Decadal and Centennial ENSO Variability via Lag-Correlation Analysis

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Abstract

The behavior of the El Niño/Southern Oscillation (ENSO) is complex; even over the dozen or so events captured by modern observations each appears slightly different in cause and development. Extended reconstructions of the observational record extend perhaps 150 years. Paleoproxies have also been used to study ENSO variability over the past two millennia. All of these records agree that ENSO amplitude, period, and mechanism varies over decadal to centennial timescales.

Recent improvements in atmospheric convection in the Community Climate System Model (CCSM) yield substantial improvement in the simulation of the modern ENSO, and importantly for this study provide intriguing decadal to centennial variability. The CCSM improvements altered the modeled ENSO from a simple delayed oscillator toward a quasi-stochastic system involving both atmospheric and oceanic feedbacks; now the ENSO dynamics exhibit a range of behavior even within a single long model run. Preliminary results indicate an important role for pre-existing conditions in the eastern Pacific on amplifying El Niño events, also unexpected correlations are seen between zonal wind/thermocline depth anomalies and variations in NINO3 index. Results also indicate that these ENSO couplings change dramatically over decadal and centennial timescales within a model run; each century displays a different balance of ENSO mechanisms. Changing wind and thermocline depth (z_{th}) forcing appears to be key to ENSO variability on decadal timescales.

Overall Lag-Correlations

Lagged correlations between NINO3 index and (left) thermocline depth in the eastern equatorial Pacific and (right) zonal wind in the off-equatorial Pacific are shown in Figure 2. **NINO3/z_{th} are negatively correlated at -4 months: a shallower-than-normal thermocline precedes an El Niño, and a deeper-than-normal thermocline precedes a La Niña.** We believe this represents an enhancement of the seasonal signal, connected with ENSO's seasonal phase locking.

Positive NINO3/z_{th} correlation is seen at -12-15 months, consistent with the recharge-discharge oscillator model. **Pre-existing thermocline depth anomalies a year before El Niño lead to stronger events than would otherwise occur!**

In order to see significant NINO3/wind correlations, you must look off the equator. **The spatial structure of wind forcing is crucial to ENSO variability.**

