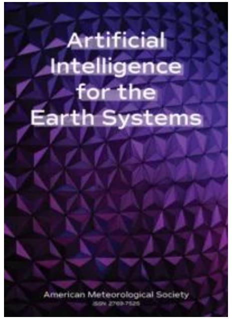
An Earth-System-Oriented View of the S2S Predictability of North American Weather Regimes

Jhayron S. Pérez-Carrasquilla and Maria Molina
University of Maryland



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[Submitted on 12 Sep 2024]

An Earth-System-Oriented View of the S2S Predictability of North American Weather Regimes

Jhayron S. Pérez-Carrasquilla, Maria J. Molina

It is largely understood that subseasonal-to-seasonal (S2S) predictability arises from the atmospheric initial state during early lead times, the land during intermediate lead times, and the ocean during later lead times. We examine whether this hypothesis holds for the S2S prediction of weather regimes by training a set of XGBoost models to predict weekly weather regimes over North America at 1-to-8-week lead times. Each model used a different predictor from one of the three considered Earth system components (atmosphere, ocean, or land) sourced from reanalyses. Three additional models were trained using land-, ocean-, or atmosphere-only predictors to capture process interactions and leverage multiple signals within the respective Earth system component. We found that each Earth system component performed more skillfully at different forecast horizons, with sensitivity to seasonality and observed (i.e., ground truth) weather regime. S2S predictability from the atmosphere was higher during winter, from the ocean during summer, and from land during spring and summer. Ocean heat content was the best predictor for most seasons and weather regimes beyond week 2, highlighting the importance of sub-surface ocean conditions for S2S predictability. Soil temperature and water content were also important predictors. Climate patterns were associated with changes in the likelihood of occurrence for specific weather regimes, including the El Niño-Southern Oscillation, Madden Julian Oscillation, North Pacific Gyre, and Indian Ocean dipole. This study quantifies predictability from some previously identified processes on the large-scale atmospheric circulation and gives insight into new sources for future study.

Comments: This work has been submitted for publication to Artificial Intelligence for the Earth Systems (AIES). Copyright in this work may be transferred without further notice
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https://doi.org/10.48550/arXiv.2409.08174

Research question

Article | Open access | Published: 04 March 2024

Quantifying sources of subseasonal prediction skill in CESM2

Jadwiga H. Richter, Anne A. Glanville, Teagan King, Sanjiv Kumar, Stephen G. Yeager, Nicholas A. Davis, Yanan Duan, Megan D. Fowler, Abby Jaye, Jim Edwards, Julie M. Caron, Paul A. Dirmeyer, Gokhan Danabasoglu & Keith Oleson

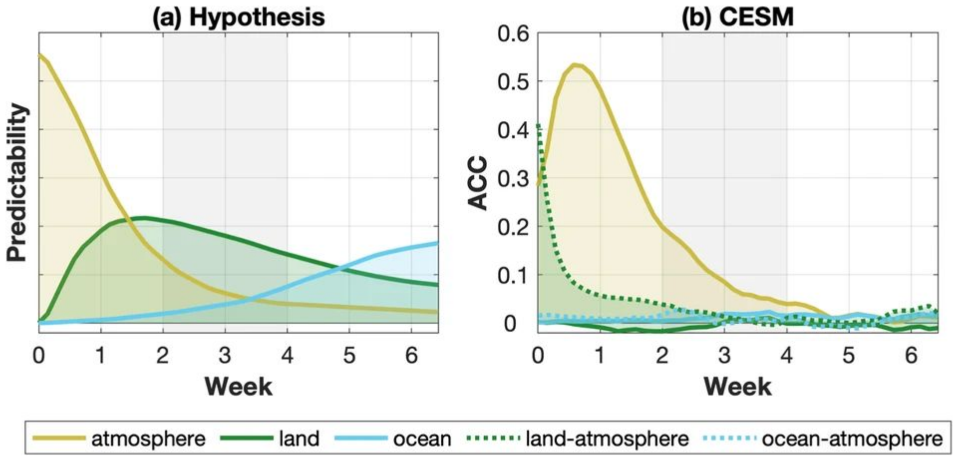
npj Climate and Atmospheric Science **7**, Article number: 59 (2024) | Cite this article

3594 Accesses | **10** Altmetric | Metrics

Where does atmospheric predictability come from?

What variables or Earth system components?

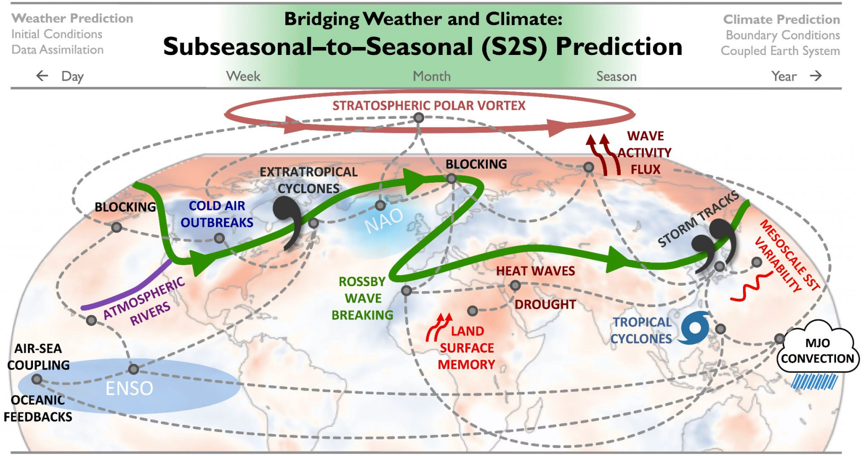
What processes?



Lang, A. L., Pegion, K., & Barnes, E. A. (2020). Introduction to special collection:“Bridging weather and climate: subseasonal - to - seasonal (S2S) prediction”. Journal of Geophysical Research: Atmospheres.
Richter, J.H., Glanville, A.A., King, T. et al. Quantifying sources of subseasonal prediction skill in CESM2. npj Clim Atmos Sci 7, 59 (2024).

Research question

ML Framework:



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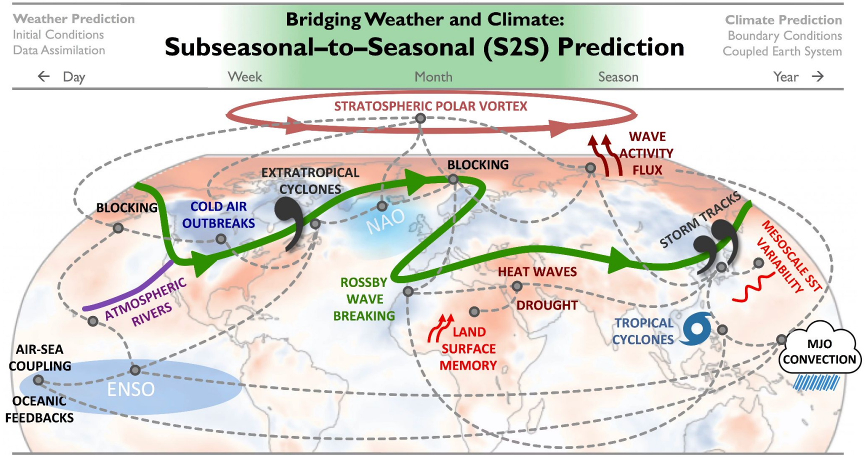
Richter, J.H., Glanville, A.A., King, T. et al. Quantifying sources of subseasonal prediction skill in CESM2. npj Clim Atmos Sci 7, 59 (2024).

Research question

ML Framework:

- What to predict?
- What variables represent the Earth system properties relevant for S2S prediction?
- What ML model to use?



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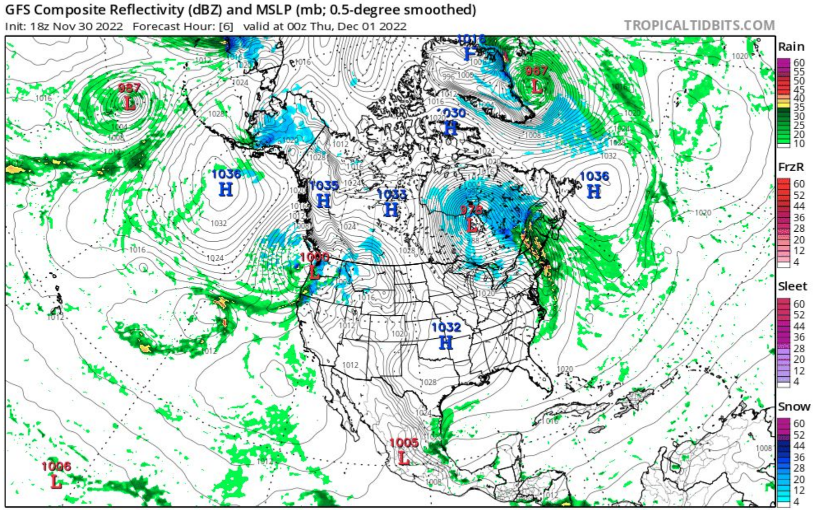
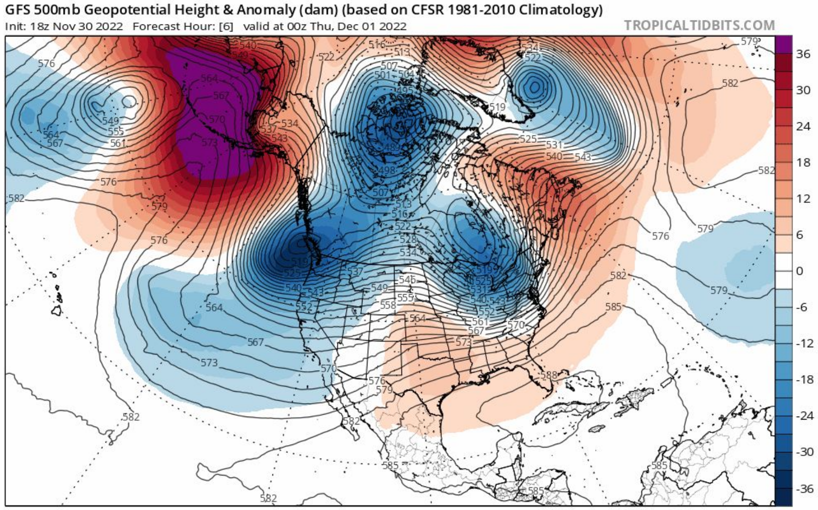
Richter, J.H., Glanville, A.A., King, T. et al. Quantifying sources of subseasonal prediction skill in CESM2. npj Clim Atmos Sci 7, 59 (2024).

What to predict? (how to make the problem simpler)



Small-scale features



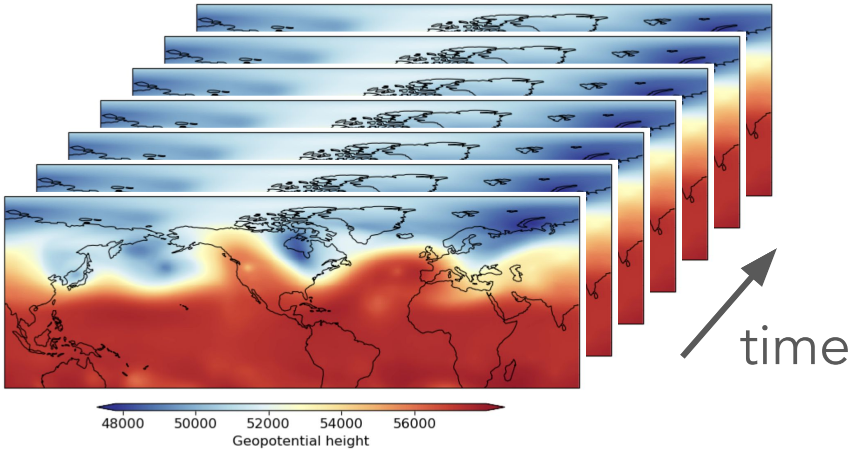
Large-scale features

Images from: https://www.tropicaltidbits.com/

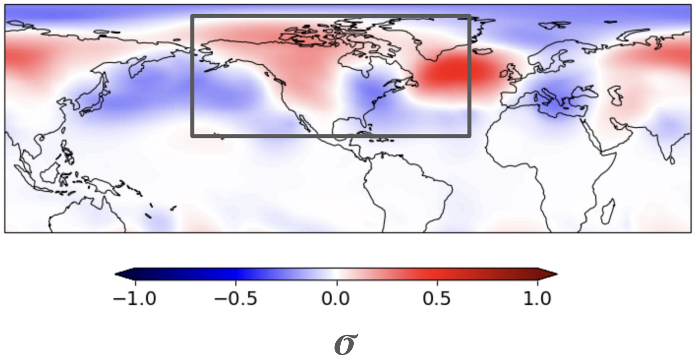
How to compute the weather regimes?

1) Daily 500hPa Geopotential height (Z500) 1981-2020

2) Extract region of interest, remove annual cycle and regional trends, standardize



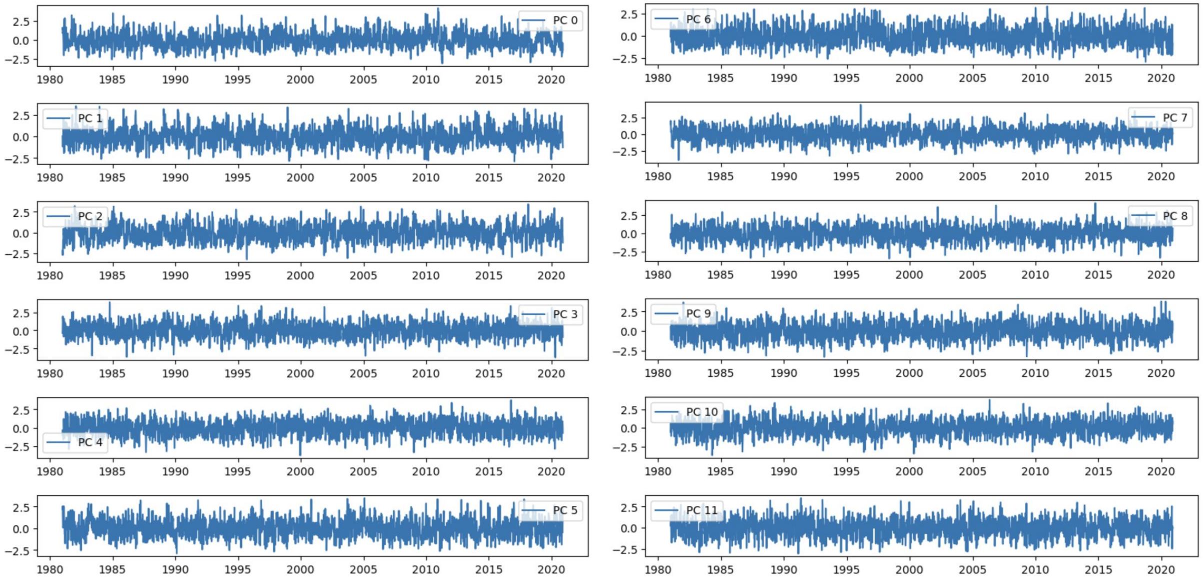
Z500 Anomalies



Lee, Simon H., Michael K. Tippett, and Lorenzo M. Polvani. "A new year-round weather regime classification for North America." Journal of Climate 36.20 (2023): 7091-7108.

