Leveraging oscillatory modes to improve forecasts of chaotic processes, with applications to the Indian monsoon

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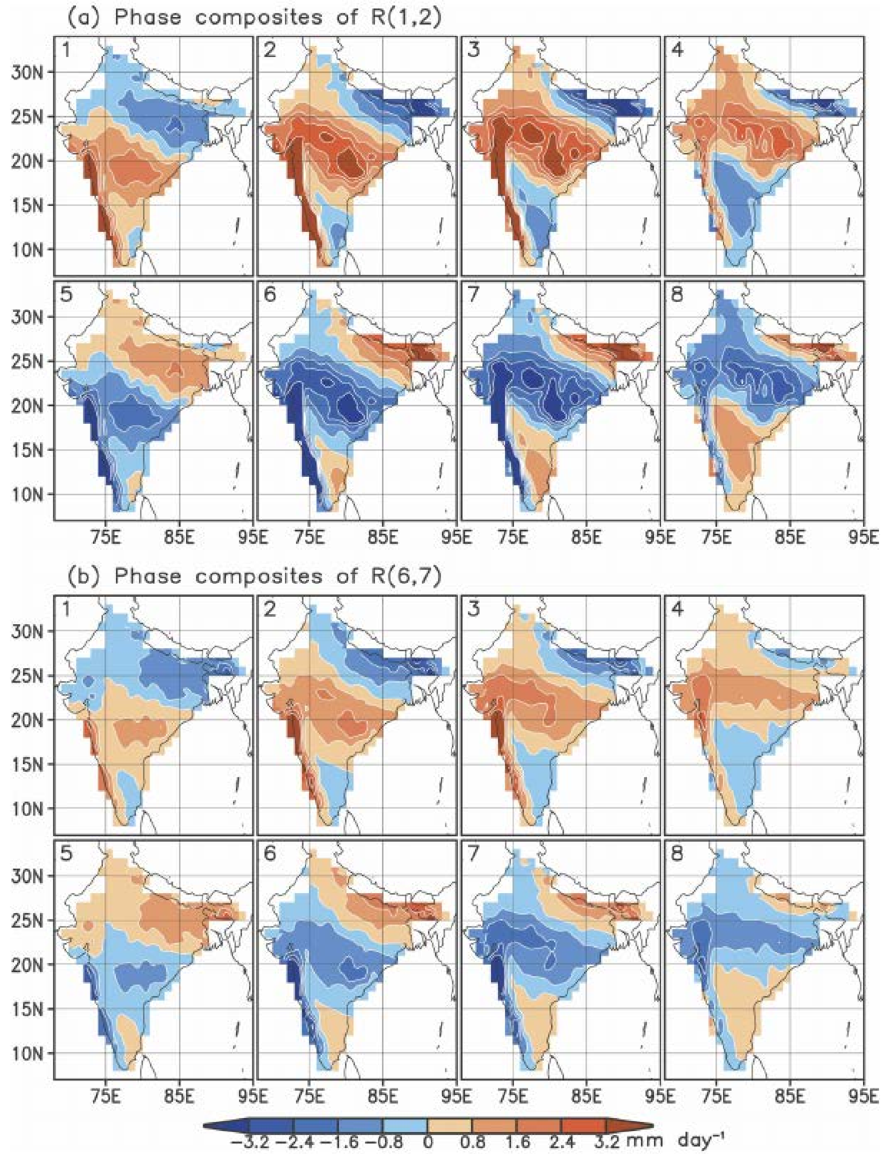
Introduction

Monsoon intraseasonal oscillations

- According to various studies (Krishnamurthy and Shukla 2000, 2007), seasonal monsoon rainfall can be considered a superposition of seasonal mean due to boundary conditions and intraseasonal oscillations.
- There are two dominant intraseasonal oscillations, with periods of about 20 days and 45 days.
- The intraseasonal oscillations characterize the active and break phases of the monsoon, and regional rainfall patterns.

