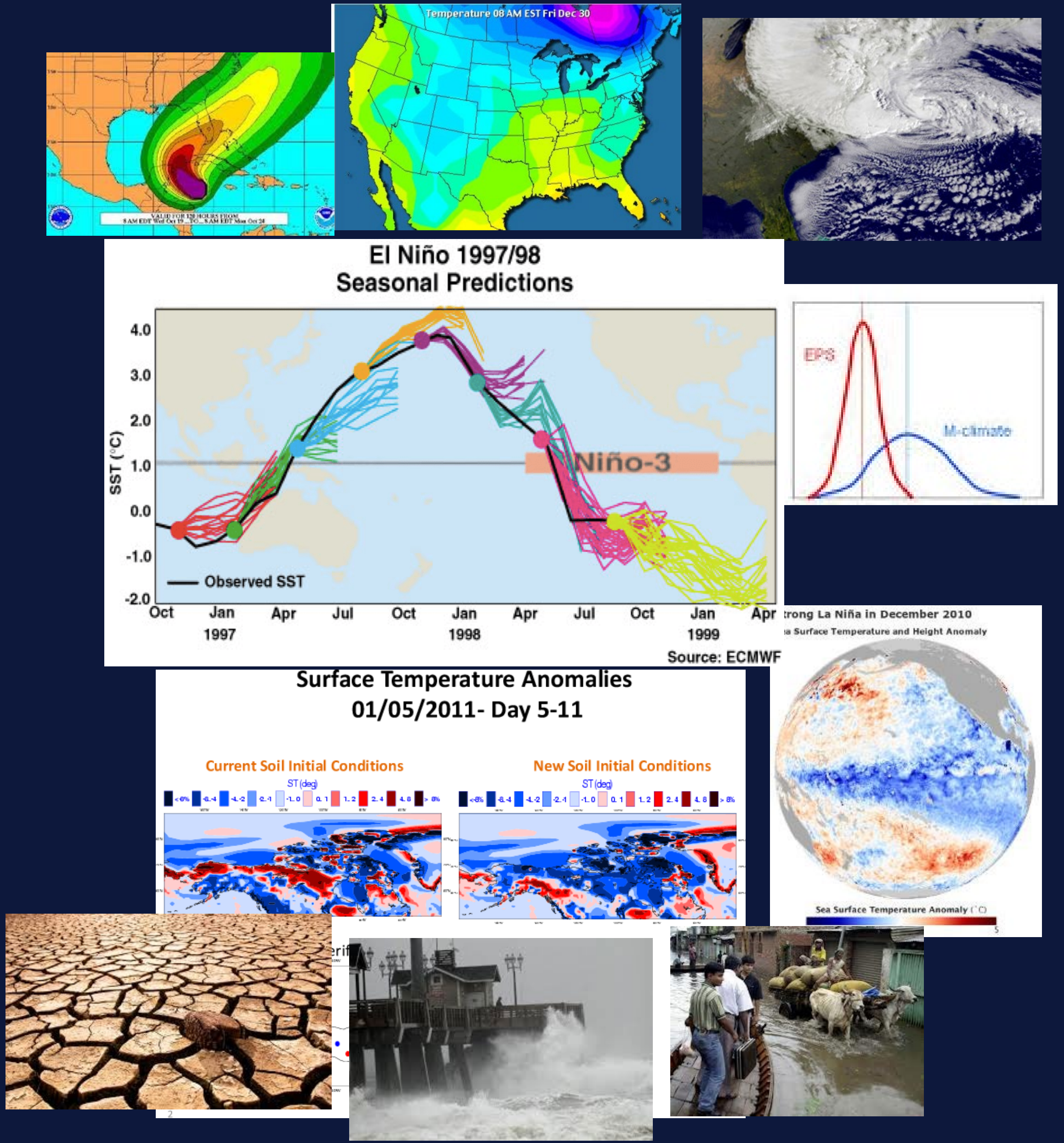
# ENSO as meeting point for weather and climate

## Lessons learnt from 25 years of ENSO forecasting at ECMWF




Magdalena Alonso Balmaseda

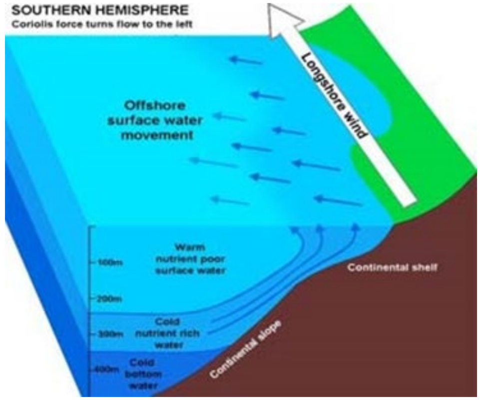
ECMWF

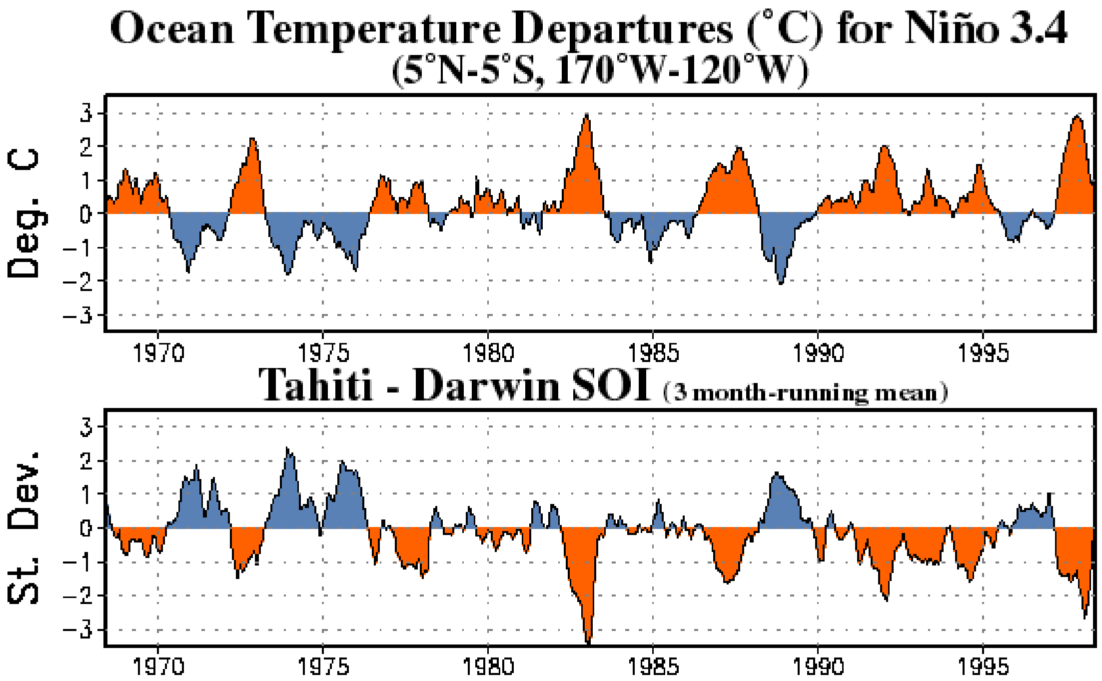
Thanks to Michael Mayer, Retish Senan, Fredric Vitart, Antje Weisheirmer, Steffen Tietsche, Tim Stockdale, Stephanie Johnson, and members of the ECMWF predictability section

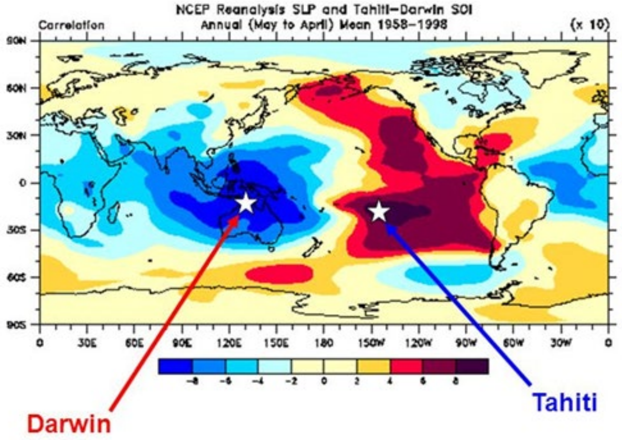
# The beginnings

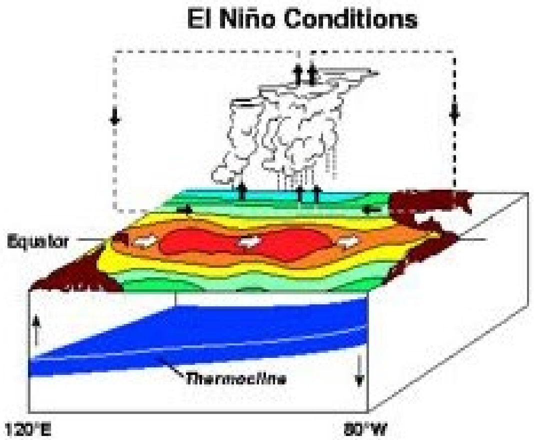
**El Niño: Named by Peruvian Fishermen**
**Oceanic impact on fisheries and nutrients**

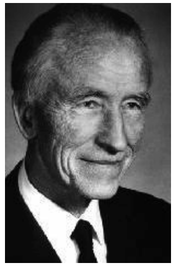
**Southern Oscillation: Gilbert Walker ~1928**
**Atmospheric impact**



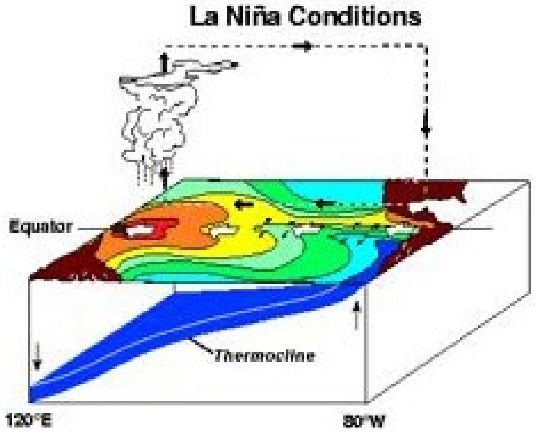



A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature

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

(Manuscript received January 18, 1966)



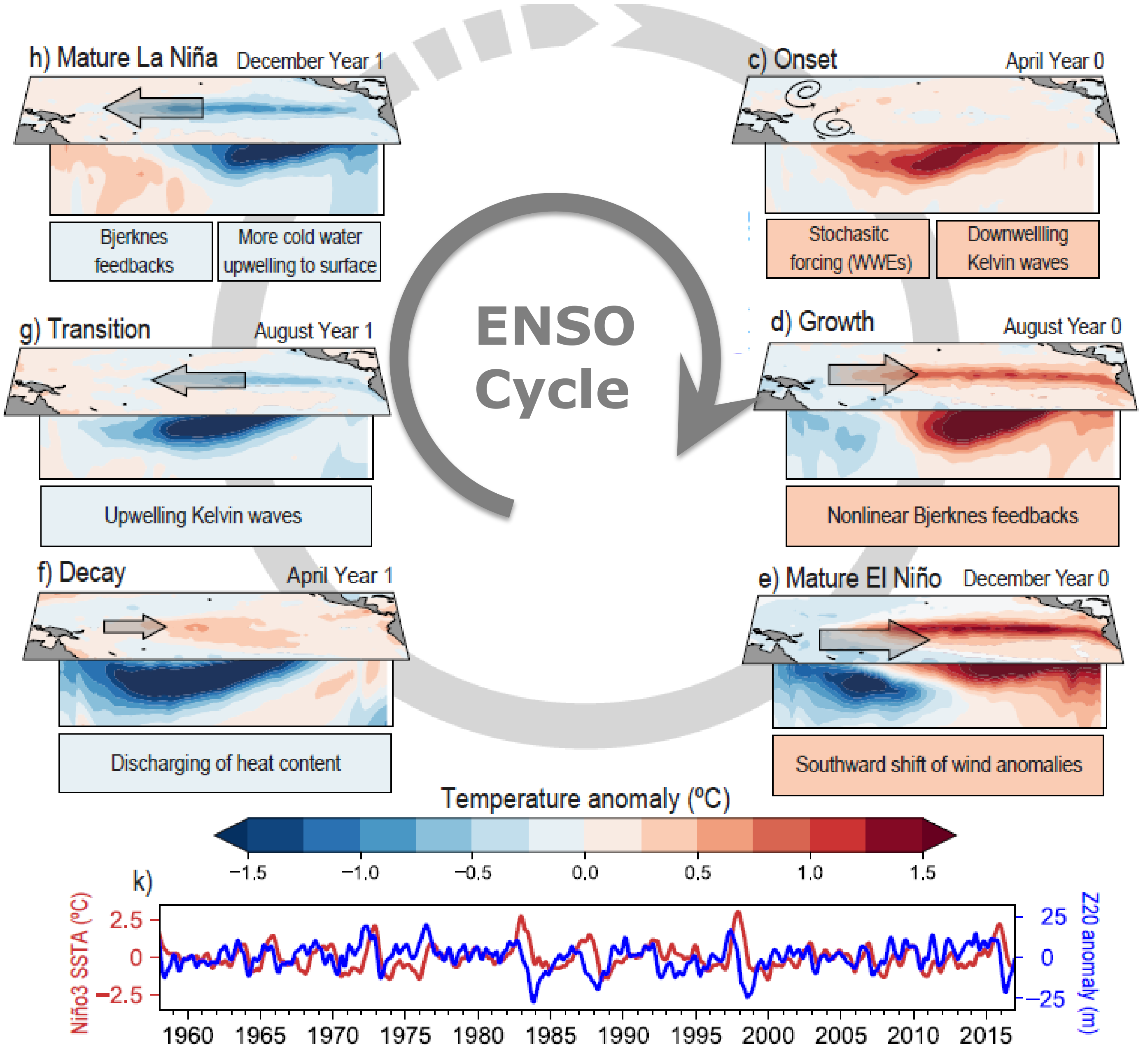



***Figure from Timmermann et al 2019***

**ENSO as a Discharged-Recharged Oscillator**

First proposed by F.F Jin 1997

Concept has been evolving over the years

See Timmermann et al 2018 for a review

**Implication: ENSO predictability resides in the ocean subsurface.**

# Some landmarks on ENSO prediction

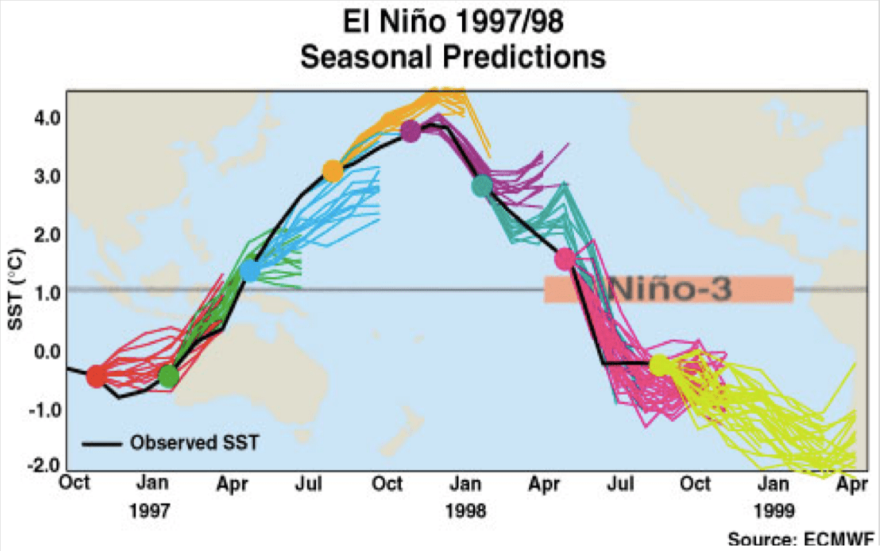
| | |
|---|---|
| 1966 | •Bjerknes: ENSO as a coupled O-A mode |
| 1975 | •Wyrtki: importance of ocean Kelvin waves. Sea level as first observing system for prediction |
| 1980's | •First attempts at modelling and prediction with simple models (Zebiak and Cane 1987) |
| Early 1990's | •Development of GCMs: Simulating ENSO as a big challenge<br>•TOGA-TAO. Sustained observations. Altimeter. Data assimilation. Conceptual models of ENSO |
| Late 1990's | •First **initialized probabilistic** predictions with GCMs |
| 2000's | •ENSO in climate change: conceptual models and projections |
| Present | •ENSO diversity: predicting ENSO and its impacts remains challenging |

