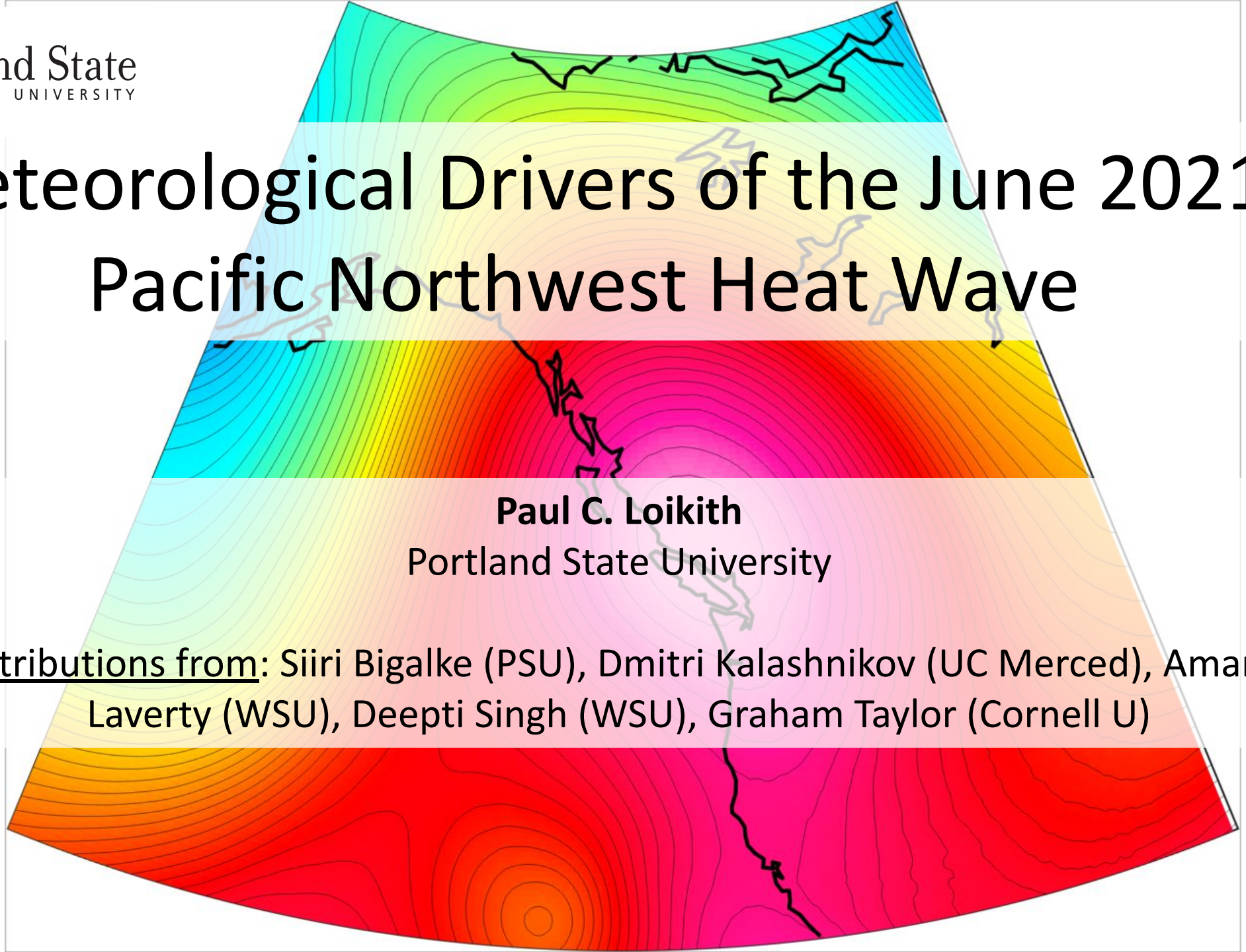
Portland State UNIVERSITY

Meteorological Drivers of the June 2021 Pacific Northwest Heat Wave



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Content in this part of the talk primarily from:

Loikith, P. C., and D. A. Kalashnikov, 2023: Meteorological Analysis of the Pacific Northwest June 2021 Heat Wave. *Monthly Weather Review,* **151**, 1303-1319, https://doi.org/10.1175/MWR-D-22-0284.1.

Fleishman, E., D. E. Rupp, P. C. Loikith, K. A. Bumbaco, and L. W. O'Neill, 2025: Synthesis of publications on the anomalous June 2021 heat wave in the Pacific Northwest, United States and Canada. *Bulletin of the American Meteorological Society*, in press, https://doi.org/10.1175/BAMS-D-24-0188.1.

The June 2021 Mega Heat Wave

- Between June 25th and July 1st, an extraordinary heat wave affected the Pacific Northwest of the US and Canada.
- Several locations broke their all-time record high temperatures, often by several degrees.
- 123 people lost their lives due to the heat in Oregon alone (Oregon Health Authority).

Oregon Records

Date	Portland Int'l Airport Max T	Pendleton Airport Max T
6/25/2021	95	94
6/26/2021	**108**	104
6/27/2021	**112**	112
6/28/2021	**116**	113
6/29/2021	93	**117**
6/30/2021	79	106
7/01/2021	75	95

From Fleishman et al. 2025, made by Larry O'Neill

Notable facts and figures

- KPDX hit 108, 112, and 116 degrees. The previous all-time record at KPDX was 107 (set on 7/30/65, 8/8/81, and 8/10/81)
  - Previous June record was 102…beat by 14 degrees!
  - Set new all-time high nighttime temperature of 75 (previous record was 74 on 7/17/41)

- KSEA hit 108, previous record was 103 (7/29/09).

- KSLE hit 117, previous record was 108 (7/23/27, 7/15/41, and 8/9/81).

- Forks, Washington hit 110 degrees. Previous all-time record was 102 set on 8/8/81 and 8/9/81.

- Astoria reached 101 degrees F on June 27. Previous all-time record at the airport was 100 (downtown it was 101 in 1942).

- Oregon tied its previous record of 119 at two stations in Wasco and Jefferson counties.

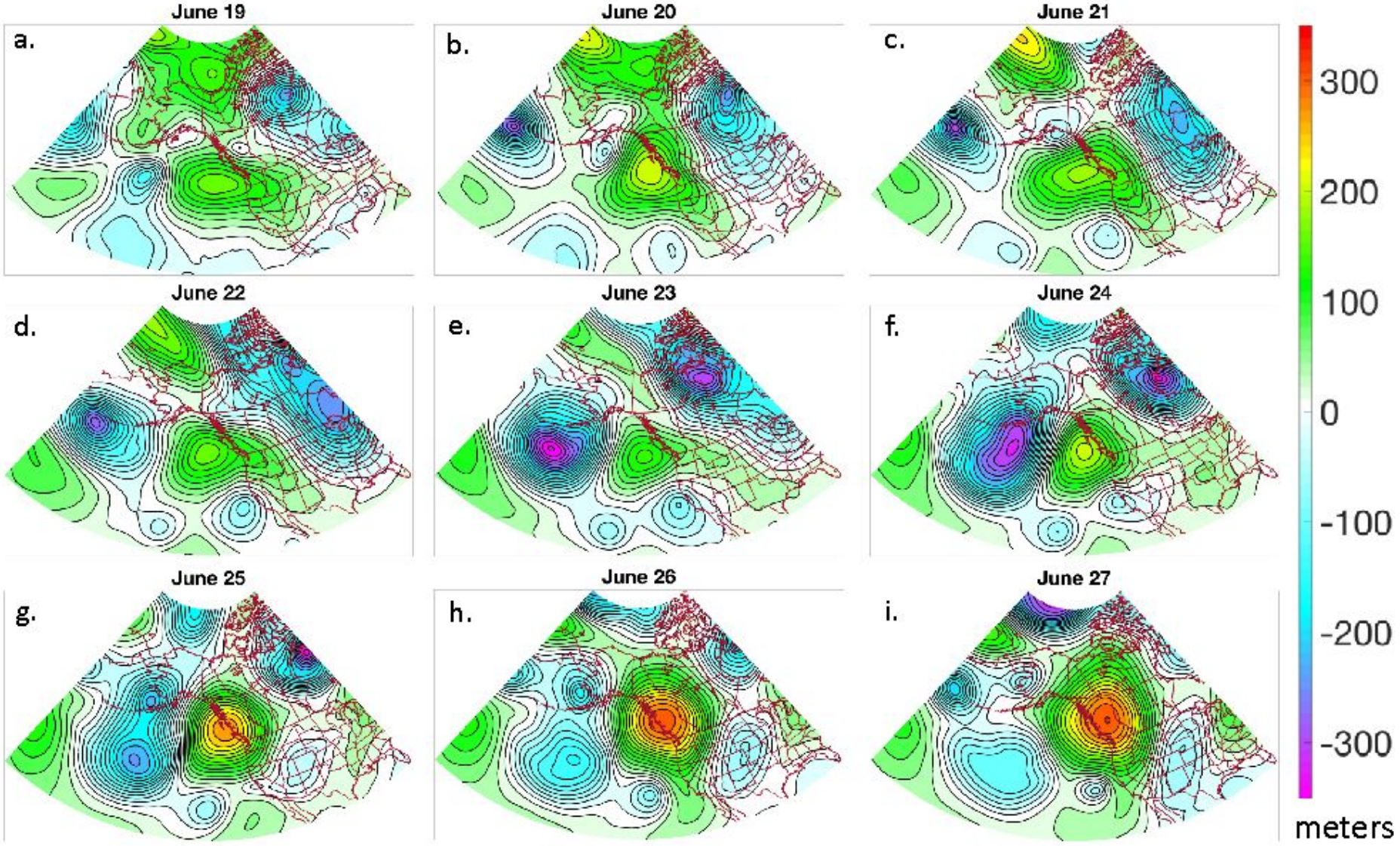
- Washington broke its state record with 120 degrees at Hanford (previous record was 118).

- Canada set a new national record of 121 degrees at Lytton, BC.

- Prior to this event, there had never been a recorded temperature above 110 in western Washington or the Willamette Valley. All major weather stations broke 110 in the Valley and many did in southwestern Washington.

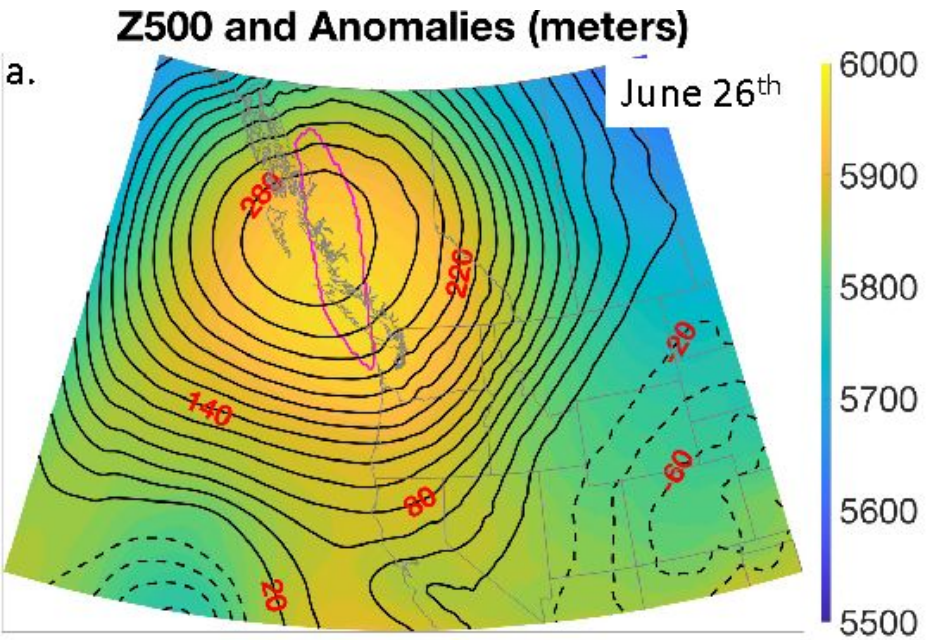
- This list could go on…..

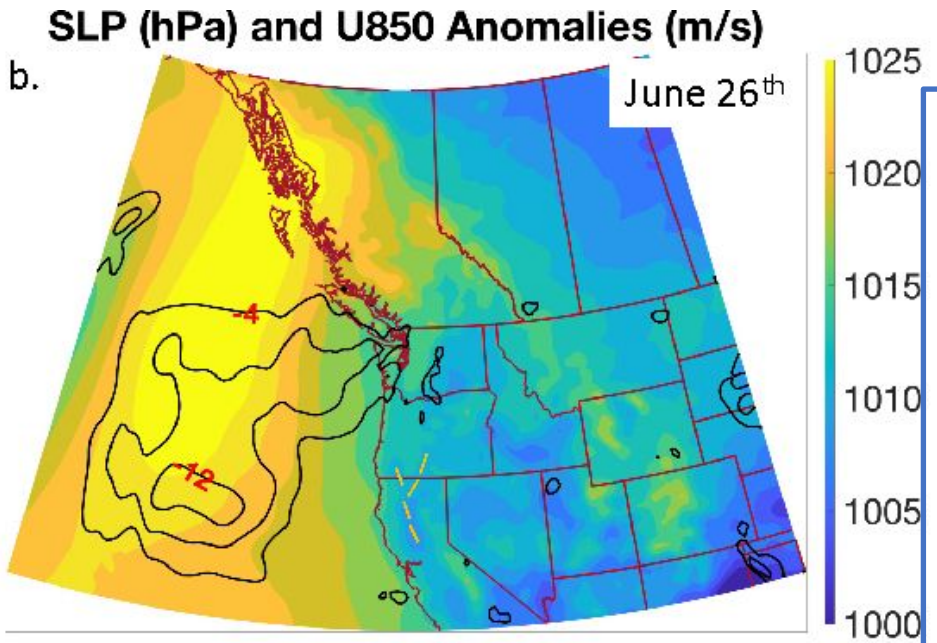
Evolution of the Record Breaking Ridge?

