Forecasting ENSO

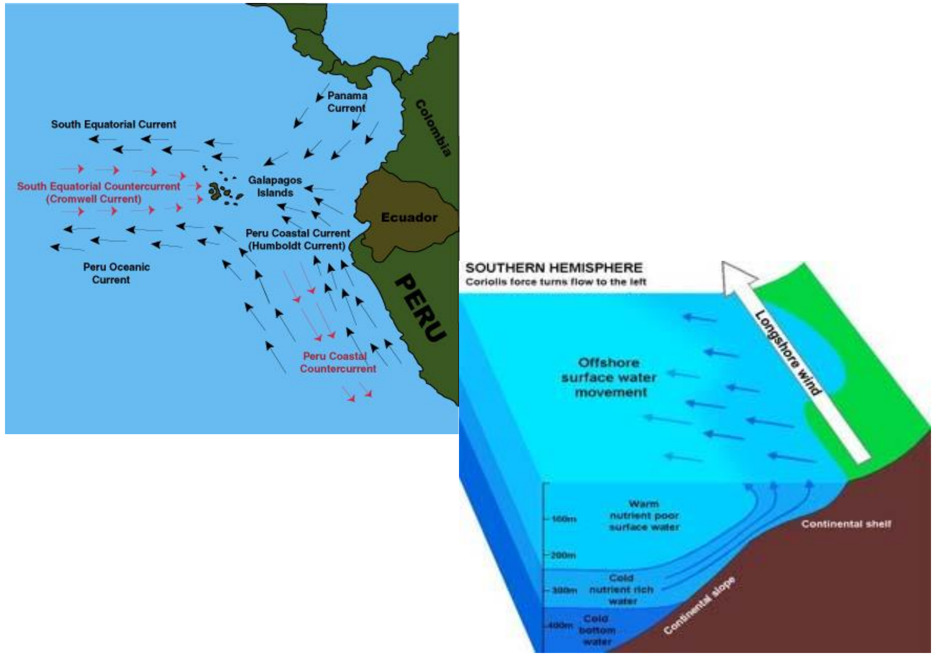
In a changing climate

- 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 current El Niño

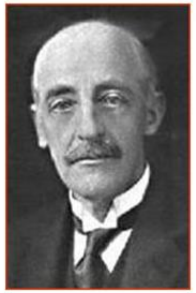
Magdalena Alonso Balmaseda

Origins of ENSO:El Nino Southern Osciallation

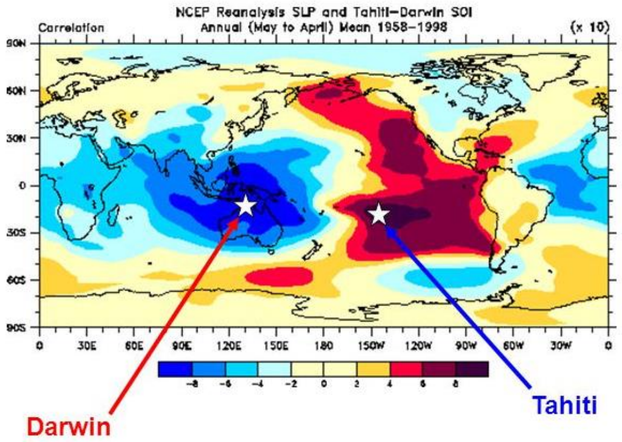
El Niño
Named by Peruvian Fishermen
Tradition
Oceanic impact on fisheries and nutrients



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



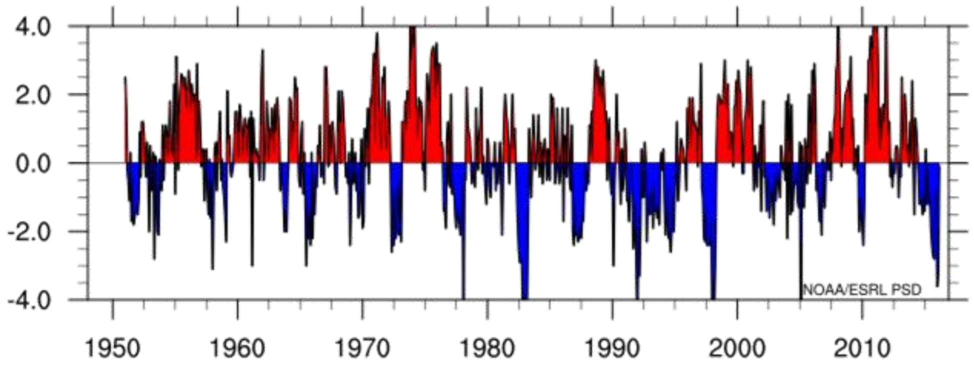
Sir Gilbert Walker
(1868-1958)

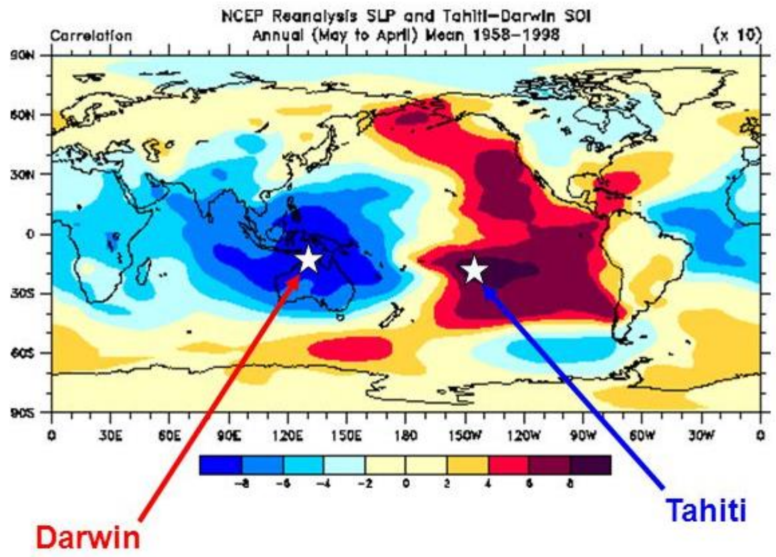


Origins of ENSO

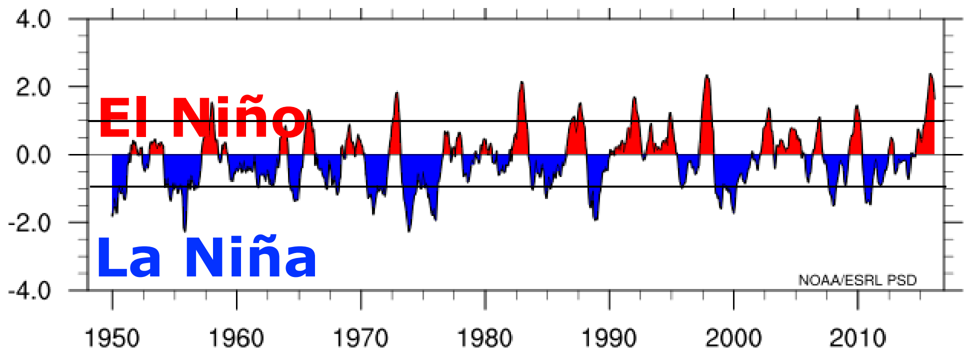
SOI in phase opposition with SST index

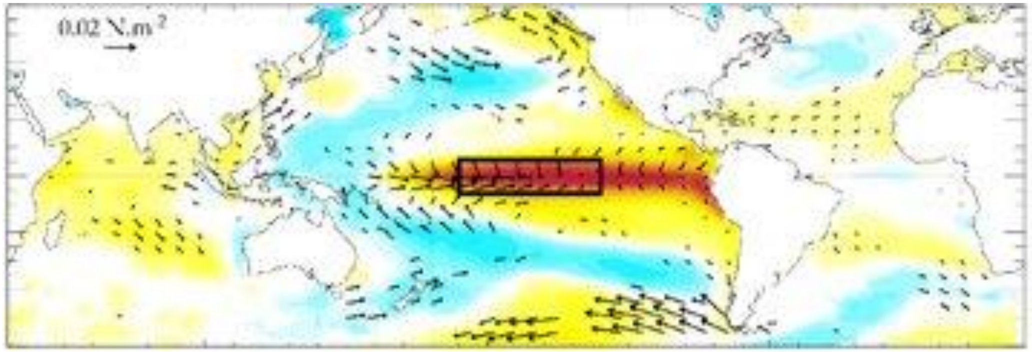
Southern Oscillation Index (SOI)
MSLP Darwin - Tahiti



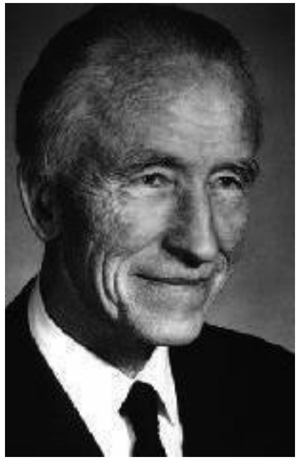


Nino3.4 SST index





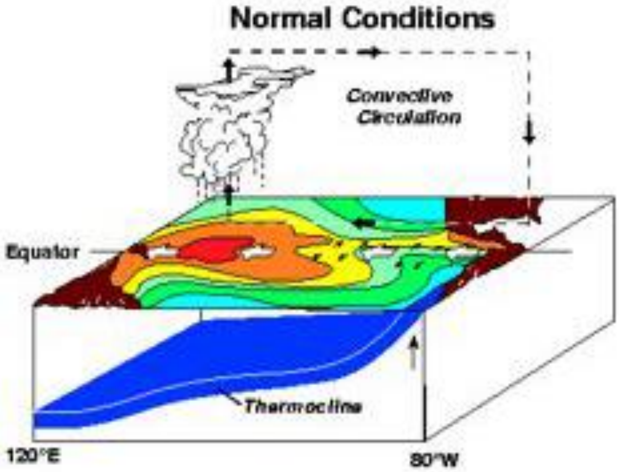
ENSO as a coupled mode

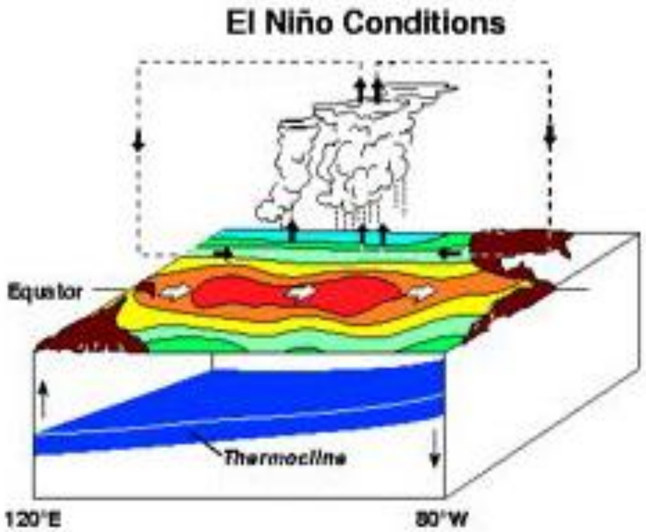


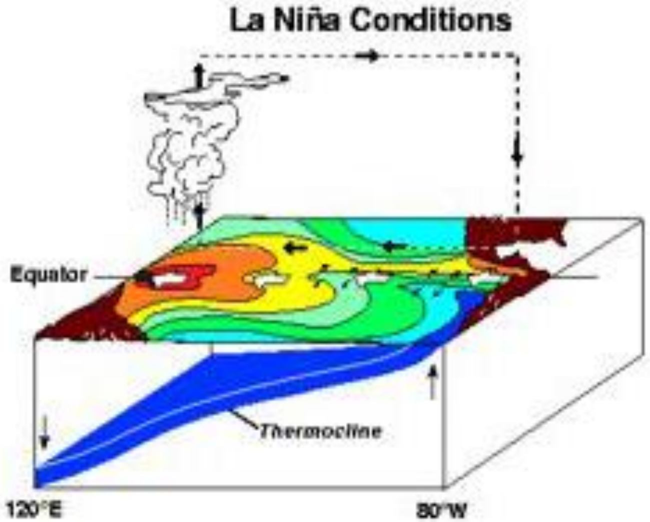
A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature

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

(Manuscript received January 18, 1966)







ENSO:El Nino-Southern Oscillation

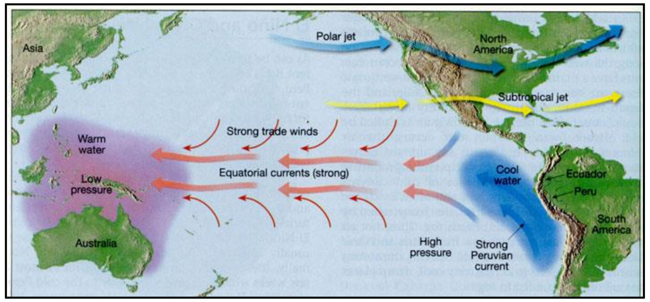
Largest mode of interannual climate variability

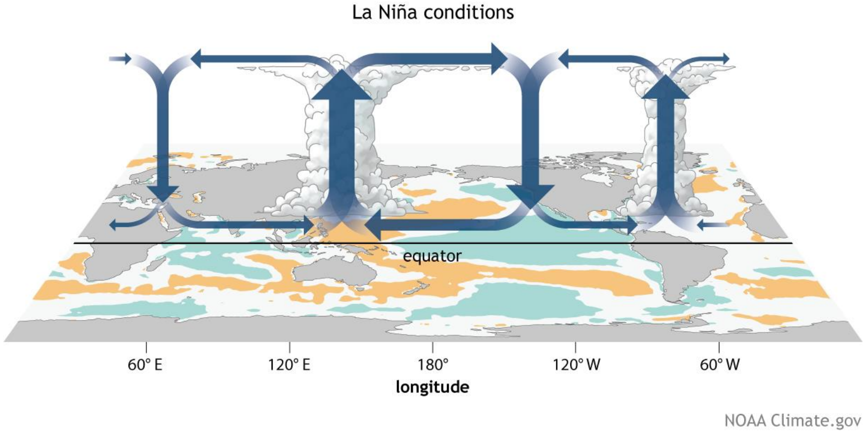
Best known source of predictability at seasonal time scales

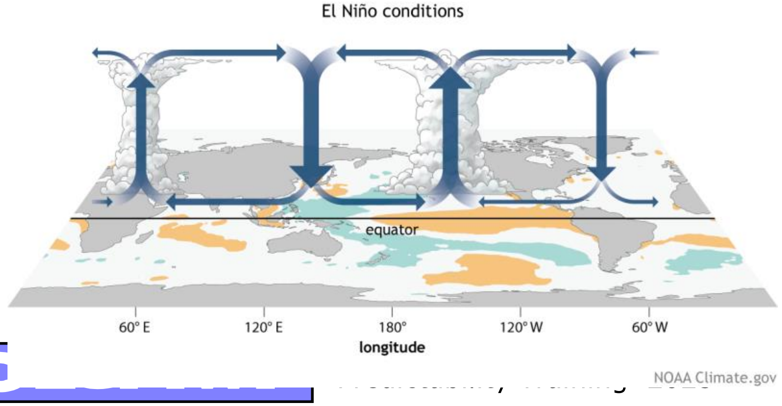
It affects global patterns of atmospheric circulation, with changes in rainfall, temperature, hurricanes, extreme events

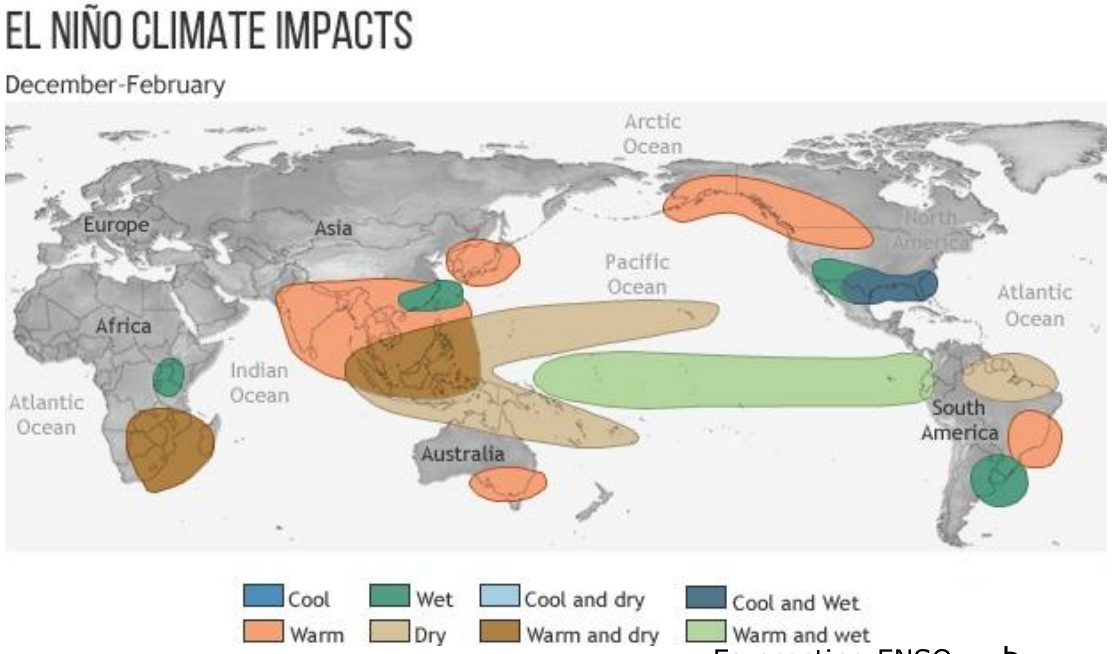
Impacts on marine ecosystems, on agriculture, health,…

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







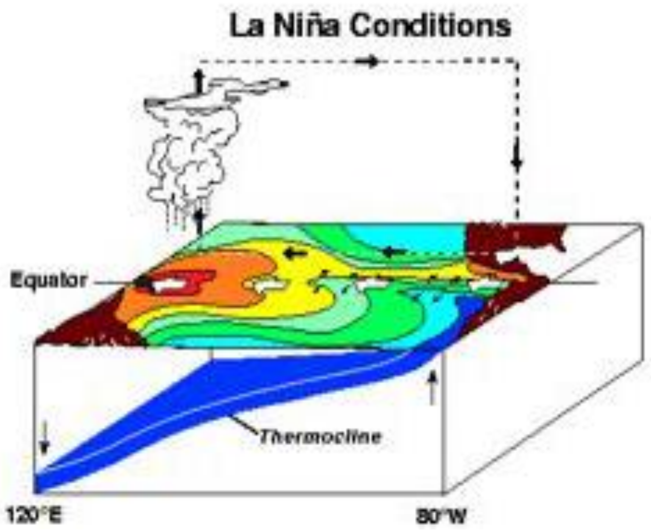


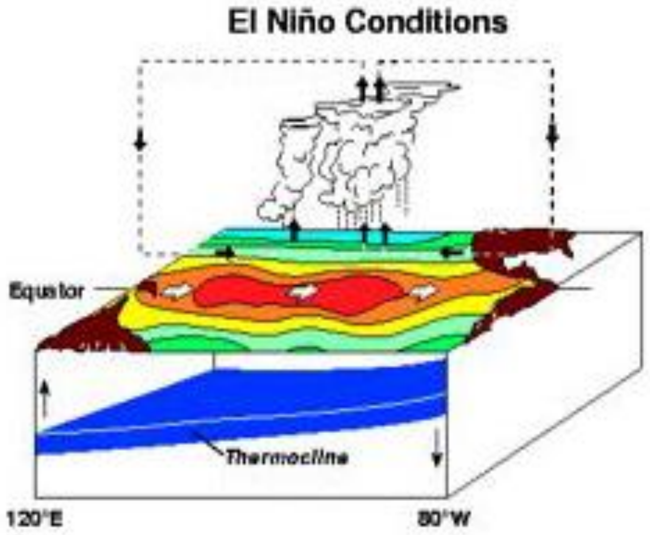
ENSO: balance of multiple feedbacks

- **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
  - B) ratio SST anomaly East/zonal_wind –depends on the "thermocline feedback" (+) and heat flux feedback (-).

