Seasonal predictability of saturation vapor pressure deficit in the western United States

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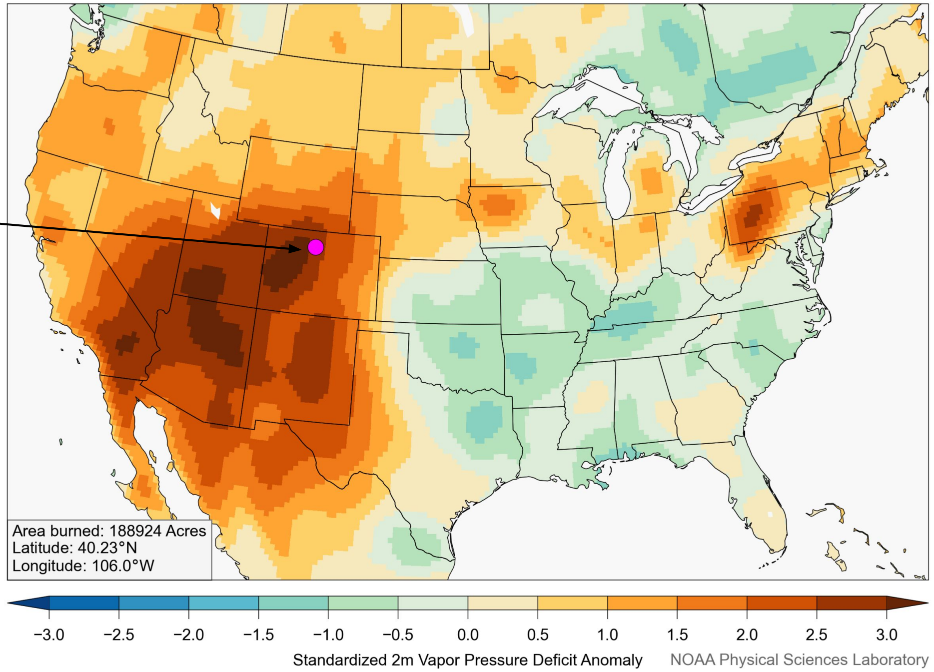
ERA5 VPD Anomaly, JAS 2020

East Troublesome Fire



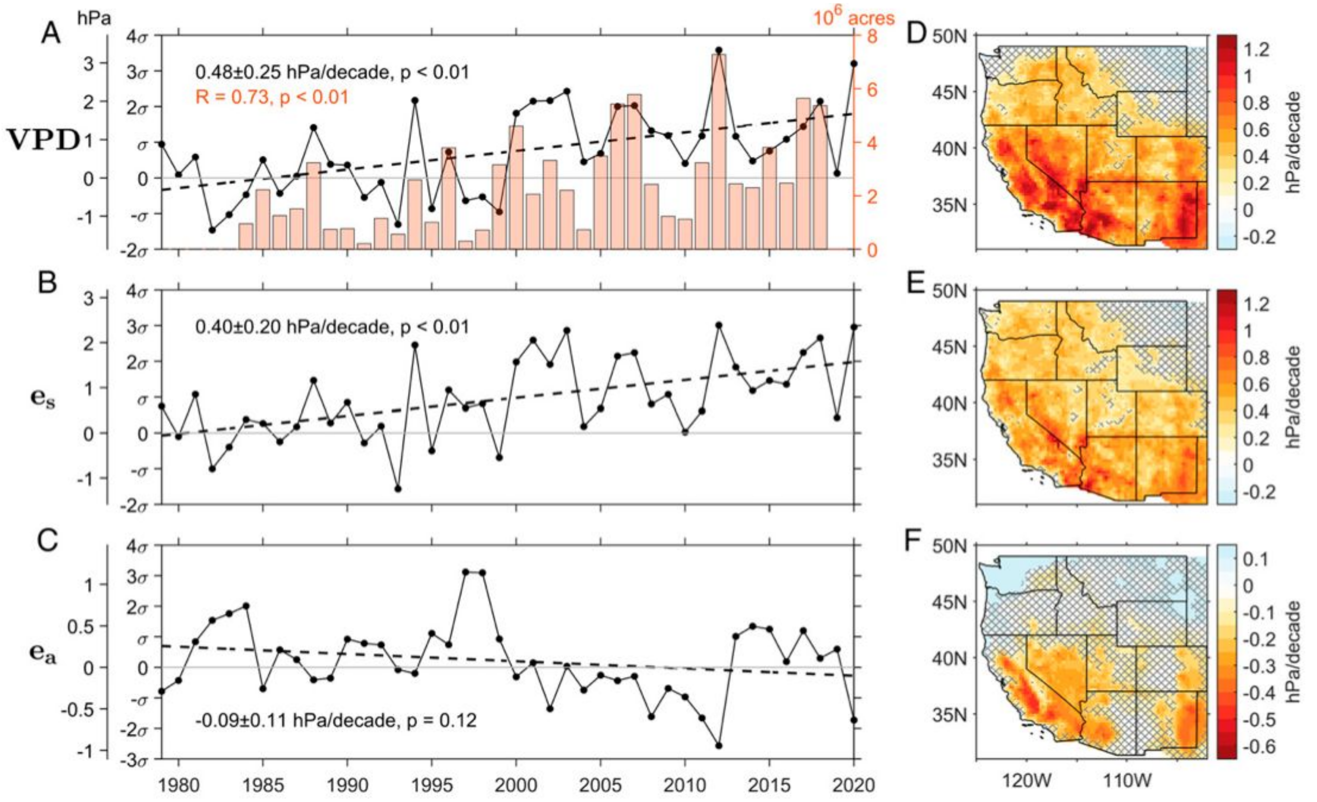
https://www.psl.noaa.gov/fire_weather/historical/

Saturation vapor pressure deficit (VPD) is highly correlated to area burned by wildfires in western US

