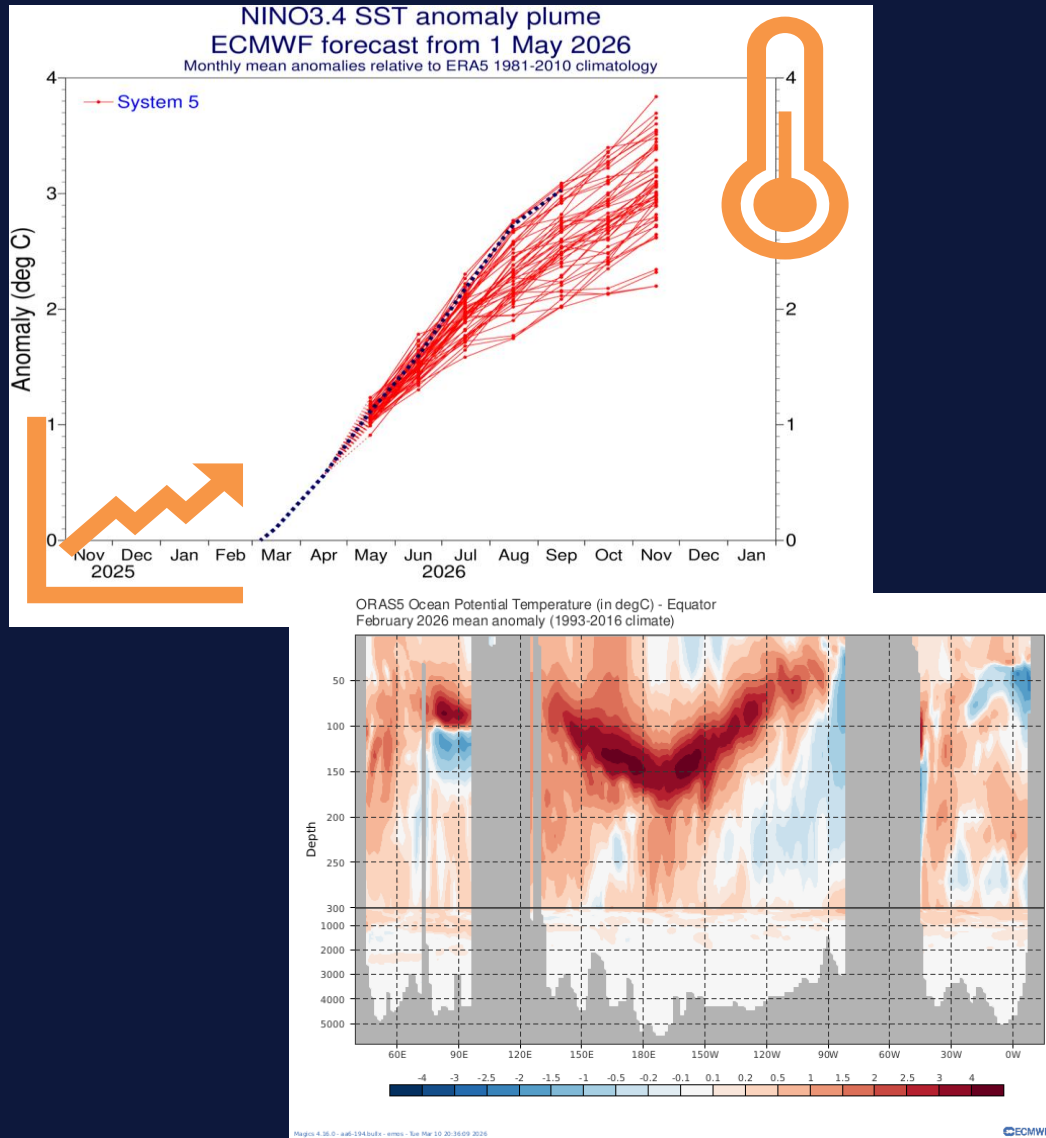


Predicting ENSO in a changing climate



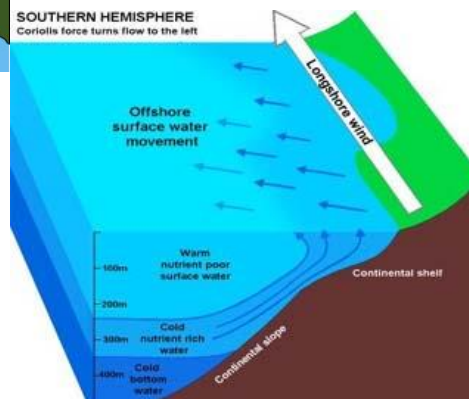
- ENSO as a coupled ocean-atmosphere mode
 - ENSO and the energy cycle
 - A brief history ENSO prediction
 - Some case studies: beyond the tropical Pacific
 - The disruptive 2014 and 2015 El Niño and implications
 - The 2023-2024 El Niño
- The ongoing 2026-2027 event

Magdalena Alonso Balmaseda

Origins of ENSO: El Niño-Southern Oscillation

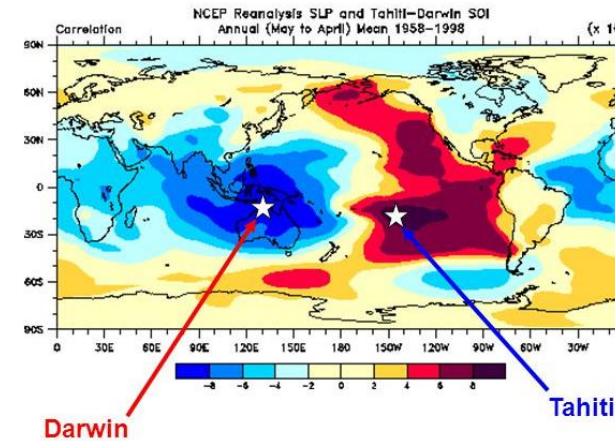
El Niño
Named by Peruvian Fishermen
Tradition

Oceanic impact on fisheries and nutrients



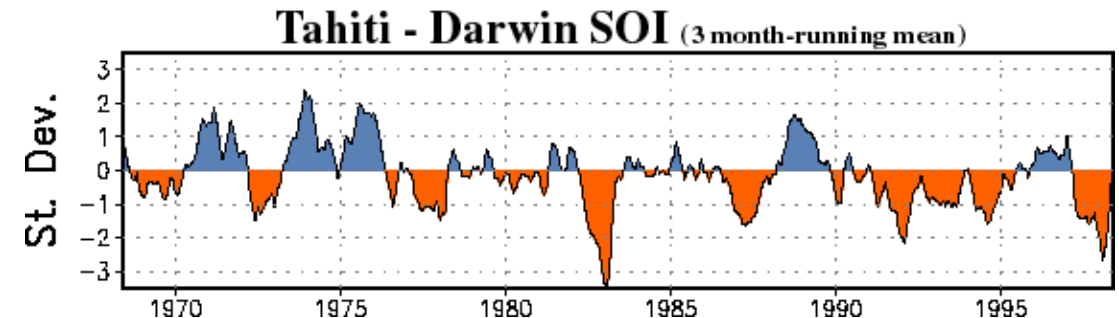
1578 is the first recorded El Niño by the Spanish colonialist, although chronicles from Pizarro arrival to Peru also mentioned the occurrence of these events.

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

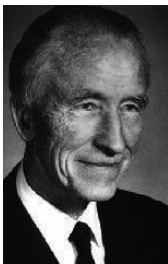


Sir Gilbert Walker
(1868-1958)

Southern Oscillation Index (SOI):MSLP Darwin - Tahiti



ENSO as coupled ocean-atmosphere mode

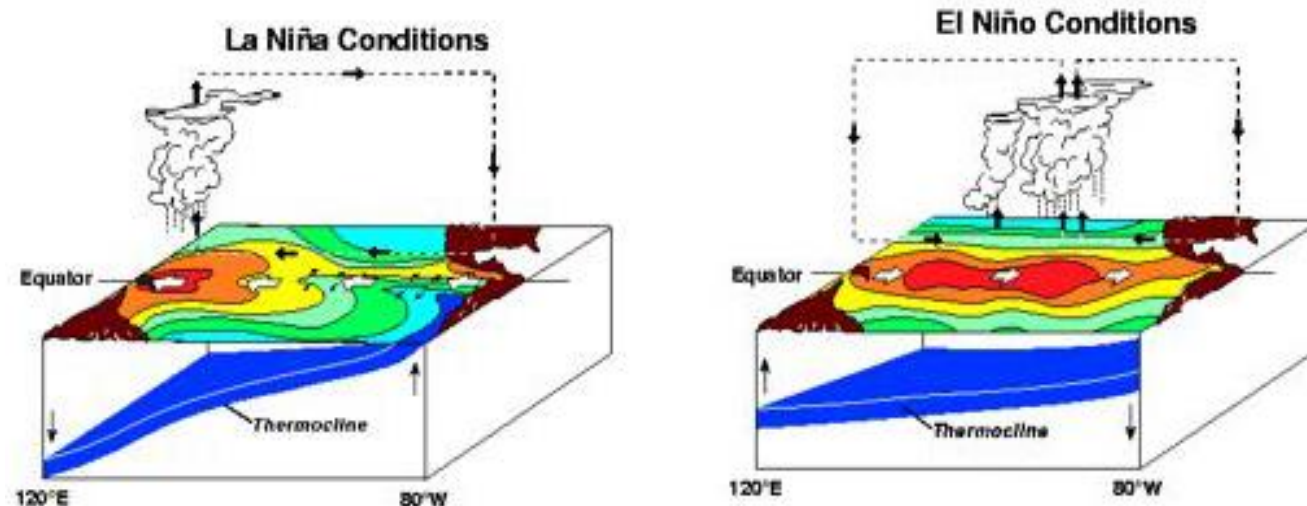


A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature

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

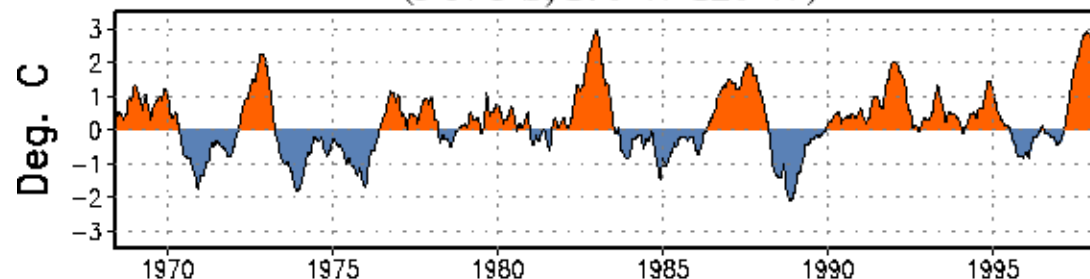
(Manuscript received January 18, 1966)

Bjerkness 1966: ENSO as a coupled mode

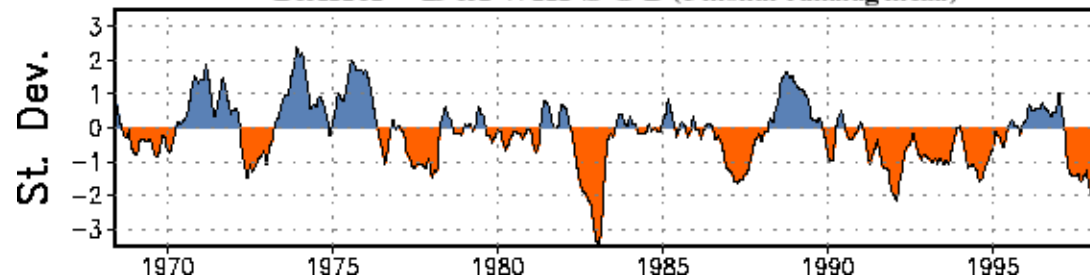
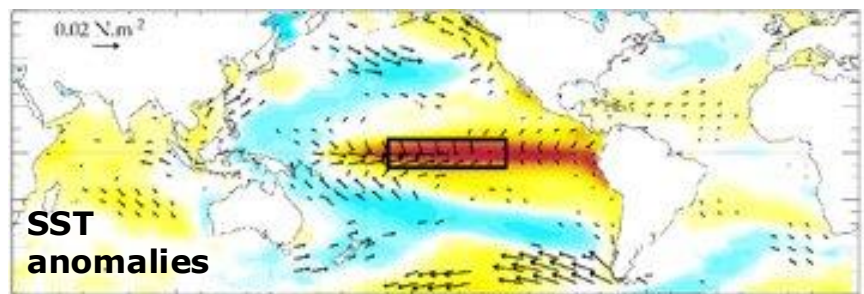
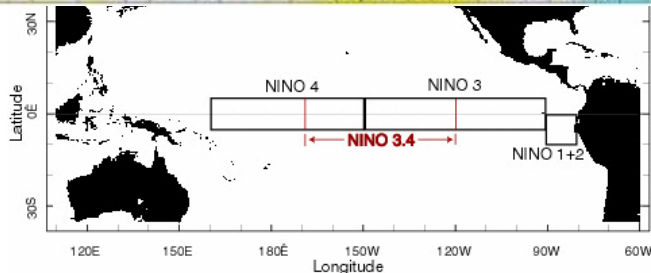


SOI in phase opposition with SST index

**Ocean Temperature Departures (°C) for Niño 3.4
(5°N-5°S, 170°W-120°W)**



Tahiti - Darwin SOI (3 month-running mean)



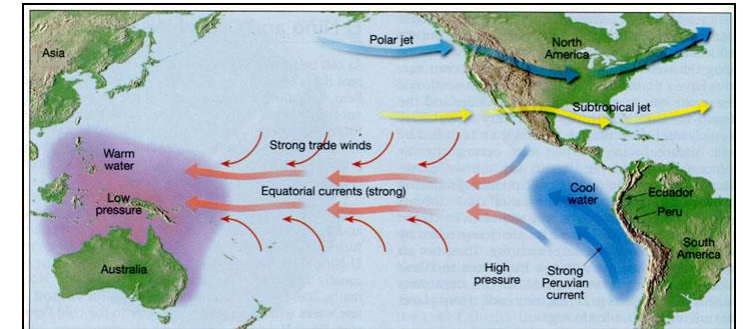
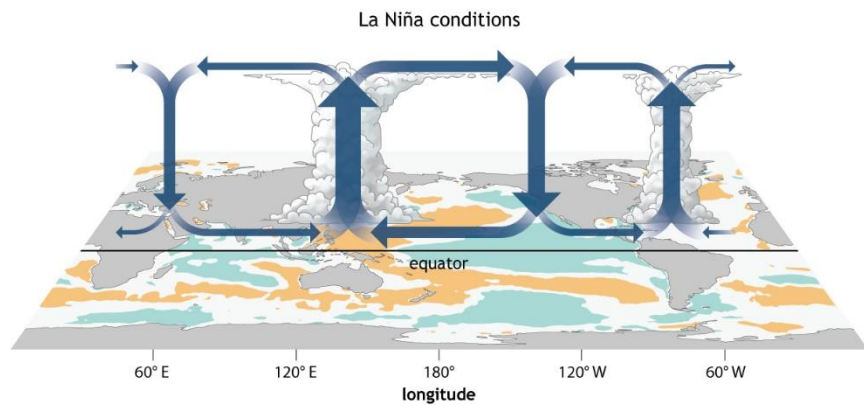
ENSO: Largest mode of interannual variability