How to compute the weather regimes?

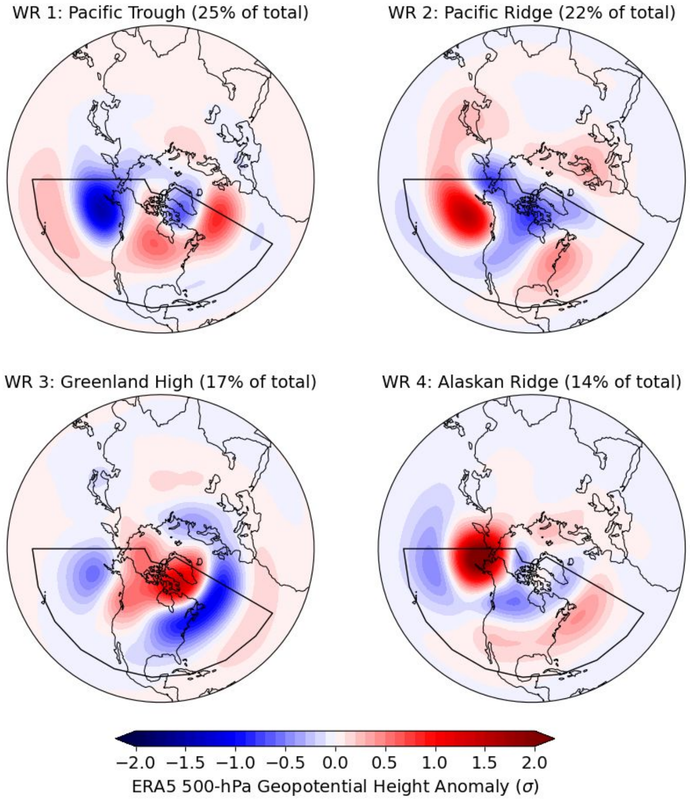
3) Dimensionality reduction: 12 first PCs (85% of variance)



k-means clustering

Lee, Simon H., Michael K. Tippett, and Lorenzo M. Polvani. "A new year-round weather regime classification for North America." Journal of Climate 36.20 (2023): 7091-7108.

Weather regimes



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Surface impact

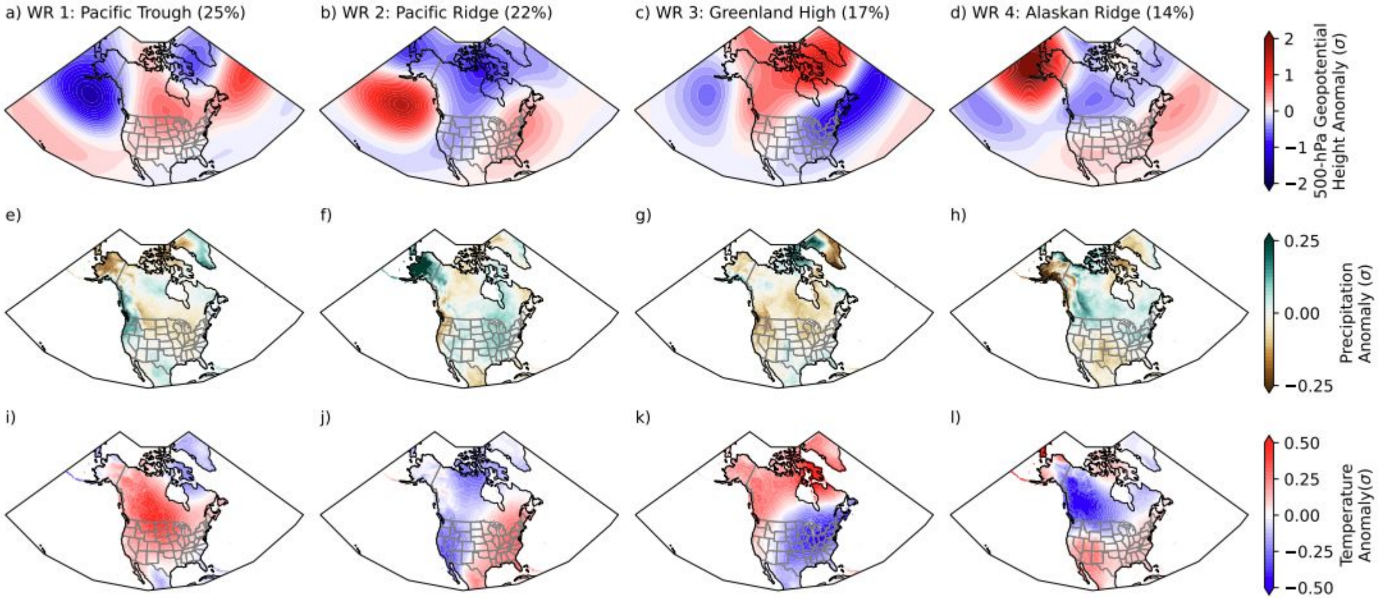


FIG. 1. The upper column (a-d) shows composites of detrended standardized ERA5 500-hPa geopotential height anomalies from 1981 to 2020 for the four weather regimes (WRs) identified. The daily frequency of each weather regime is shown in the subplot titles. The " No WR" class is not shown. The middle and bottom columns show the composited standardized daily precipitation (e-h) and temperature (i-l) anomalies for each one of the four weather regimes sourced from ERA5.

Pérez-Carrasquilla, J. S. & Molina, M. J. (under review)., An Earth-System-Oriented View of the S2S Predictability of North American Weather Regimes. Submitted to Artificial Intelligence for the Earth Systems.

Surface impact

Ensemble Predictability of Week 3/4 Precipitation and Temperature over the United States via Cluster Analysis of the Large-Scale Circulation

GREGORY JENNRICH,[a,c] DAVID STRAUS,[b] MUTHUVEL CHELLIAH,[c] AND CORY BAGGETT[c]

[a] *Earth Resources Technology Inc., Laurel, Maryland*
[b] *AOES Department, George Mason University, Fairfax, Virginia*
[c] *NOAA/Climate Prediction Center, College Park, Maryland*

(Manuscript received 13 April 2023, in final form 9 July 2024, accepted 12 August 2024)

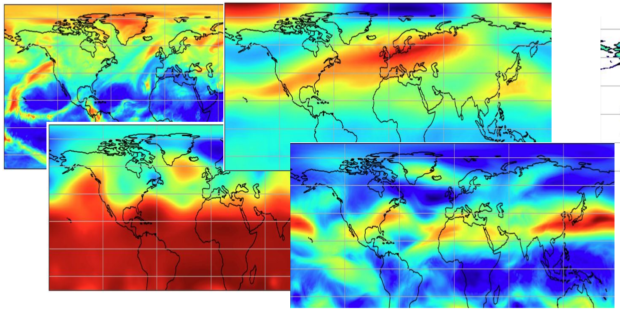
Predicting surface anomalies purely based on WR composites may be as skillful as predicting them directly.

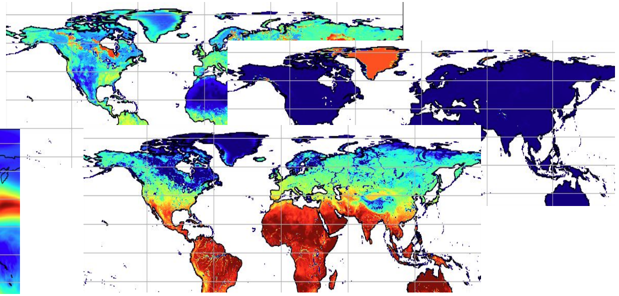
Predictors representing the initial state of the Earth system

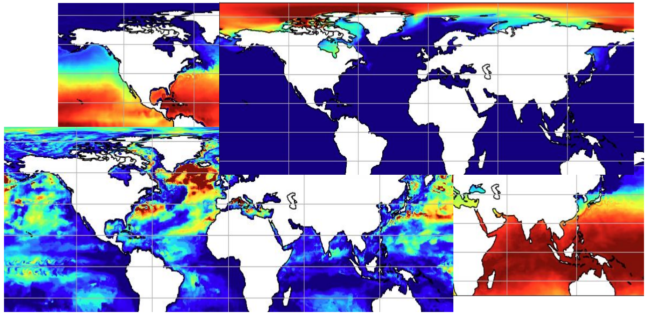
Atmosphere (ERA5) - 4 variables: Z500hPa, U10hPa and U200hPa, and OLR.

Land (ERA5) - 9 variables: Soil integrated moisture and heat for different depths, and snow depth.

Ocean (SODA) - 10 variables: OHC for different depths, SSH, SST, MLD, ice properties.







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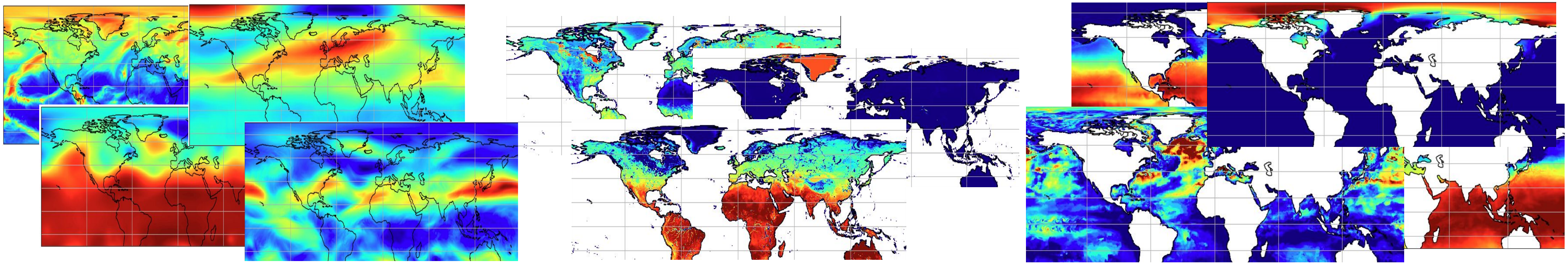
Predictors representing the initial state of the Earth system

Removed climatology

Removed trends

Weekly average

To train different models with each variable individually



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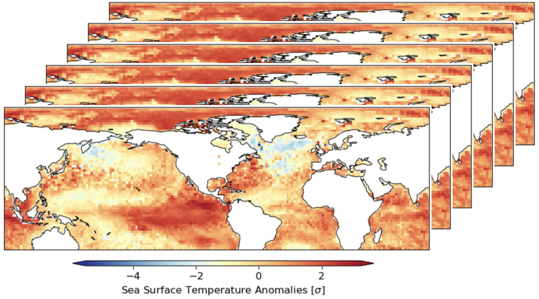
What algorithm to use for classification? Aiming for scalable and fair models

Example: SST



Shape: t(4094), lat(60), lon(180)

What ML model?

5 classes: weather regimes

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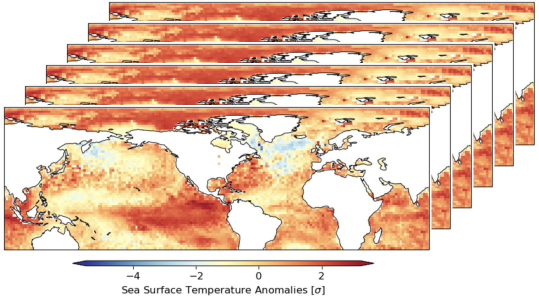

Shape: t(4094), lat(60), lon(180)

What ML model?

Artificial neural network

Long-short term memory network

Convolutional neural network

XGBoost

5 classes: weather regimes

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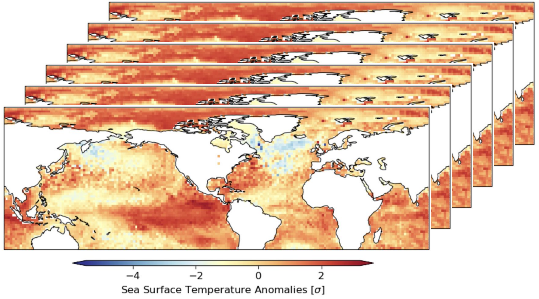
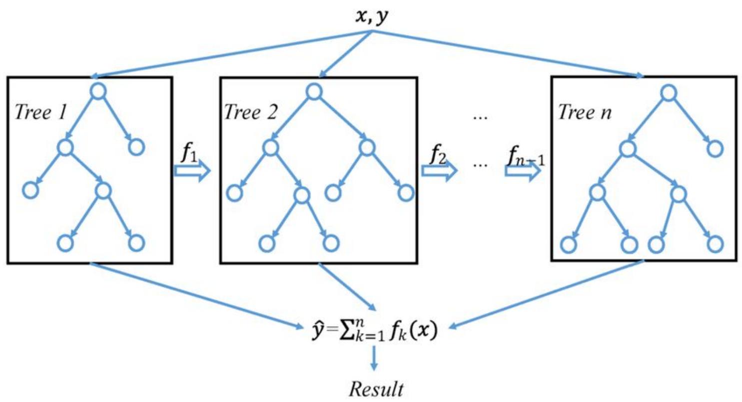


XGBoost



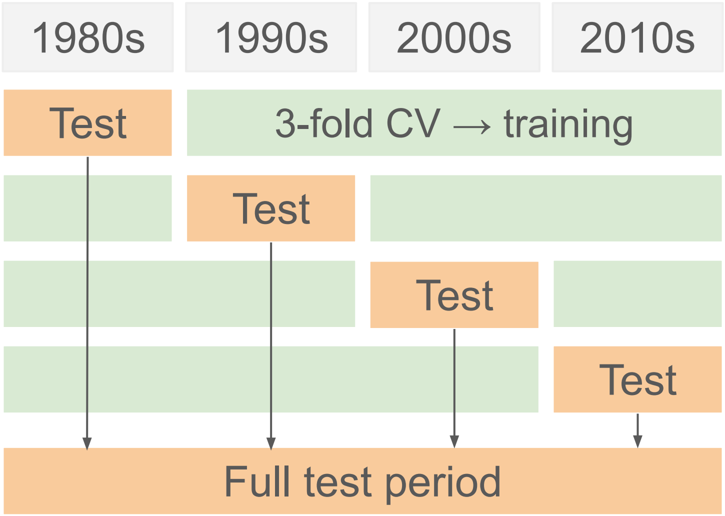
5 classes: weather regimes

Advantages: Widely used, similar performance to DL, low computational cost, fewer hyperparameters and lower sensitivity to them

Friedman, J. H., 2001: Greedy function approximation: a gradient boosting machine. Annals of statistics, 1189–1232.

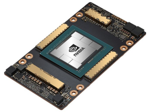
Hyperparameter optimization

Aiming to find **robust** and **fair** models.



