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Seamless Prediction

Can we use shorter timescale forecasts to calibrate climate change projections?

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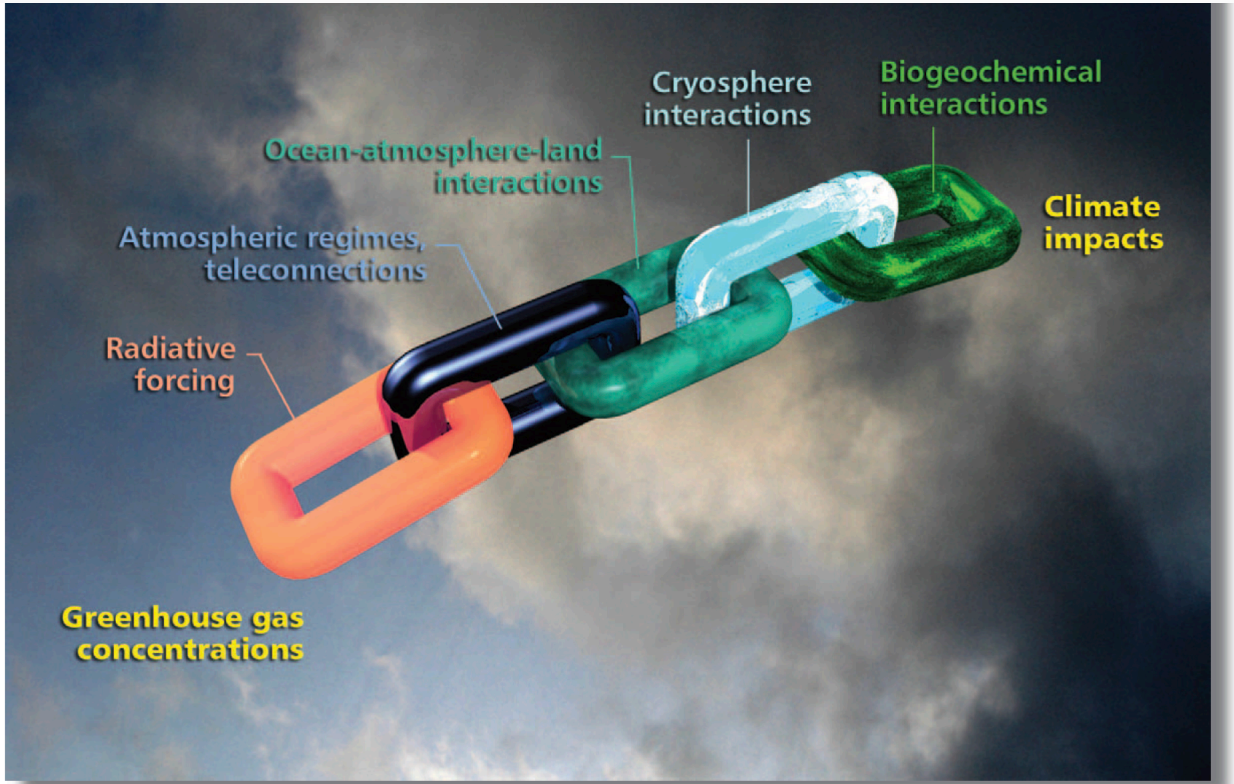
CVCWG meeting, 29th January 2018

TOWARD SEAMLESS PREDICTION

Calibration of Climate Change Projections Using Seasonal Forecasts

BY T. N. PALMER, F. J. DOBLAS-REYES, A. WEISHEIMER, AND M. J. RODWELL

In a seamless prediction system, the reliability of coupled climate model forecasts made on seasonal time scales can provide useful quantitative constraints for improving the trustworthiness of regional climate change projections.



But what is the basis for this statement?

- Is there a link between the reliability of initialised forecasts and the response of a system to an external forcing?

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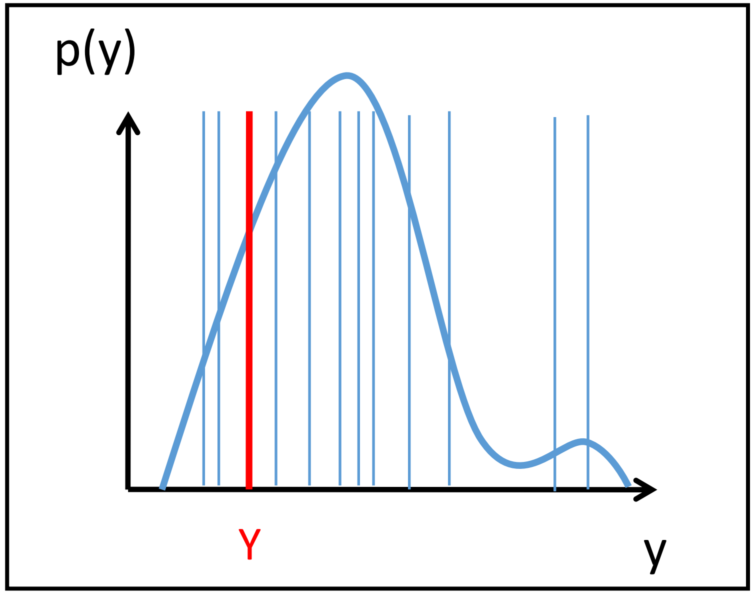
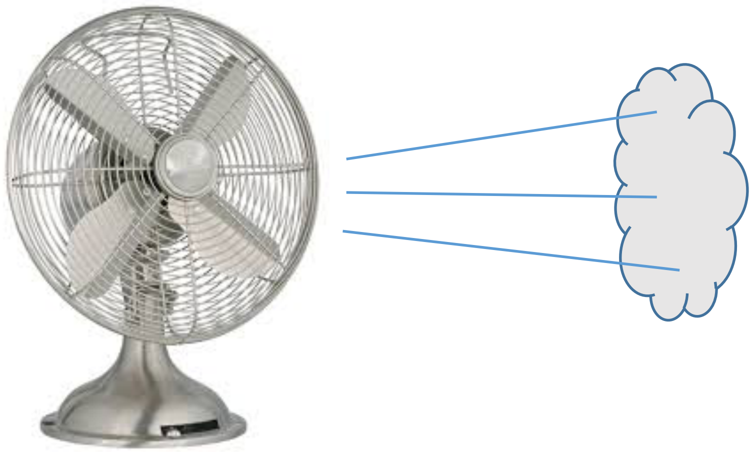
- Is there a link between the reliability of initialised forecasts and the response of a system to an external forcing?
- Reliability: How consistent is your forecast probability of an event with the measured probability of an event?

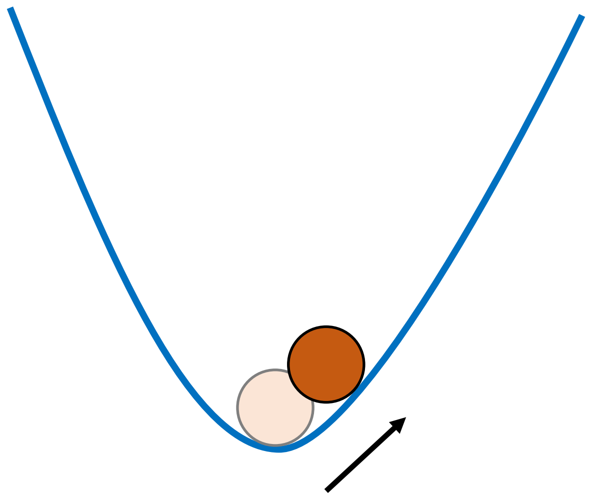


i.e. Does your observation behave as if it were drawn from the forecast pdf?

