GEFSv12 Ensemble Predictions of Heat Waves over CONUS associated with Persistent Highs in 2021–2022

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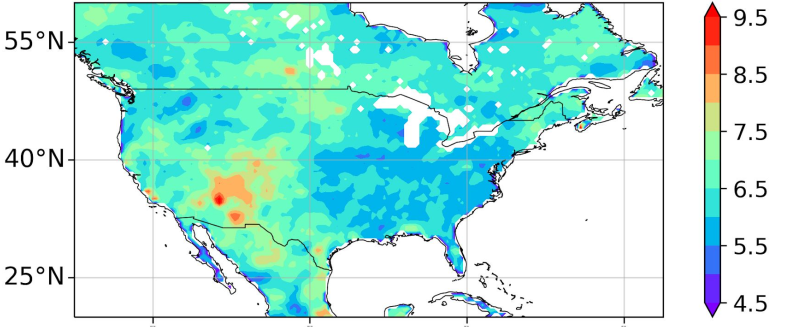
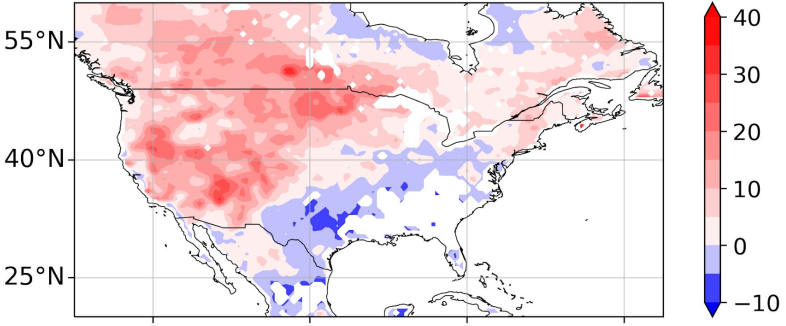
Motivation: abnormally more heat waves in 2021 and 2002

(a) Averaged HW Days (1989-2022)



(b) 2021 anomaly



(c) 2022 anomaly

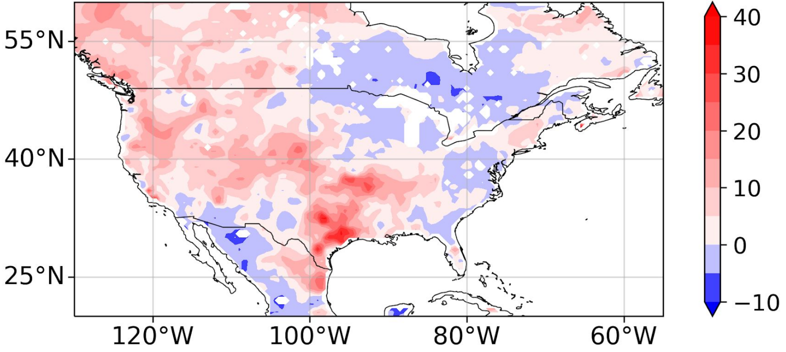


Fig. 1. Heat-wave days in JJAS seasons averaged during 1989 – 2022 (top), anomalies in 2021 (middle), and anomalies in 2022 (bottom).

3-4 times more heat wave days occurred in the Northwestern Canada-USA (extratropical) in 2021 and 2022.

How were these heat waves predicted in the 35-day 30-member ensemble forecasts of GEFSv12?

Outline

I. Motivation: Heat waves in the extratropical western USA, either stalled or fast propagating, are majorly controlled by persistent highs (as will be shown by five heat waves and persistent highs at Z500 in 2021 − 2022 and historical statistics).

II. Methodology:

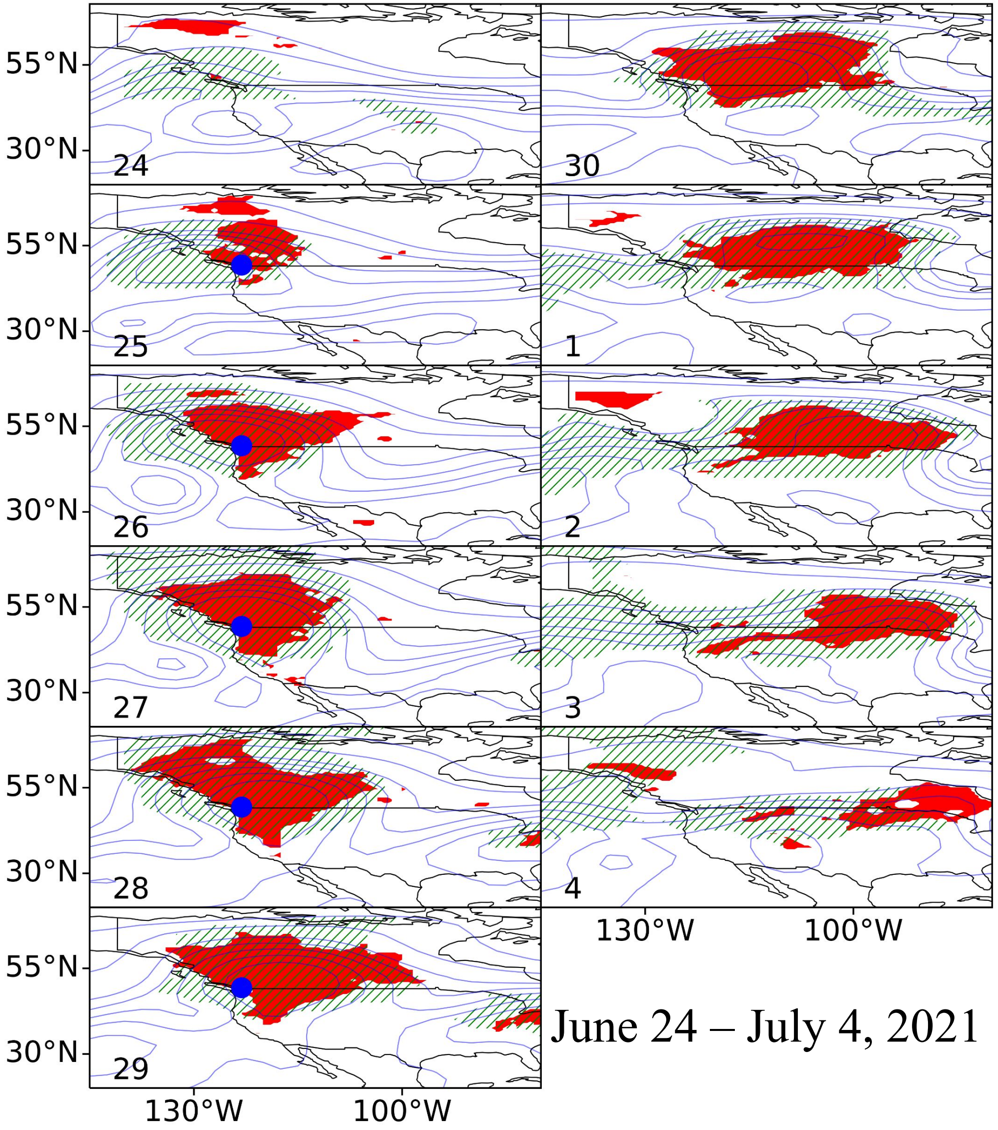
Comparison of a few definitions of heat waves

Verification metrics: verification of GEFSv12 ensemble forecasts for these five heat wave events in terms of the Hit Rate (H), False Alarm Rate (F), and Symmetric Extremal Dependence Index (SEDI) for deterministic forecasts, and Brier skill score (BSS) for probabilistic forecasts

III. Results

IV. Summary

I. Motivation: five heat waves in 2021 and 2022



June 24 – July 4, 2021

Fig. 2. A stalled heat-wave event (red) occurred over the western Canada-USA during June 24 – July 4, 2021, which was controlled by a typical blocking episode with green patches as blocking-high areas at Z500 (contours; detected with the Eddy-ABS approach in Liu 2020, Climate Dyn.).

This event impacted large areas in the western Canada-USA for a prolonged period of time, for example, five days from June 25 to 29 over Vancouver, Canada (blue dot). This site and event will be selected for verification.

