Rectification of El Nino-Southern Oscillation as a possible cause for The Tropical Pacific Decadal Variability

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TPDV and Level of ENSO Activity
employed to determine

the time-mean (or rectified) effect of

ENSO

• Compare the equilibrium state of the coupled tropical ocean-atmosphere system with the time-mean state of the system, though the use of a box model whose unstable equilibrium state can be analytically obtained (Liang et al. 2012, J. Climate, 25, 7590-7606)

• Force an Ocean GCM using surface forcing with and without ENSO fluctuations (Sun et al. 2013, J. Climate, Accepted)

• Analysis of a 2000 yr-long-run by GFDL CM2.1 (Ogata et al. 2013, J. Climate, Accepted).
Forced Ocean GCM Experiments with and without ENSO in the Surface Forcing

- The long-term mean winds are identical for A and B, but A has interannual variations and B does not.

- The thermal BCs for A and B are identical—both are restored to a prescribed potential SST
ENSO in the model and observations
ENSO in the model and observations

Observation
(a) Warm Phase

(b) Cold Phase

(c) Warm Phase + Cold Phase

Model
(a) Warm Phase

(b) Cold Phase

(c) Warm Phase + Cold Phase
ENSO in the model and observations
Upper T Difference Between Experiments with/without ENSO

Time mean (1950–2011) upper ocean temperature differences fluctuating wind runs – fixed wind runs

Longitude

Depth (m)

°C

-1.25 -1 -0.75 -0.5 -0.25 -0.1 0.1 0.25 0.5 0.75 1 1.25
The rectified effect of ENSO in the Upper Ocean T:
Sensitivity to the variance of ENSO

\[ \tau' \]

\[ 1.5\tau' \]
The Rectified Effect of ENSO on the SST: Sensitivity to the variance of ENSO

\[ \tau' \quad 1.5\tau' \]

62 yrs (1950–2011) time mean results (fluctuating wind minus fixed wind)
Difference in convergence of $\overline{V'T'}$

(with ENSO minus without ENSO)

NDH DIFF with ENSO – without ENSO 1950–2011
Difference in convergence of $\overline{V'T'}$

(with ENSO minus without ENSO)

NDH DIFF with ENSO - without ENSO 1950-2011
Key Results
From Forced Ocean GCM Experiments

• The rectified effect of ENSO events is to cool the warm-pool water, warm the subsurface equatorial thermocline water, and the surface water in the broad region of eastern Pacific. The overall structure indicates a diffusive effect that stabilizes the coupled system, but the stabilizing effect has regional differences. The reduction of the stratification in the central Pacific is accompanied by an increase in stratification in the central Pacific.

• The spatial pattern of the rectified effect of ENSO events in the eastern Pacific resembles the decadal warming in the tropical Pacific.

• The rectified effect of ENSO events increases with increases in the level of ENSO activity.

• The rectified effect of ENSO is linked to nonlinear advection (convergence of $\mathbf{V}'T'$).
Rectified effect of ENSO inferred from decadal variability in GFDL CM2.1
Future Work Planned

- Examine whether the rectification of ENSO is a significant contributor to the TPDV in CESM.

- Examine what are the causes for the decadal variability in the level of ENSO activity, in particular whether a self sustained TPDV and decadal variability in the level of ENSO activity can be maintained through the interaction between the time-mean effect of ENSO and its decadal background state.
A Hypothesis For TPDV and Decadal Modulation of ENSO

- High Level of ENSO Activity
  - Stabilization from ENSO rectification exceeds background destabilization
- Low Level of ENSO Activity
- Background destabilization retakes prominence
  - High Level of ENSO Activity
TPDV and Level of ENSO Activity in GFDL CM2.1

Decadal Variation in the STD of Nino3 SST

Decadal Variation in the Mean State (TPDV)

Spatial Pattern of TPDV in CM2.1

(sst, EOF2 (15%))
Other terms used for the rectification of El Nino-Southern Oscillation

The use of word “rectification” follows the study of Kessler and Kleeman (2000) in which they argued that an ENSO anomaly can be created by an integral effect of MJO.


The basic premise: Averaged on the decadal and longer time-scales, the effect of ENSO events does not cancel out, but is finite. Moreover, the greater the level of ENSO activity over the considered period, the greater this effect integrated over this period.
Why are we interested in the time-mean effect of El Nino--Southern Oscillation

Viewed on a decadal and longer time-scales, ENSO events are transients just as weather events viewed on the time-scale of a year or longer. We are interested in the time-mean effect of ENSO events for the same reason as we were interested in the time-mean effect of weather events. 

