The El Niño Southern Oscillation

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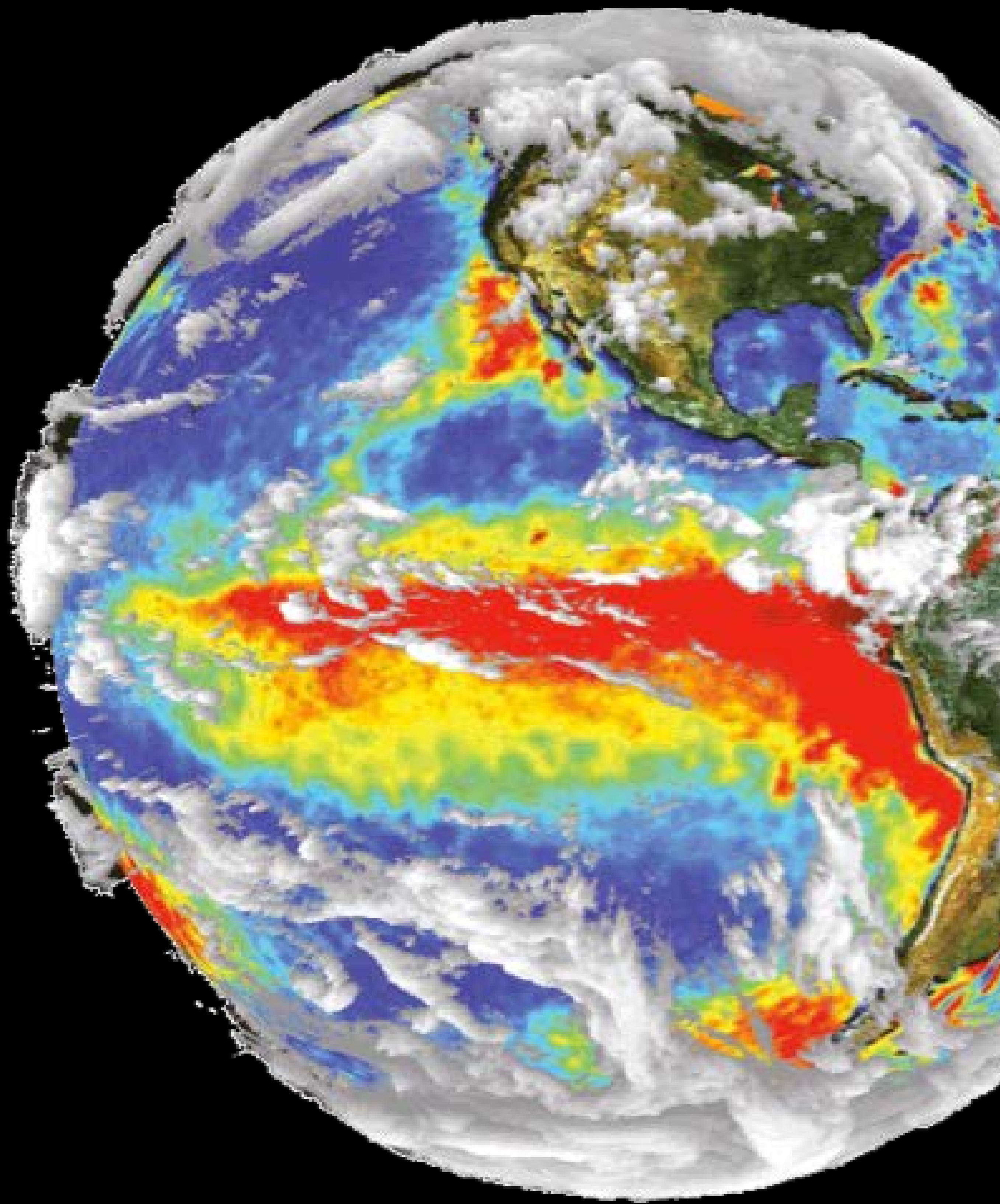
Outline

Part 1: Overview of ENSO

- El Niño
- ENSO impacts
- The 2015-16 event
- ENSO and climate change

Part 2: ENSO mechanisms

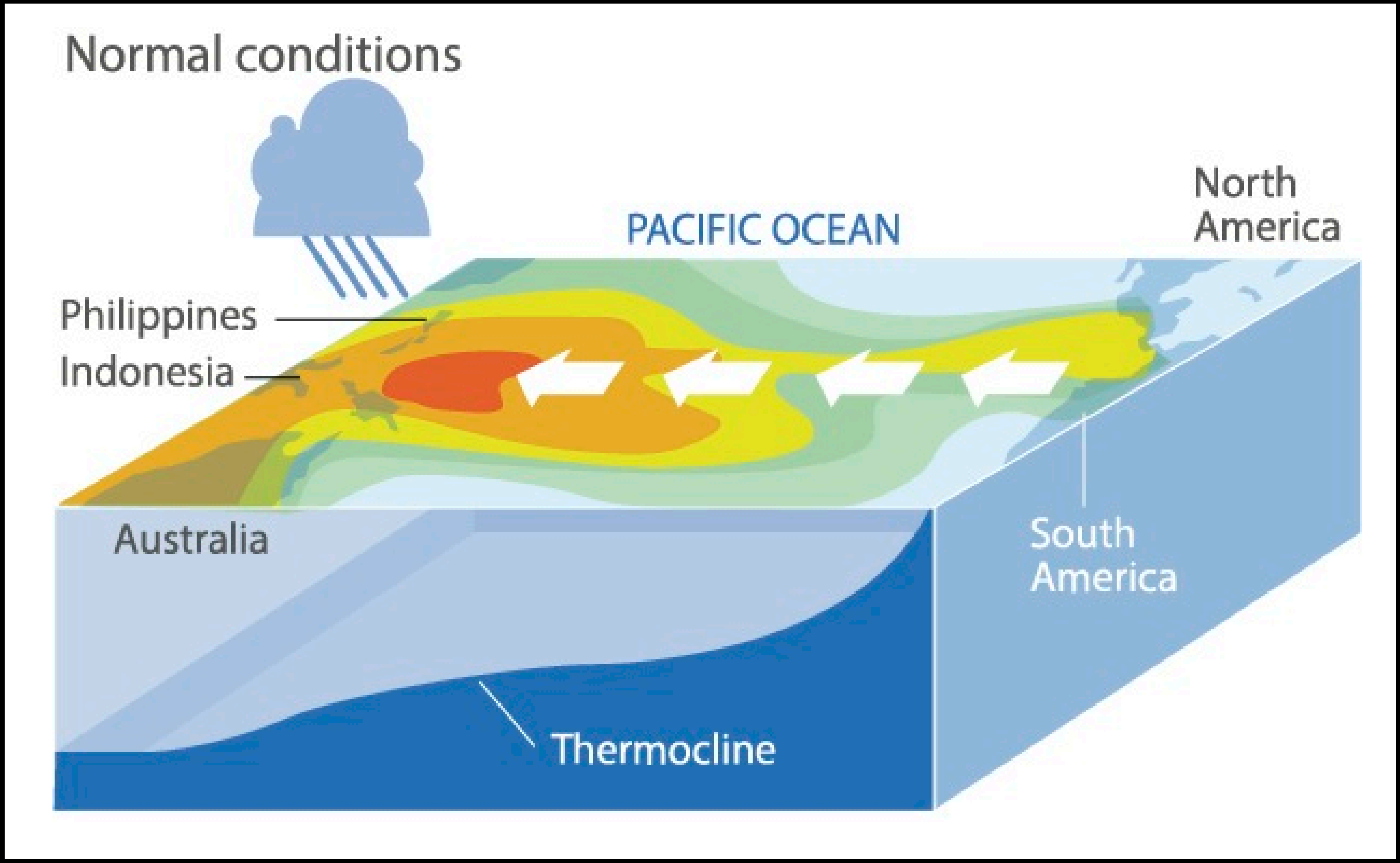
- ENSO theories
- ENSO in models
- Extreme events
- Impacts of WWEs



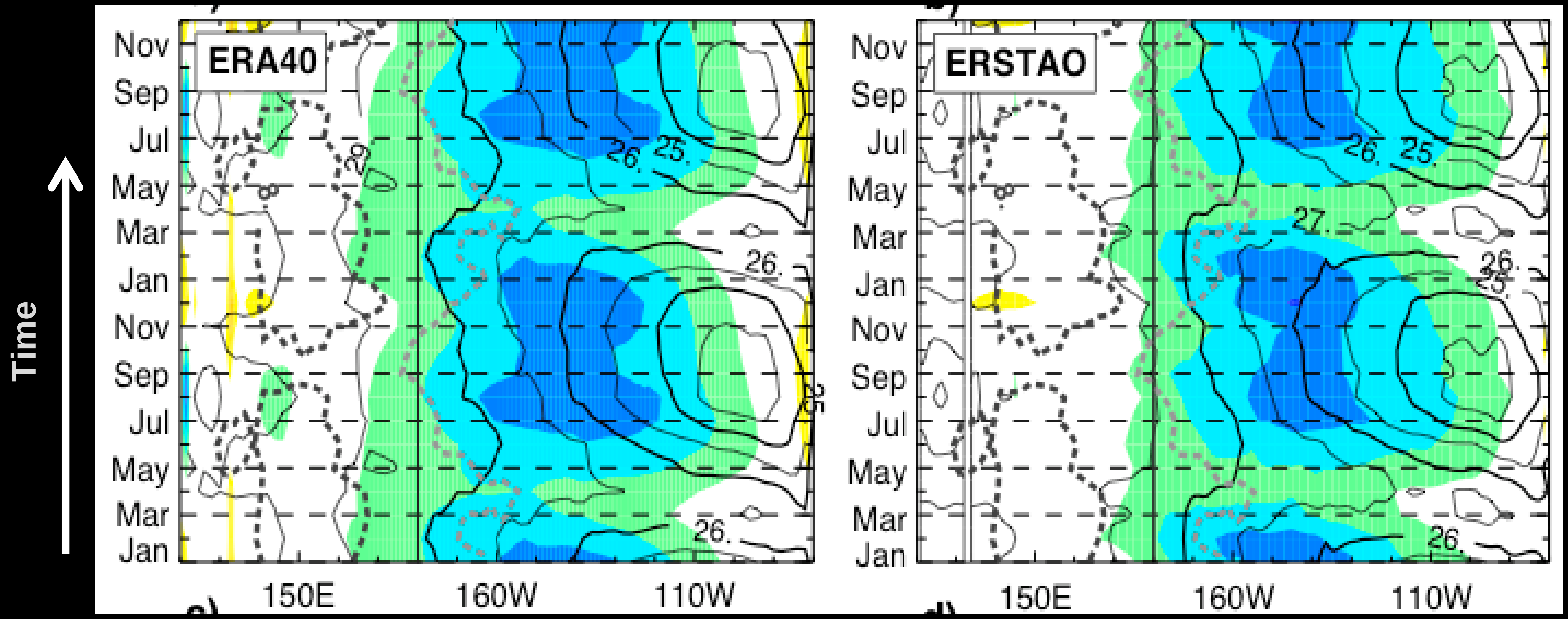
El Niño

A natural climate anomaly arising from the coupled ocean and atmosphere in the tropical Pacific

Normal situation



Mean seasonal cycle – Equatorial Pacific



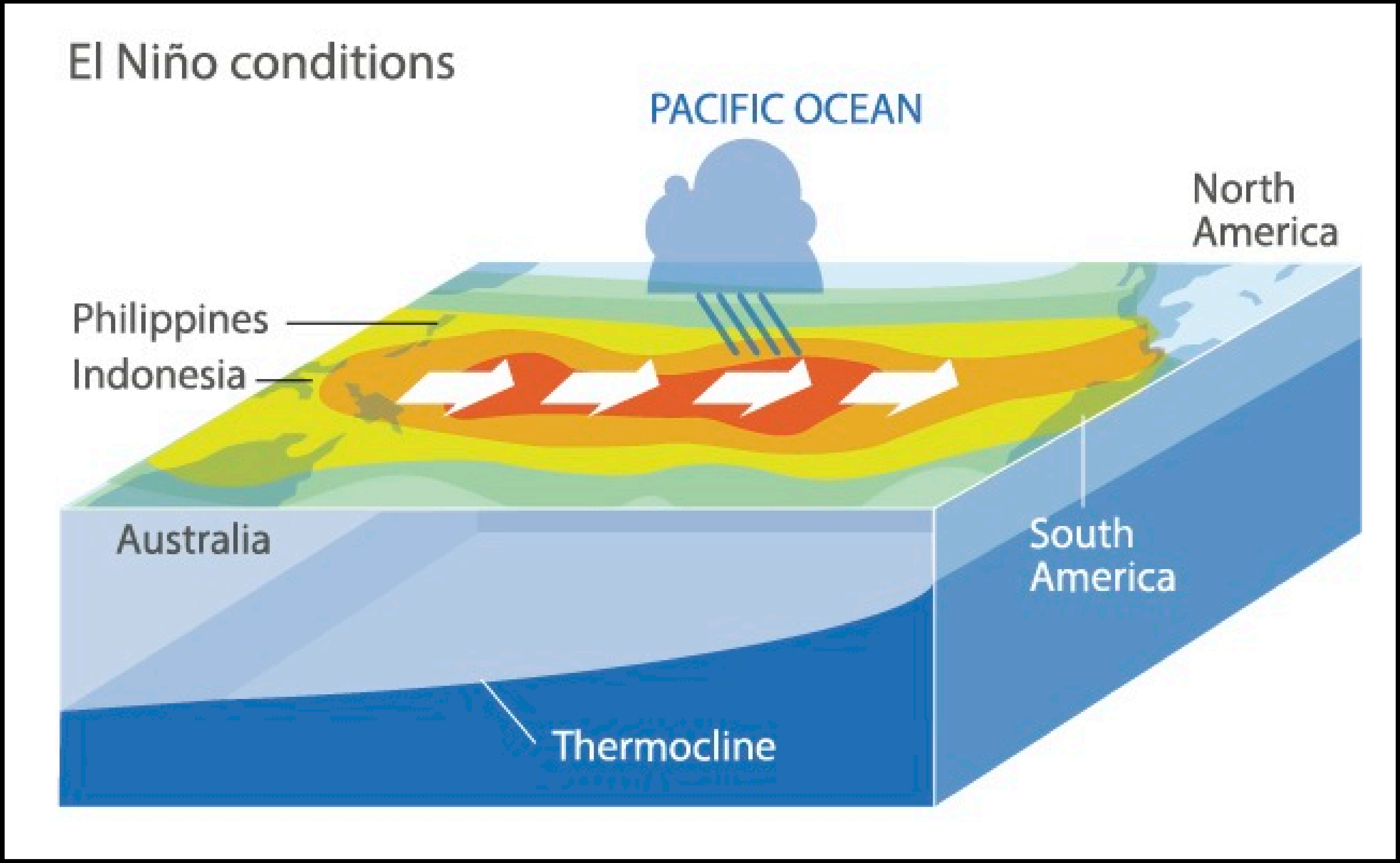
- Spring relaxation
- Fall intensification

- *Wind stress (shading)*
- *SST (solid contours)*
- *Precipitation (3 and 8 mm/day dashed)*

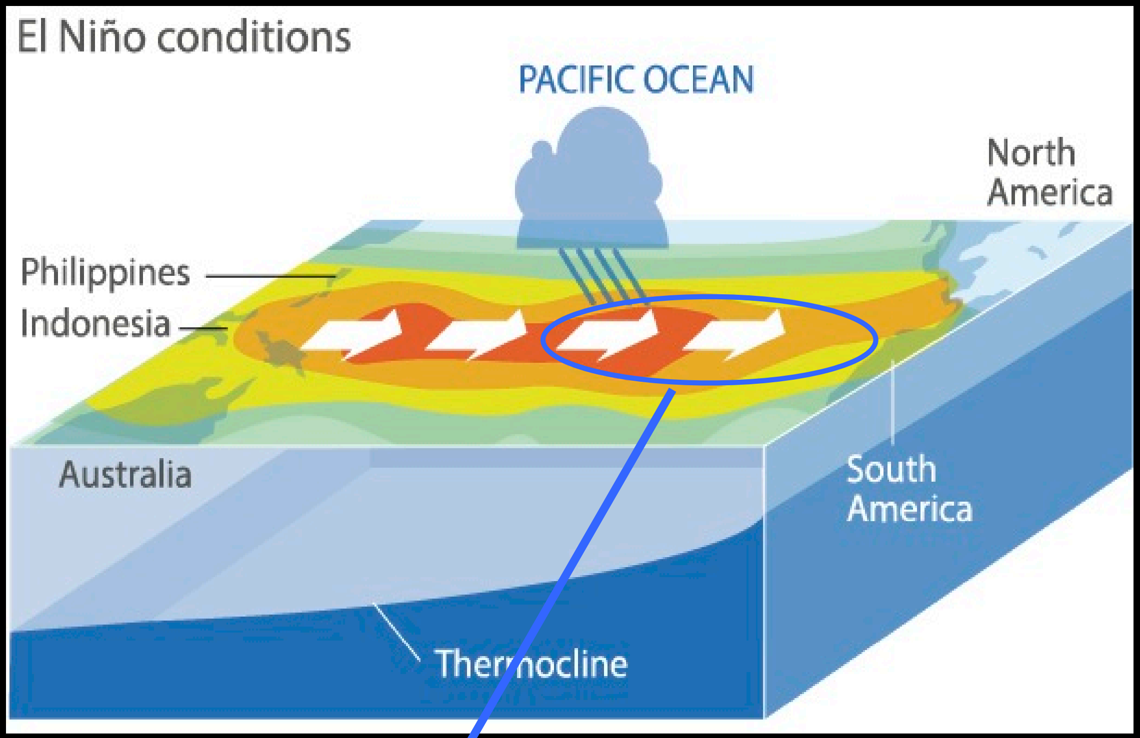
El Niño

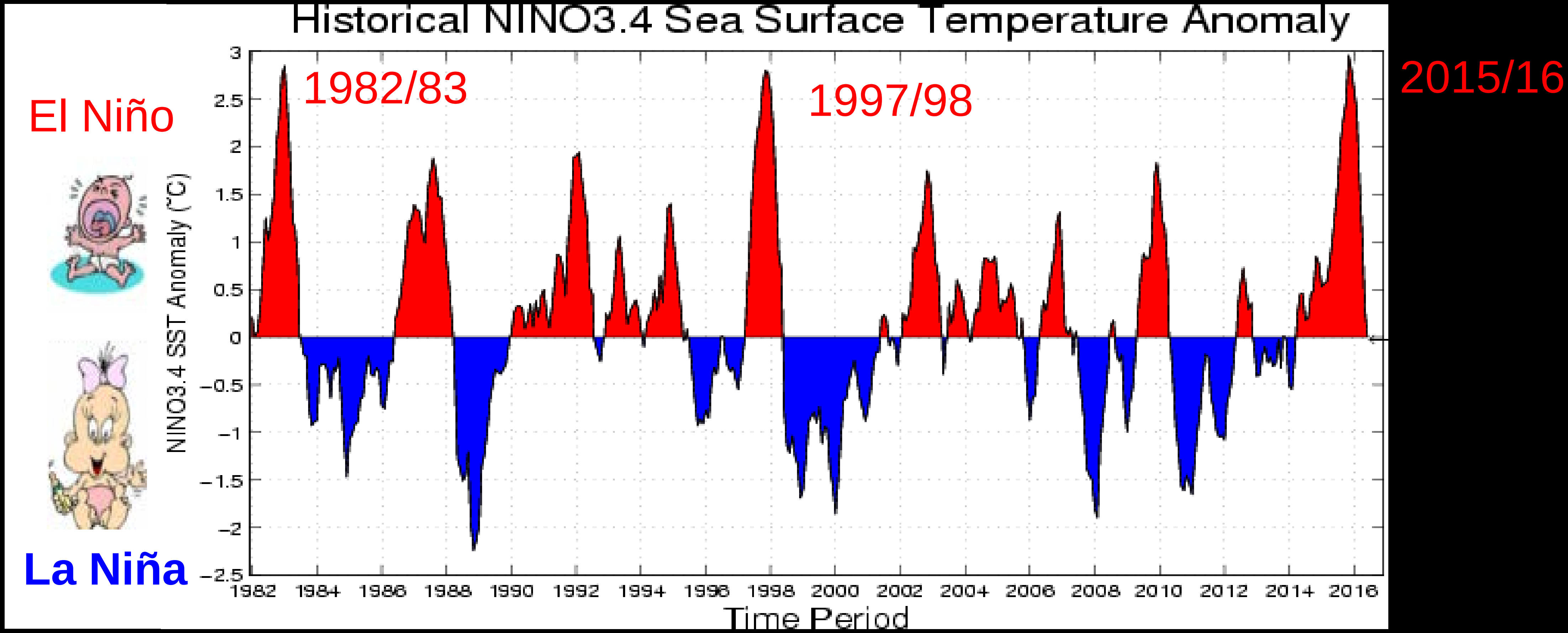
A natural climate anomaly arising from the coupled ocean and atmosphere in the tropical Pacific

