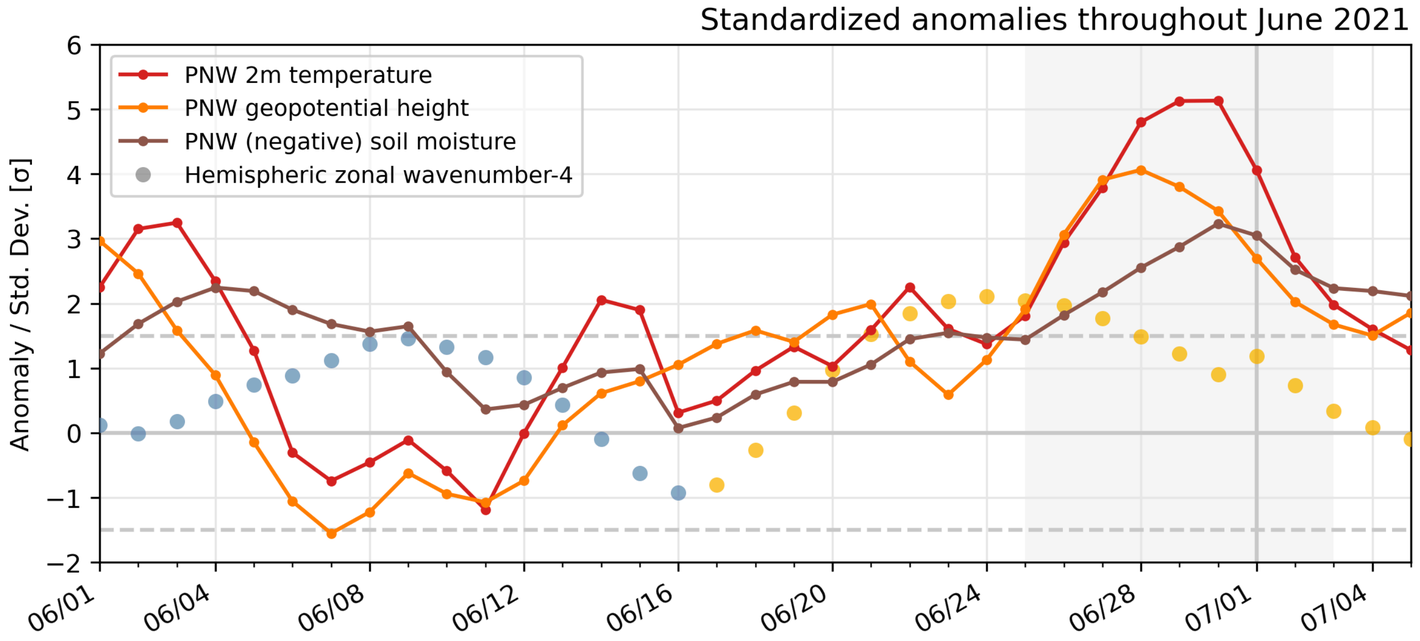
- **How can we understand the heatwave's physical drivers and relations to climate change?**

Takeaway (1/3): ***5-sigma heat event embedded in hemispheric pattern***



- Common heat drivers
  - high **geopotential height (GPH)**
  - low **soil moisture (SM)**
- Hemispheric context
  - Circumglobal **wavenumber-4** pattern of hot, high-GPH, and dry regions
  - Second synoptic wavetrain targeting PNW: **wave-wave interaction**

