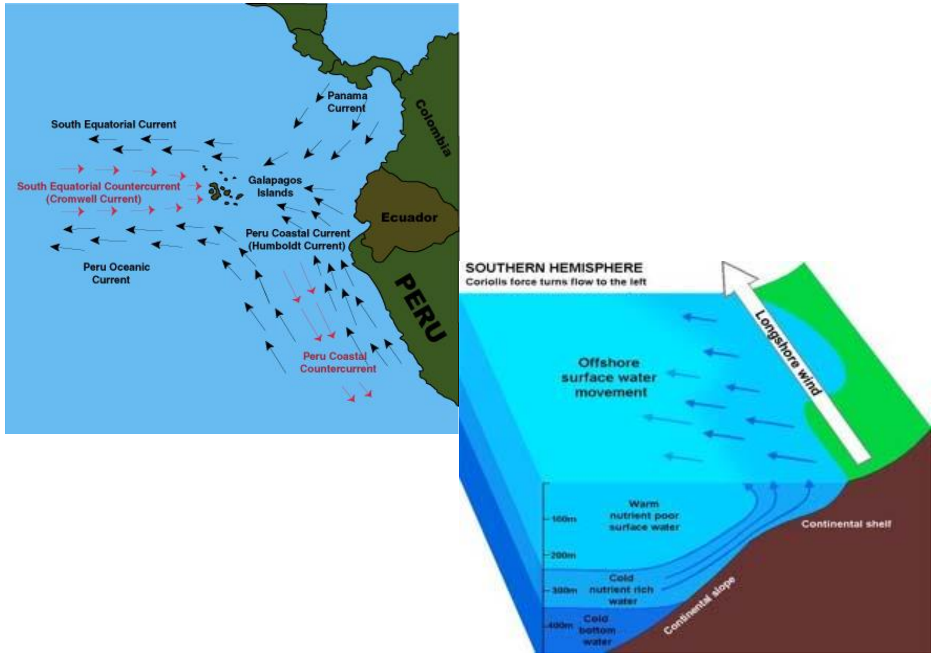
Forecasting ENSO

In a changing climate

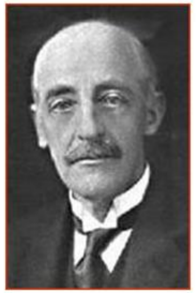
- ENSO as a coupled ocean-atmosphere mode: some facts
- ENSO and the energy cycle
- A brief history ENSO prediction
- The disruptive 2014 and 2015 El Niño and implications
- The 2023-2024 El Niño

Origins of ENSO:El Nino Southern Osciallation

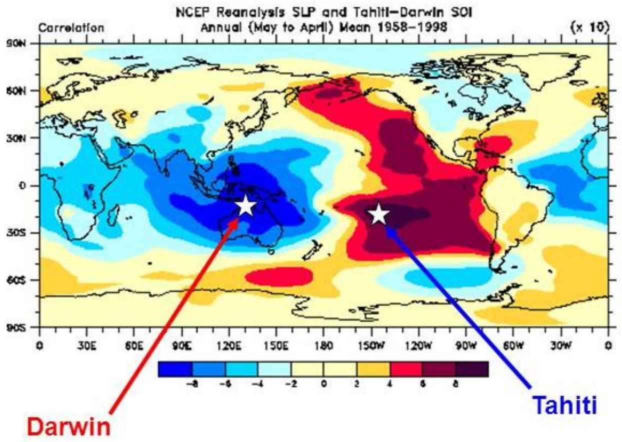
El Niño
Named by Peruvian Fishermen Tradition
Oceanic impact on fisheries and nutrients



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



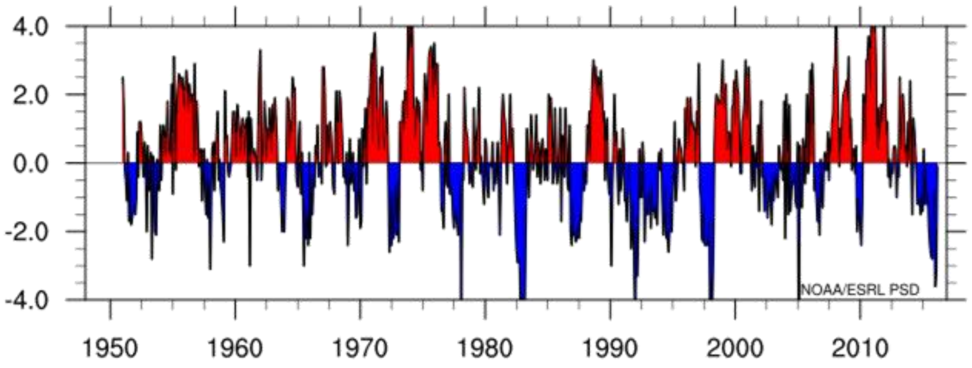
Sir Gilbert Walker
(1868-1958)

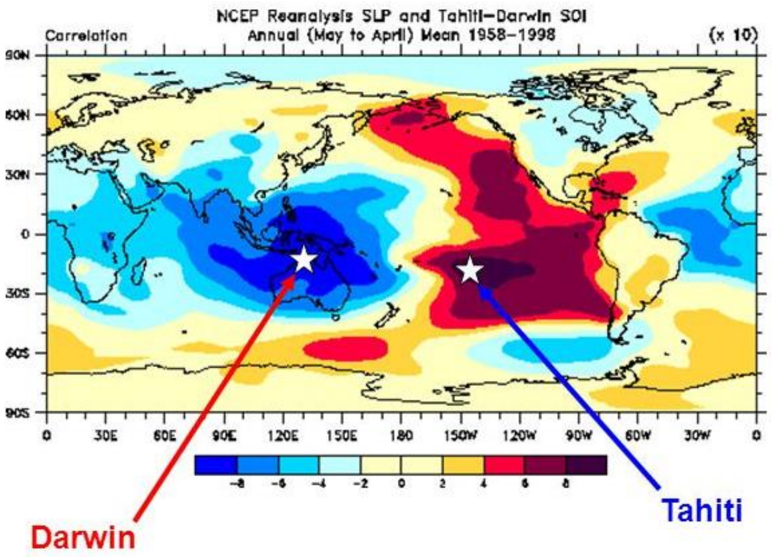


Origins of ENSO

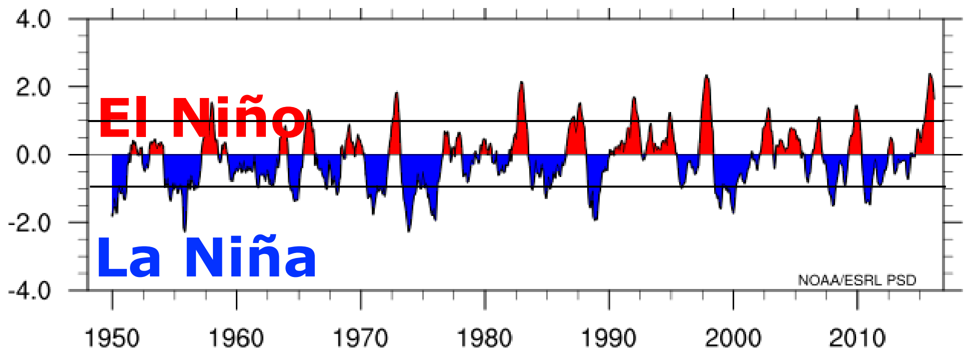
SOI in phase opposition with SST index

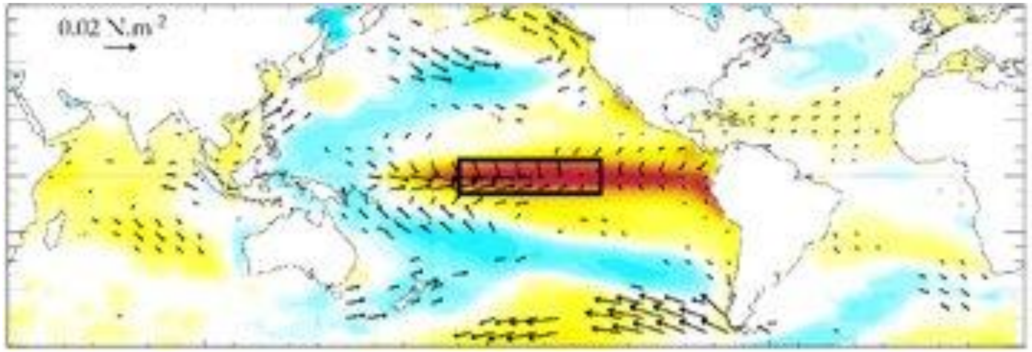
Southern Oscillation Index (SOI)
MSLP Darwin - Tahiti



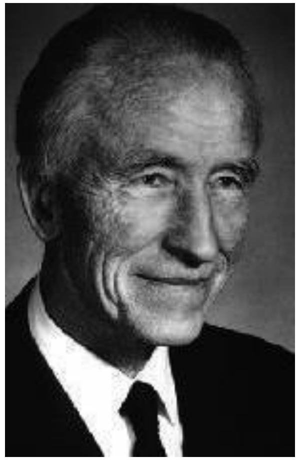


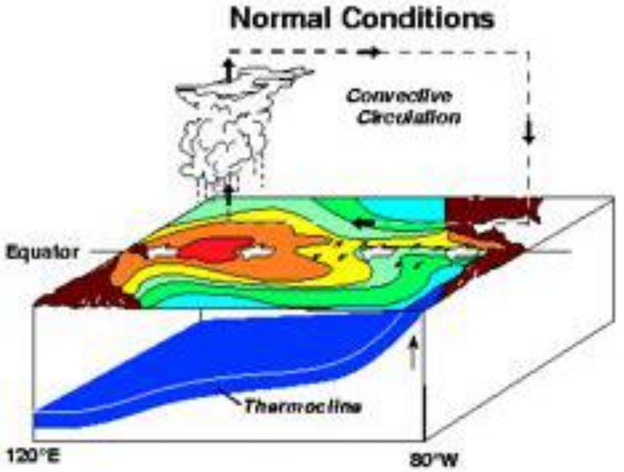
Nino3.4 SST index

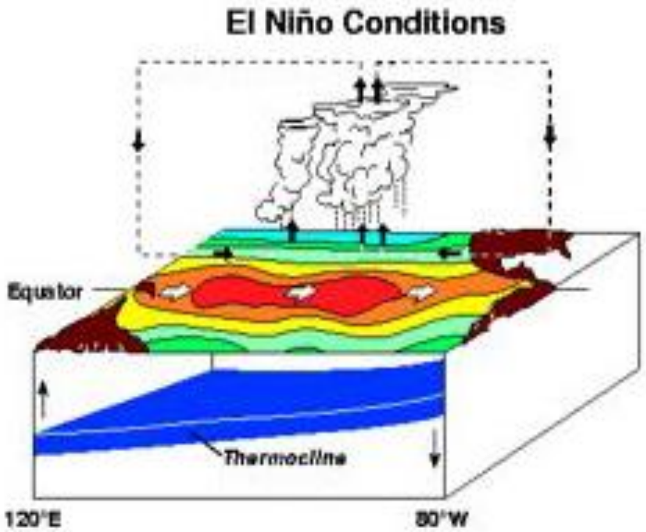


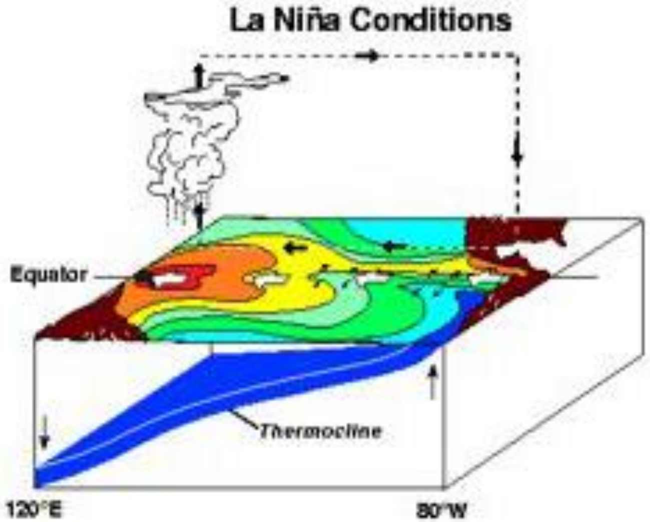


ENSO as a coupled mode









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)

ENSO:El Nino-Southern Oscillation

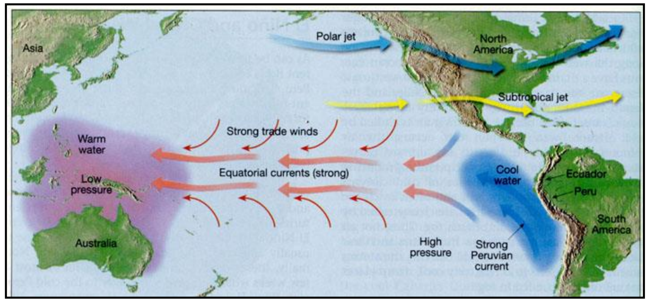
Largest mode of interannual climate variability

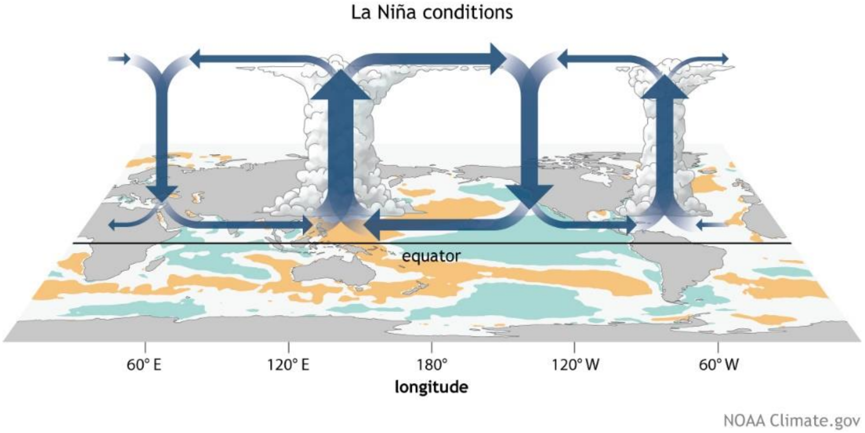
Best known source of predictability at seasonal time scales

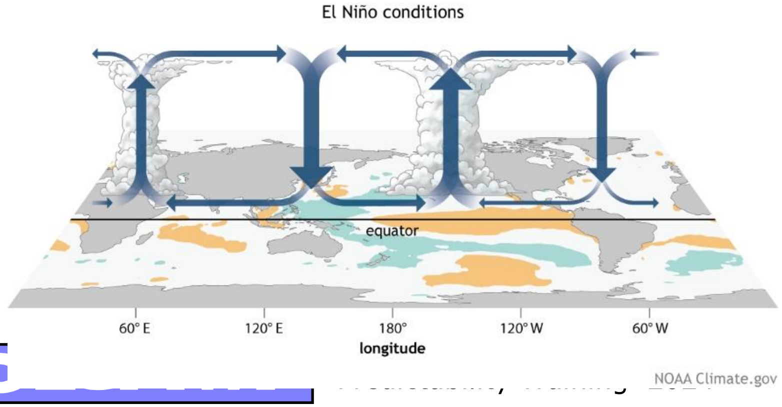
It affects global patterns of atmospheric circulation, with changes in rainfall, temperature, hurricanes, extreme events

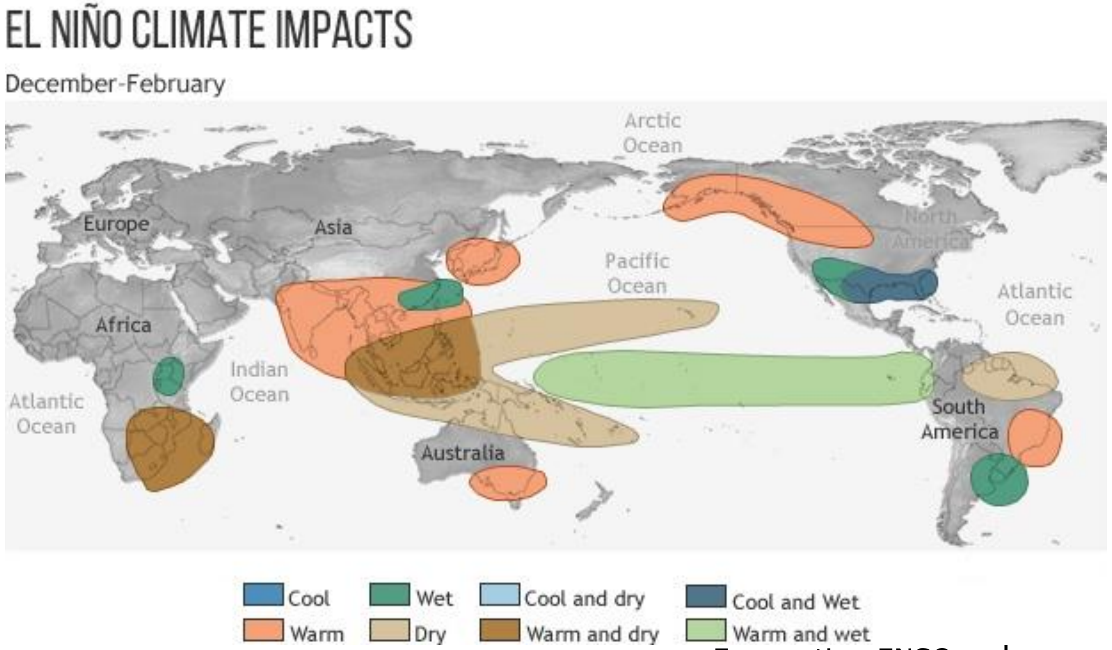
Impacts on marine ecosystems, on agriculture, health,…

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

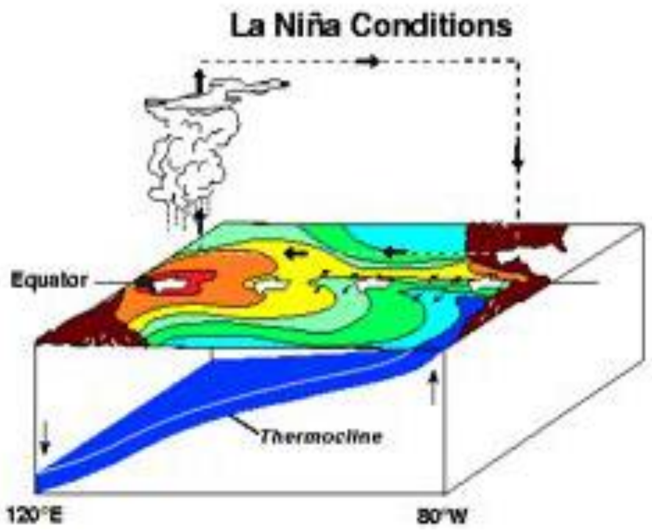






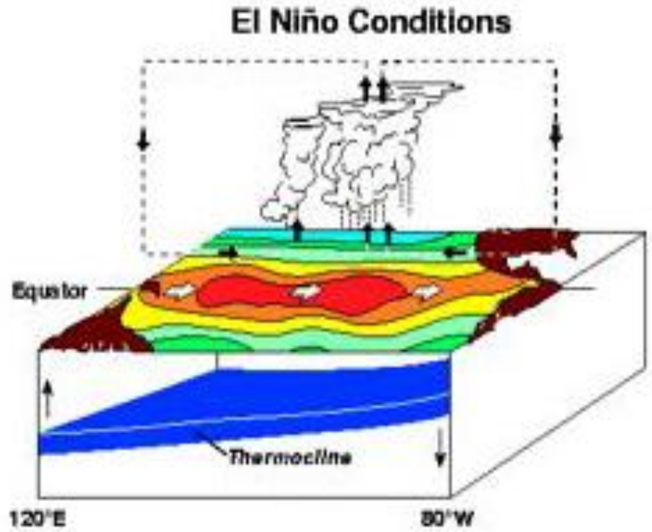


ENSO: balance of multiple feedbacks



- **Bjerkness Feedback (+):** trade winds respond to large scale SST gradients. During la Nina, West is warm - East Cold Strong winds, increased upwelling in East. During el Nino, the opposite is true, and causes the deep convection to move to the Central-Eastern Pacific. There are 2 main mechanisms
  - A) ratio zonal_wind/SST gradient. (It measures the atmospheric response to SST)
  - B) ratio SST anomaly East/zonal_wind –depends on the "thermocline feedback" (+) and heat flux feedback (-). (It measures the response to the ocean to atmospheric perturbation)