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

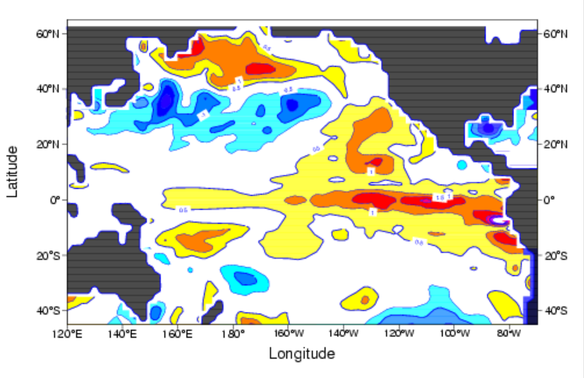
**Progress on ENSO prediction due to observations, conceptual models, GCMS, data assimilation, post-processing…**

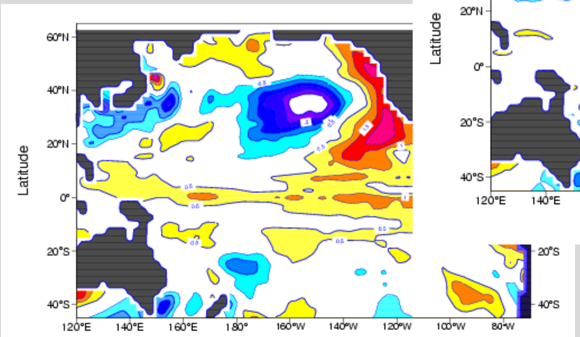
# 1997: First forecasts of ENSO and its impact at ECMWF initialized, probabilistic and calibrated

## Probabilistic ENSO prediction with GCMS

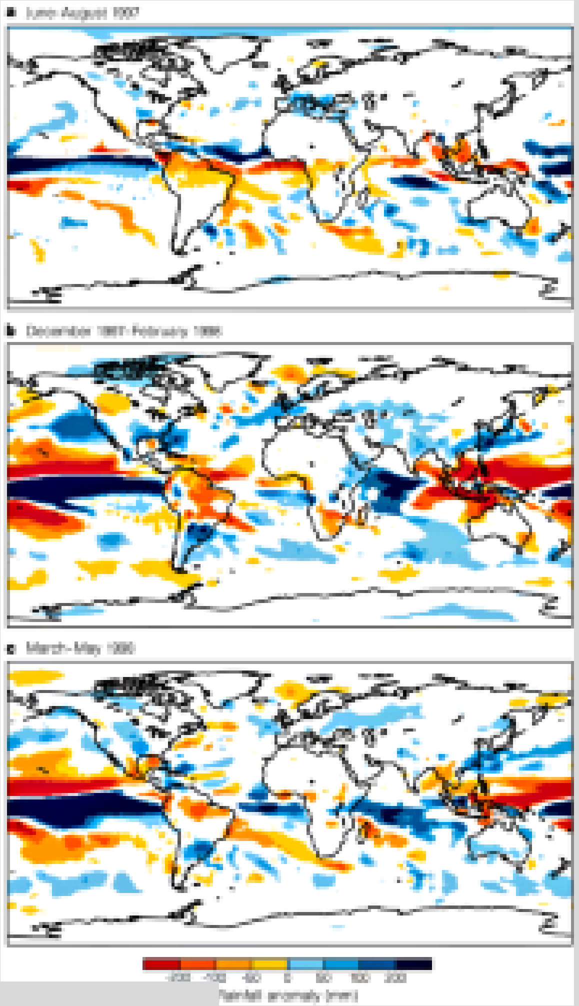



Stockdale et al 1998




## Global Probabilistic Predictions of atmospheric anomalies



**A substantial element of beginner's luck**

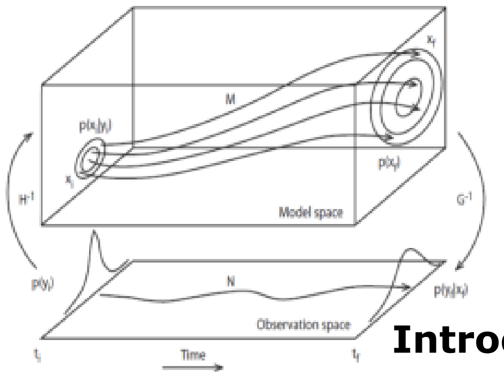
# 1995-2005: Operational Seasonal Forecasts

## clearly formulated as a probabilistic initial value problem

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

**1)Initialization**
***Data Assimilation***

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

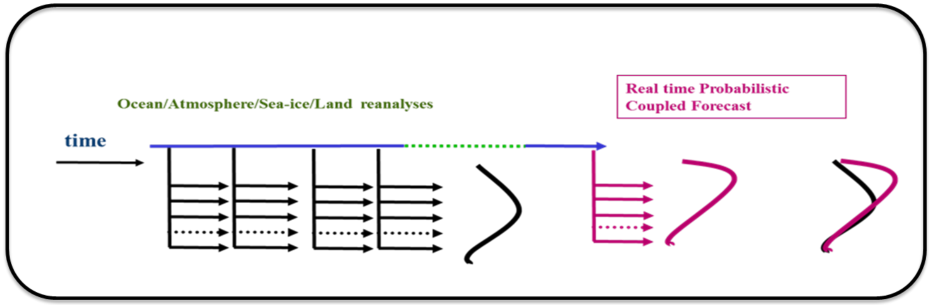



**3) Calibration**
***Forecast***
***Assimilation***

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

### 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




**Impetus from and for Reanalysis. Beginning of ocean reanalysis**

**Protocol for Subseasonal and decadal forecasts**

**Prediction of extremes at all lead times (EFI)**

### Clear need to for forecast calibration

Coupled Ocean–Atmosphere Forecasts in the Presence of Climate Drift

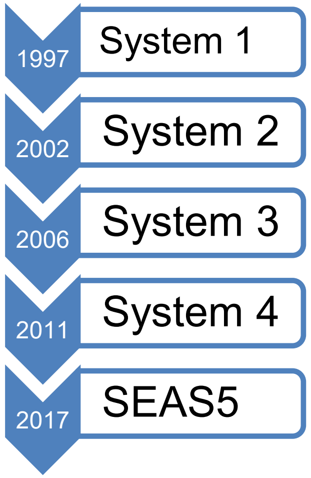
TIMOTHY N. STOCKDALE

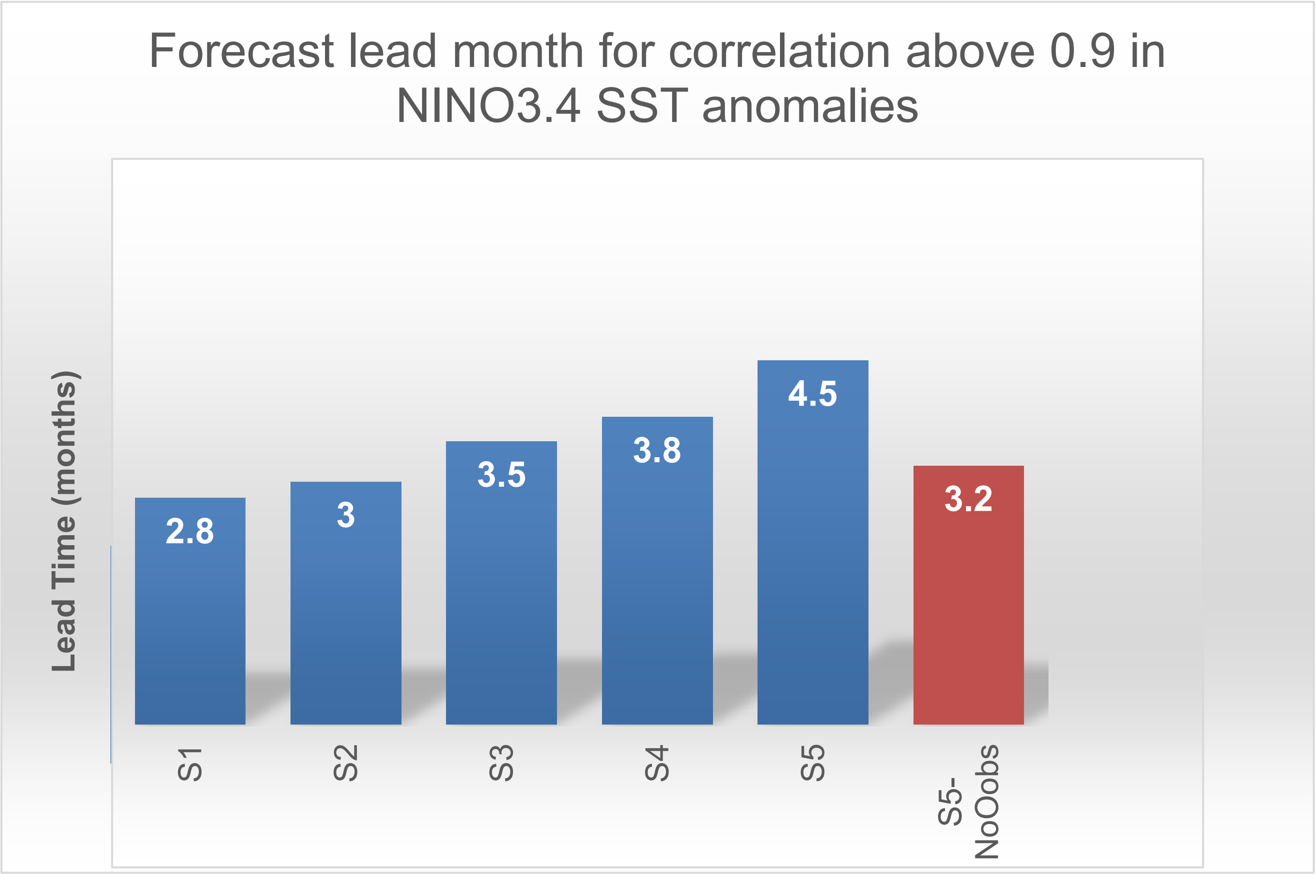
*European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom*

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

# Progress in ENSO prediction at ECMWF

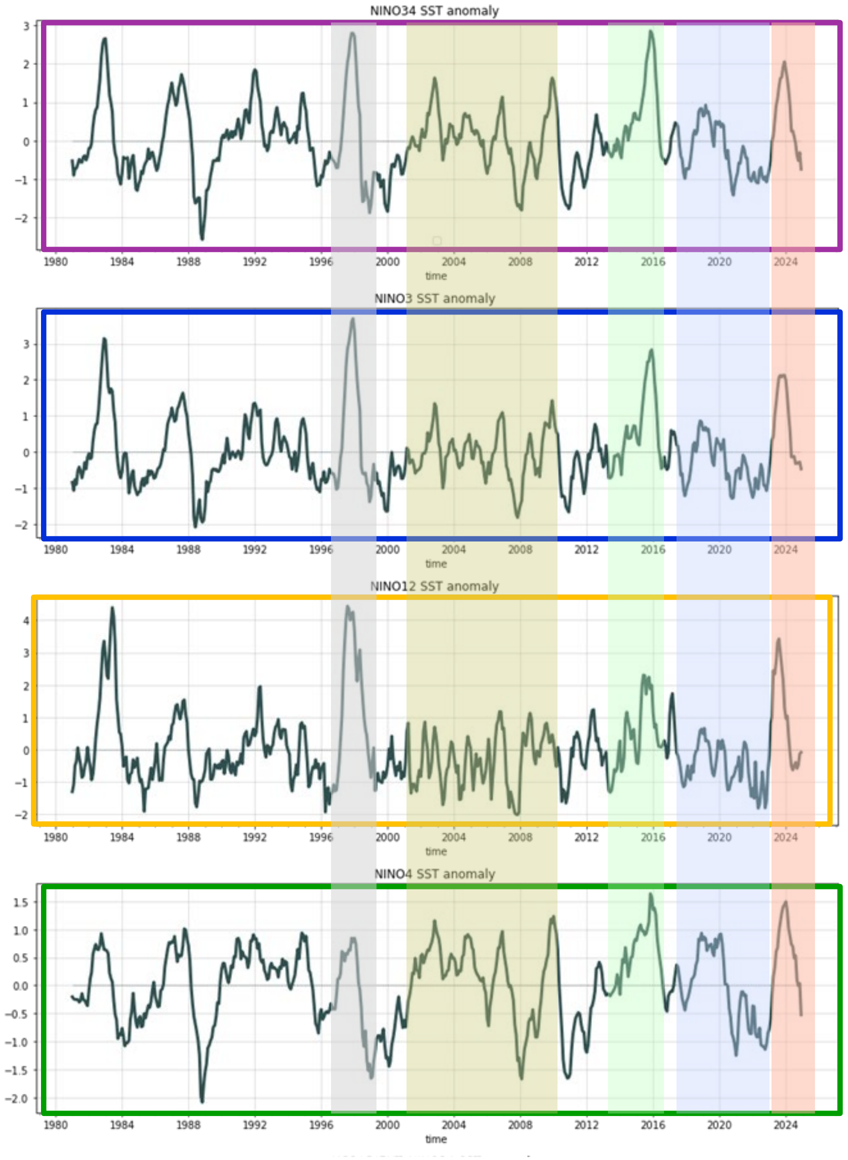
# and contribution of ocean observations




- 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 the years? interaction between time and spatial scales



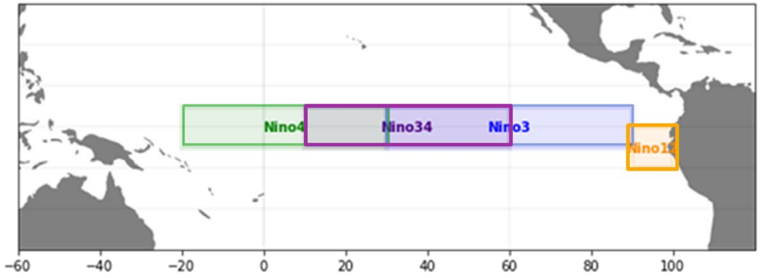

**From 1997/98 El Nino**

**From the hiatus period:**
The existence of Central Pacific ENSO (see Timmermann et al 2018 for a review)

**From 2014/2015-6 double peak El Nino**

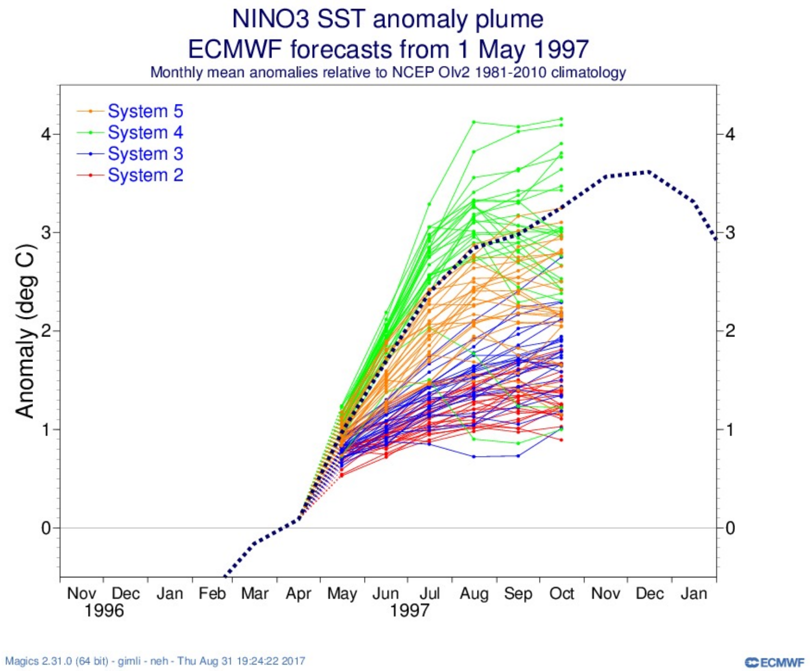
**From forecasts after ~2005, and the 2019-2022 triple deep La Nina**