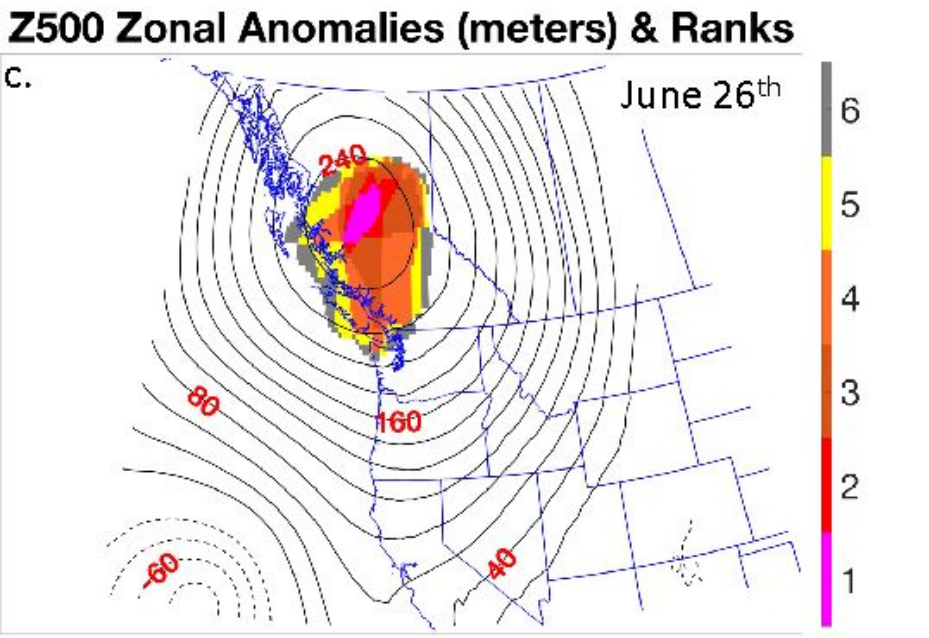


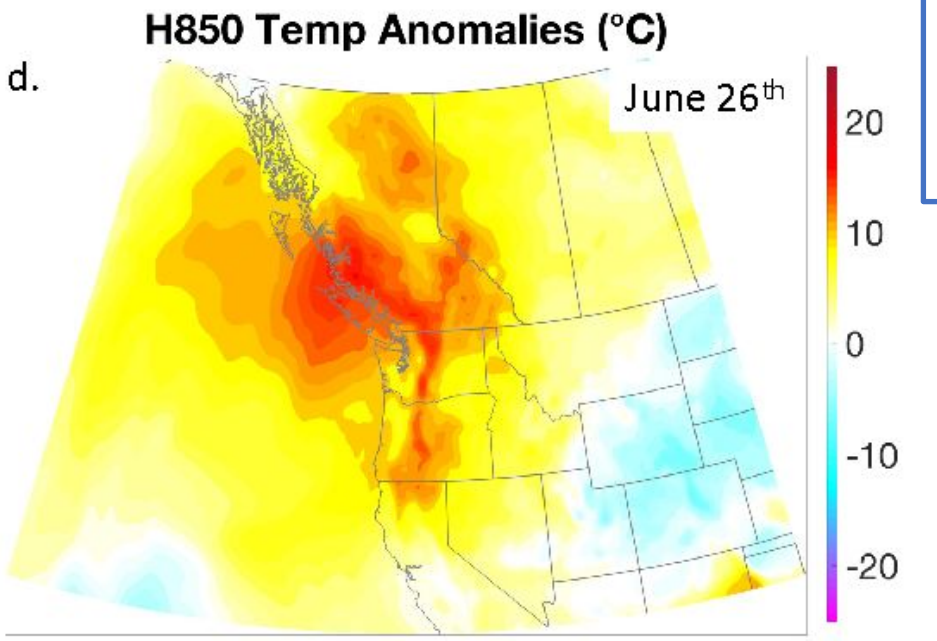
- Strong atmospheric river on upstream side of the ridge likely supplied heat to the ridge. (Mo et al. 2022)
- Ridge strength peaked over BC on June 26-27th, but heat was most severe on the 28th-29th.
- Small upper-level low to the west of NorCal was also key.

Meteorology of June 26th



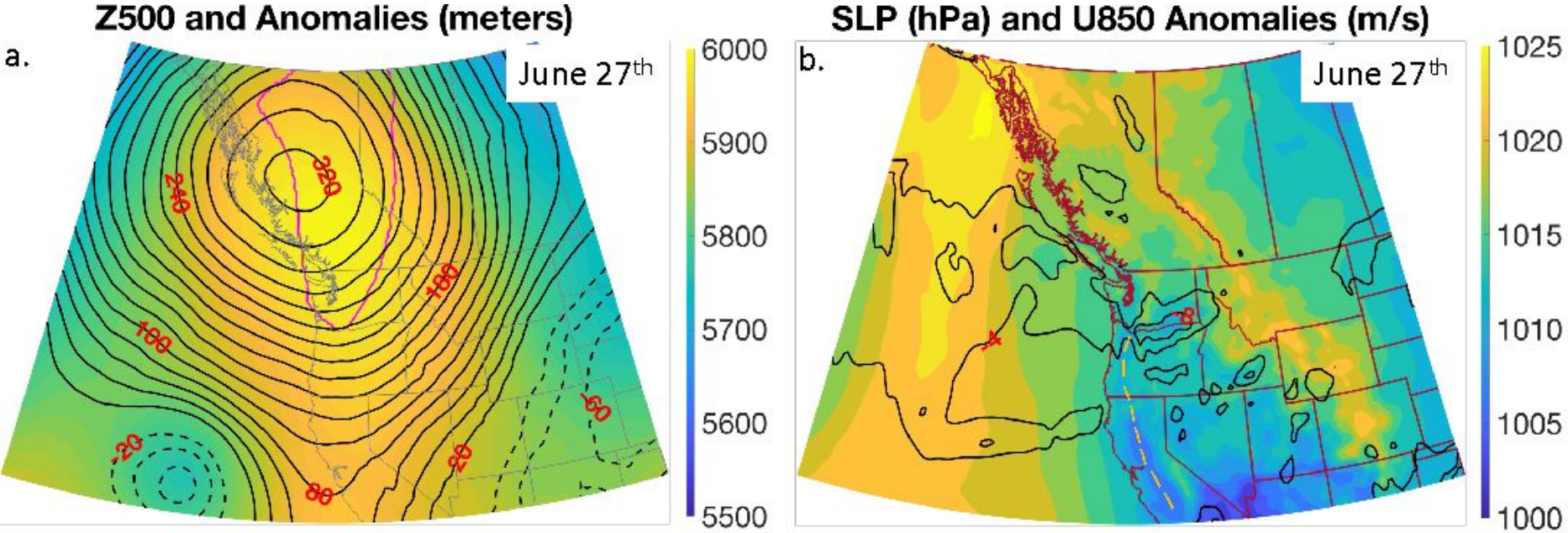


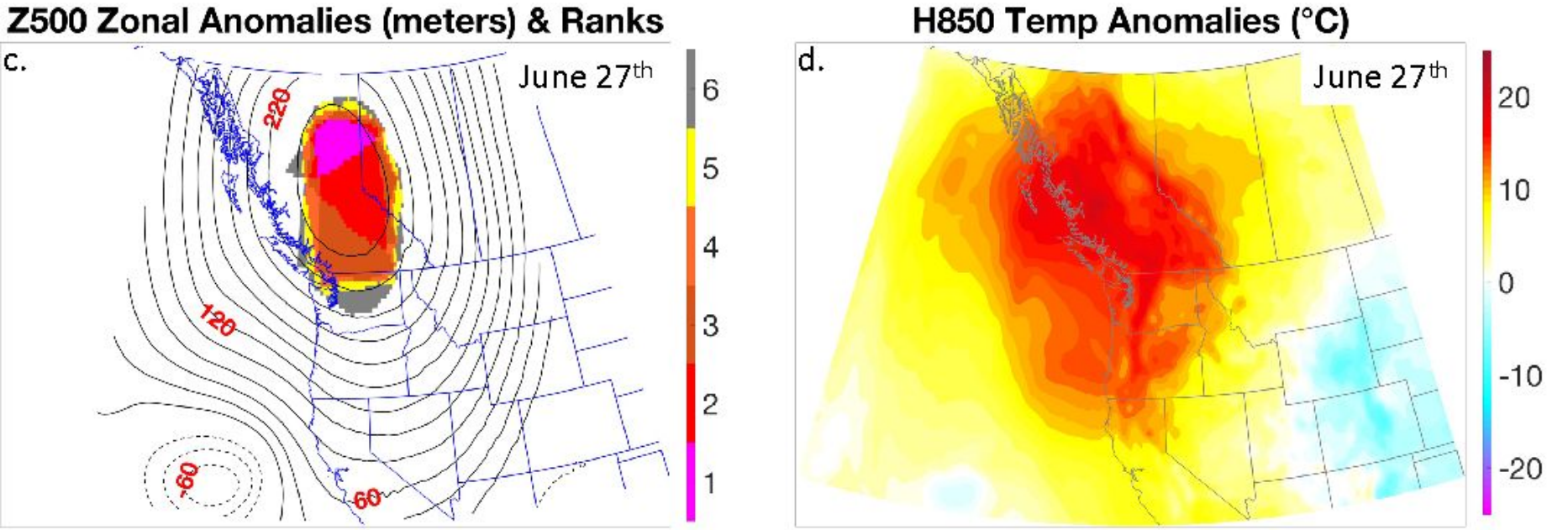




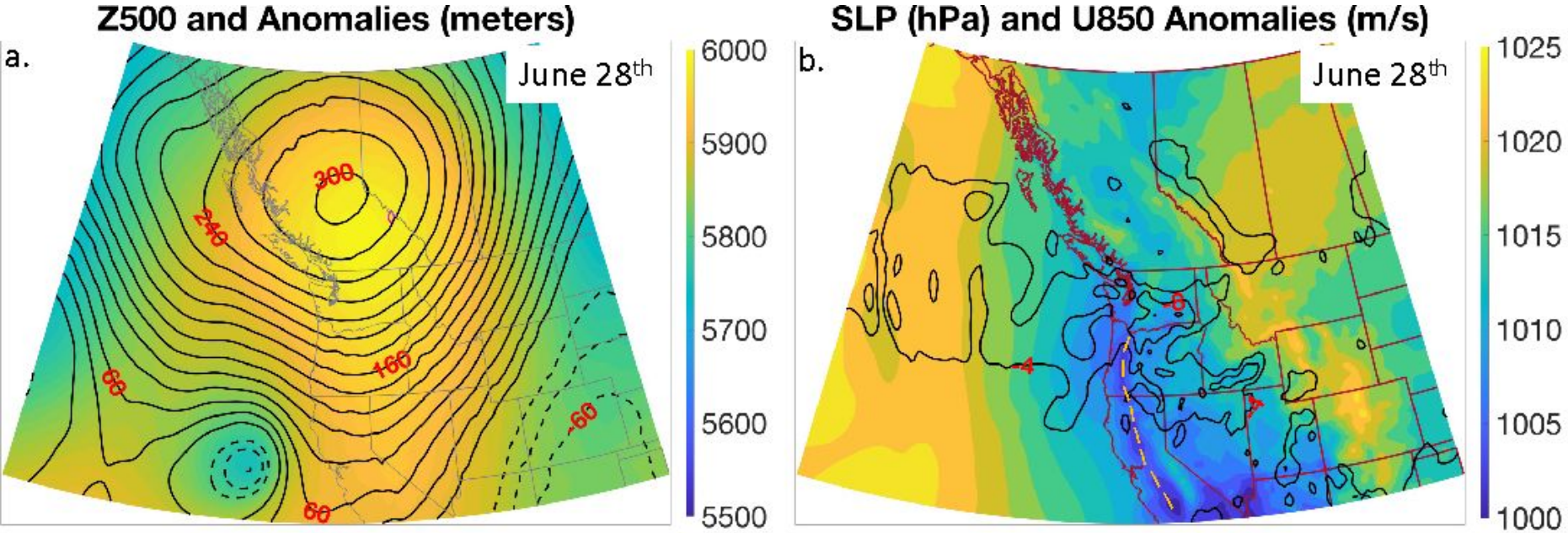
- Record breaking 500 mb geopotential height (panel a).
- Developing thermal trough, no offshore flow (panel b).
- Record breaking ridge amplitude (panel c).
- Extreme heat developing, primarily over BC and higher elevations of OR and WA.