But what is the basis for this statement?

- Is there a link between the reliability of initialised forecasts and the response of a system to an external forcing?
- Response: if we apply a small forcing perturbation to a system, how much does the average state change?





But what is the basis for this statement?

- Is there a link between the reliability of initialised forecasts and the response of a system to an external forcing?

Outline:

- Use a **dynamical systems theory** framework to explore whether there is a physical basis for this statement
- Test the predicted link between reliability and response to forcing using a simple atmospheric model

Dynamical systems theory approach

- We describe our dynamical system by a set of nonlinear differential equations

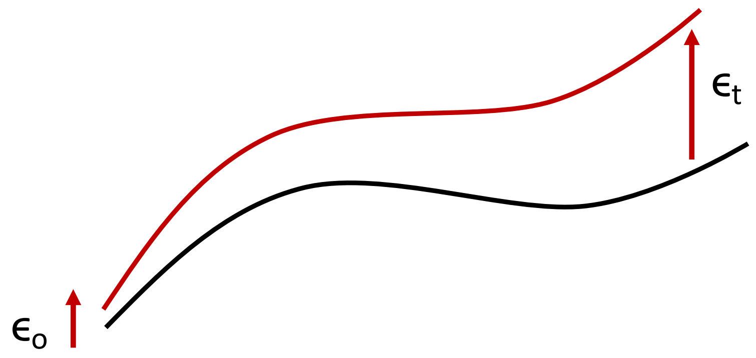
$$\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x})$$

- This is a nice framework for considering **reliability**, as the growth of small errors, $\epsilon = \mathbf{x} - \mathbf{x}_0$, can be naturally described:

$$\dot{\epsilon} = \mathbf{J}_{\mathbf{x}}\epsilon$$

- where the Jacobean is given as

$$\mathbf{J}_{\mathbf{x}} = \left.\frac{\partial \mathbf{F}}{\partial \mathbf{x}}\right|_{\mathbf{x}}$$



See, e.g. Smith et al, 1999, QJRMetS.

Reliability in dynamical systems framework

- The growth of small errors is given by $\dot{\epsilon} = \mathbf{J_x}\epsilon$

- For a reliable forecast, we would like the observation to diverge from any ensemble member

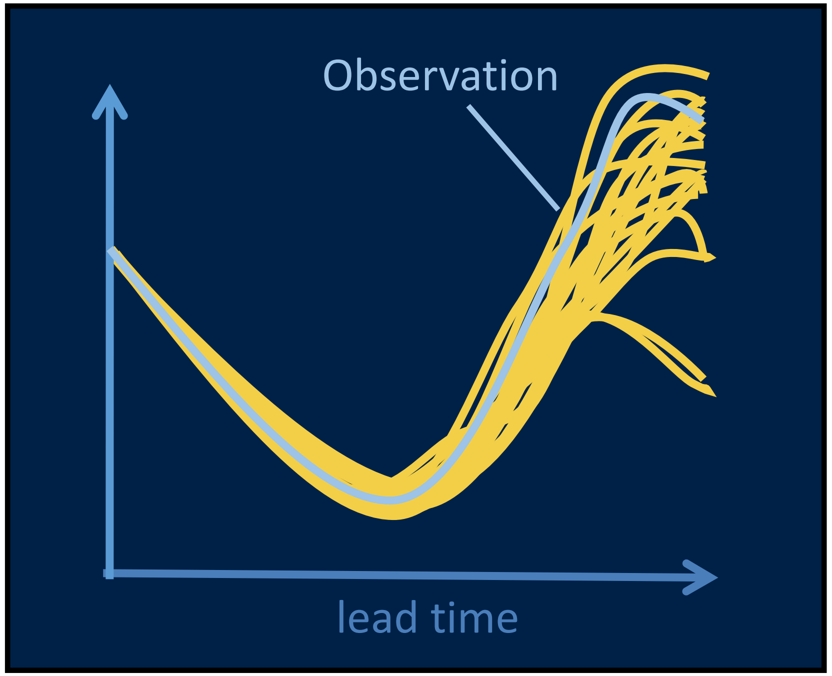
$$\dot{\delta \mathbf{x}} = \dot{\epsilon}^{\mathrm{f}} - \dot{\epsilon}^{\mathrm{t}} = \mathbf{J}^{\mathrm{f}}_{\mathbf{x}}\epsilon^{\mathrm{f}} - \mathbf{J}^{\mathrm{t}}_{\mathbf{x}}\epsilon^{\mathrm{t}}$$

… with the same characteristics as two ensemble members diverging

$$\dot{\epsilon}^{\mathrm{f}} = \mathbf{J}^{\mathrm{f}}_{\mathbf{x}}\epsilon^{\mathrm{f}}$$

- So a forecast will be reliable (trivially) if $\mathbf{J}^{\mathrm{f}} = \mathbf{J}^{\mathrm{t}}$,

- (Note that if $\mathbf{J}^{\mathrm{f}}\epsilon^{\mathrm{f}} \gg \mathbf{J}^{\mathrm{t}}\epsilon^{\mathrm{t}}$ the forecast will appear reliable)



Response of a dynamical system to a forcing

- Consider the perturbed system

$$\dot{\tilde{\mathbf{x}}} = \tilde{\mathbf{F}}(\tilde{\mathbf{x}}),$$

- Where

$$\tilde{\mathbf{F}}(\mathbf{x}) = \mathbf{F}(\mathbf{x}) + \boldsymbol{\delta}\mathbf{F}(\mathbf{x}).$$

Forcing perturbation
e.g. GHG forcing

- Also consider the difference in evolution in x between perturbed and unperturbed systems