Hyperparameter	Search range	Optimal values
Maximum depth of a tree	2-20	12-14
Minimum sum of instance weight needed in a child	1-20	10-12
Percentage of samples used for each tree construction	0.7-0.9	0.8-1
Percentage of features used for each tree construction	0.6-0.9	0-0.25
Percentage of features used for each split	0.75-1	0.83-0.88
Learning rate	0.0001-0.3	0.003-0.015
Minimum loss reduction required to make a further partition on a leaf node of a tree (gamma)	0-5	0-4
L1 regularization term on weights	4-40	6-10
L2 regularization term on weights	1-316	1.5-40
Exponential term for the weights to reduce class imbalance	0-1	0.6-0.8

23 variables x 8 lead times x 4 test-folds x 3 cv-folds



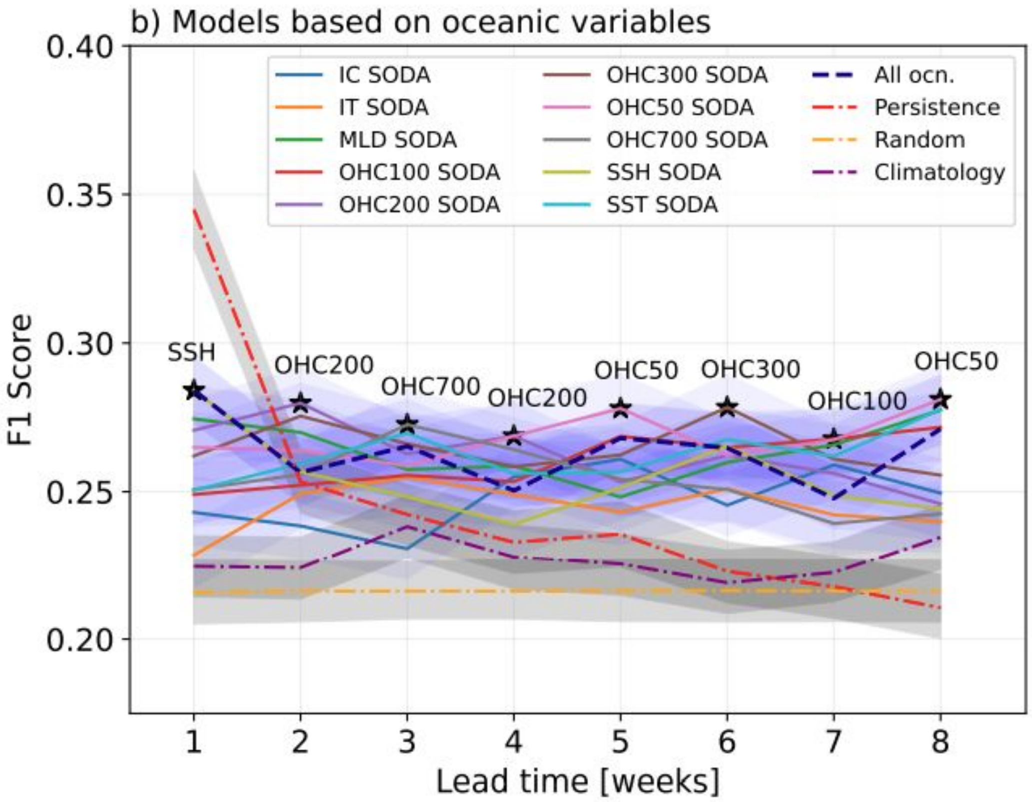
NCAR CISL

PyTorch

Train a model for each variable (23 variables) and for each lead time (8 weeks)

Perez-Carrasquilla, J., Molina, M. J. 2023. An Earth-System-Oriented View of the S2S Predictability of Weather Regimes using XGBoost. Artificial Intelligence for the Earth Systems (under review).

Results: Skill of the models



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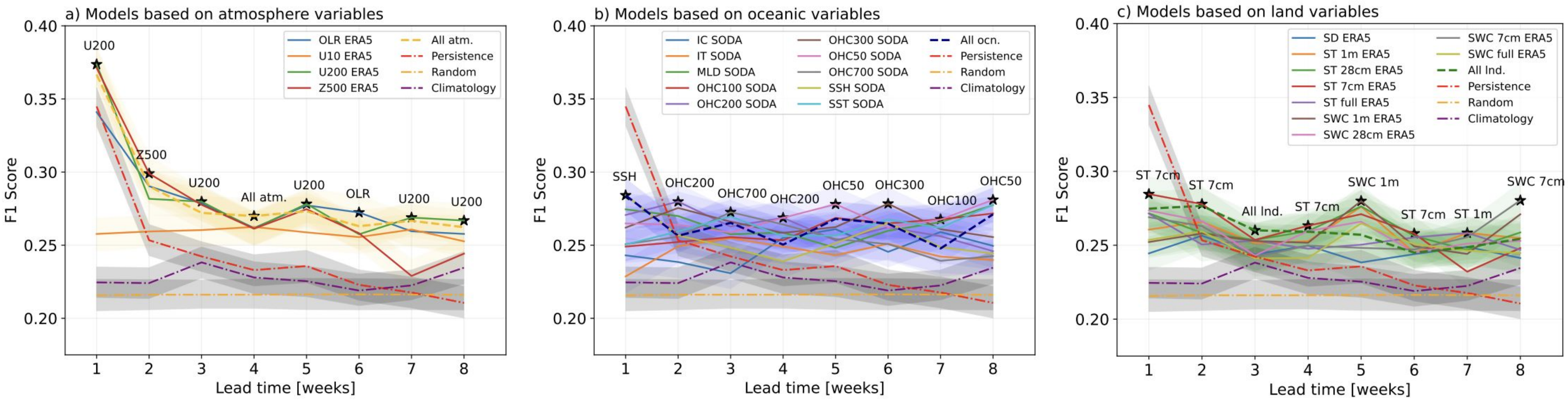

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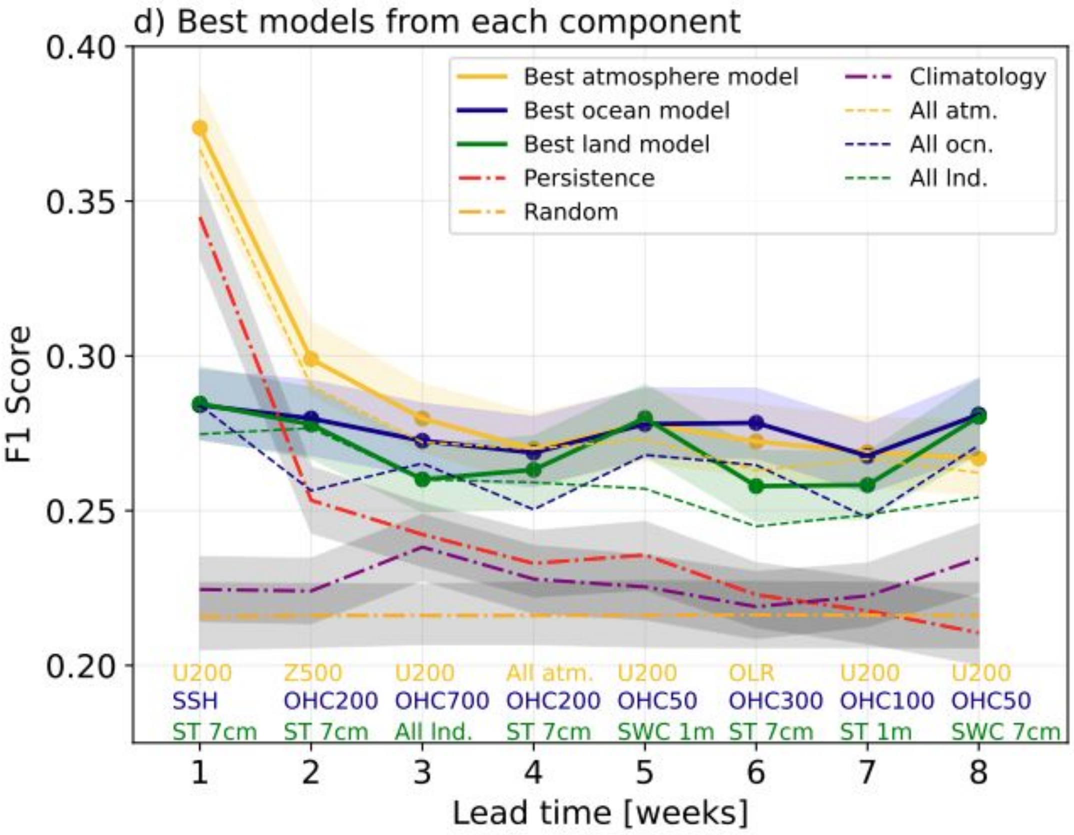

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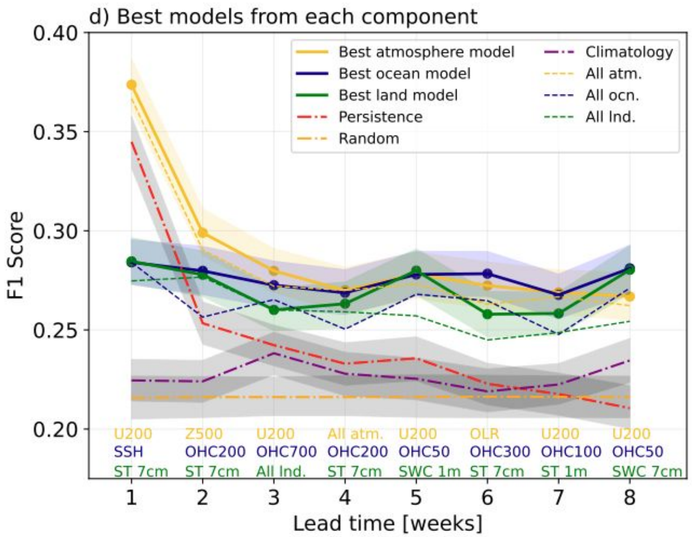

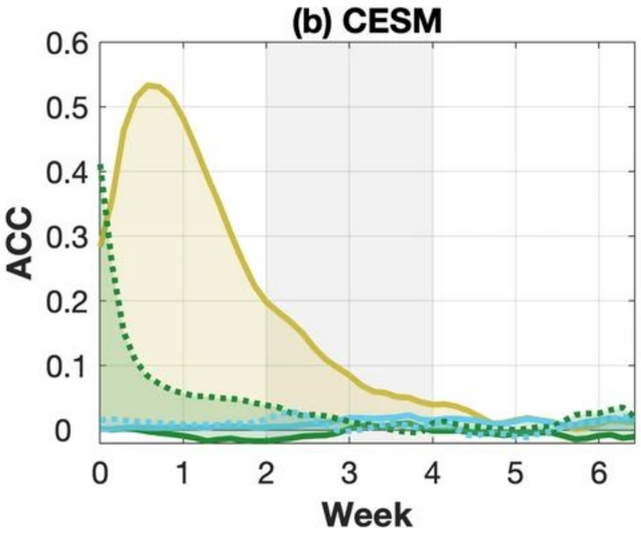

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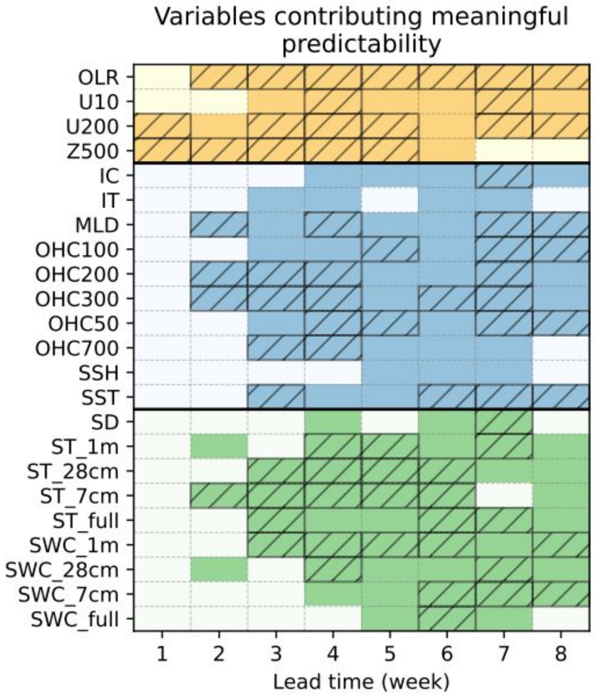
Variables and components that provide skill



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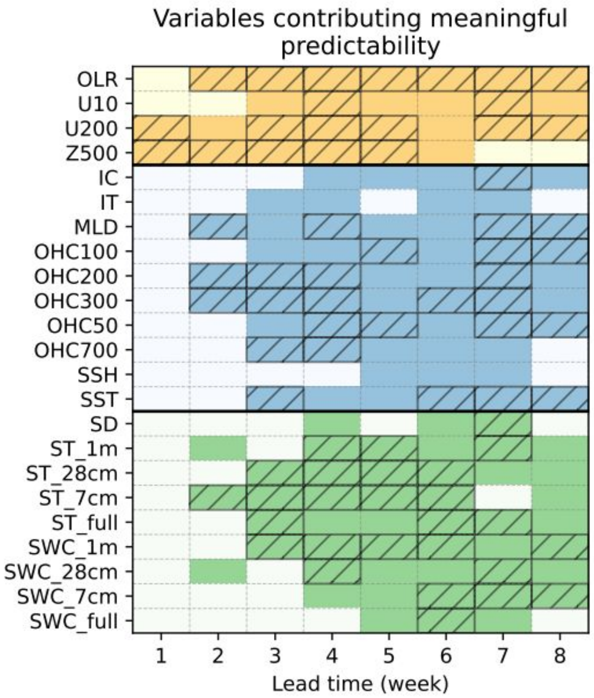


Winter Spring Summer Fall

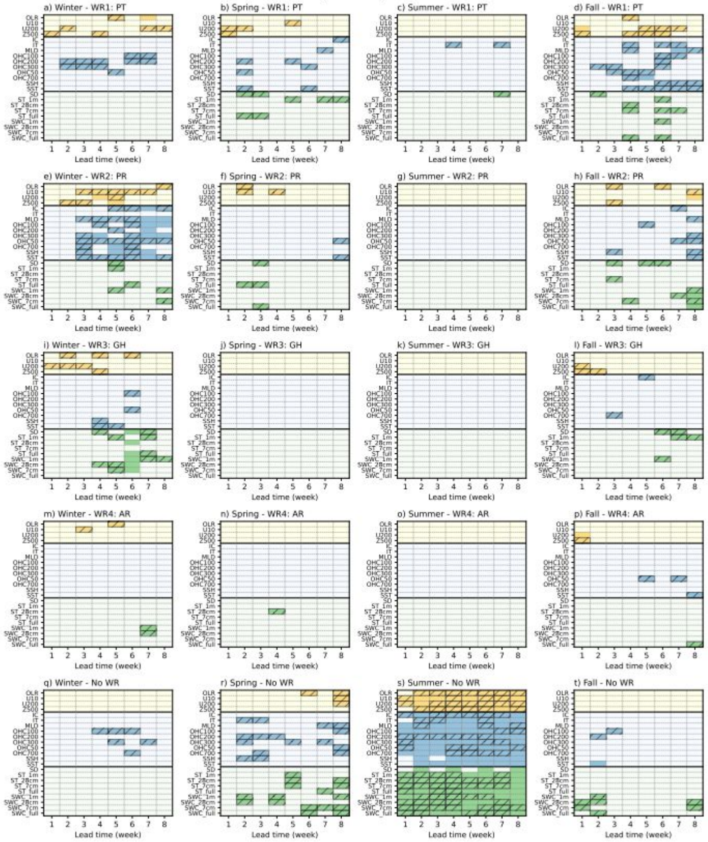
Pacific Trough

Pacific Ridge

Greenland High

Alaskan Ridge

No WR



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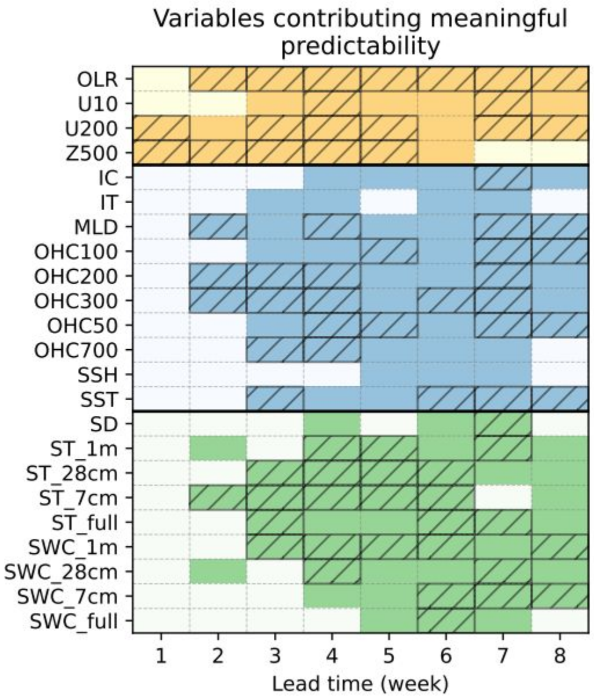