- **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).
- **Radiative feedback** is –ve over convective regions, it is +ve over cold stratocumulus regions. *Cloud properties are important!*



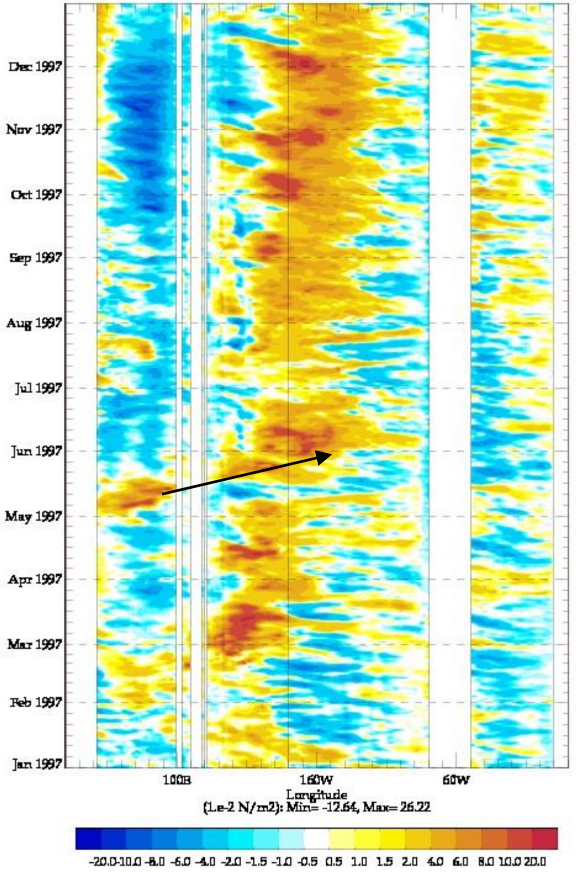


These balances are difficult to represent by models

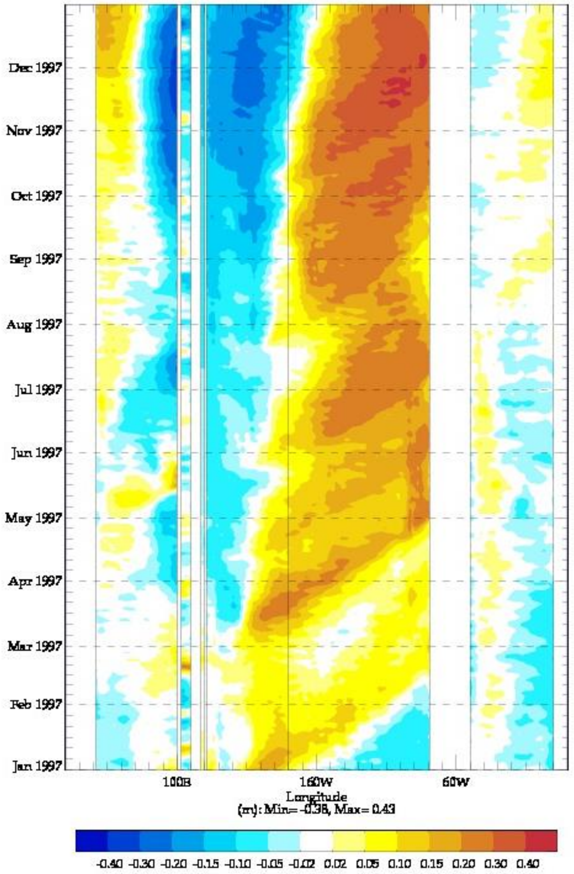
And Climate Change can affect them

Daily Equatorial Anomalies: Jan 1997-Jan 1998

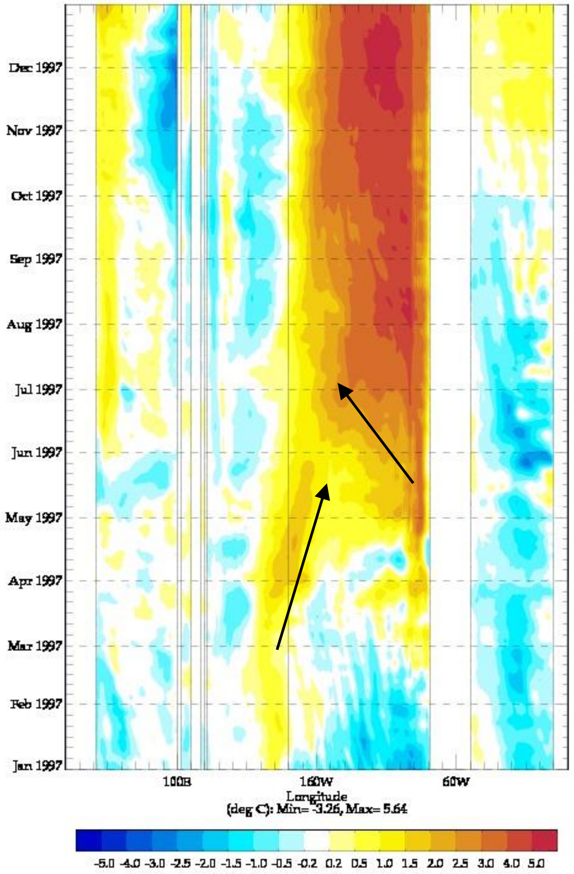
Zonal Wind Stress Anomalies



SL Anomalies



SST Anomalies



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

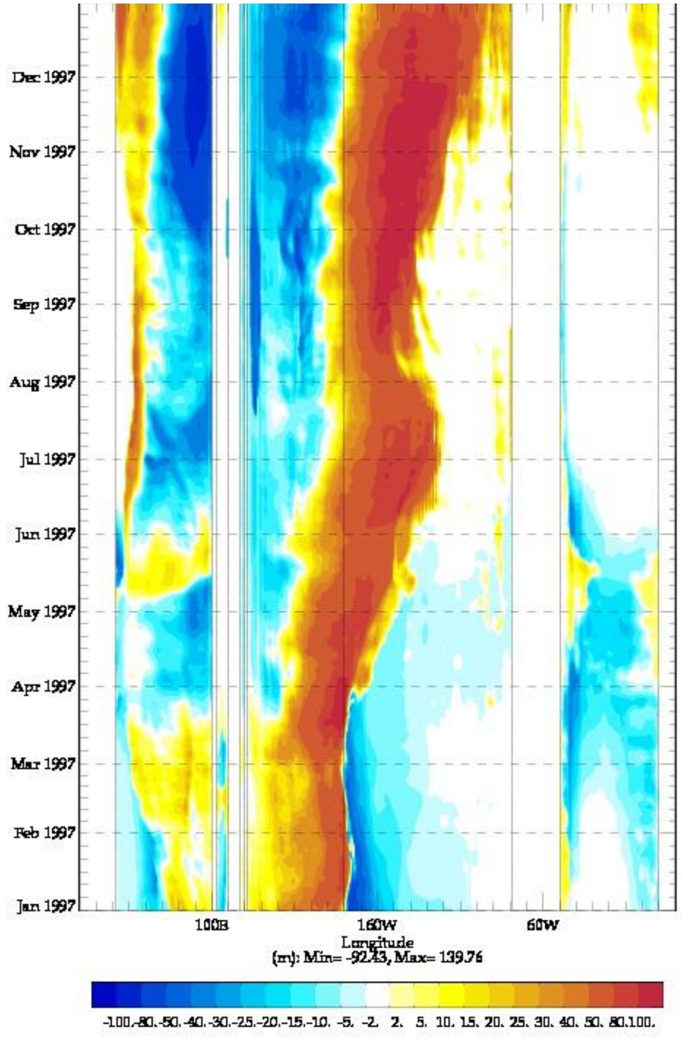
Associated eastward propagating groups of Kelvin waves in the thermocline. The latest reaching the Eastern Coast

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

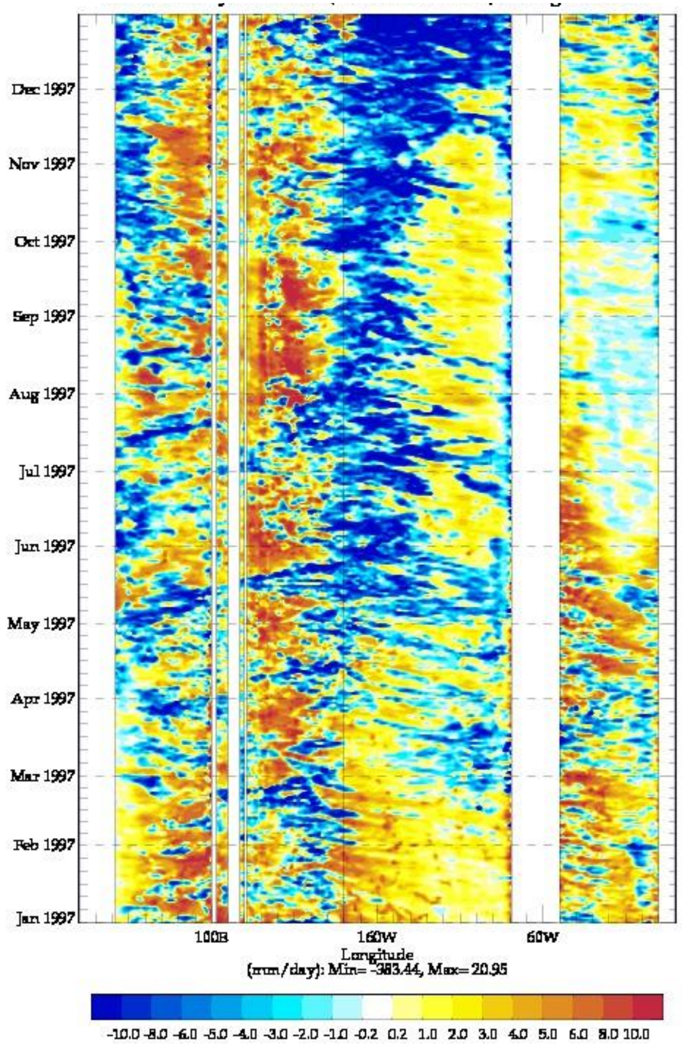
May/June 1997: More WWB . Or is this already ENSO? Bjerknes feedback in action.

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

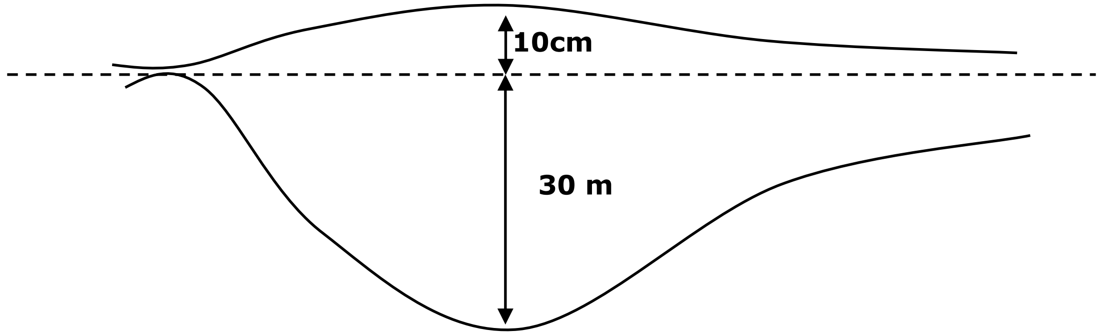
- 1966
  - Bjerknes: ENSO as a coupled O-A mode
- 1975
  - Wyrtki: importance of ocean Kelvin waves. Sea level as first observing system for prediction
- 1980's
  - First attempts at modelling and prediction with simple models (Zebiak and Cane 1987)
- Early 1990's
  - Development of GCMs: Simulating 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

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).

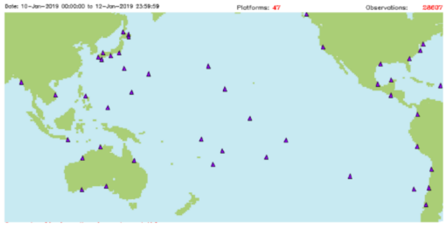


If we observe sea level, one can infer information on the vertical density structure, and we can detect propagating waves. This is why altimeter Sea-Leve is important for ENSO monitoring and prediction.

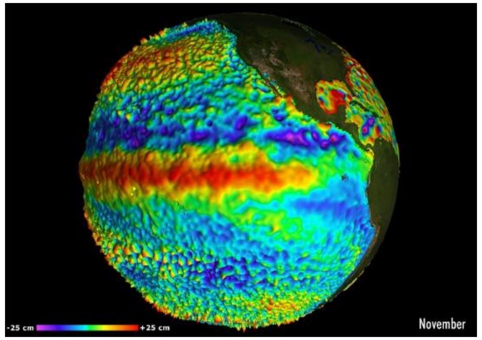
Relevance of Observations and Climate Reanalyses

SST ➕ **Atmosphere** ➕ **Ocean Subsurface**

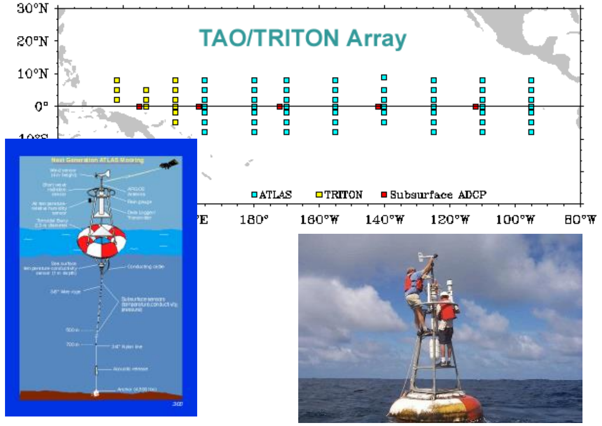
1975; Wyrtki sets Equatorial tide gauges to monitor Kelvin waves



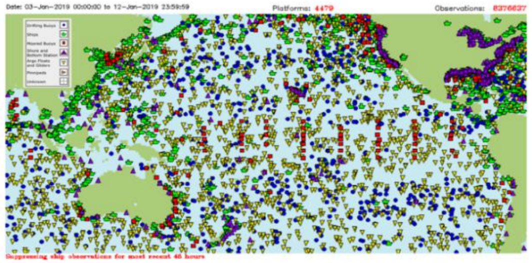
~ 1993 onwards: satellite altimeter to monitor sea level



~ 1993- TOGA-TAO program to monitor subsurface temperature



~ 2005: Argo uniform sampling of subsurface temperature and salinity

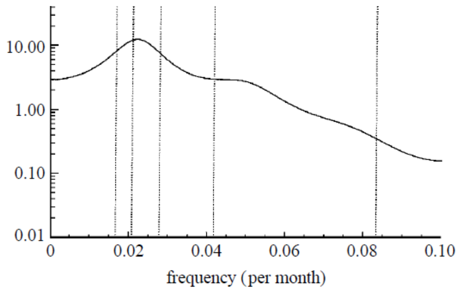


When Observations are integrated with laws of physics we obtain climate reanalyses, a essential resource of the understanding, modelling and prediction of ENSO

ENSO: other facts

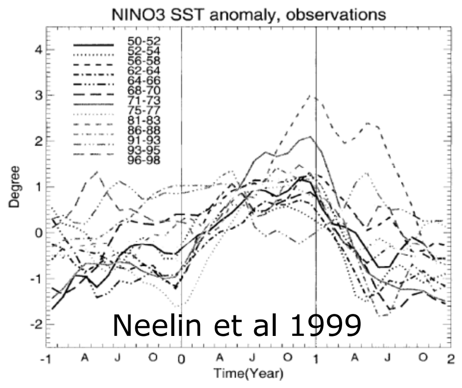
1) ENSO temporal irregularity

Broad spectral peak
Blanke et al 1997

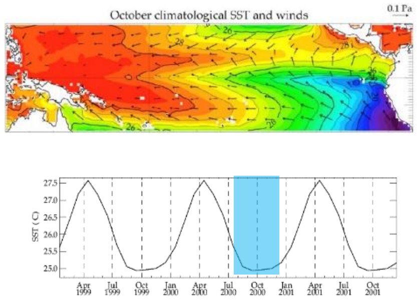


2) Phase lock to seasonal cycle

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



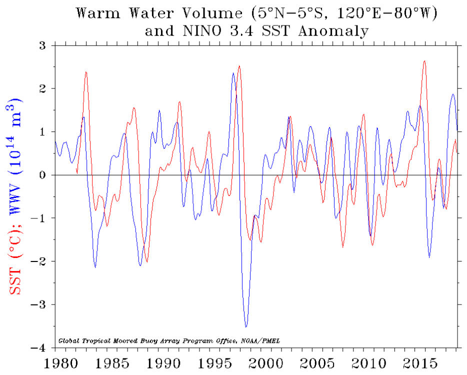
Neelin et al 1999



ENSO peaks during cold phase of seasonal cycle

3) Relationship between SST-OHC

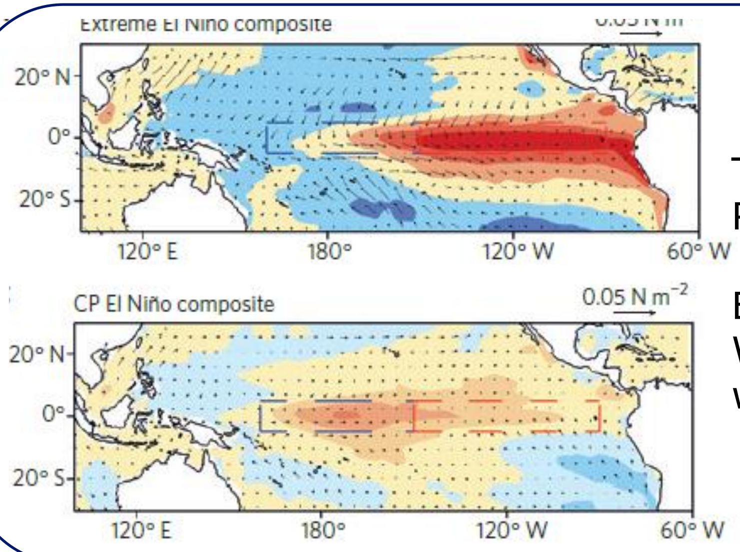
(or Warm Water Volume).



OHC precedes SST.