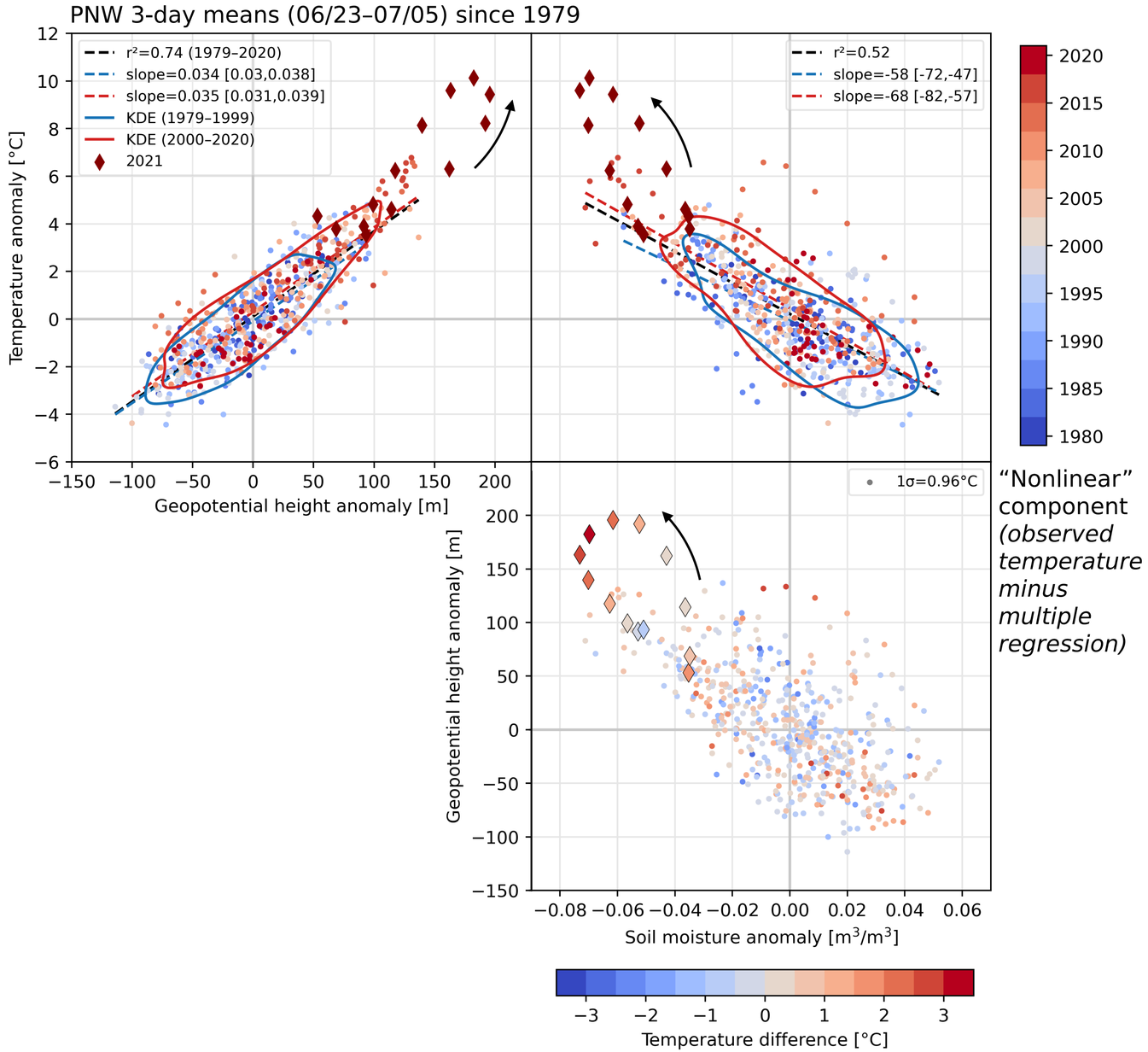
Takeaway (1/3): ***5-sigma heat event embedded in hemispheric pattern***



- Preconditions and event severity
  - Amplified **wavenumber-4** disturbance
  - Monthly-scale **dry soil** preconditions
  - Heat, GPH, SM reached **5σ**, **4σ**, **3σ** (w.r.t. 1981–2010)

- **How may interactions between drivers have amplified the heatwave's severity?**

Takeaway (2/3): ***Heat amplified 40% by (likely feedback-driven) nonlinearities***

