The Impact of increasing greenhouse gases on El Nino/Southern Oscillation (ENSO)

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1. Motivation
2. LOAM: a tool for illuminating the physics
3. ENSO in the modern climate
4. Using LOAM to analyze climate models
5. The impact of Global Warming on ENSO

1. Motivation

- How will ENSO change due to increase greenhouse gases?
  - Current climate models have biases that are too large to address this question directly
- Why does ENSO change in a climate model when the forcing/boundary conditions is changed?

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- How will ENSO change due to increase greenhouse gases?
  - Current climate models have biases that are too large to address this question directly
- Why does ENSO change in a climate model when the forcing/boundary conditions is changed?
- Introduce LOAM: a tool to address these two questions

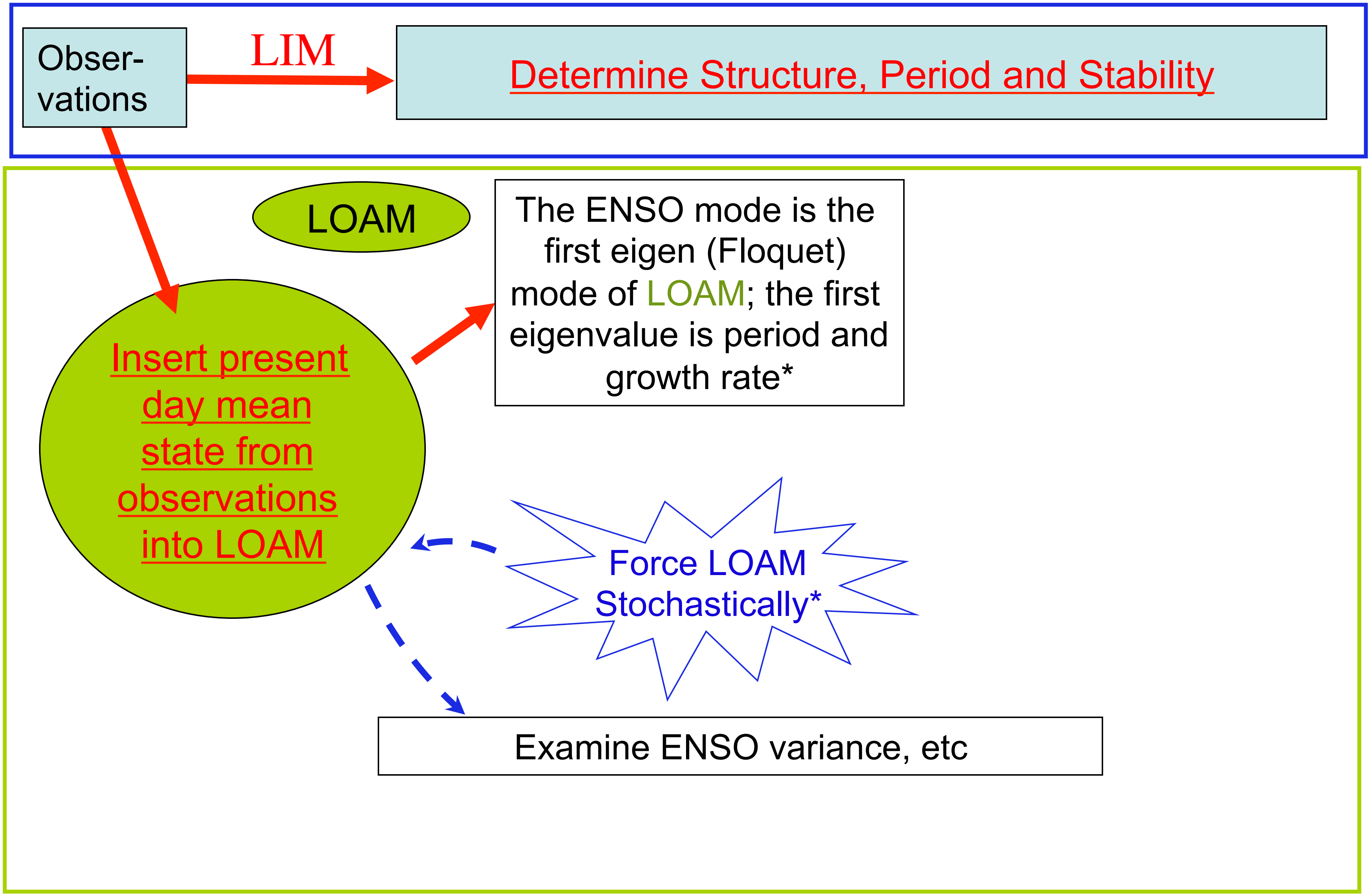
2. LOAM: A tool for illuminating the physics

- ***LOAM**: **L**inearized **A**tmosphere-**O**cean **M**odel of the tropical Pacific*
  - A model of the tropical Pacific Ocean and tropical atmosphere based on the Zebiak & Cane (1987) model
  - The physics is linearized about a *prescribed* climatological annual cycle
    - Surface winds, SST, upper ocean currents and upwelling
    - Parameter updates from Thompson and Battisti (2000)
- Mean states prescribed from observations or GCMs
- The leading eigen (Floquet) modes of LOAM are the leading coupled modes of variability

3. ENSO in the Modern Climate

Obser-
vations $\xrightarrow{\text{LIM}}$ Determine Structure, Period and Stability

