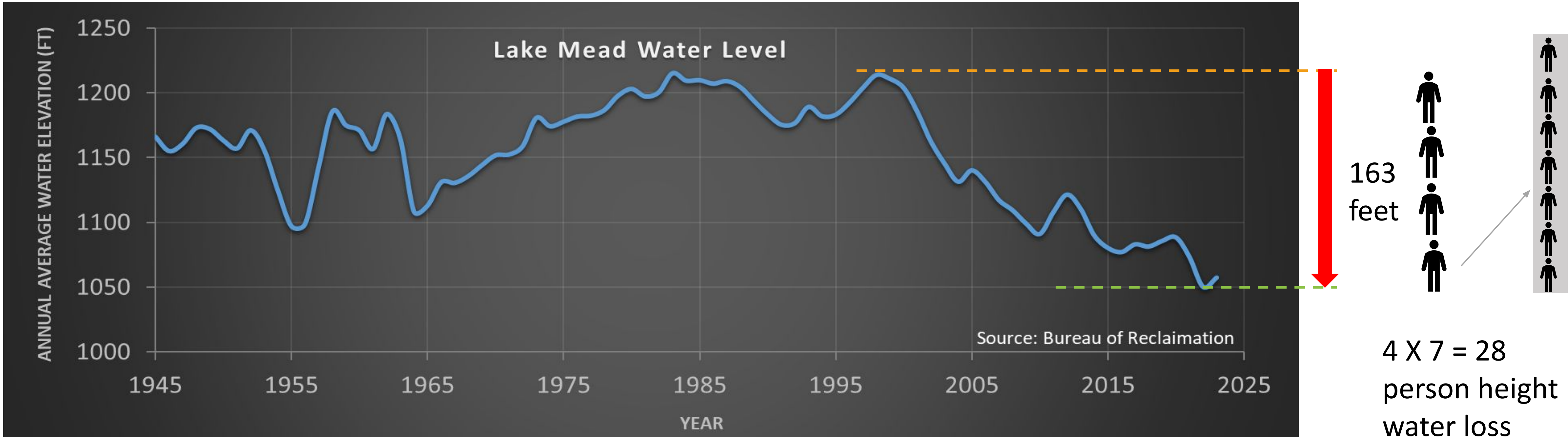
Why do climate models underpredict low-frequency hydroclimate variability?

Sanjiv Kumar, Ph.D.
Auburn University

Hoover Dam

Lake Mead Water Level Update



4 X 7 = 28 person height water loss between 1998 and 2022

After reaching its minimum annual elevation of 1050 feet in 2022, Lake Mead exhibited an increase of 8 feet in 2023.

Background 1: Red-noise process

White noise

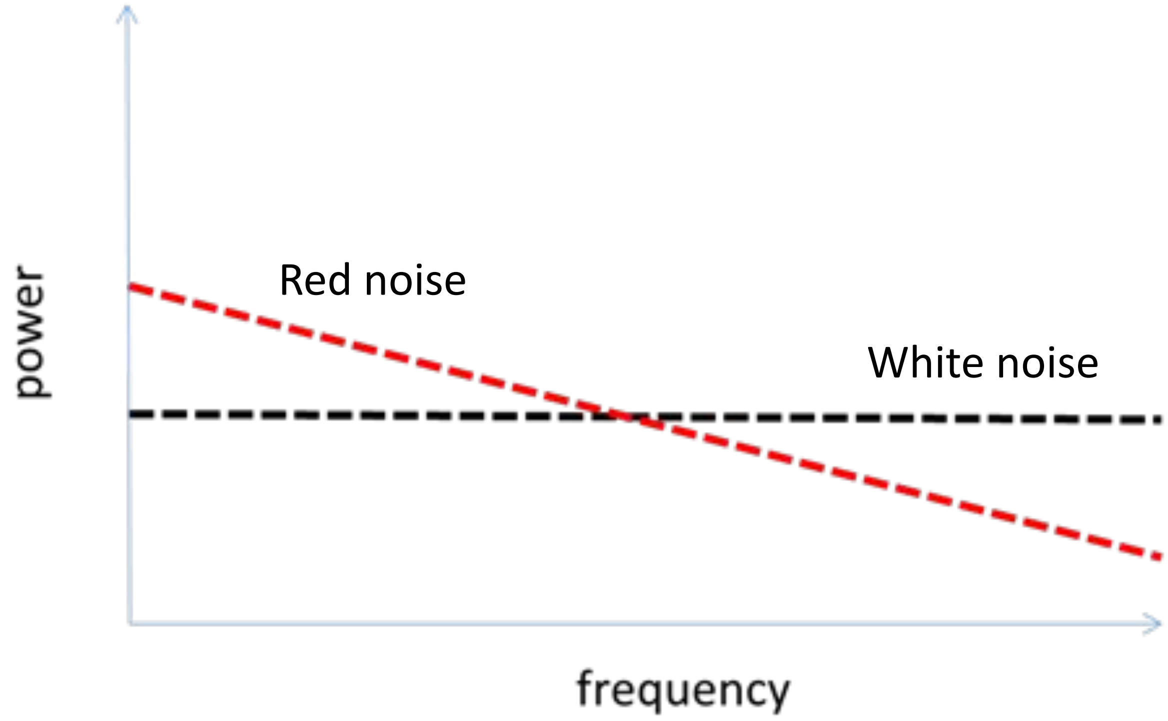
$$\frac{dx}{dt} = \varepsilon \qquad (1)$$