$$\delta\mathbf{x} = \tilde{\mathbf{x}} - \mathbf{x}$$

- We can show that

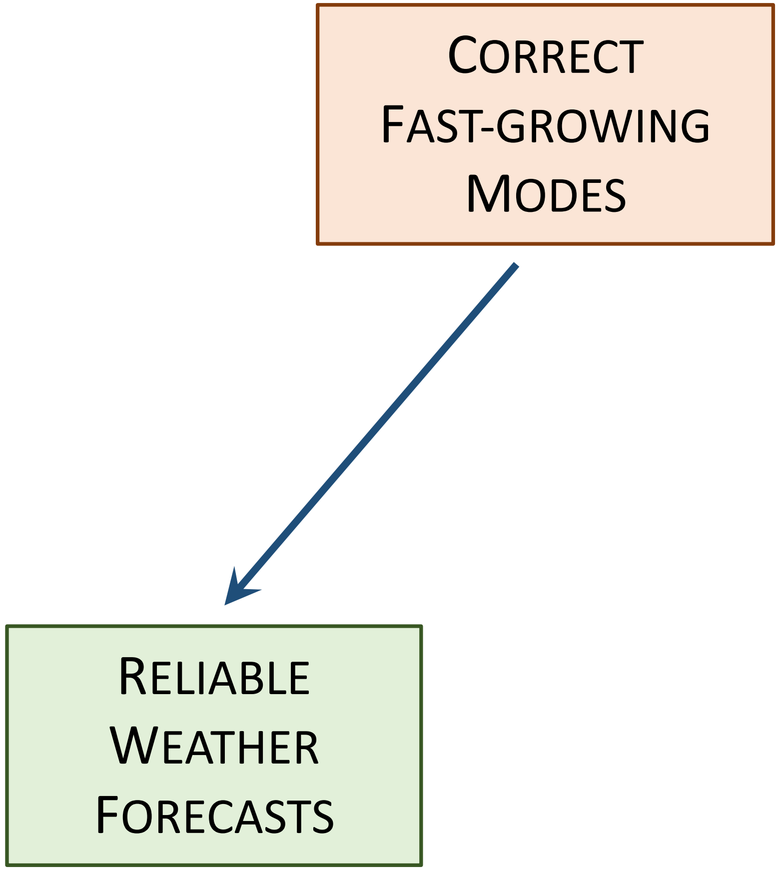
$$\langle \boldsymbol{\delta}\mathbf{x} \rangle = -\langle \mathbf{J}_{\mathbf{x}}^{-1} \boldsymbol{\delta}\mathbf{F}(\mathbf{x}) \rangle$$

- **What can we learn from this?**

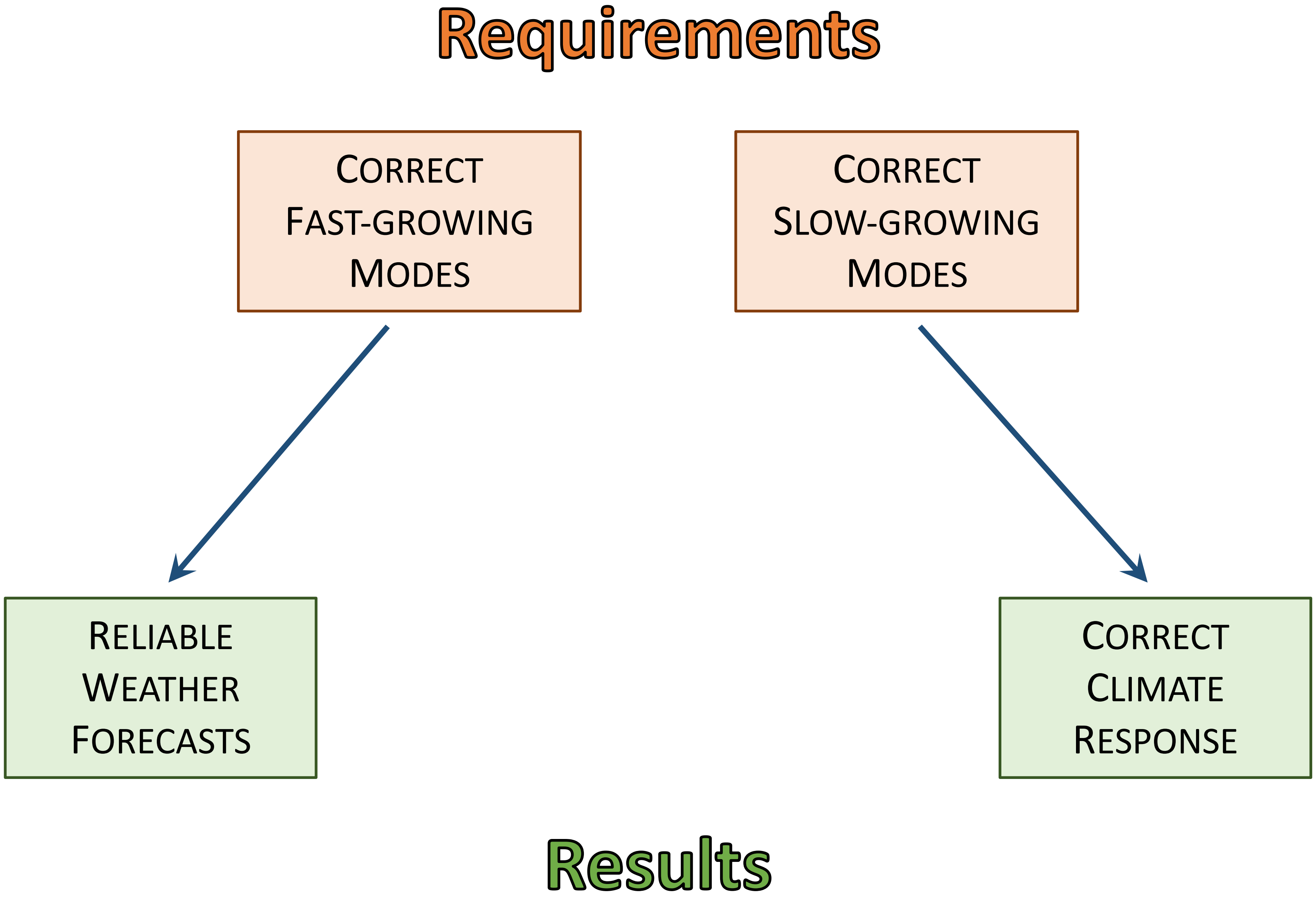
J vs J^{-1}

J	**J^{-1}**
Reliable forecasts need correct **J**	Accurate response to forcing needs **J^{-1}**
Eigenvalues λ	Eigenvalues μ = 1/λ
$\dot{\epsilon} = \mathbf{J_x}\epsilon$ $\dot{\epsilon} = \sum_i a_i \lambda_i \mathbf{e_i}$	$\langle \delta \mathbf{x} \rangle = -\langle \mathbf{J_x^{-1}} \delta \mathbf{F}(\mathbf{x}) \rangle$
Short timescale forecasts dominated by largest λ	Response dominated by smallest magnitude λ