3. ENSO in the Modern Climate



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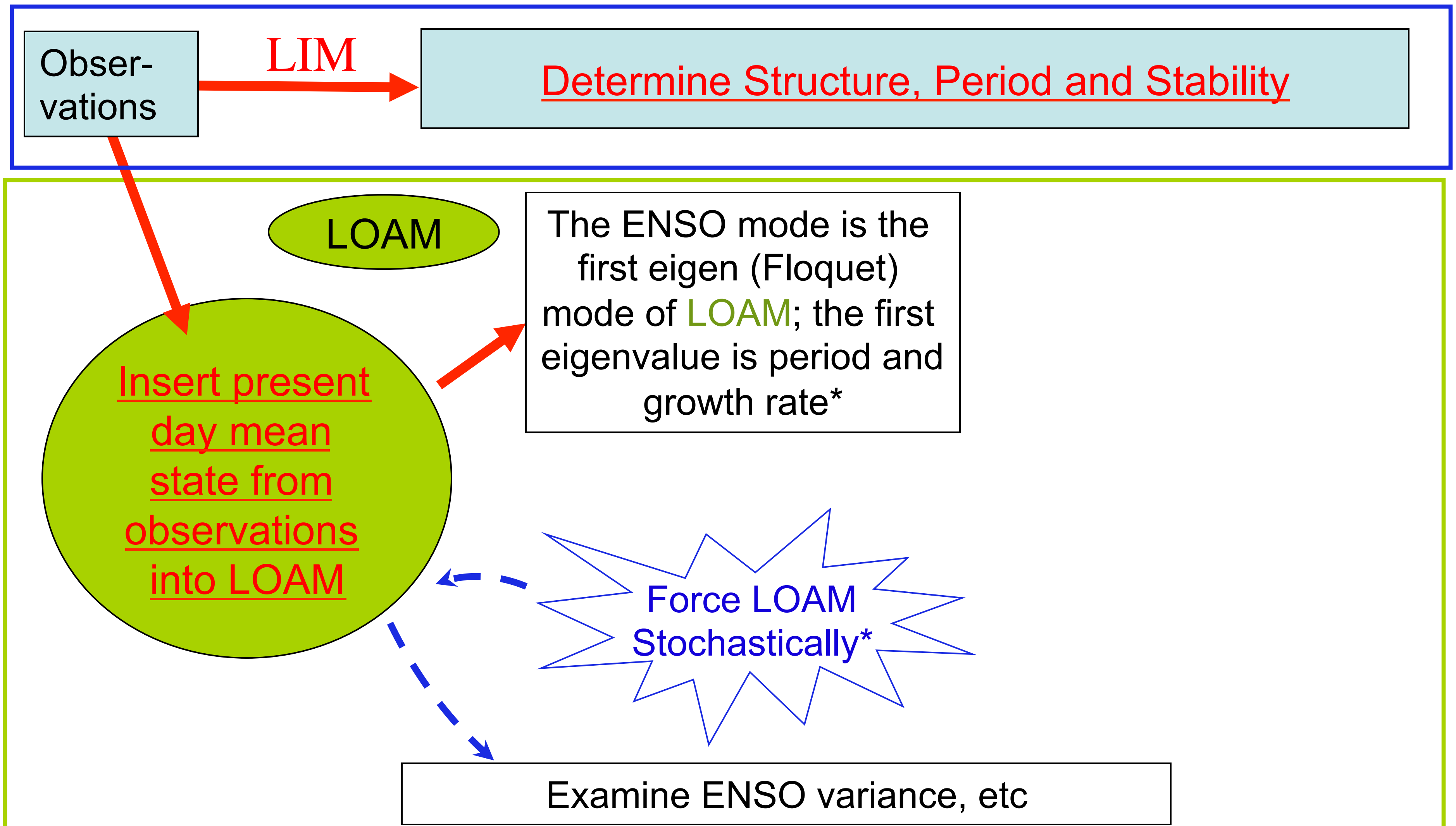

Compare the physics of the leading eigenmode of LOAM to that from the observations; examine the spatio-temporal structure of the interannual variability in LOAM and compare it to that observed

ENSO is the leading mode of LIM and LOAM …

	Model	ENSO Mode growth ($year^{-1}$)	ENSO Mode period ($years$)
Observed	*Kaplan*	0.63 (a)	4.1 (a)
	NCEP/OI	0.53 (b)	3.5 (b)
	COADS	0.22 (c)	3.8 (c)

From LIM

Roberts and Battisti 2011

ENSO is the leading mode of LIM and LOAM …

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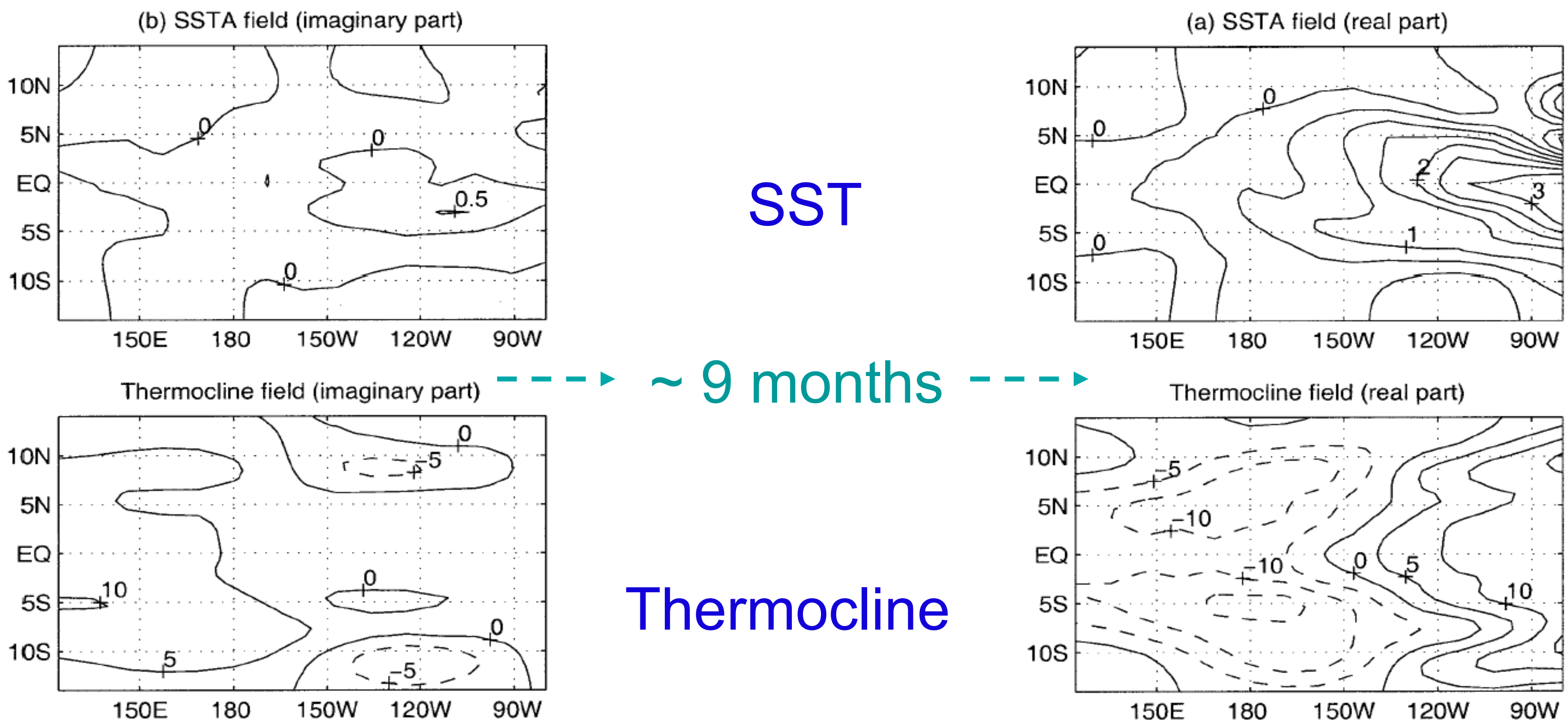
	NCEP/OI	0.53 (b)	3.5 (b)	
	COADS	0.22 (c)	3.8 (c)	
Obs Mean States	$LOAM$(a)	0.53	3.7	From LOAM
	$LOAM$(b)	0.48	4.2	
	$LOAM$(c)	0.34	4.9	

The leading eigen (Floquet) mode of LOAM with realistic mean states is the ENSO mode, and it is stable

Roberts and Battisti 2011

ENSO is the leading eigenmode of LOAM …

… given realistic mean states and parameter values.