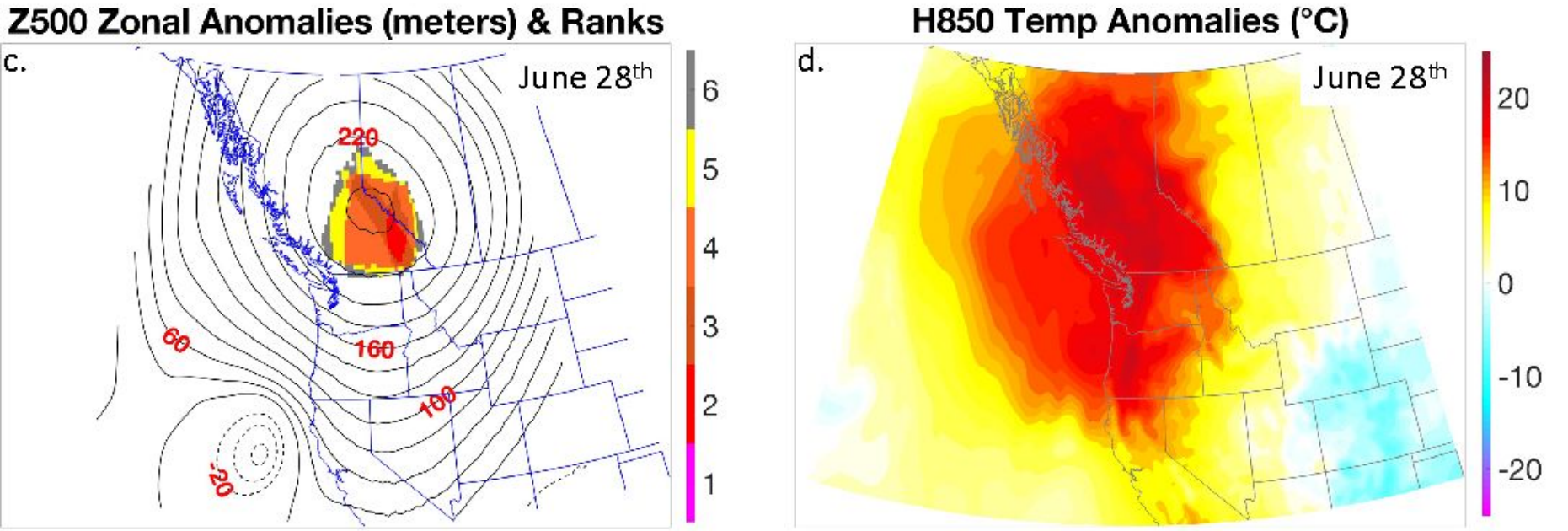
Meteorology of June 27th



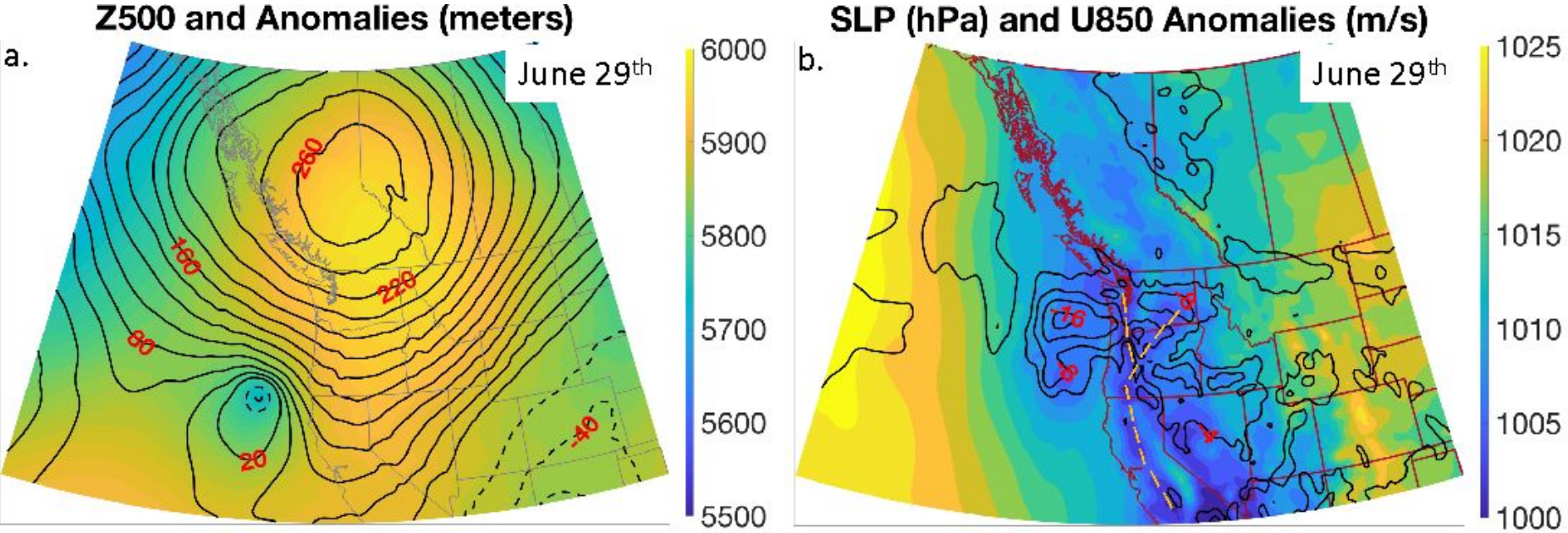


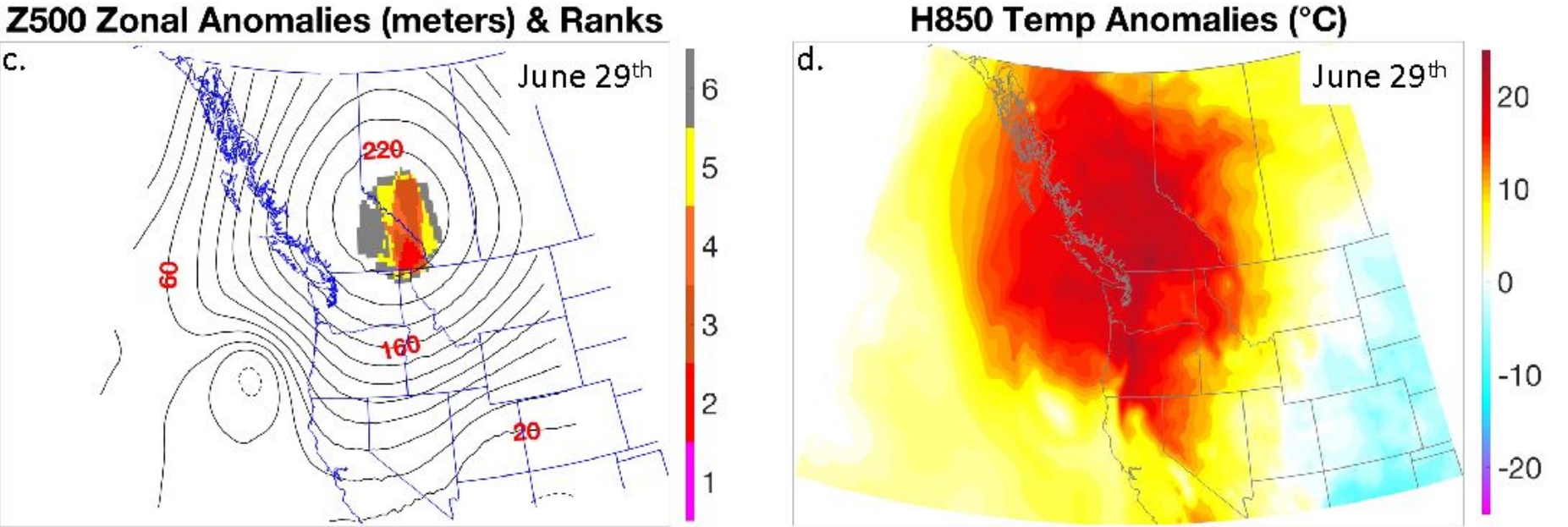
Meteorology of June 28th



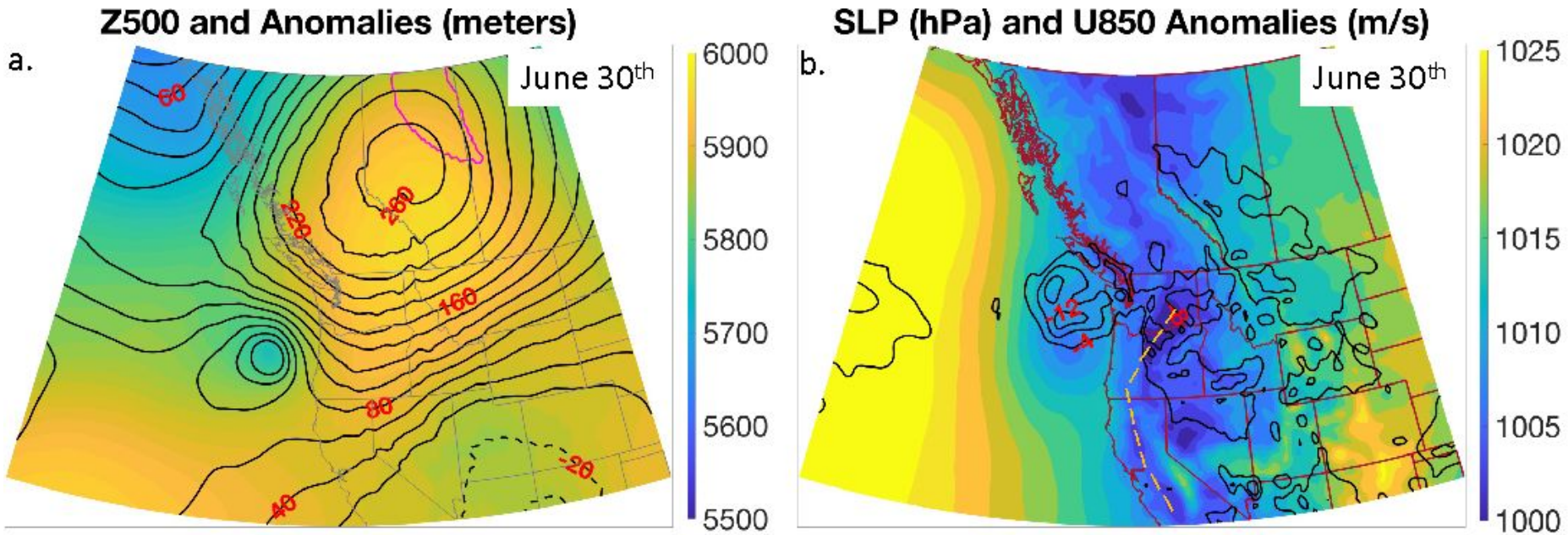


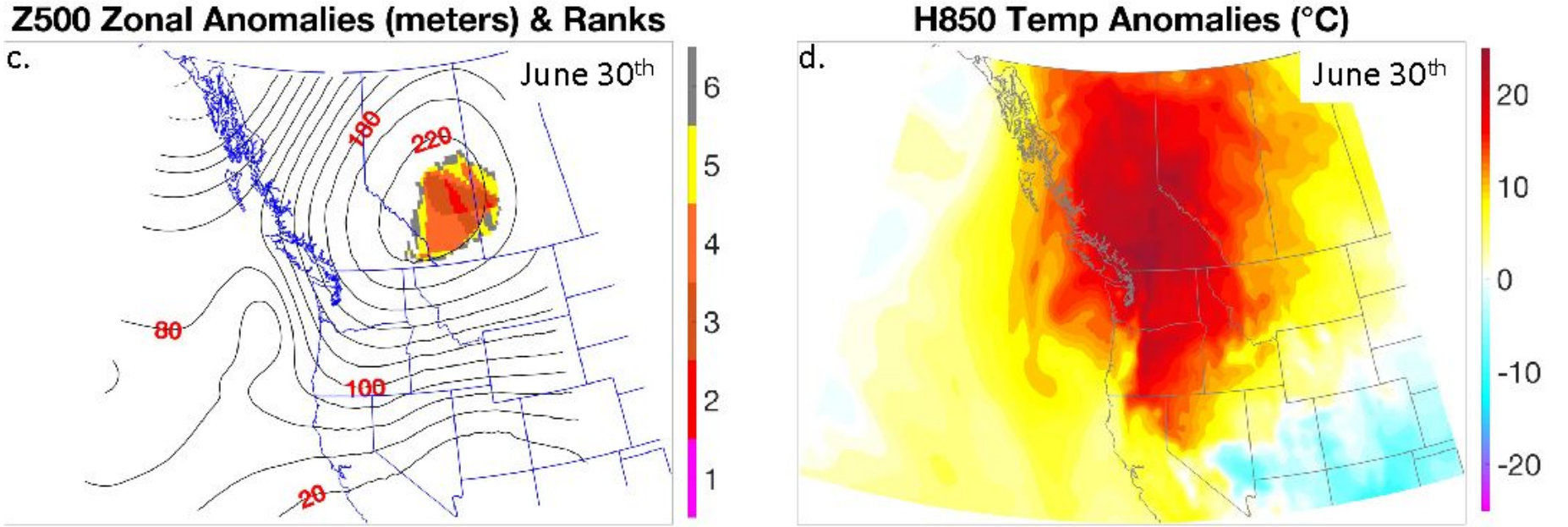
Meteorology of June 29th



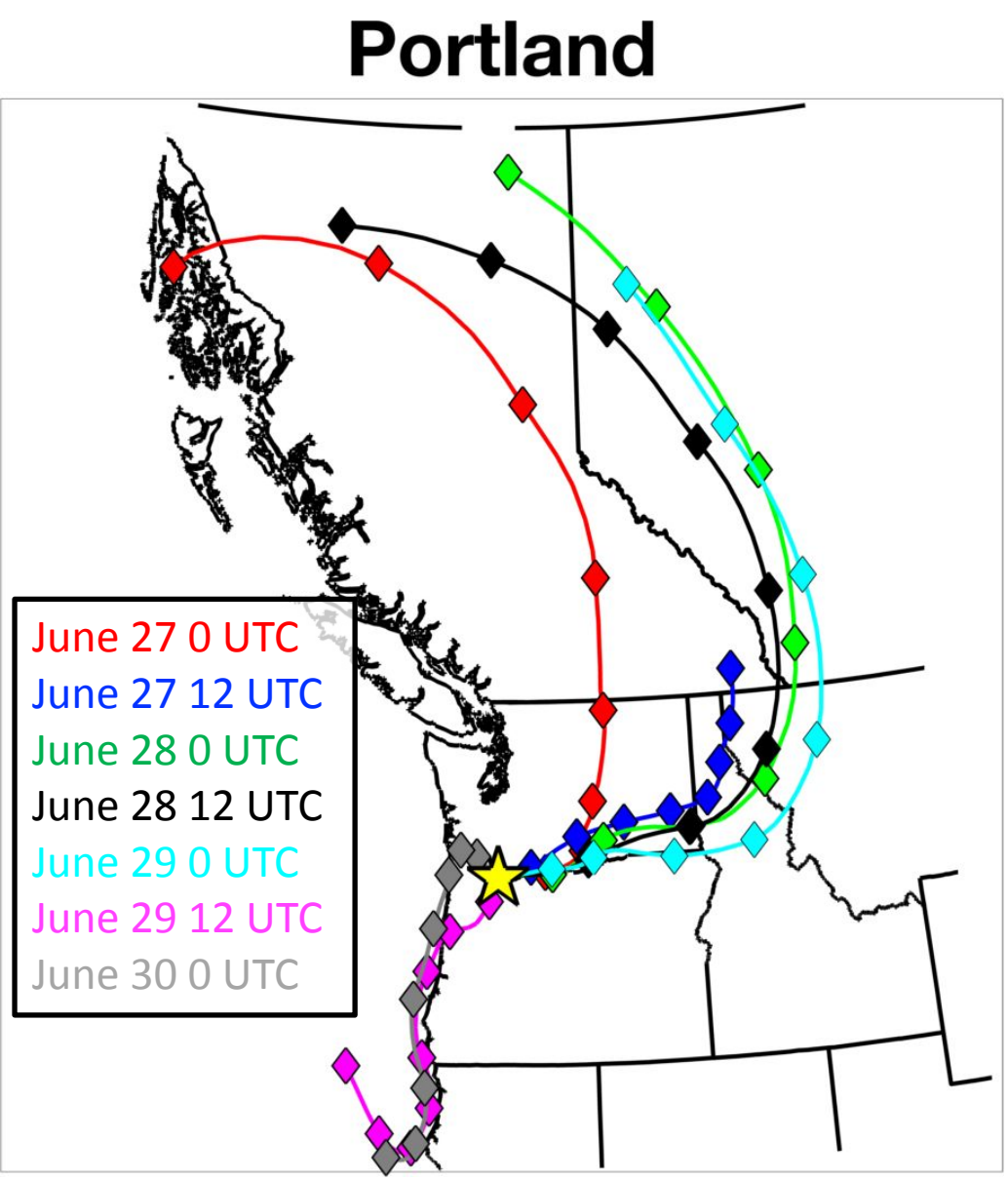