I. Motivation: five heat waves in 2021 and 2022

June 8 – 23, 2022

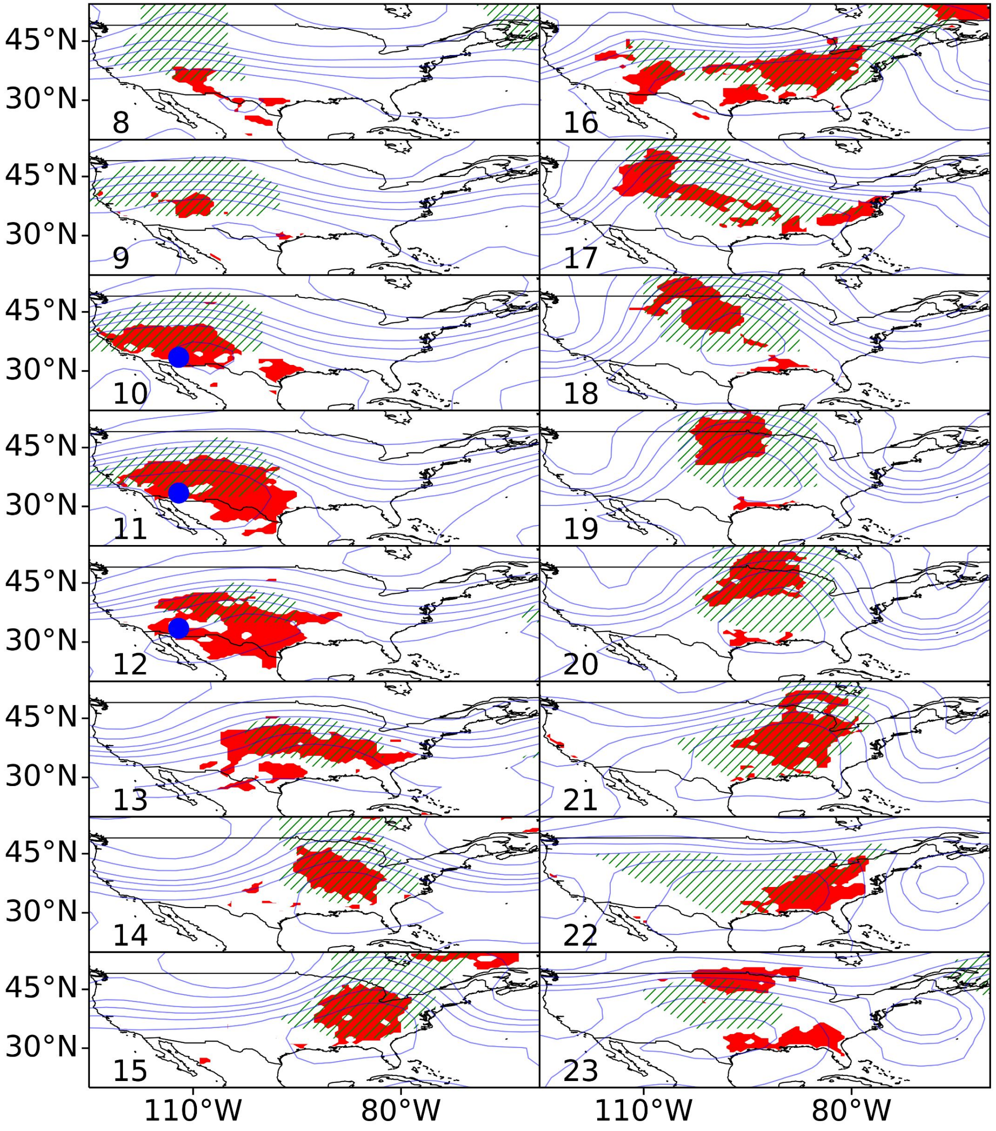


Fig. 3. Two consecutive propagating heat-wave events (red) occurred over CONUS during June 8 – 23, 2022, which were controlled by two persistent high-pressure systems (both open ridges and typical blocking patterns at Z500).

The events passed Sacramento on June 10 and Phoenix (blue dots) during June 10 – 12. These two sites will also be selected for verification to represent the western and southwestern USA.

I. Motivation: five heat waves in 2021 and 2022

July 25 – August 1, 2022

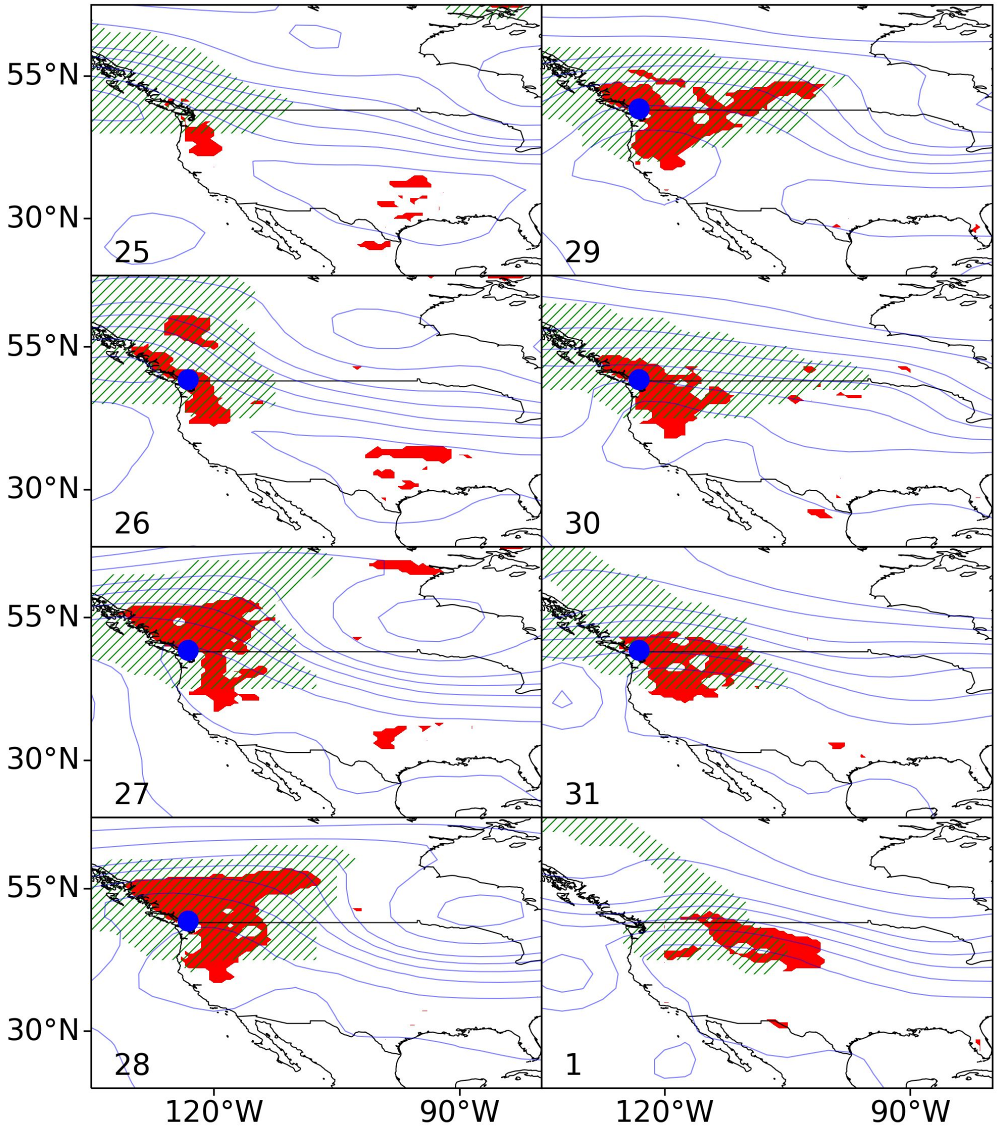


Fig. 4. The fourth event was stalled in the western Canada-USA during July 25 – August 1, 2022, which was controlled by mostly persistent open ridges at Z500.

The event impacted Vancouver during July 26 − 30 and will be selected for verification as well.

I. Motivation: five heat waves in 2021 and 2022

August 30 – September 9, 2022

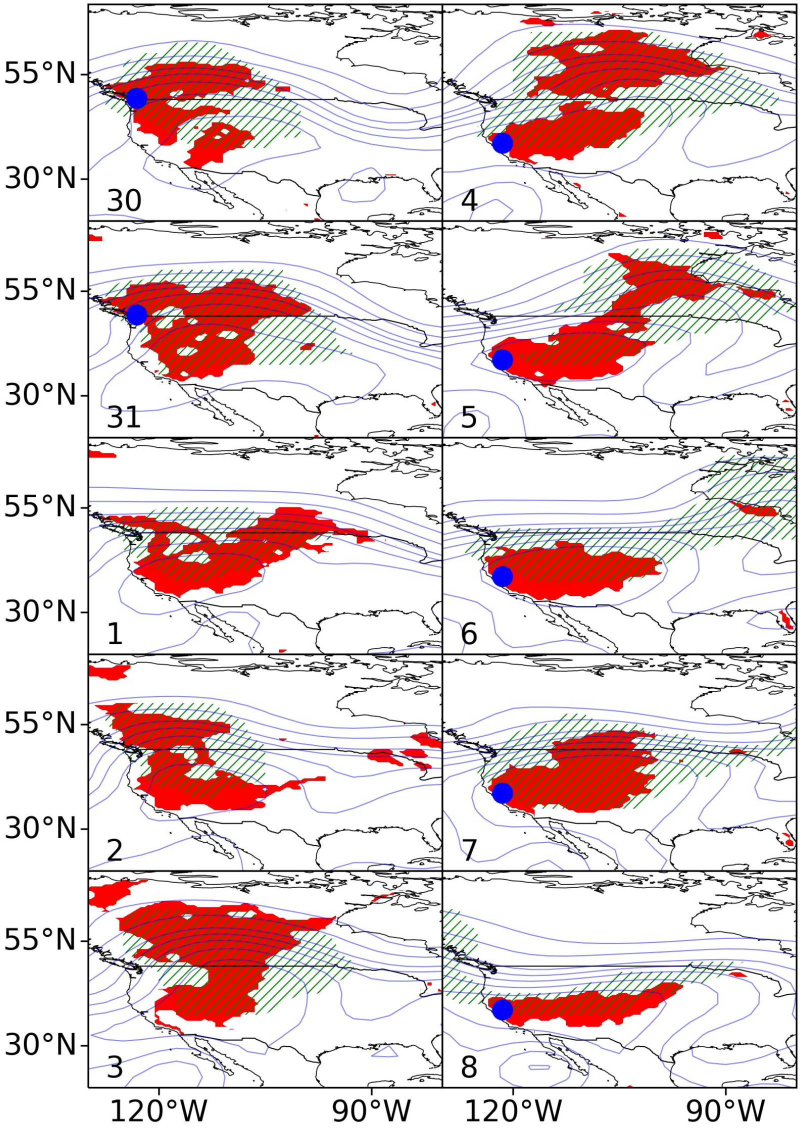


Fig. 5. The fifth event was stalled in the western USA during August 30 – September 9, 2022, which was the longest and controlled by persistent high-pressure systems at Z500.

