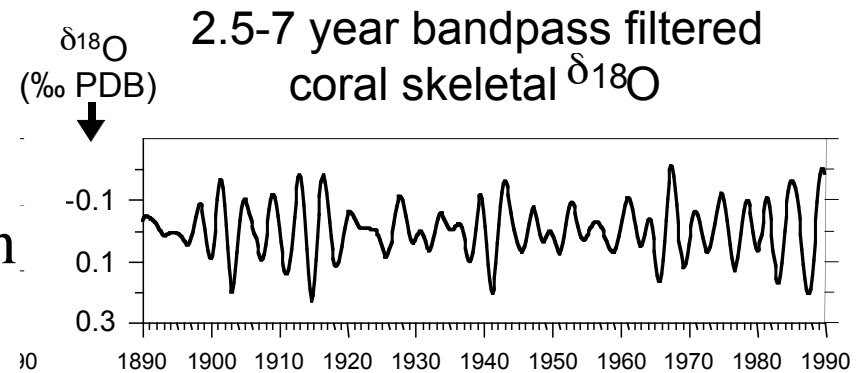


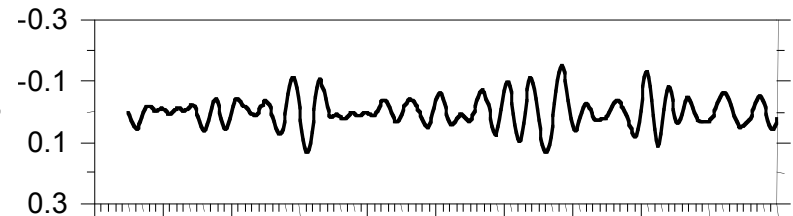
3. ENSO in the Mid Holocene



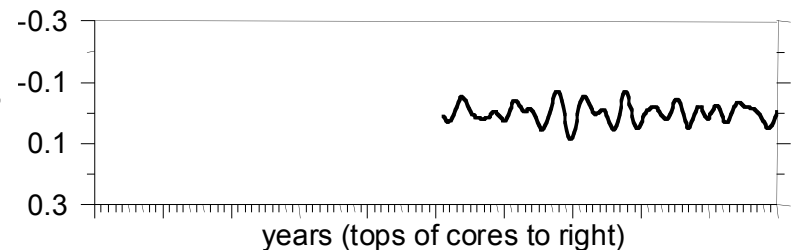
Modern



2.7 kyr BP



6.5 kyr BP



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

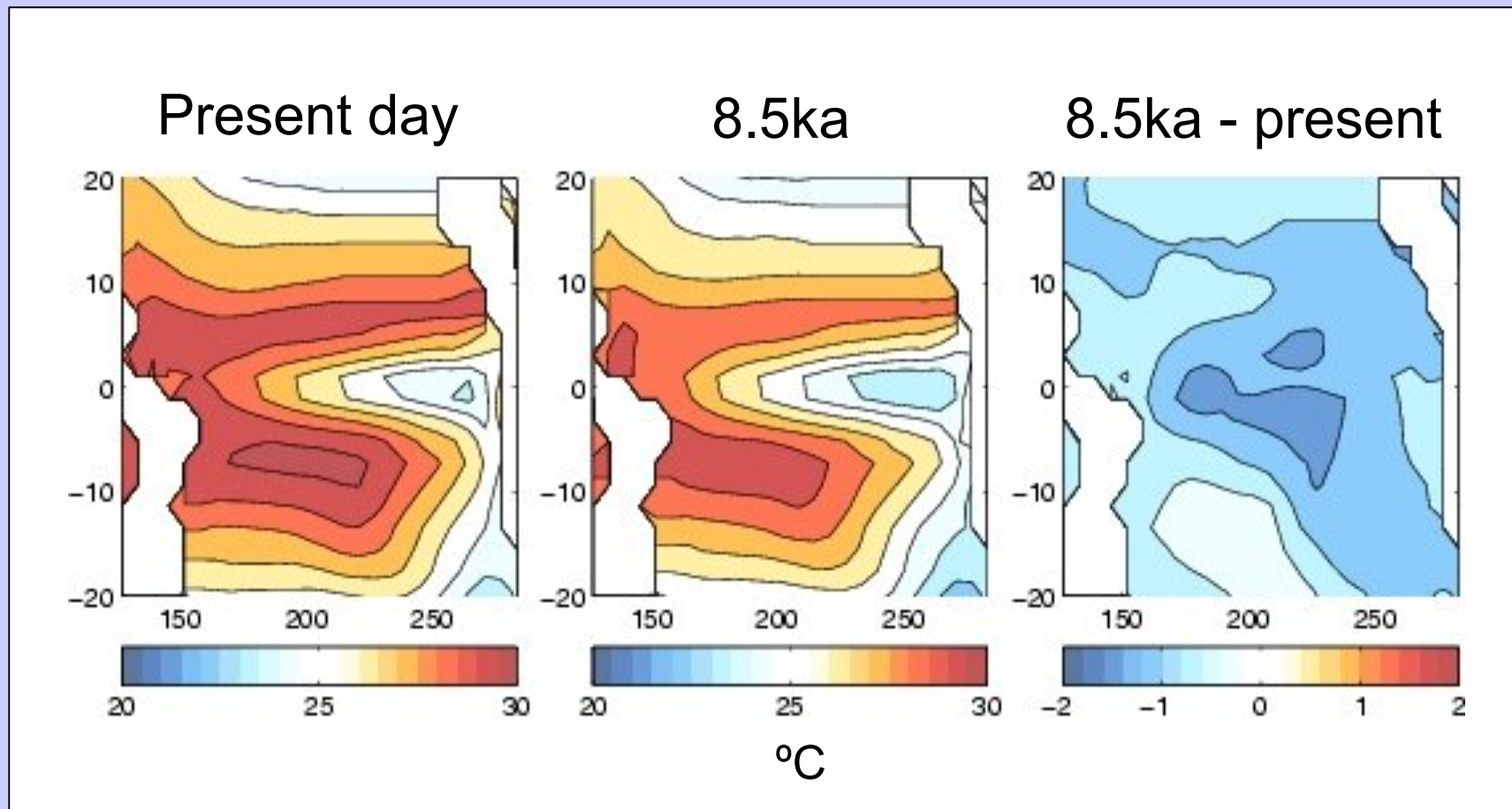
3. ENSO in the Mid Holocene

What do climate models say about the early/mid Holocene?

