ENSO Decadal Variability

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Long climate model simulations show strong decadal modulation of ENSO properties

Nino3 index from GFDL-CM2.1 model

Wittenberg, 2009
GFDL-CM2.1 also shows decadal variations in the dominant pattern of ENSO events. Choi et al. (2011)
Decadal changes in ENSO amplitude are also seen in the observational record

The 1976/77 “climate shift”

ENSO spectral characteristics also changed after 1977 with dominant timescale becoming longer

“Is El Nino Changing?” (Fedorov and Philander, Science, 2000)
Observations also show decadal differences in ENSO spatial pattern

McPhaden et al. 2011
Is El Nino *really* changing?

What causes these decadal variations in ENSO characteristics?

- Do these epochal changes happen by chance?
- Are they due to changes in the tropical climate system dynamics?
- Are they due to changes in the amplitude/pattern of the Stochastic forcing?

Capotondi and Sardeshmukh, 2017
Linear Inverse Modeling approach

\[
dx = L x \, dt + S r \, (dt)^{1/2}
\]

\[
x = [x_1, x_2, \ldots, x_n]
\]

\[
x = [\text{SST}, Z_{15}]
\]

**L** = matrix encapsulating predictable system dynamics

**S** = stochastic forcing amplitude covariance matrix

**r** = random noise vector from N(0,1)

**Predictable dynamics**

**Stochastic dynamics**

Determine **L**

\[
C(\tau) = \exp(L \, \tau) \, C(0)
\]

\[
C(\tau), C(0) \text{ covariance matrices at lags } \tau \text{ and } 0
\]

Determine **S**

\[
L \, C(0) + C(0) \, L = -S \, S^T
\]
Are the apparent changes due to sampling variability?

**Period 1: 1958-1977**

- **LIM1**: L1, G1, S1
  - Run LIM1 for 48,000 yrs = 2400 20-yr segments

**Period 2: 1978-1997**

- **LIM2**: L2, G2, S2
  - Run LIM2 for 48,000 yrs = 2400 20-yr segments

**Compare PDFs of quantities of interest**
Are the differences in the Nino3 amplitude and timescale different?

\[ \mathbf{d} \mathbf{x} = \mathbf{L} \mathbf{x} \, dt + \mathbf{S} \mathbf{r} \,(dt)^{1/2} \]
What about spectra of Nino3?

Spectral power during P2 is outside of the 90% limits of the P1 spectrum.

Except for its low- and high-frequency tails, the P1 spectrum is within the 90% limits of the P2 spectrum.

The period with the largest variance seem to also include some of the statistics of the period with weaker variance.
Where has the SST variance significantly changed?
SST variance differences between P1 and P2 are statistically significant (90% level) in large parts of the domain.
Thermocline depth variance also shows statistical significant differences between P1 and P2.

**Dotted areas**: P2 variance significantly larger than P1 variance

**Hatched areas**: P1 variance significantly larger than P2 variance
Changes in ENSO appear to be significant

What has caused this change?
If changes in some El Nino properties are significant, were they associated with changes in dynamics?

\[ \text{Has } L \text{ changed?} \]

\[ dx = L x \, dt + S \, r \, (dt)^{1/2} \]

\[ x(\tau) = \exp(L \, \tau) \, x(0) = G(\tau) \, x(0) \]

Use initial and final optimal structures as integral measures of \( L \).
How do the initial and final optimal structures look like?
Are the initial and final states between the two periods significantly different?

The pattern correlation between the initial and final fields in P1 and P2 are in the low 10th percentile of the correlations obtained with LIM1

...but a little above the 10th percentile of the correlations obtained with LIM2
Has the amplitude/pattern of stochastic forcing changed?

Examine leading eigenvectors of stochastic forcing variance ($SS^T$) in the two periods.

- **Period 1**
- **Period 2**

Leading eigenvector of stochastic forcing variance did not change significantly.
What determines these changes in dynamics?