No dependency of x on the previous state

Red noise

$$\frac{dx}{dt} = \lambda x + \varepsilon \qquad (2)$$

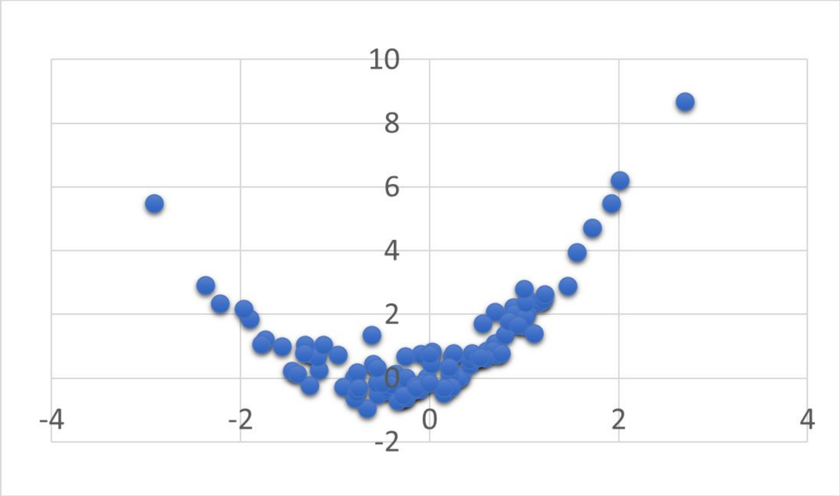
Dependency of x on the previous state



Background 2: Central-Limit Theorem

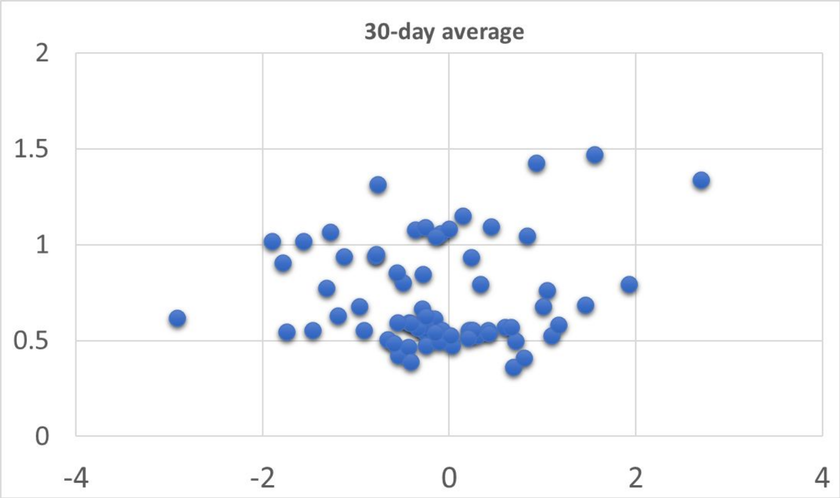
- Linear versus non-linear model

$$y = x + x^2 + \epsilon$$

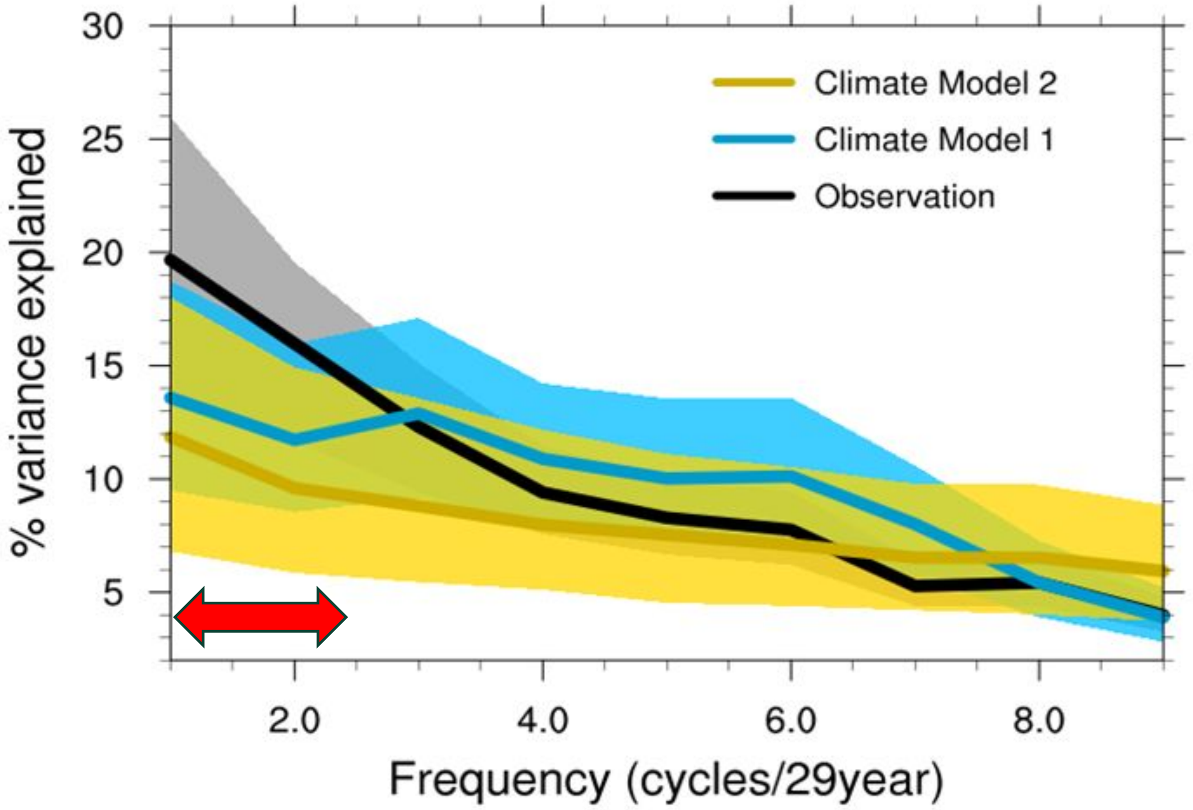


- Central-Limit Theorem (CLT) – effect of averaging

CLT states that the distribution of the sum (or average) of a large number of independent, identically distributed random variables approaches a normal (Gaussian) distribution, regardless of the original distribution of the individual variables.