Model	Reduction in nino3 variance at 6ka	comments
CCSM(1999)	none	weak ENSO in present
FOAM(02)	20%	
→ CCSM 1.4(02)	20%	
HadCM3(06)	10%	simple ocean with no change in its mean state
CAM+RGO	38%	

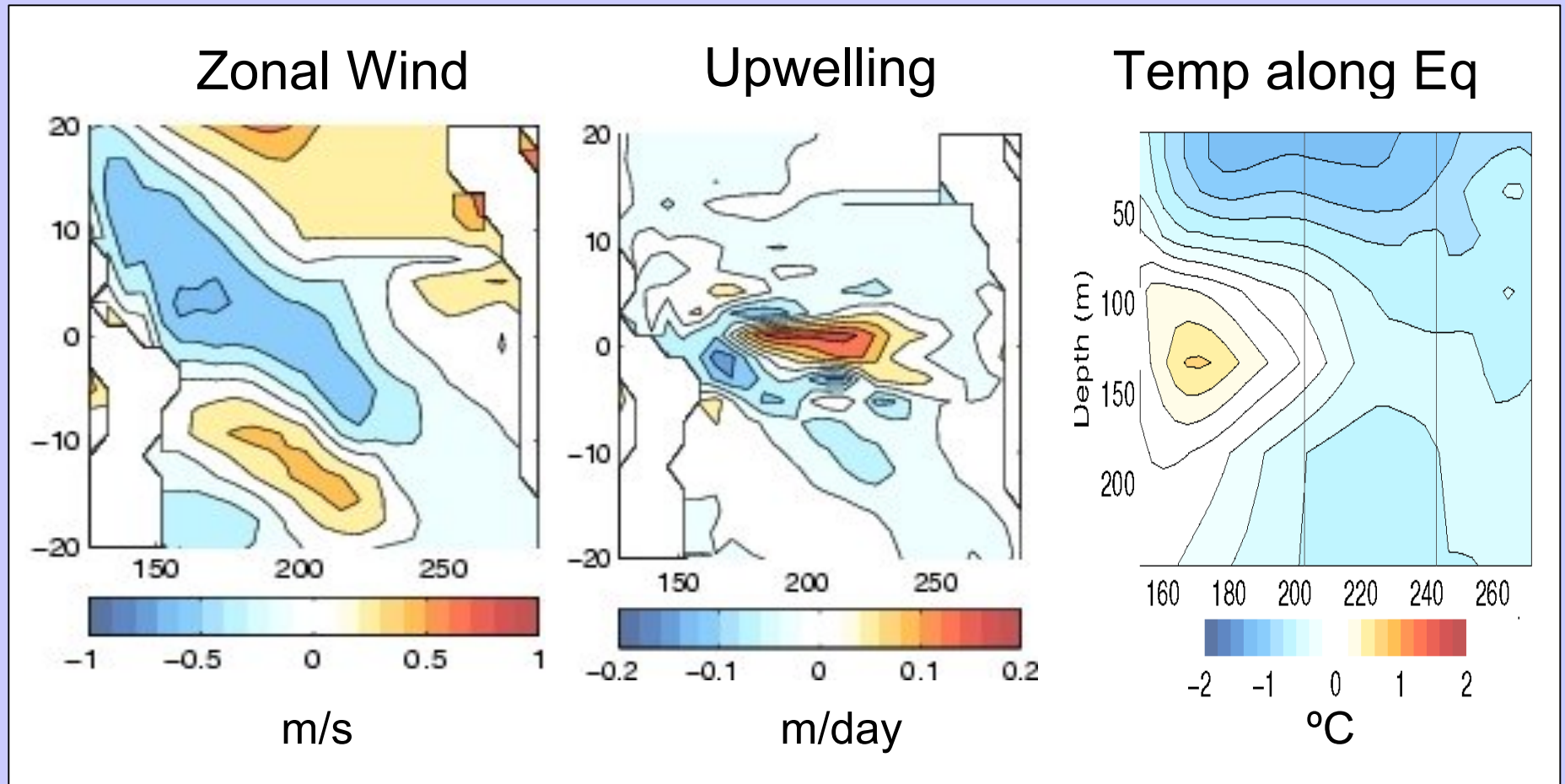
Many hypotheses for the reduced variance have been postulated, though few have been tested.