Specifically, the event impacted Sacramento during September 4 – 9 and Vancouver during August 30 and 31.

I. Motivation: persistent-high pressure systems dictates extratropical heat waves

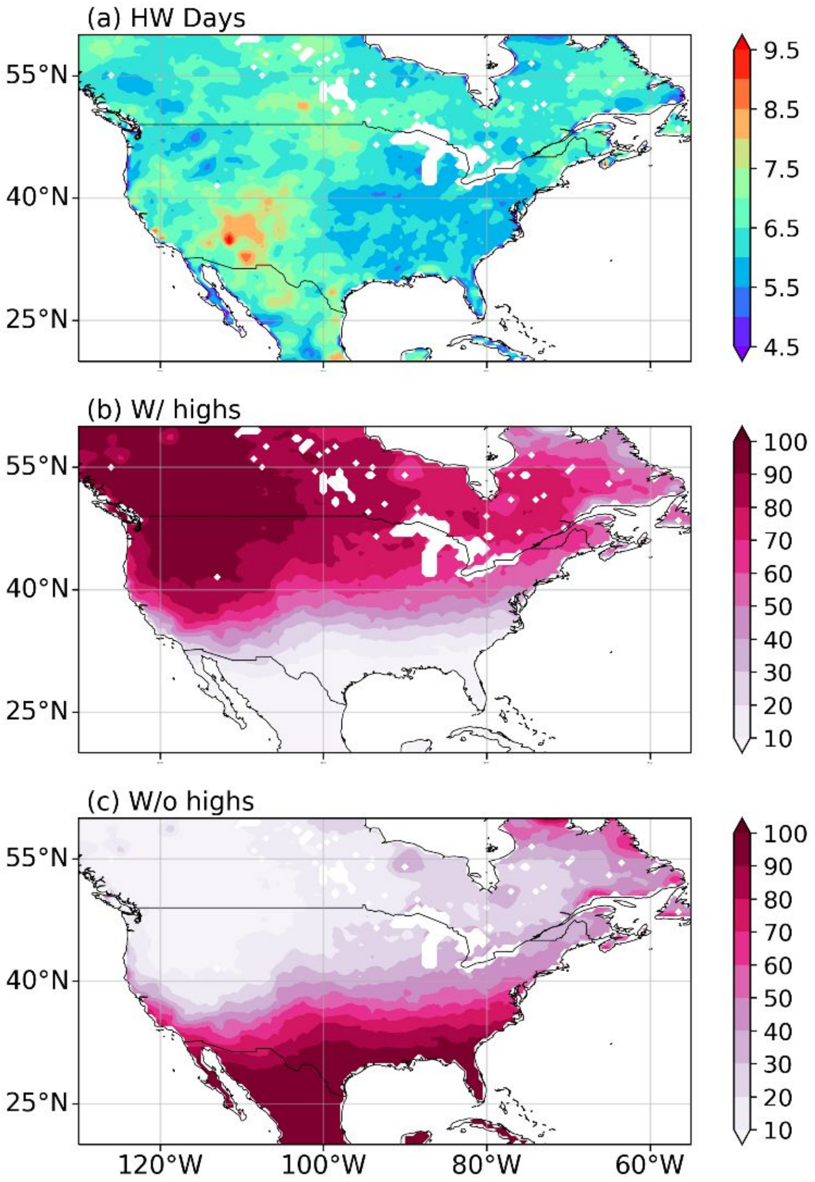


Fig. 6. Averaged heat wave days (top), percentage associated with extratropical highs (middle), and not associated with extratropical highs (bottom) in JJAS seasons during 1979 – 2022.

Clearly heat waves in the extratropical western USA are mostly controlled by high-pressure systems.

II. Methodology: comparison of heat wave definitions (Threshold, persistence and spatial extent)

Reference	HW Events	HW definition	Ensemble	Verification
Domeisen et al. 2022 BAMS	Western US, 23–29 Jul 2018 SE US, 24–30 May 2019	T2m anomalies, 90th percentile, ERA5; lead-time dependent clim.	Initialized twice weekly, 51 member; 11-member hindcast	Weeks 2–4; compare PDFs of the ENS for lead weeks
Kueh and Lin 2020 Sci Rep	2018 N. Europe	T2m anomaly, T2m-90th, EHF	Multi-model ensemble, 295 members	Bivariate and spatial correlation, MLR
Ford et al. 2018 NPJ CAS	NCEP CFSv2 over CONUS	Extreme heat factor (EHF), 90th percentile, 3-day sliding	4 members	Poisson weighted AUC, reliability, Equitable threat score (ETS)

Table 1. Several recent heat wave definitions for operational verifications

II. Methodology: comparison of heat wave definitions
(Threshold, persistence and spatial extent)

Authors	Variable	Thresholds	Duration	Spatial ext.
Karl and Knight (1997)	T_{ap}	≥75th, ≥ MAX	≥ 2 d	
Frich et al. (2002)	T_{max}	≥ 5°C above 1961–1990 climatology	≥ 5 d	
Meehl and Tebaldi (2004)	T_{min}	≥ 20°C or ≥ 16°C in the northern US	≥ 3 d	
	T_{max}	3-day and average ≥ 97.5th, all ≥ 81th	≥ 3 d	
Della-Marta et al. (2007)	T_{max}	≥ 95th	≥ 2 d	
Gershunov et al. (2009)	T_{max}, T_{min}	≥ 99th in 1950–1999	1, 2, 3d	
Anderson and Bell (2011)	T_{2m}	≥ 95th	≥ 2 d	
Lau and Nath (2012)	T_{max}	3-day and average ≥ 97.5th, all ≥ 81th	≥ 3 d	REOF region
Bumbaco et al. (2013)	T_{max}, T_{min}	≥ 99th	≥ 3 d	
Peterson et al. (2013)	T_{2m}	Highest 4-day-period-mean values	≥ 2 d	
Teng et al. (2013)	T_{2m}	≥ 97.5th	≥ 5 d	5% CONUS
Kamae et al. (2014)	T_{2m}	Monthly ≥ 2STD, 3STD	monthly	
Schoetter et al. (2015)	T_{max}	≥ 98th	≥ 3 d	30% W. EU
Jia et al. (2016)	T_{2m}	JJA anomalies		
Lee et al. (2016)	T_{2m}	≥ 90°F (33.2°C)	≥ 3d	
Shiva (2020)	T_{max}, T_{min}	≥ 90th	≥ 2d	
Thomas et al. (2020)	T_{max}, T_{min}	≥ 90th	≥ 3d	
Agel et al. (2021)	T_{max}	≥ 95th	≥ 3d	
Benson (2021)	T_{2m}	Anomaly ≥ 95th	1d	
Romps and Lu (2022)	T_{2m}, RH	Maximum heat index ≥ 99.9th	1d	
National Weather Service	T_{ap} (V_{10m})	> 80°F, 90°F, 105°F, 130°F	1d	
Hondula et al. (2022)	T_{ap}, T_{max}	> 50th, 90th, 95th, 99th	1d	
Rousi et al. (2022)	T_{max}	≥ 90th	≥ 3d, 6d	40,000km^2
Jia et al. (2022)	T_{max}	≥ 90th	1d	

Table 2. Many recent heat wave definitions for research

II. Methodology: heat-wave indices comparison

Tmax (global daily observations at $0.5^{\circ}\times0.5^{\circ}$ from CPC)

- a. percentile: 90th or 95th in centered 15-day windows of 1980 – 2021
- b. threshold: exceedance of 1 day for 95th, and 3, 6 days for 90th
  (3 and 6 days of exceedance of 90th were used in Rousi et al. 2022;
  Nature Communication; https://www.nature.com/articles/s41467-022-31432-y)

A comparison of these definitions for US heat waves 5 – 27 June 2022 and 1979 – 2022