$$VPD = e_s(T) - e_a(T_d)$$

Saturation Vapor Pressure: how much moisture the atmosphere could contain

Actual Vapor Pressure: how much moisture is actually present



Zhuang et al. PNAS 2018

Research Questions

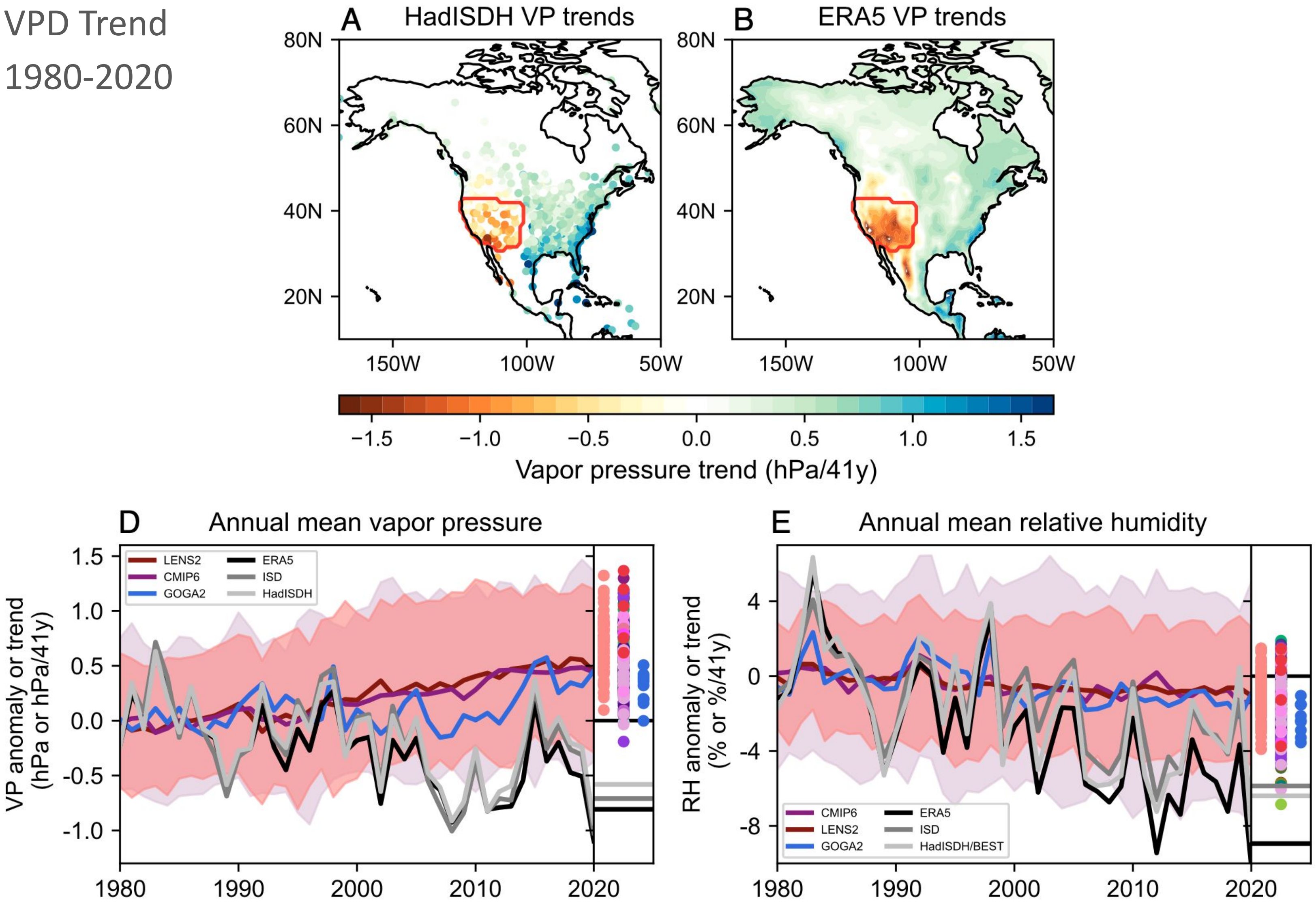
1. What are the leading sources of seasonal VPD predictability in the western US?

2. Can seasonal forecasts of opportunity (SFO)s be identified for VPD? What drives them?

Climate and seasonal forecast models struggle with actual vapor pressure, e_a

VPD Trend

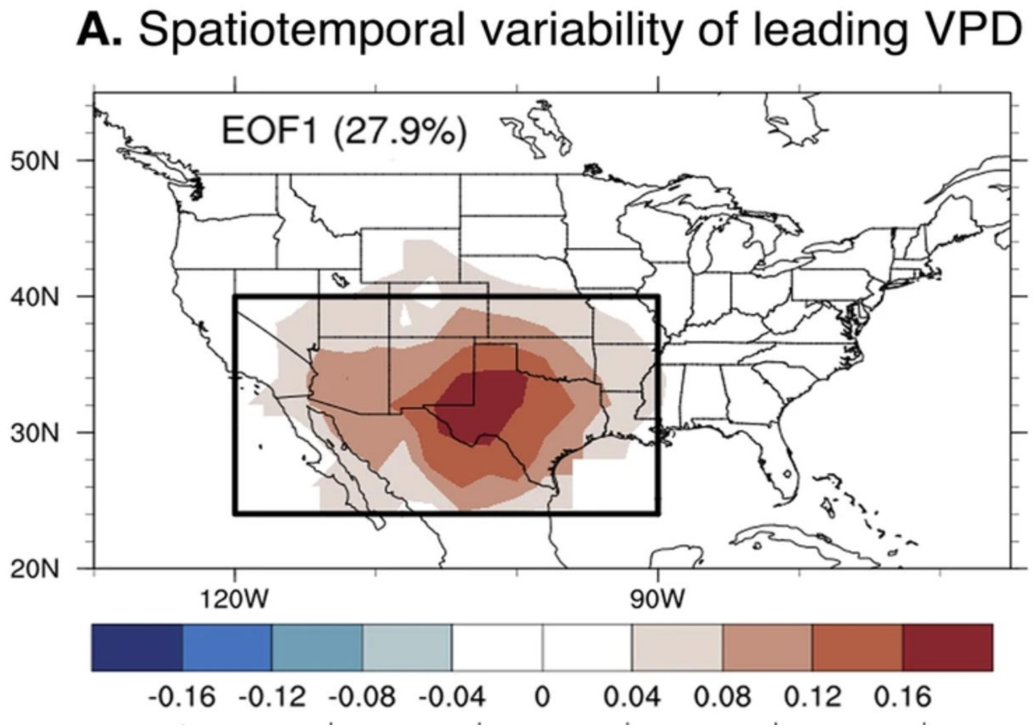
1980-2020

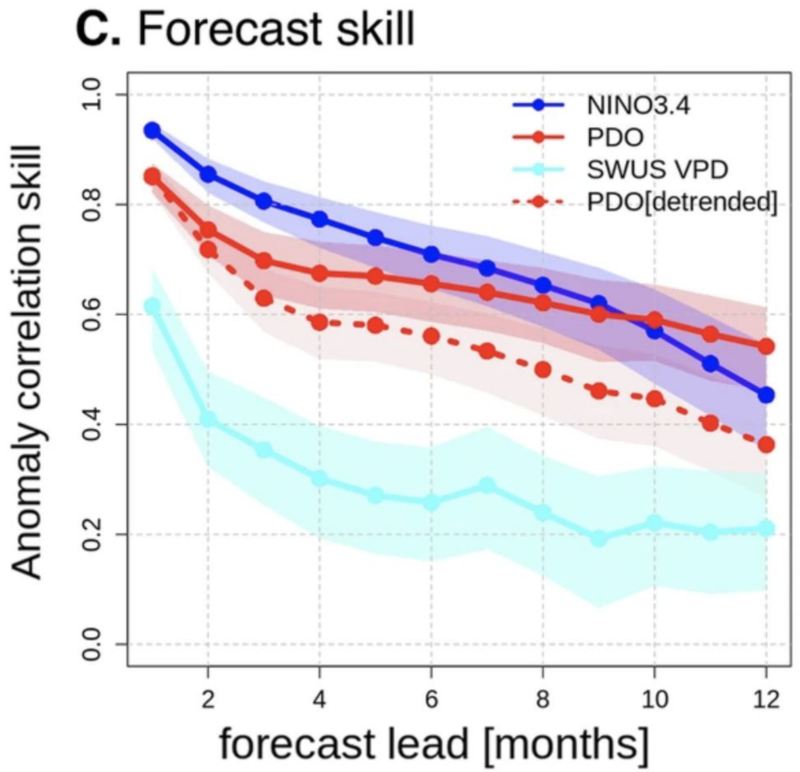


Simpson et al. 2023, PNAS

Climate and seasonal forecast models struggle with actual vapor pressure, e_a

- GFDL SPEAR forecasts have ‘terrible’ e_a skill





Lou et al. 2025, npj climate and atmospheric science

Data and Forecast Model

- Monthly mean **JRA55 Reanalysis** sea surface temperature (SST), soil moisture (SM) and VPD anomalies calculated with respect to the 1958-2021 monthly climatology

- Two **Linear Inverse Models** (LIMs; Penland and Sardeshmukh 1995) are trained to forecast VPD using covariance statistics of VPD and predictor variables SST, SM
  - LIMs are used to generate retrospective forecasts and assess VPD skill contributions from modes of variability (such as a long-term trend, ENSO)