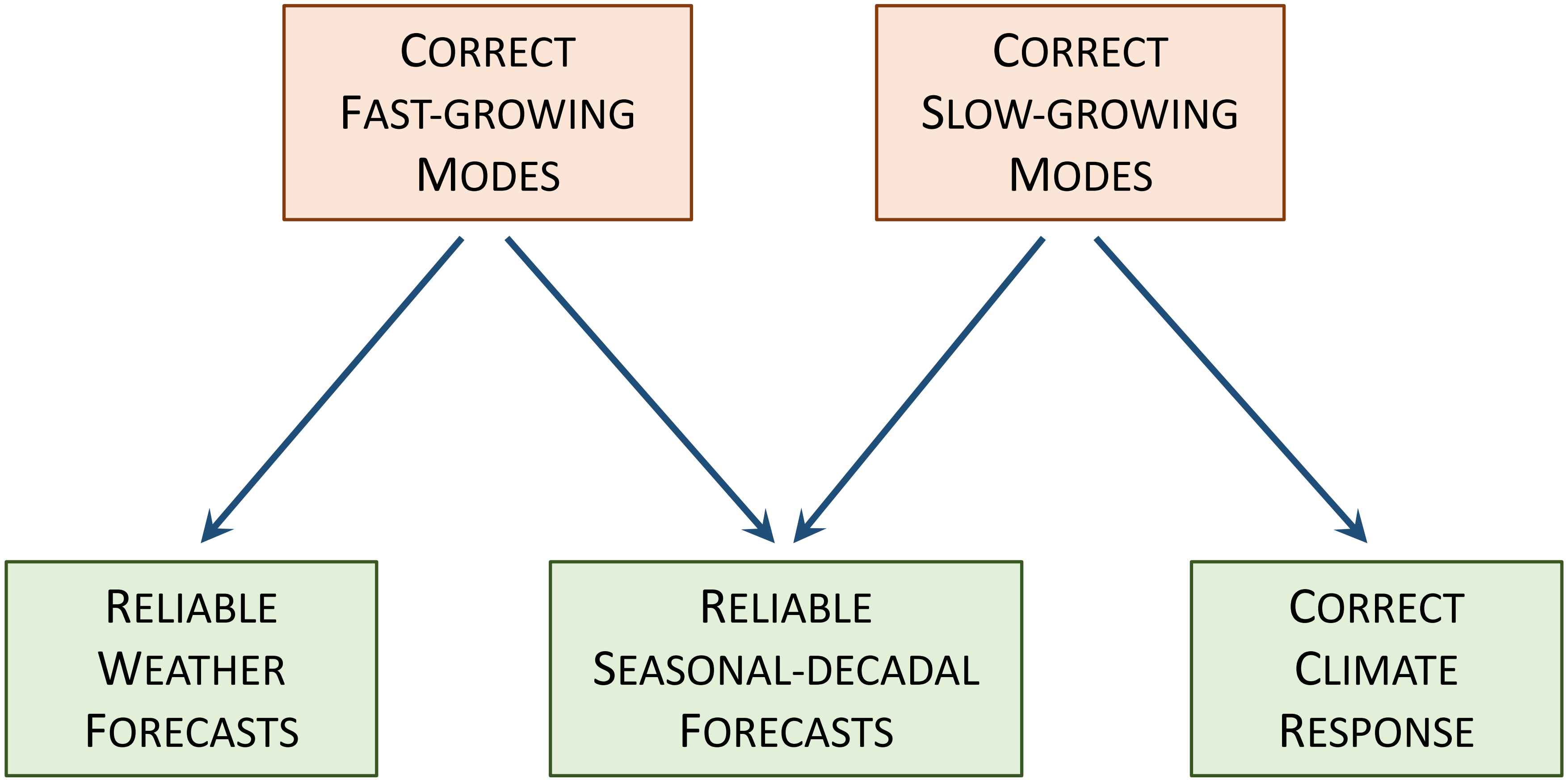
Requirements



Results


Requirements
CORRECT FAST-GROWING MODES
CORRECT SLOW-GROWING MODES
RELIABLE WEATHER FORECASTS
CORRECT CLIMATE RESPONSE
Results

Requirements



Results

Can we test this theory?

- Need a system which
  - We can treat as our ‘true’ climate system
  - We can build a number of forecast models for
  - We can perturb using an imposed forcing

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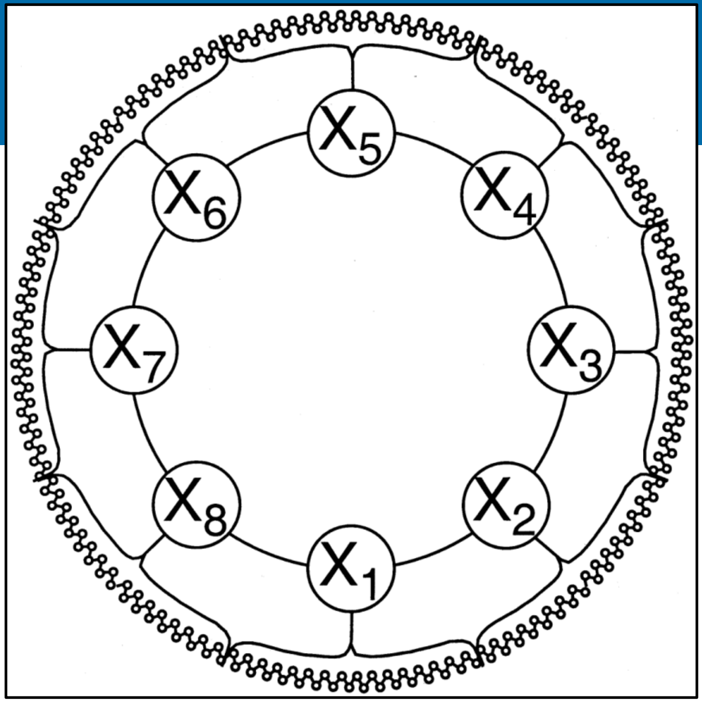


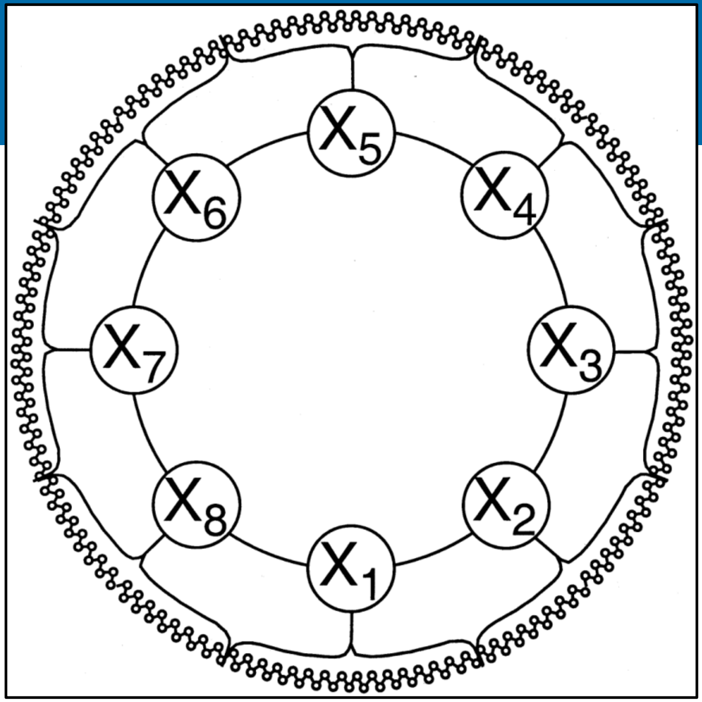
$$\frac{dX_k}{dt} = -X_{k-1}\left(X_{k-2} - X_{k+1}\right) - X_k + F + \delta F_k - \frac{hc}{b}\sum_{j=J(k-1)+1}^{kJ} Y_j$$

$$\frac{dY_j}{dt} = -cbY_{j+1}\left(Y_{j+2} - Y_{j-1}\right) - cY_j + \frac{hc}{b} X_{\mathrm{int}[(j-1)/J]+1}$$

δF	(3,0,0,0,0,0,0,0)