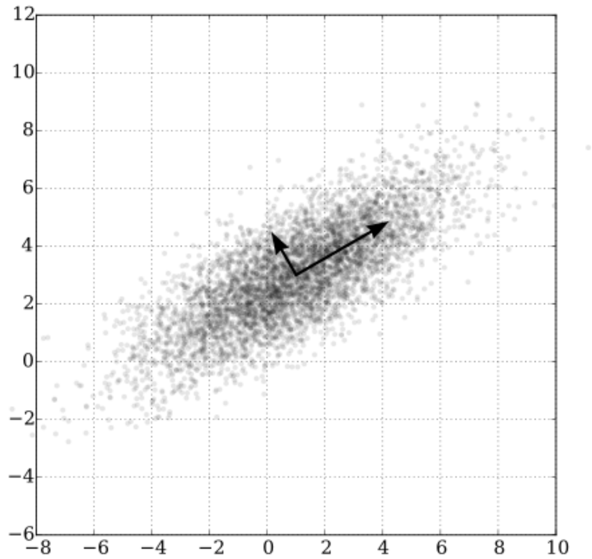
Monsoon intraseasonal oscillations



The two dominant MISOs, from Krishnamurthy and Shukla (2007)

Singular spectrum analysis

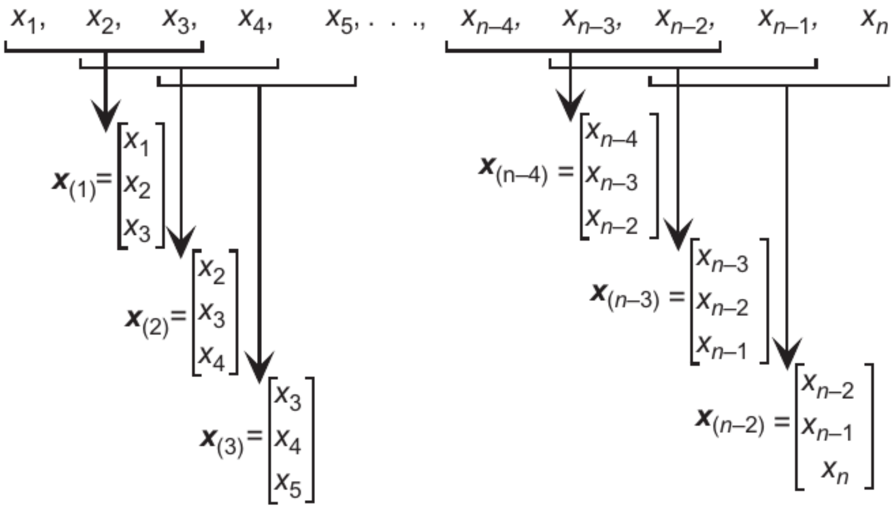
- Given some data, principal component analysis (**PCA**) finds a set of orthogonal vectors which explain the most variance.



- **Singular spectrum analysis** (SSA, Ghil et al., 2002) is PCA applied to time-series data.
- The multivariate version is called multi-channel SSA (M-SSA), same as extended empirical orthogonal functions.