LIM Including the Trend

Variable	Domain
SST	55°S – 55°N, 0-358.75°E
SM	24°N-50°N, 230-300°E
VPD	25°N-50°N, 230-300°E

LIM without the Trend

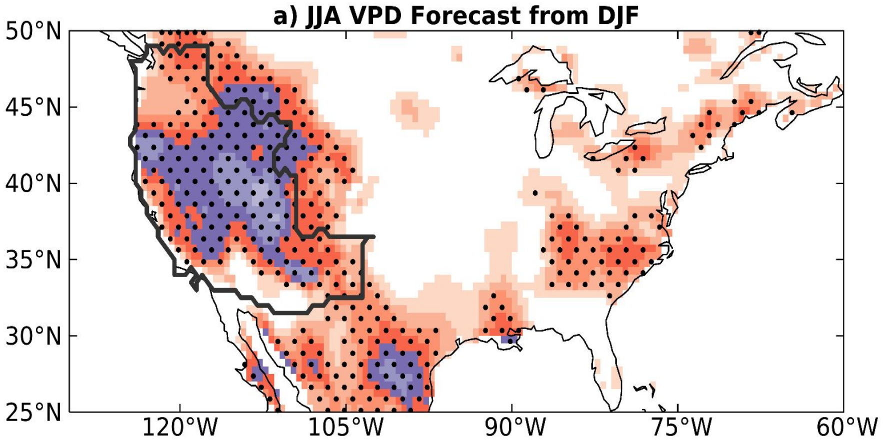
Variable	Domain
SST	25°S – 55°N, 0-358.75°E
VPD	25°N-50°N, 230-300°E

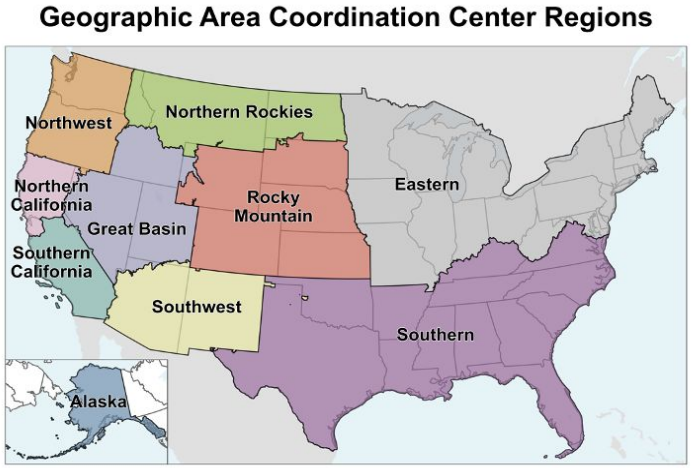
Linear Inverse Models (LIMs):

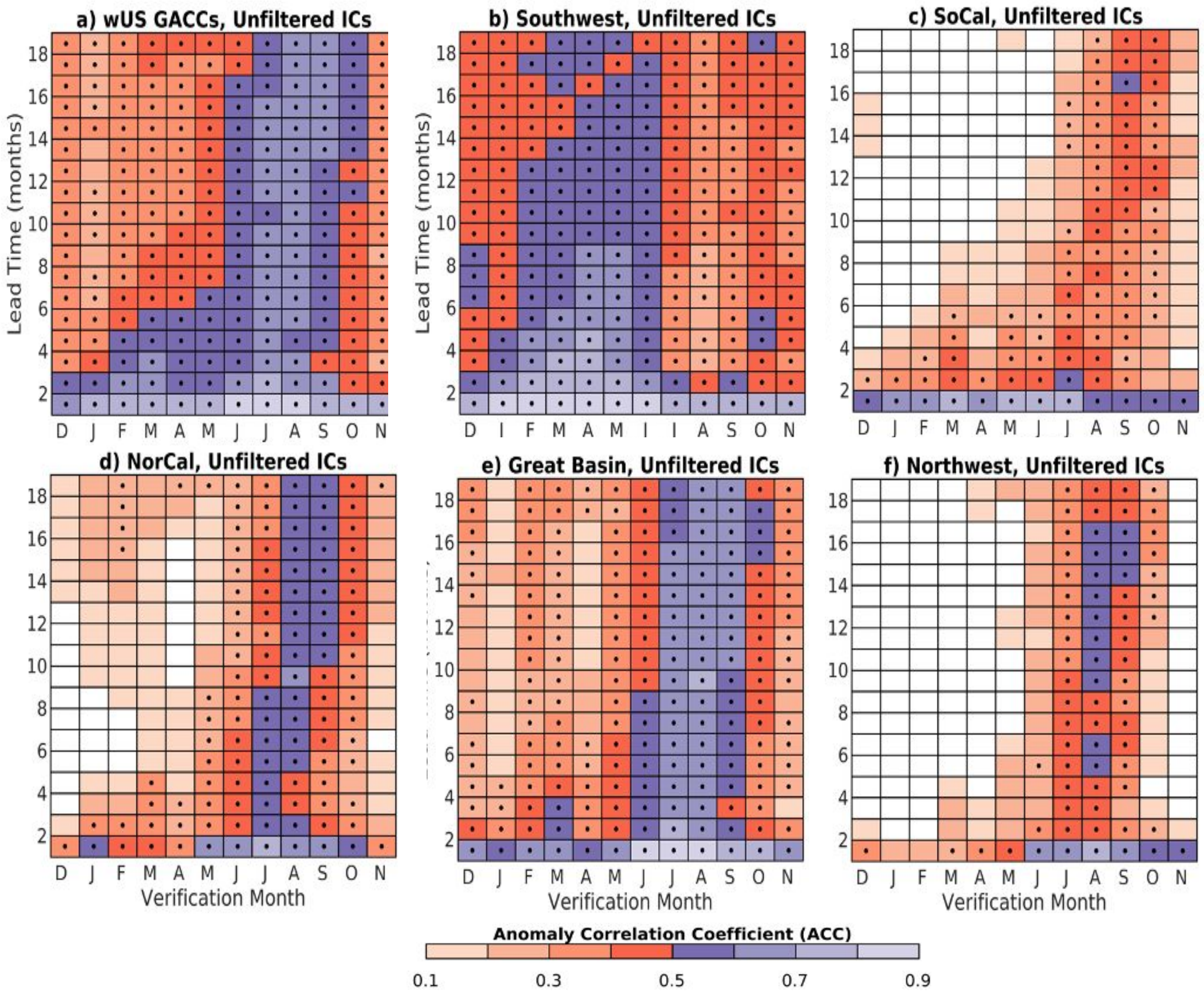
- are mean bias free, sidestepping the issue of e_a representation in climate models
- have a long history of generating competitively skillful SST / ENSO forecasts (Penland and Sardeshmukh 1995; Newman et al. 2017; Shin et al. 2021), which we want to leverage to forecast VPD based on past links between VPD and ENSO (e.g., Seager et al. 2015)
- can *explain* forecast skill by 'dynamical filtering' the deterministic forecast operator
- Can identify 'forecasts of opportunity' (Albers and Newman 2019)