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



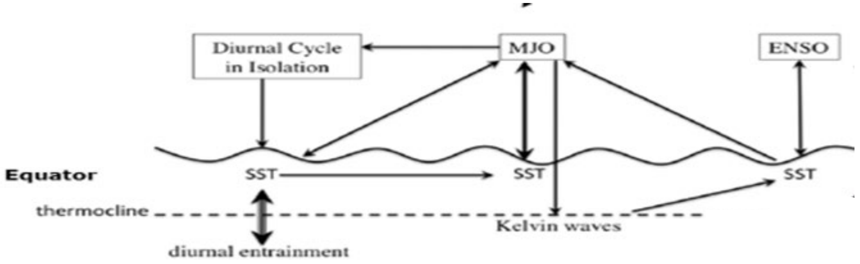
# 1. First lesson learnt from 1997-8 EL Nino
# Westerly Wind Bursts and MJO as stochastic triggers of ENSO

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




**Improved parameterization of tropical convection** was instrumental for the prediction of the MJO (Bechtold et al 2008) - (incentive from subseasonal prediction)

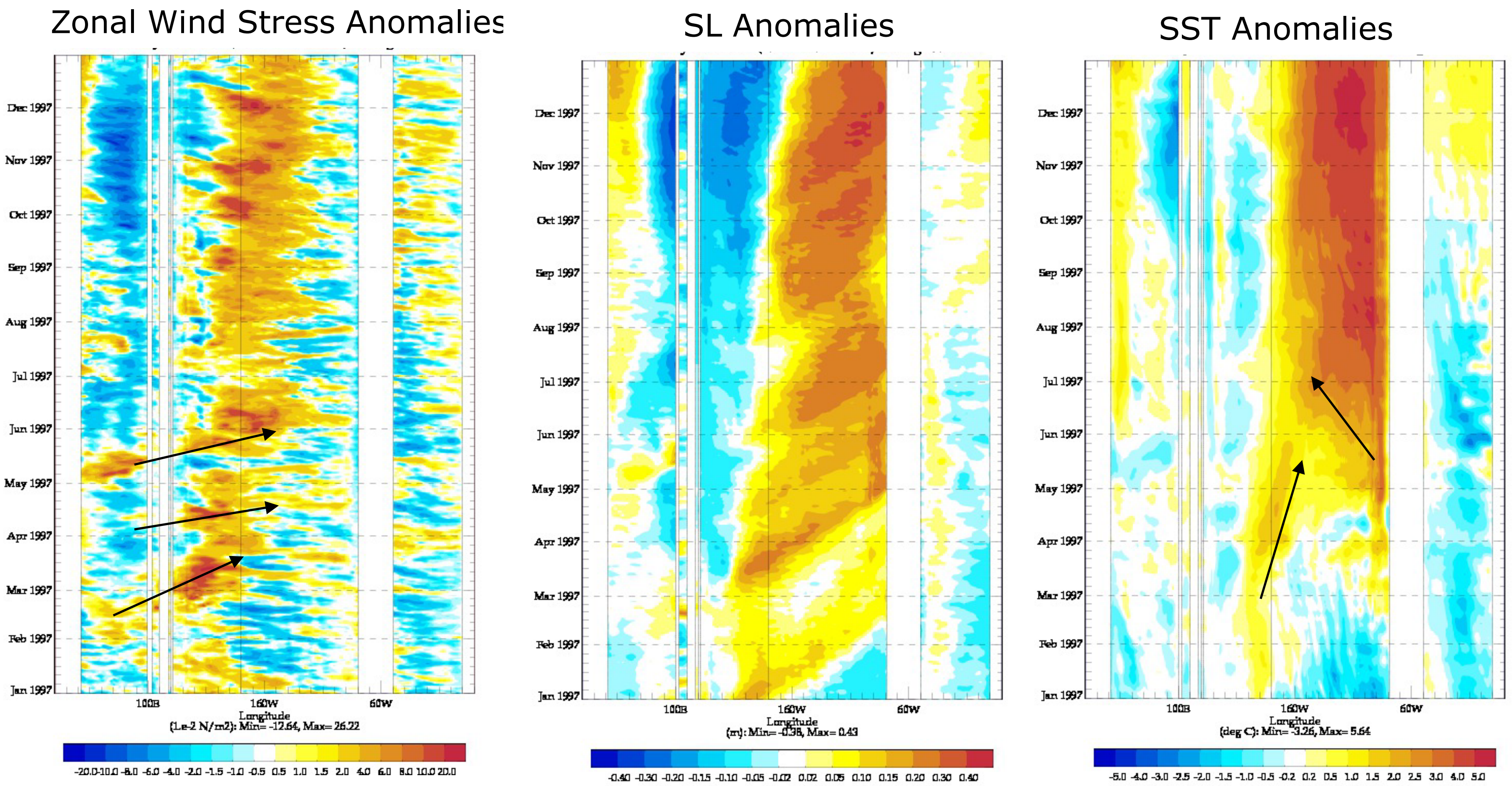
The improved representation of the diurnal cycle also helped with the representation of the MJO




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

As the coupled model improved so did the prediction of this event.

# Daily Equatorial Anomalies: Jan 1997-Jan 1998




*Data from ORAS4*

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

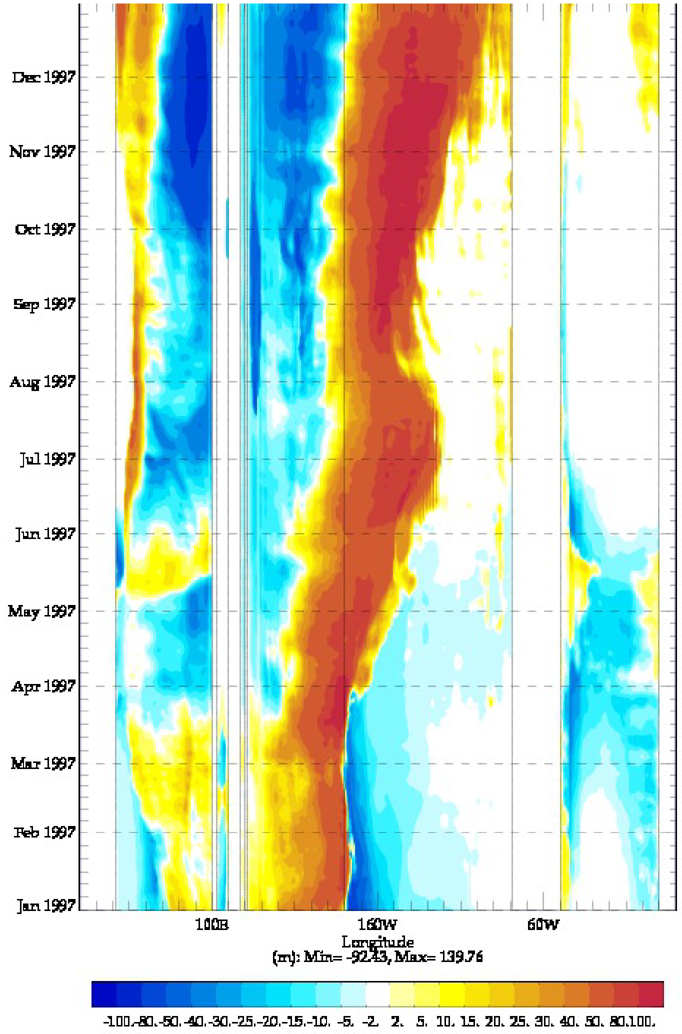
Associated eastward propagating groups of Kelvin waves in the thermocline. The latest reaching the Eastern Coast

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

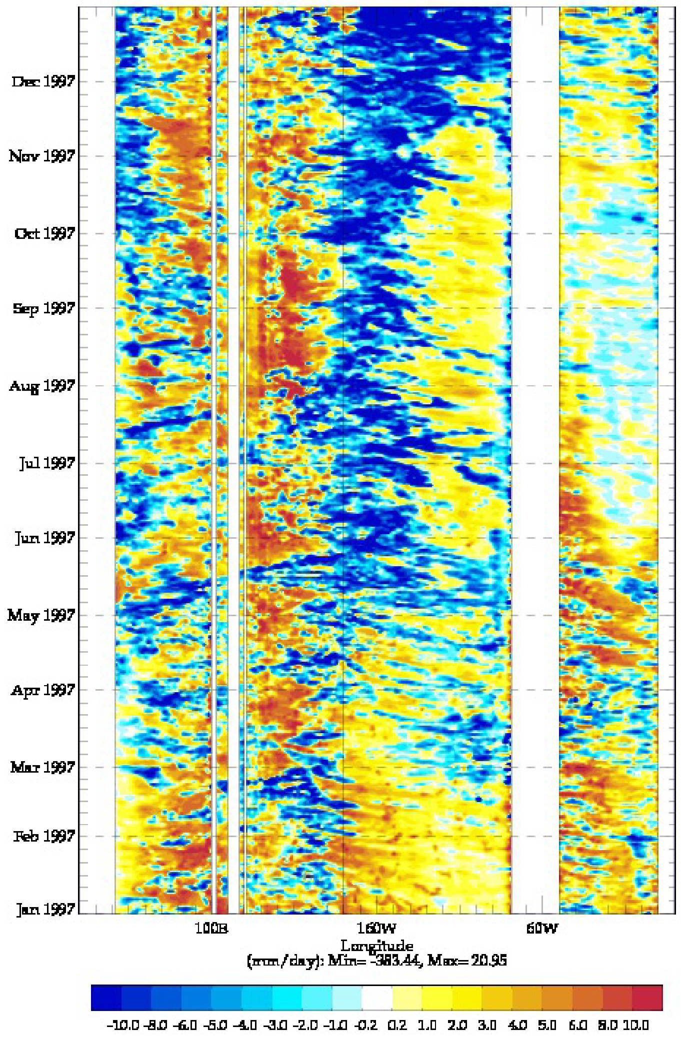
May/June 1997: More WWB . Or is this already ENSO? Bjerkness feedback in action.

# 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

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

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

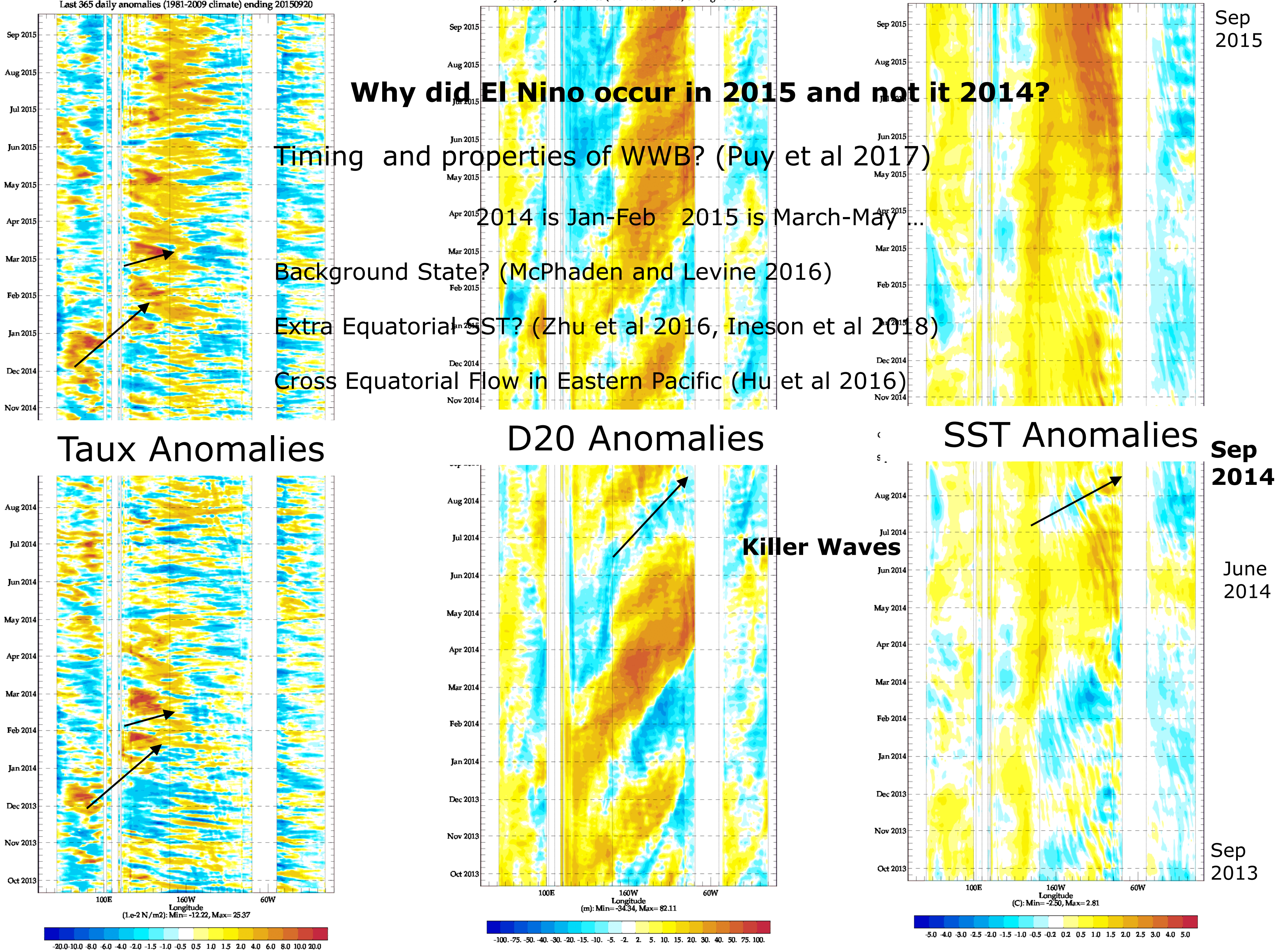
Timing and properties of WWB? (Puy et al 2017)

2014 is Jan-Feb  2015 is March-May ...

Background State? (McPhaden and Levine 2016)

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

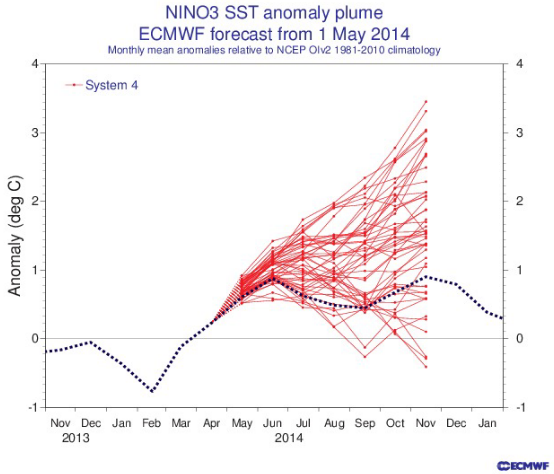
Cross Equatorial Flow in Eastern Pacific (Hu et al 2016)

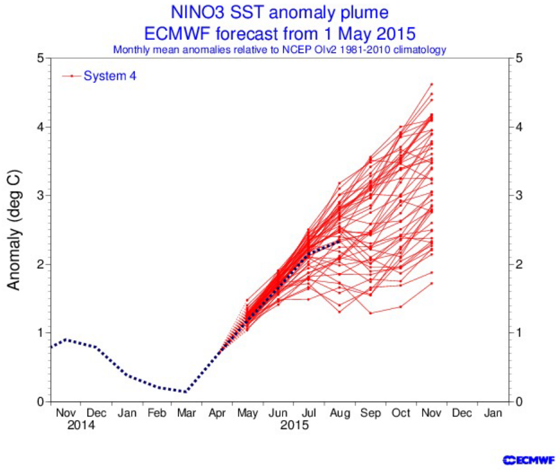



*Data from ORAS4*

# Lessons from El Nino Forecasts:  2014 v 2015

Did the forecasts capture the difference between 2014 and 2015?