Sea Surface Temperature in CCSM1.4



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

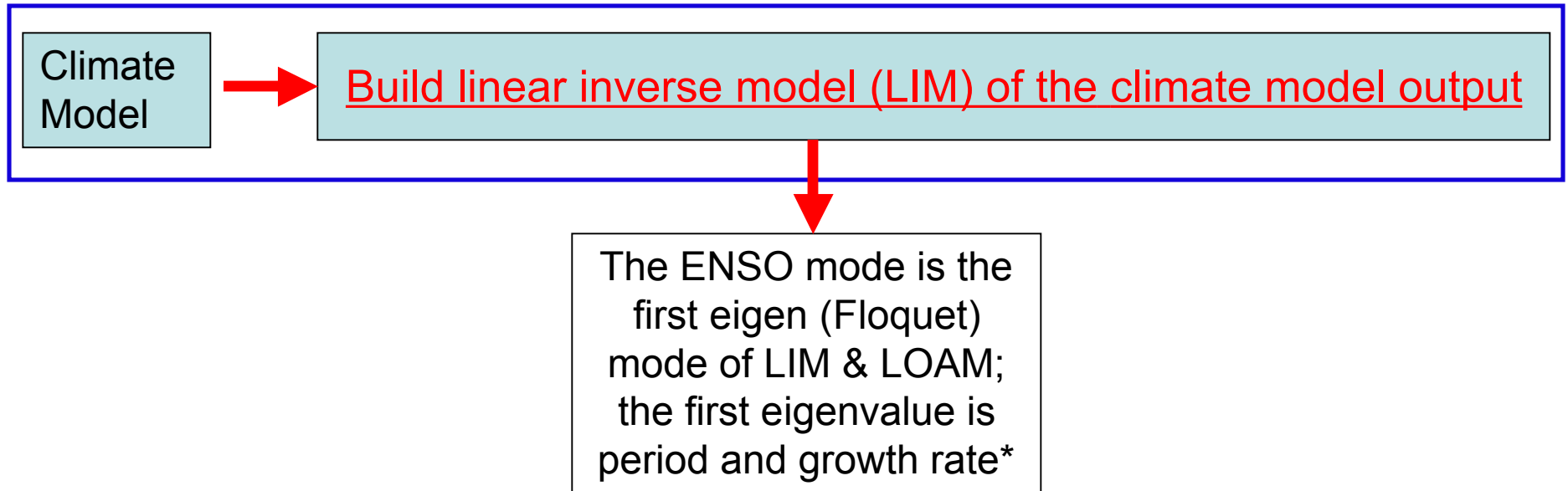
