The Complexity of ENSO Lessons learnt from initialized predictions

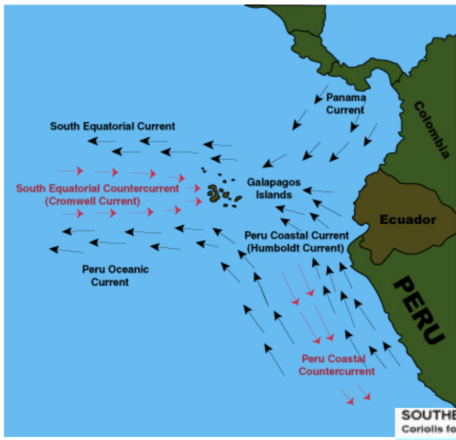
Magdalena Alonso Balmaseda

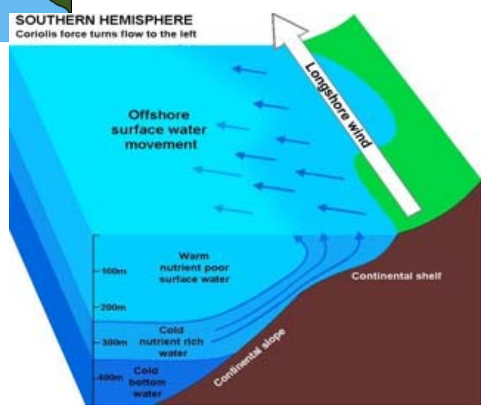
Outline

- 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

El Niño
Named by Peruvian Fishermen
Tradition
Oceanic impact

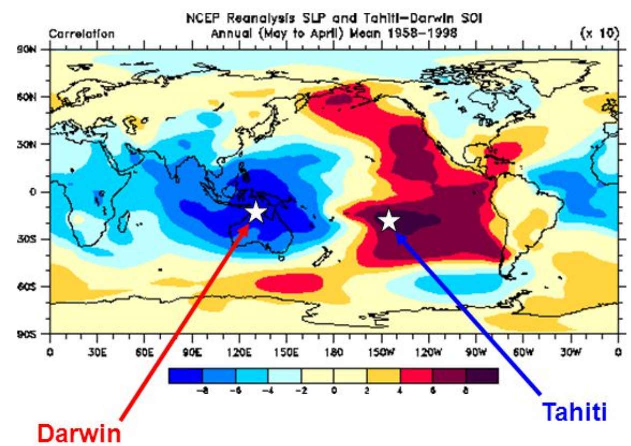




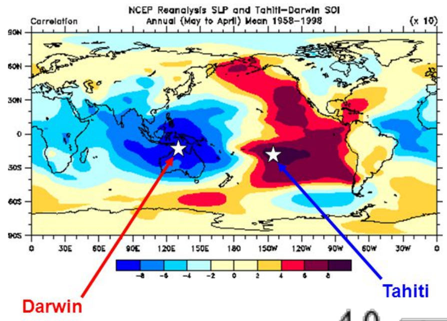
https://cmast.ncsu.edu/cmast-sites/synergy/anchovy/asecoas.html

Southern Oscillation:
Named and defined by a British Sir
~1928
Atmospheric impact

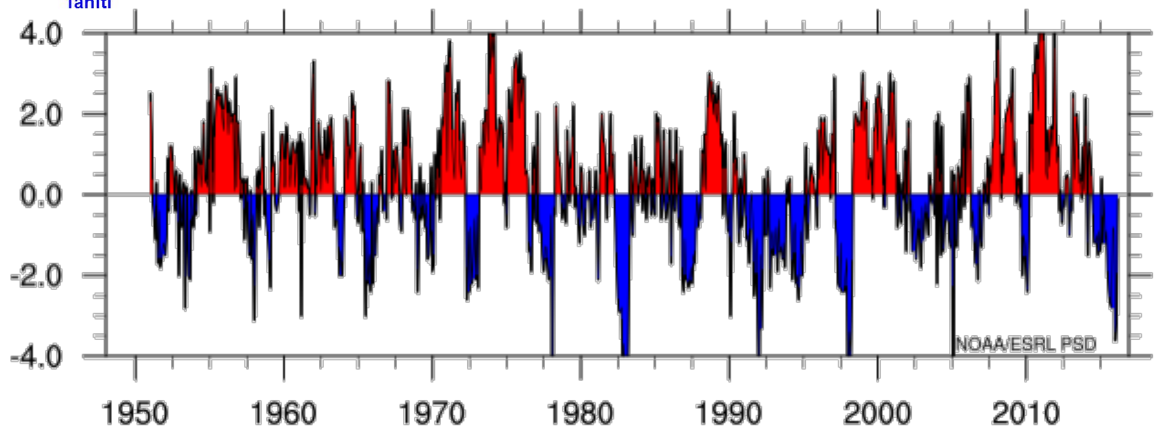
Sir Gilbert Walker
(1868-1958)



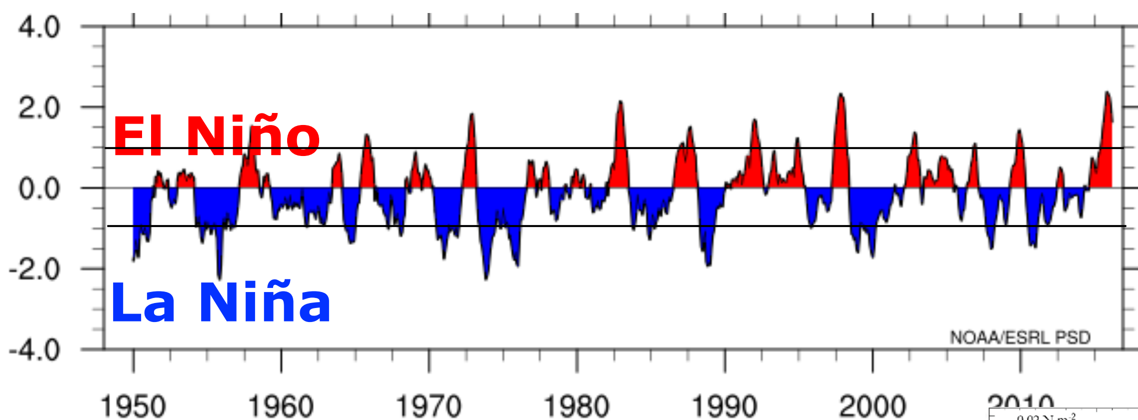
Origins of ENSO

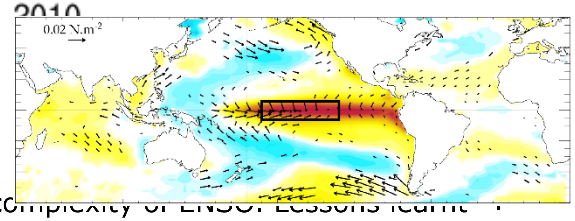


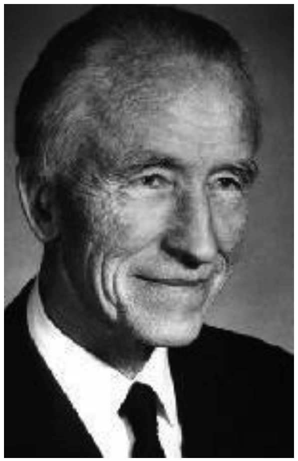
Southern Oscillation Index (SOI)

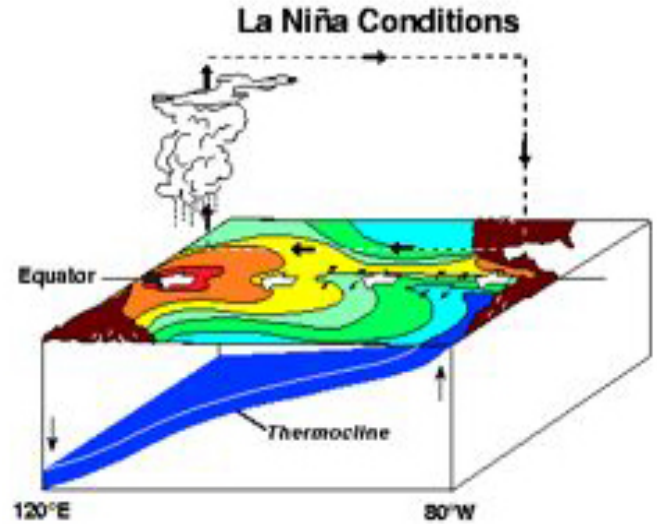


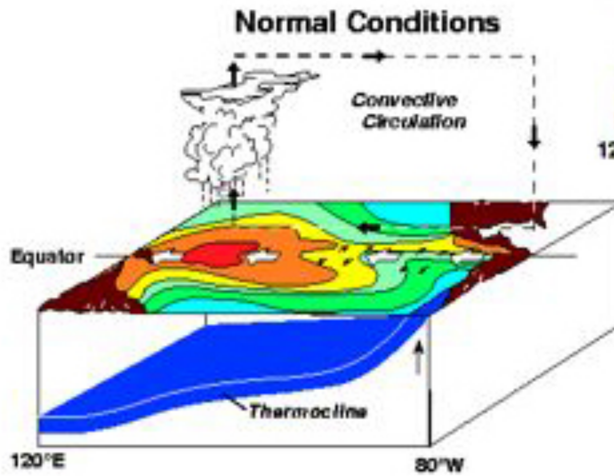
Nino3.4 SST index

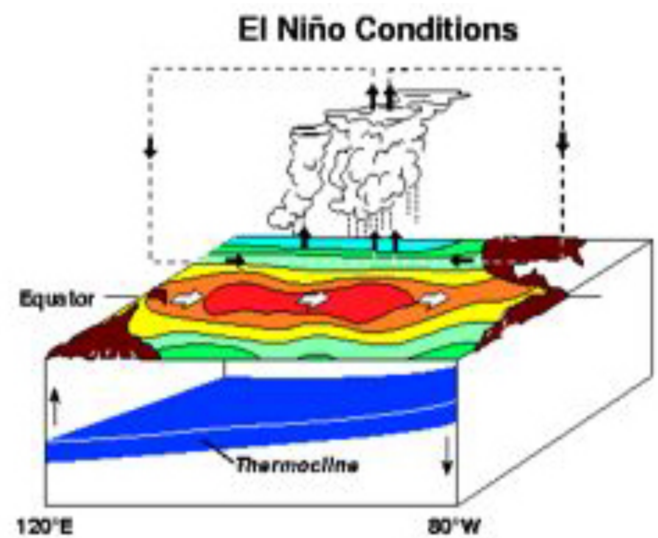










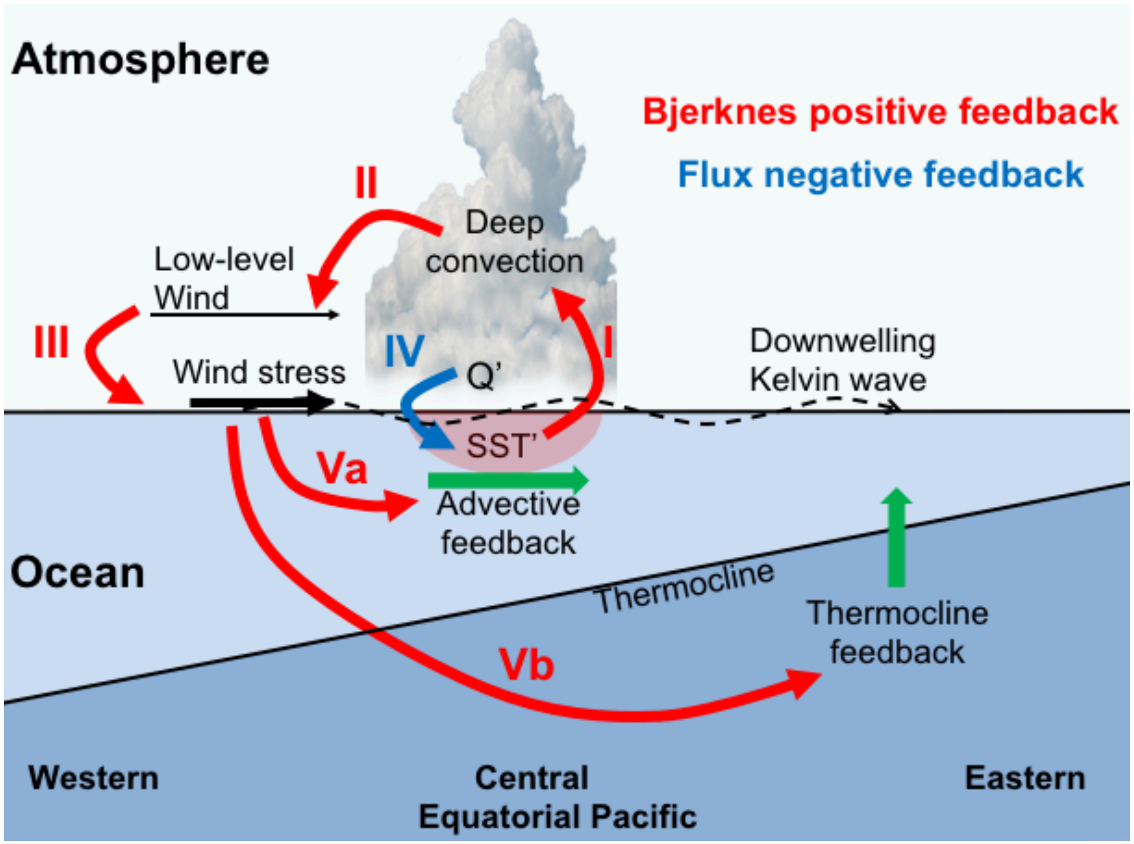


A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature

By J. BJERKNES, *University of California, Los Angeles*

(Manuscript received January 18, 1966)

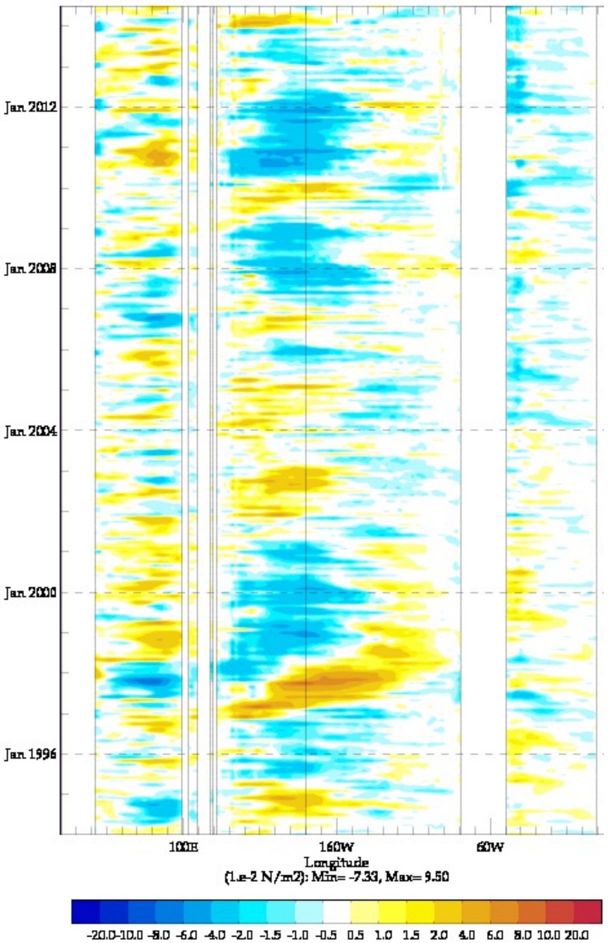
El Niño: Balance of multiple feedbacks



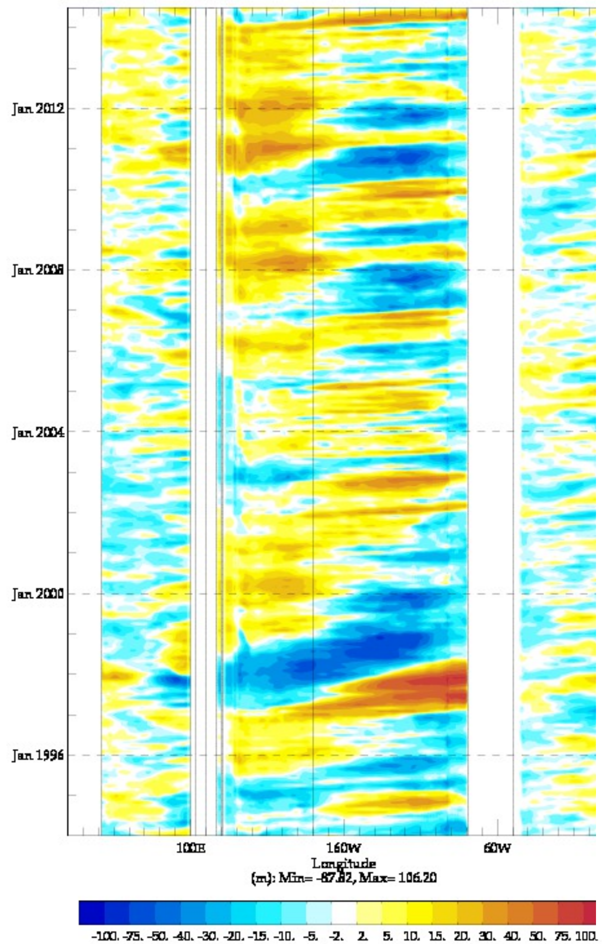
- Bjerknes: Large scale zonal SST gradients and Winds. Thermocline, Kelvin waves and upwelling.
- Warm pool instability: Interaction between SST and deep convection operates at many time scales. Role of zonal advection and ocean mixed layer processes