Thompson and Battisti 2000, Roberts and Battisti 2011

Summary of ENSO physics in the Modern Climate

- ENSO is the leading eigen (Floquet) mode of the linearized atmosphere-ocean dynamical system
  - The period 3.7 - 4.9 yr and "decay" rate 0.34 - 0.53 yr^{-1} are consistent with observations
  - The *mode* evolves in a manner consistent with observed ENSO cycle (e.g., in evolution and structure of SST and upper ocean heat content, Bjerknes feedback, coordinated to calendar year, …)

- Stochastic forcing of LOAM (mainly the ENSO *mode*) yields output that is consistent with all of the "robust observations" of ENSO*
  - EOFs, coordination to the annual cycle, broad spectral peak, etc.

Roberts and Battisti 2011

Implications of the ENSO physics

- The amplitude and spatio-temporal properties of the ENSO mode are highly sensitive to:
  - the structure in the climatological mean state
  - the spatial and temporal structure of the noise forcing (how well it projects onto the adjoint of the mode)

- Hence, for a global climate model to simulate realistic ENSOs the model has to have:
  - *a realistic mean state*
  - an adequate representation of all important processes acting in the ENSO mode
  - an adequate representation of the important noise forcing

4. Using LOAM to analyze coupled atmosphere-ocean variability in a climate model

- Insert the climatological annual cycle from the GCM into LOAM
  - Calculate eigenmodes; force stochastically and characterize the coupled variability
- If LOAM can reproduce the GCM behavior:
  - LOAM can be used to illuminate the relationship between biases in the mean fields and biases in the modes and statistical properties of the variability in the GCM
  - LOAM can also be used to illuminate *why* the coupled tropical variability changes when a forcing is applied to the GCM

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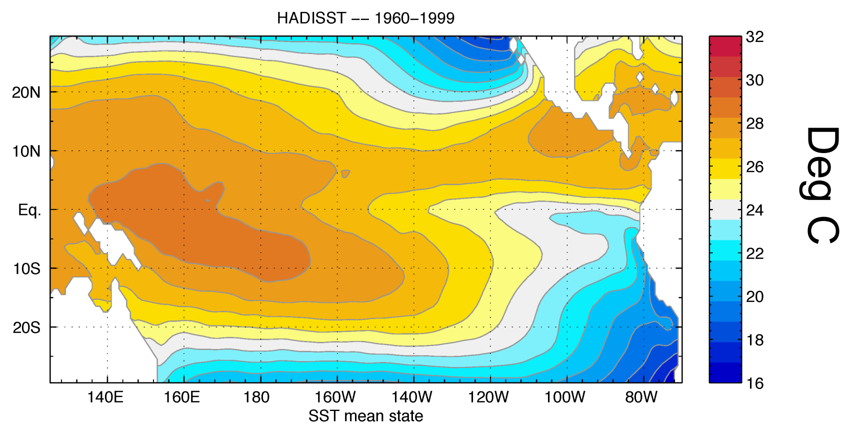
- Proof of Concept (not today):
  - ENSO in the early Holocene as simulated by CSM1.4 and HadCM3

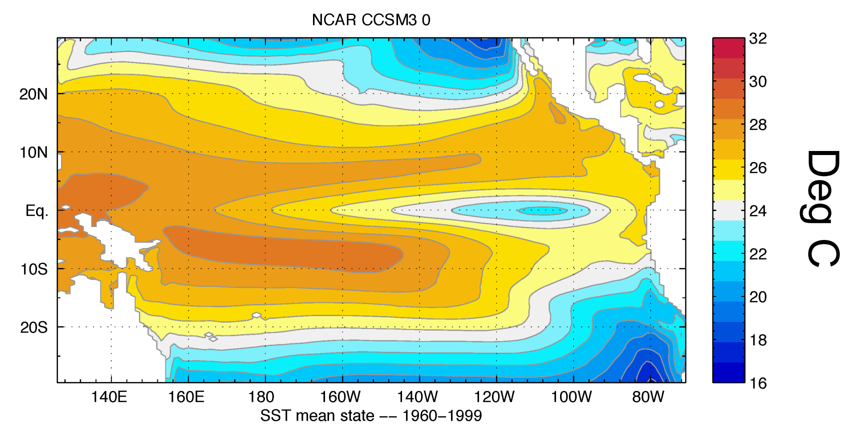
5. The impact of Global Warming on ENSO

Problem: ENSO is extremely sensitive to subtle changes in the structure of the climatology, AND the CMIP3 / AR4 models all have large biases in their mean states.

Observed Annual Ave SST



Simulated Annual Ave SST: CCSM



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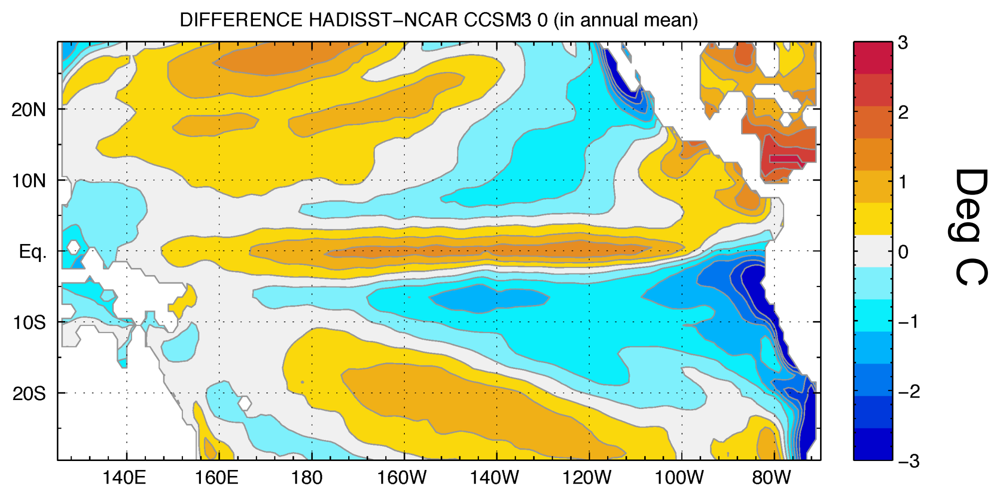
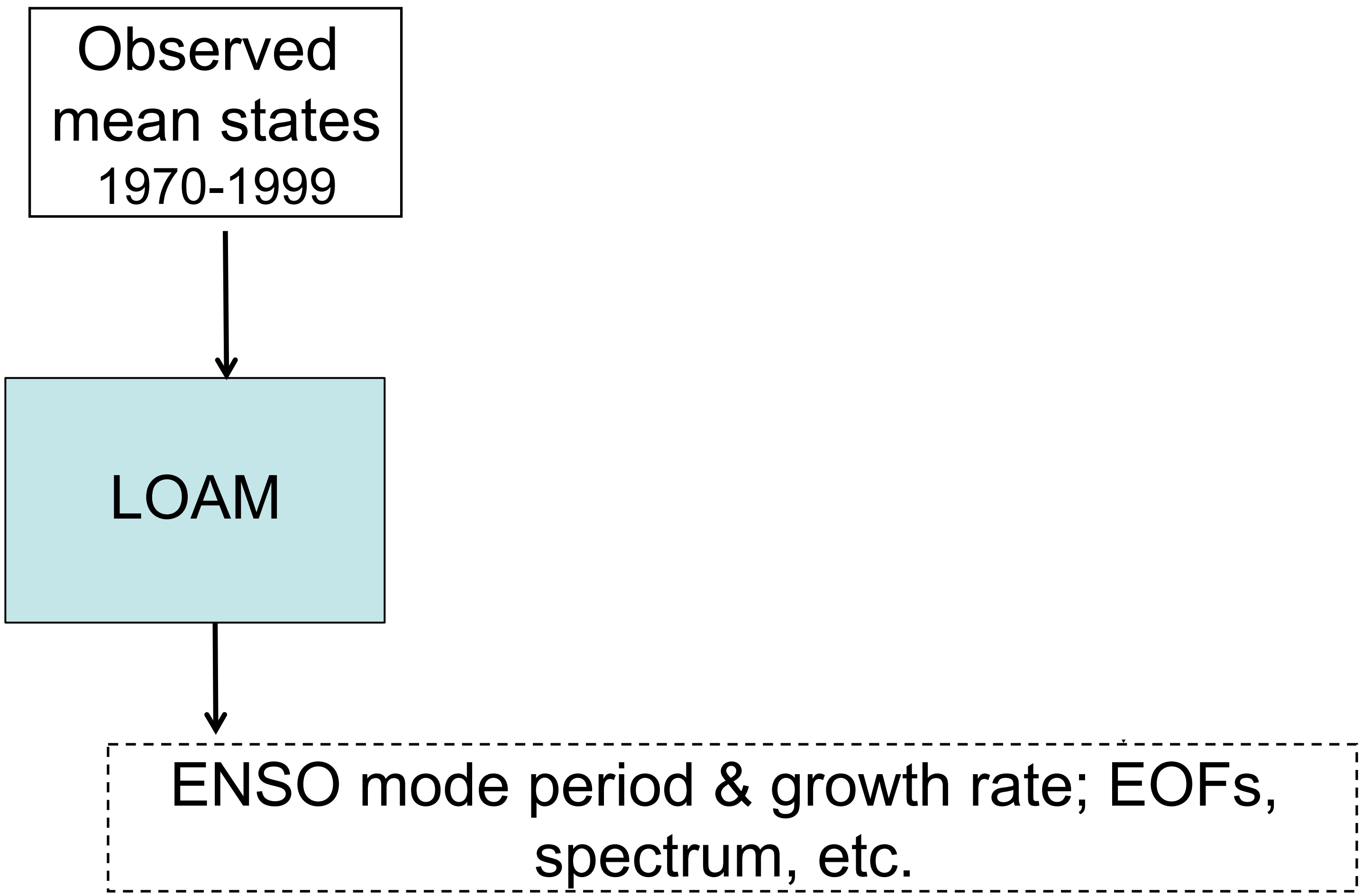
Bias



