The Complexity of ENSO
Lessons learnt from initialized predictions

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Outline

• Emergence of ENSO as a coupled ocean-atmosphere mode
• ENSO characterization from Observations and Reanalyses.
• Conceptual models of ENSO: implications for predictability
• ENSO prediction
• Example: the 2014 and 2015 El Niño
• New directions
• Summary
Origins of ENSO

Southern Oscillation Index (SOI)

Nino3.4 SST index

El Niño
La Niña

AS2019 – The complexity of ENSO. Lessons learnt
A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature

By J. BJERKNES, University of California, Los Angeles

(Manuscript received January 18, 1966)
**El Niño: Bjerknes feedback**

- Bjerknes positive feedback (strongest in spring and summer) allows ENSO to grow.
- Generalized Bjerkness feedback as interaction between SST and deep convection operates at many time scales.

Courtesy of Jerome Vialard
ENSO: El Nino-Southern Oscillation

Largest mode of interannual climate variability

Best known source of predictability at seasonal time scales

It affects global patterns of atmospheric circulation, with changes in rainfall, temperature, hurricanes, extreme events

Impacts on marine ecosystems, on agriculture, health, ...

Impact on Earth Energy Cycle and ocean as a climate thermostat.

**EL NIÑO CLIMATE IMPACTS**

December-February
A bit more history

1966
- Bjerknes: ENSO as a coupled O-A mode

1975
- Wyrtki: importance of ocean Kelvin waves. Sea level as first observing system for prediction

1980's
- First attempts at modelling and prediction with simple models (Zebiak and Cane 1987)

Early 1990's
- Development of GCMs: Simulating ENSO as a big challenge
- TOGA-TAO observational campaign

Late 1990's
- First prediction system with GCMs, data assimilation, **probabilistic**
- Conceptual models for ENSO

2000's
- ENSO in climate change: conceptual models and projections

Present
- ENSO diversity: predicting ENSO and its impacts remains challenging
Relevance of Observations and Climate Reanalyses

SST Observations + Observations of the Atmosphere + Observations of the Ocean

1975; Wyrtki sets Equatorial tide gauges to monitor Kelvin waves

~ 1993 onwards: satellite altimeter to monitor sea level

~ 1993- TOGA-TAO program to monitor subsurface temperature

~ 2005: Argo uniform sampling of subsurface temperature and salinity

When Observations are integrated with laws of physics we obtain climate reanalyses, a essential resource of the understanding, modelling and prediction of ENSO
20 years of Equatorial Anomalies

Taux Anomalies

D20 Anomalies

SST Anomalies

Note the strong 1997-8 El Nino and 1998-9 La Nina in Taux, D20 and SST

After them, ENSO has shown short-cycles of Central Pacific anomalies (no reaching the East Coast)

Until 2014, when a strong Kelvin wave was generated....
March 1997@ Strong Westerly Wind bursts (WWB) in the West Pacific.

Associated eastward propagating groups of Kelvin waves. The latest reaching the Eastern Coast

SST anomalies develop in the West (as a displacement off the warm pool), and in the East, when the Kelvin waves arrive and depress the thermocline

May/June 1997: More WWB. Or is this already ENSO? Bjerknes feedback in action.
Warm pool moves to the Central Pacific, taking with it the Atmospheric Deep Convection and Rainfall.
ENSO from observations

1) ENSO temporal irregularity
   Broad spectral peak
   Blanke et al 1997
   Irregular and Vacillating behaviour
   Kestin et al 1998

2) Phase relationship between SST-OHC (or Warm Water Volume)

3) Phase lock to seasonal cycle
   Onset ~ May-August,
   Peak ~ Oct-Jan,
   Decay ~ May

Neelin et al 1999

ENSO peaks during cold phase of seasonal cycle
ENSO from observations (and models)

4) Persistence, variance and prediction skill at a minimum during boreal spring: Predictability Spring Barrier

From Liu et al. 2019
From Observations: ENSO diversity

**ENSO diversity:**
Eastern Pacific (EP) El Nino: Extreme events. 1\textsuperscript{st} EOF
Central Pacific (CP) El Nino: Moderate events. 2\textsuperscript{nd} EOF

CP and EP El Nino have different atmospheric impacts and teleconnections (Cai et al 2012)

The predictability of CP and EP El Nino is different (Imada et al 2015, Ren et al 2019)
Even Extreme El Nino show different teleconnections

1983

1998

2016

From Laura Ferranti
ENSO diversity and Energy Exchange

• The 1997/8 and 2015/16 Warm events: similar SST indices, very different energetics

• Marked differences in Indonesian Throughflow heat transport and surface heat flux
• Differences in surface fluxes related to increased absorbed solar radiation in 2015/16

Map of 0-300m 2-yearly OHC changes (in $10^9 \text{Jm}^{-2}$) and accumulated heat fluxes (in ZJ) during El Nino events