Seasonal VPD Forecast Skill: Trend Included

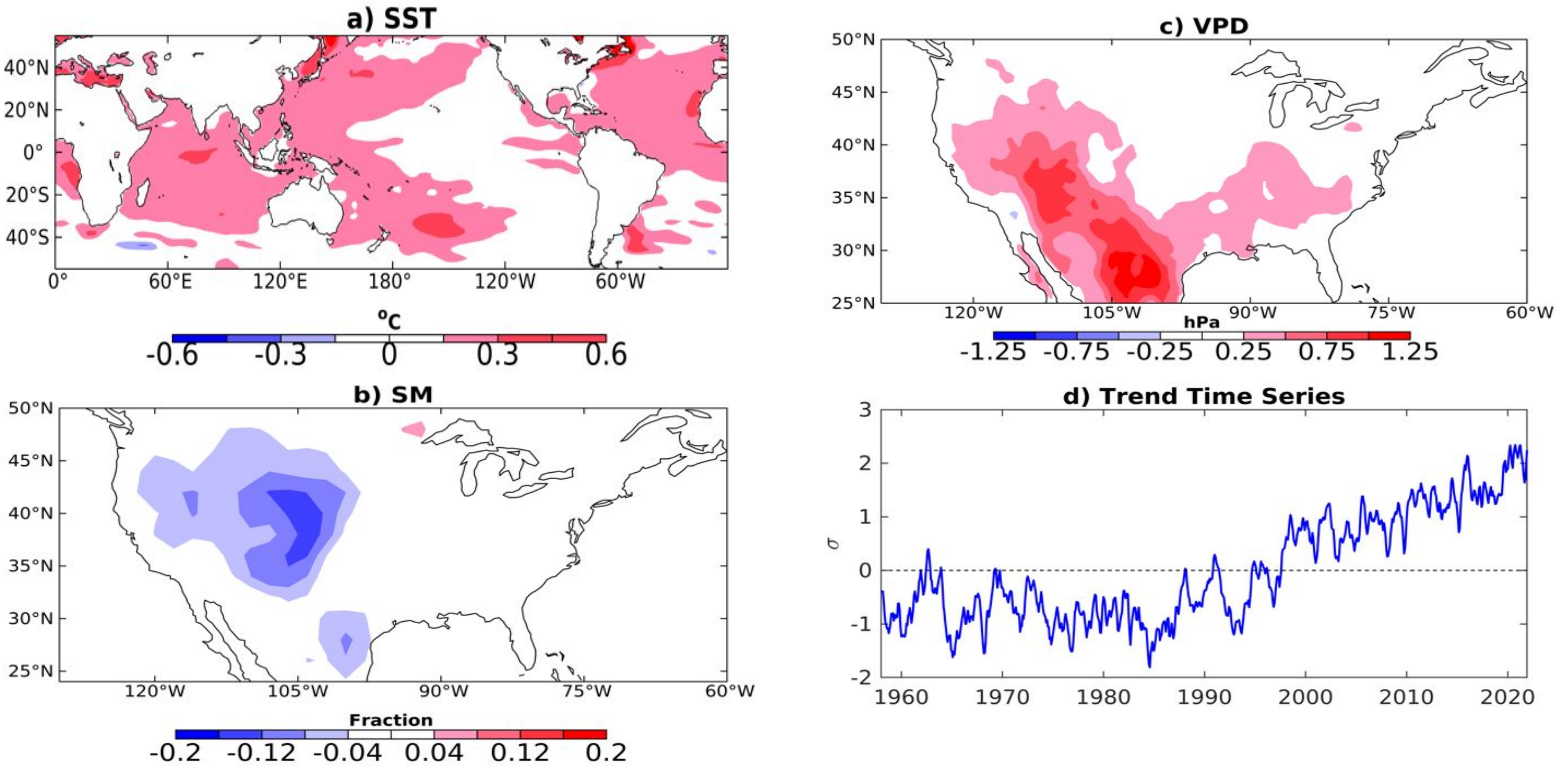
1958-2021







Removing a nonlinear trend

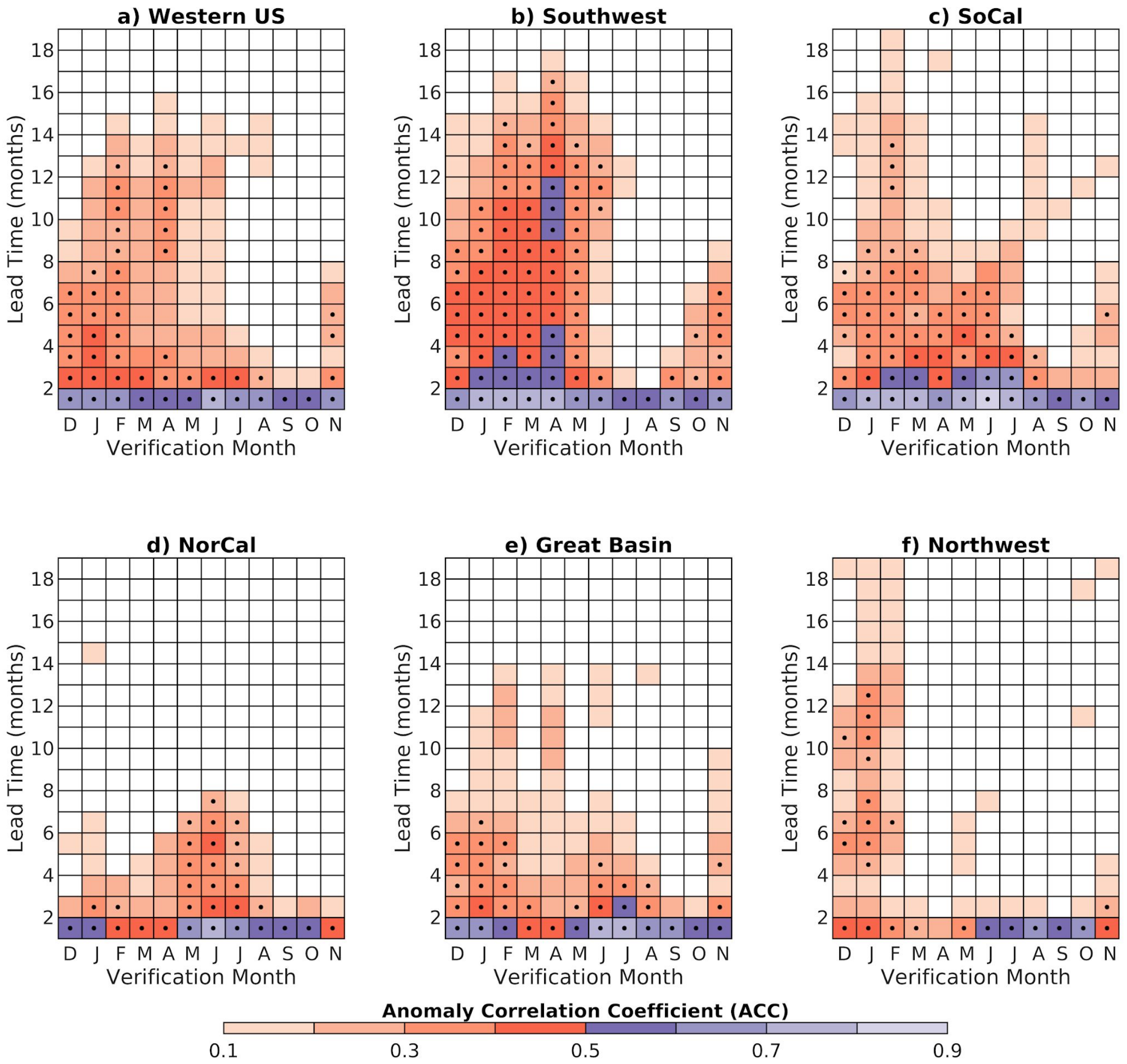


Detrended VPD Skill

1958-2021

LIM without the Trend

Variable	Domain
