ENSO Dynamics, Diversity, and Change

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NOAA
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ENSO diversity in observations

U.S. CLIVAR Working Group on ENSO Diversity: Capotondi et al. (BAMS 2015)
Kug et al. (JC 2010); Graham et al. (CD 2017); Chen et al. (JC 2017); Atwood et al. (CD 2017)
ENSO diversity in observations & models

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An ENSO continuum

CM2.1 1860 warm/neutral/cold events

DJF NINO4 SSTA (°C)

DJF NINO3 SSTA (°C)

WP

CT
Composite CM2.1 warm events (NDJ anomalies)

**SST**

**precip**

**zonal wind (925mb)**

**heat content (top 300m)**

Fig. 3. SST anomaly (°C) composite of the (a) CT El Niño and (b) WP El Niño during ND(0)J(1).

Fig. 4. As in Fig. 3, except for precipitation (mm day⁻¹).

Fig. 5. As in Fig. 3, except for zonal wind at 925 hPa (m s⁻¹).

Fig. 6. As in Fig. 3, except for heat content (K).

Kug et al. (JC 2010)
Composite CM2.1 SSTA tendency terms

**Fig. 11.** SST tendency (open bar), SST tendency according to the thermocline feedback (light-gray bar), the zonal advective feedback (dark-gray bar), and net flux (black bar) for (a),(b) CT El Niño and (c),(d) WP El Niño (K month$^{-1}$). Each magnitude is calculated over 2°S–2°N, 170°E–110°W [(b),(d) Niño-3m region] or 2°S–2°N, 140°E–170°W [(a),(c) Niño-4m region]. Period of development (decay) is defined from March (0) to November (0) [from February (1) to October (1)].

Kug et al. (JC 2010)
ENSO's impacts depend on its seasonal timing

Key archetypes of ENSO evolution

ENSO events show diverse temporal behavior in boreal spring – e.g. persisting, terminating early, resurging, or transitioning.

This significantly affects their impacts – e.g. tornado outbreak frequency over the United States.

Lee et al. (GRL 2014; ERL 2016)
ENSO's impacts on regional climates

**Obs**

![Observed Surface Temperature](image1)

![Observed Precipitation](image2)

**Model**

![Model Surface Temperature](image3)

![Model Precipitation](image4)
Extreme ENSO events have nonlinear impacts

Surface temperature teleconnections in CM2.1 (4000yr)

West Eq Pacific

East Eq Pacific

Southeast U.S.

annual (Jun-May) temperature

La Niña → El Niño
Extreme ENSO events have nonlinear impacts

**Rainfall teleconnections in CM2.1 (4000yr)**

- West Eq Pacific
- East Eq Pacific
- Southeast U.S.

**Surface temperature teleconnections in CM2.1 (4000yr)**

- West Eq Pacific
- East Eq Pacific
- Southeast U.S.

La Niña ↔ El Niño
Increasing CO$_2$ alters ENSO impacts

Rainfall teleconnections in CM2.1 (4000yr & 400yr)

Surface temperature teleconnections in CM2.1 (4000yr & 400yr)

La Niña ↔ El Niño
Both historical & paleo records suggest past modulation of ENSO. Vecchi & Wittenberg (WIREsCC 2010)

ENSO has existed for thousands, perhaps millions, of years. Obscures detection of slower climate changes (decadal, global warming).

Historical SSTA (ERSST.v3)

Palmyra corals (Cobb et al., Nature 2003)

Multiproxy reconstructions:
  e.g. Li et al. (NCC 2011);
  Emile-Geay et al. (J. Climate, 2013ab);
  McGregor et al. (CP 2013)
Proxy evidence suggests that ENSO activity has waxed & waned, with significant amplification in recent decades.

Multiproxy meta-reconstruction (from corals, tree rings, lake sediments & ice cores) of 30-year running variance of 10-yr lowpass July-June annual-mean NINO3.4 SSTs.

McGregor et al. (Clim. Past, 2013)
ENSO modulation in a 2000-year control simulation

NINO3 SST (°C): running annual mean & 20yr low-pass

Wittenberg (GRL 2009)
Epochs of unusual ENSO behavior

weak, biennial, “Modoki” (early 1990s & 2000s)

regular, westward propagating (1960s & 70s)

strong, skewed, long period, eastward propagating (1980s & late 1990s)

All from a simulation with unchanging forcings!

Wittenberg et al. (J. Climate, 2014)
ENSES modulation: Is it decadally predictable?