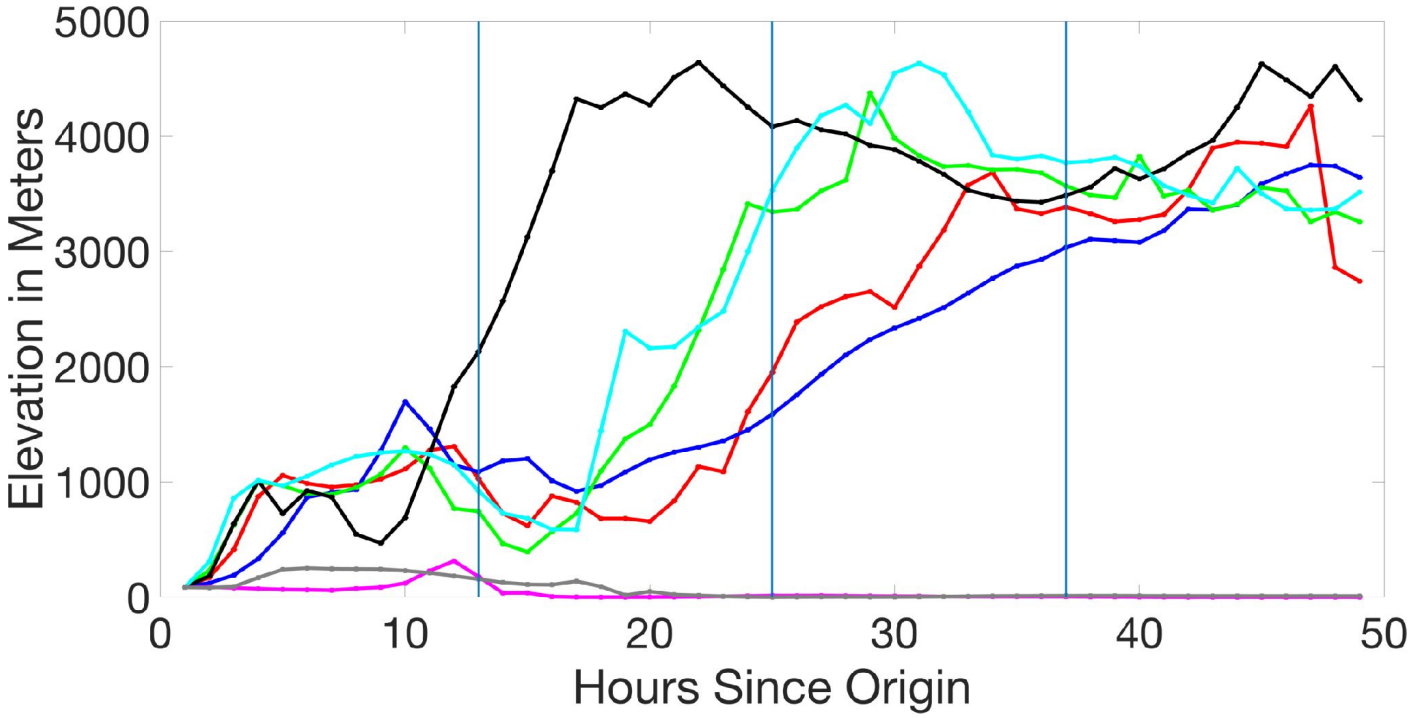
Meteorology of June 30th





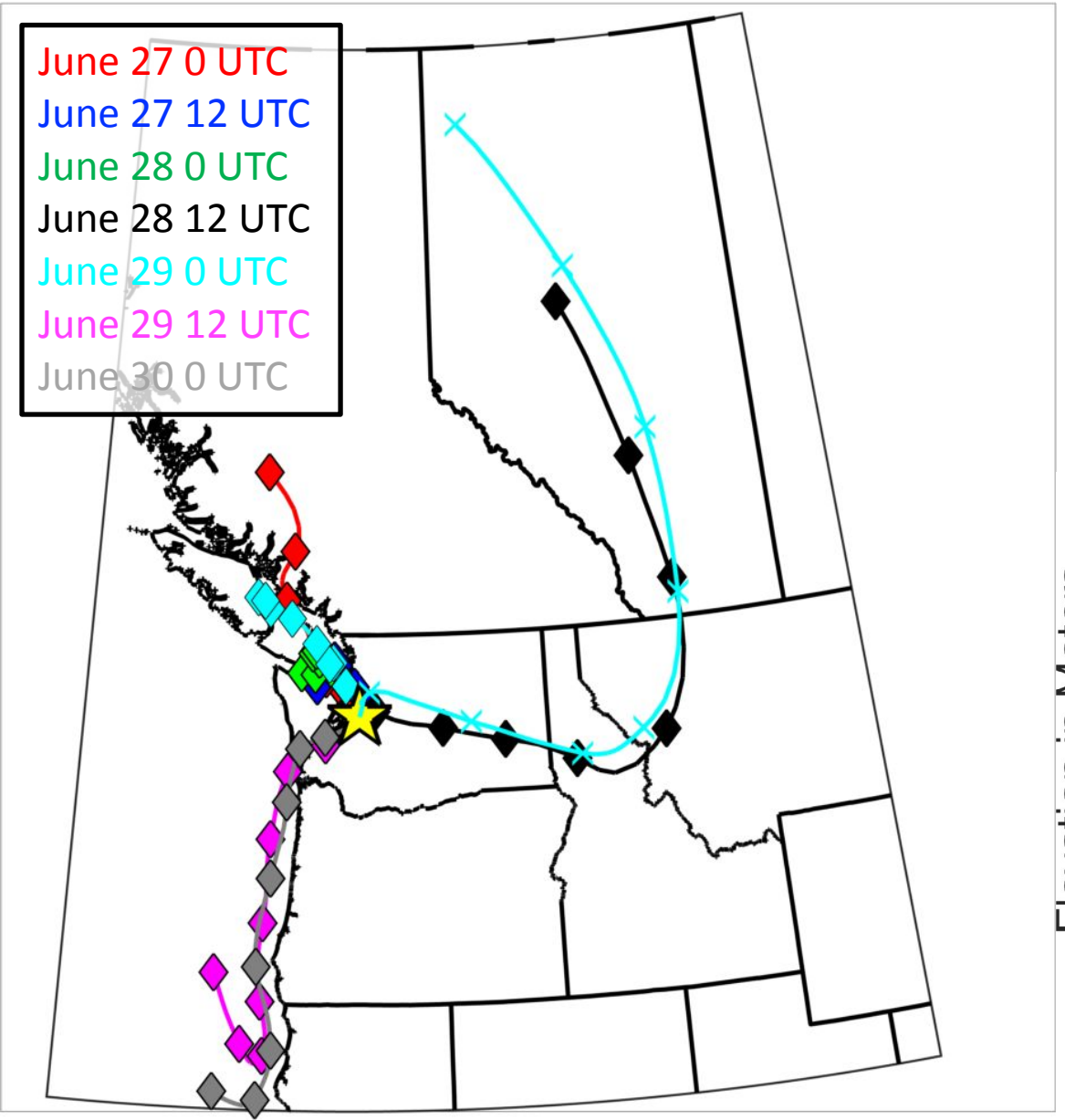
Air Parcel Trajectories for Portland



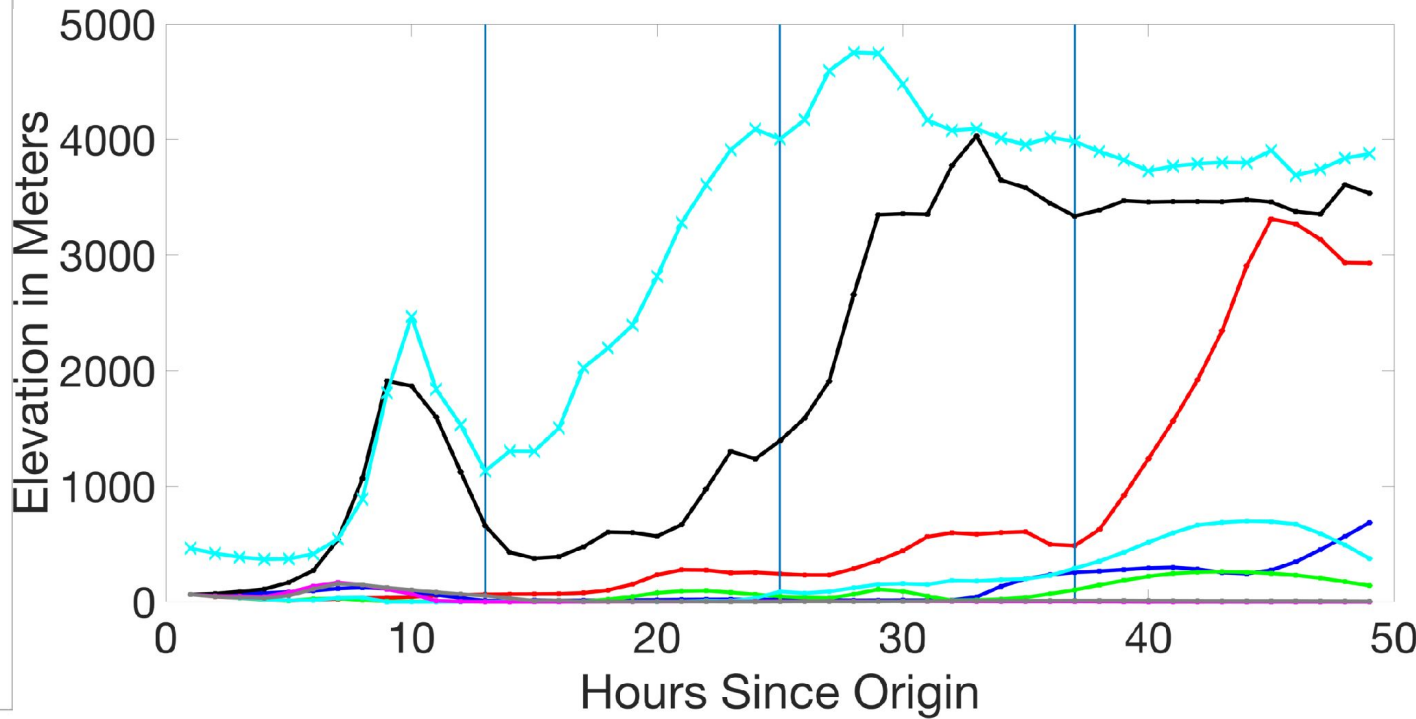


- Air parcels descended nearly 4500 meters over the 48 hours prior to arrival in Portland.
- Cool marine air at the end of the event originated from just above the ocean surface.