SST	25°S – 55°N, 0-358.75°E
VPD	25°N-50°N, 230-300°E

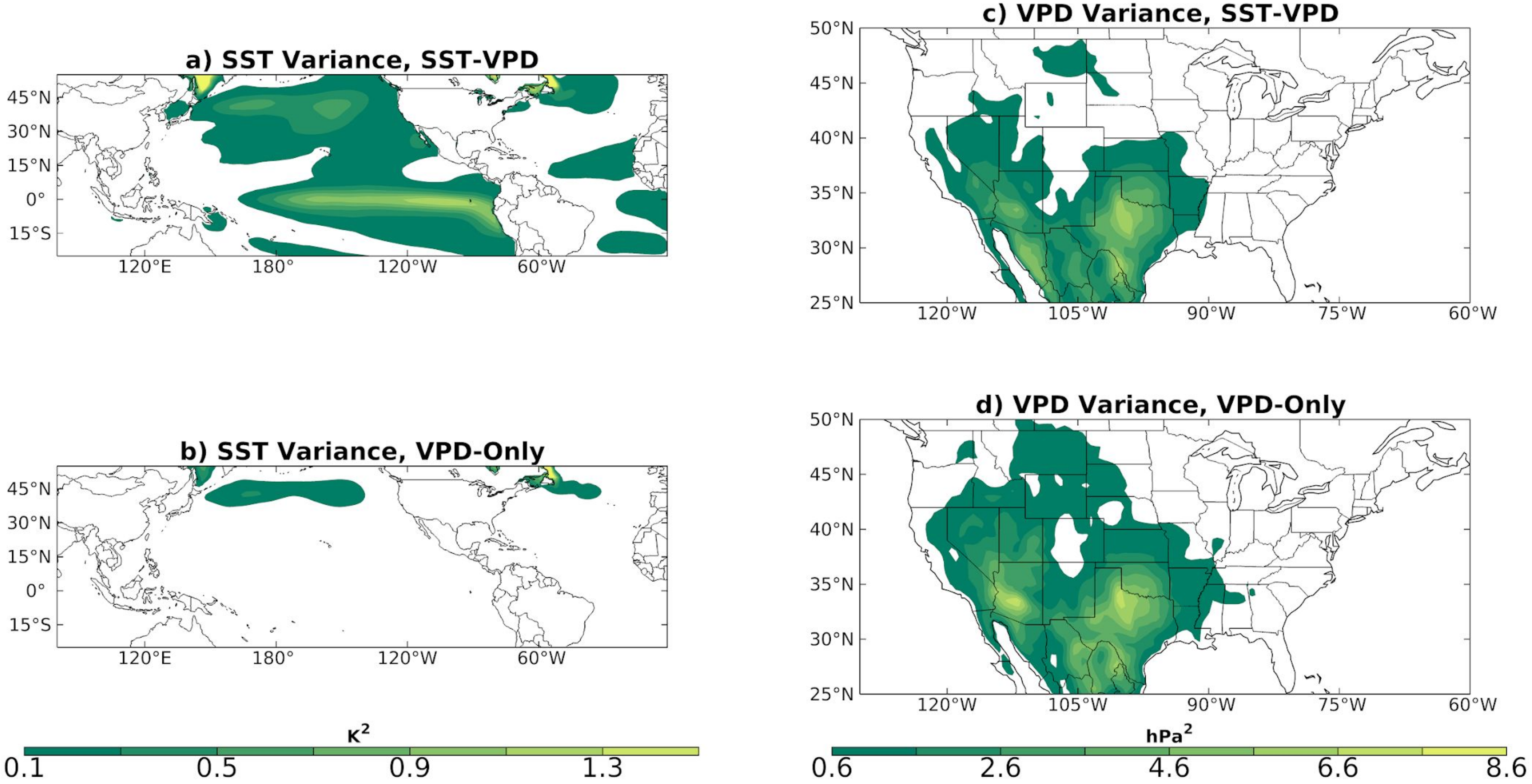


Decomposing Detrended LIM Skill

- We use the LIM to split VPD anomalies into a group associated with SSTs, 'SST-VPD', and a group with *only* VPD anomalies, 'VPD-only'