Lorenz, 1996
Arnold et al, 2013

Forecast models of U:

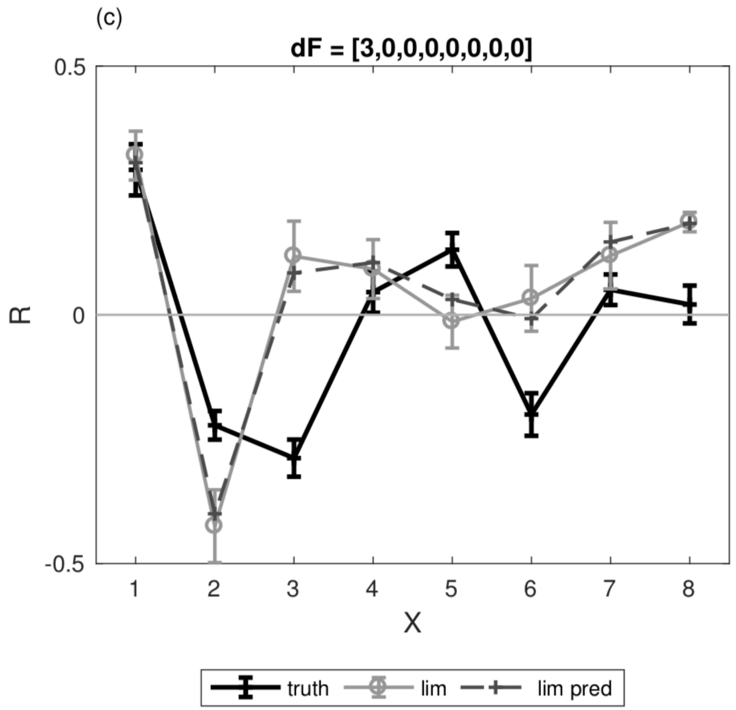


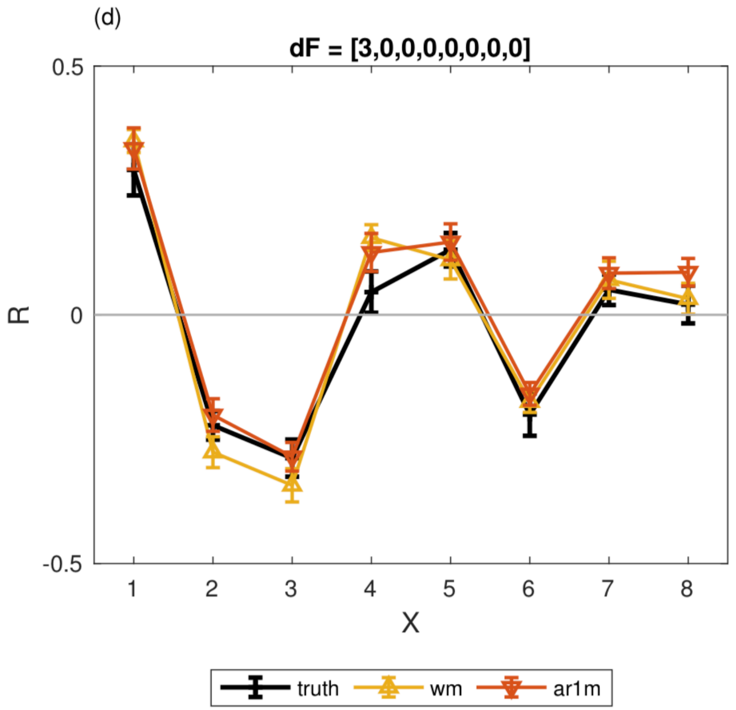
1. Statistical model
   - Replace dynamical equations with a linear model fitted to the data
2. Dynamical models
   - Assume we know the equations of motion, but cannot afford to compute the fast Y variables
   - Replace Y with an additive stochastic parametrisation
   - Test *white noise* – believed to be a poor model of sub-grid scales
   - Test *red noise* – believed to be a good model of sub-grid scales

Response to forcing

- Run the full ‘true’ system with and without forcing perturbation
- Run each model of the system with and without forcing perturbation