El Niño event



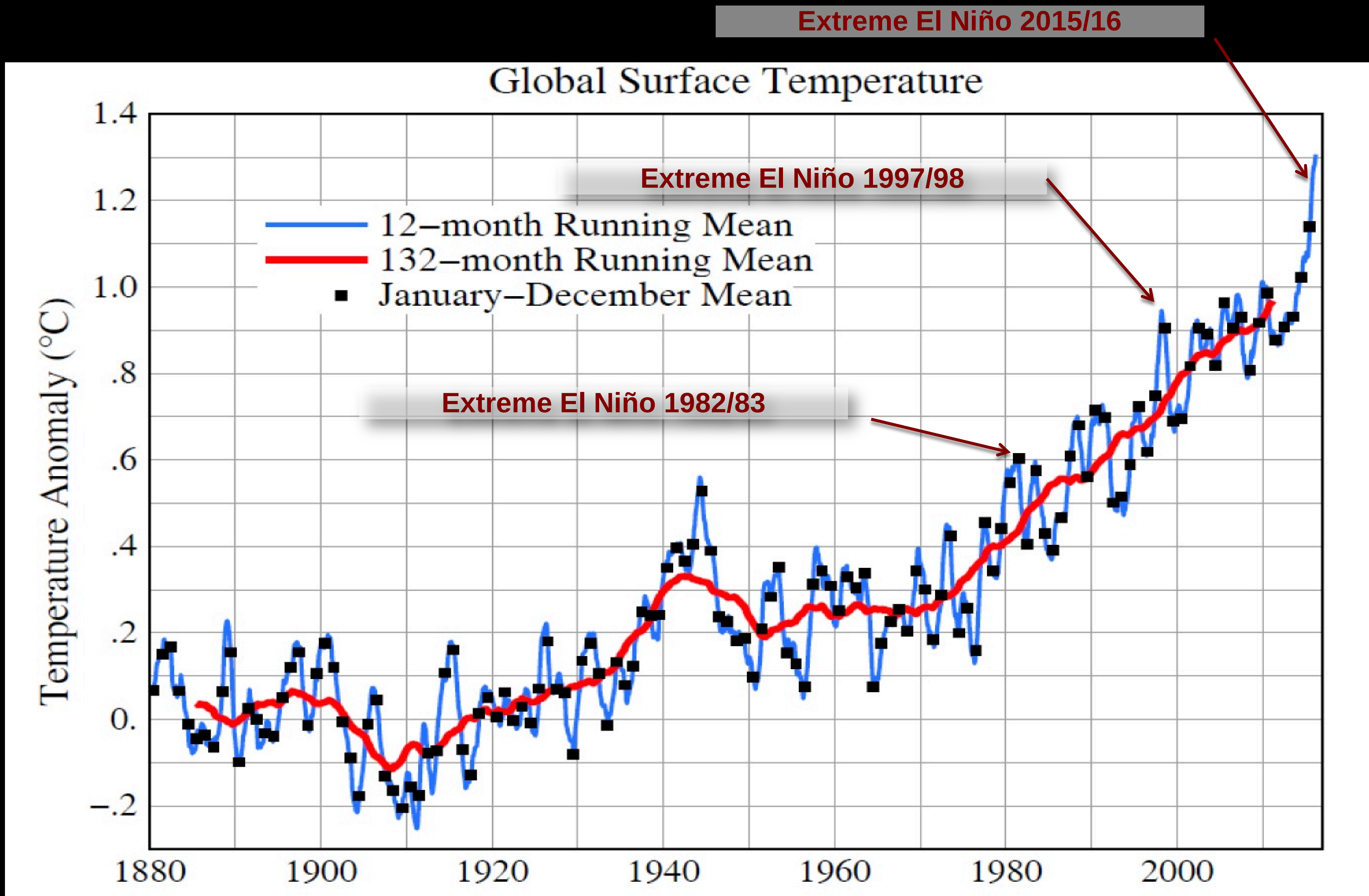
El Niño since 1982





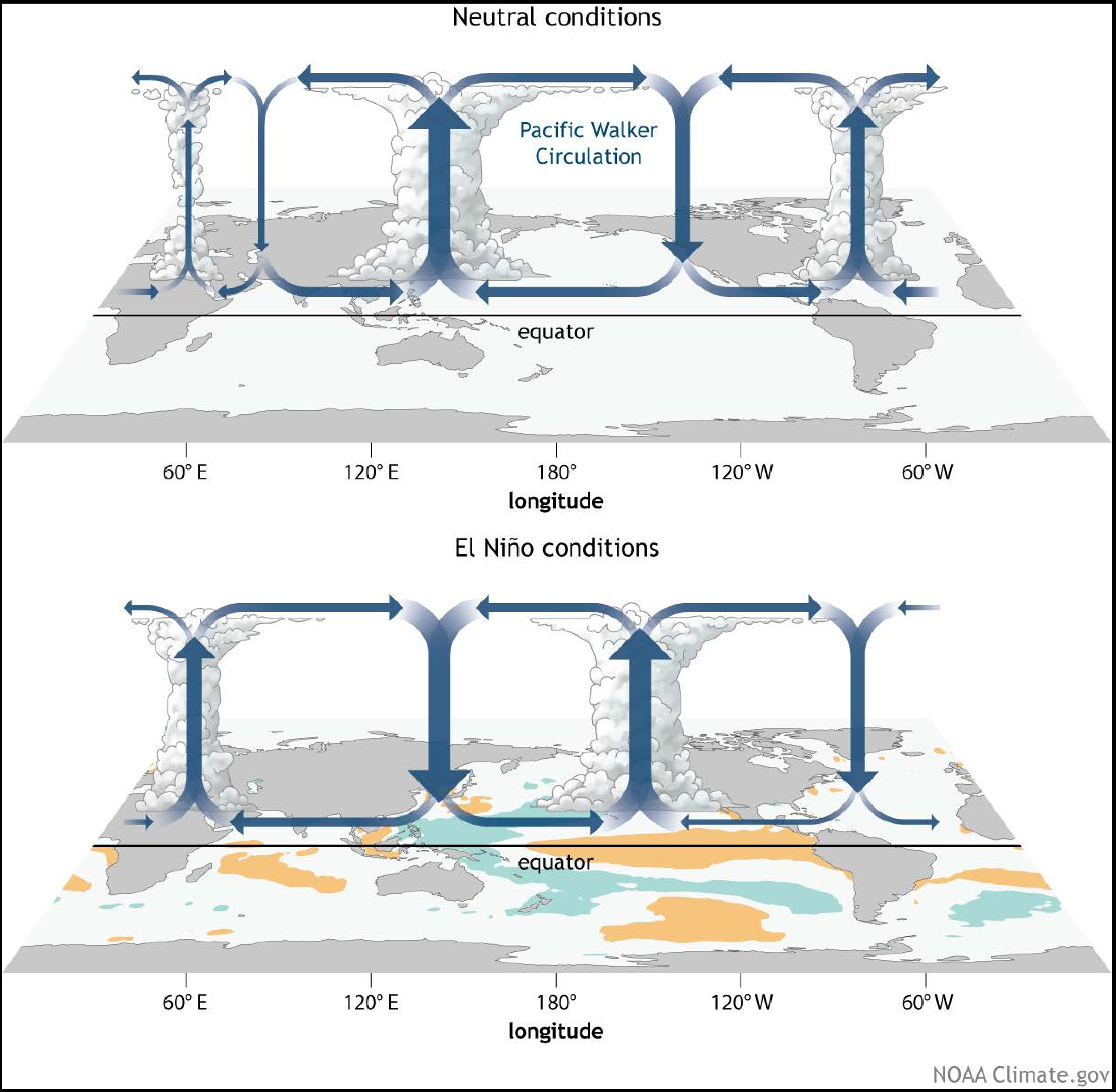
IRI

Global temperature



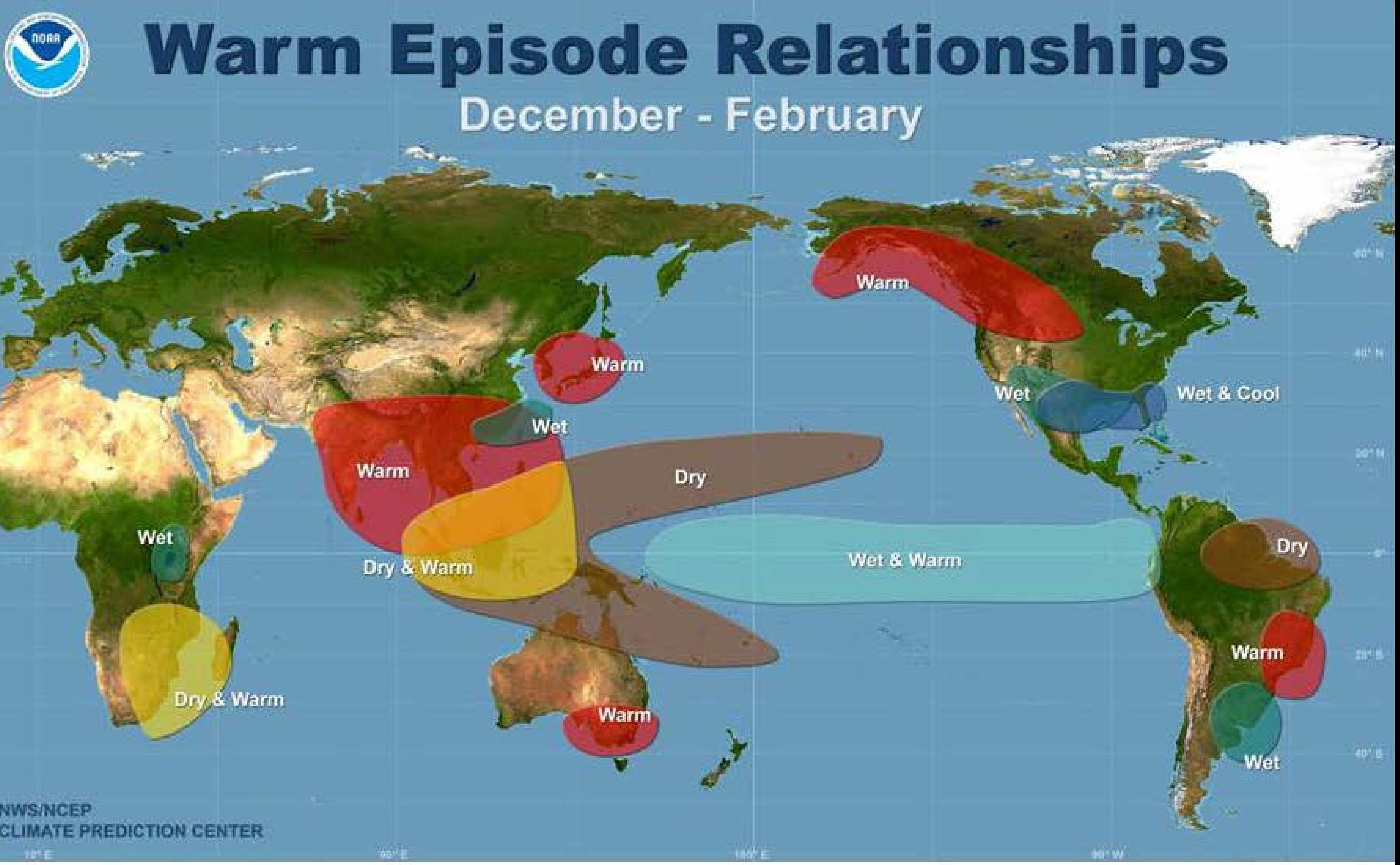
Source: GISTEMP

El Niño teleconnections

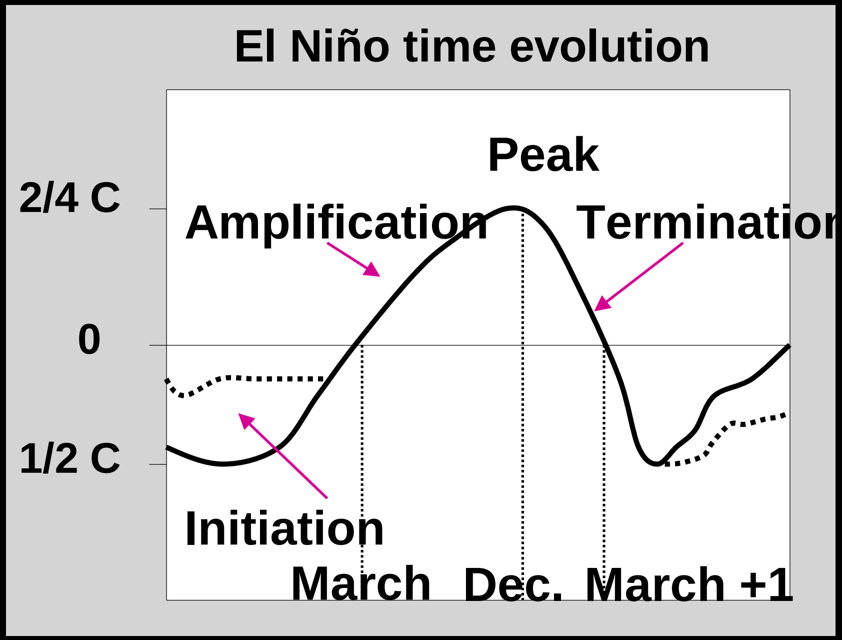


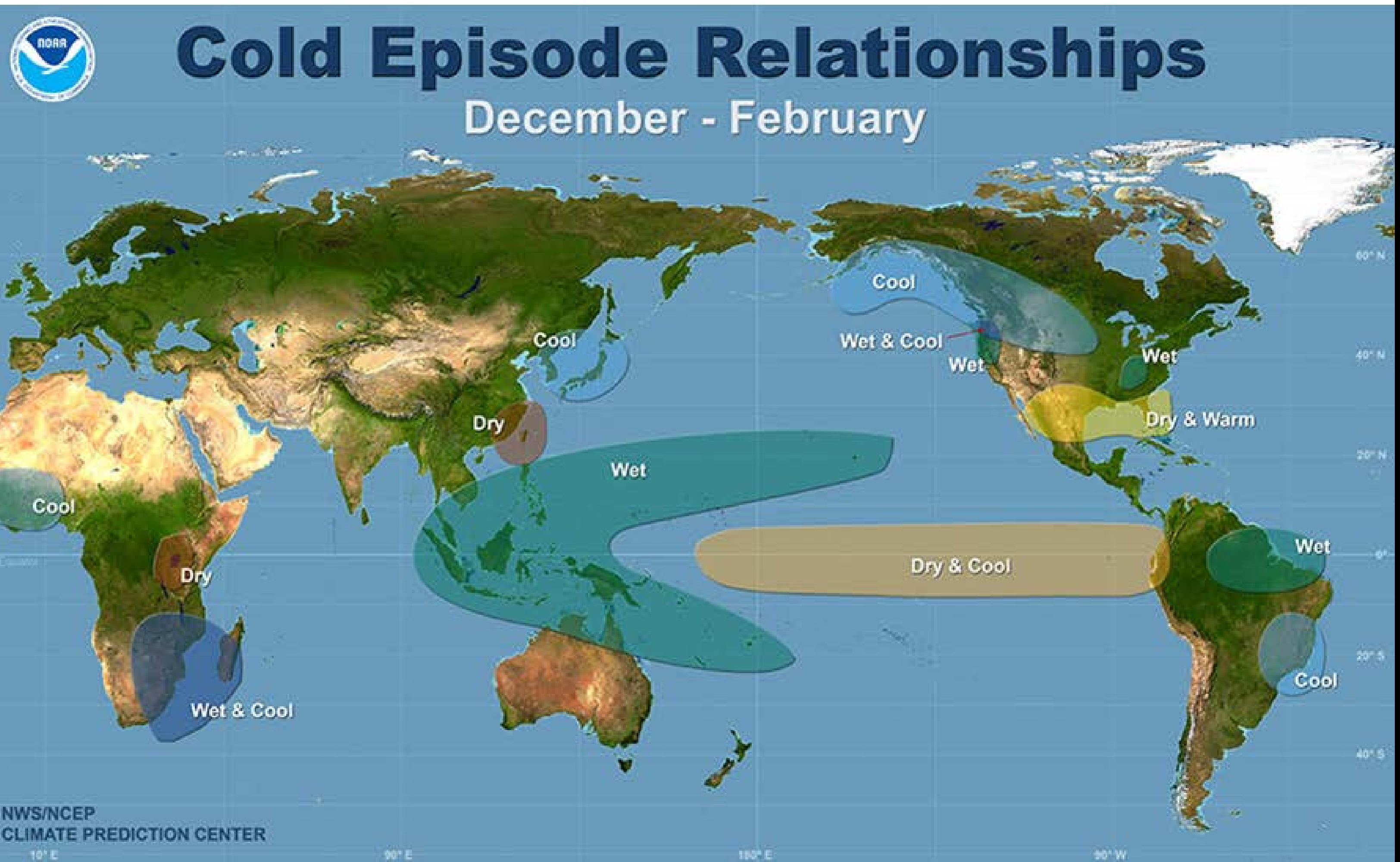
Normal circulation

Circulation during El Niño



El Niño impacts



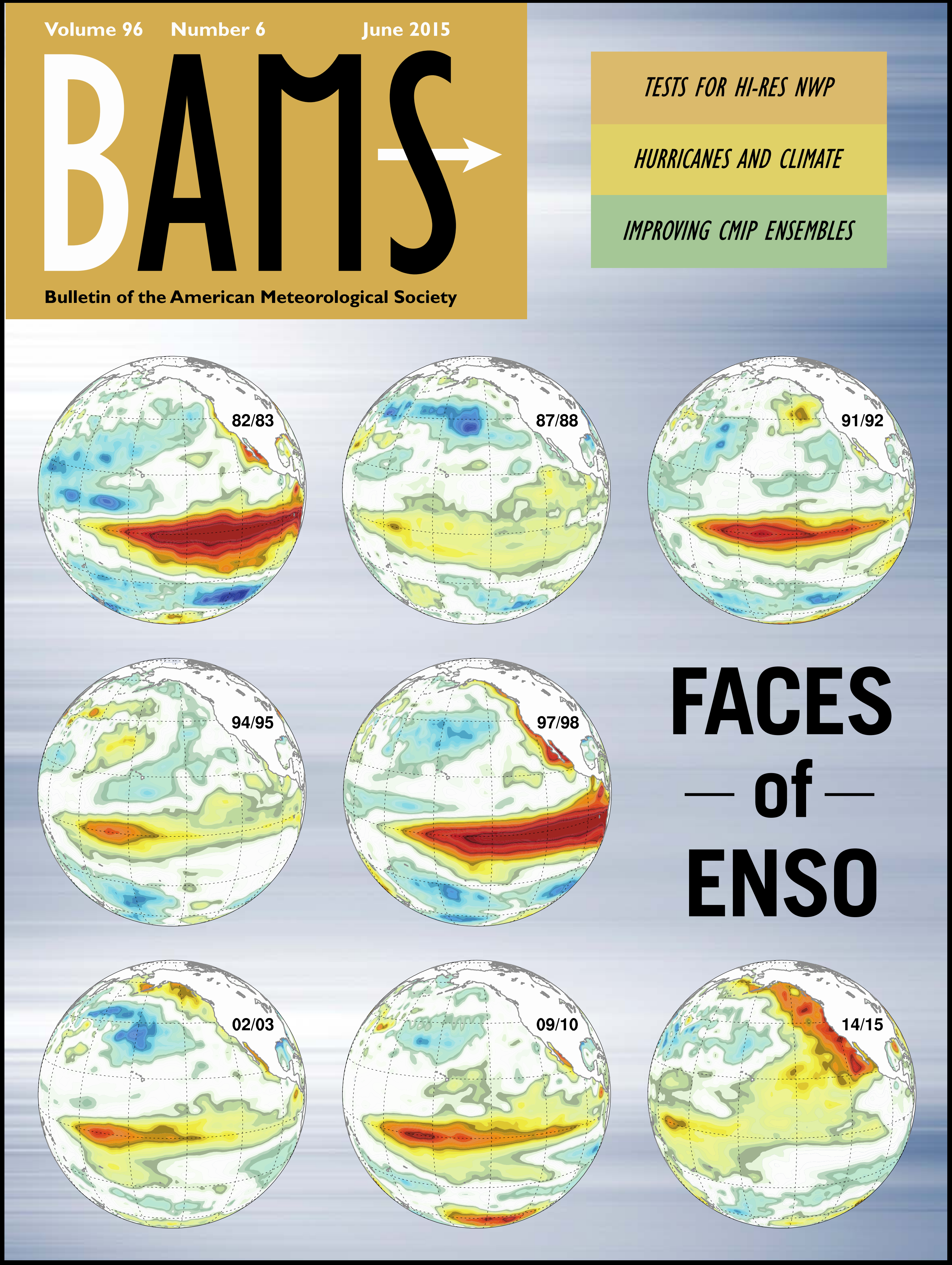


La Niña impacts

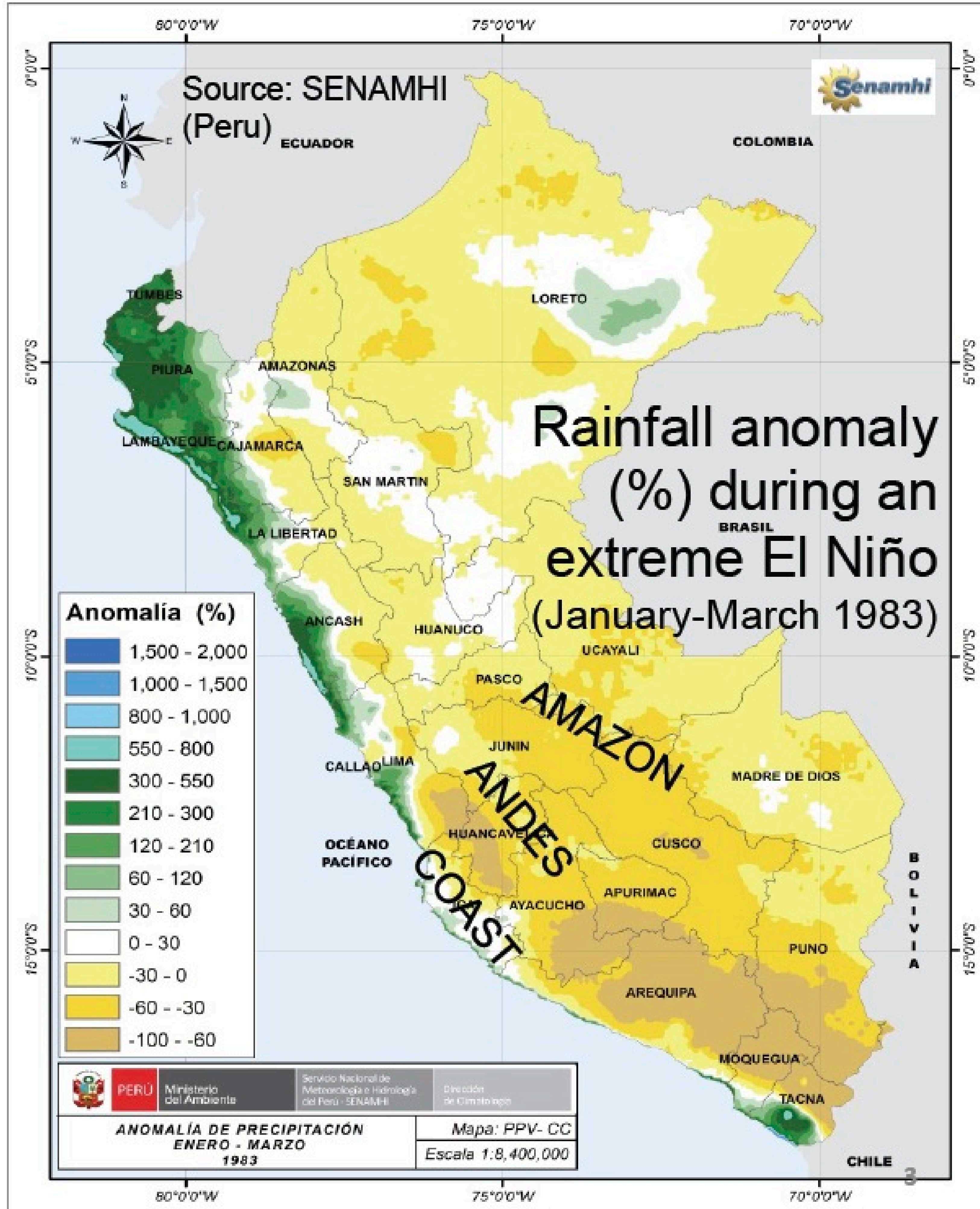
Each El Niño is different

So its impacts vary

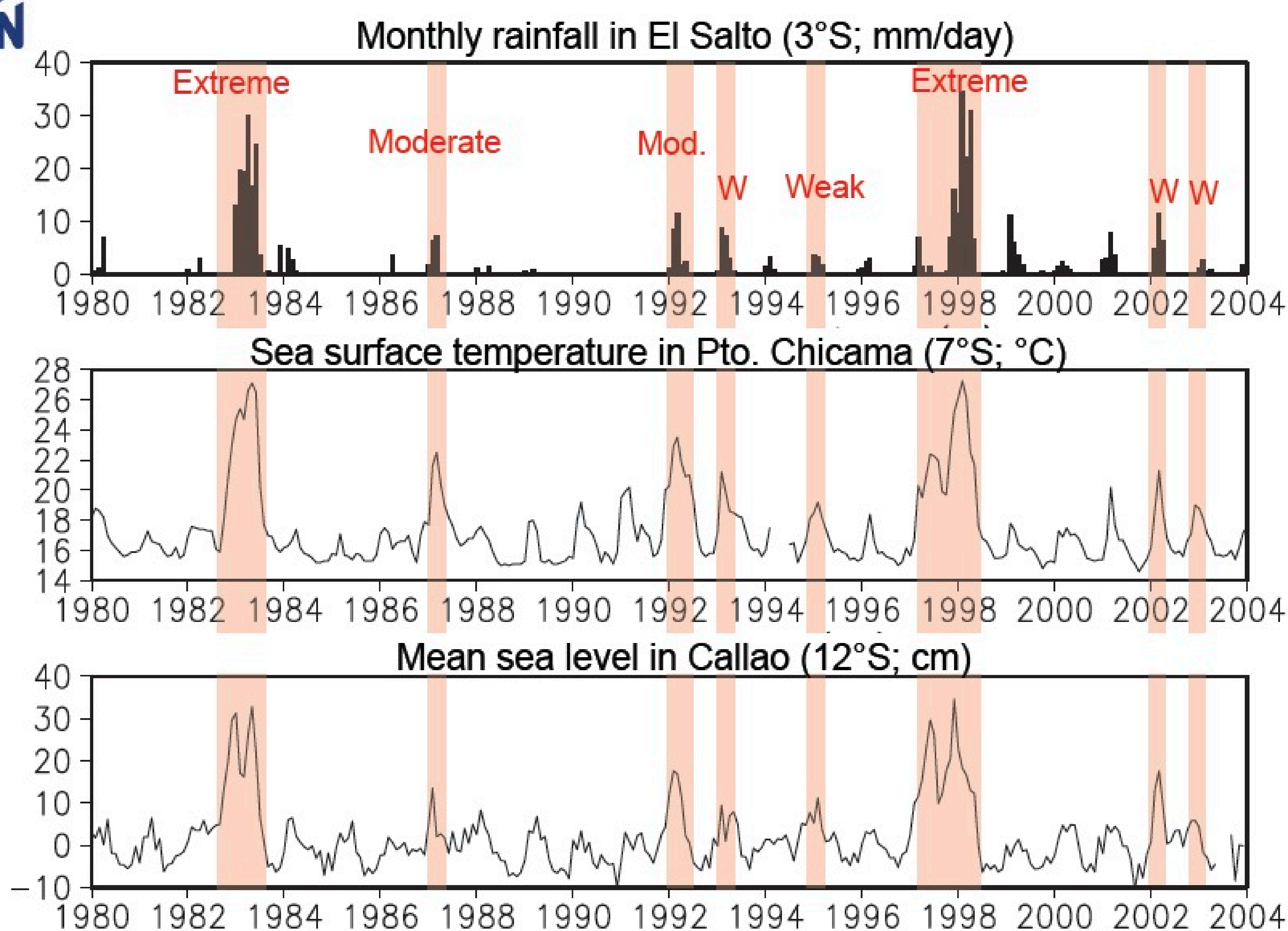
Beware of over attribution



Courtesy Ken Takahashi



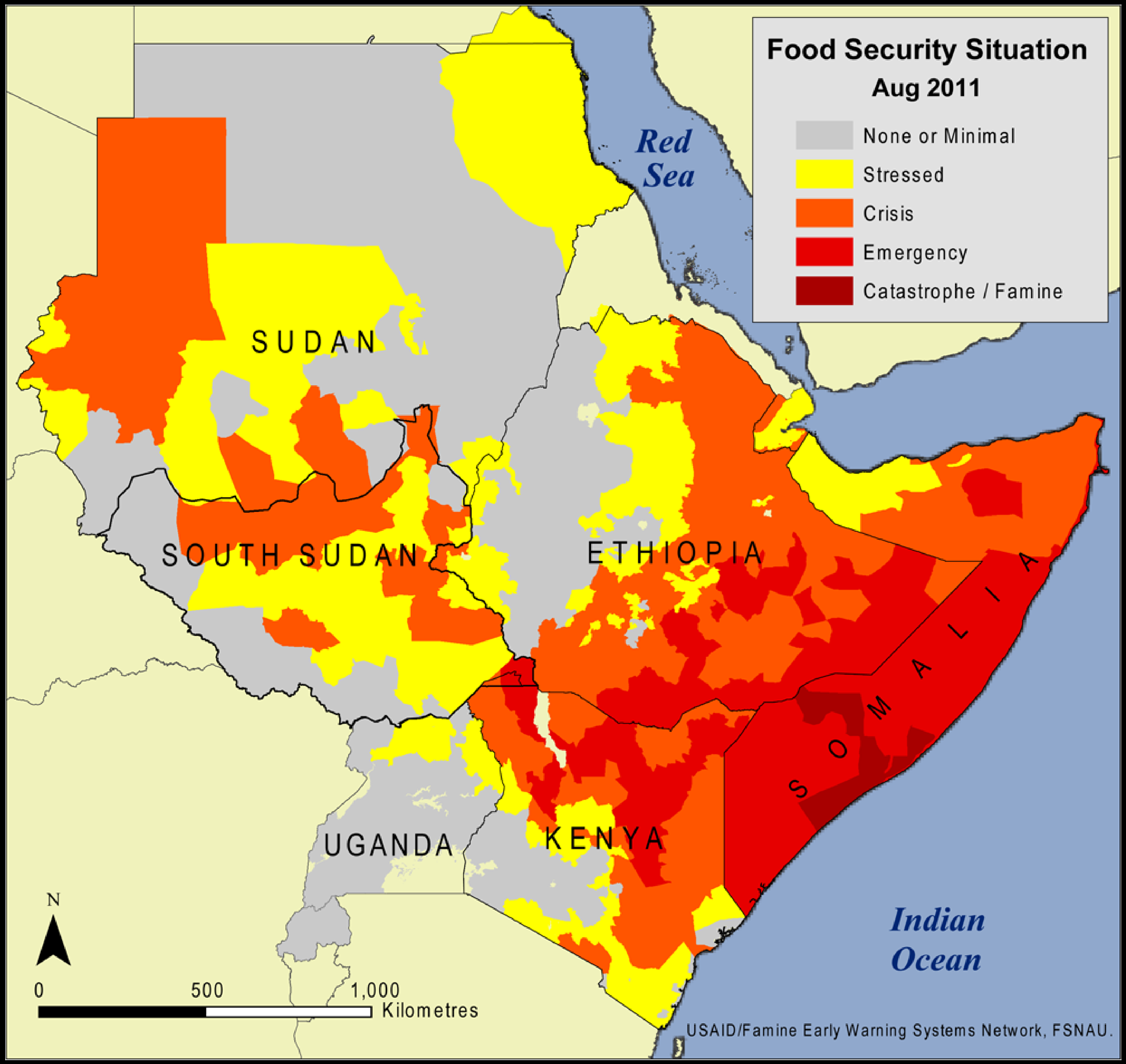
El Niño in the Peruvian coast



The extreme El Niño cost 7% (1982-83) and 4.5% (1997-98) of Peru's gross national product (CAF 2000).

