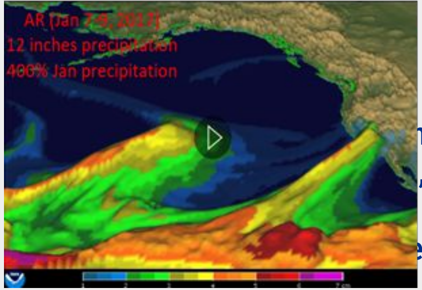
High-Impact Storms and Their Climate Connections

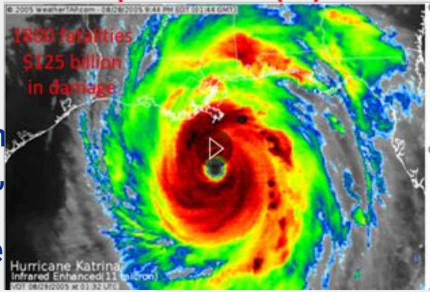
Ming Zhao

Atmospheric Rivers (AR)



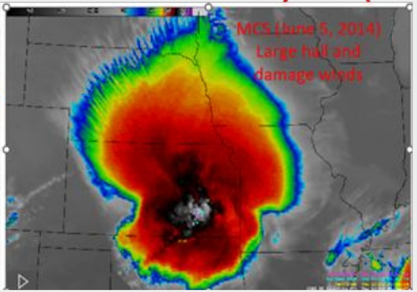
AR (Jan 7-9, 2017)
12 inches precipitation
400% Jan precipitation

Tropical Storms (TS)



1800 fatalities
$125 billion
in damage

Mesoscale Convective System (MCS)



MCS (June 5, 2014)
Large hail and
damage winds

5-Year Review
January 28-30, 2025

Motivation

Objective: Enhance the modeling and scientific understanding of high-impact storms and their climate connections, focusing on atmospheric rivers (AR), tropical storms (TS), and mesoscale convective systems (MCS), along with their associated precipitation and cloud radiative effects, in both present-day and changing climates.

Key questions:

- How does GFDL's latest atmospheric model perform in simulating AR, TS, and MCS, along with their associated precipitation, in present-day and warmer climates?
- What are the challenges in projecting regional changes in AR, TS, and MCS in the coming decades?

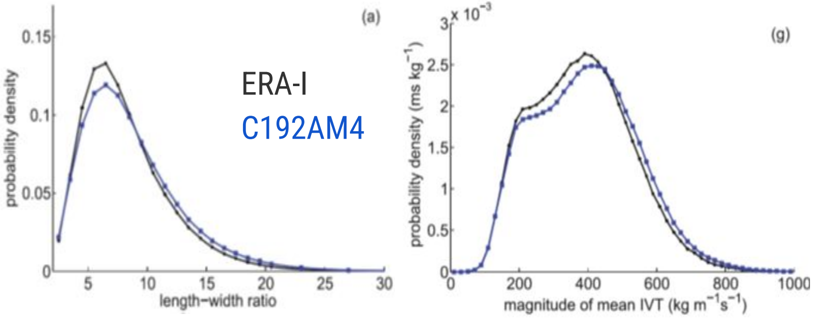
OAR mission is to conduct research to understand and predict the Earth system; develop technology to improve NOAA science, service, and stewardship; and transition the results so they help us meet the challenges faced by society.

