Prediction, projection, and detection of U.S. heat extremes using data-driven approaches with the GFDL SPEAR modeling system

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The opportunity

Given the significant environmental, economic, and societal impacts associated with heatwaves, it is crucial to better understand their sources of predictability, variability, and overall changes in a warming climate.

Our approach

To account for different physical processes and timescales, we use the fully-coupled NOAA/GFDL Seamless System for Prediction and EArth System Research (SPEAR) that offers a wide-range of large ensemble simulations that are optimized for *prediction* and *projection* within a singular modeling framework. **[1]**

The conclusions

Heat extremes are already increasing across the contiguous United States (CONUS) and are projected to rise further in response to external radiative forcing. However, there is some skill in predicting these extremes even at seasonal timescales, which can provide an early warning system for vulnerable communities.

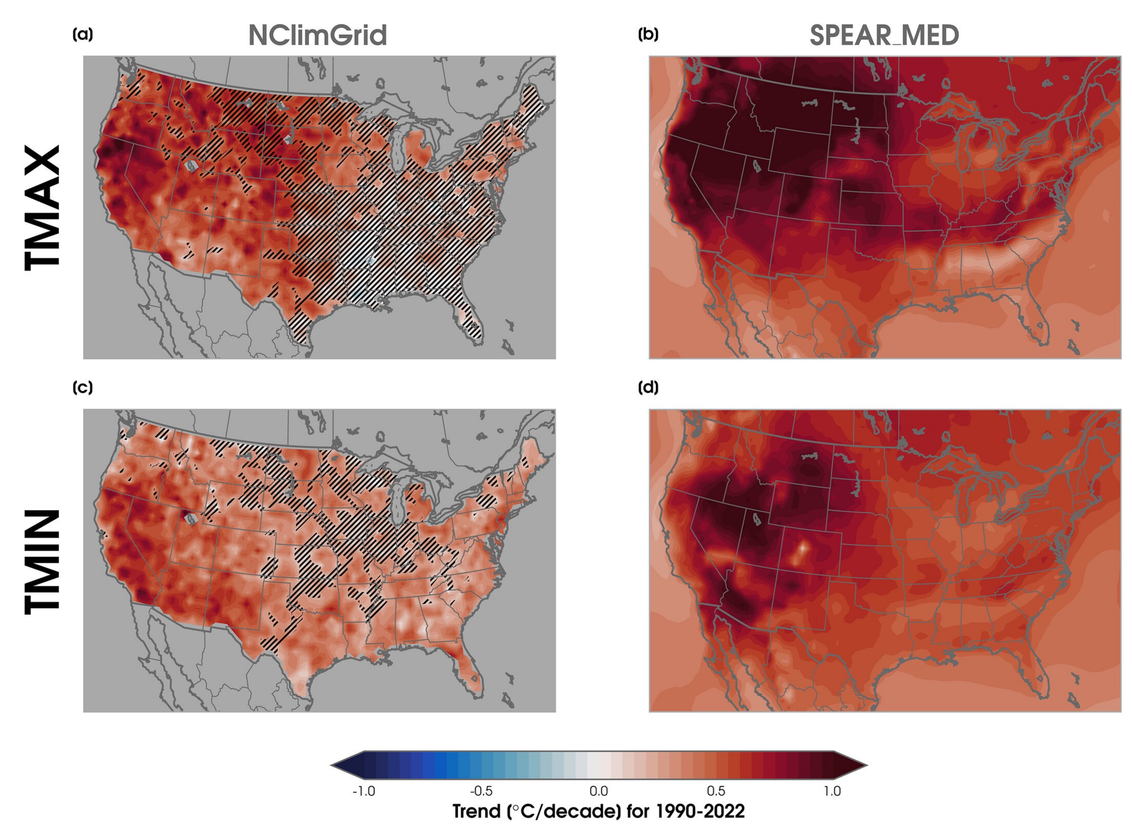
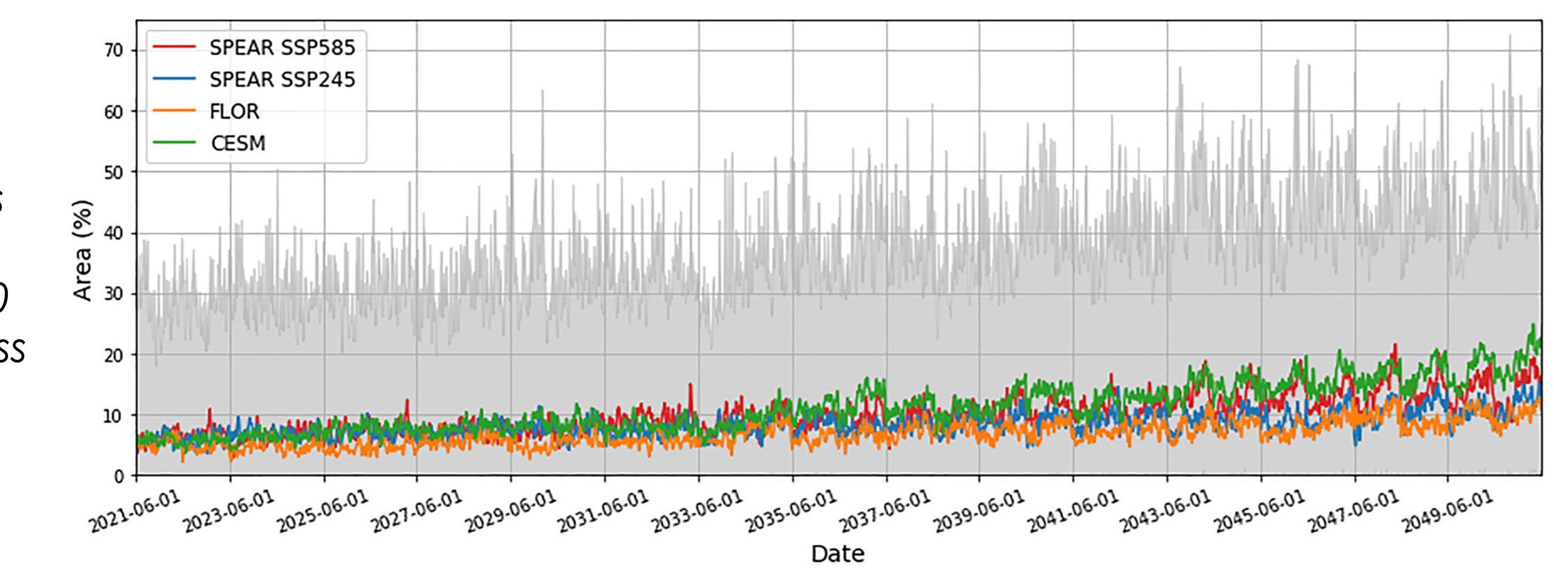