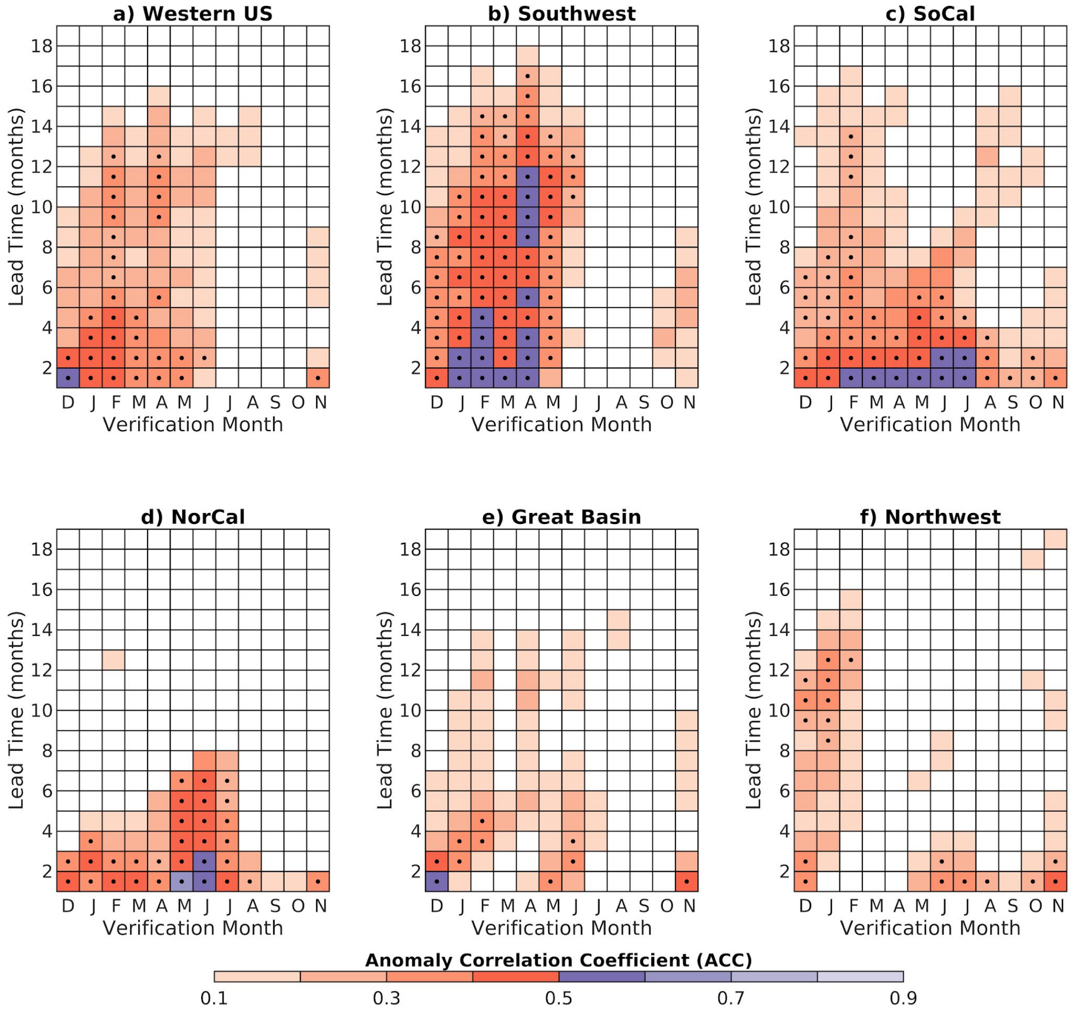
Slowly-decaying

Rapidly-decaying

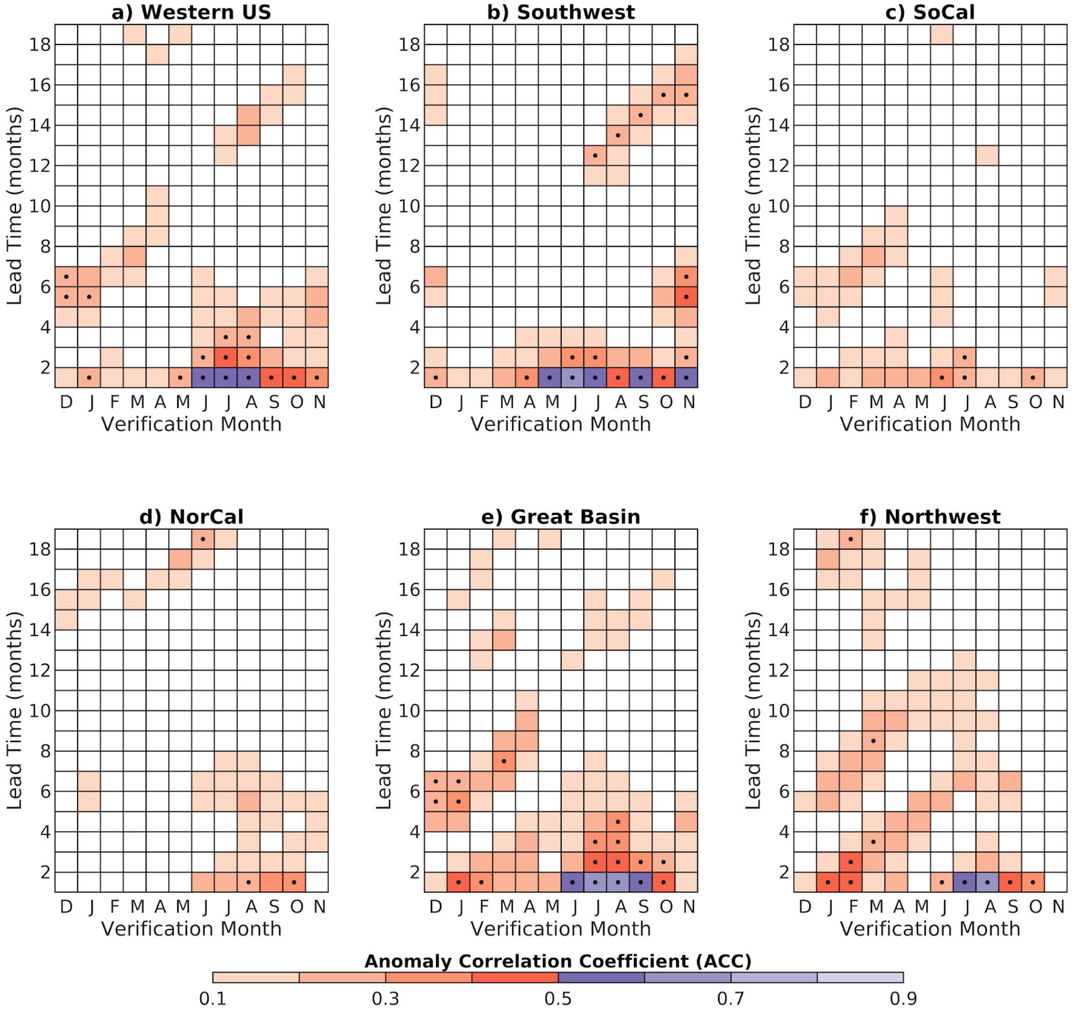


VPD skill from SST-VPD and VPD-only modes differs in timing and amplitude

SST-VPD Modes

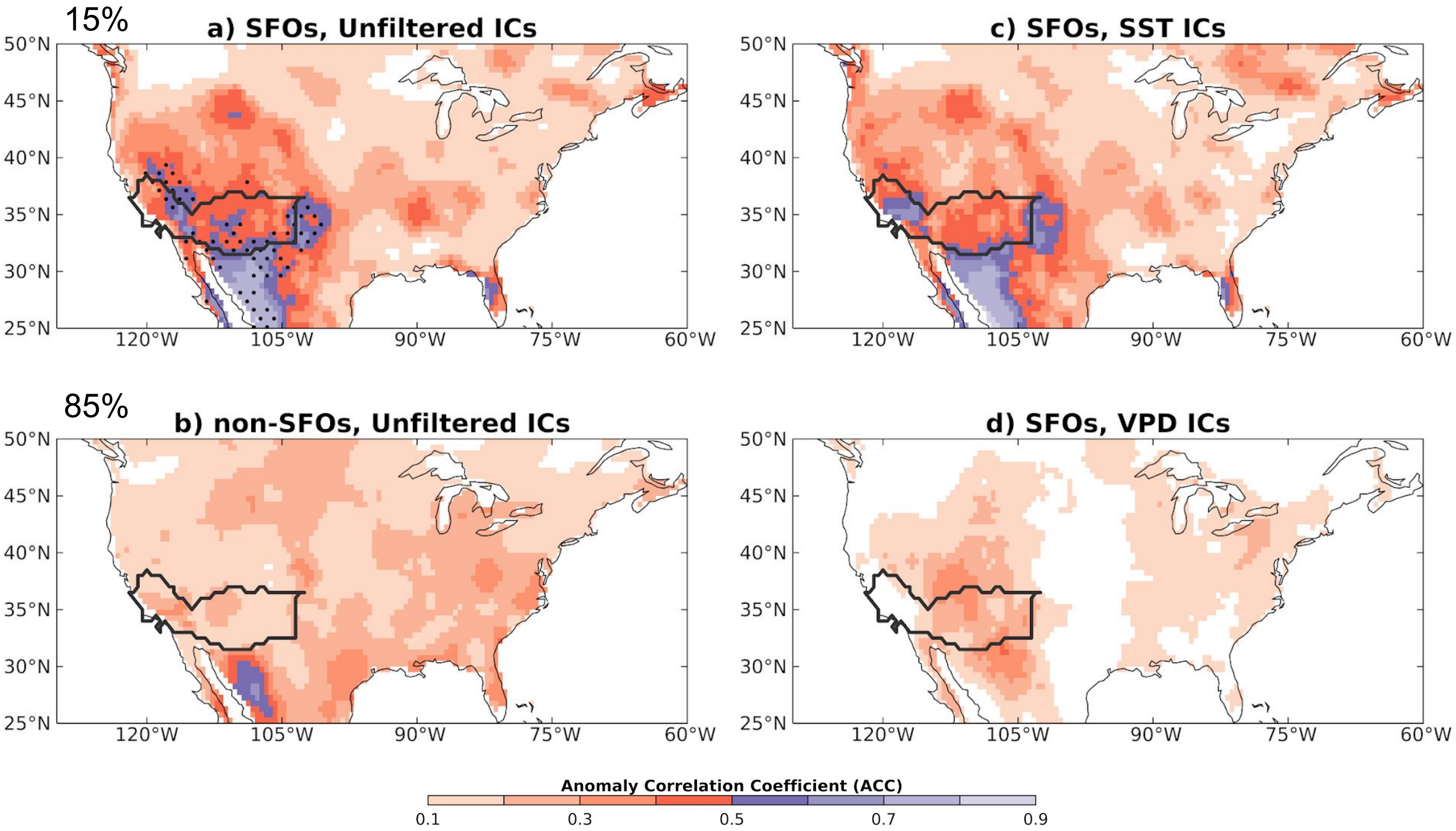


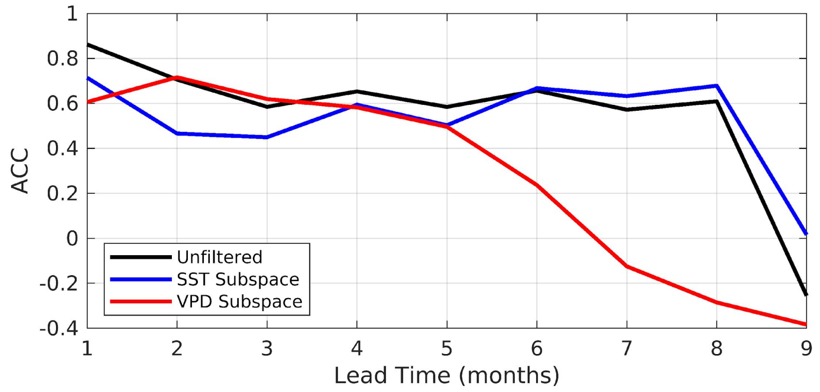
VPD-only Modes



VPD Forecasts of Opportunity can be identified for lead times up to eight months

3-month SFOs

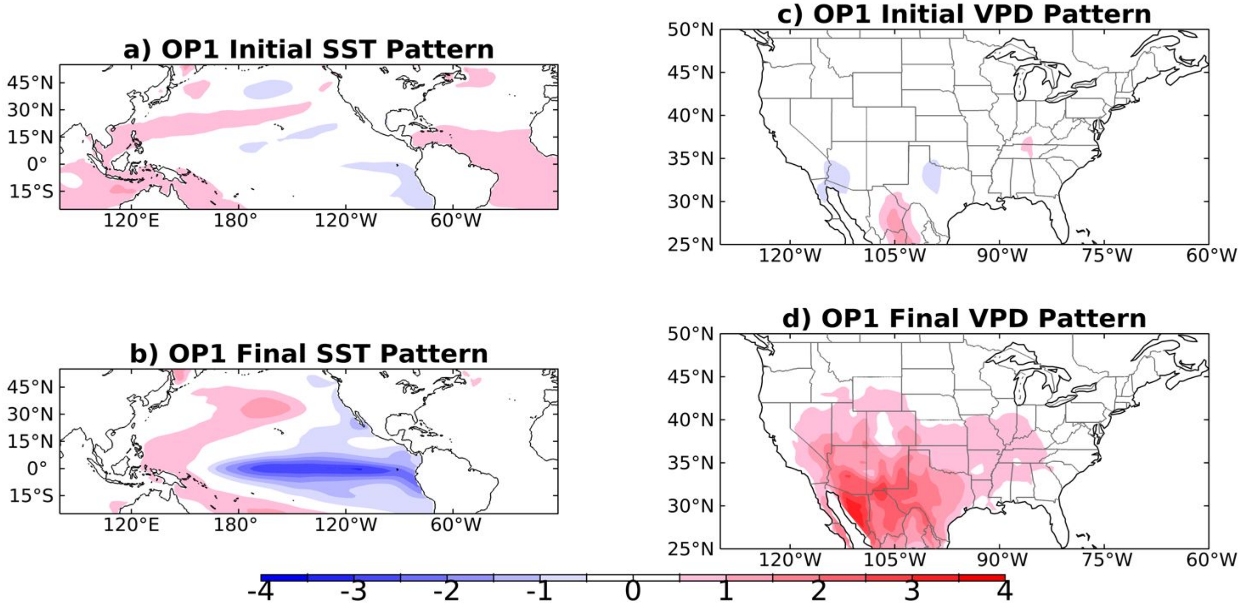




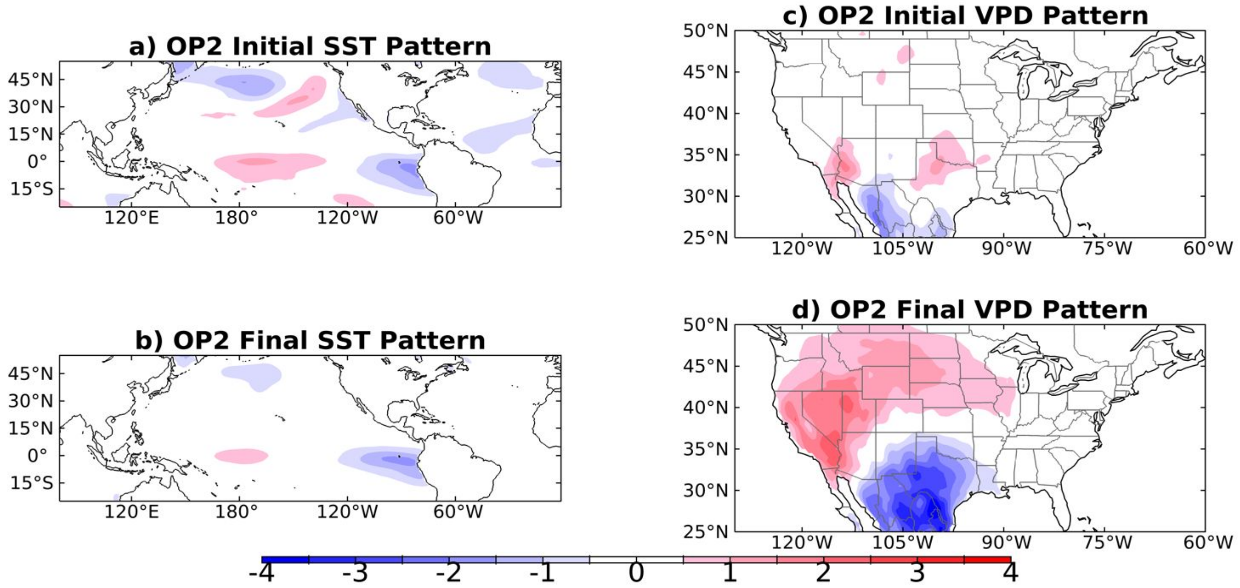
Patterns associated with forecasts of opportunity include ENSO

- Optimal patterns (OPs) maximize system growth over a specified growth period

7-month growth period



3-month growth period



Research Questions

1. What are the leading sources of seasonal VPD predictability in the western US?

→ A nonlinear warming trend and coupled SST-VPD variability contribute to VPD skill, mainly in the warm and cool seasons, respectively.

2. Can seasonal forecasts of opportunity (SFO)'s be identified for VPD? What drives them?

→ SFOs can be identified up to eight months in advance and are related to strong ENSO events

Remaining questions and gaps in understanding

- What would improve model representation of low-level moisture in semi-arid regions like the SW US? How does this model limitation affect predictions and projections of VPD?