A way forward : Apply projected ***changes*** in climatology to the 1970-1999 ***observed*** climatology and use LOAM to determine ENSO changes under this debiased climatology.



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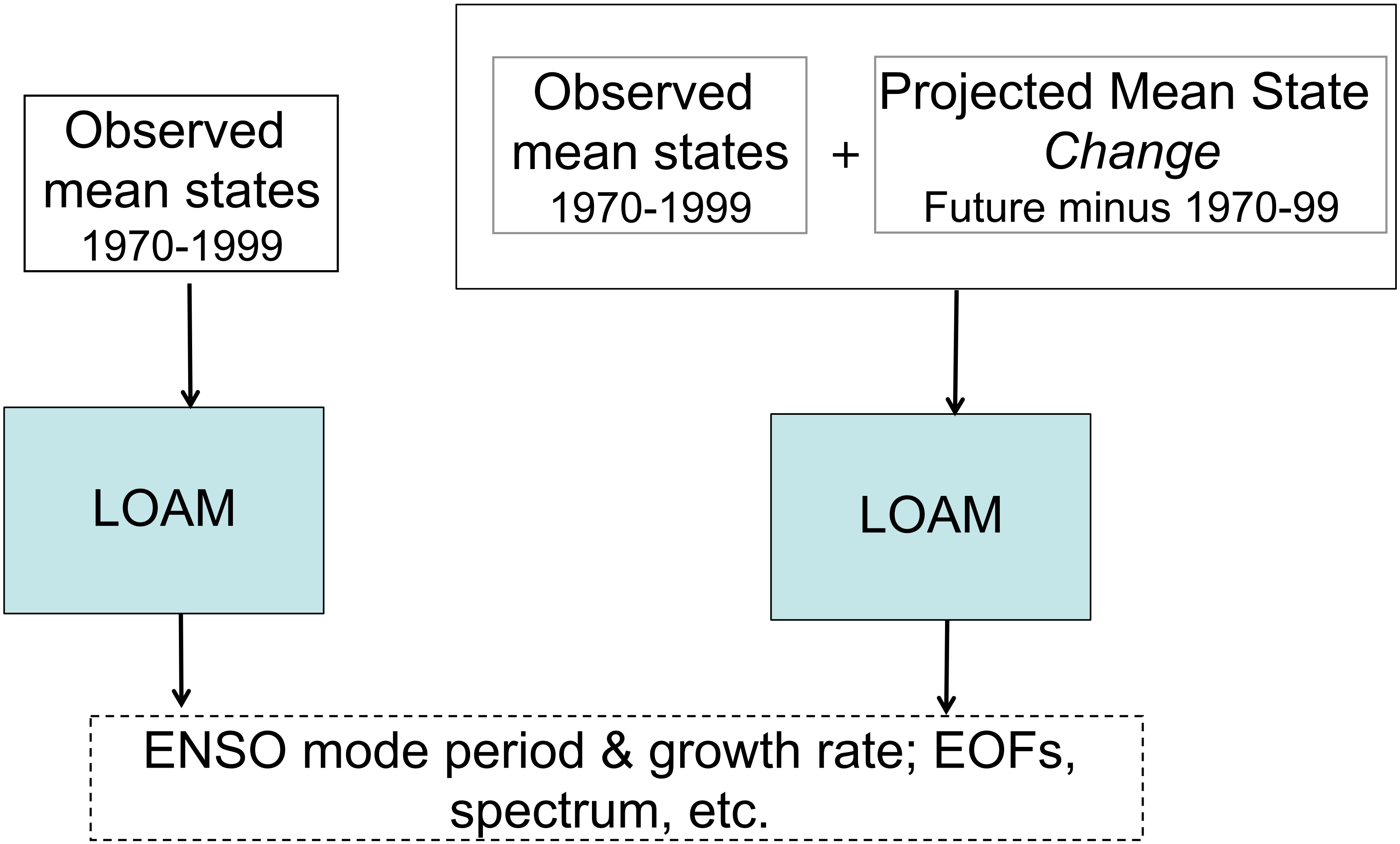
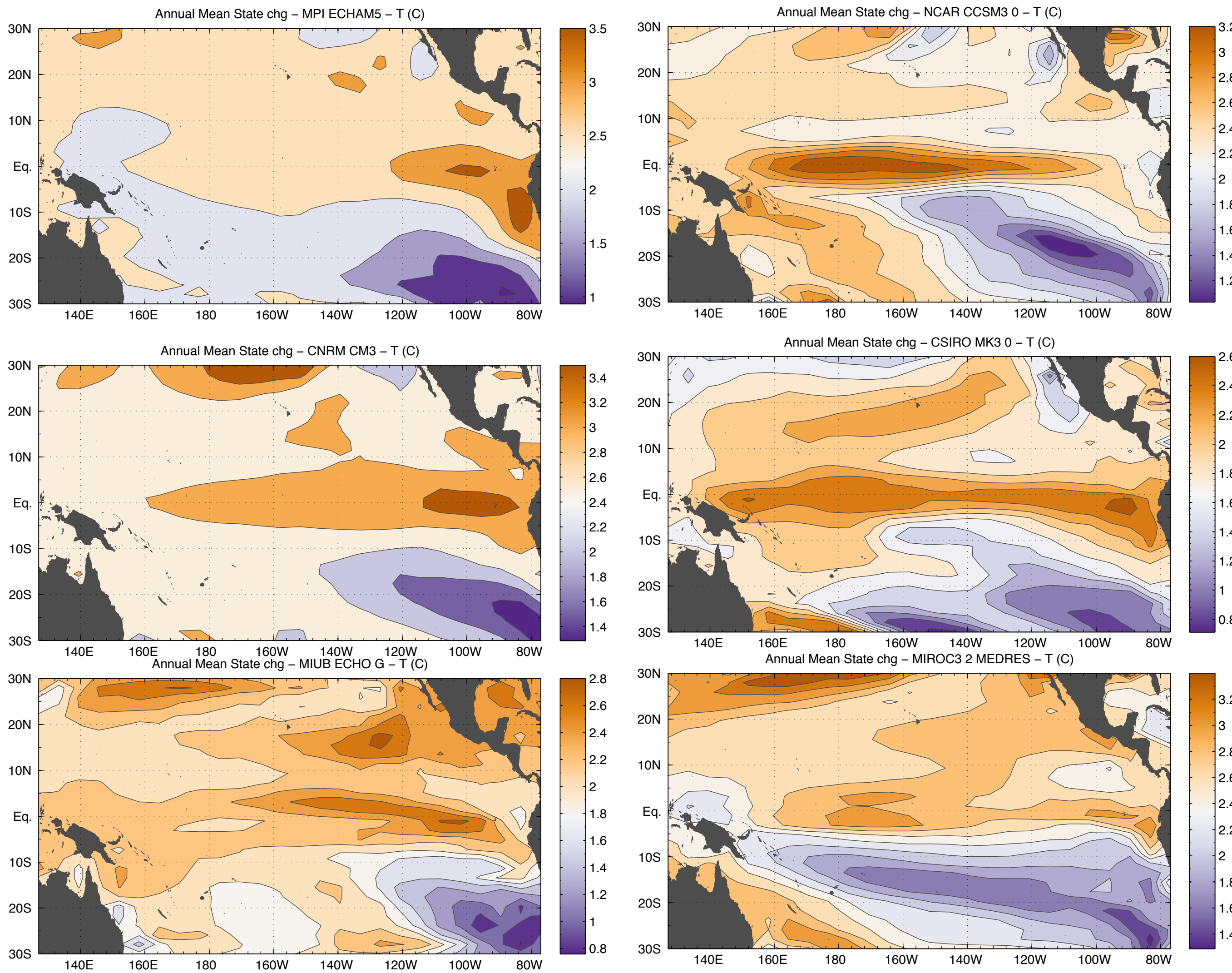