Best known source of predictability at seasonal time scales

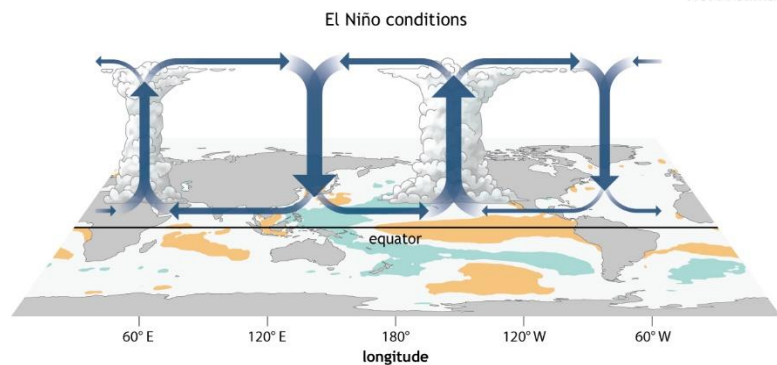
It affects global patterns of atmospheric circulation, with changes in rainfall, temperature, hurricanes, extreme events

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

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



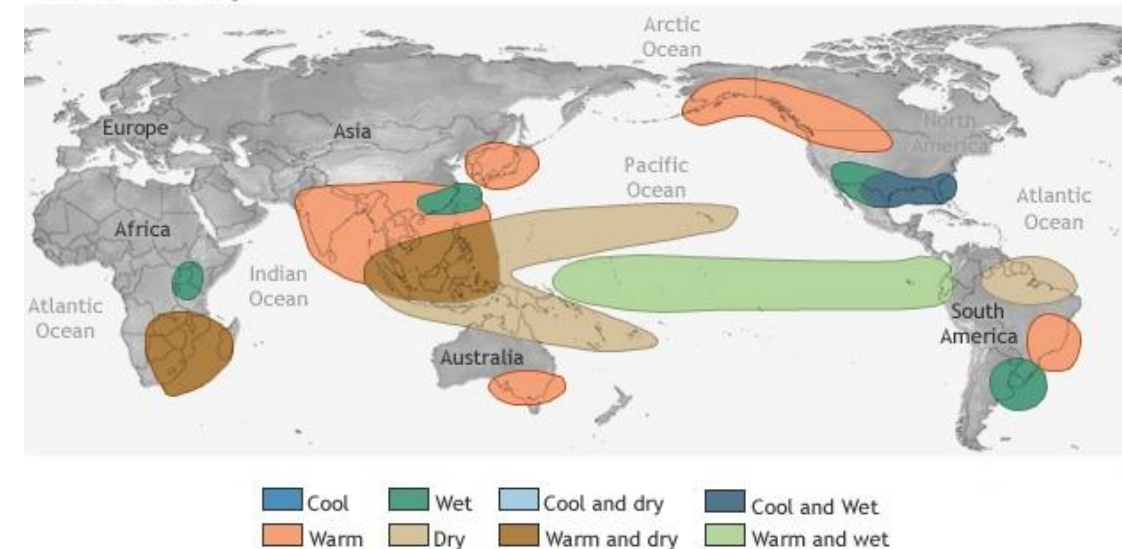
NOAA Climate.gov



NOAA Climate.gov

EL NIÑO CLIMATE IMPACTS

December-February



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 zonal gradient

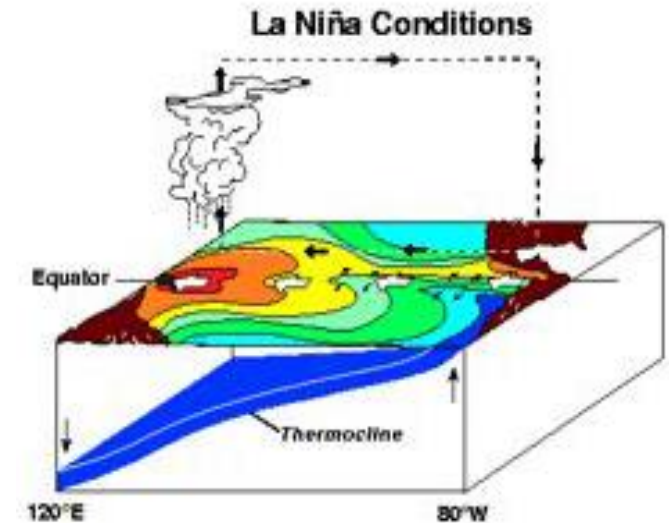
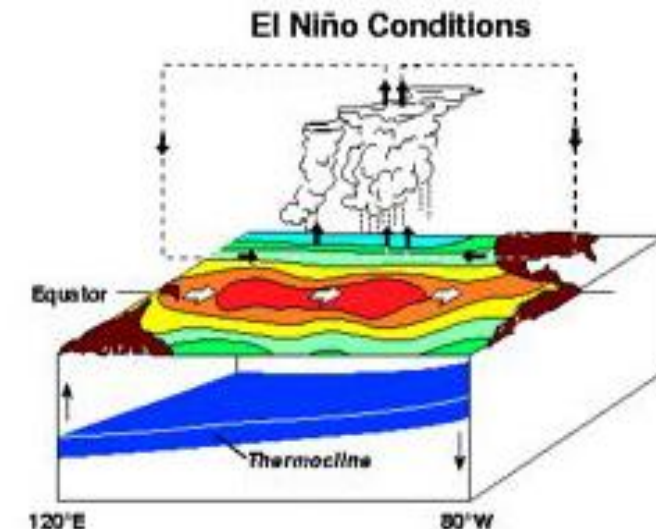
B) ratio SST anomaly East/zonal_wind anomaly in central Pacific. It depends on the “thermocline feedback” (+) and heat flux feedback (-).

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!*

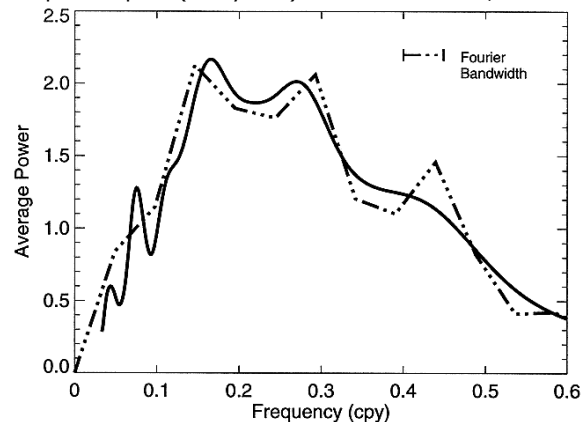
*These balances are difficult to represent by models
And Climate Change can affect them*



ENSO: spatiotemporal characteristics

1) ENSO temporal irregularity

Broad spectral peak (4-7 years) Blanke et al 1997, Kestin et al 1998



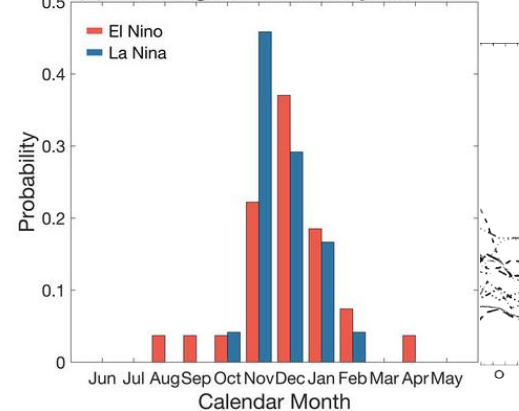
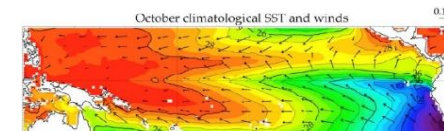
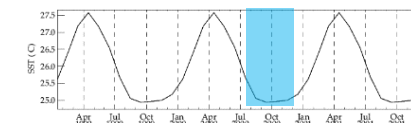
2) Phase lock to seasonal cycle

Onset ~ May-August, **Peak ~ Oct-Feb**, Decay ~ May

Boreal Spring Predictability Barrier

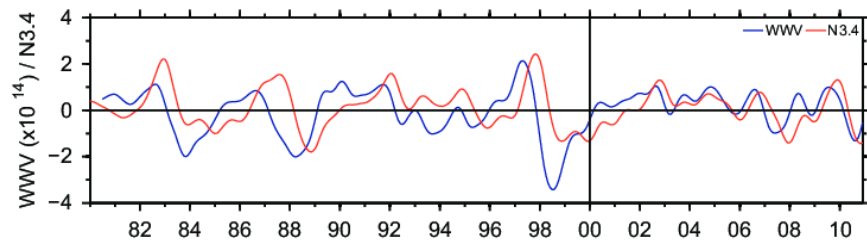
Neelin et al 1999
Chen & Jin 2020

(d) Histogram of ENSO peak



ENSO peaks during cold phase of seasonal cycle

3) Relationship between SST-WWV (or Warm Water Volume).

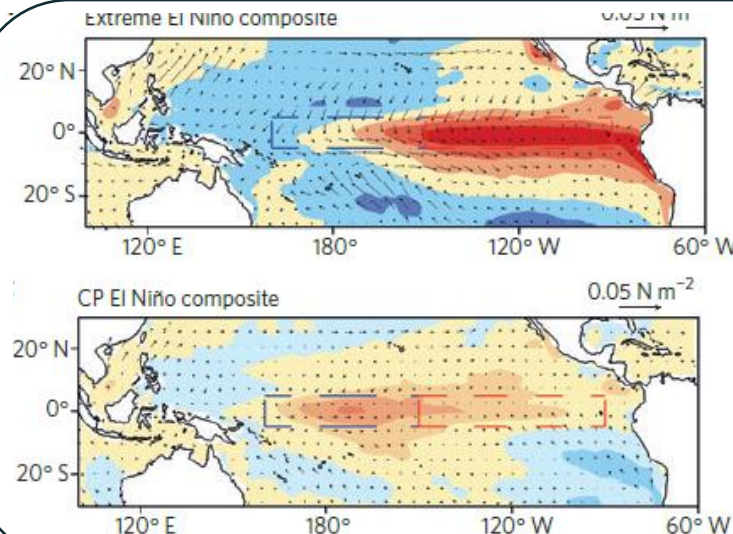


WWV (heat accumulation) precedes SST warming.

4) ENSO Diversity

Top) Eastern Pacific Warming. Related with Big El Ninos

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



Multitude of conceptual models for ENSO

1. Delayed Oscillator Mechanism: (Schopf and Suarez 1988)

Resonant Basin mode (Kelvin and Rossby Waves) amplified by Bierkness Feedback

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

1. 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 1997)

Regular or chaotic behaviour, from multiple feedbacks.

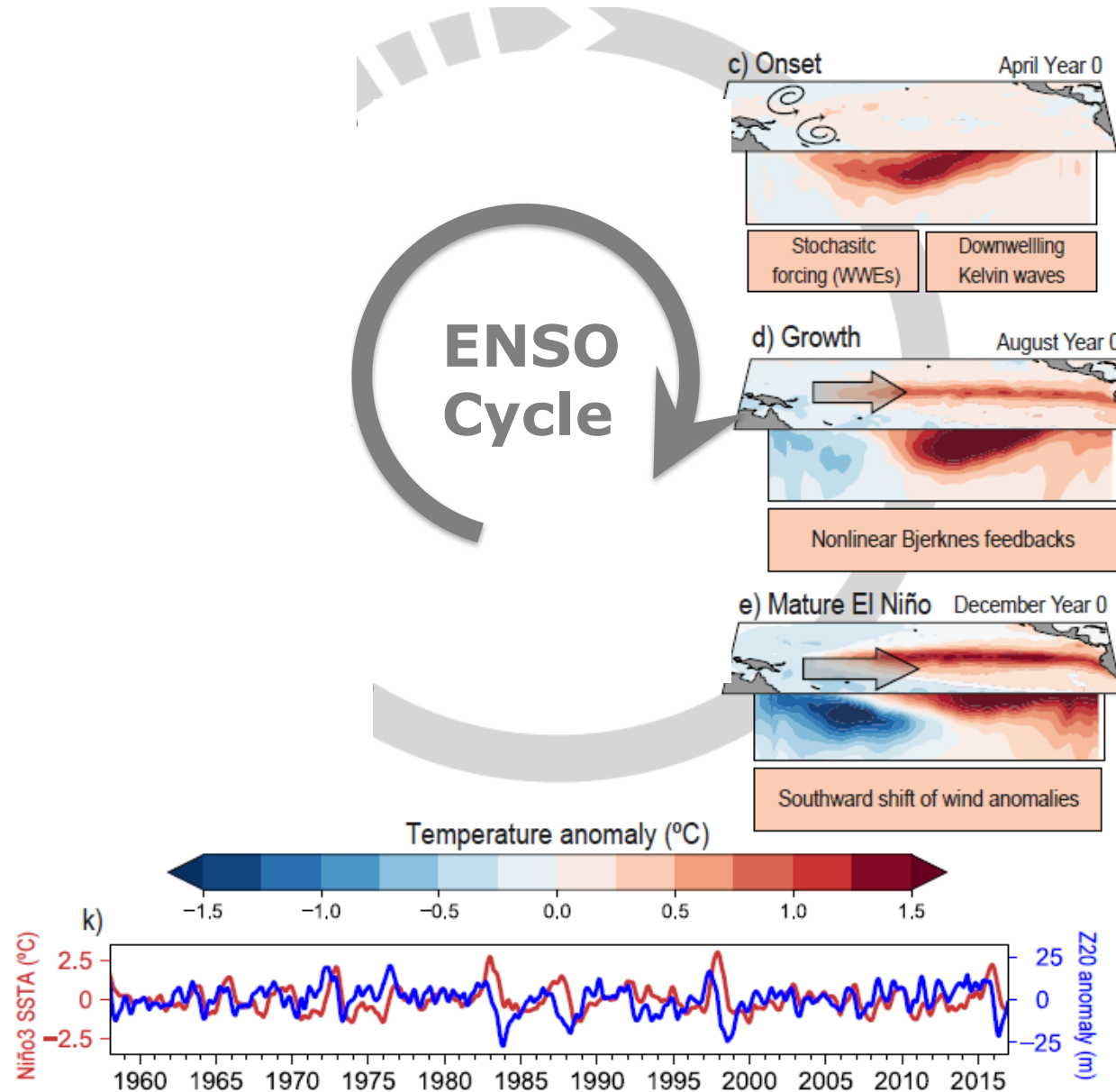
The strength of feedbacks can determine the chaotic or predictable behaviour.

This strength depends on the mean state.