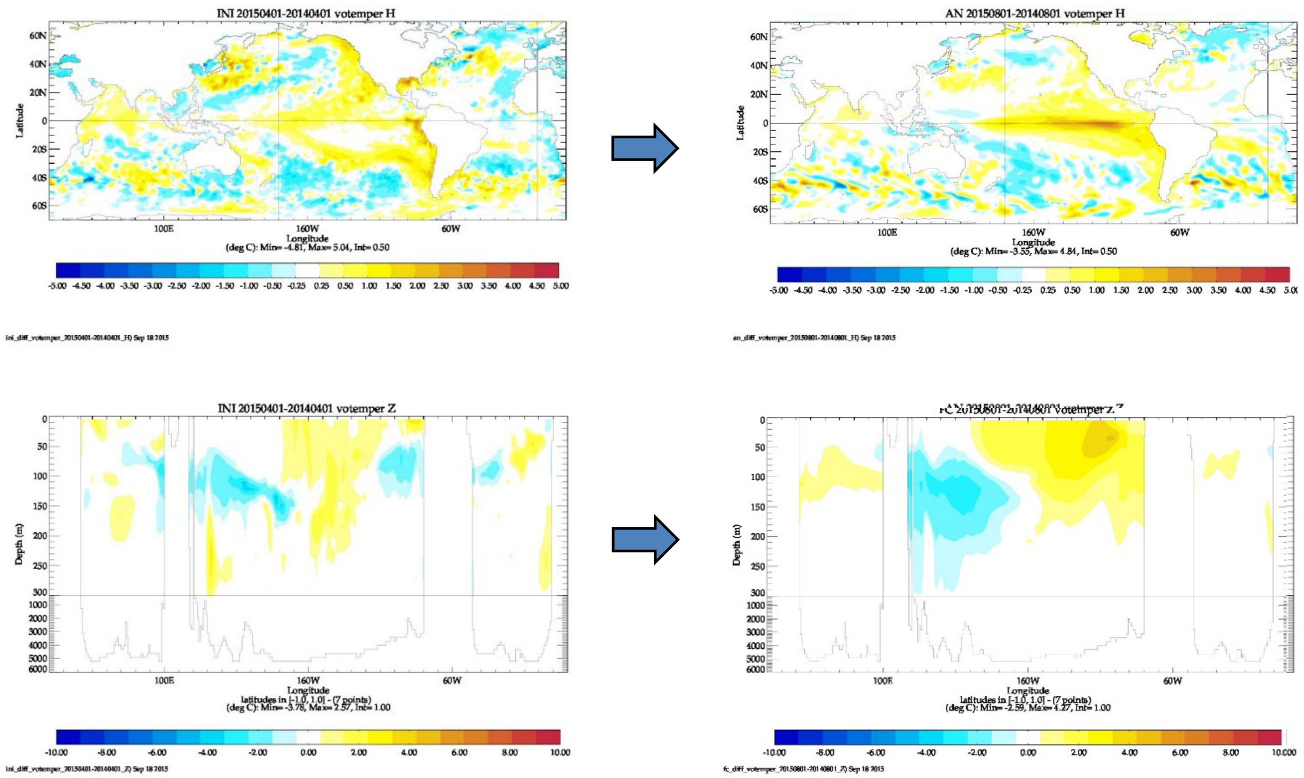




*Data from ORAS4 and SEAS4*

## Growth of Perturbations: Temperature

INI Pert: APR 2015-2014

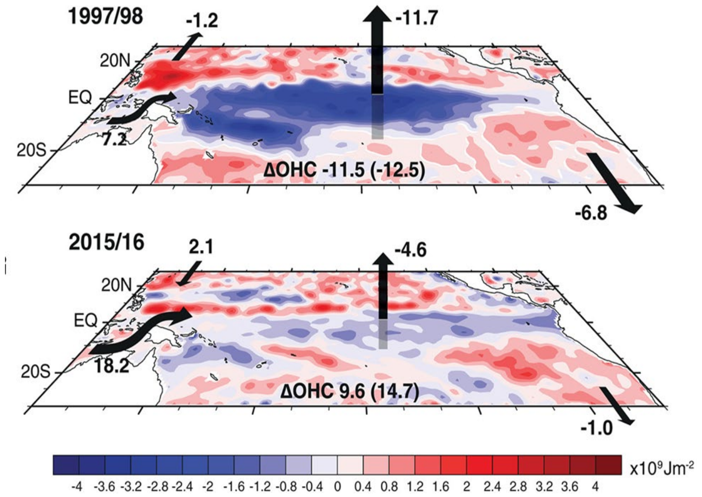
Forecast Final Pert: Aug 2015-2014




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

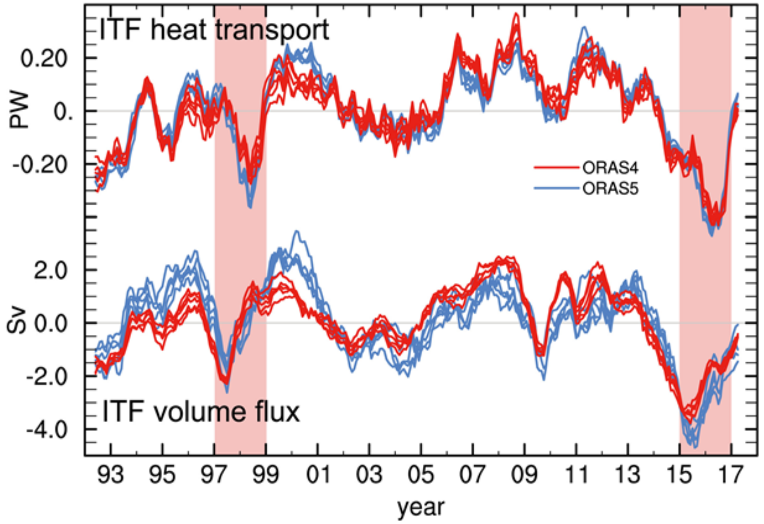
# Lesson 2: Role of the Indian Ocean in the anomalous 2014/2016 ENSO behaviour

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

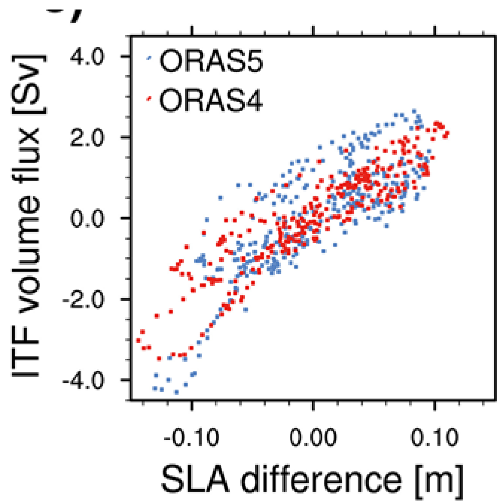



1. Contrasting energetics of the 1997/8 and 2015-16 El Nino events.

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

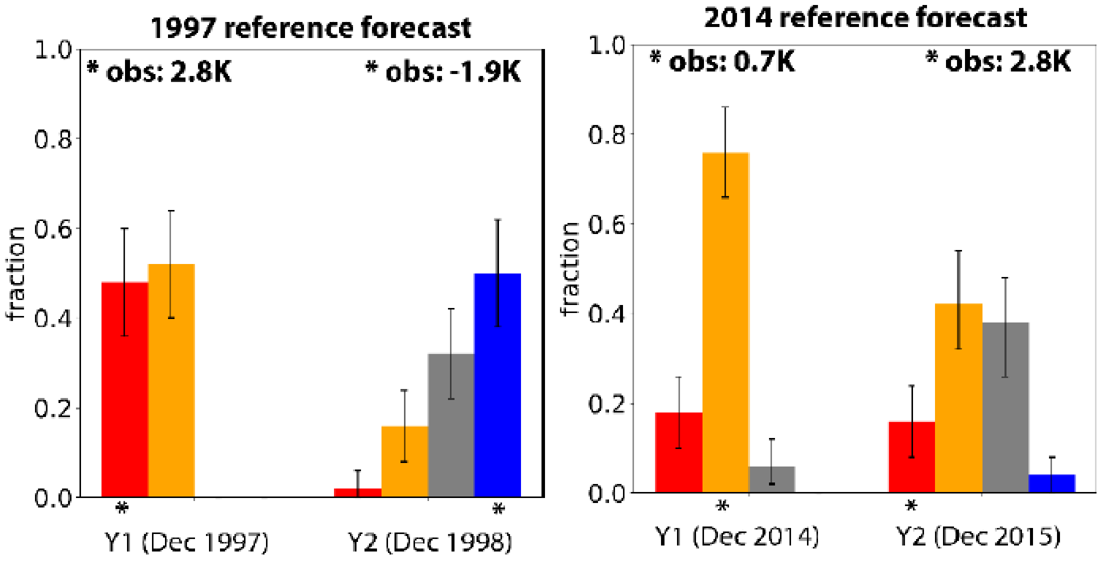
## Questions arising

- 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.**

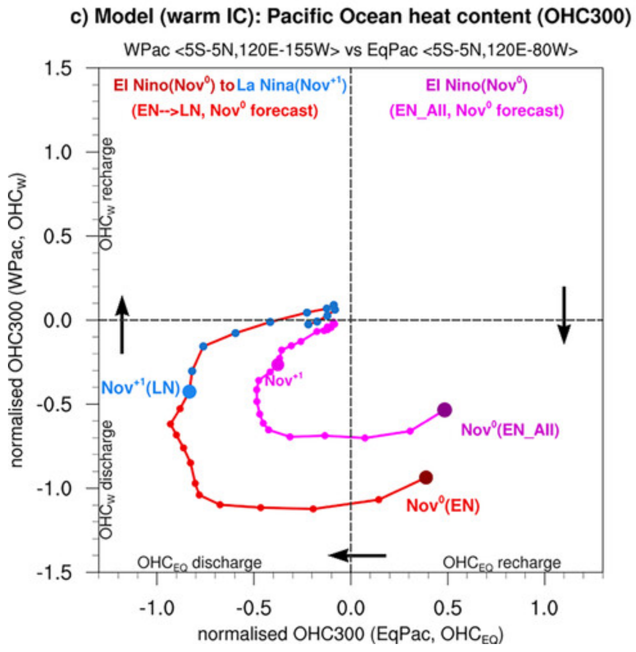
# Lesson 3: 2-year ENSO prediction: Seasonal –to-Decadal bridge

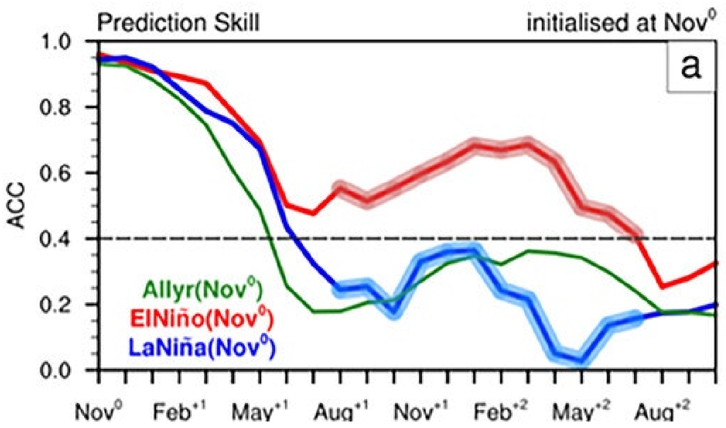
- **ENSO**: evidence of prediction skill beyond 1 year.

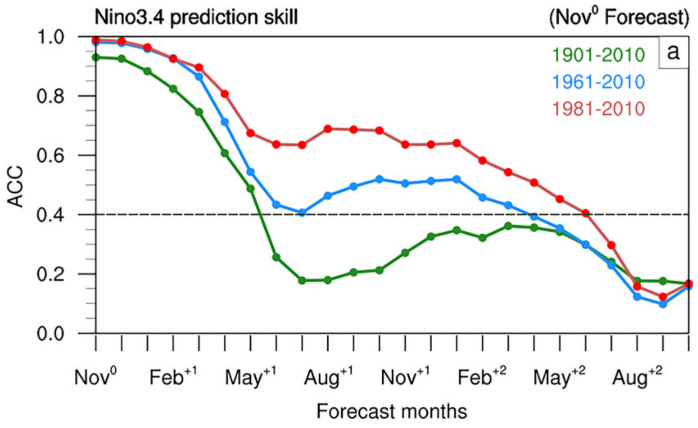
  Several systems show skill beyond 18 months for ENSO prediction.(Yeager et al 2022, Dunstone et al 2022, Sharmila et al 2023)

  In certain occasions that skill can go beyond (eg from El Nino to La Nina)
- **Radiative Forcing**
- **Ocean background state**

The orbits in Eq OHC phase space resemble a damped oscillation (in analysis and forecasts) .




El Nino events with largest Western Pacific discharge tend to be followed by La Nina events.

El Nino events with weaker Western Pacific discharge

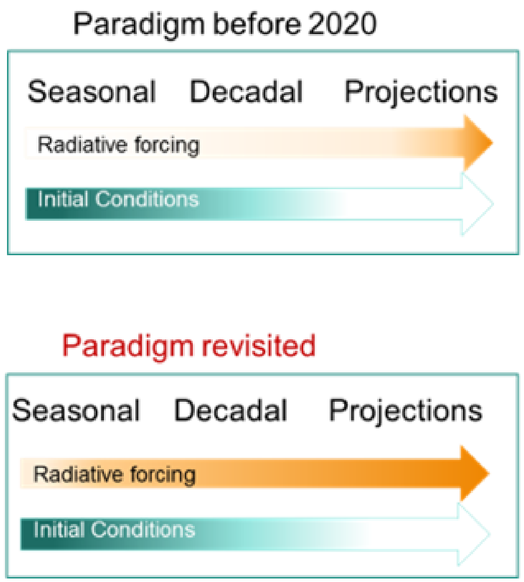
**The concept is not new, but it is good to see that current forecast models are able to reproduce this behaviour**

Weisheimer et al 2022 shows decadal modulation on ENSO skill.

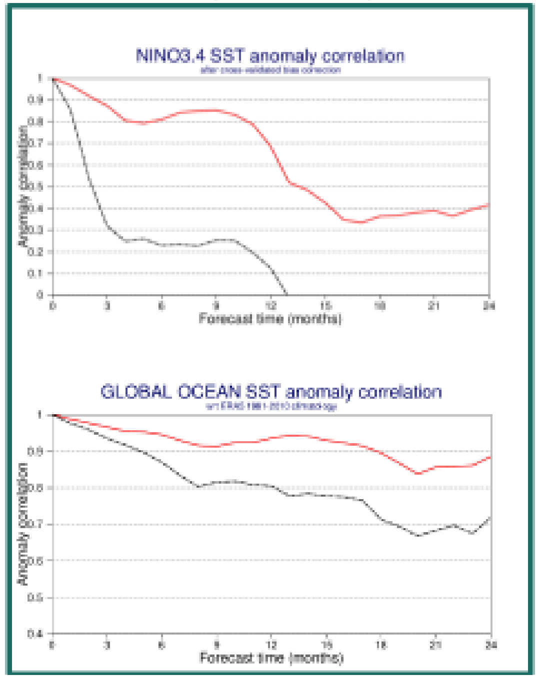
# 2-year predictions are being explored within the ASPECT project.