20 years of Equatorial Anomalies

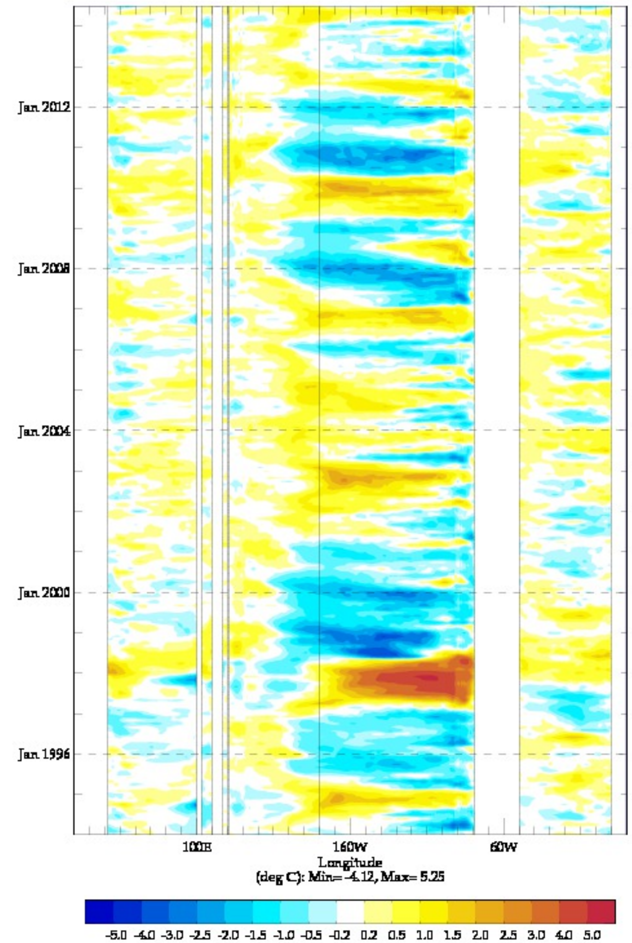
Zonal Wind Stress Anomalies



Thermocline Anomalies



SST Anomalies



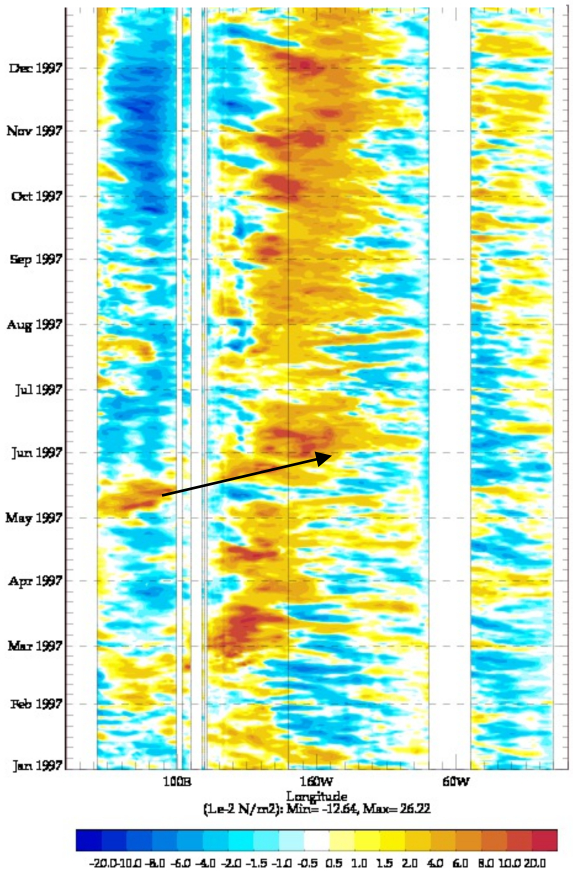
Note the strong 1997-8 El Nino and 1998-9 La Nina in Taux, D20 and SST

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

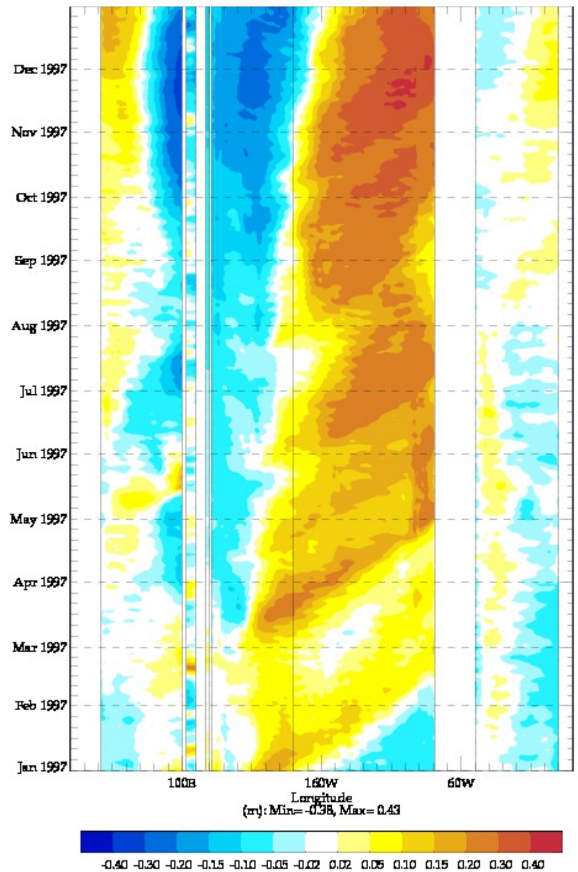
Until 2014, when a strong Kelvin wave was generated….

Daily Equatorial Anomalies: Jan 1997-Jan 1998

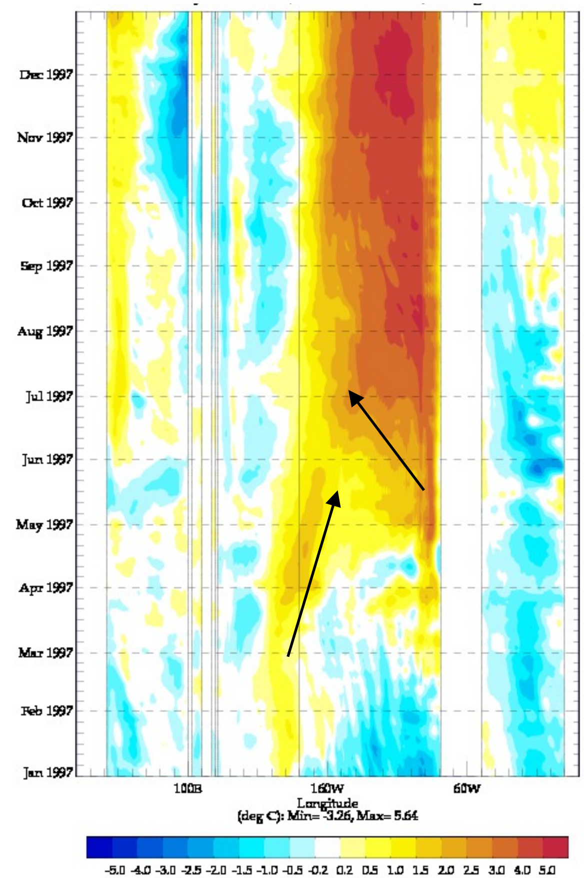
Taux Anomalies



SL Anomalies



SST Anomalies



March 1997@ Strong Westerly Wind bursts (WWB) in the West Pacific.

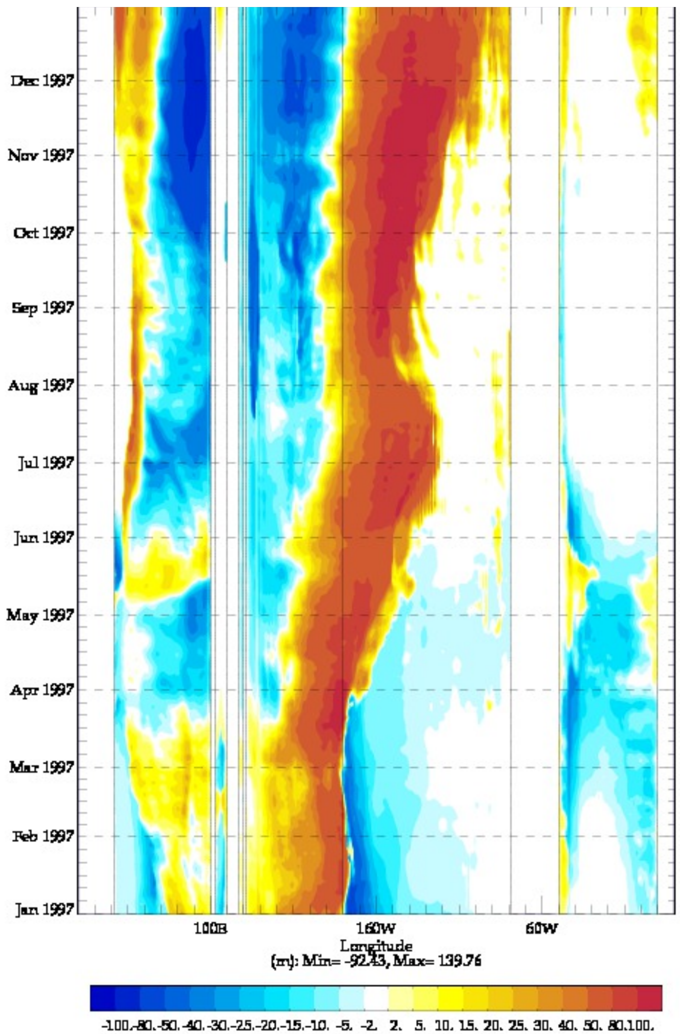
Associated eastward propagating groups of Kelvin waves. The latest reaching the Eastern Coast

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

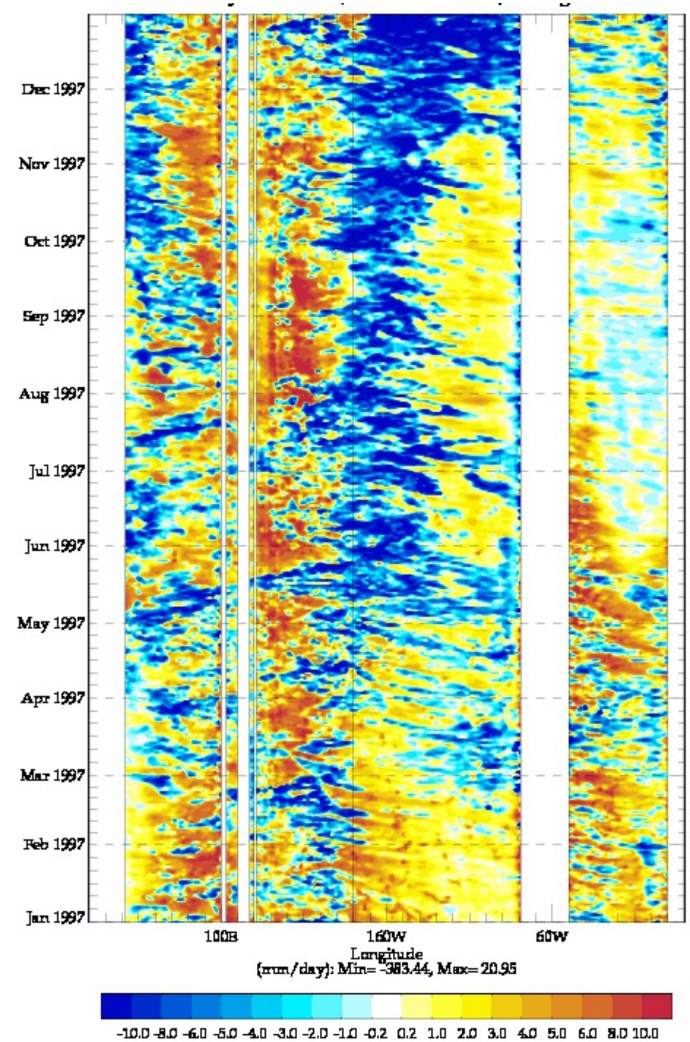
May/June 1997: More WWB . Or is this already ENSO? Bjerknes feedback in action.

