

Reservoir Computing as a tool for Climate Predictability Studies

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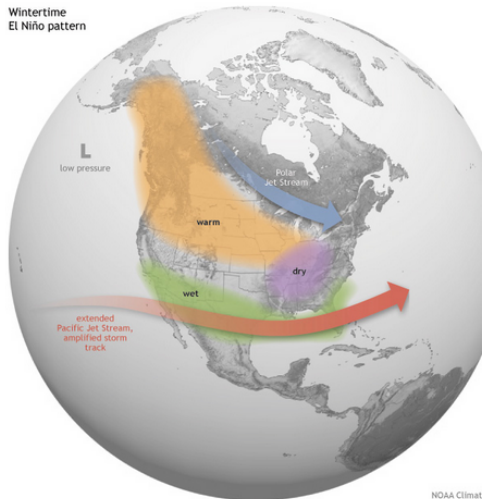
(Nadiga, B. T. "Reservoir computing as a tool for climate predictability studies." Journal of Advances in Modeling Earth Systems (2021): e2020MS002290; DOI 10.1029/2020MS002290)

Climate varies on all timescales (beyond weather)

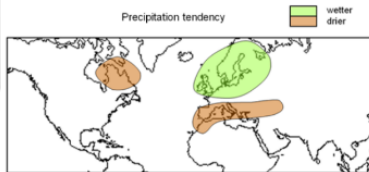
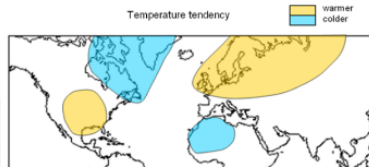
..., El Niño, NAO, ..., # of TCs, global warming, ...

By examining seasonal climate conditions in previous El Niño years, scientists have identified a set of typical impacts associated with the phenomenon (Figure 1). "Associated with" doesn't mean that all of these impacts happen during every El Niño episode. However, they happen more often during El Niño than you'd expect by chance, and many of them have occurred during many El Niño events.

Wintertime
El Niño pattern



when the winter NAO index is well above zero



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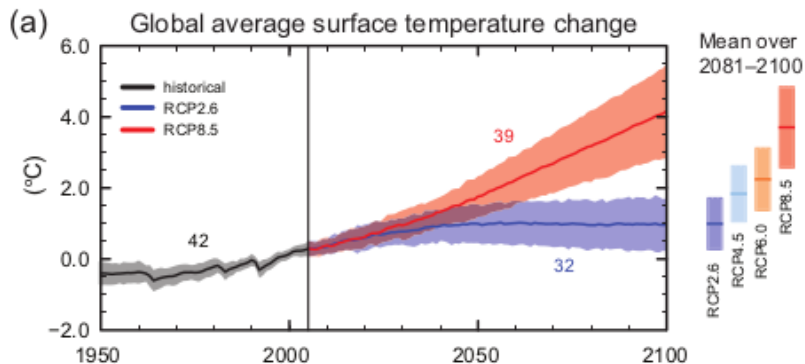
Predictability amounts to developing an “*Understanding*” of the Spatio-Temporal Characteristics of Variability

“*Understanding*” is a catch-all for mechanistic understanding, an actionable model, etc.

Two Kinds of Predictability

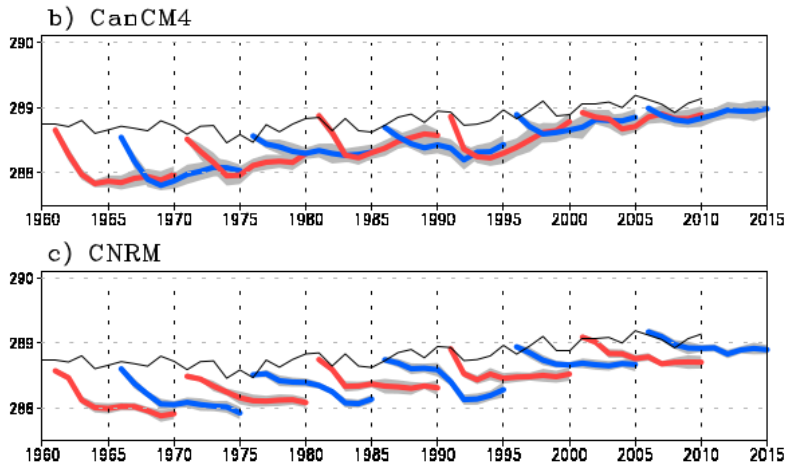
- ▶ Natural-Variability Related Predictability
- ▶ External-Forcing Related Predictability