(a) Strong ENSO

(b) Regular ENSO

(c) Weak ENSO

NINO3 SSTA, for extreme-ENSO epochs simulated by CM2.1

External forcings held fixed at 1860 values.

Add a tiny perturbation...

“Perfect-model” reforecasts: weakest, strongest, all 40 members

Wittenberg et al. (J. Climate, 2014)
Initial growth of tiny perturbations in CM2.1

Ensemble exceeds the 333yr-analog spread in 1-2 months. Climatological spread reached in as little as 7 months.

Karamperidou et al. (CD 2014)
Long-term memory?

Distribution of inter-event wait times suggests that NINO3 SSTA *might* have some memory beyond 5 years.

But beyond 10 years?

Even a *purely* memoryless ENSO would give occasional waits of 20 years or more, as seen in CM2.1.

Wittenberg (GRL 2009)
Best hope for long-term ENSO predictability?

NINO3 memory might last 5yr, following strong warm events.

20yr—return warm events

10th, 50th, 90th percentiles from 199 events
Best hope for long-term ENSO predictability?

NINO3 memory might last 5yr, following strong warm events.

100yr–return warm events
10th, 50th, 90th percentiles from 39 events
Projected surface temperature changes

Vecchi et al. (2008)
Vecchi & Wittenberg (2010)
Collins et al. (2010)
Xie et al. (2010)

Strongest warming over land & equatorial Pacific

More warming in calm areas, and where winds weaken

Feedbacks from low clouds & ocean advection
Projected rainfall changes

precipitation (mm/day)

(a) Mean of 5 CM2.1 members, 1996–2000

Broadly: “the wet get wetter, the dry get drier”.

Over tropical oceans: “the warmer get wetter”.

Held & Soden (2006)
Vecchi & Wittenberg (2010)
DiNezio et al. (2010)
Xie et al. (2010)
Projected upper-ocean temperature changes

DiNezio et al.
(JC 2009, EOS 2010)
Collins et al. (2010)

Tropical ocean more stratified

Stronger, shallower, and flatter equatorial thermocline
As CO₂ increases:

Relative to ECT SSTs, the **warm pool** contracts.

Relative to ECT SSTs, **cold water** moves closer to the surface.
ENSO response to increasing CO₂

(a) Rainfall

CO₂-induced shift of rainfall variability

1860, 1990, 2x, 4x

stronger-ENSO decades → wetter local climate

(b) SST

then weaker.

stronger ENSO...

CM2.1 simulations show interplay of intrinsic ENSO modulation, decadal variation, nonlinear sensitivity, and regional responses to increasing CO₂

Vecchi & Wittenberg (2010)
Collins et al. (2010)
Xie et al. (2010)
DiNezio et al. (2012)
Watanabe & Wittenberg (2012)
Watanabe et al. (2012)
Ogata et al. (2013)
Power et al. (2013)
Cai et al. (2014)
ENS0 response to increasing CO₂

(a) Rainfall

(b) SST

CM2.1 simulations show interplay of intrinsic ENSO modulation, decadal variation, nonlinear sensitivity, and regional responses to increasing CO₂

Vecchi & Wittenberg (2010)
Collins et al. (2010)
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Watanabe & Wittenberg (2012)
Watanabe et al. (2012)
Ogata et al. (2013)
Power et al. (2013)
Cai et al. (2014)
CMIP5 projections (PI, 1900-99, 2000-99)

All the models show significant mean warming in the 21st century. But ENSO SSTAs weaken in some models, strengthen in others.
CMIP5 projections (PI, 1900-99, 2000-99)

**SSTA peak longitude**

- Prefer EP <-> CP

**SSTA propagation direction**

- Pref. westward <-> pref. eastward

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No consensus on whether EP or CP El Ninos will be more likely in the future. But ENSO SSTAs do show **more eastward propagation**.

Chen et al. (JC 2017)
Competing changes in ENSO feedbacks

1. **Amplifiers**
   - stronger rainfall & wind stress responses to SSTAs
   - intensified thermocline, shallower mixed layer
   - weaker refresh of surface waters from below
   - weaker SST barrier for equatorial shifts of convection

2. **Dampers**
   - stronger evaporative & cloud-shading responses
   - weaker upwelling -> surface less connected to thermocline
   - smaller dynamic warm pool -> less room for warming

3. **Ambiguous effects**
   - stronger intraseasonal wind variability?