Daily Equatorial Anomalies: Jan 1997-Jan 1998

D28 Anomalies
“Warm Pool”

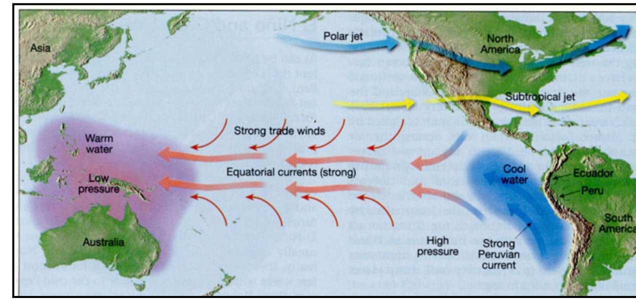


Fresh Water Flux Anomalies
Blue is into the ocean



Warm pool moves to the Central Pacific, taking with it the Atmospheric Deep Convection and Rainfall

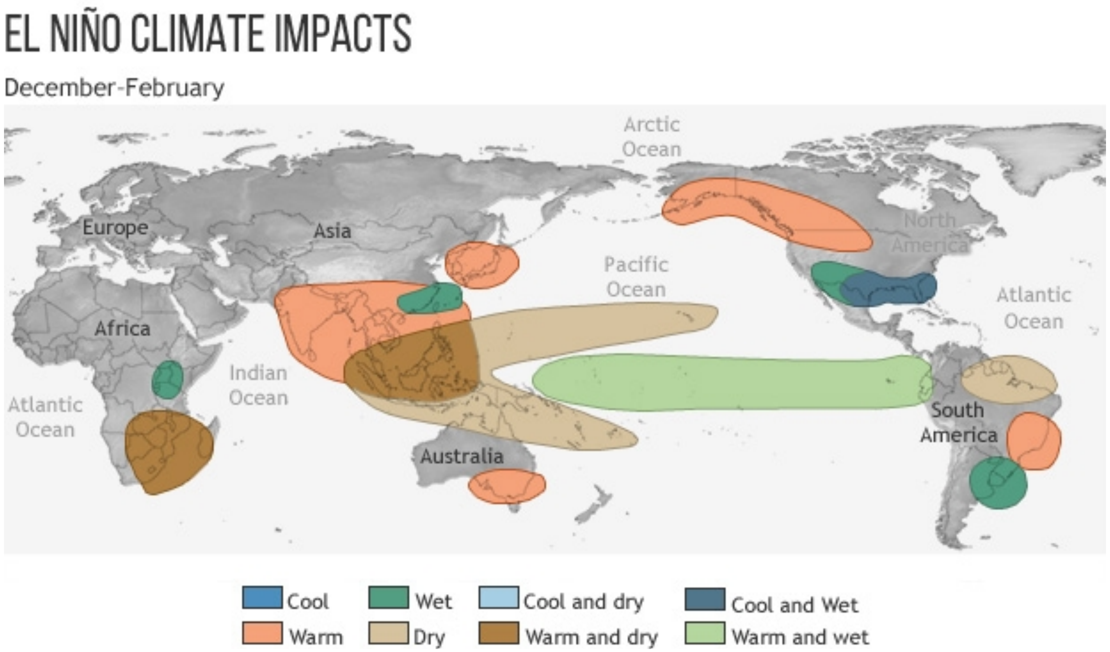
ENSO: El Nino-Southern Oscillation

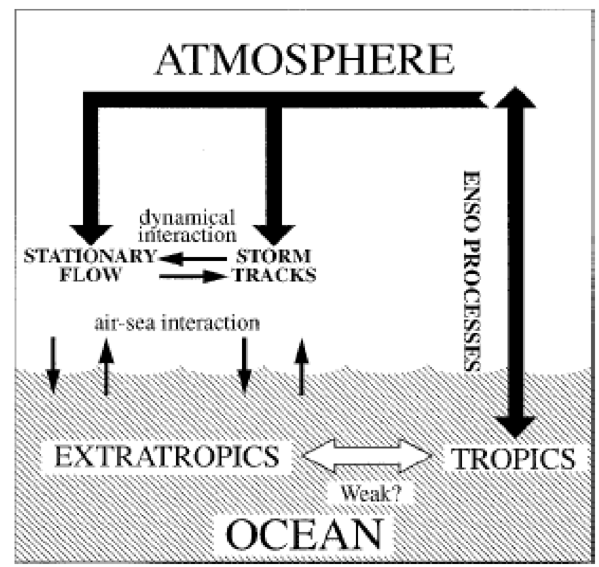


Largest mode of interannual climate variability

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 thermostate.





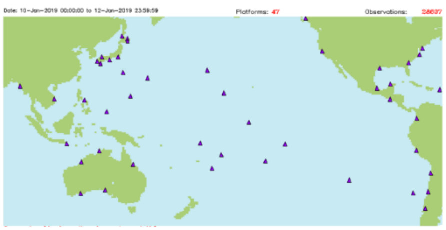
A bit more history

- **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

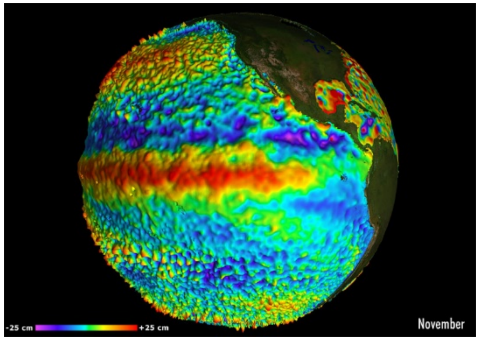
Relevance of Observations and Climate Reanalyses

SST ✚ Atmosphere ✚ Ocean Subsurface

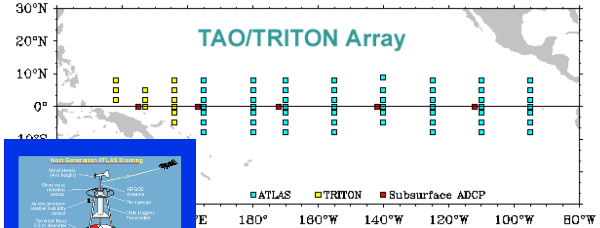
1975; Wyrtki sets Equatorial tide gauges to monitor Kelvin waves

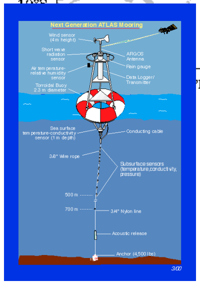


~ 1993 onwards: satellite altimeter to monitor sea level

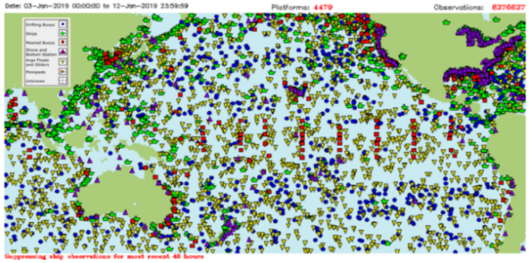


~ 1993- TOGA-TAO program to monitor subsurface temperature





~ 2005: Argo uniform sampling of subsurface temperature and salinity



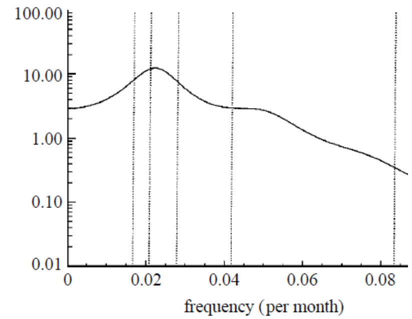
When Observations are integrated with laws of physics we obtain climate reanalyses, a essential resource of the understanding, modelling and prediction of ENSO

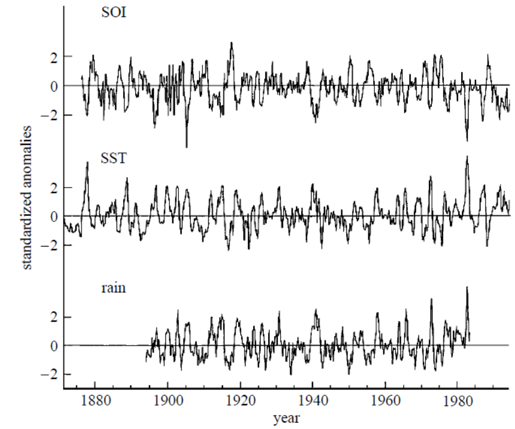
ENSO from observations

1) ENSO temporal irregularity

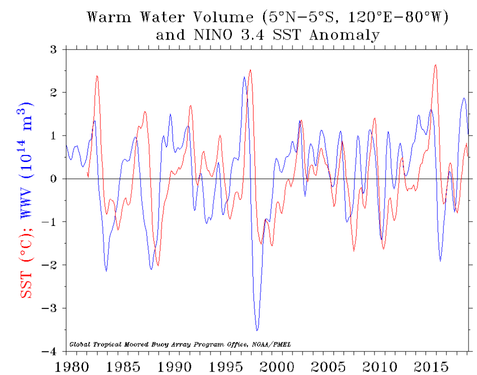
Broad spectral peak
Blanke et al 1997

Irregular and Vacillating behaviour
Kestin et al 1998



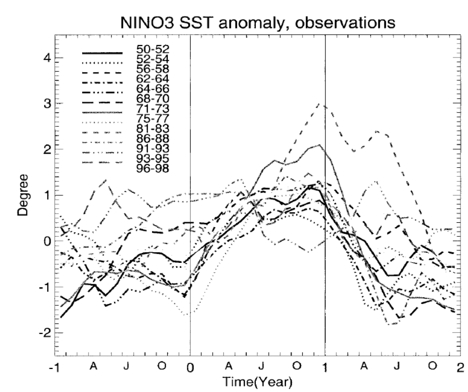


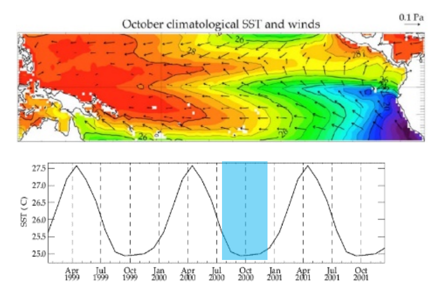
2) Phase relationship between SST-OHC (or Warm Water Volume)



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

Neelin et al 1999

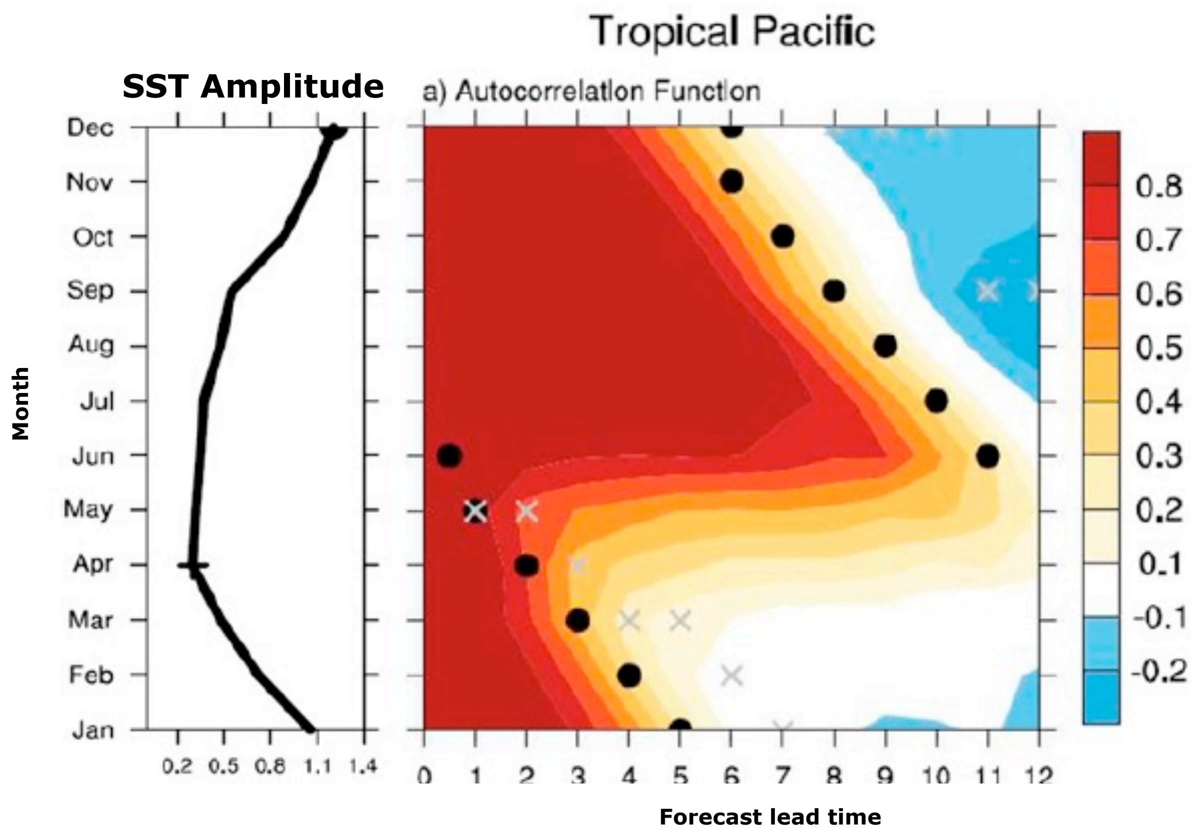




ENSO peaks during cold phase of seasonal cycle

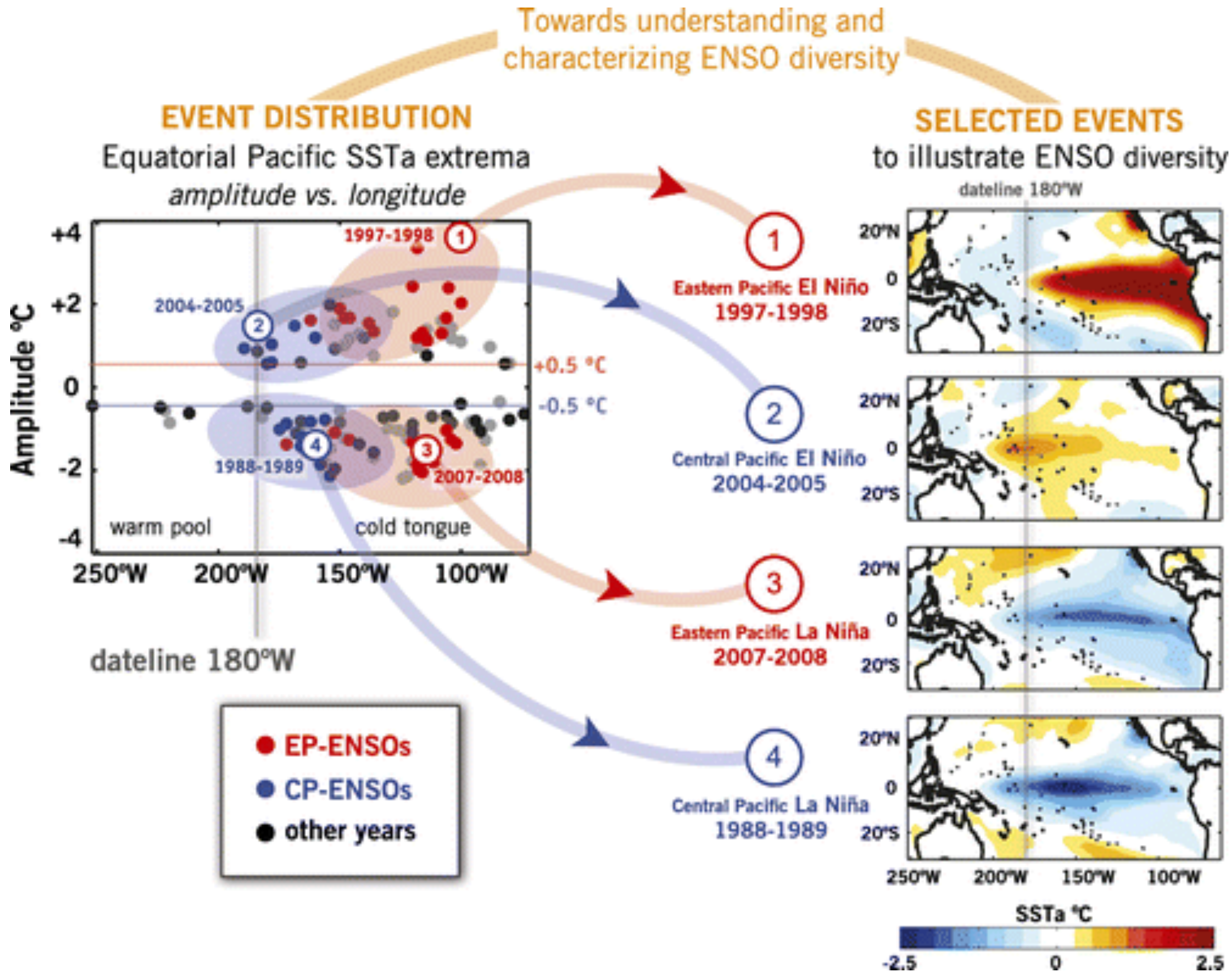
ENSO from observations (and models)