## In a multi model context. Bridging Seasonal and Decadal Predictions

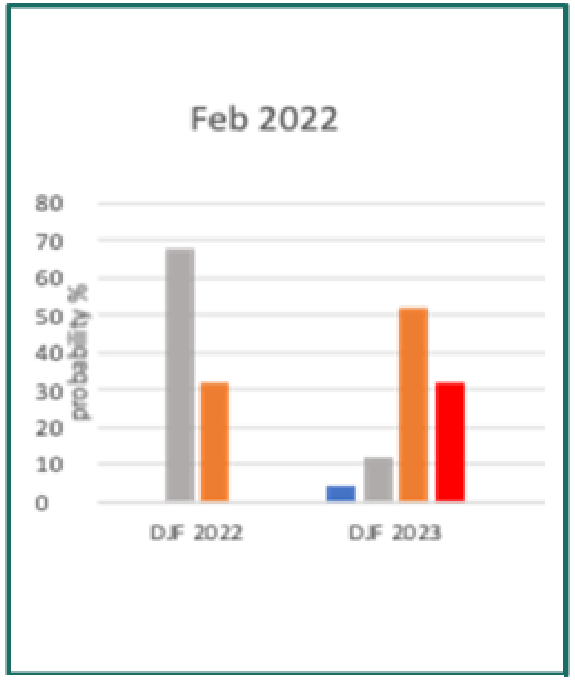
- The climate is changing. Increased demand of information for adaptation (e.g. water management, agriculture)
- A changing climate not only makes past climate less informative, but can be an additional source of predictability




Global and regional skill beyond one year




The 2023-4 El Niño was predicted two-years ahead



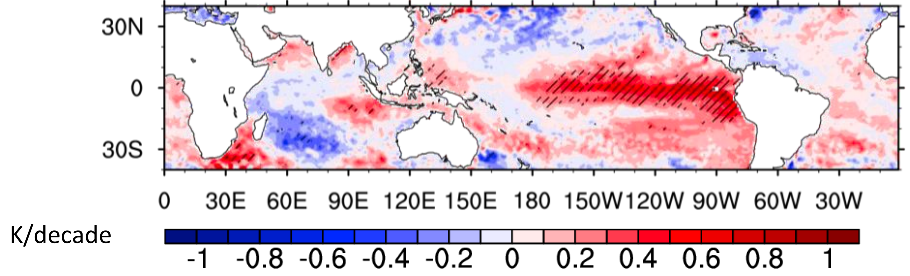

Experimental 2-year forecasts with SEAS5

SEAS6 will offer operational 2-year predictions

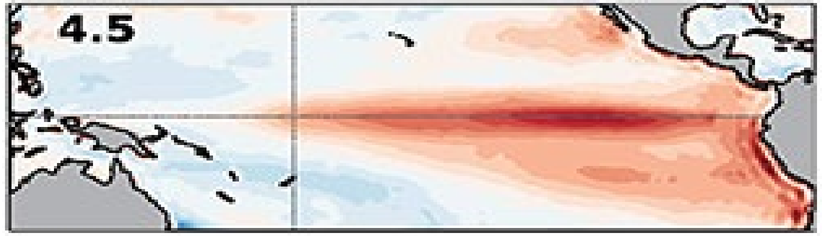
# Lessons 4: Seasonal forecast of ENSO struggle to capture recent trends.
# Why SEAS5 tended to terminate La Nina too early in forecasts initialized Nov21-Feb22?

There is a significant overprediction of SST over the Eastern Equatorial Pacific (2000-2016) . Similar errors seen in NMME (L'Heraux et al 2022 and CMIP6 models (Seager 2019, Beverly et al 2024)

SEAS5 SST trend error (Mayer et al, 2025accepted in J.Clim)

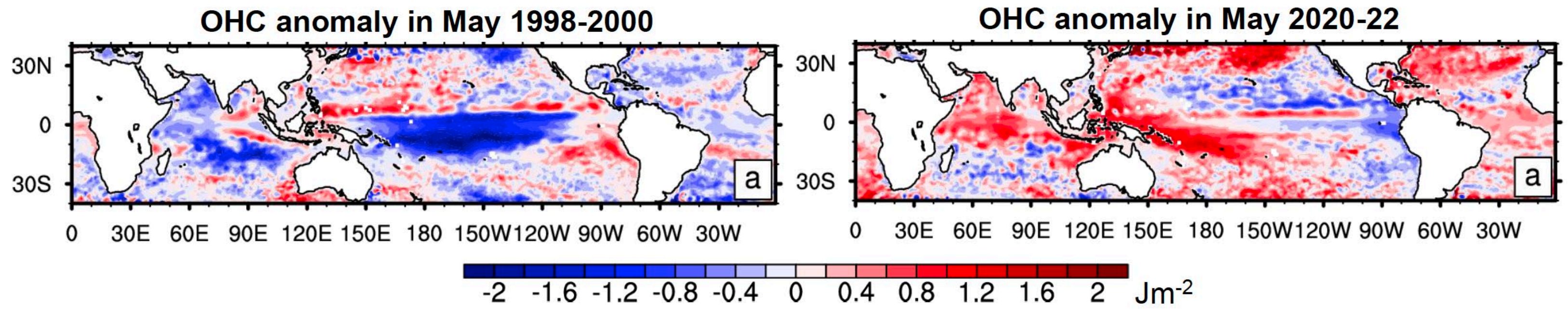



NCEP-CFSv2 SST trend error (L'Hearaux et al 2022)




Mayer et al 2025 show that these errors are related with errors in surface winds and develop at very short time scale (they are also apparent in ERA5 assimilation increments). Likely related with radiative forcing and cloud feedbacks. Although the ocean initial conditions also contribute (Balmaseda et al 2024)

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

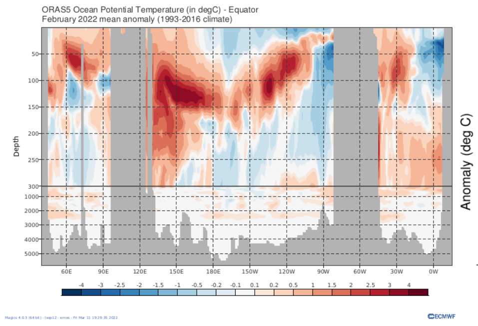
We have had a prolonged 3-years La Nina conditions.

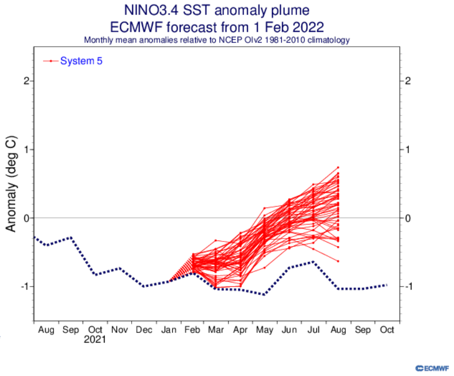
Q1. Since Nov-2021, SEAS5 had been predicting end of La Nina, which did not happen. Why should we trust the forecasts now?

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

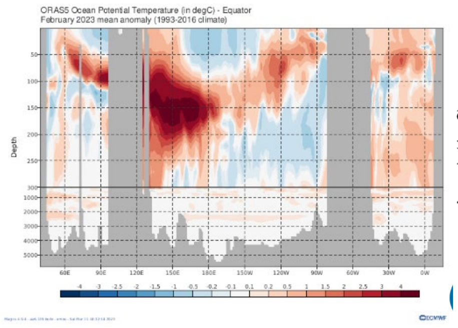
At least from May 2022 onwards, ocean subsurface and forecasts seem different in 2022 and 2023.

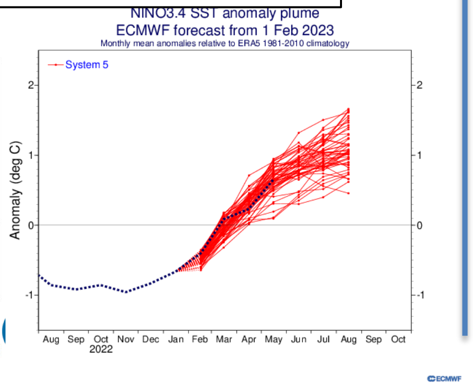
**Feb 2022 Ocean Initial conditions and forecast**



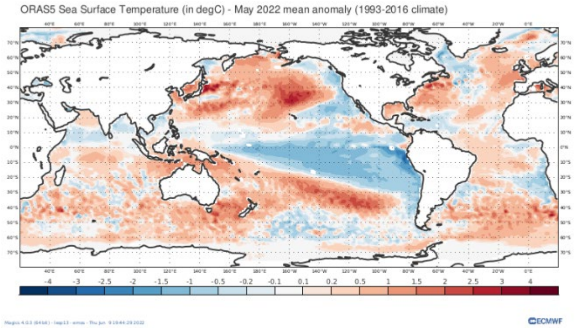

**Feb 2023 Ocean Initial and forecasts**

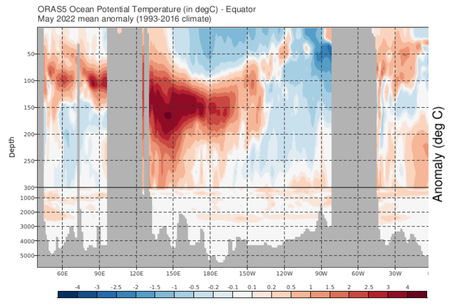


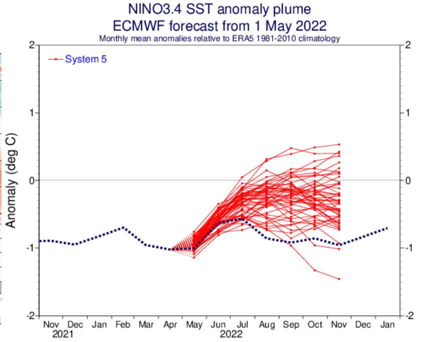

*Data from ORAS5*

**Ocean state in May 2022**

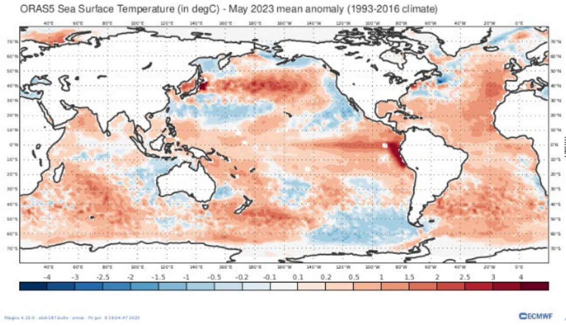


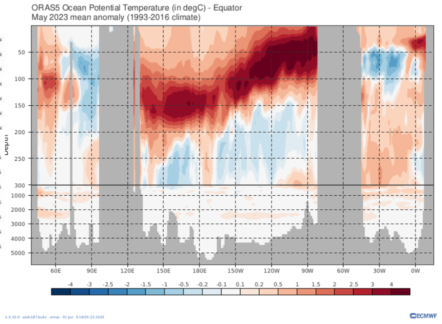




**Forecast from May 2022**

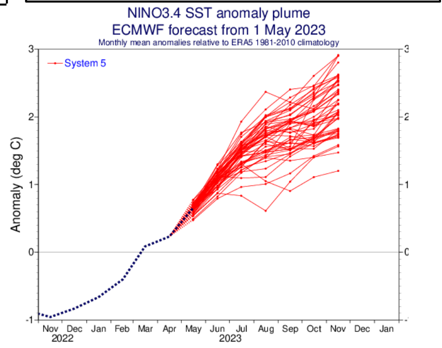



**Ocean state in May 2023**




**Forecast from May 2023**



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

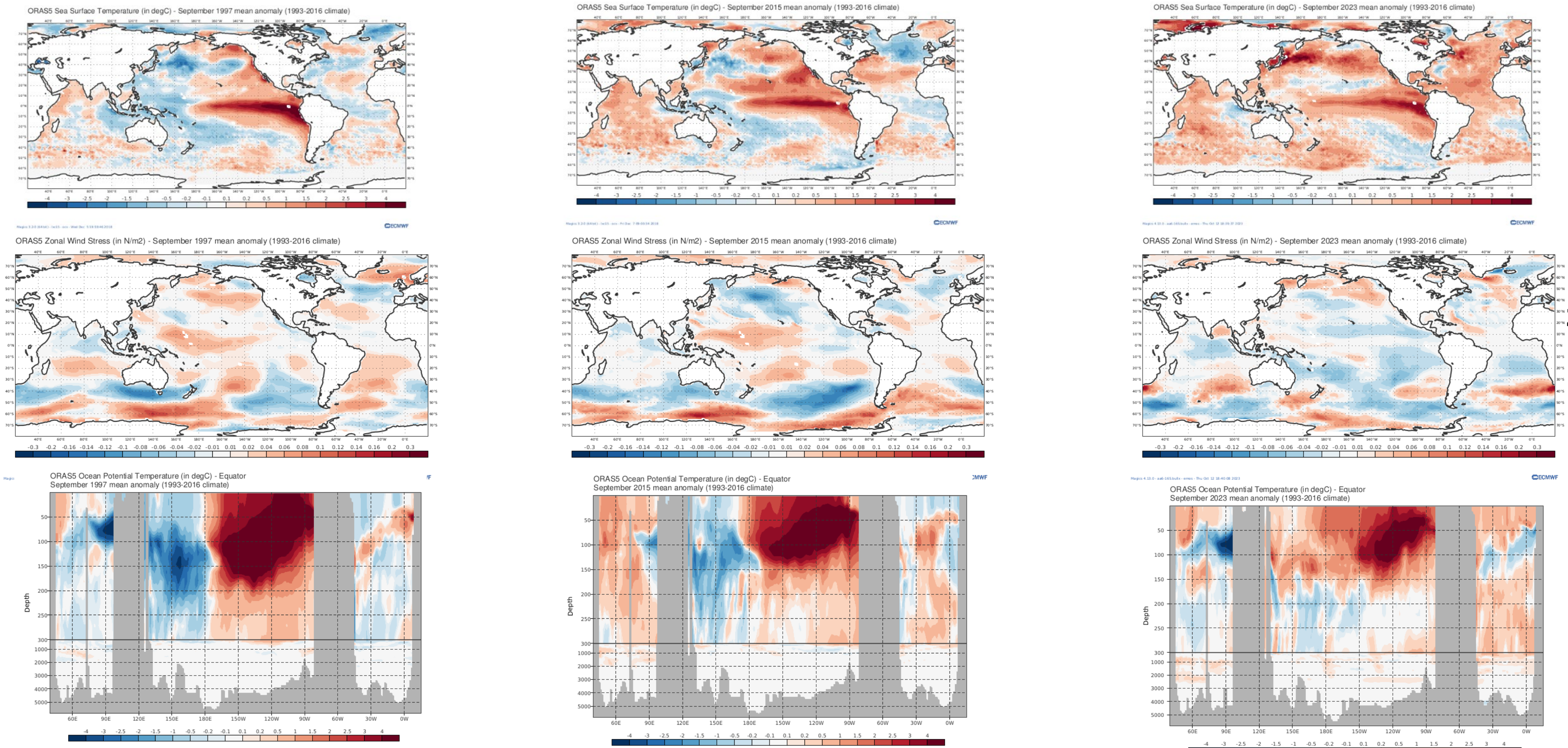
## Equatorial Conditions in Sep 2024

Sep 1997 | Sep 2015 | Sep 2023

SST

Zonal Wind Stress Taux

Subsurface T

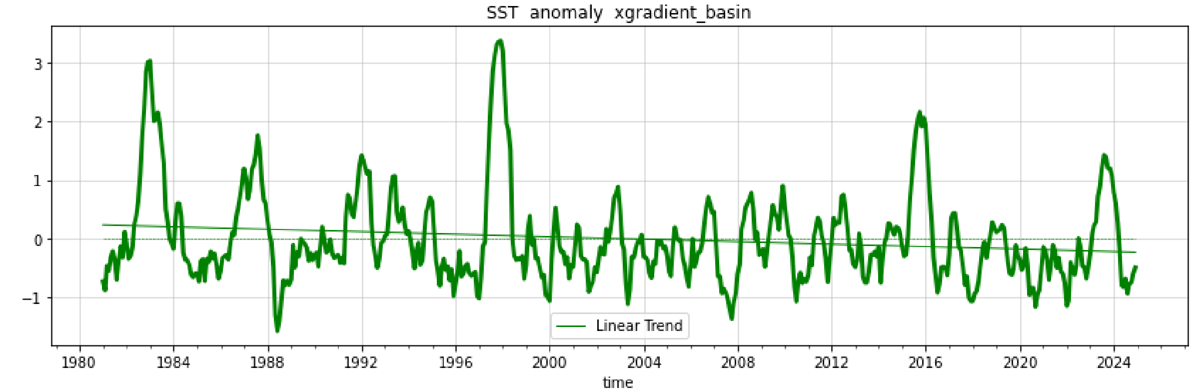


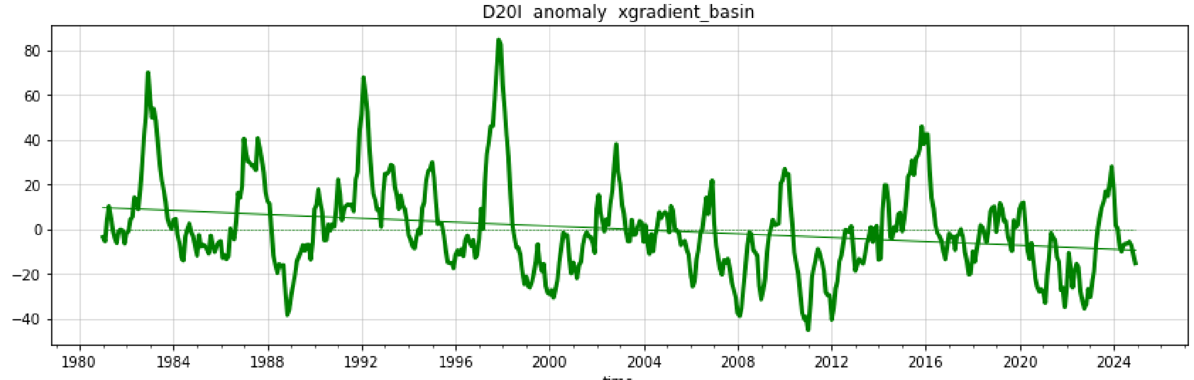

The zonal wind response is weaker this year than in previous big El Nino, and so is the Eastern Pacific heat reservoir. **And without the atmospheric feedback, the subsurface temperature anomaly was weakening…**