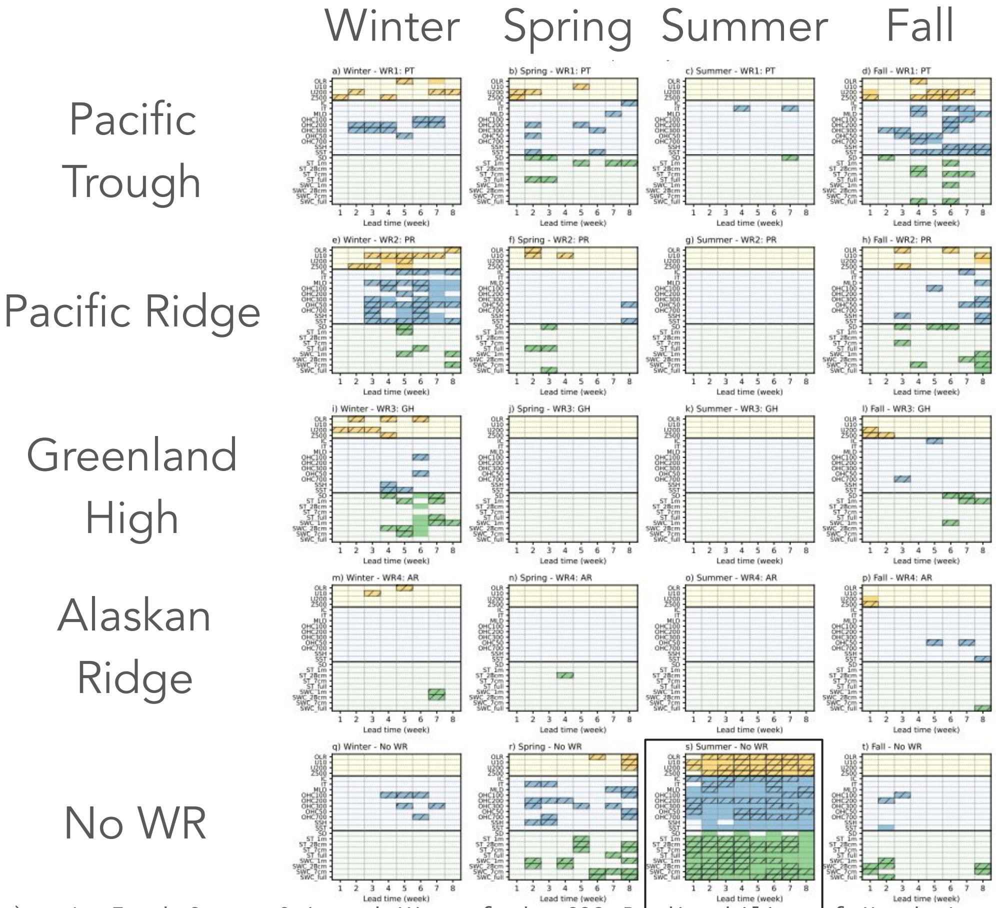

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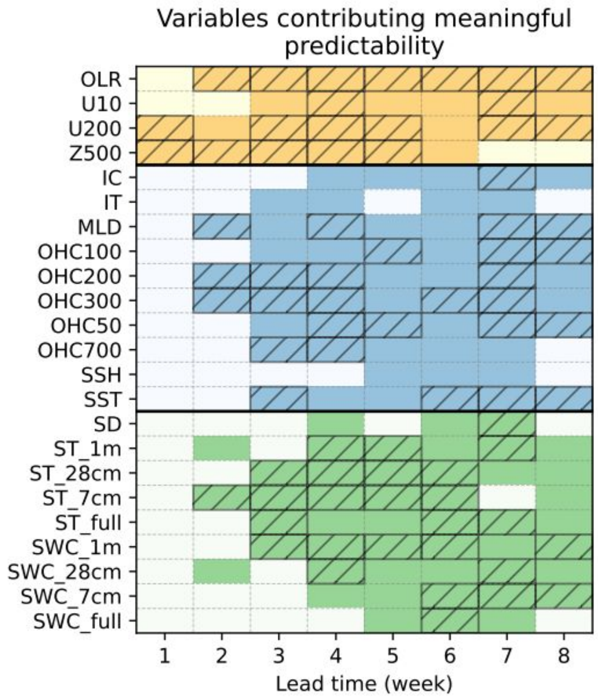
Variables and components that provide skill



Winter Spring Summer Fall

Pacific Trough

Pacific Ridge

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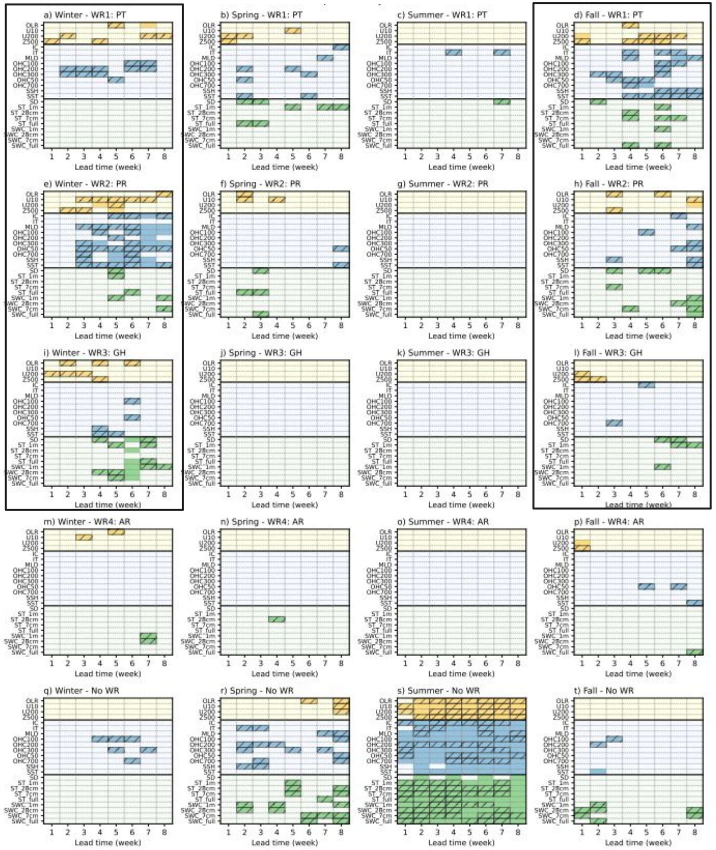

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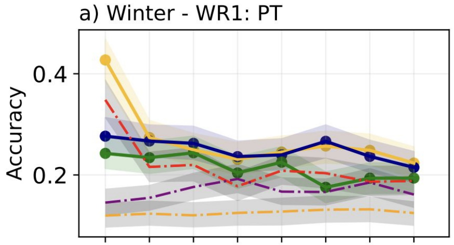
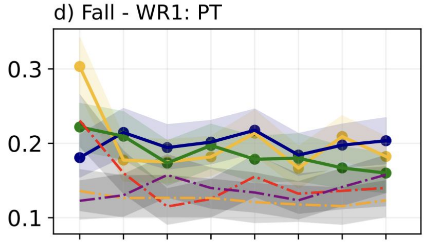
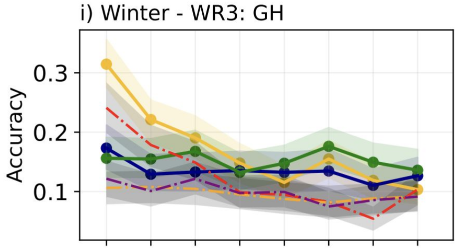
Variables and components that provide skill

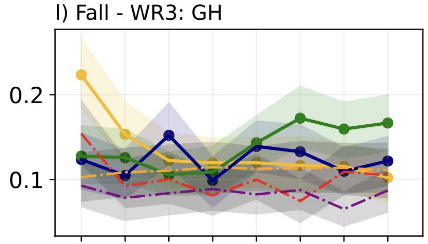
Pacific Trough (ocean)



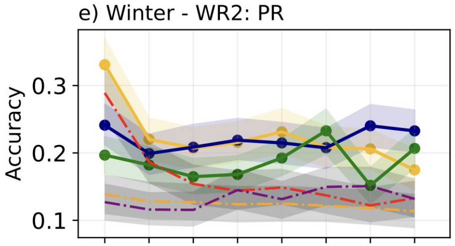


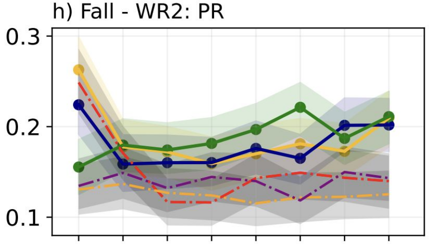
Greenland High (atmosphere and land)





Pacific Ridge (ocean, land, atmosphere)





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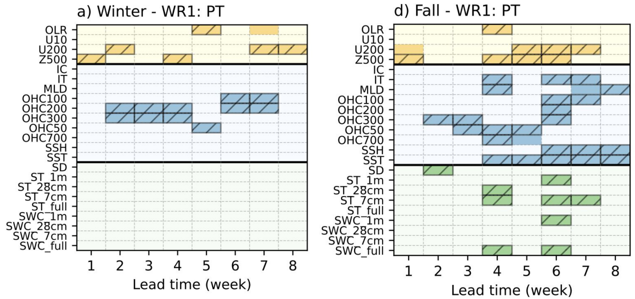
Variables and components that provide skill

Pacific Trough



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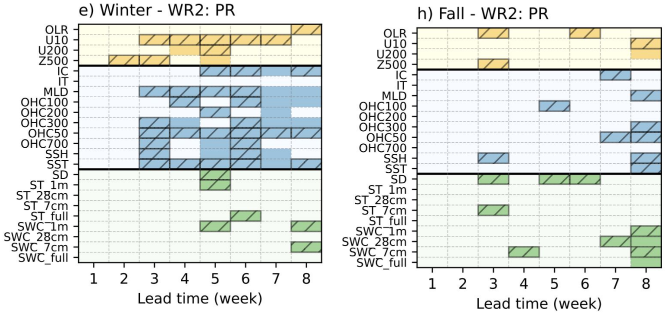
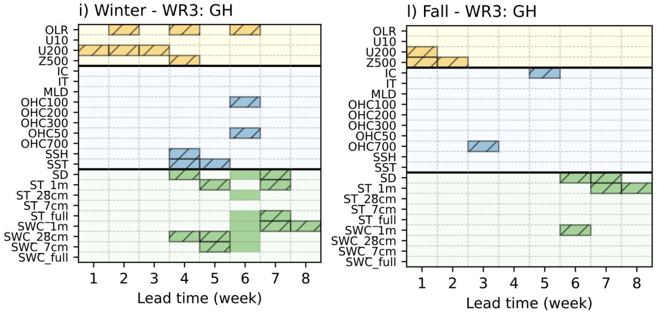


Greenland High



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Variables and components that provide skill

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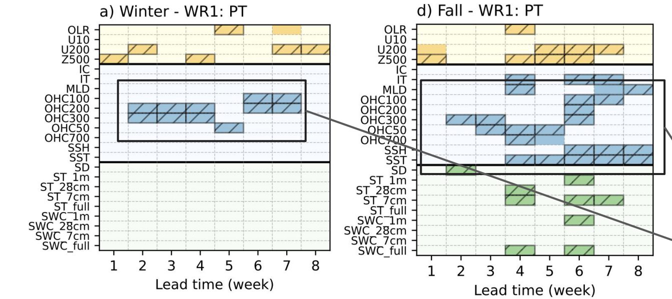
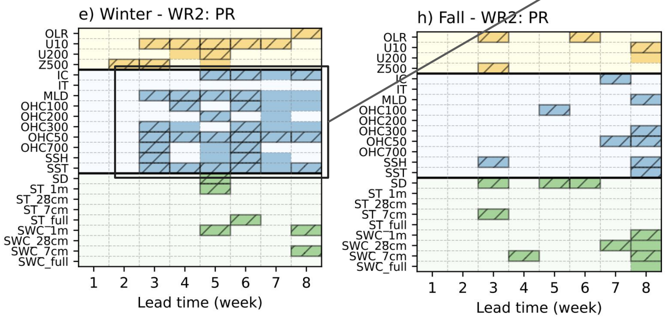
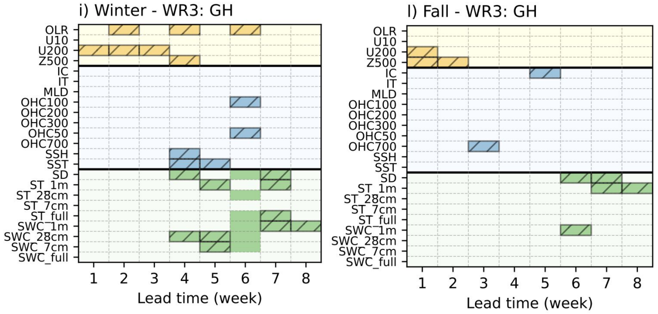


OHC/SST

Pacific Ridge



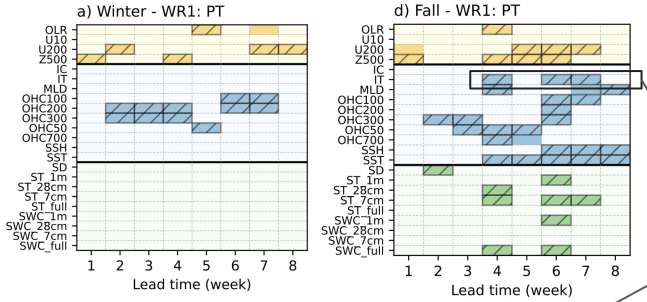
Greenland High



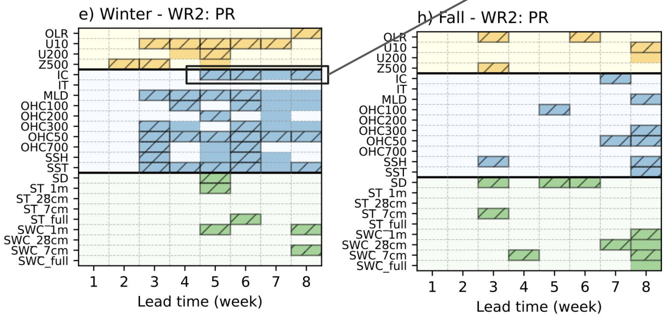
Pérez-Carrasquilla, J. S. & Molina, M. J. (under review)., An Earth-System-Oriented View of the S2S Predictability of North American Weather Regimes. Submitted to Artificial Intelligence for the Earth Systems.