- **Warm Pool Instability (+):** westerly wind bursts, MJO, can cause the warm pool to displace eastward, dragging with it the deep atmospheric convection, and weakening the trade winds. *Intraseasonal variability and ocean mixed layer are important*

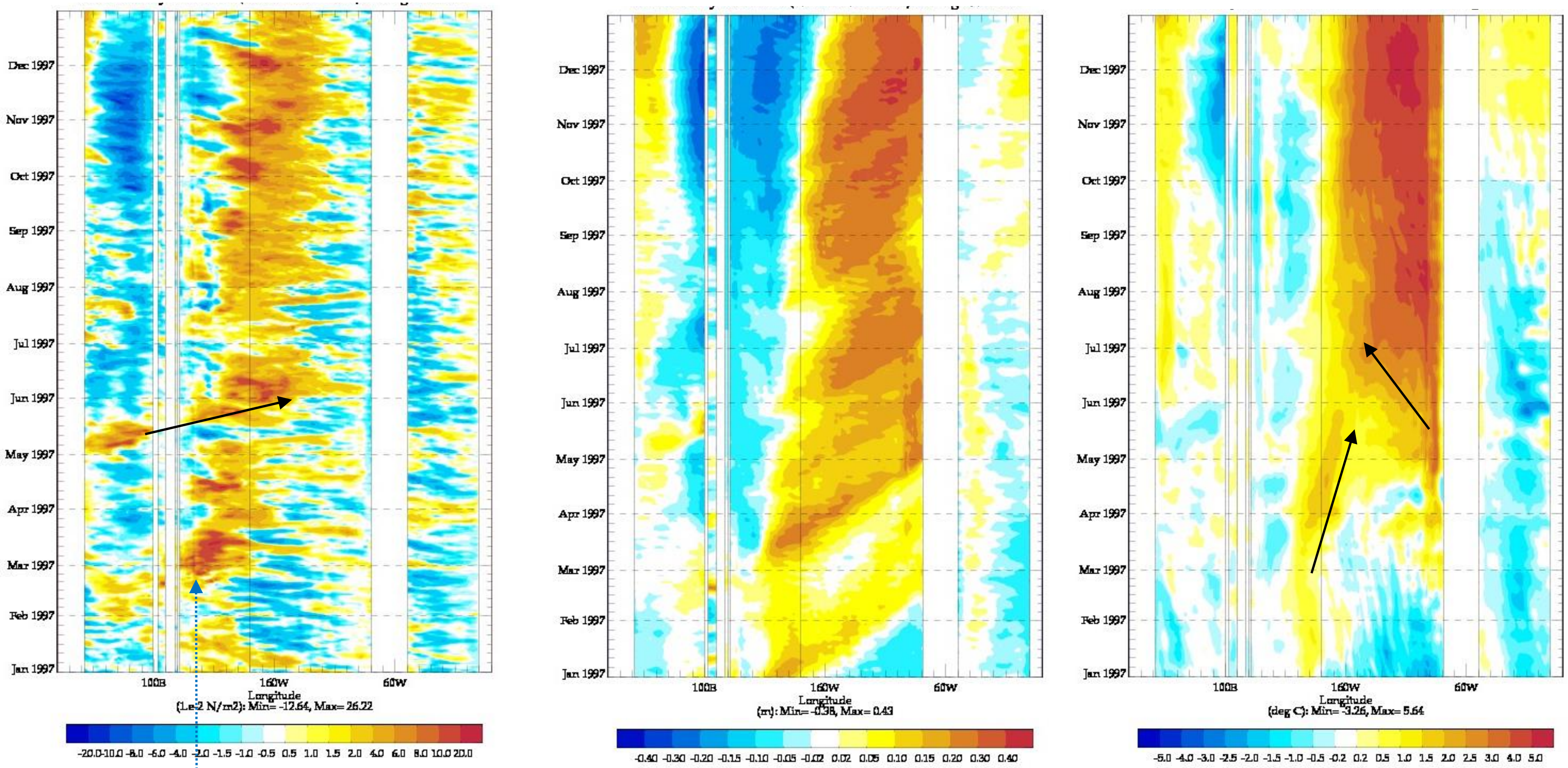


- **Latent/Sensible Heat flux feedback (-):** the atmosphere extracts heat from warm ocean (latent-sensible), reducing the amplitude of the SST anomaly.
- **Radiative feedback: cloud properties are important!!**
  - It is –ve over convective regions (deep clouds over warm SST reduce solar radiation, reducing warming).
  - it is +ve over cold stratocumulus regions (warm SST reduces stratocumulous clouds, increasing solar radiation)

These balances are difficult to represent by models. And Climate Change can affect them

Daily Equatorial Anomalies: Jan 1997-Jan 1998

Zonal Wind Stress Anomalies | SL Anomalies | SST Anomalies



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

Associated eastward propagating groups of Kelvin waves in the thermocline. 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

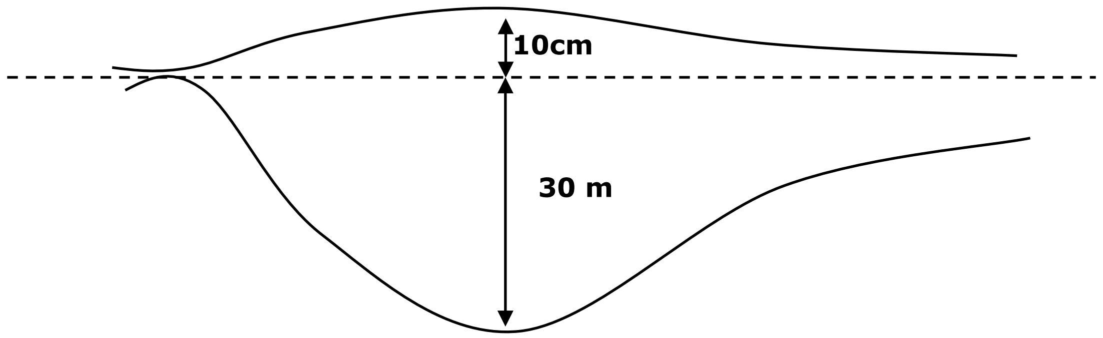
May/June 1997: More WWB . Or is this already ENSO? Bjerknes feedback in action.

Observing interior ocean Kelvin and Rossby waves: Vertical Stratification and Sea Level

- The ocean is stratified. The density of the layer below the thermocline is greater than that of the layer above.

Typically g'~g/300

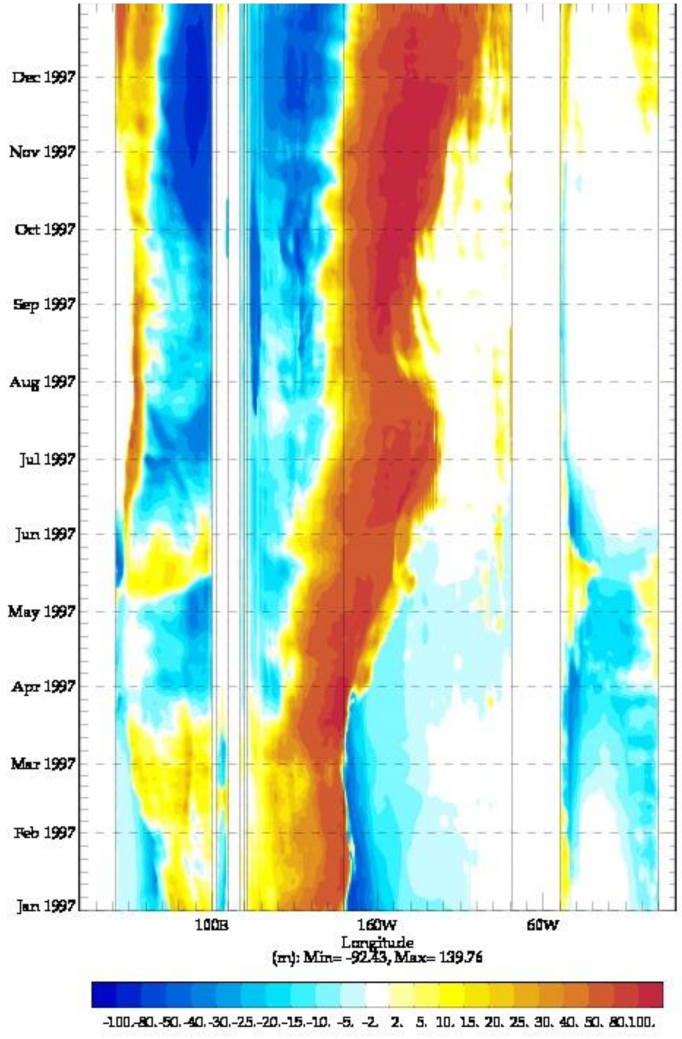
- A 10cm displacement of the top surface is associated with a 30m displacement of the interface (the thermocline).



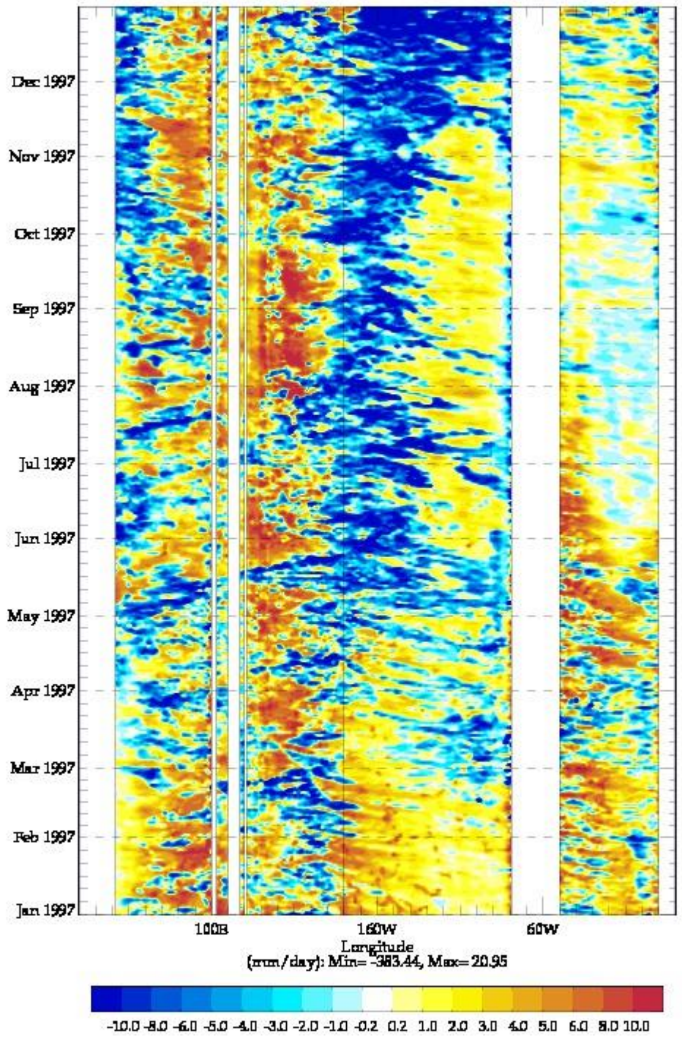
If we observe sea level, one can infer information on the vertical density structure, and we can detect propagating waves. This is why altimeter Sea-Leve is important for ENSO monitoring and prediction.

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

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

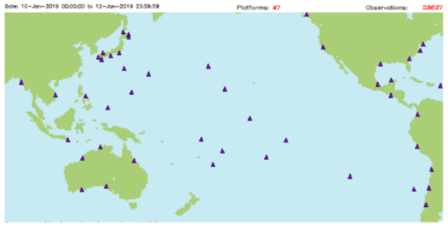
2000's
- ENSO in climate change: conceptual models and projections

Present
- ENSO diversity: predicting ENSO and its impacts remains challenging

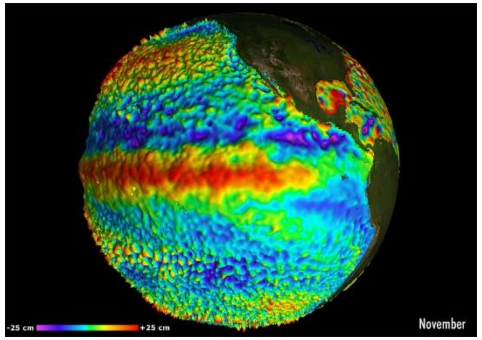
Relevance of Observations and Climate Reanalyses

SST ✚ **Atmosphere** ✚ **Ocean Subsurface**

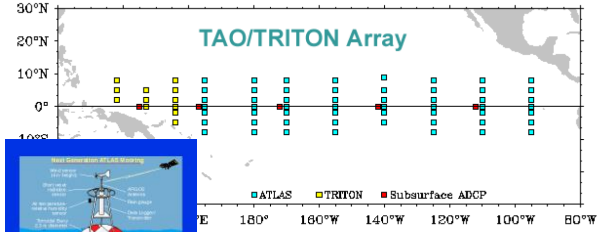
1975; Wyrtki sets Equatorial tide gauges to monitor Kelvin waves

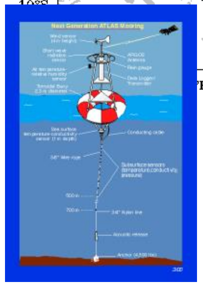


~ 1993 onwards: satellite altimeter to monitor sea level

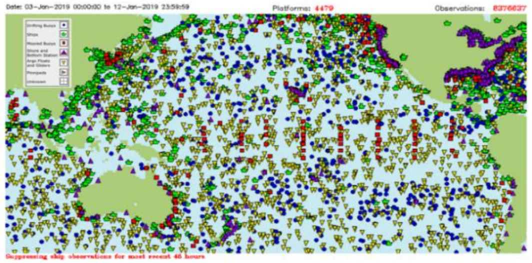


~ 1993- TOGA-TAO program to monitor subsurface temperature





~ 2005: Argo uniform sampling of subsurface temperature and salinity

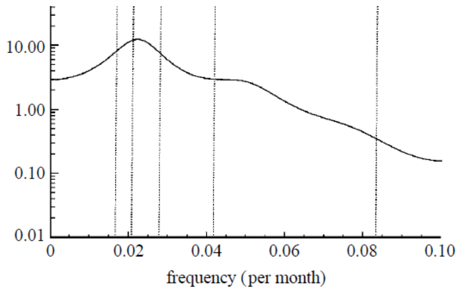


When Observations are integrated with laws of physics we obtain climate reanalyses, an essential resource for the understanding, modelling and prediction of ENSO

ENSO: other facts

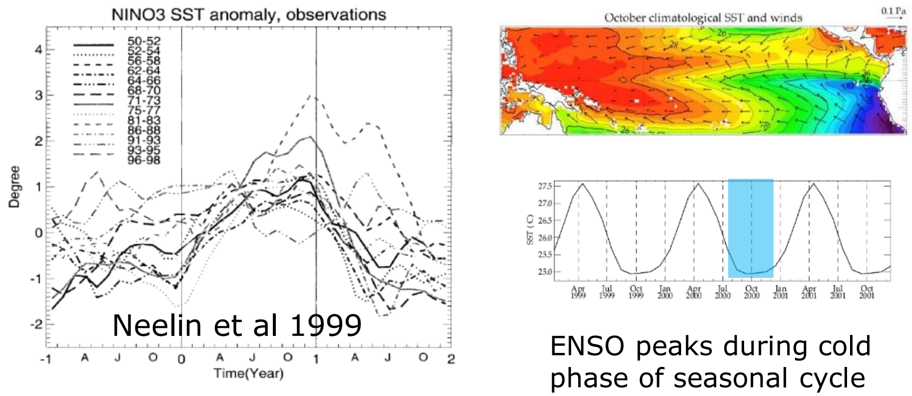
1) ENSO temporal irregularity

Broad spectral peak
Blanke et al 1997



2) Phase lock to seasonal cycle

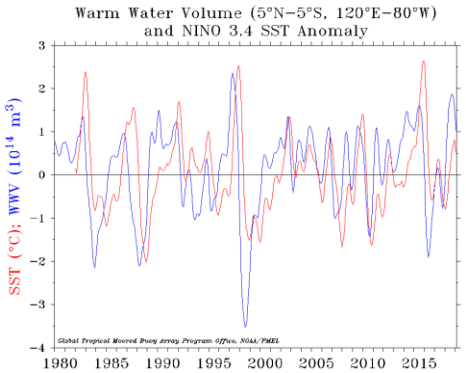
Onset ~ May-August, Peak ~ Oct-Feb, Decay~May
Boreal Spring Predictability Barrier



ENSO peaks during cold phase of seasonal cycle

3) Relationship between SST-OHC

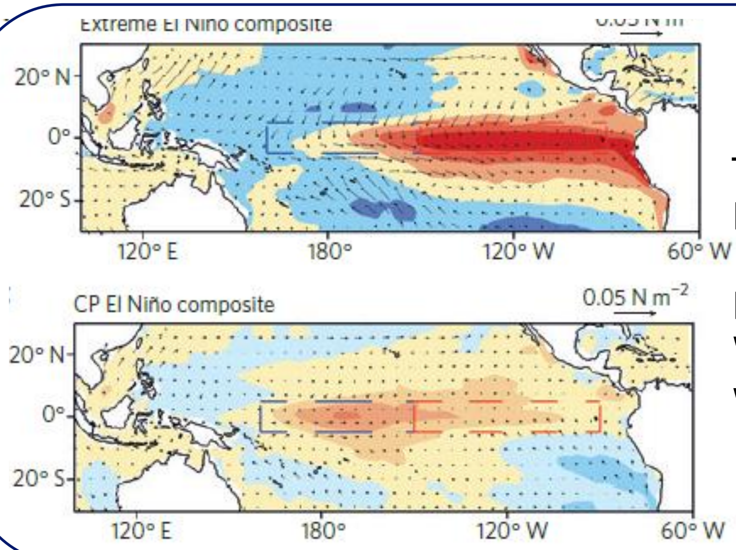
(or Warm Water Volume).



OHC precedes SST.

