ENSO modes-annual cycle interaction and ENSO complexity

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ENSO/El Niño complexity

- Diverse patterns

  ![Selected Events](image1.png)

  Capotondi et al. 2015

- Complex frequencies

  ![PSD of Nino](image2.png)

  Rich combination tones

  \[ f_1 \approx 0.25 \]
  \[ f_2 \approx 0.4 \]
  \[ f_1 + f_2 \approx 0.65 \]
  \[ 1+f_1 \approx 0.75 \]
  \[ 1+2f_2 \approx 1.75 \]
  \[ 1+f_0 \approx 1.1 \]
  \[ 1+f_1 \approx 1.25 \]
  \[ 2-f_0 \approx 1.9 \]
### Genesis of El Niño complexity

#### 1. Induced by westerly winds events (WWEs)

<table>
<thead>
<tr>
<th><strong>1) different strength and propagation of WWEs</strong></th>
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<tbody>
<tr>
<td><strong>strong &amp; cross-dateline WWEs</strong></td>
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<tr>
<td>→ EP El Niño</td>
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<tr>
<td><strong>weak &amp; western Pac. confined WWEs</strong></td>
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<tr>
<td>→ CP El Niño</td>
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**SSTA and WWEs**

#### 2) WWEs interaction with initial thermocline state

<table>
<thead>
<tr>
<th><strong>WWEs + recharged thermocline state</strong></th>
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<tbody>
<tr>
<td>→ EP El Niño</td>
</tr>
<tr>
<td><strong>WWEs + near neutral thermocline state</strong></td>
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<tr>
<td>→ CP El Niño</td>
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</tbody>
</table>

**WWEs-initial ocean state interaction**

- **WWEs + neutral**
- **WWEs + recharged**

**See also** Lengaigne et al. 2004; Fedorov et al. 2015; Hu et al. 2014; Chen et al. 2015; Hayashi and Watanabe 2017

**Lian et al. 2014**

**Fedorov et al. 2015**

**See also** Lengaigne et al. 2004; Hu et al. 2014
2. **our theory**: Induced by two co-existent ENSO modes

**EP** and **CP** ENSO-like oscillatory modes **coexist** in:

1) intermediate ENSO model (such as Zebiak-Cane-type model)
   
   Bejarano and Jin 2008; Xie and Jin 2018; also in Fedorov and Philander 2000, 2001

2) observations (re-analysis data)
   
   Newman et al. 2011; Vimont et al. 2014; Capotondi and Sardeshmukh 2015;

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**Mature SST A patterns of ENSO modes in ZC model and observations**

**EP/4-yr ENSO eigenmode/ZC**

**EP/2-yr ENSO eigenmode/ZC**

**Shadings: SST A**

**EP ENSO eigenmode/LIM. Obs**

**CP ENSO eigenmode/LIM. Obs**

**Vimont et al. 2014**

**Xie and Jin 2018**
Linear bimodal ENSO theory

EP and CP ENSO-like oscillatory modes are the most outstanding eigensolutions of a modified linear Zebiak-Cane model.

...resembling the two types of ENSO/El Niño in the observation

Linear bimodal ENSO theory

different dependences on mean states

**EP ENSO mode**

**CP ENSO mode**

**EP/4-yr ENSO mode/SSTA**

**CP/2-yr ENSO mode/SSTA**
Linear bimodal ENSO theory

different initial conditions

**EP ENSO mode**

Initial CP warming | **Strong & basin-wide** thermocline deepening (strongly recharged state)

**CP ENSO mode**

Initial CP warming | **weak & CP-confined** thermocline deepening (weakly recharged state)
Linear bimodal ENSO theory

EP/4-yr ENSO mode/SSTA

CP/2-yr ENSO mode/SSTA

different triggering terms

Zonal advective feedback

Thermocline feedback
Linear bimodal ENSO theory

Enhancement of the instability of CP mode increases the occurrence rate of CP El Niño in nonlinear simulations.

Two El Niño clusters in nonlinear simulations

<table>
<thead>
<tr>
<th>EP regime</th>
<th>EP&amp;CP regime</th>
<th>CP dominant regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) EP El Nino cluster</td>
<td>(c) EP El Nino cluster</td>
<td>(e) EP El Nino cluster</td>
</tr>
<tr>
<td>(b) CP El Nino cluster</td>
<td>(d) CP El Nino cluster</td>
<td>(f) CP El Nino cluster</td>
</tr>
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</table>

CP/EP: 0.176
CP/EP: 0.375
CP/EP: 0.52
At the heart of our explanation for the spatial flavors of ENSO is the aforementioned multiplicity of coupled ENSO eigenmodes as seen in an intermediate ENSO model.

Furthermore, the temporal complexity is generated in part by the different oscillation frequencies of the quasi-quadrennial and quasi-biennial modes and additionally by different external excitation processes.
More evidences from nonlinear simulations in ZC model will be shown to bridge the linear theory and the nonlinear phenomenon.