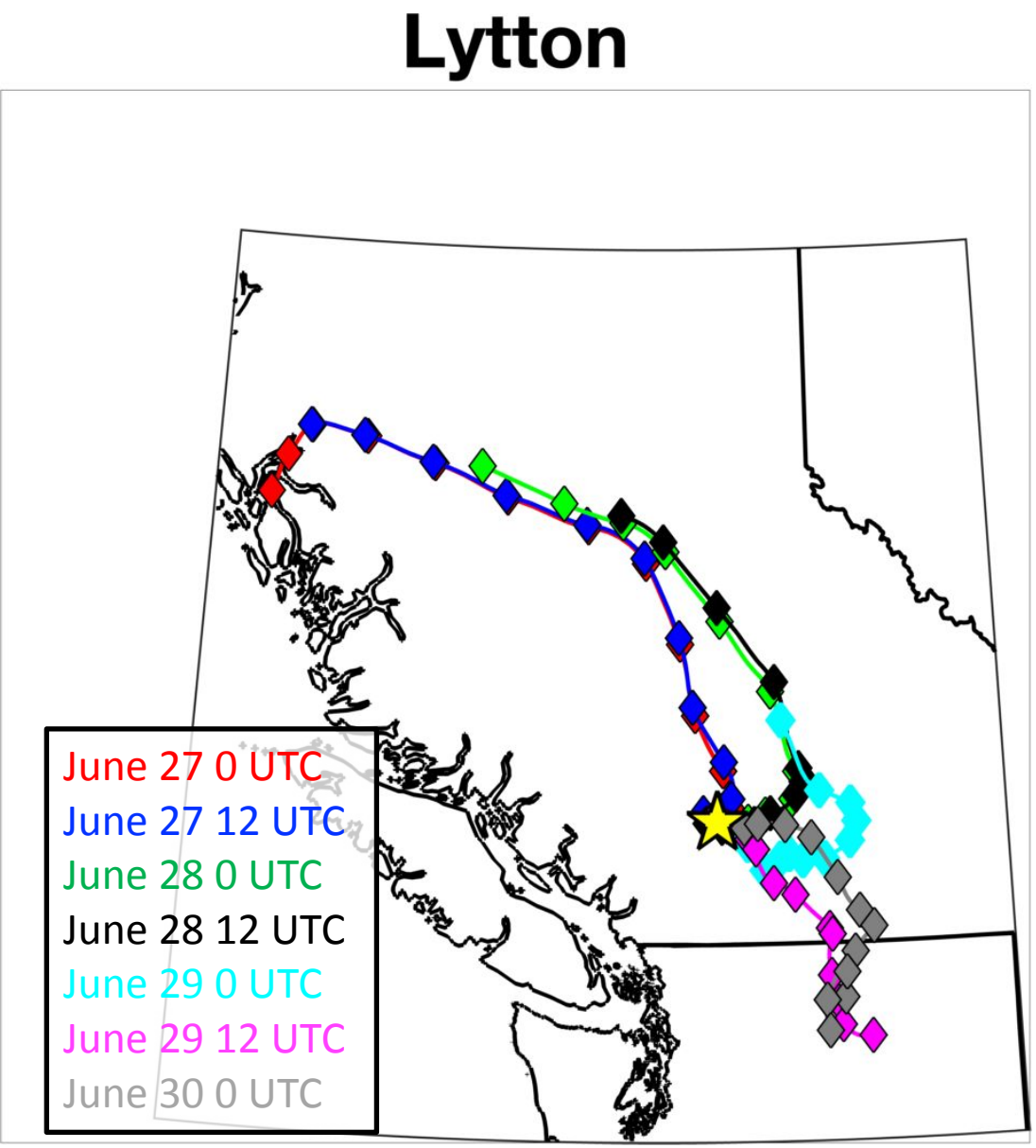
Air Parcel Trajectories for Seattle



- At start of heat wave, parcels traveled over Puget Sound before arriving in Seattle. How did that not cool them off?
  - Extreme sinking air suppressed the cool layer over the water, mixing of warmer air from just above the surface likely also contributed.
- Additional warming from air sinking down west slopes of the Cascades.
- Southerly wind reversal ended heat wave at Seattle too.

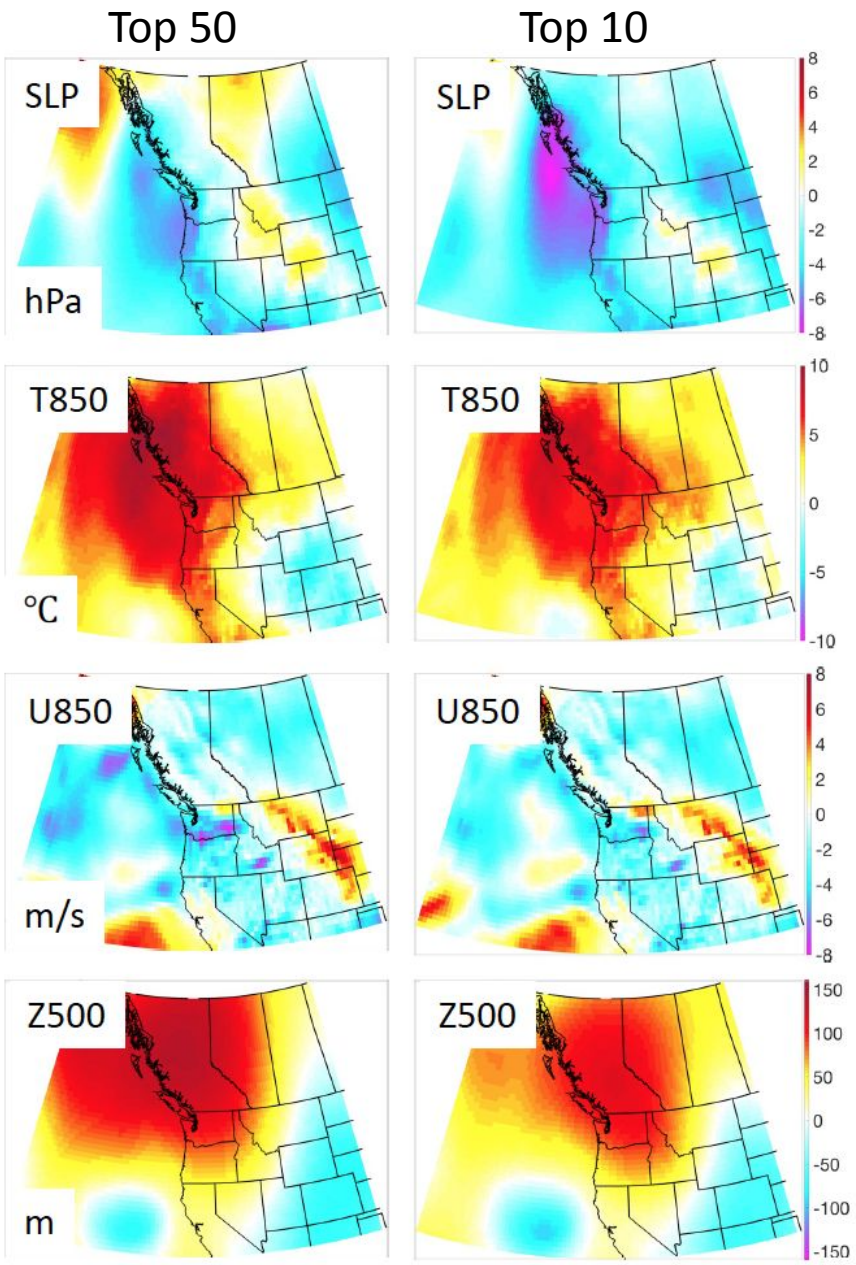


Air Parcel Trajectories for Lytton



- Lytton was closer to the core of the ridge, where winds are light.
- Air parcels did not travel long distances to get to Lytton in days prior.
- Hot air under the ridge got progressively hotter each day due to solar heating and large-scale suppression of vertical mixing.
- Lytton's local geography also likely played a role in the 121 degree reading.

Why was this heat wave so much worse than others?



- Compared with other highly amplified summer ridges, the June 2021 event had more of everything that is important for heat.
- Stronger thermal trough.
- Much hotter lower tropospheric temperatures.
- Stronger offshore winds.
- Much stronger ridge.

Why was this heat wave so much worse than others?

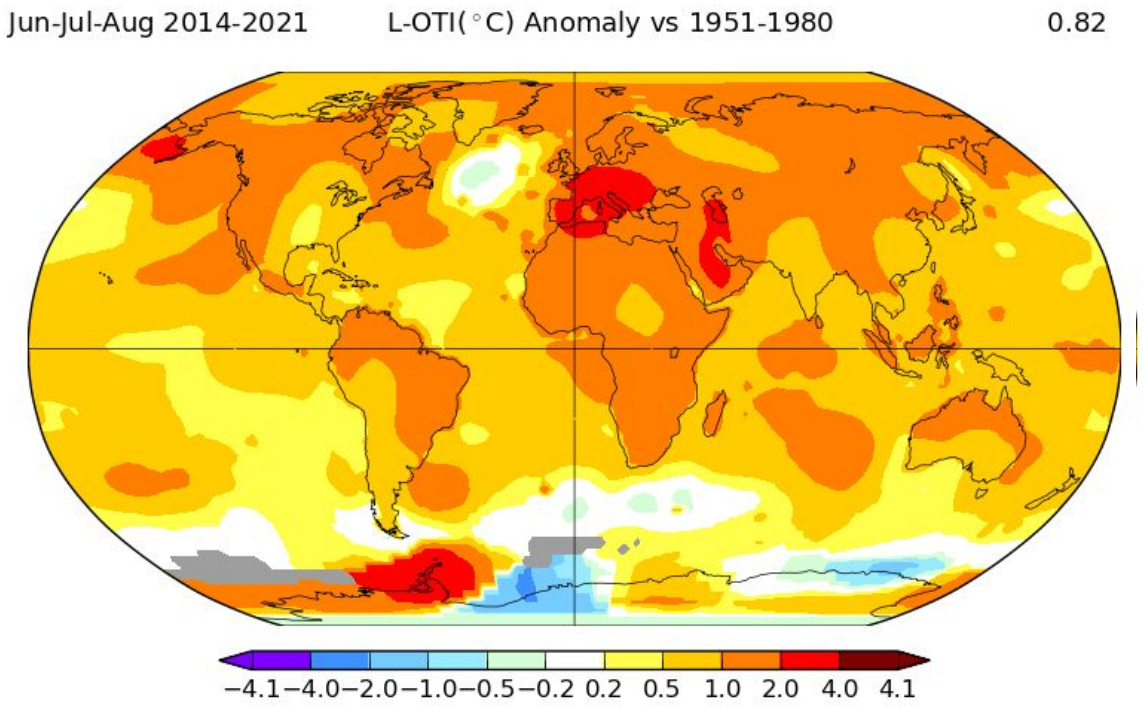
1) Stronger mid-tropospheric ridge

2) Stronger offshore wind

3) Near summer solstice (maximum solar heating)

4) Drier than average soil moisture

5) Global warming



- The Pacific Northwest summer average temperature was generally about 1-2 degrees C warmer than it was in the mid-20th century.
- Simplest way to assess the impact of global warming on this heat wave is to add regional warming to the event.
- In this sense the heat wave was 1-2 degrees C warmer than if it had occurred in the mid-20th century.

How Likely is a Repeat?