Possibility of modulation by decadal variability or climate change

ENSO as a Discharged-Recharged Oscillator

First proposed by F.F Jin 1997



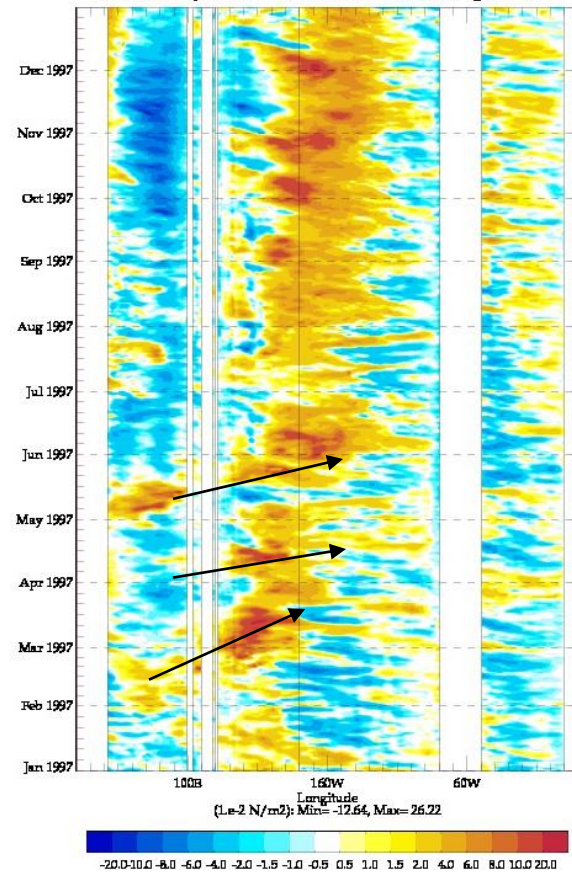
Implication:
ENSO predictability
resides in the ocean
subsurface.

Concept has been evolving over the years. See Timmermann et al 2019 for a review

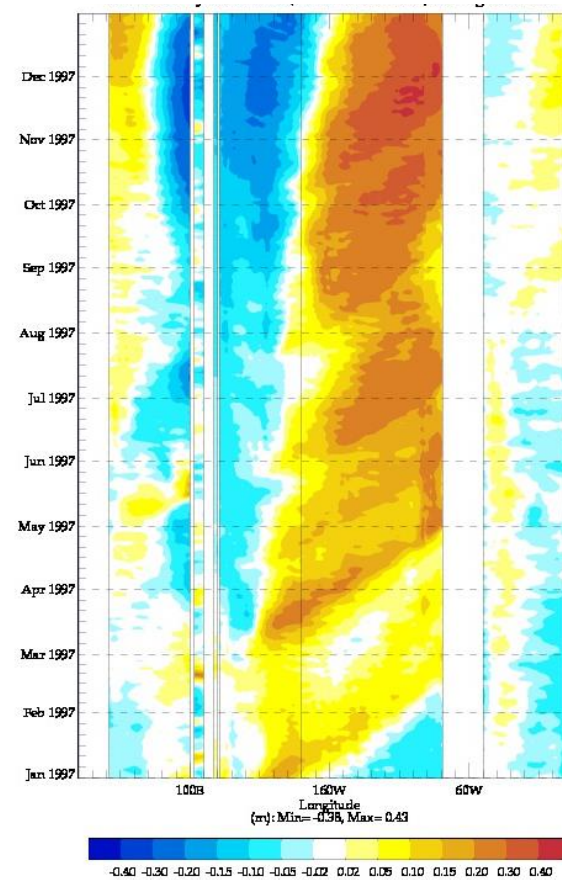
Figure from Timmermann et al 2019

Daily Equatorial Anomalies: Jan 1997-Jan 1998

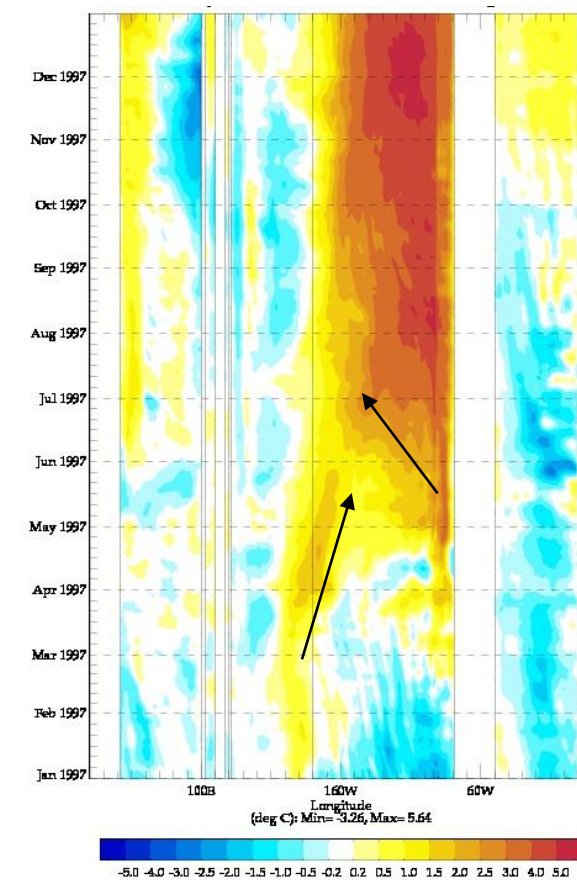
Zonal Wind Stress Anomalies



SL Anomalies



SST Anomalies



Data from ORAS4

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

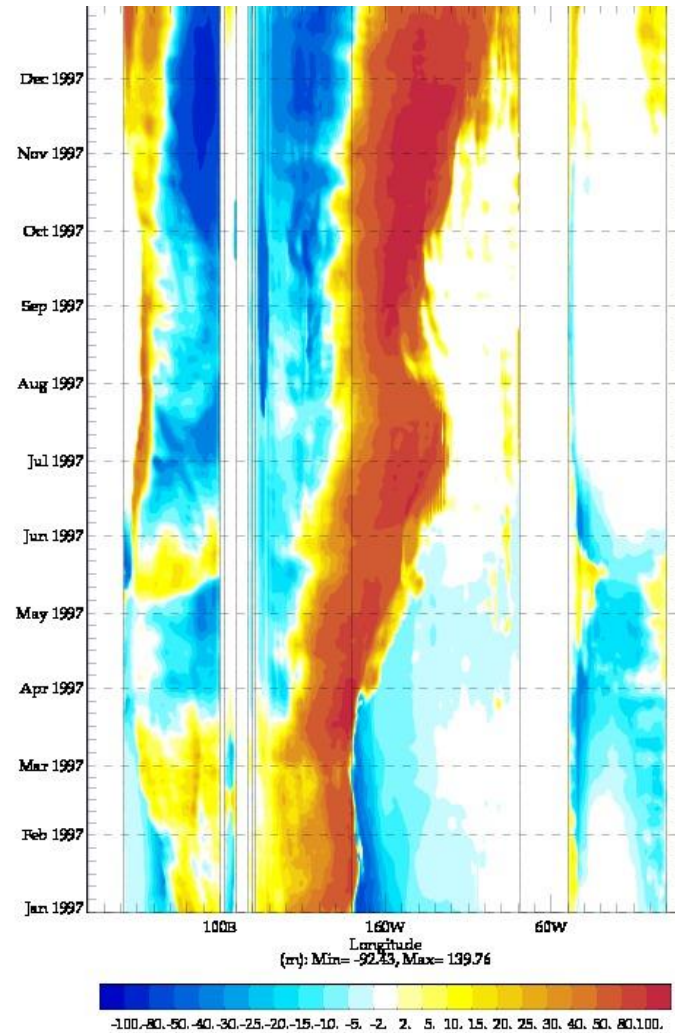
Associated eastward propagating groups of Kelvin waves in the thermocline. The latest reaching the Eastern Coast

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

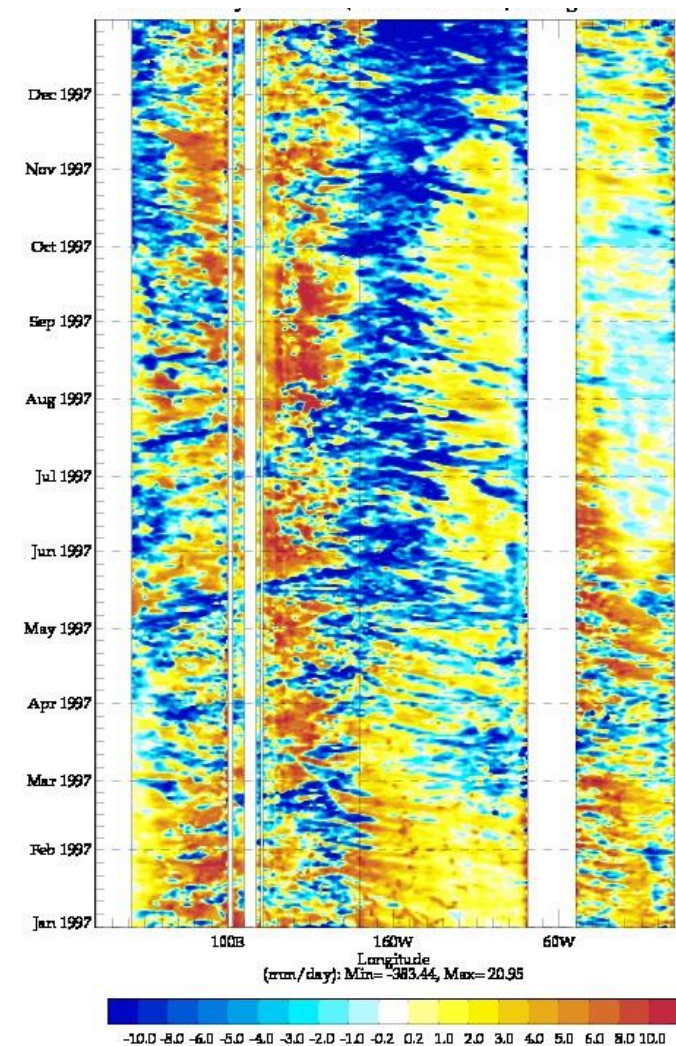
May/June 1997: More WWB . Or is this already ENSO? Bjerkness feedback in action.

Daily Equatorial Anomalies: Jan 1997-Jan 1998

D28 Anomalies "Warm Pool"



Fresh Water Flux Anomalies Blue is into the ocean



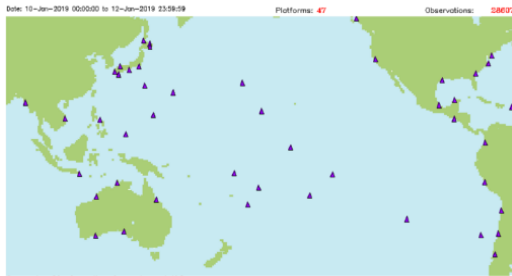
Data from ORAS4

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

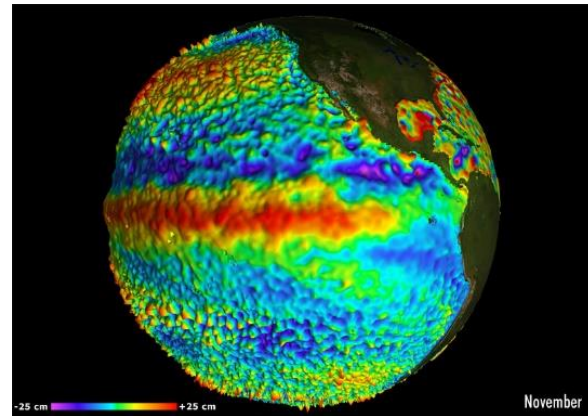
ENSO monitoring and prediction: relevance of the ocean observing system

SST + Atmosphere + Ocean Subsurface

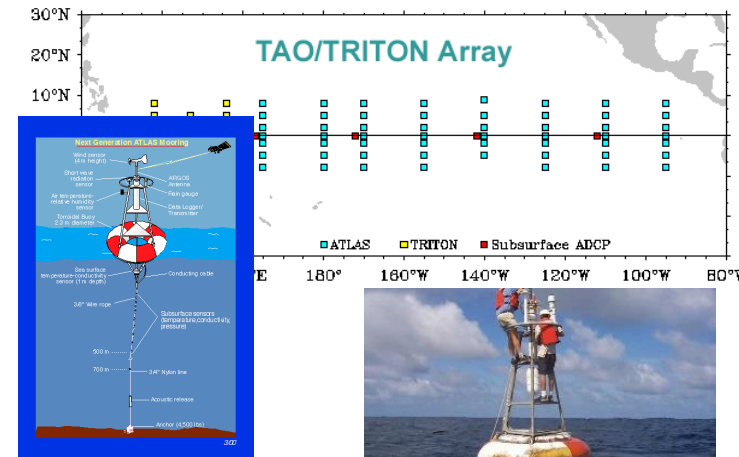
1975; Wyrтки sets Equatorial tide gauges to monitor Kelvin waves



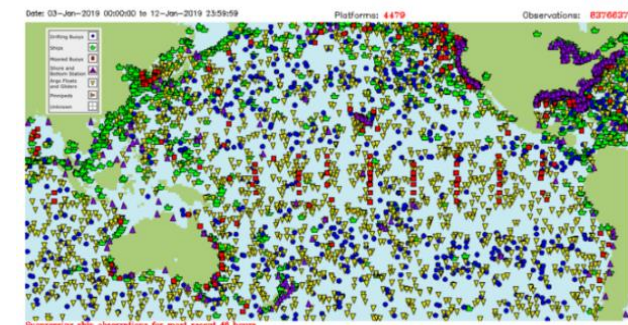
~ 1993 onwards: satellite altimeter to monitor sea level



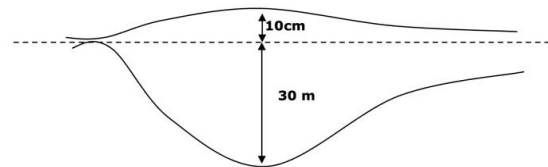
~ 1993- TOGA-TAO program to monitor subsurface temperature



~ 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

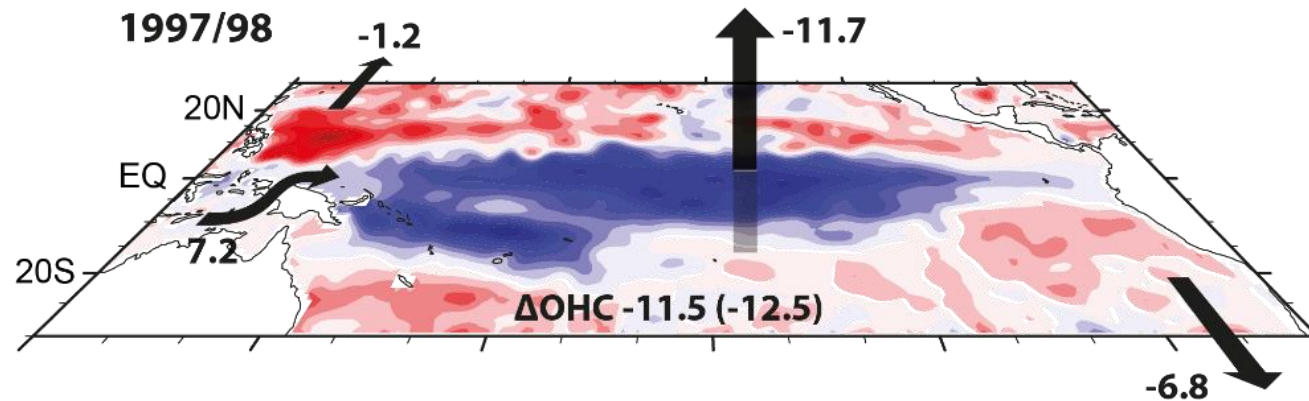


If we observe sea level, we can infer information on the vertical density structure, and we can detect propagating waves. This is why altimeter Sea-Level is important for ENSO monitoring and prediction.