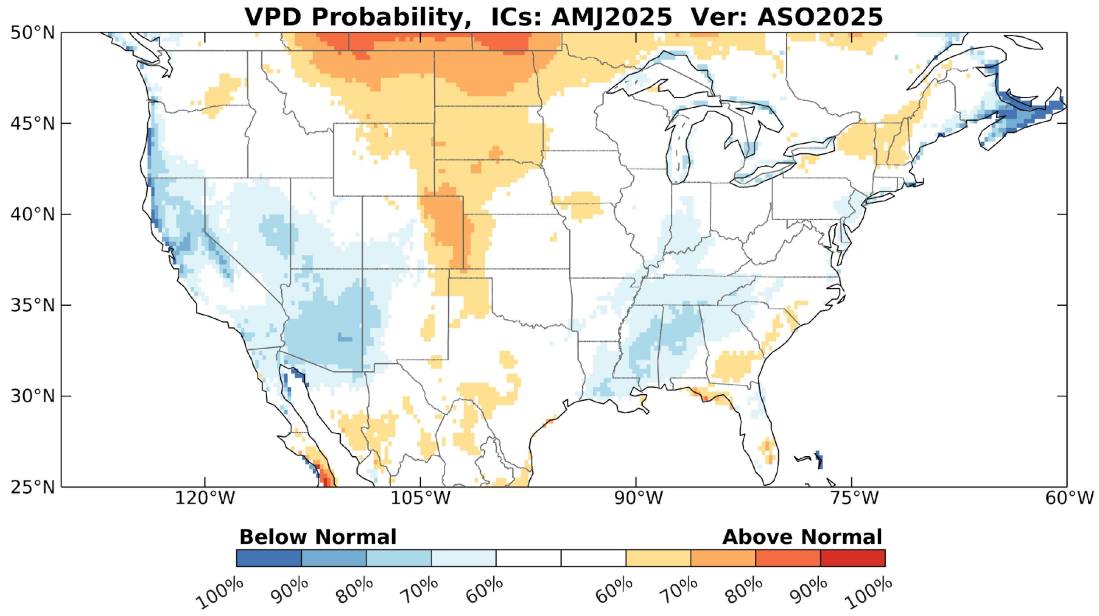
- S2S predictability of other components of wildfires (low-level winds, ignition)?

- Can LIM VPD forecasts be improved with models that can better learn nonlinearities?

More Information

Breeden, M. L., Hoell, A., Worsnop, R. P., Albers, J. R., Hobbins, M. T., Robinson, R. M., and Vimont, D. J.: Seasonal Predictability of Vapor Pressure Deficit in the western United States, in review at *Weather and Climate Dynamics*

preprint: https://egusphere.copernicus.org/preprints/2025/egusphere-2025-115/



Realtime VPD forecasts!

https://www.psl.noaa.gov/forecasts/seasonal_vpd/

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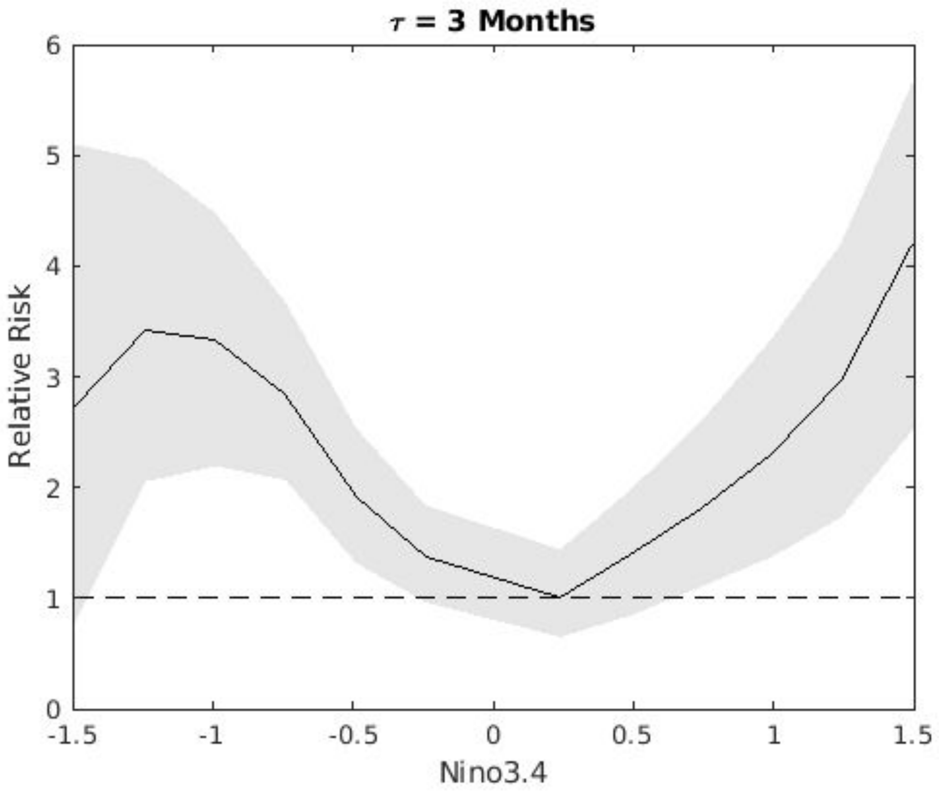
References

1. Albers, J.R., and Newman, M.: A priori identification of skillful extratropical subseasonal forecasts. Geophysical Research Letters, 46, 12527–12536, https://doi.org/10.1029/2019GL085270, 2019.
2. Lou, J., Joh, Y., Delworth, T. L., and Jia, L.: Identifying source of predictability for vapor pressure deficit variability in the southwestern United States, npj Clim Atmos. Sci, 8, 139, 2025.
3. Penland, C., and Sardeshmukh, P. D.: The optimal growth of tropical sea surface temperature anomalies, J. Climate, 8, 1999–2024, https://doi.org/10.1175/1520-0442(1995)008<1999:TOGOTS>2.0.CO;2, 1995.
4. Newman, M., and Sardeshmukh, P. D.: Are we near the predictability limit of tropical Indo-Pacific sea surface temperatures? Geophys. Res. Lett., 44, 8520–8529, https://doi.org/10.1002/2017GL074088, 2017.
5. Shin, S., P. D. Sardeshmukh, M. Newman, C. Penland, and M. A. Alexander, 2021: Impact of Annual Cycle on ENSO Variability and Predictability. *J. Climate*, 34, 171–193, https://doi.org/10.1175/JCLI-D-20-0291.1.
6. Seager, R., Hooks, A., Williams, A. P., Cook, B., Nakamura, J., and Henderson, N.: Climatology, variability, and trends in the U.S. vapor pressure deficit, an important fire-related meteorological quantity,J. Appl. Meteorol. Clim., 54, 1121–1141, https://doi.org/10.1175/JAMC-D-14-0321.1, 2015.
7. Simpson, I.R. Simpson, McKinnon, K.A., Kennedy, D., Lawrence, D.M., Lehner, F., & R. Seager, Observed humidity trends in dry regions contradict climate models, *Proc. Natl. Acad. Sci. U.S.A.* 121 (1) e2302480120, https://doi.org/10.1073/pnas.2302480120, 2024.
8. Zhuang, Y., Fu, R., Santer, B. D., Dickinson, R. E., and Hall, A.: Quantifying contributions of natural variability and anthropogenic forcings on increased fire weather risk over the western United States, P. Natl. Acad. Sci. USA, 118(45), e2111875118, https://doi.org/10.1073/pnas.2111875118, 2021.

Forecasts of opportunity are more frequent during strong ENSO events



Linear Inverse Model (LIM)

For state vector $\mathbf{x} = \{\mathrm{VPD}, \mathrm{SM}, \mathrm{SST}\}$, → All from JRA55 reanalysis

$$\frac{d\mathbf{X}}{dt} = \mathbf{Lx} + \boldsymbol{F_S}$$

Evolution of system — Slow, predictable — Fast, rapidly decorrelating, unpredictable

Dynamic Operator: $\mathbf{L} = \boldsymbol{log}(\mathbb{C}\tau * \boldsymbol{inv}(\mathbb{C}_0))/\tau$

LIM Forecast: $\mathbf{x(t) = x(0) *exp(Lt) = x(0)G(t)}$

Penland and Sardeshmukh 1995