Human-driven increase in Pacific Trough frequency intensify winter-spring North American heat extremes

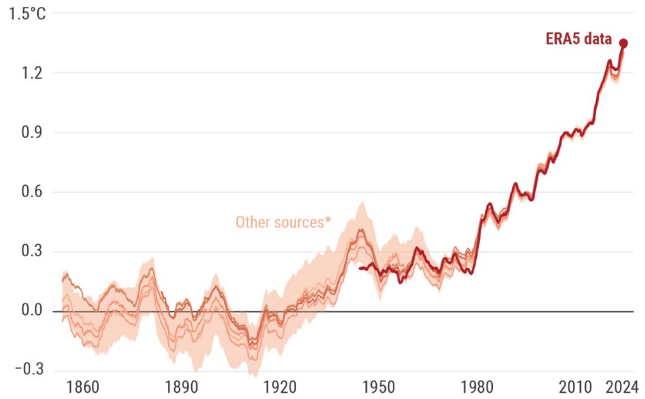
Jhayron S. Pérez-Carrasquilla, Maria J. Molina, Kirsten J. Mayer, Katherine Dagon, Isla R. Simpson, John T. Fasullo

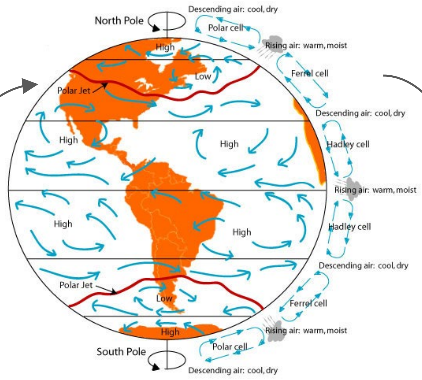
Department of Atmospheric and Oceanic Science (AOSC). University of Maryland (UMD), College Park.
Climate and Global Dynamics Laboratory, US NSF National Center for Atmospheric Research (NCAR).

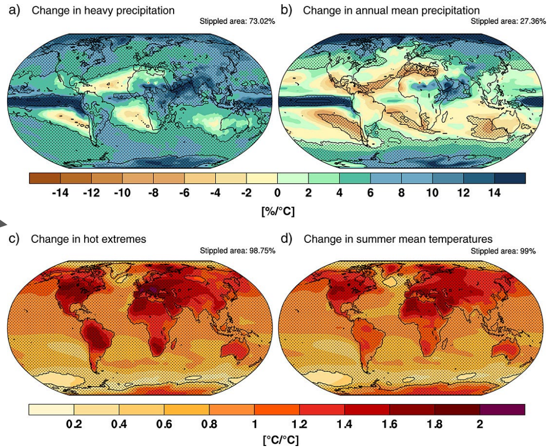
June 10, 2025

jhayron@umd.edu

Motivation: Uncertain large-scale circulation changes







There is high uncertainty in long-term changes in the large-scale circulation and the surface response: lack of understanding and model-observation discrepancies.

Images from https://climate.copernicus.eu/, https://www.labxchange.org/,
Fischer et al (2014). Models agree on forced response pattern of precipitation and temperature extremes, Geophys. Res. Lett.
Shaw et al (2024). Emerging climate change signals in atmospheric circulation. AGU Adv.
Simpson et al (2025). Confronting Earth System Model trends with observations. Sci. Adv.

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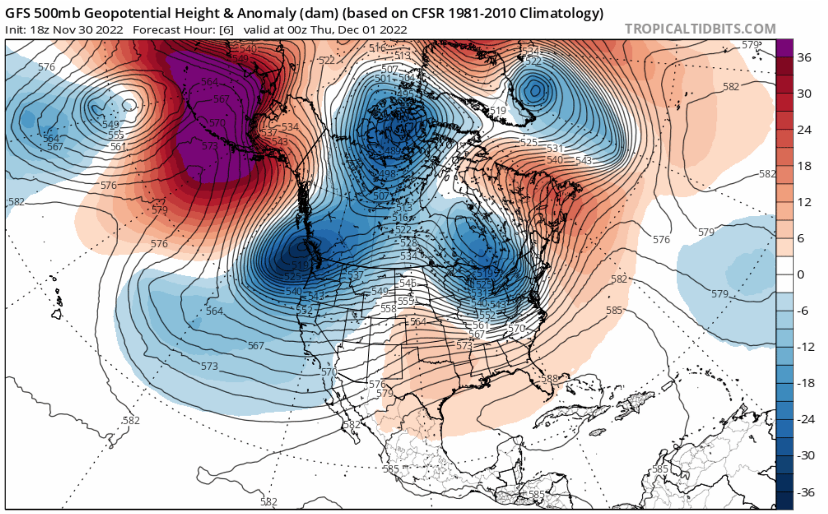
Introduction: Weather regimes

Large-scale atmospheric flow configurations that are persistent (last around 5 days) and recurrent.

- A way to "simplify" the representation of large-scale dynamics
- Significant impacts on the surface



How are weather regime characteristics changing long-term?

Lee et al (2023). A New Year-Round Weather Regime Classification for North America. J. Climate
Michelangeli et al (1995). "Weather regimes: Recurrence and quasi stationarity." Journal of Atmospheric Sciences 52.8
Image from: https://www.tropicaltidbits.com

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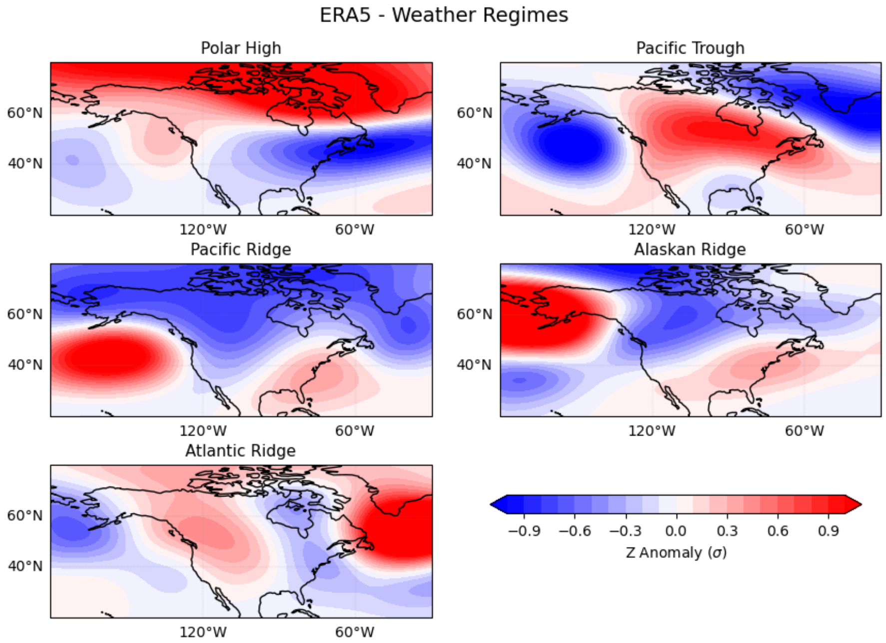
Introduction: Weather regimes

Steps for daily classification:

- Computing 500 hPa geopotential height anomalies, detrending (regionally) and standardizing
- Extracting principal components
- k-means clustering (unsupervised ML)