Simulations of atmospheric rivers (AR) using GFDL C192AM4

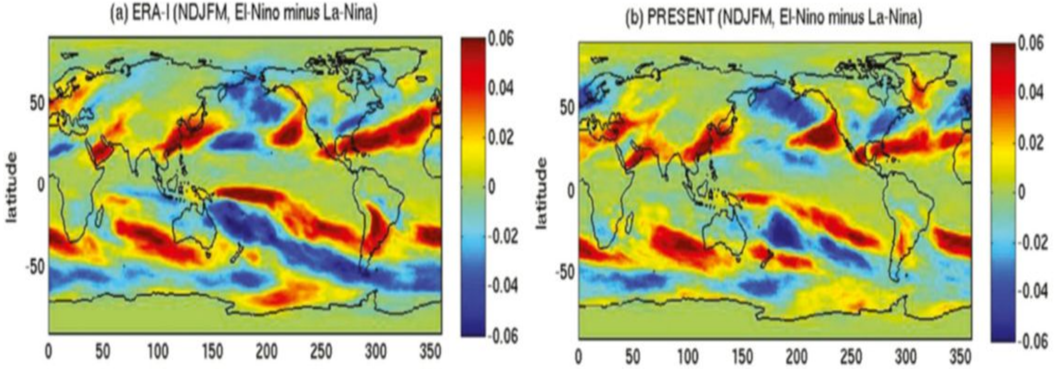
Zhao 2020, *J. Climate* (highlighted in BAMS)

Compared to ERA-Interim, C192AM4 captures key AR characteristics, including distributions of length, width, length-width ratio, location, and IVT magnitude and direction, with the model tending to produce narrower and stronger ARs.

C192AM4 reasonably reproduces the observed geographical distribution of AR frequency and its variability in response to large-scale circulation patterns like ENSO, NAM/SAM, and PNA, despite significant regional biases.



Comparison of ERA-Interim and C192AM4 simulated PDFs for AR length-width ratio and mean IVT magnitude.



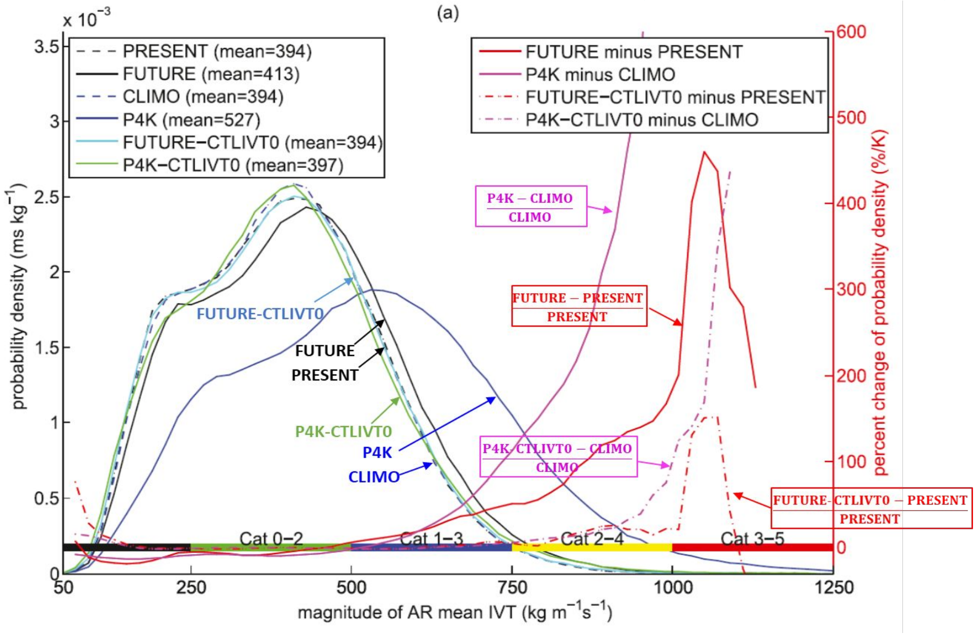
Comparison of Nov-May AR frequency differences between El Niño and La Niña conditions in ERA-I and C192AM4.

Quantification of AR Response to Warming Depends on IVT Thresholds

C192AM4 produces a modest increase (1-2%/K) in AR occurrence frequency with warming, but a larger increase in stronger ARs, with Cat 3-5 ARs rising by 100-300%/K. The global mean AR intensity increases by 5-8%/K, roughly following C-C scaling of vapor. AR response to warming depends on the IVT thresholds used in warmer climate simulations.