Variables and components that provide skill

Pacific Trough

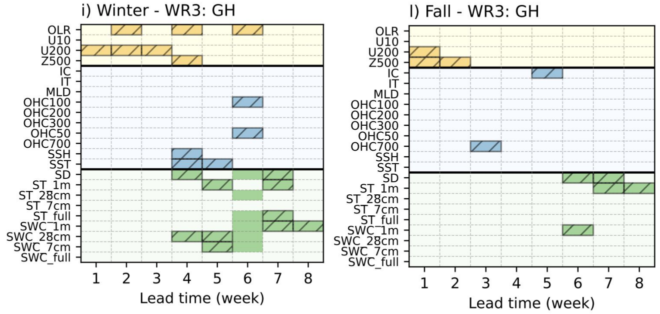


Pacific Ridge



Sea Ice

Greenland High



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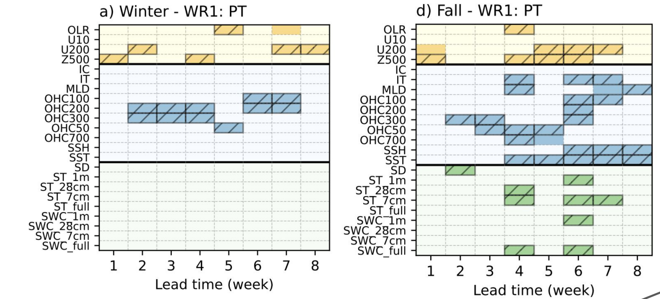
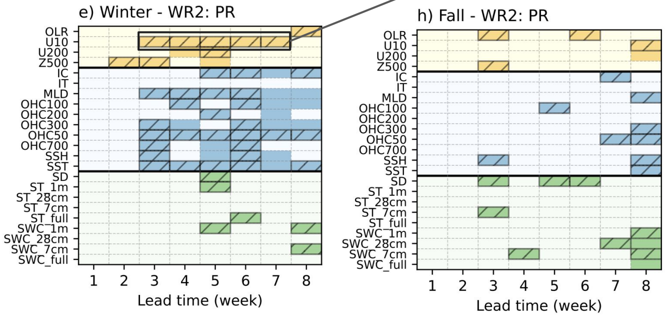
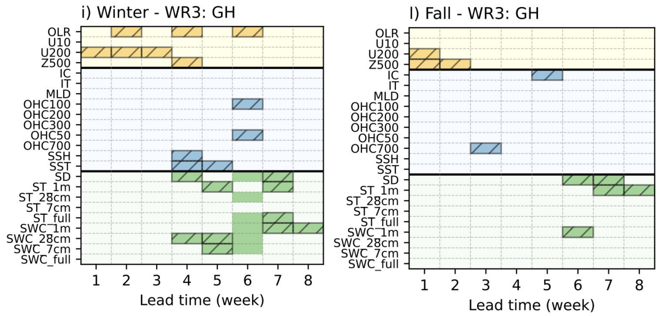


Stratosphere

Pacific Ridge



Greenland High



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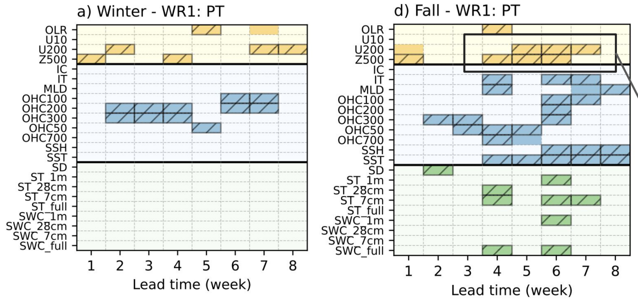
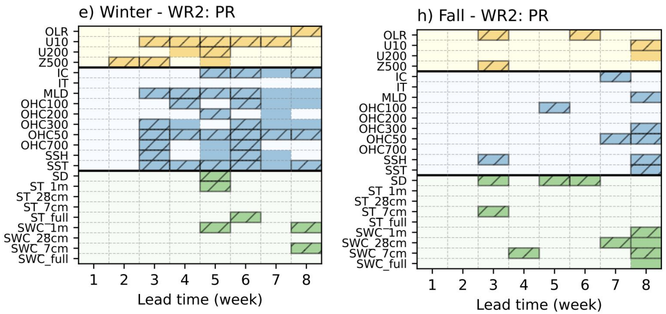
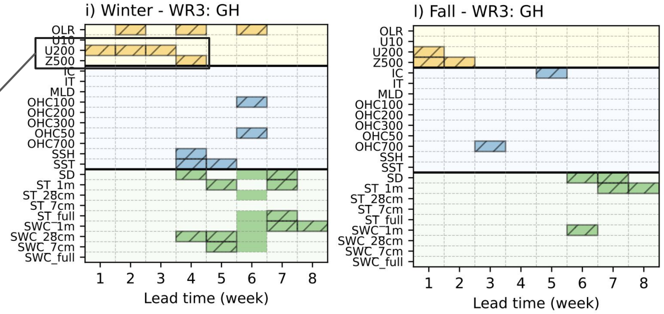


Pacific Ridge



Large-scale troposphere

Greenland High



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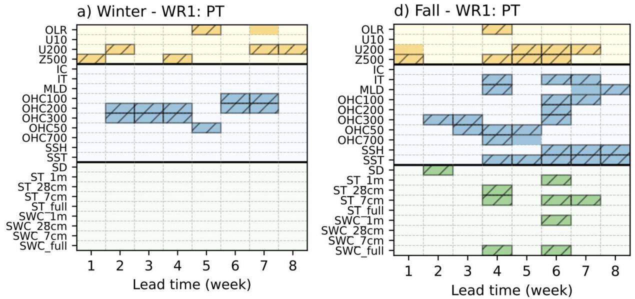

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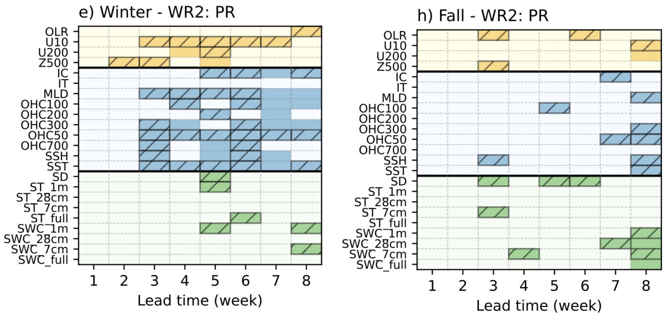
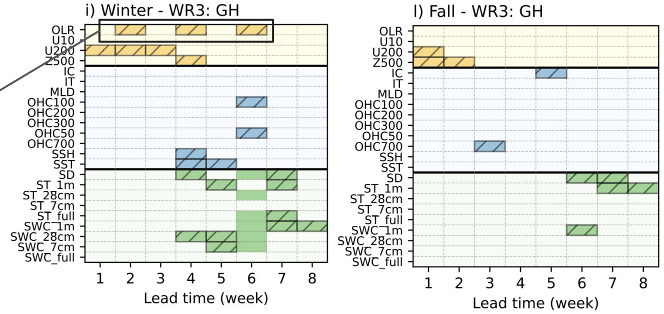


OLR

Greenland High



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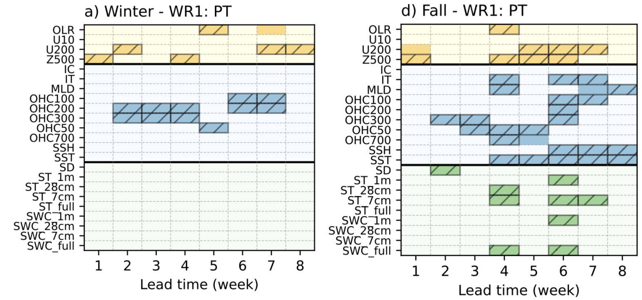
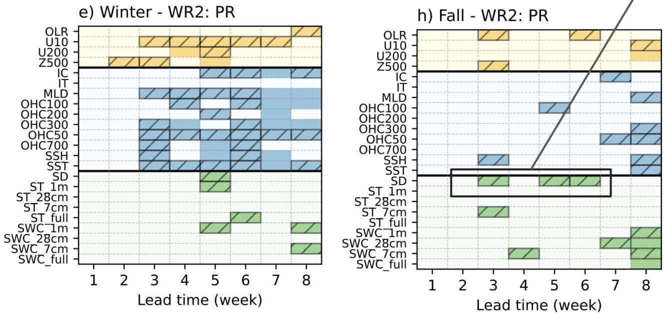
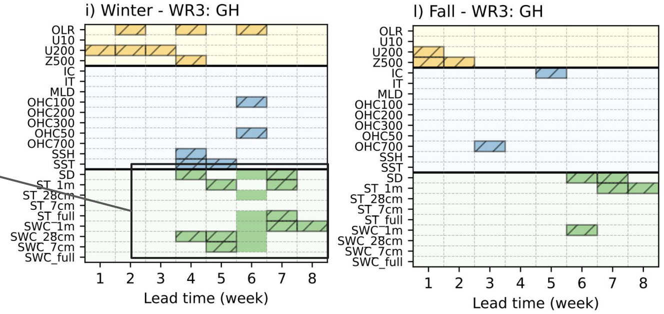


Pacific Ridge



Snowpack and soil moisture

Greenland High



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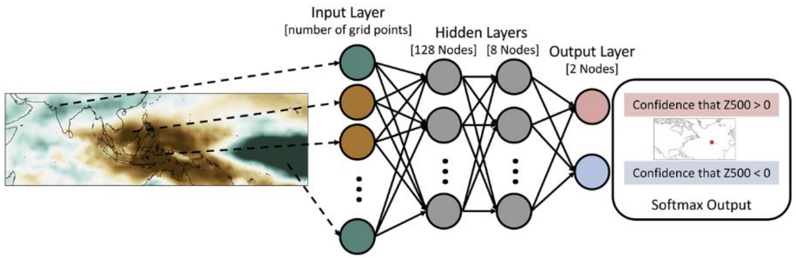
eXplainable AI

Research Letter | Open Access

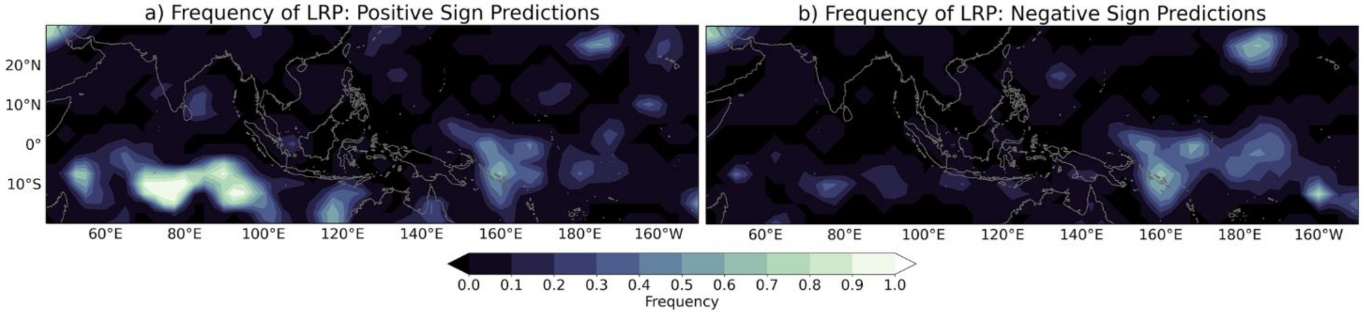
Subseasonal Forecasts of Opportunity Identified by an Explainable Neural Network

Kirsten J. Mayer, Elizabeth A. Barnes

First published: 04 May 2021 | https://doi.org/10.1029/2020GL092092 | Citations: 34



Layer-wise relevance propagation: Relevance index – where did the models look?



Shapley Values and SHAP (SHapley Additive exPlanations) - Game Theory:

Shapley values quantify the contribution of each feature (player) to the final prediction (outcome) in each instance.

Properties:

- Local accuracy, missingness, consistency
- Can be computed exactly with the XGBoost model

Lundberg, Scott. "A unified approach to interpreting model predictions." arXiv preprint arXiv:1705.07874 (2017).

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shapley value of feature i

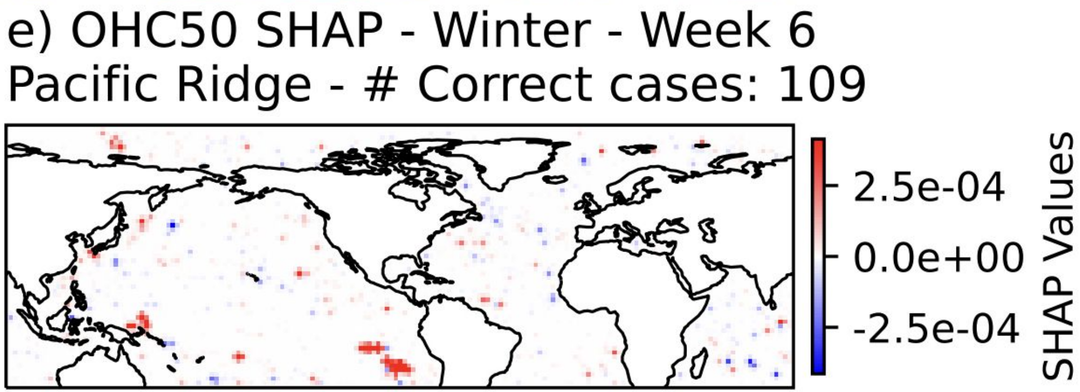
Base value

$$y_{WR}(x) = e^{\phi_0} + e^{\sum_i \phi_i}$$

↳ Output: likelihood of each WR

Lundberg, Scott. "A unified approach to interpreting model predictions." arXiv preprint arXiv:1705.07874 (2017).