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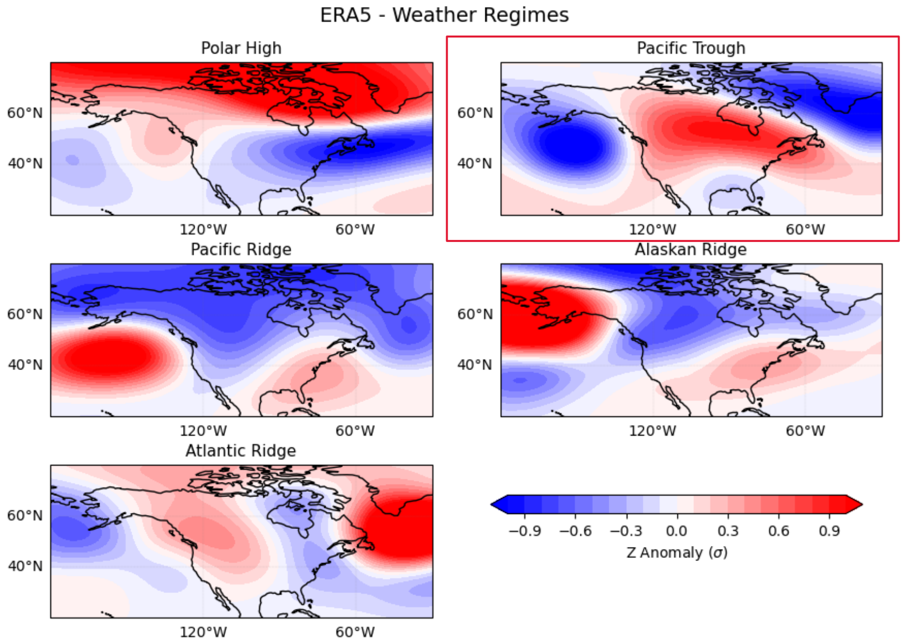

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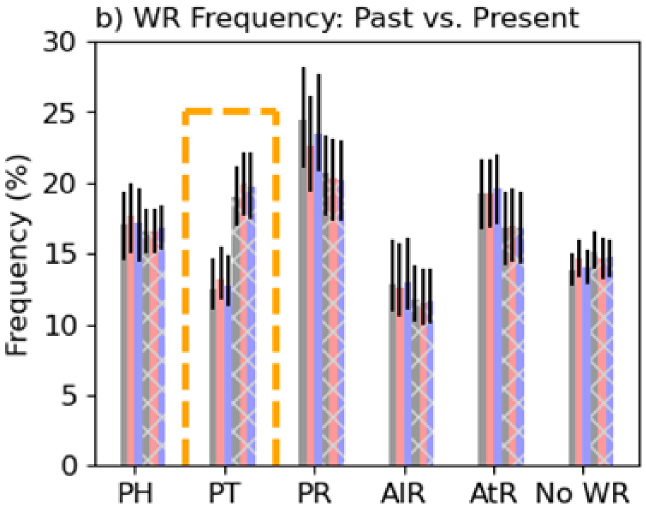
Results: Changes during winter-spring

Winter-spring Pacific Trough frequency has increased from 12% to 19%



Present = 1994-2023; Past = 1948-1977

ERA5 (gray), JRA3Q (red), NCEP/NCAR (blue)
Black bars: uncertainty bootstrapping years within each 30-year period

Pérez-Carrasquilla et al (2025, in prep). Human-driven increase in North American Pacific Trough intensifies winter and spring heat extremes.

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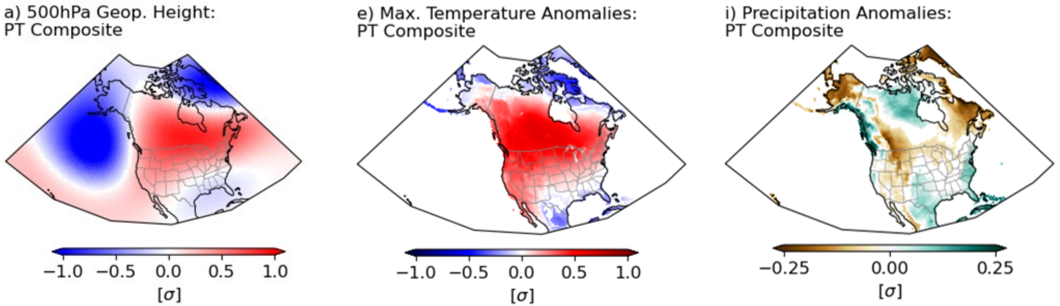
Results: Pacific Trough characteristics



Results for winter-spring

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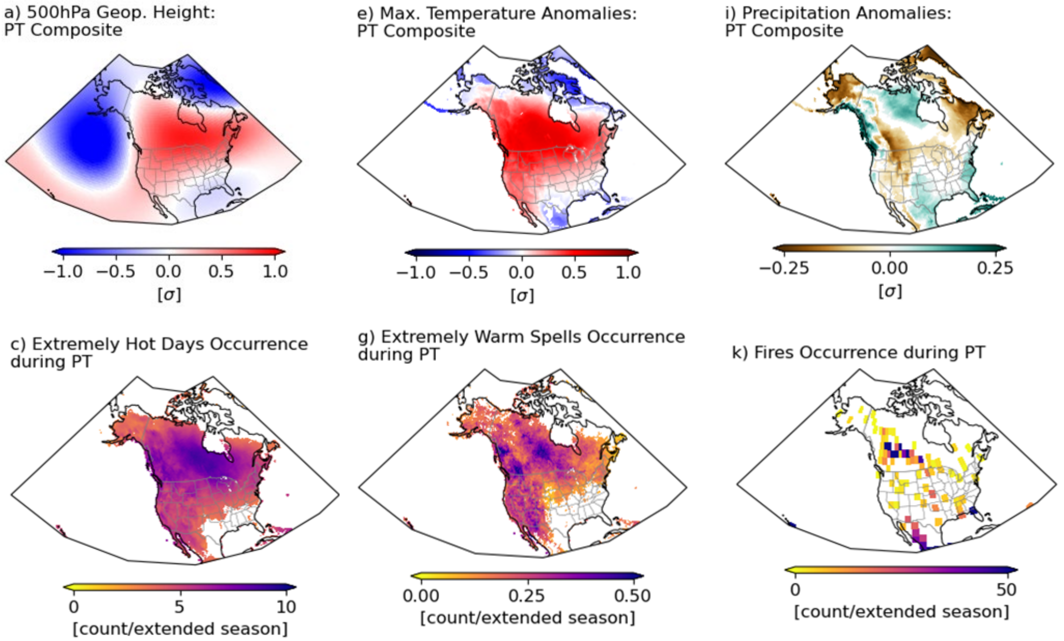
Results: Pacific Trough characteristics



Results for winter-spring

Extremely hot days > TX90p w.r.t. 1961-1990
Extremely warm spells = 6 consecutive days > TX90p
Fires from MODIS 2004-2023

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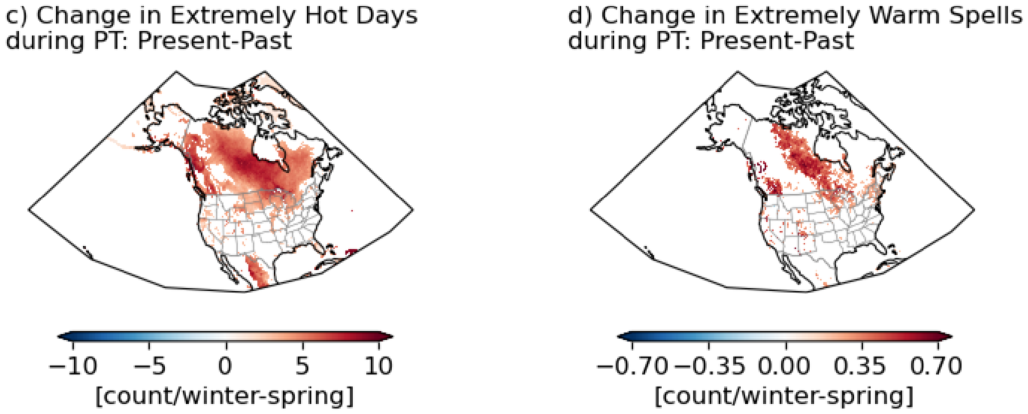
Results: Pacific Trough increase