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



From Liu etal 2019

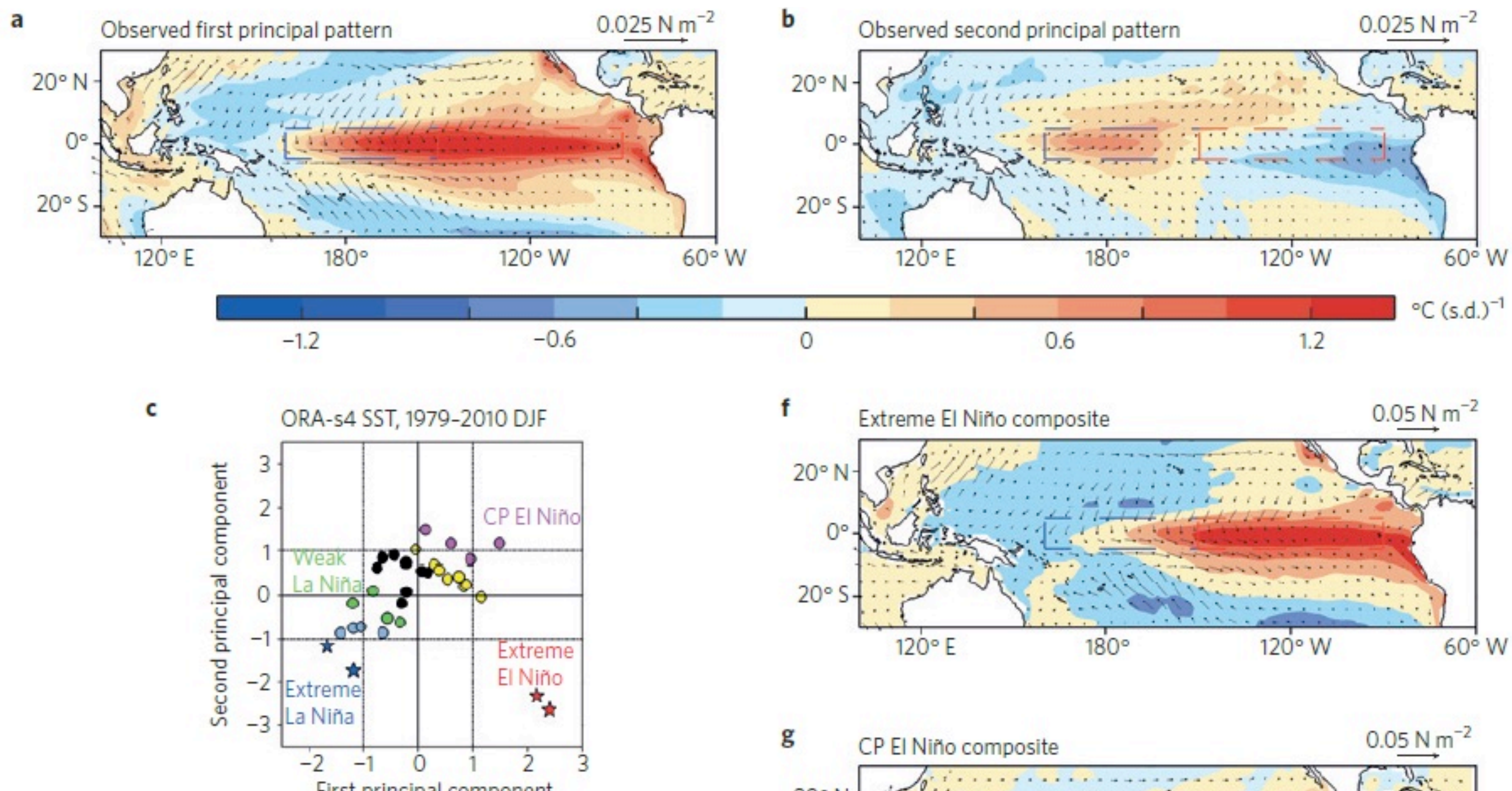
ENSO DIVERSITY



From Capatondi et al 2015

From Observations: ENSO diversity

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

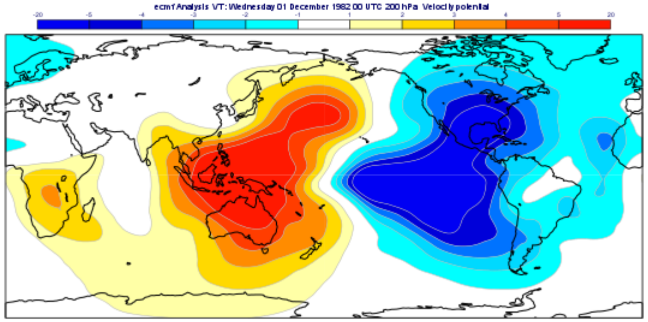
Capatondi et al 2015
Cai et al 2015

From Observations: Diversity in ENSO teleconnections

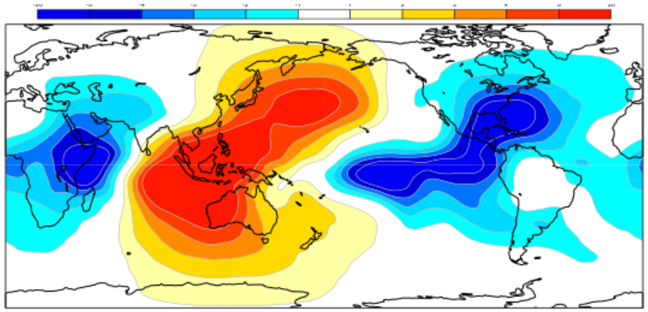
Even Extreme El Nino show different teleconnections

Velocity Potential 200hPa

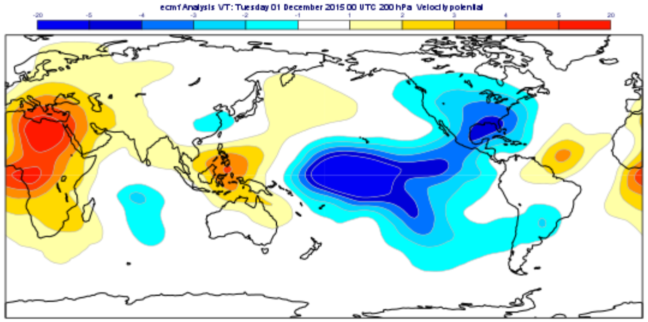
1983



1998



2016

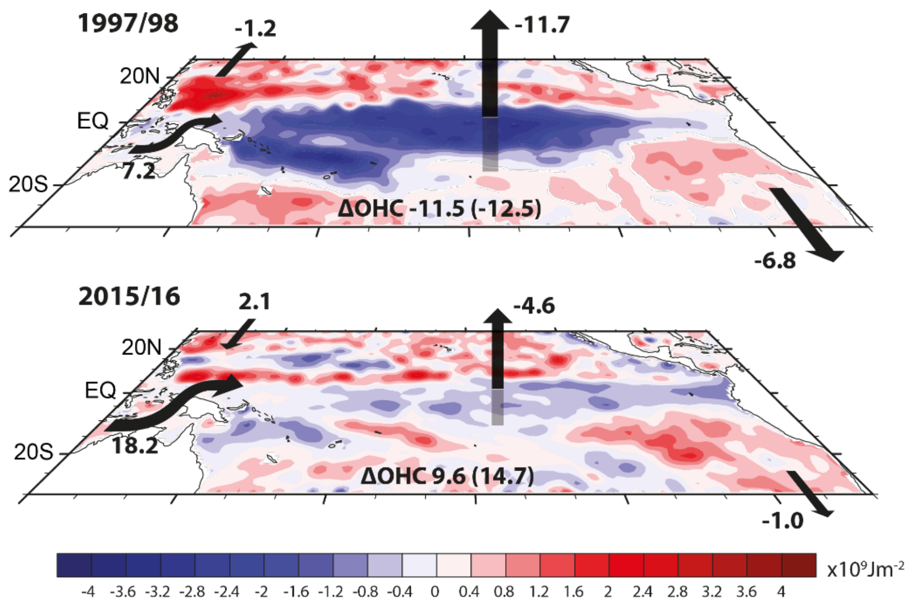


From Laura Ferranti

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 $10^9 Jm^{-2}$) and accumulated heat (ZJ) during El Nino events

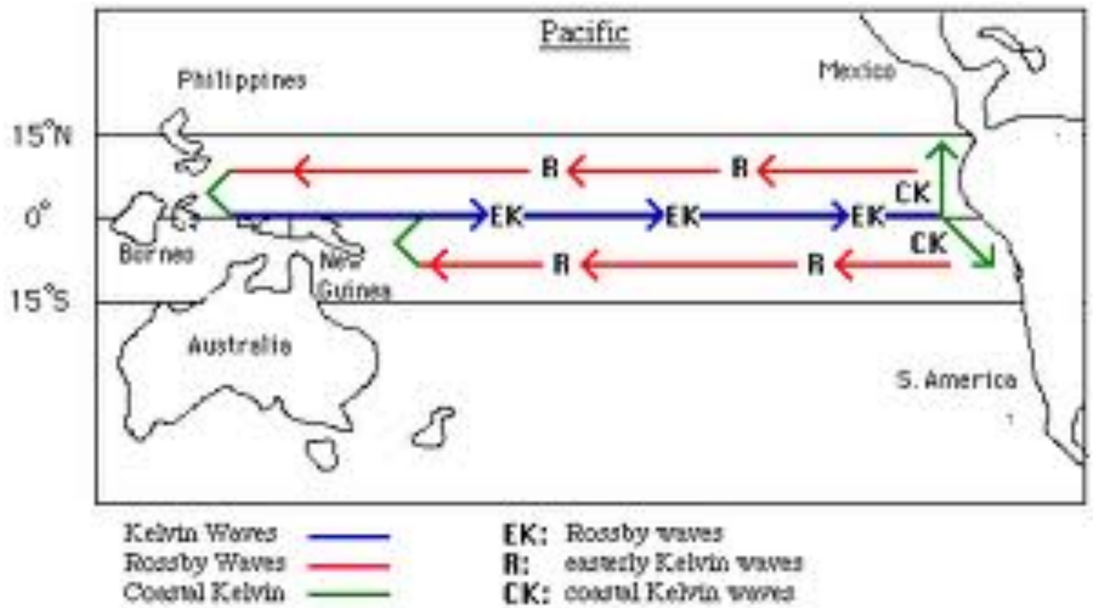
(1 ZJ = 10^{21} J. Annual human energy consumption is ~ 0.5 ZJ)

From Mayer, Balmaseda and Haimberg 2018

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 explains relationship between thermocline and SST
   Very predictable

   It does not explain the "a-periodicity".
   It does not explain phase-locking to the seasonal cycle

2. **Coupled Instability, stochastically triggered.**
   System with 2 time scales. Atmospheric noise triggers ENSO.
   Limited predictability Moore and Kleeman J.Clim 1999)

Stochastically forced ENSO: System with 2 time scales

$$\mathbf{x}_{t+1} = \mathbf{A}\mathbf{x}_t + \varepsilon_t \;\; ; \;\; \varepsilon_t \equiv \text{white gaussian noise } \mathrm{N}(0, \sigma_\varepsilon{}^2)$$

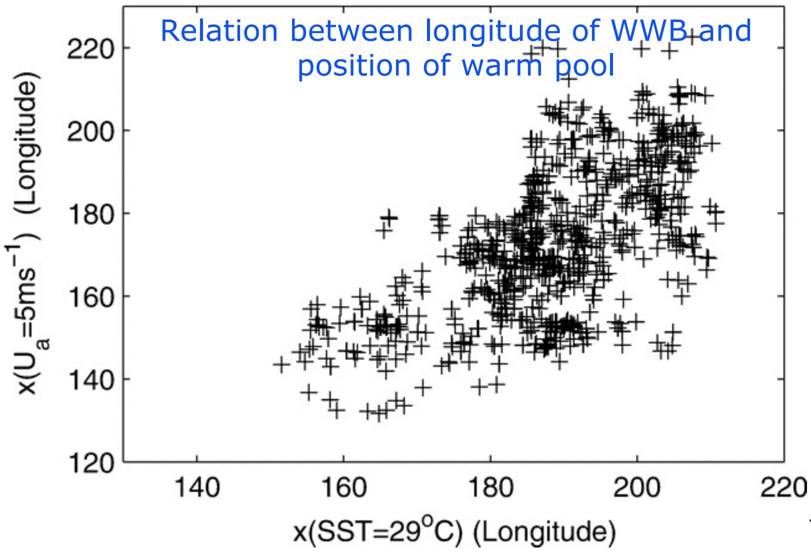
Weather noise ε can trigger a coupled instability (Westerly Wind Bursts –WWB)

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



Einsman et al 2005

Multitude of conceptual models for EL Nino

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   System with 2 time scales. Atmospheric noise triggers ENSO.
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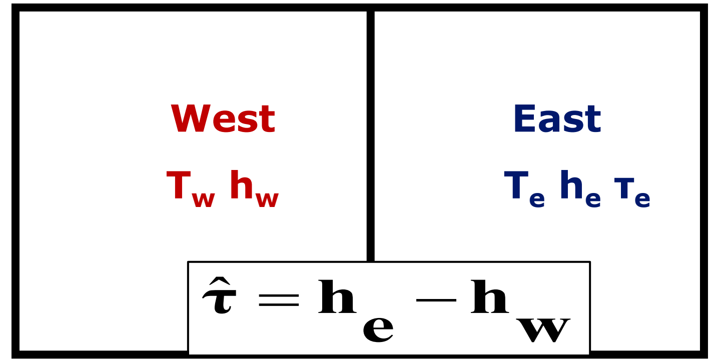
3. **Recharge/Discharge mechanism**. (Jin 1995)
   Regular or chaotic behaviour, from multiple feedbacks.
   The strength of feedbacks-hence chaos-depends on the mean state

Recharge/Discharge mechanism

$$\frac{dh_W}{dt} = -rh_W - \alpha\hat{\tau}.$$

$$\frac{dT_E}{dt} = -cT_E + \gamma h_E + \delta_s \tau_E.$$

$$\hat{\tau} = bT_E,\ \tau_E = b'T_E,$$



R describes the Bjerkness Feedback for tropical ocean-atmosphere interaction. It leads to instability when

$$(R - r)/2 > 0$$

αbγ is the recharge/discharge mechanism, leading to oscillations for real **ω**

$$\omega = \sqrt{\alpha b\gamma - (r + R)^2/4}$$

$$\frac{dh_W}{dt} = -rh_W - \alpha bT_E$$

$$\frac{dT_E}{dt} = RT_E + \gamma h_W,$$

$$R = \gamma b + \delta_s b' - c$$

μ Is the coupling intensity

$$b = b_0\mu,$$

F.F Jin, Parts I and II, JAS, 1997

Kind of solutions

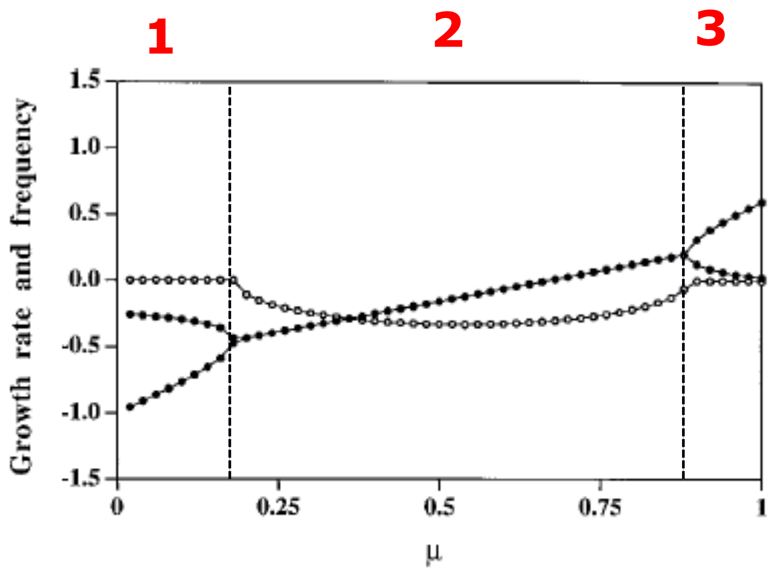


FIG. 2. Dependence of the eigenvalues on the relative coupling coefficient. The curves with dots are for the growth rates, and the curve with circles is for the frequency when the real modes merge as a complex mode (corresponding periods in years equal $\pi/3$ divided by the frequencies).

