ML for improved Earth System Understanding:
a Forecast of Opportunity Lens

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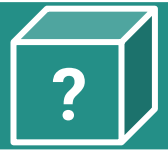
NSF National Center for Atmospheric Research

21 July 2025

How can we explore Earth System sources of predictability beyond weather timescales with ML?

ML-Identified Forecasts of Opportunity

Explainable & Interpretable AI

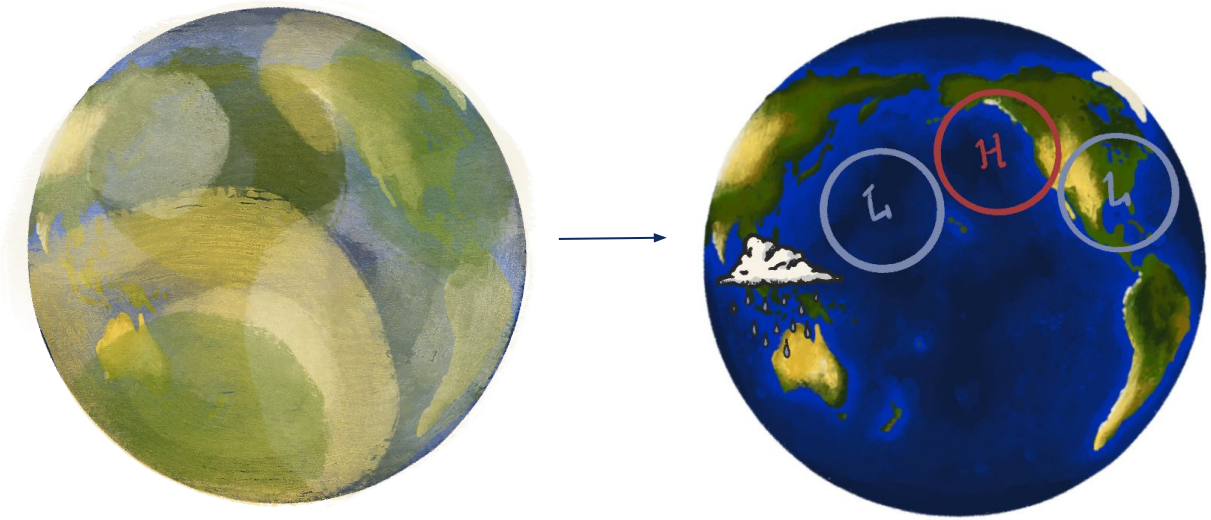


post-hoc method

intentionally designed

Forecasts of Opportunity/State-Dependent Predictability

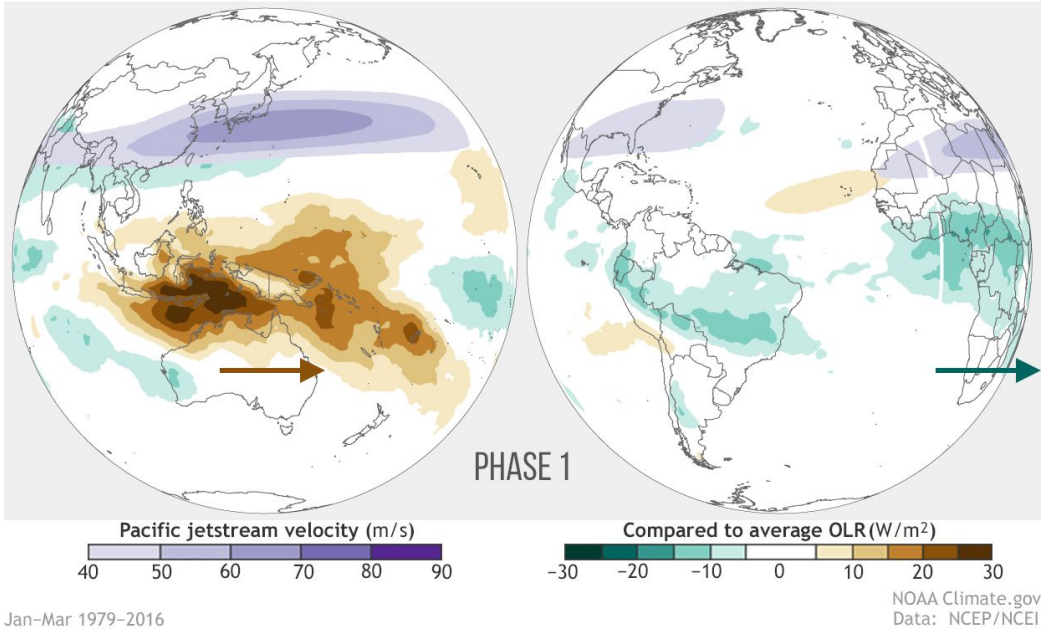
specific conditions in the earth system that lead to enhanced predictable behavior



Vitart et al., 2012, 2017; Mariotti et al., 2020

The Madden-Julian Oscillation (MJO)

The MJO is an eastward propagating anomalous tropical heating (~20 to 90 days)