Impact on extremes



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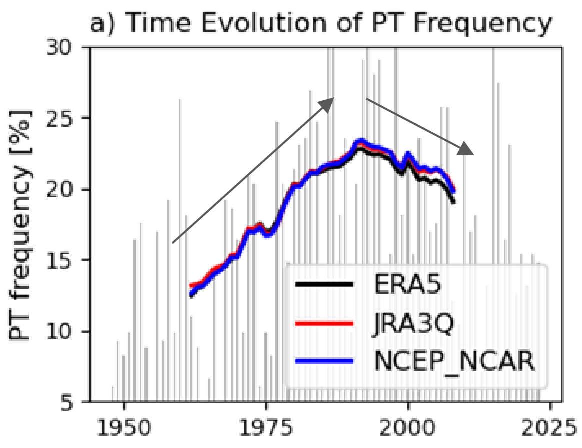
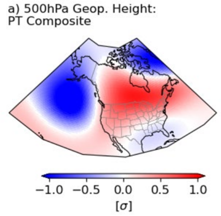
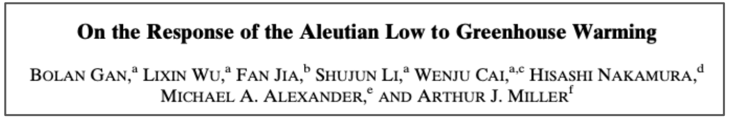
Results: Pacific Trough increase



Contradictory signals over time, consistent with the literature for the Aleutian low





On the Response of the Aleutian Low to Greenhouse Warming

Bolan Gan,[a] Lixin Wu,[a] Fan Jia,[b] Shujun Li,[a] Wenju Cai,[a,c] Hisashi Nakamura,[d] Michael A. Alexander,[e] and Arthur J. Miller[f]

Anthropogenic Aerosols Contribute to the Recent Decline in Precipitation Over the U.S. Southwest

Yan-Ning Kuo[1], Hanjun Kim[1], and Flavio Lehner[1,2,3]

Attributing the U.S. Southwest's Recent Shift Into Drier Conditions

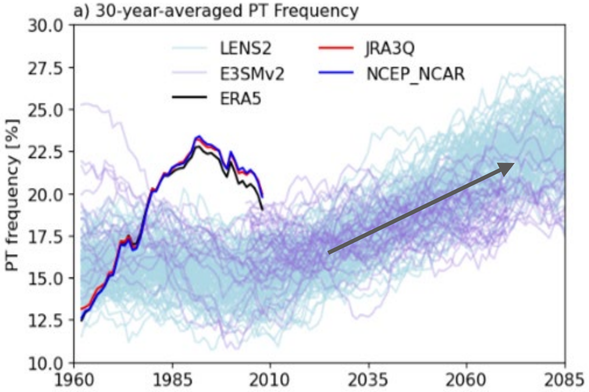
Flavio Lehner[1], Clara Deser[1], Isla R. Simpson[1], and Laurent Terray[2]

Pérez-Carrasquilla et al (2025, in prep). Human-driven increase in North American Pacific Trough intensifies winter and spring heat extremes.

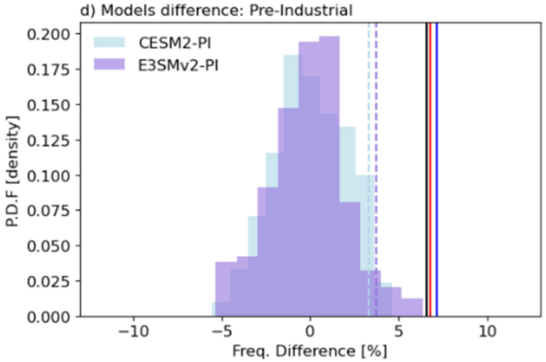
- ➔ How well is this change represented by ESMs?
- ➔ Could the changes be explained by internal variability or some specific forcing?

Pérez-Carrasquilla et al (2025, in prep). Human-driven increase in North American Pacific Trough intensifies winter and spring heat extremes.

Results: Changes in ESMs



Coupled climate models: CESM2-LE and E3SMv2-LE



Differences between all periods of 76 years within pre-industrial simulations.

Models show an increase but in the future, not the past.

The observed increase is outside modeled internal variability

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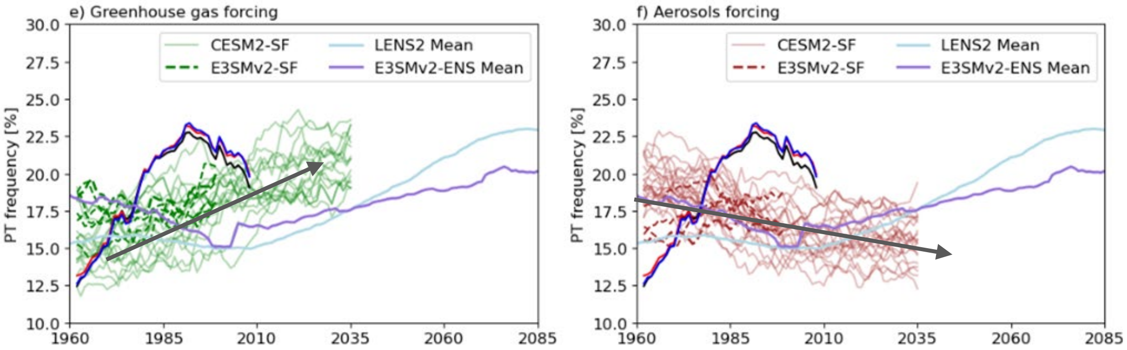
Results: Changes in ESMs - Single forcing experiments

The observed Pacific Trough increase is only possible in models due to increasing GHGs. Aerosols forcing produces the opposite increasing trend.



CESM2 and E3SMv2 single forcing experiments

Under largely increased CO_2 conditions, the PT frequency increase, as well as the associated surface response, are of similar magnitude to observations.

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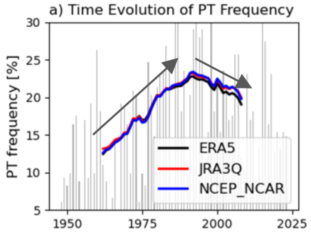
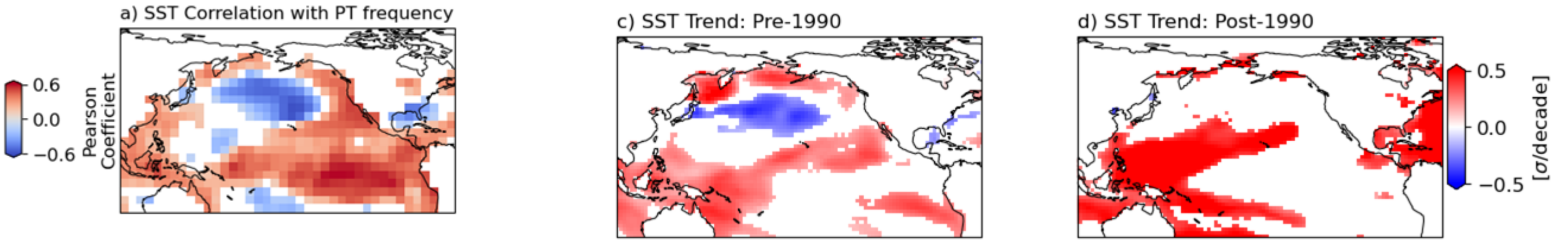
Results: Physical drivers



ERA5 and Kaplan v2



Correlations of DJFMAM averages (1950-2023).