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Guilyardi et al. (BAMS 2009); Vecchi & Wittenberg (WIREs CC 2010)
Collins et al. (Nature Geosci. 2010); DiNezio et al. (JC 2009; EOS 2010; JC 2012); Cai et al. (2014)

Ongoing activities with CLIVAR Working Groups,
D. Battisti, A. Atwood, M. Cane, C. Karamperidou, F.-F. Jin, J. Brown, F. Graham
Can we extrapolate ENSO projections to reality?

The “most realistic” pre-industrial ENSOs show amplification at 2xCO$_2$

Merryfield (JC 2006)

Vecchi & Wittenberg (WIREsCC 2010)
ENSO improvements with increasing resolution

Delworth et al. (2012); Vecchi et al. (JC 2014); Jia et al. (JC 2015); Wittenberg et al. (in prep)
Seasonality & diversity of ENSO events

Seasonality of ENSO events >1°C

- **NOAA ER.v4 (1875–2014)**
- **CM2.1 (1–300)**
- **FLOR (1–300)**
- **hiFLOR (1–300)**
- **CM2.6 (1–140)**
- **FLORFA (1–300)**

**Obs events peak in Nov/Dec.**

**CM2.1 was semiannually synchronized!**

Atmos/ocean refinement slightly improves seasonality, but weakens skewness.

**Flux adjustment nails the seasonality, due to improved SST/rain/wind climatologies.**
Summary

1. ENSO diversity
   a. **Continuum of flavors;** strong El Niños are different
   b. **Nonlinear regional impacts:** stakeholder-dependent
      - various paleo proxies record different aspects of ENSO
   c. **Intrinsic modulation:** may be unpredictable
      - may dominate the ENSO we experience in the next few decades
      - Have we observed long enough? How long must we run models?

2. ENSO changes
   a. **Stronger ENSO** in past 30yr than previous 400yr
   b. **Changing patterns of variability,** especially for rainfall
   c. **Unprecedented climates:** Change in mean state vs. variance
      - West Pacific SST; central Pacific rainfall
   d. **Future vulnerability** depends on region & stakeholder
   e. Competing feedbacks + optima + model biases → **uncertainty in projections**

3. ENSO models & dynamics
   a. **CGCMs are improving:** teleconnections, dynamics, predictions
      - atmospheric & oceanic formulations both matter
      - correcting the climatology improves ENSO's seasonal timing
   b. **Renewed attention to conceptual frameworks & metrics**
      - e.g. nonlinear delayed oscillator → captures key ENSO asymmetries
Next steps

1. Improve AGCM climatology & ENSO feedbacks
   a. **Moisture budget**: reduce tropical evap/rainfall; improve rainfall gradients
   b. **Surface fluxes**: bulk formulae, skin temperature, diurnal cycle
   c. **Clouds** & cloud radiative feedbacks
   d. **Off-equatorial wind stress curl** response to ENSO (precip pattern, CMT)

2. Improve OGCM climatology & ENSO feedbacks
   a. **Shoal the equatorial thermocline** (mixing, solar penetration, diurnal cycle)
   b. **Resolve TIWs** (critical during La Niña)
   c. **Mixed layer heat budget** (need obs constraints → TPOS-2020)

3. Improve coupled interactions
   a. **Seasonal dT/dy** in east Pacific (ENSO seasonality)
   b. **Coupled feedback** diagnostics (need obs constraints!)
   c. **Subsurface flux adjustments** (3D-FA)
Reserve Slides
The double-peaked El Niño

Composite El Niño in CMIP5 models (equatorial SSTA)

If warm pool is too far west, get more double-peaked El Niños, with western peaks that are farther west.

Present-day simulations show fewer double-peaked El Niños than pre-industrial.

Graham et al. (CD 2017)
**ENSO amplitude & period**

*NINO3 SST wavelet spectra from 1990 control simulations.*

- **CM2.1** ENSO was too strong, but time scale looked good.
- **FLOR's atmos refinement** shortens period, narrows spectrum.
- **HiFLOR's atmos refinement** weakens ENSO.
- **CM2.6's oceanic refinement** weakens ENSO, shortens period.
- **Surface flux adjustment** weakens ENSO.
East Pacific climatological SST & rainfall

SST climatology (°C), averaged 150°W–110°W

(a) FLOR
(b) FLOR–FA
(c) Change due to FA

FLOR overestimates dT/dy in the eastern equatorial Pacific during Jul-Nov.

FA weakens this dT/dy, facilitating equatorial shifts of ITCZ during ENSO growth season.