More Mean State Changes in CCSM1.4



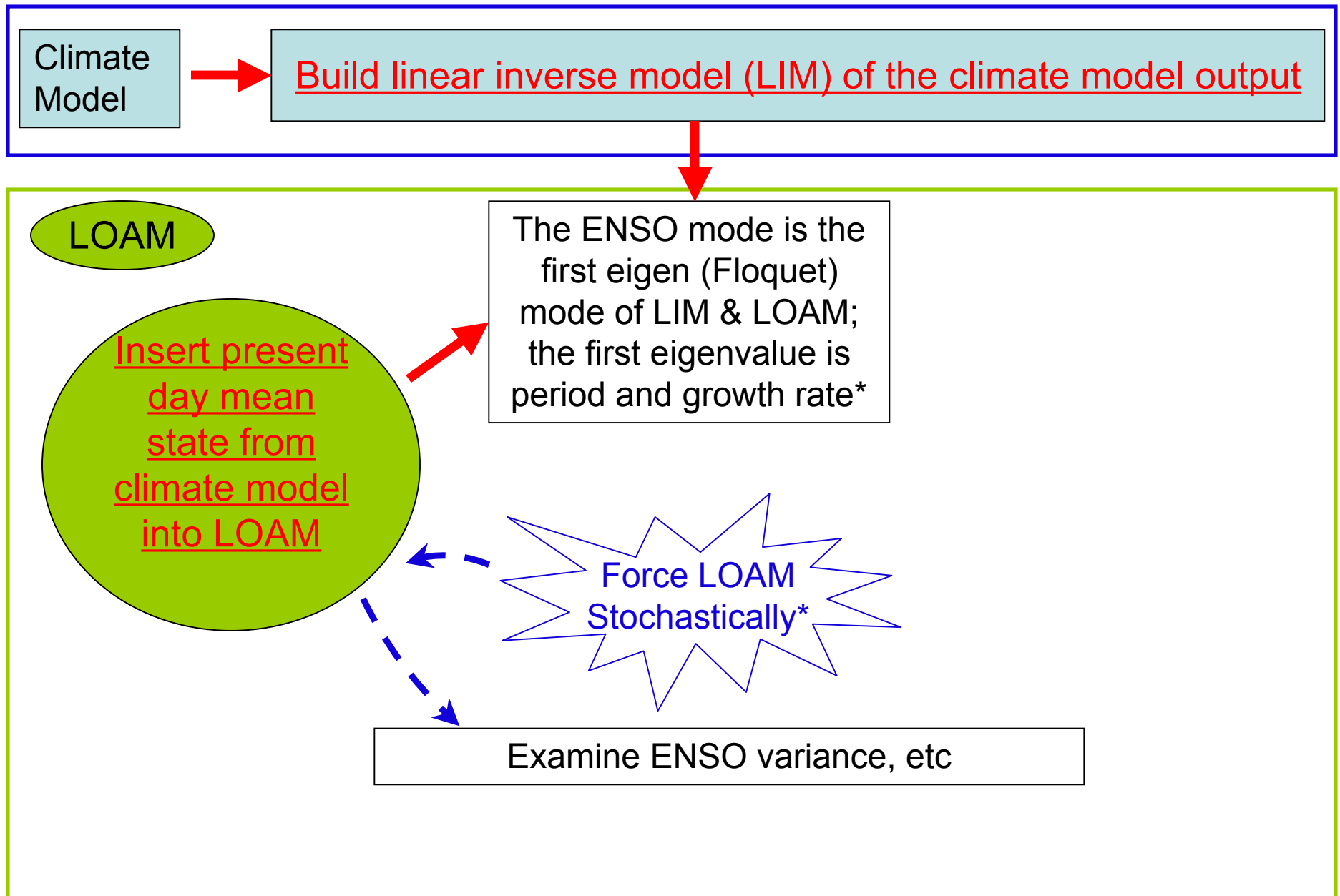
Changes in each mean field are typical 10% of the climatology