Pacific SSTs control a large part of the variability in PT frequency

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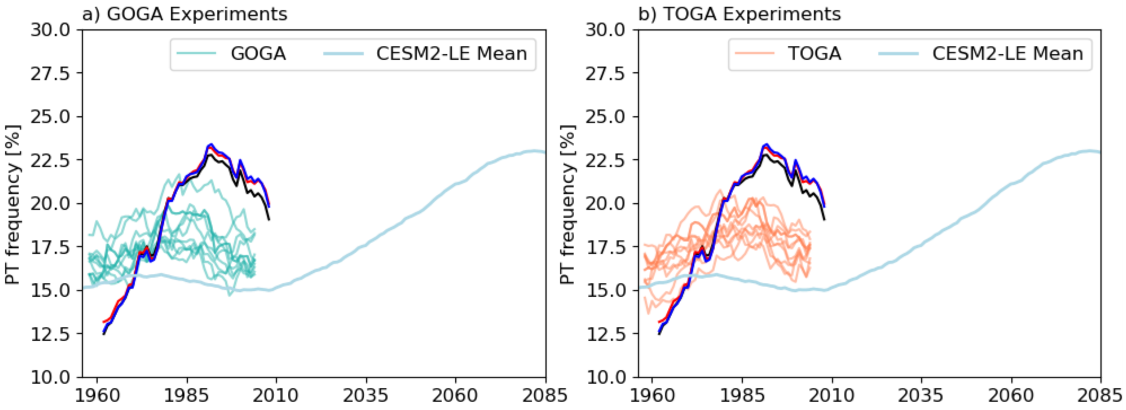
Results: Physical drivers - SST-forced experiments



Even with forced SSTs, the observed changes do not fit within the ensembles

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Conclusions

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- ➔ The Pacific Trough frequency has increased (likely outside internal variability) likely due to GHGs and is modulated by Pacific SSTs variability, with relevant impacts for surface hot extremes
- ➔ Since the recent decrease in Pacific Trough frequency seems to be related to the La Niña-like warming trend, future increases depend on the potential onset of the El Niño-like response to GHGs
- ➔ More research is needed on the role of aerosols

? Do high-resolution (MESACLIP) simulations improve the trends representation?

Pérez-Carrasquilla et al (2025, in prep). Human-driven increase in North American Pacific Trough intensifies winter and spring heat extremes.

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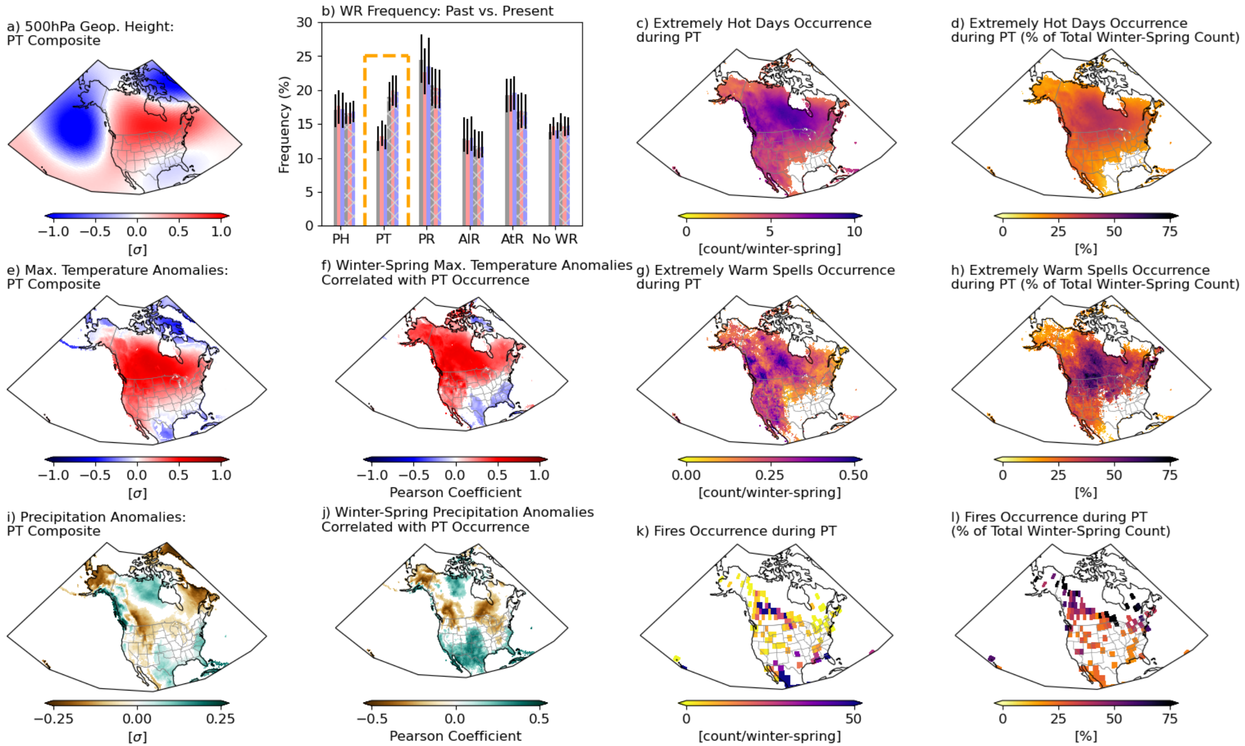

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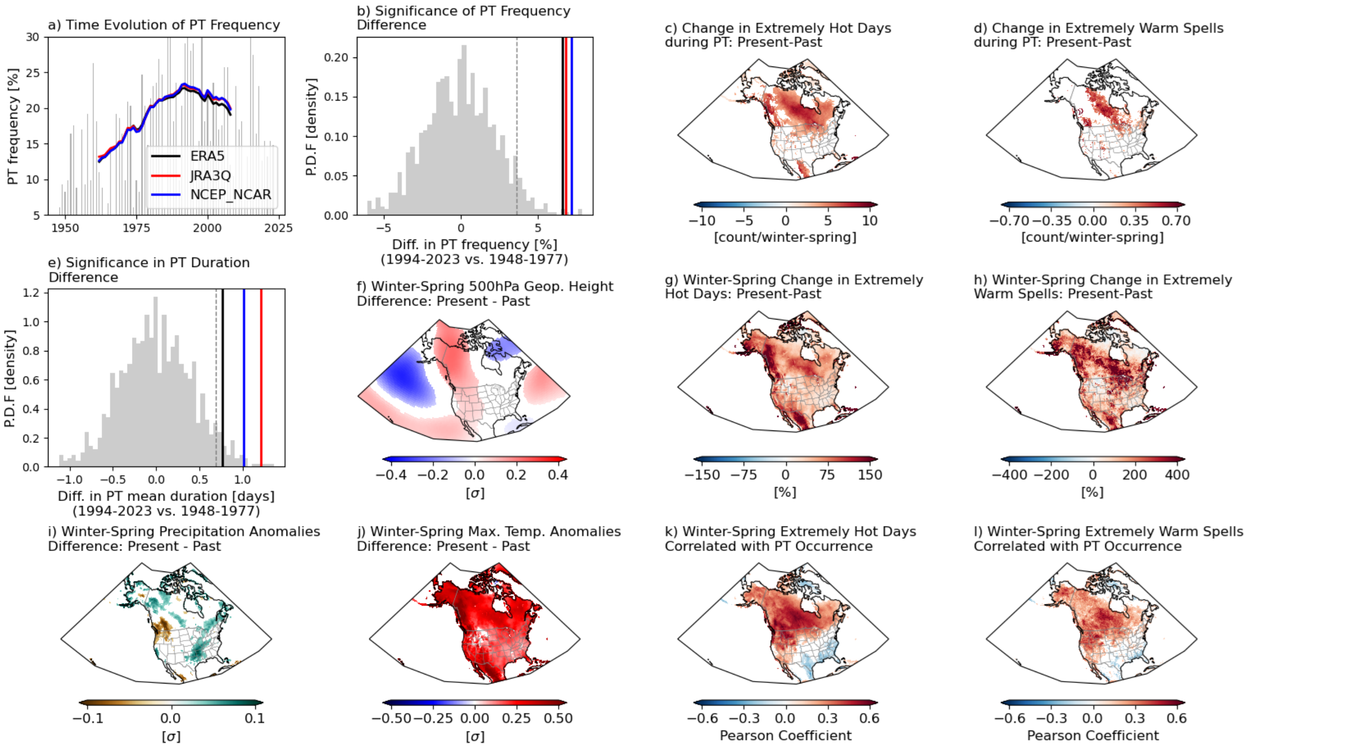