Today: Insert projected mean state changes from 7 AR4 Models (SRESA2) into LOAM

Annual Mean SST Change



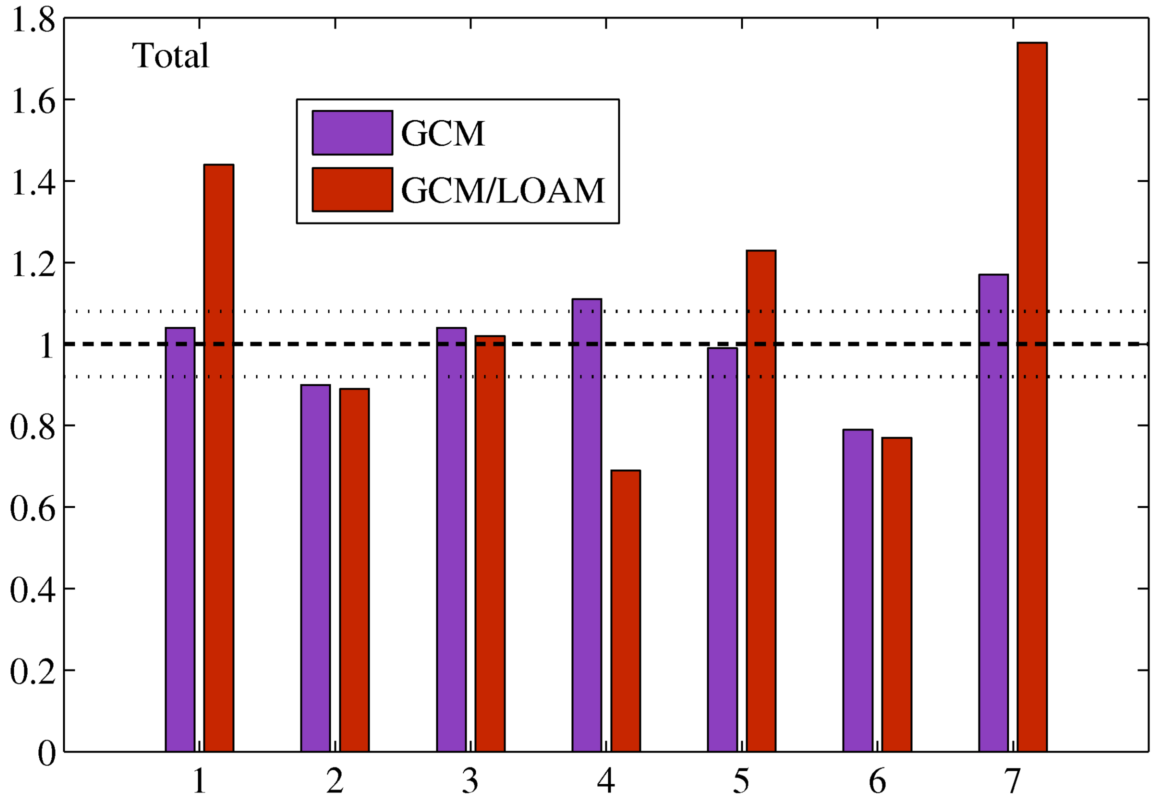
2070-2100
minus
1971-2000

Deg C

Change in ENSO variablity

2071-2100 minus 1971-2000

σ(Nino3):
“future”
divided by
“today”