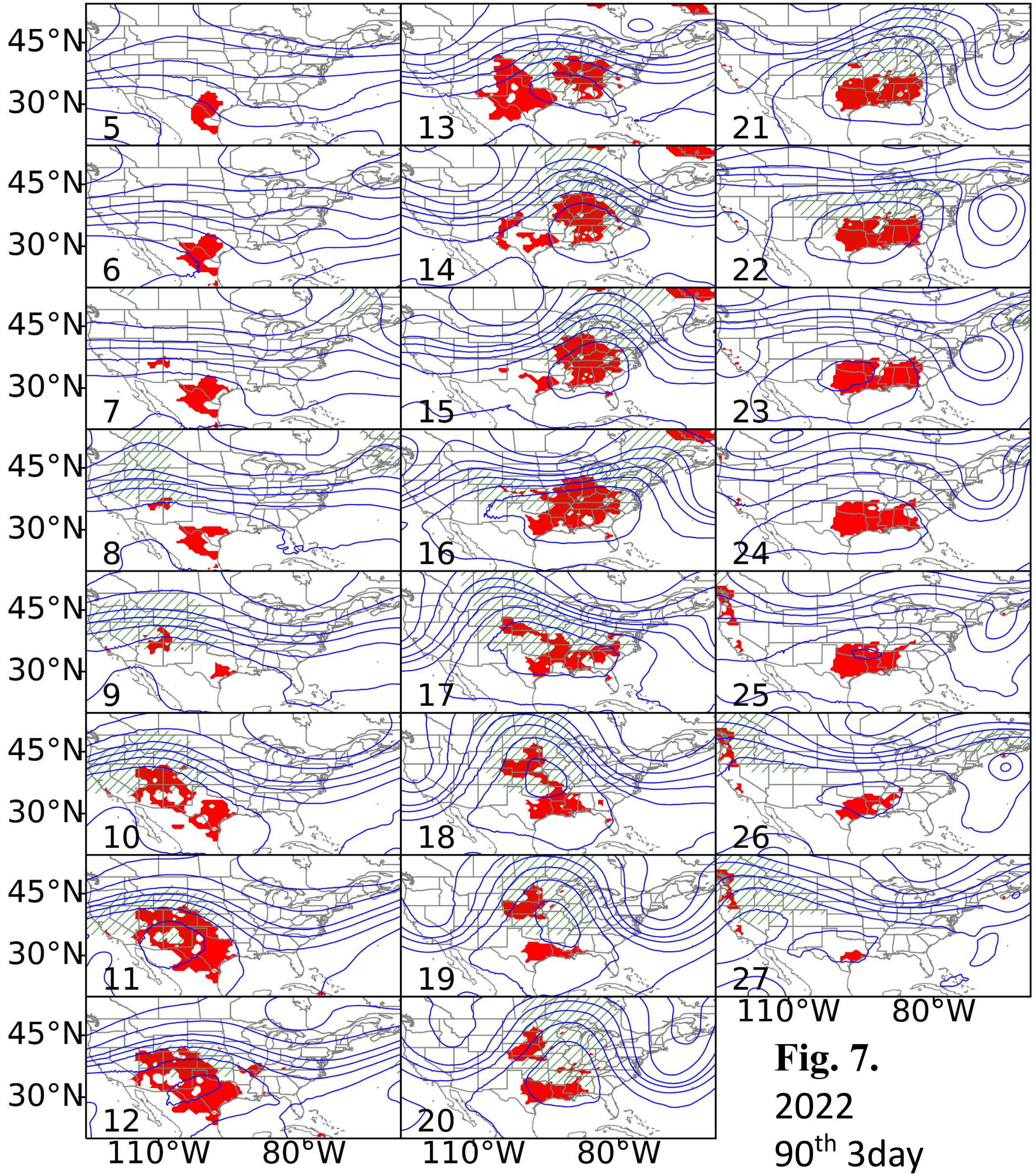
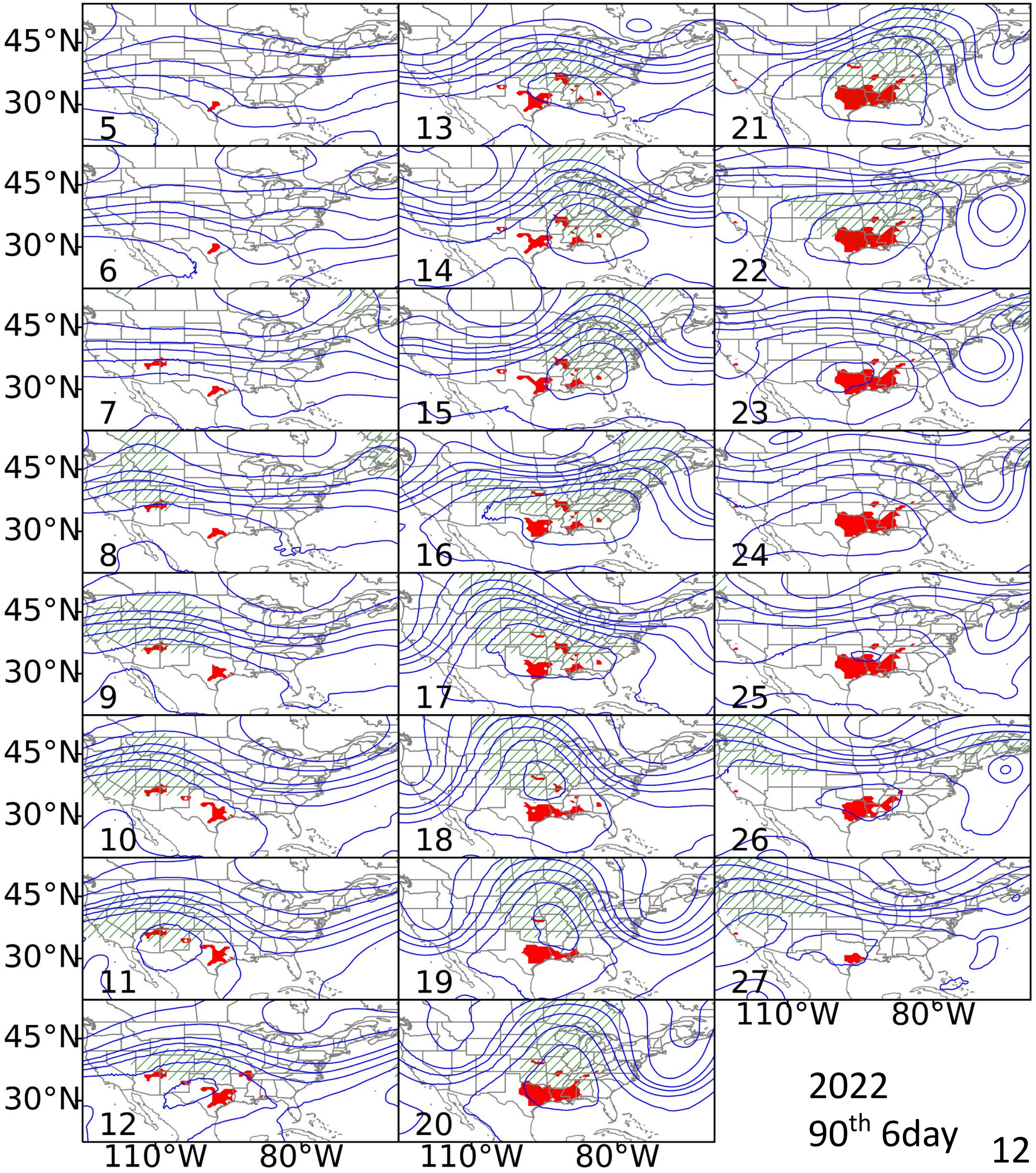


Fig. 7.

2022

90th 3day



2022

90th 6day

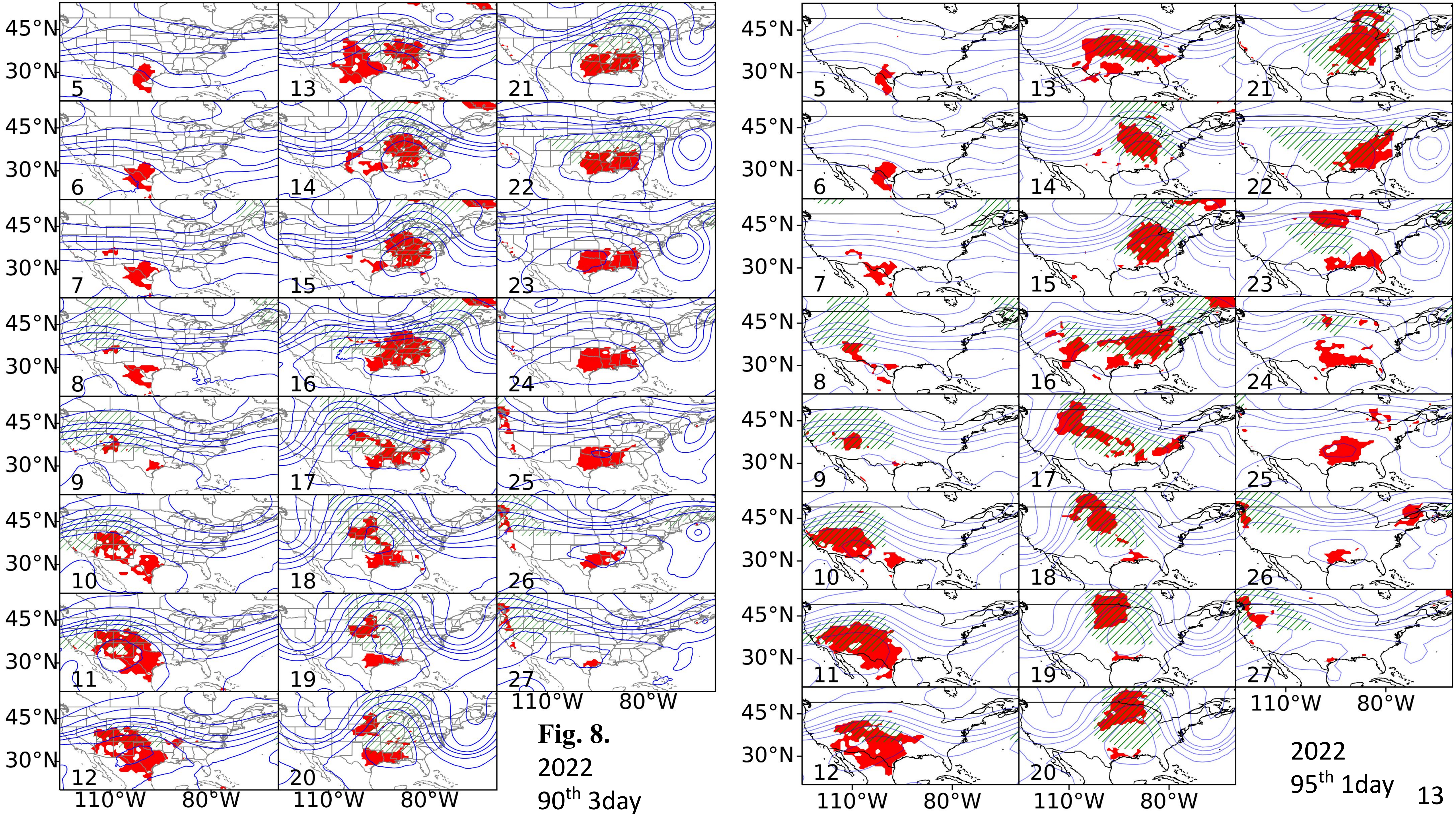


Fig. 8.