Specially after a warming

4)ENSO Diversity

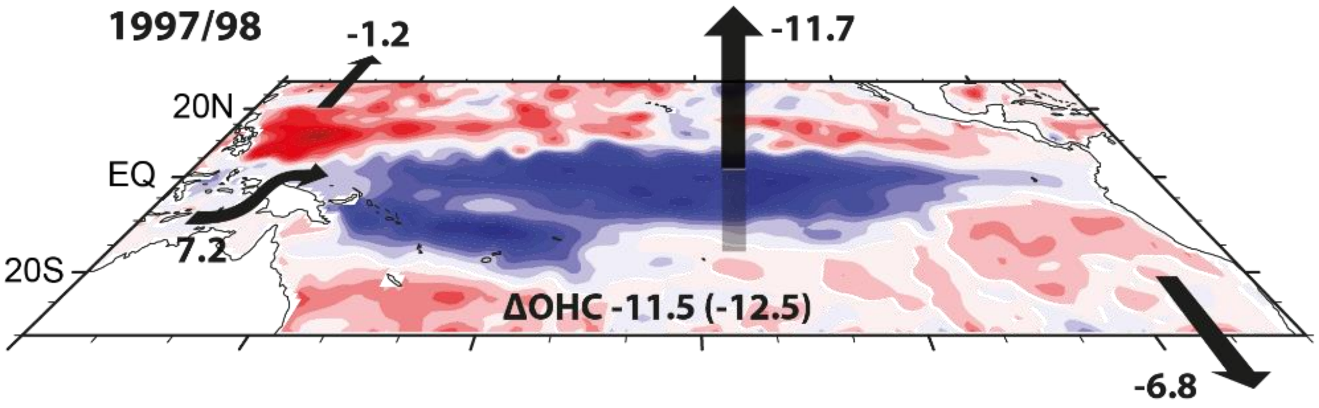


Top) Eastern Pacific Warming. Related with Big El Ninos

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).**
  - **Traditionally 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
   Very predictable

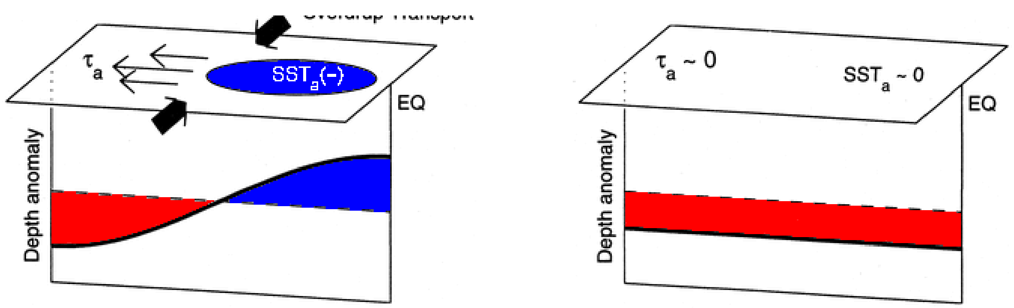
2. **Coupled Instability, stochastically triggered.**
   System with 2 time scales. Atmospheric noise triggers ENSO.
   Limited predictability Moore and Kleeman J.Clim 1999)

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

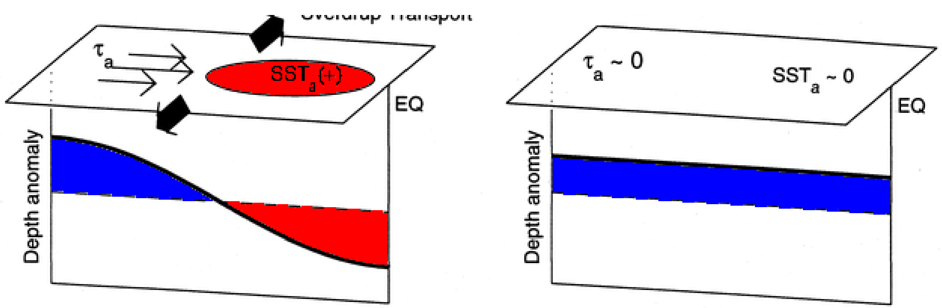
The Recharge/Discharge oscillator

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

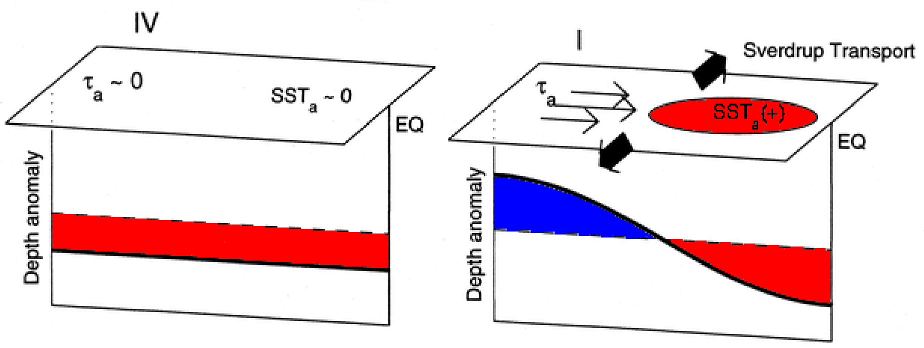
III. During El Niño: westerlies induce discharge via Sverdrup transport.

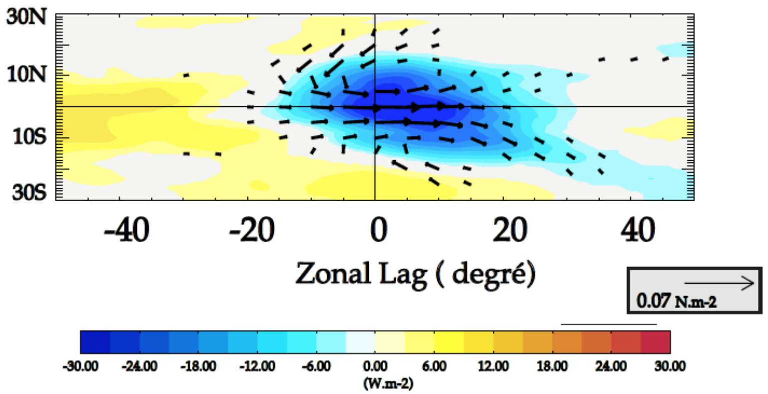
IV. A Discharged Pacific favours the occurrence of La Niña. And the cycle continues

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

The spark & the fuel (© M. McPhaden)

Stochastic discharge/recharge oscillator





The fuel: ocean heat content

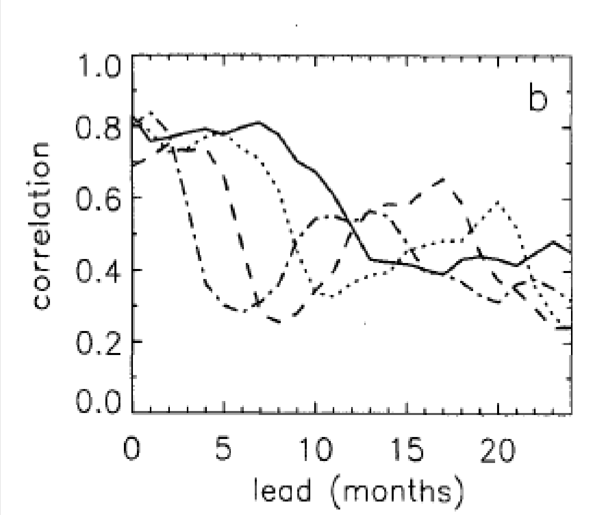
The spark: Westerly Wind Events

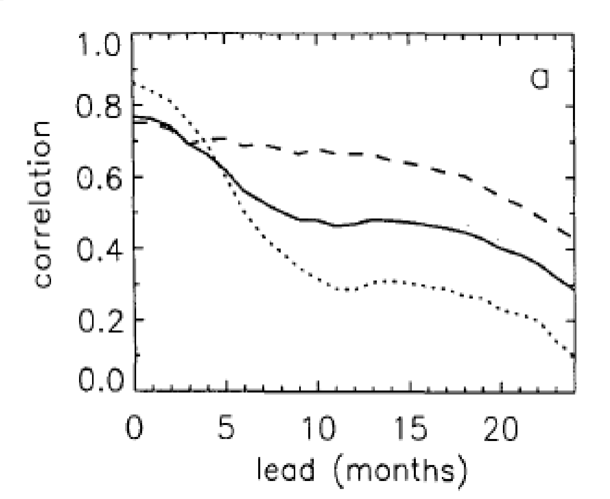
The background state sets the level of instability: it explains ENSO diversity and helps to understand model errors, predictions and ENSO projections

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

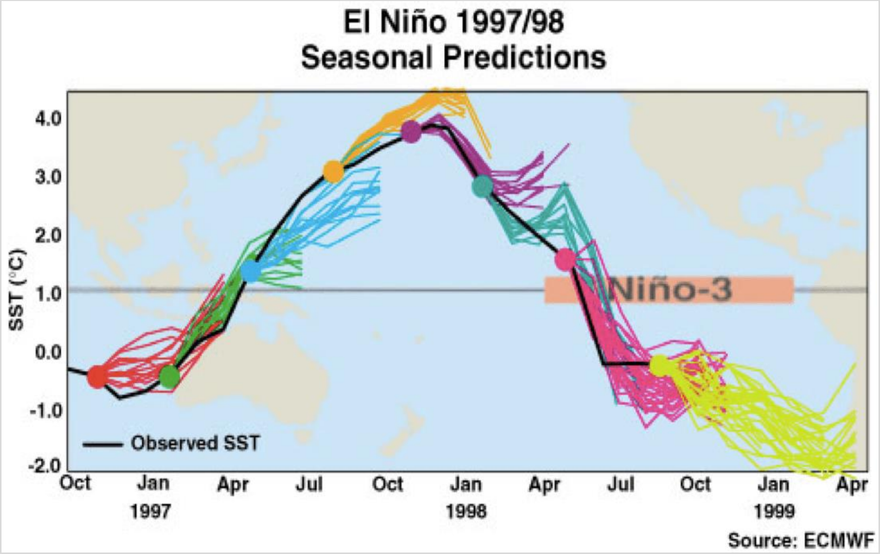
3) decadal variations on ENSO prediction skill

1965-1980
1980-1994
1965-1994

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

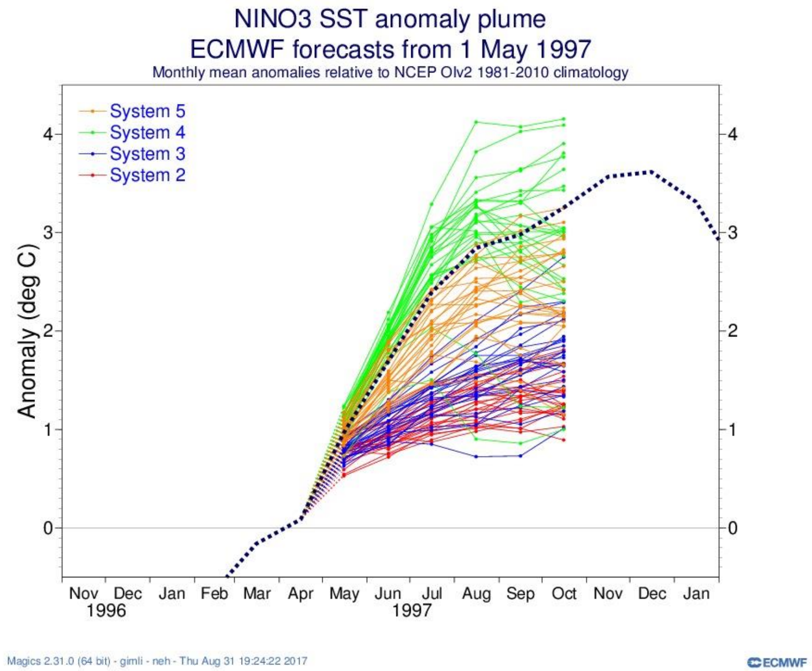
Several contributing factors converging:

- 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**



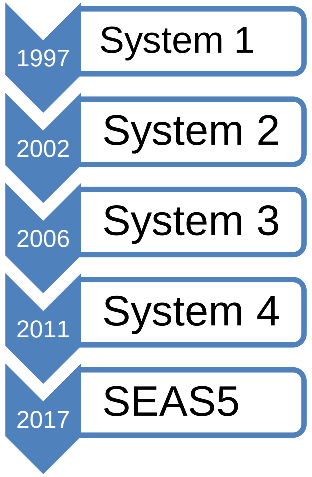
S2 inability to generate WWB caused under prediction of 1997/98 ENSO
(Vitart et al 2004).

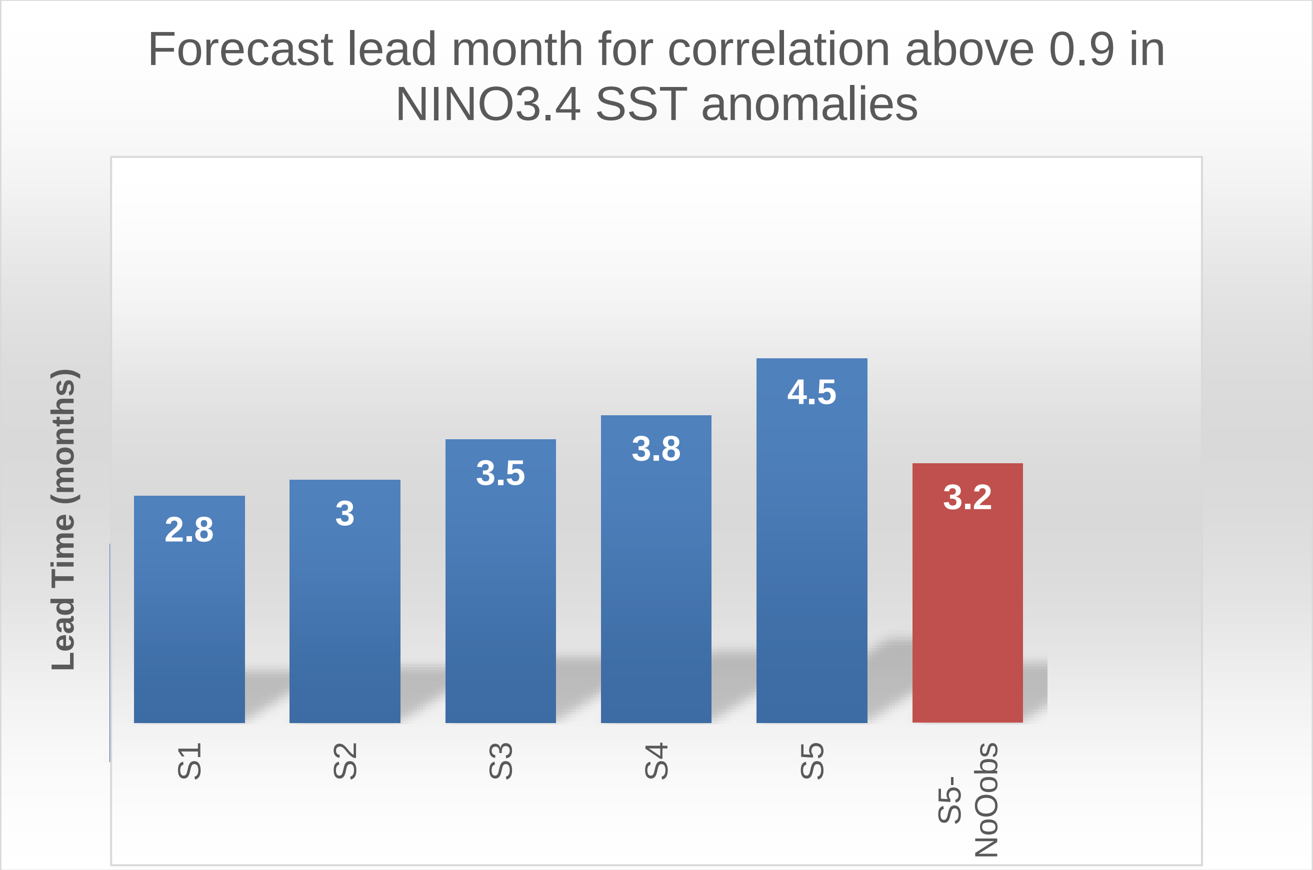
As the model improved

SEAS5 became operational in Nov 2017

20 years or progress in ENSO prediction at ECMWF

and contribution of ocean observations

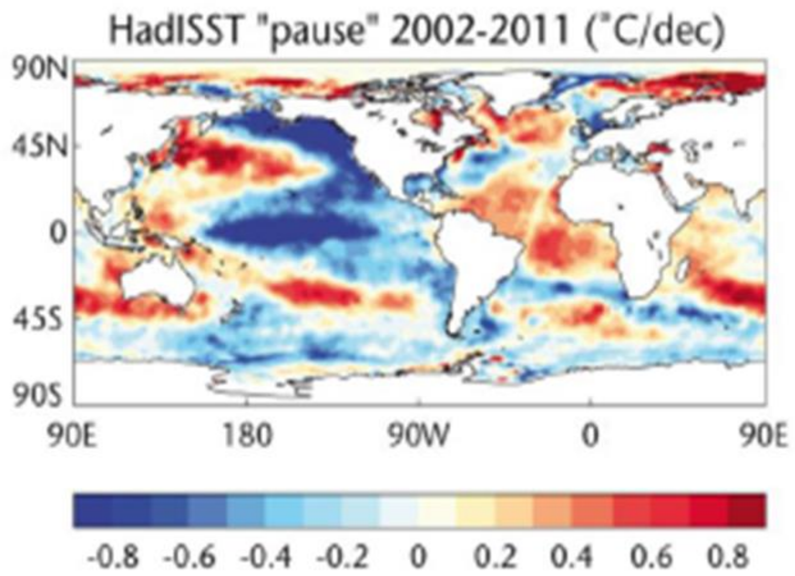




- S1 was the first ECMWF seasonal forecasting system. Implemented as a pilot in 1997
- SEAS5 is the latest ECMWF seasonal forecasting system. Implemented in November 2017. Contributes to Copernicus Climate Change Services C3S.

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

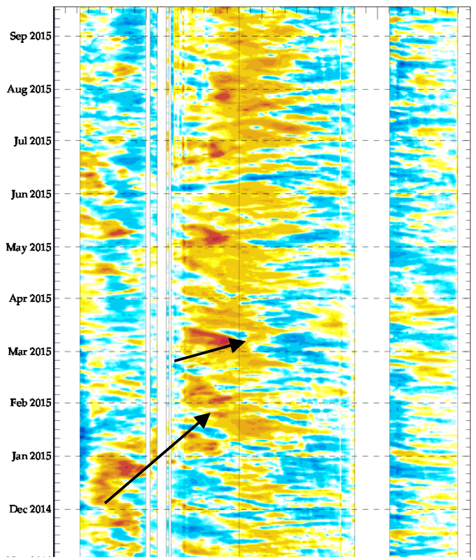
- Great expectation in 2014 for a big El Nino
  - Last one was in 1997/98
  - There had been a hiatus decade (since ~2005) with negative phase of PDO
  - Long lasting Californian drought
  - Models and Experts predicted the possibility of a large warm event