Currently, Models are Good at Realizing External-Forcing Related Predictability



IPCC AR5

but, currently models are bad at predicting natural var.



(From Kim et al., 2012)

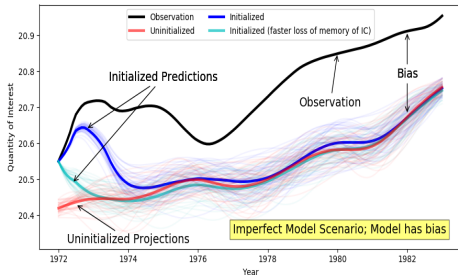
Initialized Predictions of Various Qols in Various Models (Surface Temperature in CanCM4 and CNRM) Display a Jump Behavior

Because models are bad at predicting natural variability, it is important to understand the predictability of such variability

Climate Models are Biased

- ▶ Extremely difficult to model the exact balance (small residual) of myriad (large) processes that lead to the mean state of the climate system and modes of variability
- ▶ Small difference between large numbers

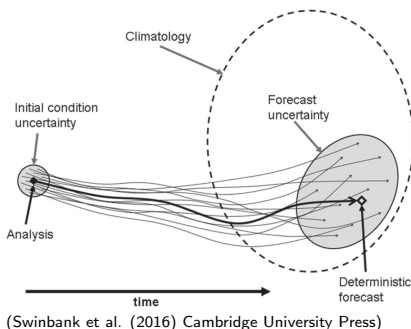
Explanation of Jump-like Behavior of Initialized Predictions



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Chaotic Nature of Natural Variability (Lorenz, 1969)

- ▶ Conduct initial condition ensemble simulations with climate model
- ▶ Obtain forecast dist. $P(v|\theta)$ (θ is obs.) and climatological dist. $P(v)$



- ▶ Conduct analysis of forecast error covariance Σ_F and climatological covariance Σ_C (assuming normal dist.)
 - ▶ Canonical Correlation Analysis
 - ▶ Discriminant Analysis
 - ▶ Predictive Component Analysis

Predictability has to do with Dynamics of Error Growth

A Roadmap for using ML for Predictability Studies

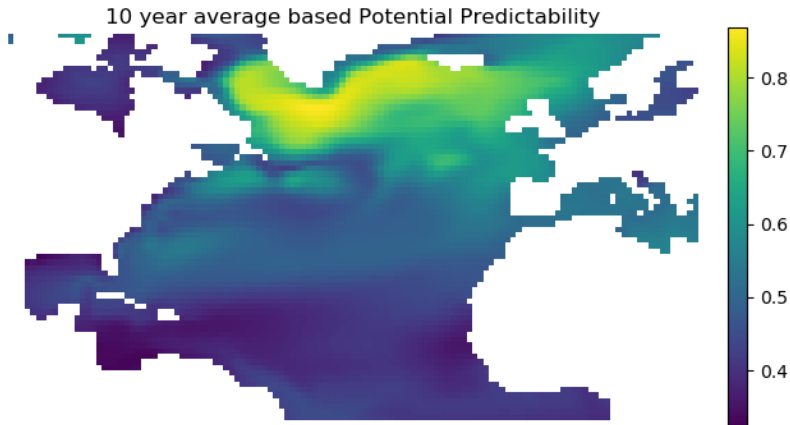
A Data-centric Approach based on Learning Spatio-Temporal Variability of Climate