PRESENT: C192AM4 present-day simulation (1980-2014)
FUTURE: As in PRESENT but for future SSTs (2015-2050)
CLIMO: C192AM4 present-day climatological simulation
P4K: As in CLIMO, but with SST + 4K
P4K-CTLIVT0: As P4K, but using CLIMO IVT threshold
FUTURE-CTLIVT0: As FUTURE, but using PRESENT IVT threshold

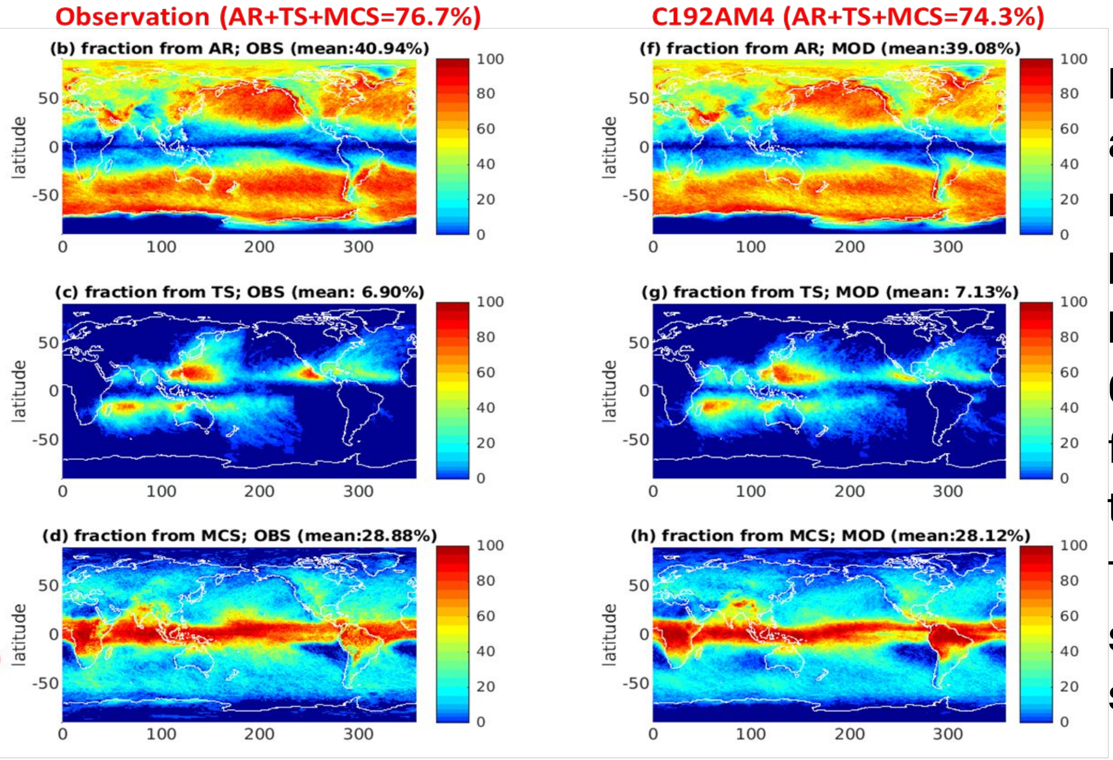
Zhao 2020, *J. Climate* (highlighted in BAMS)



Left legend/ordinate: PDF of mean AR IVT magnitude from two pairs of warming simulations. Right legend/ordinate: percentage change in PDF between warmer and control experiments.

C192AM4 realistically simulates observed extreme daily precipitation events

Zhao 2022, *J. Climate*



Distribution of the local 1% heaviest daily precipitation events from AR, TS, and MCS days.