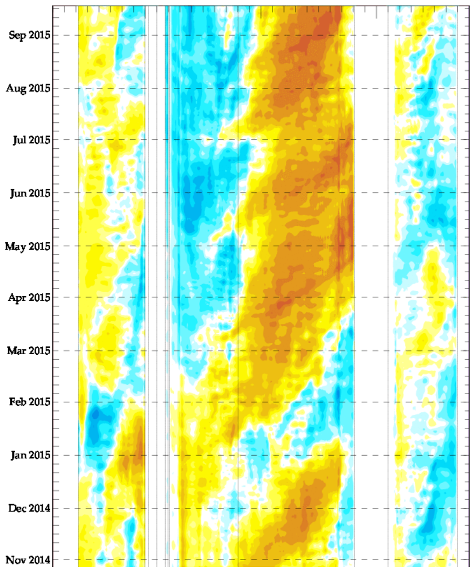


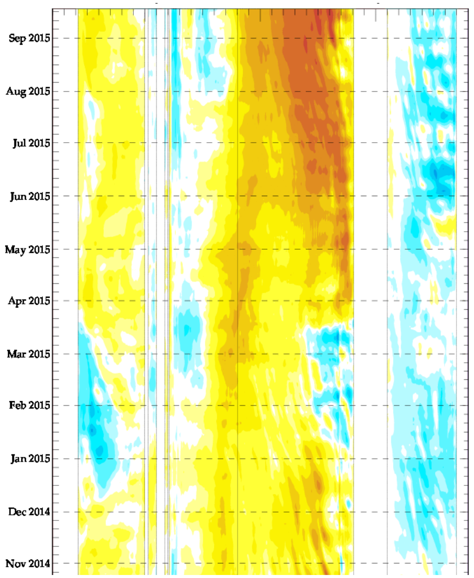
Taux Anomalies

D20 Anomalies

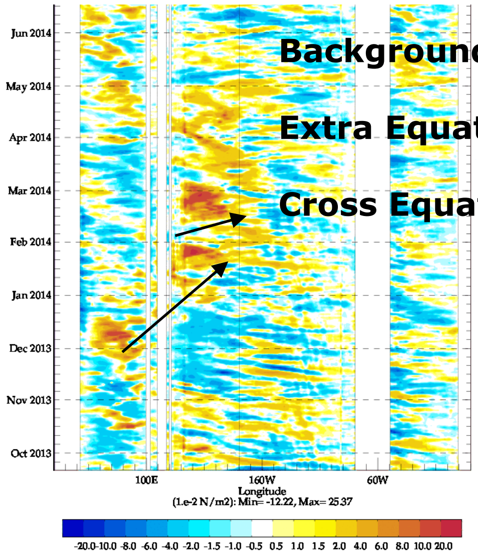
SST Anomalies

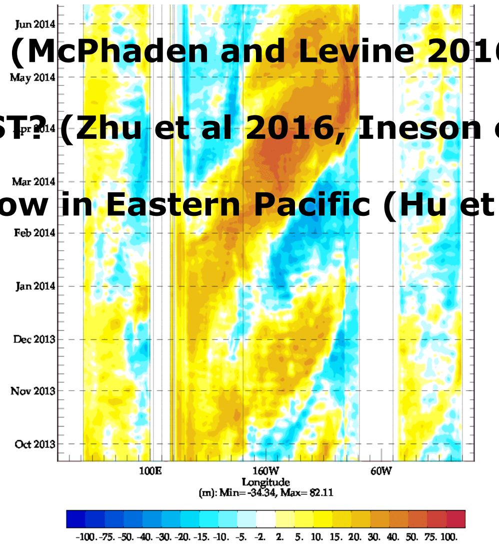


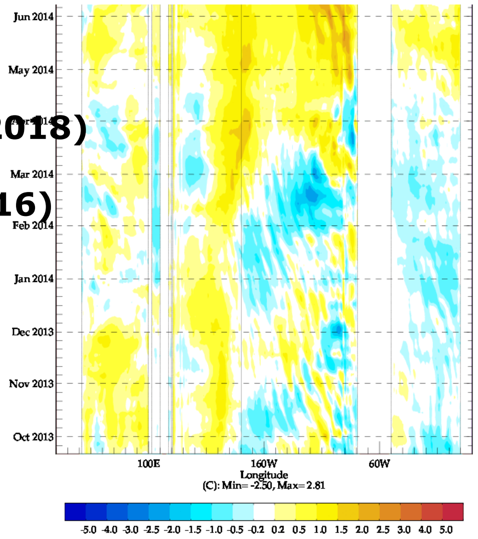




Sep 2015







June 2014

Sep 2013

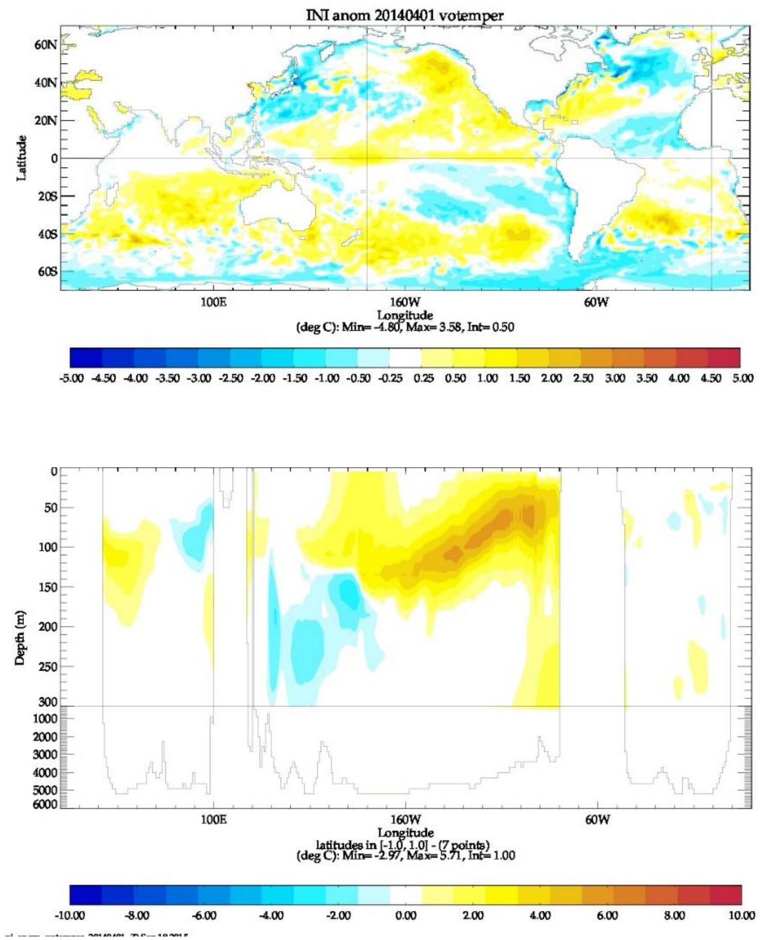
Background State? (McPhaden and Levine 2016)

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

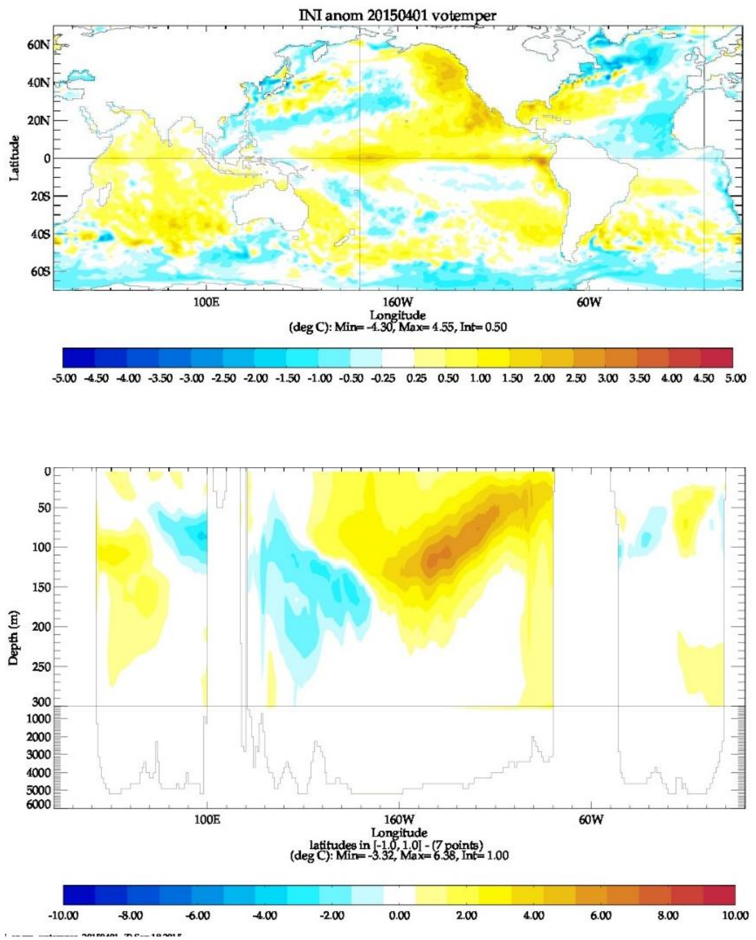
Cross Equatorial Flow in Eastern Pacific (Hu et al 2016)

Temperature Anomalies From Ocean Reanalysis

APR 2014

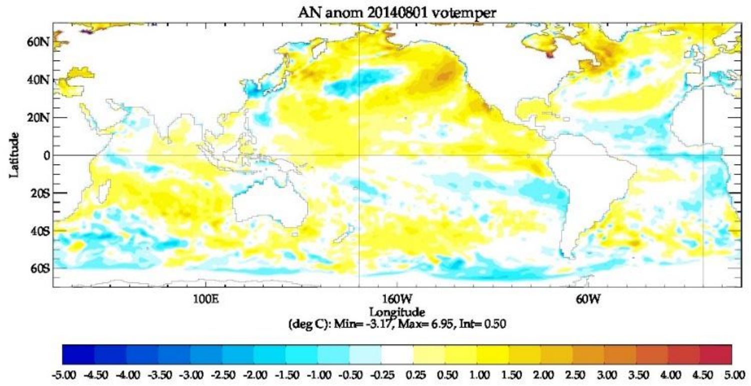


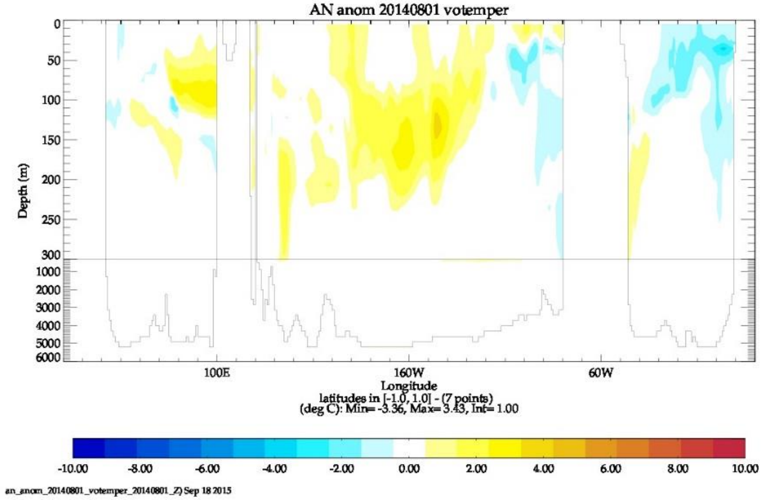
APR 2015



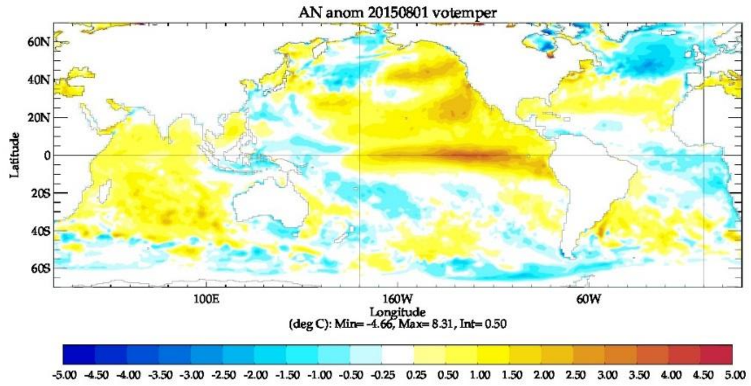
Temperature Anomalies From Ocean Reanalysis

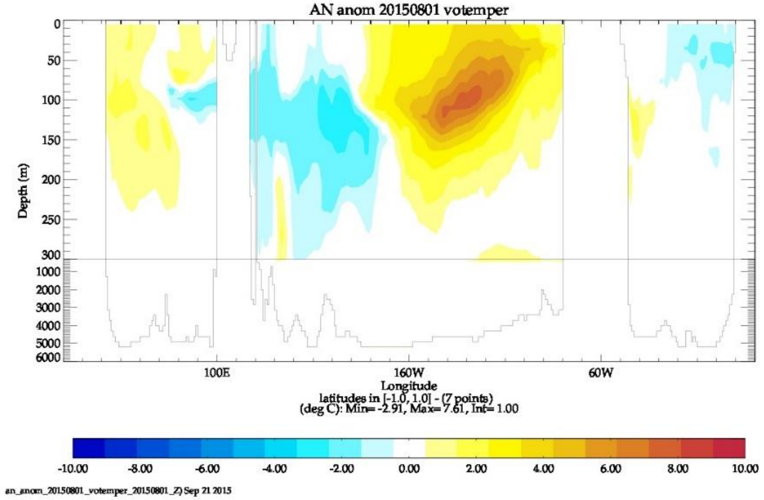
AUG 2014



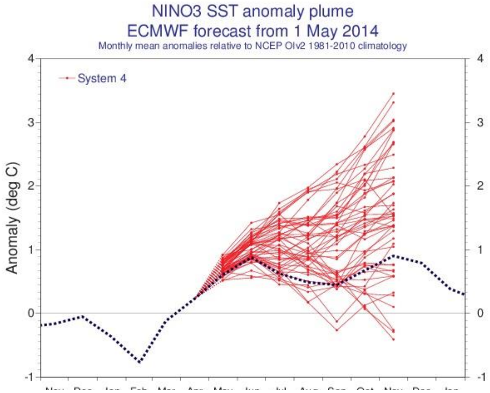


AUG 2015

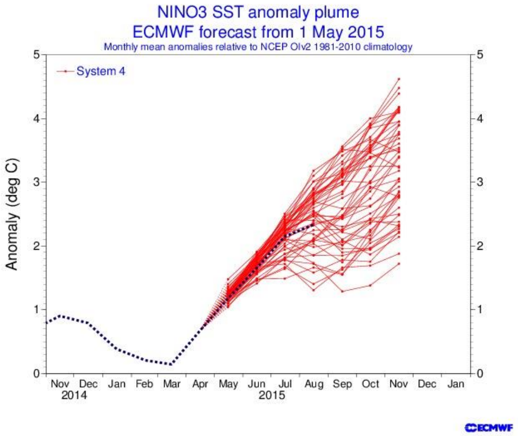




S4 El Nino Forecasts: 2014 v 2015?



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

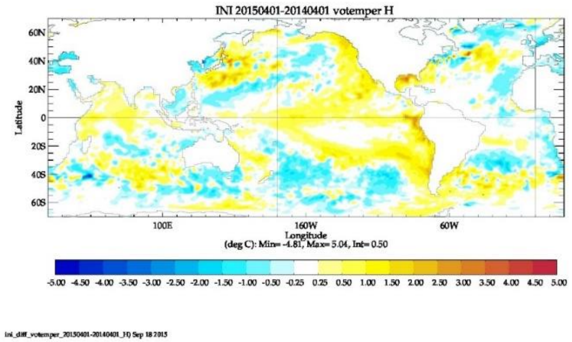


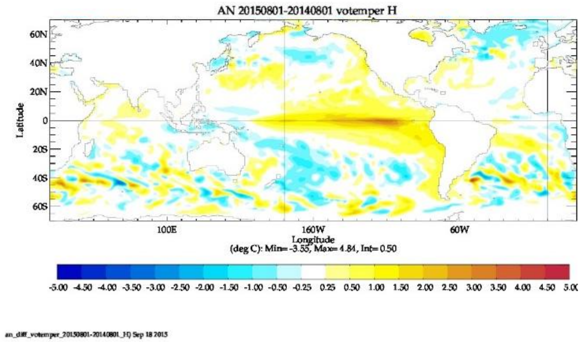
- What causes the large spread in the fc? Is that spread a good estimation for predictability?

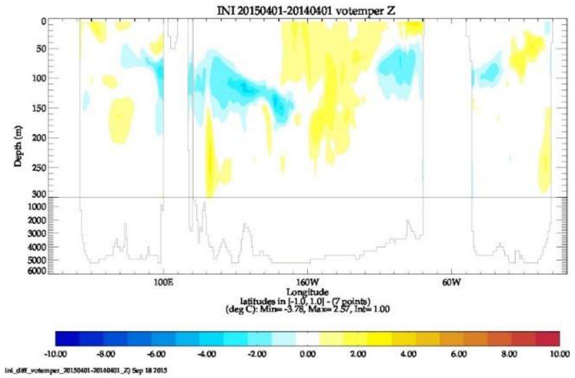
Growth of Perturbations: Temperature

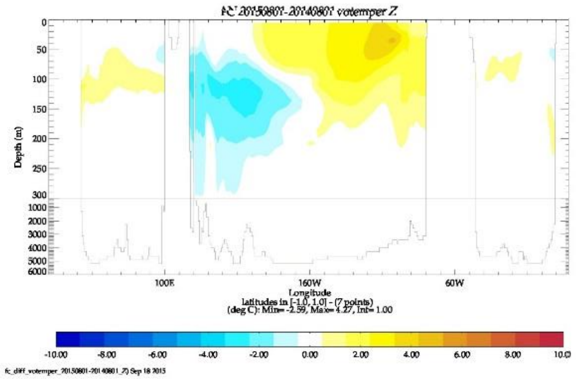
INI Pert: APR 2015-2014

Forecast Final Pert: Aug 2015-2014









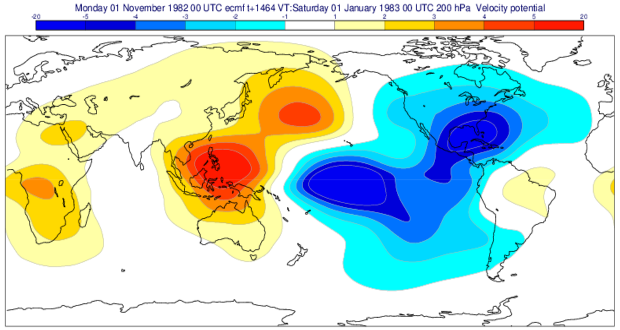
- S4 Seas Fc are discerning: they capture differences between 2015 and 2014.
- Skill beyond persisting the initial differences.