Specially after a warming

4)ENSO Diversity

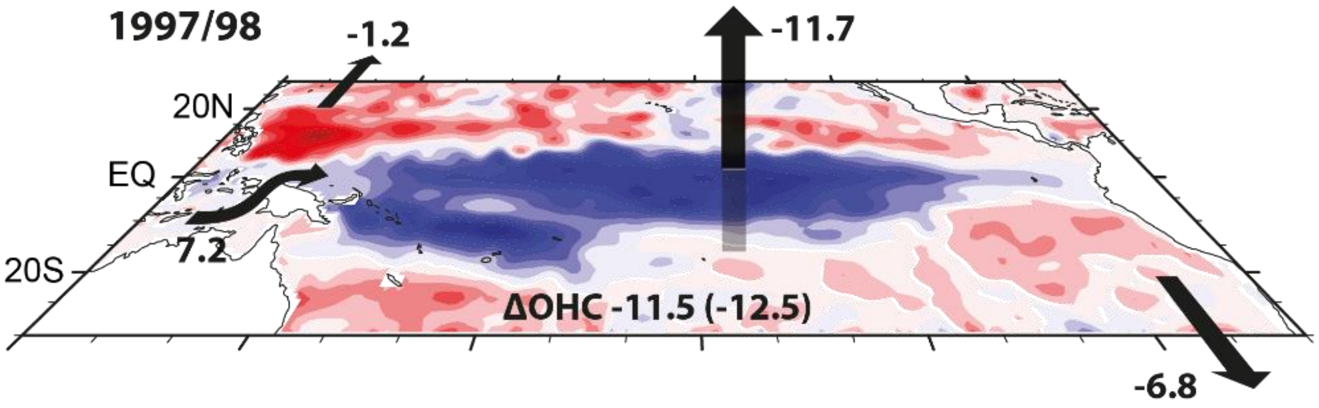


Top) Eastern Pacific Warming. Related with Big El Ninos

Bottom) Central Pacific Warming (Modoki). Related with moderate El Nino

ENSO and the Energy Cycle (from reanalyses)

- **ENSO has profound on the energy cycle:**
  - **During the 1997-98 El Nino the Tropical Pacific exchanged ~ 11 ZJ with the climate system (~50 times the annual human energy consumption).**
  - **Most of that energy is made available to the atmosphere, and eventually is lost to outer space. El Nino acts to refrigerate the climate system**
  - **The energy transport pathways are greatly modified during El Nino: export to the atmosphere, poleward (net exchange of heat from north to southern hemispheres), and import of heat from Indian Ocean**



From Mayer, Balmaseda and Haimberg 2018

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)

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
   It implies that ENSO is very predictable

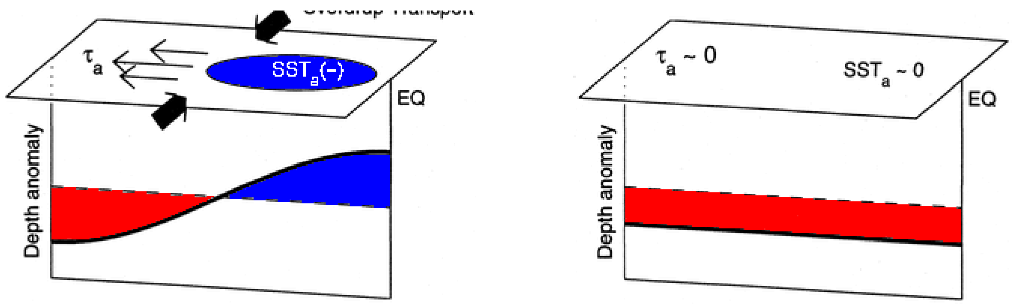
2. **Coupled Instability, stochastically triggered.**
   System with 2 time scales. Atmospheric noise triggers ENSO.
   Limited predictability (Moore and Kleeman J.Clim 1999)

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

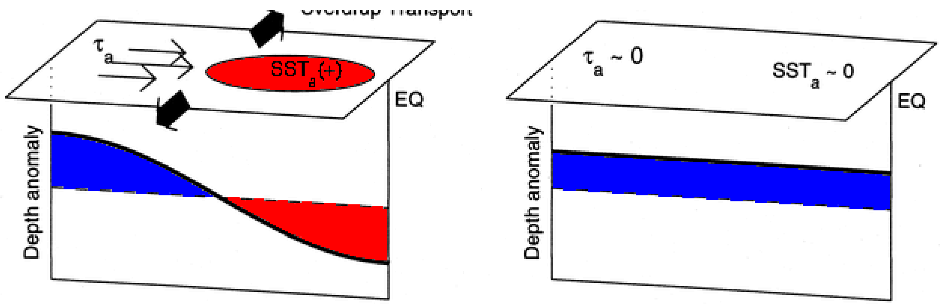
The Recharge/Discharge oscillator

Equatorial Ocean Heat Reservoirs provides Memory/Stability across ENSO phases

I & II. Recharge during La Nina



III & IV Discharge during El Nino



I. During La Niña, the easterlies induced recharge via oceanic Sverdrup transport

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

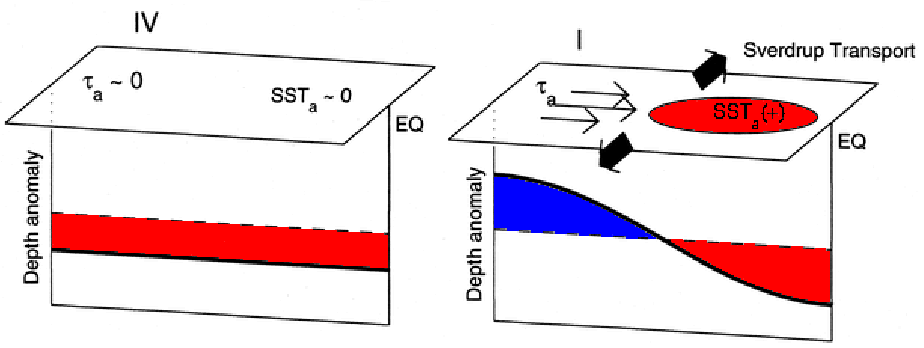
III. During El Niño: westerlies induce discharge via Sverdrup transport.

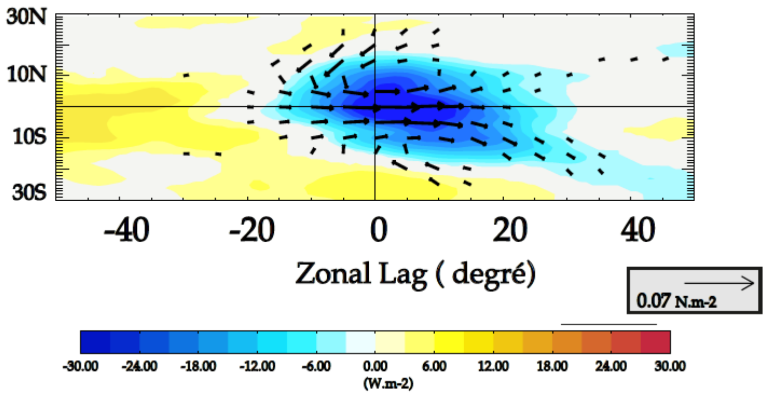
IV. A Discharged Pacific favours the occurrence of La Niña. And the cycle continues

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

The spark & the fuel (© M. McPhaden)

Stochastic discharge/recharge oscillator





The fuel: ocean heat content

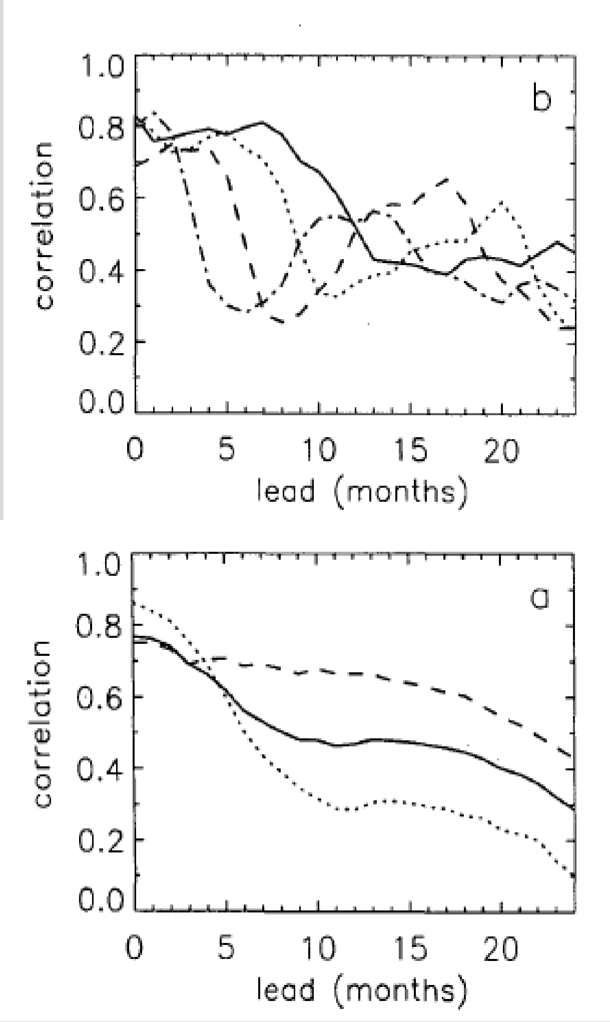
The spark: Westerly Wind Events

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

1980's early 1990's: With statistical & simplified numerical models (not GCMs)



First ENSO predictions were
a) deterministic
b) at 24 months lead time

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

2) Re-emergence of skill

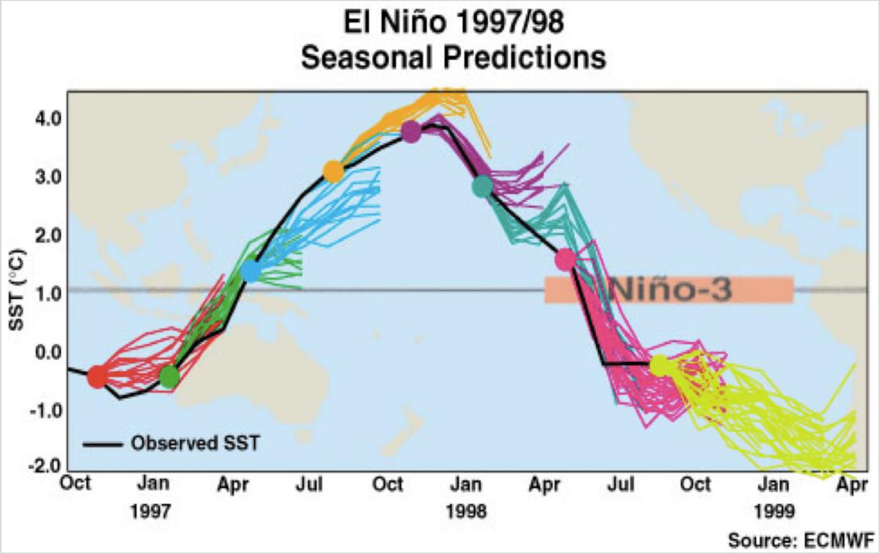
3) decadal variations on ENSO prediction skill

....	1965-1980
– – –	1980-1994
——	1965-1994

From late 90's: Start of operational predictions with GCMS start

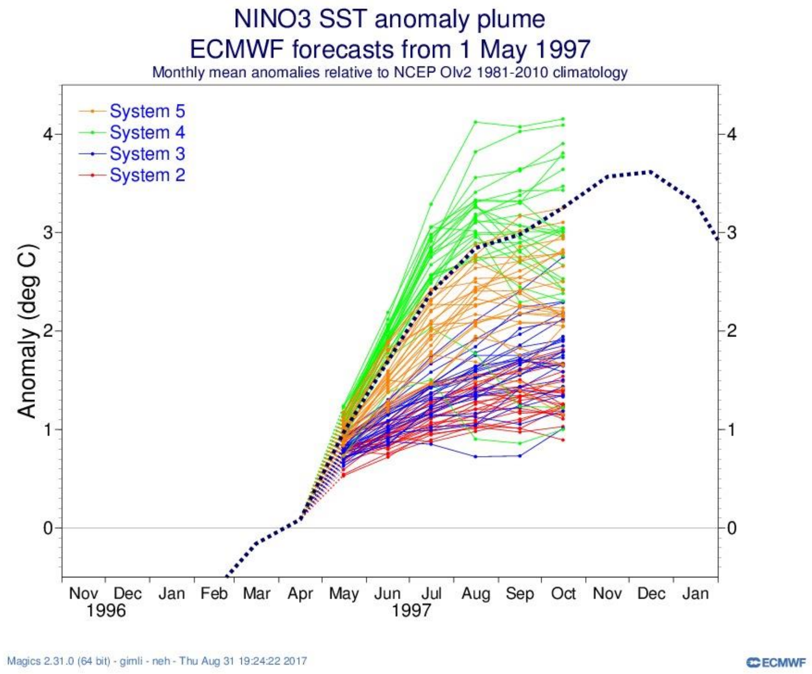
Several contributing factors converging:

- Maturity of coupled GCMs.
- Availability of first atmospheric reanalysis (e.g. ERA15)
- Advances on ocean observing system, mainly TAO moorings and altimeter
- And the developments of ensembles
- For ECMWF, this led to the introduction of the ocean model and ocean data assimilation.



Stockdale et al 1998

Over the years: SEAS2 – SEAS3 –SEAS4 – **SEAS5**



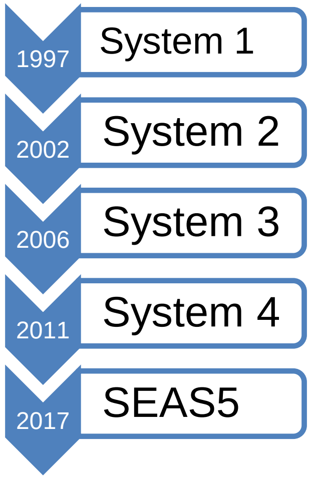
S2 inability to generate WWB caused under prediction of 1997/98 ENSO
(Vitart et al 2004).

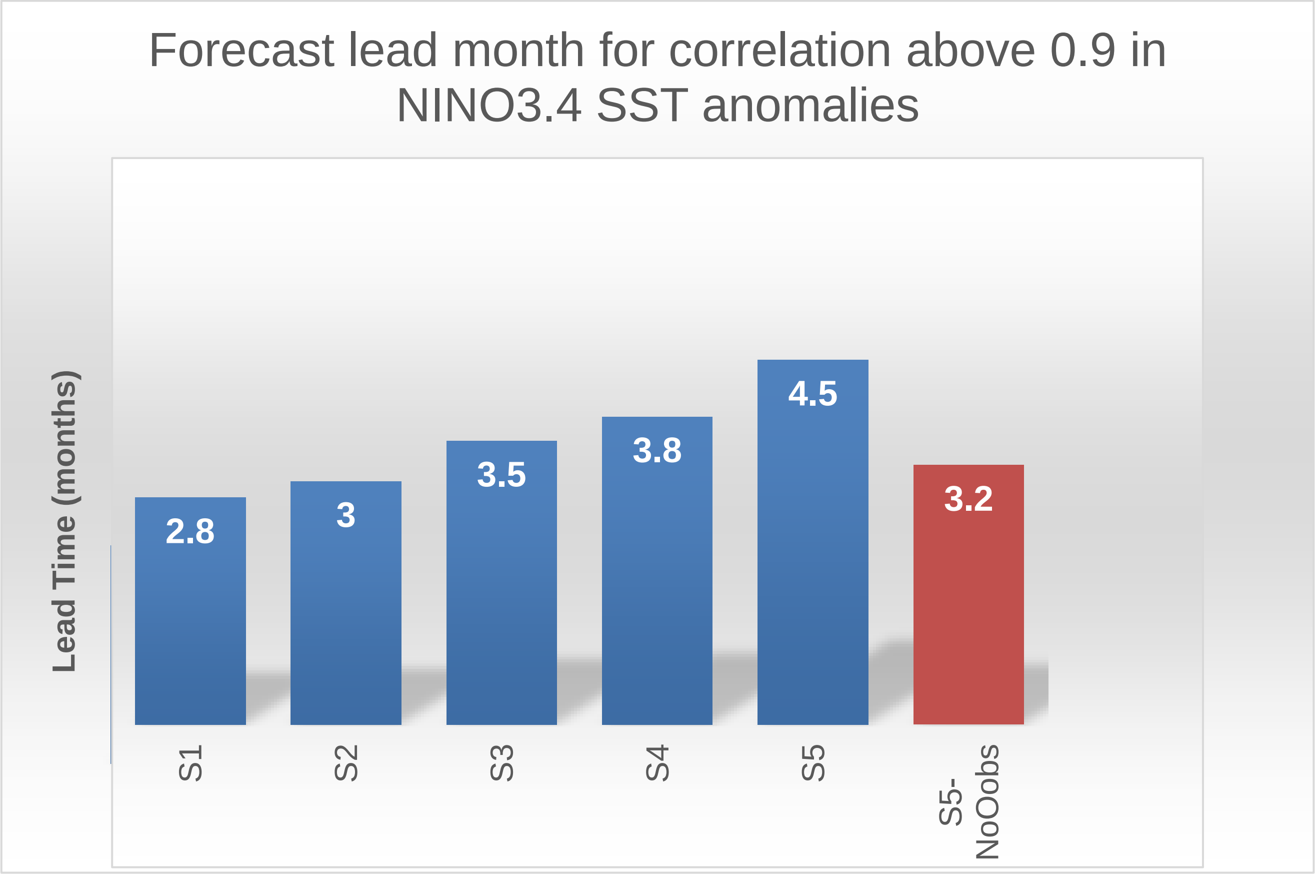
As the model improved

SEAS5 became operational in Nov 2017

20 years or progress in ENSO prediction at ECMWF

and contribution of ocean observations

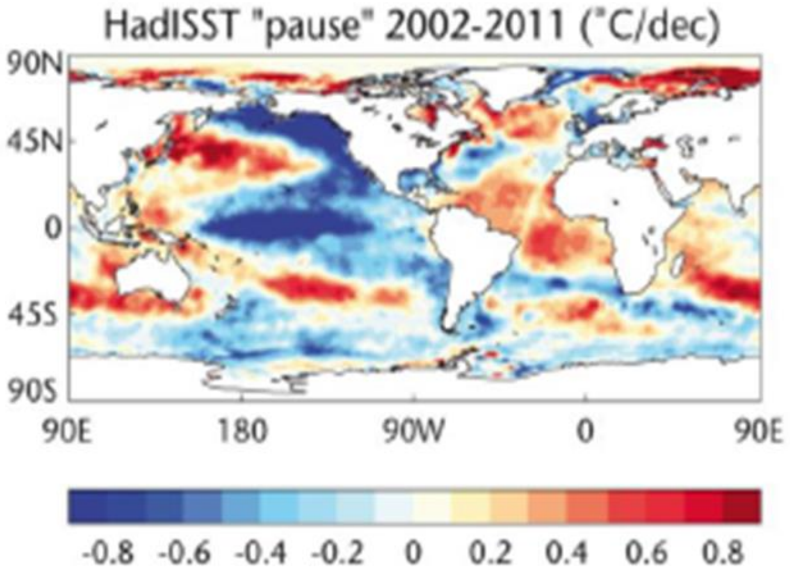




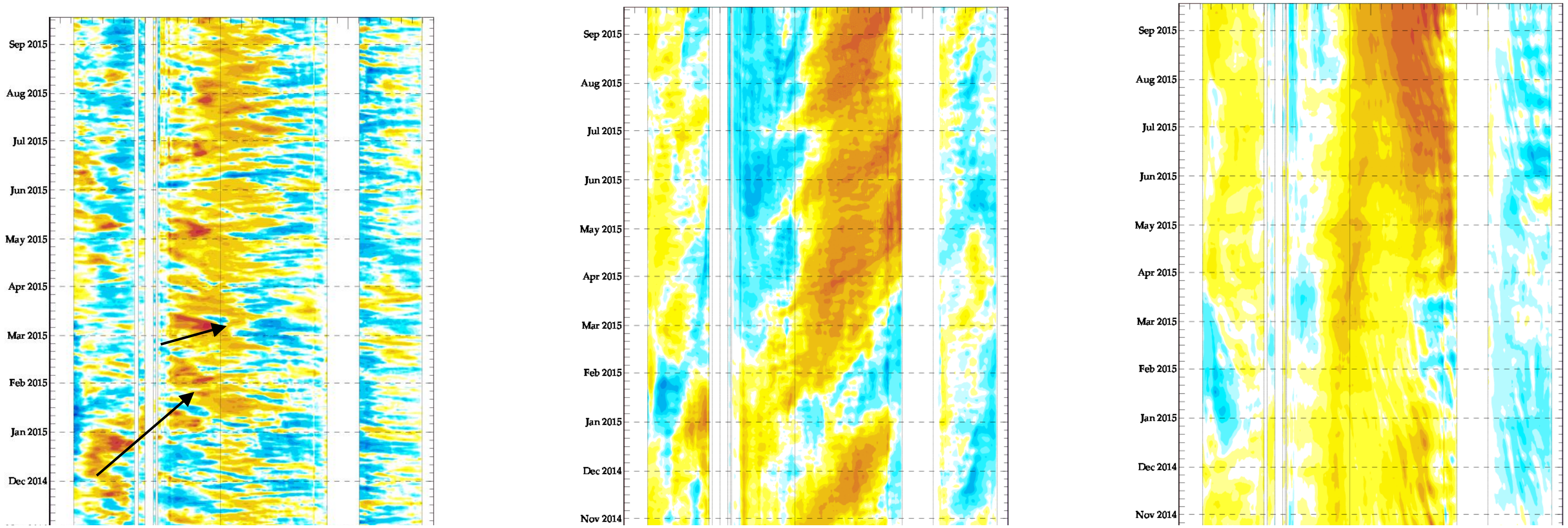
- S1 was the first ECMWF seasonal forecasting system. Implemented as a pilot in 1997
- SEAS5 is the latest ECMWF seasonal forecasting system. Implemented in November 2017.
  Contributes to Copernicus Climate Change Services C3S.