Courtesy Ken Takahashi

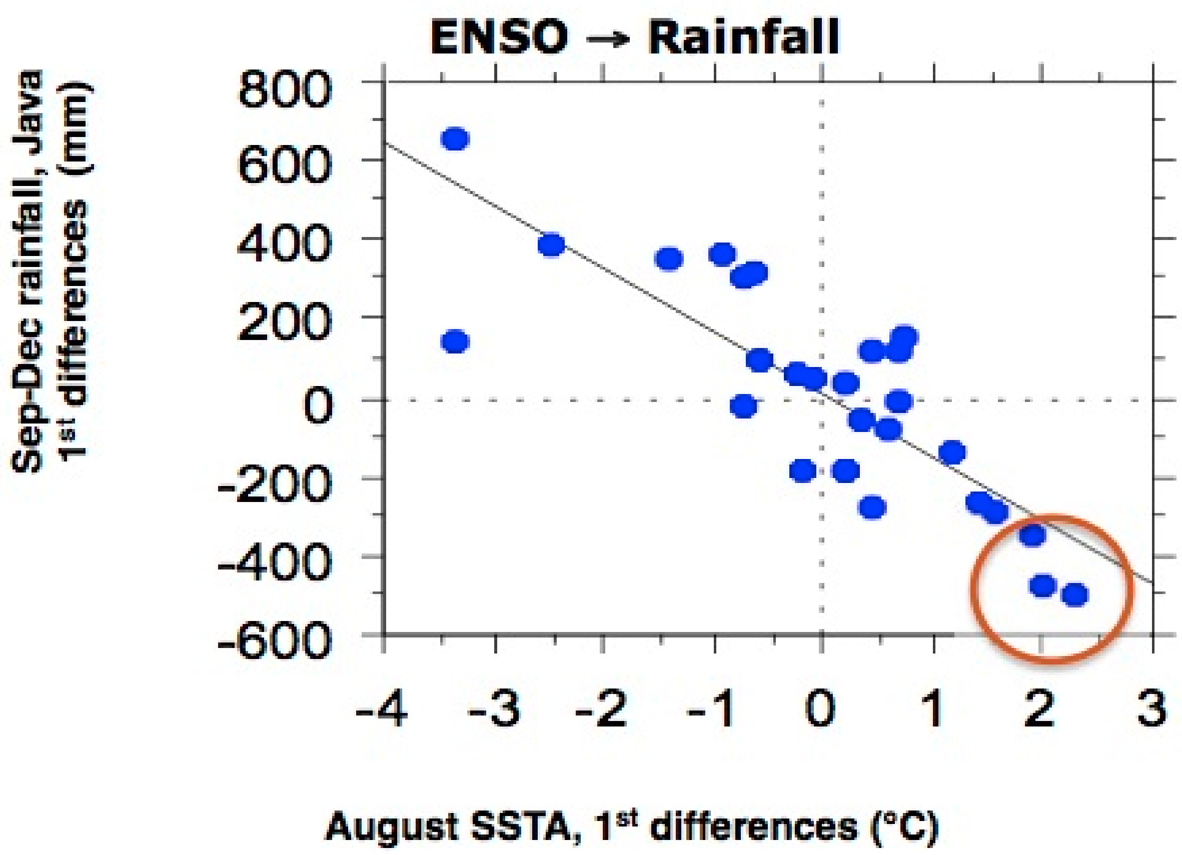
2011 La Niña in east Africa

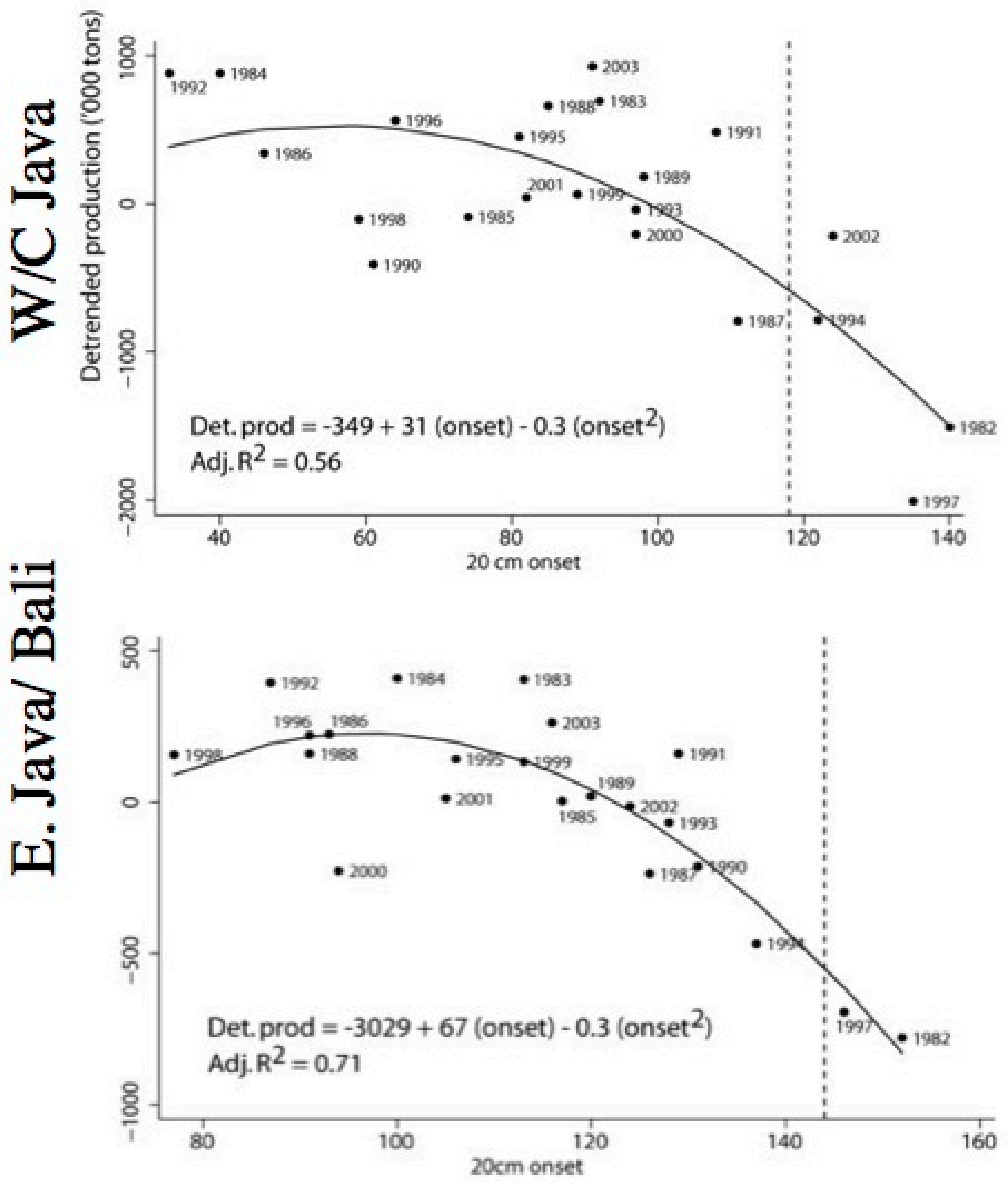


Food emergency due to worst drought in 60 years (UN)

Rice crops in Indonesia

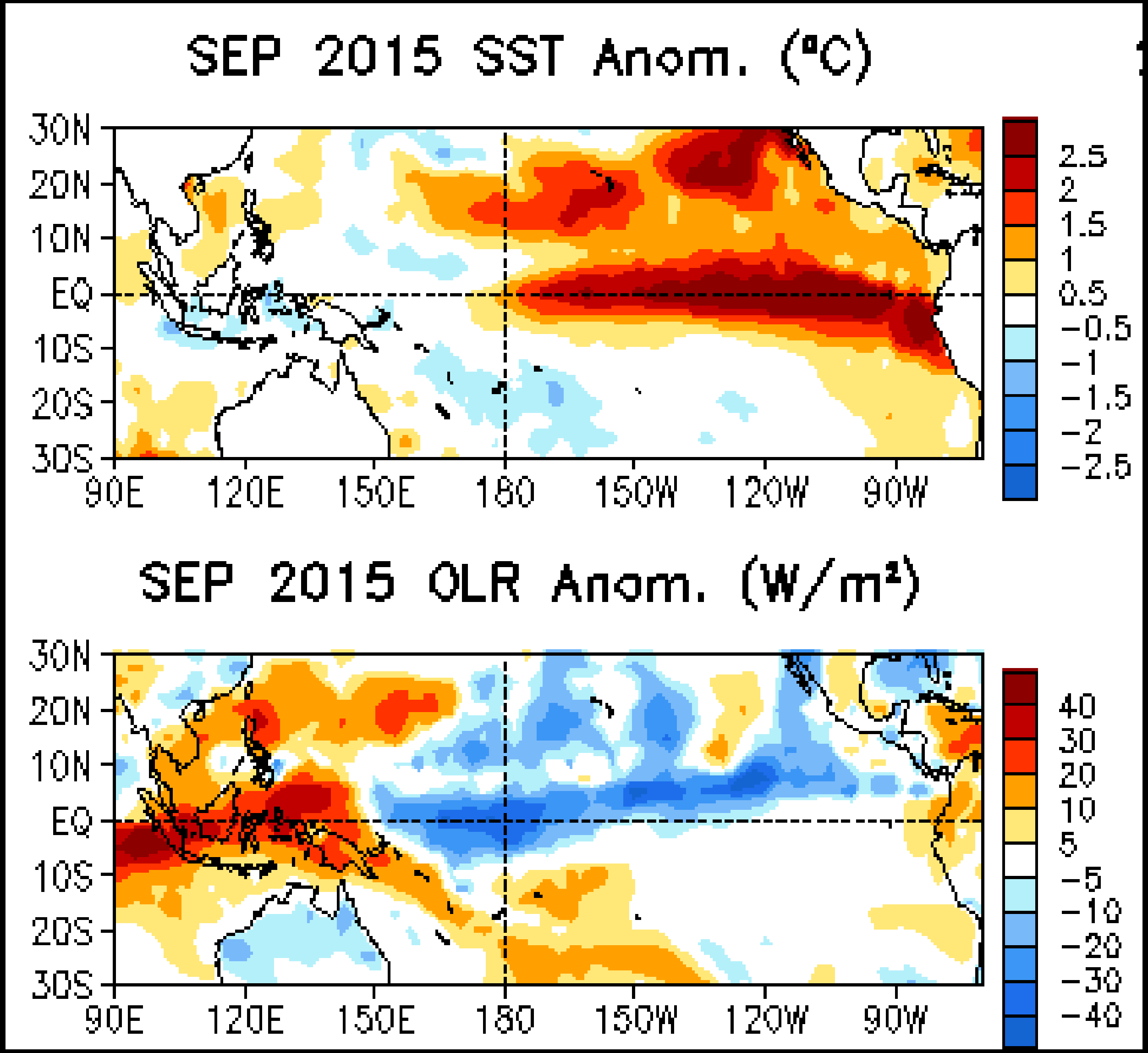
Yield is divided by two during extreme El Niño years (lack of rainfall)