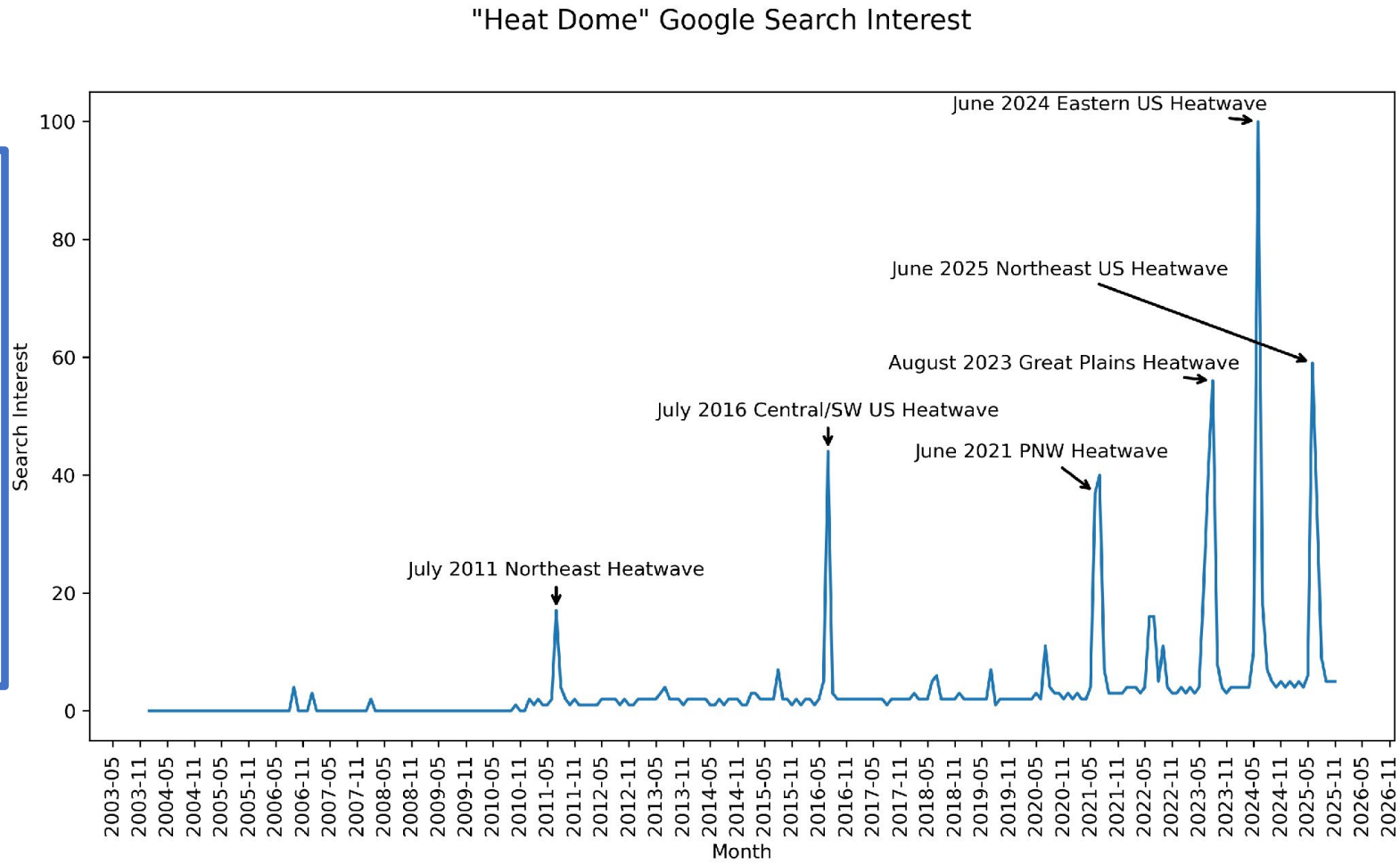
- It is difficult to estimate return intervals based on something so far outside the range of observations.
- Model-based studies estimated the return interval for the event between a 1 in 127 to a 1 in 100,000-year event in the current climate.
- Based on several studies, the contribution from warming to the heatwave was between .8 and 3.1 degrees C.
- Studies suggest that that by mid-century an event of similar or greater magnitude increasing to a 1 in 3 to 1 in 10-year return period.
- As the climate warms, it won't take such an extreme heat dome to cause temperatures as high as this event.

What is a heat dome? Was the June 2021 event a heat dome? Was it THE heat dome?

Loikith, P. C., S. Bigalke, G. Taylor, and D. Kalashnikov, D. Singh, and A. Laverty, 2025: A Climatology of Heat Domes Over North America, *Weather and Climate Extremes*, **53**, 100913, https://doi.org/10.1016/j.wace.2026.100913. .

Background

- Use of the term “heat dome” has gained popularity in recent years, largely outside of the meteorological community.
- A definition was recently added to the AMS Glossary.
- A meteorologically-based quantitative definition of what is and what is not a heat dome is still lacking.



Heat Dome Definition

"an exceptionally warm air mass at middle latitudes during the warm season that is associated with a synoptic-scale area of high pressure aloft…" AMS Glossary (2024)

Component 1: Temperature

- Extreme heat objects – spatially contiguous* regions exceeding the 99th percentile of the local 1981-2010 MJJAS daily maximum temperature

- 99th percentile isolates the most climatologically extreme events with potential for significant societal impacts

Component 2: High pressure aloft

- Extreme heat objects (EHOs) must be spatially coincident or within close proximity* to a distinct closed anticyclone center at 500 hPa

- The anticyclone center/peak is labeled the heat dome center and the extreme heat object is deemed associated with a heat dome.

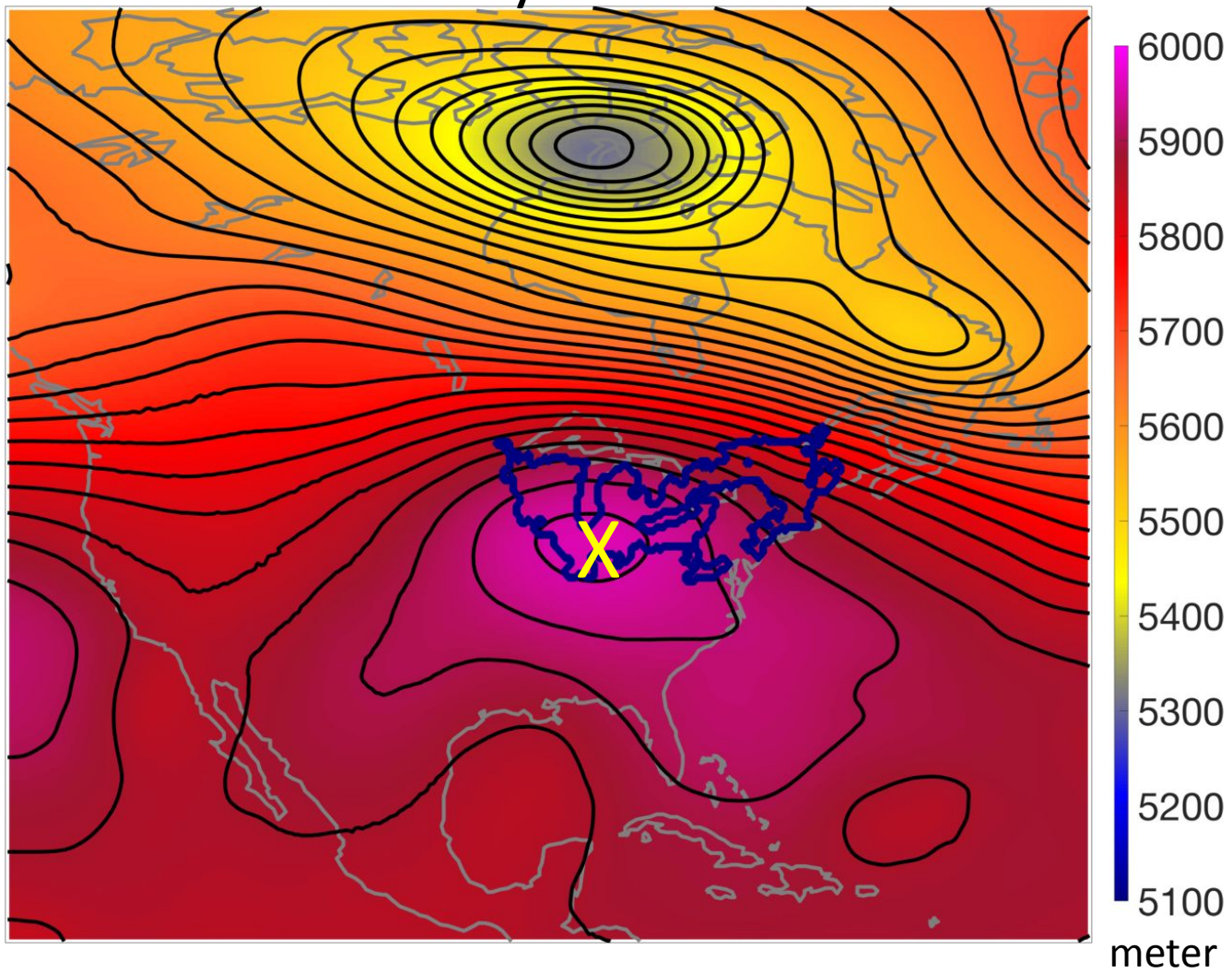
Climatology is built for May-September 1940-2025 using ERA5 Reanalysis

Heat domes are defined as a circulation feature associated with extreme heat.
Extreme heat objects can be part of or not part of a heat dome.

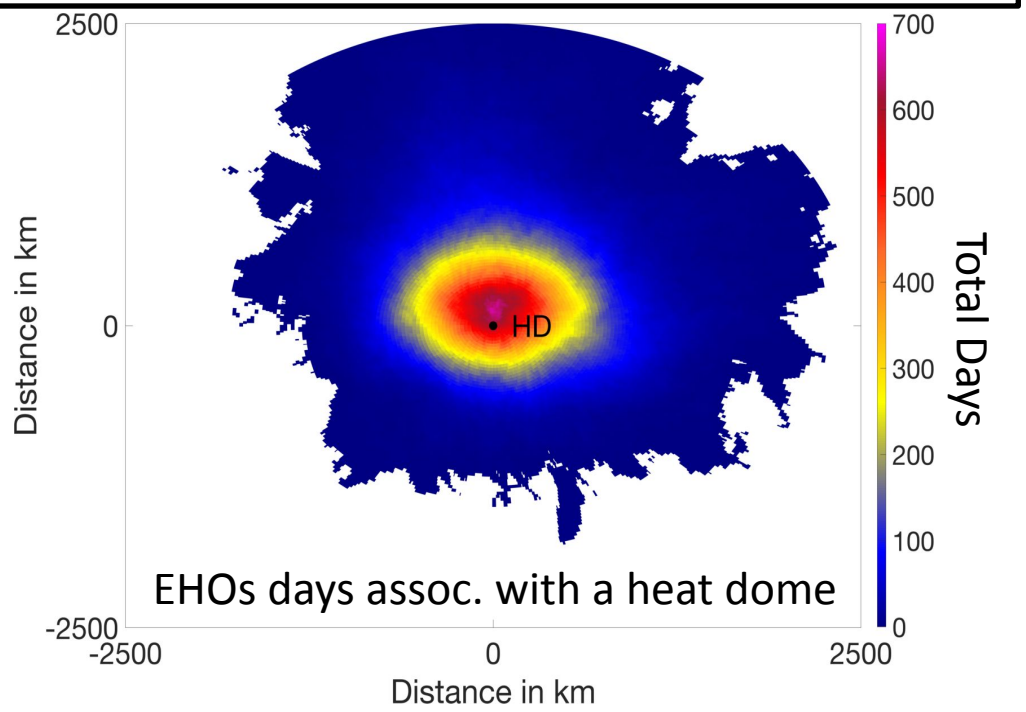
**Regions must exceed 150,000 km^2 in area and be within 5 mb & 900 km of anticyclone center*

Heat Dome Example

14 July 1995

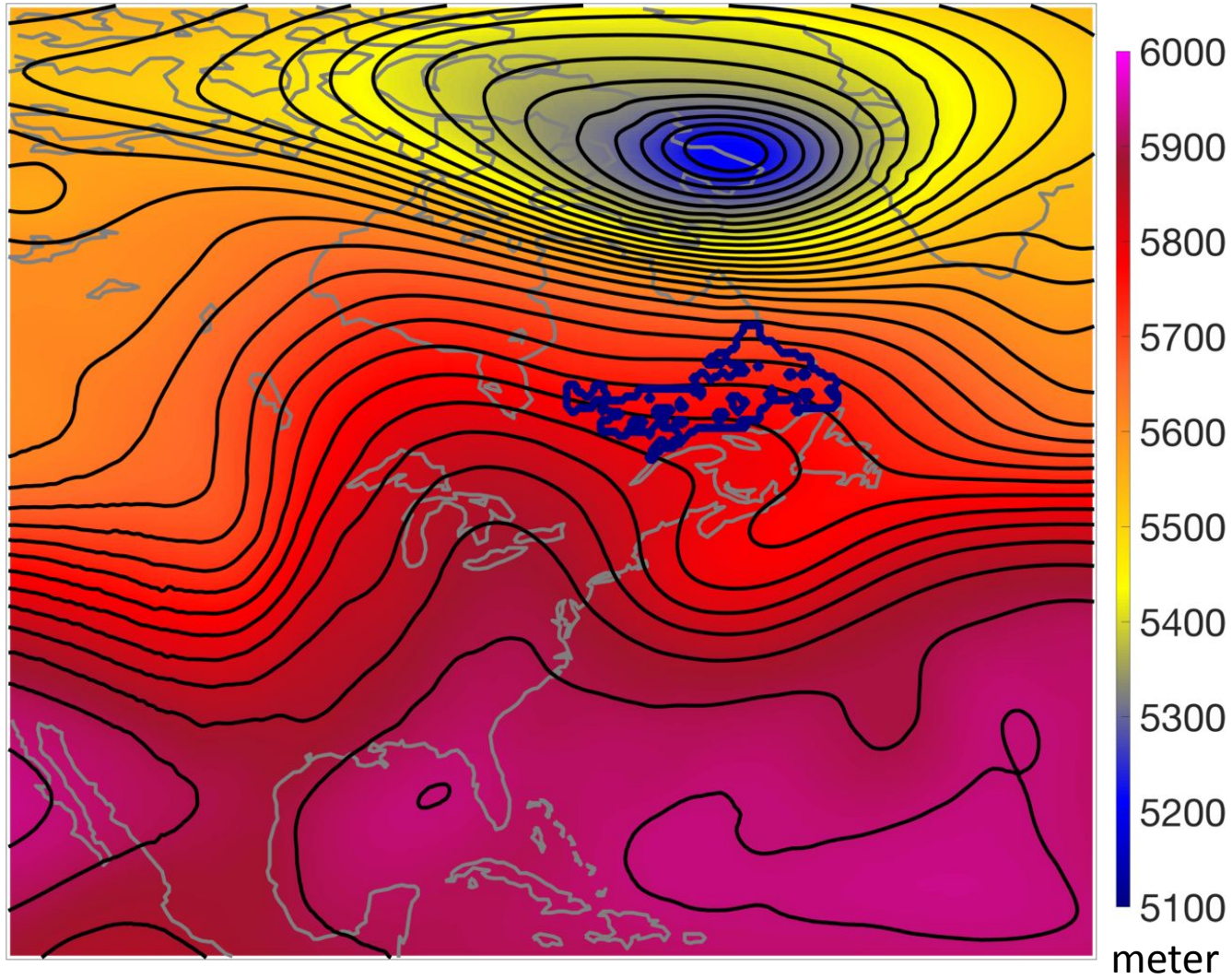


- Heat dome and associated heat wave during the historical Chicago 1995 heat wave.
- Extreme heat object (blue) overlaps the heat dome center.
- EHOs are most common to the north of the heat dome center as in this example.