*Data from ORAS5*

# The anomaly on the basin wide zonal gradients was comparatively weak in 2023-24

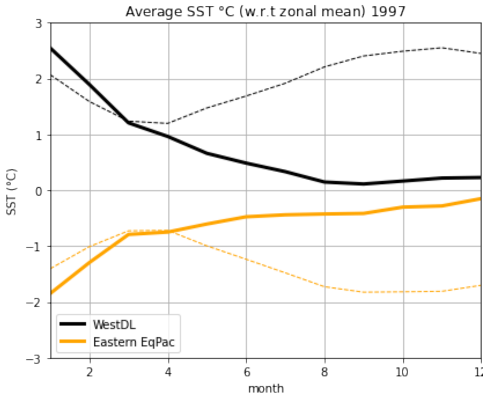
## SST zonal gradient (deg C)



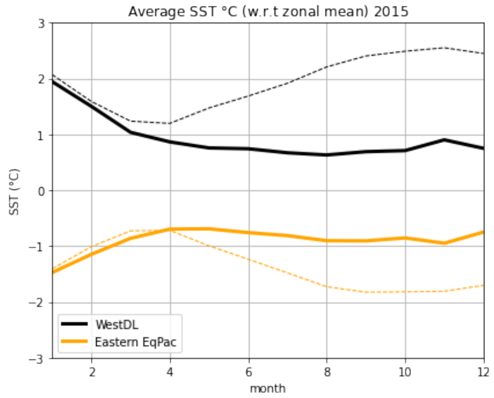




## Thermocline zonal gradient anomaly (m)

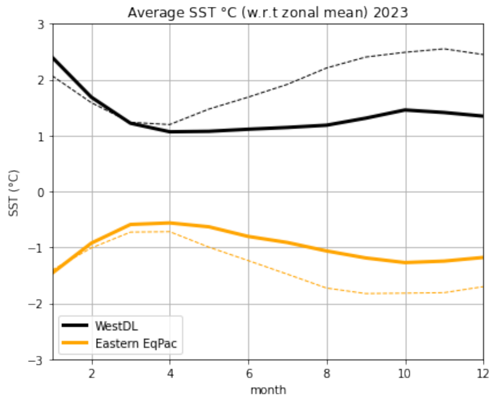
### 1997




### 2015




### 2023




Western Pac SST

Eastern Pacific SST

----- Seasonal cycle

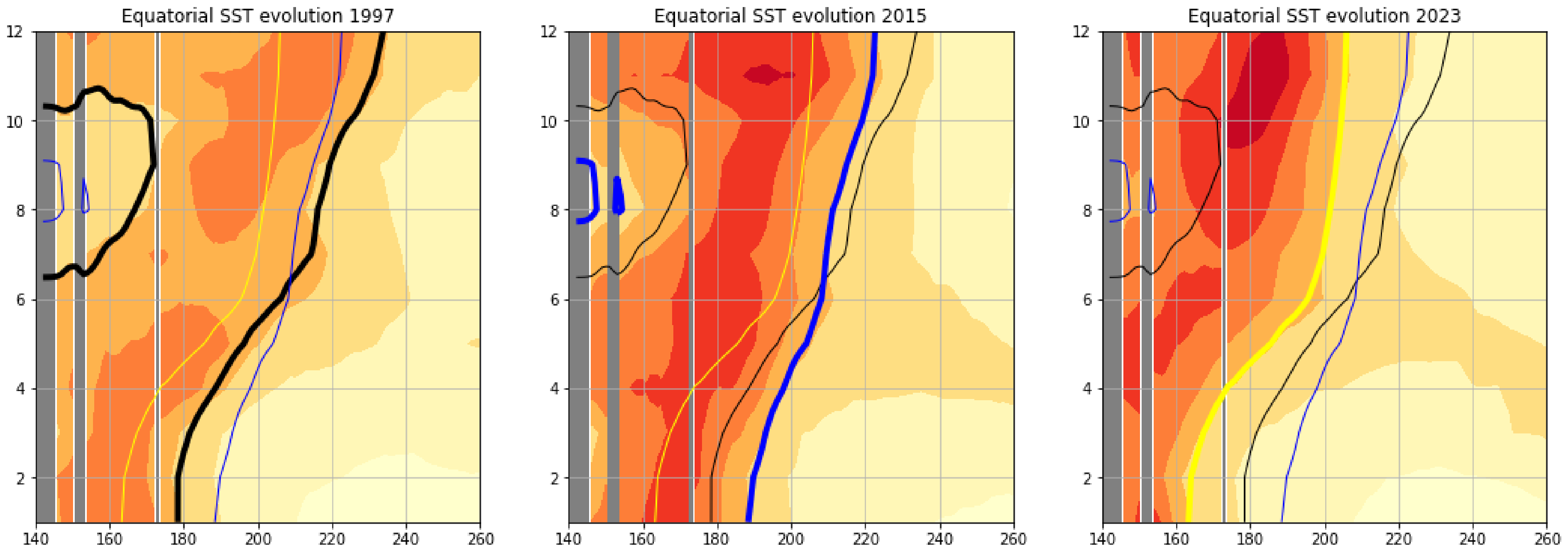
Large fluctuations on zonal gradients is the signature of the ENSO cycle.

These fluctuations appear to be getting weaker

*Data from ORAS5*

# Comparative evolution of Pacific Warm Pool

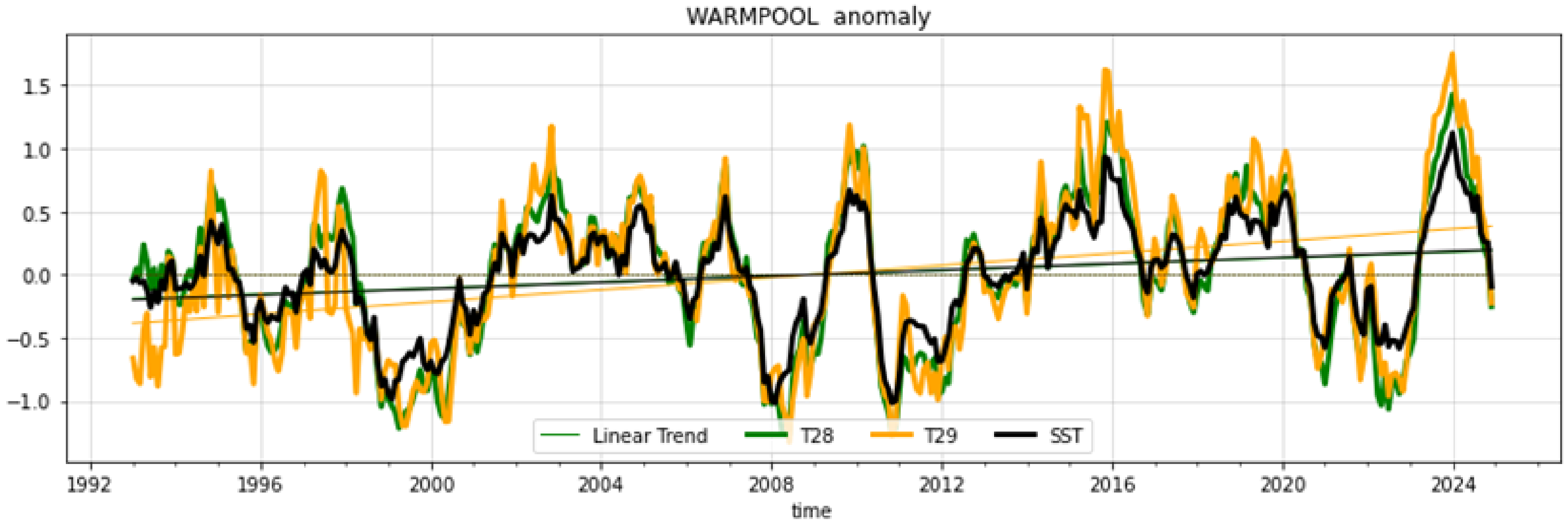
**1997** **2015** **2023**




**1997 29ºC-contour** **2015 29ºC-contour** **2023 29ºC-contour**

The warm pool during 2023 did not migrate as far east as in previous El Ninos.

The warm waters in the far Western Pacific remained above 29 deg C




The warmer waters of the Pacific Warmpool **are getting warmer**

Note larger trends in waters above 29 deg.

*Data from ORAS5*

# Diversity in the atmospheric response to ENSO

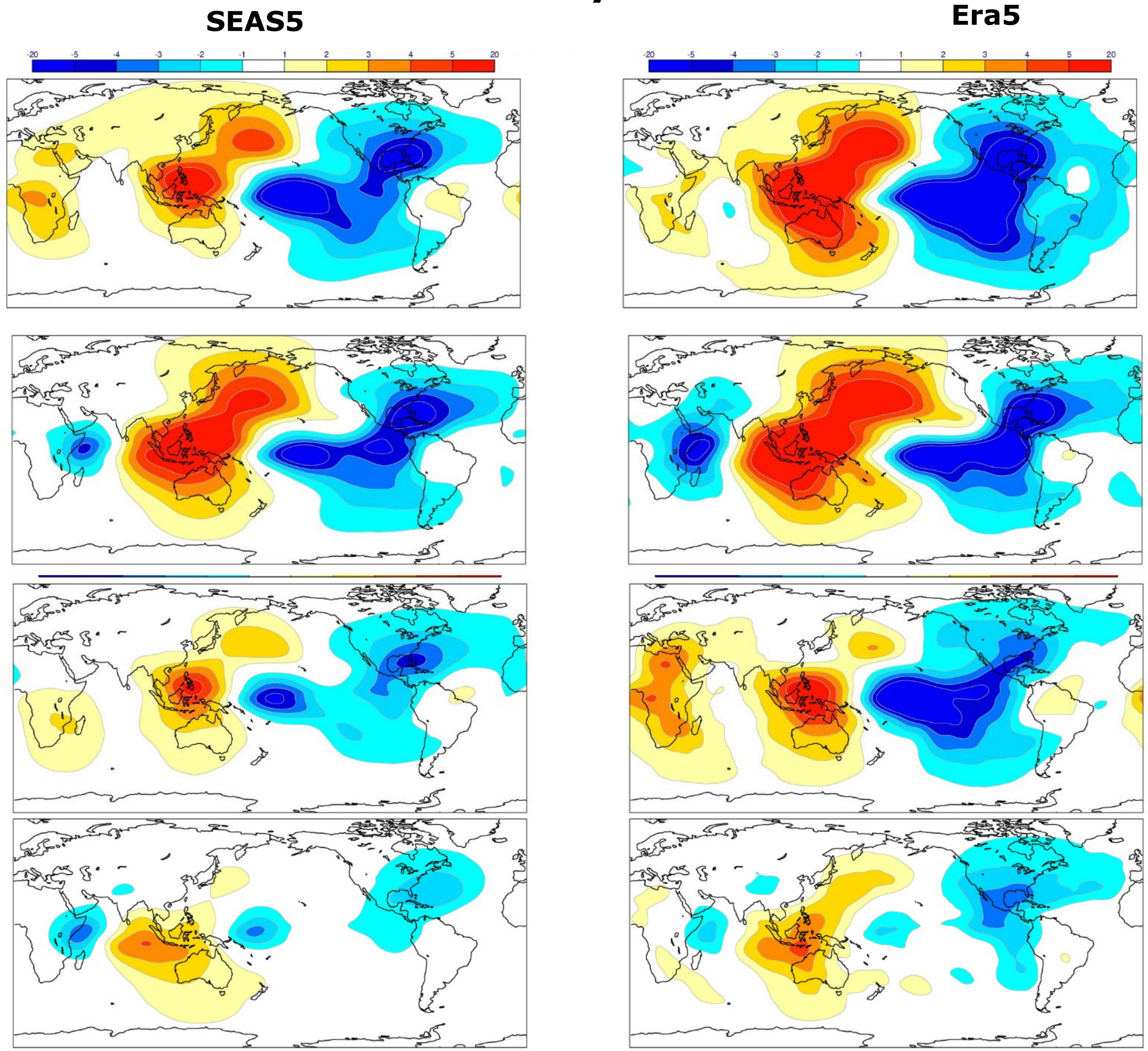
## DJF Velocity Potential 200hPa

El Nino 1982-83

El Nino 1997-98

El Nino 2014-16

El Nino 2023-24




**The atmospheric response was very weak during El Nino 2023-24.**

**Why?**

Tropical Atmosphere responds to both spatial gradients and large scale warm SST (e.g. warm pools).