Precip climatology (mm/day), averaged 150°W–110°W

(a) FLOR
(b) FLOR–FA
(c) Change due to FA

FA weakens the spurious Jan-May southern ITCZ.

During Jul-Nov, FA shifts the northern ITCZ slightly closer to the equator.

FA sensitizes the northeast Pacific ITCZ to equatorial SSTAs in Jul-Nov, seasonalizing the Bjerknes feedback and synchronizing ENSO to the end of the calendar year.
SSTA amplitude, pattern, and propagation vary from decade to decade in obs & simulations. FLOR SSTAs are too strong, frequent, and eastward-propagating, especially for cold events. FA leads to a weaker ENSO, with more westward propagation.
Summary: ENSO in a flux-adjusted CGCM

1. FLOR global coupled GCM
   a. **High-res atmosphere** → climate & ENSO forecasts improved over CM2.1
   b. But ENSO too strong & frequent, not seasonally synchronized

2. FLOR with flux adjustments (FLOR-FA)
   a. **Corrects climatological SST/winds**, greatly improves mean rainfall
   b. **Deepens climatological thermocline along equator**
      - weaker off-equatorial trade winds → less Sverdrup divergence from equator
      - reveals a latent OGCM bias → motivates attention to equatorial mixing & solar penetration

3. FA impacts on ENSO in FLOR
   a. **ENSO weakens**
      - *despite* weaker SSTA→flux damping and stronger SSTA→wind coupling
      - trumped by deeper mean thermocline, weaker h'→Te' coupling
      - weaker thermocline feedback → more westward propagation of SSTAs
      - less interdecadal modulation of ENSO
   b. **ENSO period doesn't change**
      - off-equatorial anomalous cyclonic curl still too strong → excessive Sverdrup feedback
   c. **Atmospheric responses/teleconnections shift westward**
      - drier central equatorial Pacific + weaker ENSO → harder to shift convection eastward
   d. **ENSO synchronizes to end of calendar year**
      - eastern equatorial Pacific dT/dy barrier weakens in Jul-Nov relative to Jan-May
      - stronger Bjerknes feedback in Jul-Nov → ENSO peaks near Dec
Key ENSO feedbacks

- SST
- u, w, mixing
- wind stress
- noise
- heat fluxes (evaporation, cloud shading)

h
Projected ENSO changes (CMIP3/AR4)

Projected ENSO changes (CMIP3/AR4)

CM2.1

Weak/ambiguous near-term anthropogenic impacts on ENSO

Intrinsic modulation

Reviews:
- Meehl et al. (IPCC-AR4 2007)
- Guilyardi et al. (BAMS 2009)
- Vecchi & Wittenberg (WIREs CC 2010)
- Collins et al. (Nature Geosci. 2010)

std(SLP,PC1 of SRES A2/2051-2100) / std(SLP,PC1 of 20C3M) van Oldenborgh et al. (OS 2005)

corr(SST trend of 1%/yr, SST,PC1 of PICTRL)
10S-10N, 120E-80W
Yamaguchi & Noda (JMSJ 2006)
**ENSO theory revisited**

Existing conceptual models of ENSO have issues:

- Linear frameworks miss key asymmetries in obs (Choi et al. 2013)
- “BJ index” accumulates errors (Graham et al., CD 2014)
- “Unified Oscillator” at odds with obs & CGCMs (Graham et al., JC 2015)

**Back to basics:**

At ENSO time scales, a delayed oscillator with

\[
\frac{dT(t)}{dt} = \frac{T(t)}{6.25\text{mo}} - \frac{T(t - 5\text{mo})}{5\text{mo}}
\]

captures **94% of the variance** of obs NINO3 dT/dt. (Graham et al., JC 2015)

Good reference point... **but what about ENSO nonlinearity?**
Modified delayed oscillator

\[ \tau^x = \gamma (T + r|T|) + \text{noise} \]

\[ \dot{T}(t) = -bT(t) + c' \tau^x (t - t_1) - d' \tau^x (t - t_2) \]

Reproduces observed asymmetries in
- **Amplitude**: warm events stronger than cold events
- **Transition**: warm → cold more likely than vice versa
- **Duration**: cold events last longer than warm events

Stronger coupling during El Niño → stronger growth, faster transition & overshoot
Weaker coupling during La Niña → milder, slower, susceptible to noise
CM2.1 SSTA peaks vs. calendar month

abs(NINO3) > 1 stddev

warm events are stronger & rarer than cold events

**strong** warm events peak in SON

less synchronization of cold events & weak warm events