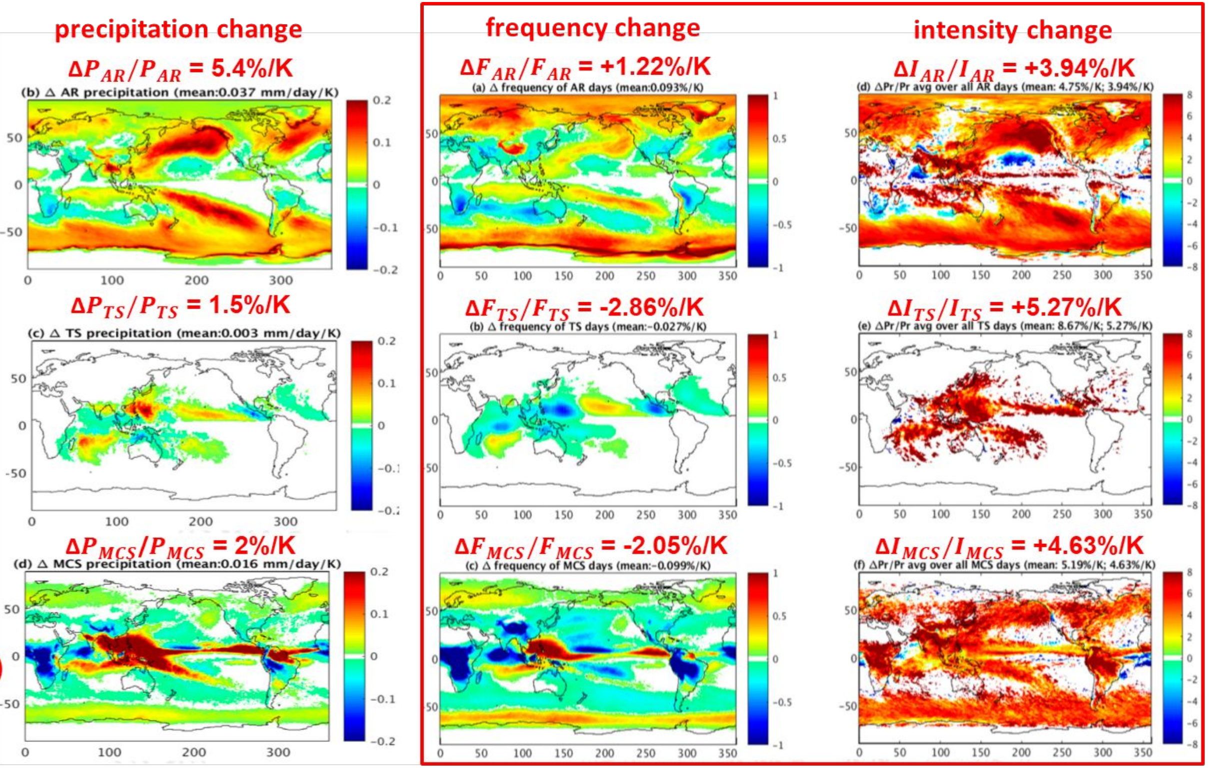
Despite their occasional occurrence, AR, TS, and MCS days account for ~55% of global mean precipitation and ~75% of extreme precipitation exceeding the local 99th percentile.

C192AM4 realistically simulates the observed frequency of AR, TS, and MCS days, along with their mean and extreme precipitation.

The model's quality in simulating present-day storm activities indicates its utility for studying storm changes in a warmer climate.

C192AM4 simulated changes in AR-, TS-, MCS-associated precipitation under warming

Zhao 2022, *J. Climate*



Changes in AR, TS, and MCS precipitation and their frequency-intensity decomposition.