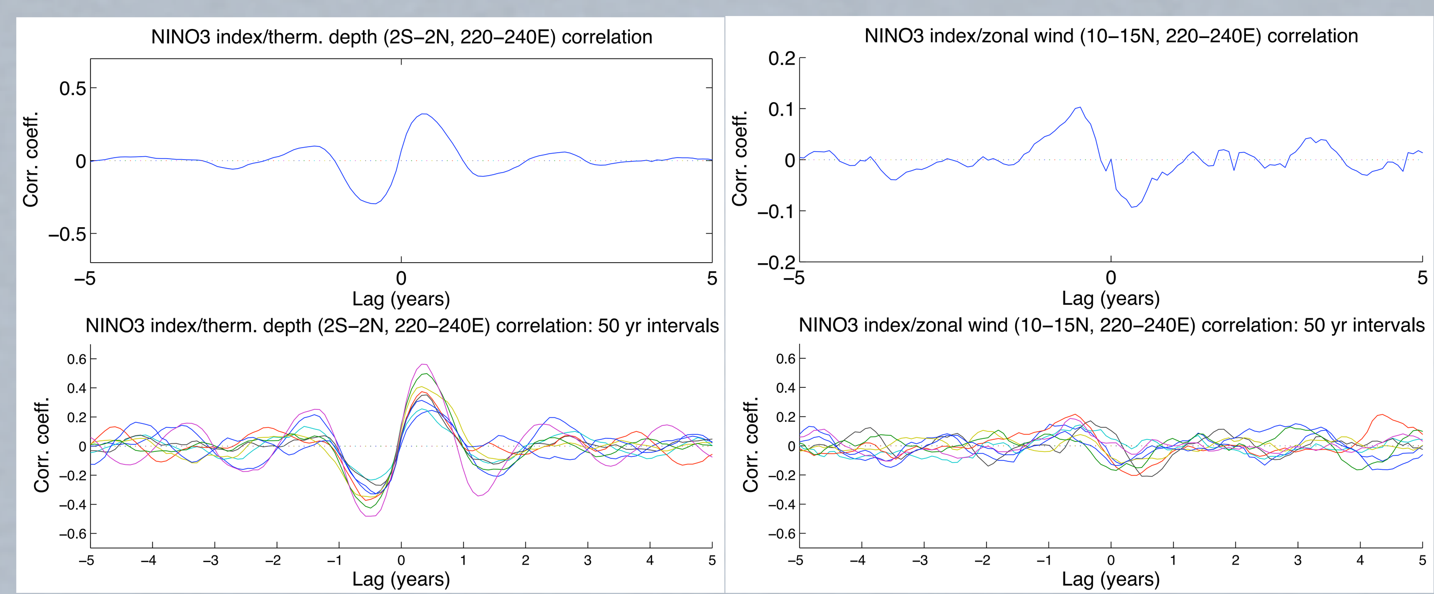

Figure 2. Lag-correlation plots for NINO3 index and eastern Pacific thermocline depth (left) and mean zonal wind (right) anomalies from 10yr running mean climatology. Negative lag values indicate wind/thermocline depth leading NINO3 index.