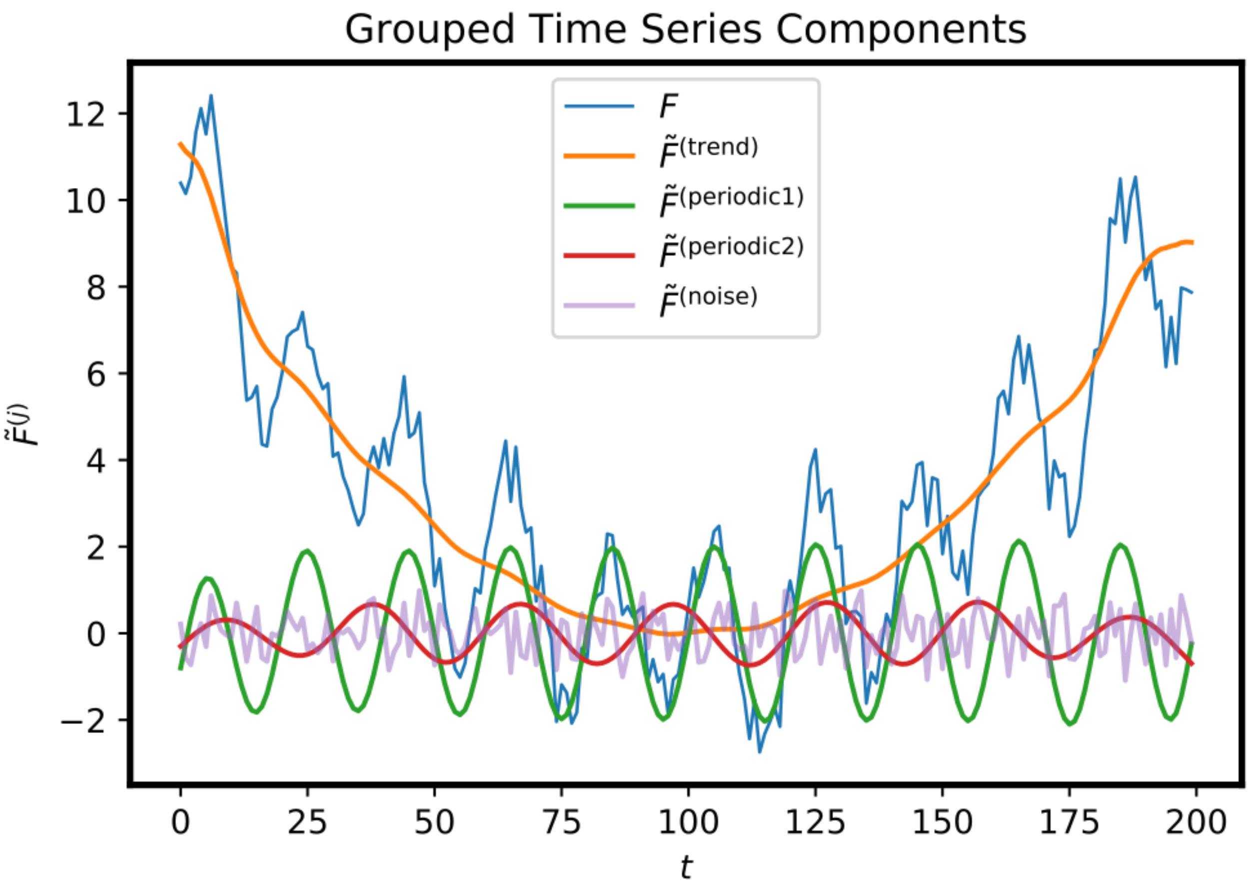
Singular spectrum analysis

- We form sliding windows of length M (embedding dimension) of a time-series and apply PCA to them.



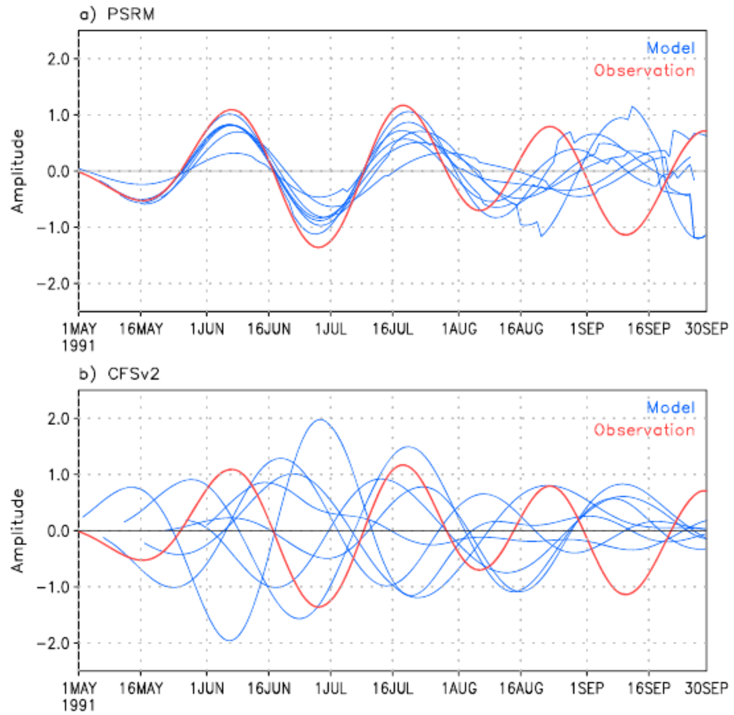
- This gives a set of modes that explain the most variance in the time-series.
- Trend, oscillatory, and noise modes can be identified.

- By projecting original time-series onto the eigenvectors for each mode, the **reconstructed components** (**RCs**) corresponding to each mode can be recovered.
- Example:



Predictability of MISO

- Krishnamurthy and Sharma (2017) have demonstrated predictability of MISO using a data-driven forecast:
- This data-driven method predicts MISO much better than the Climate Forecasting System (CFS):



Data-driven MISO forecasts (top), and MISO predicted by CFS (bottom). From Krishnamurthy and Sharma (2017).