Statistical model



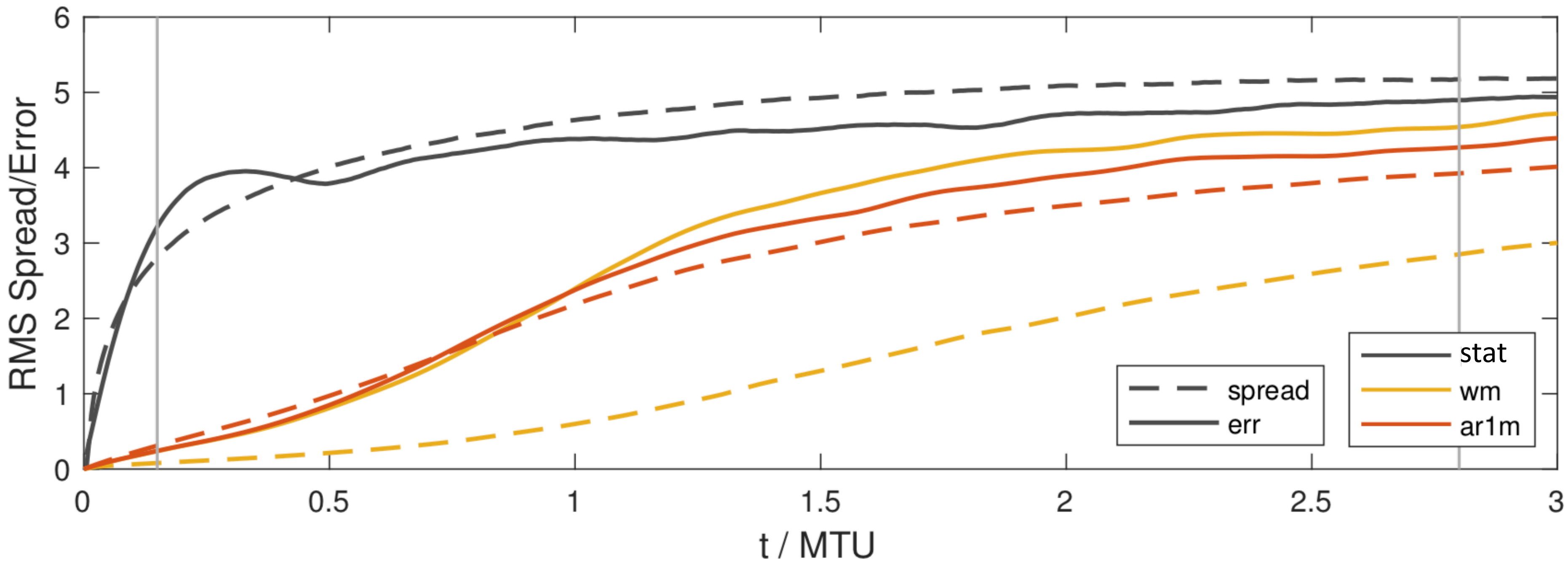


Dynamical models

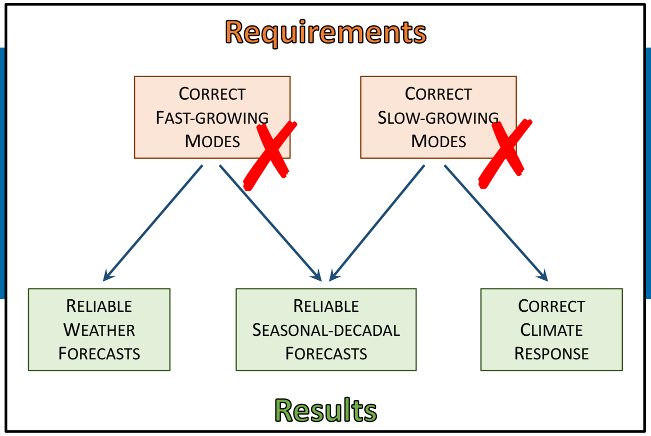
Now consider reliability

- Run 40-member ensemble forecasts of the unperturbed system from 300 start dates
- Statistical model seems pretty reliable
- White noise not reliable
- Red noise seems pretty reliable

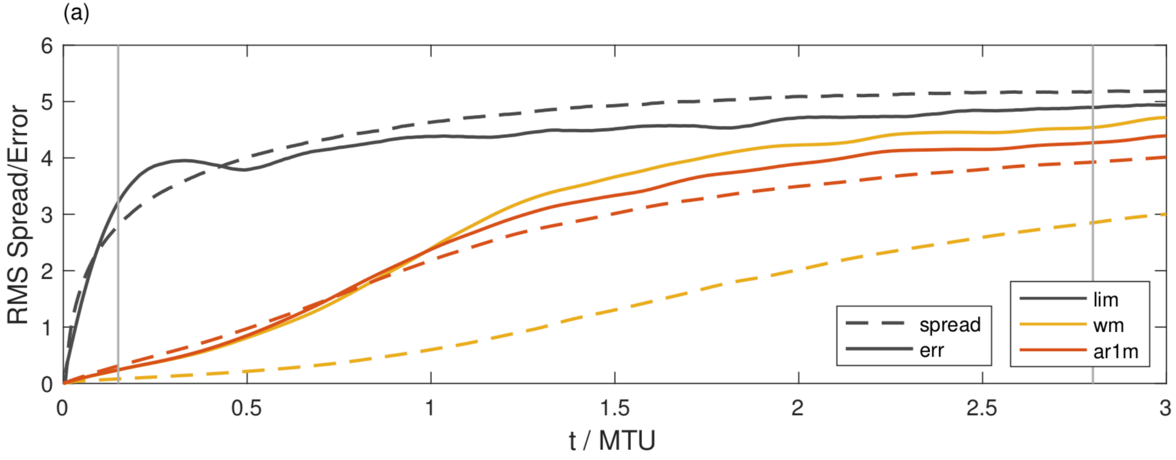
N.b. 3 MTU ~= 15 ‘days’,
which is about as long as we have
predictability for in L96

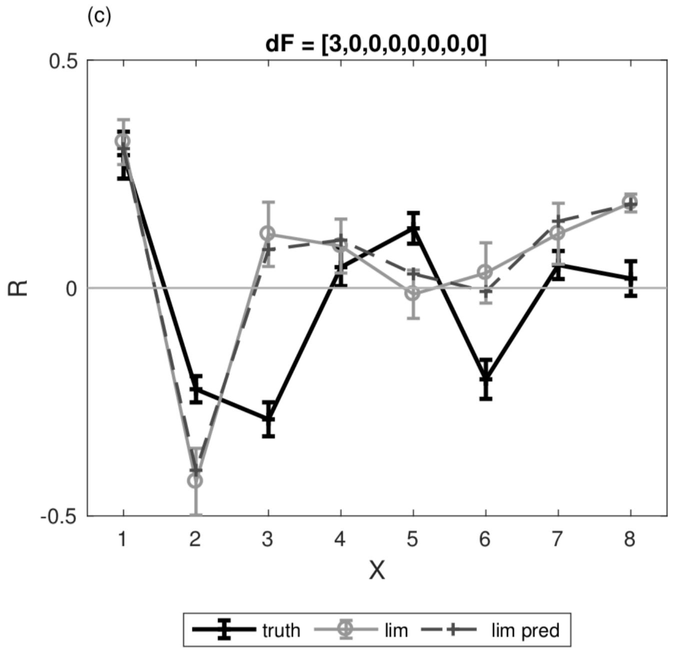


Interpretation?



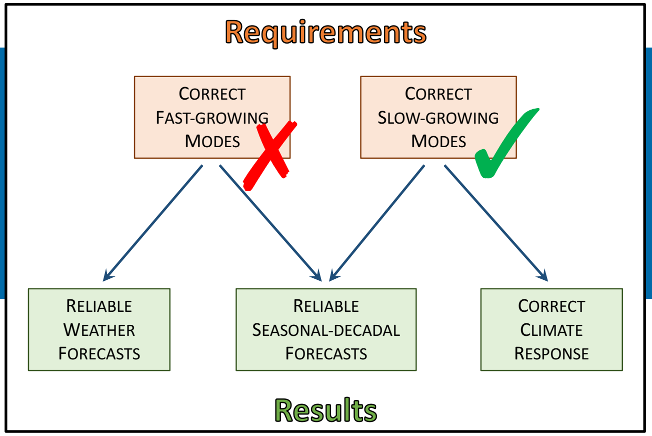
- Statistical model
  - Seems reliable at all timescales
  - But has poor response to forcing!