Composite Shapley values for correct predictions



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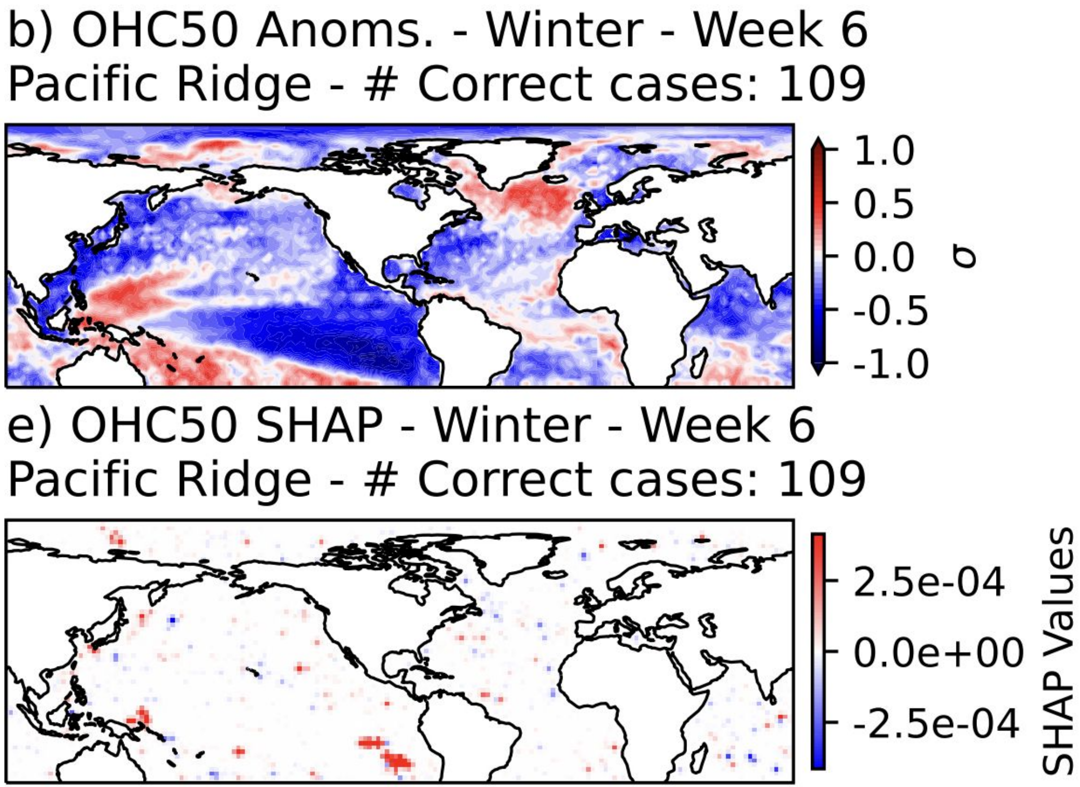

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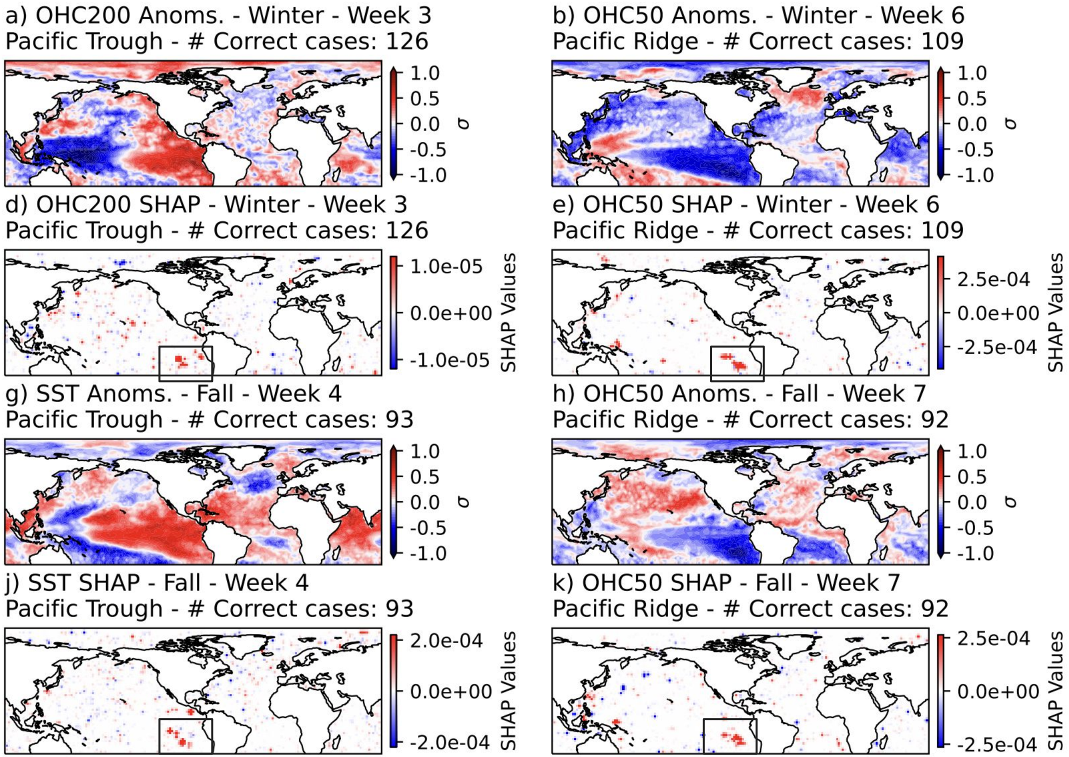
Processes that provide skill/Forecasts of opportunity: ENSO



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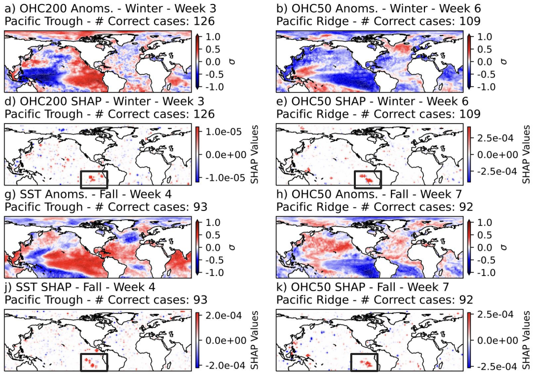

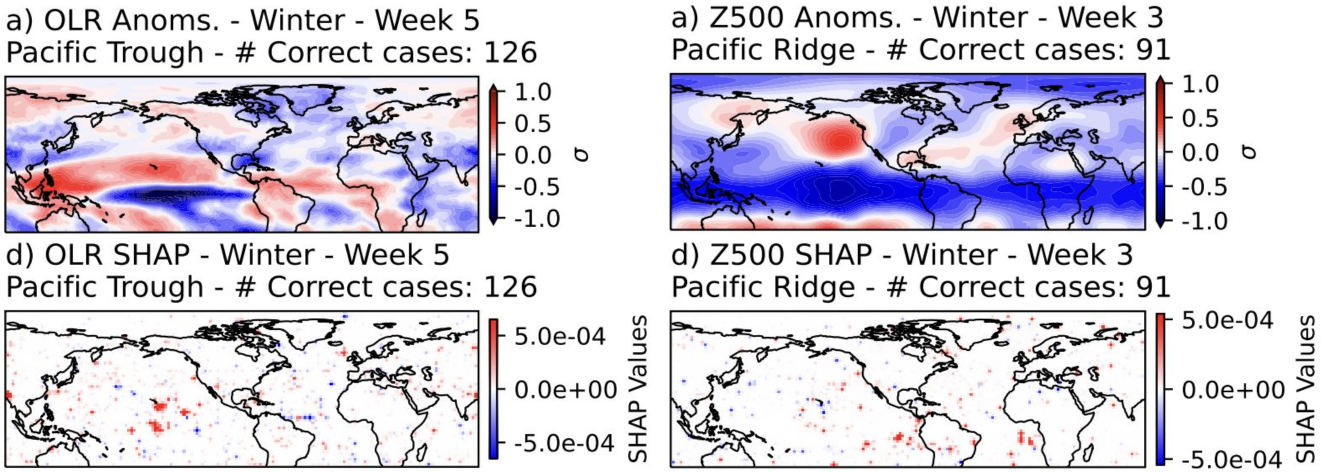

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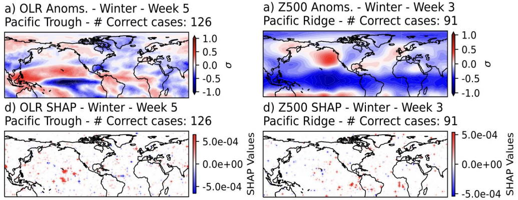
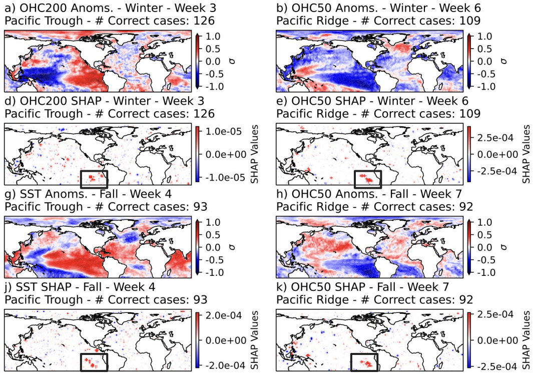
Processes that provide skill/Forecasts of opportunity: ENSO





The Northern Hemisphere Extratropical Atmospheric Circulation Response to ENSO: How Well Do We Know It and How Do We Evaluate Models Accordingly?

Clara Deser, Isla R. Simpson, Karen A. McKinnon, and Adam S. Phillips

Print Publication: 01 Jul 2017

DOI: https://doi.org/10.1175/JCLI-D-16-0844.1

Page(s): 5059–5082

Circulation Regimes: Chaotic Variability versus SST-Forced Predictability

David M. Straus, Susanna Corti, and Franco Molteni

Print Publication: 15 May 2007

DOI: https://doi.org/10.1175/JCLI4070.1

Page(s): 2251–2272

Subseasonal Representation and Predictability of North American Weather Regimes Using Cluster Analysis

Maria J. Molina, Jadwiga H. Richter, Anne A. Glanville, Katherine Dagon, Judith Berner, Aixue Hu, and Gerald A. Meehl

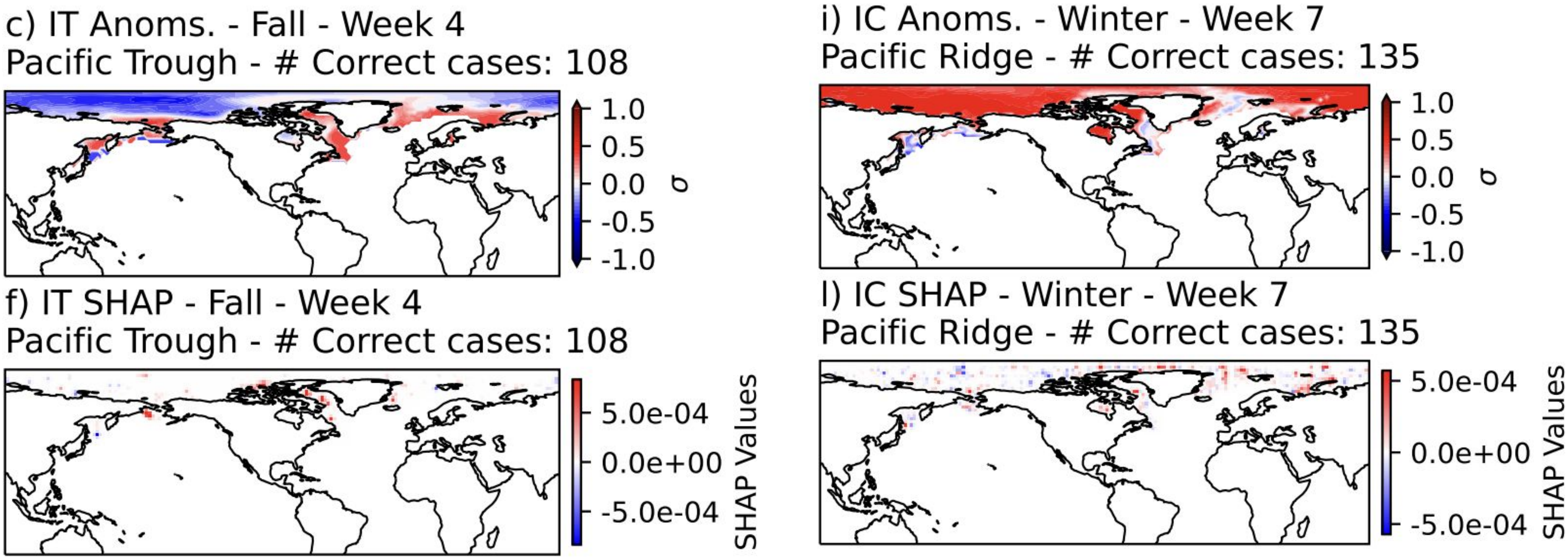
Online Publication: 21 Apr 2023

Print Publication: 01 Apr 2023

DOI: https://doi.org/10.1175/AIES-D-22-0051.1

Pérez-Carrasquilla, J. S. & Molina, M. J. (under review)., An Earth-System-Oriented View of the S2S Predictability of North American Weather Regimes. Submitted to Artificial Intelligence for the Earth Systems.

Processes that provide skill/Forecasts of opportunity: Sea Ice



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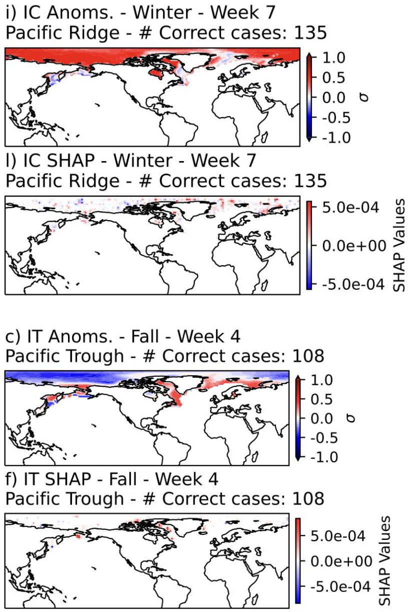

Impacts of Projected Arctic Sea Ice Loss on Daily Weather Patterns over North America

Melissa Gervais, Lantao Sun, and Clara Deser

Online Publication: 17 Jan 2024

Print Publication: 01 Feb 2024

DOI: https://doi.org/10.1175/JCLI-D-23-0389.1

Page(s): 1065–1085

"Less ice over the North Pole favors the occurrence of Aleutian lows."