Model Validation

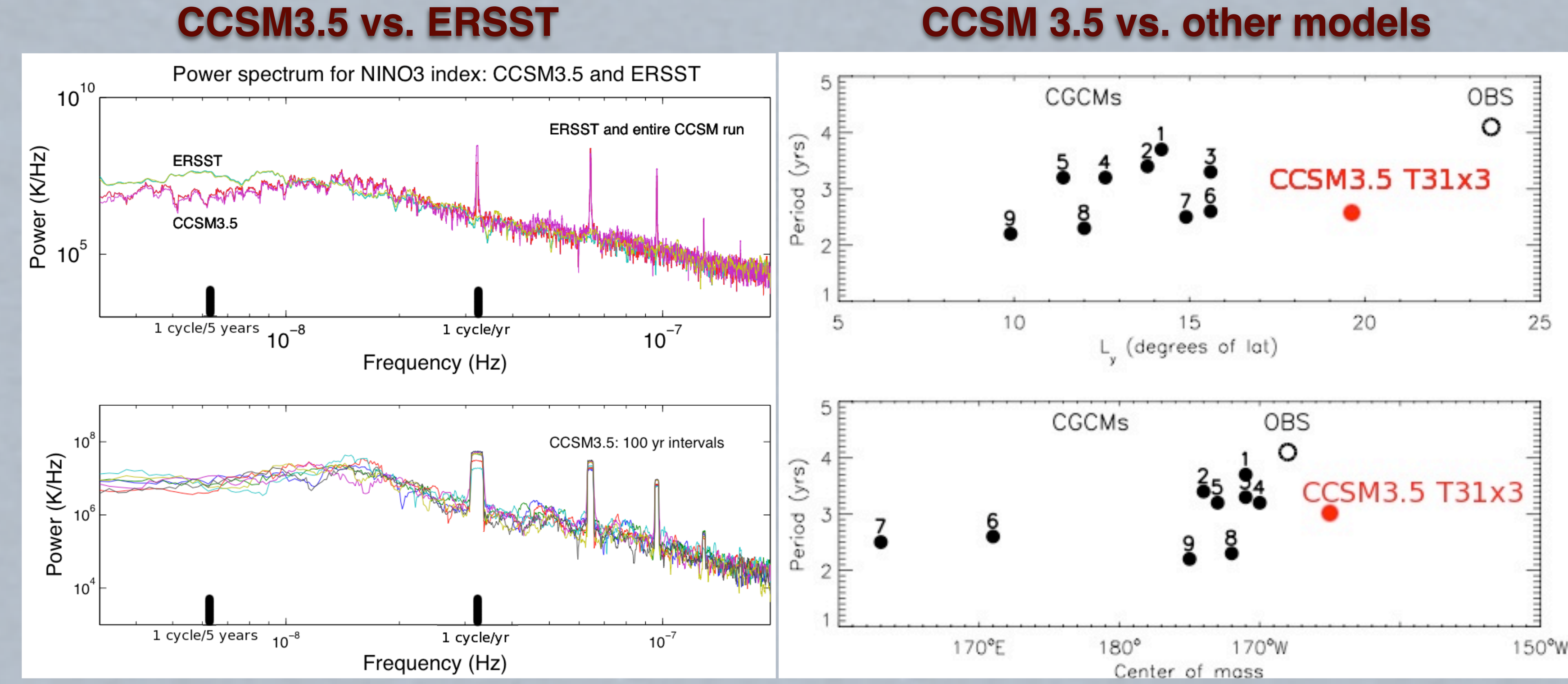

Figure 1: CCSM model validation. Left: Power spectra for the NINO3 index generated by the CCSM, and for the NINO3 index computed from NOAA's Extended Reconstructed SST (ERSST) dataset. Right: Diagnostics of wind stress meridional extent and wind center of mass from Capotondi et al. (2006). Red circle indicates the position of the coarse-resolution (T31x3) CCSM3.5 (other models shown are 1=UKMO-HadCM3, 2=PCM, 3=GISS-EH, 4=CNRM-CM3, 5=CSIRO-Mk3.0, 6=MRI-CGCM2.3.2, 7=GFDL-CM2.0, 8=IPSL-CM4, and 9=CCSM3).

The overall power spectrum of the NINO3 index in CCSM3.5 is globally similar to observations: Figure 1, left, taken from NOAA's Extended Reconstructed SST (ERSST) dataset. However, **CCSM3.5 and ERSST differ at low (decadal) frequencies, comparable to the internal variability in 50-year chunks of the same model run! Is this due to model error, or real ENSO variability??**

Capotondi et al. (2006) have laid out several diagnostics, designed to assess the IPCC-AR4 models (Figure 1, right). CCSM3.5 appears in red on all plots. Here the period of ENSO variability is compared to the meridional extent of wind stress regressed onto the NINO3.4 index and the "center of mass" of this quantity. These relate ENSO variability to the location of forcing.

CCSM3.5 equals or outperforms all of the AR4 models, despite its relatively low resolution. Most notable is the position of CCSM3.5 relative to CCSM3 (#9 on the figure). Although ENSO variability remains somewhat too frequent in CCSM3.5, its position is much improved, and is close to matching observations.

Periods of Interest

We have chosen two representative 50-year intervals in the 700-year CCSM3.5 run analyzed: P_HI and P_LO, so named for their NINO3 variances. Dynamics are vastly different in P_HI and P_LO!

	Years	σ_{NINO3} (C^2)	Δz_{th} (m)	Mean z_{th} (m)	u (m/s)	σ_u (m^2/s^2)
P_LO	350-399	0.534	91.58	95.82	-14.64	0.517
P_HI	600-649	1.041	93.36	97.51	-14.86	0.528