1. **Weak coupling: 2 decaying modes**
2. **Medium coupling: Oscillations**
3. **Strong coupling: 2 unstable modes**

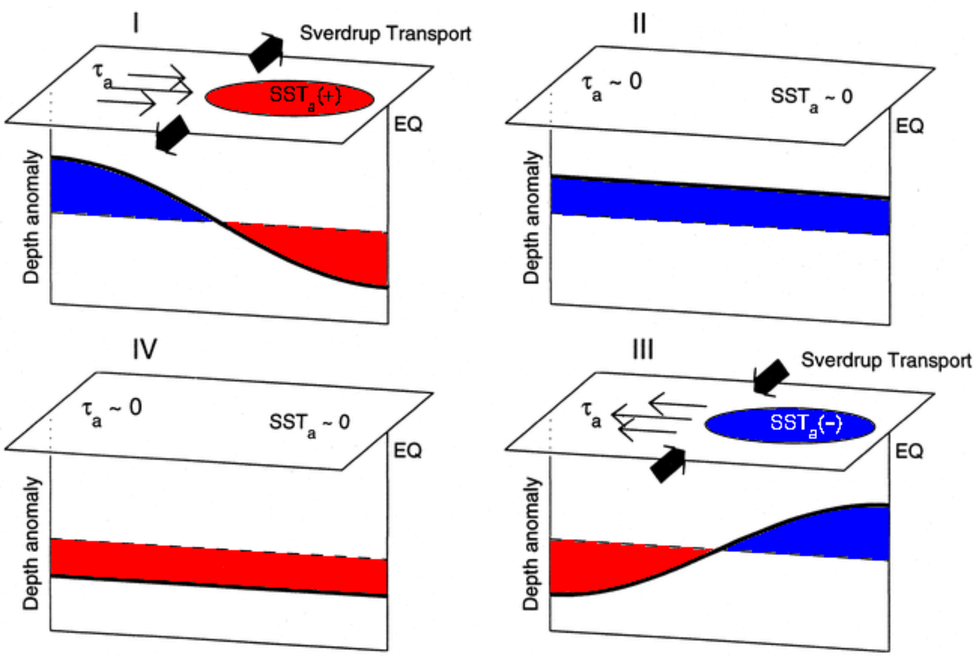
The parameters depend on the background ocean state

The presence of bifurcation leads to chaotic behaviour

Generalizations can include:

- **Seasonal cycle**
- **Stochastic forcing**
- **Variations of background state (climate change, decadal)**

The Recharge/Discharge oscillator



F.F Jin, Parts I and II, JAS, 1997

Equatorial Ocean Heat Reservoirs provides Memory/Stability across ENSO phases

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

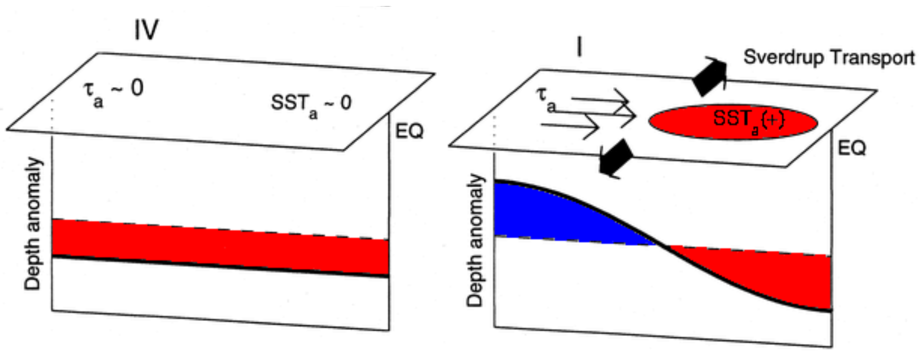
II. A Discharged Pacific favours the occurrence of La Niña

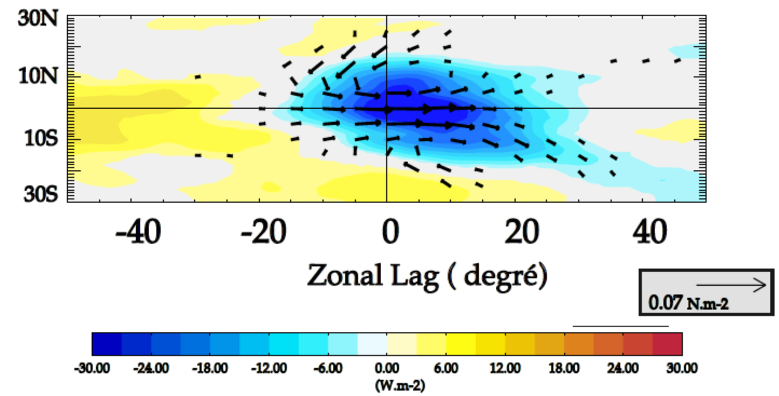
III. During La Niña, the easterlies induced recharge.

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

The spark & the fuel (© M. McPhaden)

Stochastic discharge/recharge oscillator





The fuel: ocean heat content

The spark: Westerly Wind Events

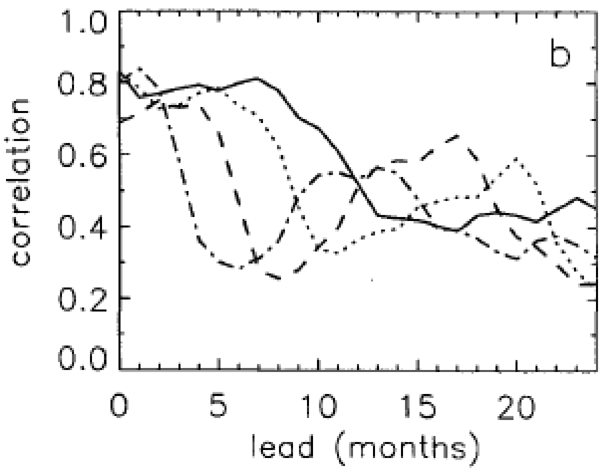
The background state sets the level of instability: it explains ENSO diversity and helps to understand model errors, predictions and ENSO projections

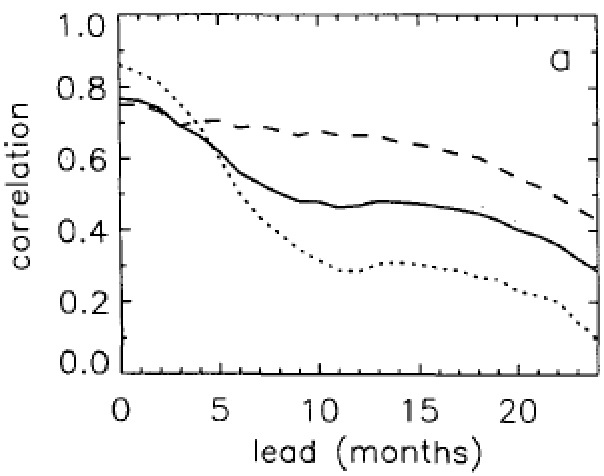
The occurrence of WWE is modulated by background SST: importance for predictability and projections of ENSO on a warmer climate.

PREDICTING ENSO

First attempts were deterministic

With Statistical/Simplified dynamics/hybrid models





1965-1980
1980-1994
1965-1994

Balmaseda et al 1995

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

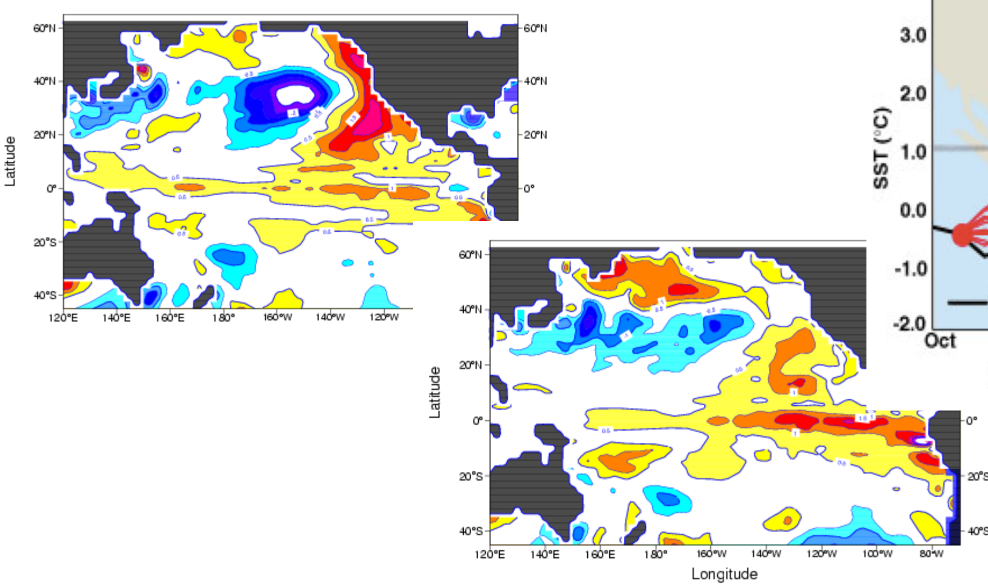
2) Re-emergence of skill

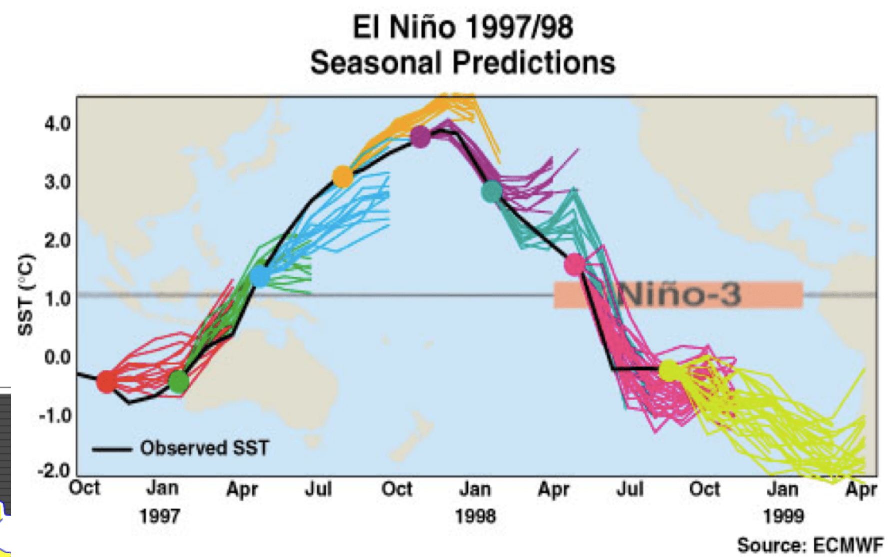
3) decadal variations on ENSO prediction skill

Note first ENSO predictions were made at 24 months lead time

Predicting ENSO

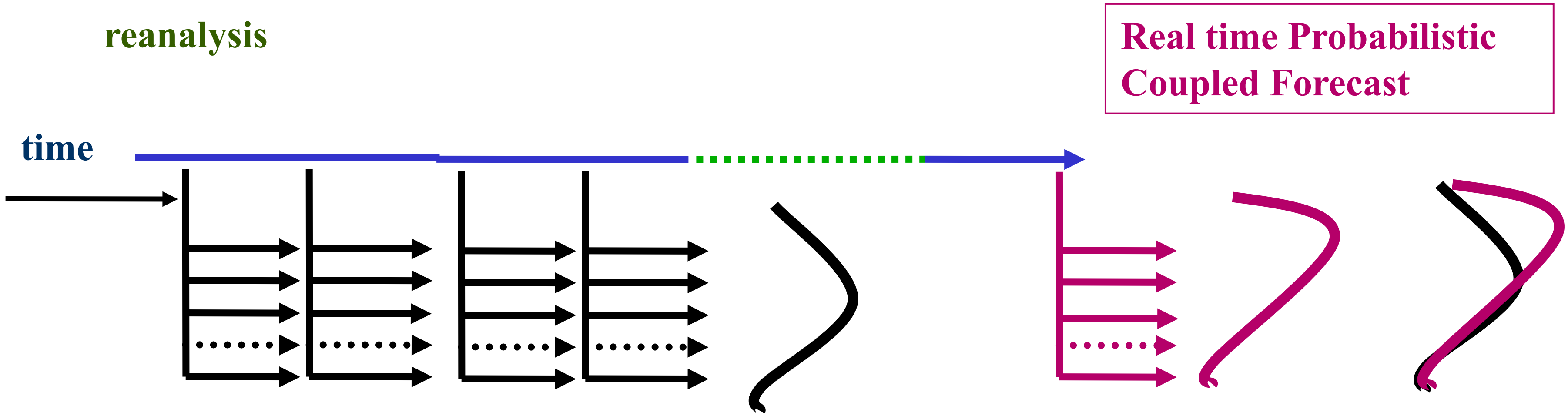
- From mid 90’s: with GCMs
  - Ocean initial conditions (reanalyses)
  - Coupled model
  - **Ensembles**
  - **Reforecast for calibration and skill assessment**





Stockdale et al 1998

Dealing with model error: Reforecast



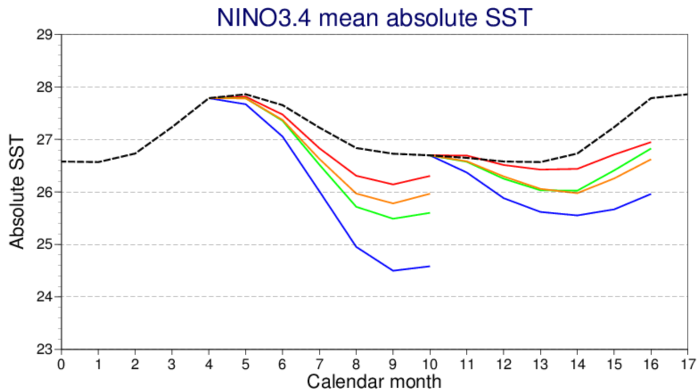
Coupled reforecasts, needed to estimate climatological PDF, require a historical reanalysis

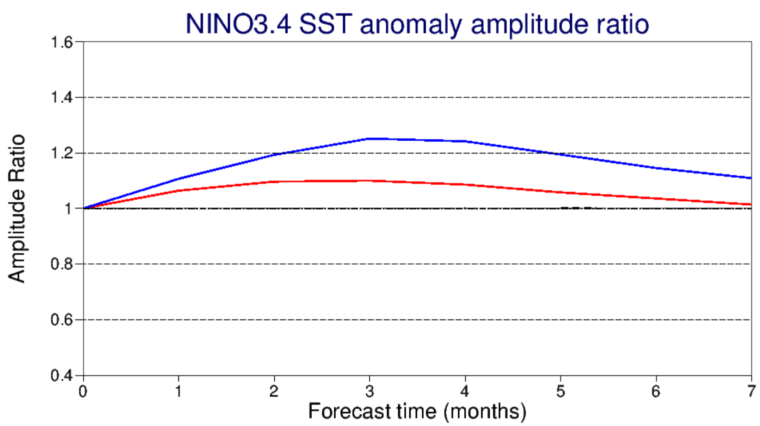
Consistency between historical and real-time initial conditions is required.