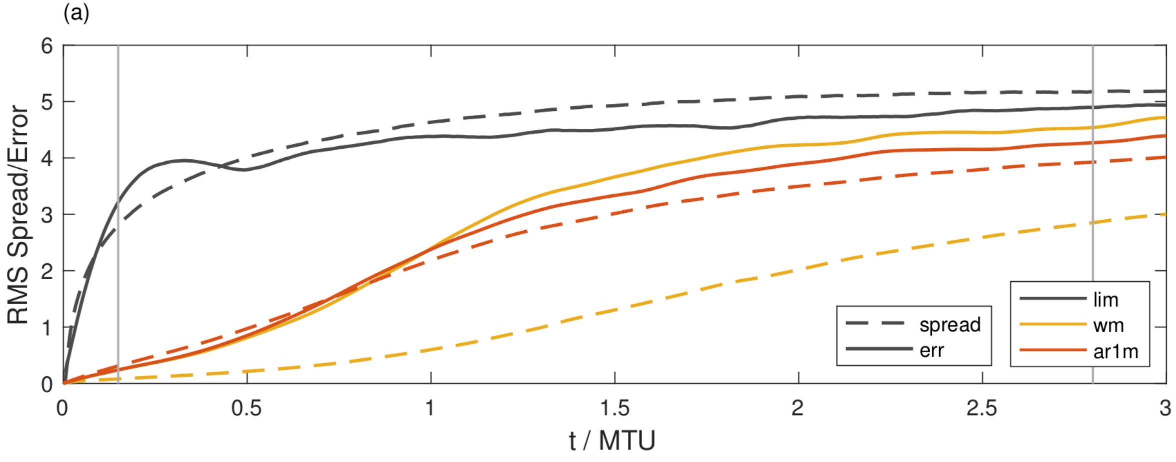


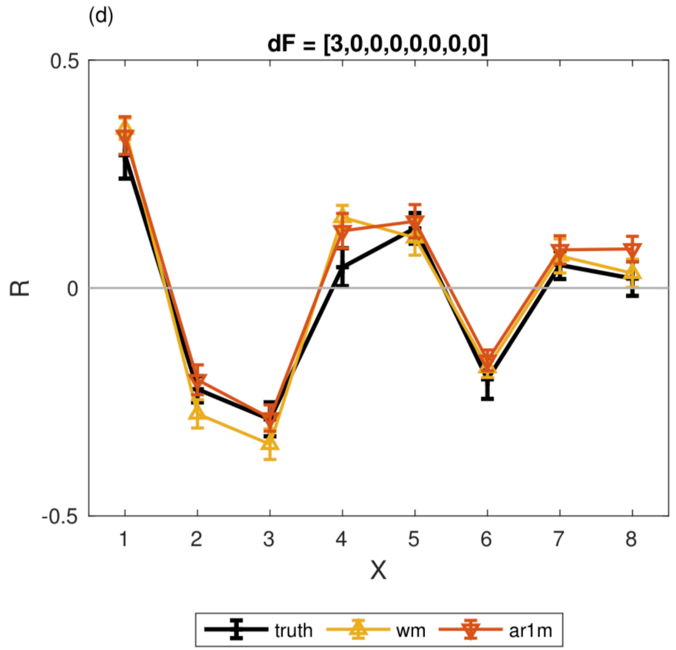
$$\mathbf{J^f}\epsilon^{\mathbf{f}} \gg \mathbf{J^t}\epsilon^{\mathbf{t}}$$

Interpretation?



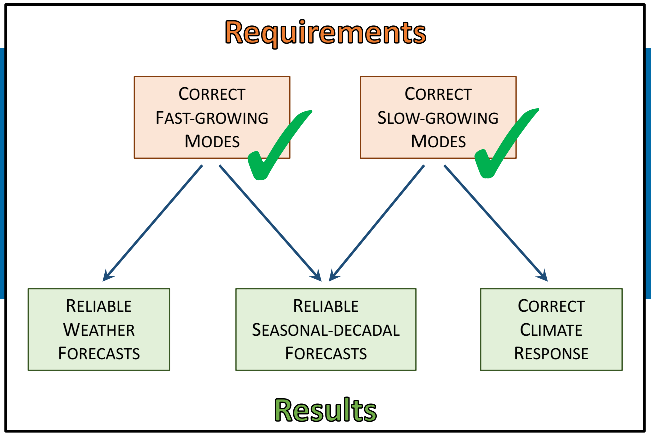
- White noise
  - Is not reliable at any timescale
  - Has a good response to the forcing



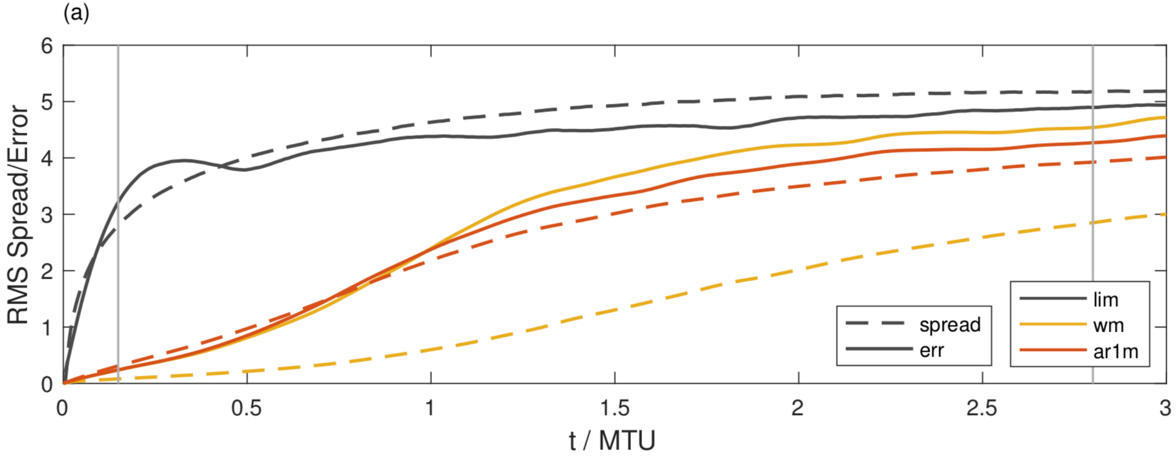


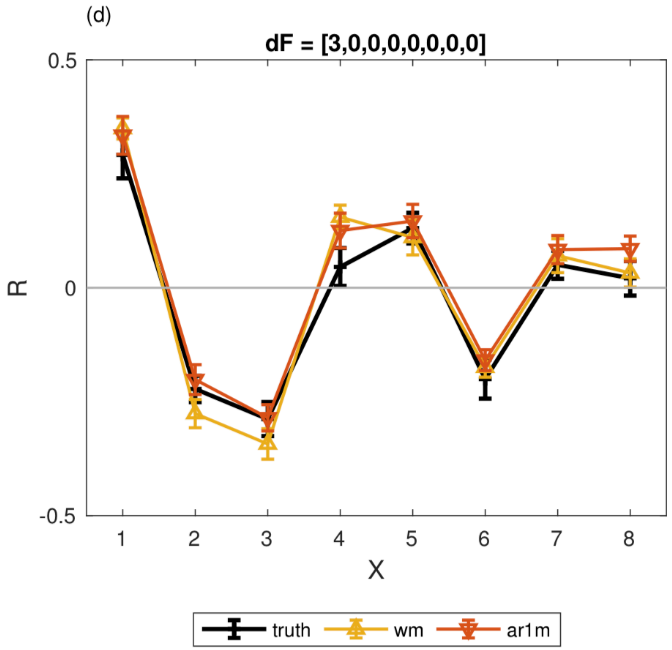
Lesson in caution:
White noise poorly represents fastest scales, but we still have the L96 dynamics to correctly represent the slowest scales

Interpretation?