Seasonal Forecasts Diversity in ENSO teleconnections

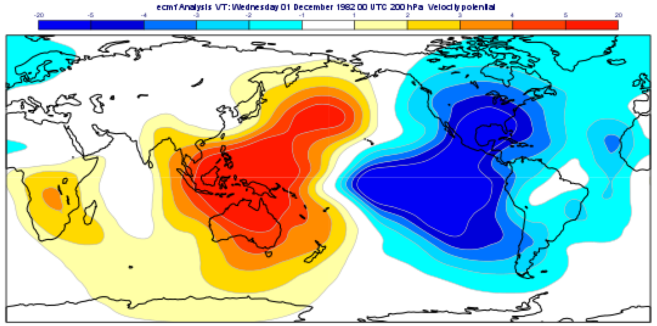
Velocity Potential 200hPa

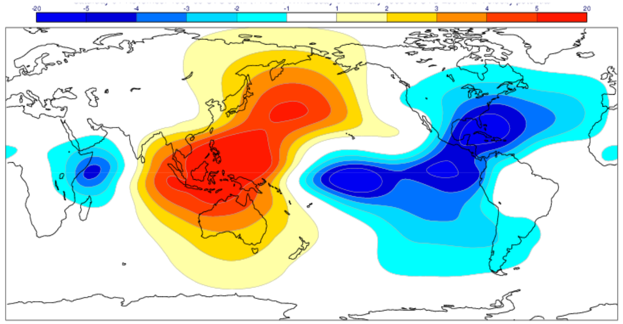
SEAS5

Era-Interim

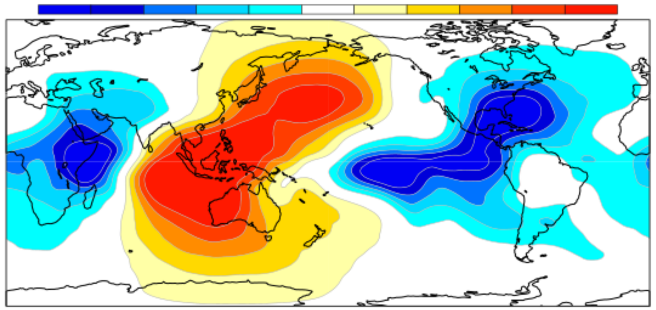


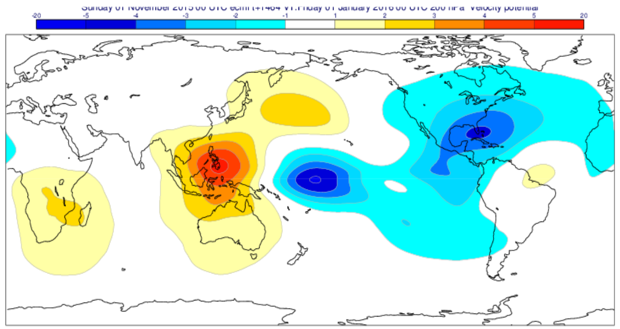
1983



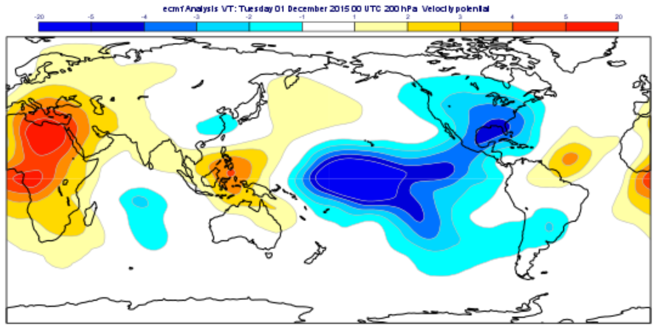


1998





2016

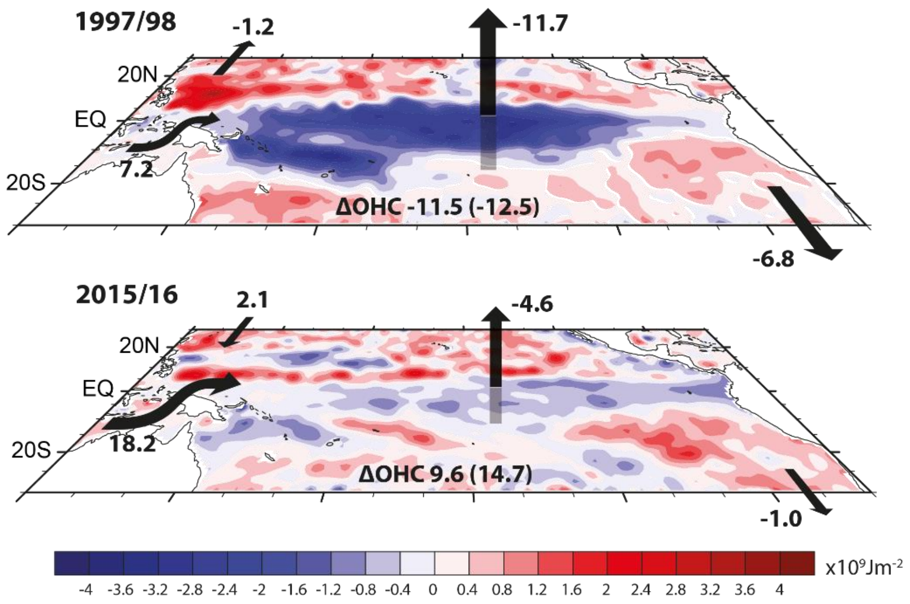


From Laura Ferranti

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

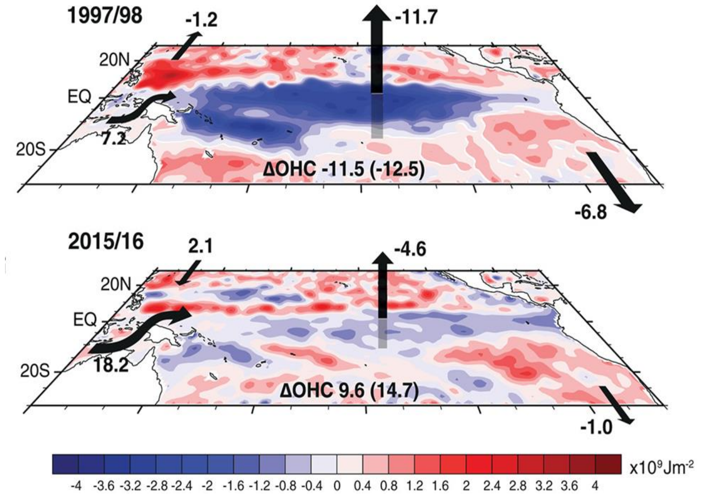


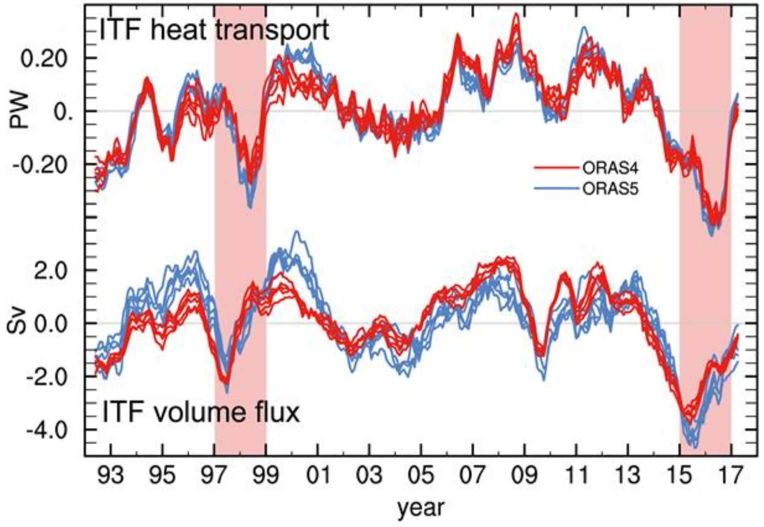
- As a consequence, the Tropical Pacific remained in a recharge state.
- And El Nino did not manage to refrigerate the the earth system

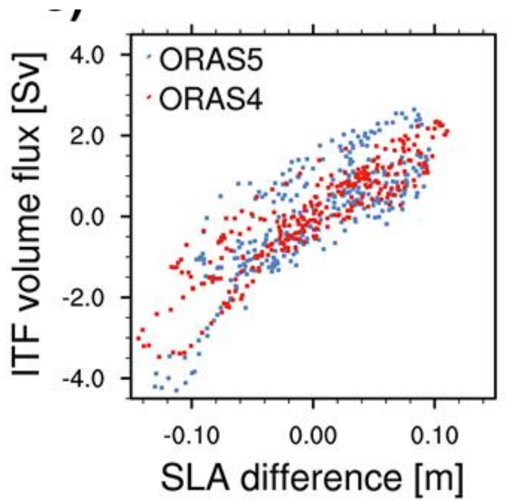
From Mayer, Balmaseda and Haimberg 2018

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

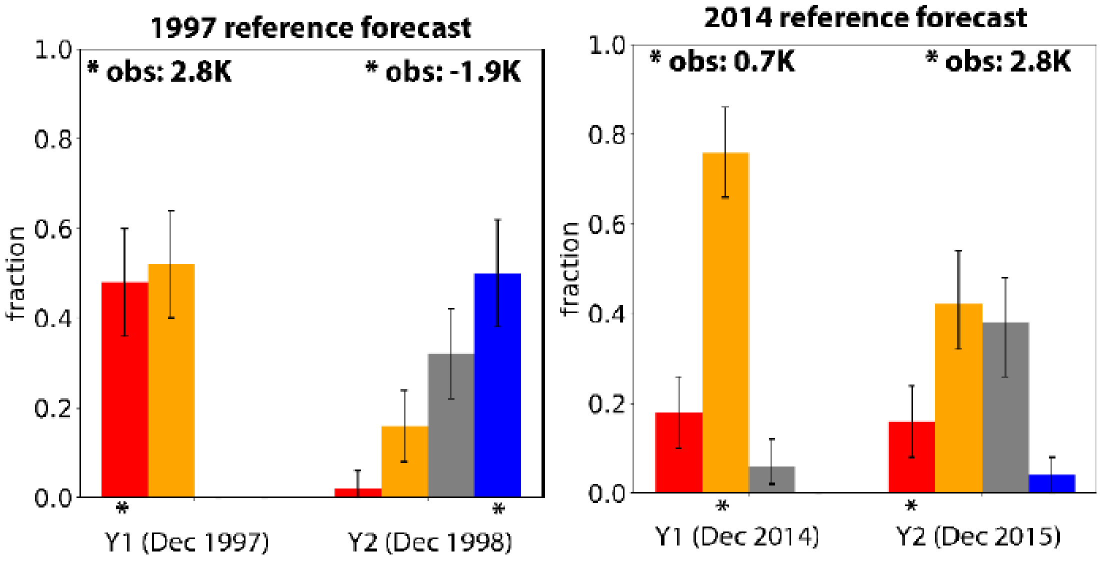
Questions arising

- 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

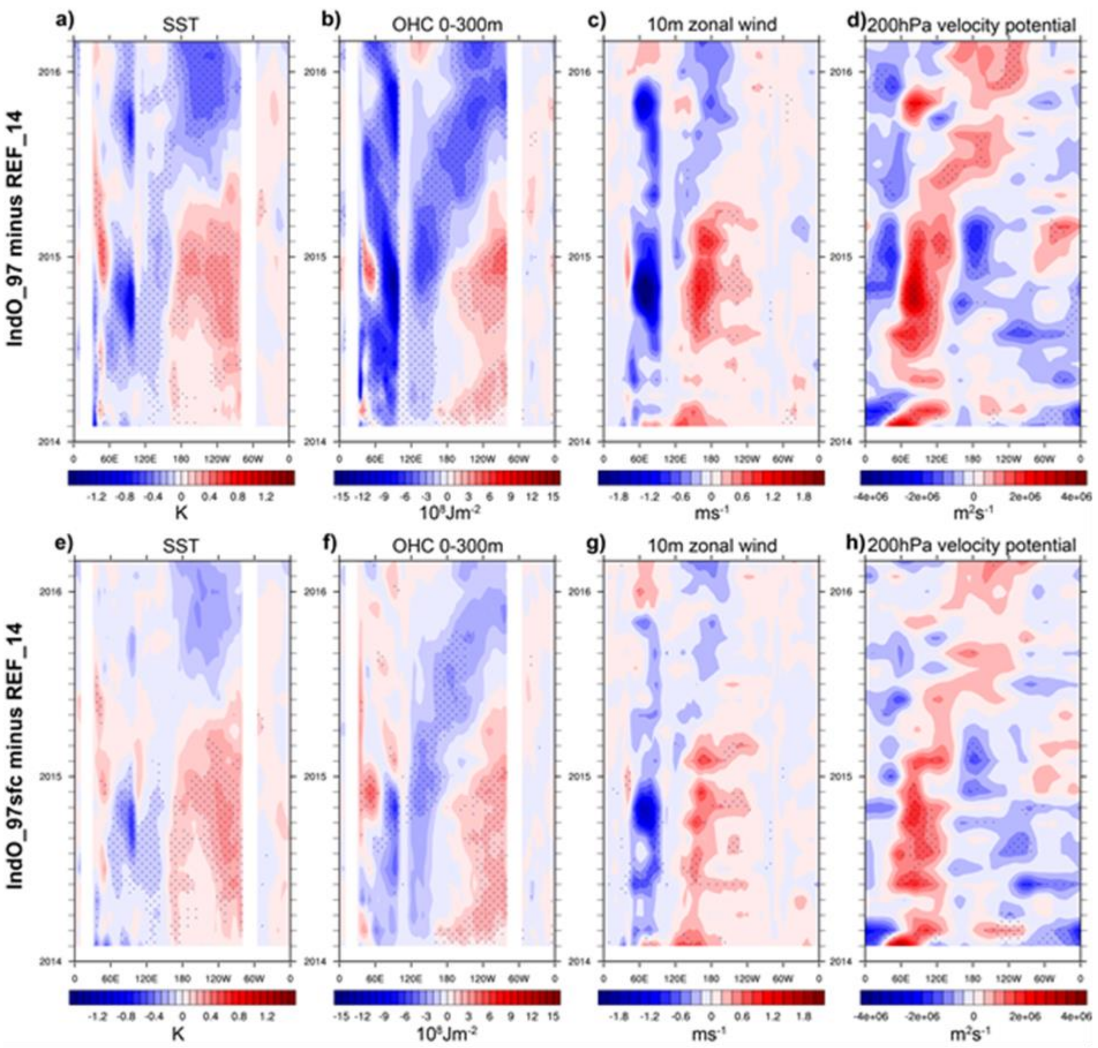
Experiments: SEAS5 up to 24 months from 1st Feb

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.

Indian Ocean Influences the Pacific at year 1, via atmospheric bridge, and at year 2 via ocean tunnel

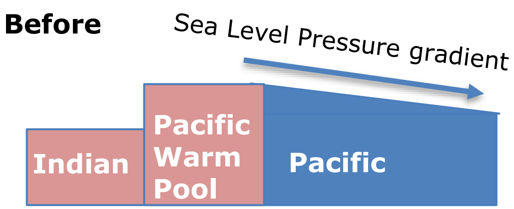


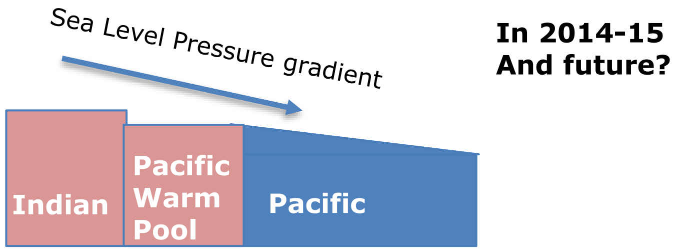
Experiment with 1997 Indian Ocean I.c strengthens the East Pac warming in first year, and cooling in second year. Note also strong IOD in year 1

The stronger E.Pac warming and IOD in first year appears by replacing only the upper 50 m. of the Indian Ocean

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 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?

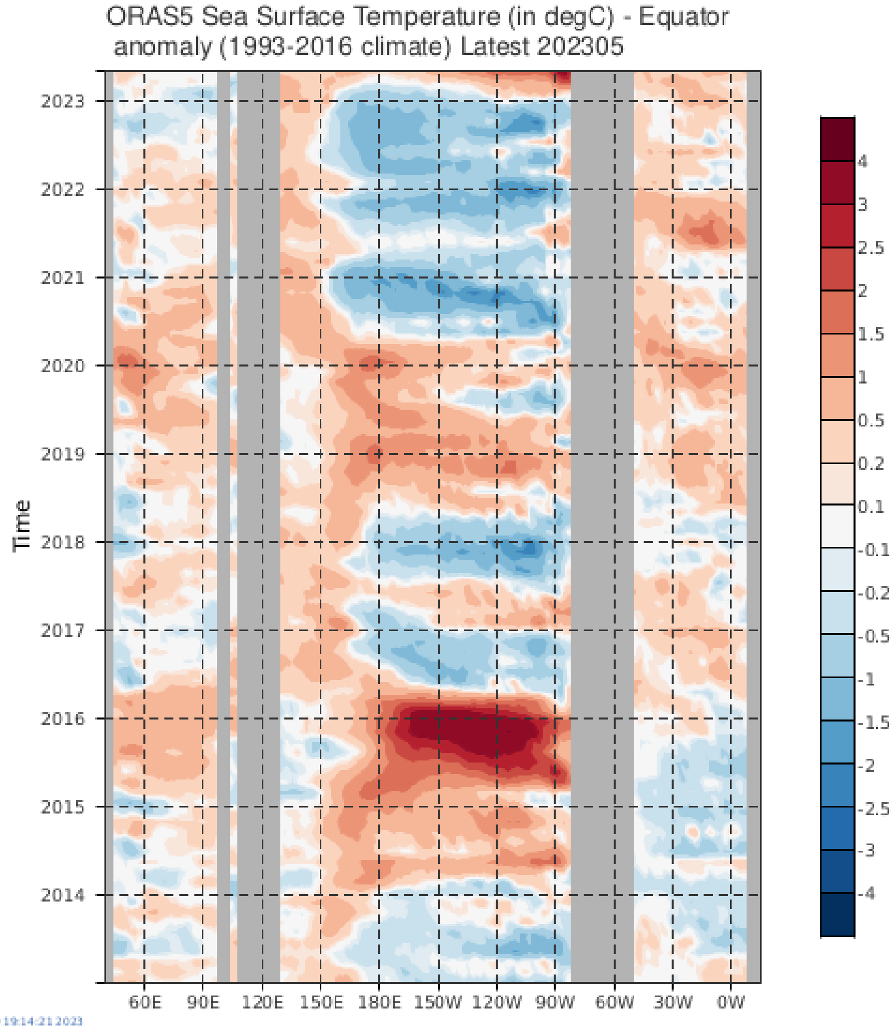
What about the current El Nino?

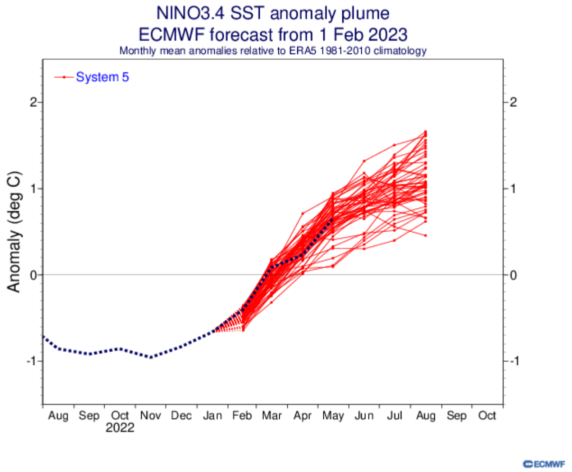
El Nino has been declared. Why, and how confident are we?

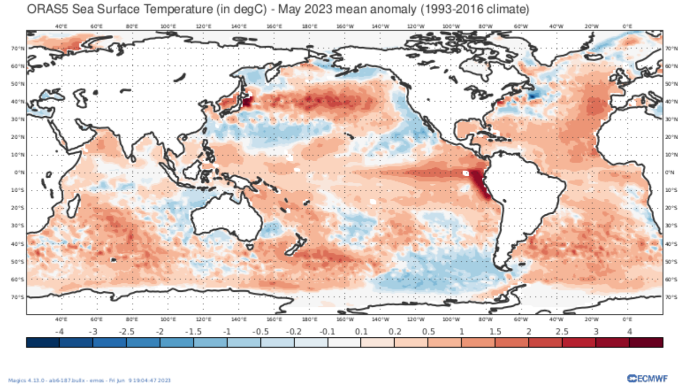
We have had a prolonged 3-years La Nina conditions.

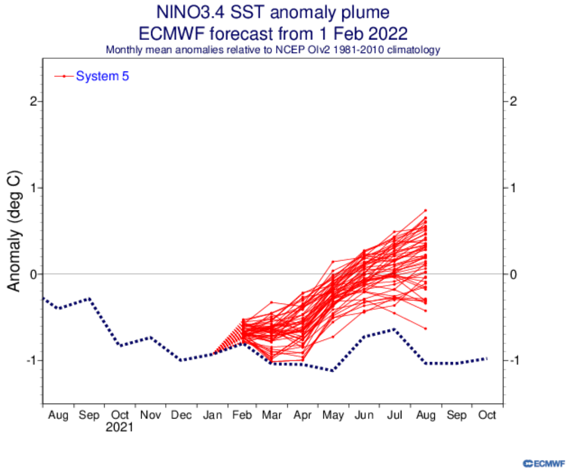
Q1. Since Nov-2021, SEAS5 Feb-22 has been predicting end of La Nina in 2022, which did not happen. Why should we trust the forecasts now?

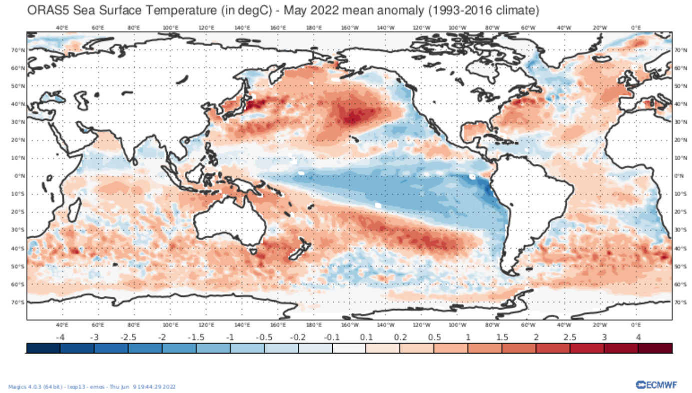
Q2. Is the expectation bias affecting our interpretation again, as for the 2014-15 “perceived false alarm”?