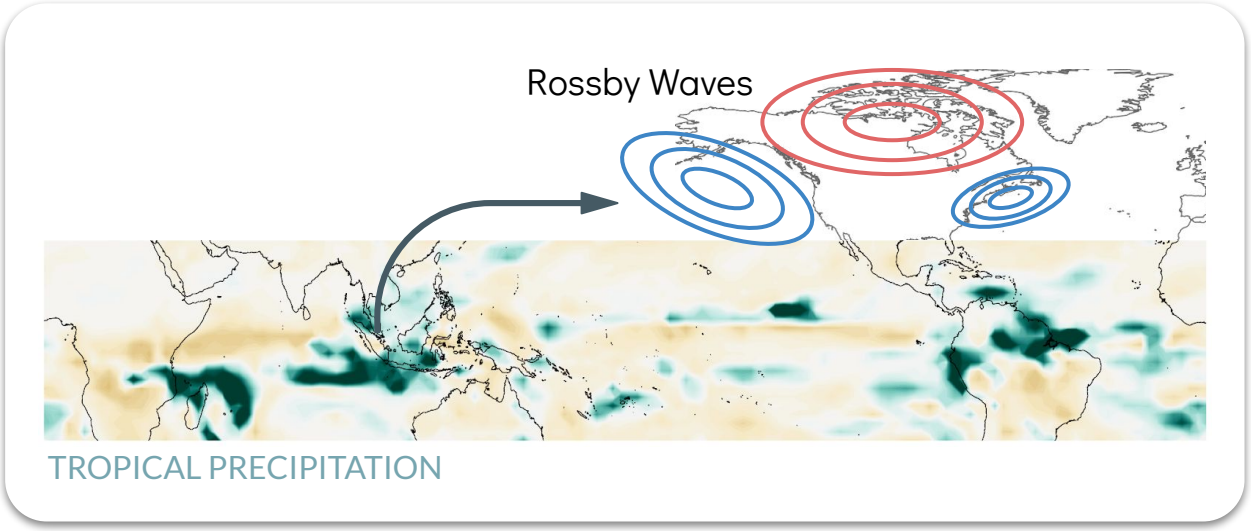


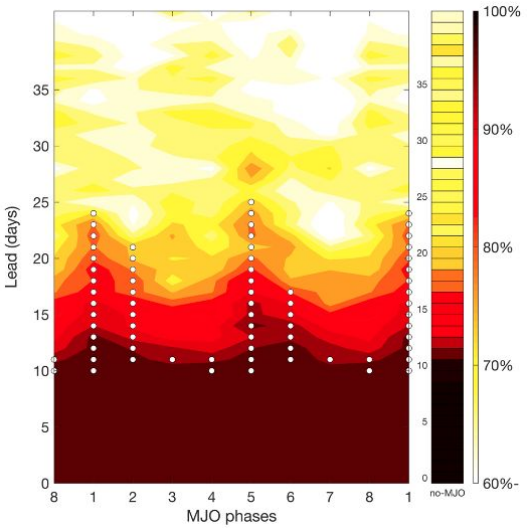
When the MJO is active , we use information about the state of the MJO today to predict what will happen to NH weather in the coming weeks

Madden & Julian, 1971, 1972, 1994

Tropical-Extratropical Teleconnections

The tropics can influence midlatitude weather on subseasonal timescales & impact prediction skill





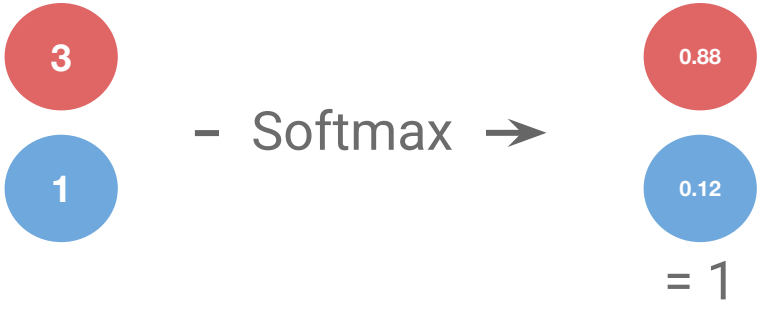
ML to identify Forecasts of Opportunity

Categorical [predict categories]

Regression [predict number]

ML to identify Forecasts of Opportunity

Categorical [predict categories]

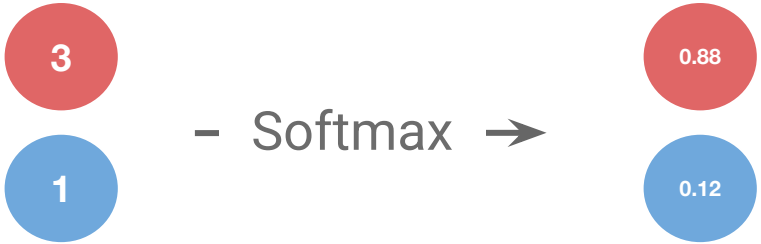


Network Confidence

Regression [predict number]

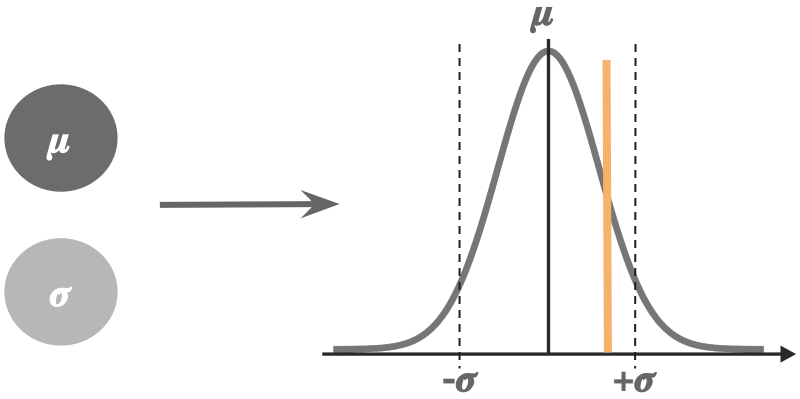
ML to identify Forecasts of Opportunity

Categorical [predict categories]



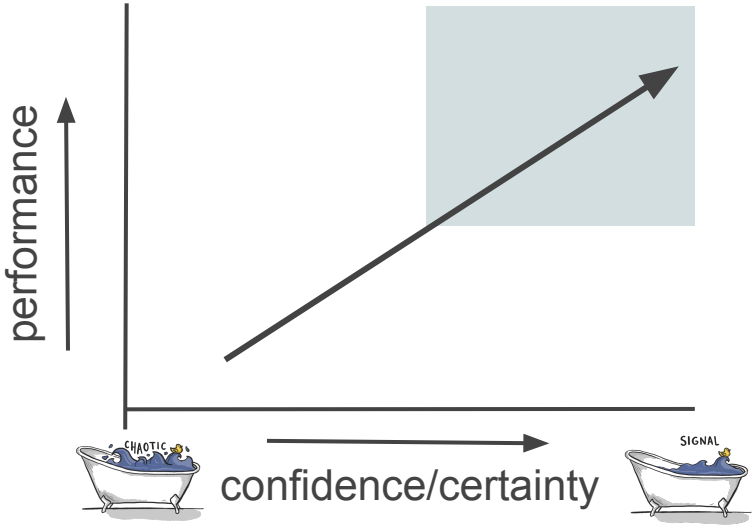
Network Confidence

Regression [predict number]