ENSO Energy Cycle (from reanalyses)

- **ENSO has profound on the energy cycle:**

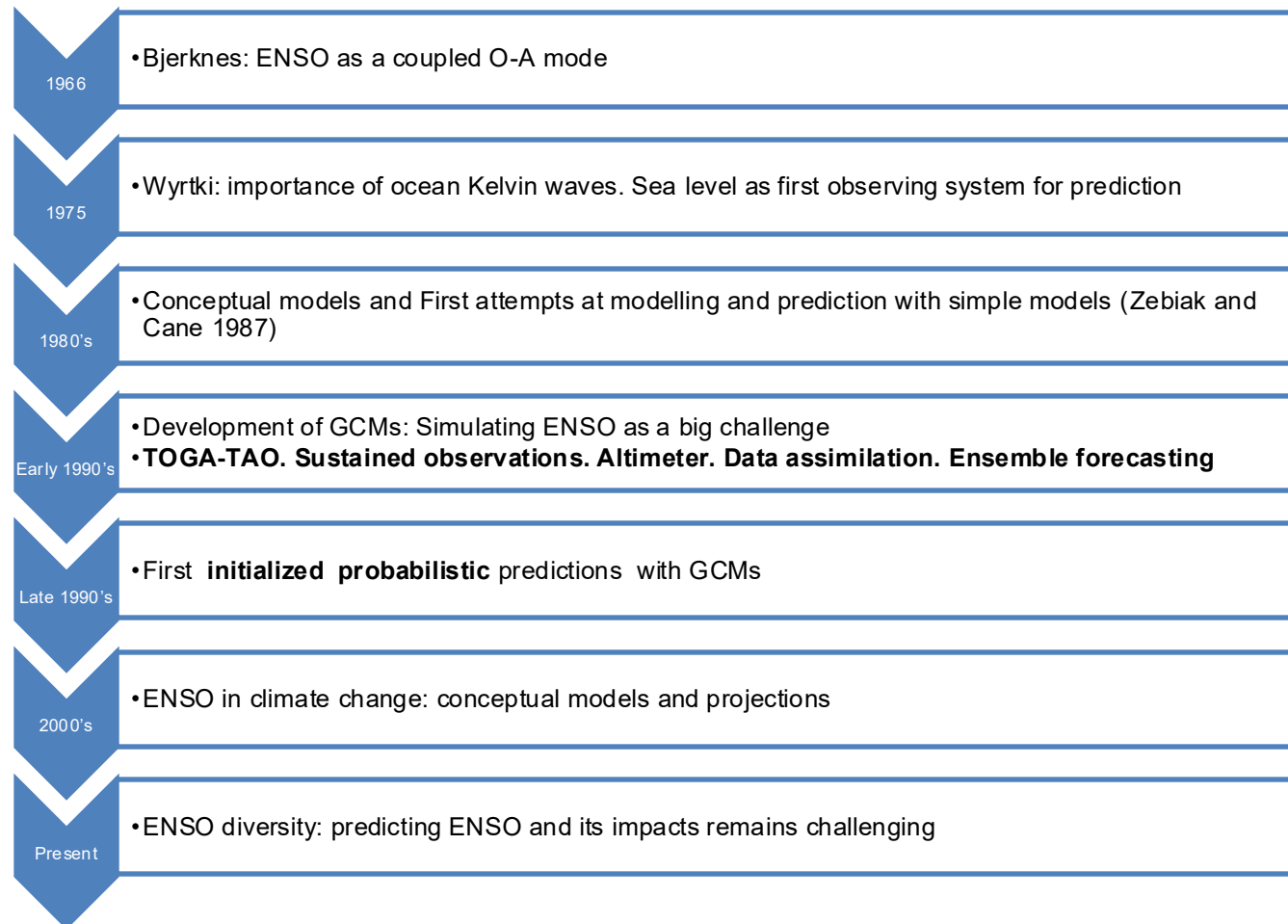
- During the 1997-98 El Nino the Tropical Pacific exchanged ~ 11 ZJ with the climate system (~10 times the annual human energy consumption in that year).
- Most of that energy is made available to the atmosphere, and eventually is lost to outer space. El Nino acts to refrigerate the climate system
- 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 Ocean Heat Content (OHC) and energy exchanges (ZJ) during the 1997/98 El Nino event
(1 ZJ = 10^{21} J. Annual human energy consumption in 1997 ~ 1 ZJ)

Some landmarks on ENSO prediction

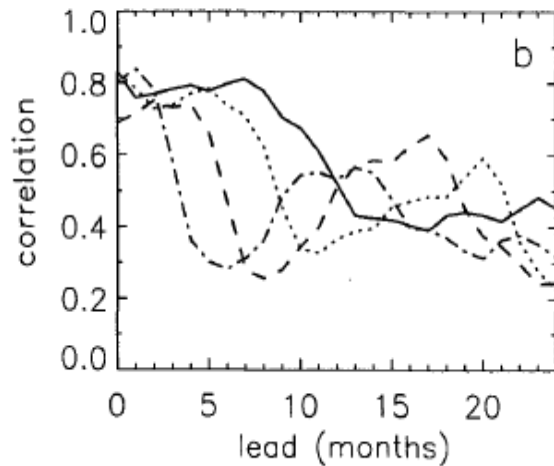
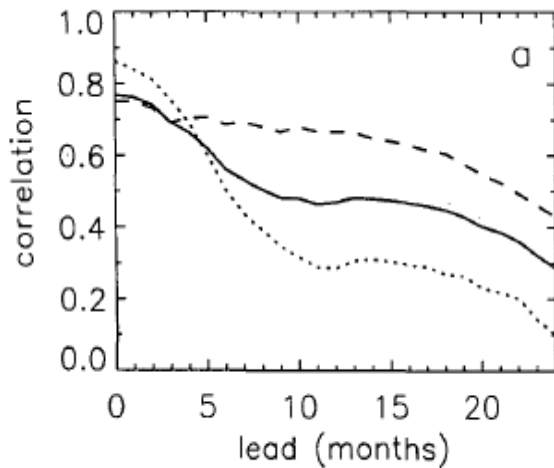


Operational seasonal forecasts started by attempting to predict ENSO and its impact worldwide

Progress on ENSO prediction due to observations, conceptual models, GCMS, data assimilation, post-processing...

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**

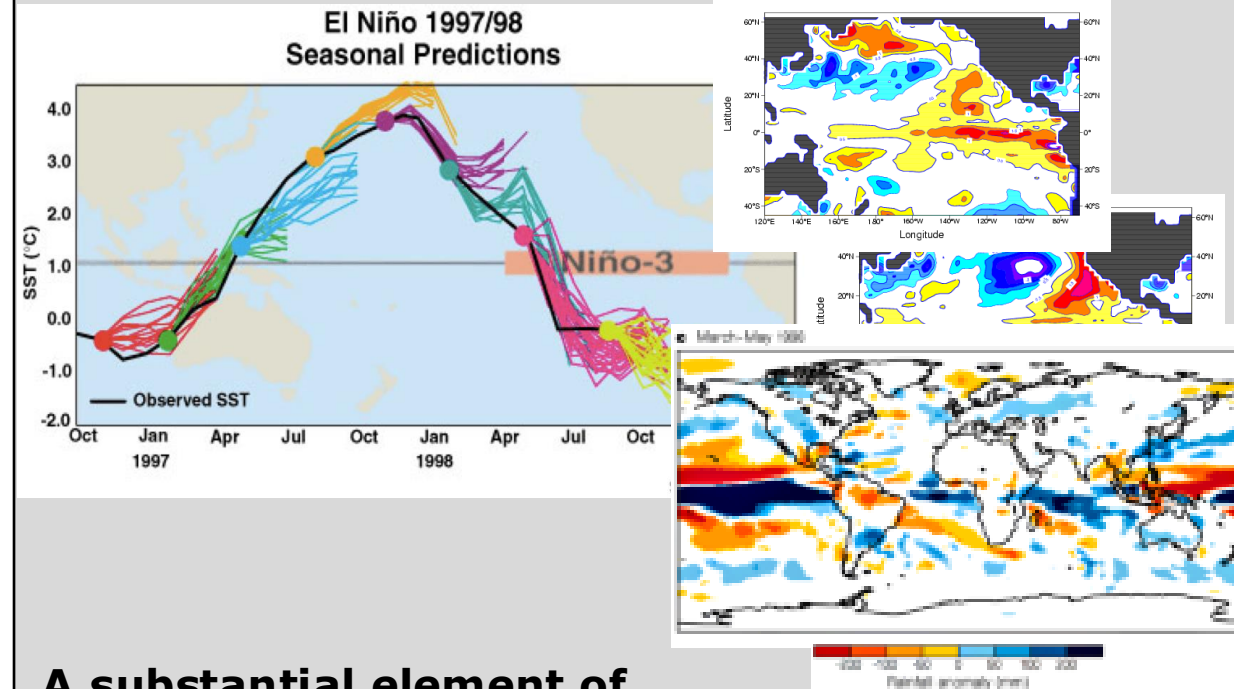
3) **decadal variations on ENSO prediction skill**

..... 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 ocean data assimilation
- And the developments of ensembles



A substantial element of beginner's luck

Stockdale et al 1998

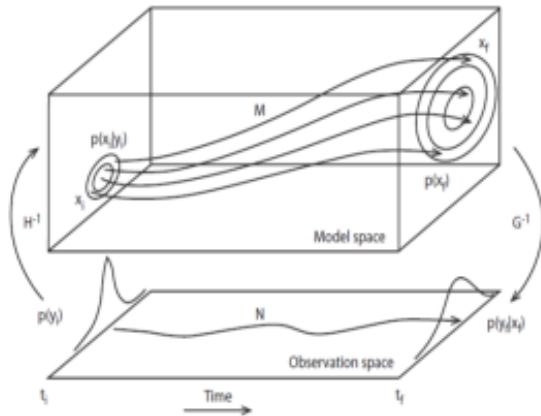
1995-2005: Operational Seasonal Forecasts

clearly formulated as a probabilistic initial value problem

2) Propagating information and uncertainty into the future: *Forecast model*

1) Initialization
Data Assimilation

$$p(x_i|y_i) = \frac{p(y_i|x_i)p(x_i)}{p(y_i)}$$

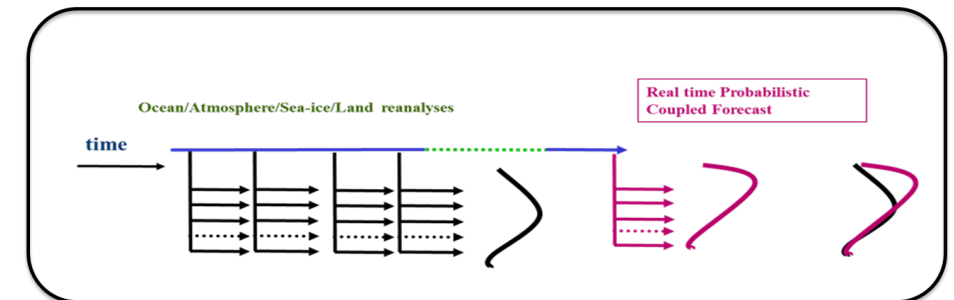


3) Calibration
Forecast Assimilation

$$p(y_f|x_f) = \frac{p(x_f|y_f)p(y_f)}{p(x_f)}$$

Introduction of reforecasts as integral part of the forecasting systems

- Reforecasts are needed for calibration of forecast products and skill estimation
- **Reanalysis of the Earth System** are needed to initialize and verify the reforecasts



Clear need to for forecast calibration

Coupled Ocean–Atmosphere Forecasts in the Presence of Climate Drift

TIMOTHY N. STOCKDALE

European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom

(Manuscript received 18 June 1995, in final form 29 April 1996)

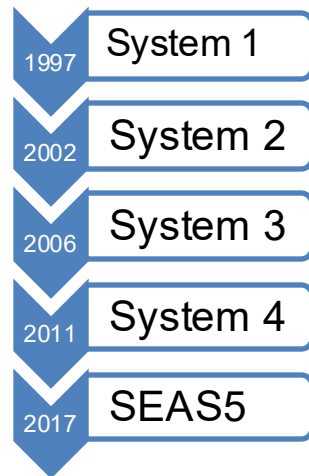
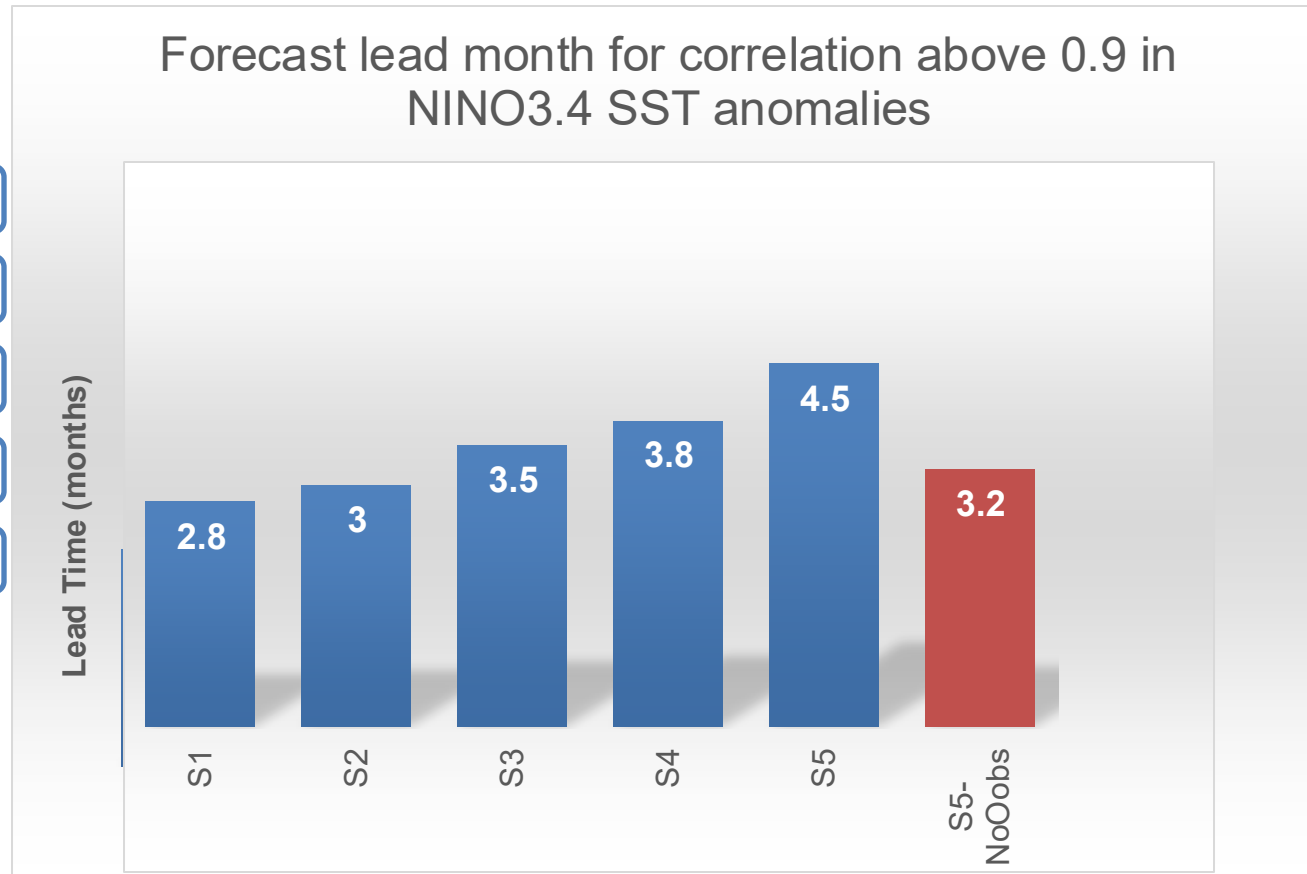
Impetus from and for Reanalysis. Beginning of ocean reanalysis