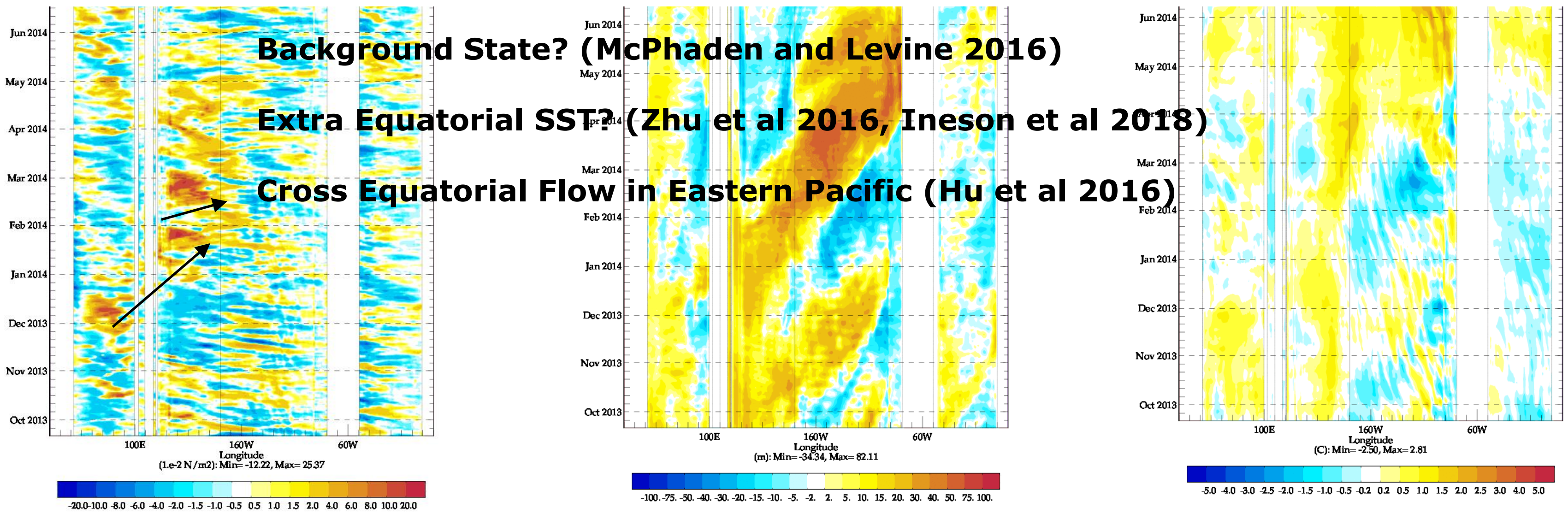
The 2015/16 strong El Nino and the false alarm in 2014

- 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





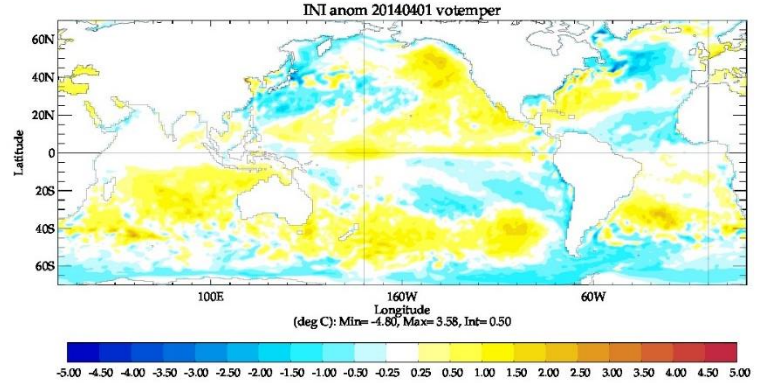
Background State? (McPhaden and Levine 2016)

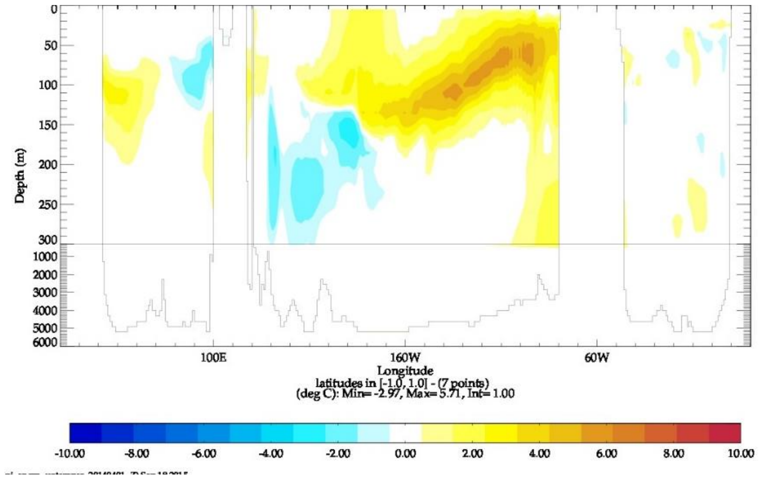
Extra Equatorial SST? (Zhu et al 2016, Ineson et al 2018)

Cross Equatorial Flow in Eastern Pacific (Hu et al 2016)

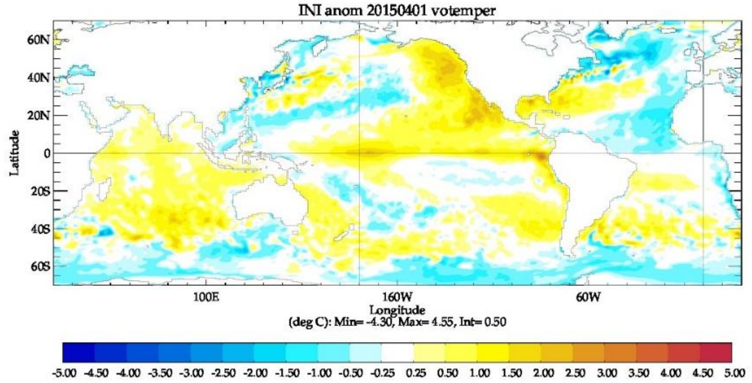
Temperature Anomalies From Ocean Reanalysis

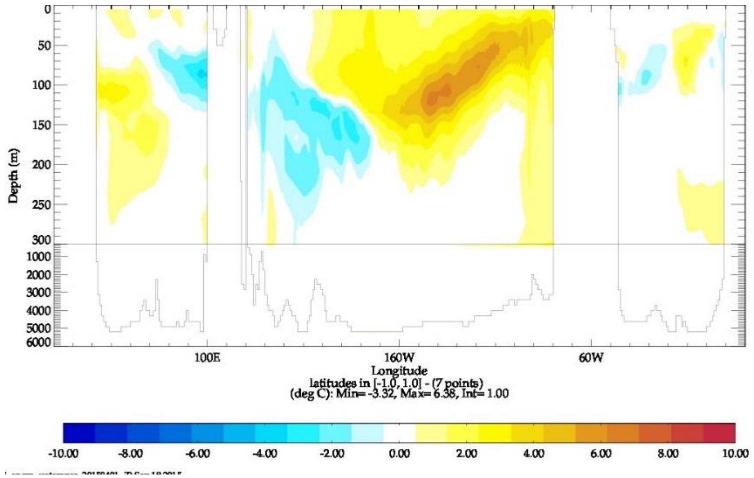
APR 2014





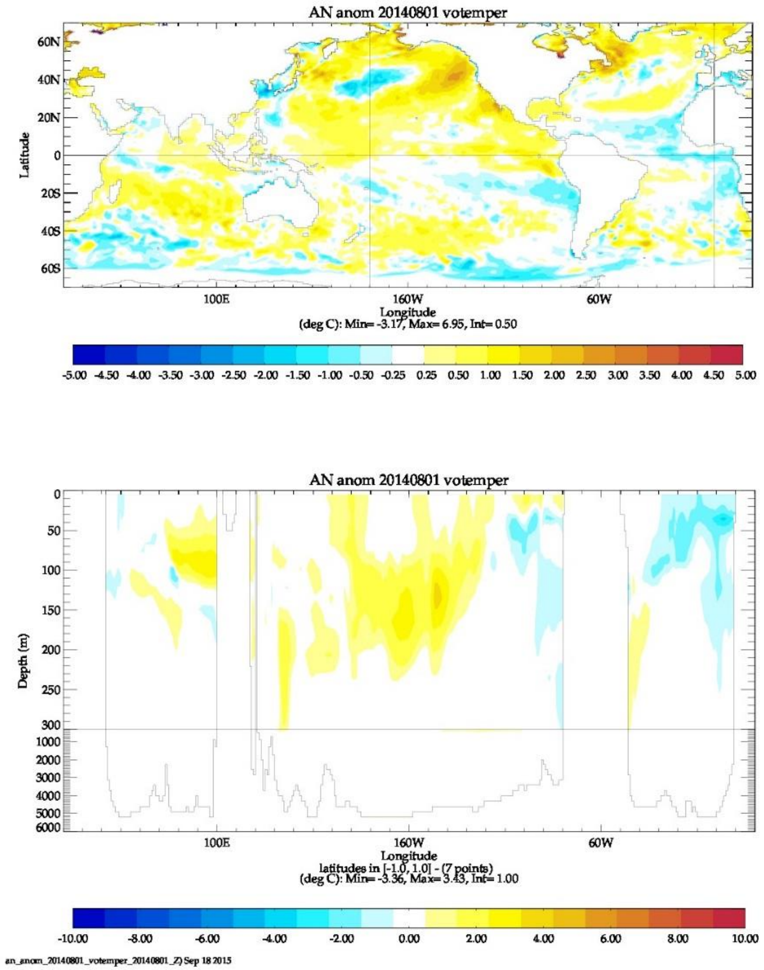
APR 2015



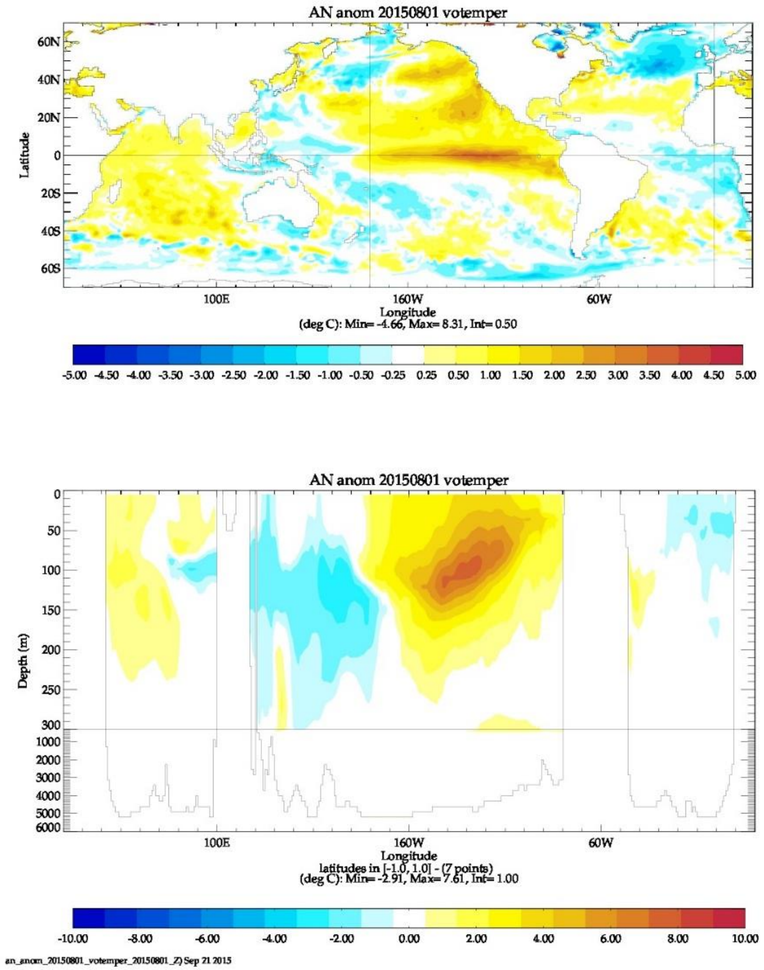


Temperature Anomalies From Ocean Reanalysis

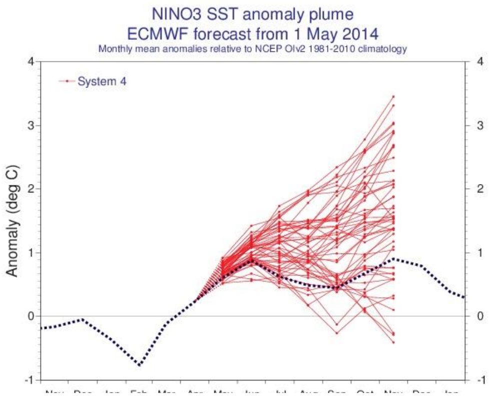
AUG 2014



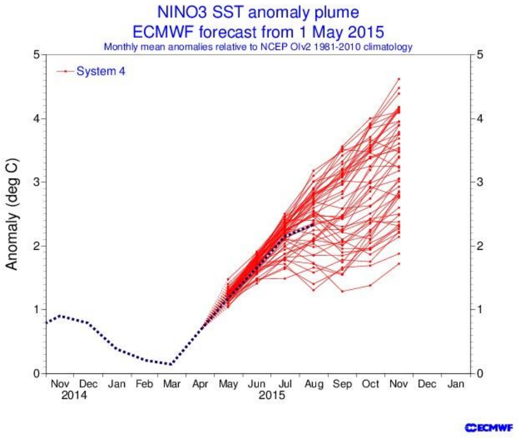
AUG 2015



S4 El Nino Forecasts: 2014 v 2015?



- Did the forecasts capture the difference between 2014 and 2015

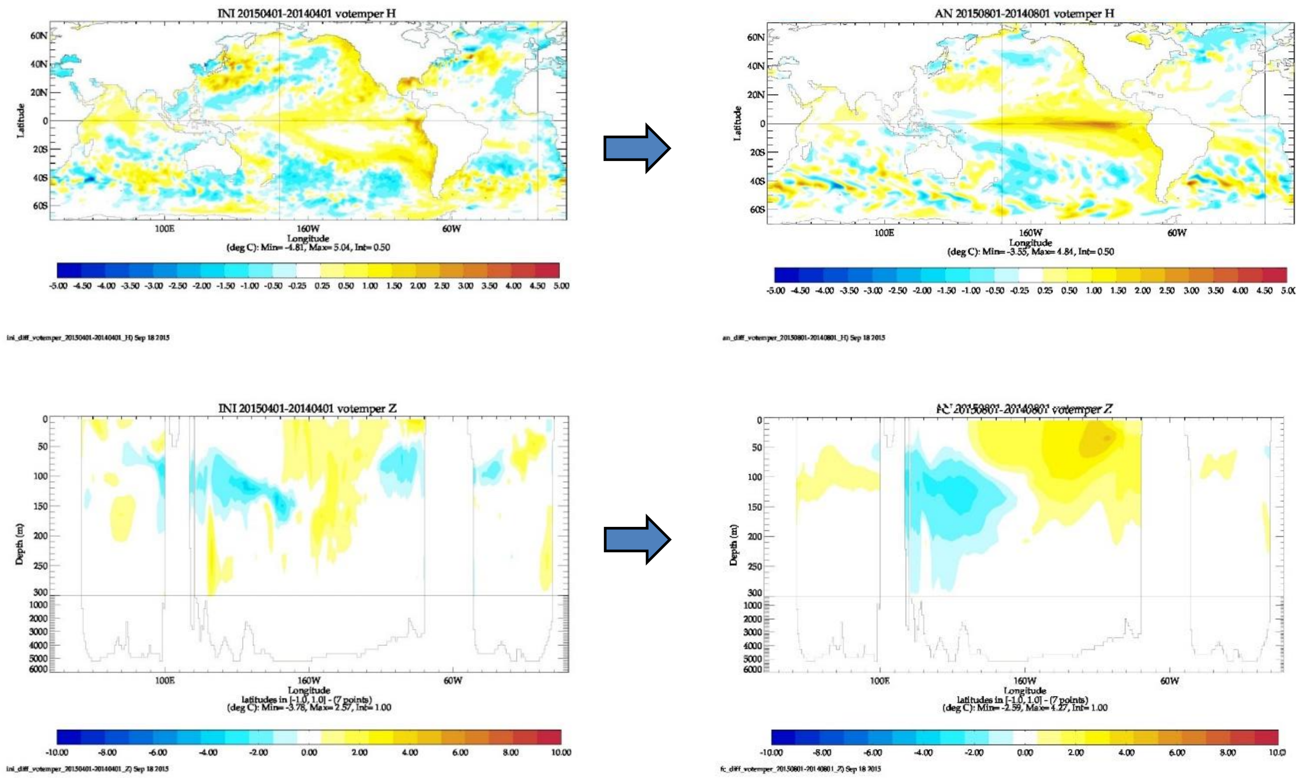


- What causes the large spread in the fc? Is that spread a good estimation for predictability?