Network Certainty

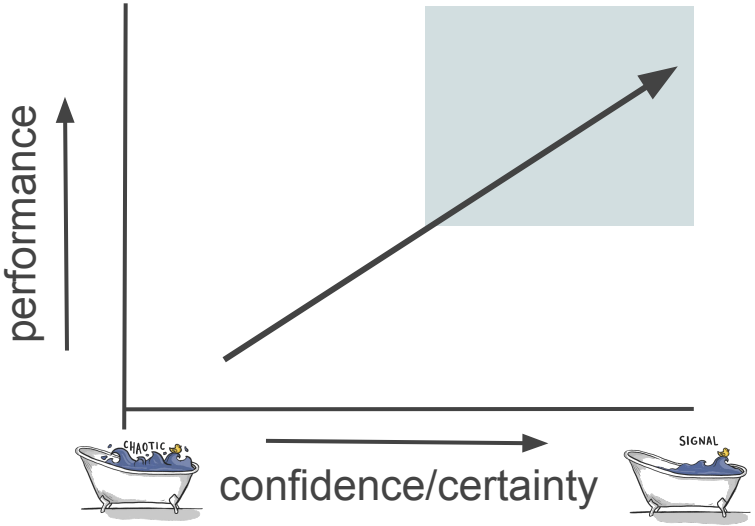
ML to identify Forecasts of Opportunity



Forecasts of Opportunity

periods of enhanced predictability
identified using network confidence/certainty

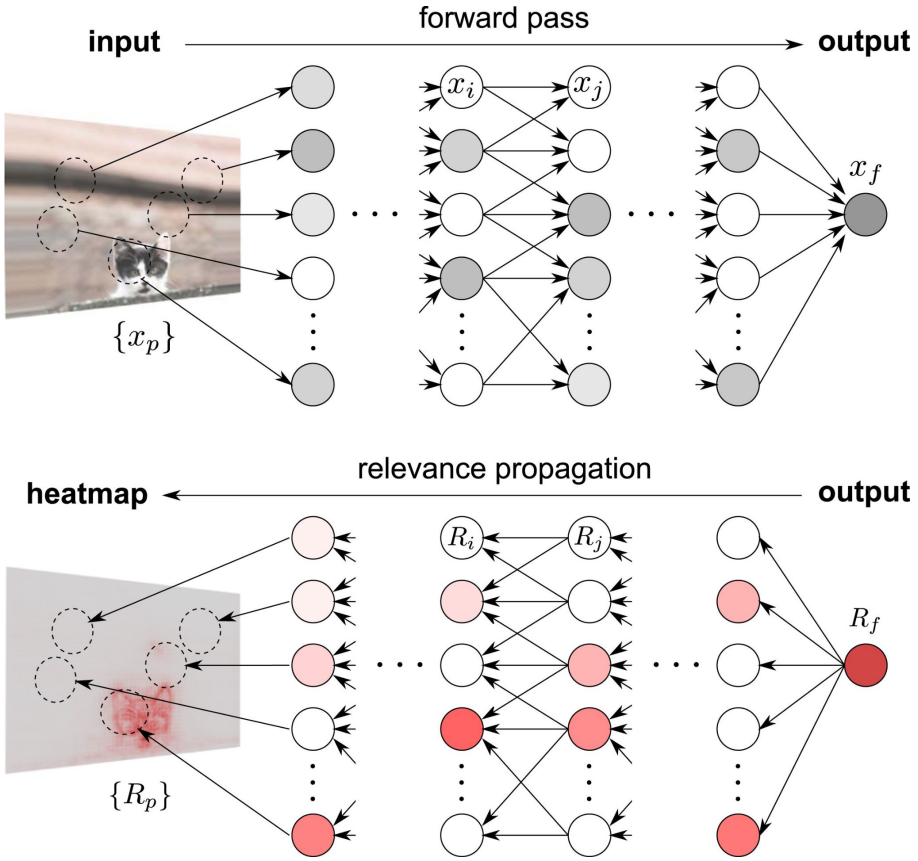
ML to identify Forecasts of Opportunity



… but is it physical

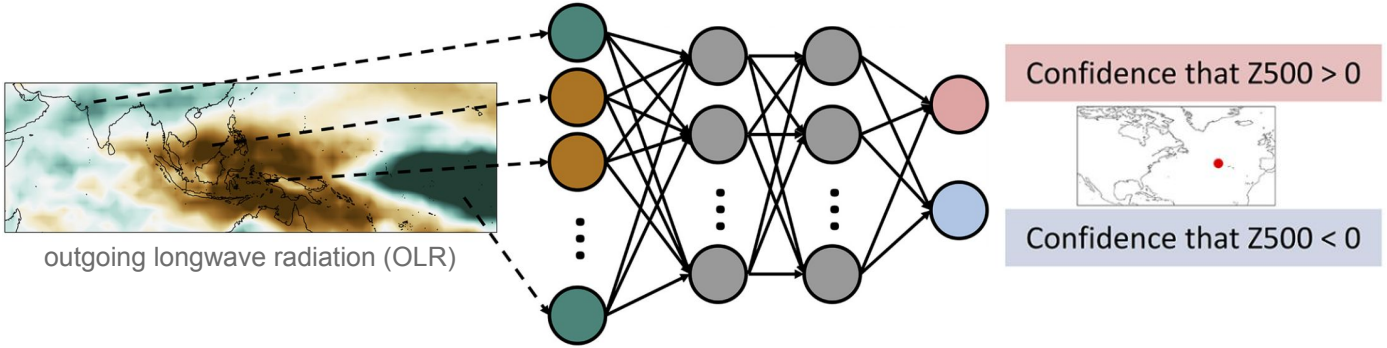
eXplainable AI (XAI)