From Mayer and Balmaseda 2017
Multitude of conceptual models for EL Nino

1. Delayed Oscillator Mechanism: BF+ Resonant Basin mode

Suarez and Schopf 1988
Multitude of conceptual models for EL Nino

1. Delayed Oscillator Mechanism: BF+ Resonant Basin mode
   - It does not explain the “a-periodicity”.
   - It does not explain phase-locking to the seasonal cycle
   - It explains relationship between thermocline and SST
   - Very predictable

2. Coupled Instability, stochastically triggered.
   - System with 2 time scales. Atmospheric noise triggers ENSO.
Stochastically forced ENSO: System with 2 time scales

\[ x_{t+1} = Ax_t + \epsilon_t \quad ; \quad \epsilon_t \equiv \text{white gaussian noise } N(0, \sigma_\epsilon^2) \]

Weather noise \( \epsilon \) can trigger a coupled instability (Westerly Wind Bursts – WWB)

Growth/decay rate given by \( A \). If system is not self adjoint, even a damp system can exhibit temporary growth. (Moore and Kleeman 1999)

Growth rate or atmospheric weather may be seasonal dependent: it can explain predictability barrier (Liu et al 2019).

**Noise can be multiplicative**, depending on ENSO state (Eisenman et al 2005)

Coupling ocean-atmosphere also affects the weather noise in the tropics. Therefore WWB become predictable in the probabilistic sense

Relation between longitude of WWB and position of warm pool

Einsman et al 2005
Multitude of conceptual models for EL Nino

1. **Delayed Oscillator Mechanism: BF+ Resonant Basin mode**
   - It does not explain the “a-periodicity”.
   - It does not explain phase-locking to the seasonal cycle.
   - It explains relationship between thermocline and SST.
   - Very predictable.

2. **Coupled Instability, stochastically triggered.**
   - System with 2 time scales. Atmospheric noise triggers ENSO.

3. **Recharge/Discharge mechanism.** (Jin 1995)
   - Regular or chaotic behaviour, from multiple feedbacks.
   - The strength of feedbacks-hence chaos-depends on the mean state.
The Recharge/Discharge oscillator

I. During El Niño: westerlies induce discharge via Sverdrup transport.

II. A Discharged Pacific favours the occurrence of La Niña.

III. During La Niña, the easterlies induced recharge.

IV. A Recharged Eq. Pacific favours the occurrence of El Niño.

F.F Jin, Parts I and II, JAS, 1997
The complexity of ENSO. Lessons learnt

The spark & the fuel (© M. McPhaden)

Stochastic discharge/recharge oscillator

The fuel: ocean heat content

The spark: Westerly Wind Events

The background state sets the level of instability: it explains ENSO diversity and helps to understand model errors, predictions and ENSO projections.

The occurrence of WWE is modulated by background SST: importance for predictability and projections of ENSO on a warmer climate.
PREDICTING ENSO
First attempts were deterministic

With Statistical/Simplified dynamics/hybrid models

1) Skill of ENSO forecast shows a minimum across boreal spring (correlation drop), irrespective of the initialization month.

2) Re-emergence of skill

3) Decadal variations on ENSO prediction skill

Note first ENSO predictions were made at 24 months lead time

Balmaseda et al 1995
Predicting ENSO

- From mid 90’s: with GCMs
  - Ocean initial conditions (reanalyses)
  - Coupled model
  - Ensembles
  - Reforecast for calibration and skill assessment

Stockdale et al 1998
Dealing with model error: Reforecast

Coupled reforecasts, needed to estimate climatological PDF, require a historical reanalysis.

Consistency between historical and real-time initial conditions is required.

Reforecasts are also needed for skill estimation.
Example of fc drift in Seasonal Forecast

**FC drift depends on the model**

**Fc drift in the mean: first moment of distribution (bias)**
- Bias depends on model (not on the initialization)
  - Bias depends on model resolution
  - Bias depends on lead time
  - Bias depends on the phase of seasonal cycle

**Fc drift in the variance (the second moment)**
- The interannual variability is affected
- The figure shows the ratio model/obs variability.

Drift and variance also depend on initialization!!

*Balmaseda and Anderson 2019*

**Bias correction a-posteriori only valid if**
- Bias is stationary
- System is linear

Stockdale et al 2018. ECMWF Tech Memo 835
Johnson et al 2019, GMD
Over the years: SEAS2 – SEAS3 – SEAS4 – SEAS5

S2 inability to generate WWB caused under prediction of 1997/98 ENSO (Vitart et al 2004).

As the model improved

SEAS5 became operational in Nov 2017
20 years or progress in ENSO prediction at ECMWF and contribution of ocean observations

- S1 was the first ECMWF seasonal forecasting system. Implemented as a pilot in 1997.