Fig 1. Decadal trends in near-surface temperatures between observations and SPEAR for June-August.

Future projections of record-breaking heat

Fig 3. Percent of CONUS where the Tmax value exceeds the daily record relative to 1991–2020 in June-August across different models.



- SPEAR large ensemble captures the observed variability and trend of heat records across CONUS, but overestimates the frequency and amplitude. **[4]**
- Largest amplitude of new daily Tmax records is projected across the Central and Northern Plains by the mid-21st century.
- Frequency of heat extremes toward the end of the 21st century is highly dependent on the emissions scenario and extent of mean warming.

Seasonal prediction of heat extremes

- June-August heat extremes (Tx90) can be skillfully predicted by SPEAR up to 9 months in advance. **[2]**
- Sources of prediction skill arise from the long-term warming trend, modes of sea surface temperature variability (AMO, PDO, ENSO), and soil moisture anomalies.

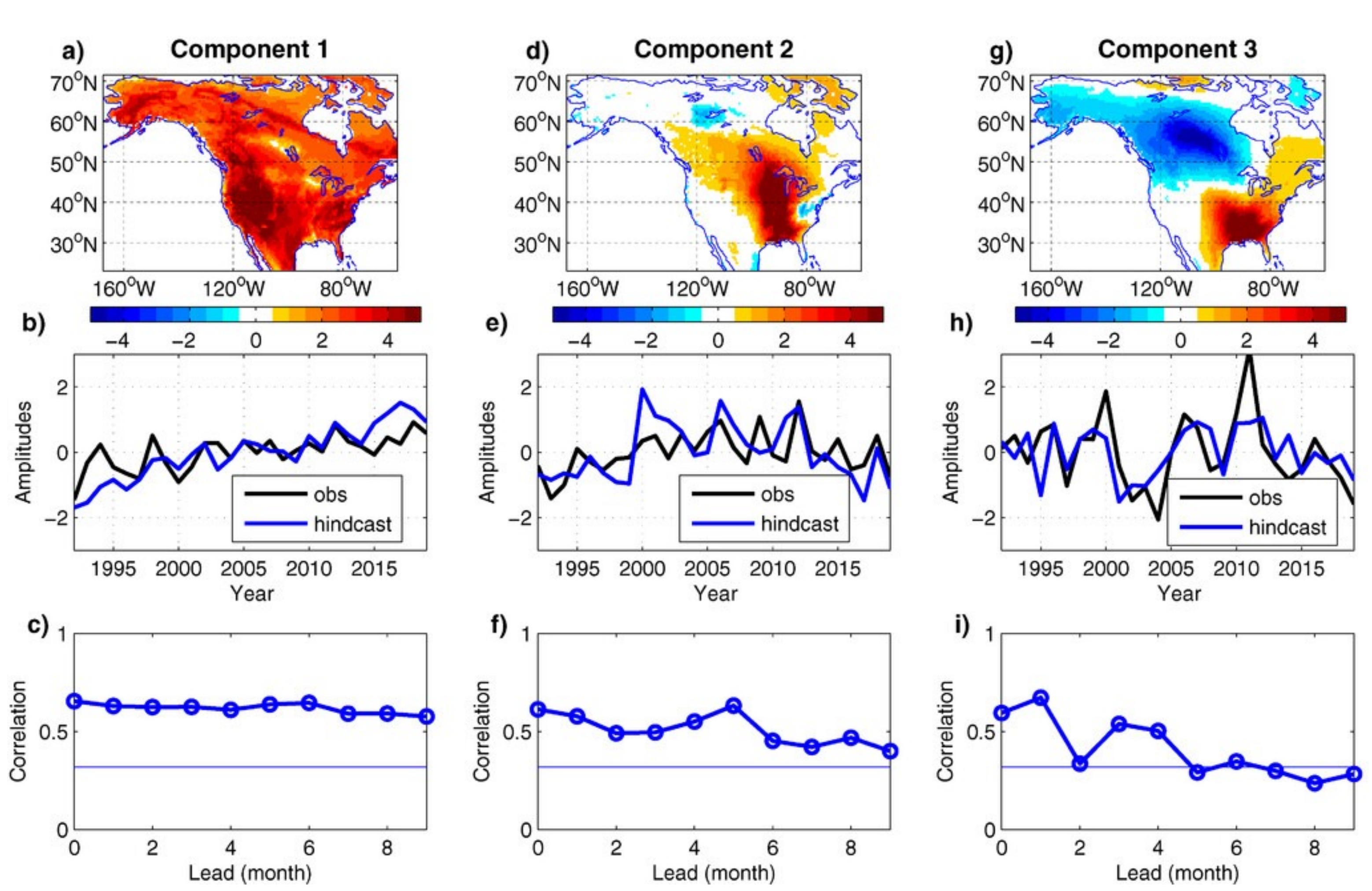


Fig 2. Average predictability time (APT) is used to decompose SPEAR hindcasts into the three large-scale climate components that maximum predictability.

Detecting regional temperature change with explainable AI

- An explainable artificial neural network is designed to assess the timing of emergence for seasonally-averaged temperature extremes across CONUS. **[3]**
- Forced temperature changes have emerged in observations during summer, especially for Tmin.
- Increasing the horizontal (spatial) resolution of the training data improves the network prediction skill.
- Western CONUS land surface properties contribute to earlier timing of emergence predictions for SPEAR.