Do ENSO events collectively play a role in maintaining the climatological state of the tropical Pacific, and if so, what is this role?
A Conceptual Picture for the Time-Mean Effect of ENSO: A Heat Mixer

- **Tw**: Warm-pool water
- **Tc**: Thermocline water
Equilibrium State, Time-Mean State and the level of transient activities

The System: \[ \frac{dA}{dt} = f(A, \lambda) \] (1)

Equilibrium State: \[ f(A_0, \lambda) = 0 \] (2)

Time Mean State: \[ f(\bar{A} + A', \lambda) = 0 \] (3)

\[ f(A_0, \lambda) + \frac{\partial f}{\partial A}(\bar{A} + A' - A_0) + \frac{\partial^2 f}{\partial^2 A}(\bar{A} + A' - A_0)^2 + ... = 0 \] (4)

When \( f(A, \lambda) \) is nonlinear and \( A'^2 \neq 0, \bar{A} \neq A_0 \) (5)

Time-mean effect: \[ \bar{A} - A_0 = F(\bar{A'}^2) \] (6)
A Box Model for the ENSO System

\[ \frac{dT_1}{dt} = c(T_e - T_1) + sq(T_2 - T_1) \]

\[ \frac{dT_2}{dt} = c(T_e - T_2) + q(T_{sub} - T_2) \]

\[ q = \frac{\alpha}{\alpha} (T_1 - T_2) \]

\[ T_{sub} = \Phi(-H_1 + h'_2) \]

\[ \Phi(z) = T_e - \frac{T_e - T_b}{2} (1 - \tanh(z + z_0)) \]

\[ h'_2 - h'_1 = -\frac{H_1}{H_2} H \frac{\alpha}{b^2} (T_1 - T_2) \]

\[ \frac{1}{r} \frac{dh'_1}{dt} = -h'_1 + \frac{H_1}{2H_2} H \frac{\alpha}{b^2} (T_1 - T_2) \]

Jin 1996, Sun 1997
TPDV and Level of ENSO Activity in observations
TPDV and Level of ENSO Activity in observations
Tropical Pacific SST as a Function of Radiative Heating

\[ T_e - T_b \text{ (° C)} \]

Equilibrium SST

Time-Mean SST

--- Equilibrium SST

--- Time-Mean SST

Pitch-fork bifurcation

Hopf bifurcation

\[ T_e \text{ (° C)} \]

\[ SST \text{ (° C)} \]
Asymmetry in the Oscillation

![Graphs showing oscillations in temperature and height.](image)
In the strongly forced regime, El Nino event may be viewed as an episodic “flooding” event of the eastern Pacific region—a region that is otherwise cold (when instability does not take place)—by warm water in the western Pacific. In this conceptual picture of ENSO, La Nina is more an artifact from the way we define what is normal than a real physical phenomenon.
Implication for the causes of the tropical Pacific decadal variability

Forced by an elevated ENSO activity?
Implication for Understanding Climate Response to The Rise of CO2 Concentration

Existing Paradigm:

A Revised Paradigm:
Why no trend has shown up in the zonal SST contrast in the observations?

Vecchi et al. 2008
The Excessive Cold-tongue

SST climatology (degree)
The Excessive Cold-tongue
Tropical Pacific Climate as a Function of $T_e$.

--- Equilibrium SST
__ Time-Mean SST

Amplitude of ENSO
Key Results from the Box Model

- The time-mean SST in the eastern equatorial Pacific is found to be significantly different from the corresponding equilibrium SST, with the former being warmer than the latter. The difference is found to be proportional to the amplitude of ENSO.

- The zonal SST contrast of the time-mean state is found to be less sensitive to increases in external forcing than that of the equilibrium state, due to warming effect of ENSO events on the eastern Pacific.

- This rectification effect of ENSO events owns to the nonlinear advection term in the heat budget equation.

- The asymmetry of the oscillation relative to the time-mean state stems fundamentally from the asymmetry of the dynamics relative to the equilibrium state of the system.

- In the strongly forced regime, El Nino event may be viewed as an episodic “flooding” event of the eastern Pacific region—a region that is otherwise cold (when instability does not take place)—by warm water in the western Pacific. In this conceptual picture of ENSO, La Nina is more an artifact than a real physical phenomenon.
Difference in convergence of $\overline{V'T'}$

(with ENSO minus without ENSO)
Difference in convergence of $\overline{V'T'}$

(with ENSO minus without ENSO)

NDH DIFF with ENSO - without ENSO 1950-2011
**Implications**

- The decadal warming in the recent decades in the eastern tropical Pacific may be more a consequence than a cause of the elevated ENSO activity during the same period.

- The lack of a significant long-term trend in the zonal SST contrast may be due to the feedback from ENSO events due to the time-mean effect.
Tropical Pacific SST as a Function of Radiative Heating

\[ T_e - T_b \ (° \ C) \]

--- Equilibrium SST
--- Time-Mean SST

Pitch-fork bifurcation
Hopf bifurcation

25 26 27 28 29 30 31 32 33 34

24 25 26 27 28 29 30 31 32 33 34

T_e (° C)

--- Nonlinear

\[ T_e \ (° \ C) \]
Upper T Difference Between Experiments with/without ENSO

50 yrs time mean results: fluctuating wind (tau\textsubscript{xc} + 1.5tau\textsubscript{xano}) minus fixed wind

The upper ocean temperature differences in the time mean
SST Difference Between Experiments with/without ENSO
The Effects of ENSO on the SST: Sensitivity to the amplitude of ENSO