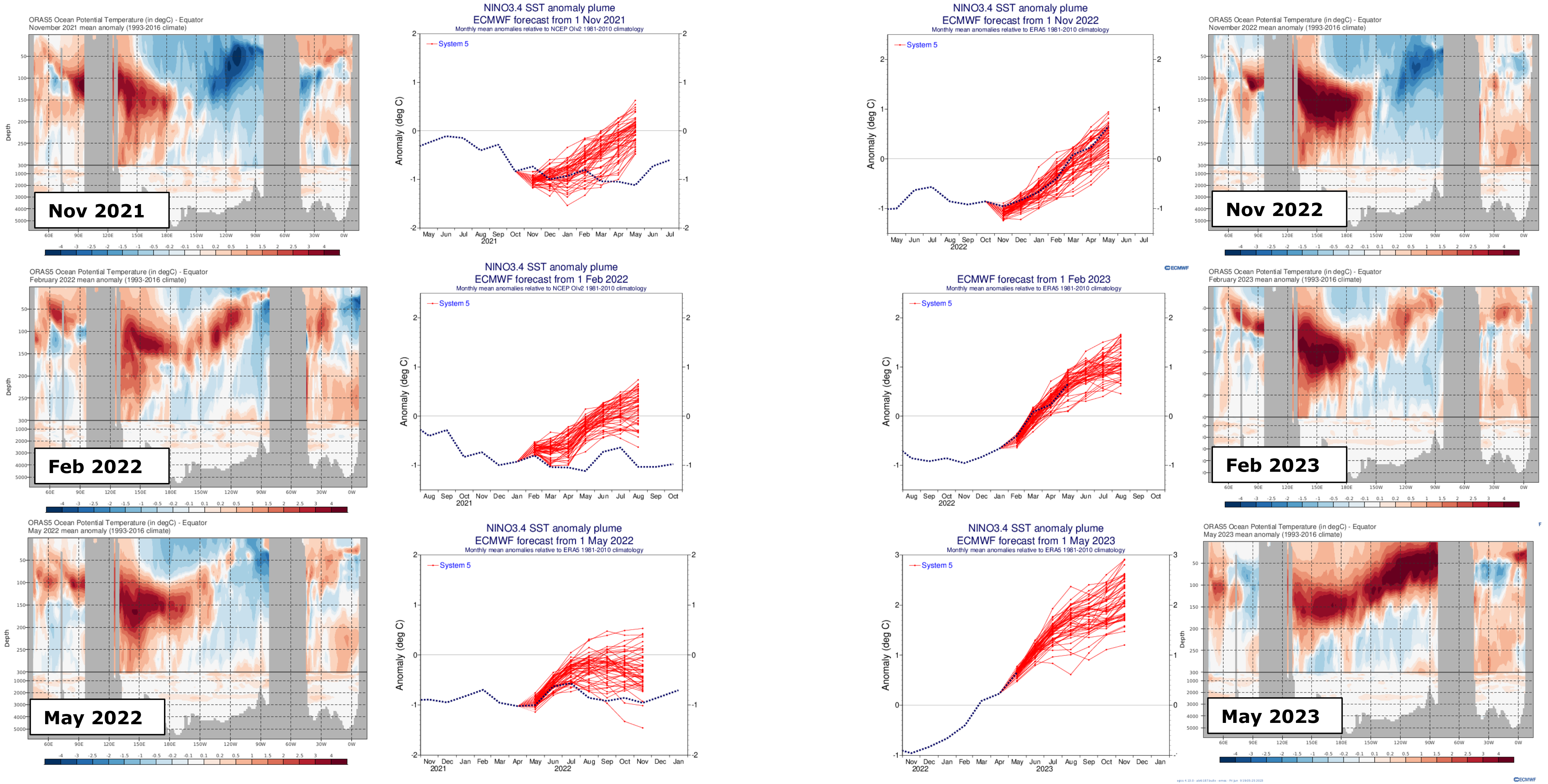






From ORAS5 ocean monitoring pages
https://charts.ecmwf.int/catalogue/packages/oras5/

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



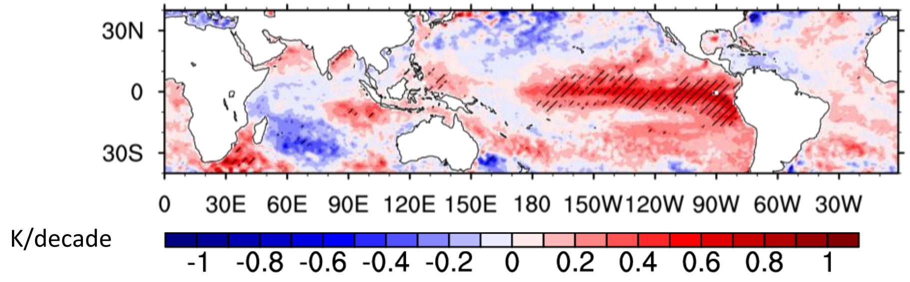
From ORAS5 ocean monitoring pages https://charts.ecmwf.int/catalogue/packages/oras5/

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

Why SEAS5 tended to terminate La Nina too early in forecasts initialized Nov21-Feb22?

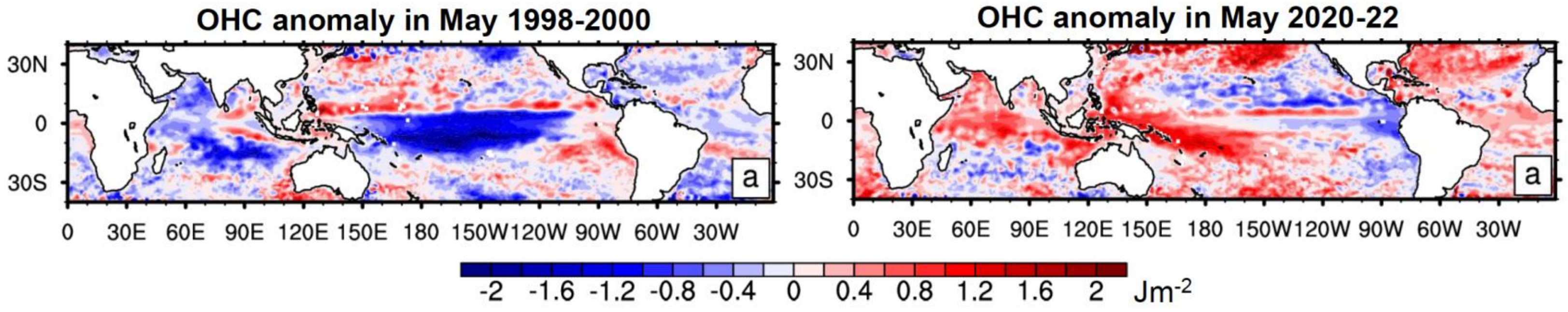
- Related to errors in the trends on the tropical Pacific (work as part of UGROW trends)
- There is a significant overprediction of SST over the Eastern Equatorial Pacific (2000-2016) . Related with errors in surface winds. This trend is also apparent in ERA5 assimilation increments. Work in progress by Michael Mayer. Similar errors seen in NMME and CMIP6 models

SEAS5 SST trend error (Mayer et al, in preparation)

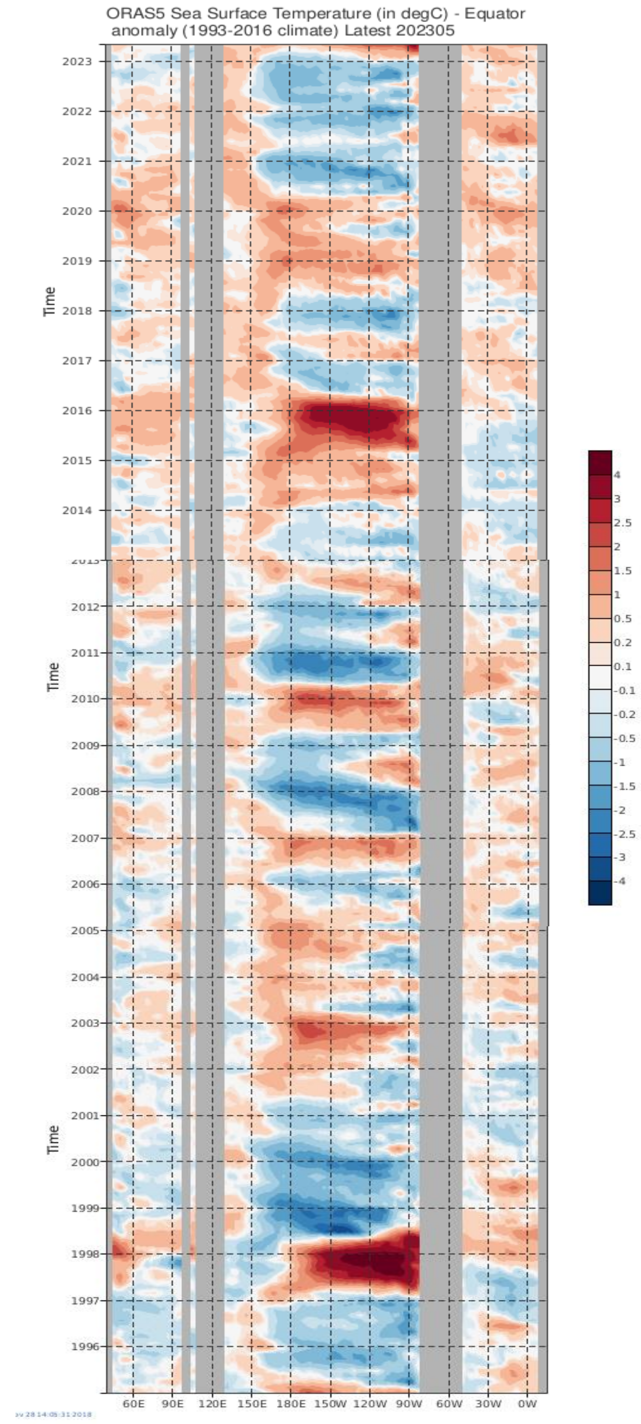


NCEP-CFSv2 SST trend error (L'Hearaux et al 2022)

- One of the reasons for this is anomalously recharge (warm) estate of the Tropical Pacific. The question can be reversed: why Nature did not go to La Nina earlier?



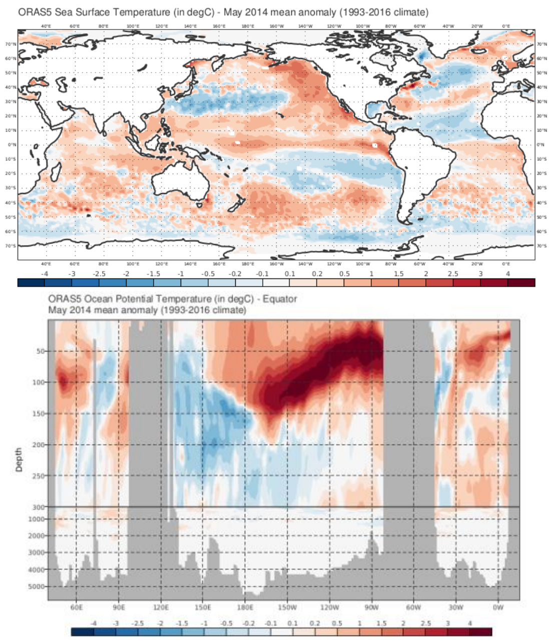
But in spite of the trend error, there is evidence that forecast are different this year than the previous one. Especially the fact that there has been a clear warming in May, and forecasts from May/June continue predicting consistently a warm event (previous slide)



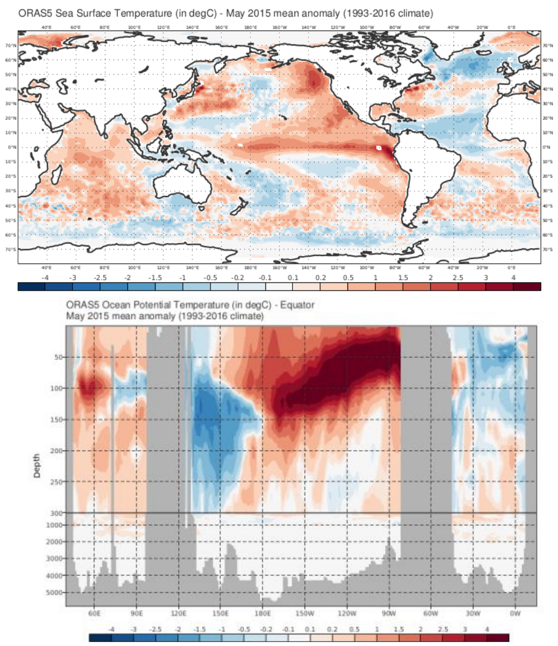
Will the El Nino peak in 2023/24 or in 2024/25?

- 1997/8 was a strong event lasting 1 year
- 2014-16 was a 2-year event: 2014 had weak early warming, and 2015/16 was strong

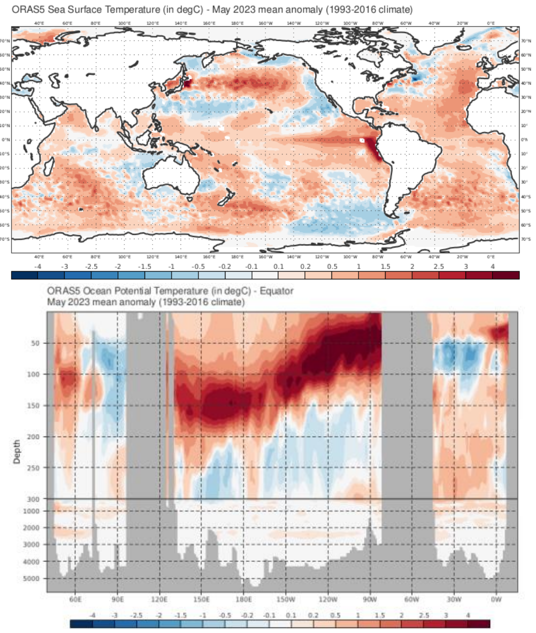
May 2014



May 2015



May 2023

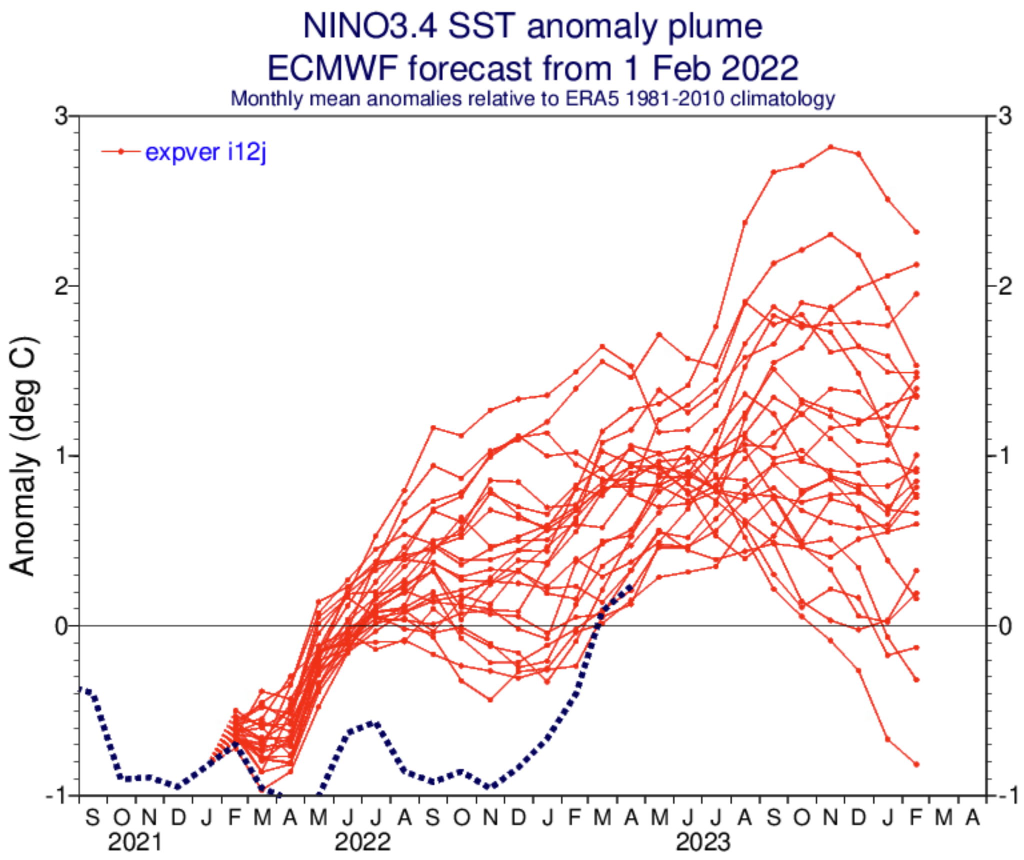


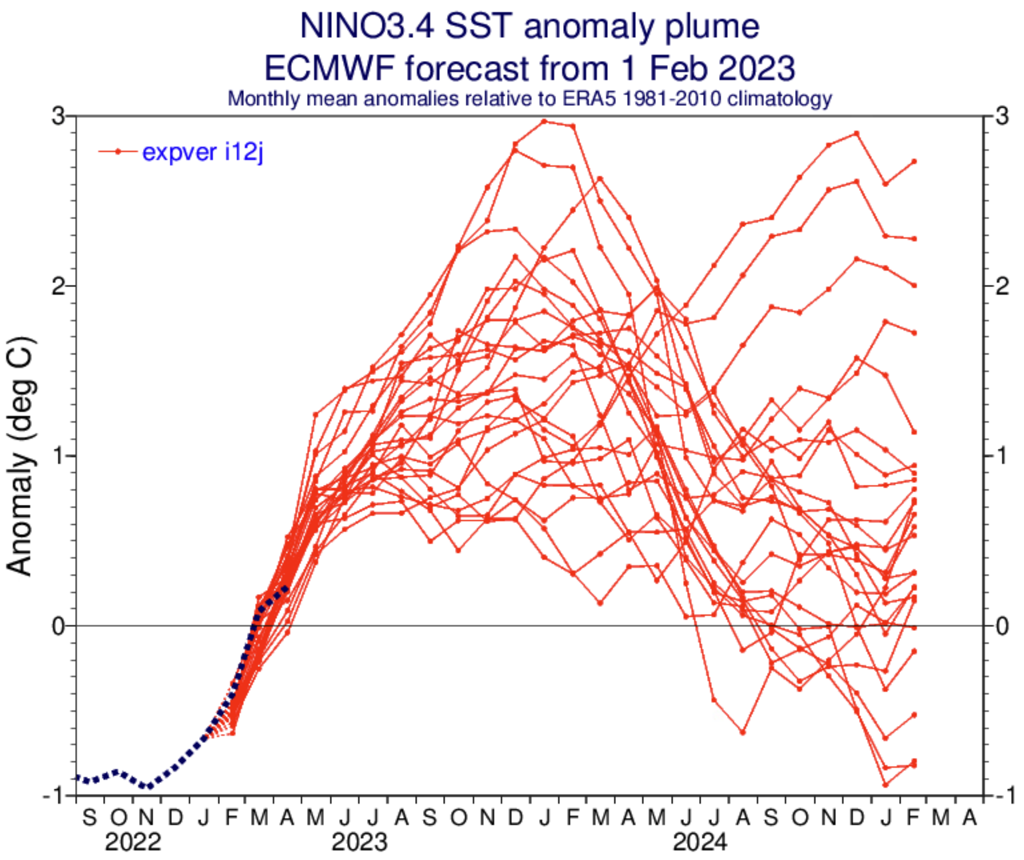
SST anomalies

Subsurface Temperature anomalies

Can we see any difference between the 3 ocean states above?
-2023 has more widespread surface warming.
-South-tropical Eastern Pacific is warm (In 2014/5 the North-tropical Eastern Pac was warm)
-Indian Ocean is cooler in 2023, but Atlantic is warmer.
-Warm Pool is still warm in 2014 and 2023
-In 2023 there is still heat available in the Western Pacific subsurface

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



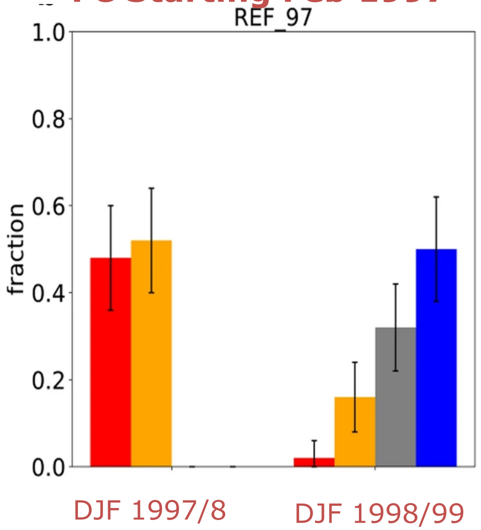


Feb 2022 forecast suggests weak warming in 2022 (which was wrong), followed by likelihood of stronger warming in 2023, with the possibility of a strong El Nino peaking in 2023/24

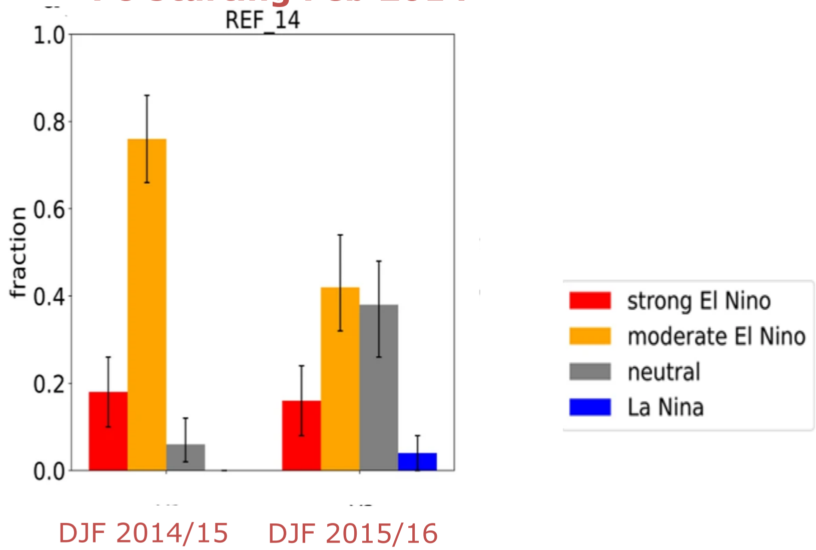
Feb 2023 forecast is for a moderate to strong El Nino in 2023/24, with a strong event followed by a return to neutral or La Nina conditions; but the possibility of a moderate warming strengthening to give a strong 2-year event.