layerwise relevance propagation



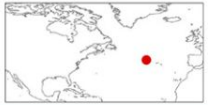
Montavon et al. 2017

ML Identified S2S Forecasts of Opportunity

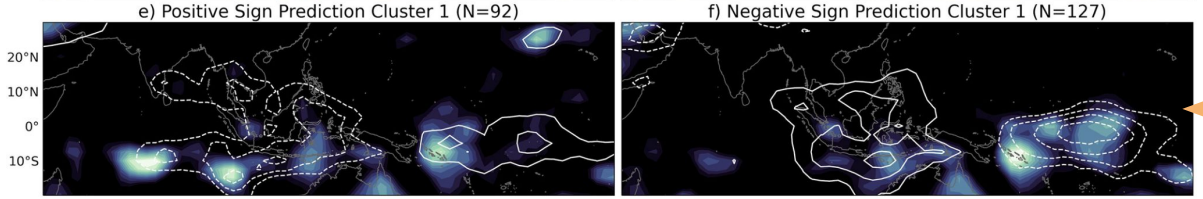


ML Identified S2S Forecasts of Opportunity

Confidence that Z500 > 0



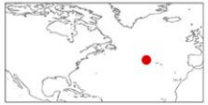
Confidence that Z500 < 0



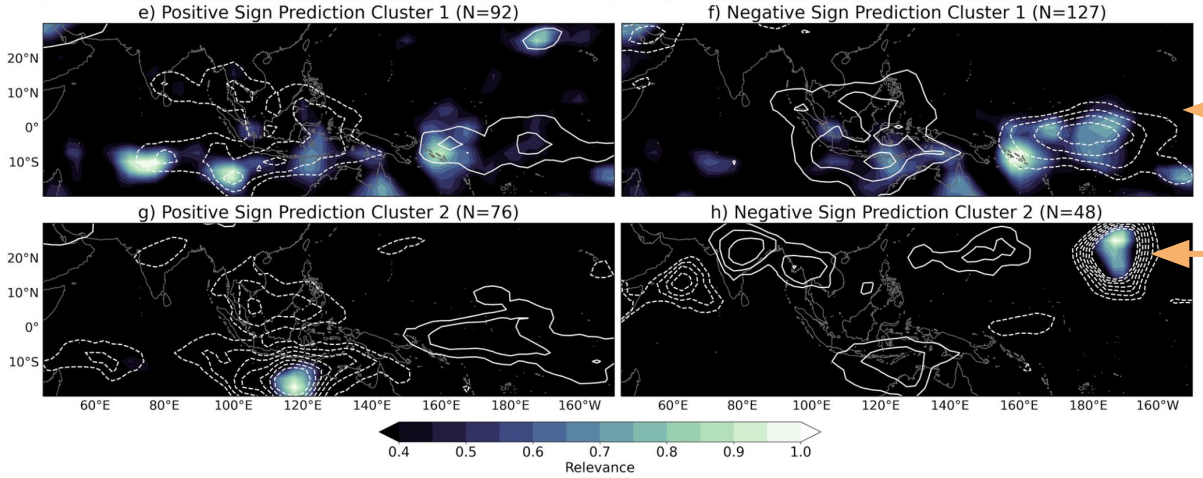
MJO-like structure

ML Identified S2S Forecasts of Opportunity

Confidence that Z500 > 0



Confidence that Z500 < 0

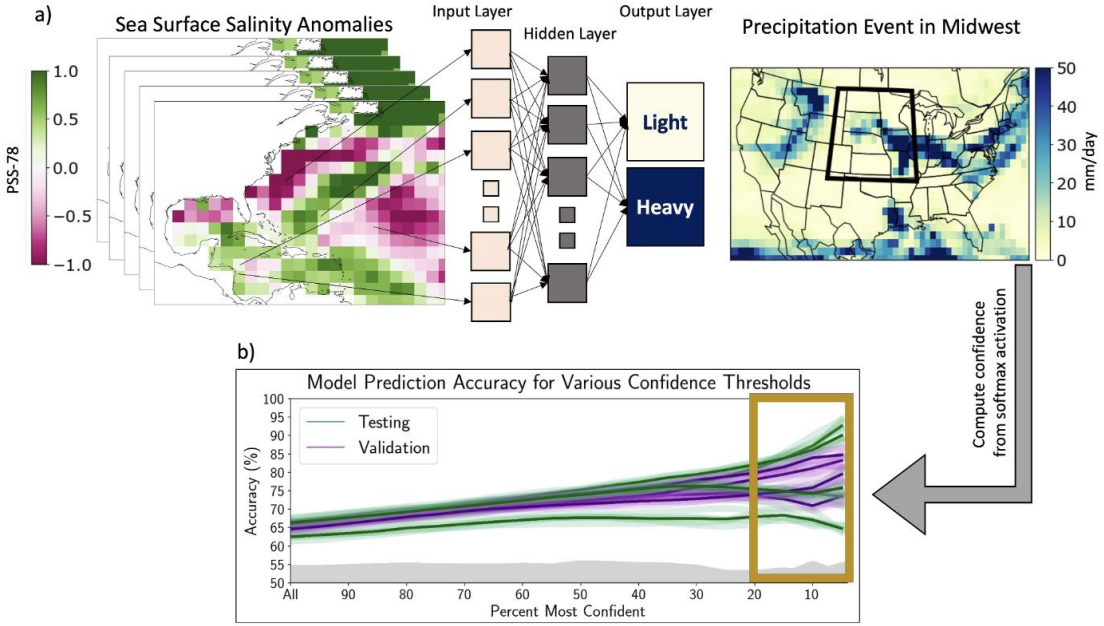


MJO-like structure

new forecast of opportunity?