- ▶ Data: Observations & Reanalysis, CMIP (IPCC class models)
- ▶ Formulate problem with different forms/complexity, model order reduction, data augmentation, ...
- ▶ Develop learning based prediction system with different architectures
- ▶ Analyze and quantify learning in best formulation/model, e.g., using XAI methods, and establish predictability

Methods and Architectures

- ▶ Classical Statistical Methods (e.g., Linear Inverse Modeling)
- ▶ Advanced Statistical Mechanical Methods (e.g., Mori-Zwanzig formalism for memory)
- ▶ Deep Learning: MLP, LSTM, PCA-LSTM, convLSTM, Attention, Transformer, Reservoir Computing, etc.

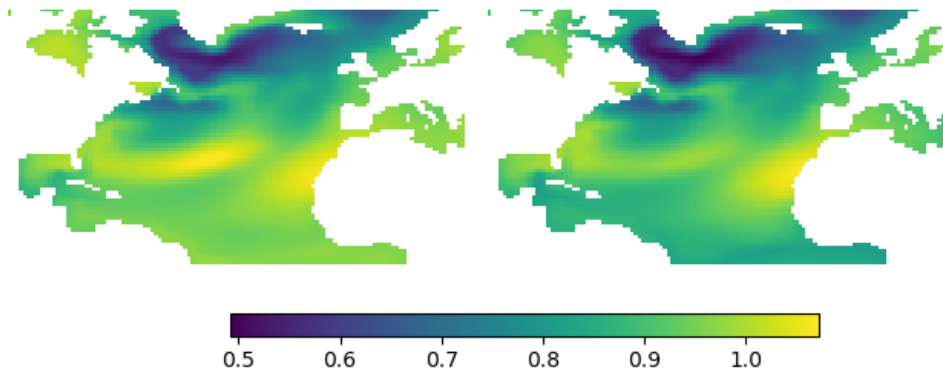
Prediction of SST in the North Atlantic



Potential Predictability as the ratio of variances of N-year average and 1-year average of SST

Reservoir Computing vs. Linear Inverse Modeling

Learning from Long Runs of Data. 800 years split 80:20

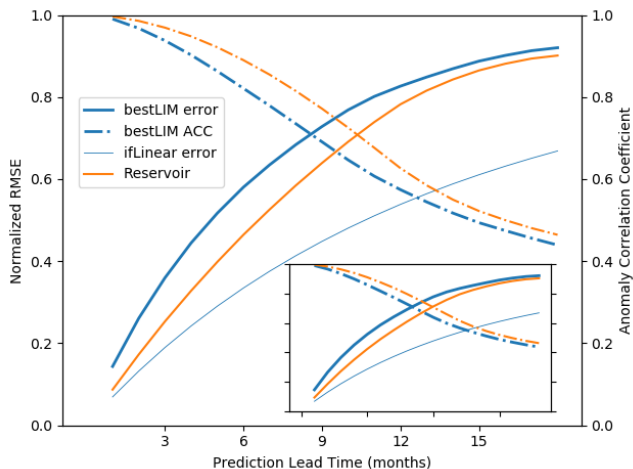


Normalized RMSE (Lower values $\Rightarrow$ Higher skill)

(Nadiga, RC as a tool for climate predictability studies, JAMES 2021)

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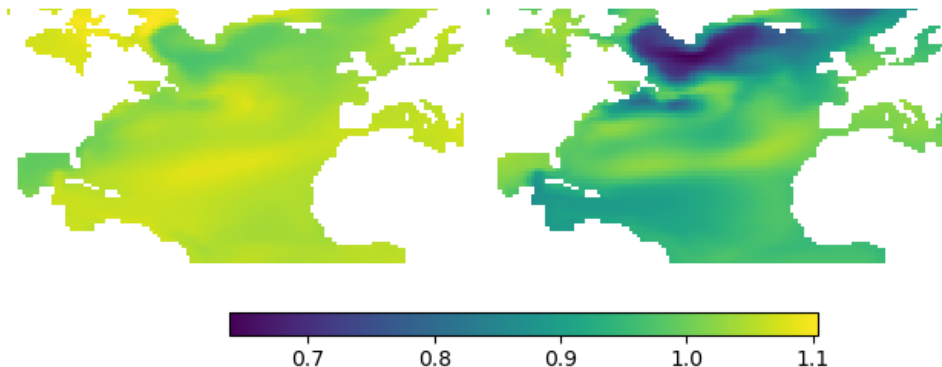