AR4 models w/ SRES A2

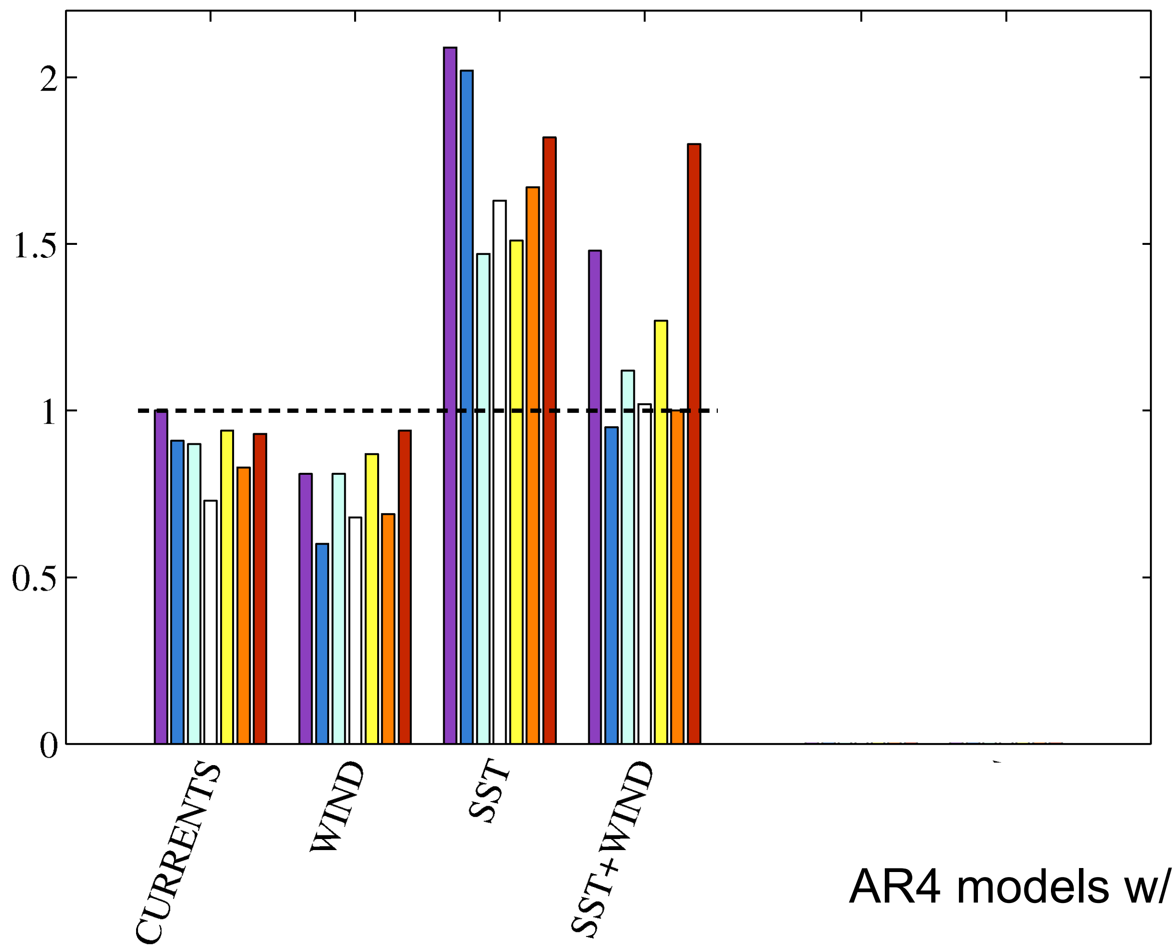
1 = cccma cgcm3.1 2 = cnrm cm3 3 = csiro mk3.0 4 = miroc3.2 (medres)
5 = miub echo(g) 6 = mpi echam5 7 = ncar ccsm3.0

Change in ENSO variability

2071-2100 minus 1971-2000

Normalized standard deviation of Nino3: “future” divided by “today”

σ(Nino3): “future” divided by “today”



AR4 models w/ SRES A2

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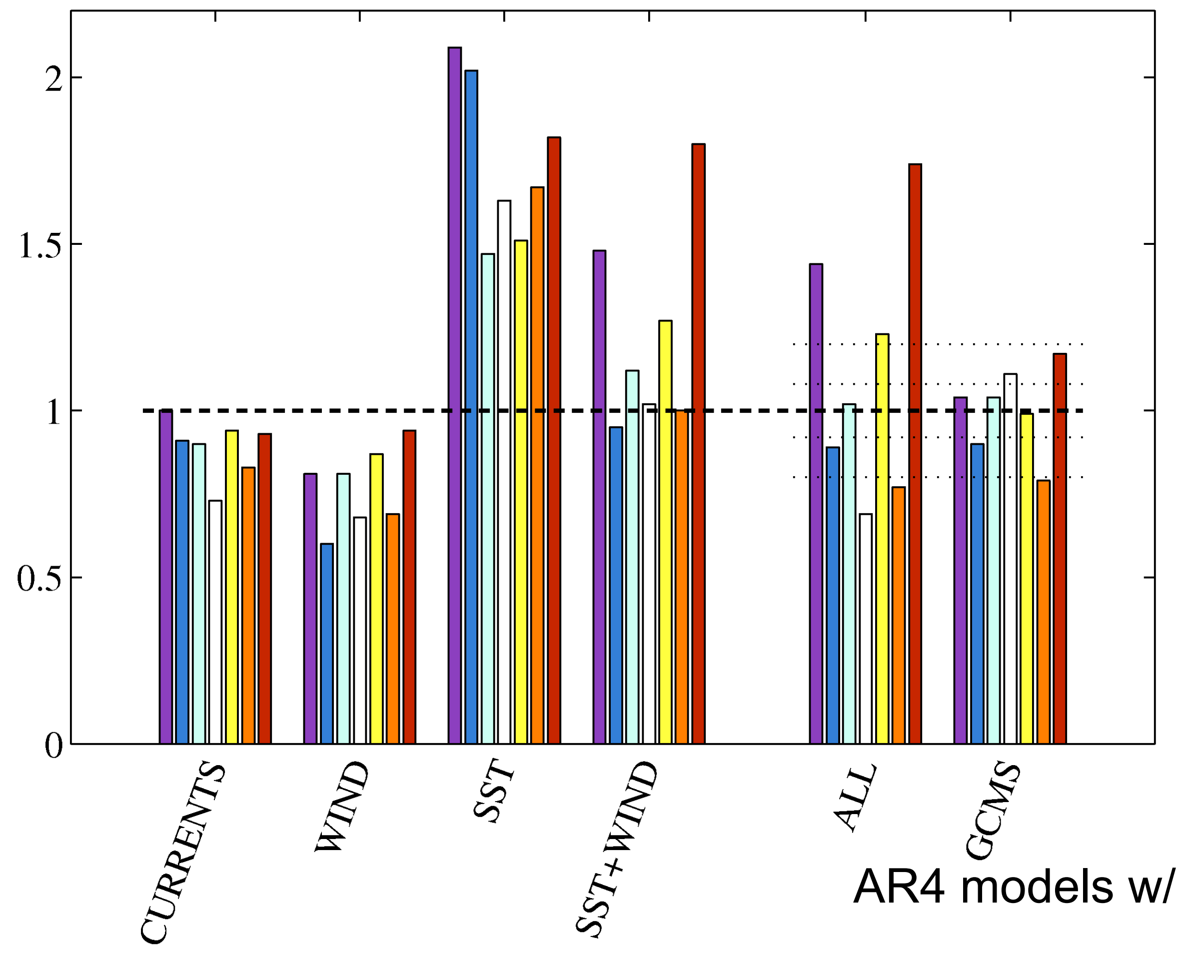


AR4 models w/ SRES A2

5. Summary

- Using realistic parameters and the observed climatological mean states, the leading eigen (Floquet) mode of the coupled atmos/ocean system in the tropical Pacific is consistent with the robust observations of ENSO
  - Spatial structure of composite anomalies in SST, precipitation, winds, etc.; processes responsible for evolving the SST anomalies; a concentration of variance at 3-7 years; peaking at the end of the calendar; etc.