Roberts 2007; Battisti et al 2008

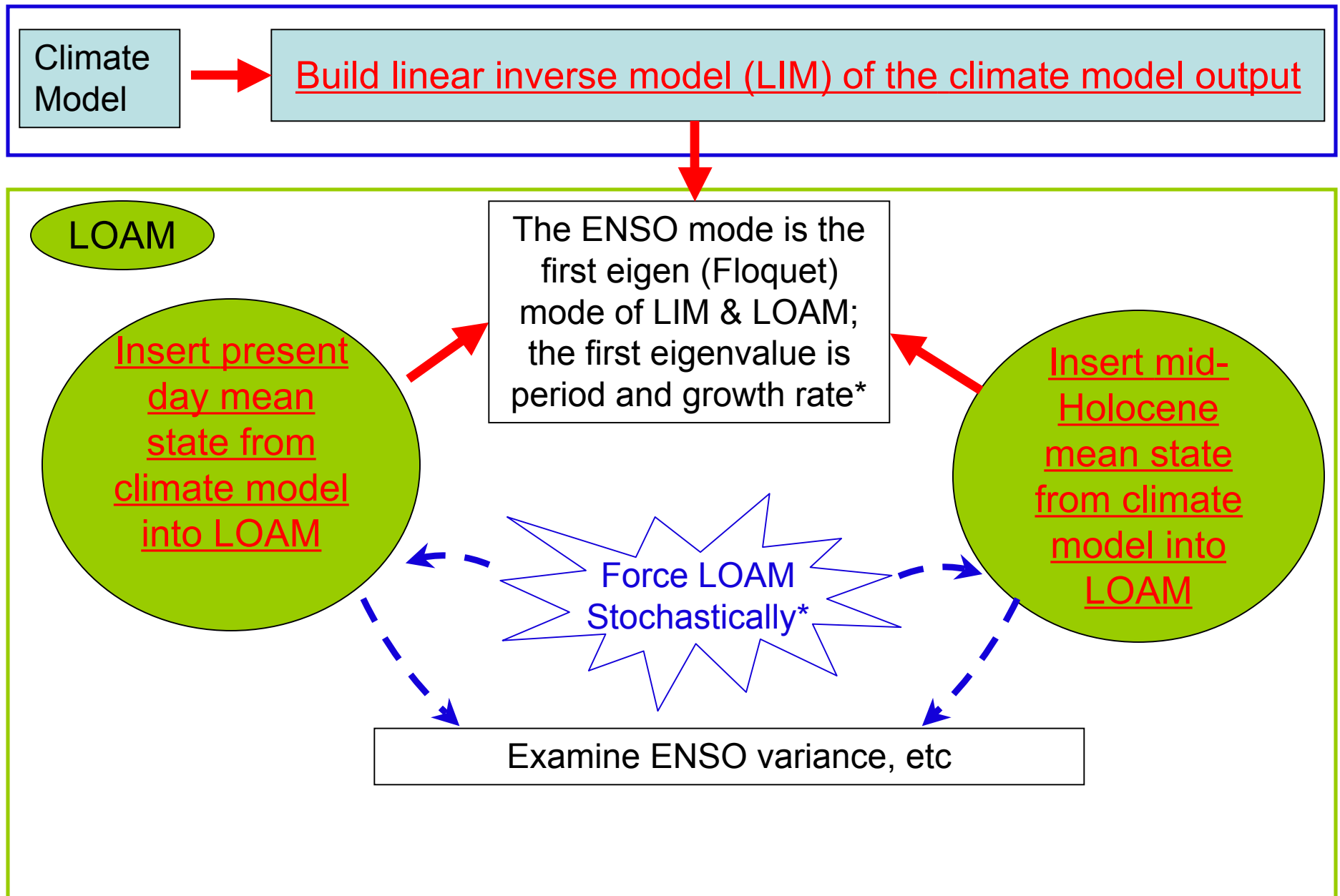
How can we *know* why ENSO changed?