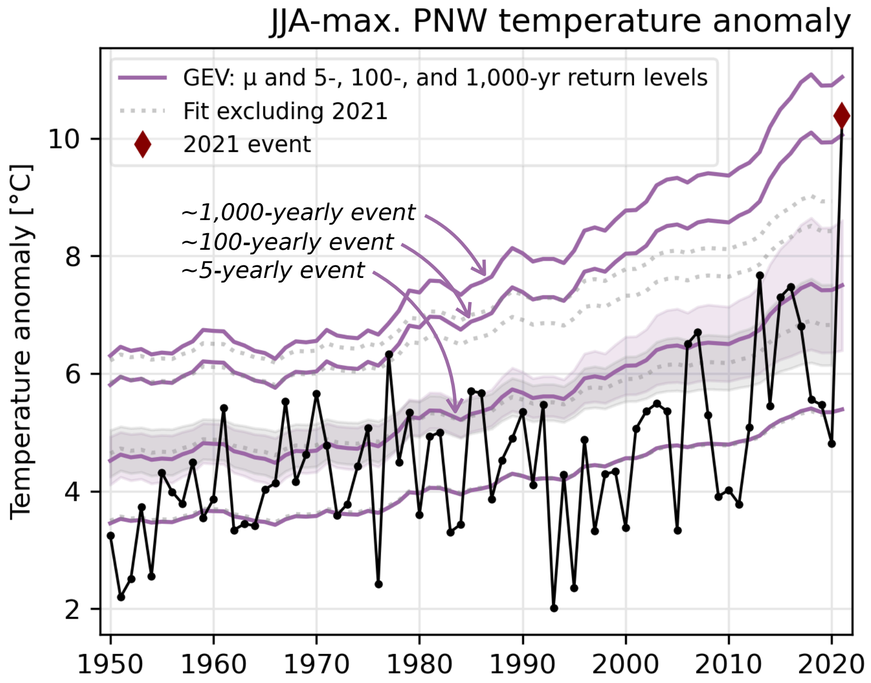


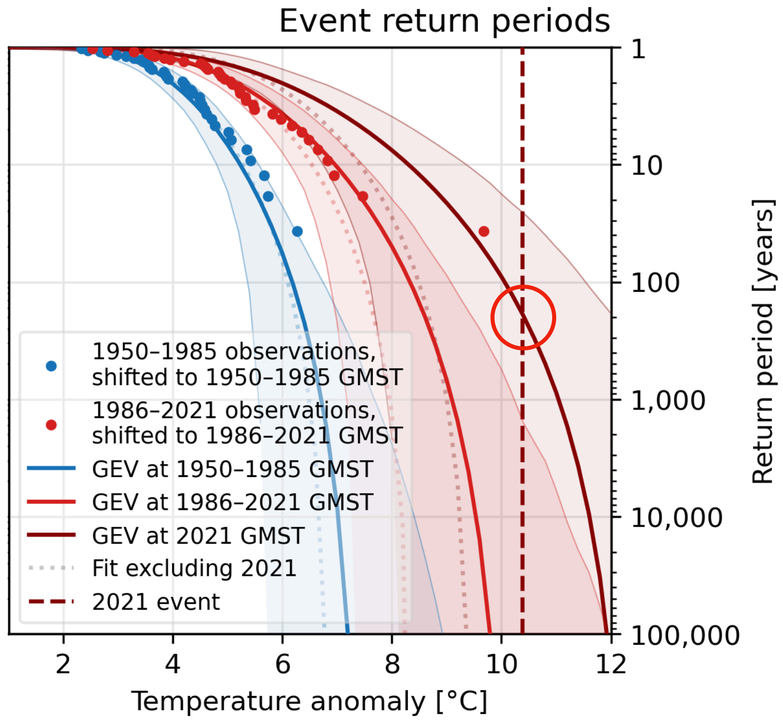
"Nonlinear" component *(observed temperature minus multiple regression)*

- Temperatures generally followed underlying relationships,
  - but **exceeded linear regressions** by ~5°C
- Event peak exceeded *multiple* linear regression by ~3°C (~40% **nonlinear amplification**)
  - Amplification in phase with soil dryness
- (Not shown) Long-term model runs with/without land–atmosphere feedbacks: 2021-level heat in PNW **~35x more likely with feedbacks**
- Slope of temperature vs. SM has **steepened** historically

▸ **How has background warming affected the likelihood of this event?**

Takeaway (3/3): ***Rapidly-increasing likelihood of event driven by warming***





- Nonstationary GEV model fit to PNW summer-maximum temperature anomalies since 1950
  - Extreme heat likelihood has drastically increased (temperature skewness has increased; not shown)
  - A 2021-level anomaly has transformed from **virtually impossible** to a **~1-in-200-year** event (with very large uncertainty)