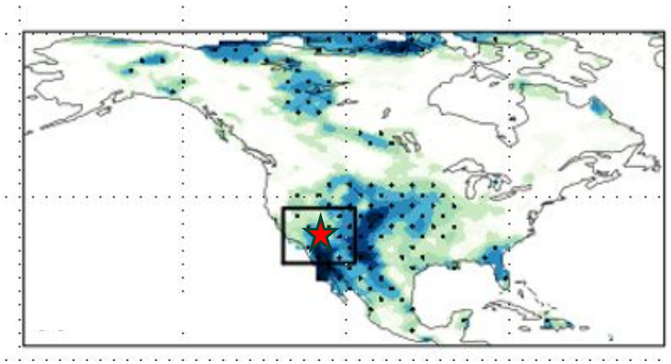


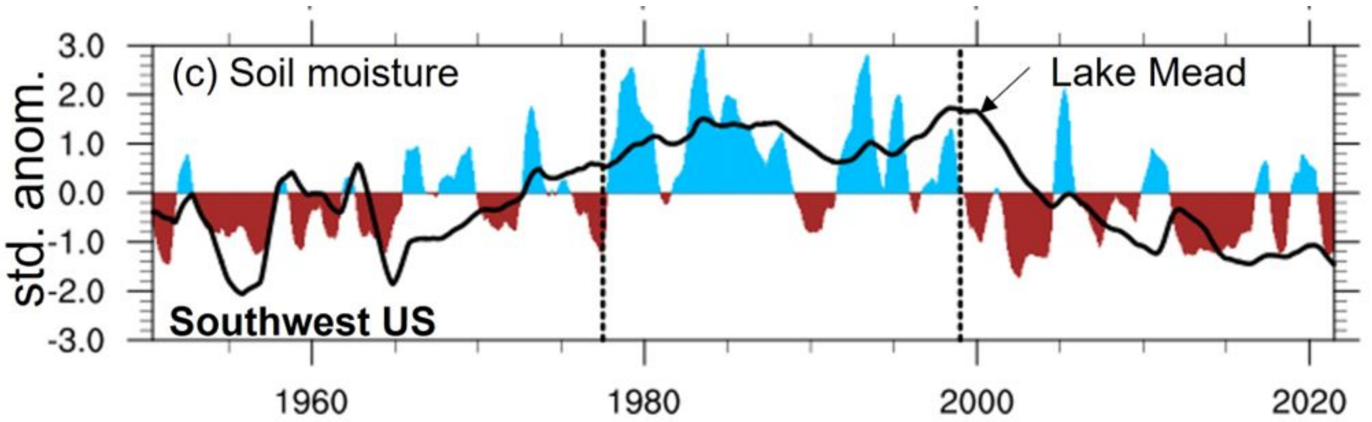
A Red Spectrum of Soil Moisture Variability in the US Southwest



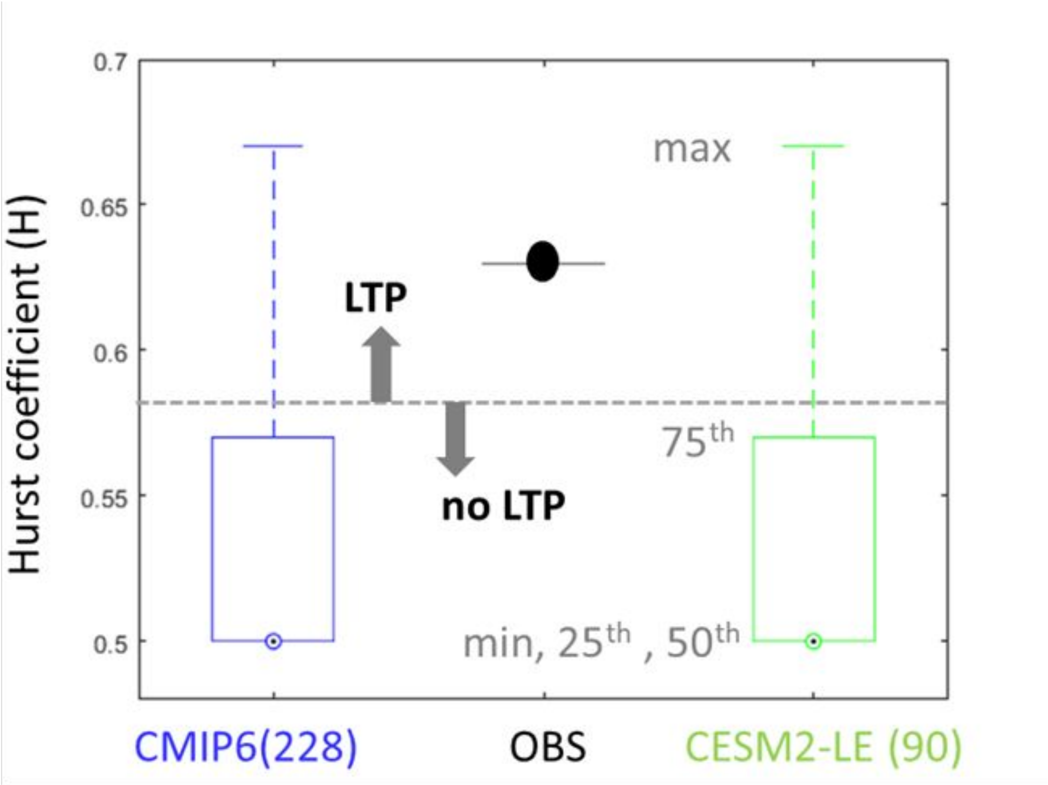
- Higher power at a lower frequency
- Climate Models underestimate those low-frequency soil moisture variability

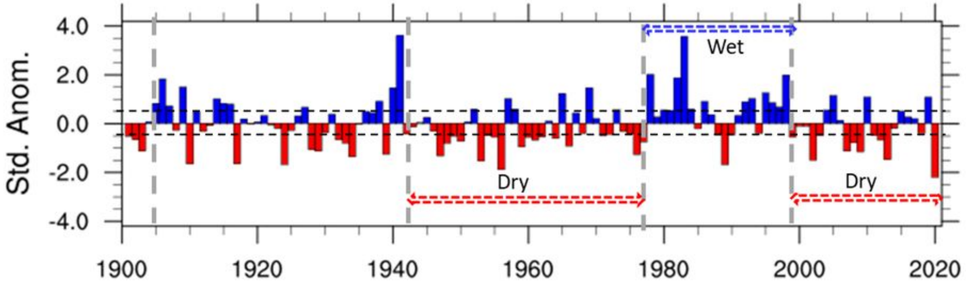
Kumar, Dewes et al. (2023); Earth's Future