Growth of Perturbations: Temperature

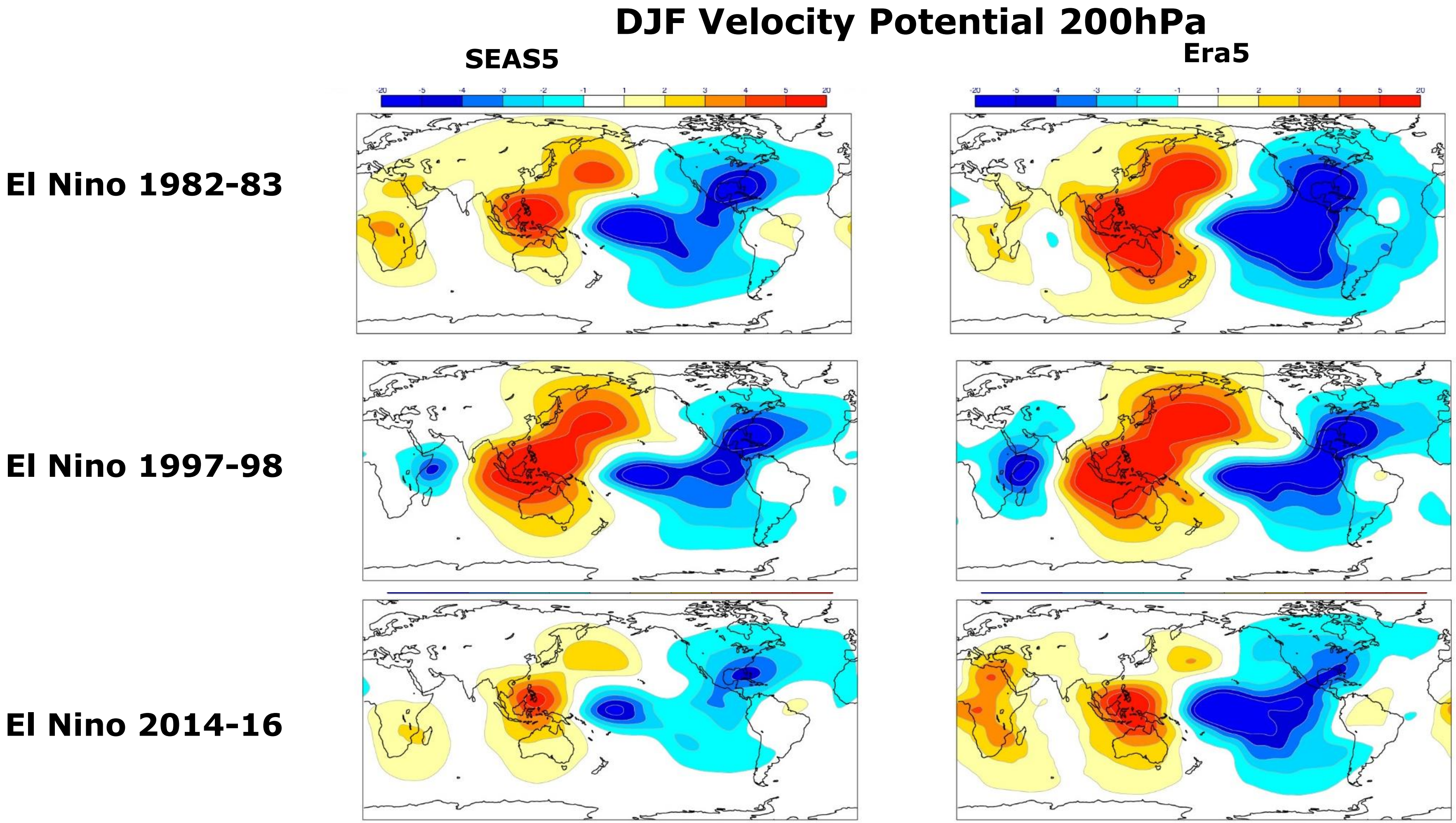
INI Pert: APR 2015-2014

Forecast Final Pert: Aug 2015-2014



- S4 Seas Fc are discerning: they capture differences between 2015 and 2014.
- Skill beyond persisting the initial differences.

Diversity in atmospheric response to ENSO



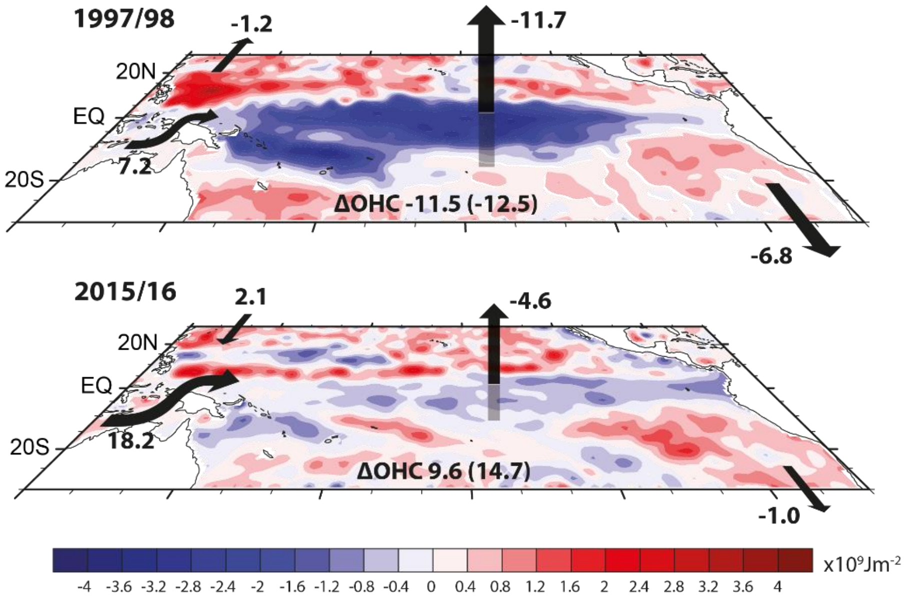
In ERA the different ENSO have different atmospheric response: intensity, meridional and zonal extent. This may be related to the SST anomalies in other ocean basins (e.g. Indian Ocean)

SEAS5 forecasts relatively well the tropical atmospheric response, and the ENSO diversity, although some deficiencies are apparent

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

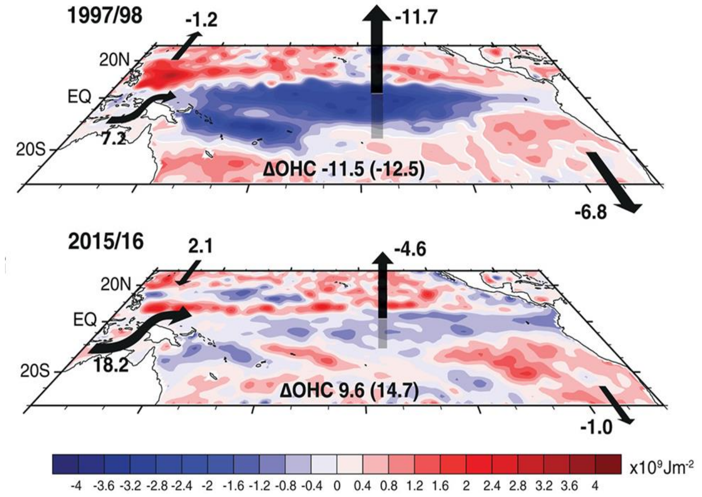


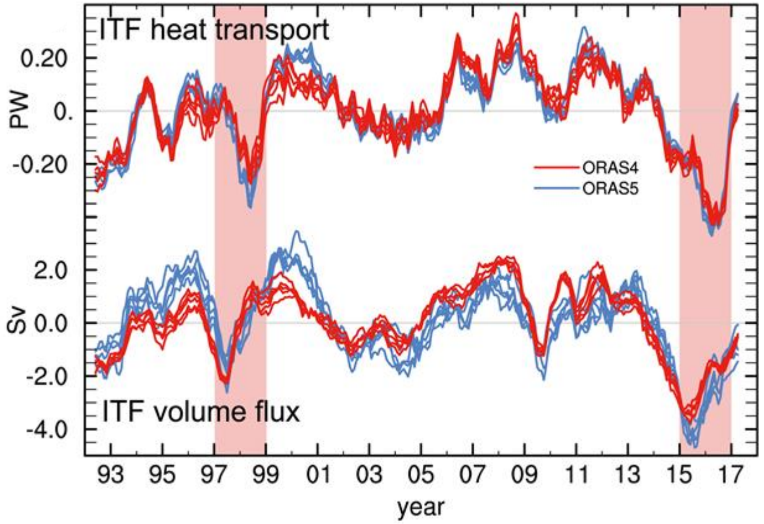
- As a consequence, the Tropical Pacific remained in a recharge state.
- And El Nino did not manage to refrigerate the the earth system

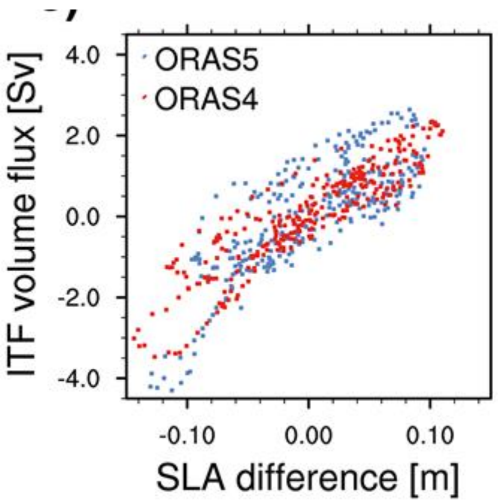
From Mayer, Balmaseda and Haimberg 2018

Role of the Indian Ocean in the anomalous 2014/2016 ENSO behaviour

In the processes we noticed the unprecedented weakening of the Indonesian Throughflow anomalies in ORAS5







1. Contrasting energetics of the 1997/8 and 2015-16 El Nino events.

Mayer, Balmaseda, Haimberger, GRL, 2018

2. The unprecedented weak Indonesian Throughflow Transport (ITF) was the main contributor to weak Tropical Pacific heat discharge.

3. The SLA gradient between West Pacific and Eastern Indian Ocean appears as a proxy for the ITF strength

ECMWF

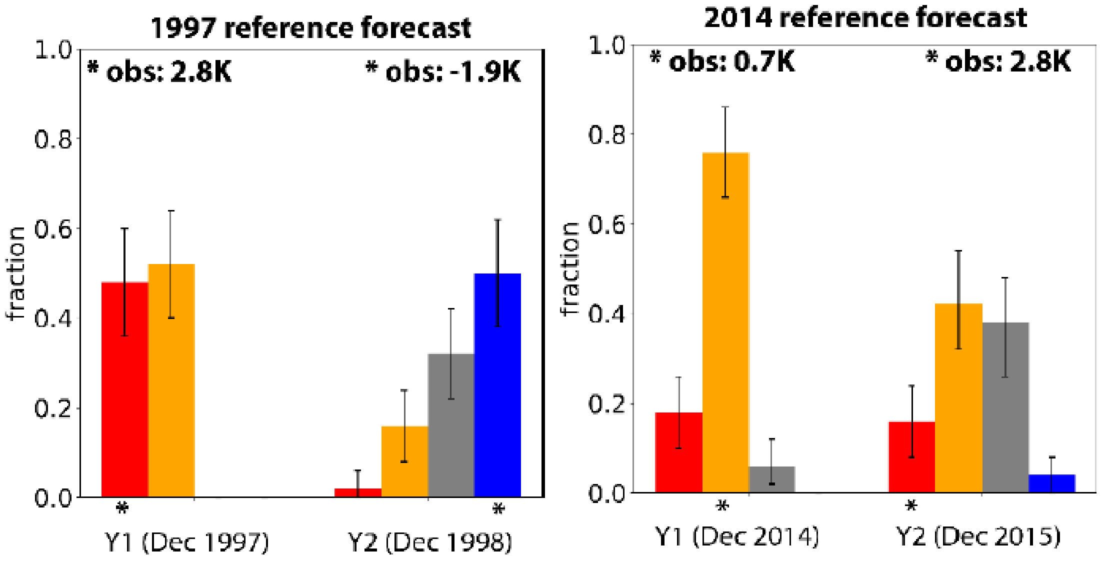
Questions arising

- Did the Indian Ocean state influence the (weak) 2014 and (strong) and 2015 El Nino?
- Does the Indian Ocean state influence the predictability of ENSO in the second year?

Mayer and Balmaseda 2021

Experiments: SEAS5 up to 24 months from 1st Feb

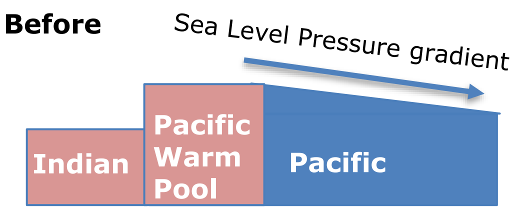
Ref 1997: as SEAS5
Ref 2014: as SEAS5
Perturbed 2014: as SEAS5 with Indian Ocean Initial conditions from 1997

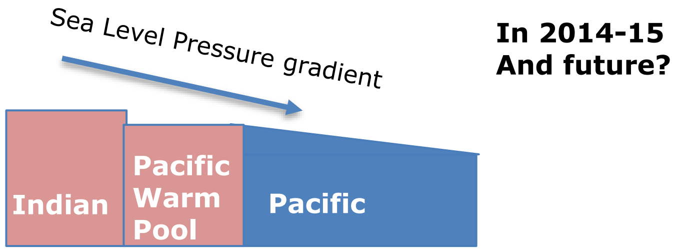


Indian Ocean State influences the probability of extreme warm events in year 1 and year 2.

Impact of 2014-2015 El Nino in our way of thinking

- The 2014-2015 event revived the interest on ENSO prediction
  - **Double peak El Nino**
  - **Influence of the Indian Ocean**
    - Is this consequence of global warming? the Indian Ocean being the tropical basin with stronger SST trends.
    - In this event, the Indian Ocean acted as heat reservoir, meaning that more ”fuel” was available for El Nino, with consequences for longer duration and/or intensity
    - The connection between Indian Ocean and Pacific adds another predictability driver (the sea level difference between Indian Ocean and Western Pacific, relevant for forecasts 2-years ahead





  - **Forecasts had to be carefully interpreted. Relevance of forecasts at 2-year lead times.**
  - **Changes in the ENSO energy cycle:**
    - The Tropical Pacific was not able to discharge all its energy. In fact, it gained, remaining in a recharged state.
    - Much less energy was released to the atmosphere. We do not understand why. Role of clouds?
    - Larger heat reservoir if the Indian Ocean acts as accumulator: What are the implication for the frequency/intensity and duration of El Nino/La Nina?

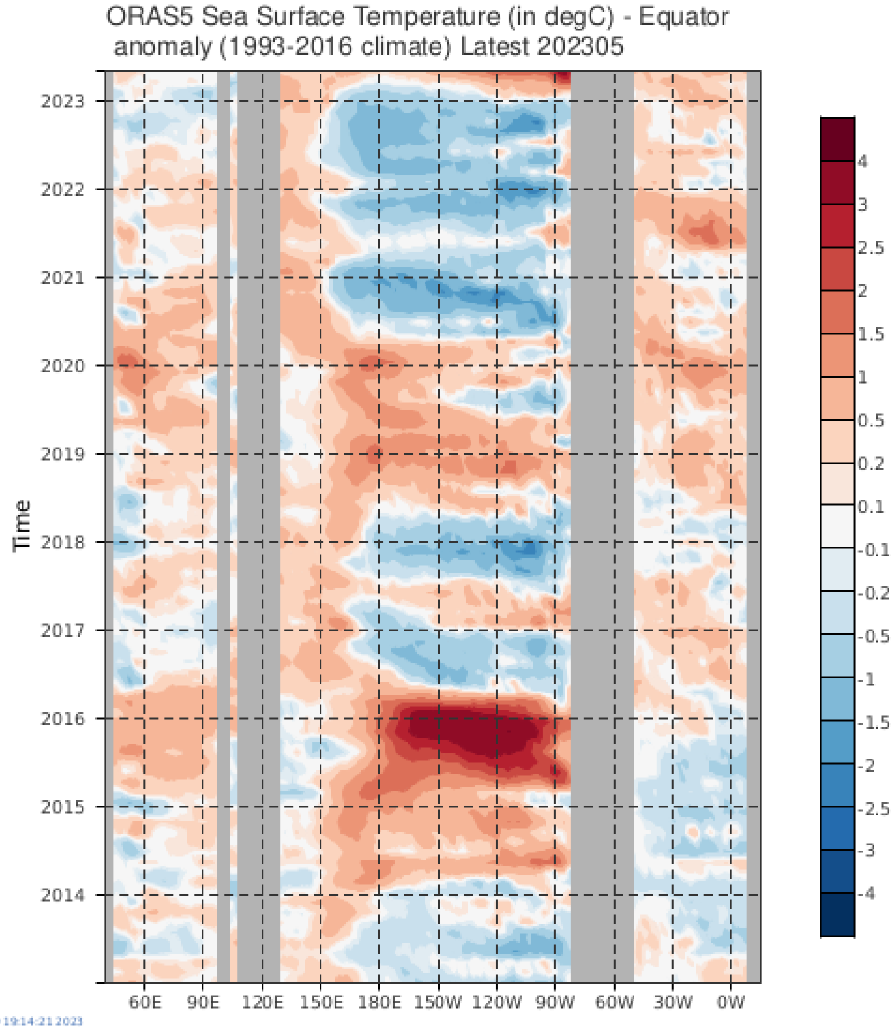
What about the recent El Nino?

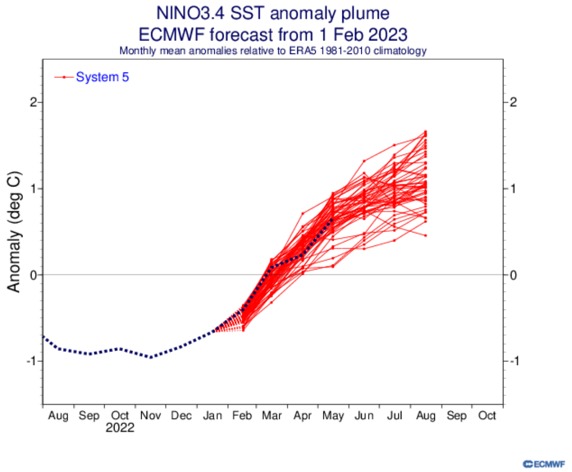
El Nino was declared in May-June 2023.
Why, and how confident were we?