Ensemble oscillation correction

Motivation

- The oscillatory modes are much more predictable than the overall time-series.
- Forecasting methods have been developed for individual modes.
- However, there is no way to go backwards, from the Reconstructed Components (unless we forecast all the modes) to the original time-series.
- How do we use forecasts of the RCs to improve prediction of the full time-series?

Motivation

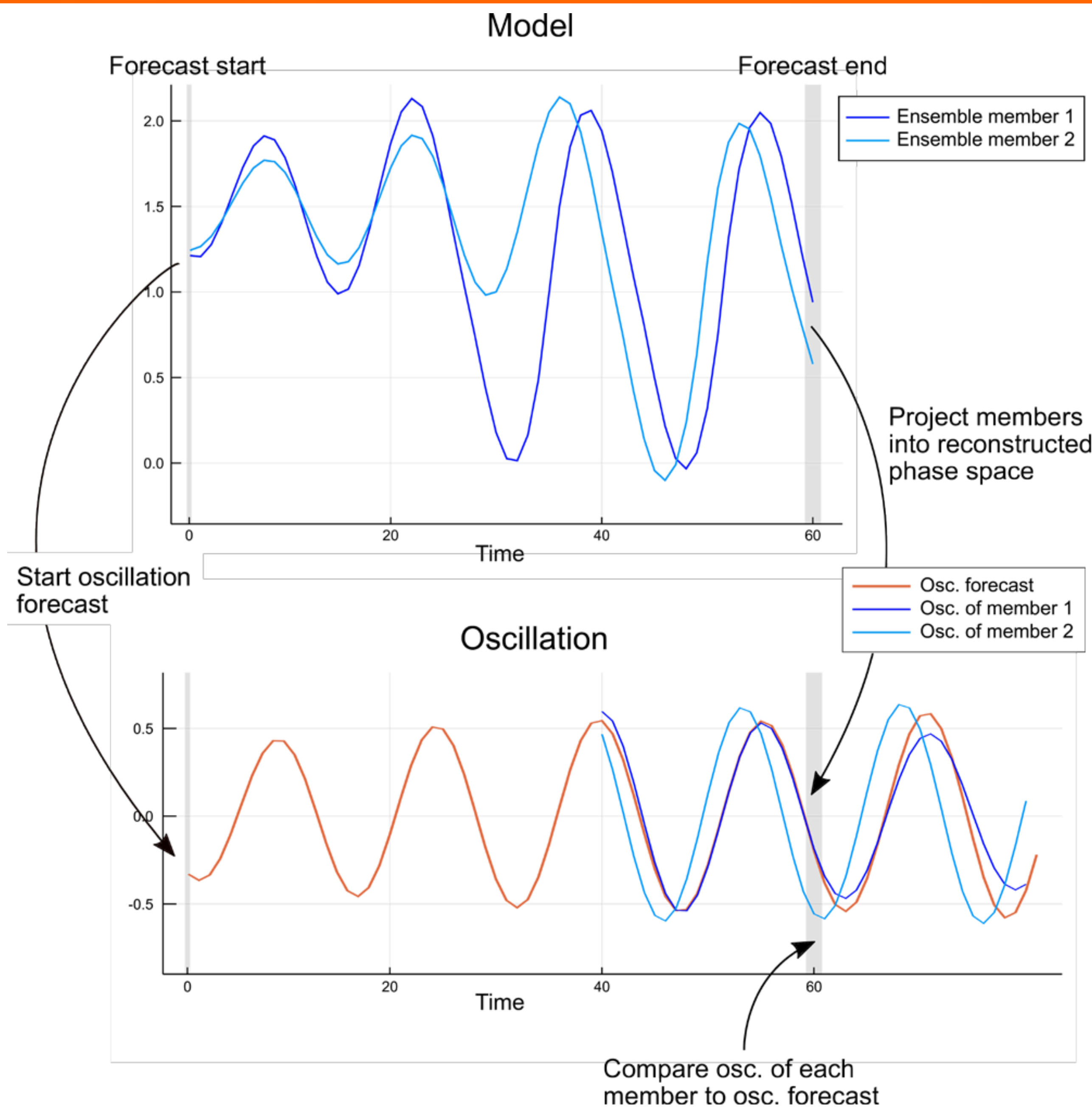
- Generally, in ensemble forecasting, it is better to use as many ensemble members as possible.
- However, what if we have some reason to believe some ensemble members are better than others?
- We can forecast oscillatory Reconstructed Components accurately purely from data.
- Idea: **for the ensemble mean, use only the ensemble members whose oscillation is close to that of a data-driven oscillation forecast.**