Sources of Predictability on

1. Subseasonal
2. Seasonal
3. Decadal



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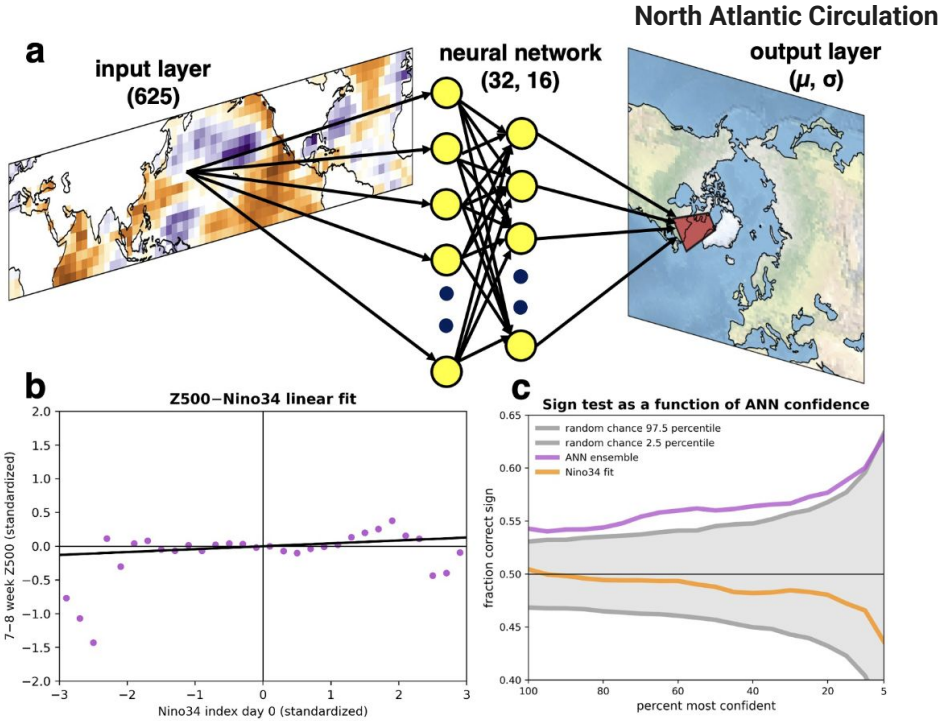

Shackelford et al. 2025

Sources of Predictability on

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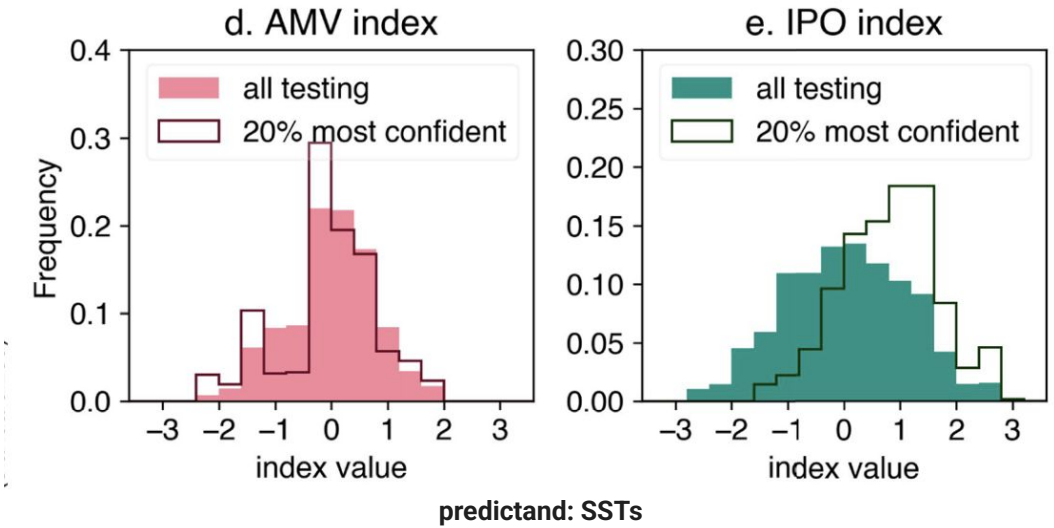
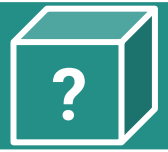


predictand: SSTs

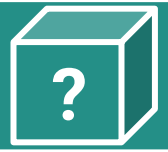
ML-Identified Forecasts of Opportunity

Explainable AI



ML-Identified Forecasts of Opportunity

Explainable and **Interpretable AI**



… how can we use IAI to identify forecasts of opportunity important for predictability?

using an inherently interpretable neural network to

Explore the Relative Importance of the MJO & ENSO to North Pacific Subseasonal Predictability

Kirsten J. Mayer*, Will Chapman*, & Tony Manriquez (2024; GRL)
*contributed equally

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El Niño Southern Oscillation (ENSO)

ENSO is an anomalous sea surface temperature pattern in the tropical Pacific, which can influence midlatitude weather on seasonal timescales