- When forced stochastically, LOAM with the observed mean states reproduces the observed statistics and ENSO temporal structure
  - Eg, EOFS, ENSO spectrum, the spring barrier, etc.

5. Summary

- ENSO is poorly represented in high end climate models
  - Only a few IPCC-class models (two, if you aren’t squeamish) have a realistic ENSO
  - Likely due to biases in the climatological mean states (work underway w/ LOAM to prove this)

- LOAM and the mean states *changes* projected by the AR4 models is a plausible way forward for estimating the impacts of increasing greenhouse gases on ENSO

Next Steps

- Use LOAM to project the future characteristics of ENSO using mean state changes simulated by *each* of the AR5 models

- Analyze the interannual variability, including the ENSO mode, in all AR5 models using LOAM
  - What is the relationship between mean state biases and distortions in the simulated ENSO

- Perform TOGA experiments to assess changes in ENSO teleconnections due to
  - Change in atmospheric mean state
  - Change in ENSO characteristics

Thank you: Jim Todd (NOAA) and our Colleagues

ENSO in the Early Holocene vs today

- ENSO variance is reduced in the mid and early Holocene compared with today (Tudhope et al 2001)

- GCMs have been used to study this:
  - Modern day and 8.5kyr BP simulations using CSM1.4 (Otto-Bliesner et al 2003)
  - Modern day and 6kyr BP simulations using HadCM3 (Brown et al 2006)

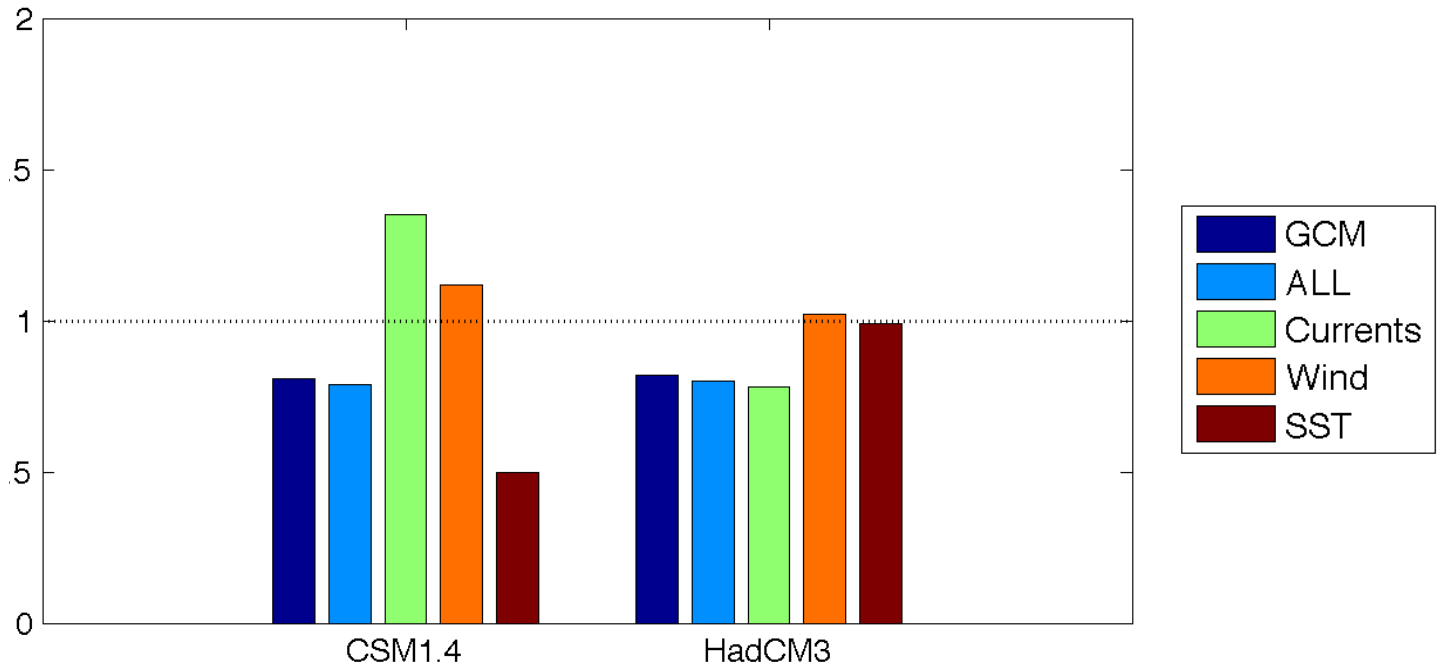
- In each case, LOAM reproduces the GCMs:
  - ENSO period, growth rate and structure, EOFs etc

- LOAM shows *why* ENSO variance is reduced

ENSO in the Early Holocene vs today

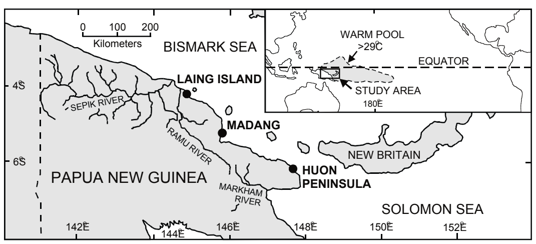
ENSO variance is reduced by ~20% in both models