Decadal Variability

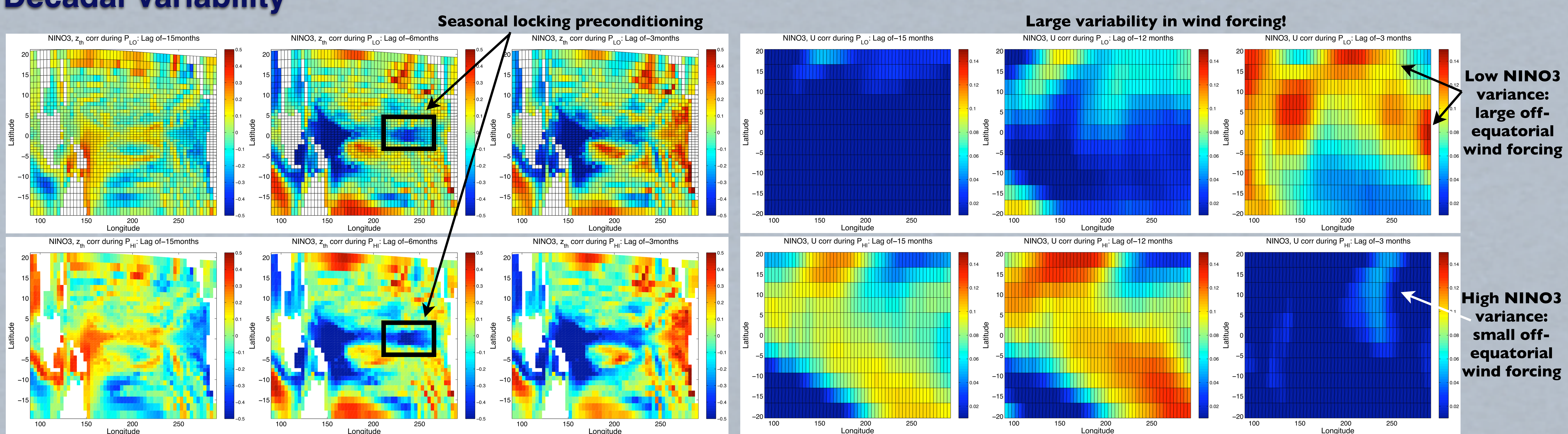

Figure 3: Left: Lag correlation of NINO3 index and thermocline depth anomalies from 10yr running mean climatology, shown at lag intervals of -15months (left), -6 months (center) and -3 months (right). Top row: maps for model years 351-401 (P LO; low NINO3 variance). Bottom row: maps for model years 601-651 (P HI; high NINO3 variance). Negative lag times indicate thermocline depth leading; negative correlation implies a deeper thermocline preceding an El Niño. .
Right: Lag correlation of NINO3 index and zonal wind, shown at lag intervals of -15 months (left), -12 months (center), and -3 months (right). Top row: maps for P LO. Bottom row: maps for P HI. Negative lag times indicate wind leading; positive correlation implies a more westerly wind preceding an El Niño.

For P_HI (lower left panels of Figure 3), NINO3/thermocline depth are negatively correlated in the eastern Pacific at -6 months. This is stronger during P_HI than P_LO, suggesting that **seasonal locking preconditioning is more important when El Niño is more frequent.** The earlier preconditioning, (-15 months) extends across most of the Pacific. This **recharge-oscillator-like preconditioning is stronger in P HI than in P LO.**

During P_LO, NINO3/wind are highly correlated at short lead times (-6 to -3 months) north of the equator. In contrast, during P_HI, the correlation occurs much earlier (-15 to -12 months lead) and is centered about the equator. We speculate that when NINO3 variance is large, wind plays a role in generating large SST anomalies only at large lead times; thermocline wave propagation then takes over and carries on through the event.

Conclusions & Future Work

Using preliminary 700-year CCSM runs with the updated convection scheme of Neale et al. (2008), we have shown that there is significant decadal variability; 50-year segments appear to have drastically different properties, even under the same mean thermocline and wind conditions. Not only does NINO3 variance change significantly throughout the model run, but **the atmosphere-ocean coupling mechanism for ENSO appears to alter radically on decadal timescales**. Using a simple lag-correlation analysis, we have been able to show that thermocline depth anomalies are highly correlated with the appearance of El Niño events most of the time. Yet, **additional thermocline preconditioning appears to lead to stronger ENSO events within a 50 year period.**

The role of wind stress is more complicated. **Wind stress anomalies are much more highly correlated with NINO3 index during periods where the overall NINO3 variance is weaker; the role of off-equatorial wind forcing also appears to be important during those time periods.**

Clearly, more work remains to detail the precise mechanisms at work in the model. In order to understand the variability one might expect from ENSO over decades–either natural or due to climate change–it is necessary to understand not just a few centuries of simulation, but millennia. Future work will include conducting long simulations under a variety of conditions, and to statistically process the model output to identify the mechanisms underlying distinct dynamical regimes.