Protocol for Subseasonal and decadal forecasts

Prediction of extremes at all lead times (EFI)

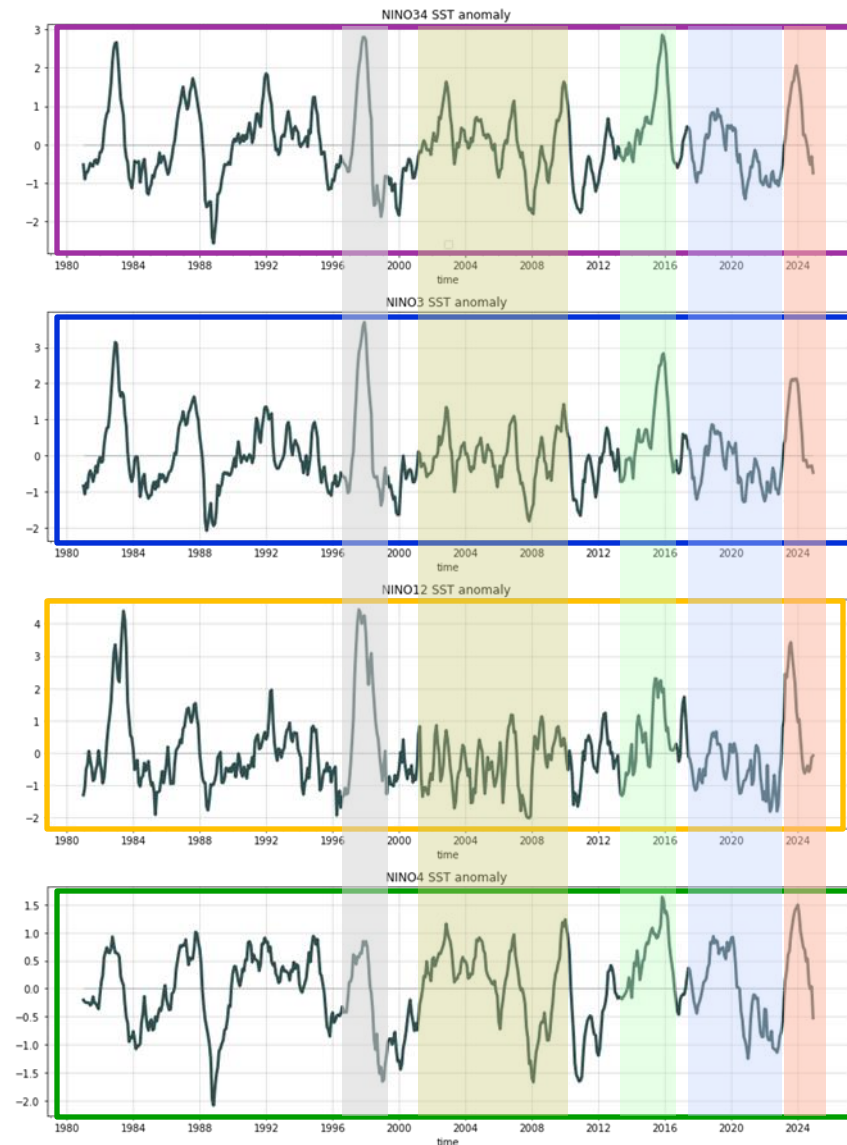
Progress in ENSO prediction at ECMWF

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.

What have we learnt over 25 years of operational ENSO prediction? : interaction between time and spatial scales



From 1997/98 El Niño

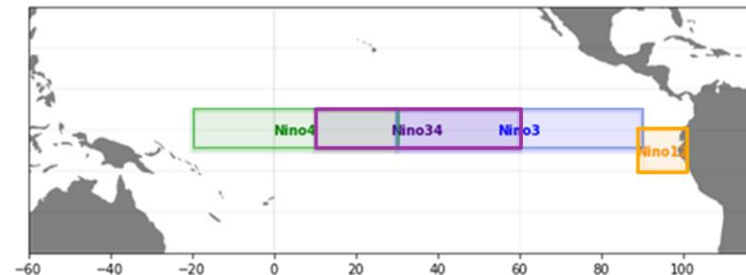
From the hiatus period (2003-2013)

The existence of Central Pacific ENSO (see Timmermann et al 2018 for a review)

From 2014/2015-6 double peak El Niño

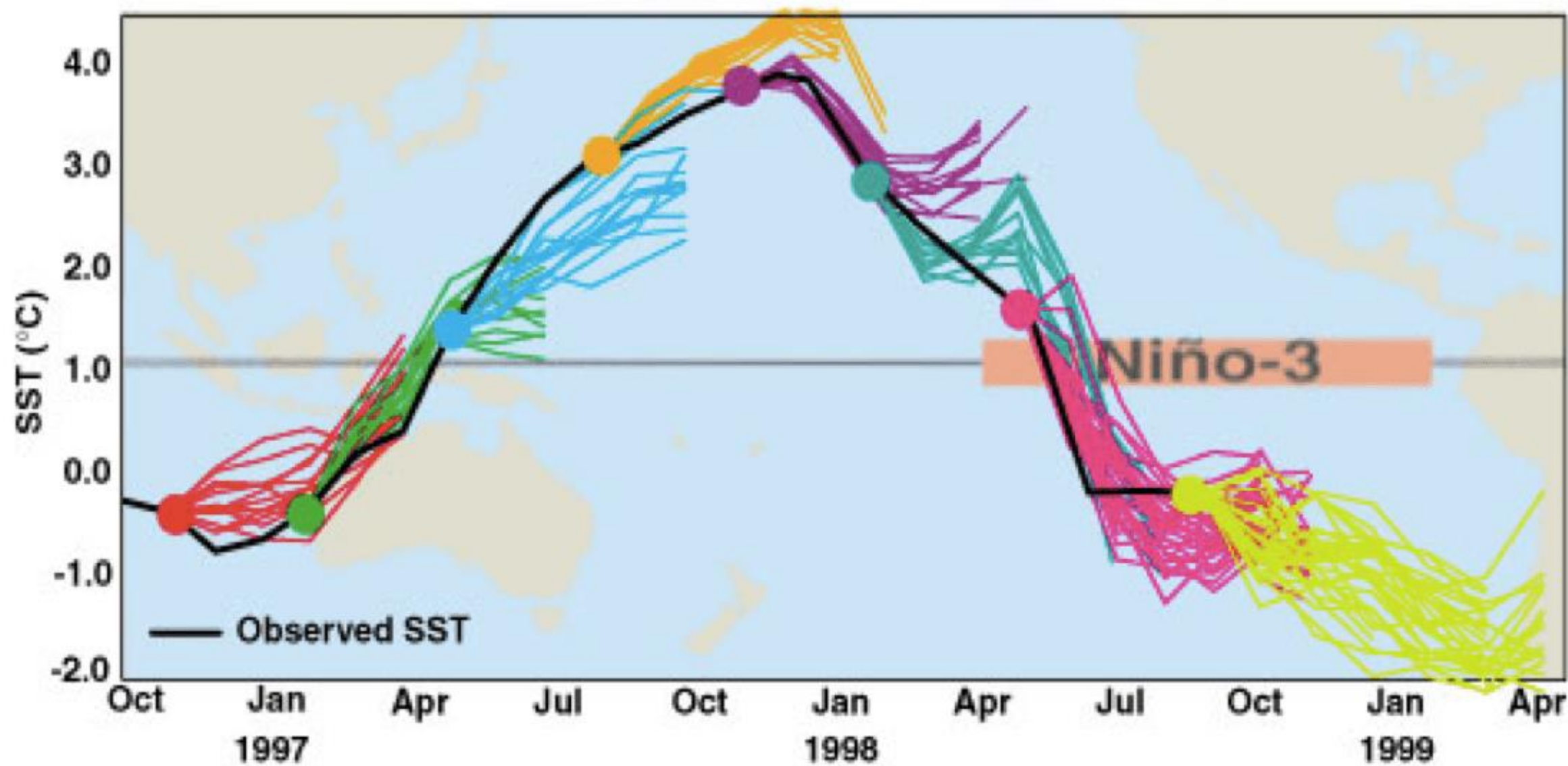
From the 2019-2022 triple deep La Niña

From the recent 2023-2024 El Niño



El Niño 1997/98

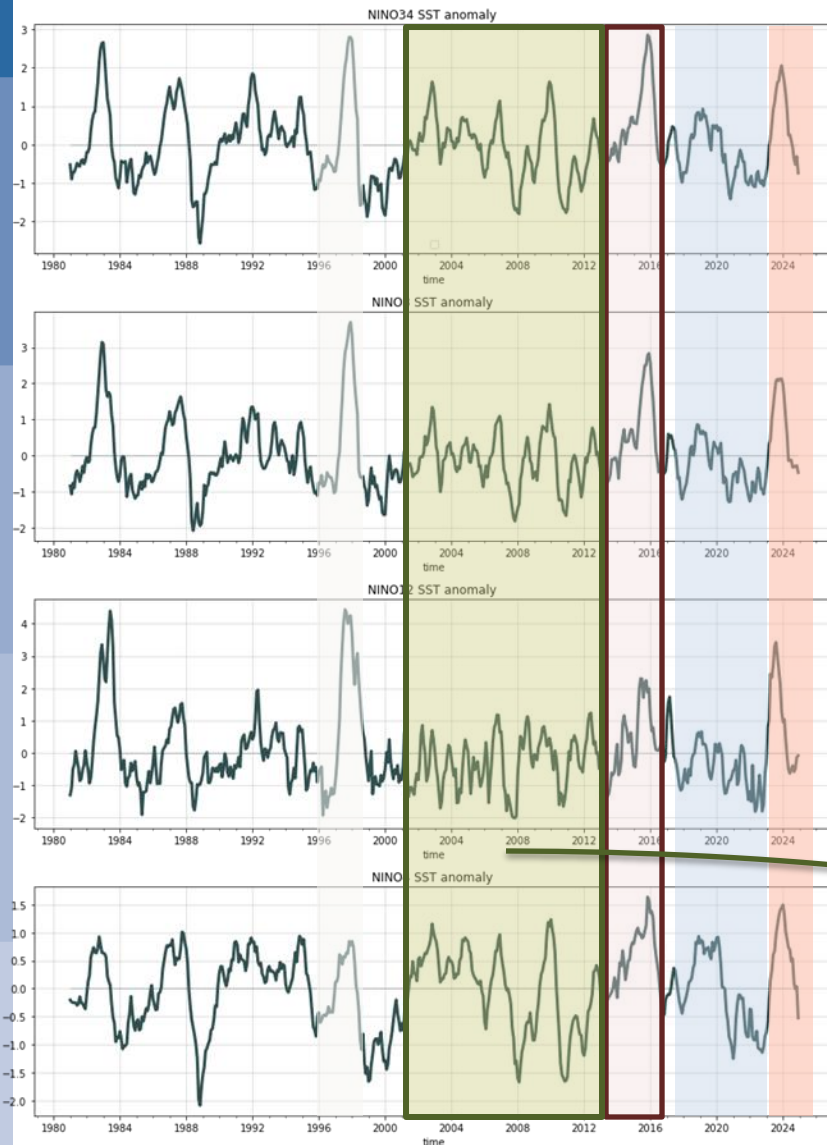
Seasonal Predictions



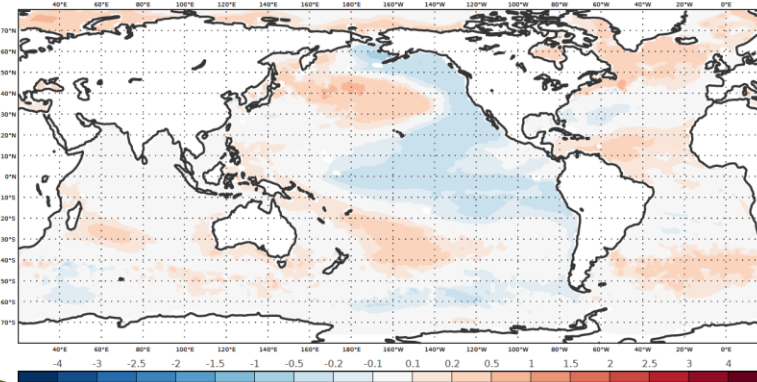
Source: ECMWF

2. Lessons from the 2014 failed El Nino and the following 2015-16 extreme warming

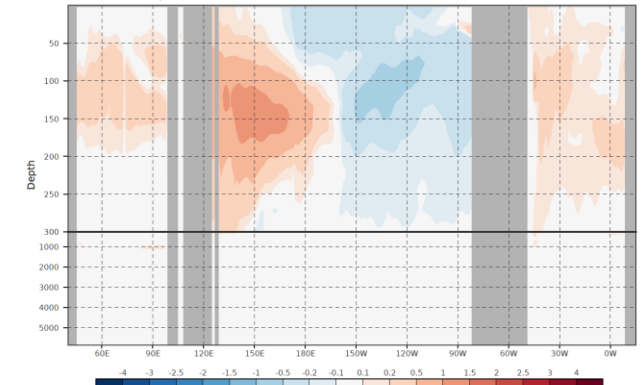
- Great expectation in 2014 for a big El Nino
 - Last one was in 1997/98
 - There had been a hiatus decade (since ~2005) with negative phase of PDO
 - Long lasting Californian drought
 - Models and Experts predicted the possibility of a large warm event