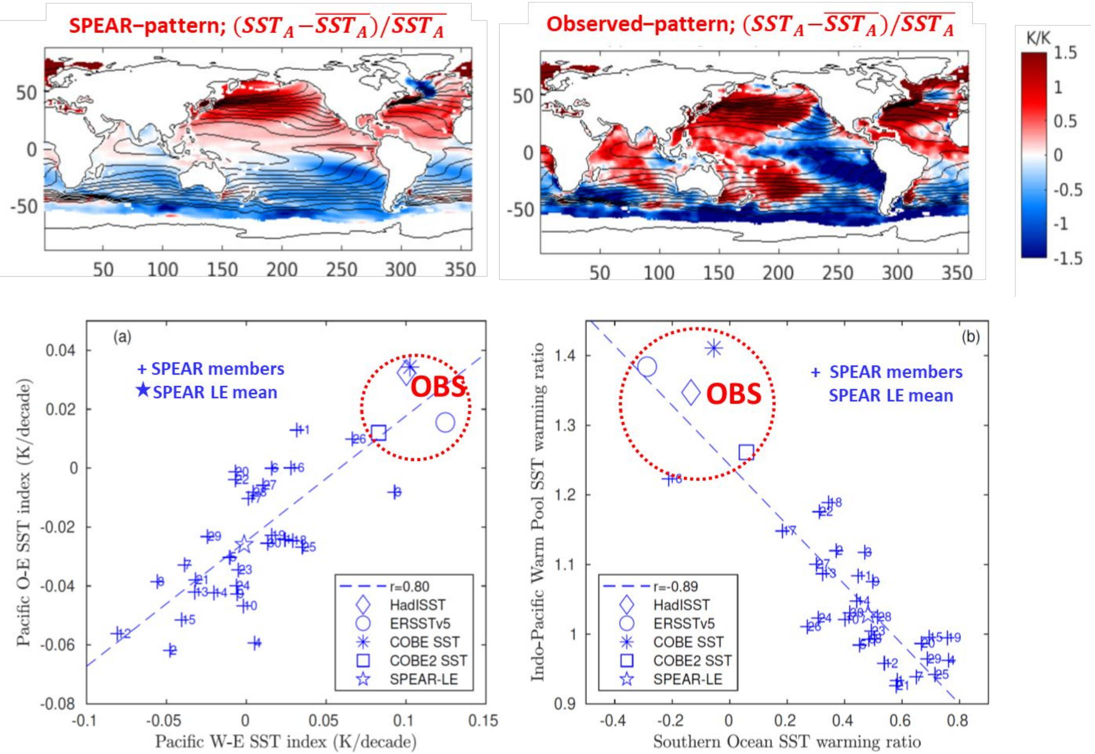
In a warmer climate, C192AM4 projects a mix of increases and decreases in frequency of AR, TS, and MCS days.

The intensity of AR, TS, MCS mean precipitation increases by 4-5%/K .

Intensity increases are mainly caused by the moistening of the atmosphere, with the changes due to dynamic and microphysical factors playing a secondary role.

1979-2020 SST trend patterns in GFDL SPEAR & observation

[Zhao and Knutson 2024, *npj Clim. Atmos. Sci*]