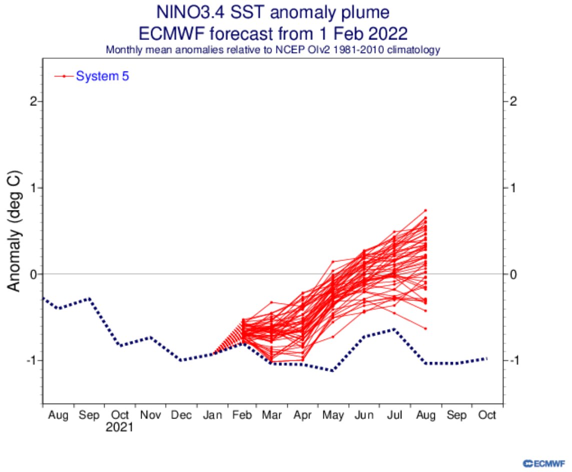
We have had a prolonged 3-years La Nina conditions.

Q1. Since Nov-2021, SEAS5 Feb-22 has been predicting end of La Nina in 2022, which did not happen. Why should we trust the forecasts now?

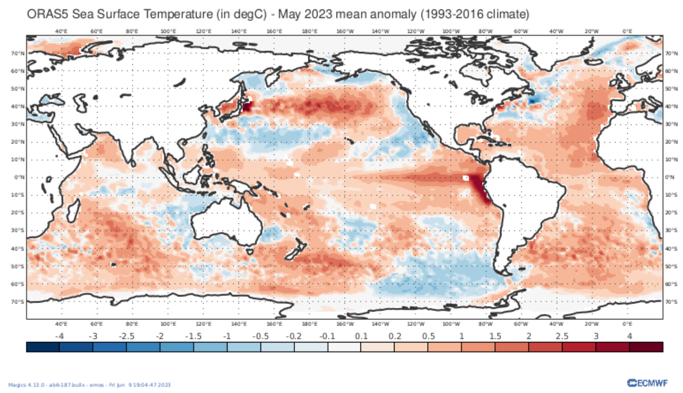
Q2. Is the expectation bias affecting our interpretation again, as for the 2014-15 “perceived false alarm”?



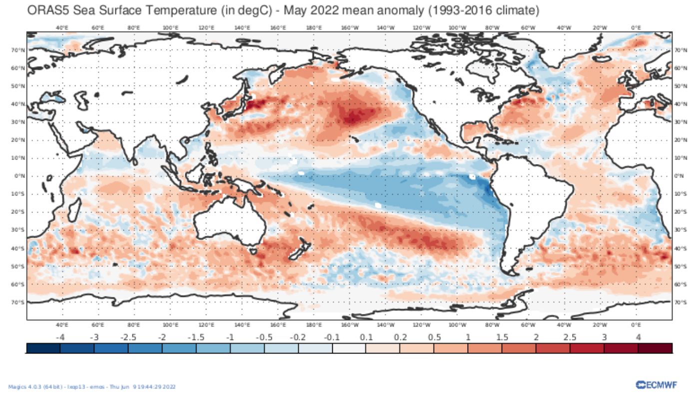




May 2023 SST anomalies

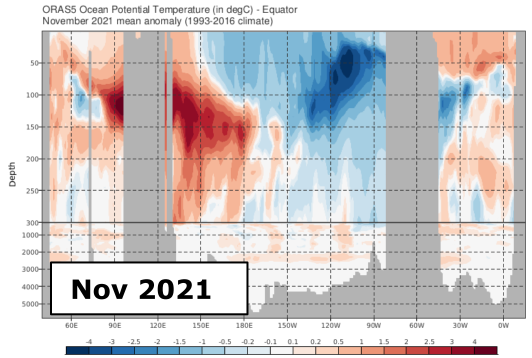


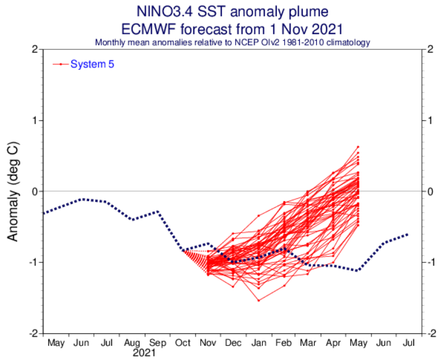
May 2022 SST anomalies

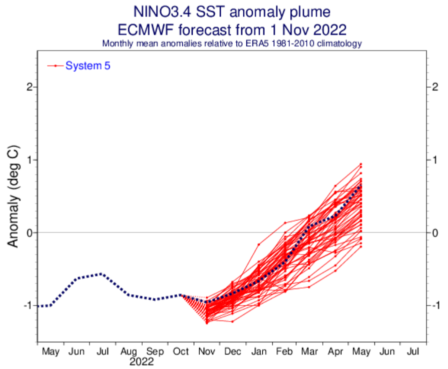


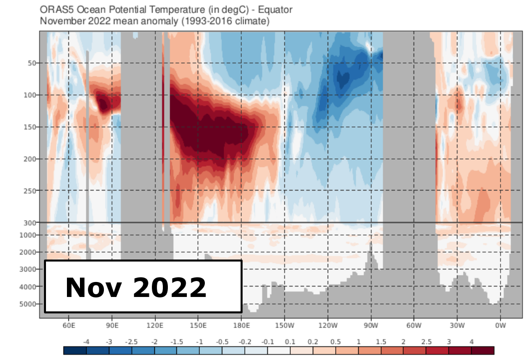
From ORAS5 ocean monitoring pages
https://charts.ecmwf.int/catalogue/packages/oras5/

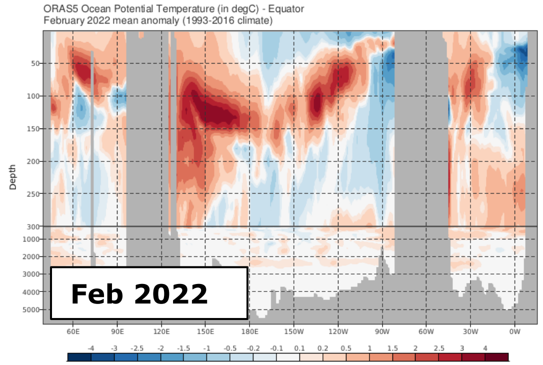
Thanks to the ORAS5 monitoring pages we can have a look at the ocean initial conditions in different years

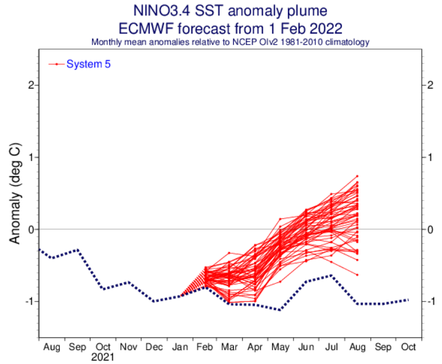


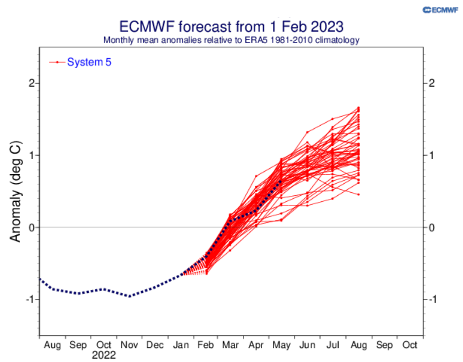


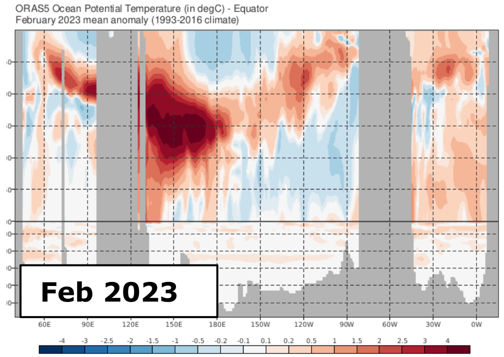


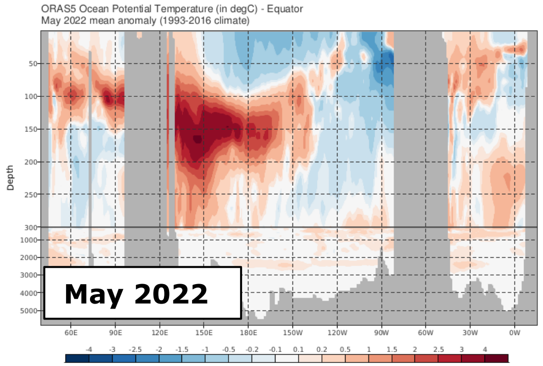


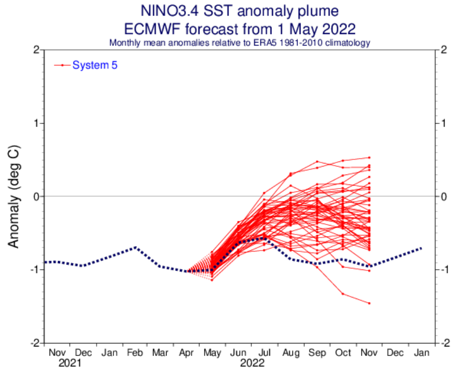


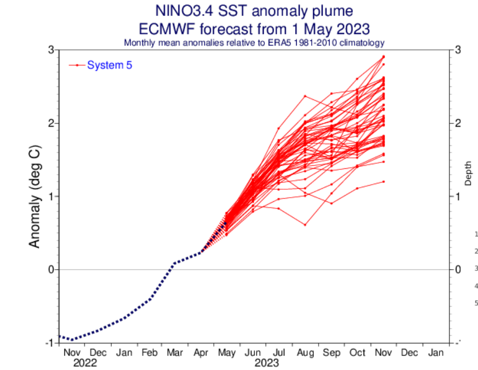


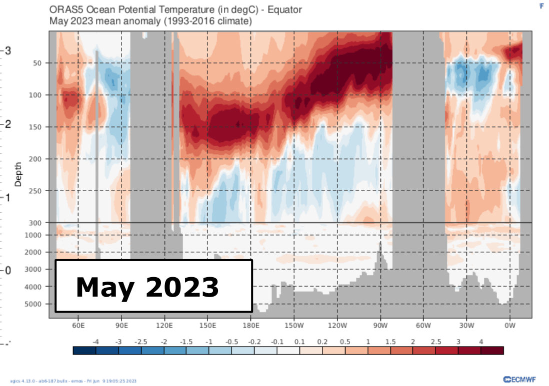










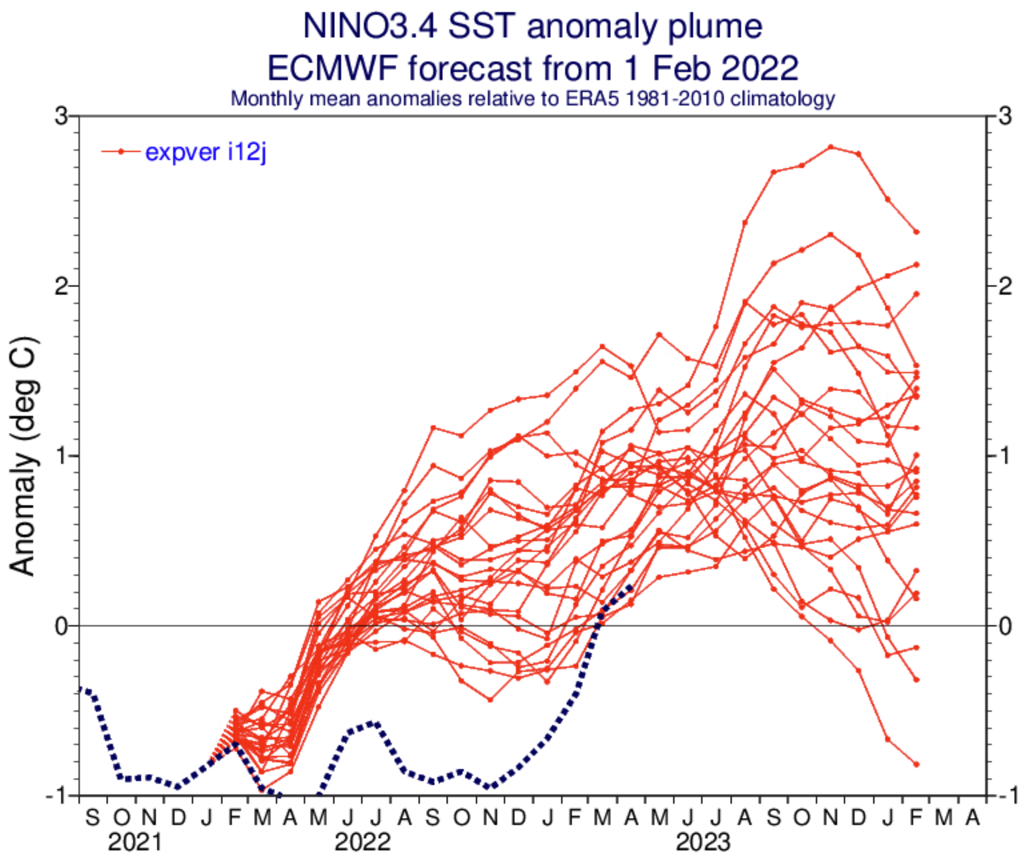


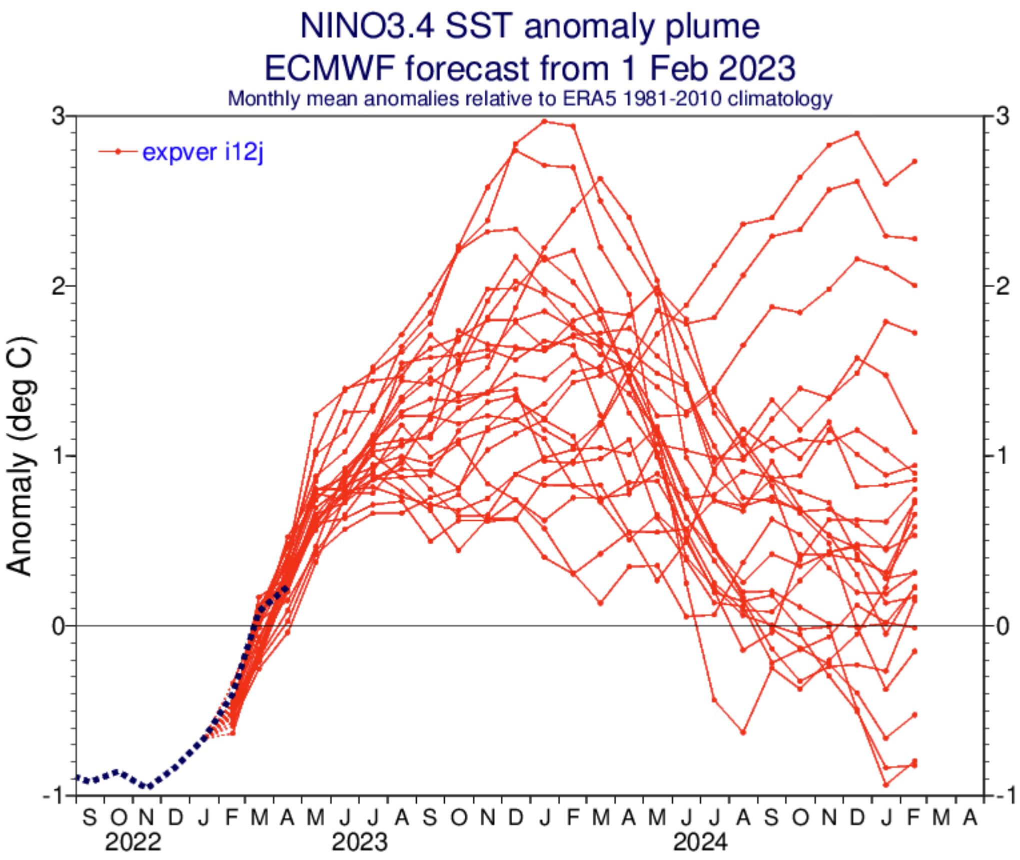
From ORAS5 ocean monitoring pages https://charts.ecmwf.int/catalogue/packages/oras5/

At least from May onwards, forecasts and ocean subsurface seem to be different in 2022 and 2023. Perhaps Feb?

Will the El Nino peak in 2023/24 or in 2024/25?

Two-year forecasts: SEAS5-based for 2023 El Nino

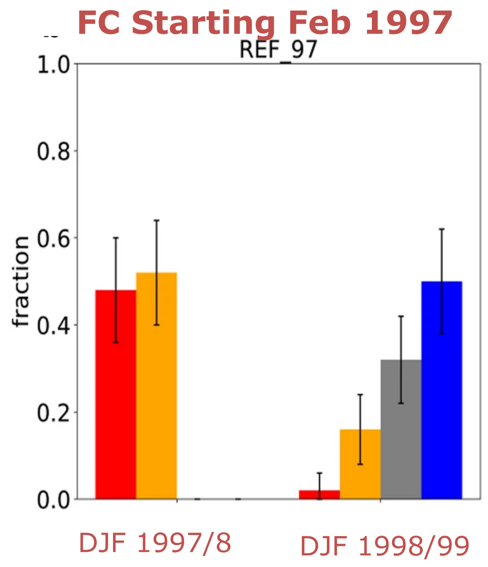


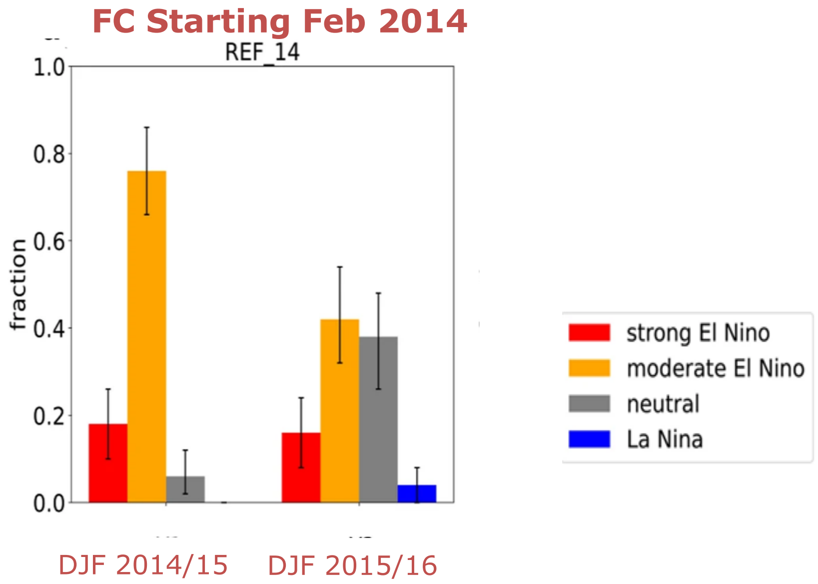


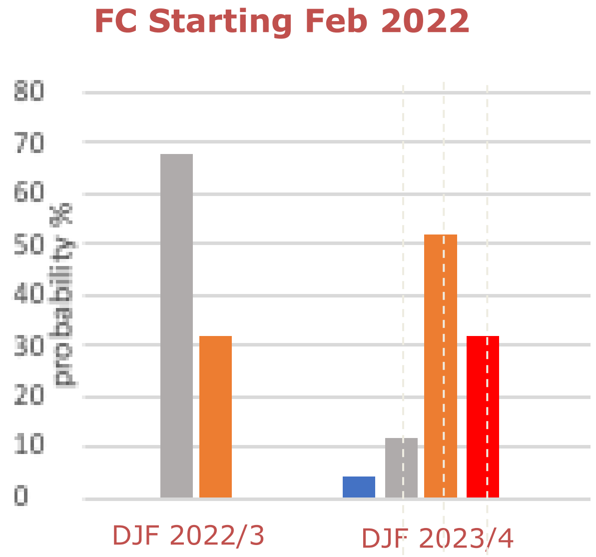
Feb 2022 forecast suggests weak warming in 2022 (which was wrong), followed by likelihood of stronger warming in 2023, with the possibility of a strong El Nino peaking in 2023/24

Feb 2023 forecast is for a moderate to strong El Nino in 2023/24, with a strong event followed by a return to neutral or La Nina conditions; but the possibility of a moderate warming strengthening to give a strong 2-year event.