Takeaways

5-sigma heat was embedded in hemispheric pattern

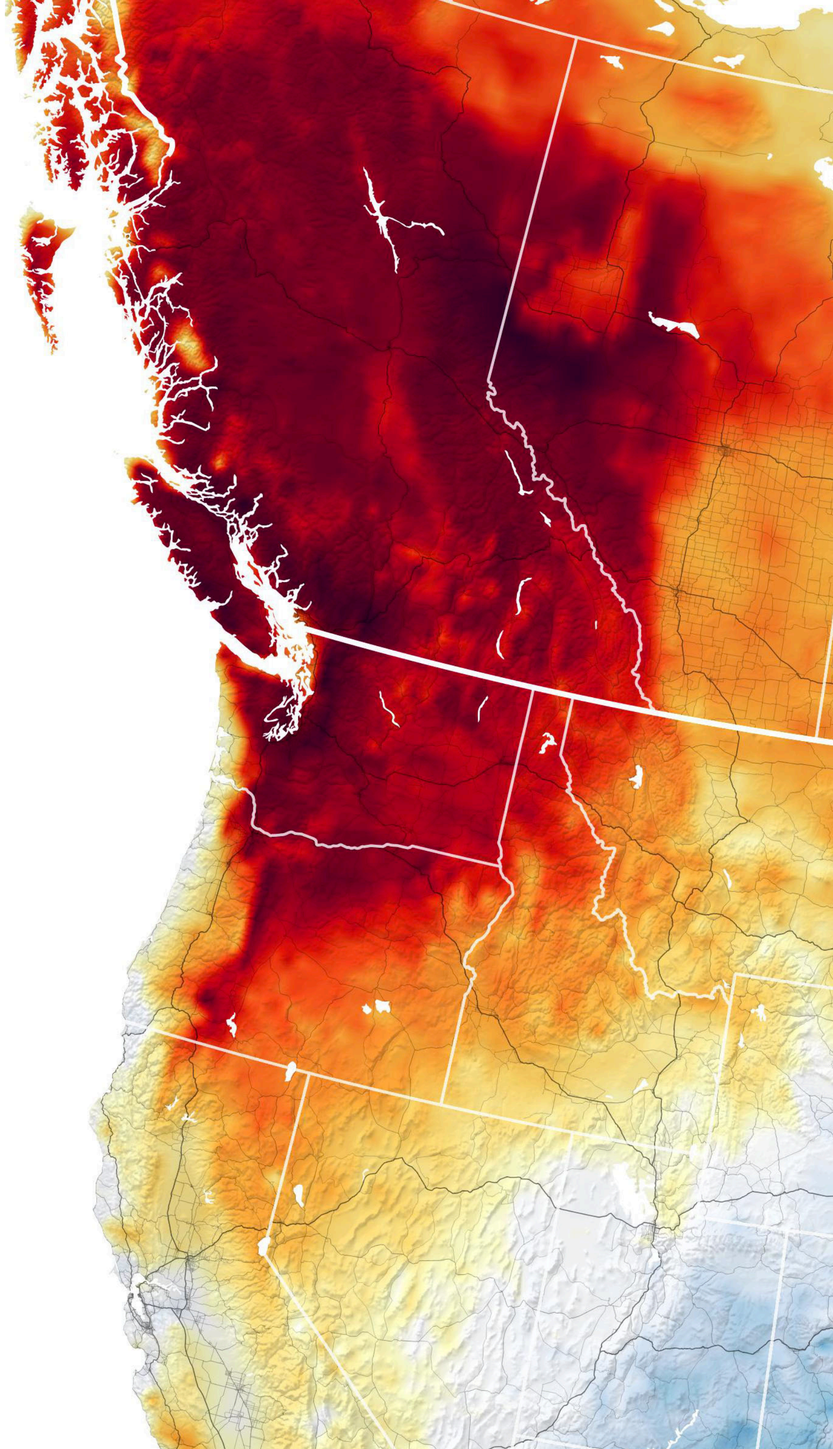
- Interacting hemispheric **wavenumber-4** and synoptic wavetrains provided extreme dynamical forcing

Heat amplified ~40% by (likely feedback-driven) nonlinearities

- Land-atmosphere feedbacks may be **strengthening in a historically wet region**
- Model experiment suggests that **land interaction can amplify PNW extreme heat**

Rapidly-increasing event likelihood driven by warming

- Warming since 1950 has dramatically transformed the rarity of this event: it has been refigured from **virtually impossible** to **plausible and somewhat expected** (a one-in-hundreds-of-years event)



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