Changes in background conditions can control ENSO stability characteristics.

- Period
- Growth rate
- Minimum S in the East (zonal SST gradient)
- Mean thermocline depth

Fedorov and Philander, 2000
What causes the changes in background conditions?

1. **Sampling**: An epoch with more El Nino events will have a more El Nino-like mean state

2. **Amplitude rectification**. Since El Nino events are overall stronger than La Nina events, epochs with enhanced ENSO variability will be more El Nino like

3. **Spatial pattern rectification** (Choi et al. 2011, McPhaden et al. 2011)
Subtropical-Tropical Cells can influence the tropical ocean at decadal timescales

Decrease in interior flux convergence during 1950-2000 was associated with low-frequency equatorial (9°S-9°N) SST increase

McPhaden and Zhang 2002
Origin of cross-eq. wind strengthening: remote component

Trend in SST (degC/decade) & Surface Wind (m/s/decade) Anomaly

Courtesy of Dr. Shineng Hu
Is El Nino really changing?
Using a Linear Inverse Model to assess statistical significance we have shown that there were significant changes from 1958-1977 to 1978-1997. These changes were due to changes in ENSO dynamics.

What causes the changes in dynamics?
Changes in dynamics can be expected to be associated to changes in the mean state.

What causes the changes in background conditions?
Nonlinear rectification, climate change, influences from regions outside the tropical Pacific.
The relative contribution of these various processes and their influence on predictability remains a big open question.
Sensitivity patterns do not resemble the mature ENSO pattern at shorter lags. Correlations with SST$^C$ and SSH$^C$ increase.

- $\tau = 9$ months
- $\tau = 6$ months
- $\tau = 3$ months

Monthly standard deviation
Are the differences in the Nino3 amplitude and timescale different?

\[ dv_1 = 0.59 \]
\[ dv_2 = 0.91 \]

\[ d\mathbf{x} = L \mathbf{x} \, dt + S \mathbf{r} \, (dt)^{1/2} \]
**Linear Inverse Modeling approach**

\[
\begin{align*}
\mathbf{d} \mathbf{x} &= \mathbf{L} \mathbf{x} \, dt + \mathbf{S} \mathbf{r} \,(dt)^{1/2} \\
\mathbf{x} &= [x_1, x_2, \ldots, x_n] \\
\mathbf{x} &= [\text{SST, Z}_{15}] \\
\mathbf{L} &= \tau_o^{-1} \log [\mathbf{C}(\tau_o) \, \mathbf{C}(0)^{-1}] \\
\mathbf{x} &= \text{14-components state vector of 10 SST (78%), and 4 Z15 (40.5%) PCs} \\
\mathbf{L} &= \text{matrix encapsulating predictable system dynamics} \\
\mathbf{S} &= \text{stochastic forcing amplitude covariance matrix} \\
\mathbf{r} &= \text{random noise vector from } \mathcal{N}(0,1)
\end{align*}
\]
Are the differences in the Nino3 amplitude and timescale different?

\[ \text{var} = 0.61 \quad \text{var} = 0.83 \]

\[ \text{dx} = L \text{x dt} + S r (\text{dt})^{1/2} \]
Spatial Pattern Rectification: Mean changes are similar to El Nino changes

Differences between (2000-2010) and 1980-1999

McPhaden et al. 2011
Processes originating from the extra-equatorial Pacific can alter the equatorial Pacific mean state.

Temperature standard deviation at 200m **1958-1997**

Waves propagate westward in the northern tropics, southward along the western boundary to the Equator, producing a low-frequency thermocline depth change.

Capotondi and Alexander 2001
Subtropical-Tropical Cells can also impact interannual timescales and produce a decadal modulation of equatorward transport.

Capotondi, Alexander, Deser and McPhaden 2005
Initial states associated with the maximum growth are the right singular vector of $G$. These singular vectors provide an integral measure of the dynamical operators.