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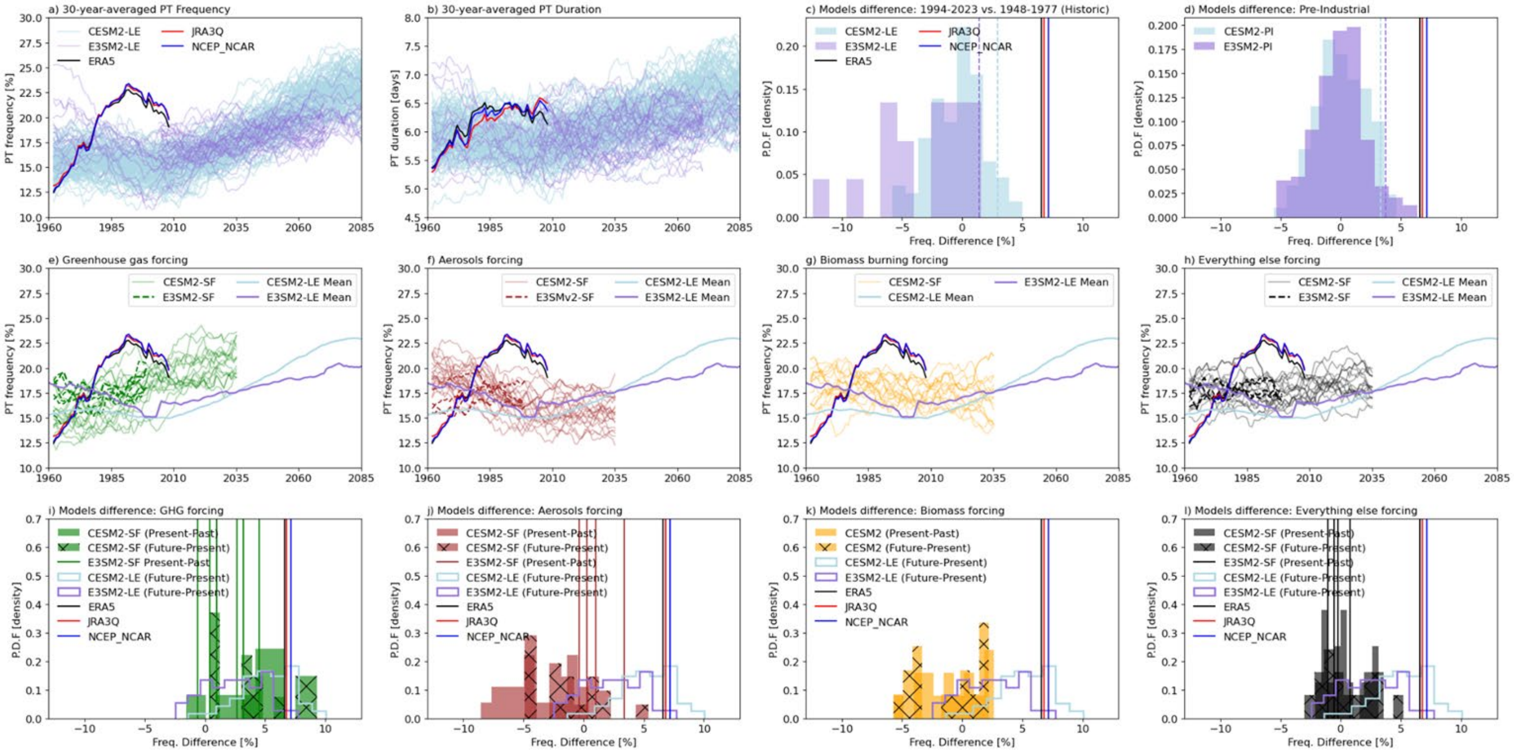

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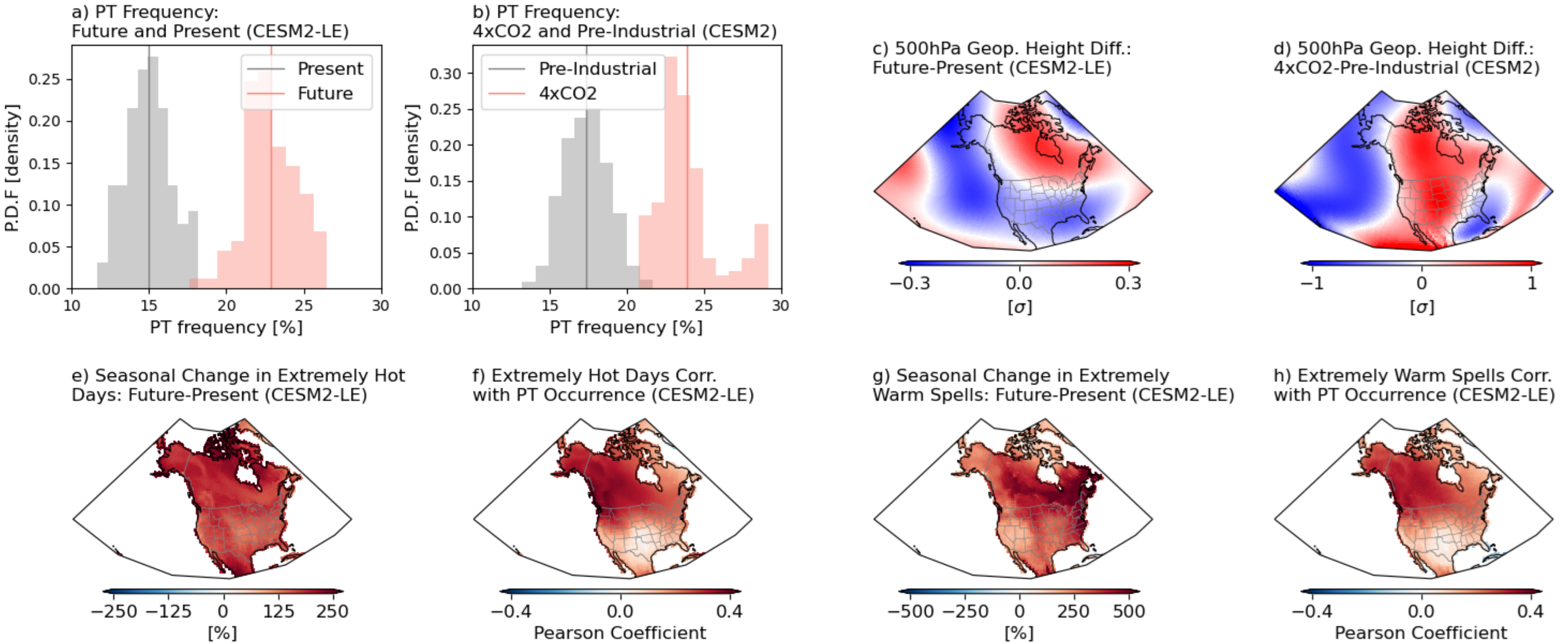