Main plot: prediction with 20 EOFs. Inset: 30 EOFs

RC is slightly better than LIM

Reservoir Computing vs. Linear Inverse Modeling

Learning from limited data (more nonlinear; reduced emphasis on generalization)



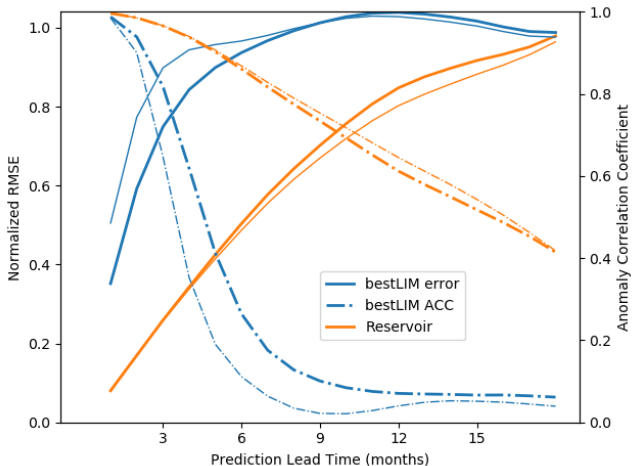
Normalized RMSE (Lower values $\Rightarrow$ Higher skill)

RC Vastly OutPerforms LIM

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Reservoir Computing vs. Linear Inverse Modeling

Learning from limited data. 13 year segments split as 88:12

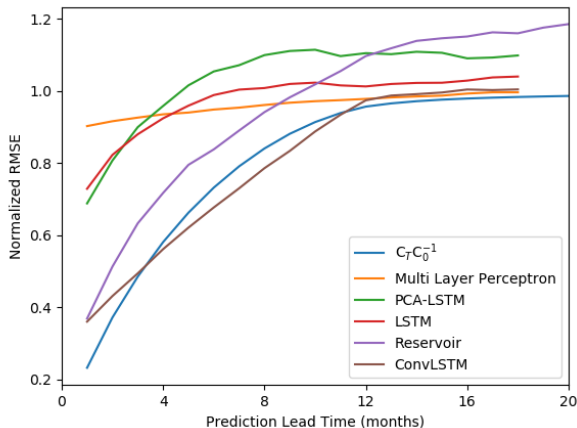


Thicker lines: prediction with 20 EOFs. Thinner lines: 30 EOFs

RC Vastly OutPerforms LIM

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Comparison of Predictive Skill Across DNN Architectures

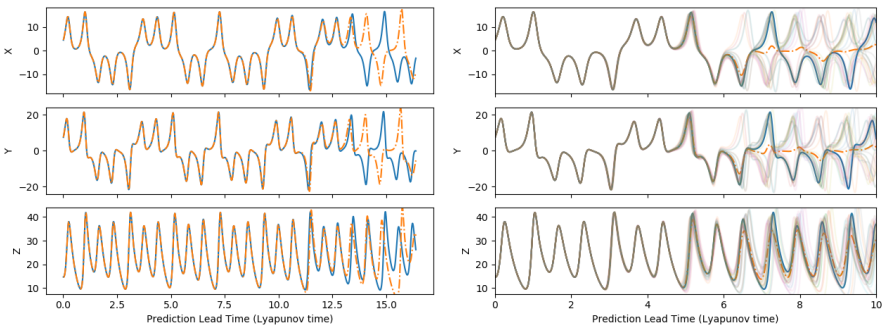


It is difficult to improve skill beyond a certain level

Use XAI to explain spatiotemporal characteristics of predictive skill
of the best model to establish predictability

Performance of RC in more Controlled Settings

When system is fully observed, the Lorenz-63 (L63) attractor can be learnt and predicted for insane lengths of time!