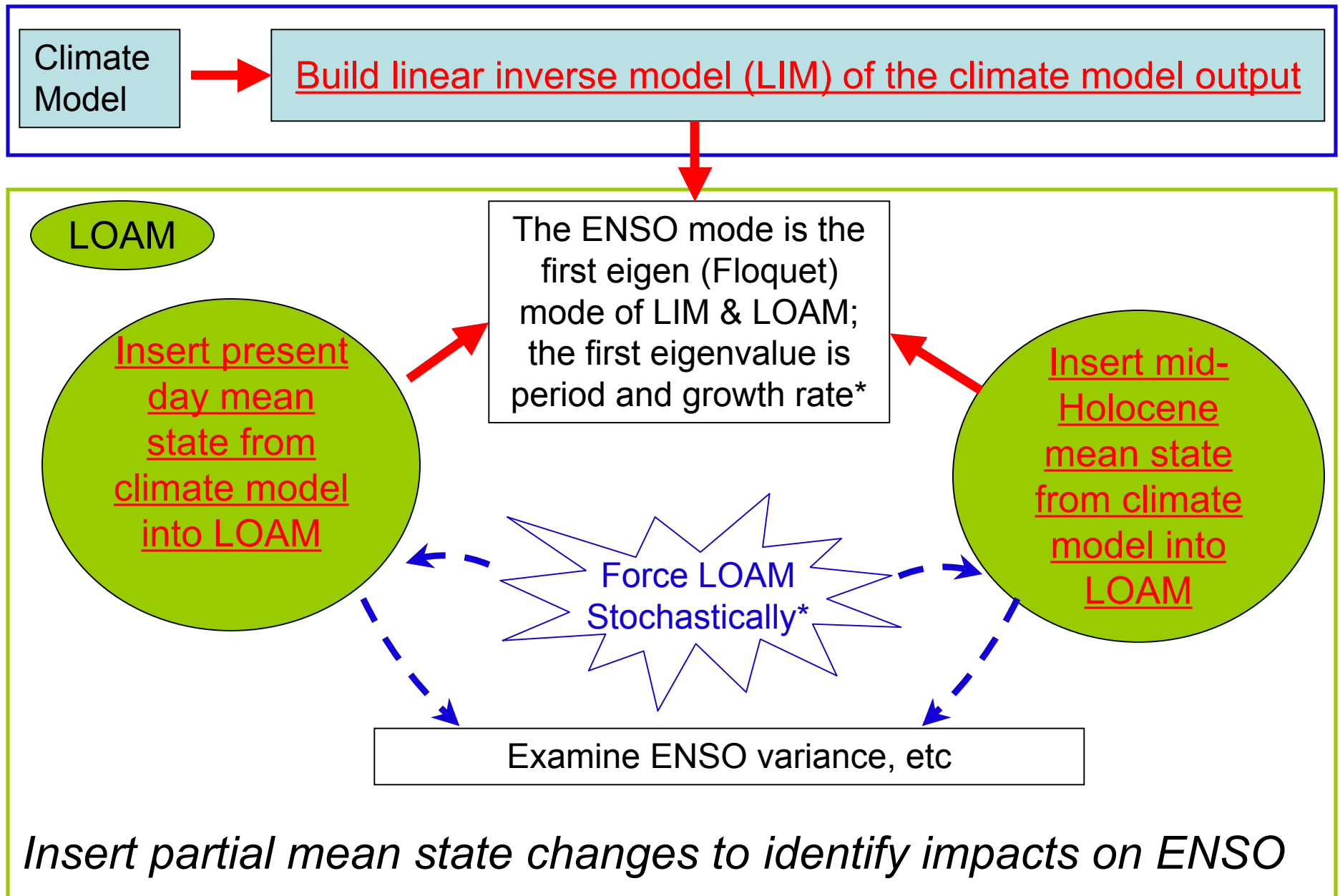
How can we *know* why ENSO changed?



How can we *know* why ENSO changed?



How can we *know* why ENSO changed?



The ENSO Mode in CCSM

		The ENSO Mode*	
	var(nino3) / var(nino3 pres)	period (years)	decay (year ⁻¹)
CCSM(pres)	1.00	3.27	0.55
CCSM(8.5ka)	0.81	3.78	0.56

*The ENSO Mode in the CCSM is obtained by fitting a linear inverse model to the simulated SST anomalies, and taking the leading eigenmode of the dynamical operator (see, eg, Penland and Sardeshmukh 1995)

Does LOAM capture the mid Holocene ENSO changes in CCSM?

The ENSO Mode			
	$\text{var}(\text{nino3}) / \text{var}(\text{nino3 pres})$	period (years)	decay (year^{-1})
CCSM(pres)	1.00	3.27	0.55
CCSM(8.5ka)	0.81	3.78	0.56
LOAM(pres)	1.00	2.15	0.70
LOAM(8.5ka)	0.79	2.92	0.74

LOAM captures the increase in the period of the ENSO, and (not shown) the structural changes seen in the early Holocene CCSM simulation.

Is the ocean important?

The ENSO Mode

	var(nino3) / var(nino3 pres)	period (years)	decay (year ⁻¹)
LOAM(pres)	1.00	2.15	0.70
LOAM(8.5ka)	0.79	2.92	0.74
LOAM(pres) + ocn	1.35	2.87	0.81

Yes. Changes in the ocean mean states along *enhance* the variance of ENSO (stronger currents, SST gradients, upwelling)

Is the atmosphere important?

The ENSO Mode			
	$\text{var}(\text{nino3}) / \text{var}(\text{nino3 pres})$	period (years)	decay (year^{-1})
LOAM(pres)	1.00	2.15	0.70
LOAM(8.5ka)	0.79	2.92	0.74
LOAM(pres) + atm	0.51	2.27	0.63
LOAM(pres) + T_{atm}	0.49	2.30	0.62
LOAM(pres) + u_{atm}	1.12	2.11	0.71

Yes. Colder mean state SST renders the atmosphere less responsive to SST anomalies (reduced Bjerknes feedback).