Many different names and manifestations: Underestimation of low-frequency precipitation variability





Precipitation anomaly in the US Southwest (Observation, Climate Research Unit)

- **Long-term Persistence (LTP)** Quantified using the **Hurst Coefficient** (for method, See Kumar et al., 2009, and 2013)
- 90% of CMIP6 and CESM2-LE ensembles show a smaller persistence than the observations

The problem has continued through generation of climate models

JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 58, No. 5 AMERICAN WATER RESOURCES ASSOCIATION October 2022

Evaluating Global Climate Models for Hydrological Studies of the Upper Colorado River Basin

David W. Pierce, Daniel R. Cayan, Jordan Goodrich, Tapash Das, and Armin Munévar

Research Impact Statement: The latest CMIP6 generation of climate models still have biases in the Upper Colorado River Basin but show clear improvements over previous generations after a simple bias correction is performed.

ABSTRACT: Three generations of global climate models (GCMs), Coupled Model Intercomparison Project version 3 (CMIP3), CMIP5, and CMIP6, are evaluated for performance simulating seasonal mean and annual-to-decadal variability of temperature and precipitation in the Upper Colorado River Basin. Low-frequency precipitation variability associated with drought is a particular focus and found to be a significant model shortcoming. The evaluation includes remote teleconnected atmospheric responses to the Pacific Ocean, including the El Niño/Southern Oscillation and Pacific Decadal Oscillation. GCMs have improved their simulation of the Upper Basin over model generations, but primarily in atmospheric circulation metrics. Persistent winter precipitation biases have changed little, including in multiyear precipitation variability. Users generally bias-corrected GCM data before use; evaluation using a simple spatially and temporally averaged bias correction shows that the CMIP6 models outperform earlier generations after the bias correction, although more complex precipitation biases remain even after the simple bias correction. These model rankings will be useful when selecting GCMs for a variety of hydrological and ecological climate studies in the Upper Basin.

Comparison of Low-Frequency Internal Climate Variability in CMIP5 Models and Observations

ANSON H. CHEUNG

Department of Geosciences, The University of Arizona, Tucson, Arizona

MICHAEL E. MANN

Department of Meteorology and Atmospheric Science, and Earth and Environmental Systems Institute, The Pennsylvania State University, University Park, Pennsylvania

BYRON A. STEINMAN

Department of Earth and Environmental Sciences, and Large Lakes Observatory, University of Minnesota Duluth, Duluth, Minnesota

LEELA M. FRANKCOMBE AND MATTHEW H. ENGLAND

ARC Centre of Excellence for Climate System Science, and Climate Change Research Centre, University of New South Wales, Sydney, New South Wales, Australia

SONYA K. MILLER

Department of Meteorology and Atmospheric Science, and Earth and Environmental Systems Institute, The Pennsylvania State University, University Park, Pennsylvania

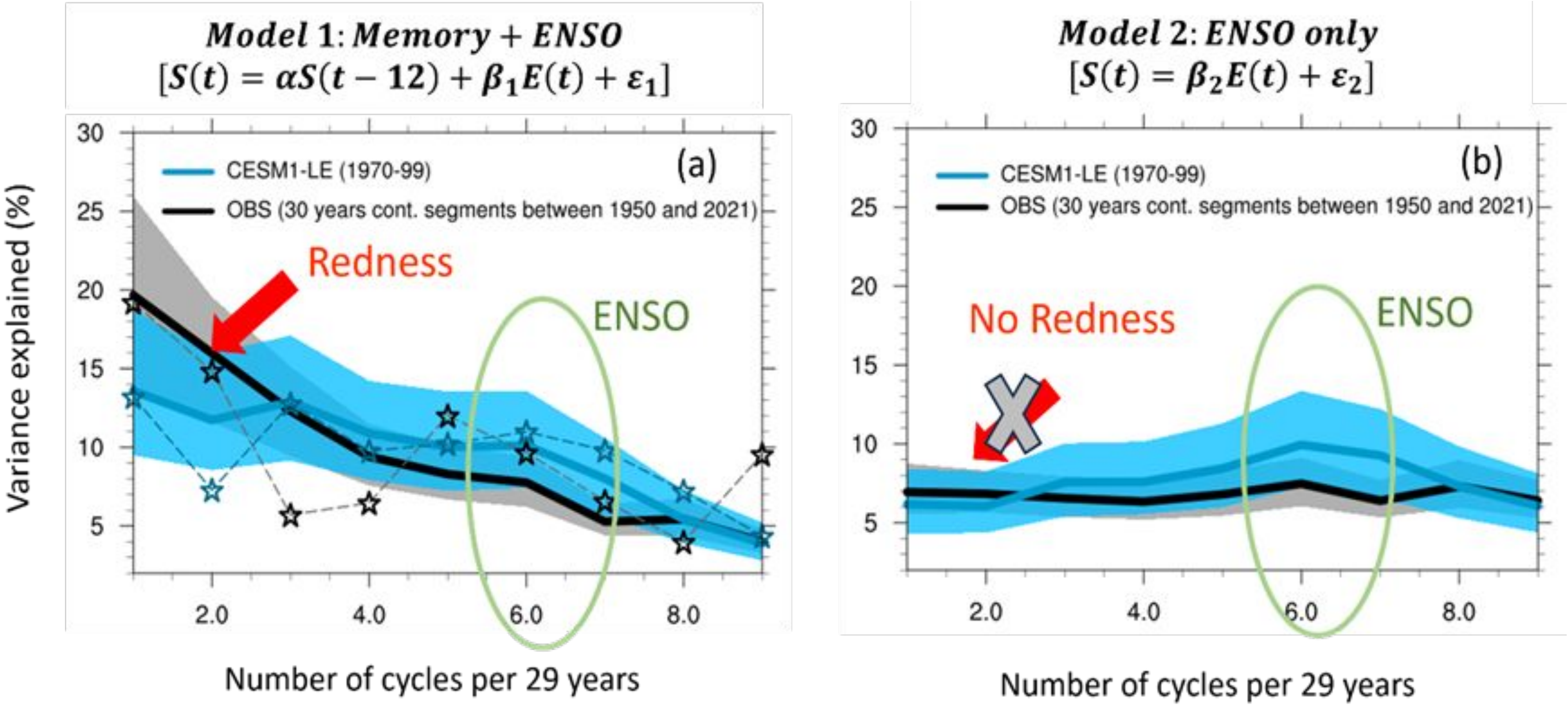
(Manuscript received 4 October 2016, in final form 28 February 2017)