Ensemble oscillation correction

Ensemble oscillation correction algorithm:

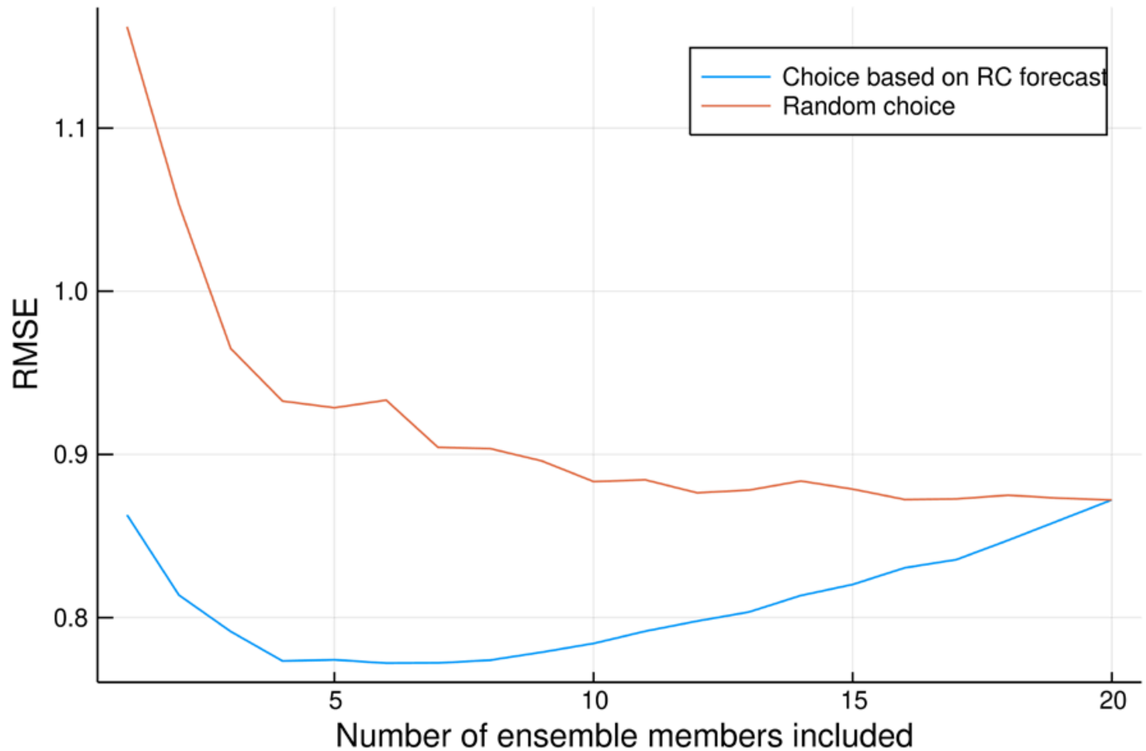
- Using best estimate of the system state, map into oscillatory RC space and forecast the oscillation a window h into the future.
- Integrate ensemble members window h into the future.
- Map each ensemble member into oscillation space, and compare to oscillation forecast.
- Compute the ensemble mean using the best ensemble members, as determined by their discrepancy from the oscillation forecast.

Ensemble oscillation correction



Choosing optimal number of ensemble members to average over

- If we care only about error in ensemble mean, we can easily find the optimal number of ensemble members to average over using a historical ensemble + estimate of true state.
- Trade-off between benefits of large ensemble, detriment of including inaccurate members.