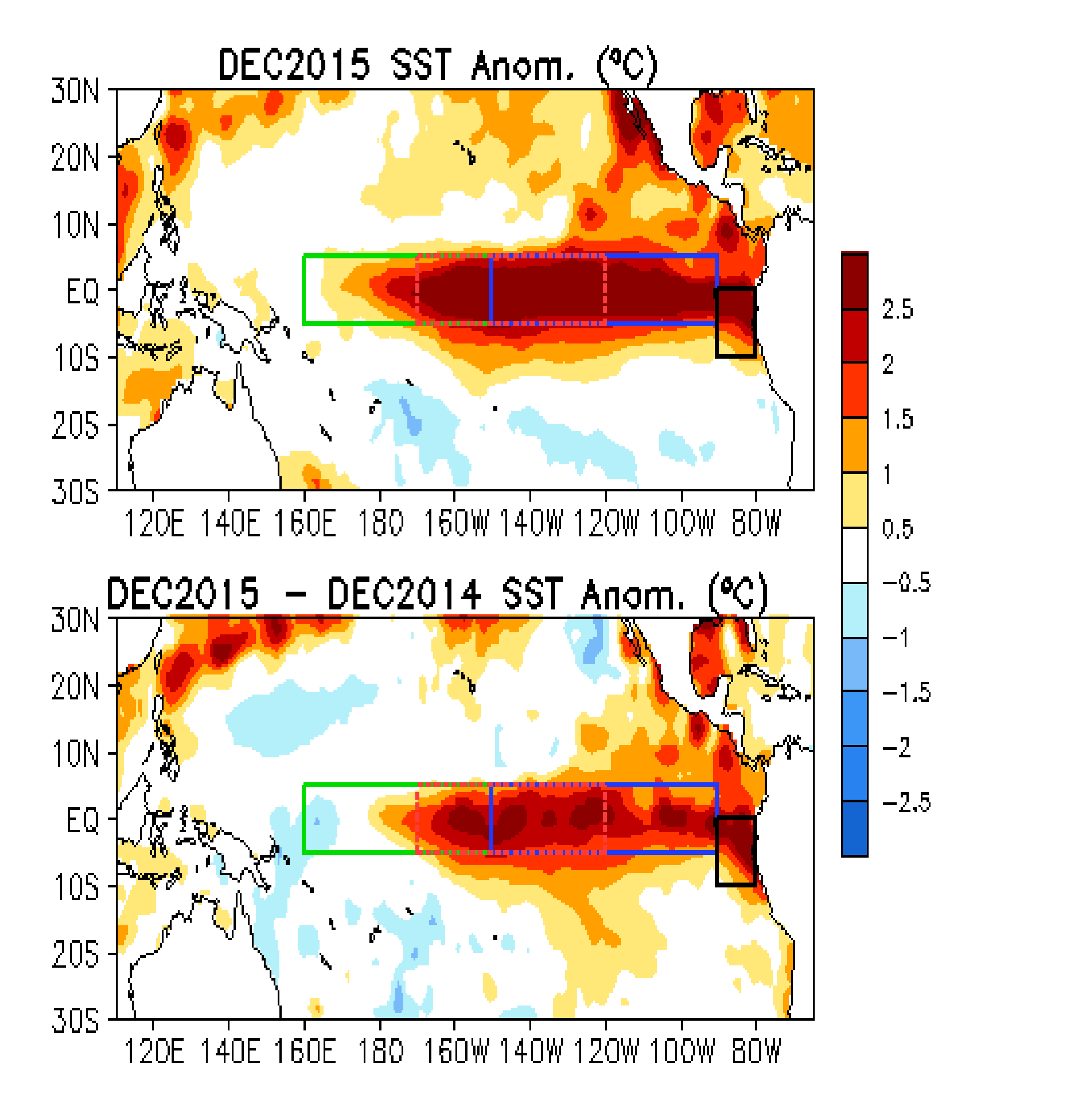




Courtesy Roz Taylor and David Battisti

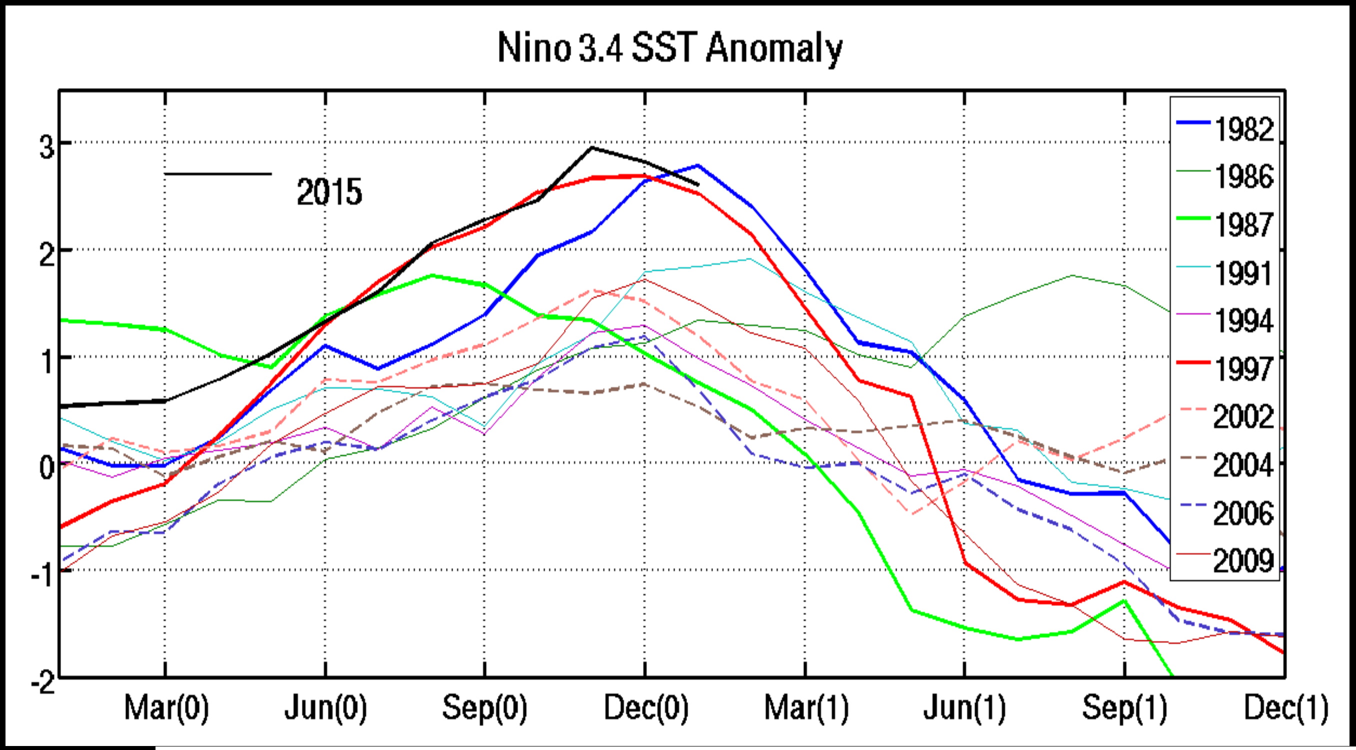
El Niño 2015-2016: an extreme event

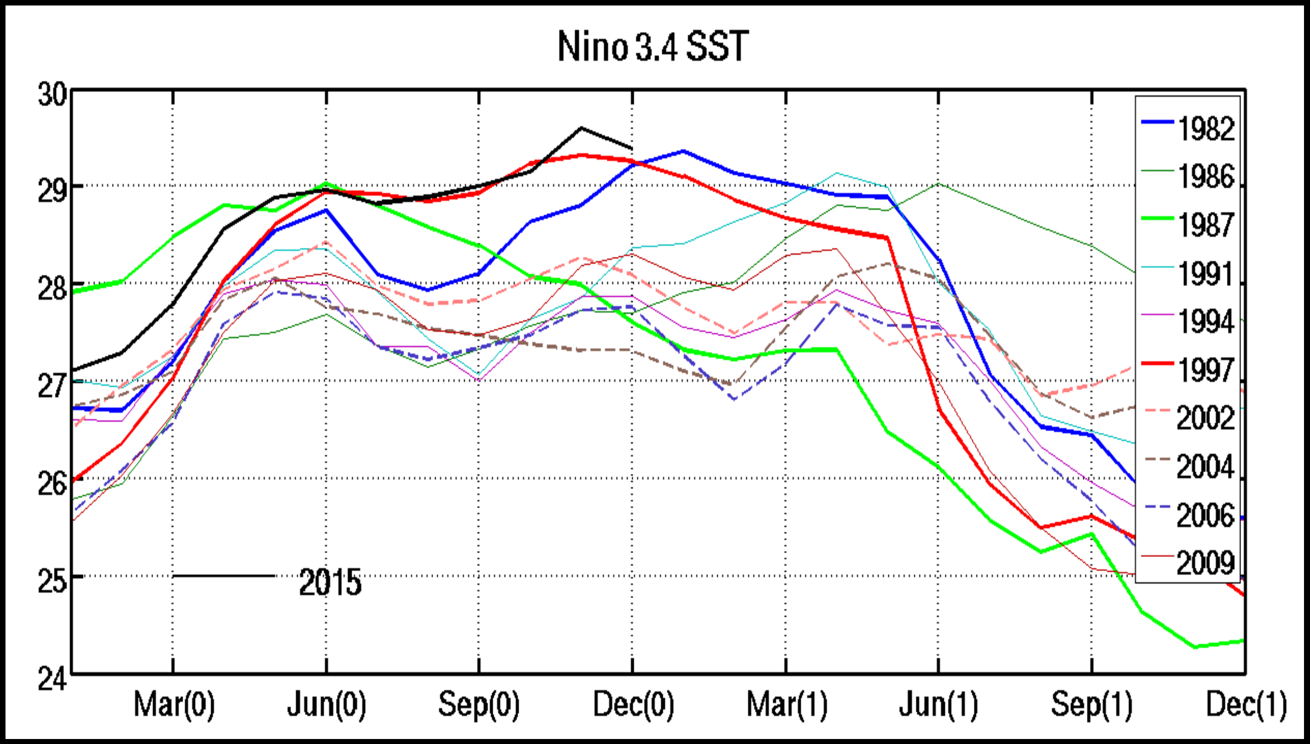


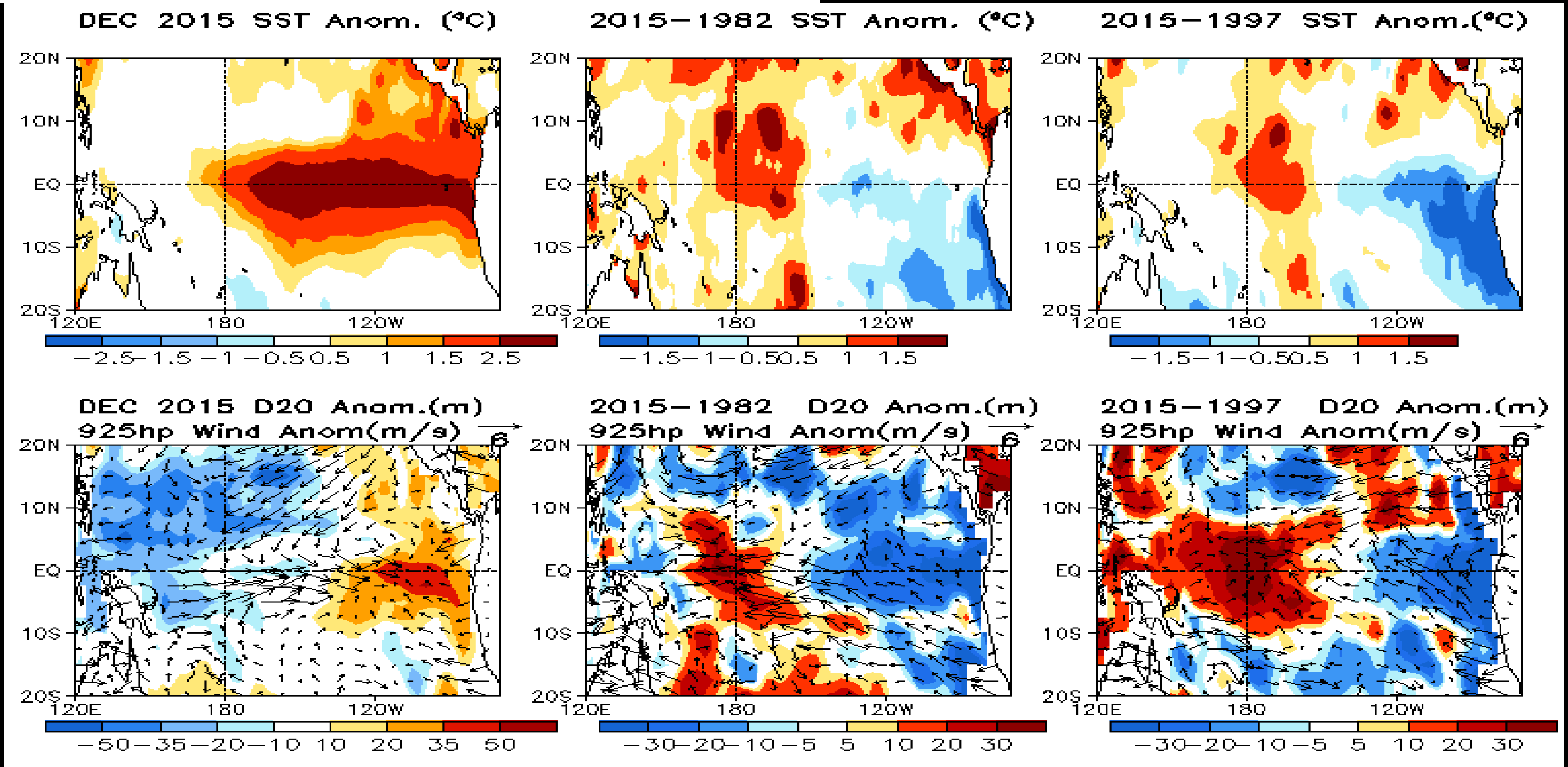


NCEP/NOAA

2015-16 El Niño vs. previous extremes

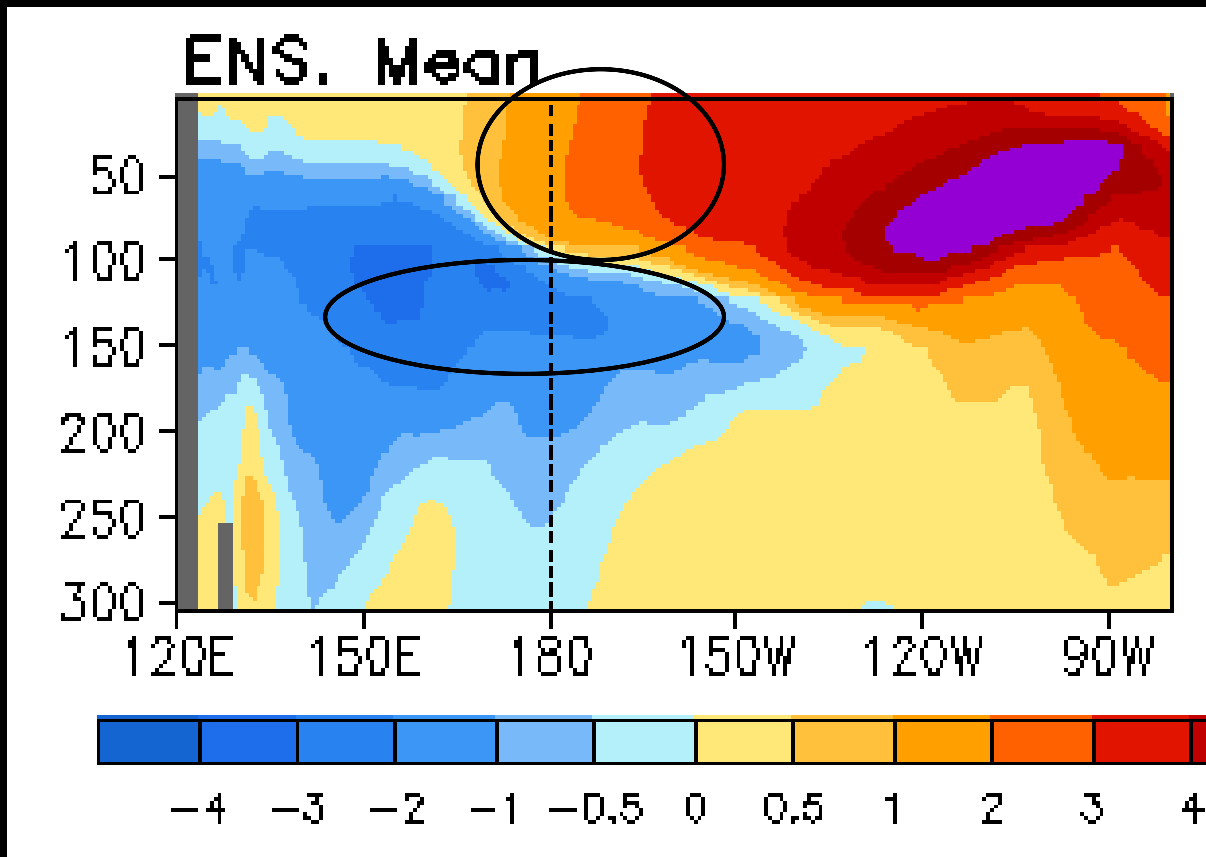






Temperature anomaly at equator

Dec 2015

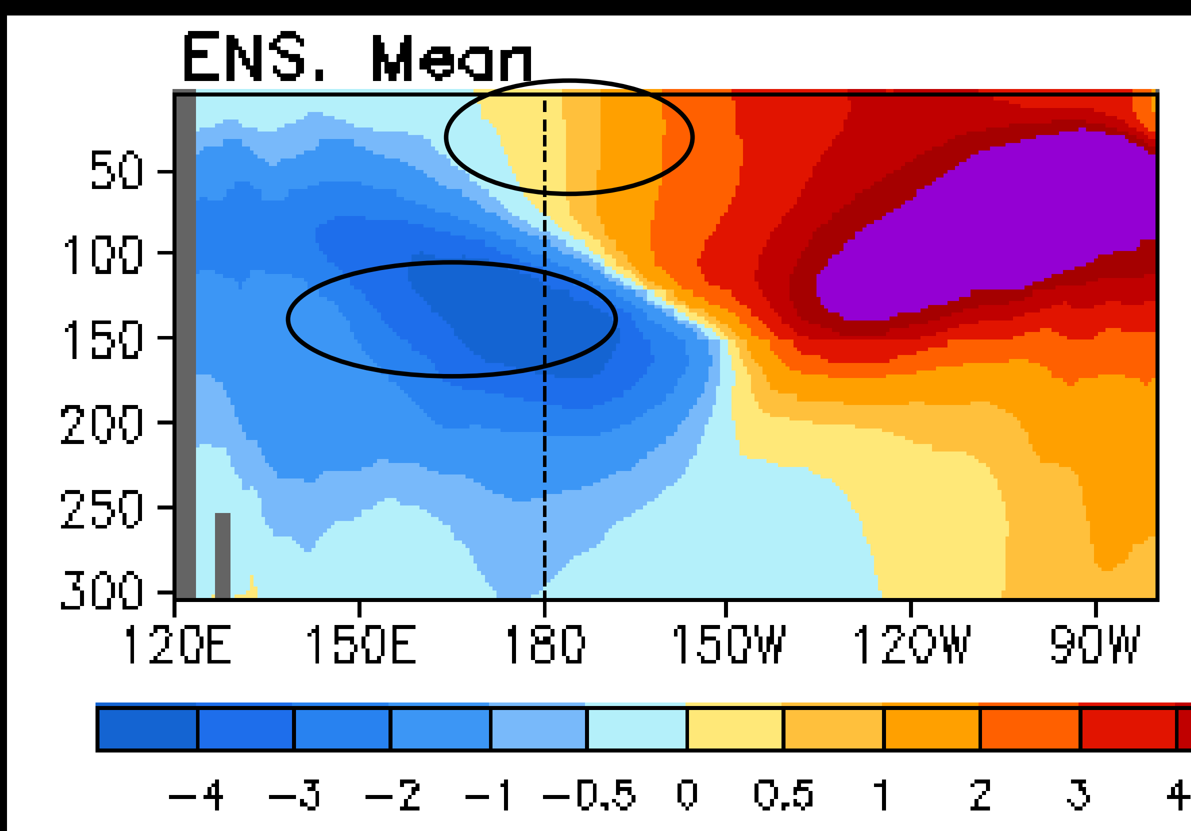


Real-time Ocean Reanalysis Intercomparison Projec

(http://www.cpc.ncep.noaa.gov/products/GODAS/multiora_body.html)

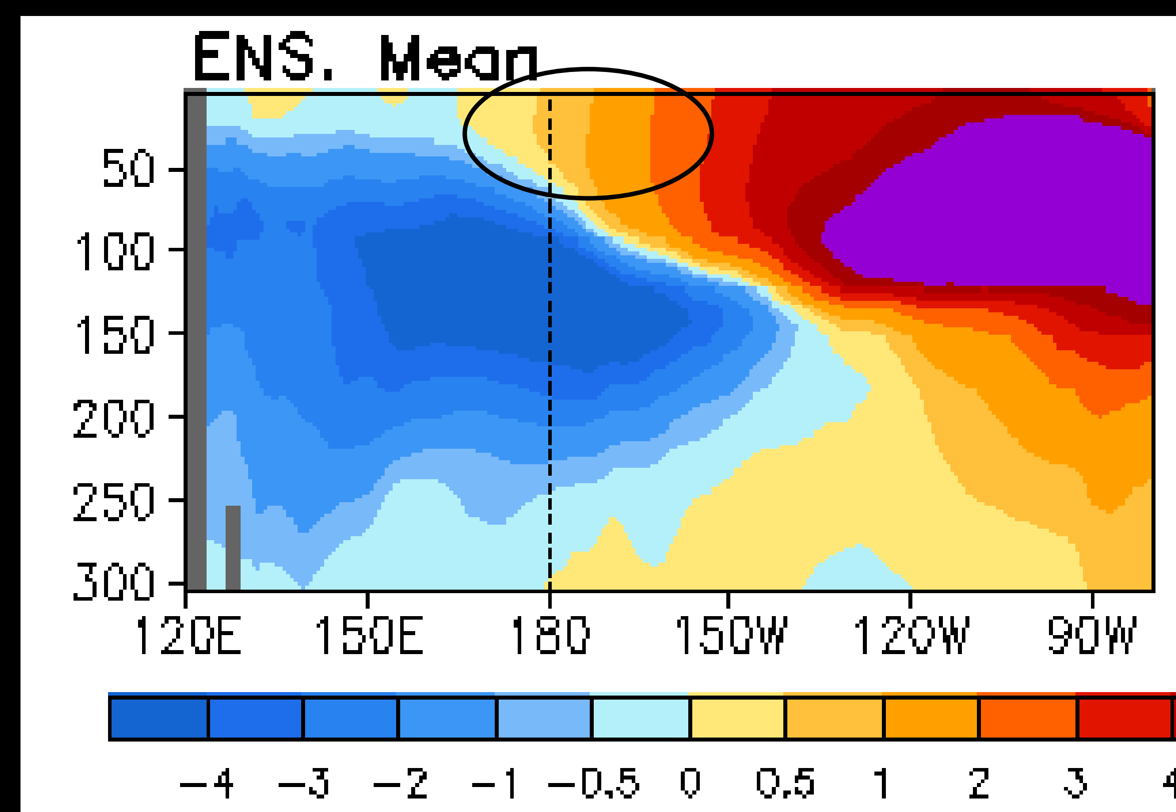
- The subsurface temperature anomaly averaged in 1ºS-1ºN in Dec 2015 was warmer (colder) in the western-central (eastern) equatorial Pacific than in Dec 1982 and 1997, suggesting a westward shift of maximum warm anomaly and overall weaker amplitude of anomaly.

Dec 1982

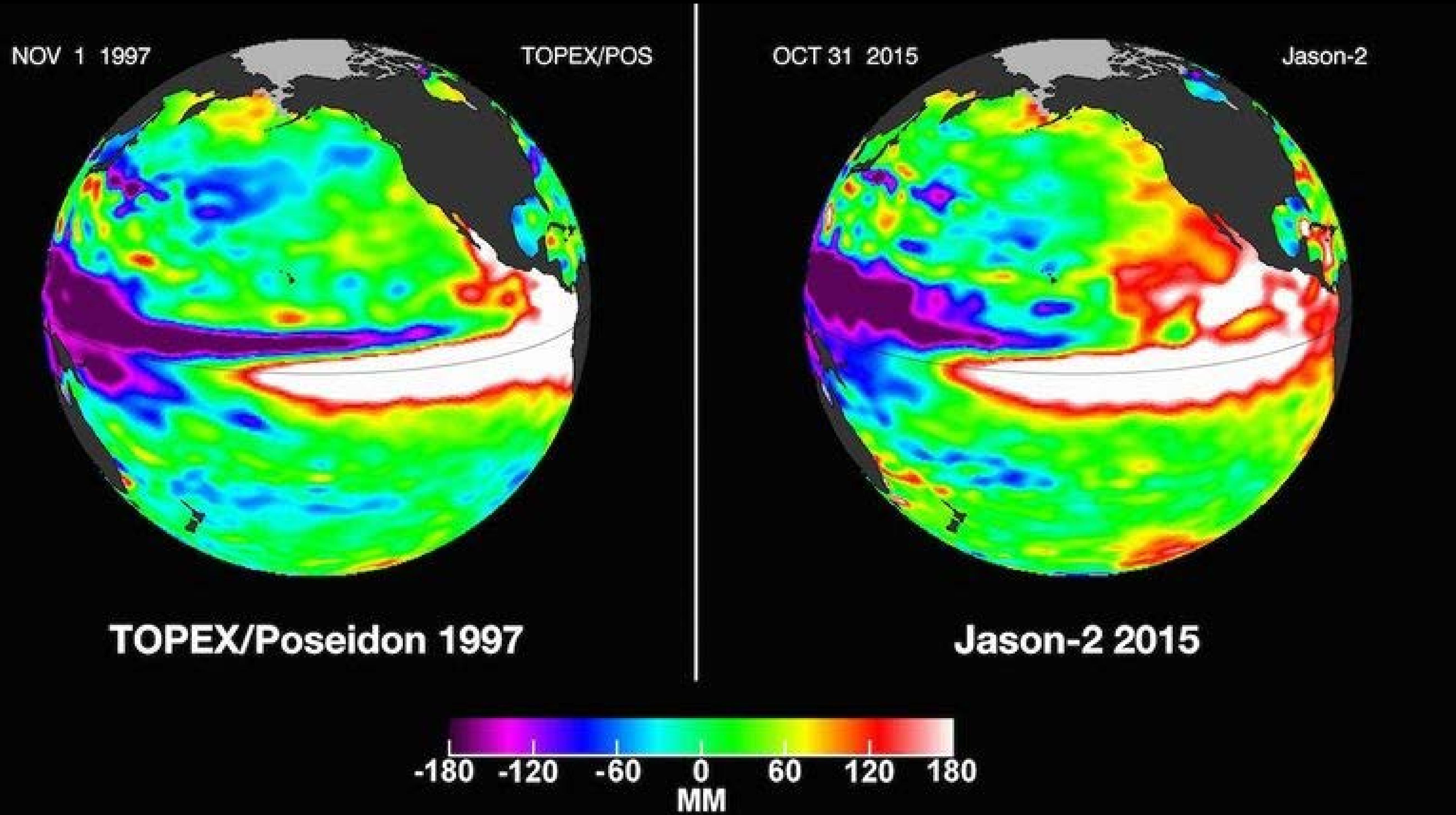


Dec 1997

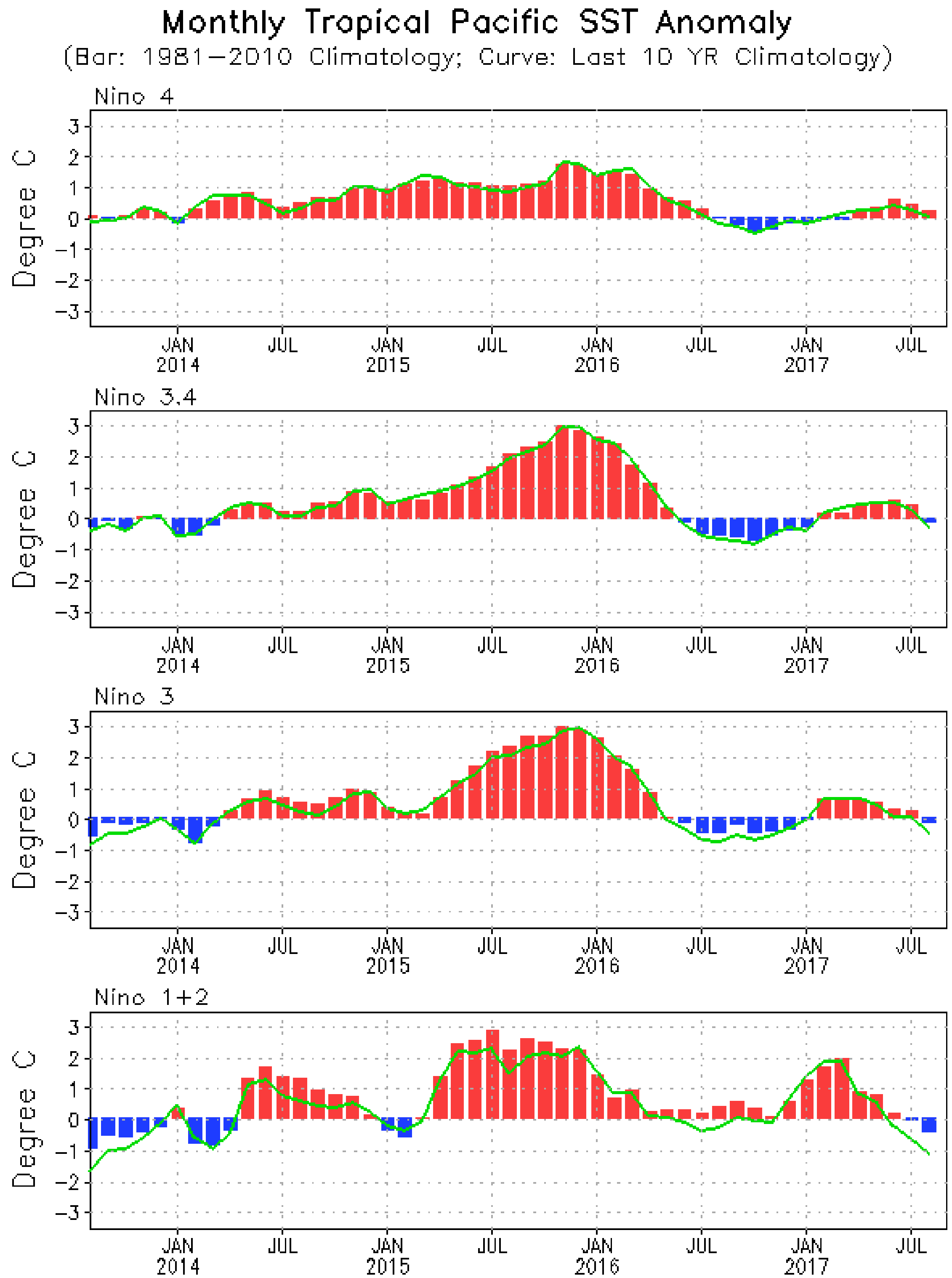
NCEP/NOAA

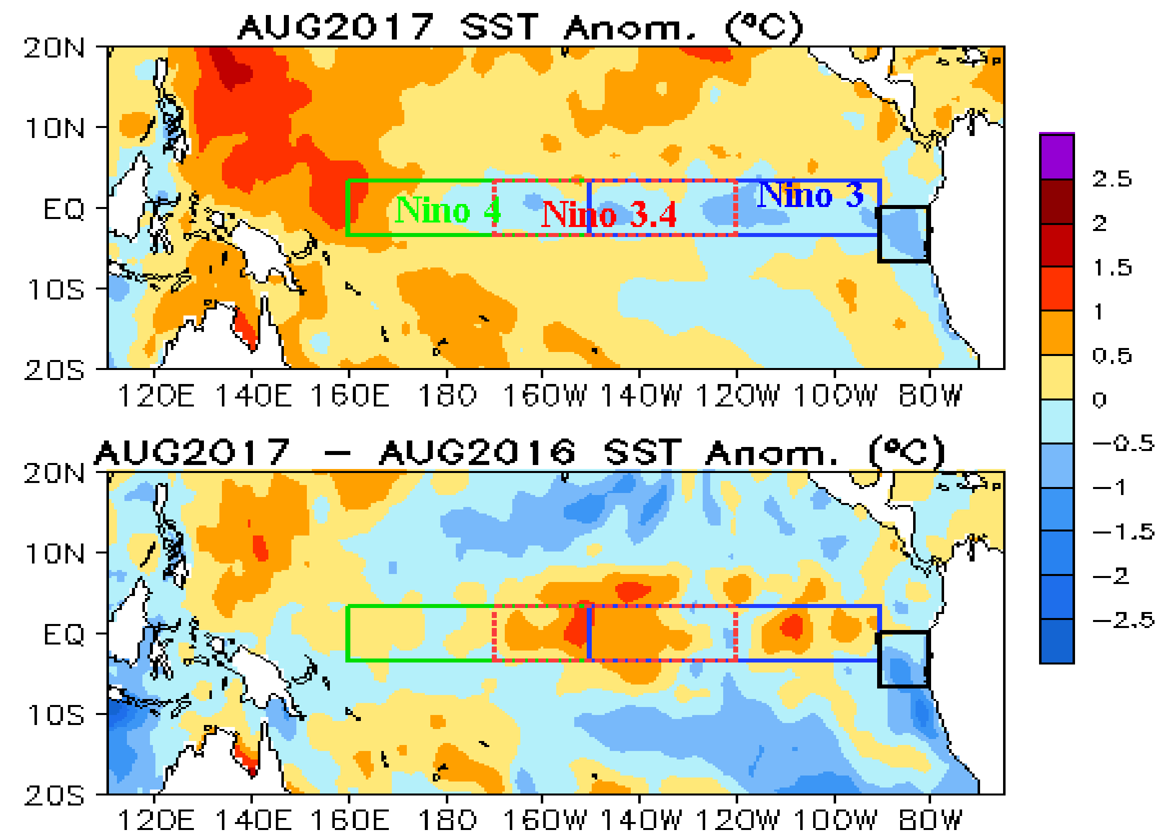


Sea level anomaly



Current (Aug 2017) evolution of Pacific NINO SST Indices





- **Nino 3.4, Nino 3 and Nino 1+2 were below-average in Aug 2017.**

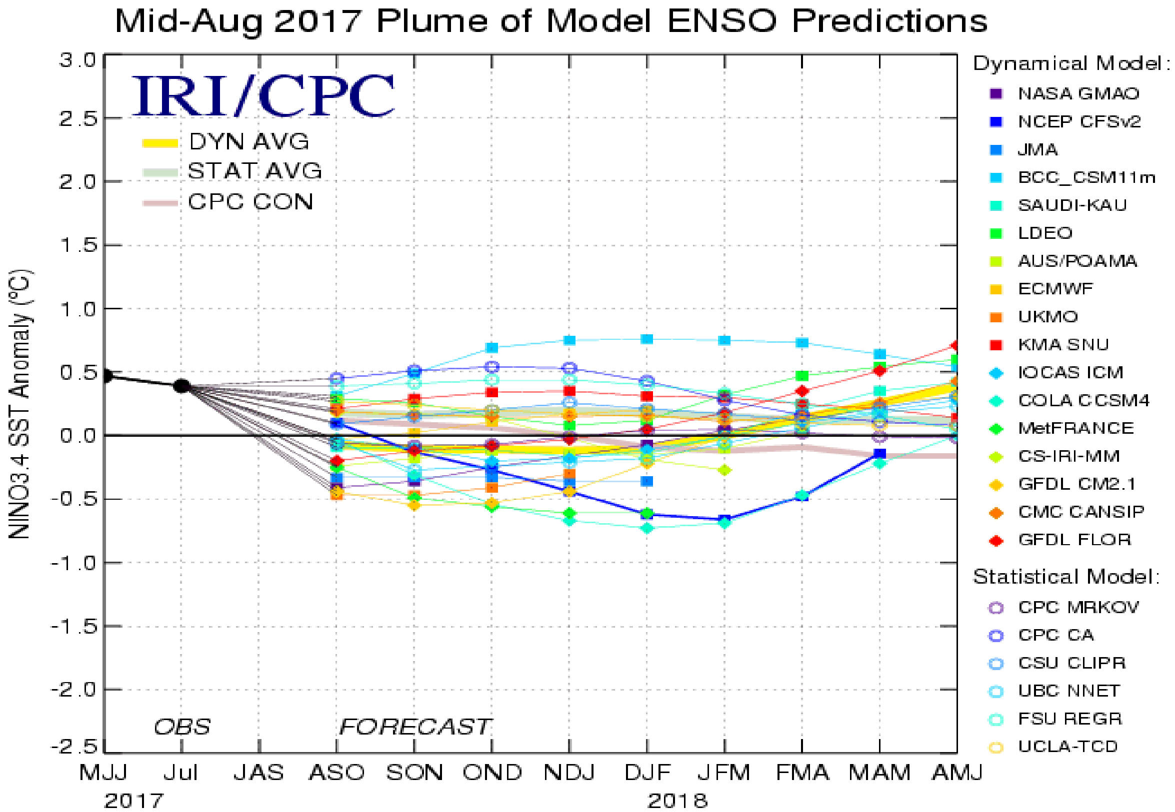
- **Nino3.4 = -0.15ºC in Aug 2017.**

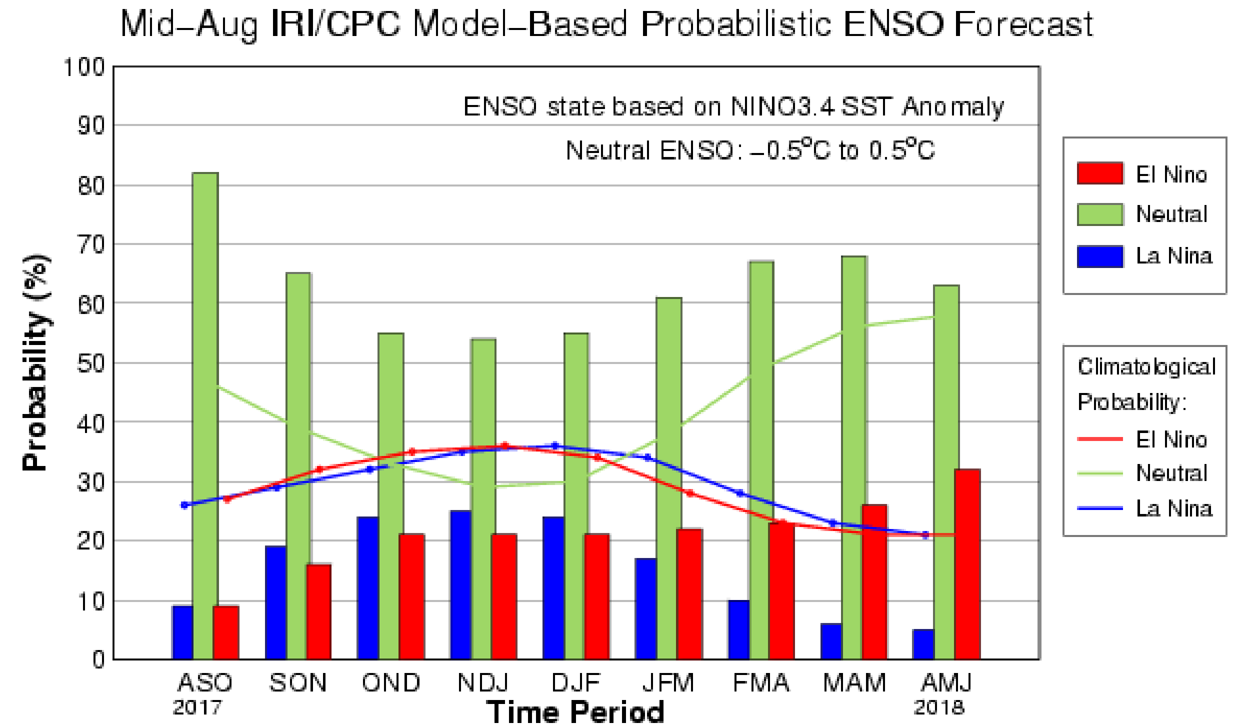
- **Compared with last Aug, the central and eastern equatorial Pacific was warmer in Aug 2017.**

- **The indices were calculated based on OISST. They may have some differences compared with those based on ERSST.v4.**

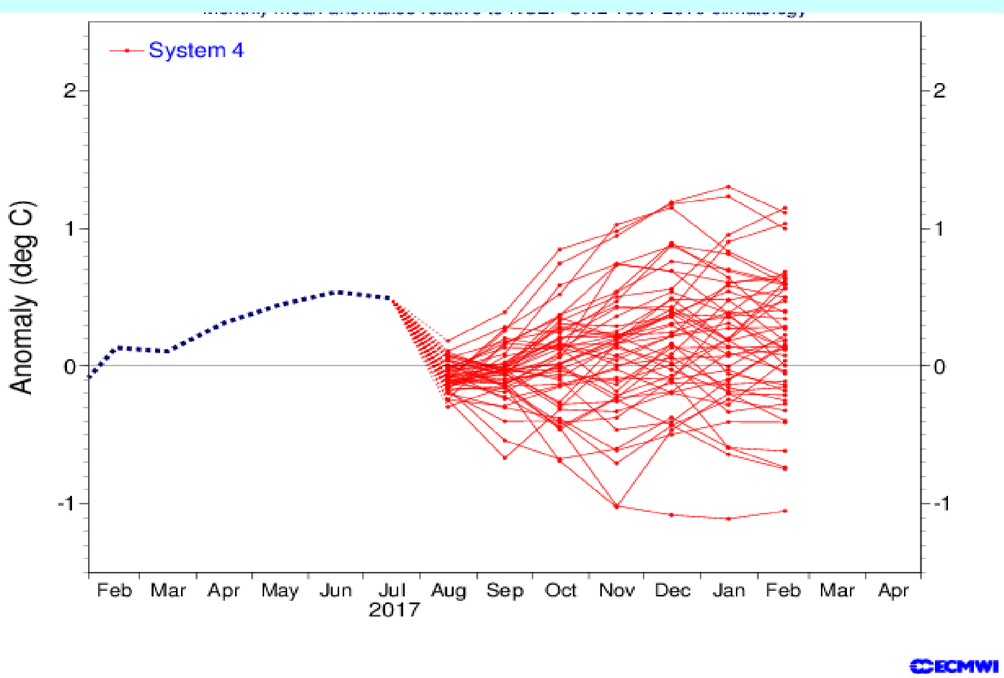
Fig. P1a. Nino region indices, calculated as the area-averaged monthly mean sea surface temperature anomalies (ºC) for the specified region. Data are derived from the NCEP OI SST analysis, and anomalies are departures from the 1981-2010 base period means.