ENSO in the mid Holocene (in the CCSM): a summary

- LOAM with CCSM1.4 mean states captures the CCSM1.4 ENSO characteristics
- ENSO is reduced in mid Holocene mainly because the ENSO mode is more stable:
 - Lower climatological SST renders the atmosphere less responsive to SST anomalies (reduced Bjerkness feedback)
 - Ocean mean state changes lengthen the period of the mode and shift its peak to the east Pacific
- No change in the amplitude of stochastic forcing is necessary to explain the reduction in ENSO variance

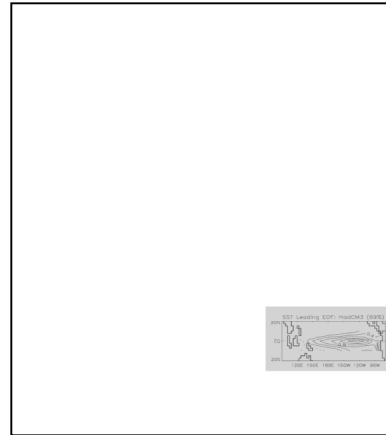
Why is ENSO reduced in the mid Holocene in other models?

Model	Reduction	Hypothesis	Actual Reason
FOAM (Liu et al 2000)	20%	Increase stability of ENSO mode due to weakened thermocline	Unknown; poor ENSO physics in control
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 <i>instability</i> in the ENSO mode due to enhanced Trades and & changed seasonality	Numerical inconsistencies; ENSO mode is actually more unstable (Roberts 2007)
CCSM1.4 (Otto-Bliesner et al 2003)	20%	Ditto	Increase stability of ENSO mode due to stabilized atmosphere (Battisti et al 2008)
HADCM3 (Brown et al 2006)	12%	Ditto	Increase stability of ENSO mode due to weaker thermocline (Battisti et al 2008)

ENSO in the Last Glacial Maximum (in the CCSM): a summary

- Observations suggest the variance in ENSO was enhanced by ~25% or more compared to that in the present day (Tudhope et al 2001)
- In the CCSM, ENSO variance increases by 14%
- LOAM with mean states from the LGM CCSM reproduces the changes in the stability and temporal and spatial structure of ENSO seen in the CCSM
- ENSO variance is enhanced in the LGM compared because the ENSO mode is less stable:
 - Lower climatological SST renders the atmosphere less responsive to SST anomalies (reduced Bjerkness feedback), but ...
 - The ENSO mode is much less stable because of changes in the mean state of the ocean (sharper and shallower thermocline)
 - (There is no change in the amplitude of stochastic forcing)

4. ENSO in the future: the impact of Global Warming



Only one model used in the last IPCC assessment simulated ENSO variability that did not violate the robust observational constraints.

First EOF of tropical Pacific SST (all AR4 IPCC models) Models w/ realistic ENSO space/time variability