ORAS5 SST anomaly 2005-2013

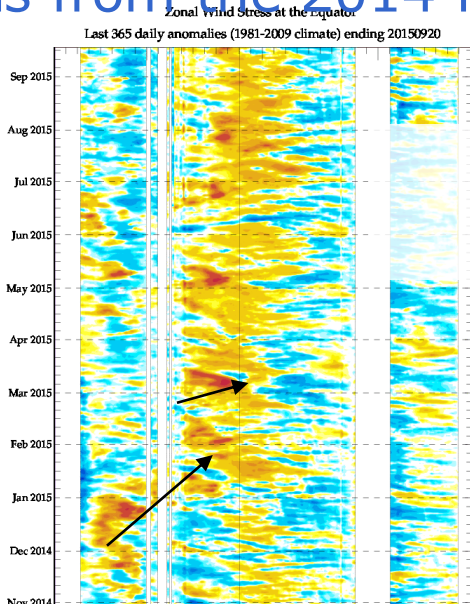
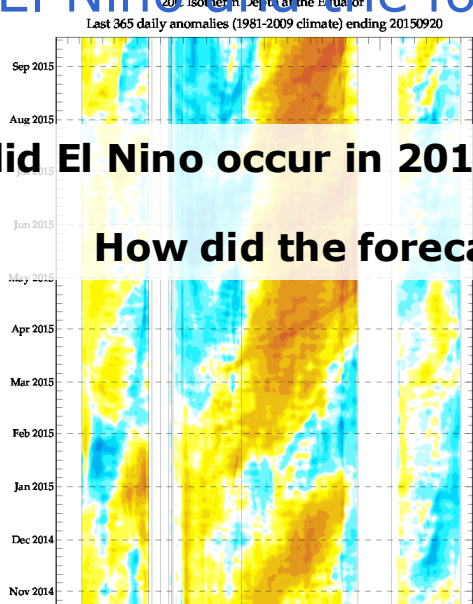
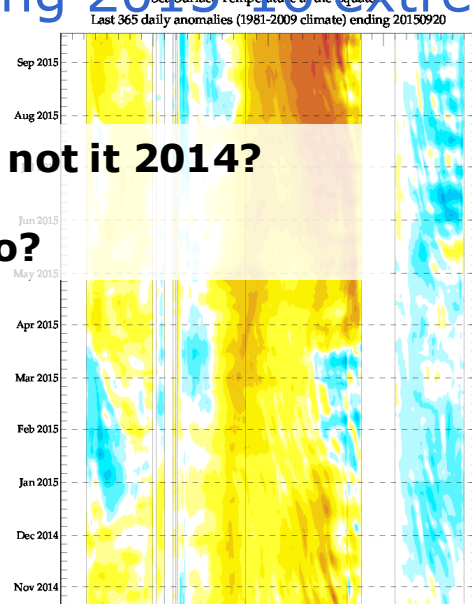


ORAS5 T anomaly 2005-2013



2. Lessons from the 2014 failed El Nino and the following 2015-16 extreme warming

2015



Sep
2015

Why did El Nino occur in 2015 and not it 2014?

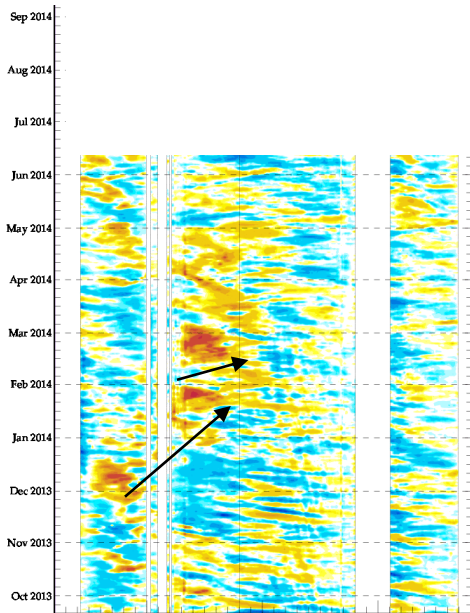
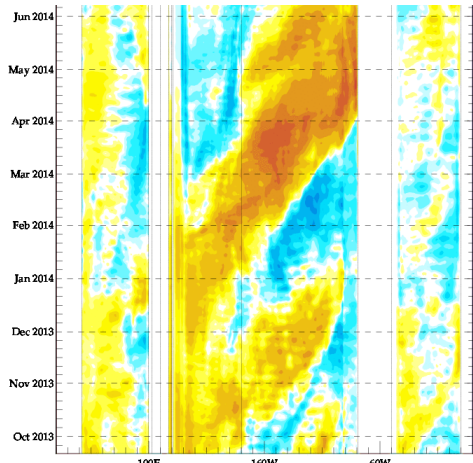
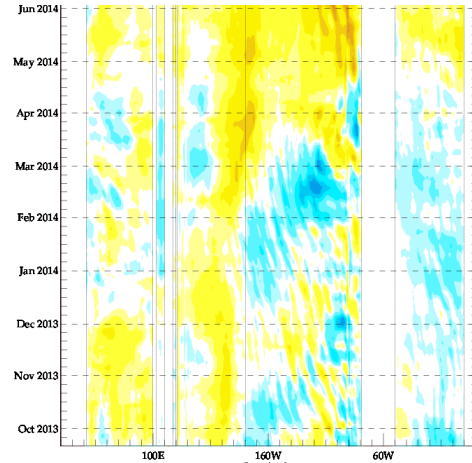
How did the forecasts do?

Wind Stress Anomalies

Depth of Thermocline Anomalies

SST Anomalies

2014



Sep
2014

June
2014

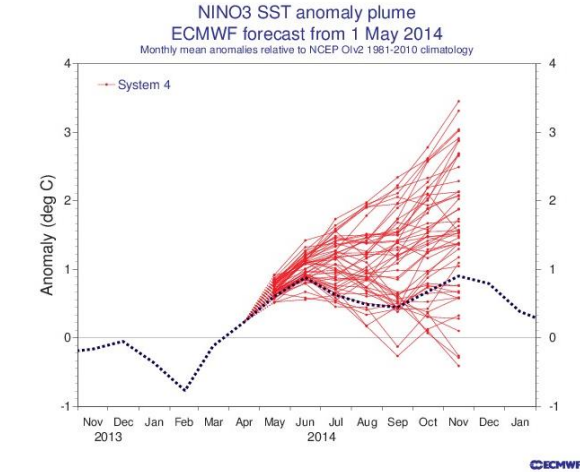
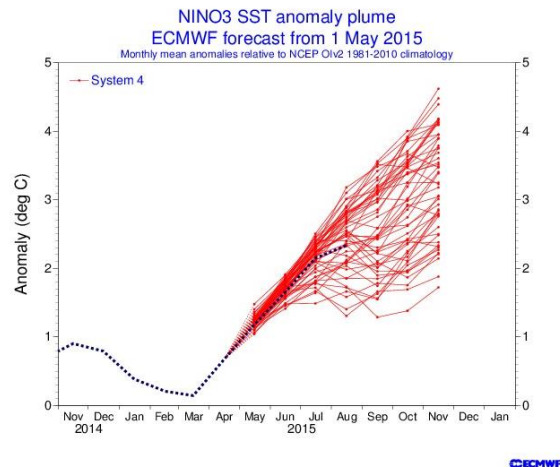
Sep
2013

Data from ORAS4

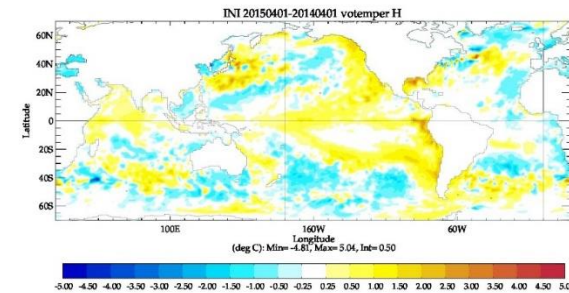
Lessons from El Nino Forecasts: 2014 v 2015

Did the forecasts capture the difference between 2014 and 2015?

Growth of Perturbations: Temperature

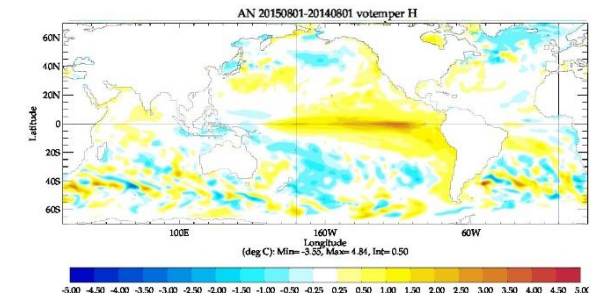


INI Pert: APR 2015-2014

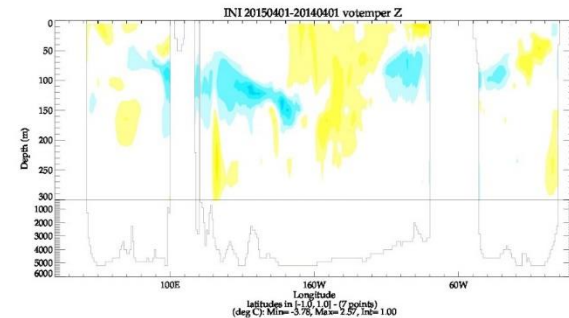


ini_diff_votemper_20150401-20140401_10 Sep 18 2015

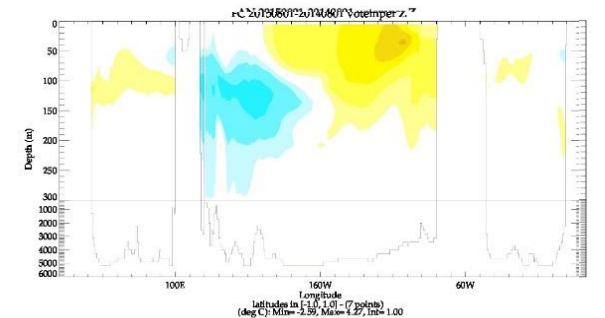
Forecast Final Pert: Aug 2015-2014



an_diff_votemper_20150801-20140801_10 Sep 18 2015



ini_diff_votemper_20150401-20140401_10 Sep 18 2015

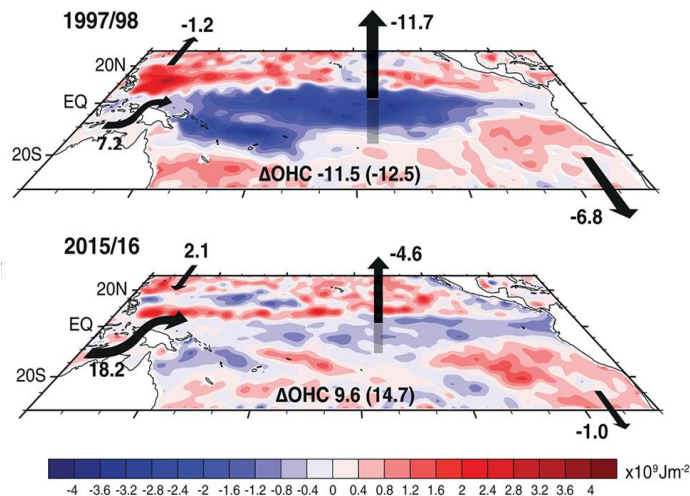
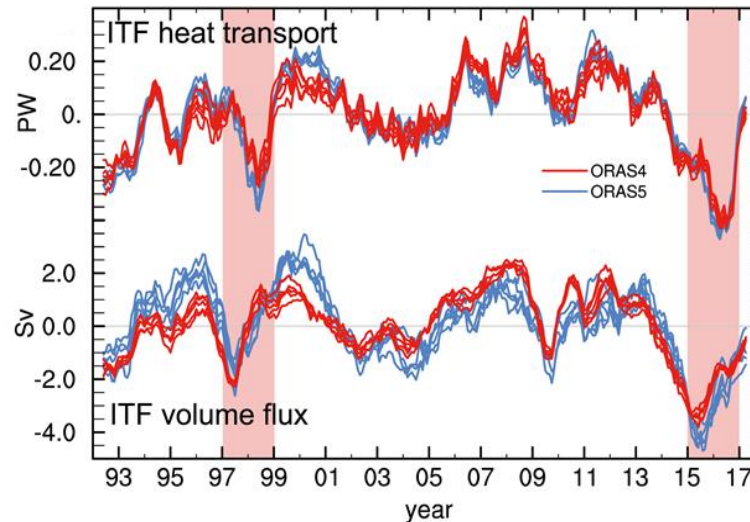


an_diff_votemper_20150801-20140801_10 Sep 18 2015

- Seas Fc (SEAS4) were discerning: they capture differences between 2015 and 2014.
- Skill beyond persisting the initial differences.

Lesson 2: 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



The Indonesian Throughflow(ITF) links the Pacific and Indian Ocean.

In normal conditions, the Pacific exports heat towards the Indian Ocean.

During El Niño, the ITF weakens.

During 2014/15 the ITF was less than half than in 1997/8, (unprecedented weakening), so that the heat export to the Indian ocean decreased dramatically, remaining in the Pacific.