Predicting ENSO 2-years ahead: two case studies



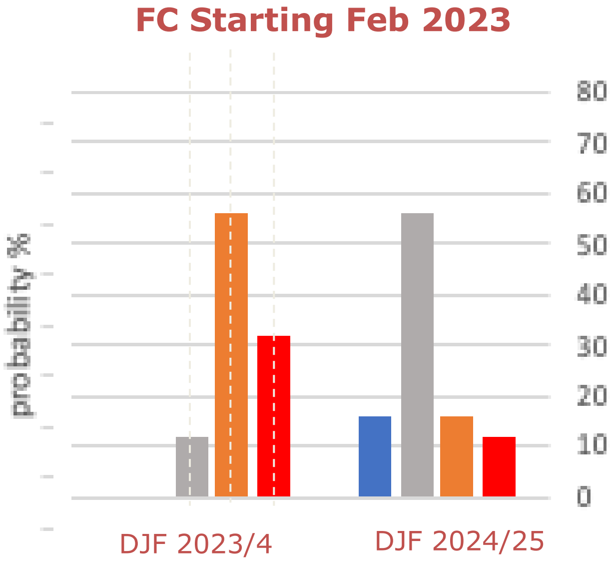




ENSO predictions for 2023/4 remarkably similar in forecasts initialized in Feb 2022 and Feb 2023

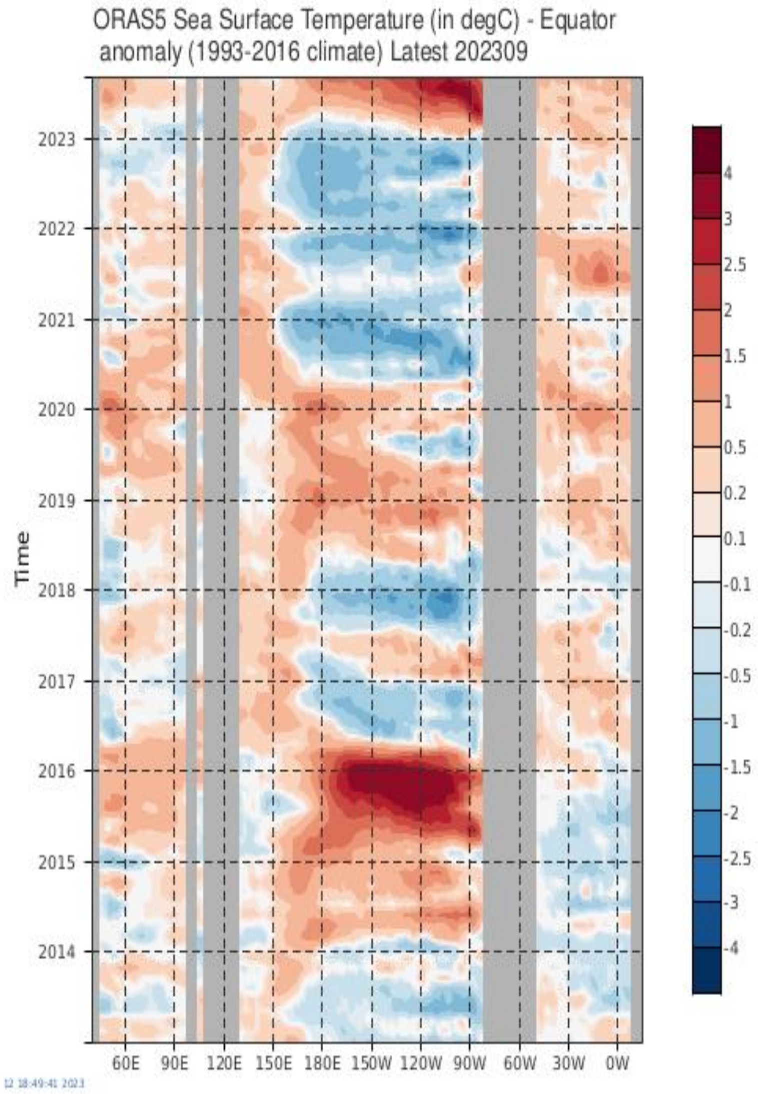
According to Feb-23 SEAS5;
~85% of El Nino on 2023/4
~30% prob of that El Nino being strong in 2023/4 and 10% prob of being strong in 2024/5.

There is only ~15% of La Nina following this warm event.

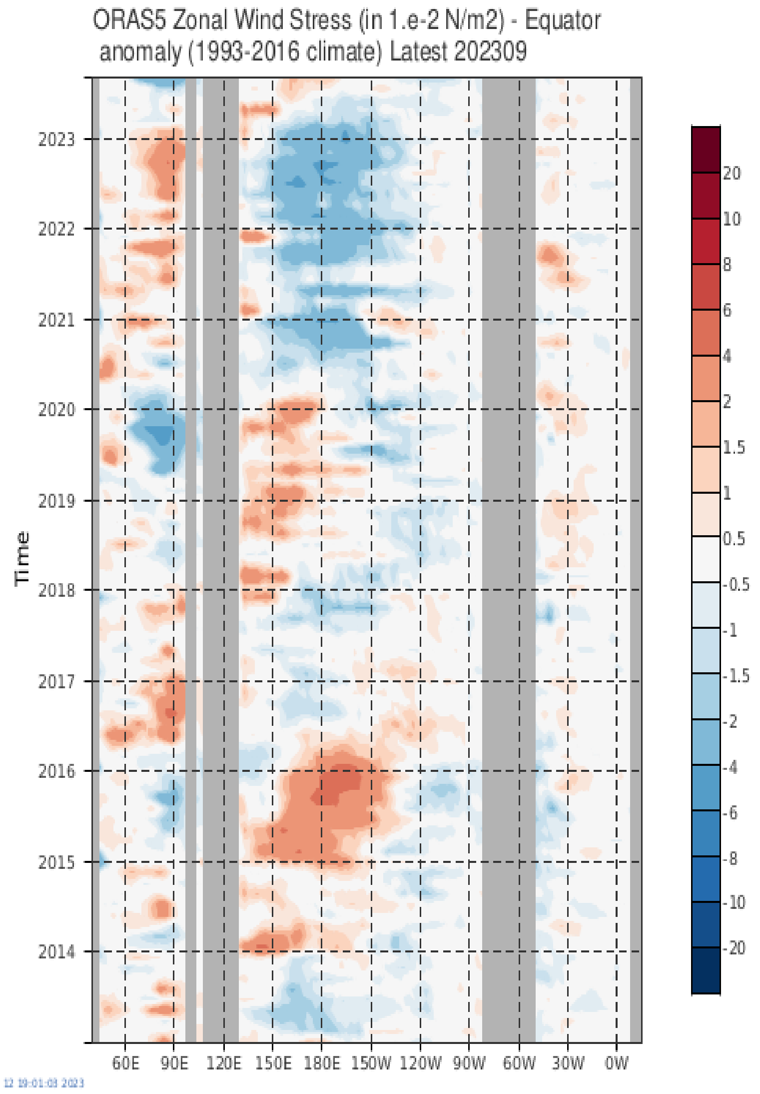


But by Autumn we were getting nervous: the atmosphere was not responding …
Equatorial Conditions in October 2024

SST anomalies

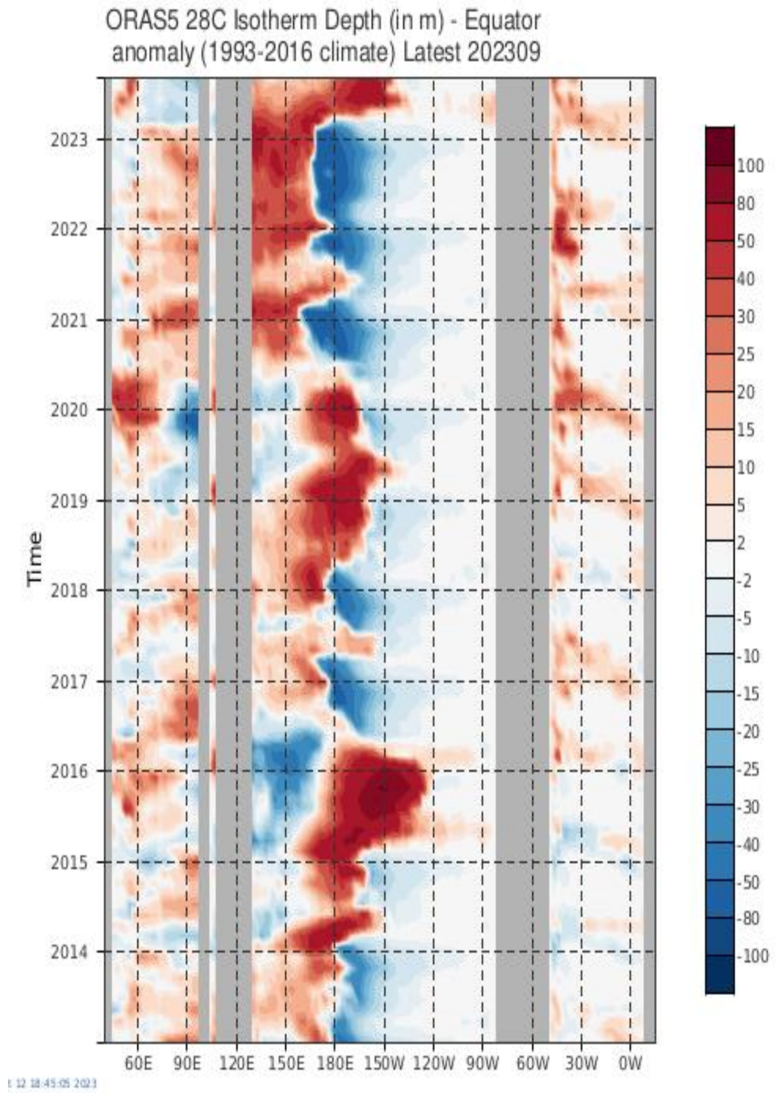


Zonal Wind stress anomalies



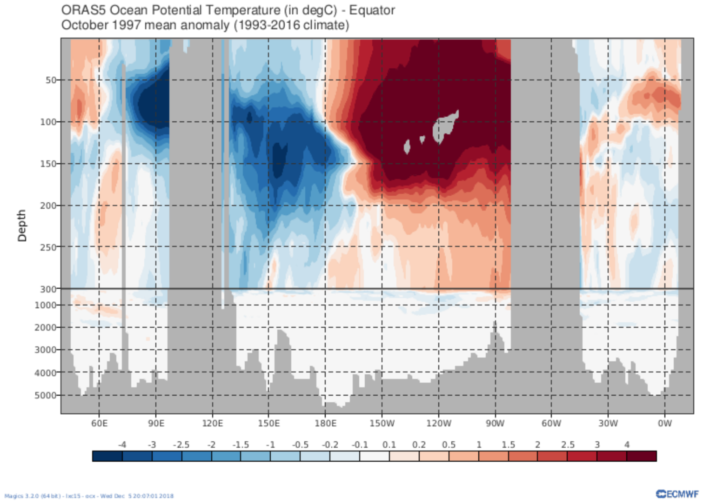
Slow response of zonal winds?

Depth 28º Isotherm anomalies

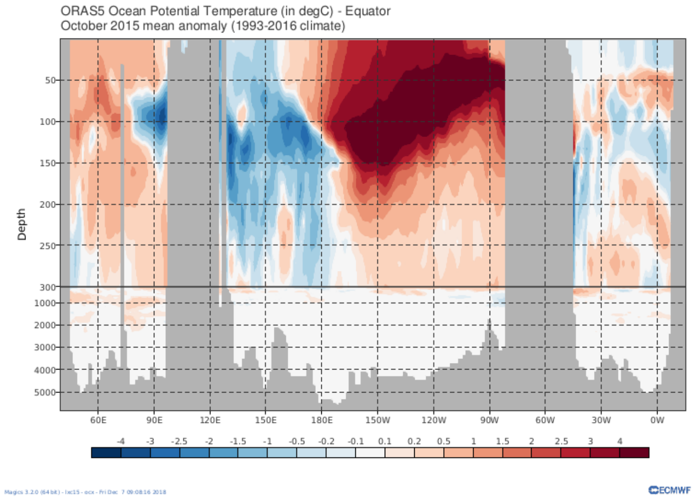


Western Pac Warm Pool still warm

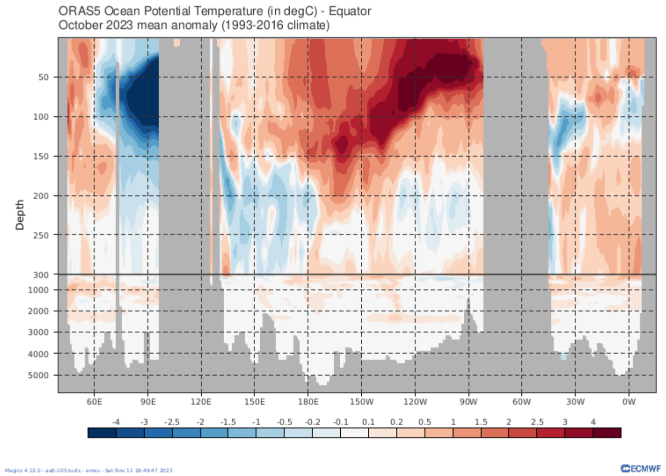
Oct 1997



Oct 2015



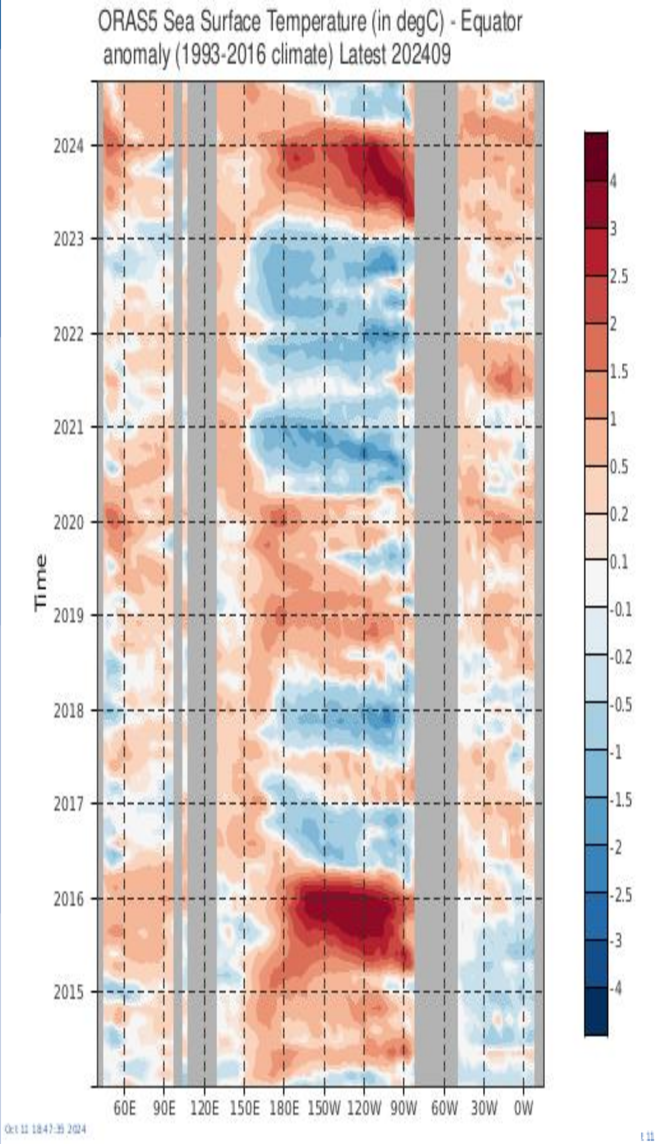
Oct 2023



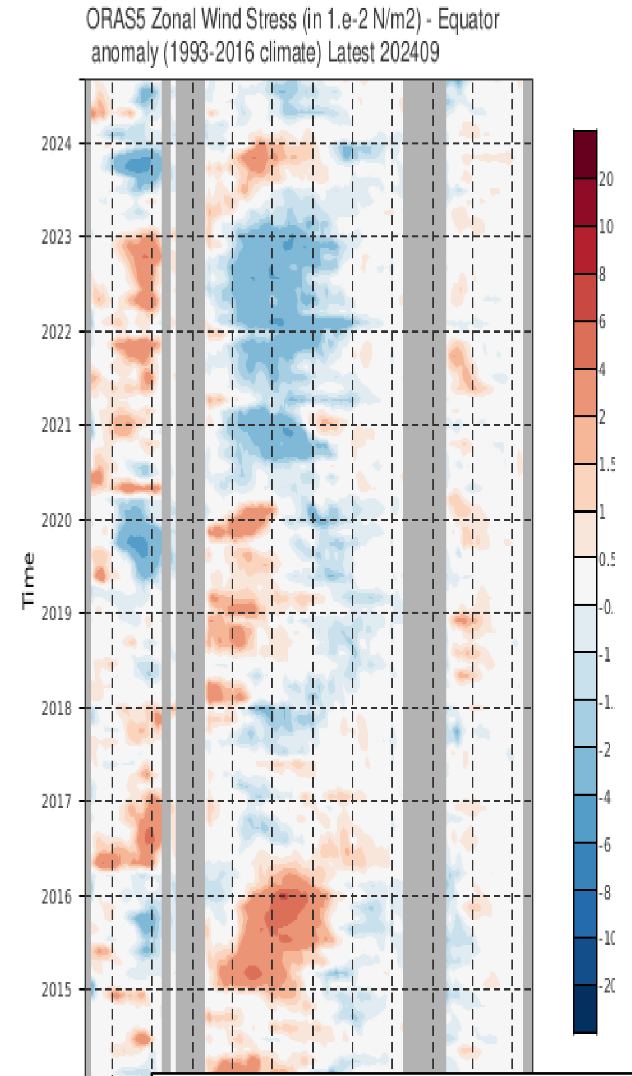
And without the atmospheric feedback, the subsurface temperature anomaly was weakening…