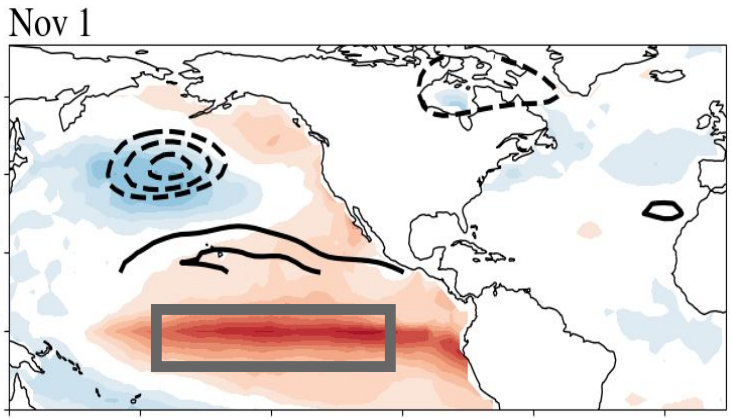


Figure courtesy of Will Chapman

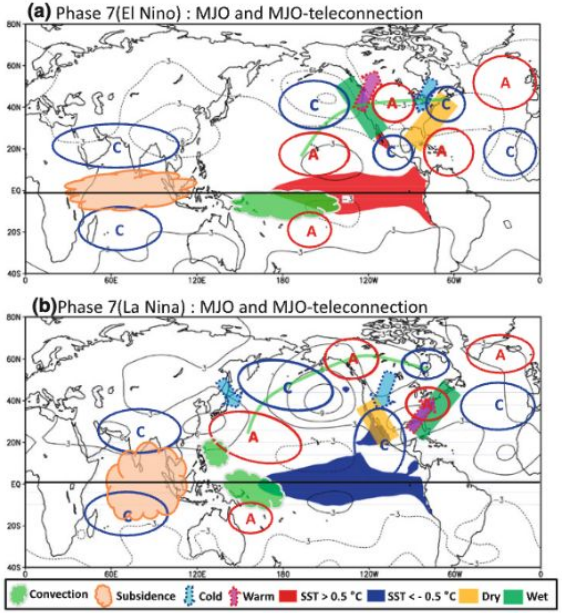


Figure 10 (Moon et al. 2011)

e.g., Trenberth, 1997, Gibson et al., 2021; Winkler et al., 2001

e.g. Pohl & Matthews 2007; Moon et al. 2011; Johnson et al. 2014; Tseng et al. 2020; Arcodia et al. 2020; Arcodia & Kirtman et al. 2023

Subseasonal Evolution of ENSO teleconnections

ENSO teleconnection evolves over boreal winter due to changes in strength of midlatitude jet

Editorial Type: Article

Article Type: Research Article

Monthly Modulations of ENSO Teleconnections: Implications for Potential Predictability in North America

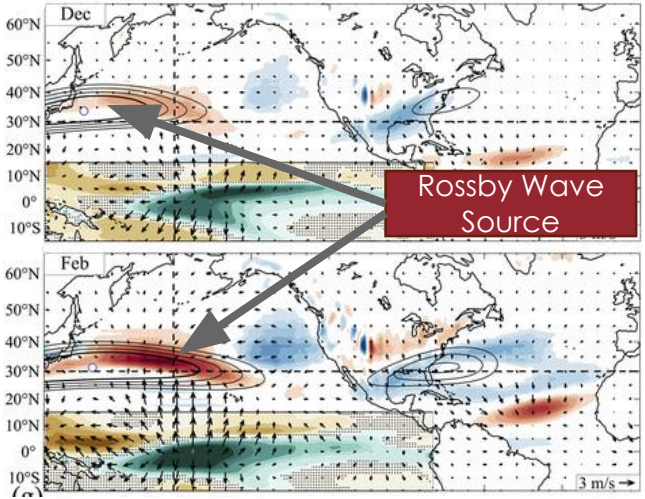
William E. Chapman, Aneesh C. Subramanian, Shang-Ping Xie, Michael D. Sierks, F. Martin Ralph, and Youichi Kamae