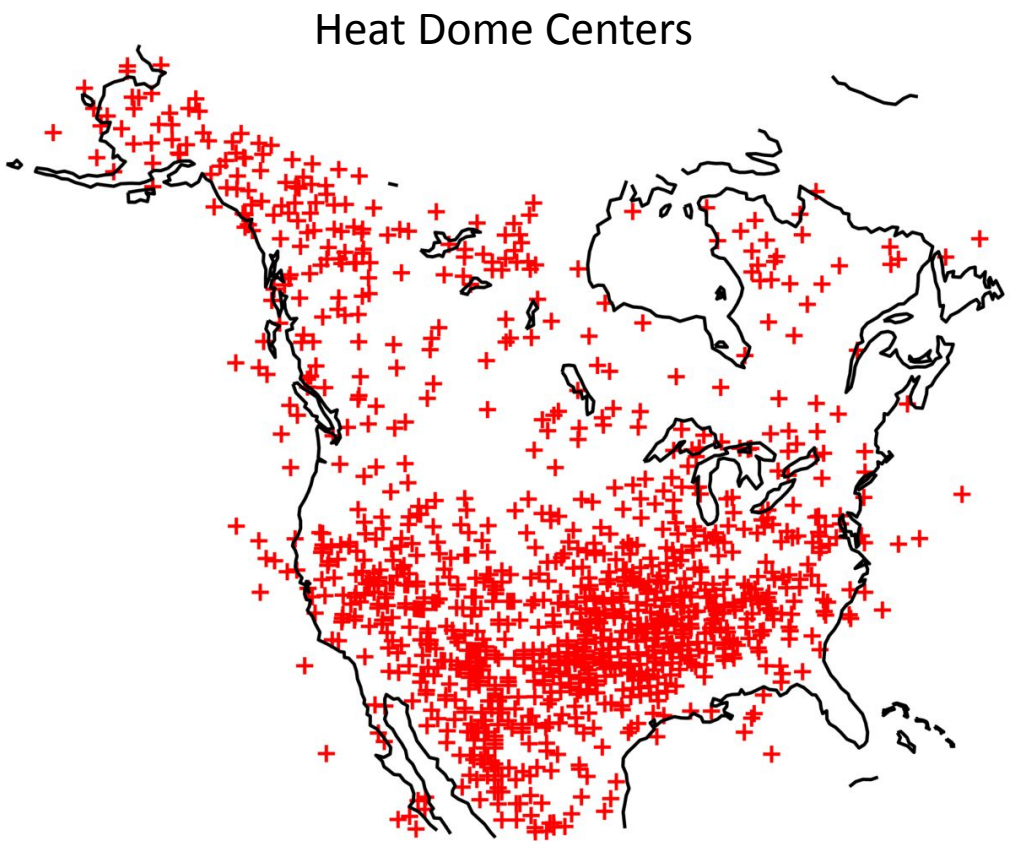
Non Heat Dome Example

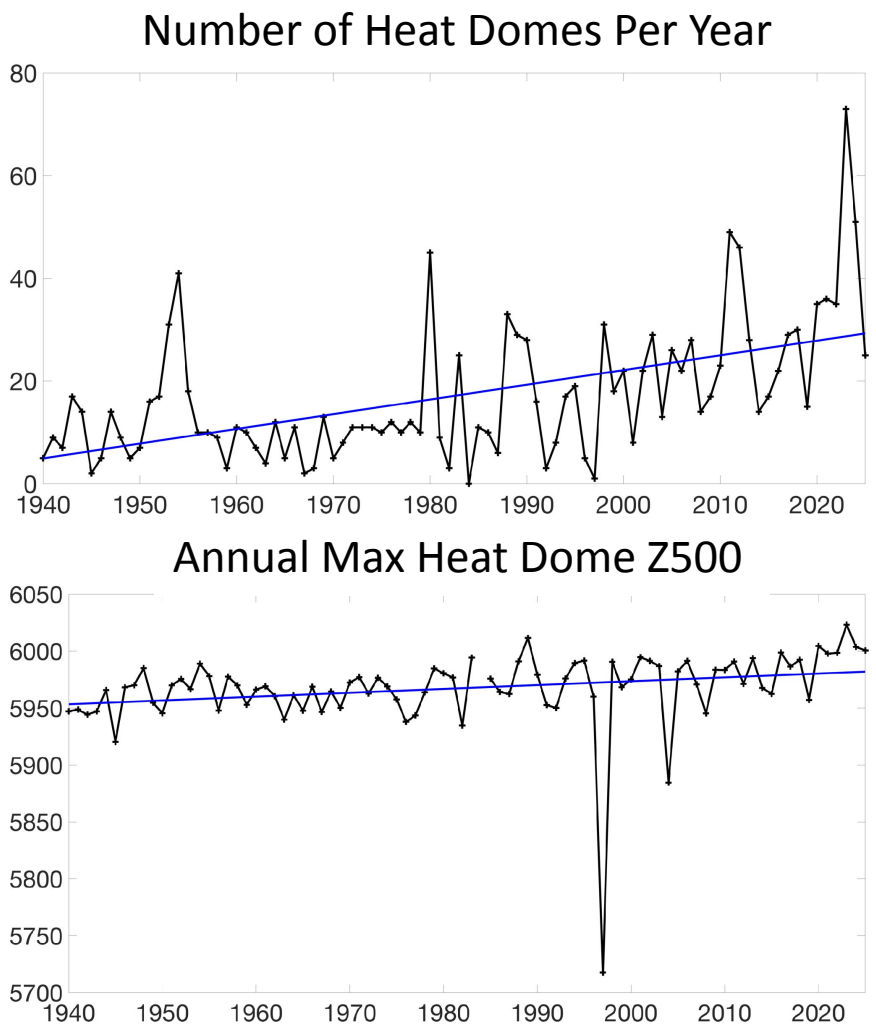
28 June 2014



- Extreme heat object not connected to a closed anticyclone
- Extreme heat object is collocated with largely zonal flow at 500 hPa.
- Meteorological processes not captured by Z500 are likely important.
- Not part of a multi-day event that included a heat dome.

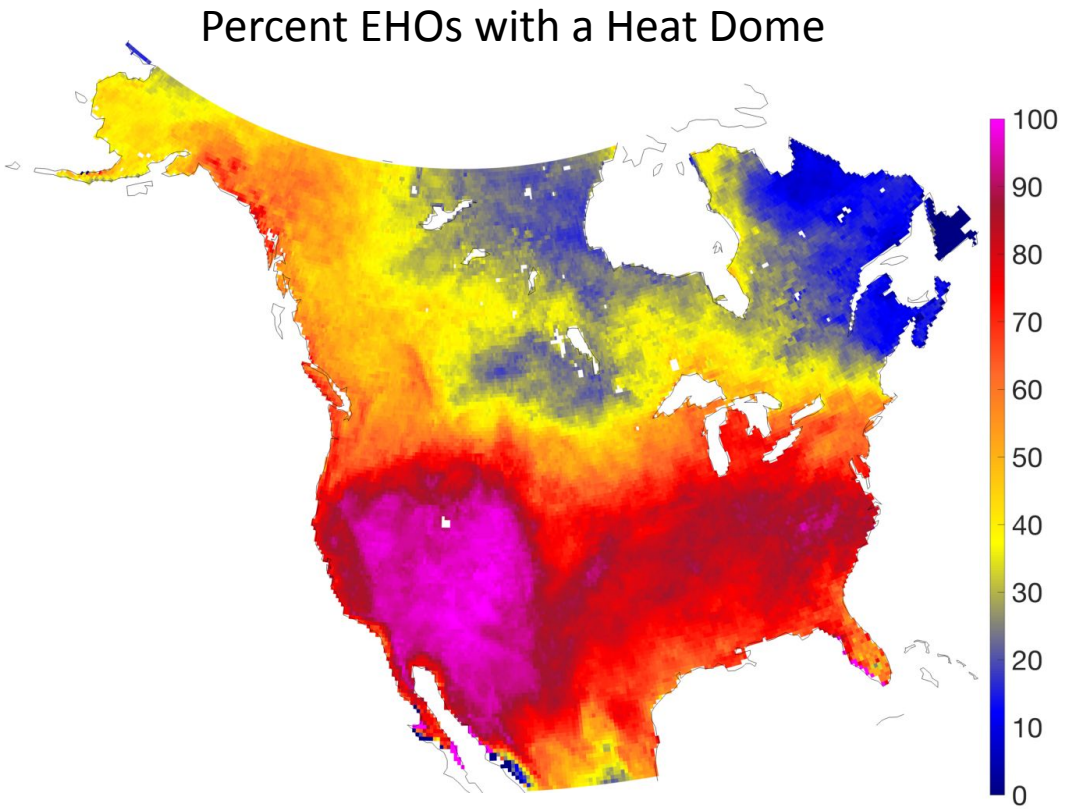
Heat Dome Climatology

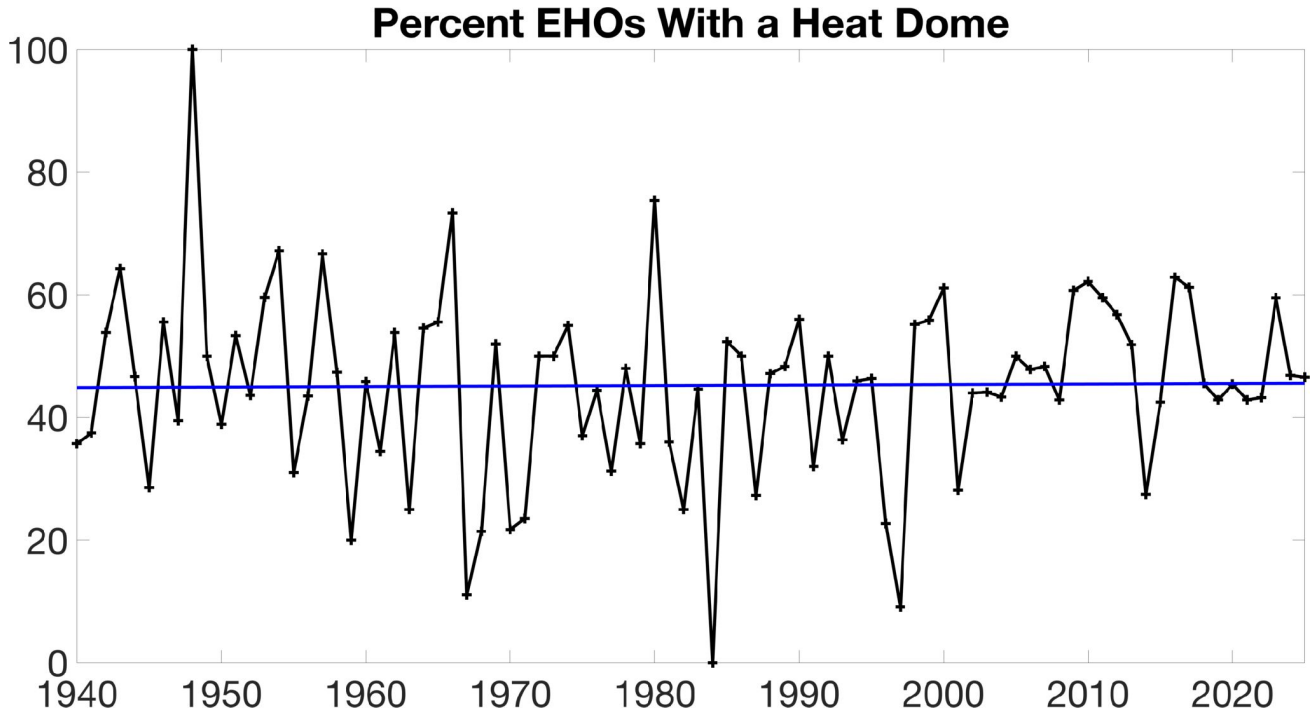




- 1473 heat domes identified between 1940 and 2025.
- Using a fixed temperature threshold to identify extreme heat objects results in an increasing trend.
- The highest annual heat dome center Z500 has been increasing (not statistically significant).