What happened? Time evolution at Eq. Last 11 years prior to Sep 2024

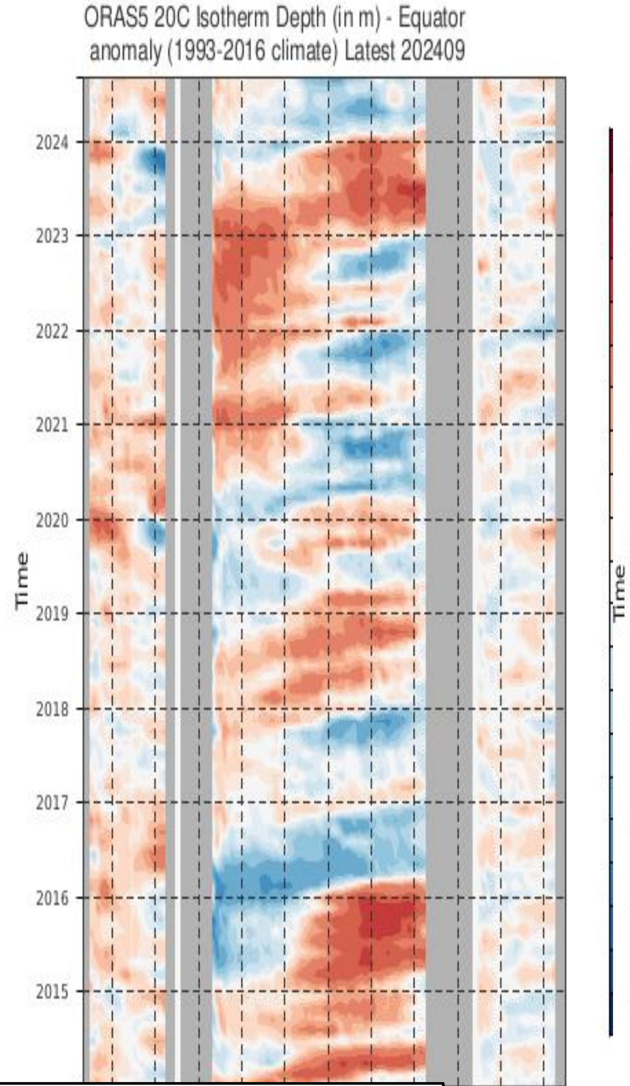
SST anomalies



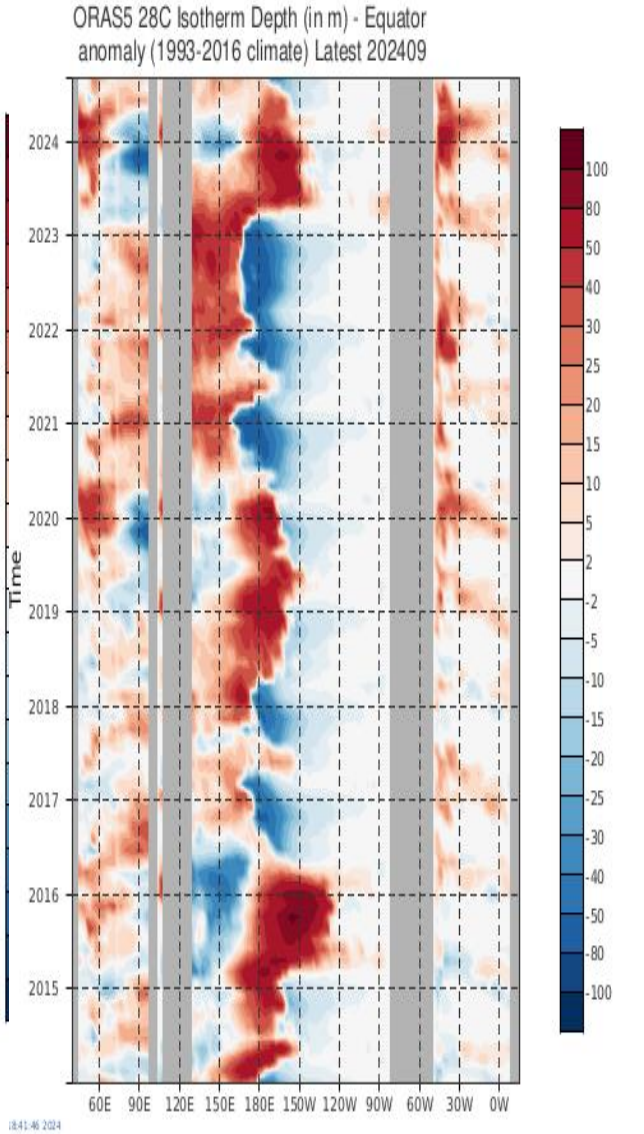
Zonal Wind stress anomalies



Depth 20º Isotherm anom



Depth 28º Isotherm anom



Weaker, earlier and shorter anomalies in the Ocean
Weaker atmospheric response –weak zonal winds

Diversity in atmospheric response to ENSO

DJF Velocity Potential 200hPa

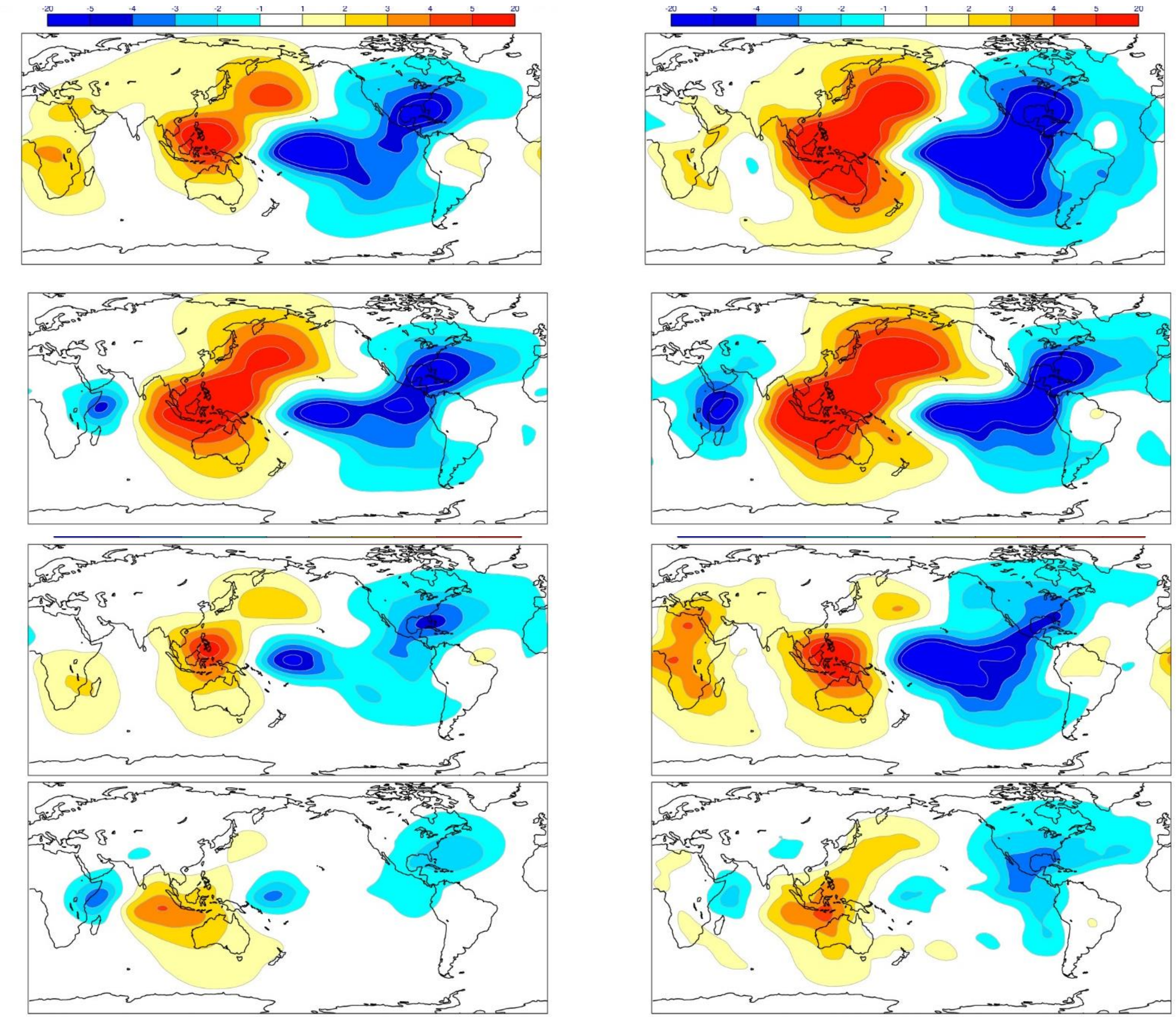
SEAS5 **Era5**

El Nino 1982-83

El Nino 1997-98

El Nino 2014-16

El Nino 2023-34



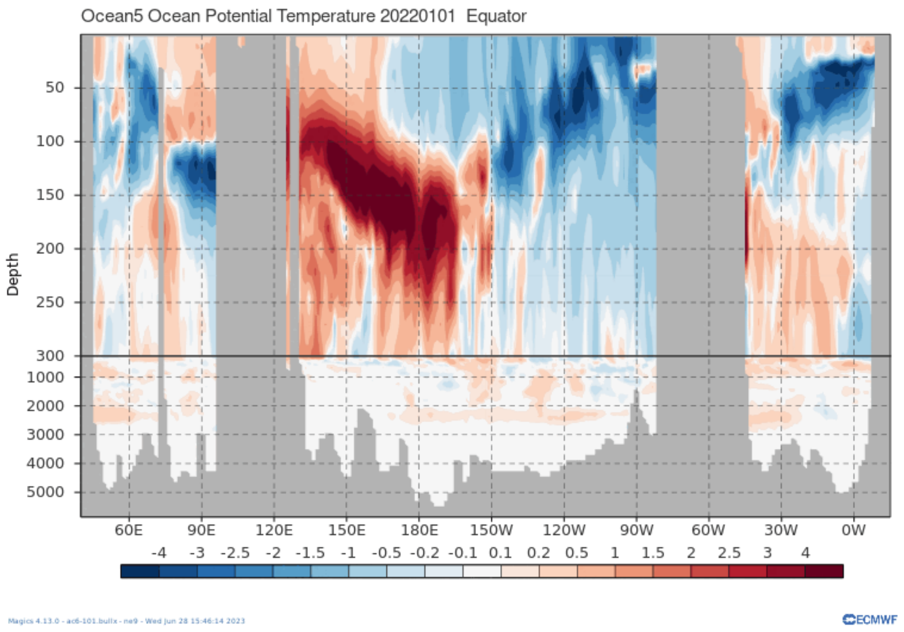
Summary

- ENSO as largest coupled mode of the climate system:
  - Ocean-Atmosphere Bjerkness 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?)

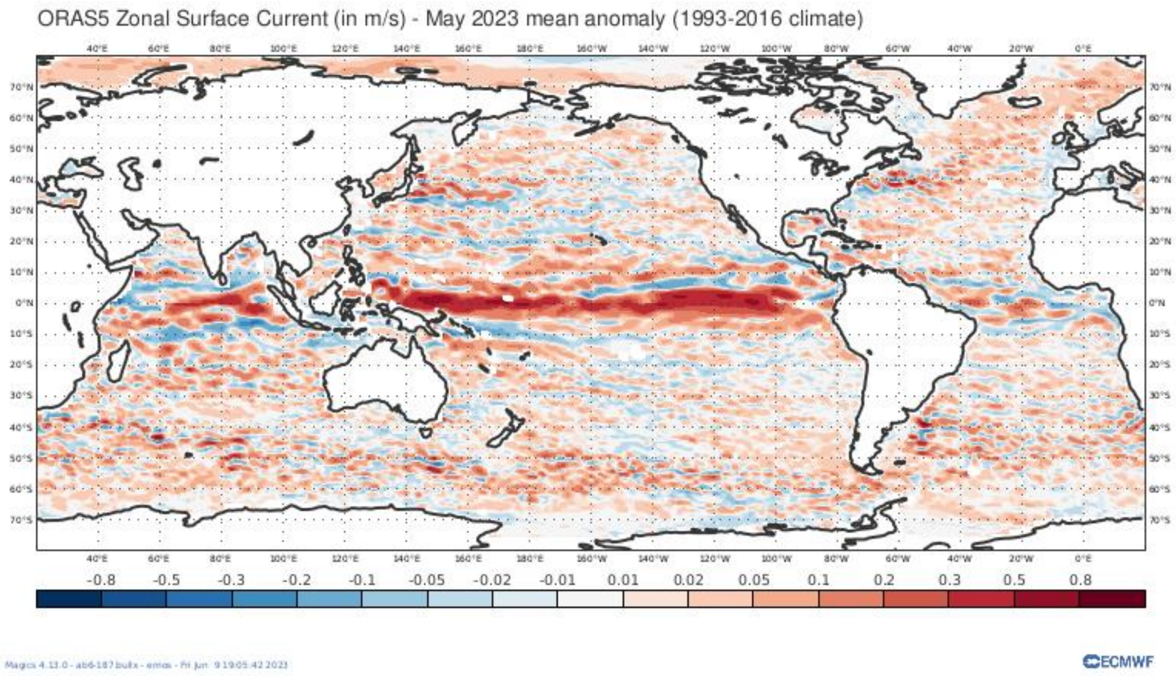
- ENSO prediction and predictability: time scale interaction
  - ENSO predictions are probabilistic. There is a large degree of stochasticity due to interaction with the subseasonal time scale.
  - ENSO properties depend on background mean state, giving rise to ENSO diversity.
    - In forecast, background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

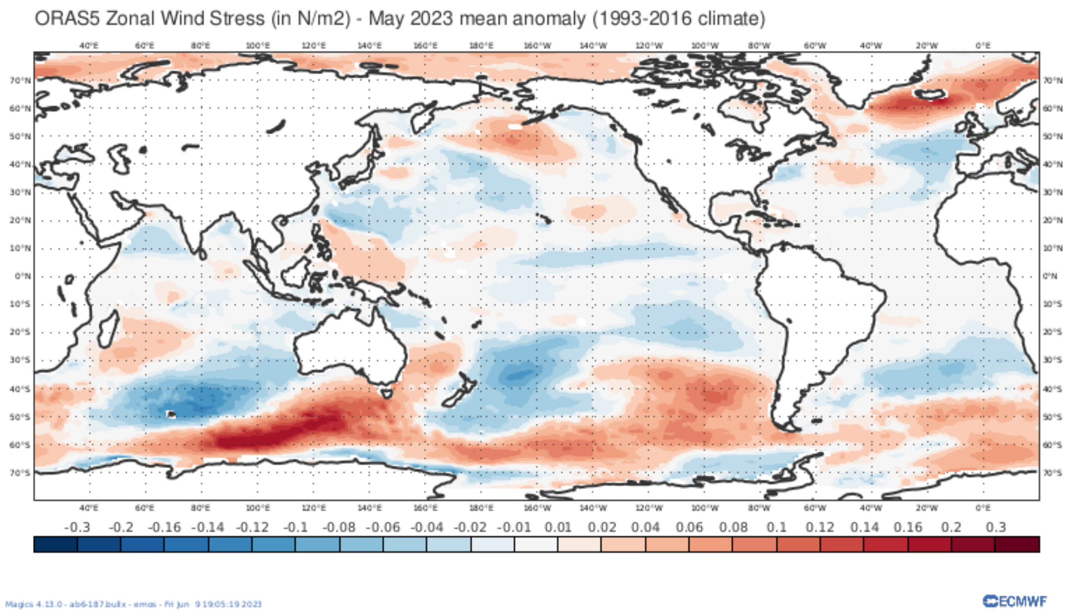
- Continuous progress on ENSO prediction
  - Observations + data assimilation + GCM Model development+ Conceptual diagnostics
  - In a changing climate, ENSO prediction is increasingly important: both impacts, mechanism and effect on Earth Energy balance
  - In SEAS6, the next ECMWF prediction system, there will be 24-months ENSO outlooks twice a year

Back up slides



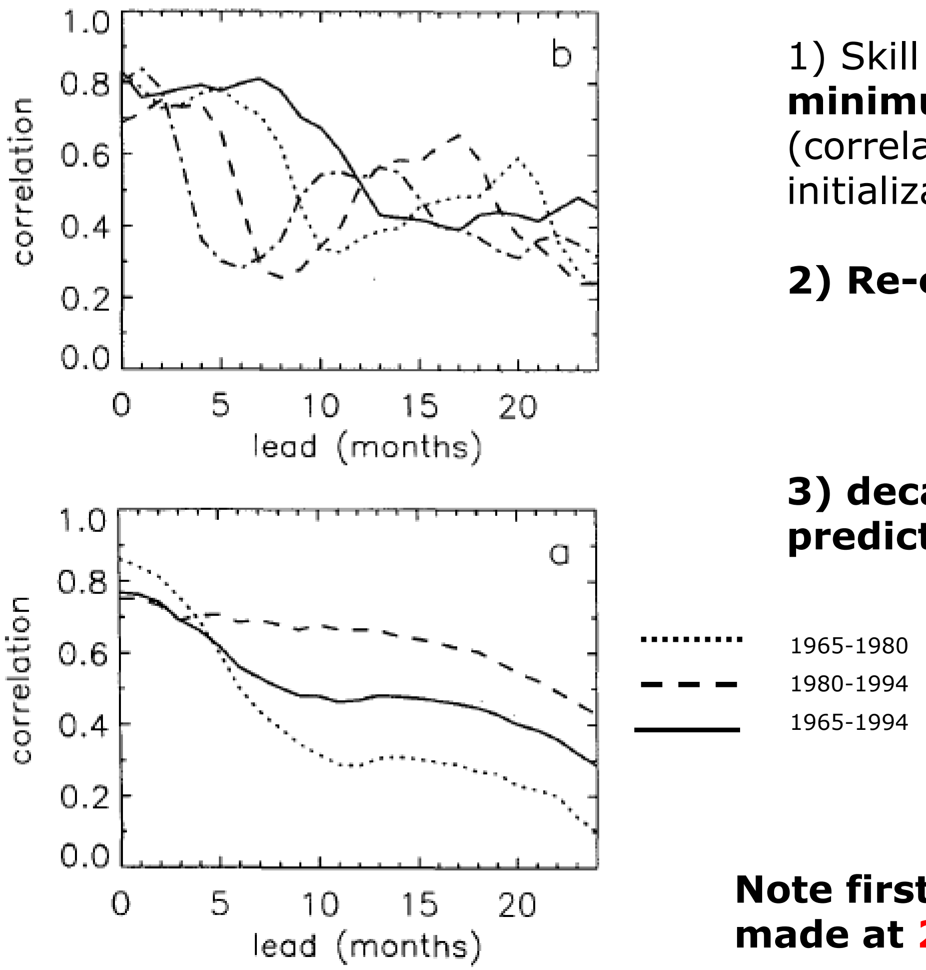
Ocean5 Ocean Potential Temperature 20220101 Equator
Depth
50
100
150
200
250
300
1000
2000
3000
4000
5000
60E
90E
120E
150E
180E
150W
120W
90W
60W
30W
0W
-4
-3
-2.5
-2
-1.5
-1
-0.5
-0.2
-0.1
0.1
0.2
0.5
1
1.5
2
2.5
3
4
ECMWF


ORAS5 Zonal Surface Current (in m/s) - May 2023 mean anomaly (1993-2016 climate)
-0.8 -0.5 -0.3 -0.2 -0.1 -0.05 -0.02 -0.01 0.01 0.02 0.05 0.1 0.2 0.3 0.5 0.8
ECMWF


ORAS5 Zonal Wind Stress (in N/m2) - May 2023 mean anomaly (1993-2016 climate)
-0.3 -0.2 -0.16 -0.14 -0.12 -0.1 -0.08 -0.06 -0.04 -0.02 -0.01 0.01 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.2 0.3
ECMWF

First attempts were deterministic

With Statistical/Simplified dynamics/hybrid models



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