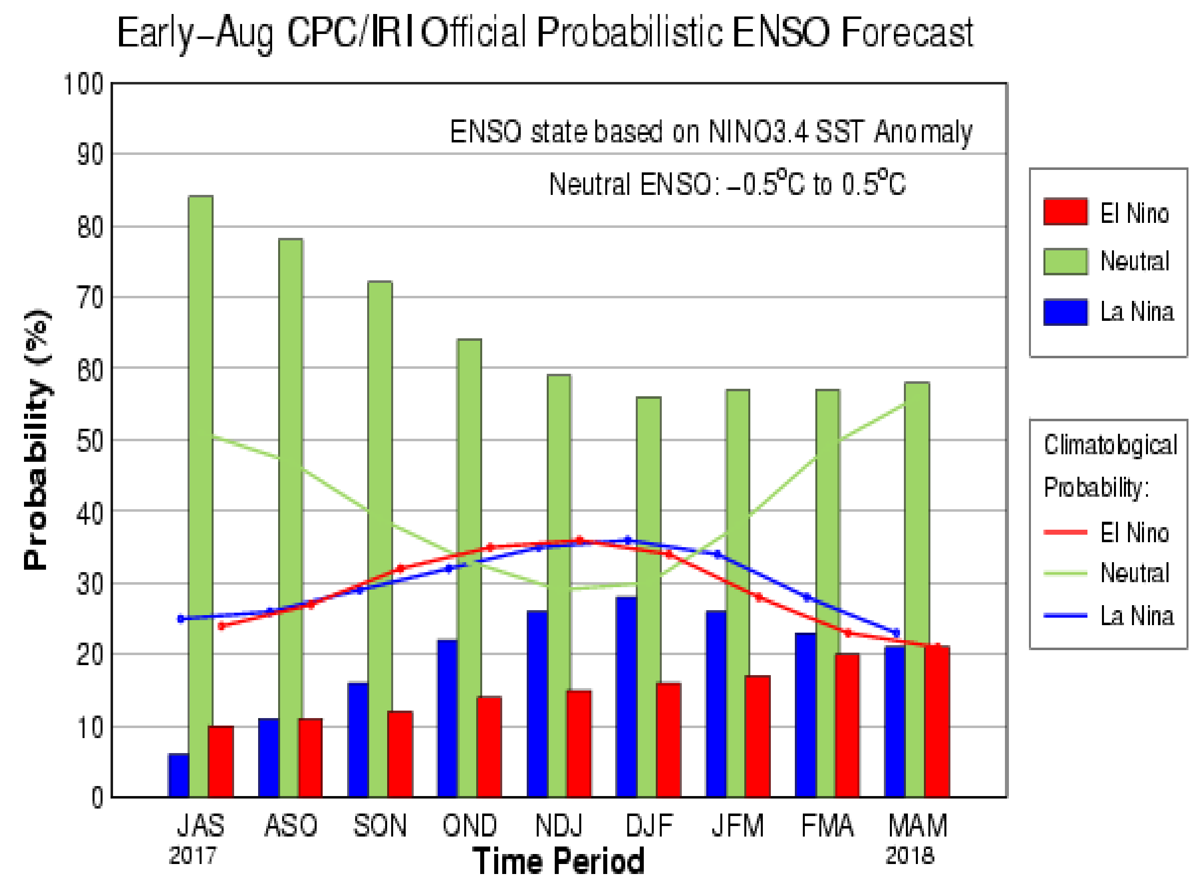
Current ENSO forecasts

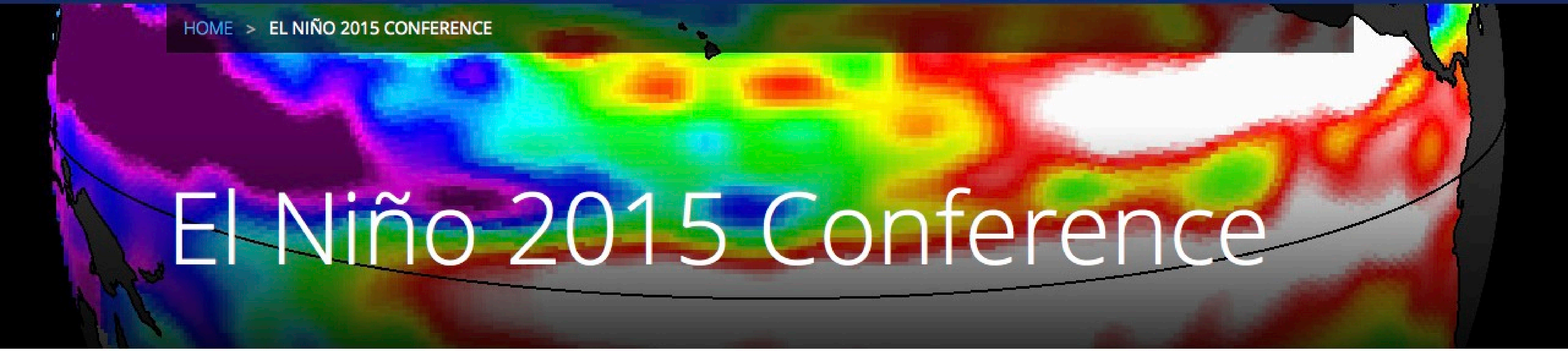




- **The majority of models favor ENSO-neutral through the Northern Hemisphere winter 2017-18 .**







El Niño 2015 Conference

Shared Experiences: 20 Years of Climate Services and Framing the Next Steps in the Research and Development for Climate Resilience

To view the recordings of the videos, please click on the following links. There are some technical problems with Day 1, and it ends around 12:30. We are working on resolving this. Please contact the IRI webmaster <webmaster@iri.columbia.edu> if you want to be notified when the issue is resolved.

Recording of Day 1: https://livestream.com/LDEO/IRI-elninoconf-1

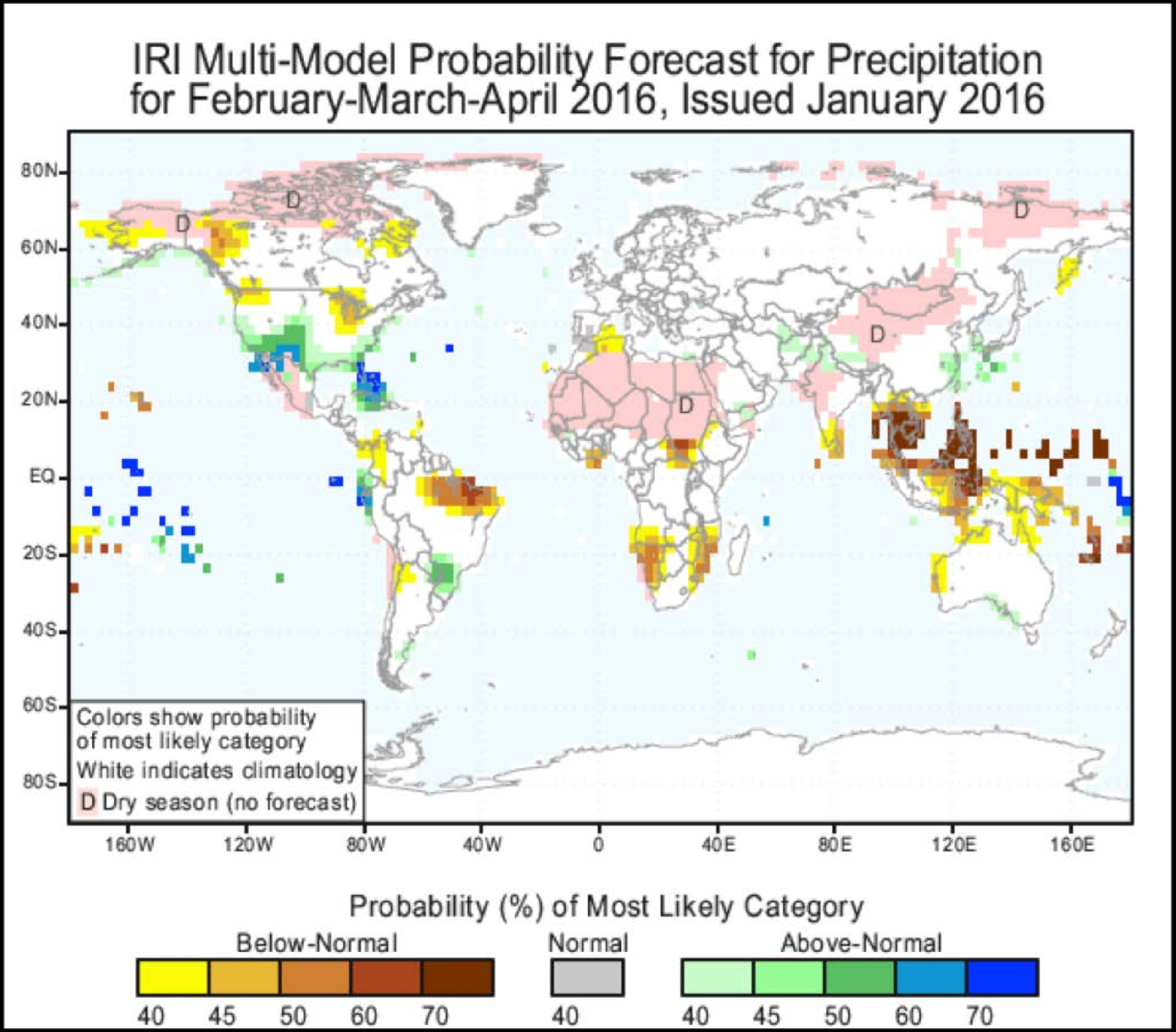
Recording of Day 2: https://livestream.com/LDEO/IRI-elninoconf-2

Full Agenda

IRI WMO OMM USAID FROM THE AMERICAN PEOPLE NOAA

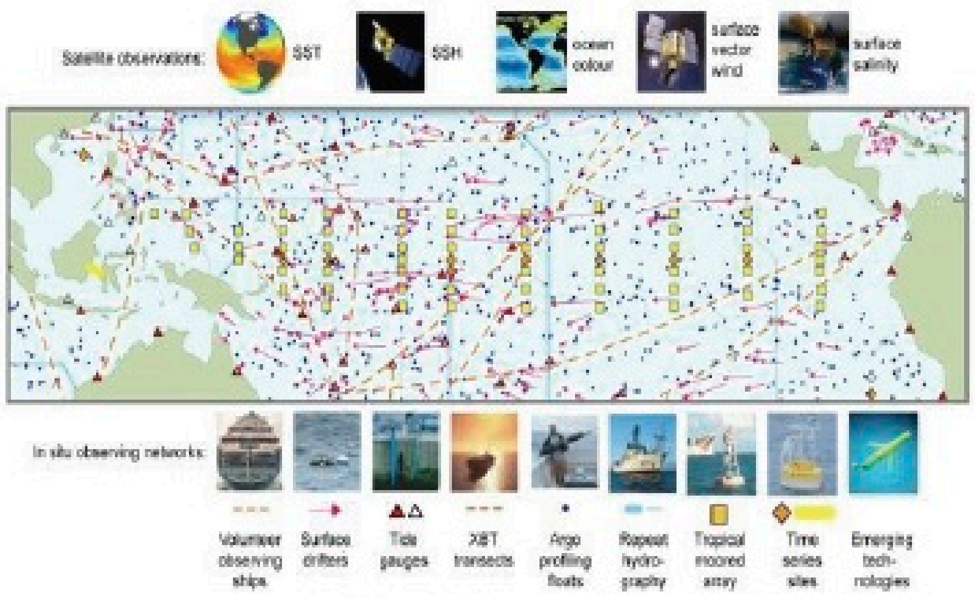
Tuesday, November 17 – Wednesday, November 18, 2015

El Niño 2015-2016: precipitation anomaly forec



Predicting El Niño in Peru

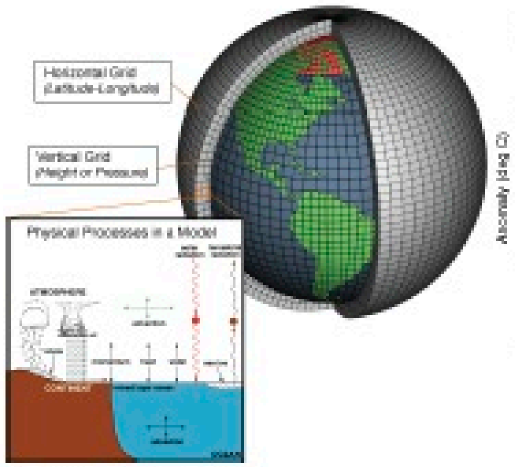
Observational data

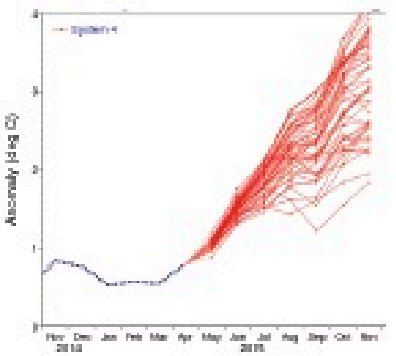


Expert assessment

Scientific knowledge

Climate model forecasts

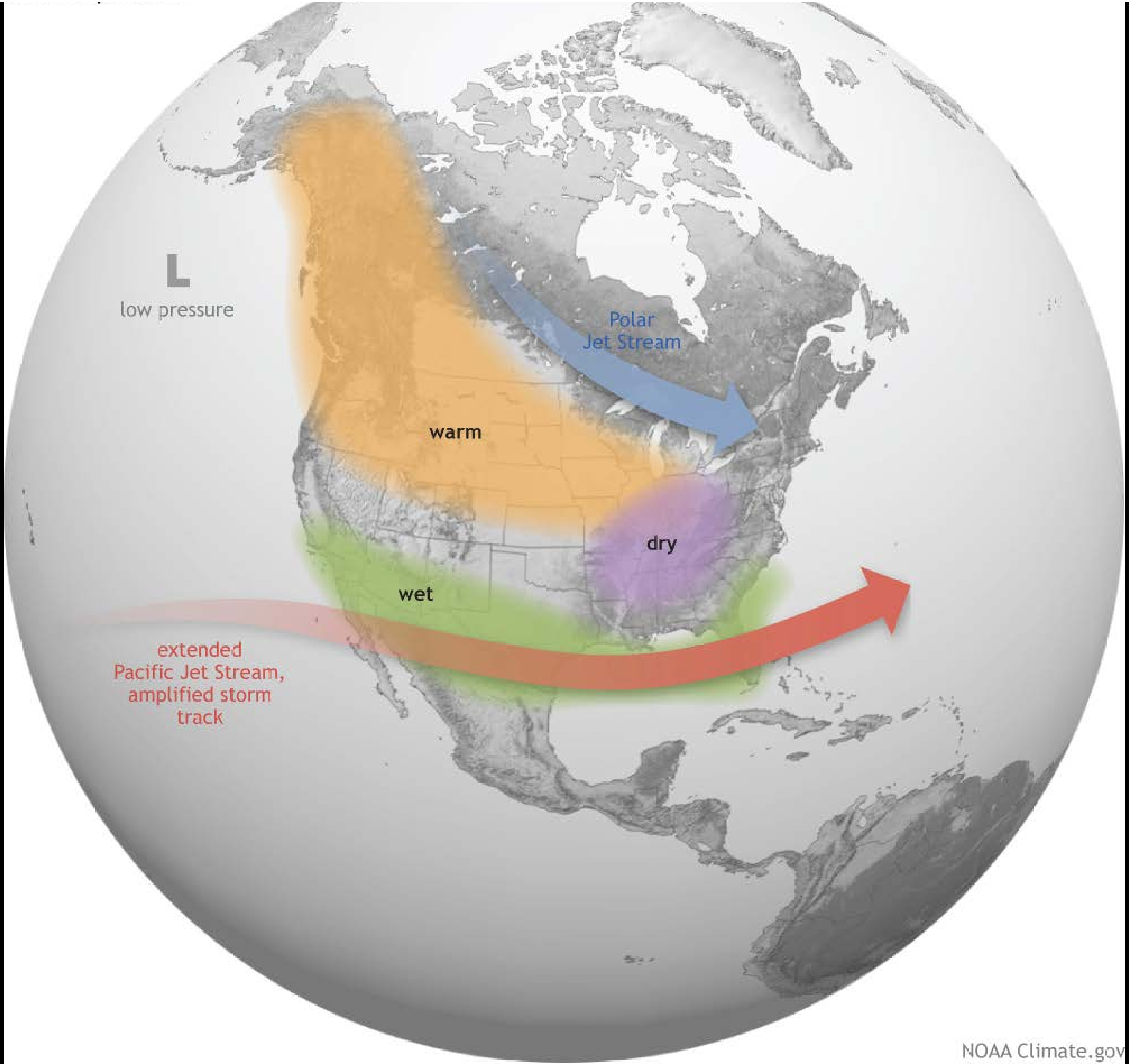


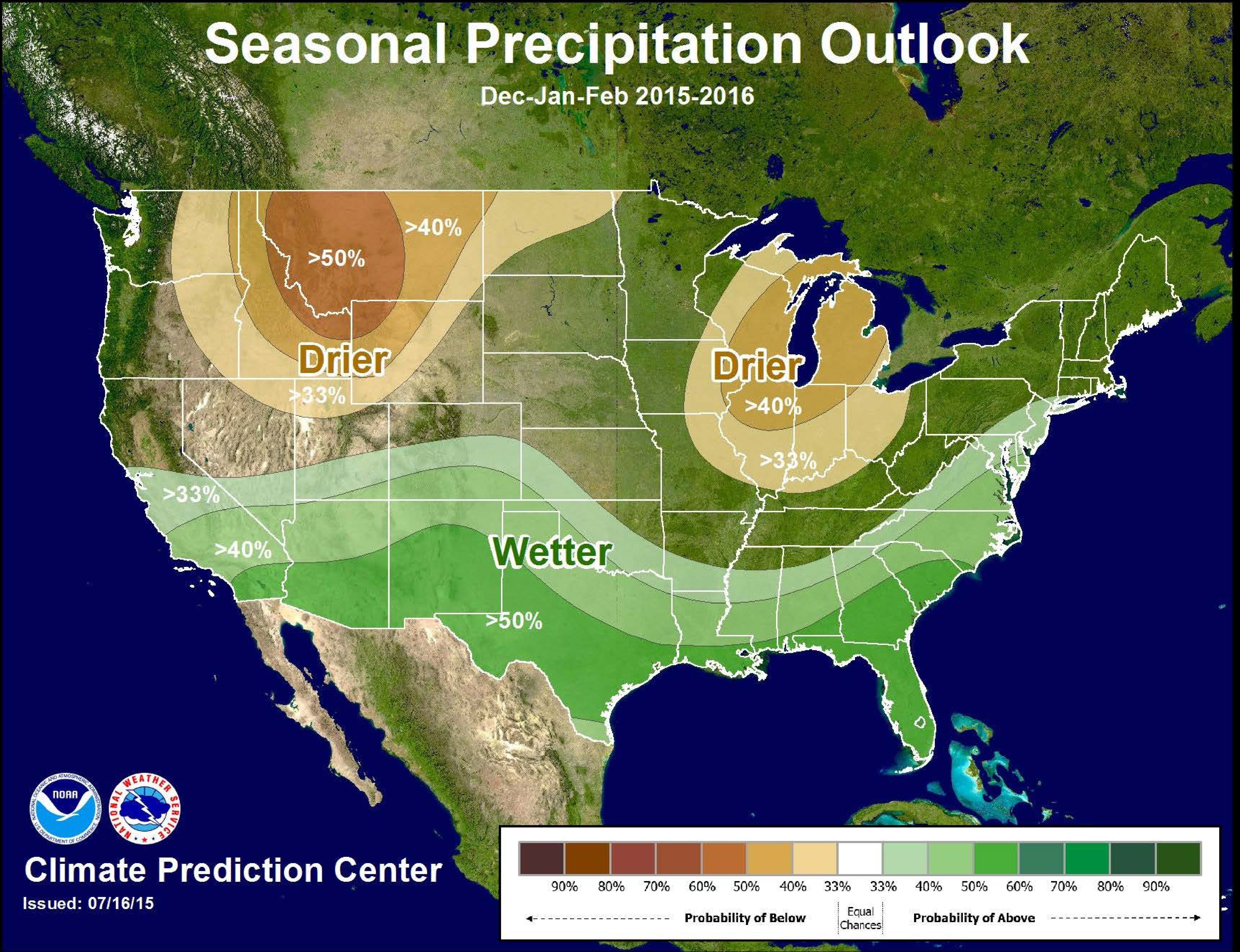


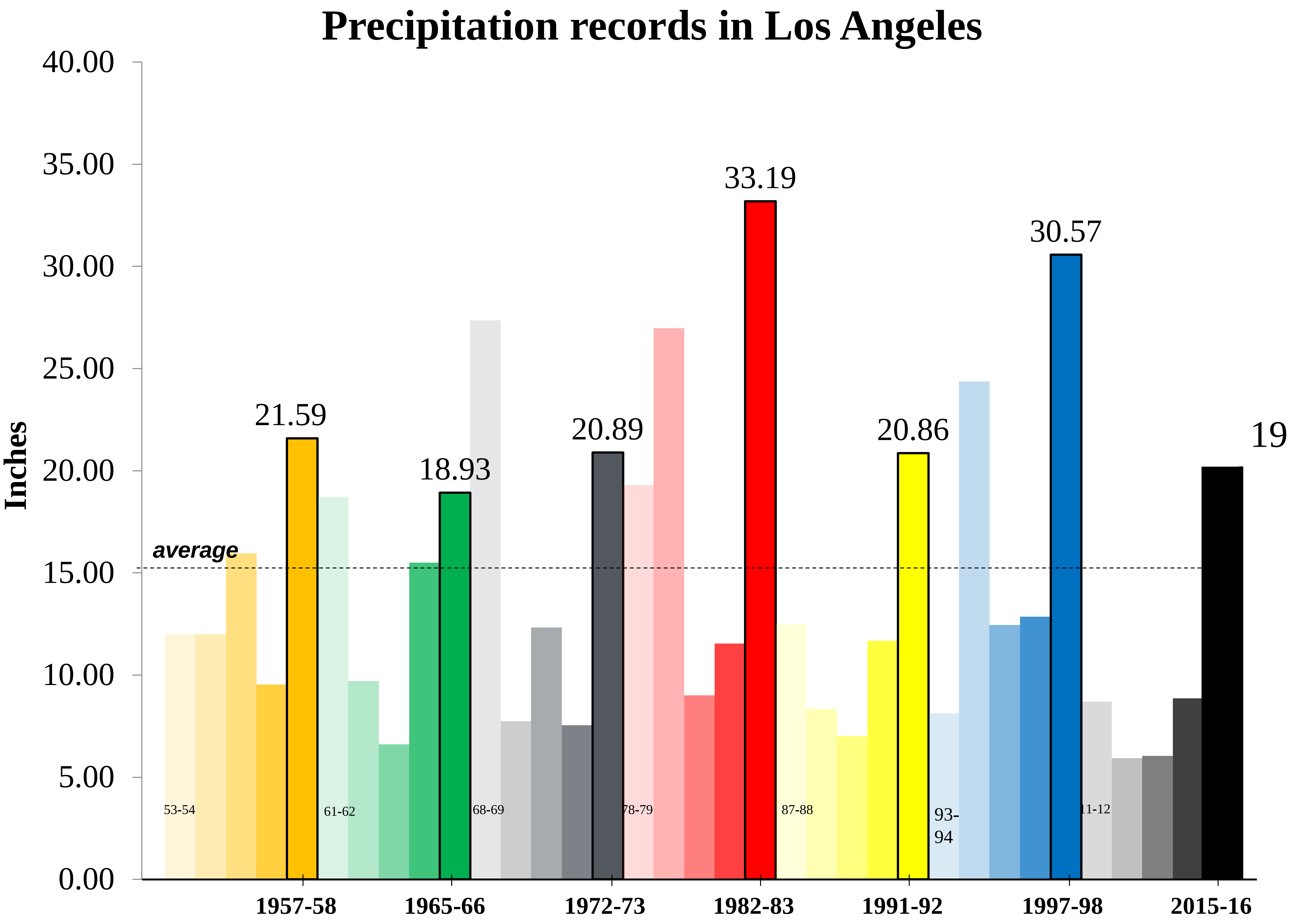
Prediction

Magnitud del evento durante diciembre 2015-marzo2016	Probabilidad de ocurrencia
Normal o La Niña costera	5%
El Niño costero débil	5%
El Niño costero moderado	40%
El Niño costero fuerte (como en 1982-1983)	45%
El Niño costero extraordinario (como en 1997-1998)	5%