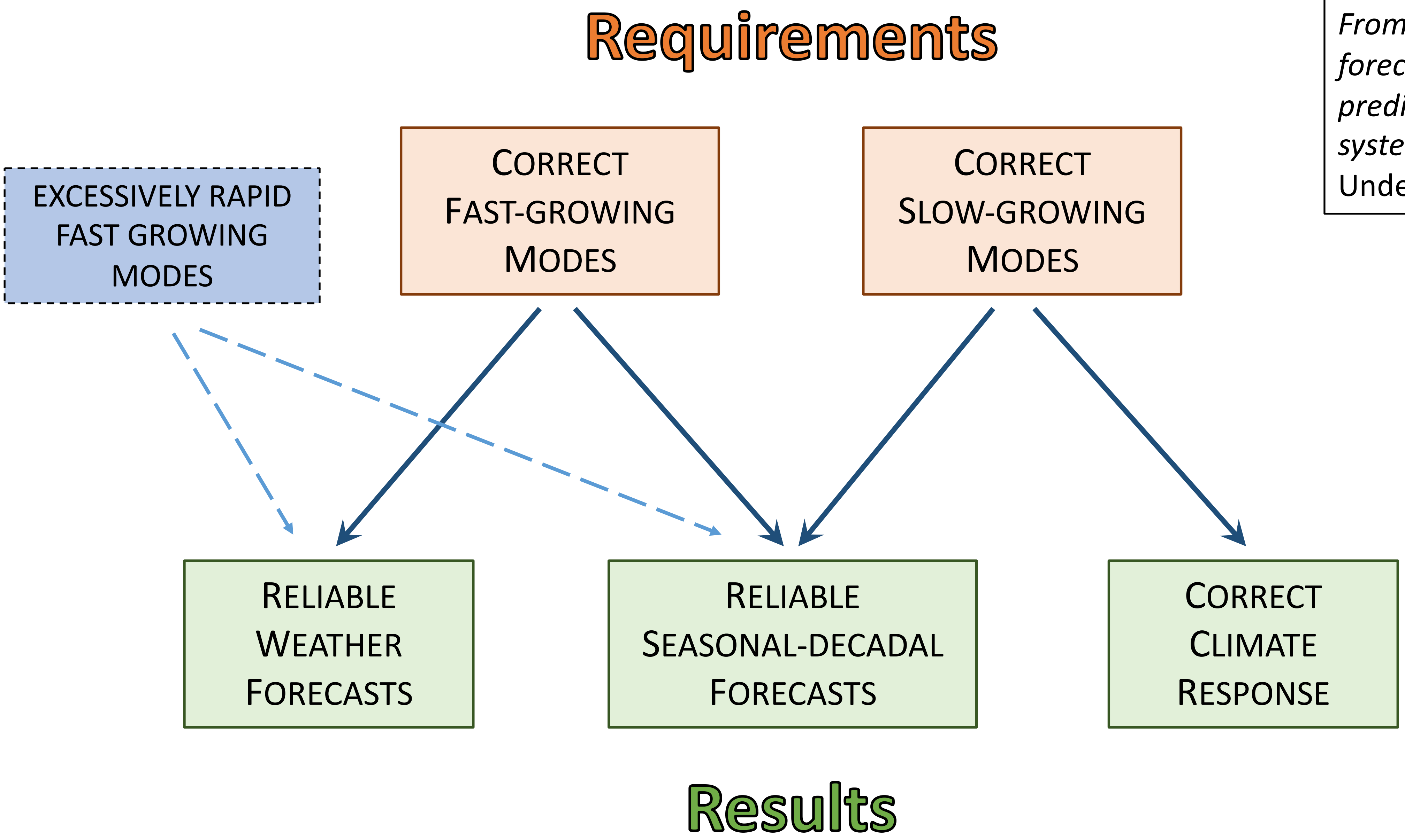


- Red noise
  - Seems reliable at *all* timescales
  - And has a good response to forcing!





Red noise captures the fastest scales well, and we still have the L96 dynamics to correctly represent the slowest scales



Christensen and Berner,
From reliable weather forecasts to skilful climate prediction: a dynamical systems approach
Under review in QJRMetS

Extra slides

Response of a dynamical system to a forcing I

$$\dot{\tilde{\mathbf{x}}} = \mathbf{F}(\tilde{\mathbf{x}}) + \boldsymbol{\delta}\mathbf{F}(\tilde{\mathbf{x}})$$

$$= \mathbf{F}(\mathbf{x} + \boldsymbol{\delta}\mathbf{x}) + \boldsymbol{\delta}\mathbf{F}(\mathbf{x} + \boldsymbol{\delta}\mathbf{x})$$

$$= \mathbf{F}(\mathbf{x}) + \left.\frac{\partial \mathbf{F}}{\partial \mathbf{x}}\right|_{\mathbf{x}} \boldsymbol{\delta}\mathbf{x} + \boldsymbol{\delta}\mathbf{F}(\mathbf{x}) + O(\boldsymbol{\delta}^2)$$

So $$\boldsymbol{\delta}\dot{\mathbf{x}} = \dot{\tilde{\mathbf{x}}} - \dot{\mathbf{x}}$$

$$= \left.\frac{\partial \mathbf{F}}{\partial \mathbf{x}}\right|_{\mathbf{x}} \boldsymbol{\delta}\mathbf{x} + \boldsymbol{\delta}\mathbf{F}(\mathbf{x})$$

Response of a dynamical system to a forcing II

- So

$$\delta\dot{\mathbf{x}} = \mathbf{J}_\mathbf{x}\delta\mathbf{x} + \delta\mathbf{F}(\mathbf{x}) \qquad (1)$$

- We want to know $\langle\delta\mathbf{x}\rangle$
- We can rearrange (1) and say

$$\langle\mathbf{J}_\mathbf{x}^{-1}\delta\dot{\mathbf{x}}\rangle = \langle\delta\mathbf{x} + \mathbf{J}_\mathbf{x}^{-1}\delta\mathbf{F}(\mathbf{x})\rangle,$$

While in equilibrium, $\langle\delta\dot{\mathbf{x}}\rangle = 0,$
This term is not necessarily zero

But … if we assume the forcing is small, the response can be assumed almost linear, in which case this is a higher order term

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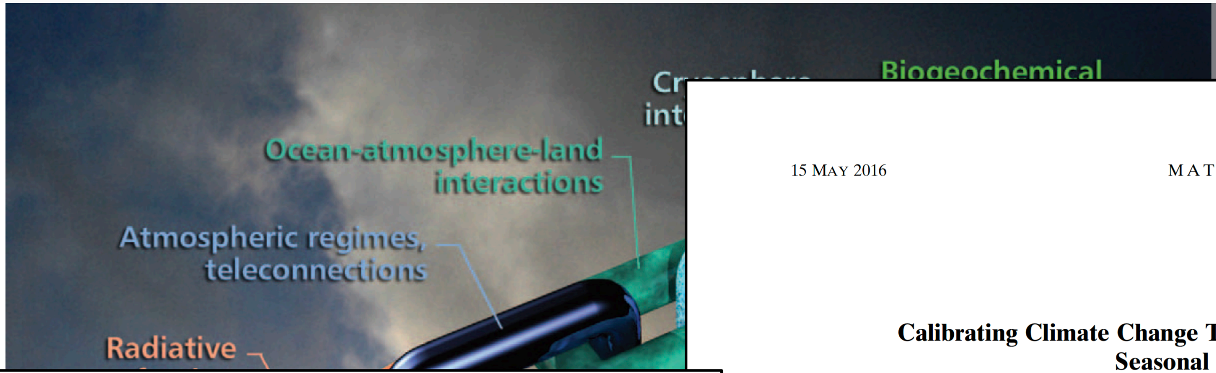

Calibrating Climate Change Time-Slice Projections with Estimates of Seasonal Forecast Reliability

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ABSTRACT

In earlier work, it was proposed that the reliability of climate change projections, particularly of regional

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Using numerical weather prediction to assess climate models

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