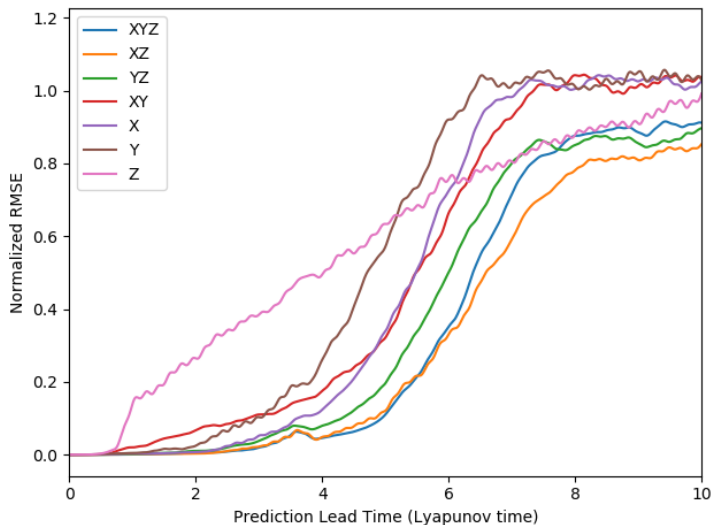


Left: A single good prediction. Right: All ensemble members

(cf. Kuramoto-Shivashinsky PDE: Pathak, J. et al. "Model-free prediction of large spatiotemporally chaotic systems from data: A reservoir computing approach." Physical review letters 120.2 (2018): 024102)

Performance of RC in more Controlled Settings

However, with partial obs. predictions good for much shorter periods, even for L63



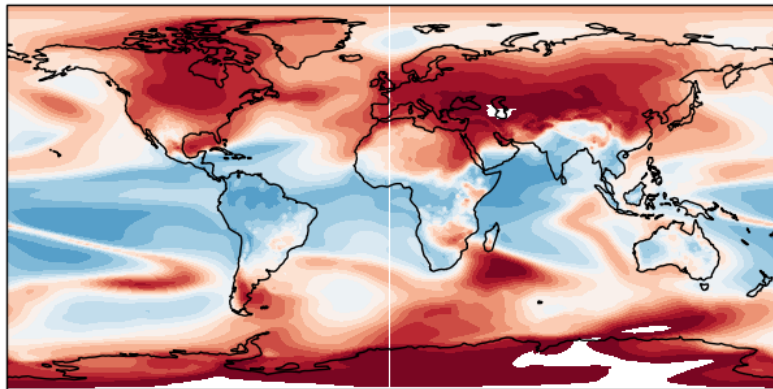
Summary

- ▶ Presented a roadmap for using ML for predictability studies
- ▶ Predictability studies conducted in perfect model settings suggest that predictability extends to the decadal timescale
- ▶ The data-centric approach suggests much shorter predictability horizons

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- ▶ Presented a roadmap for using ML for predictability studies
- ▶ Predictability studies conducted in perfect model settings suggest that predictability extends to the decadal timescale
- ▶ The data-centric approach suggests much shorter predictability horizons
- ▶ A simple problem form. was considered in this initial work
- ▶ Further meaningful problem formulations can, however, be similarly addressed
- ▶ Here we take a data-centric/data analysis perspective. Learning can be used in a very different fashion in the modeling context itself.

Extras: Global Surface Temperature Prediction Error Map



Errors greater at mid and high latitudes
Errors greater over land

Near-term and Long-term:

We split future climate into near-term and long-term and define near-term to mean the period over which initial conditions (IC) matter. Thus while long-term predictability is solely determined by boundary conditions (BC) and/or forcing, near-term predictability is affected by both BC/forcing and IC. We focus on the near-term.