2022
90th 3day

2022
95th 1day

II. Methodology: heat-wave definition used in this study

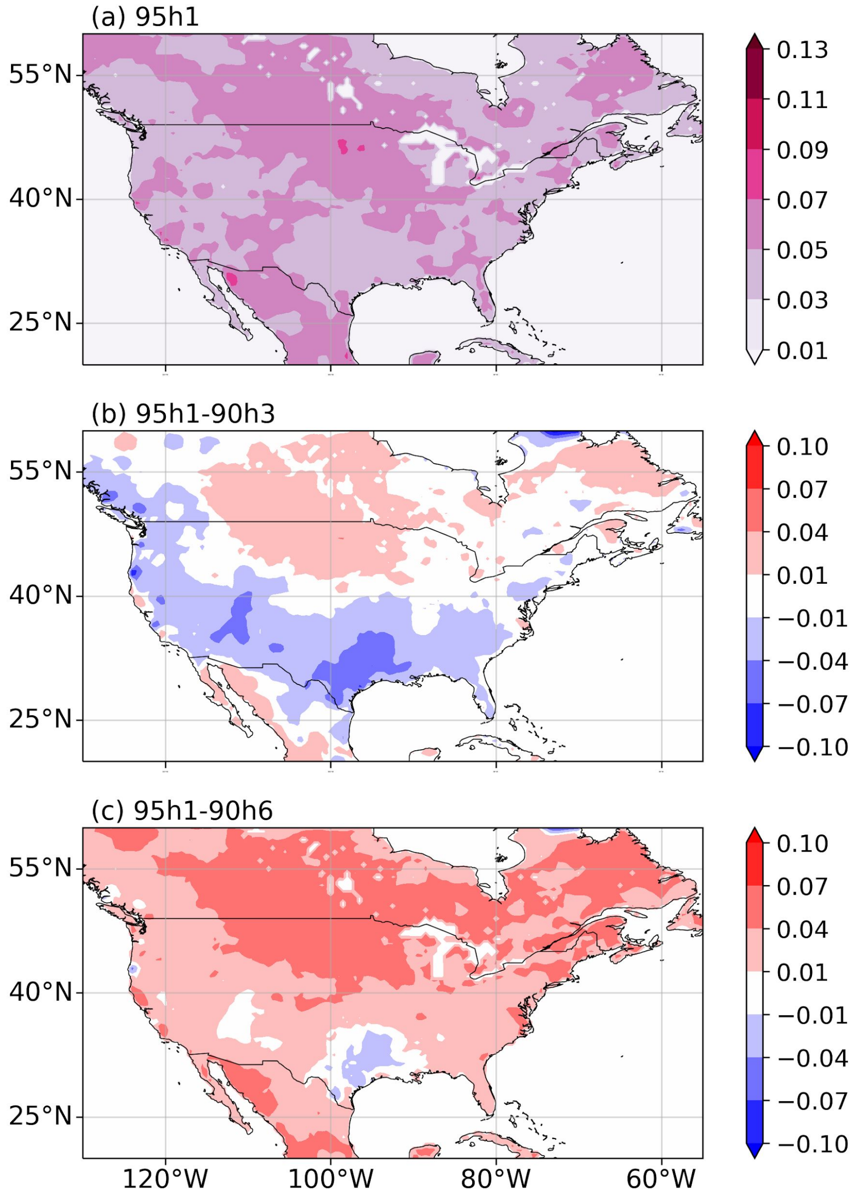


Fig. 9. (a) Heat wave frequency (base rate) during JJAS averaged in 1979 − 2022 and defined by Tmax exceeding the 95th percentile; (b) the difference between (a) and that defined by Tmax exceeding the 90th percentile for at least 3 days; (c) same as (b) but for at least 6 days.

Clearly the single threshold of the 95th percentile identifies heatwave frequencies between 3-day and 6-day persistence.

II. Methodology: heat-wave definition used in this study

Tmax (CPC)
  a. percentile: 95th, centered 15-day windows in 1989 – 2019
  b. threshold: exceedance of 1 day

We chose Tmax from CPC observations during 1989 –2019, not from GEFSv12 reforecasts during the same time, because of some differences between the two, as demonstrated in Figs. 10 and 11 below. Meanwhile, these years cover the GEFSv12 reforecasts and recent warming trend in instrumental observations.

Despite the differences, the results are nearly identical when the 95th percentile of Tmax from GEFSv12 reforecasts is used. We will show this in the Brier Skill Score (BSS) near the end.

II. Methodology: heat-wave definition used in this study

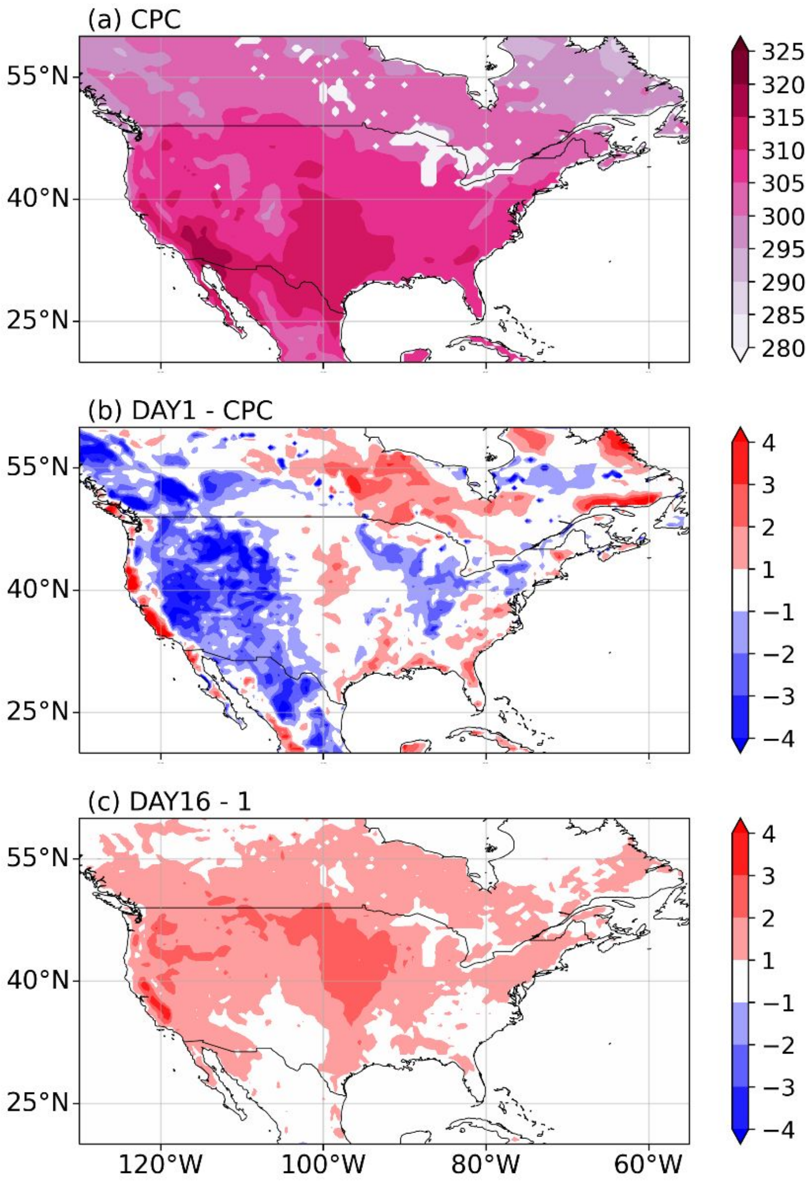


Fig. 10. The 95th percentiles of Tmax (K) averaged in the JJAS season from 1989 to 2019 for CPC (a), the difference between day-1 reforecasts and CPC (b), and the difference between day-16 and day-1 reforecasts (c). Reforecasts up to 16 days of lead time were derived from the GEFSv12 control run during the same time period.

Tmax on Day-1 is lower by 2-3K in the western USA except for the coastal area in California with 3K higher. The cooler Tmax is reduced by 1-2K while even higher in the coastal California on Day-16, indicating the model has a warmer tendency with lead time.

The warmer bias at medium-extended ranges also occurred over central USA in the GFSv16 (Geoffrey Manikin et al.)