Winter impact of El Niño in North America

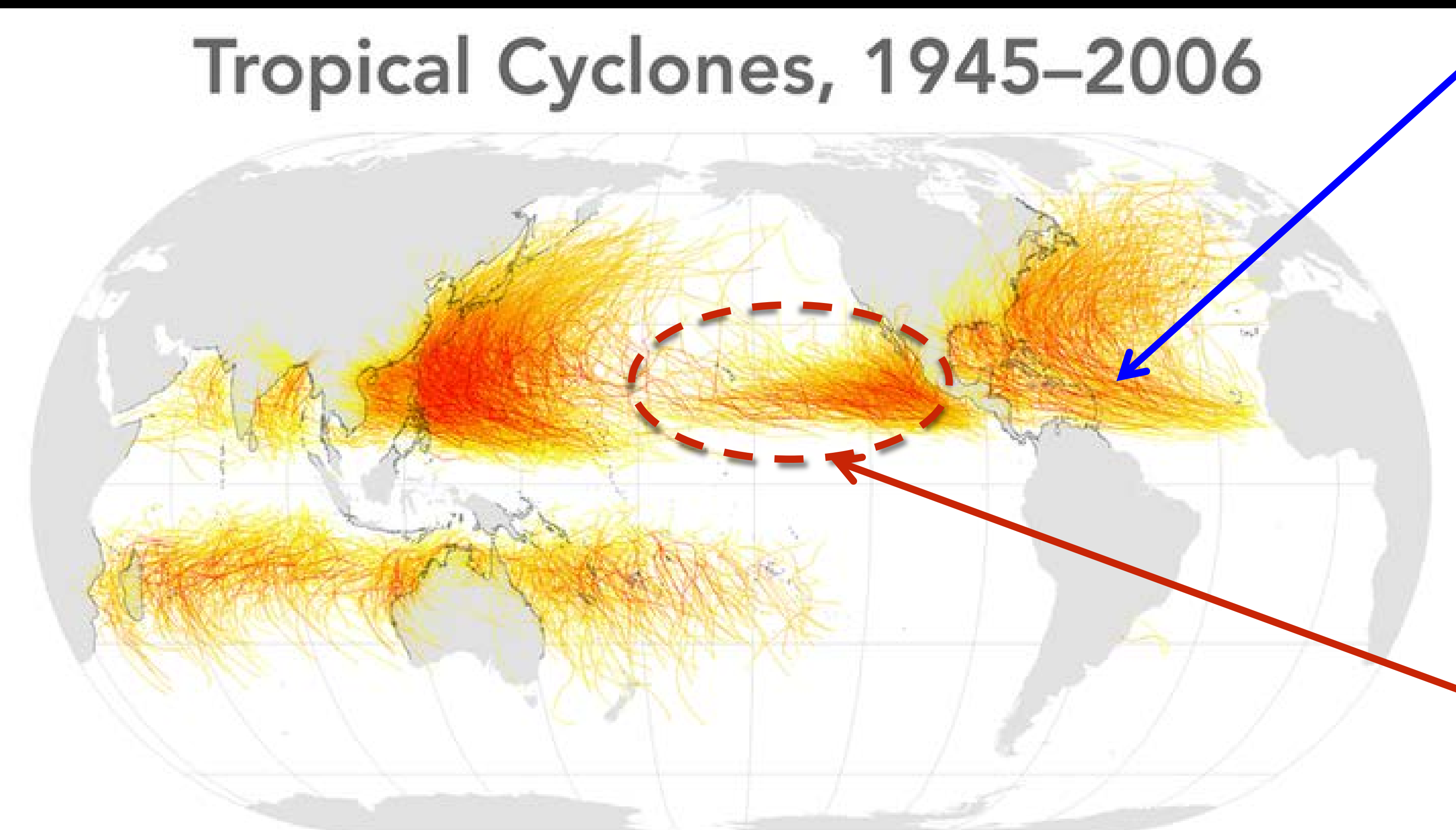


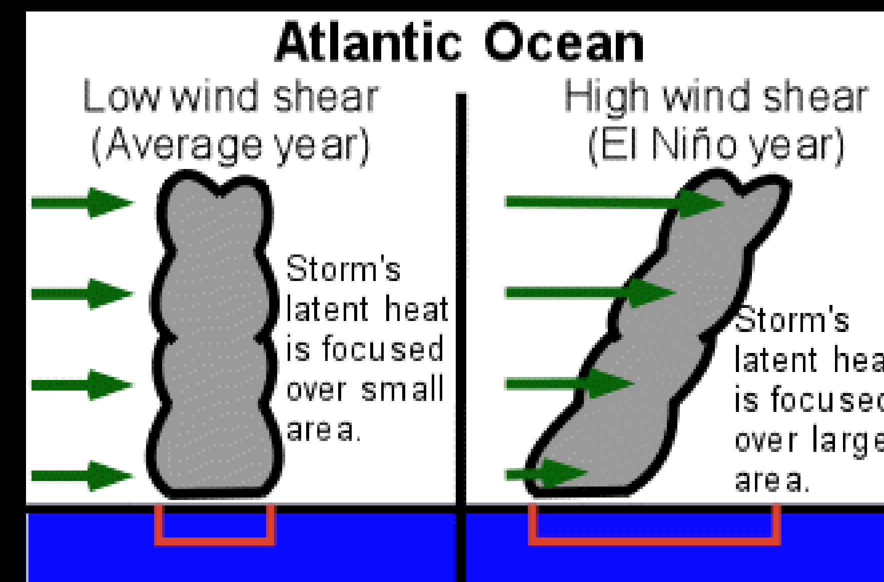

Seasonal Precipitation Outlook
Dec-Jan-Feb 2015-2016
>50%
>40%
Drier
>33%
Drier
>40%
>33%
>33%
>40%
Wetter
>50%
Climate Prediction Center
Issued: 07/16/15
90% 80% 70% 60% 50% 40% 33% 33% 40% 50% 60% 70% 80% 90%
Probability of Below
Equal Chances
Probability of Above


Precipitation records in Los Angeles
Inches
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
average
21.59
18.93
20.89
33.19
20.86
30.57
19
53-54
61-62
68-69
78-79
87-88
93-94
11-12
1957-58
1965-66
1972-73
1982-83
1991-92
1997-98
2015-16

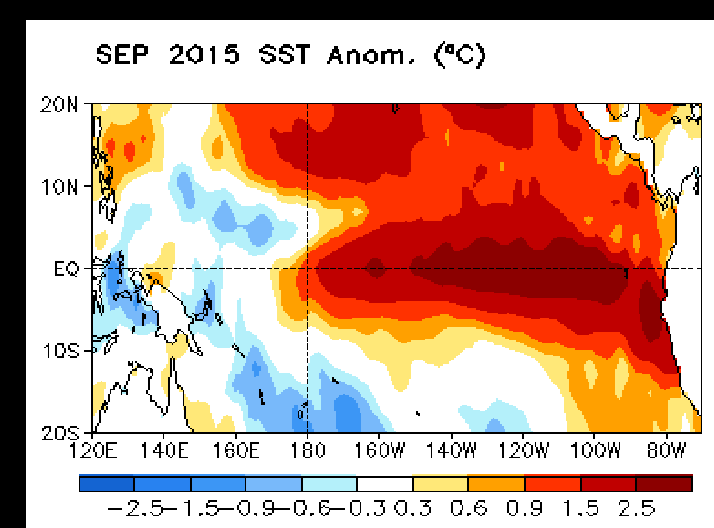
Impacts of El Niño on tropical cyclones

Reduction





Increased activity



2015: 23 tropical cyclones over the Pacific

- Previous record: 18
- Patricia: strongest cyclone ever recorded (320 km/h)

… until Irma in Sept. 2017 (360 km/h)

ENSO and climate change

Two possible links:

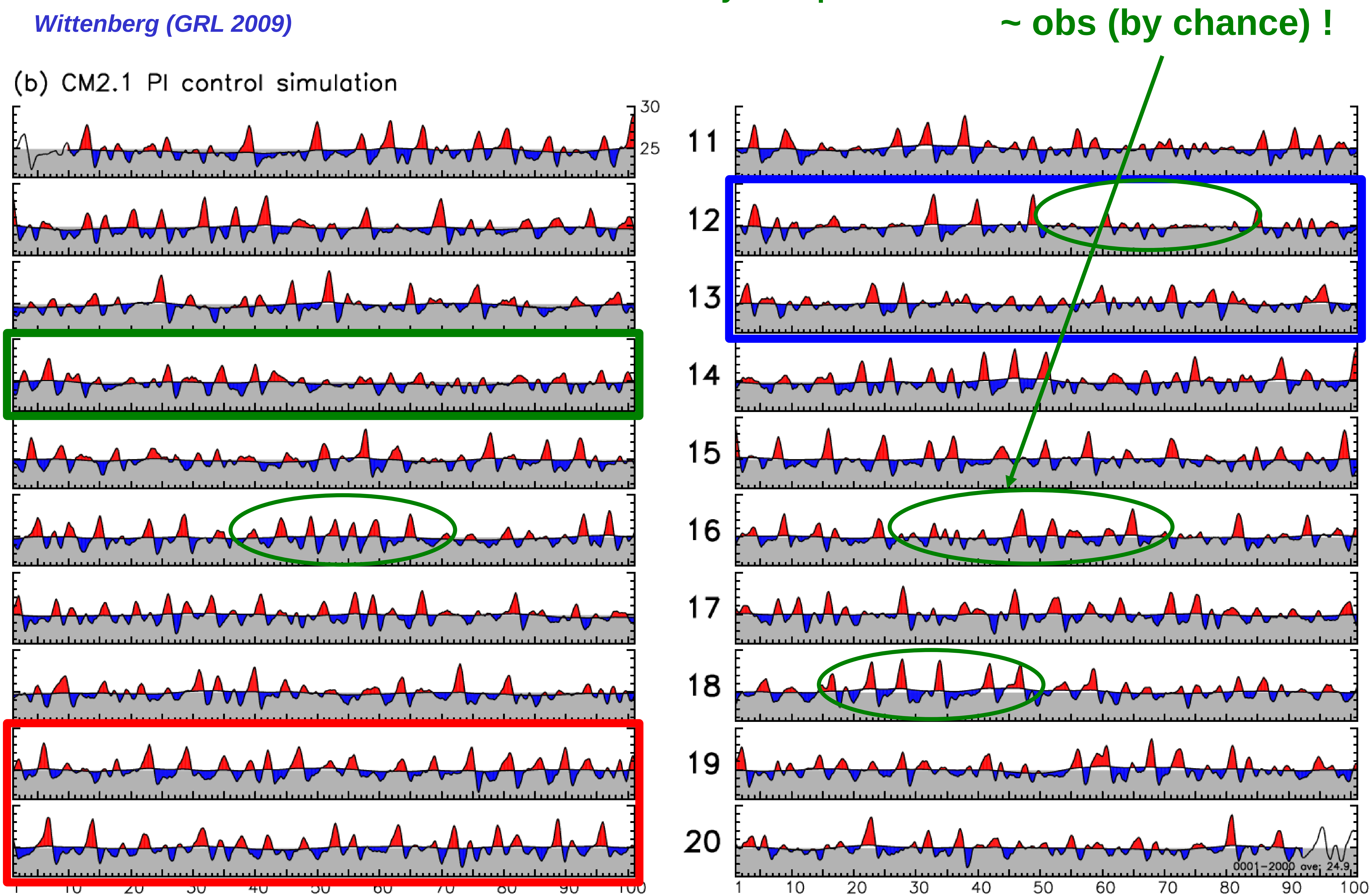
1. **El Niño impacts are modified**
    - **Warmer atmosphere holds more moisture**
    - **Precipitation anomalies and floods more intense**
    - **More and stronger tropical cyclones**

2. **El Niño itself can change**

20 centuries of NINO3 SSTs in GFDL 2.1

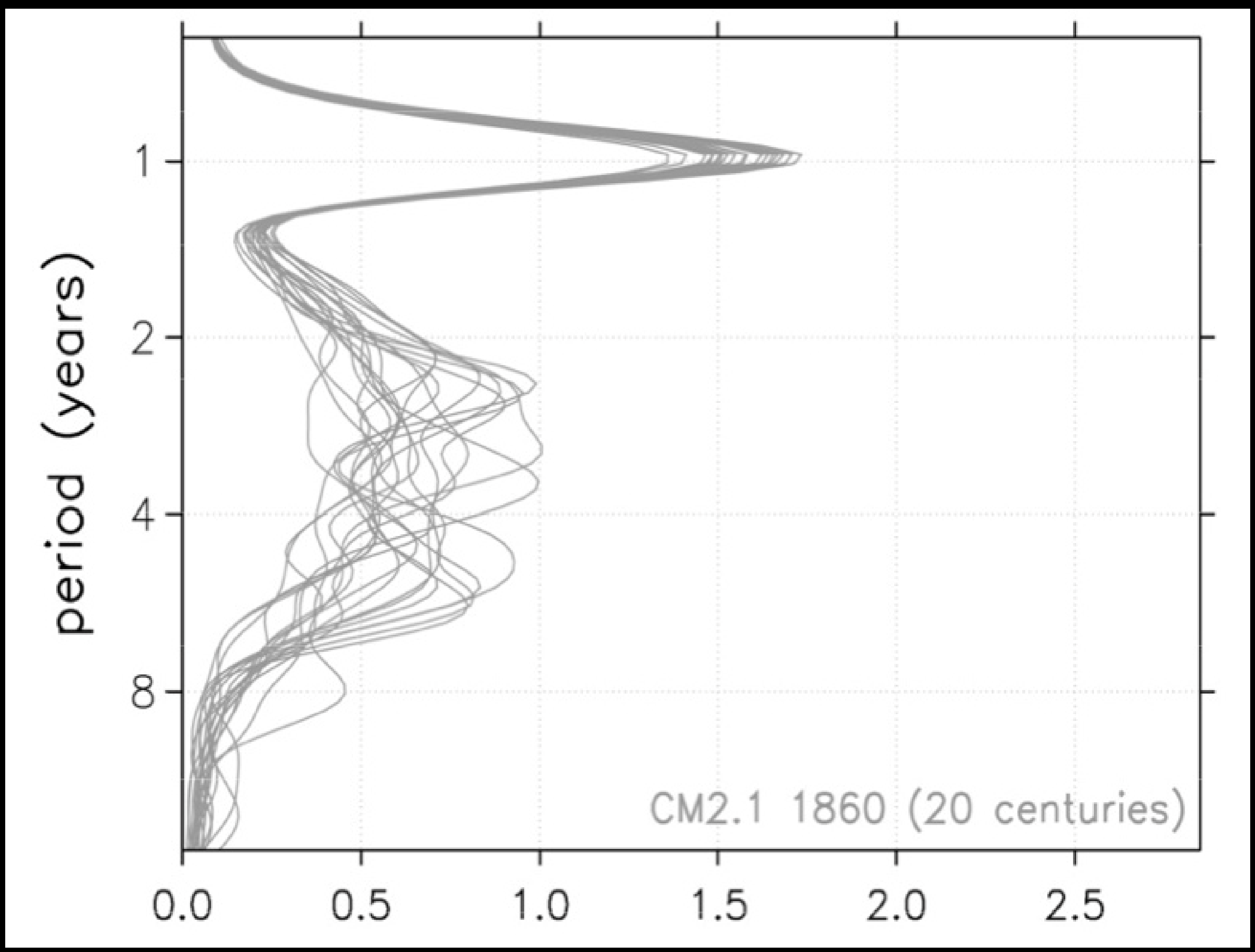
annual means & 20yr low-pass

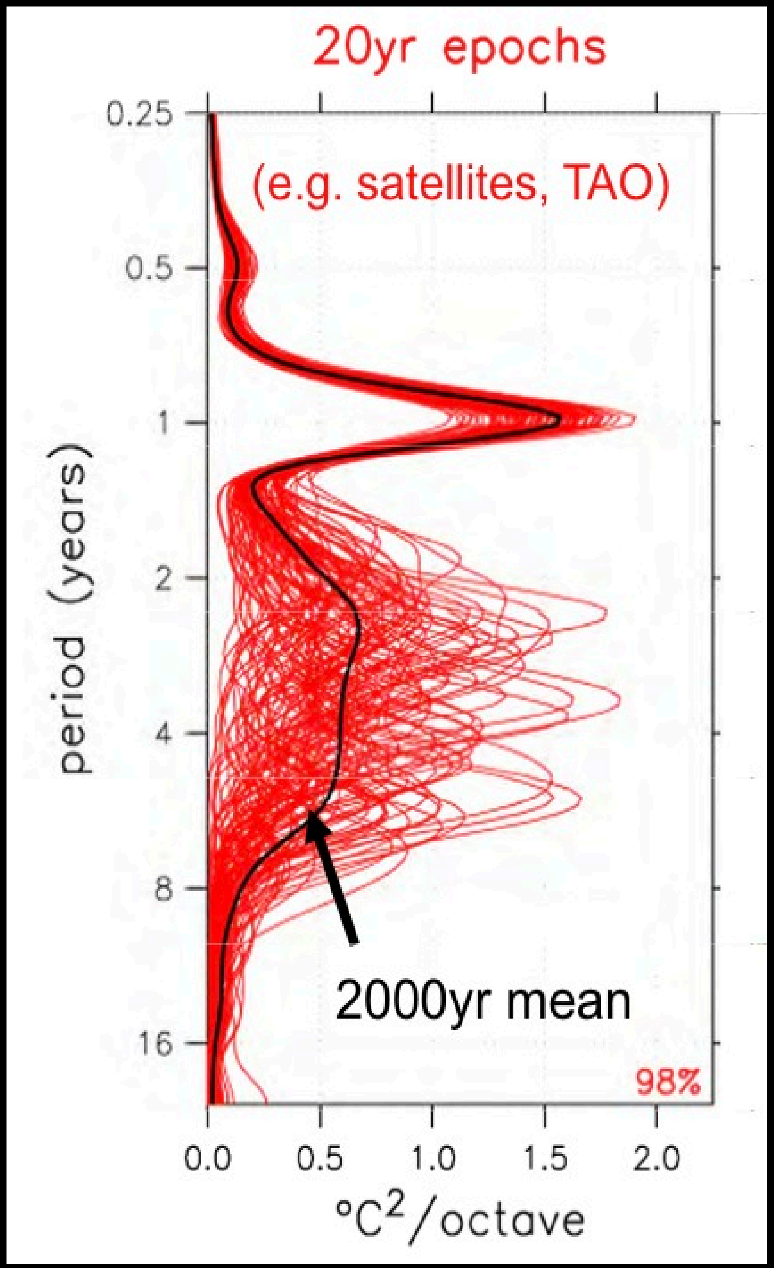
Wittenberg (GRL 2009)



How long do we need to observe El Niño to detect a change ?

100y epochs





2000 years simulation GFDL 2.1

Wittenberg (GRL 2009)

How long do we need to observe El Niño to detect a change ?

TABLE 1. Dependence of the 90% WPI confidence interval width on model subinterval length, from confidence intervals averaged over the 2–6-yr band. The $\Delta\beta_0$ and $\Delta\beta_1$ refer to the bounds of the 90% confidence intervals on those coefficients; L_{min} is the minimum length required to achieve 90% convergence in Niño-3.4 statistics for each model and ΔL_{min} is the range between the upper and lower limits on L_{min}.

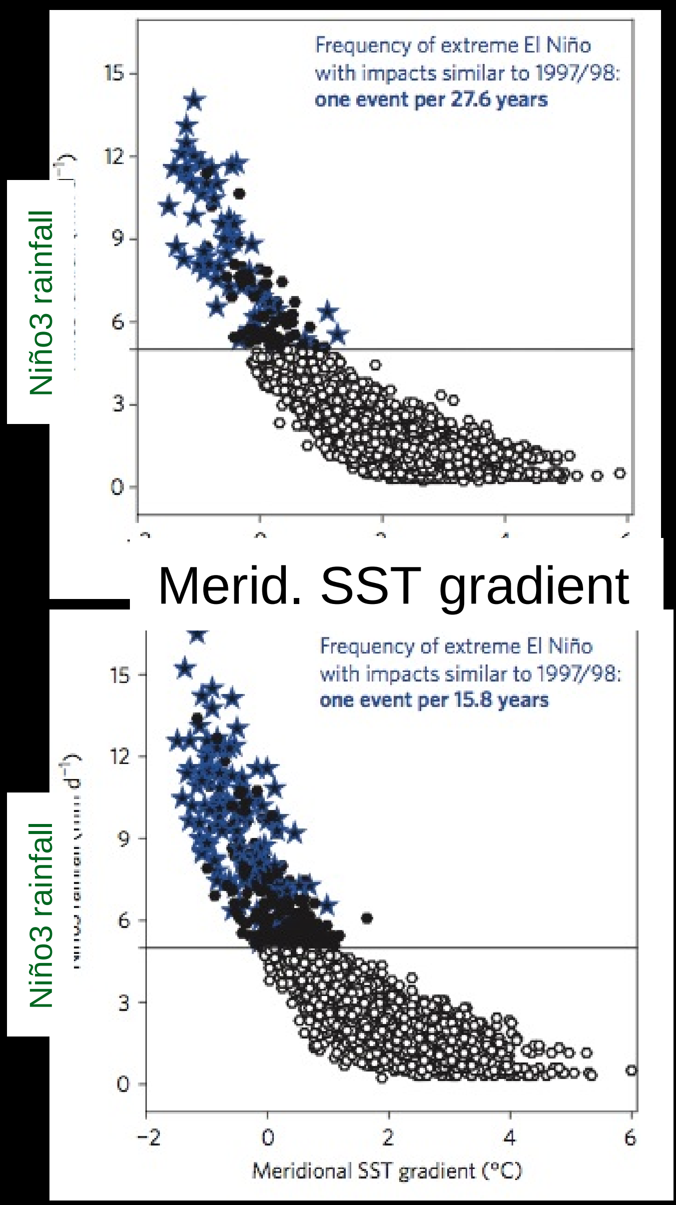
Simulation	β_0	β_1	$\Delta\beta_0$	$\Delta\beta_1$	L_{min}	ΔL_{min}
CCSMcontrol	−0.891	−0.0057	−1.09 to −0.694	−0.0067 to −0.0047	247	180–342
GFDL CM2.1	−0.956	−0.0042	−1.06 to −0.852	−0.048 to −0.0037	320	258–391
IPSL CM4	−0.504	−0.0048	−0.683 to −0.324	−0.0057 to −0.0039	374	283–507

Stevenson et al. (2010)

Minimum length of simulation needed to distinguish ENSO amplitude change: 250-300 years !