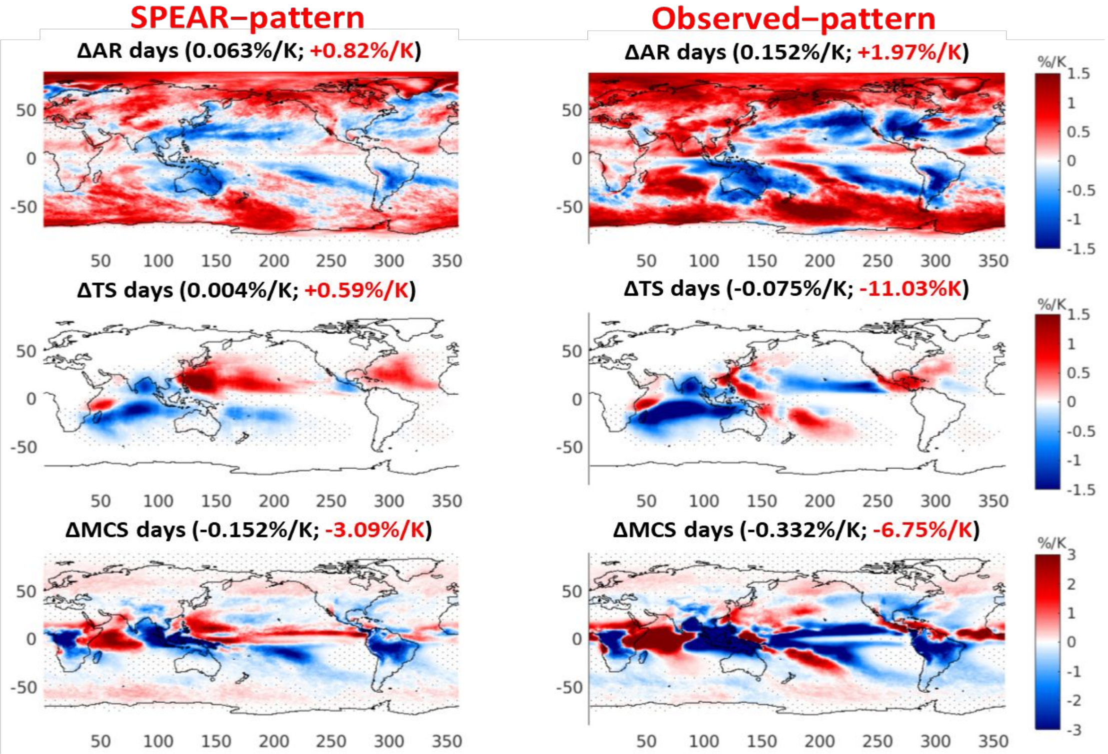


Comparison of GFDL SPEAR LE and observed SST warming patterns

GFDL SPEAR, like all other state-of-the-art GCMs, struggles to accurately simulate recent SST trend patterns. The biases include excessive relative warming in the E. Pacific and Southern Ocean and insufficient relative warming over the Indo-Pacific Warm Pool. These biases are correlated and significant, even when considering internal variability.

AR, TS, and MCS frequency changes depend on SST warming patterns

Zhao and Knutson 2024, *npj Clim. Atmos. Sci*



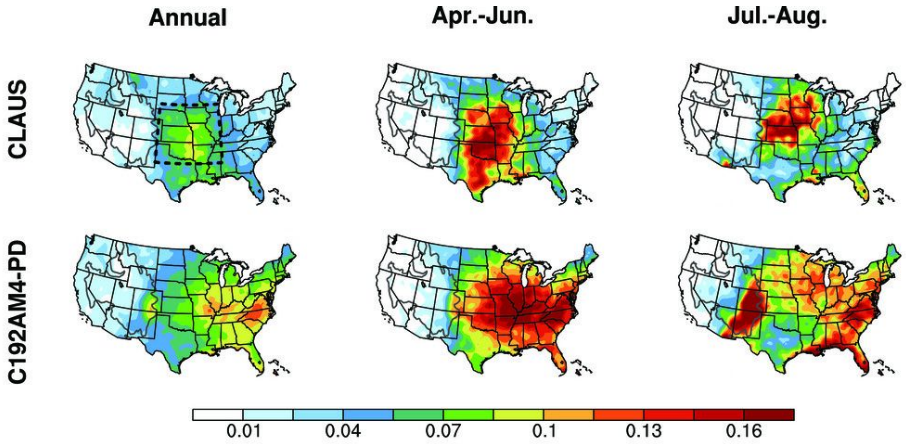
Change in AR, TS, and MCS frequency with the two warming patterns

The biases in SST warming patterns have profound implications for near-term projections of AR, TS, MCS, and global hydrological and climate sensitivity. If future SST warming continues to follow the observed pattern rather than model simulations, our results suggest: 1) drastically different predictions of extreme weather and hydroclimate changes, 2) stronger global hydrological sensitivity to warming, and 3) substantially less global mean warming due to stronger negative feedback and lower climate sensitivity.