- SEAS5 is the latest ECMWF seasonal forecasting system. Implemented in November 2017. Contributes to Copernicus Climate Change Services C3S.
Seasonal Forecasts Diversity in ENSO teleconnections

Velocity Potential 200hPa

From Laura Ferranti
The 2015/16 strong El Nino and the false alarm in 2014

- Great expectation in 2014 for a big El Nino
  - Last one was in 1997/98
  - There had been a hiatus decade (since ~2005) with negative phase of PDO
  - Long lasting Californian drought
  - Models and Experts predicted the possibility of a large warm event
The complexity of ENSO. Lessons learnt

Taux Anomalies

D20 Anomalies

SST Anomalies

Background State? (McPhaden and Levine 2016)


Cross Equatorial Flow in Eastern Pacific (Hu et al 2016)
Temperature Anomalies From Ocean Reanalysis

AUG 2014

AUG 2015
• North-West Trop Pac thermocline is deeper in JFM 2014. Possibly causing off Equatorial SST peak values later in June and associated convection.

• In Central/East Eq Pac thermocline is deeper in 2015, possibly helping to lock convection at Equator, and preventing the seasonal northward migration of the ITZC
Weak or strong El Niño: role of WWEs.

- Initial & summer WWEs: necessary condition for extreme El Niño
- Summer WWEs seem to matter more (make extreme El Niño ≈ 5 more likely)

(Puy et al. 2017)
S4 El Nino Forecasts: 2014 v 2015?

- Did the forecasts capture the difference between 2014 and 2015?

- What causes the large spread in the fc? Is that spread a good estimation for predictability?
Growth of Perturbations: Temperature

INI Pert: APR 2015-2014

Forecast Final Pert: Aug 2015-2014

• S4 Seas Fc are discerning: they capture differences between 2015 and 2014.
• Skill beyond persisting the initial differences.
El Nino 2015/16: example of scale interactions

• Interaction with low frequency variability:
  • The events of 2014 prepare the ground for El Nino 2015

• Interaction of intraseasonal variability:
  • Do some properties of the WWB determine the outcome (timing, freq, strength, fetch)
    • Are these properties “random”? Or are they modulated by background state?

• Interaction with the seasonal cycle: poleward migration of ITZC
  • Possible role of the extra Equatorial anomalies.

• Interaction with mean state:
  • threshold values of SST to trigger deep convection
SEAS5 Non stationary errors in ENSO

SST normalized error in the anomaly. May starts

Eastern-Central Pacific: Apparent tendency to produce +ve SST errors
The tendency appears already in the first month.
Trends in 1993-2017 (May starts, verifying in August)

Marked differences in trends between reanalysis and seasonal forecast related with recent forecast errors.

Trends in reanalyses have been reported in the meridional winds (Hu et al 2016)

New directions

ENSO predictions at 24 months
Decadal variations in ENSO predictability

Anomaly correlation NINO 3.4 SST anomalies

1901-1950

1950-1981

1981-2009

C20C  C20C-NoAssim

Centennial reanalyses are key for seasonal and decadal predictions

Courtesy of Antje Weisheimer
Summary

• ENSO as largest coupled mode of the climate system:
  ➢ Ocean-Atmosphere Bjerknes feedback and disruption of Walker Circulation
  ➢ Impacts worldwide: precipitation, temperature, marine ecosystems, carbon cycle, energy cycle.
  ➢ Basis for predictability at seasonal time scales (and beyond? At 24 months?)

• ENSO prediction and predictability: time scale interaction
  ➢ ENSO predictions are probabilistic. There is a large degree of stochasticity due to interaction with the subseasonal time scale.
  ➢ ENSO properties depend on background mean state, giving rise to ENSO diversity.
    o In forecast, background state depends on model quality and initialization.
    o Difficult to capture trends and decadal variations of background state in fc.
  ➢ Spring predictability barrier present in ENSO forecast. Need to understand further.

• Slow but continuous progress on ENSO prediction
  ➢ Observations + data assimilation + GCM Model development + Conceptual diagnostics
  ➢ The value of initialized predictions for understanding ENSO is underestimated

• Ongoing research areas:
  o ENSO prediction beyond year 1
  o ENSO modulation by decadal variations and climate change using Centennial Reanalyses
Back up slides
ENSO from observations

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ENSO from observations

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Initialization and forecast drift and shock

Different initializations produce different drift in the same coupled model.

- Warm drift in **ALL** caused by Kelvin Wave, triggered by the slackening of coupled model equatorial winds
- **SST only** has very little equatorial heat content, and the SST cool down very quickly.
- **SST+ATMOS** seems balanced in this region. Not in others

Sign of non linearity:

The drift in the mean affects the variability
Evolution of Initial Differences

• S4 Seas Fc are discerning: they capture differences between 2015 and 2014.
• Skill beyond persisting the initial differences.
Evolution of Initial Differences

INI AN diff: APR 2015-2014

AN Tendency

Final AN diff: Aug 2015-2014

FC Tendency

Final FC diff: Aug 2015-2014
From Observations: ENSO DIVERSITY

Towards understanding and characterizing ENSO diversity

From Capatondi et al 2015