$\tau'$

$1.5 \tau'$
Upper T Difference Between Experiments with/without ENSO

\[ \tau' \]

Time mean (1950–2011) upper ocean temperature differences
fluctuating wind runs – fixed wind runs

[Diagram showing temperature differences in depth and longitude]

\[ 1.5\tau' \]

50 yrs time mean results: fluctuating wind (\tau\text{vec} + 1.5\tau\text{ovena}) minus fixed wind
The upper ocean temperature differences in the time mean

[Diagram showing temperature differences in depth and longitude]
References


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SST Difference Between Experiments with/without ENSO
Tsub, q, h1, and h2 as a function of $T_e$. 

\[ s = \frac{1}{3} \]

(a) 

- **Tsub (°C)**
  - Time mean solution
  - Equilibrium solution

(b) 

- **q (s^-1)**
  - Time mean solution
  - Equilibrium solution

(c) 

- **h2 (m)**
  - Time mean solution
  - Equilibrium solution

(d) 

- **h1 (m)**
  - Time mean solution
  - Equilibrium solution
An Increase in Te Leads to Greater Asymmetry in the Oscillation
Tropical Pacific Climate as a function of $T_e$

Equilibrium and Time-Mean SST

$$\Phi(z) = T_{s0} + \gamma(z + H_1)$$

$$T_{sub} = T_{s0} + \gamma h_2$$

Amplitude of ENSO
ENSO In the Forced Experiment
Who Drives Who in Decadal Changes in Tropical Pacific in GCMs?

Decadal Variation in the STD of Nino3 SST

Decadal Variation in the Mean State
Tropical Pacific Climate as a Function of $T_e$
Sensitivity to Parameter $S$
The Heating From ENSO Events
(convergence of $\overline{V'T'}$)

NDH (5S–5N), 50–99 mean (C/month)
fluctuating wind run

Depth (m)

120E 140E 160E 180 160W 140W 120W 100W 80W
The Heating From ENSO Events (convergence of \( \overline{VT'} \))
Upper T Difference Between Experiments with/without ENSO

From An IAP Model--LICOM2.0 (Hua et al. 2013)
SST Difference Between Experiments with/without ENSO

From An IAP Model--LICOM2.0 (Hua et al. 2013)
Upper T Difference Between Experiments with/without ENSO

From A GFDL Model—MOM3 (Ogata et al. 2013)
Upper T Difference Between Experiments with/without ENSO

50 yrs time mean results: fluctuating wind \( (\text{tauxc}+1.5\text{tauxano}) \) minus fixed wind

The upper ocean temperature differences in the time mean
Response of the equatorial ocean temperature to tropical heating

Without ENSO

With ENSO

Response in the upper ocean temperature to extratropical cooling

Without ENSO

With ENSO
Why are we interested in the time-mean effect of El Nino-Southern Oscillation

Viewed on a decadal and longer time-sales, ENSO events are transients just as weather events viewed on the time-scale of a year or longer. We are interested in the time-mean effect of ENSO events for the same reason as we were interested in the time-mean effect of weather events.

*Do ENSO events play a role in maintaining the climatological state of the tropical Pacific, and if so, what is this role?*
Feedback from ENSO onto the mean state

Response of Tw-Tc with and without ENSO

From Tropical Heating Experiments

<table>
<thead>
<tr>
<th>perturbation type</th>
<th>experiment type</th>
<th>change of $T_w$ (°C)</th>
<th>change of $T_c$ (°C)</th>
<th>change of $T_w-T_c$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair I (5°S-5°N)</td>
<td>No ENSO</td>
<td>1.03</td>
<td>0.0050</td>
<td>1.02</td>
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<tr>
<td></td>
<td>With ENSO</td>
<td>0.81</td>
<td>0.76</td>
<td>0.053</td>
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<td>Pair II (10°S-10°N)</td>
<td>No ENSO</td>
<td>1.38</td>
<td>0.036</td>
<td>1.34</td>
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<td></td>
<td>With ENSO</td>
<td>0.97</td>
<td>0.83</td>
<td>0.14</td>
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<tr>
<td>Pair III (15°S-15°N)</td>
<td>No ENSO</td>
<td>0.95</td>
<td>0.24</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>With ENSO</td>
<td>0.55</td>
<td>0.63</td>
<td>-0.085</td>
</tr>
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</table>

Underestimate ENSO Asymmetry in CMIP5 Models
Underestimate ENSO Asymmetry in CMIP5 Models
Who Drives Who in Decadal Changes in Tropical Pacific in GCMs?

Decadal Variation in the STD of Nino3 SST

Decadal Variation in the Mean State
ENSO Asymmetry in IPCC AR4 Models

Niño3 Index Skewness

Probability Density Function

Skewness of Niño3 SSTA 1950-1999 (°C²)

OBS

Model Mean

Mean

-0.6

0.44

0.88
Variations in the Level of ENSO activity in the IPCC AR4 Models

Normalized Running Variance

Normalized Running Variance

The profile for the reference subsurface temperature
ENSO In the Forced Experiment