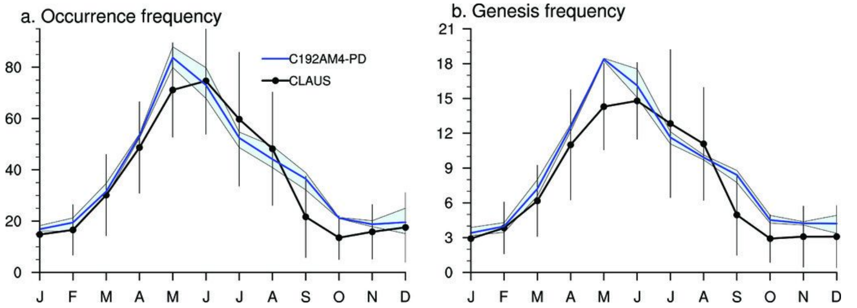
Simulation of US mesoscale convective systems using C192AM4

Dong et al. 2023, *J Climate*

C192AM4 reasonably simulates the spatial distribution, seasonality, and genesis frequency of MCSs over the central United States during April–June and July–August. It accurately reproduces observed MCS duration, translation speed, size, and the associated large-scale circulation patterns. However, it misrepresents the diurnal cycle of MCSs and overestimates their frequency over the eastern United States.



Comparison of MCS occurrence frequency over the U.S. between C192AM4 and observational estimates from CLAUS

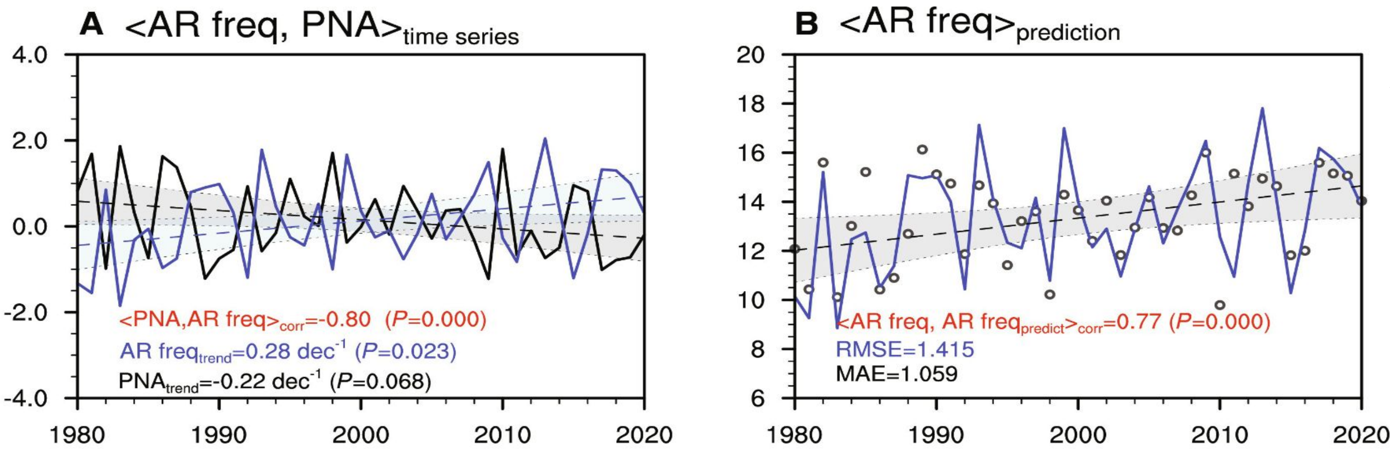


Comparison of the seasonal cycle of MCS occurrence and genesis frequencies over the central U.S. between C192AM4 and CLAUS estimates

Observed and C192AM4 simulated ARs trends over the Eastern US

Dong et al. 2024, *Sci. Adv.*

Using observations and C192AM4, we find a significant increase (~10% per decade) in winter AR frequency over the eastern U.S. in the past four decades. A strong correlation (R = 0.8; P < 0.001) exists between interannual AR variations and the PNA teleconnection pattern, confirmed by large-ensemble simulations. A statistical model based on this linkage predicts AR frequency at monthly and seasonal scales using the PNA index, which is crucial for addressing AR-related extreme precipitation and flooding concerns



A: Time series of winter PNA index and normalized AR frequency based on ERA5.

B: Time series of winter AR frequency (blue line) and the predicted AR frequency (black circle) based on a statistical model