II. Methodology: heat-wave definition Adopted in this study

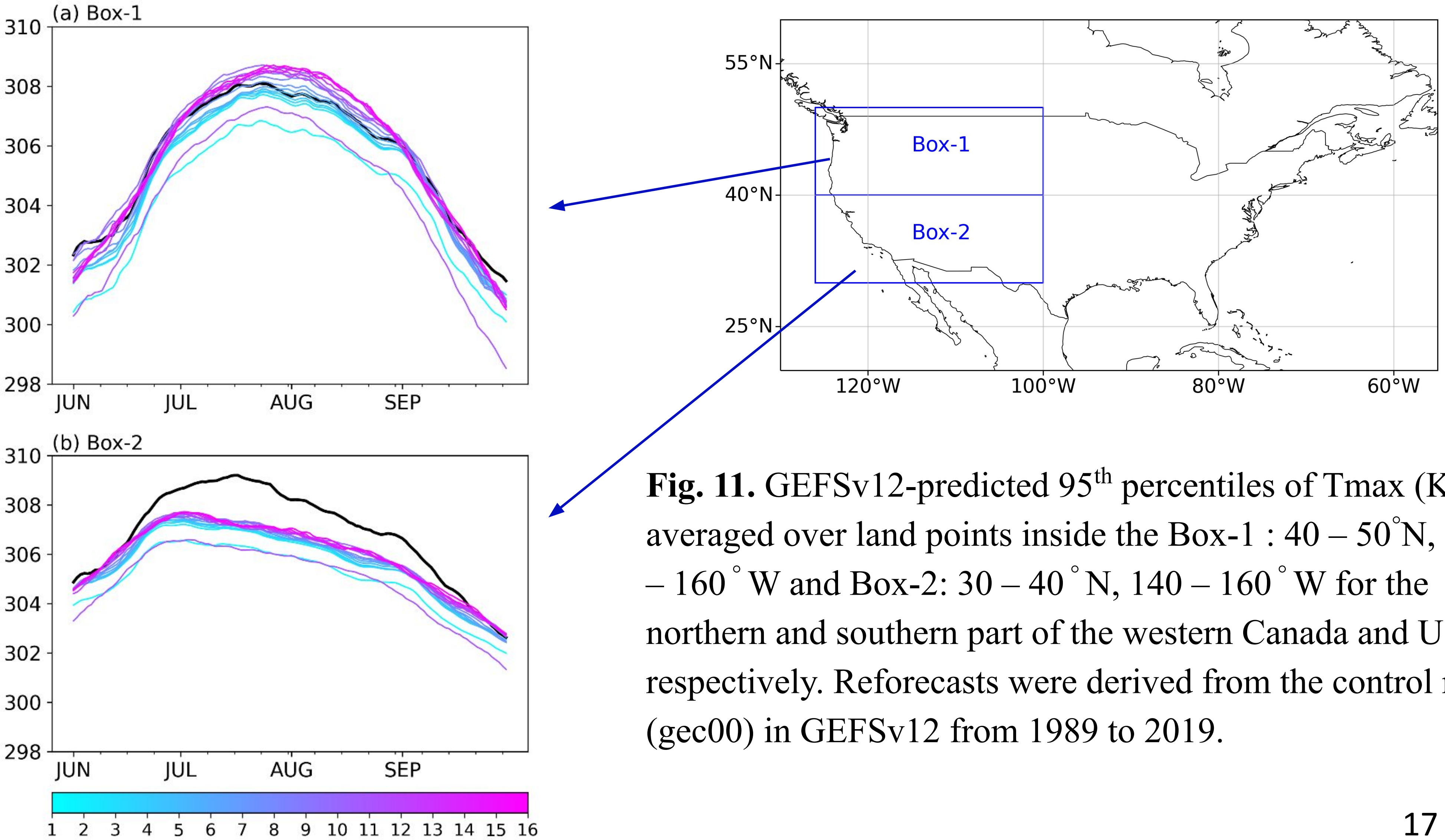


Fig. 11. GEFSv12-predicted 95th percentiles of Tmax (K) averaged over land points inside the Box-1 : 40 – 50°N, 140 – 160 ° W and Box-2: 30 – 40 ° N, 140 – 160 ° W for the northern and southern part of the western Canada and USA, respectively. Reforecasts were derived from the control run (gec00) in GEFSv12 from 1989 to 2019.

II. Methodology: verification metrics

1. Hit rate (H)

H = a/(a+c), where a and c are hits and misses in the contingency table, respectively. For ensemble forecasts, a hit means more than half of the members predicted a heat wave correctly.

2. False alarm rate (F)

F = b/(b+d), where b and d are false alarms and correct rejections (negatives) in the contingency table, respectively.

3. Brier skill score (BSS) – probabilistic and > 0 meaning more skillful

$BSS = 1 - BS / BSref$, and $BS = \frac{1}{N}\sum_{i}^{N}(p_i - o_i)^2$

where N is total forecasts, p_i and o_i are each forecast probability and observation, respectively. BS is the Brier score for the five heat events, and BSref is the Brier score for forecasts of all heat waves during the summers of 2021 and 2022.

II. Methodology: verification metrics

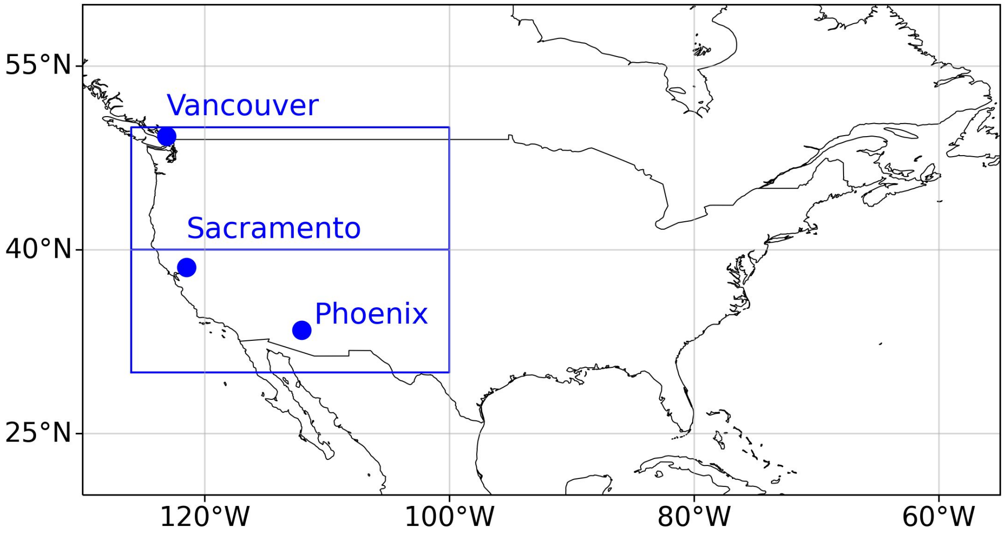
4. The Symmetric Extremal Dependence index (SEDI) > 0 means skill
(Ferro and Stephenson 2011; Weather and Forecasting)

$$\mathrm{SEDI} = \frac{\log F - \log H - \log(1 - F) + \log(1 - H)}{\log F + \log H + \log(1 - F) + \log(1 - H)}$$

where H and F are the hit rate and false alarm rate, respectively. The SEDI is "nondegenerating, base-rate independent, asymptotically equitable, harder to hedge, and have regular isopleths that correspond to symmetric and asymmetric relative operating characteristic curves."

The SEDI is deterministic in the gec00 forecast (a single integration similar to the one made by the GFS), and it is probabilistic in the 30-member forecasts where a hit means more than half of the members predict a heat wave correctly. The number of hits is reduced to 30% or about 10 members for a sensitivity test.

III. Results: verification of heat wave events in GEFSv12 predictions



Cities	Latitude	Longitude	Number of heat waves by duration (days)						
			1	2	3	4	5	6	7
Vancouver	49.2827° N	123.1207° W	66	33	17	5	2		
Sacramento	38.5816° N	121.4944° W	59	36	16	3	1	4	
Phoenix	33.4484° N	112.0740° W	62	26	16	10		1	3

Table 3. Number of heat waves days during JJAS in 1989 – 2022 over the three sites. Observational and forecast data were selected nearest to their longitudes and latitudes.

III. Results: verification of heat wave events in GEFSv12 prediction

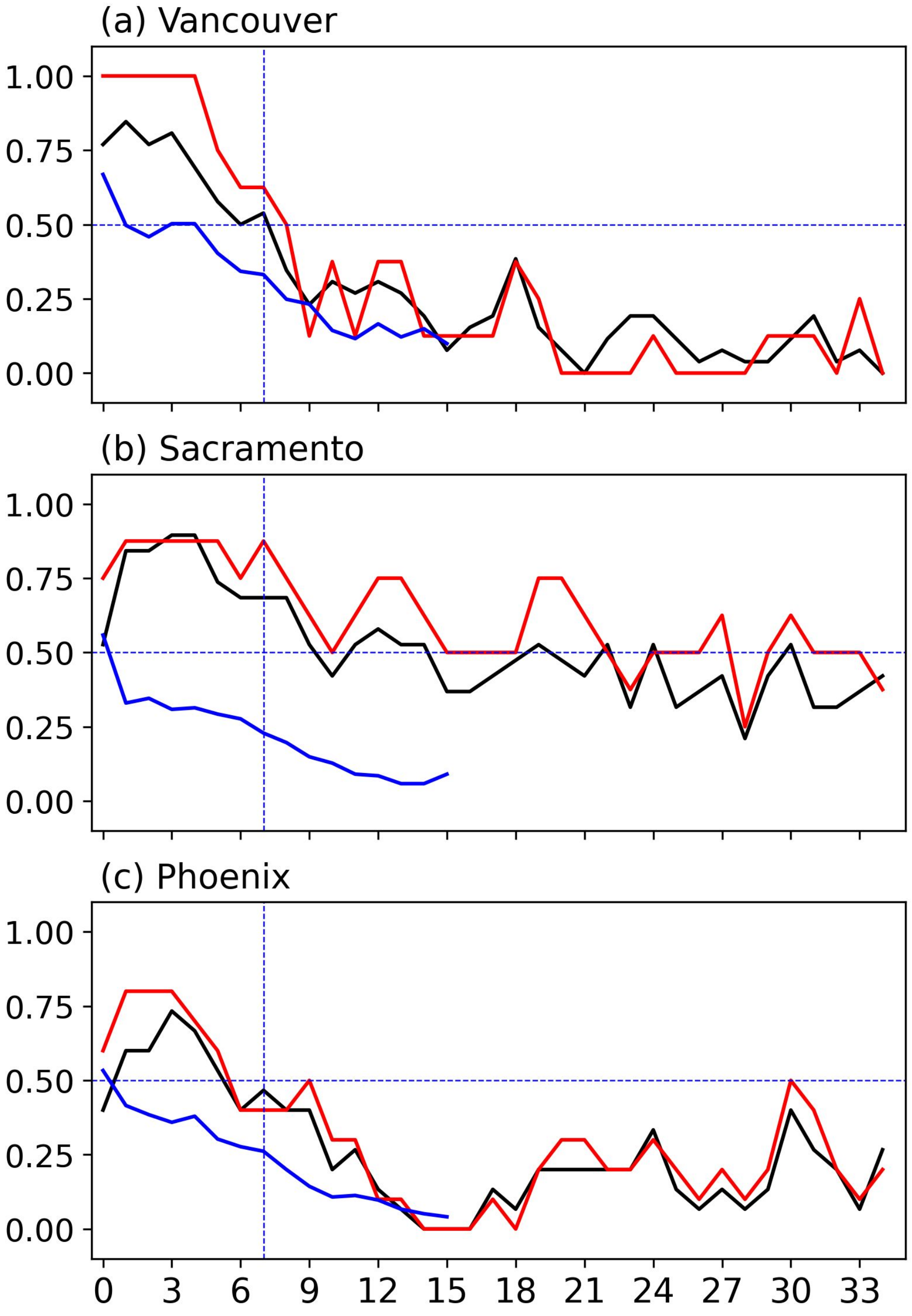
Vancouver
2021-06-01 2021-06-02 2
2021-06-21 2021-06-21 1
2021-06-25 2021-06-29 5
2021-07-30 2021-07-30 1
2021-08-12 2021-08-13 2
2022-06-26 2022-06-27 2
2022-07-26 2022-07-26 1
2022-07-29 2022-07-31 3
2022-08-18 2022-08-18 1
2022-08-24 2022-08-25 2
2022-08-30 2022-08-31 2
2022-09-10 2022-09-10 1
2022-09-20 2022-09-20 1
2022-09-26 2022-09-27 2