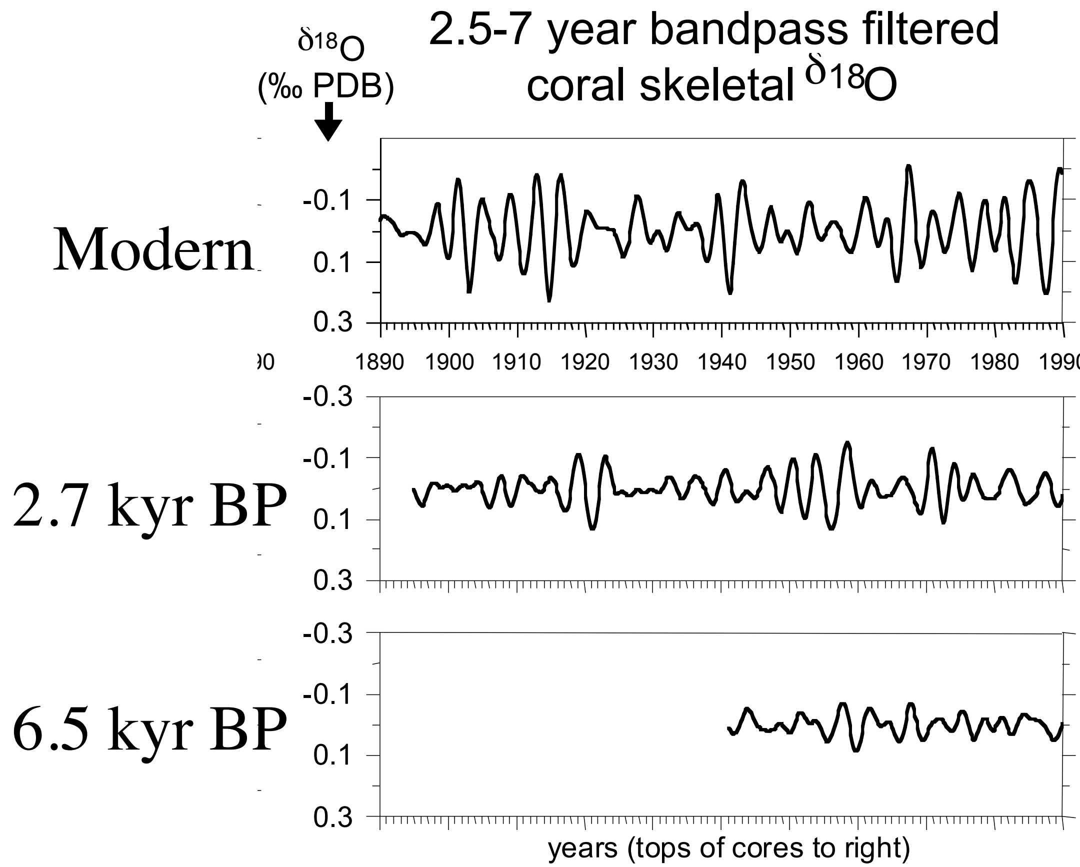
var(Nino3): “Early/Mid Holocene” divided by “today”



… but for very different reasons

Example: ENSO in the Mid Holocene





Paleo data indicates interannual variability in the tropical Pacific was reduced by up to ~80% from the modern.

(reduction seen in proxy data throughout the equatorial band)

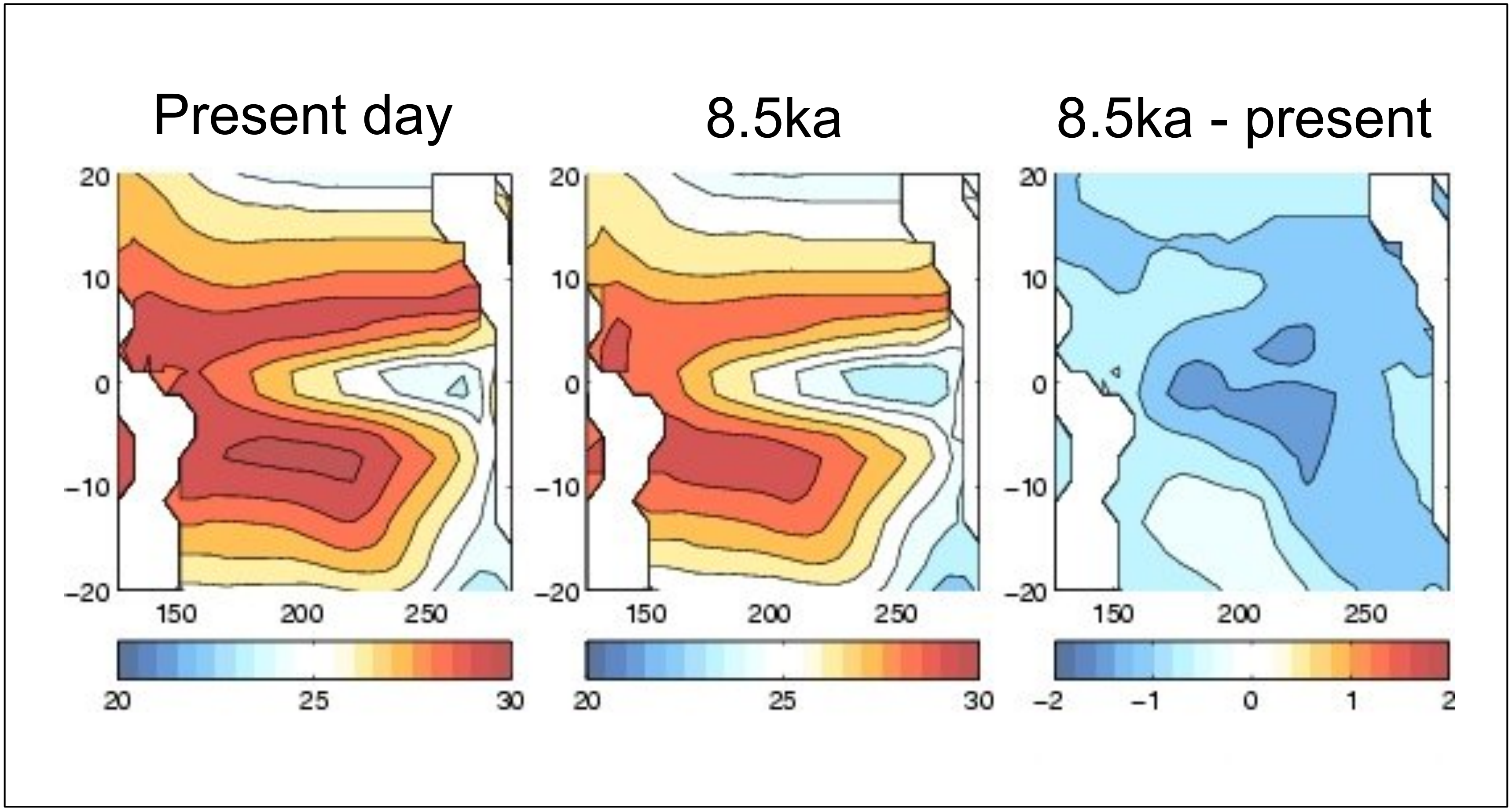
Tudhope et al. 2001

Why is ENSO reduced in the mid Holocene?

Model	Reduction	Hypothesis	Actual Reason
FOAM (Liu et al 2000)	20%	Increase stability of ENSO mode due to weakened thermocline	Unknown
CAM+RGO (Chiang et al 2008)	38% constrained ENSO mode		Reduction in the amplitude of stochastic forcing (Chiang et al 2008)
Zebiak/Cane (Clement et al 2000)	Smaller amplitude; less frequent ENSO events	Decreased *instability* in the ENSO mode due to enhanced Trades and & changed seasonality	Complicated (see Clement et al 2000; Roberts 2007). ENSO *mode* is actually more unstable
CCSM1.4 (Otto-Bliesner et al 2003)	20%	Ditto	??
HADCM3 (Brown et al 2006)	12%	Ditto	??

Use LOAM to find out!

Sea Surface Temperature in CCSM1.4



SST in the mid Holocene is ~1 ºC cooler than the modern tropics

HOW DO MEAN STATE CHANGES AFFECT ENSO?