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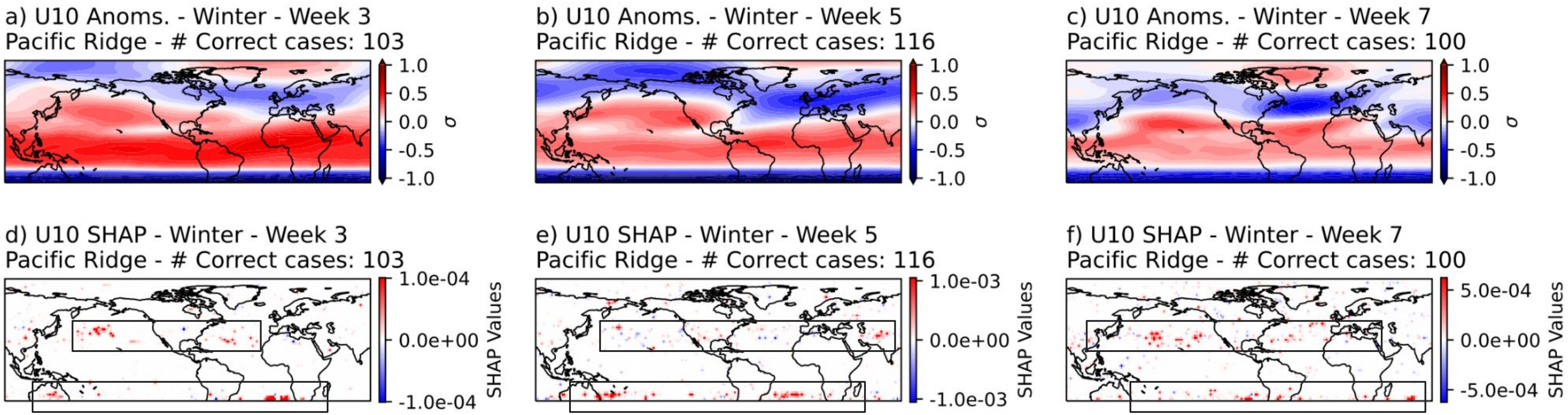
Processes that provide skill/Forecasts of opportunity: Stratospheric structure



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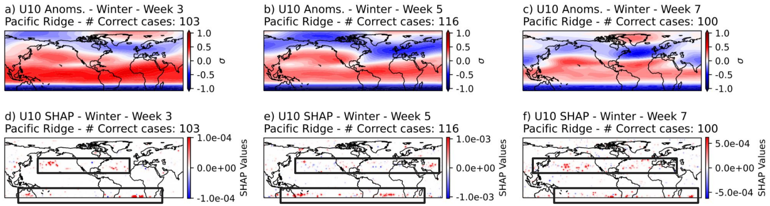

Research Letter | Free Access

Wintertime North American Weather Regimes and the Arctic Stratospheric Polar Vortex

S. H. Lee, J. C. Furtado, A. J. Charlton-Perez

First published: 27 December 2019 | https://doi.org/10.1029/2019GL085592 | Citations: 55

Research Article | Free Access

Evaluating the Joint Influence of the Madden-Julian Oscillation and the Stratospheric Polar Vortex on Weather Patterns in the Northern Hemisphere

Matthew R. Green, Jason C. Furtado

First published: 10 September 2019 | https://doi.org/10.1029/2019JD030771 | Citations: 12

Research Article | Free Access

Tropospheric and Stratospheric Causal Pathways Between the MJO and NAO

Elizabeth A. Barnes, Savini M. Samarasinghe, Imme Ebert-Uphoff, Jason C. Furtado

First published: 16 August 2019 | https://doi.org/10.1029/2019JD031024 | Citations: 46

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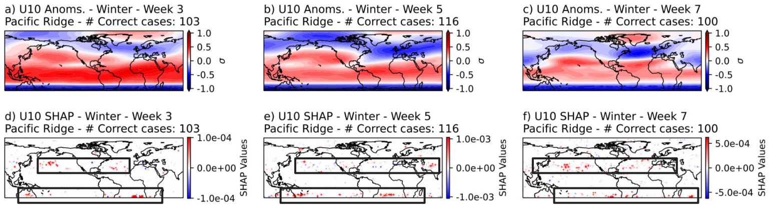
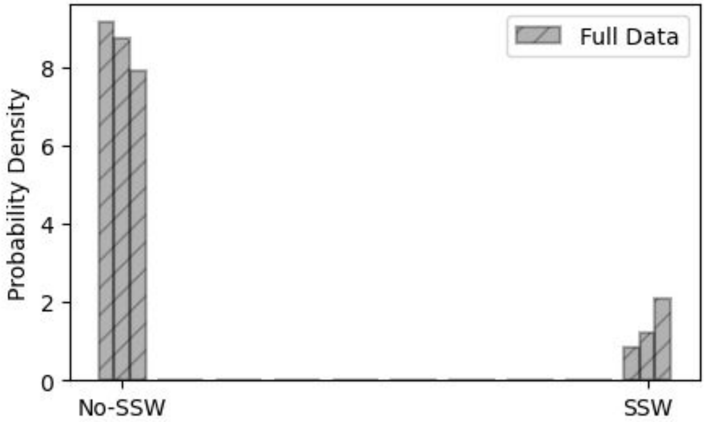


SSW vs. non SSW months



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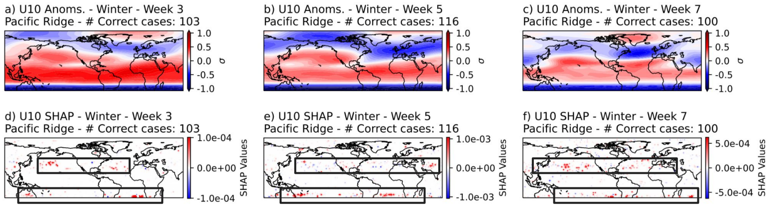

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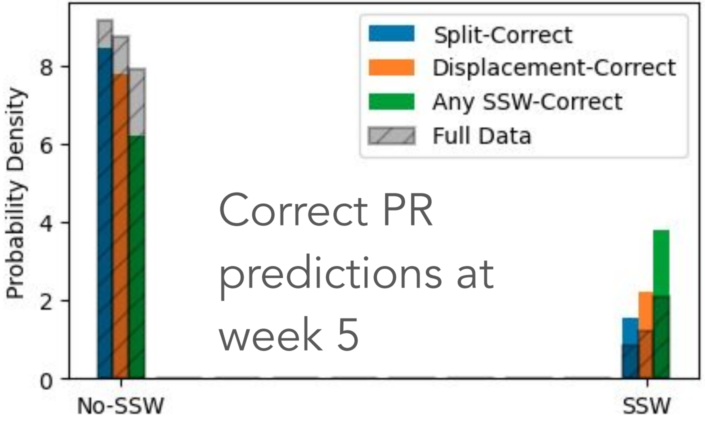

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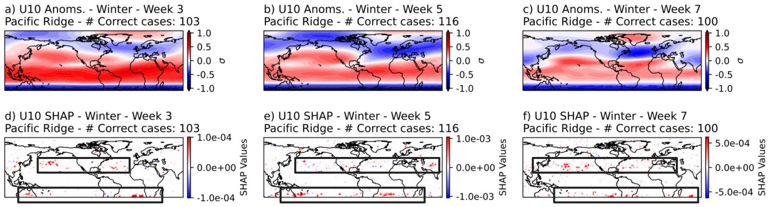

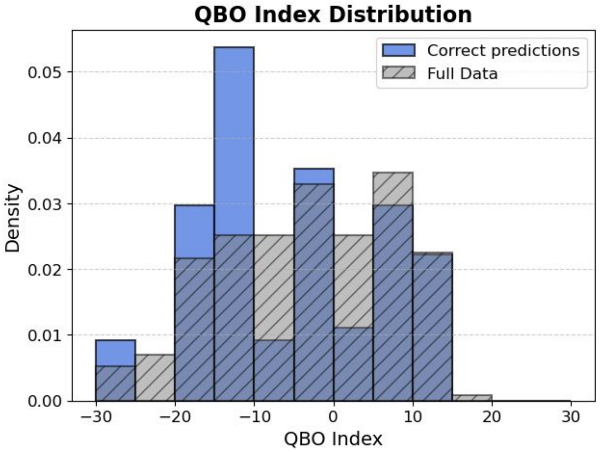

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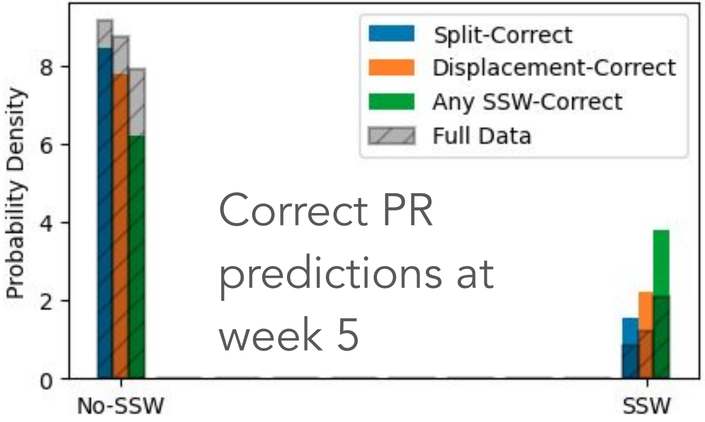

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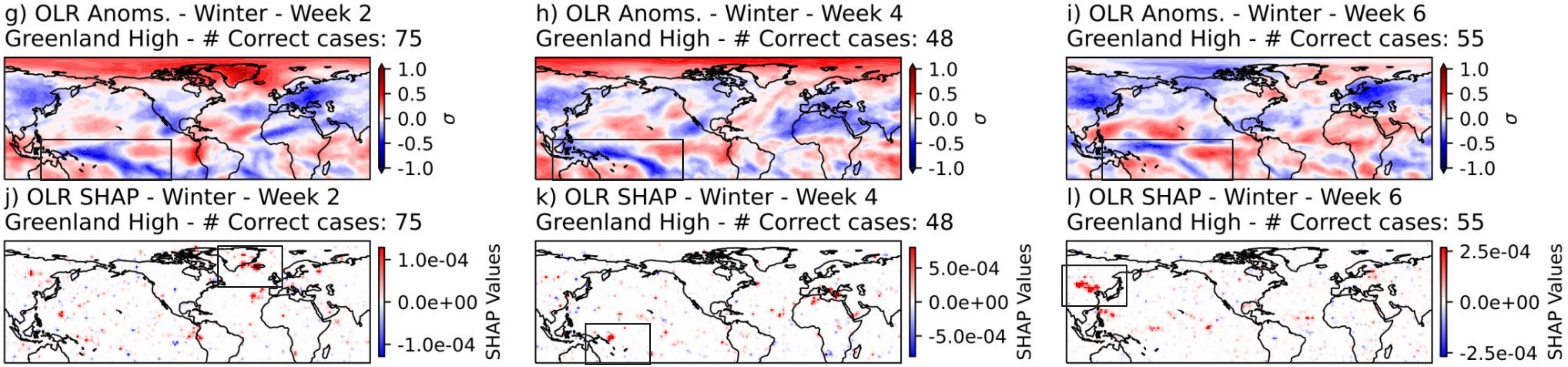
Processes that provide skill/Forecasts of opportunity: OLR/MJO



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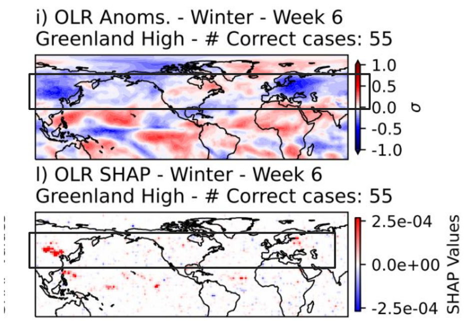


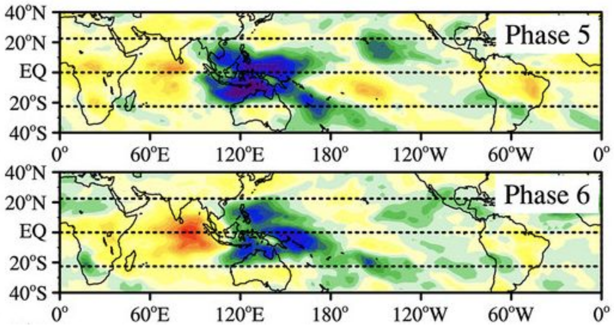
Effect of Madden–Julian Oscillation Occurrence Frequency on the Interannual Variability of Northern Hemisphere Stratospheric Wave Activity in Winter

Feiyang Wang, Wenshou Tian, Fei Xie, Jiankai Zhang, and Yuanyuan Han

Print Publication: 01 Jul 2018

DOI: https://doi.org/10.1175/JCLI-D-17-0476.1

Page(s): 5031–5049



RESEARCH ARTICLE | Open Access

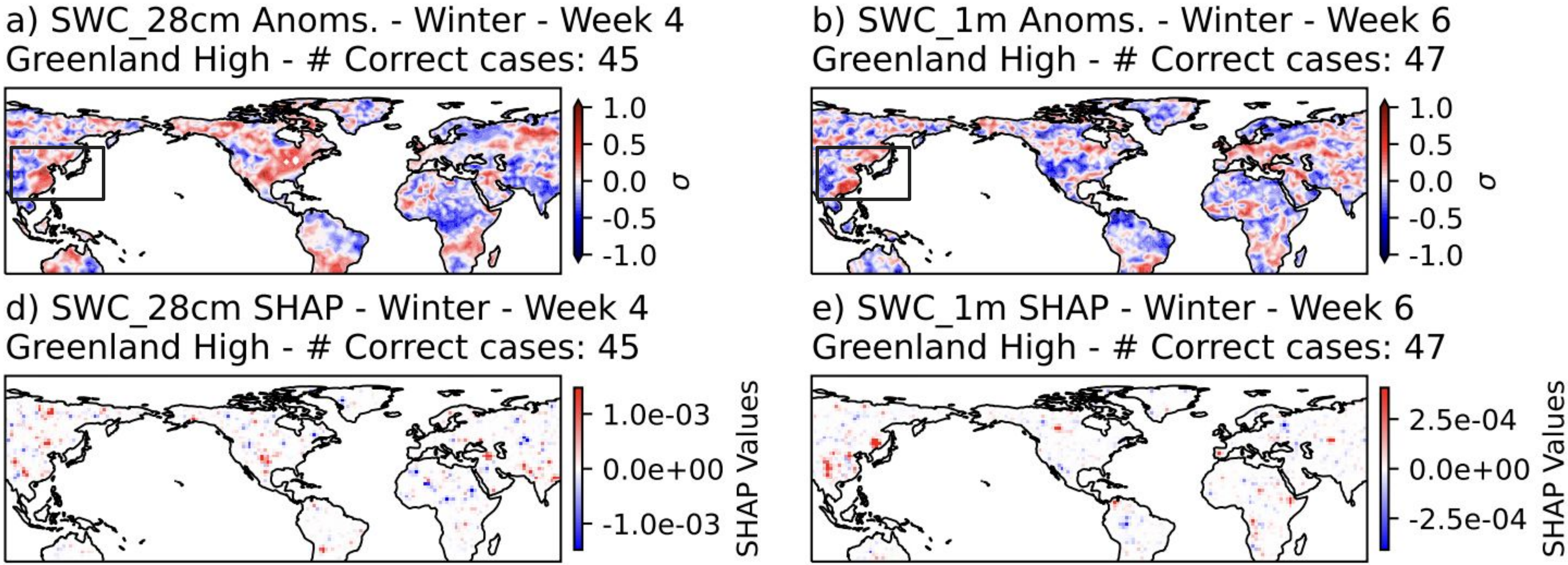
Ensemble sensitivity analysis of Greenland blocking in medium-range forecasts

Tess Parker, Tim Woollings, Antje Weisheimer

First published: 09 August 2018 | https://doi.org/10.1002/qj.3391 | Citations: 6

Pérez-Carrasquilla, J. S. & Molina, M. J. (under review)., An Earth-System-Oriented View of the S2S Predictability of North American Weather Regimes. Submitted to Artificial Intelligence for the Earth Systems.