Sacramento
2021-06-17 2021-06-18 2
2021-07-09 2021-07-10 2
2021-09-06 2021-09-08 3
2022-06-10 2022-06-10 1
2022-06-21 2022-06-21 1
2022-08-16 2022-08-16 1
2022-08-20 2022-08-20 1
2022-09-01 2022-09-02 2
2022-09-04 2022-09-09 6
2023-07-01 2023-07-02 2

09/03/2022 break

Phoenix
2021-06-13 2021-06-19 7
2021-08-27 2021-08-27 1
2021-09-09 2021-09-09 1
2021-09-12 2021-09-13 2
2022-06-10 2022-06-12 3
2022-07-11 2022-07-11 1
2023-07-03 2023-07-03 1

Table 4. Heat wave events over the three sites to be verified

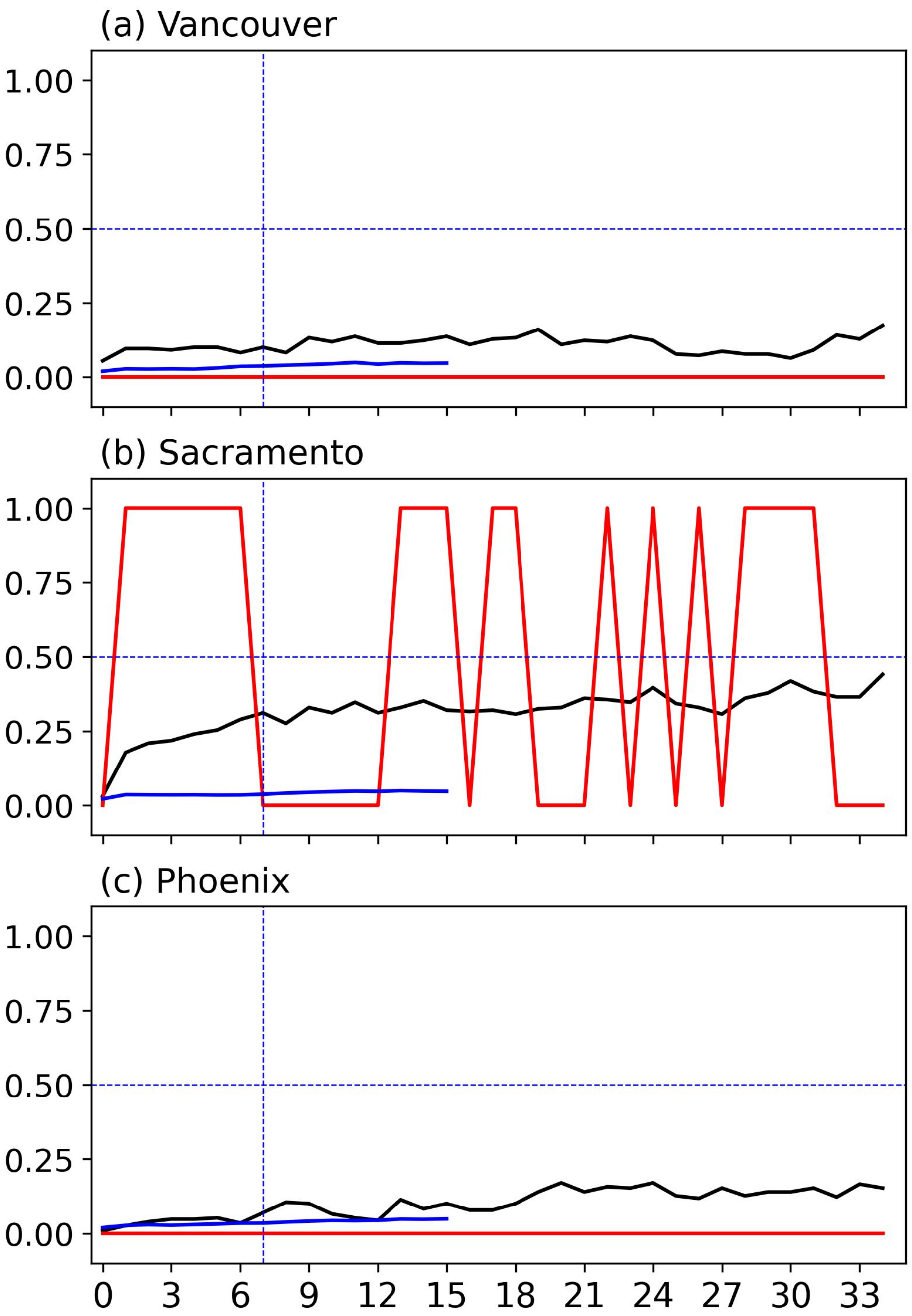


III. Results: hit rates

Fig. 12. Hit rates [H = a/(a+c)] for heat waves predicted by the GEFSv12 gec00. The x-axis is the forecast lead-time in days. The red line is for the highlighted persistent events in Table 2; the black line is for the JJAS in 2021 and 2022; and the blue is for all JJAS seasons in 1989 – 2019.

Heat waves are more predictable in 2021 and 2022 than earlier years. Persistent heat waves in the extratropical CONUS are the most predictable.

Heatwaves in Sacramento in 2021 and 2022 are predictable even at 35-day lead time.



III. Results: false alarm rates

Fig. 13. Same as Fig. 12 but for false-alarm rates [FAR = b/(b+d)].

FAR = 0 if both b and d are 0.

False alarm rates are zero for selected persistent heat waves over Vancouver and Phoenix (red), but 1 for days 2-6 forecasts over Sacramento. The high FAR in Sacramento may also contribute to the outstanding prediction skill.

III. Results: SEDI – persistent vs. non-persistent heatwaves in gec00

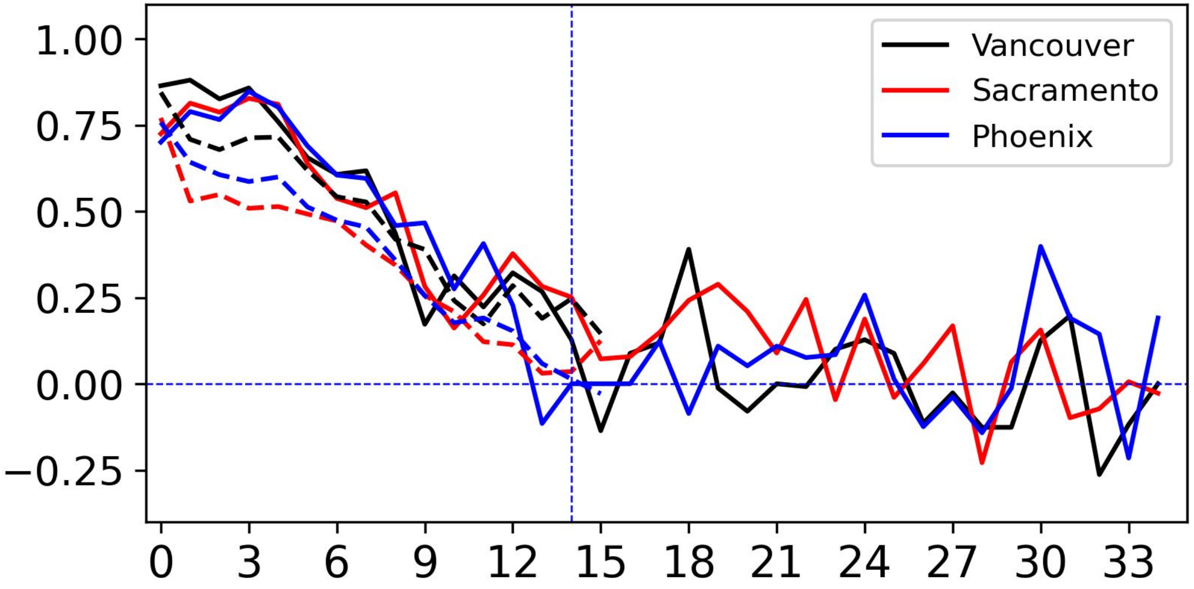


Fig. 14. The SEDI for selected persistent events in Table 2 (solid lines) and for all summers in 1989 – 2019 (dashed) over the three sites: Vancouver, Sacramento, and Phoenix.