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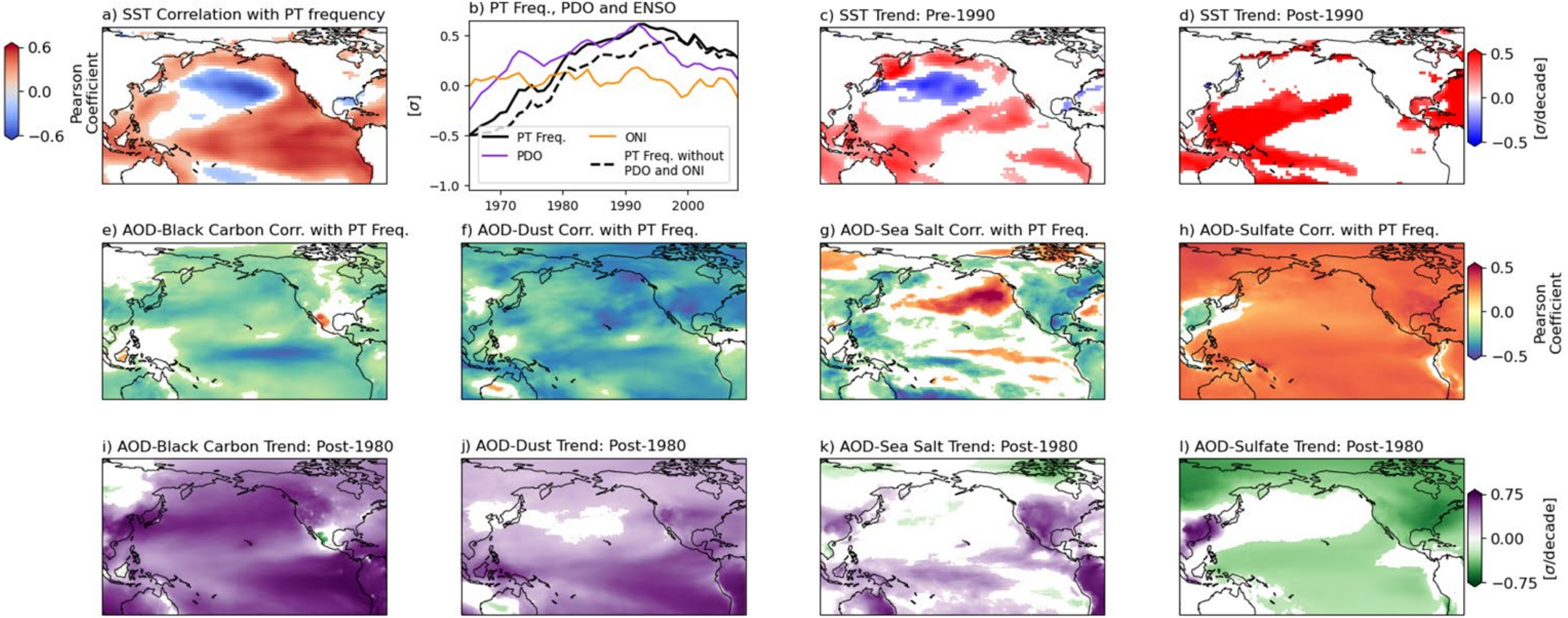

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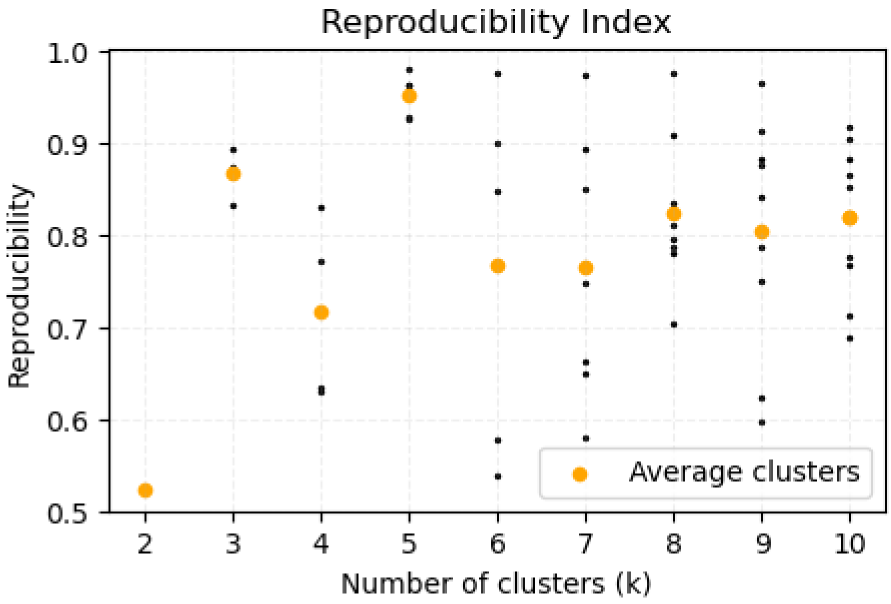

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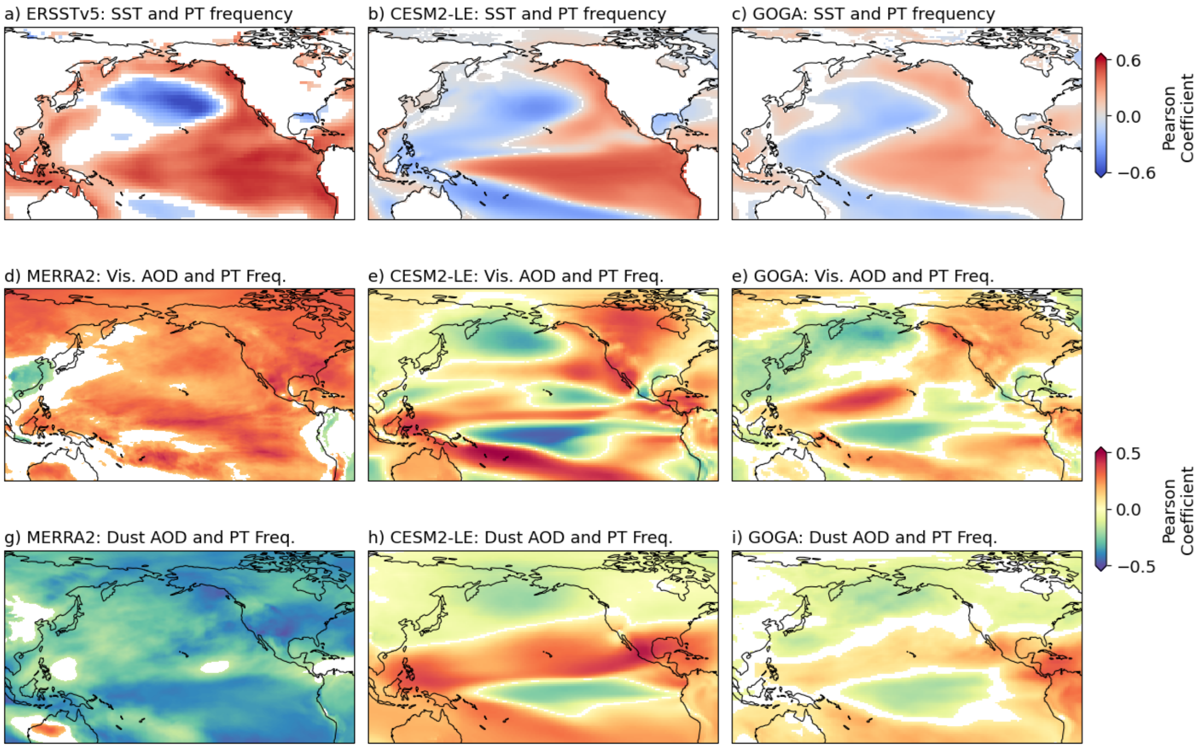