Collins et al. 2005

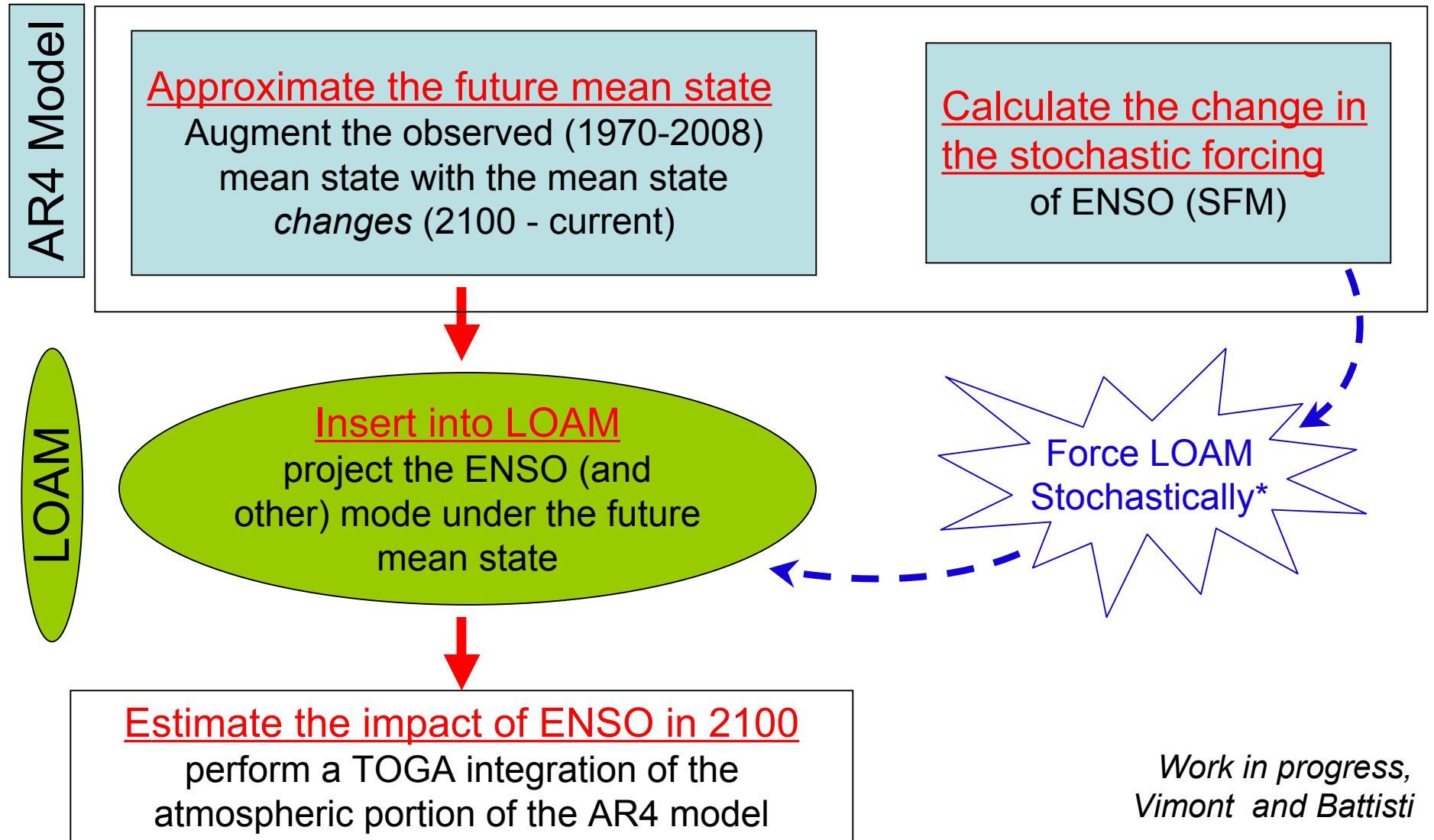
Why? The leading candidate is unrealistic mean states in the tropical Pacific:

- ENSO is extremely sensitive to subtle changes in the structure of the climatology (Zebiak 1987 ... Neelin et al 1988 ... Fedorov and Philander 2001 ...)
- inadequate representation of the processes acting in the ENSO mode (e.g., ocean mixing; atmospheric convection; horizontal resolution)

Little progress after two decades of working on the models.

4. ENSO in the future: the impact of Global Warming

A pathway forward: living with biases in the tropical Pacific climatology



5. Summary

- ENSO is the leading pattern of interannual climate variability:
 - due to coupling between atmosphere & ocean in the tropical Pacific;
 - atmosphere and ocean teleconnections broadcast climate anomalies on a global scale;
- The theory of ENSO is well established:
 - ENSO is the leading eigenmode of coupled atmos/ocean system in the tropical Pacific; features Bjerknes Feedbacks and basin scale dynamical adjustment of the ocean
- The ENSO mode is consistent with the ‘robust observations’:
 - 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.
 - Theory is also consistent with weak (no) ENSO-like variability in the Atlantic (Indian) Ocean basins.

5. Summary

- ENSO theory/mode suggests ENSO is predicable up to two years in advance
 - provided the foundation for designing the observing system that is now in place to initialize the the forecast models.
- The amplitude, spatial and temporal structure of ENSO is highly dependant on:
 - The mean state of the tropical Pacific
 - The structure and amplitude of the noise forcing
- The Linear Atmosphere/Ocean model is an effective tool for evaluating the physics of ENSO
 - In the modern day climate
 - In kitchen sink climate models

5. Summary

- The amplitude of ENSO was greatly reduced in the mid Holocene. Why?
 - Several climate models reduce ENSO, and analysis using LOAM shows that they do so for different reasons
- We don't yet know how ENSO (or its teleconnected impacts) will change in the future due to greenhouse warming
 - only one IPCC-class model has a realistic ENSO due to biases in the climatological mean state
- Combining the future mean states projected by the AR4 models with the linearized atmosphere/ocean model (LOAM) is a plausible way forward