Predicting ENSO 2-years ahead: two case studies

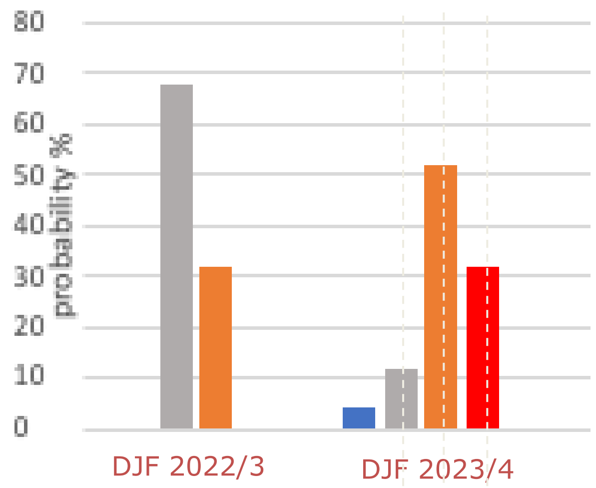
FC Starting Feb 1997



FC Starting Feb 2014



FC Starting Feb 2022

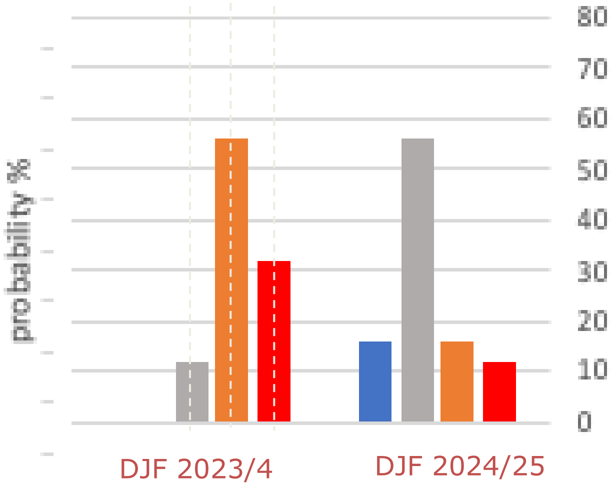


ENSO predictions for 2023/4 remarkably similar in forecasts initialized in Feb 2022 and Feb 2023

FC Starting Feb 2023

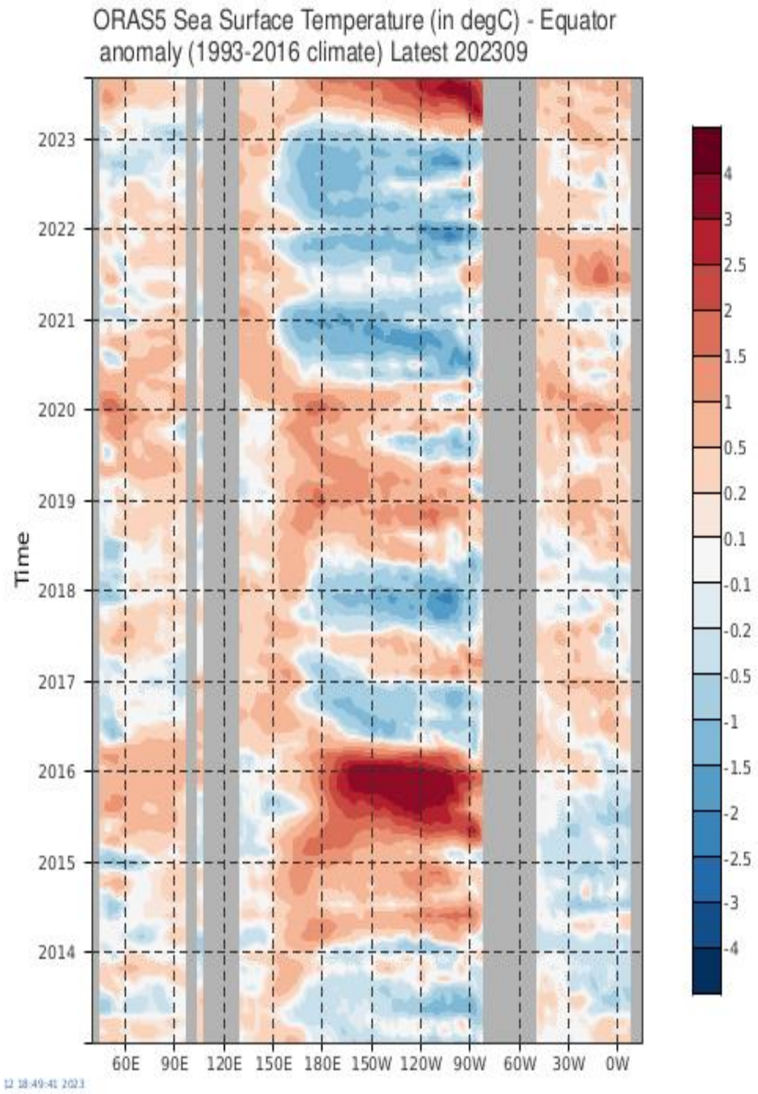
According to Feb-23 SEAS5;
~85% of El Nino on 2023/4
~30% prob of that El Nino being strong in 2023/4 and 10% prob of being strong in 2024/5.

There is only ~15% of La Nina following this warm event. Is that a model problem?

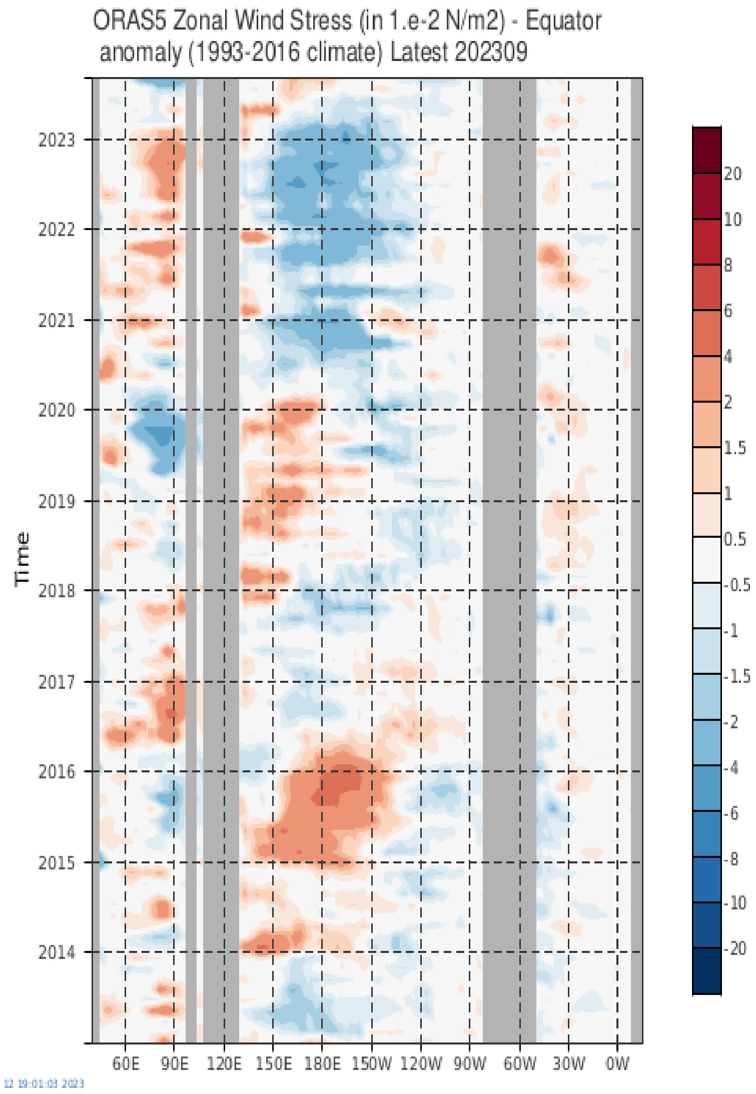


Latest Equatorial Conditions

SST anomalies

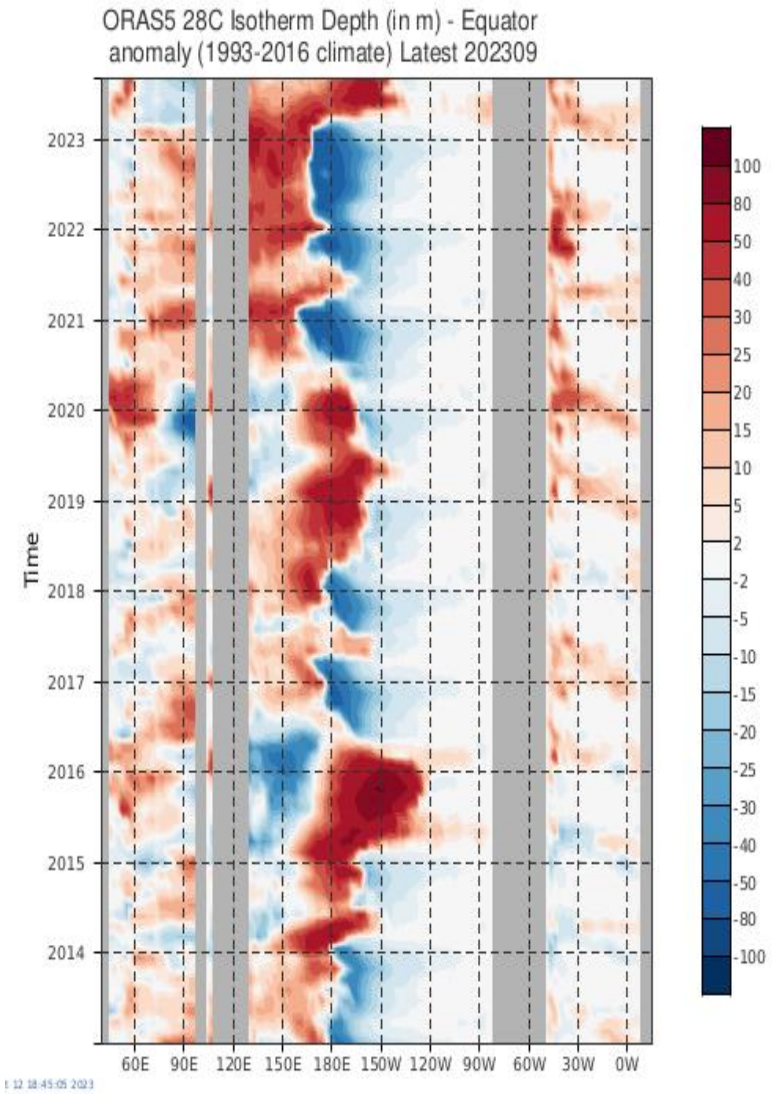


Zonal Wind stress anomalies

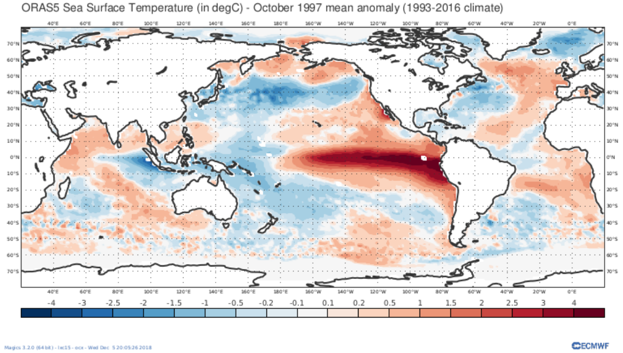
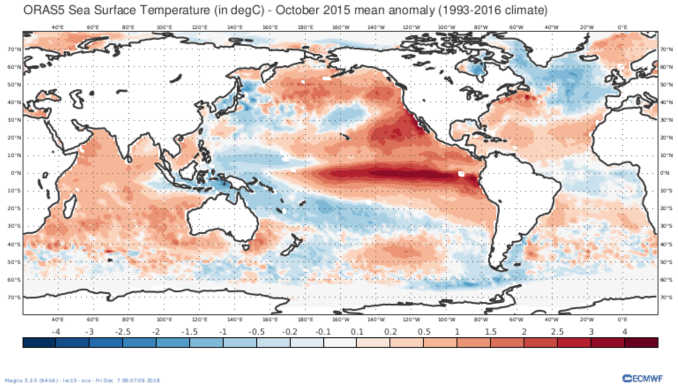
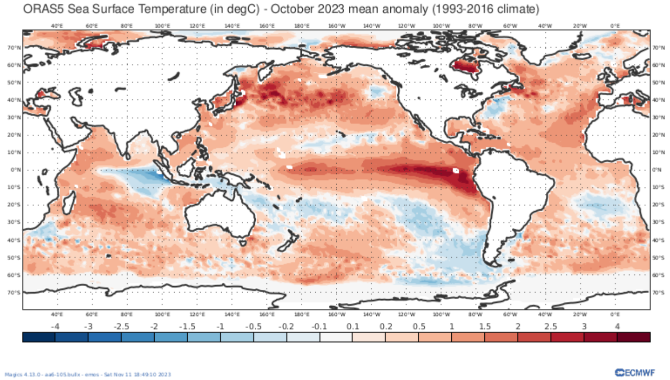
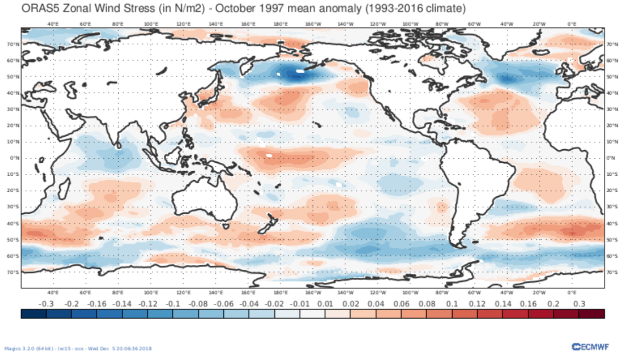
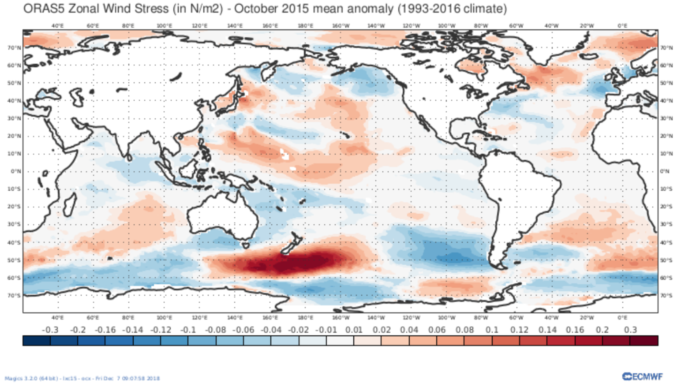
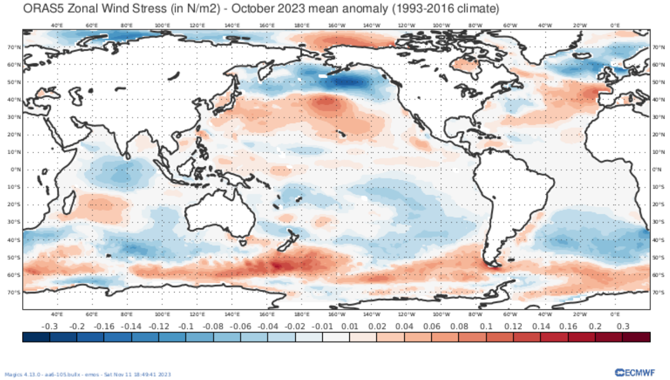
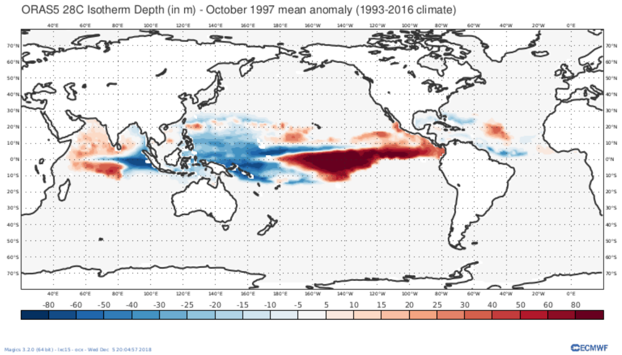
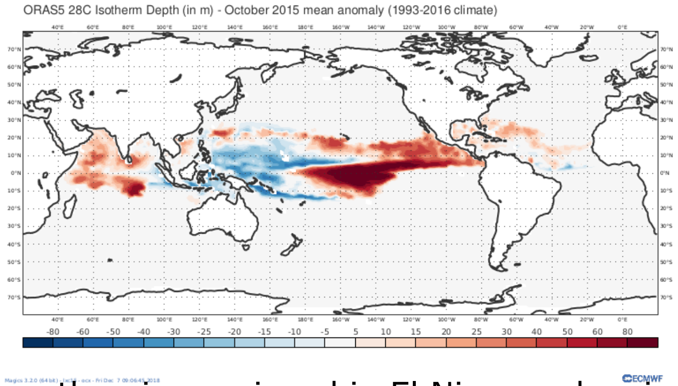
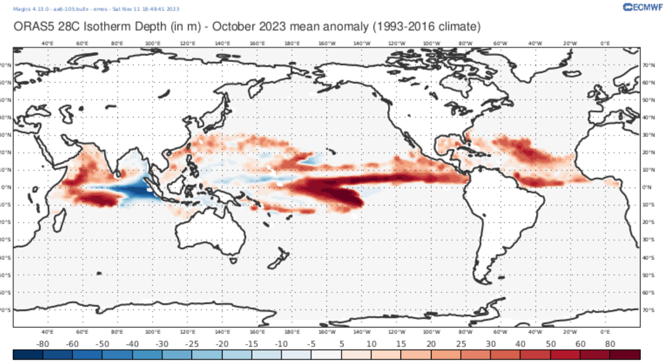


Slow response of zonal winds?