Online Publication: 15 Jun 2021

Print Publication: 01 Jul 2021

DOI: https://doi.org/10.1175/JCLI-D-20-0391.1

Page(s): 5899–5921

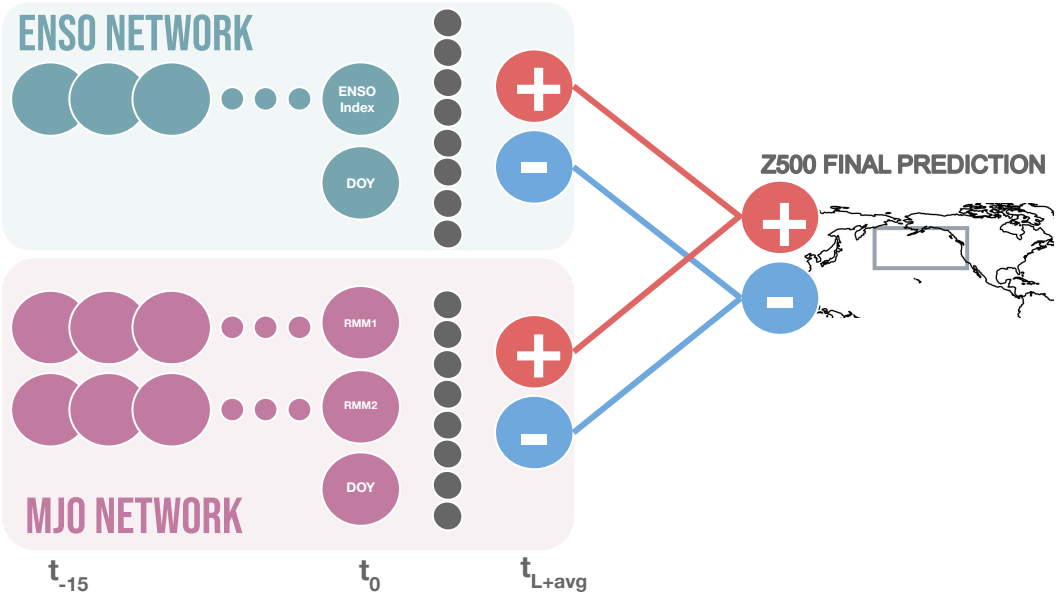


Chapman et al. 2021

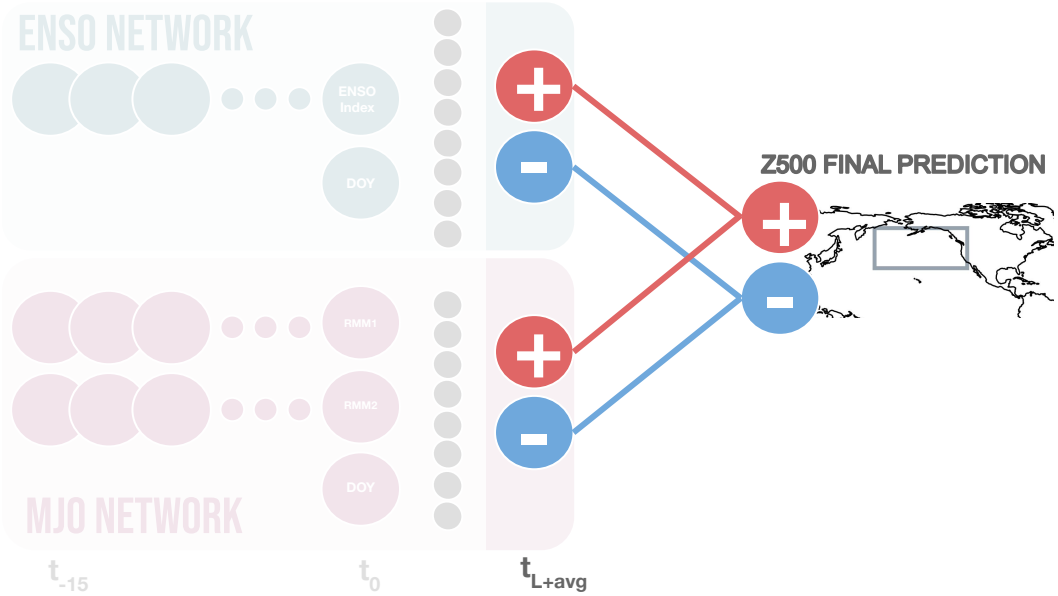
e.g. Newman and Sardeshmukh 1998; Kumar & Hoerling 1998

Exploring the relative importance of sources of predictability

**network architecture adapted from Gordon et al. (2023)



Exploring the relative importance of sources of predictability



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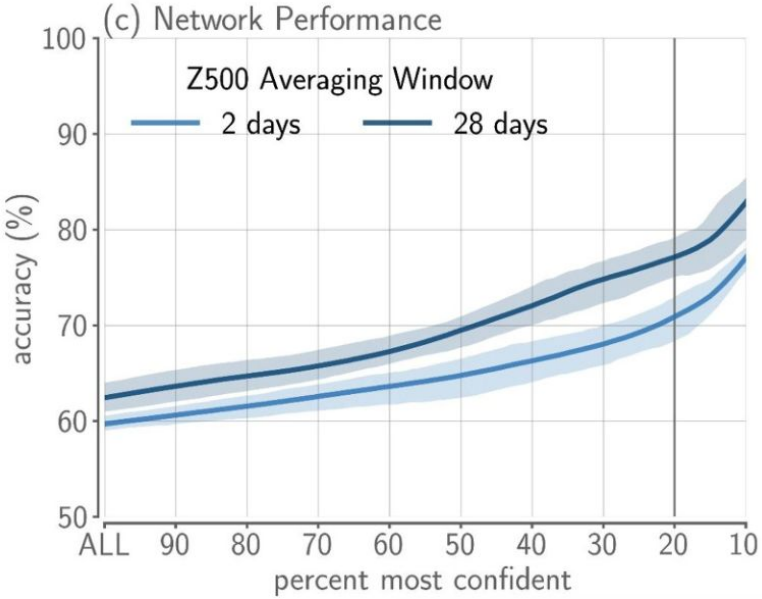
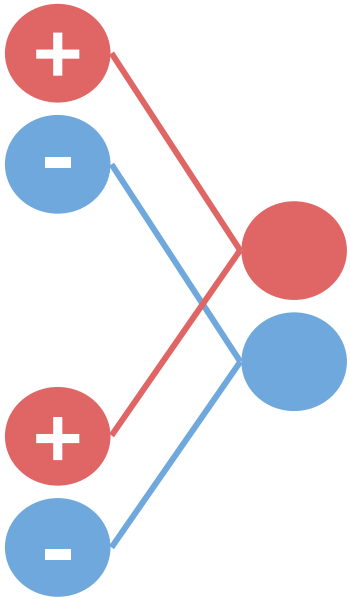


Rather than specifying a threshold for ENSO & MJO, we use confidence to determine forecasts of opportunity.

As confidence increases, accuracy increases, suggesting our network **can identify forecasts of opportunity**

Exploring the relative importance of sources of predictability

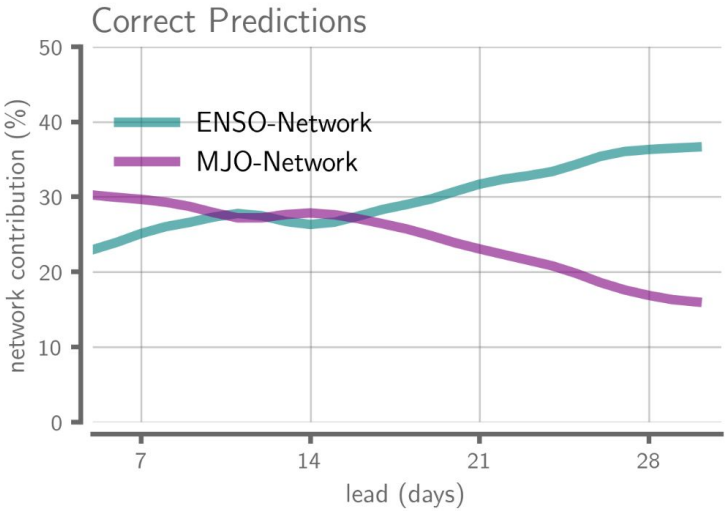


Let's say the correct prediction is **positive**… there are a couple ways to get a correct prediction:

- **ENSO** *and* **MJO** network correctly predict **positive**
- **ENSO** network correctly predicts **positive**
- **MJO** network correctly predicts **positive**