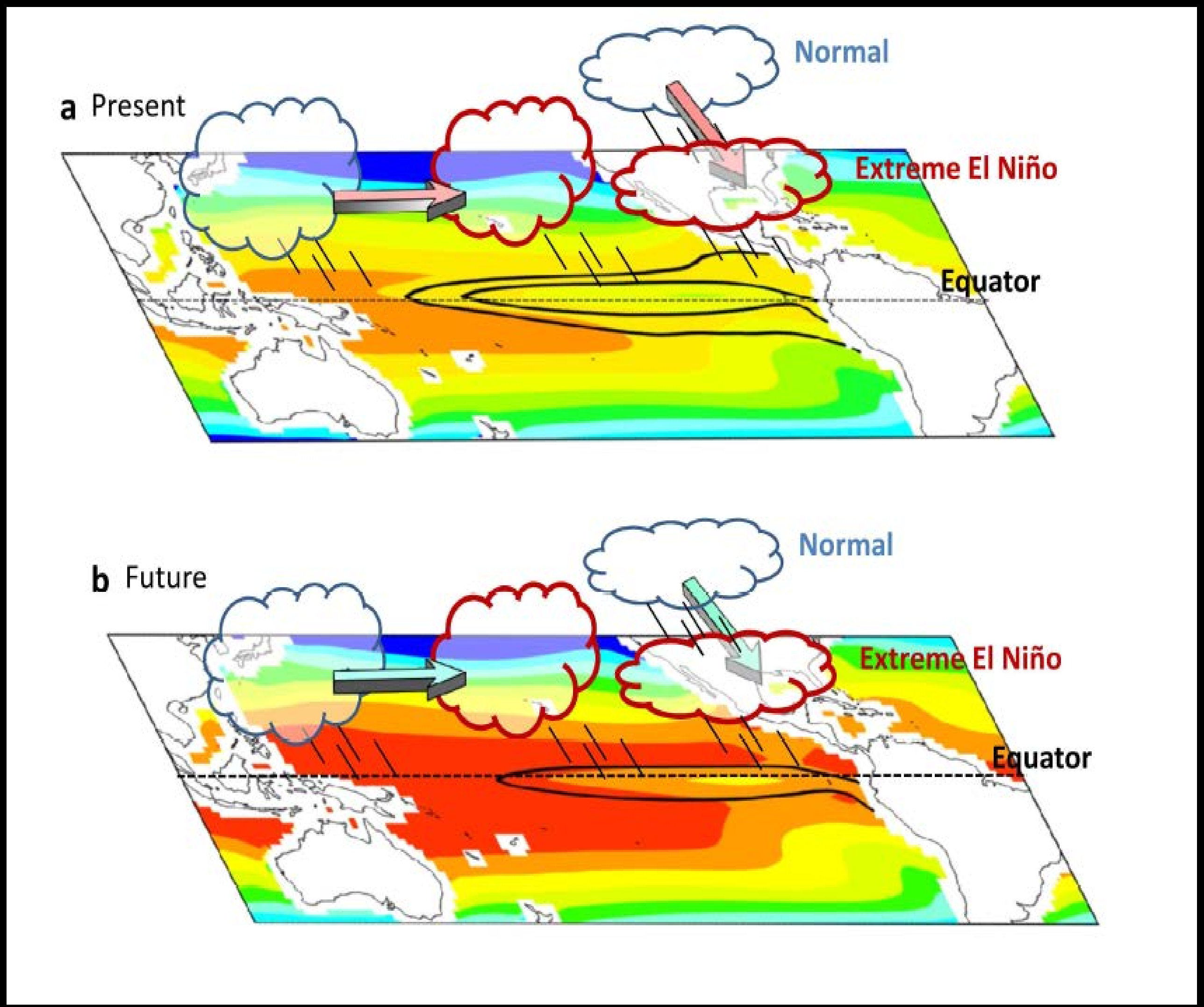
ENSO in changing climate

- No change of *mean* El Niño SST statistics from CMIP scenario
- Using a process-based criteria (rainfall > 5 mm/day in east Pacific)
- Doubling of occurrence of extreme El Niños in unmitigated climate change



Historical
1 extreme El Niño out of 6 events

RCP8.5
1 extreme El Niño out of 3 events



Cai et al. (2014, 2015)

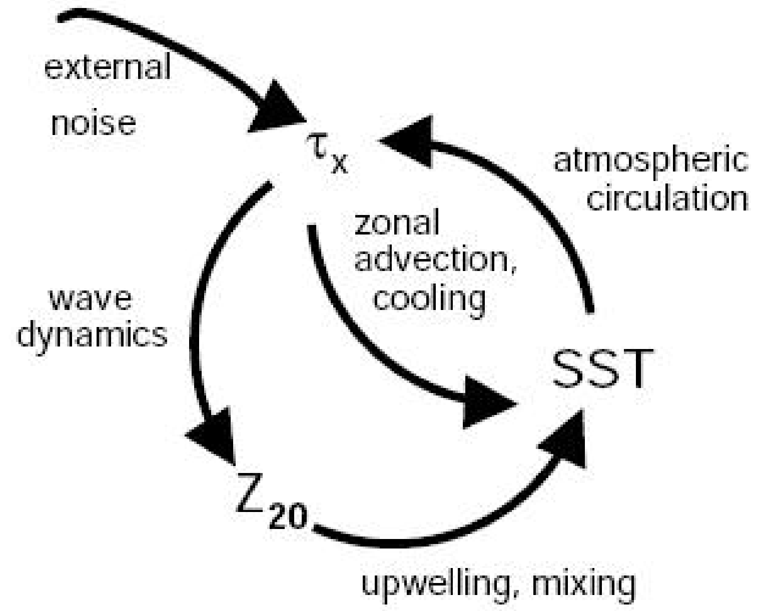
- But no change before 2050 or under RCP2.6

Will ENSO change ? – some thoughts

- Local impacts of climate change strongly influenced by ENSO and its potential changes
- ENSO in a changing climate:
  - Model ENSO right for the right reasons (correct processes)
  - Better processes, and ENSO, also come with better mean state
  - To understand if ENSO has changed, statistics will only help us in 200+ years. In the mean time we have to rely on physical understanding
  - Model evidence of increased frequency of extreme El Niño in RCP8.5
- But still many open science questions

Part 2: ENSO mechanisms, extreme events and role of intraseasonal variations

ENSO mechanisms



van Oldenborgh al. 2005

Atmosphere response to SSTA

- **Bjerknes wind stress feedback**
- **Heat flux feedbacks**

Non linear processes:

- **NL dynamical heating ($\square_x$T + U in phase)**
- **"Multiplicative noise" - WWE**

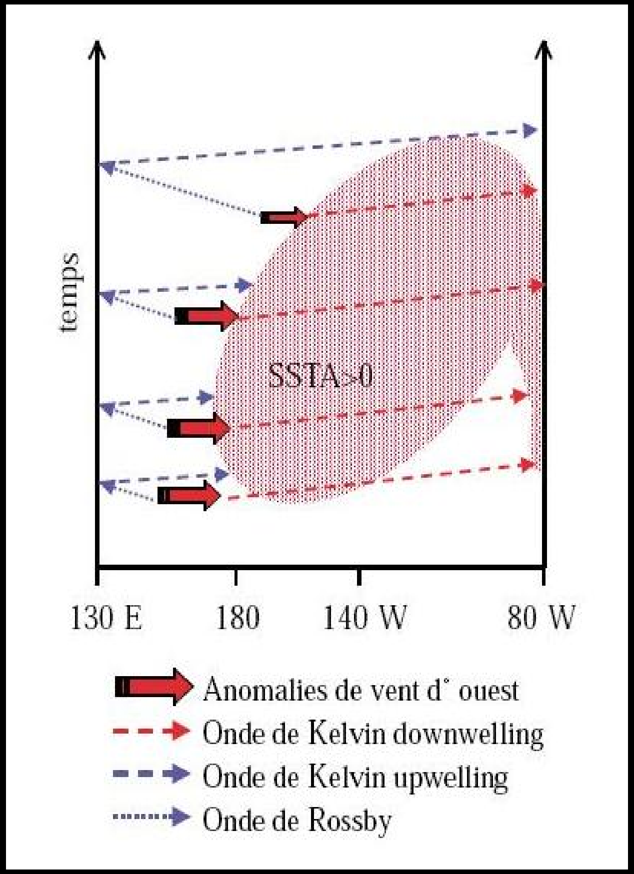
Ocean response to | and HF anomalies

- **Upwelling, mixing,** ("thermocline feedback", "cold tongue dynamics")
- **Zonal advection**
- **Wave dynamics**
- **Energy Dissipation**

El Niño theories

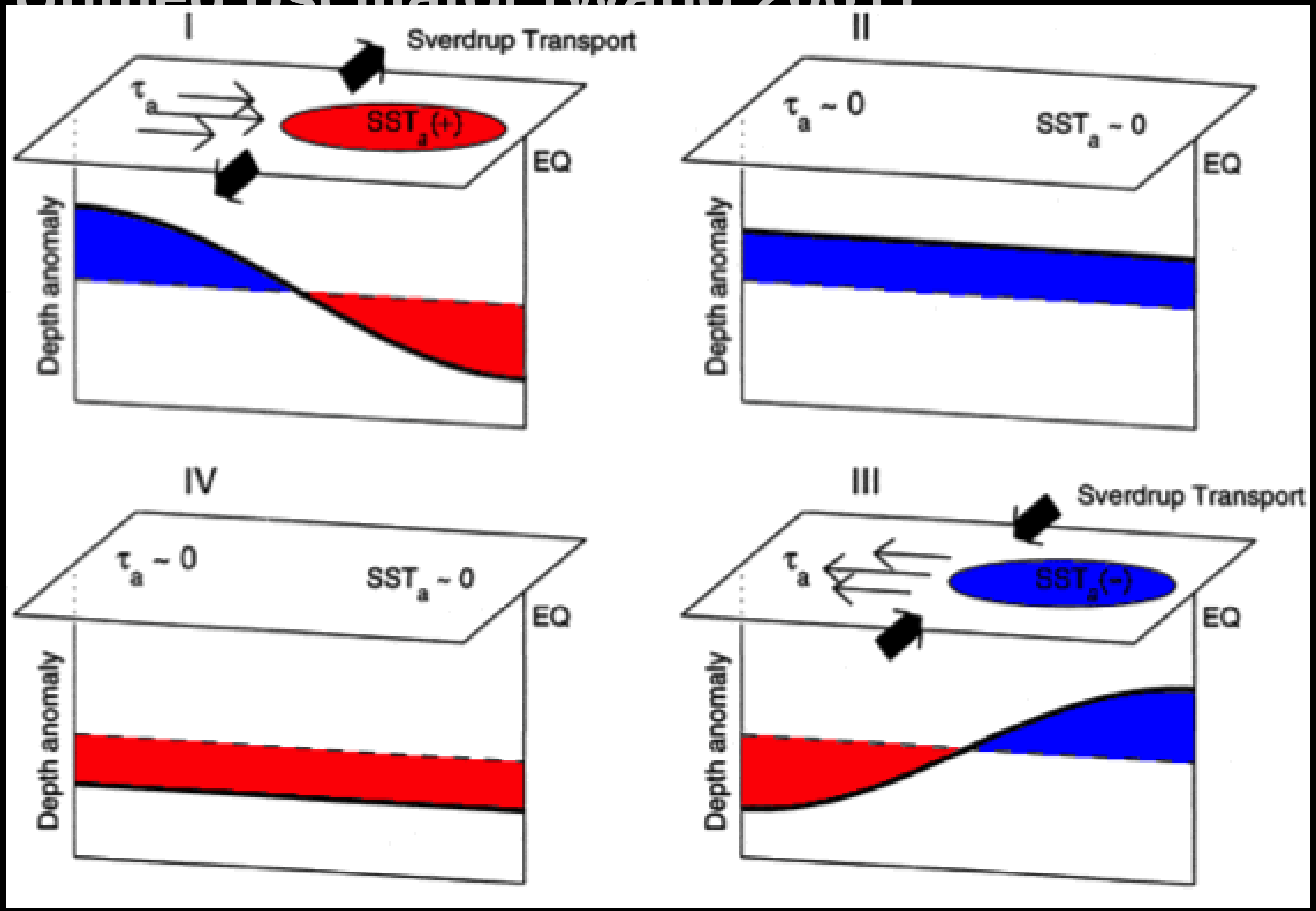
1. The "self-sustained oscillatory theories":

- Delayed oscillator (Suarez ,Schopf 1988, Battisti,Hirst 1989)
- Recharged/discharged oscillator (Jin 1997)
- West Pacific oscillator (Weisberg and Wang 1997)
- Advective-reflective oscillator (Picaut et al. 1997)
- Unified oscillator (Wang 2001)



Delayed oscillator

<u>Assumption:</u> delay (several years) is set by ocean dynamics



Recharged/discharged oscillator

El Niño theories

1. The “self-sustained oscillatory theories”:

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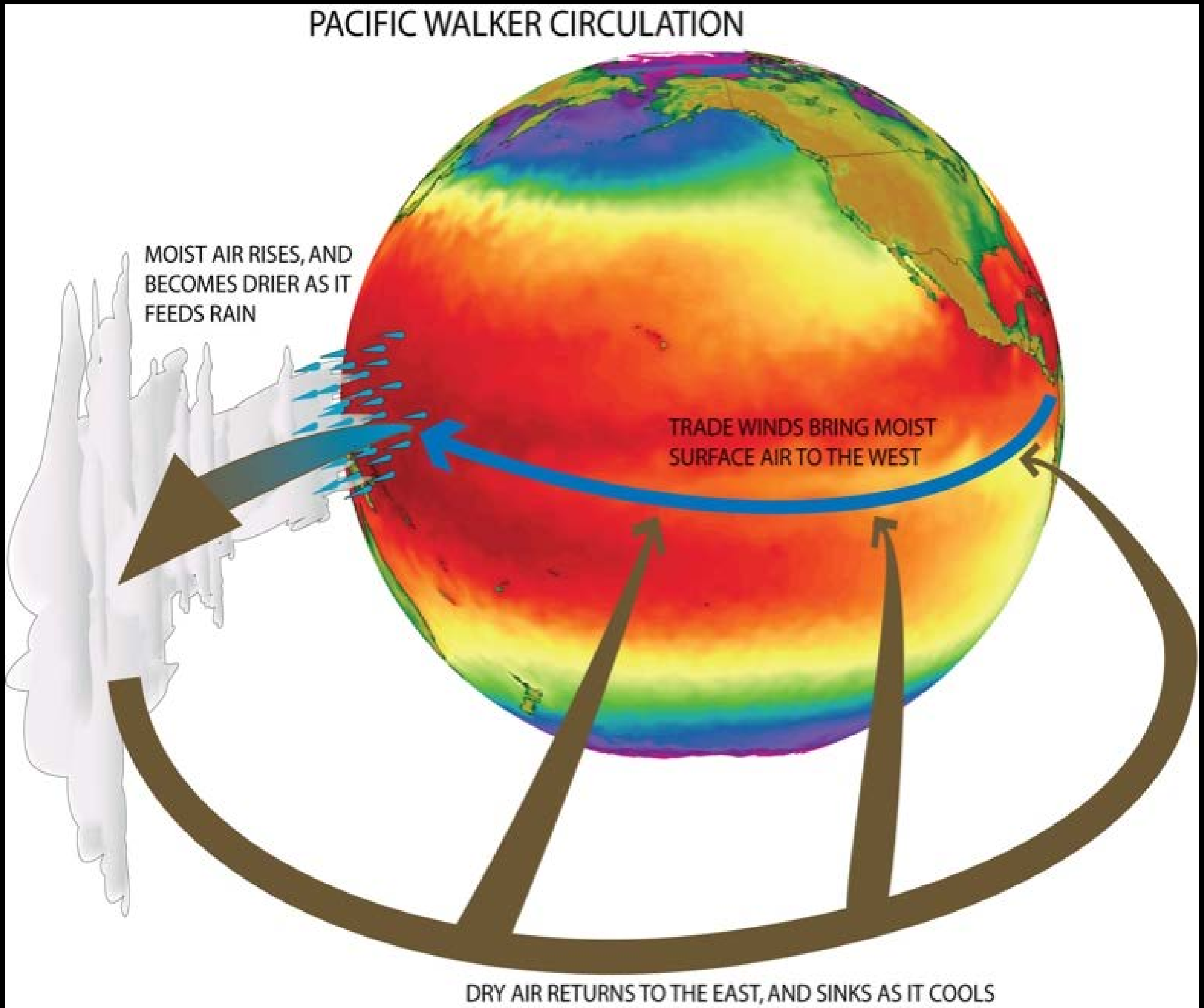
2. Stable mode (or weakly damped) triggered by stochastic atmospheric forcing *(Lau 1985, Moore and Kleeman 1999, Philander and Fedorov 2003, Kessler 2003,...)*

- Can help explain observed events irregularity
- Role of atmospheric higher frequency (MJO, WWE)

Atmosphere feedbacks during ENSO



Gabe's art...

Dynamical: Bjerknes feedback

East-west SST gradient
↓
Trade winds
↓
Equatorial upwelling in the east

Heat flux feedback

SST increase in the east
↓
Modified heat fluxes (SHF, LHF)

The BJ coupled-stability index for ENSO I_{BJ}

Mean advection and upwelling (damping)

$$\frac{\partial\langle T\rangle}{\partial t} = 2I_{BJ}\langle T\rangle + F[h],$$

$$2I_{BJ} = -\left(\frac{\langle\bar{u}\rangle}{L_x} + \frac{\langle -2y\bar{v}\rangle}{L_y^2} + \frac{\langle H(\bar{w})\bar{w}\rangle}{H_m}\right) - \alpha$$

$$+ \mu_a\beta_u\left\langle -\frac{\partial\bar{T}}{\partial x}\right\rangle + \mu_a\beta_w\left\langle\frac{\partial\bar{T}}{\partial z}H(\bar{w})\right\rangle$$

$$+ \mu_a^*\beta_h\left\langle\frac{H(\bar{w})\bar{w}}{H_m}a\right\rangle,$$

$$\beta_u = \beta_{um} + \beta_{us}, \quad F = -\left\langle\frac{\partial\bar{T}}{\partial x}\right\rangle\beta_{uh} + \left\langle\frac{H(\bar{w})\bar{w}}{H_m}a\right\rangle.$$

Zonal advection feedback

Ekman pumping feedback

Thermocline feedback

Jin et al. 2006

α *: atmosphere heat flux feedback*

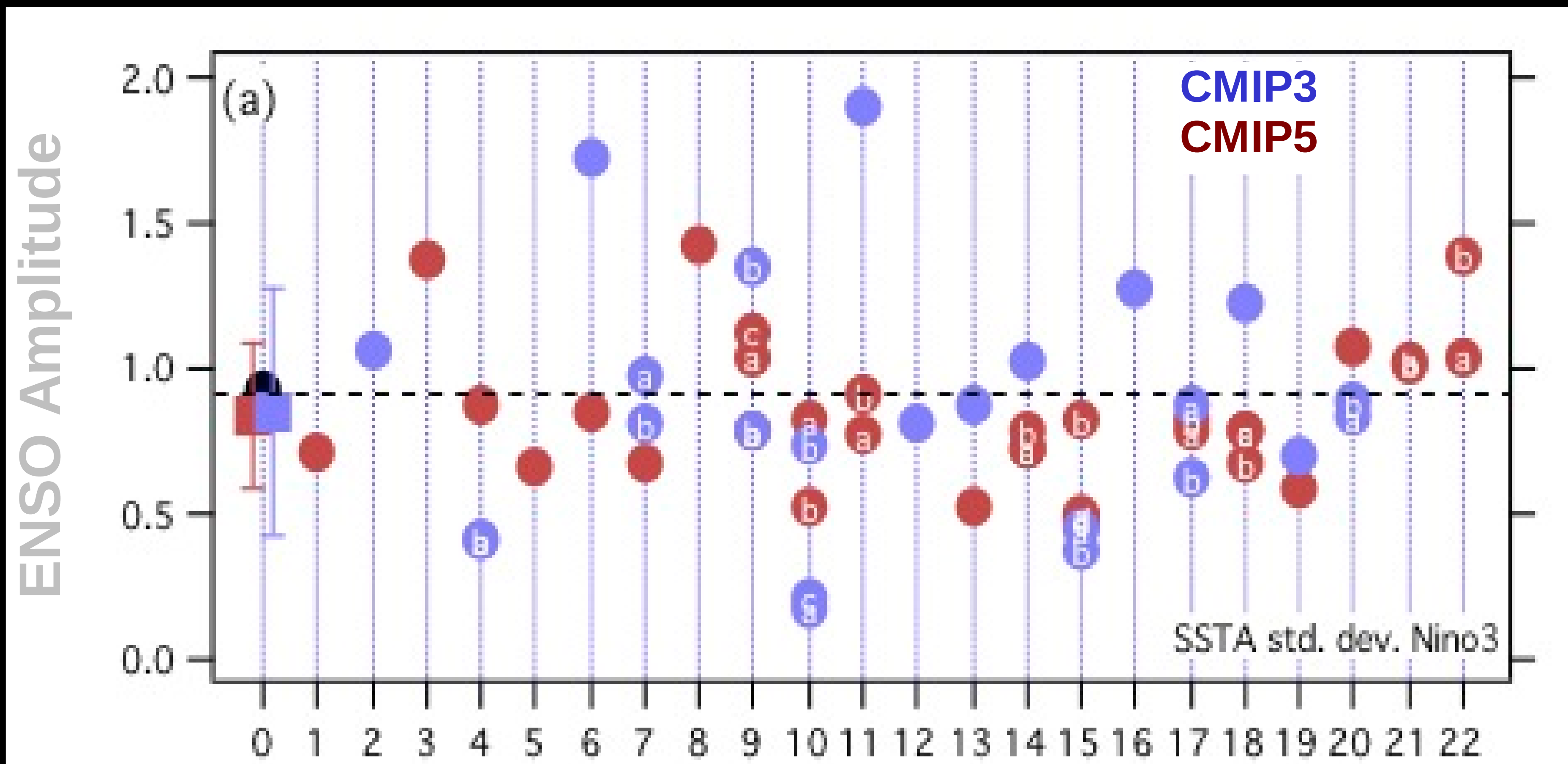
μ_a *: Bjerknes feedback or "coupling strength"*

α is a negative feedback (damping)

μ is a positive feedback (amplification)

El Niño in coupled GCMs - amplitude

Standard deviation SSTA (C) in



ENSO Amplitude

Observations

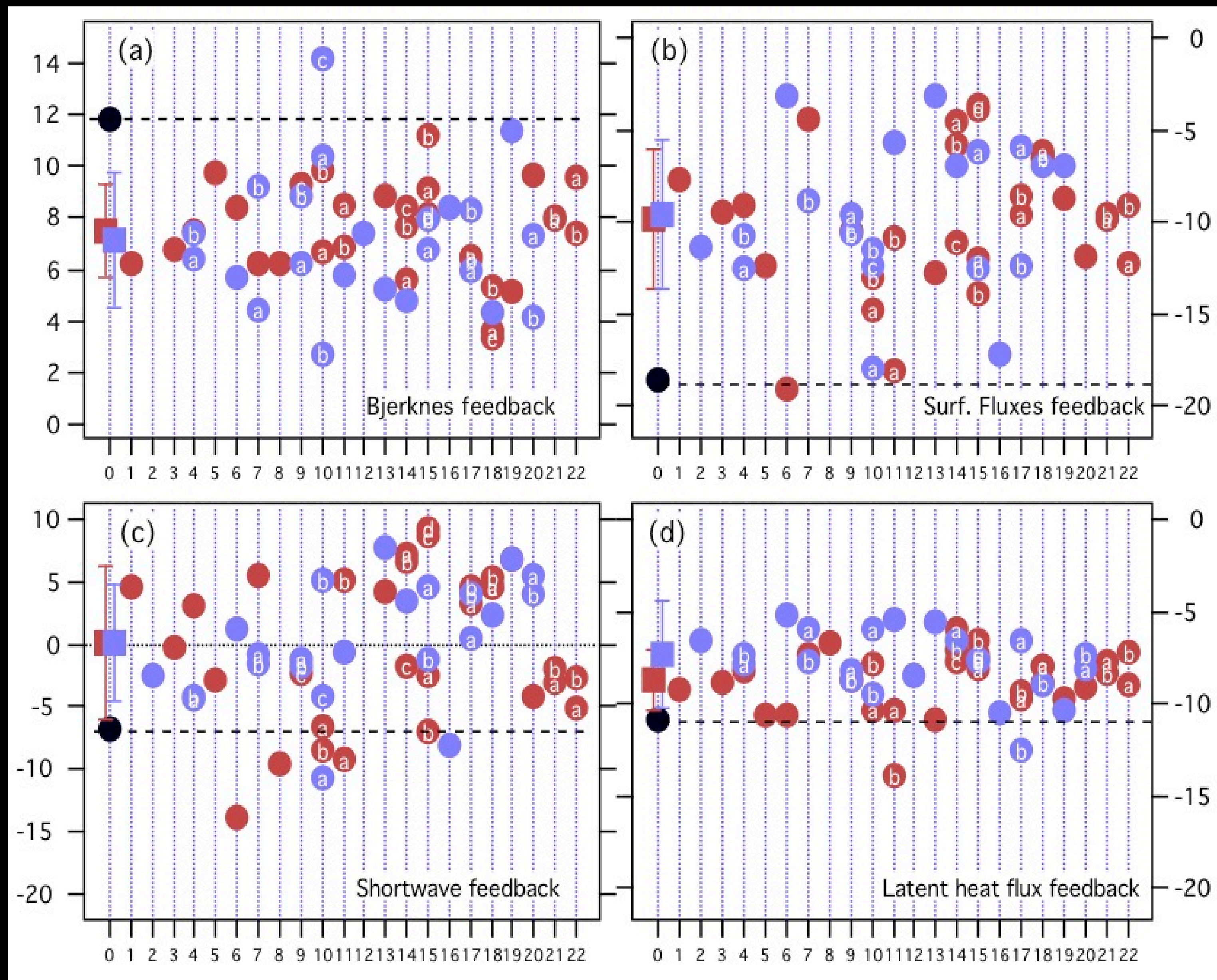
Modelling centers

- ENSO amplitude in CMIP3: very large diversity of simulated amplitude
- Range reduced in CMIP5 (improved mean state ? tuned in modelling development process ?)

Bellenger et al. 2013

Atmosphere feedbacks in CMIP3/CMIP5

Bjerknes m



a Total Heat Flux

SW Heat Flux a_{SW}

a_{LH} Latent Heat Flux

Models underestimate both m and a (error compensation)

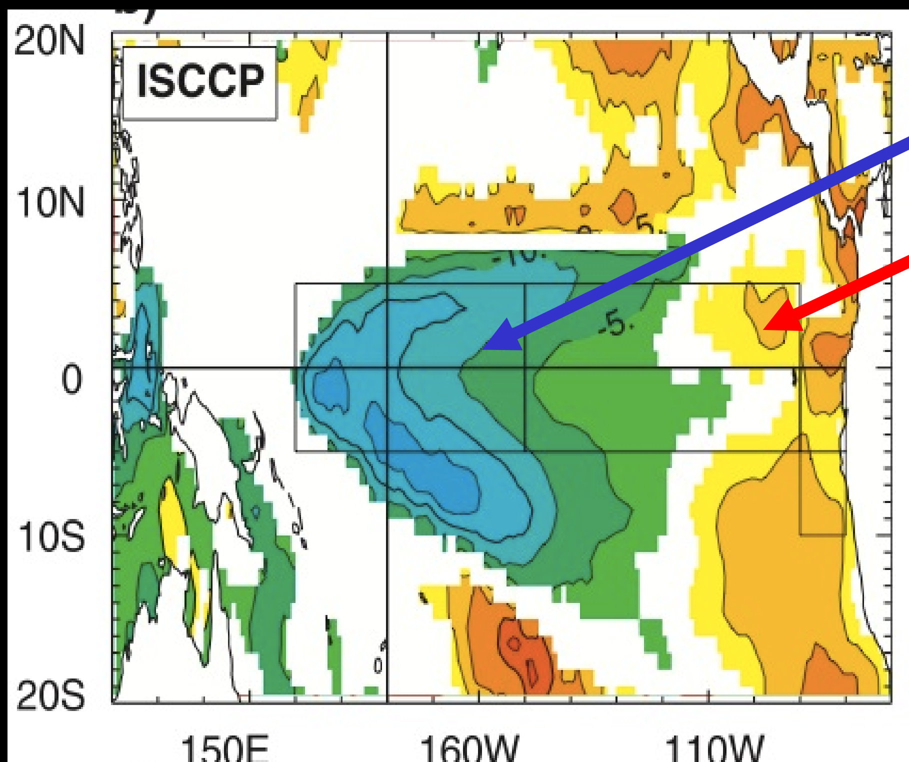
Shortwave feedback a_{SW} main source of errors and diversity (sign change !)