The Indian Ocean is the tropical basin with faster warming, with consequent increase of the sea level. This changes the zonal pressure gradients, which can affect the weakening of the ITF

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

Mayer, Balmaseda, Haimberger, GRL, 2018

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

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

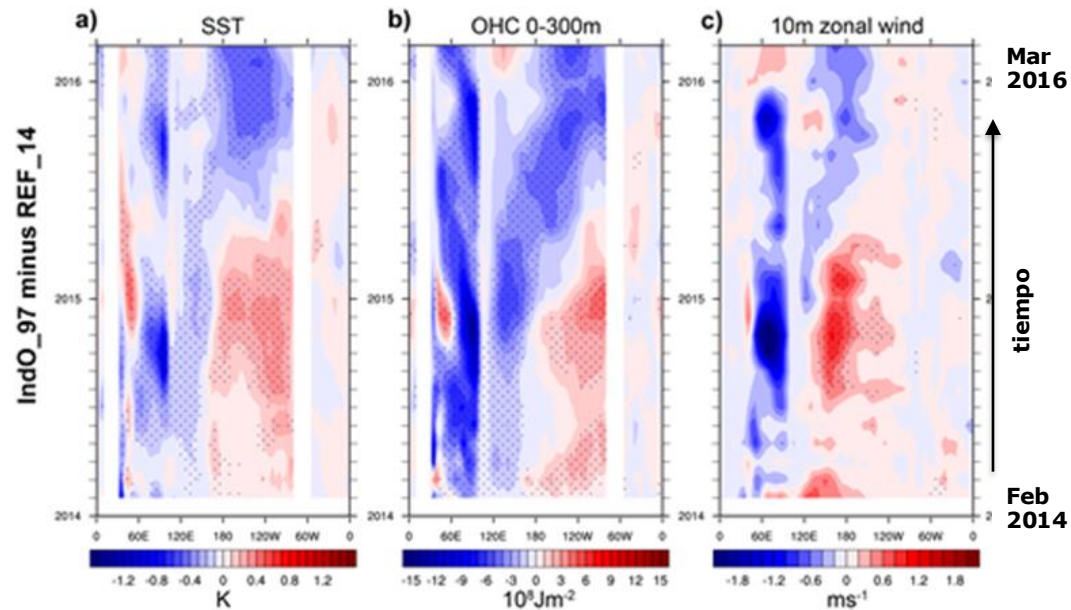
Experiments: SEAS5 up to 24 months from 1st Feb

Ref 1997: as SEAS5

Ref 2014: as SEAS5

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

Perturbed – Reference 2014

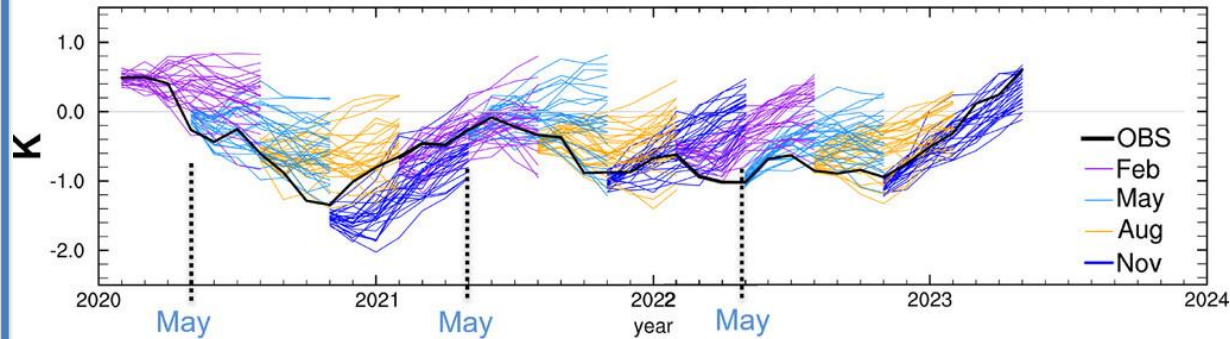


With the 1997 Indian Ocean I.c, El Nino would have occurred in 2014 and La Nina transition would have started in 2015.

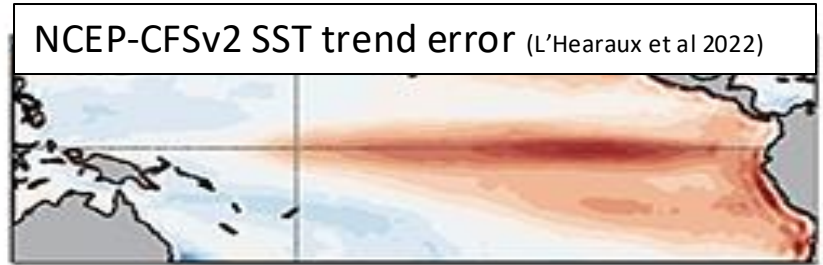
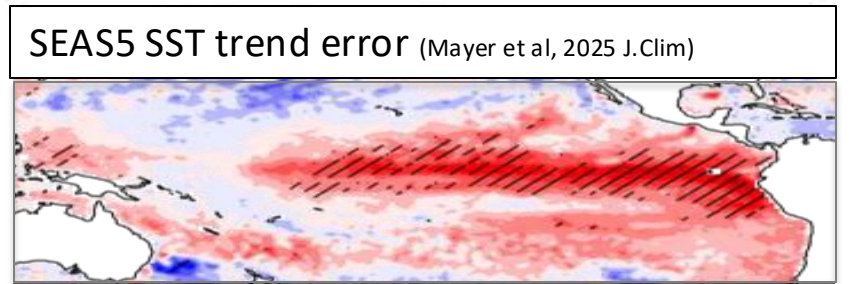
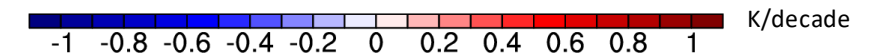
Lessons 3: Tripple dip La Nina. Seasonal forecast of ENSO struggle to capture recent trends.

SEAS5 tended to terminate the triple dip La Nina too early
(forecasts initialized Nov21-Feb22). Why?

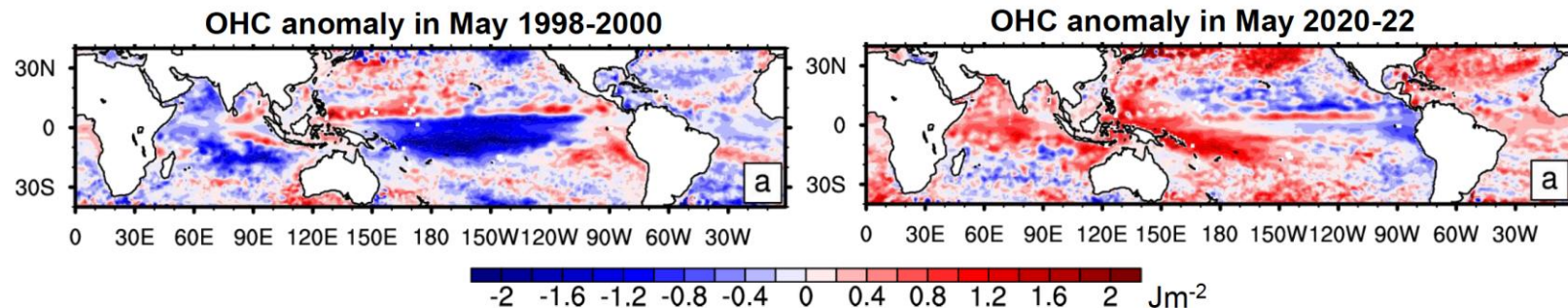
a) Niño 3.4 anomaly forecasts (SEAS5)



Mayer et al 2025 show that there is a significant overprediction of SST over the Eastern Equatorial Pacific (2000-2016), due to fast developing wind errors. Similar errors seen in NMME (L'Heraux et al 2022 and CMIP6 models (Seager 2019, Beverly et al 2024).



The question can be reversed: Given the unusual recharged state in the Western Pacific, why did not Nature go to El Nino earlier?



What can we learn from the recent 2023-2024 El Nino?

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

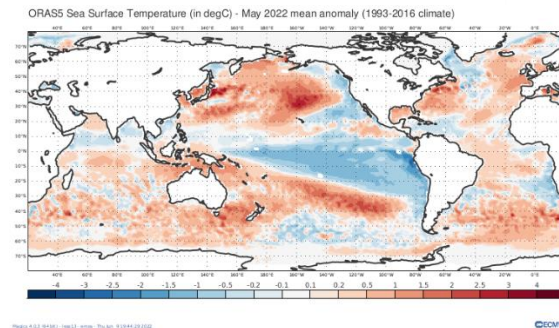
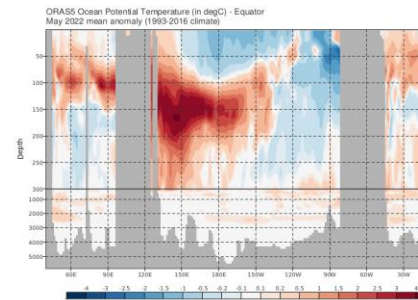
We have had a prolonged 3-years La Nina conditions.

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

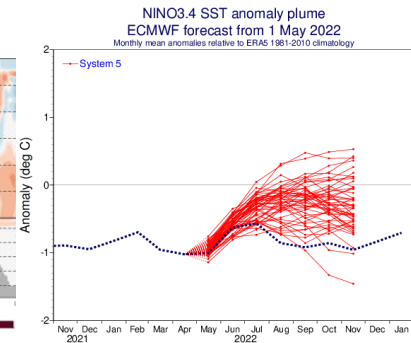
Q2. Is the expectation bias affecting our interpretation again, as for the 2014-15 "perceived false alarm"?

At least from May 2022 onwards, ocean subsurface and forecasts were very different in 2022 and 2023.

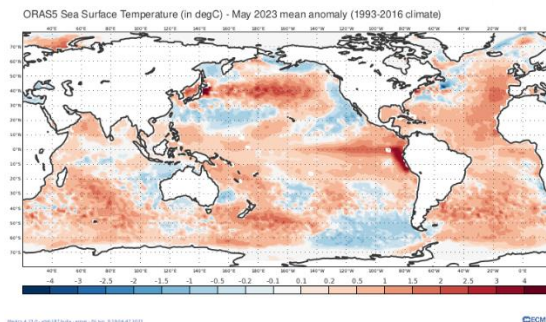
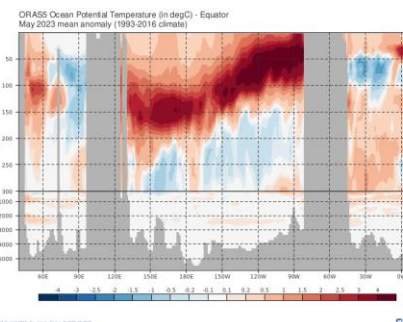
Ocean state in May 2022



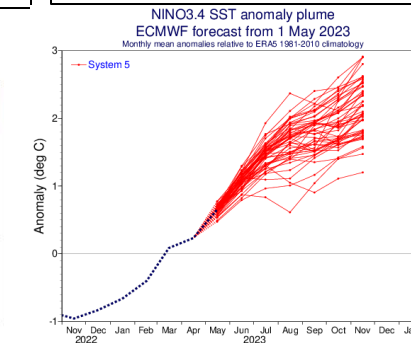
Forecast from May 2022



Ocean state in May 2023



Forecast from May 2023



But by Autumn 2023 we were getting nervous: the atmosphere was not responding ...

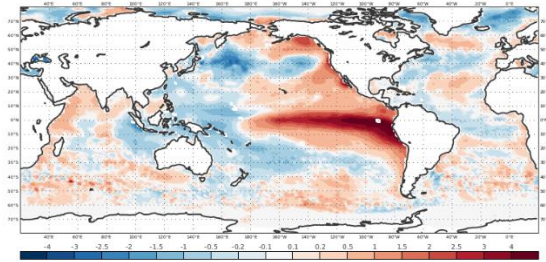
Equatorial Conditions in Sep 2024

Sep 1997

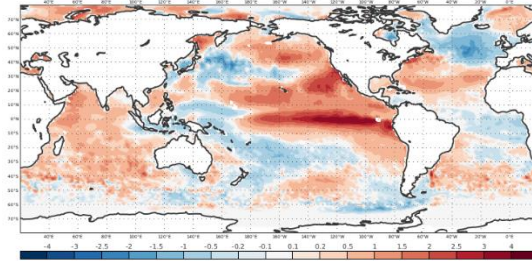
Sep 2015

Sep 2023

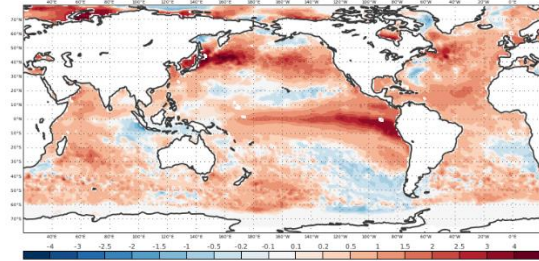
ORASS Sea Surface Temperature (in degC) - September 1997 mean anomaly (1993-2016 climate)



ORASS Sea Surface Temperature (in degC) - September 2015 mean anomaly (1993-2016 climate)

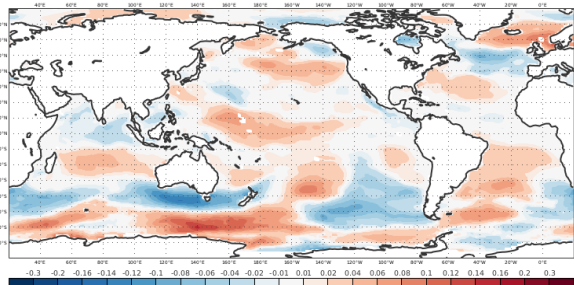


ORASS Sea Surface Temperature (in degC) - September 2023 mean anomaly (1993-2016 climate)

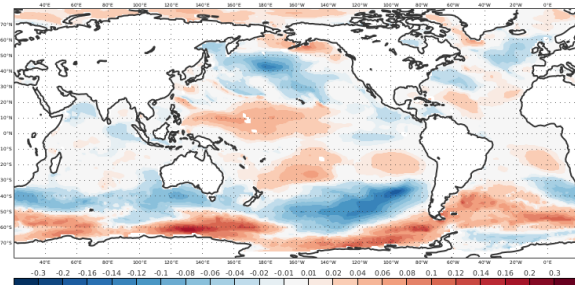


SST

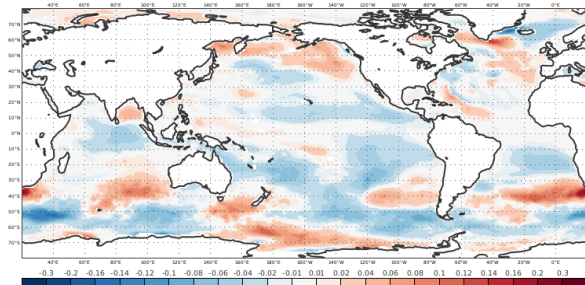
ORASS Zonal Wind Stress (in N/m2) - September 1997 mean anomaly (1993-2016 climate)



ORASS Zonal Wind Stress (in N/m2) - September 2015 mean anomaly (1993-2016 climate)

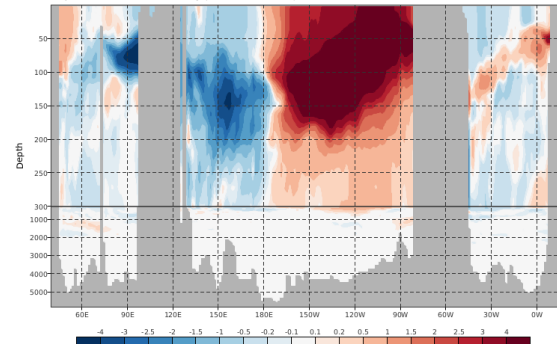


ORASS Zonal Wind Stress (in N/m2) - September 2023 mean anomaly (1993-2016 climate)