Reforecasts are also needed for skill estimation

Example of fc drift in Seasonal Forecast

SEAS5 **S4** **S5-lr** **S5-mr**





SEAS5: Current ECMWF Seasonal Forecasting System
S4 : Previous " " " "
S5-lr : As SEAS5, with low resolution ocean and atmos
S5-mr: As SEAS5, with low resolution ocean, high res atmos

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 of 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!!

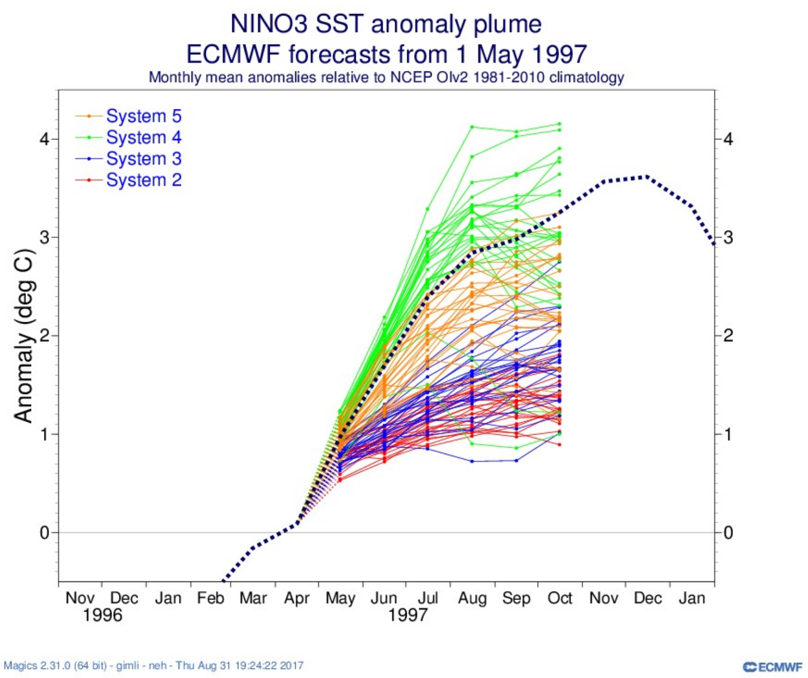
Balmaseda and Anderson 2009

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**



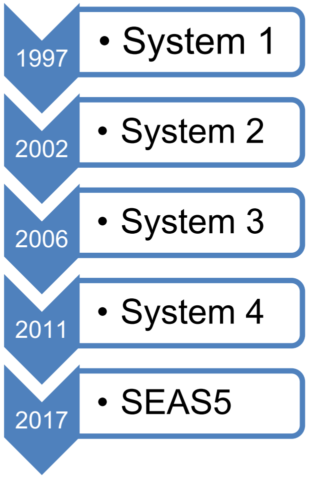
S2 inability to generate WWB caused under prediction of 1997/98 ENSO
(Vitart et al 2004).

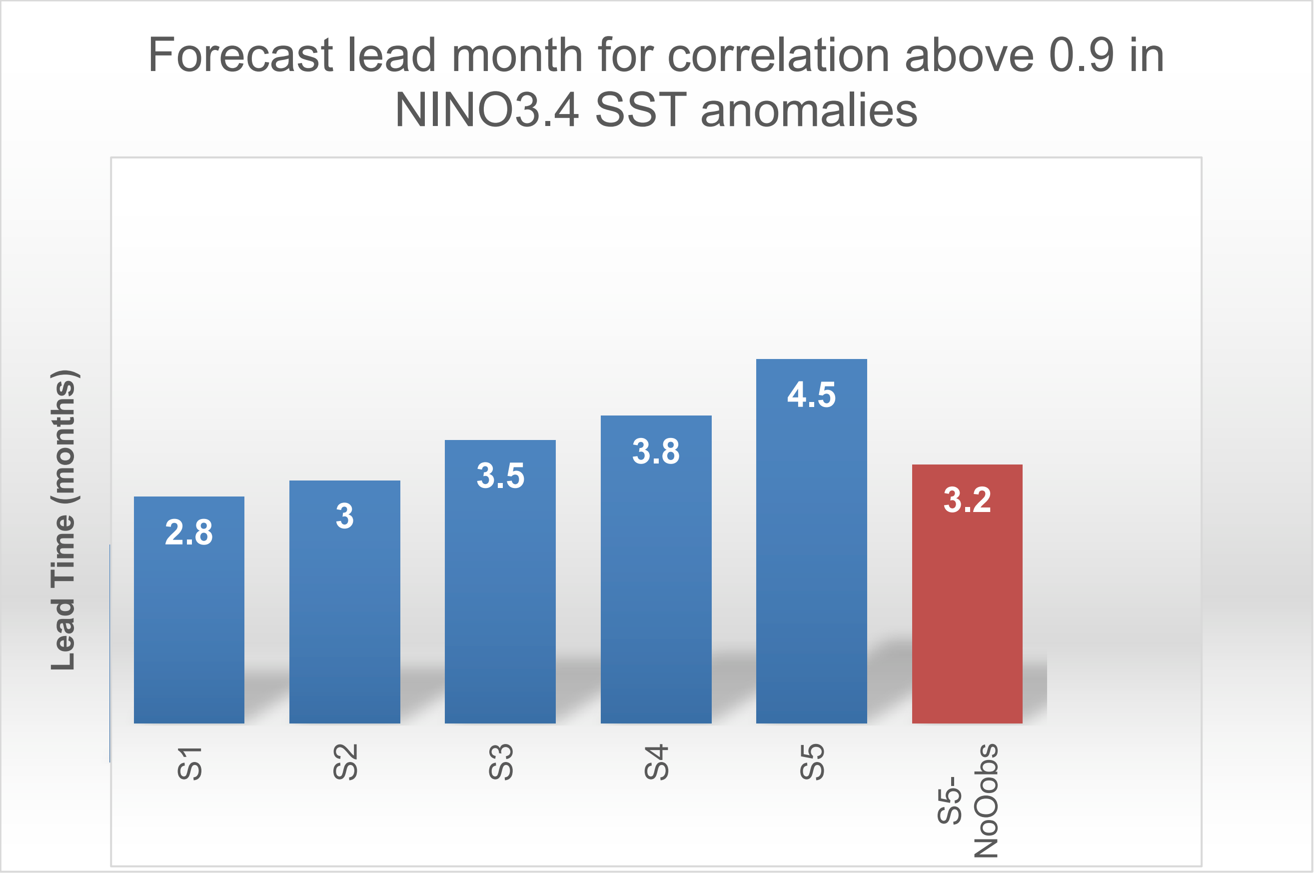
As the model improved

SEAS5 became operational in Nov 2017

20 years or progress in ENSO prediction at ECMWF

and contribution of ocean observations





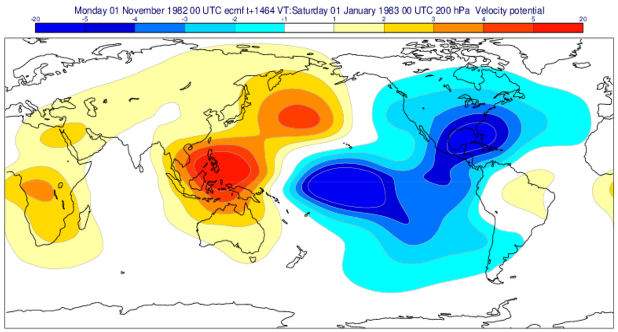
- S1 was the first ECMWF seasonal forecasting system. Implemented as a pilot in 1997
- SEAS5 is the latest ECMWF seasonal forecasting system. Implemented in November 2017.
  Contributes to Copernicus Climate Change Services C3S.