Individual Network Contribution

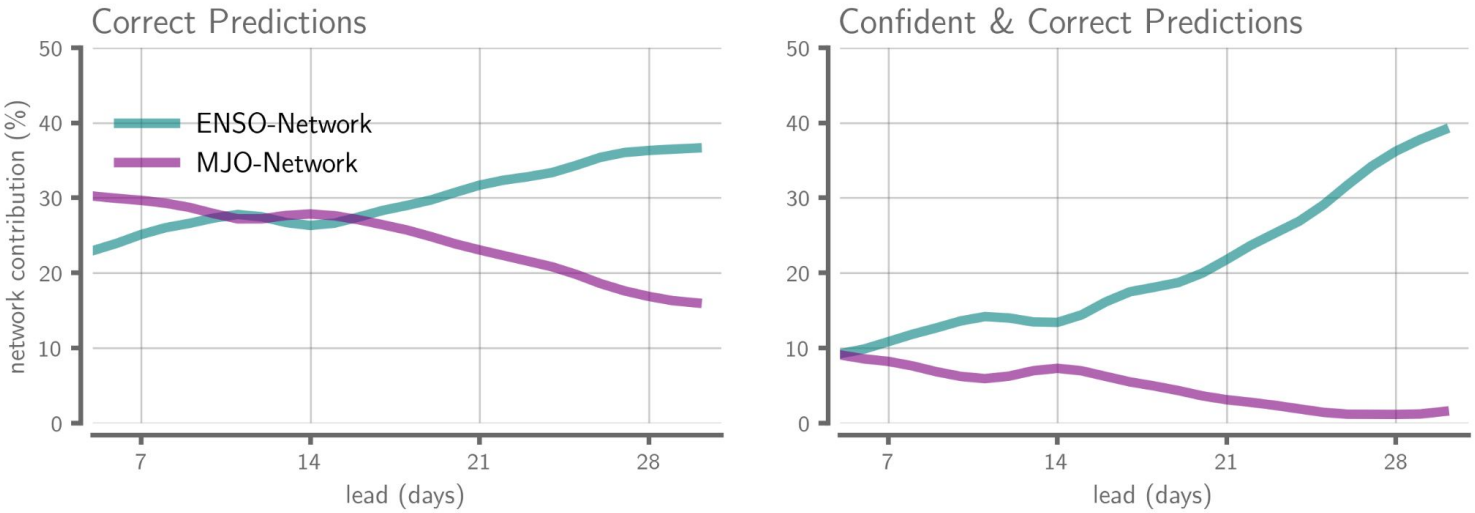
frequency that a specific network makes a correct (and confident) prediction



ENSO network contributes more frequently to **correct predictions** than the MJO network after ~2 weeks

Individual Network Contribution

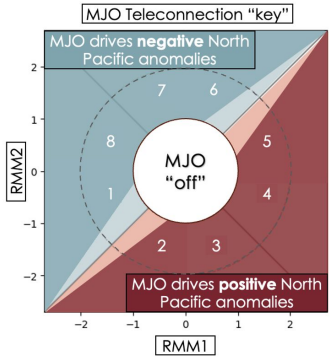
frequency that a specific network makes a correct (and confident) prediction



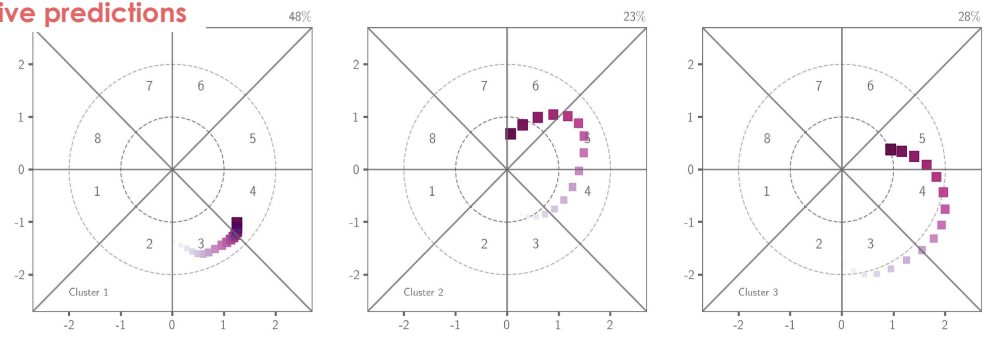
ENSO network contributes more frequently to **correct predictions** than the MJO network after ~2 weeks

ENSO network alone contributes more frequently during **forecasts of opportunity** than the MJO network

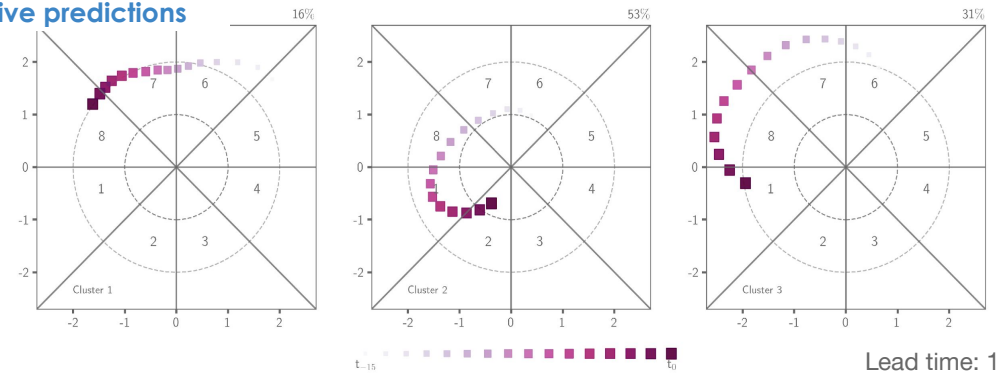
Confident & Correct Predictions: ENSO Neutral



positive predictions



negative predictions



Clustered network-identified MJOs useful for subseasonal predictability:

- Anomalous strong
- Strong then decays to neutral
- Persistent

Lead time: 10 days
Averaging window: 5 days

Exploring the relative importance of sources of predictability

- With this specific architecture we were able to explore sources of predictability
- We found **ENSO** is a greater source for state-dependent subseasonal predictability
- When ENSO is neutral, there are **3 MJO states** that lead to enhanced predictability

- Results may change if framed as a regression problem or in a future, warmer climate
  - (Mayer & Barnes 2022; Du et al. 2023)

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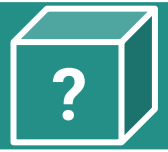

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