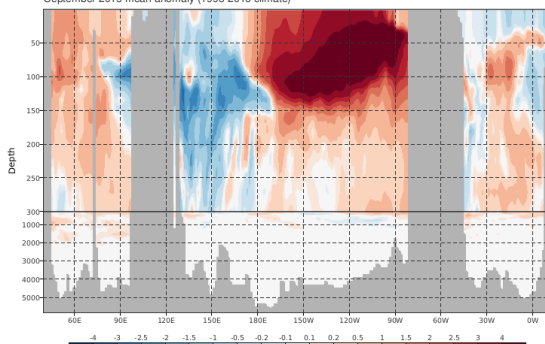


Zonal Wind Stress
Taux

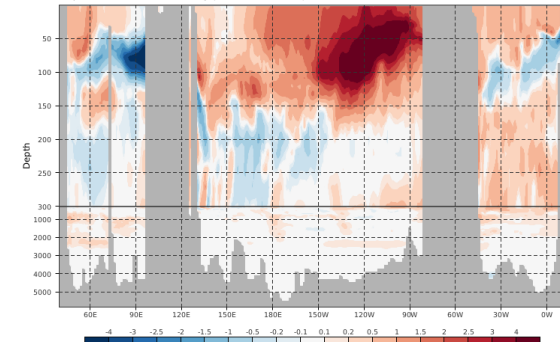
ORASS Ocean Potential Temperature (in degC) - Equator
September 1997 mean anomaly (1993-2016 climate)



ORASS Ocean Potential Temperature (in degC) - Equator
September 2015 mean anomaly (1993-2016 climate)



ORASS Ocean Potential Temperature (in degC) - Equator
September 2023 mean anomaly (1993-2016 climate)



Subsurface T

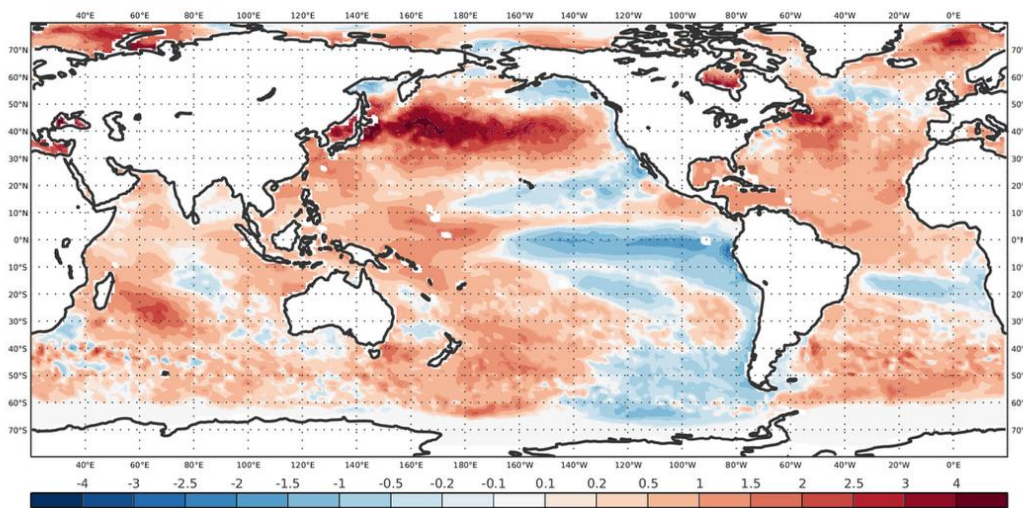
The zonal wind response is weaker this year than in previous big El Nino, and so is the Eastern Pacific heat reservoir. **And without the atmospheric feedback, the subsurface temperature anomaly was weakening...**

Data from ORASS

SEAS5 forecast were successful. As an example, they captured well the differences between 2023 and 1997

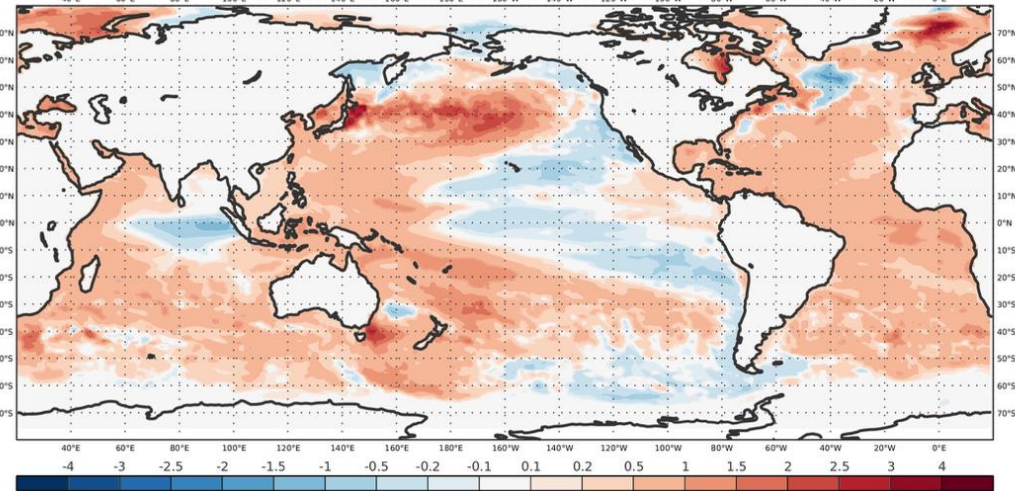
ORAS5 SST 2023-1997

ORAS5 SON 2023 - 1997



Seas5 ensemble mean SST 2023-1997

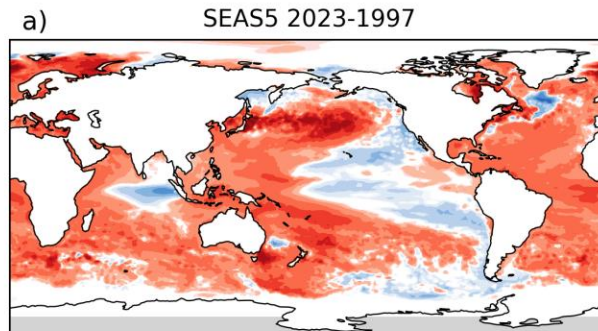
SEAS5 SON 2023 - 1997



So we can use the SEAS5 system to investigate why El Nino did not grow as much as anticipated by the initial conditions

Explaining differences between 2023 and 1997 via SEAS5 perturbation experiments

SST Differences SON: 2023 v 1997



1) What was the impact of difference in the Tropical Indian Ocean initial conditions in 2023 versus 1997?

2) What was impact of the the different Atmosphere (and land) in 2023 versus 1997?

3) What if the impact of the differences in Tropical Atlantic Ocean initial conditions in 2023 v 1997?

4) Combined result
Differences in Atmosphere + Indian+ Atlantic in 2023 v 1997

5) Residual: contribution of the tropical Pacific + extratropics

Tropical Atlantic plus long term warming of extratropical ocean + atmosphere major factors contributing to the weaker intensity of ENSO in 2023

Lessons learnt over the years:

interaction between time and spatial scales

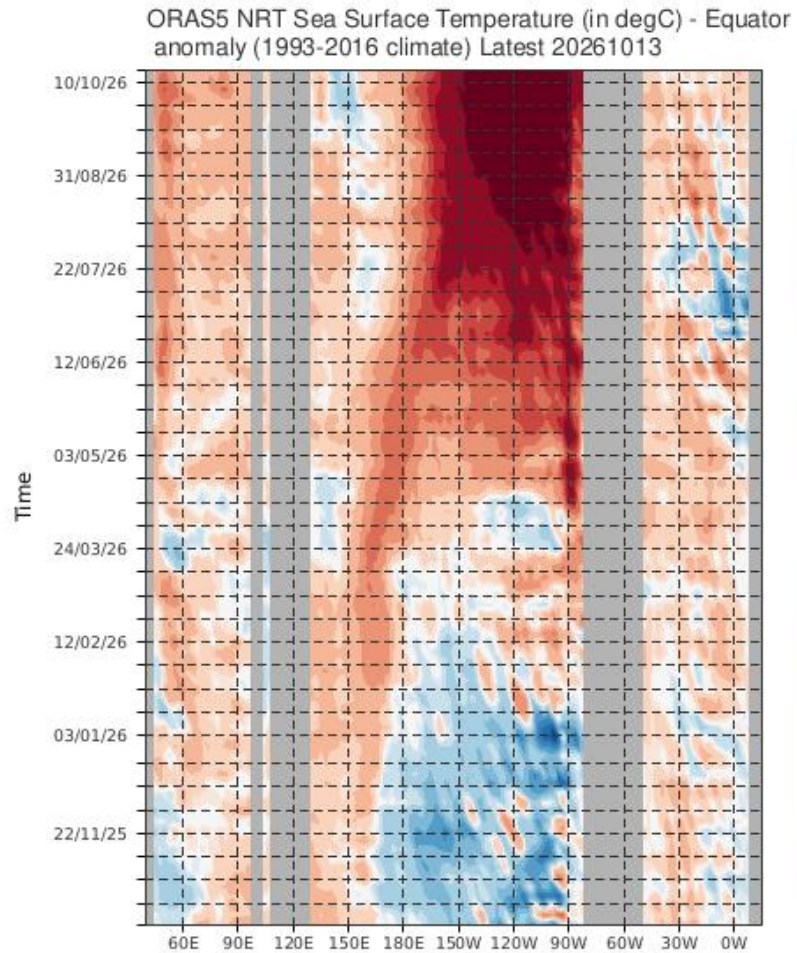
We have seen how ENSO prediction has evolved over the years from simple conceptual models to complex GCMs. In the process we have learnt several lessons

- **Lesson 1: From 1997/98 El Nino**
WWB as stochastic triggers for ENSO. Interaction between subseasonal and interannual variability
- **Lesson 2: From 2014/2015-6 double peak El Nino**
Role of other ocean basins (the role of Indian Ocean via atmospheric bridge and ocean tunnel)
- **Lesson 3: From forecasts after ~2005, in particular 2019-2022 triple deep La Nina**
Errors in ENSO trends. Shared with CMIP models. Not exclusively an initial value problem
- **Lesson 4: From the anomalous evolution the 2023-2024 El Nino**
Very weak response of the Walker Circulation. Important role of the Atlantic basin and atmosphere state. Is this weak response caused by global warming?
- **Lesson 5: From 2014/2015-6 double peak El Nino, from long historical reforecasts and more recent experiments**
Windows of opportunities for predictions beyond 1-year
Seas6 will include forecasts of ENSO for the 2-year forecast range

What about current conditions?

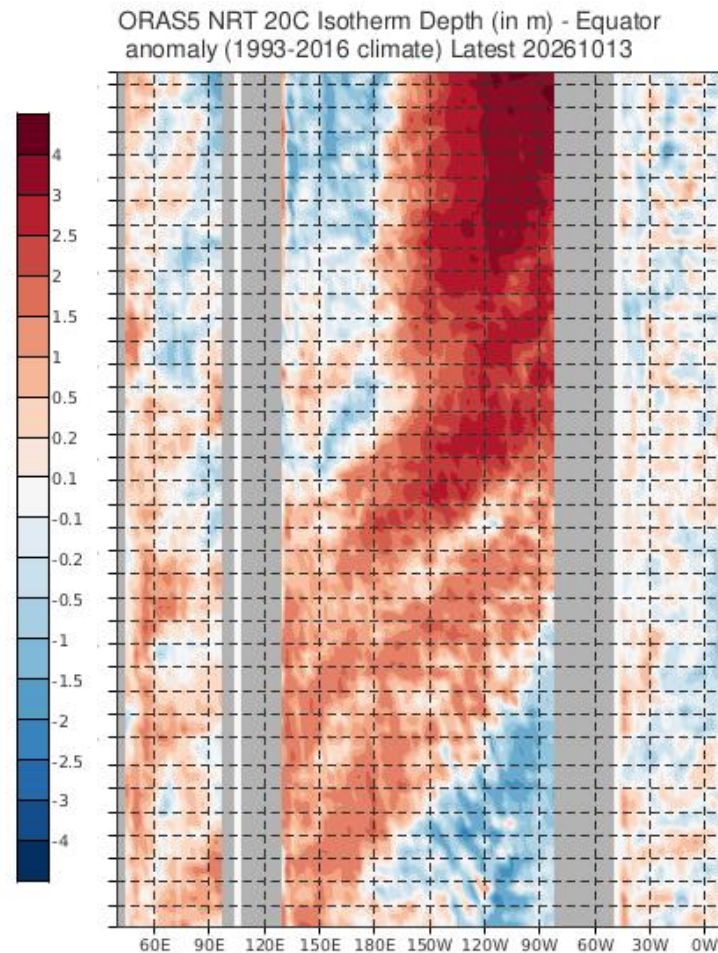
Daily Eq. Anomalies over the past year

SST



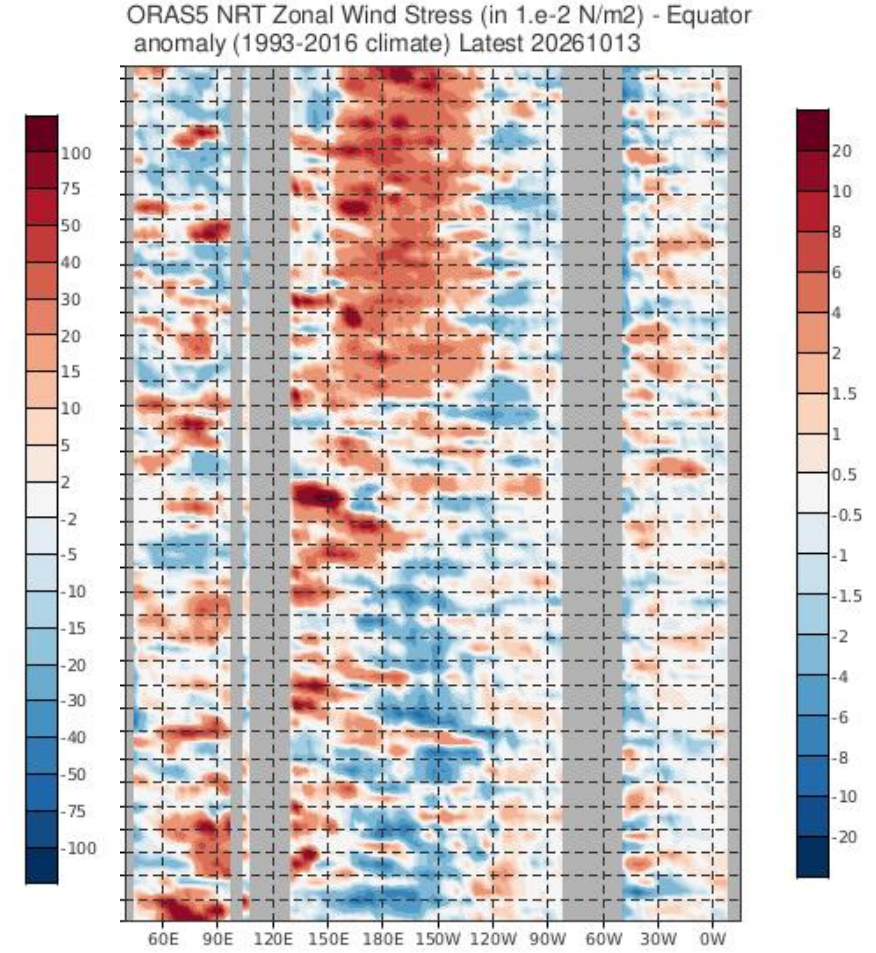
10s - Tue Oct 13 16:37:04 2026

D20



10s

Taux



10s