Seasonal Forecasts Diversity in ENSO teleconnections

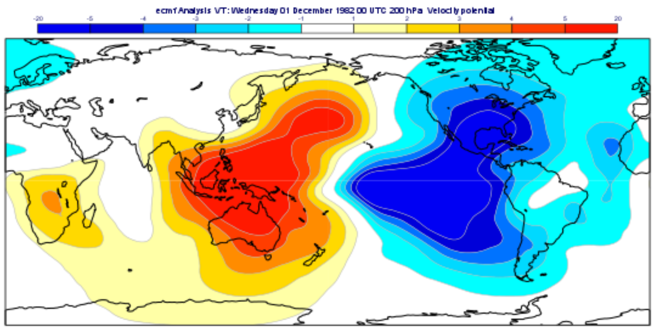
Velocity Potential 200hPa

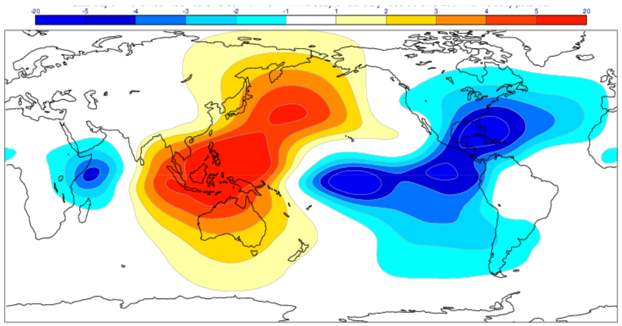
SEAS5

Era-Interim

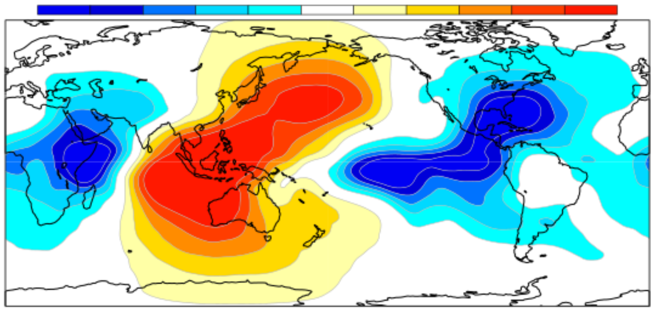


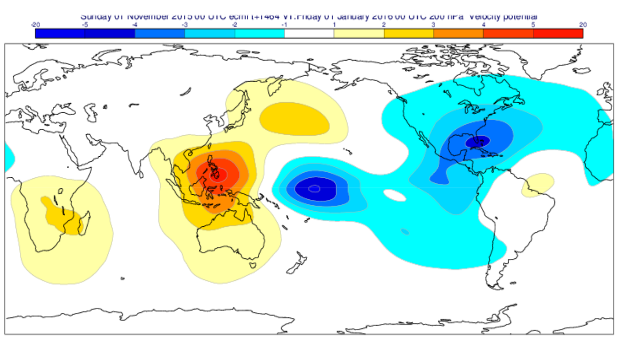
1983



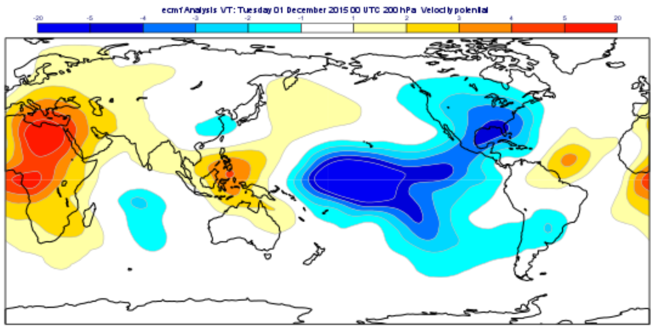


1998





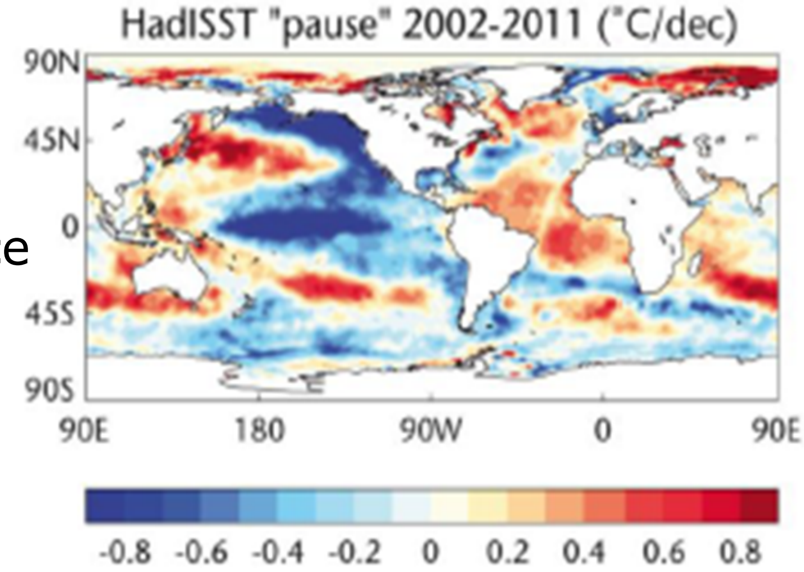
2016



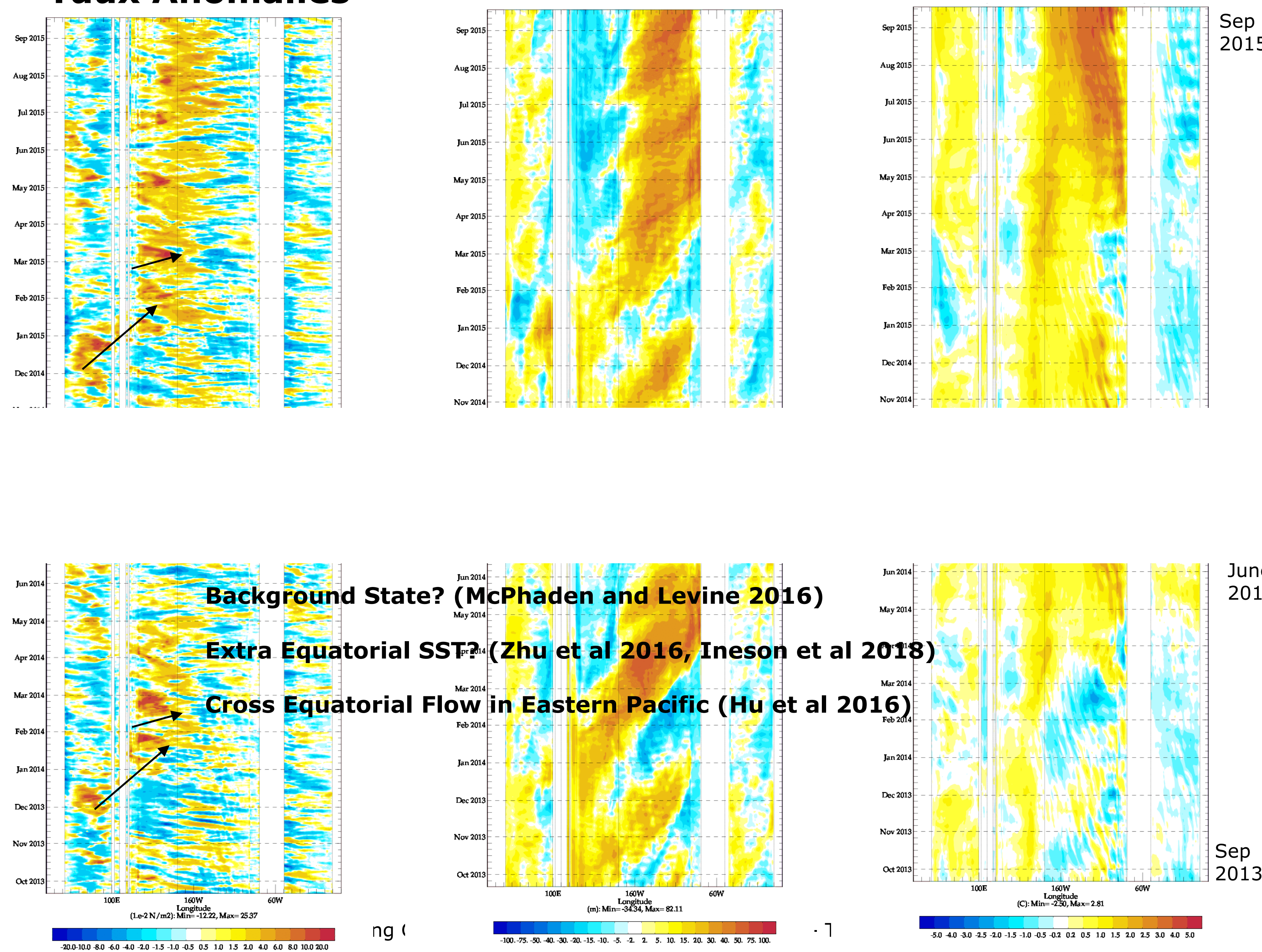
From Laura Ferranti

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

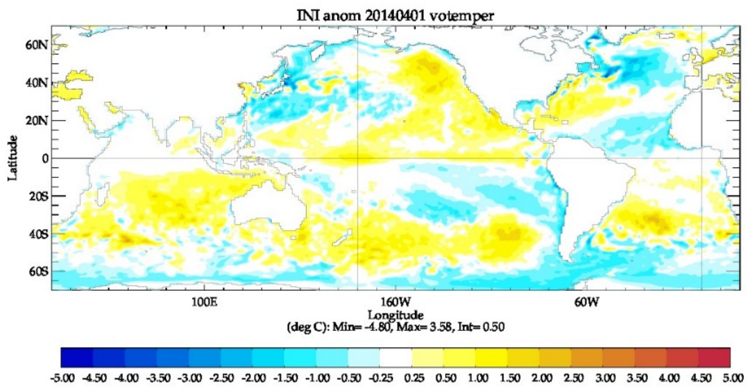


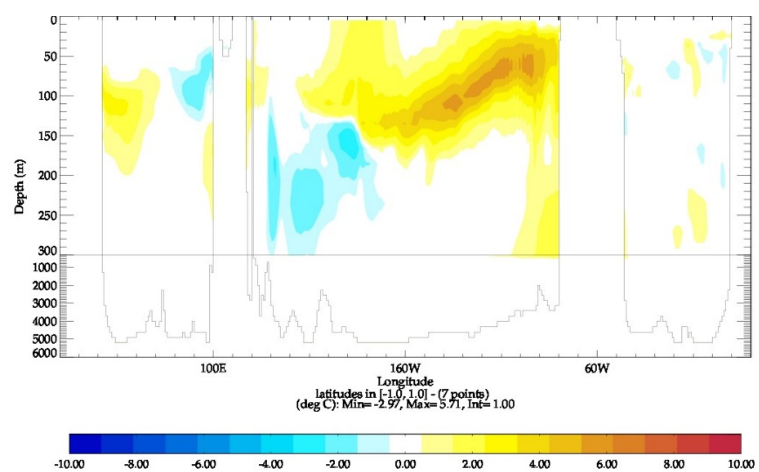
Taux Anomalies D20 Anomalies SST Anomalies



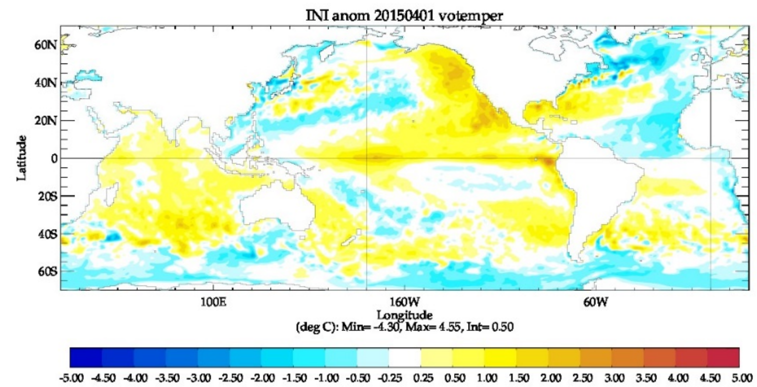
Temperature Anomalies From Ocean Reanalysis

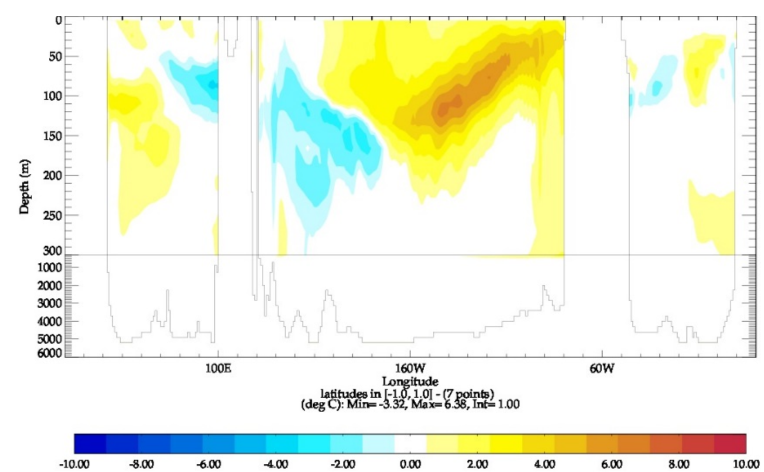
APR 2014





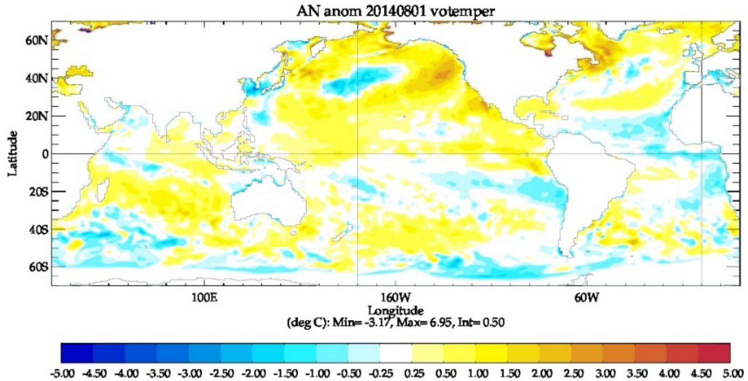
APR 2015

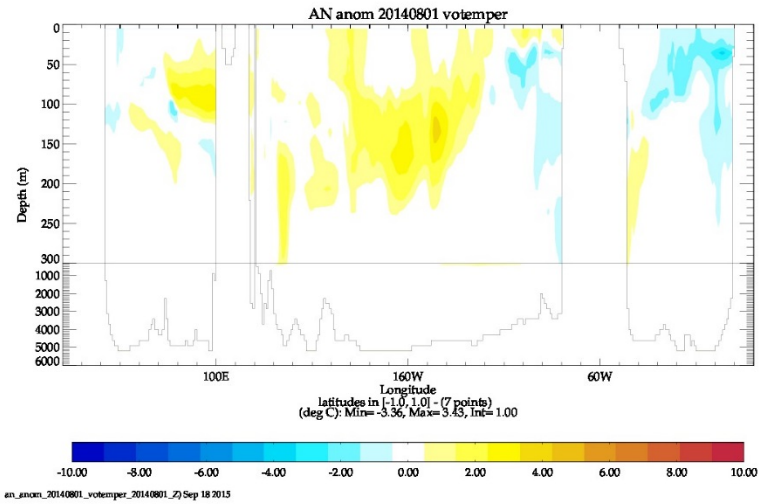




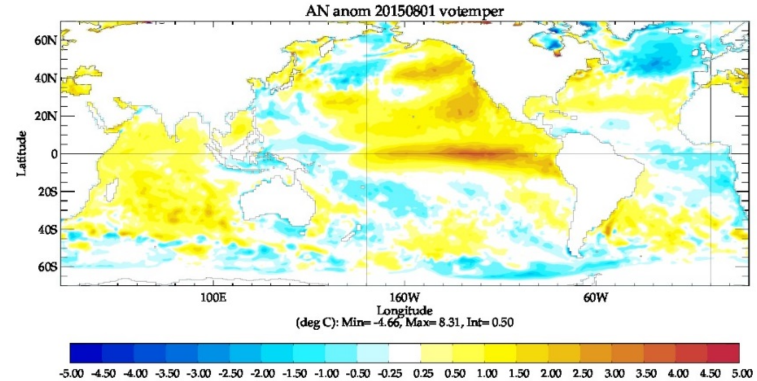
Temperature Anomalies From Ocean Reanalysis

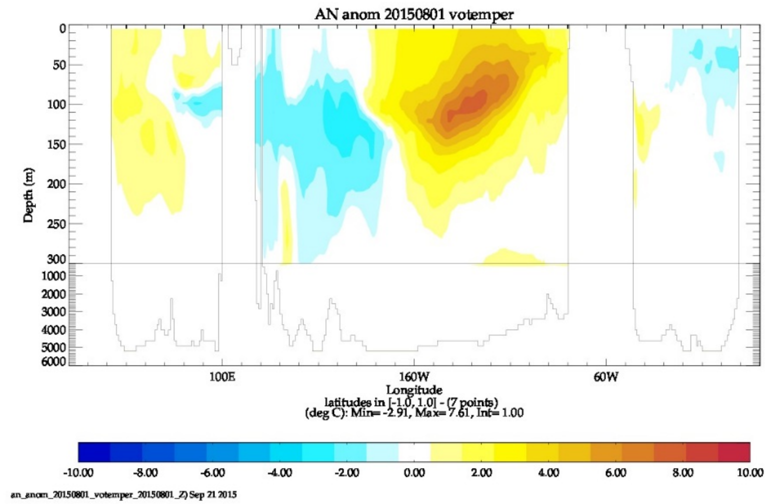
AUG 2014





AUG 2015

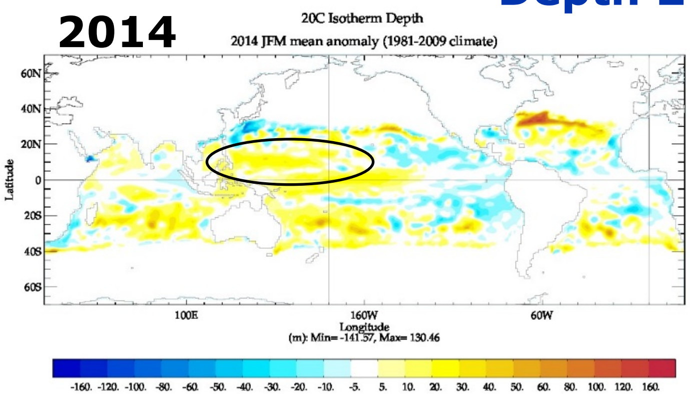




Another view

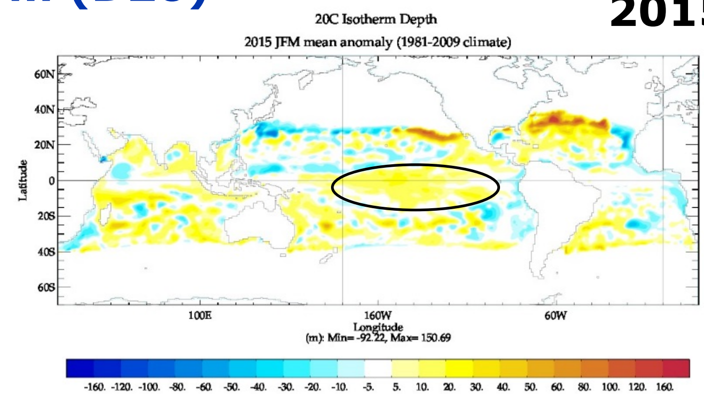
Depth 20C Isotherm (D20)

2014

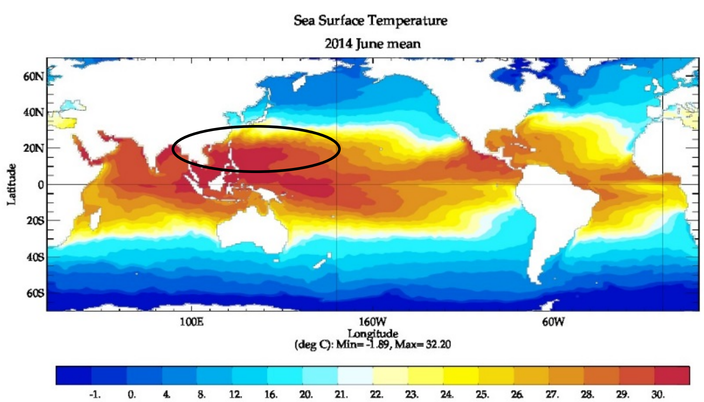


JFM

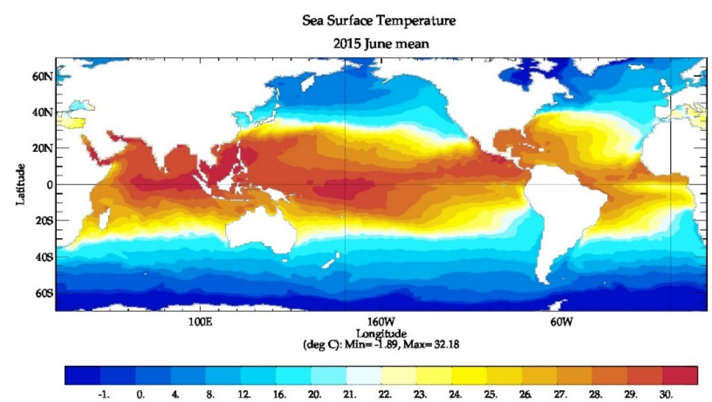
2015



SST



June



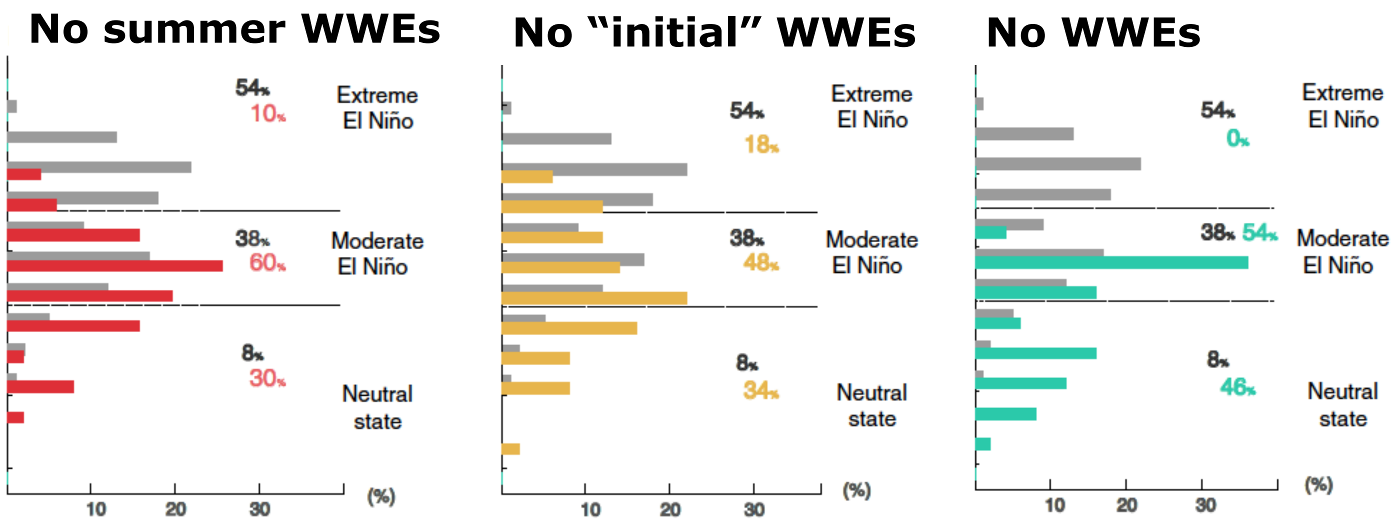
- North-West Trop Pac thermocline is deeper in JFM 2014. Possibly causing off Equatorial SST peak values later in June and associated convection.