Processes that provide skill/Forecasts of opportunity: Soil Moisture



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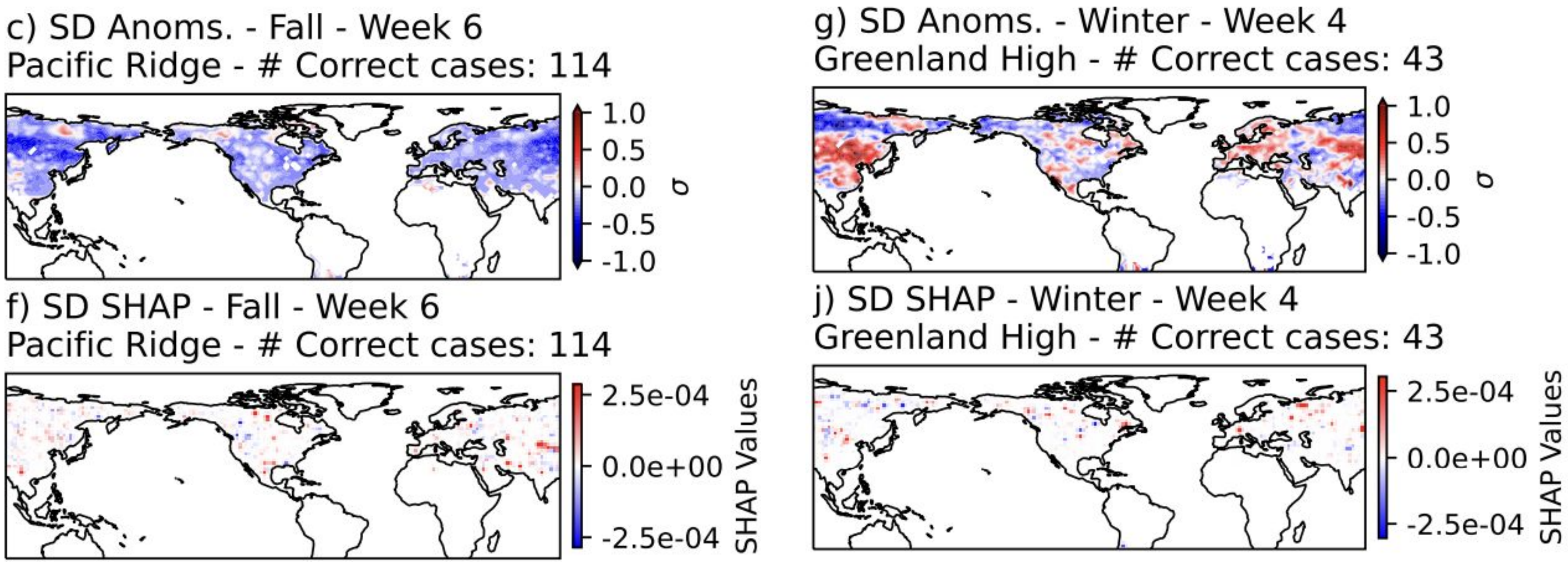
Processes that provide skill/Forecasts of opportunity: Snow Depth



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Summary

XGBoost could “see” previously identified sources of predictability and shed light into potential new ones.

Relevance of Processes (cold season)

- ENSO relevant for Pacific Trough and Pacific Ridge
- MJO relevant for Greenland High

Exploring the Relative Importance of the MJO and ENSO to North Pacific Subseasonal Predictability

Kirsten J. Mayer, William E. Chapman, William A. Manriquez

First published: 25 May 2024 | https://doi.org/10.1029/2024GL108479 | Citations: 1

Kirsten J. Mayer and William E. Chapman contributed equally to this work.

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- ENSO relevant for Pacific Trough and Pacific Ridge
- MJO relevant for Greenland High
- Stratosphere relevant for Pacific Ridge (why?)
- Snowpack and soil moisture relevant for Greenland High and Pacific Ridge (why?)

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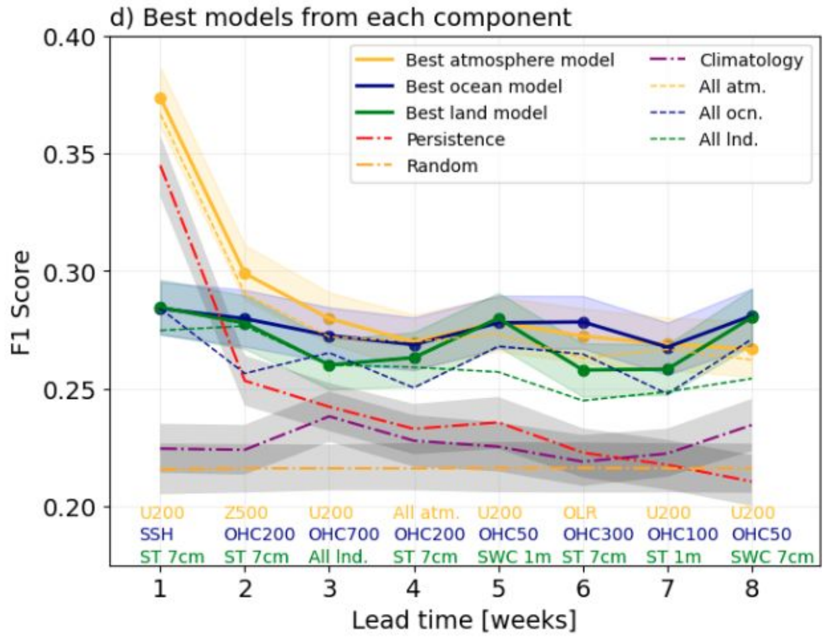
Could AI leverage all this information to do improved predictions?



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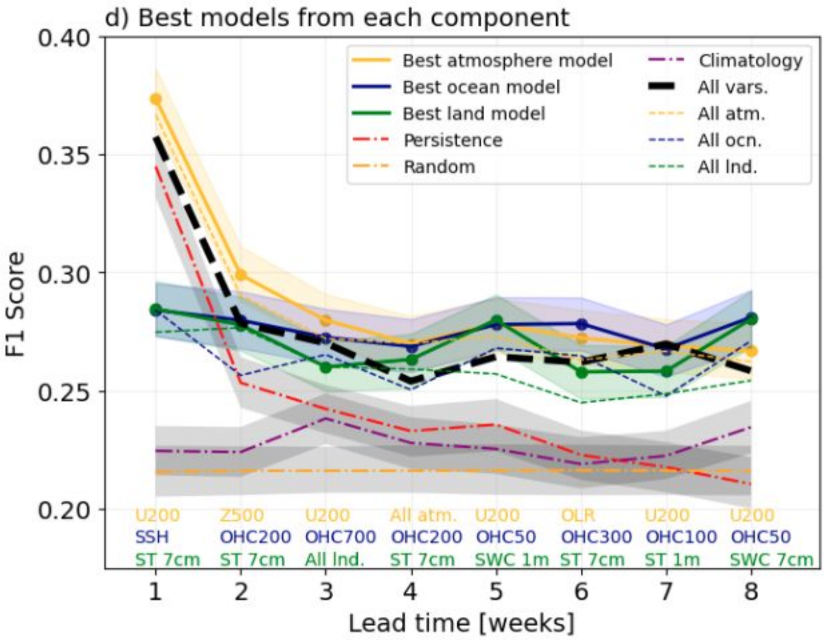
Could AI leverage all this information to do improved predictions?



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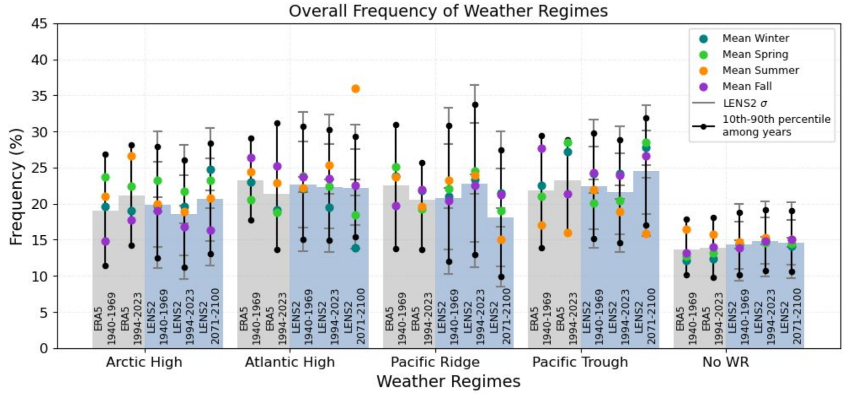
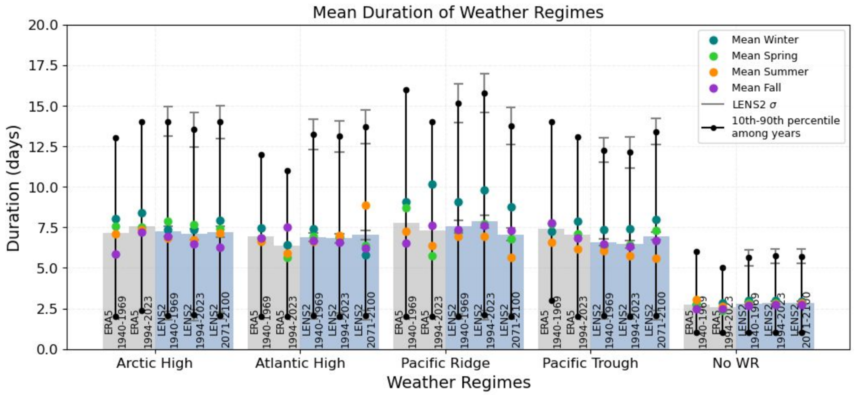
Other work with LENS2 and WRs

Long-term changes in the characteristics of North American weather regimes

Jhayron S. Pérez-Carrasquilla[1] (jhayron@umd.edu), Maria J. Molina[1], Kirsten J. Mayer[2], Katherine Dagon[2], and Isla R. Simpson[2]
[1]University of Maryland, Atmospheric and Oceanic Science Department
[2]NSF National Center for Atmospheric Research

LENS2 provides a good representation of the frequency and duration of the WRs





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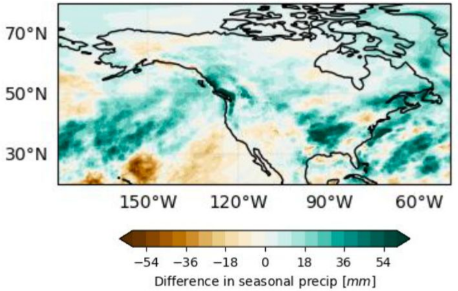
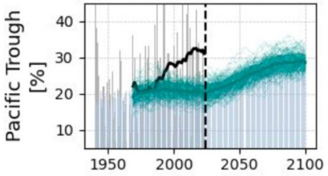
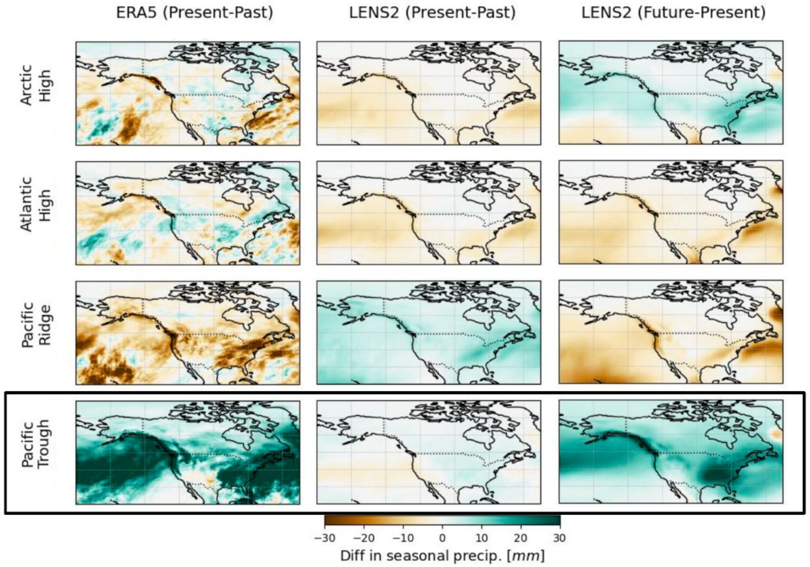
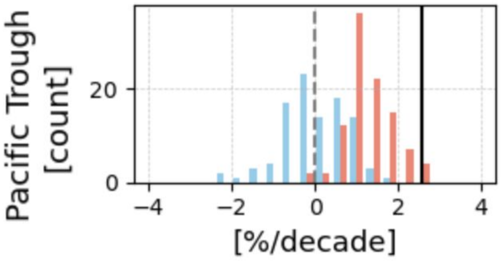
Pacific Trough during spring - forced change?

ERA5 - Seasonal changes



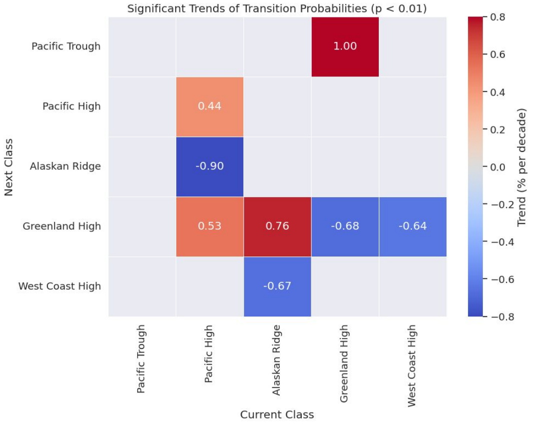


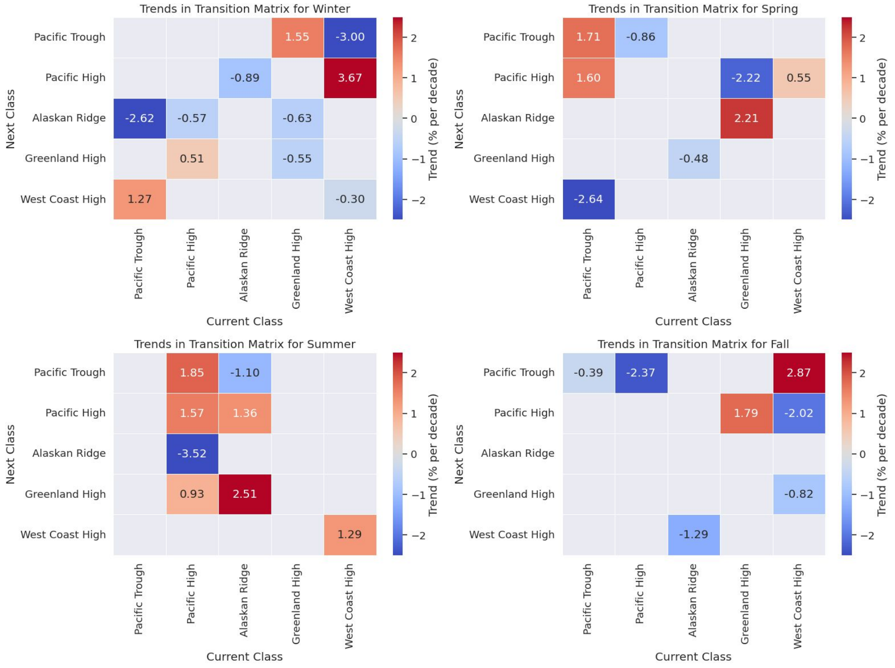




Other work with LENS2 and WRs

WR-Transitions and long-term changes: Will it get easier or harder to predict the WRs?





Thanks!!!!

Summary

XGBoost could “see” previously identified sources of predictability and shed light into potential new ones.

Relevance of Processes (cold season)

- ENSO relevant for Pacific Trough and Pacific Ridge
- MJO relevant for Greenland High
- Stratosphere relevant for Pacific Ridge (why?)
- Snowpack and soil moisture relevant for Greenland High and Pacific Ridge (why?)

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