Depth 28º Isotherm anomalies

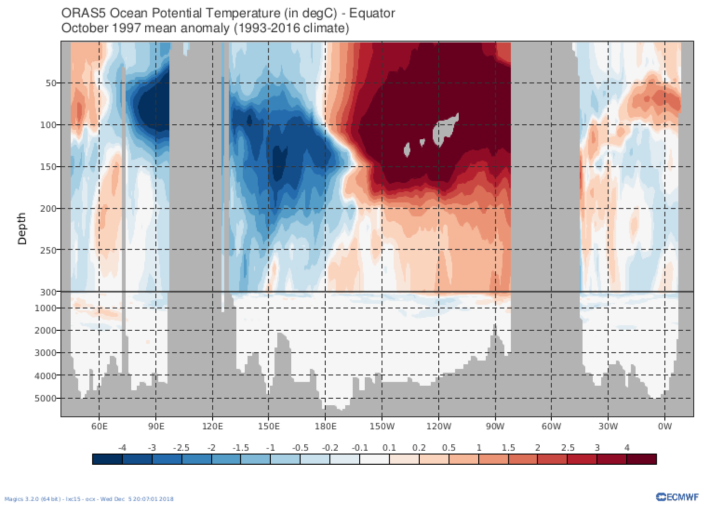


Western Pac Warm Pool still warm

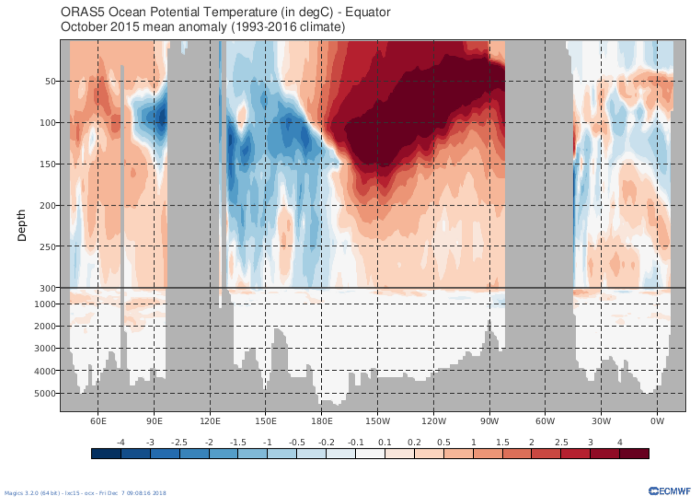
	Oct 1997	Oct 2015	Oct 2023
SST			
Taux			
D280			

The zonal wind response is weaker this year than in previous big El Nino, and so is the Eastern Pacific heat reservoir. Perhaps a moderate El Nino?

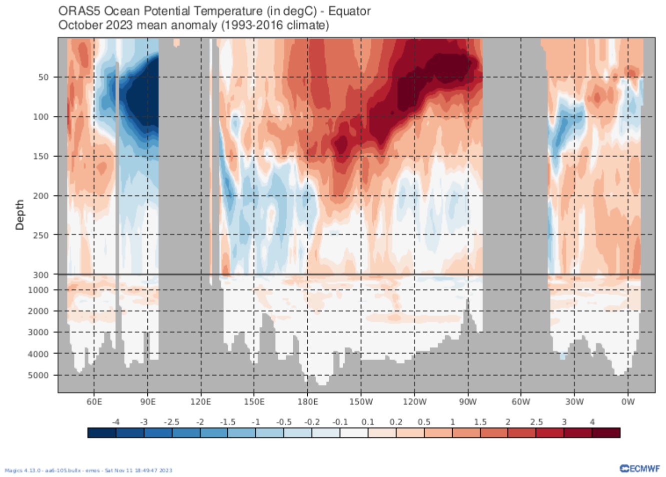
Oct 1997

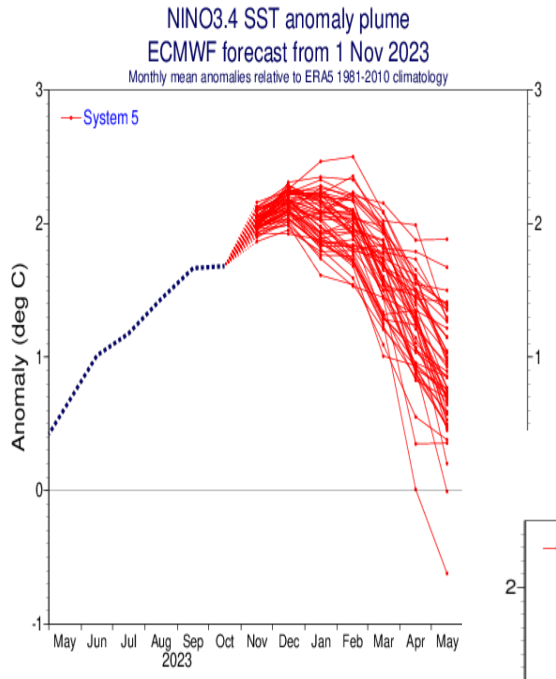


Oct 2015



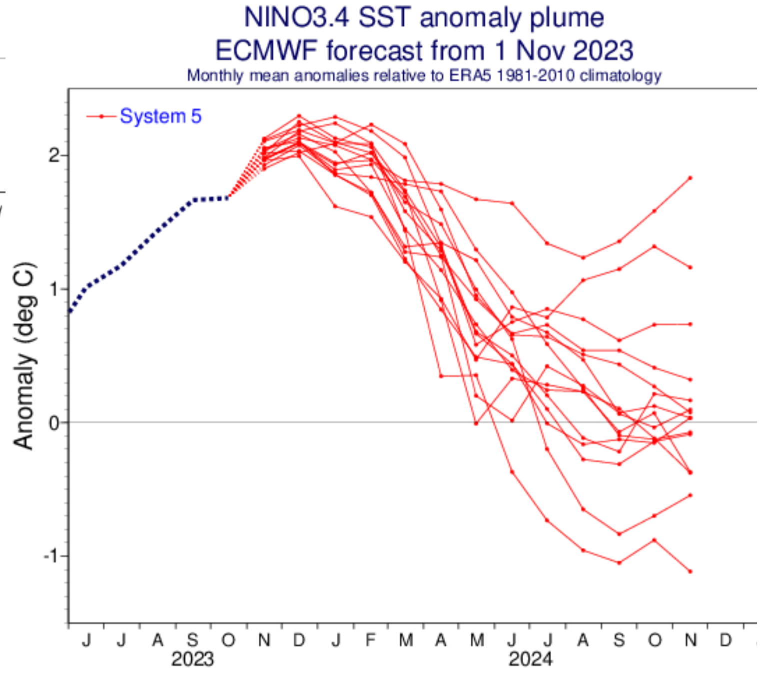
Oct 2023

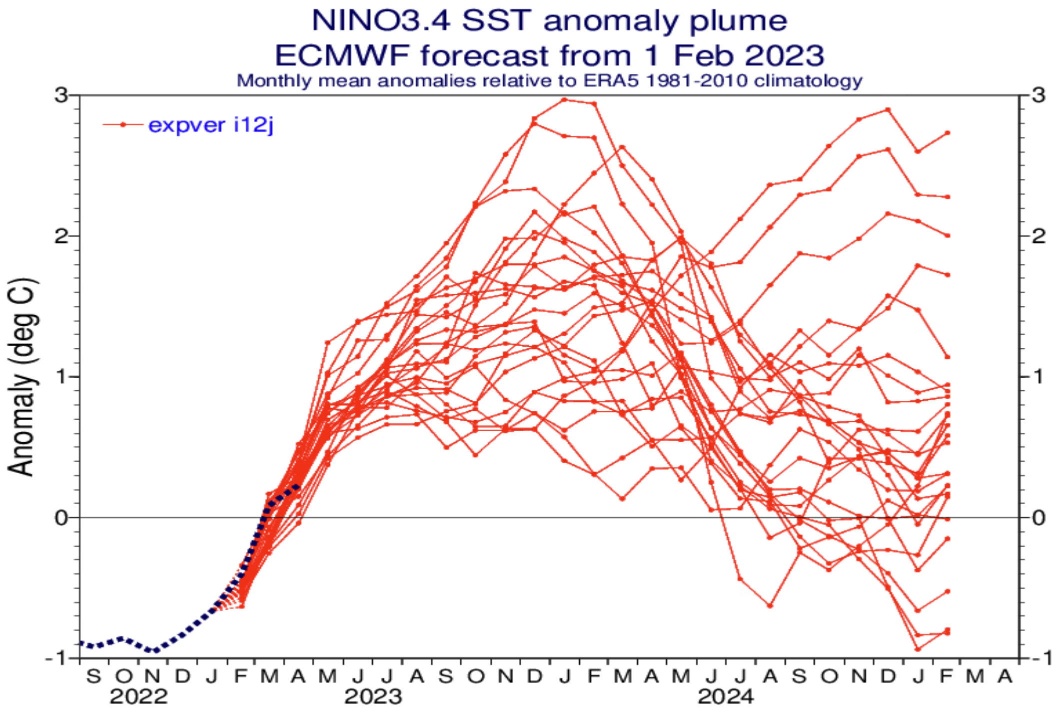




Latest forecasts are still for moderate-strong El Nino

Will there be a transition to La Nina in 2024?





ECMWF

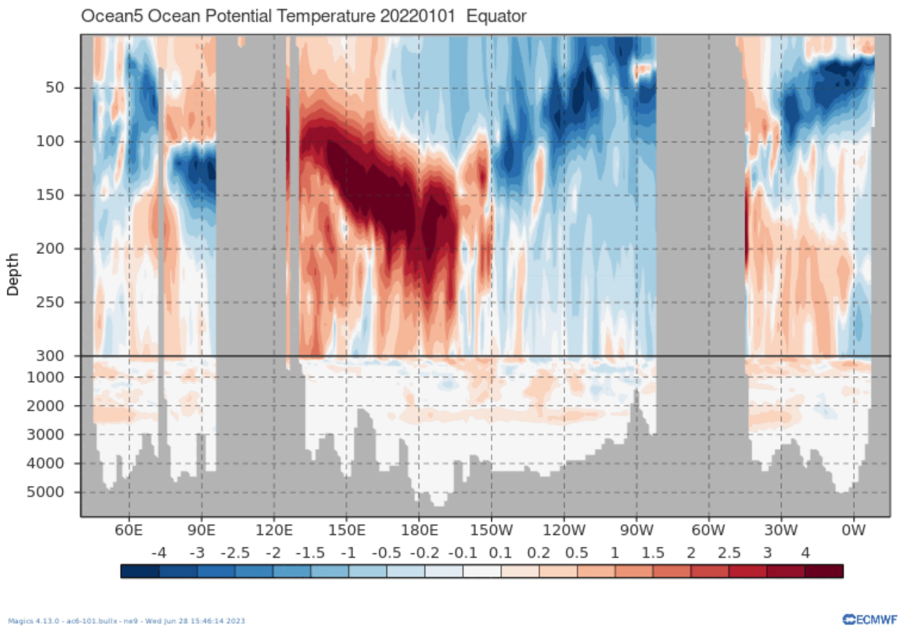
Summary

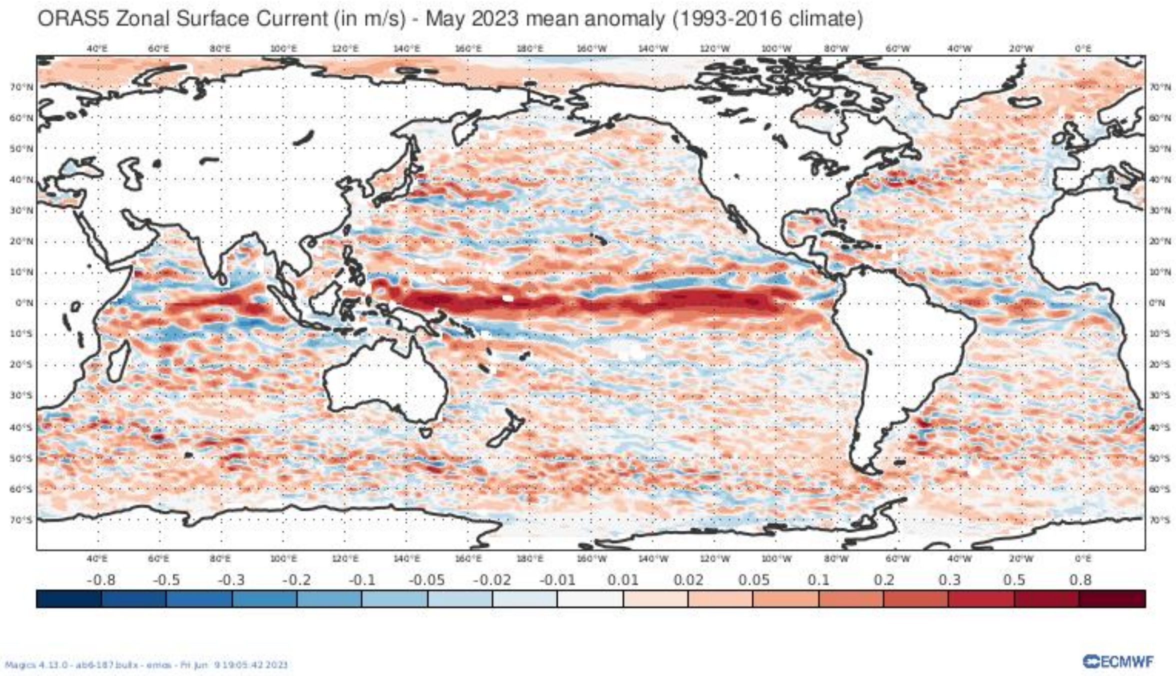
- ENSO as largest coupled mode of the climate system:
  - Ocean-Atmosphere Bjerkness feedback and disruption of Walker Circulation
  - Impacts worldwide: precipitation, temperature, marine ecosystems, carbon cycle, energy cycle.
  - Basis for predictability at seasonal time scales (and beyond? At 24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

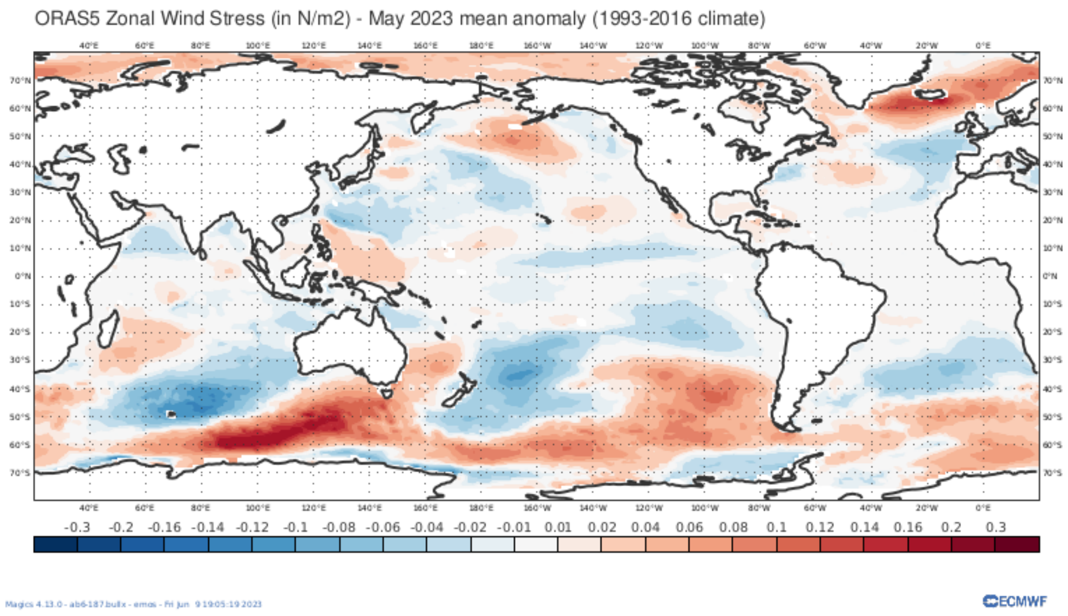
- ENSO prediction and predictability: time scale interaction
  - ENSO predictions are probabilistic. There is a large degree of stochasticity due to interaction with the subseasonal time scale.
  - ENSO properties depend on background mean state, giving rise to ENSO diversity.
    - In forecast, background 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

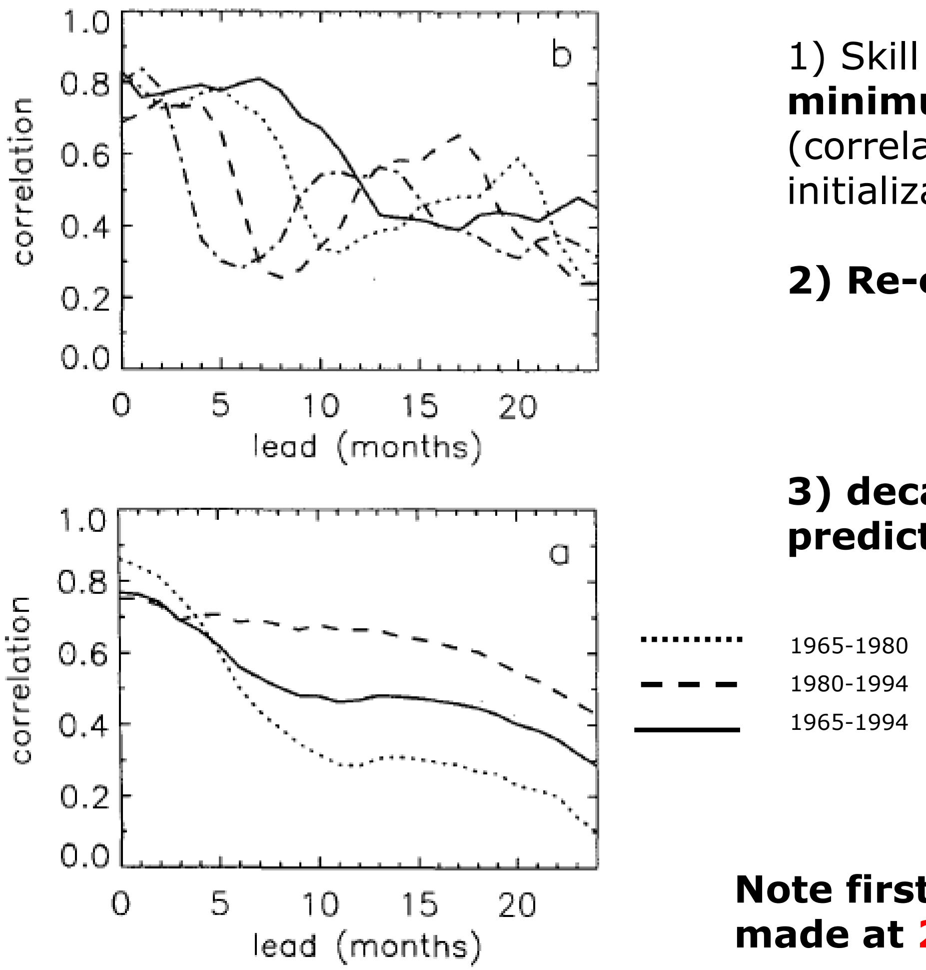

Ocean5 Ocean Potential Temperature 20220101 Equator
Depth
50
100
150
200
250
300
1000
2000
3000
4000
5000
60E
90E
120E
150E
180E
150W
120W
90W
60W
30W
0W
-4
-3
-2.5
-2
-1.5
-1
-0.5
-0.2
-0.1
0.1
0.2
0.5
1
1.5
2
2.5
3
4
ECMWF


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