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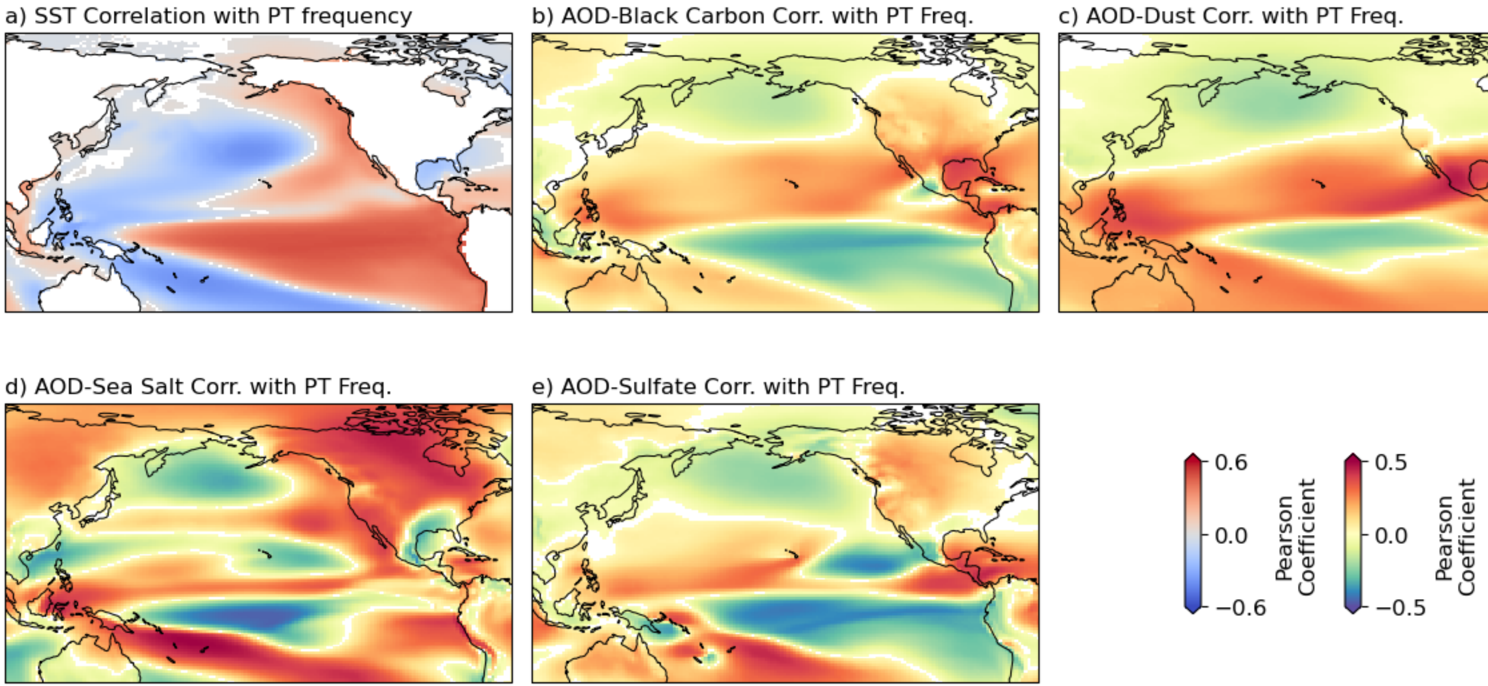

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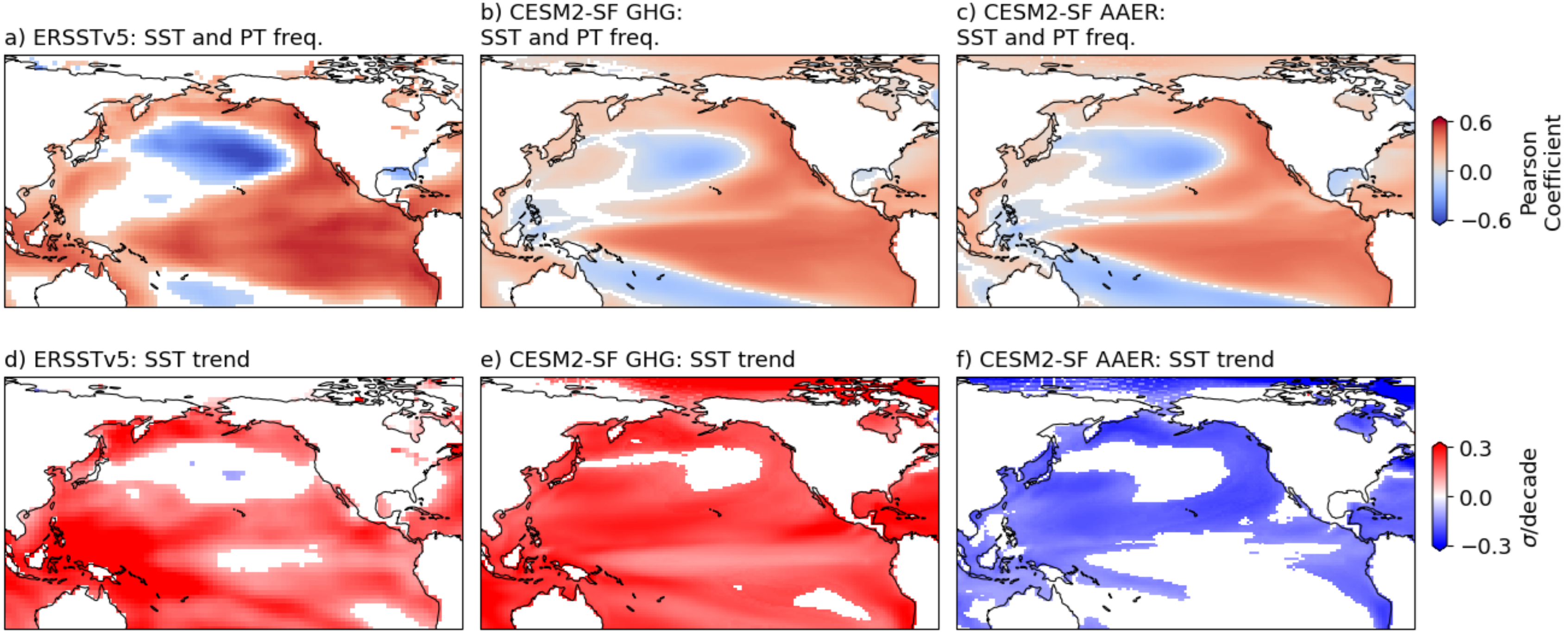