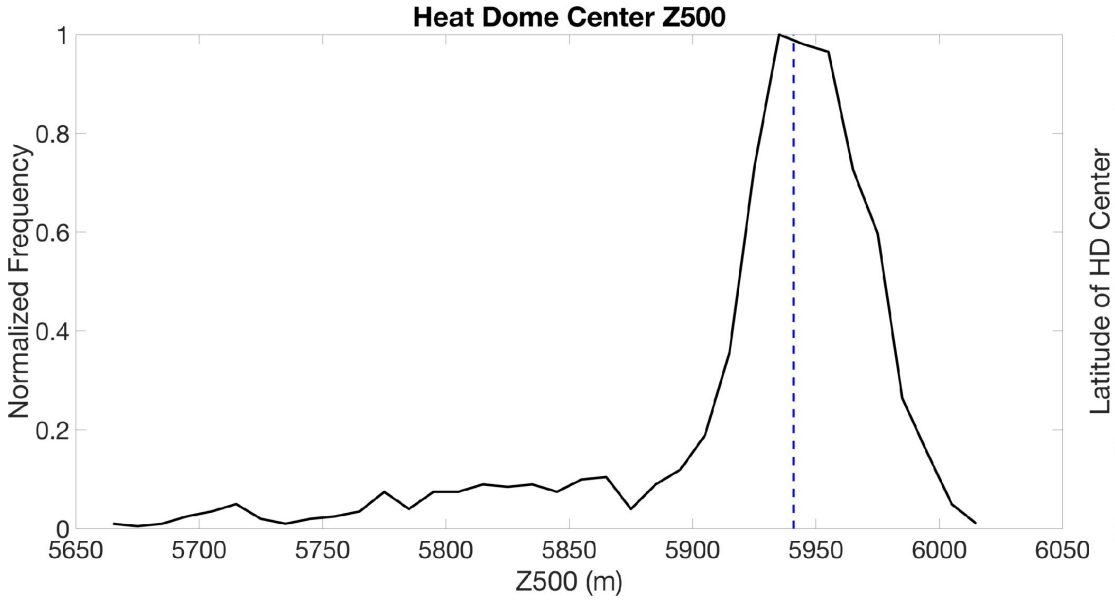
Prevalence of Heat Domes

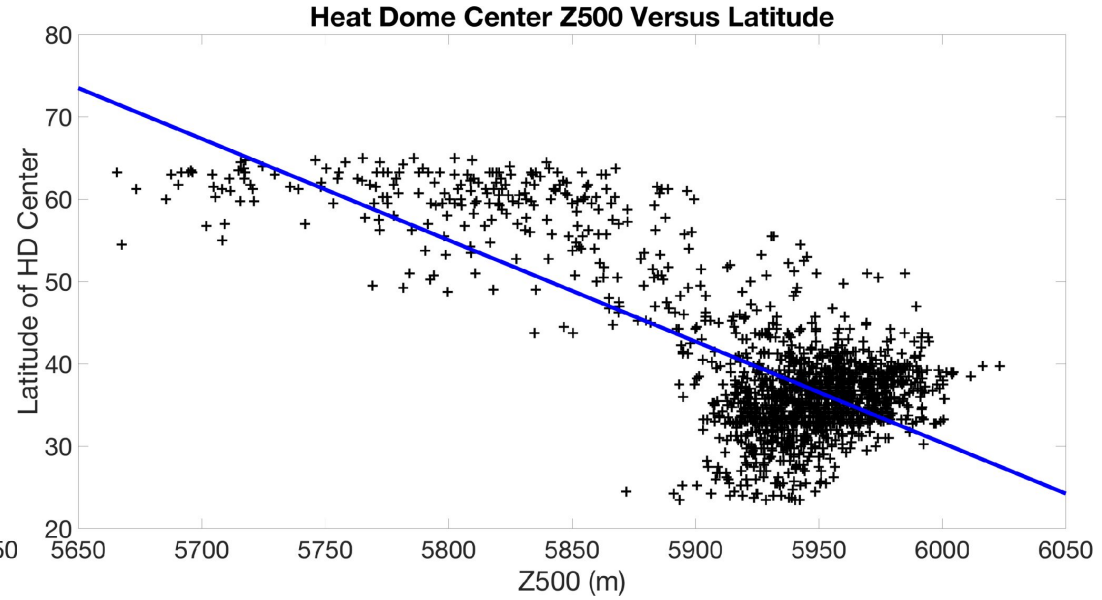


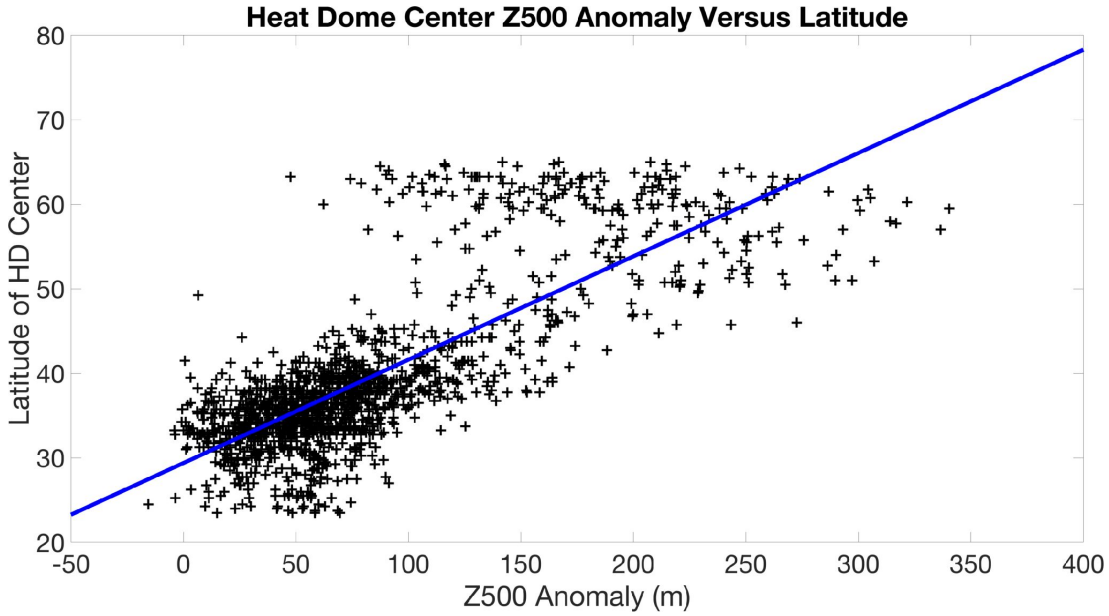


- Nearly all extreme heat objects are associated with heat domes across the southwestern US and northwester Mexico.
- The proportion of all extreme heat objects associated with heat domes has not changed since 1940.
- Results suggest increase in heat domes is due to thermodynamic change (warming) not changes in extreme heat dynamics.

Heat Dome Climatology

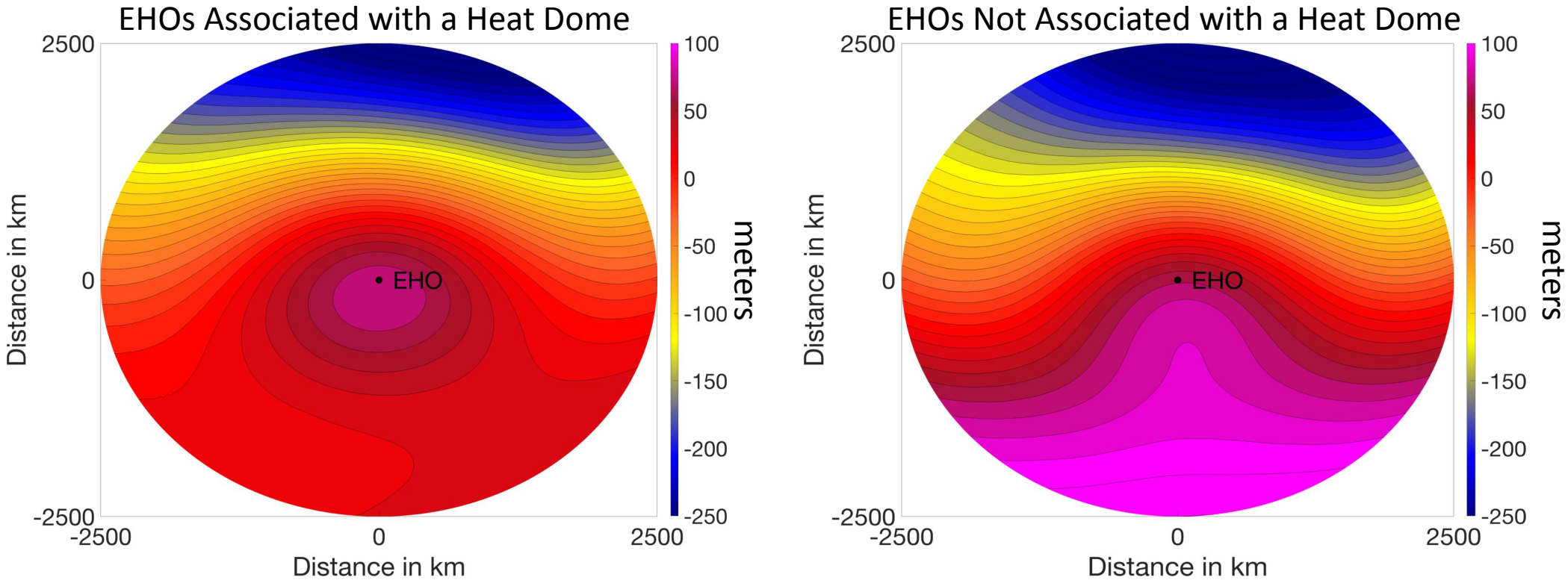






- Most heat dome centers have a Z500 value of around 5950 meters.
- Lower values are from higher latitudes where heat domes are less common.
- High latitude heat domes have lower geopotential height but are more anomalous relative to local climatology.

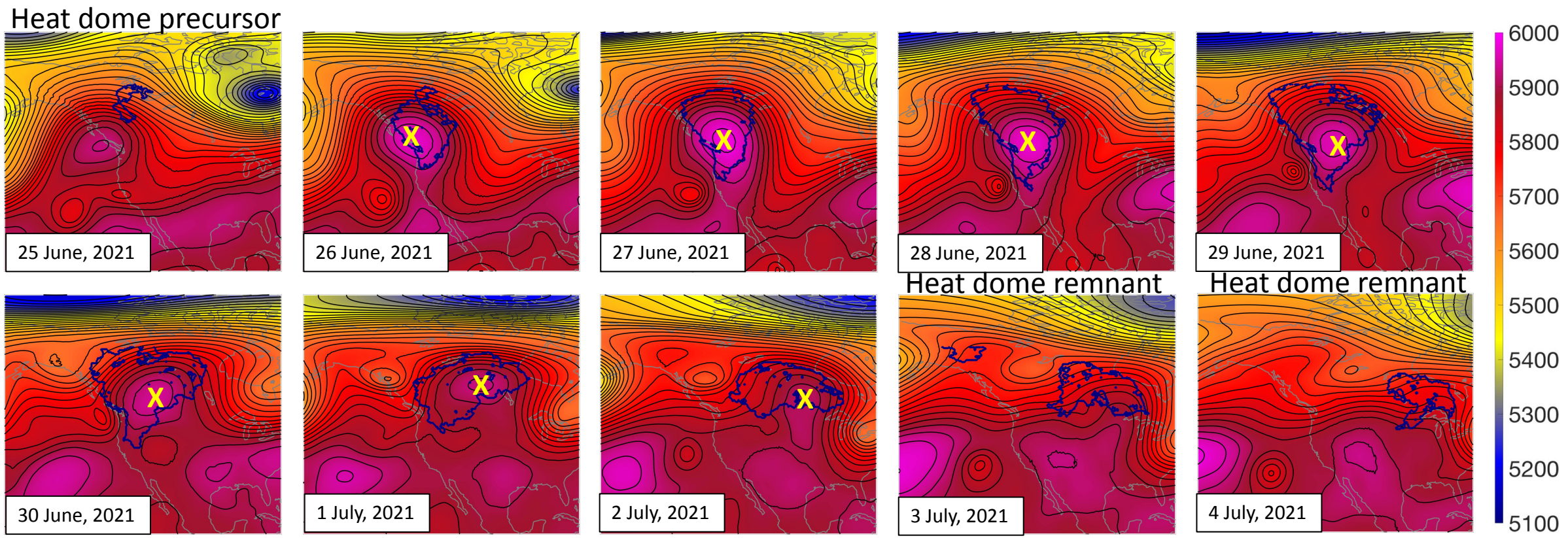
EHO Circulation Patterns



- EHOs associated with a heat dome are centered just to the north of anticyclone center, on average.
- EHOs not associated with a heat dome are on the northern periphery of an open Z500 ridge, on average.
- There are distinctly different upper-level circulation patterns associated with similarly extreme heat episodes.

*Values are Z500 (meters) with spatial mean removed from each contributing daily radial plot to highlight gradient and curvature.

Heat Dome Remnants and Precursors



- 26% of EHOs not associated with a heat dome are heat dome remnants.
- 21% of EHOs not associated with a heat dome are heat dome precursors.
- 69% of EHOs are associated with a heat dome directly, as a precursor, or as a remnant.

Concluding Remarks

- By combining atmospheric circulation and extremely high surface temperatures, heat domes carry societal and meteorological significance.

- Heat domes are a special class of meteorological drivers of extreme heat
  - Heat domes are directly associated with nearly half of all daily extreme heat events (as defined here).
  - Extreme heat events of similar magnitude often occur with non-heat dome circulation features.

- 69% of daily extreme heat events (as defined here) are connected to a heat dome in the past or future

- Use of heat dome in reference to any very extreme heat event is inaccurate making a more robust definition useful for communicating heat risk in a meteorologically sound way.

- Defining a heat dome requires some subjectivity and other variations on this definition may also be appropriate.

Special Thanks:

Siiri Bigalke (PSU)
Dmitri Kalashnikov (UC Merced)
Amanda Laverty (WSU)
Deepti Singh (WSU)
Graham Taylor (Cornell U)

The entire PSU Climate Science Lab

Thank you!

Support by NSF AGS-2206997