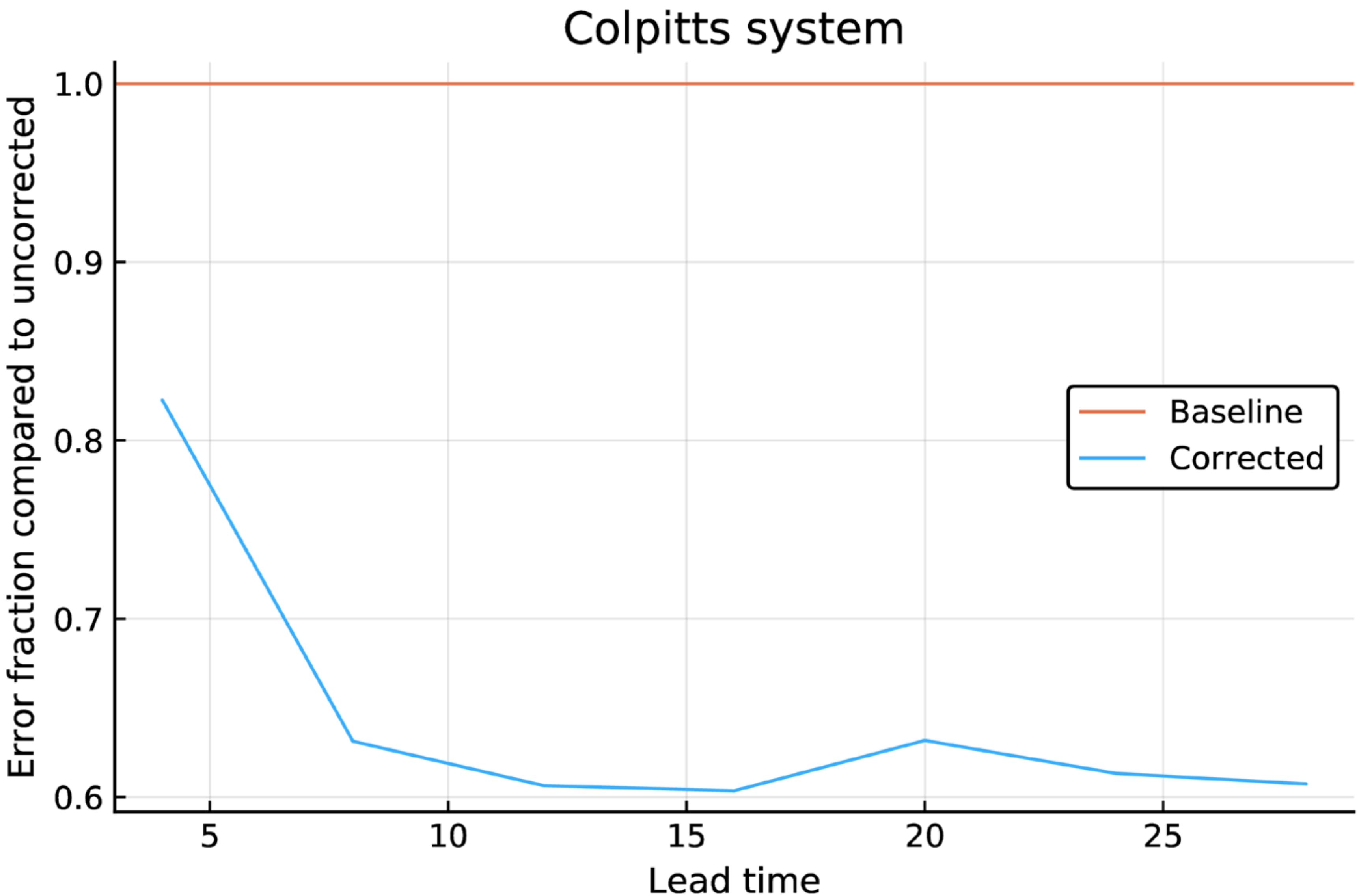
Error with number of ens. members included