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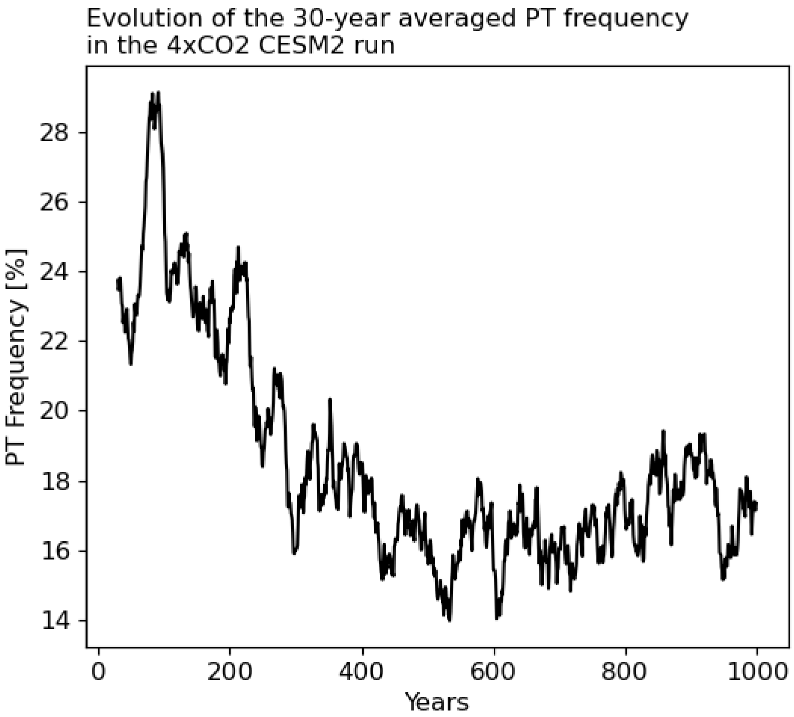

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Table 1. Summary of data products used in this analysis. To use consistent periods, and bearing in mind that the exact periods don't alter resultant conclusions, the windows were adjusted based on data availability.

Product	Past	Present	Future
ERA5	1948-1977	1994-2023	N/A
JRA-3Q	1948-1977	1994-2023	N/A
NCEP/NCAR Reanalysis 1	1948-1977	1994-2023	N/A
CESM2-LE	1948-1977	1994-2023	2040-2069; 2071-2100
E3SM2-LE	1948-1977	1994-2023	2040-2069
CESM2-SF	1948-1977	1994-2023; 1985-2004	2021-2050
E3SM2-SF	1939-1968	1985-2014	N/A
GOGA and TOGA	1944-1973	1990-2019	N/A

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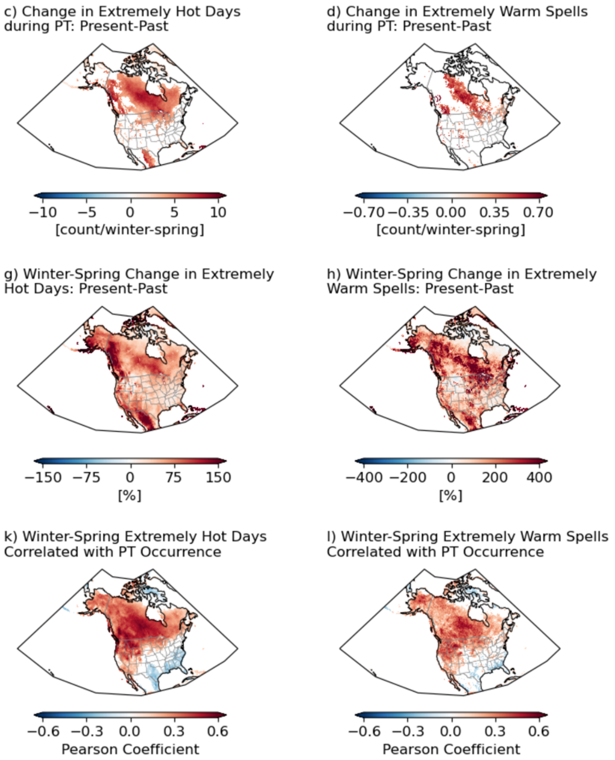
Results: Pacific Trough increase

Impact on extremes: PT explains a large part of the variability



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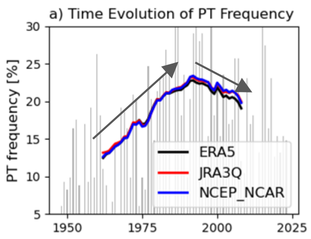
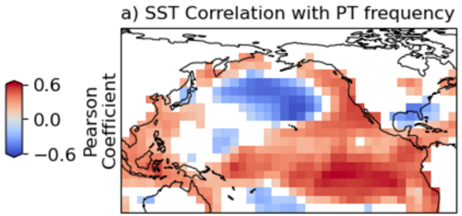
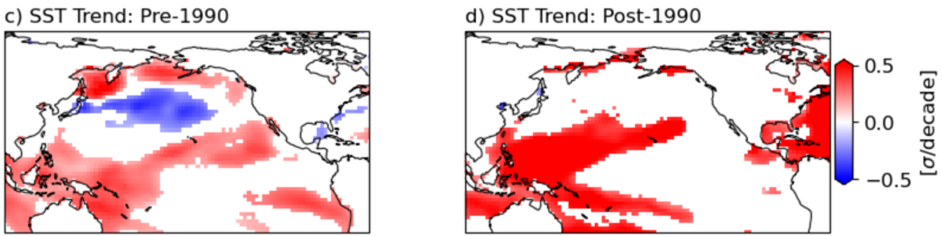
Results: Physical drivers



ERA5 and ERSSTv5



Correlations of DJFMAM averages (1950-2023).



The reason behind Pacific SST trends is still an open question:
If the current La Niña-like response to anthropogenic forcing stops and we go to an El Niño-like state, PT frequency would increase again.

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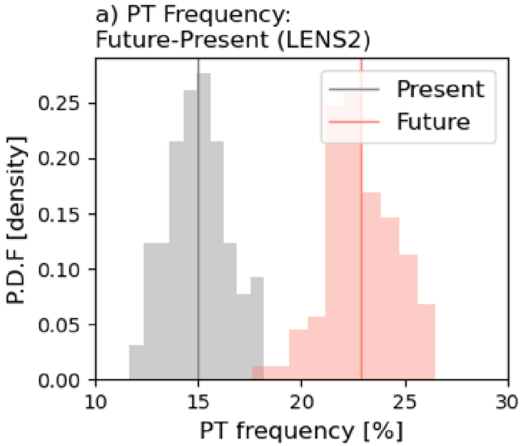
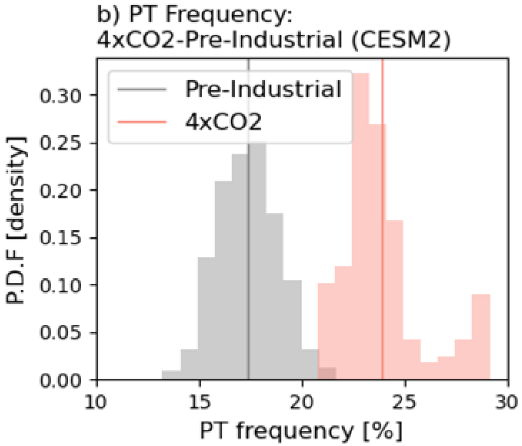
Results: Changes in ESMs - Increased CO2



Future = 2071-2100
Present = 1994-2023



First 200 years of abrupt CO2 increase run vs. pre-industrial

Under largely increased CO2 conditions, the PT frequency increase, as well as the associated surface response, are of similar magnitude to observations.

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