ABSTRACT

Low-frequency internal climate variability (ICV) plays an important role in modulating global surface temperature, regional climate, and climate extremes. However, it has not been completely characterized in the instrumental record and in the Coupled Model Intercomparison Project phase 5 (CMIP5) model ensemble. In this study, the surface temperature ICV of the North Pacific (NP), North Atlantic (NA), and Northern Hemisphere (NH) in the instrumental record and historical CMIP5 all-forcing simulations is isolated using a semiempirical method wherein the CMIP5 ensemble mean is applied as the external forcing signal and removed from each time series. Comparison of ICV signals derived from this semiempirical method as well as from analysis of ICV in CMIP5 preindustrial control runs reveals disagreement in the spatial pattern and amplitude between models and instrumental data on multidecadal time scales (>20 yr). Analysis of the amplitude of total variability and the ICV in the models and instrumental data indicates that the models underestimate ICV amplitude on low-frequency time scales (>20 yr in the NA; >40 yr in the NP), while agreement is found in the NH variability. A multiple linear regression analysis of ICV in the instrumental record shows that variability in the NP drives decadal-to-interdecadal variability in the NH, whereas the NA drives multidecadal variability in the NH. Analysis of the CMIP5 historical simulations does not reveal such a relationship, indicating model limitations in simulating ICV. These findings demonstrate the need to better characterize low-frequency ICV, which may help improve attribution and decadal prediction.

Journal of Climate

A Reddened ENSO Framework



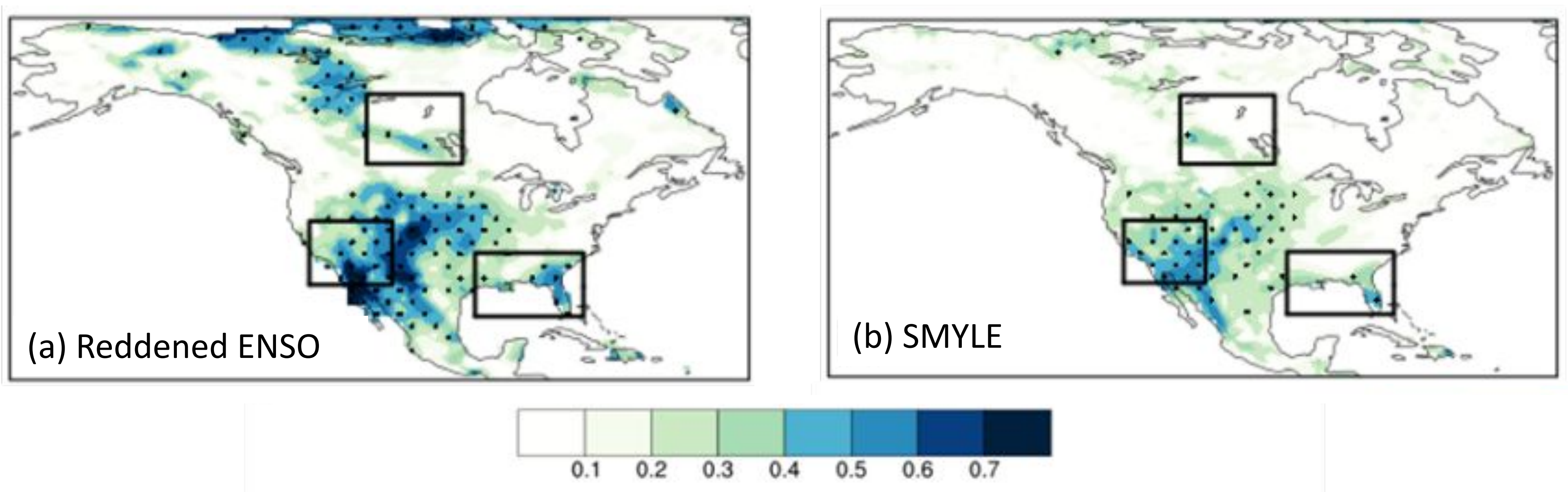
A Reddened ENSO model (Model 1) to predict inter-annual soil moisture variability and its comparison with the ENSO-only model (Model 2)

Assumption: ENSO is accurately predicted for the given year (taken either from observation or the climate model's Large ensemble data).

Kumar, Dewes et al. (2023); Earth's Future

Matt Newman, NOAA

How good is the Reddened ENSO Model in comparison to the dynamical prediction system, e.g., SMYLE?