A follow-up study of Xie and Jin (2018):
Interactions of EP, CP ENSO modes and annual cycle in the Zebiak-Cane model with emphases on

1. interaction between EP and CP modes (no annual cycle)
   \[ EP \times CP \]

2. interaction between EP or CP mode and annual cycle
   \[ EP \times AC \quad \text{or} \quad CP \times AC \]

3. interactions of EP, CP modes and annual cycle
   \[ EP \times CP \times AC \]
Nonlinear ENSO bimodal interaction

Model Settings

1. Modified Zebiak-Cane model
   atmospheric model (Xie et al. 2015) + ocean dynamic model (Bejarano 2006; Bejarano and Jin 2008)

2. ENSO regimes (selections of annual mean states and parameters)

![Chart showing instability of two ENSO modes]

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<tbody>
<tr>
<td>mean state and R</td>
<td>H150S100, 1.0</td>
<td>H146S104, 1.0</td>
<td>H142S108, 1.0</td>
<td>H136S104, 1.5</td>
<td>H140S110, 2.0</td>
</tr>
<tr>
<td>growth rate</td>
<td>0.19 : -0.44</td>
<td>0.43 : 0.10</td>
<td>0.38 : 0.91</td>
<td>-0.09 : 1.13</td>
<td>-0.17 : 0.13</td>
</tr>
<tr>
<td>mark</td>
<td>$E^+C^-$</td>
<td>$E^+C^0$</td>
<td>$E^+C^+$</td>
<td>$E^0C^+$</td>
<td>$E^-C^+$</td>
</tr>
<tr>
<td>bimodal interaction</td>
<td>no</td>
<td>weak</td>
<td>strong</td>
<td>weak</td>
<td>no</td>
</tr>
</tbody>
</table>

\[
\frac{\partial T'}{\partial t} = \cdots - R \cdot \alpha_s T'
\]

marks of instability
+ : unstable (>0.1 yr⁻¹)
0 : near neutral ([-0.1~0.1])
- : damped (<-0.1 yr⁻¹)
Nonlinear ENSO bimodal interaction

Model Settings

3. Annual cycle (AC)

\[ F_{AC} = F_{AM} + a \cdot f_{AC} \]

Three types of AC settings:
1) \( a=0 \), no AC case;
2) \( a=1 \), AC case;
3) \( a=0\sim1.5 \), varying AC case

5. Simulation length

10,000 years for each case
... divided into 100×100-yr segments

6. Statistical analysis methods

in each segment, we analyze the
1) periods (MTM method)
2) mature SSTA pattern clusters (fuzzy cluster method)
3) ratio of CP/EP event numbers

definition of mature phase:
a) no AC case: peak of Nino 3.4 index and Nino 3.4 >0.5 stdv
b) AC case: peak of NDJF Nino 3.4 index and NDJF Nino 3.4 >0.5 stdv

ENSO features are averaged in the 100 segments.

4. Initial forcing

weak (5%) stochastic wind stress forcing (of a unit variance) in the western Pacific

weak STOC, weak ENSO irregularity
Nonlinear ENSO bimodal interaction

no bimodal interaction cases | EP regime \((E^+C^-)\)

no AC case

major period: 4.5 yrs

minor \(f_{CP}\)

mean CP/EP ratio: 0.19 0.26
Nonlinear ENSO bimodal interaction

**no bimodal interaction cases | CP regime (E\textsuperscript{−}C\textsuperscript{+})**

**no AC case**

30-yr Eq. SSTA

major period: 1.6 yrs

\(f_{CP}\) only

weak CP ENSO events
Nonlinear ENSO bimodal interaction

**weak bimodal interaction cases | EP dominant \((E^+ C^0)\)**

no AC case

![Graphs showing 30-yr Eq. SSTA, mature SST pattern clusters, and period analysis](image)

Mean CP/EP ratio: 0.45 0.58

Periods:
- 4.2 yrs (major), 2.2 yrs

**Note:** The image contains graphs illustrating the bimodal interaction patterns, including period analysis and mature SST pattern clusters.
Nonlinear ENSO bimodal interaction

**weak** bimodal interaction cases | **CP dominant** ($E^0C^+$)

no AC case

**periods:**
1.8 yrs (major), 3.6 yrs
Nonlinear ENSO bimodal interaction

**strong** bimodal interaction cases | **EP-CP** ($E^+ C^+$)

**no AC case**

**periods:**
- 3.8 yrs
- 2.3 yrs

**mean CP/EP ratio:** 0.61 all CP
Nonlinear ENSO bimodal interaction

Varying AC cases

\[ \bar{F}^{AC} = \bar{F}^{AM} + a \cdot f^{AC}, \quad a=0 \sim 150\%, \text{ increment of } 25\% \]

AC does not change the EP ENSO mode when EP mode dominates.

Stronger AC leads to larger destabilization (stabilization) of the EP (CP) ENSO mode, and causes ENSO regime shift when modes coexist.

AC weakens CP mode and shifts \( f_{CP} \) towards lower end, when CP mode dominates.
Implication of modern and Mid-Holocene ENSO

Modern era (1980-2016)

More unstable CP mode after 2000

E^+C^-  E^0C^+  calculated in ZC model

Intensity of SST AC = SST(MAM) - SST(SON)

Weaker SST AC after 2000

Mid-Holocene (~6kyr BP)

Weaker SST AC during MH

Carre et al. 2014

Negative skewness of EP SSTA

Carre et al. 2014

Weakened AC helps to maintain a higher occurrence rate of CP El Niño.
Summary

• The 4-yr EP ENSO mode and 2-yr CP ENSO mode can interact to exhibit both the ENSO pattern diversity and frequency complexity.

• Annual cycle modulates the two modes differently.
  when modes coexist: AC destabilizes EP (stabilizes CP) ENSO mode.
  when EP mode dominates: AC changes little to EP mode.
  when CP mode dominates: AC stabilizes CP mode and shifts its frequency.

• Changes in the intensity of AC causes ENSO regime shift.

• In plain language, the two ENSO modes can be viewed as two genes of ENSO, and the role of bimodal interaction played for ENSO diversity/complexity is also similar to the genetic recombination for the genetic diversity in one species.
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