The SEDI is clearly higher in selected persistent heat waves (solid) than other non-persistent ones (dashed) during the first 16 days forecasts.

The SEDI is still mostly above 0 up to four weeks, indicating some prediction skills.

III. Results: SEDI – persistent heatwaves in gec00 and ensemble run

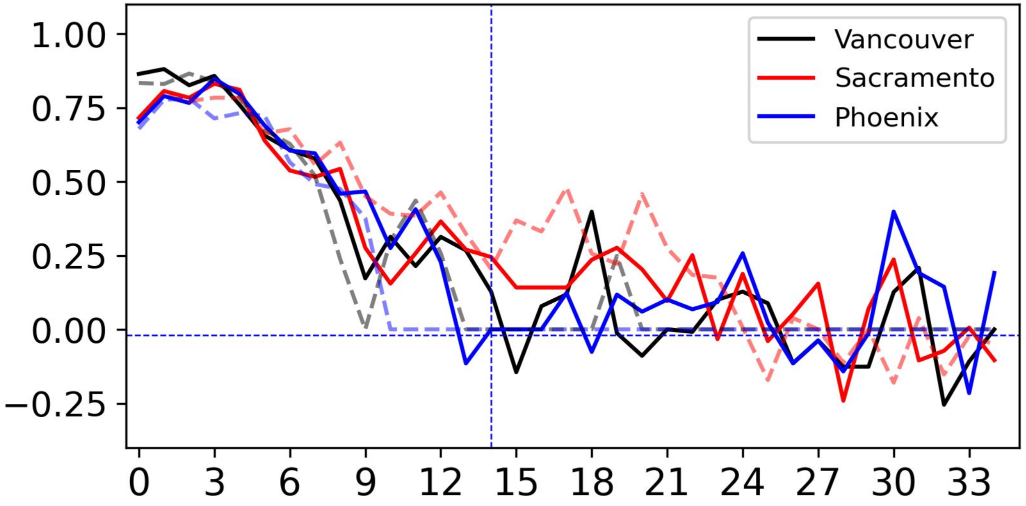
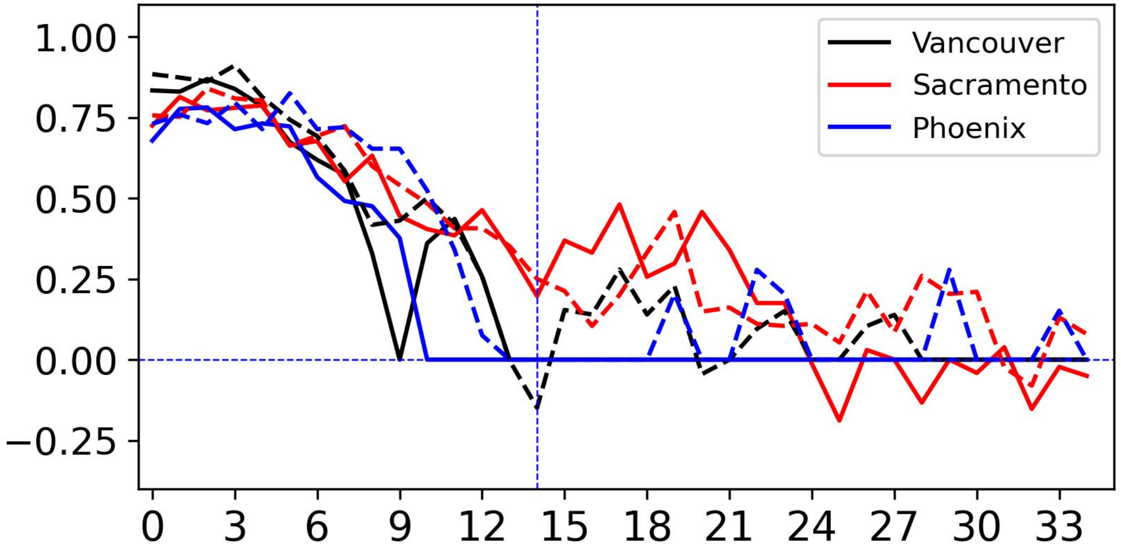


Fig. 15. The SEDI for selected persistent events in Table 2 forecasted by gec00 (solid lines) and ensemble mean (dashed) over the three sites.

The deterministic forecast gec00 is overall better than the ensemble mean of the 30 members where hits are more than half of the members (or H > 0.5) predict a heat wave.

The SEDI in the ensemble mean drops to 0 after 9 days over Vancouver and Phoenix, while persists after 24 days in Sacramento

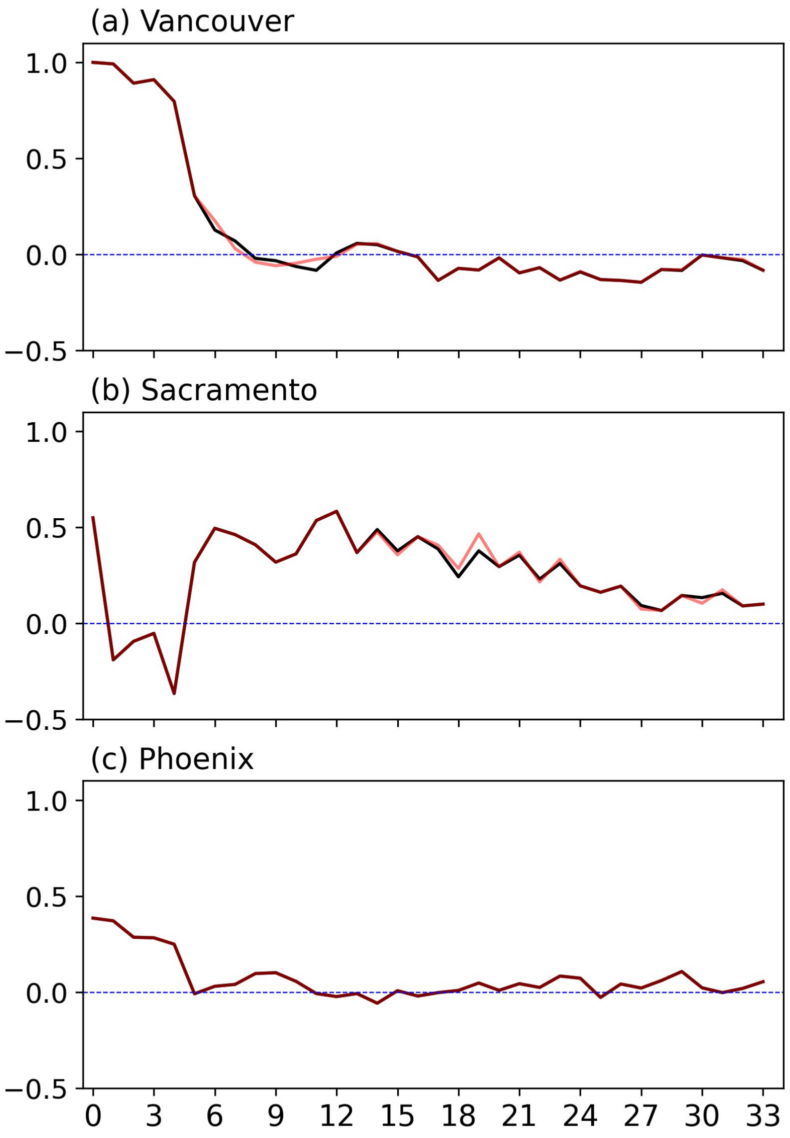
III. Results: SEDI – sensitivity to the ensemble threshold as 0.3



Lower the threshold of H to 0.3 (dashed) from 30 ensemble members marginally increases the SEDI beyond 14 days, suggesting a useful calibration

Fig. 16. The SEDI for selected persistent events in Table 2 forecasted by the ensemble runs with H > 0.5 (solid) or H > 0.3 (dashed) over the three sites.

III. Results: BSS



Forecast lead (day)

Vancouver: in the first seven days, forecasts are more skillful for persistent heat waves than all heat waves, but less skillful afterwards

Sacramento: persistent heat waves are more skillful up to 35 days except in days 2-5

Phoenix: persistent heat waves are apparently more skillful in the first 5 days and remain slightly skillful afterwards

Fig. 17. The BSS for selected persistent events in Table 2 in reference to heatwaves during JJAS in 1989 – 2019 over the three sites. Very small difference is seen when using the 95th percentile of Tmax from CPC observations (red) and GEFSv12 reforecasts (black)

IV. Summary

Heat waves in 2021 and 2022 appears to be more predictable than earlier years. Persistent heat waves in 2021 and 2022 appears to be the most predictable in the extratropical CONUS.

Heatwaves in Sacramento in 2021 and 2022 were demonstrated predictable even at 35-day lead time.

Predictions of extratropical heat waves in the USA are majorly controlled by persistent high-pressure systems, indicating a direction of model improvement in addition to model initialization, soil moisture, and land-air interaction etc.