- 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

Zhu et al 2016, Hu et al 2016, McPhaden et al 2016, Inesson et al 2018 (among others)

Weak or strong El Niño: role of WWEs.

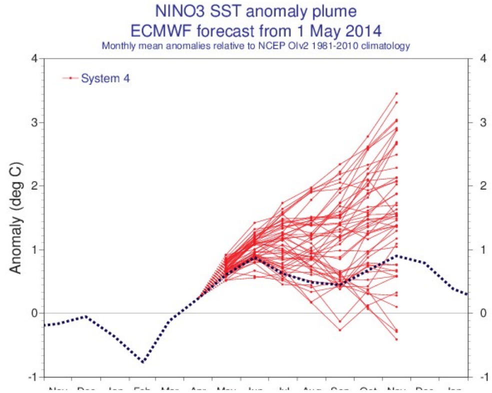
(Puy et al. 2017)



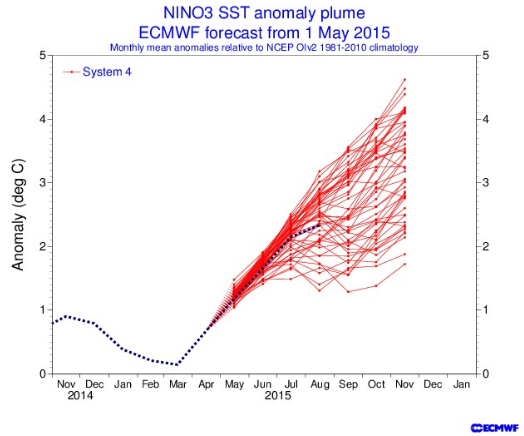
- Initial & summer WWEs: necessary condition for extreme El Niño
- Summer WWEs seem to matter more (make extreme El Niño ≈ 5 more likely)

S4 El Nino Forecasts: 2014 v 2015?

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



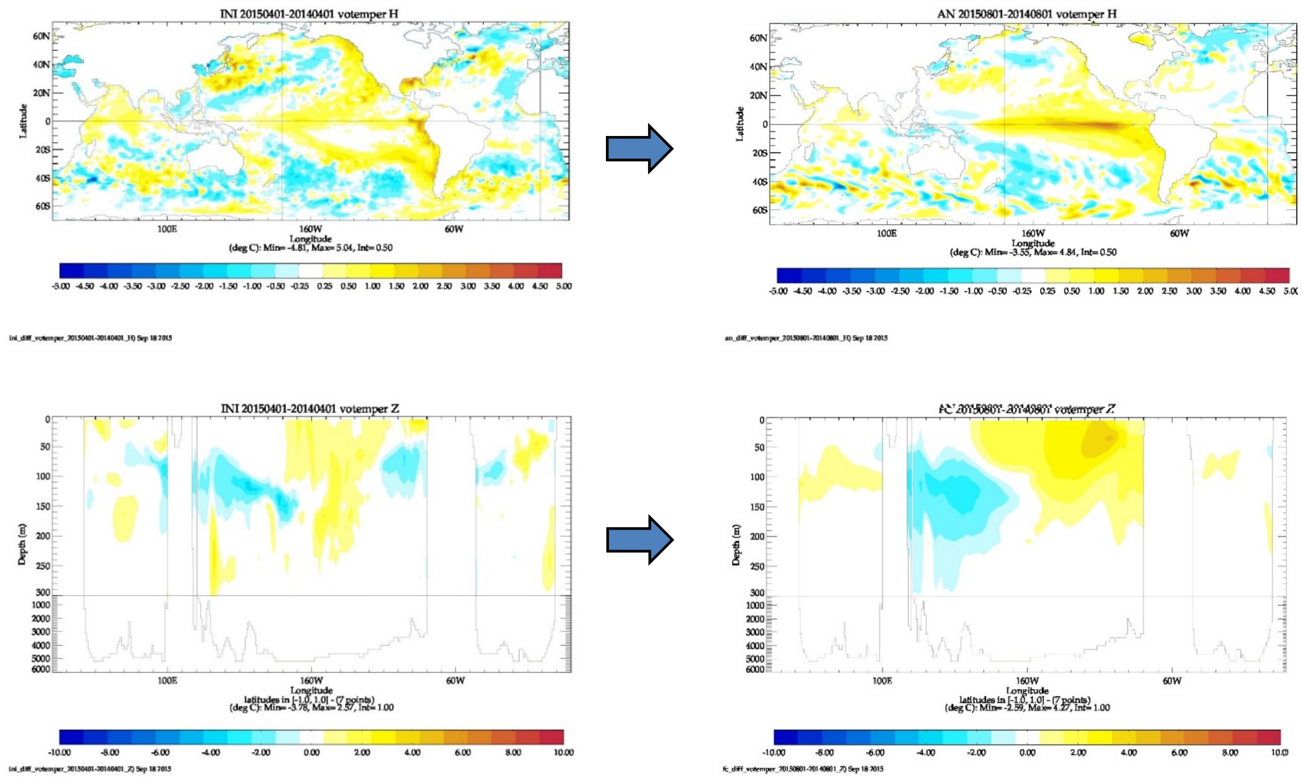
- What causes the large spread in the fc? Is that spread a good estimation for predictability?



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.

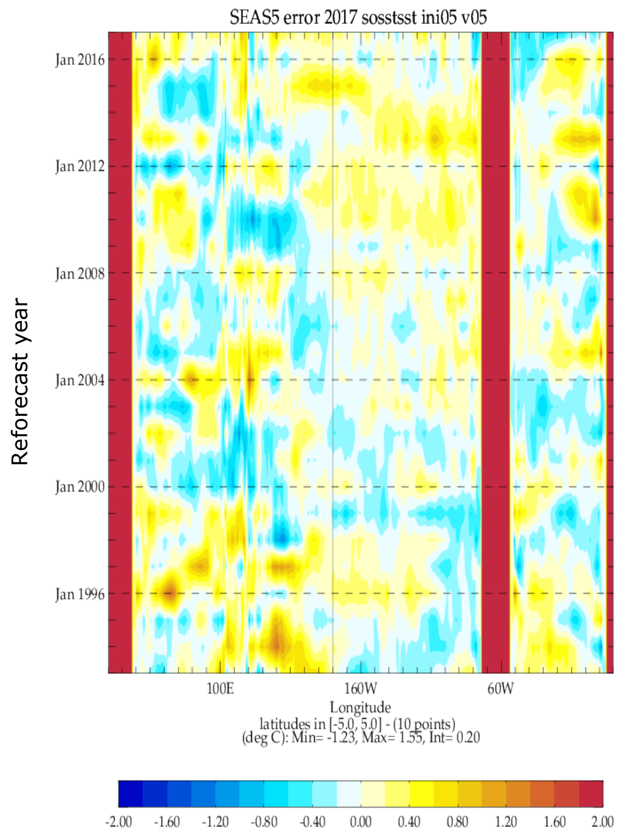
El Nino 2015/16: example of scale interactions

- **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

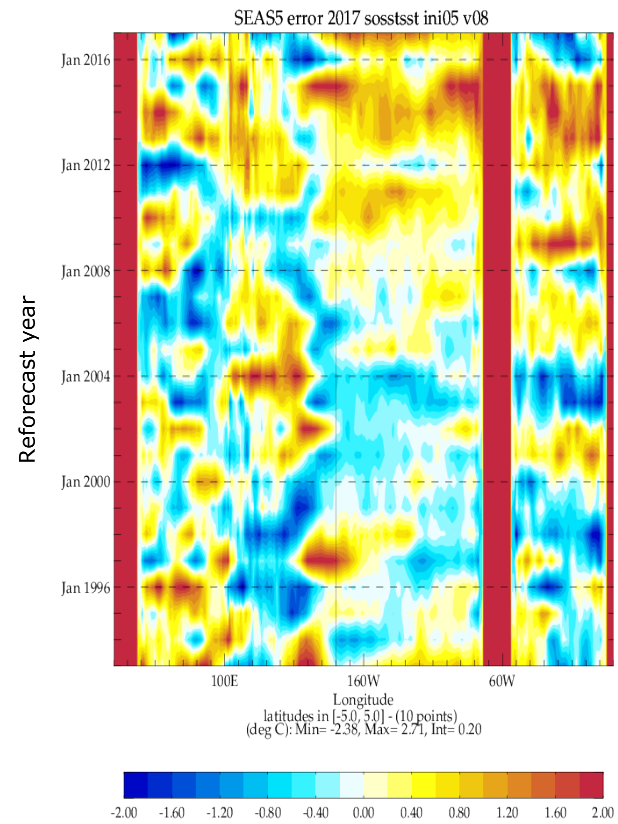
SEAS5 Non stationary errors in ENSO

SST normalized error in the anomaly. May starts

May (1m lead time)



August (4m lead time)



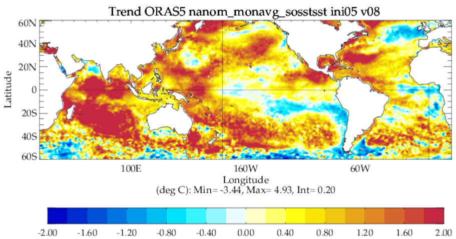
Eastern-Central Pacific: Apparent tendency to produce +ve SST errors
The tendency appears already in the first month.

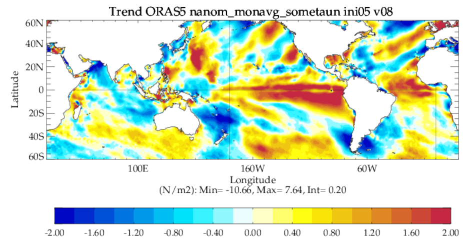
SEAS5 Non stationary errors in ENSO

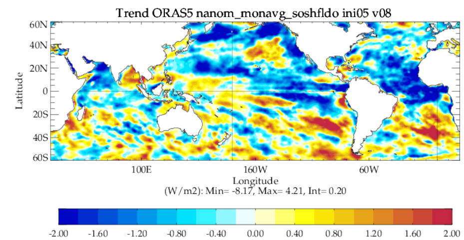
Trends in 1993-2017 (May starts, verifying in August)

SST | Meridional wind stress | Absorbed Solar Radiation

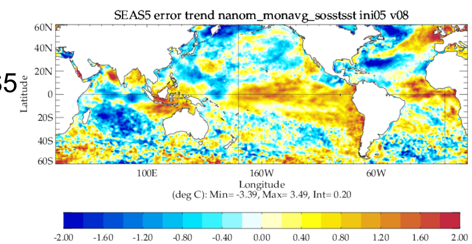
ORAS5

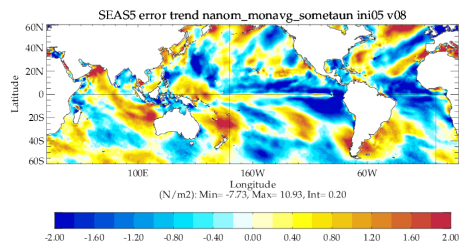


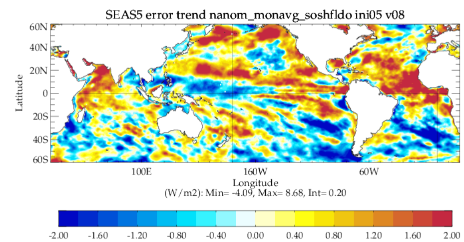




SEAS5-ORAS5







Normalized anomalies

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)

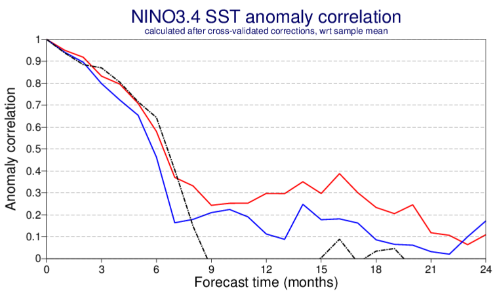
Same results obtained by difference in errors in (2014-2017) – (1993-2014)

New directions

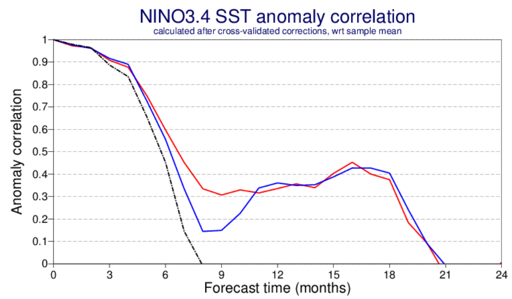
1. ENSO predictions at 24 months
2. Decadal variations in ENSO predictability

Anomaly correlation NINO 3.4 SST anomalies

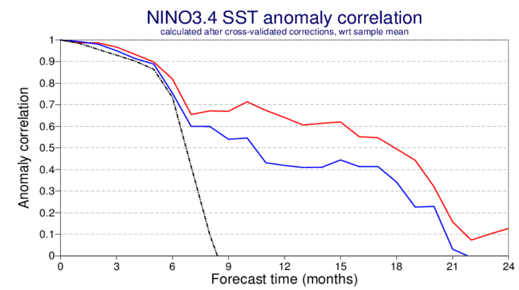
1901-1950



1950-1981



1981-2009



Initialization A **Initialization B**

Courtesy of Antje Weisheimer

Centennial reanalyses are key for seasonal and decadal predictions

3. Interbasin connections
4. Meridional circulation

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.
    - In forecast, background state depends on model quality and initialization.
    - 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
  - Initialized predictions have a great potential for further understanding ENSO in a changing climate

- Ongoing research areas:
    - ENSO prediction beyond year 1
    - ENSO modulation by decadal variations and climate change using Centennial Reanalyses
    - Interbasin connections and meridional circulation

Back up slides

SEAS5: Typical bias and ACC

Bias

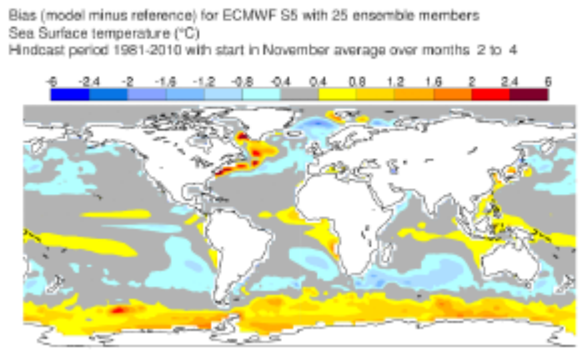
System 5

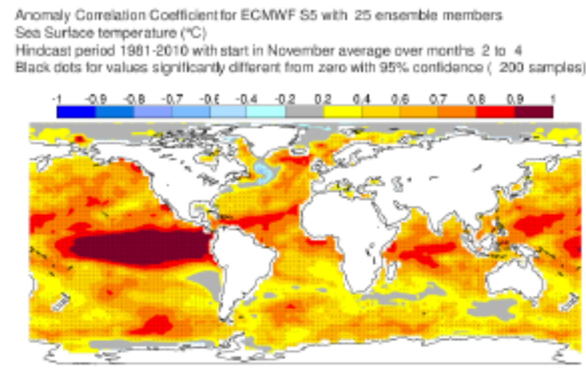
DJF

Anomaly Correlation

System 5

SST





Precip