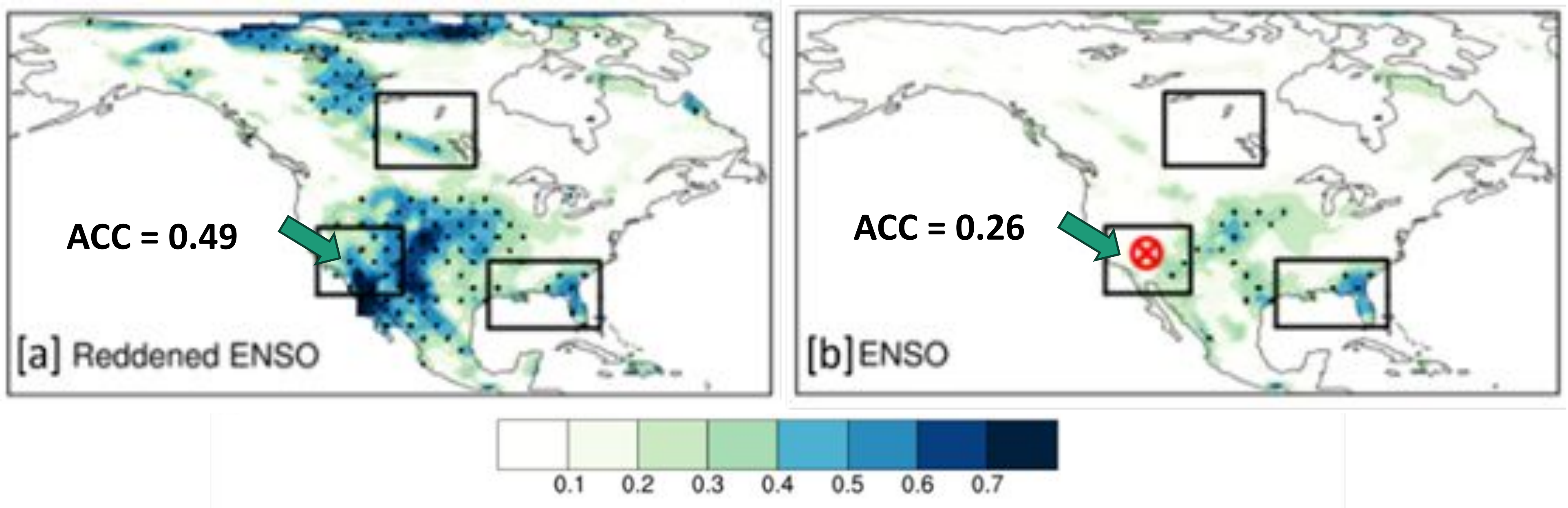
Anomaly correlation between predicted soil moisture and *observation* (ERA5)

Answer – Equally good or even better!

Caveat: Only the top 10 cm soil moisture data is available from SMYLE

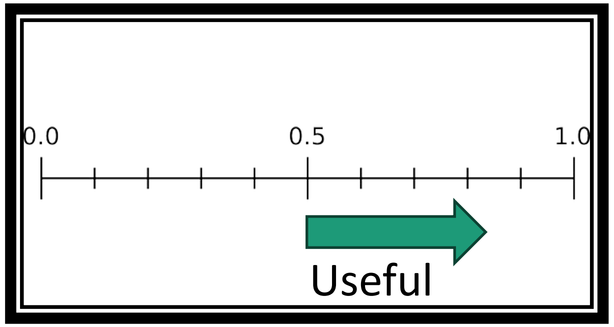
Yanan Duan, AU

Can the ENSO-Only model usefully predict inter-annual hydroclimate variability in North America?

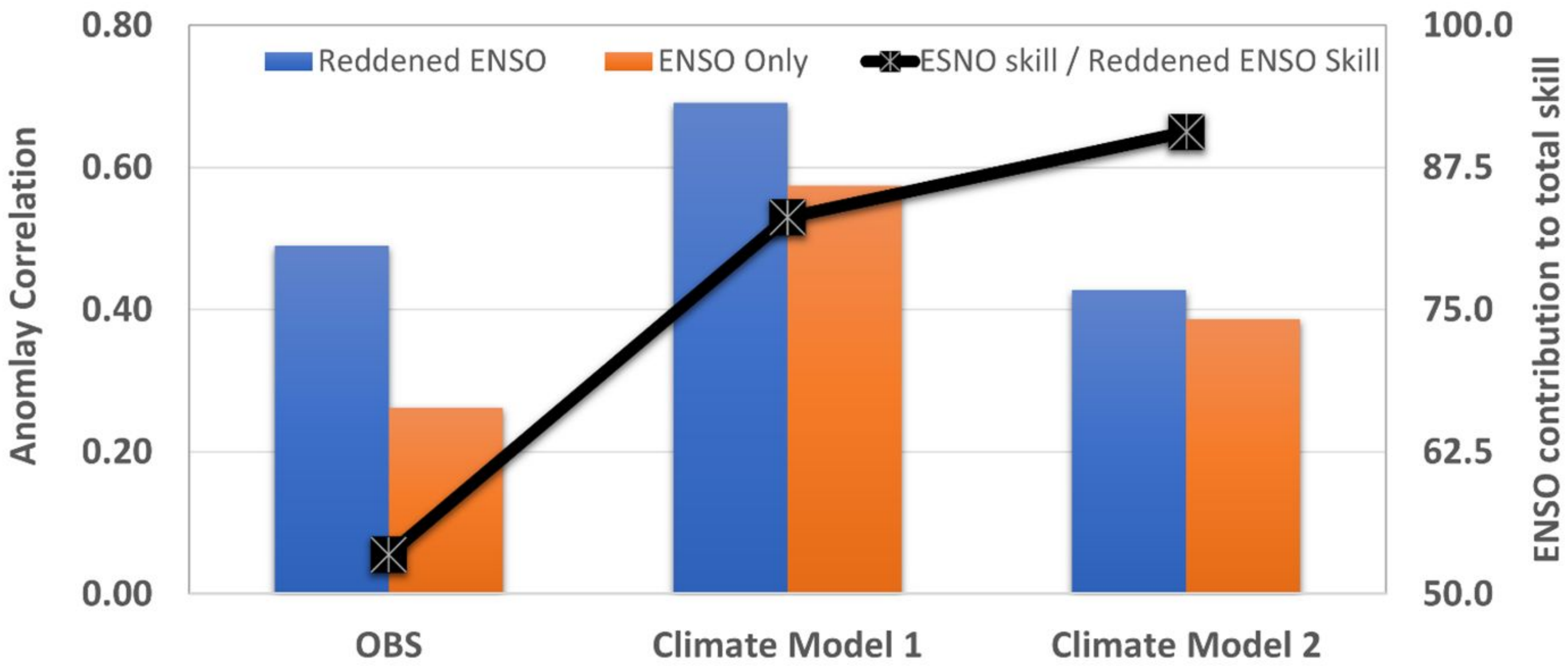


Anomaly correlation between predicted soil moisture and *observation* (ERA5)

Answer – No (using the scale shown)!