1) **Weak Bjerkness feedback**: Anomaly in SST gradients was weak during 2023-24, and therefore the zonal wind anomaly was weak

2) **Weak warm pool instability**: The warm pool had enough fuel to feed the ascending branch of the Walker Circulation, which remained active in the Western Pacific until quite late (October-Nov)

Because a delayed atmospheric response, Eastern Pacific SST anomalies were not so strong during DJF 2023-4

-

# How would the atmospheric respond to uniform SST warming?

**Experiment** with SEAS5-like uncoupled

**Ref**: forced by Observed Daily SST. 50 ens.

**Exp:** as before but imposing uniform warming/cooling

**Imposing uniform warming induces structure in the response of the atmospheric circulation**

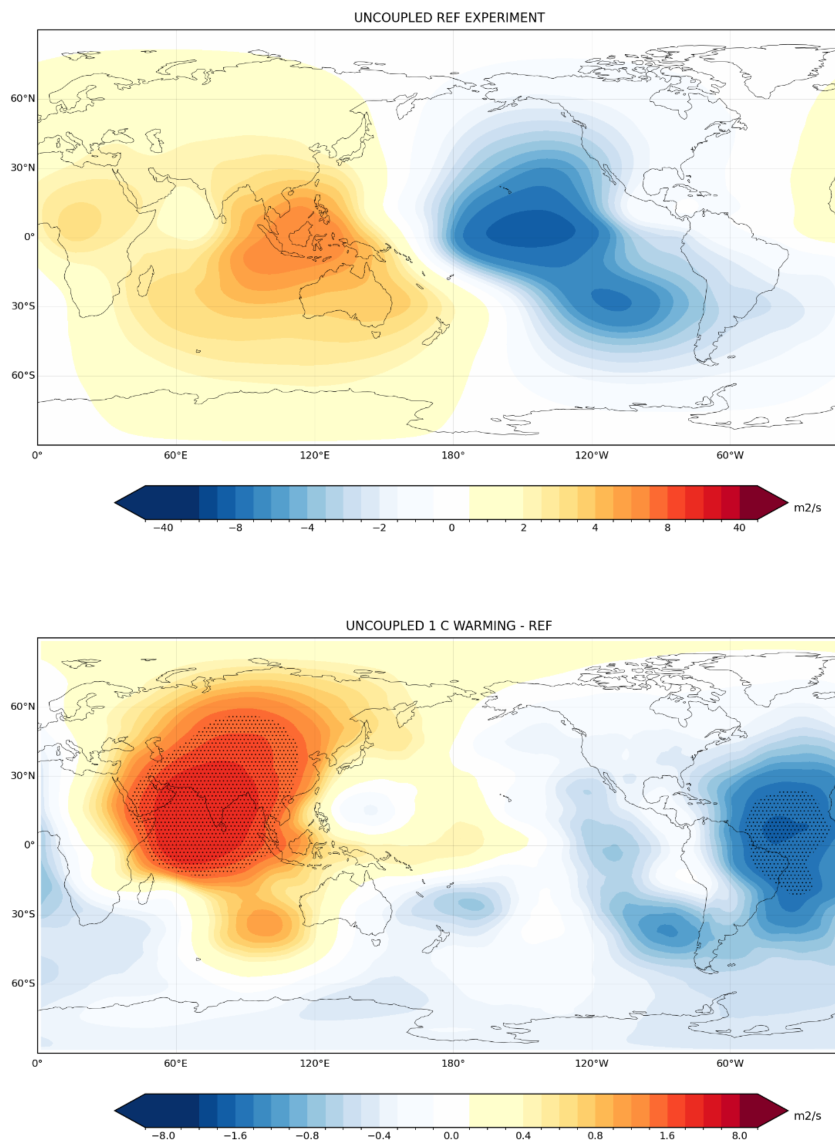
**Top panel shows the 1997 VP200 anomaly in the Reference experiment, initialized in May**

**Bottom panel shows the impact of 1 decC uniform warming (note different colour scale)**

**Warming favours the tropical Atlantic for the ascending branch or Walker Circulation**

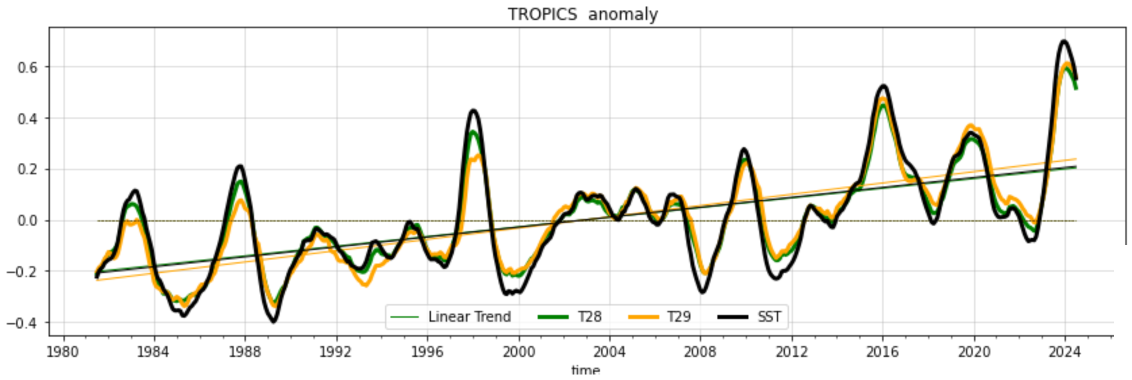
Velocity Potential 200hPa. JJA 1997/1998

forecasts initiliazed 19970501

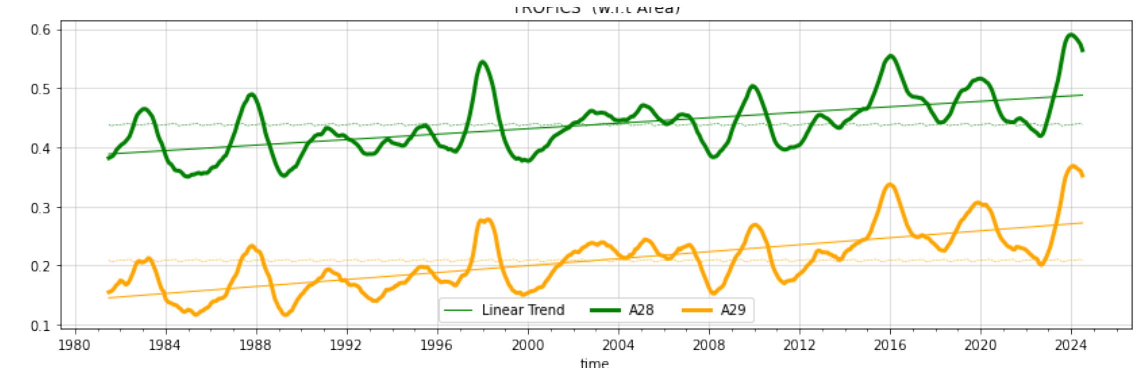


# Changes in tropical warm pools: warmer – larger -deeper

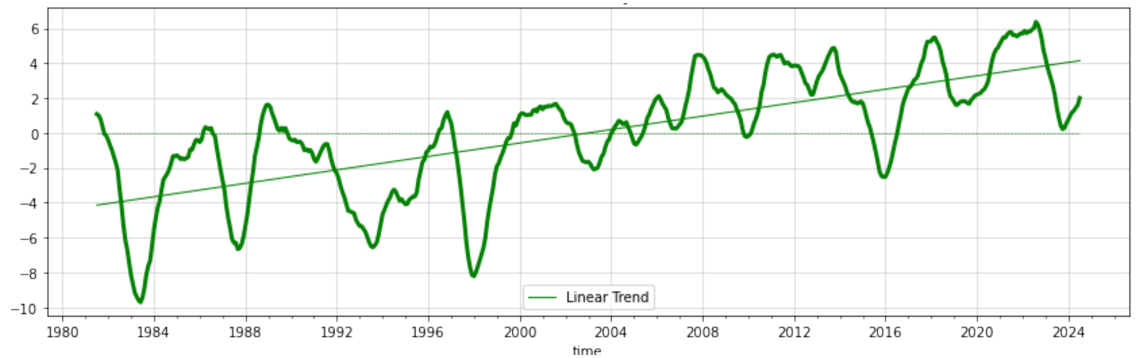
**SST anomaly (deg C): All, above 28 and above 29 deg C**




**Area fraction covered by waters above 28 and 29 deg C (10^6 km2)**

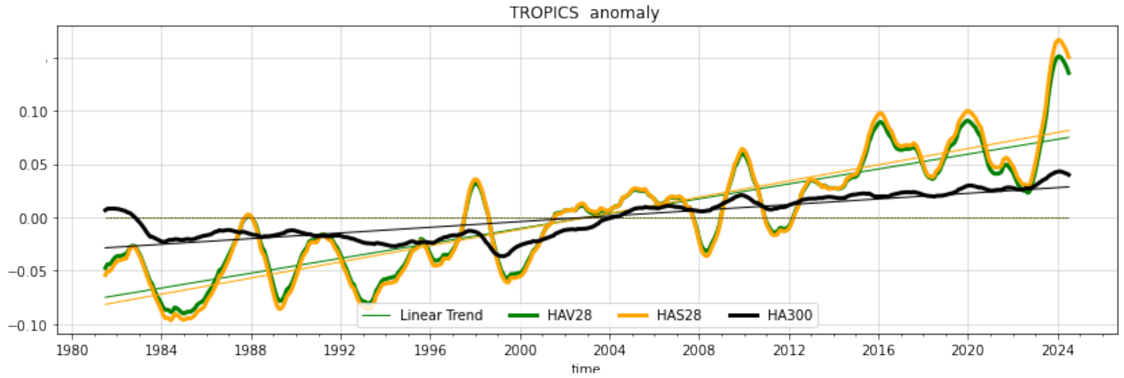



**Depth of 28 deg Isotherm (m)**




**Hence absorbing more heat**

**Tropical Ocean Heat Content anomaly (TeraJ) upper 300m, in waters above 28 and 29 deg C**




The tropical ocean heat storage is dominated by the warm pools.

*Data from ORAS5, Zuo et al 2019*

# Lessons learnt over the years:
# interaction between time and spatial scales

- **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 in the 2014-15 El Nino)

- **Lesson 3: From 2014/2015-6 double peak El Nino and historical reforecasts**
  Windows of opportunities for predictions beyond 1-year

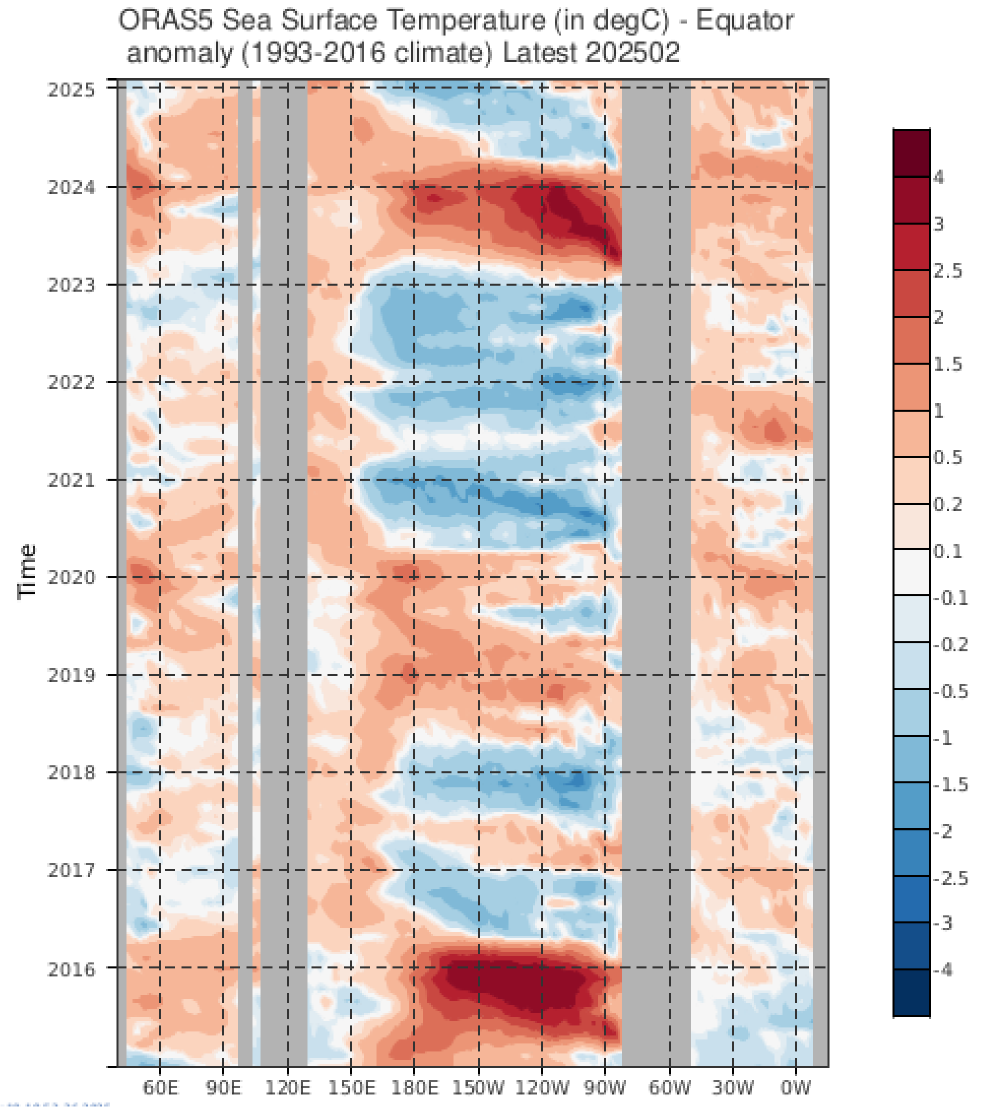
- **Lesson 4:  From forecasts after ~2005, in particular 2019-2022 triple deep La Nina**
  Errors in ENSO trends. Not exclusively an initial value problem

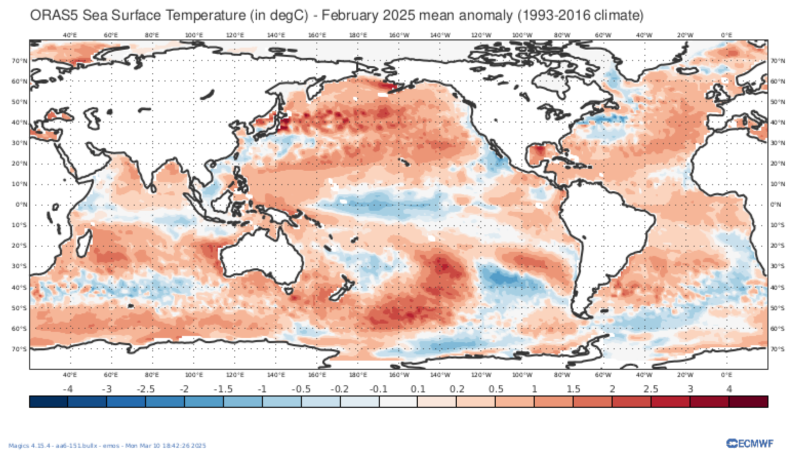
- **Lesson 5: From the anomalous evolution the 2023-2024 El Nino**
  Very weak response of the Walker Circulation. Warm pool did not displaced, weak SST gradients
  Is this weak response caused by global warming?

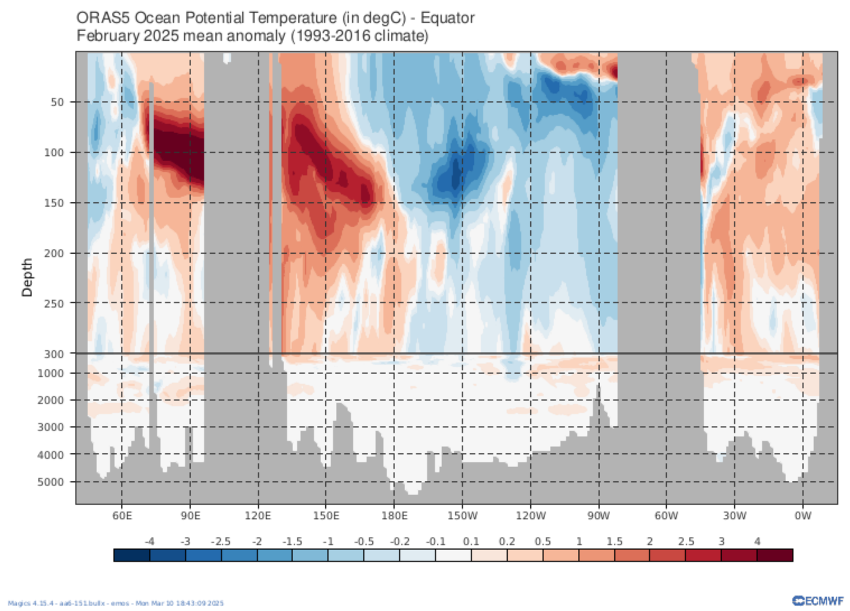
Tropical warm pools are getting hotter-larger-deeper

What are the implications for the large scale organized tropical convection?