Experiments

Experiments

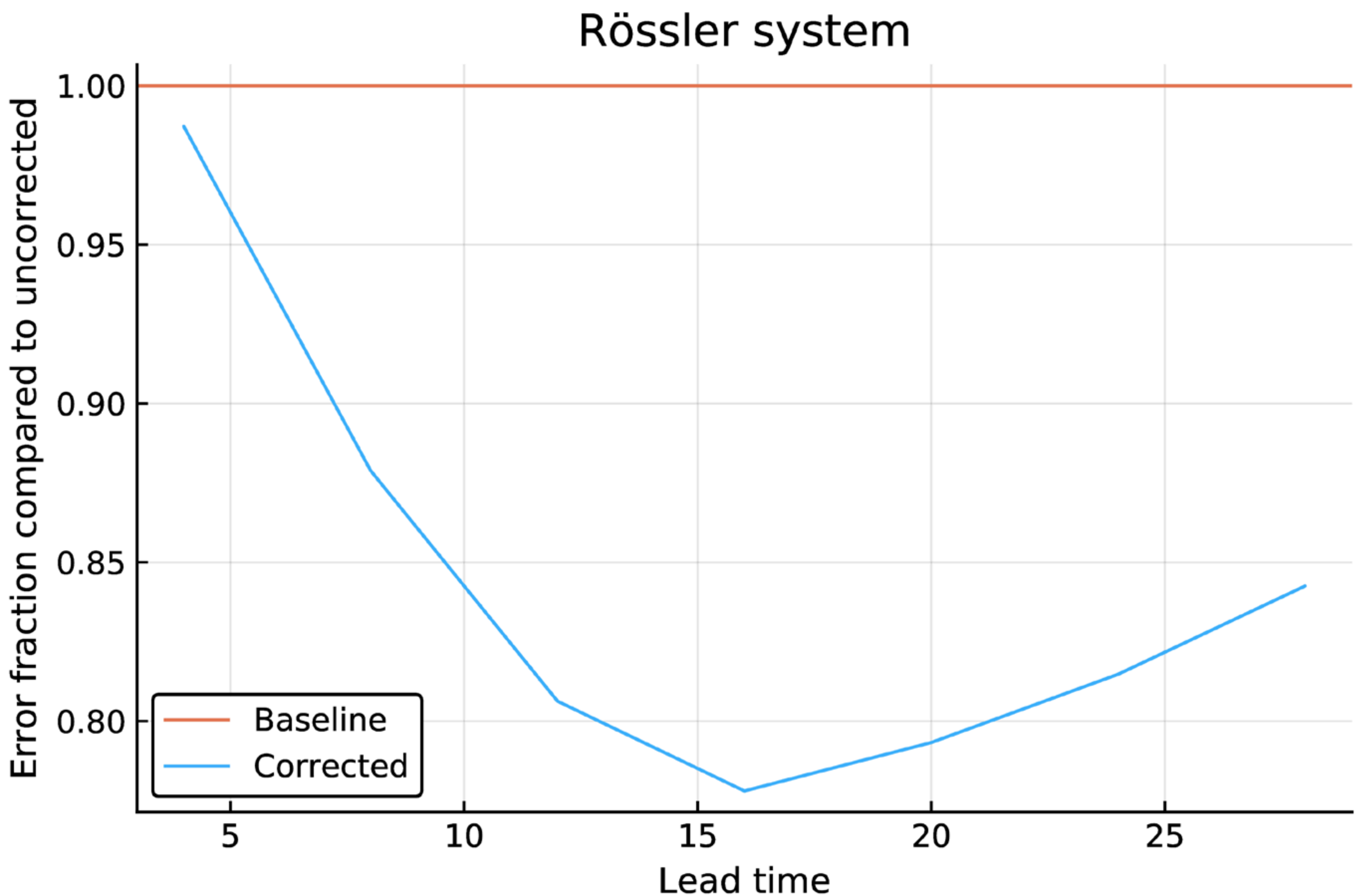
- We show results of the method applied to toy chaotic oscillators with parametric model error.
- This is meant to emulate the case of MISO, where the oscillatory mode is badly predicted by the model.
- In general, error reduction depends on:
  - Portion of variance from oscillations (e.g., MISO represents ~14% of the variance)
  - Window at which regular ensemble loses skill
  - Window for which Reconstructed Components forecast is skillful
  - Model error
  - Ensemble spread