Fig 4. Schematic of the neural network frame-work used for calculating the timing of emergence of summertime heat.

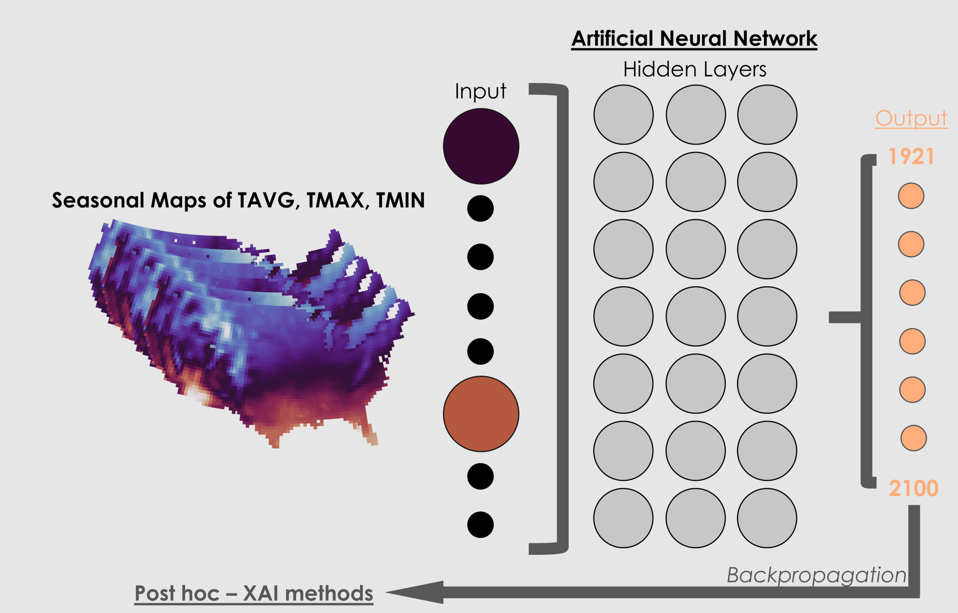
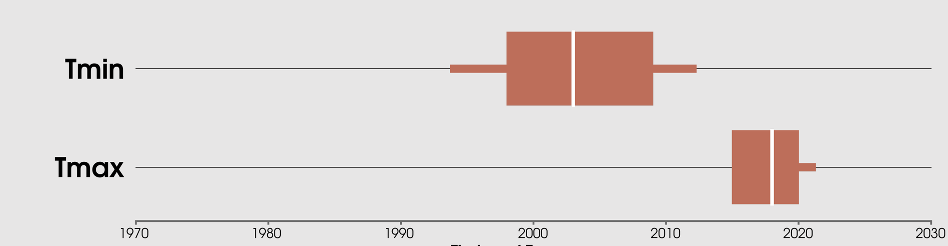


Fig 5. Distribution of timing of emergence predictions for CONUS using observations.



References

[1] Delworth. et al. (2020): SPEAR – the next generation GFDL modeling system for seasonal to multidecadal prediction and projection. *Journal of Advances in Modeling Earth Systems*, 12(3), DOI:10.1029/2019MS001895

[2] Jia, L., T.L. Delworth, S.B. Kapnick, X. Yang, N.C. Johnson, W.F. Cooke, F. Lu, M.J. Harrison, A. Rosati, F. Zeng, C. McHugh, A.T. Wittenberg, L. Zhang, H. Murakami, and K.-C. Tseng (2022): Skillful seasonal prediction of North American summertime heat extremes. *Journal of Climate*, 35(13), DOI:10.1175/JCLI-D-21-0364.14331-4345

[3] Labe, Z.M., N.C. Johnson, and T.L. Delworth (2024): Changes in United States summer temperatures revealed by explainable neural networks. *Earth's Future*, 12(2), DOI:10.1029/2023EF003981

[4] McHugh, C., T.L. Delworth, W.F. Cooke, and L. Jia (2023): Using large ensembles to examine historical and projected changes in record-breaking summertime temperatures over the contiguous United States. *Earth's Future*, 11(12), DOI:10.1029/2023EF003954