# Current conditions: Average of Feb 2025



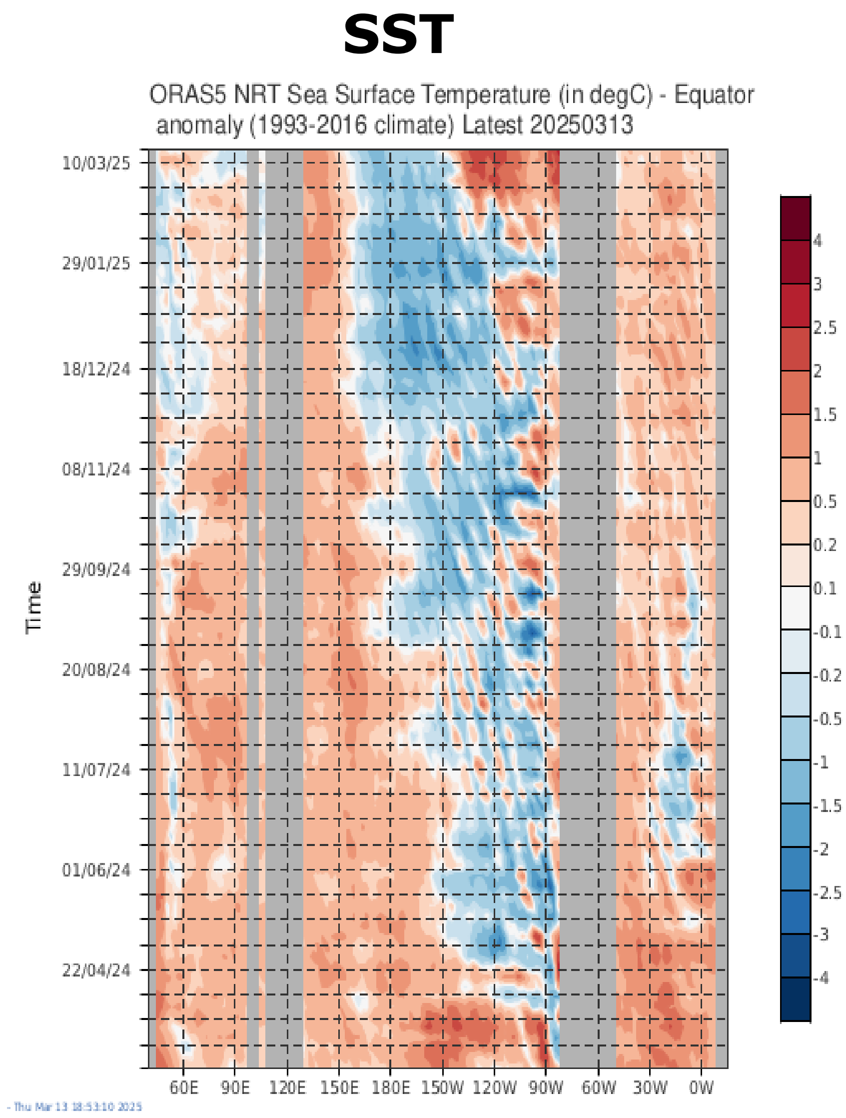

A warm anomaly is developing in the Eastern Pacific?

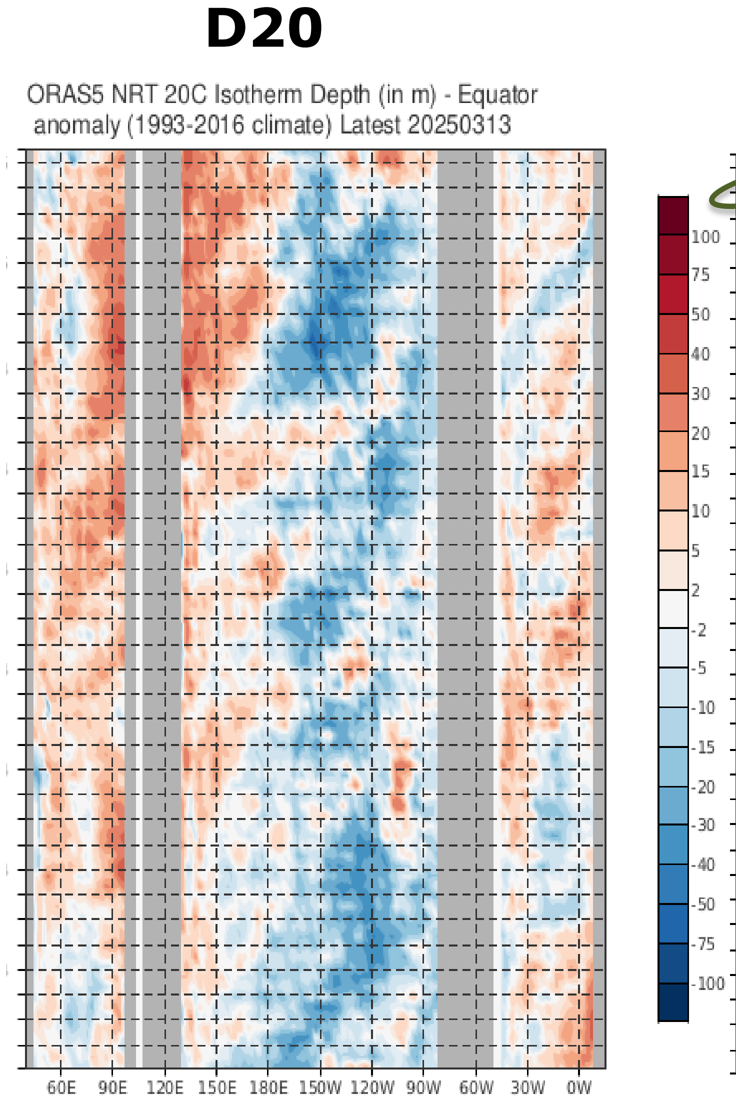
Why?

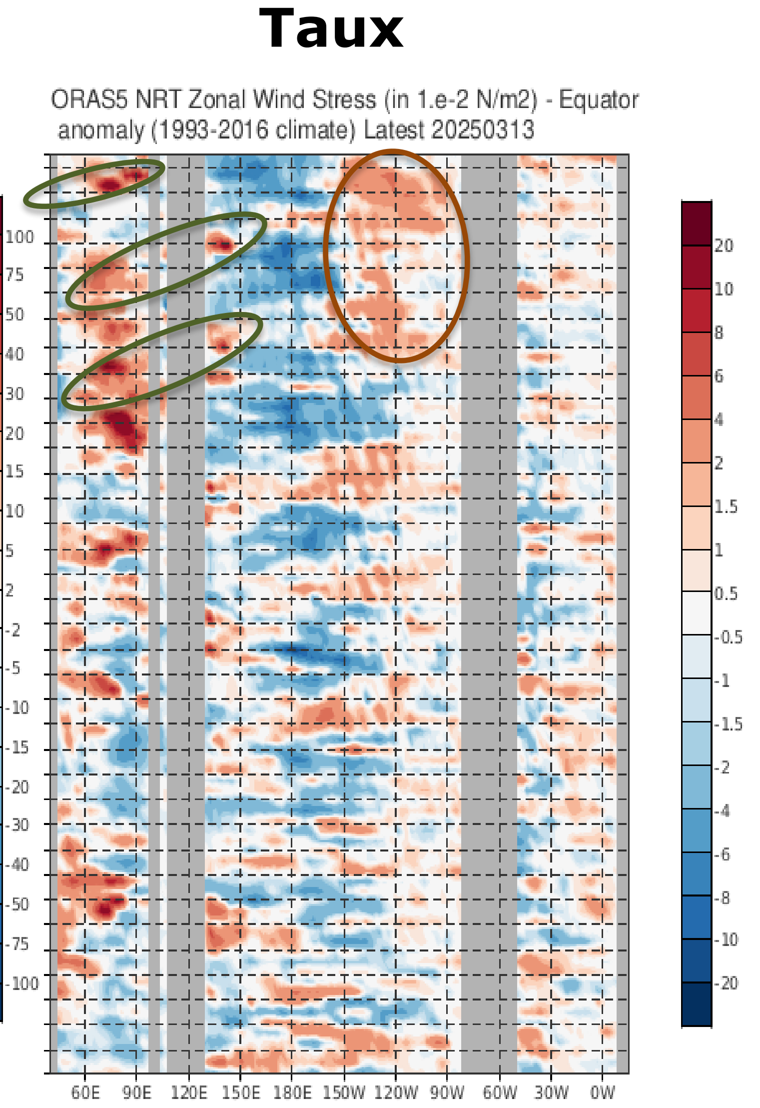
Will it grow or decay?

# Why has caused the Epac SST warming?

**Daily Eq. Anomalies over the past year**

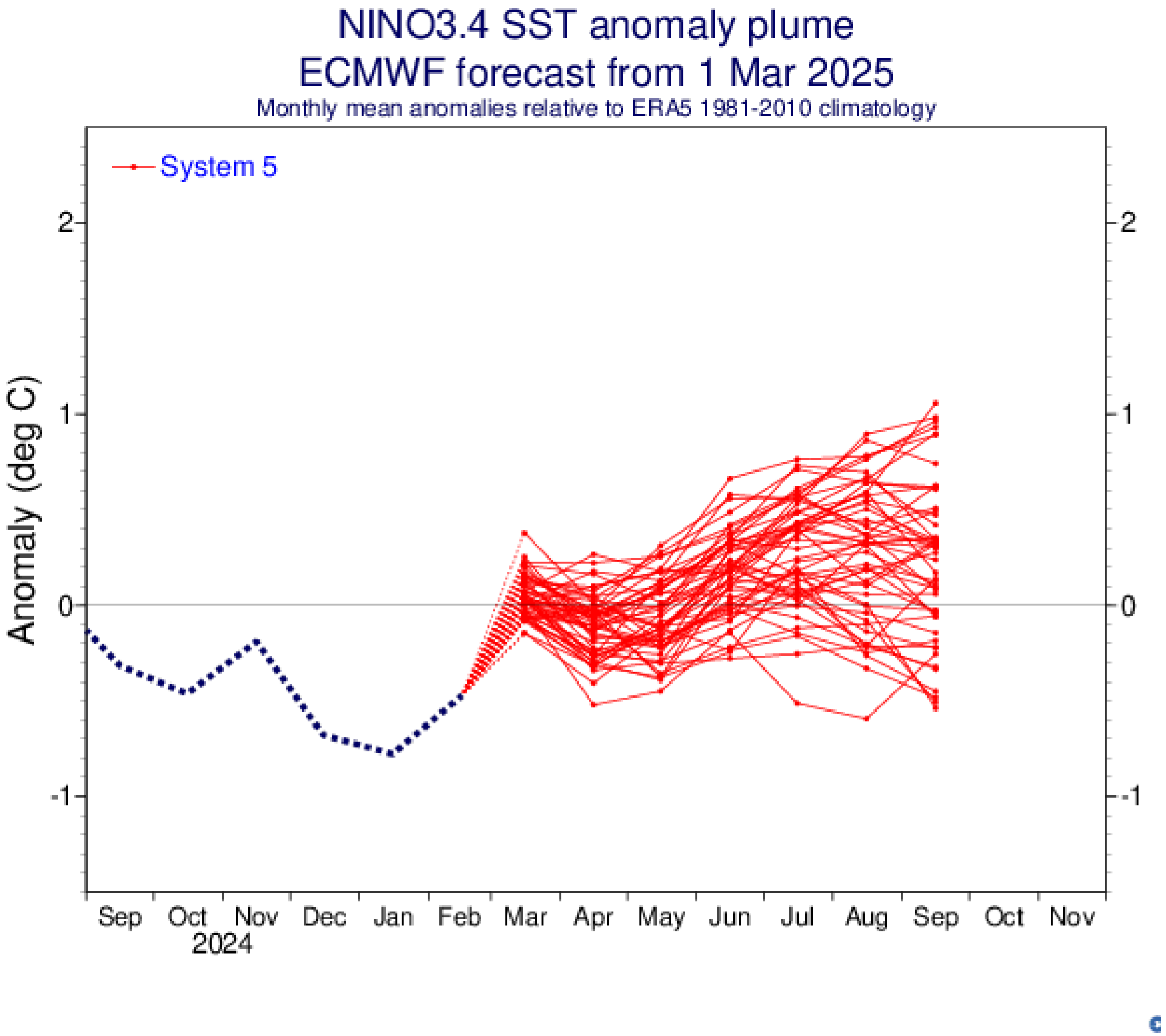


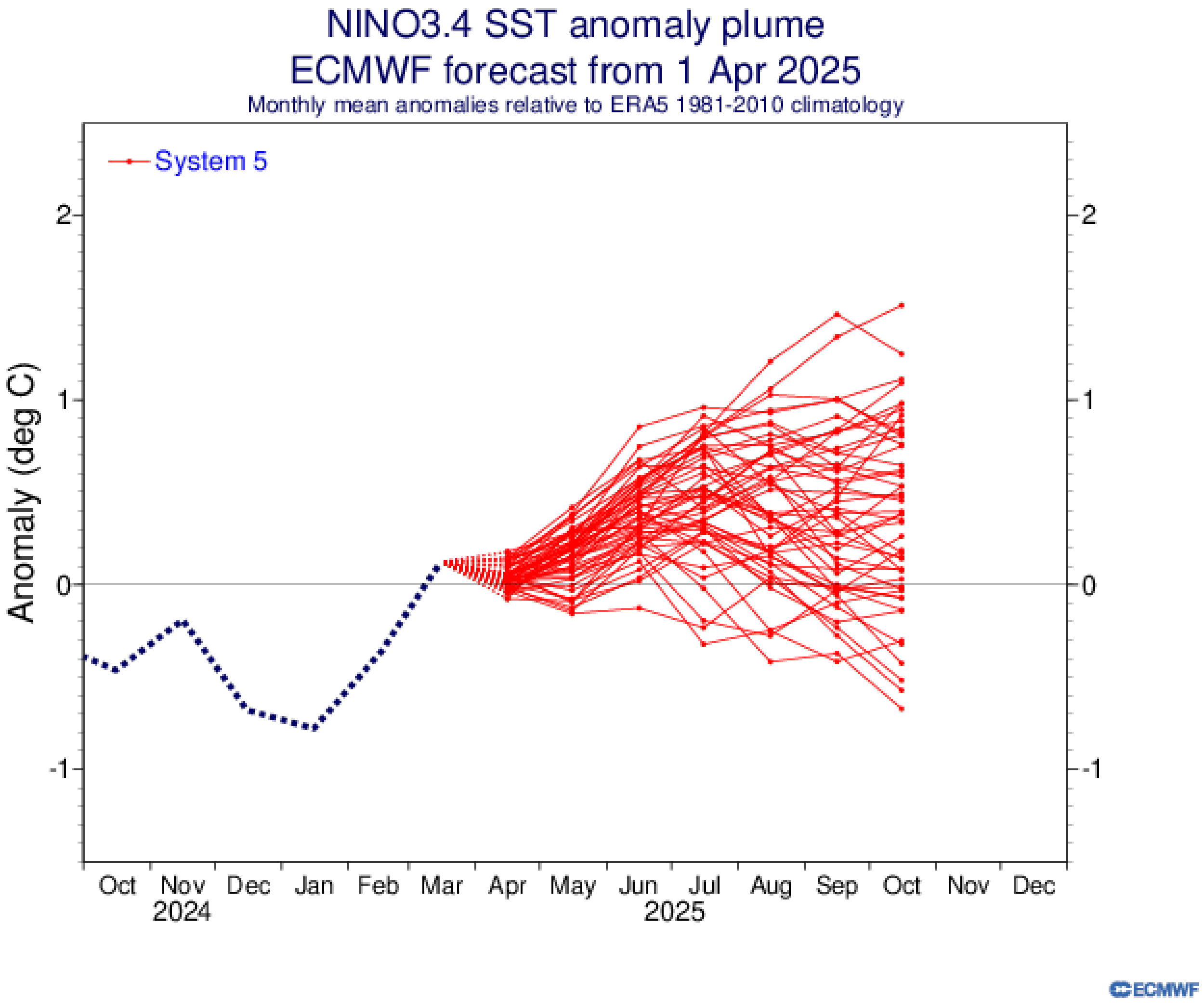




Strong WWB in West Pac associated with MJO activity (end Dec and end of Jan. Another coming?

Westerly anomalies over East Pac: Local or part of the MJO? Related with warm SST over Atlantic and Caribbean?




# Thanks for your attention