Colpitts oscillator



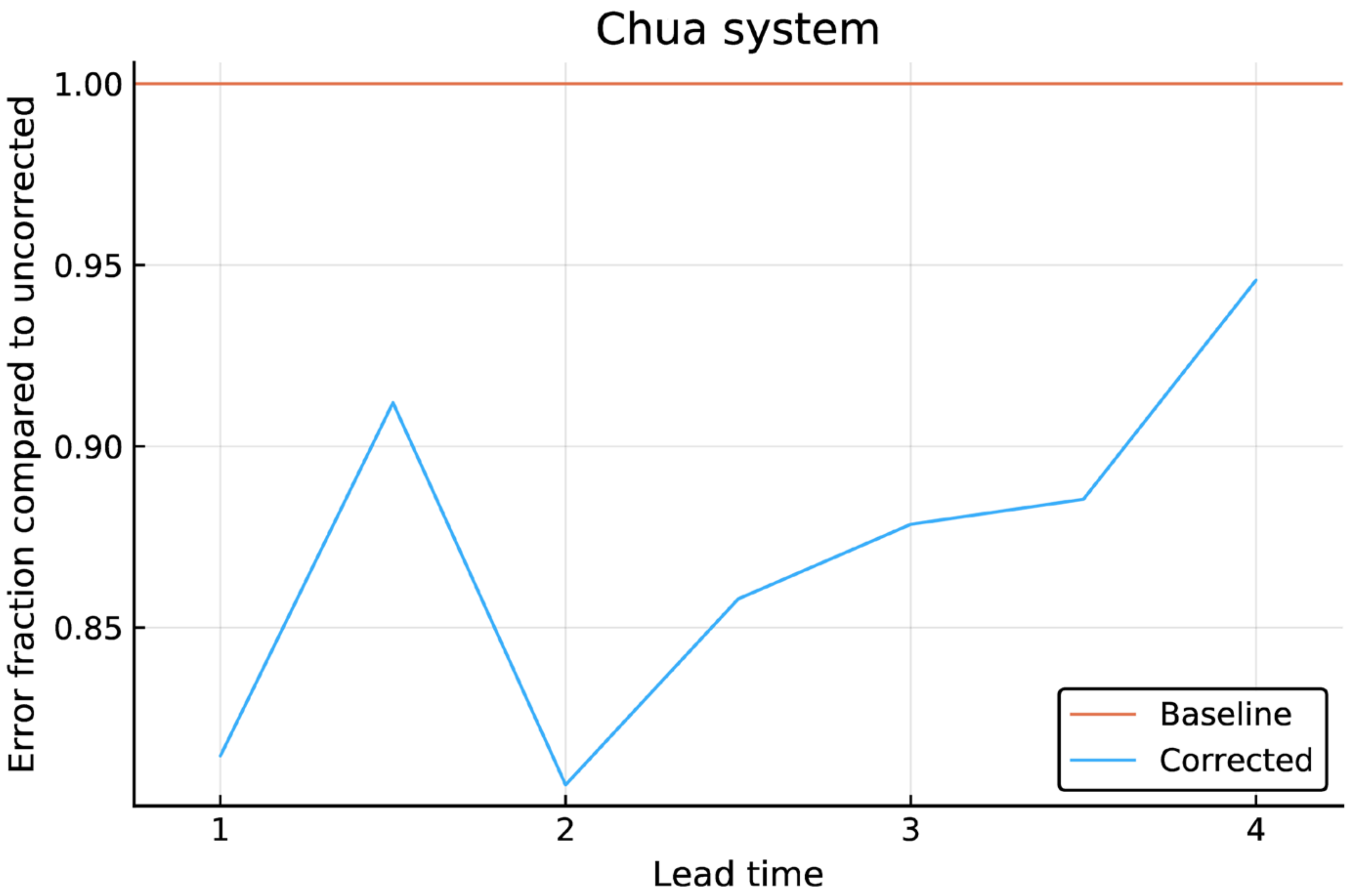
RMSE corrected over uncorrected

Rössler oscillator



RMSE corrected over uncorrected

Chua oscillator



RMSE corrected over uncorrected

Error analysis

- Under some assumptions, we can derive an estimate of the RMSE reduction of this method:

$$\frac{\text{RMSE}_{\text{corrected}}}{\text{RMSE}_{\text{uncorrected}}} \approx \sqrt{1 - \binom{\text{\% of variance of}}{\text{osc. modes}}}$$

- Numerical experiments show that this is a reasonable estimate when the method works well.

Future plans

Future plans

- Paper on the method and tests with toy models soon to be submitted to *Journal of Climate*.
- Test ensemble oscillation correction method with Indian monsoon and MISO:
  - Use India Meteorological Department (IMD) gridded rainfall data to run SSA and predictions of MISOs.
  - Using an ensemble of CFS runs, implement ensemble oscillation correction at different lead times.
- The MISOs make up ~14% of daily variance, from which we could estimate an error reduction of about 7%, higher or lower depending on the region.
- Could improve other variables too, due to correction of the potential vorticity field (Lien et al., 2013)

Future plans

- Following the implementation of ensemble oscillation correction, we plan on developing a new hybrid of data assimilation, machine learning, and a physical model.
- Machine learning is generally inadequate for predicting high-dimensional geophysical systems, but previous work has shown hybrids of machine learning and a model are better than either separately.
- Idea: use data assimilation formalism to optimally combine forecasts of model and machine learning.
- Potential to improve monsoon rainfall forecasts.

References

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