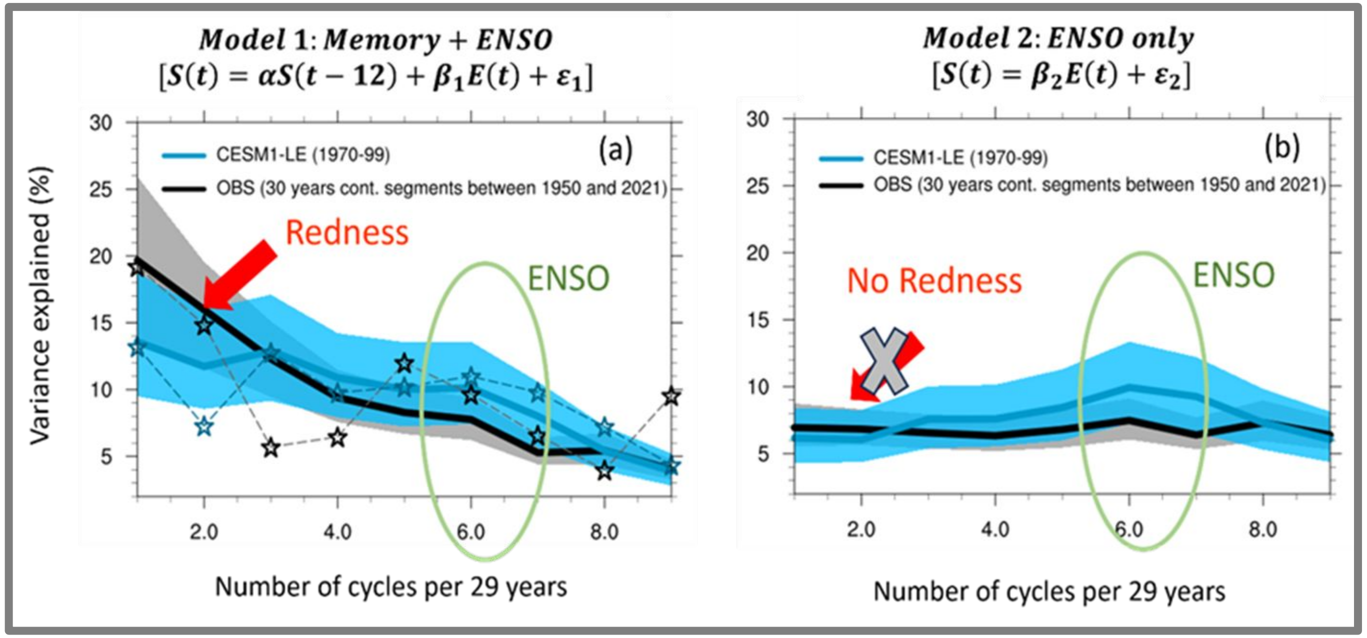
Why do climate models underpredict low-frequency hydroclimate variability?



Answer: **Too much reliance on ENSO in climate models (~90%) leads to underestimation of low-frequency hydroclimate variability** compared to the observations (50%).

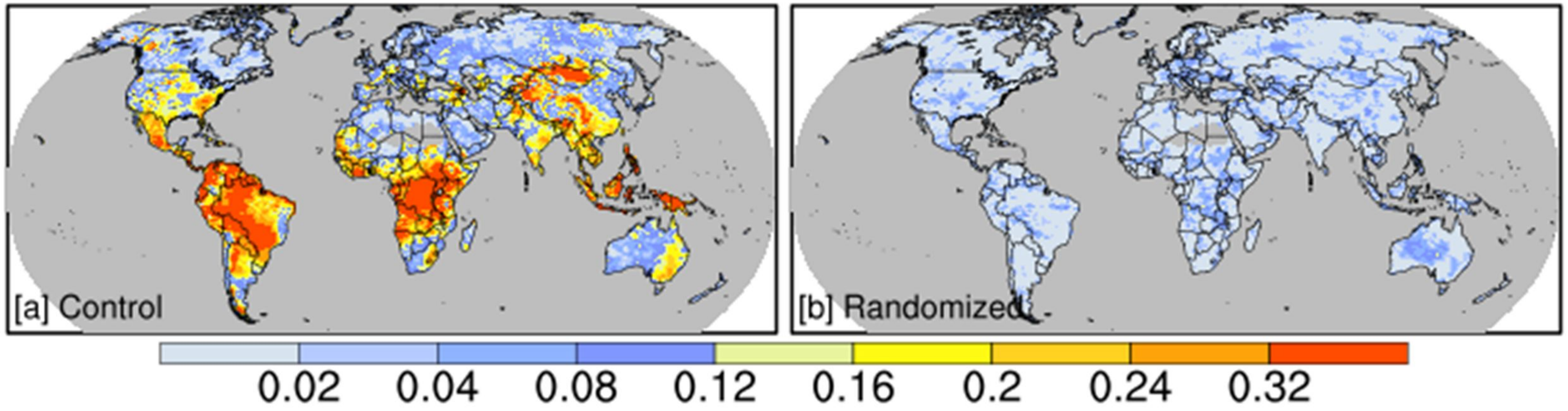
A Land-Atmosphere Interaction Hypothesis

A relatively whiter atmospheric variability input, e.g., precipitation is reddened by the land-atmosphere interaction processes, e.g., soil moisture memory and reemergence, resulting in a long-term variability in hydroclimatic observations, e.g., soil moisture, streamflow, and reservoir-level data. **Contrary, if we remove the land-atmosphere interaction effects, then redness in hydroclimatic data goes away.**

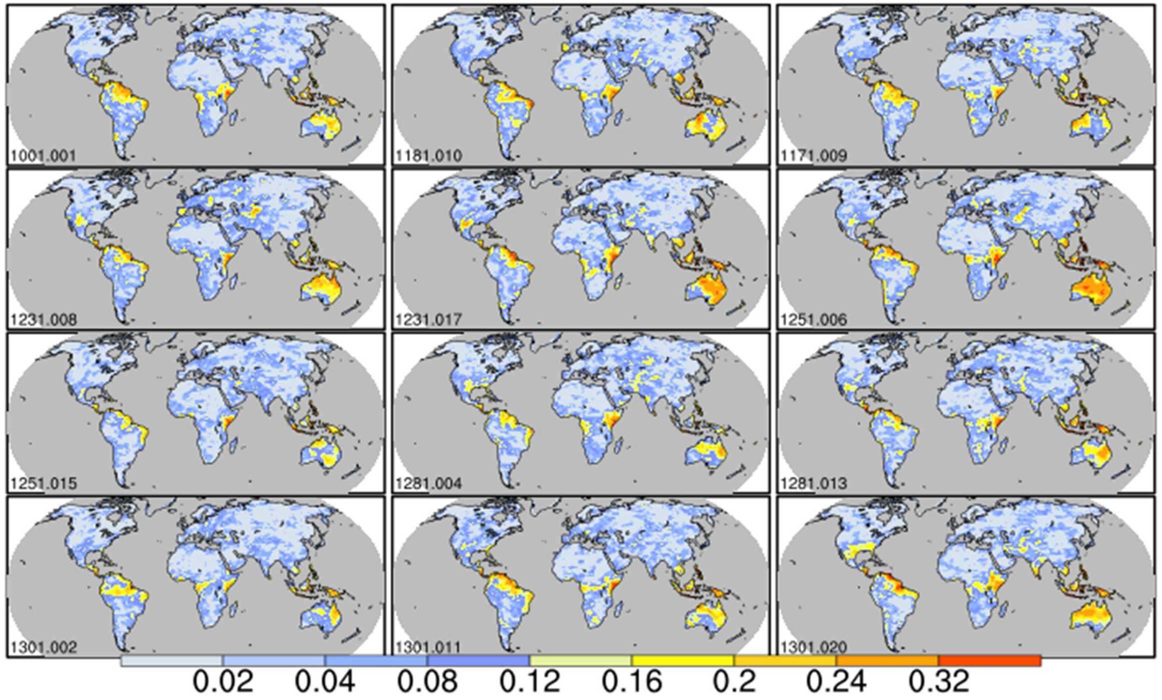


Implications on predictability across scales

One month lead-lag anomaly correlation between soil moisture (t-1) and precipitation (t)



CLM5 offline run using CFSR forcings: (a) Control (OBS), and (b) Randomized forcing

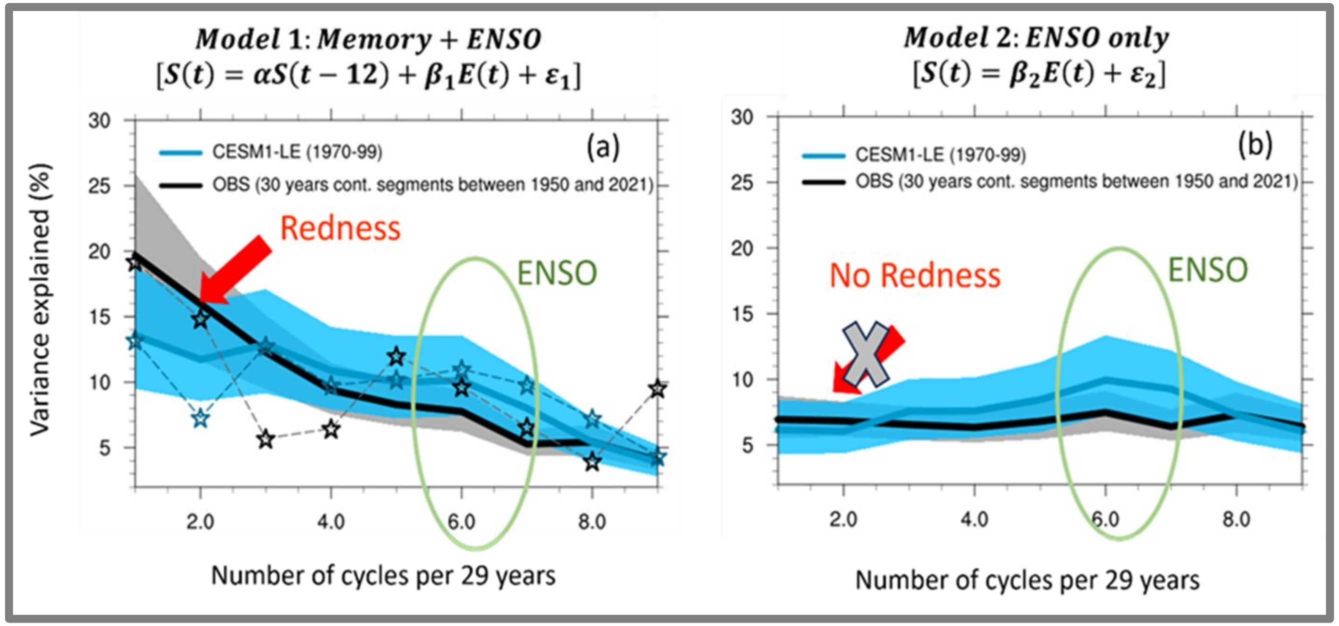


Same as above using CESM2-LE data => look closer to the randomized run than the control run (=> a weak soil moisture to precipitation feedback loop in CESM2)

Montasir Maruf, AU

Summary: A Land-Atmosphere Interaction Hypothesis

A relatively whiter atmospheric variability input, e.g., precipitation is reddened by the land-atmosphere interaction processes, e.g., soil moisture memory and reemergence, resulting in a long-term variability in hydroclimatic observations, e.g., soil moisture, streamflow, and reservoir-level data. **Contrary, if we remove the land-atmosphere interaction effects, then redness in hydroclimatic data goes away.**



References

Kumar, S., Dewes, C. F., Newman, M., & Duan, Y. (2023). Robust changes in North America's hydroclimate variability and predictability. *Earth's Future*, *11*(4), e2022EF003239.

Kumar, S., Merwade, V., Kinter III, J. L., & Niyogi, D. (2013). Evaluation of temperature and precipitation trends and long-term persistence in CMIP5 twentieth-century climate simulations. *Journal of Climate*, *26*(12), 4168-4185.

Kumar, S., Merwade, V., Kam, J., & Thurner, K. (2009). Streamflow trends in Indiana: effects of long term persistence, precipitation and subsurface drains. *Journal of Hydrology*, *374*(1-2), 171-183.