No clear evolution from CMIP3 to CMIP5

Bellenger et al. 2013, based on Lloyd et al. (2009, 2010, 2012)

Source of α_{SW} errors

α_{SW} map (ISCCP)



Convective regime α_{SW} < 0

Both co-exist in Niño3

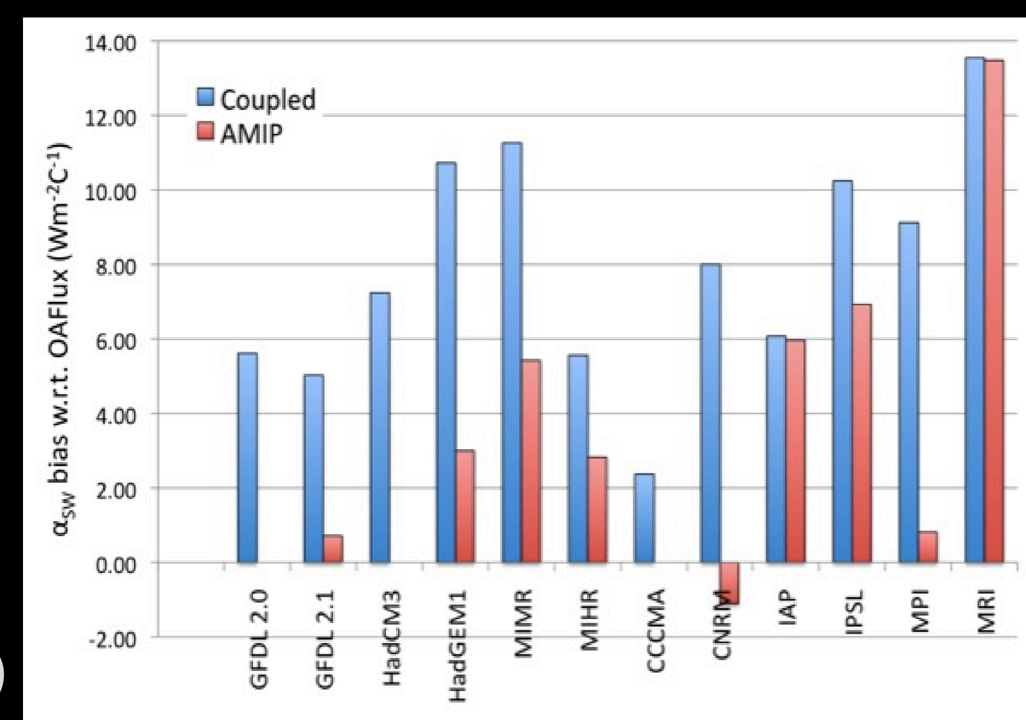
Subsidence regime α_{SW} > 0

$$\frac{\partial SW}{\partial SST} = \frac{\partial \omega_{500}}{\partial SST} \times \frac{\partial TCC}{\partial \omega_{500}} \times \frac{\partial SW}{\partial TCC} \approx \alpha_{SW}$$

AMIP

Coupled

α_{SW} errors wrt OAFlux

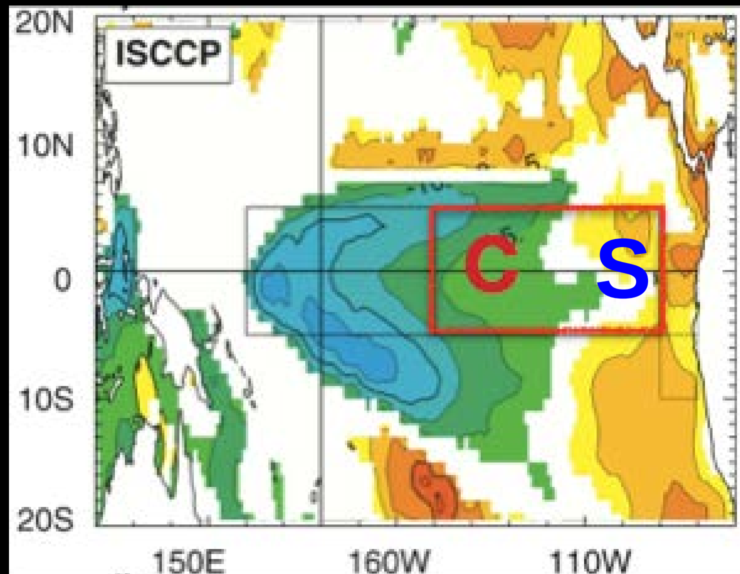


- α_{SW} error have their origin in the AGCM
- cloud response to dynamics
- (low) cloud properties

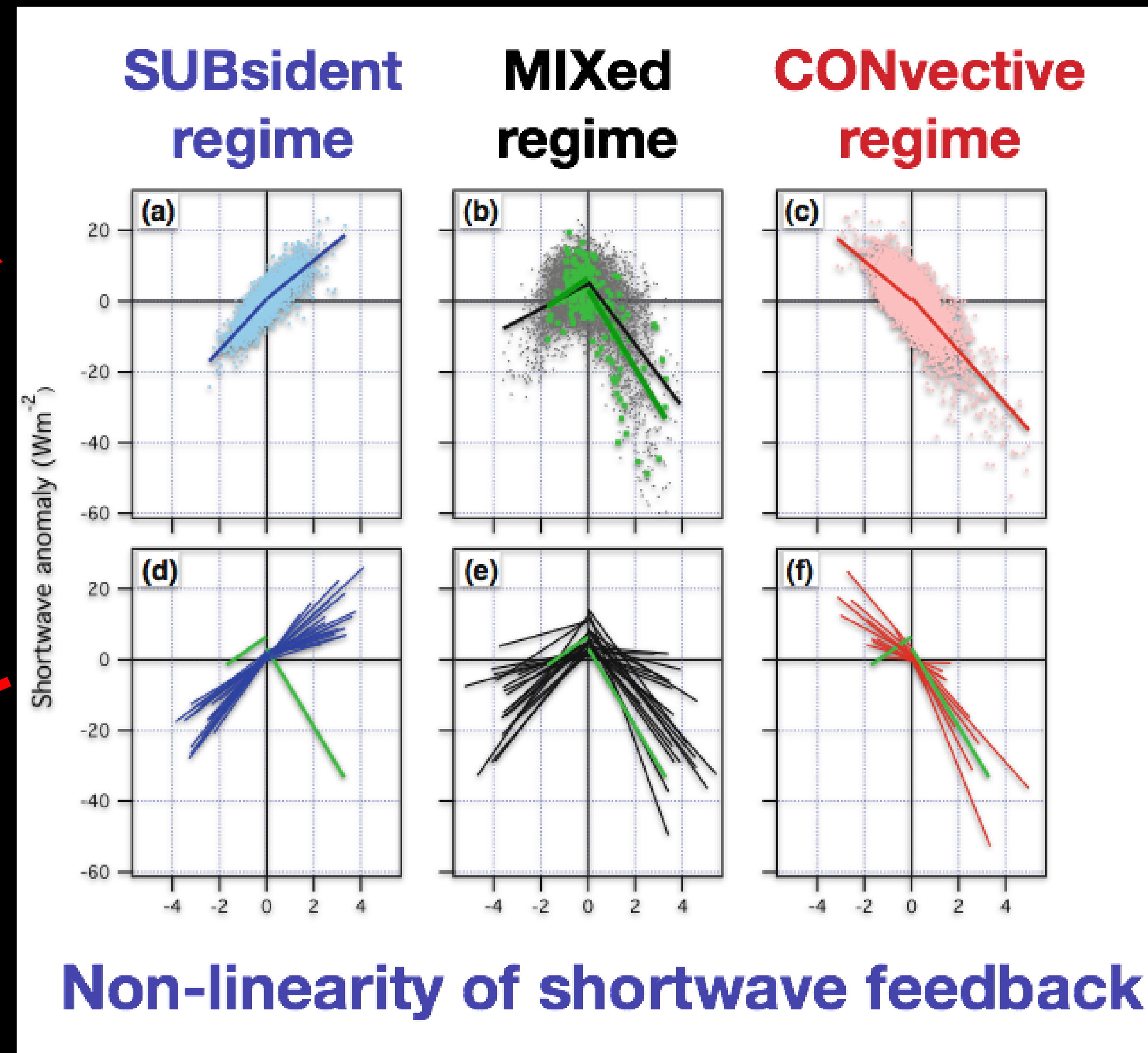
- When coupled, the dynamics also plays a role (SST drift)

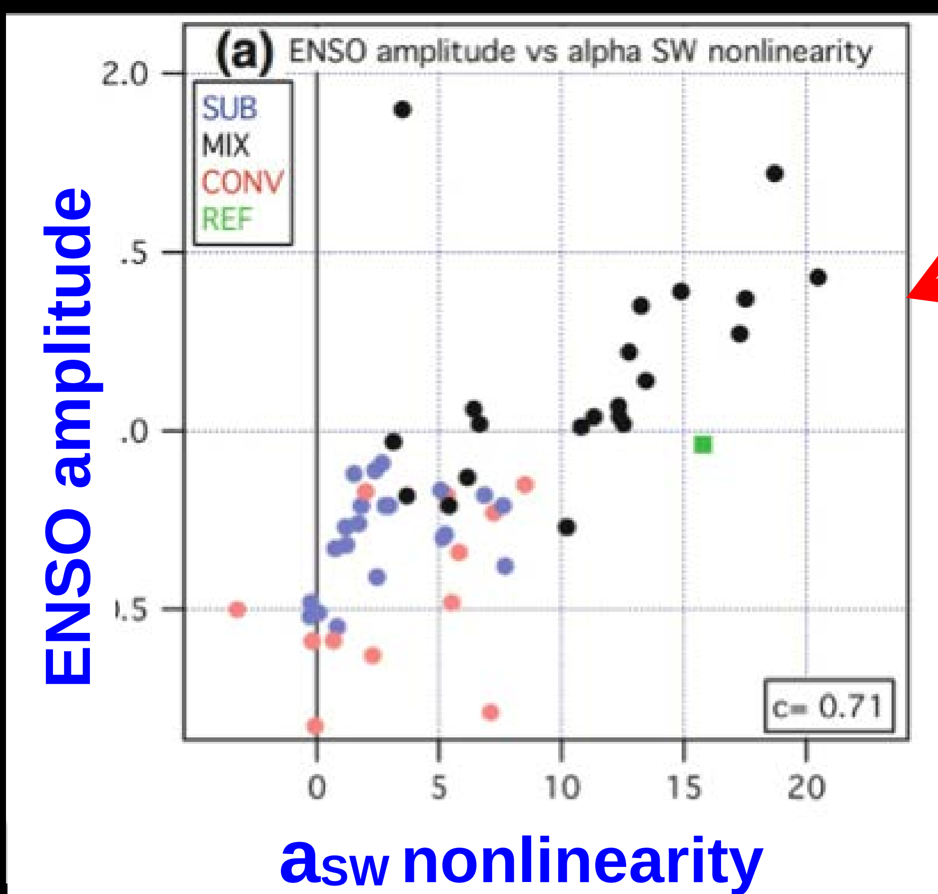
Lloyd et al. (2011, 2012)

Extreme El Niño related to atmosphere non-linearity



SWFA vs. SSTA in Niño 3





Bellenger et al. (2013)

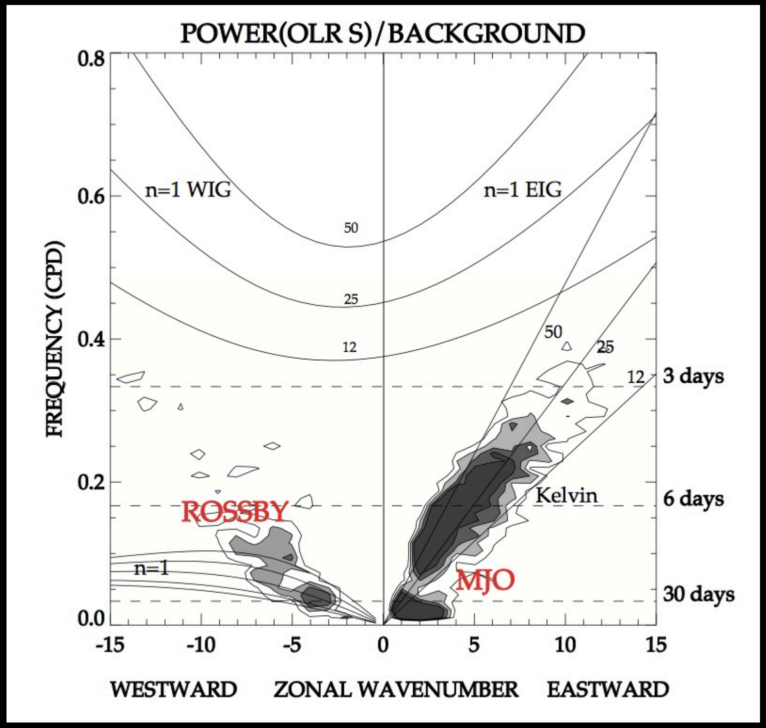
Strong to extreme El Niño simulation requires a_{SW} non-linearity

Impact of intraseasonal variability on El Niño

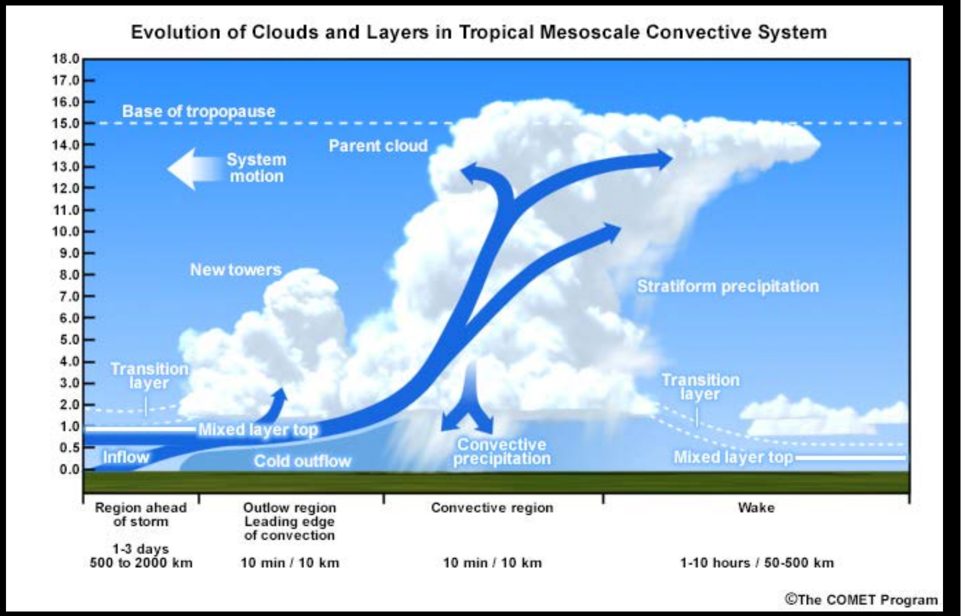
Puy et al. (2015, 2016, 2017)
And now with Yann Planton, Matthieu Lengaigne and Jérôme Vialard

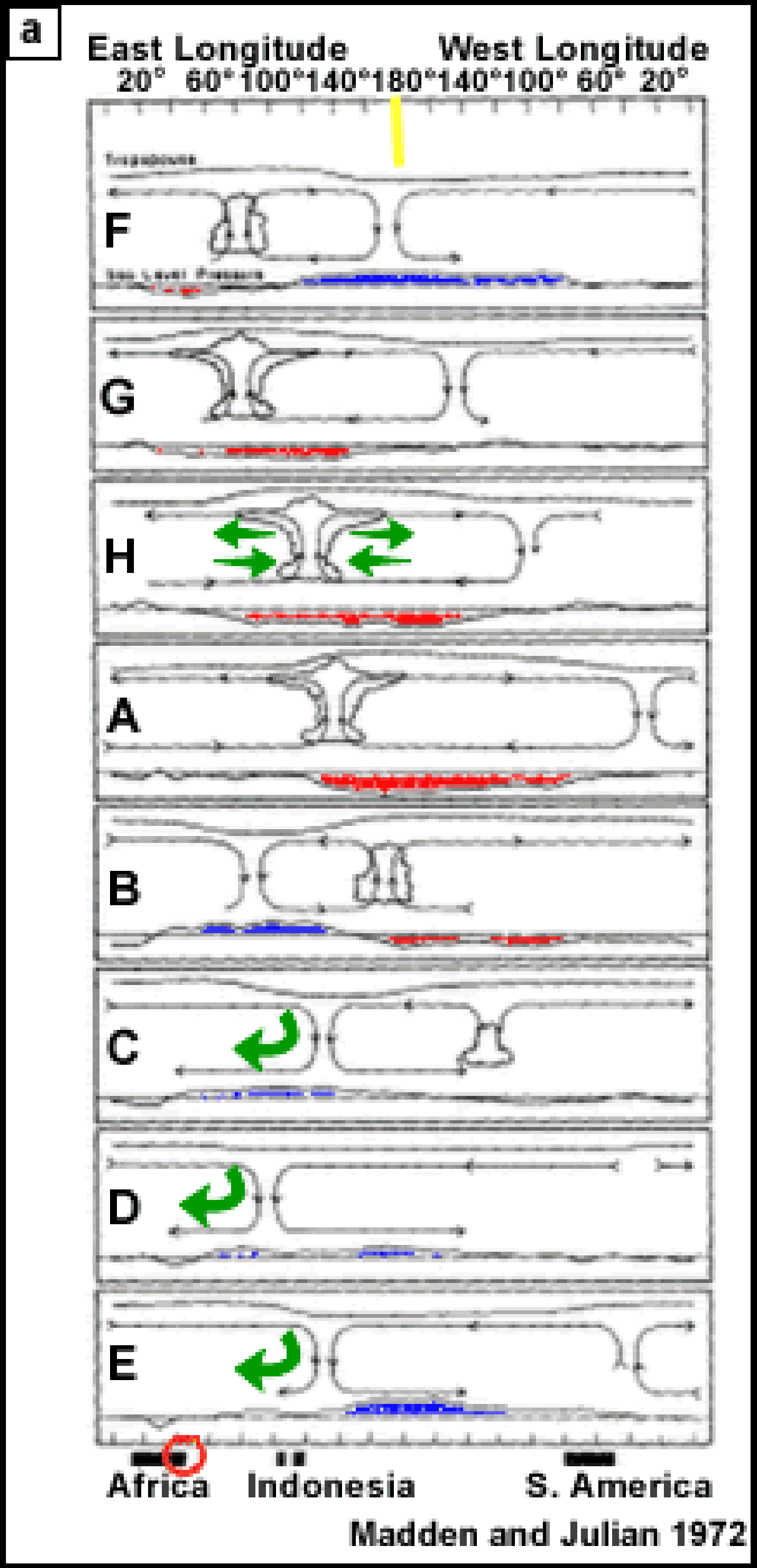
Madden-Julian Oscillation (MJO)

- Atmosphere equatorial intraseasonal mode (30-90 days)
- Involves moist convection
- Slower mode over warm sphere (IndoPac WP), faster over cooler waters (East Pacific)
- Active phase generates Westerly Wind Events (WWEs)



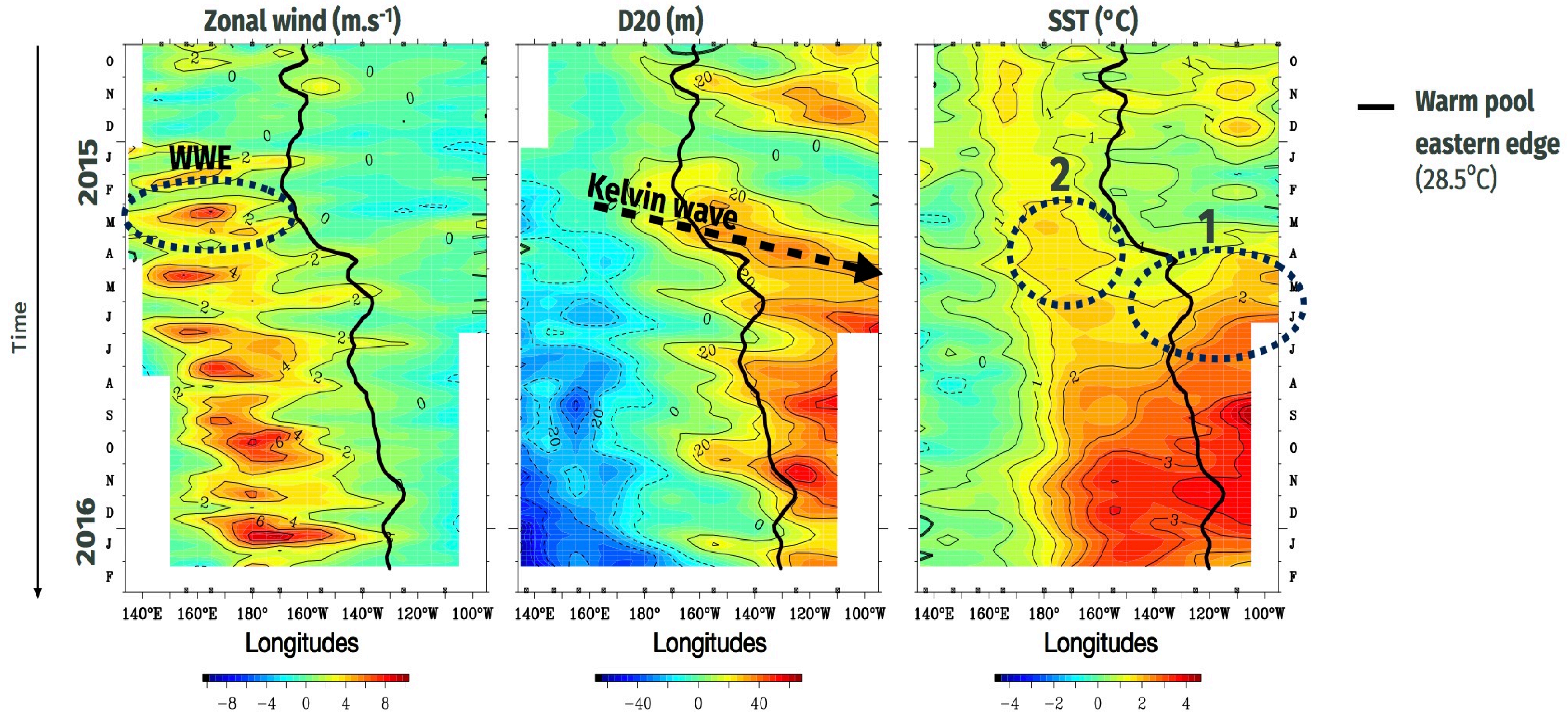
Wheeler and Kiladis (1999)





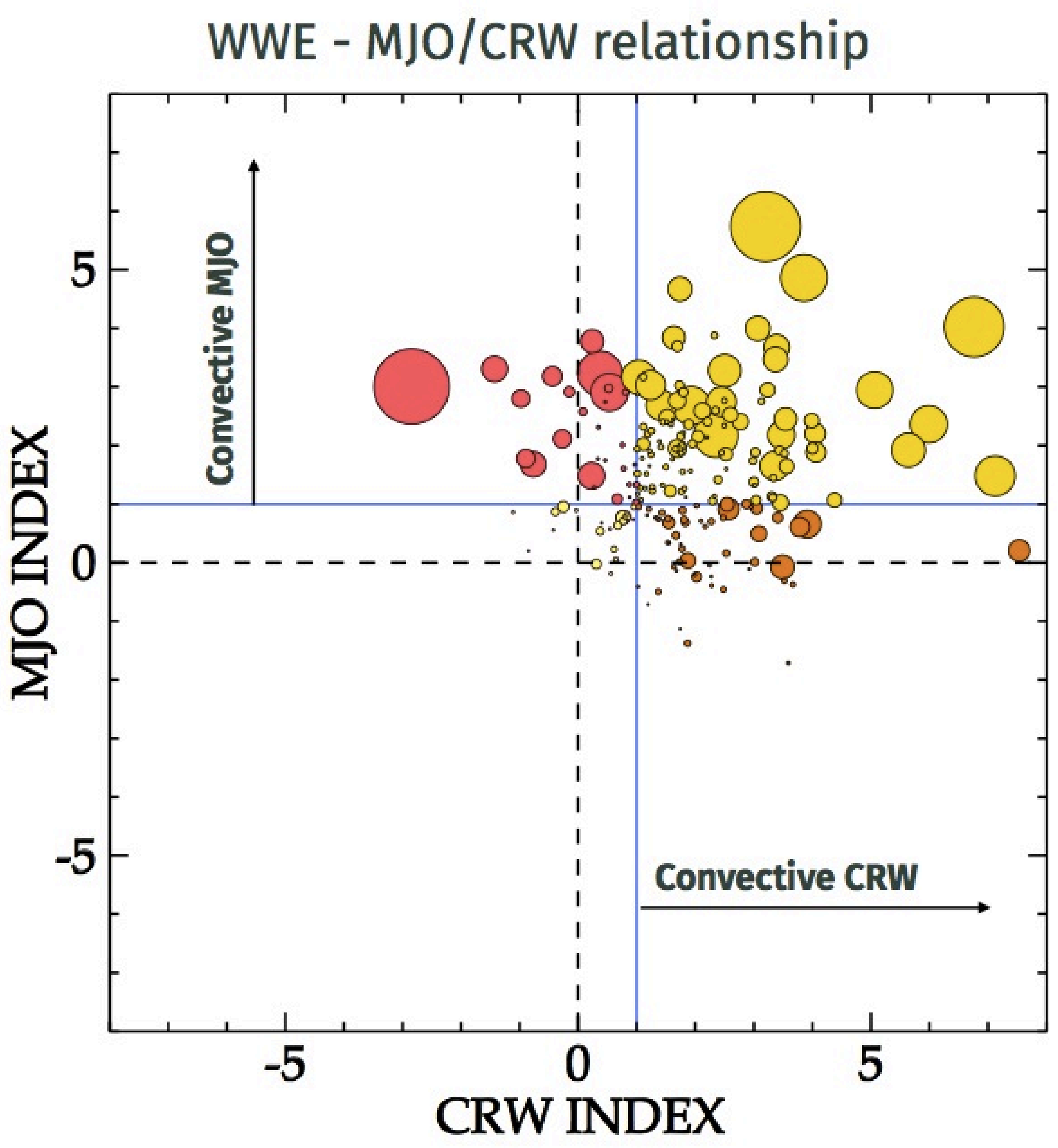
WWEs promote the onset/development of El Niño

- **WWE :** Unpredictable high frequency (5-30 days) westerly wind anomaly



- **Onset :** 1. Eastern Pac = Deepen thermocline / 2.Central Pac = Advect warm pool eastward
- **Development :** Favor the occurence of subsequent WWEs (Fedorov 2002; Boulanger et al 2004; Lengaigne et al 2004)

The active phase of the MJO/CRW favours WWE occurence



- Virtually all (89%) WWEs are associated with the occurence of MJO and CRW
- WWE associated with the MJO last longer and have a larger fetch.

  → More likely to impact EL Niño

- Not all MJO are associated with WWE
- Sensitivity tests = Very robust

Puy et al. (2015) *Climate dynamics*

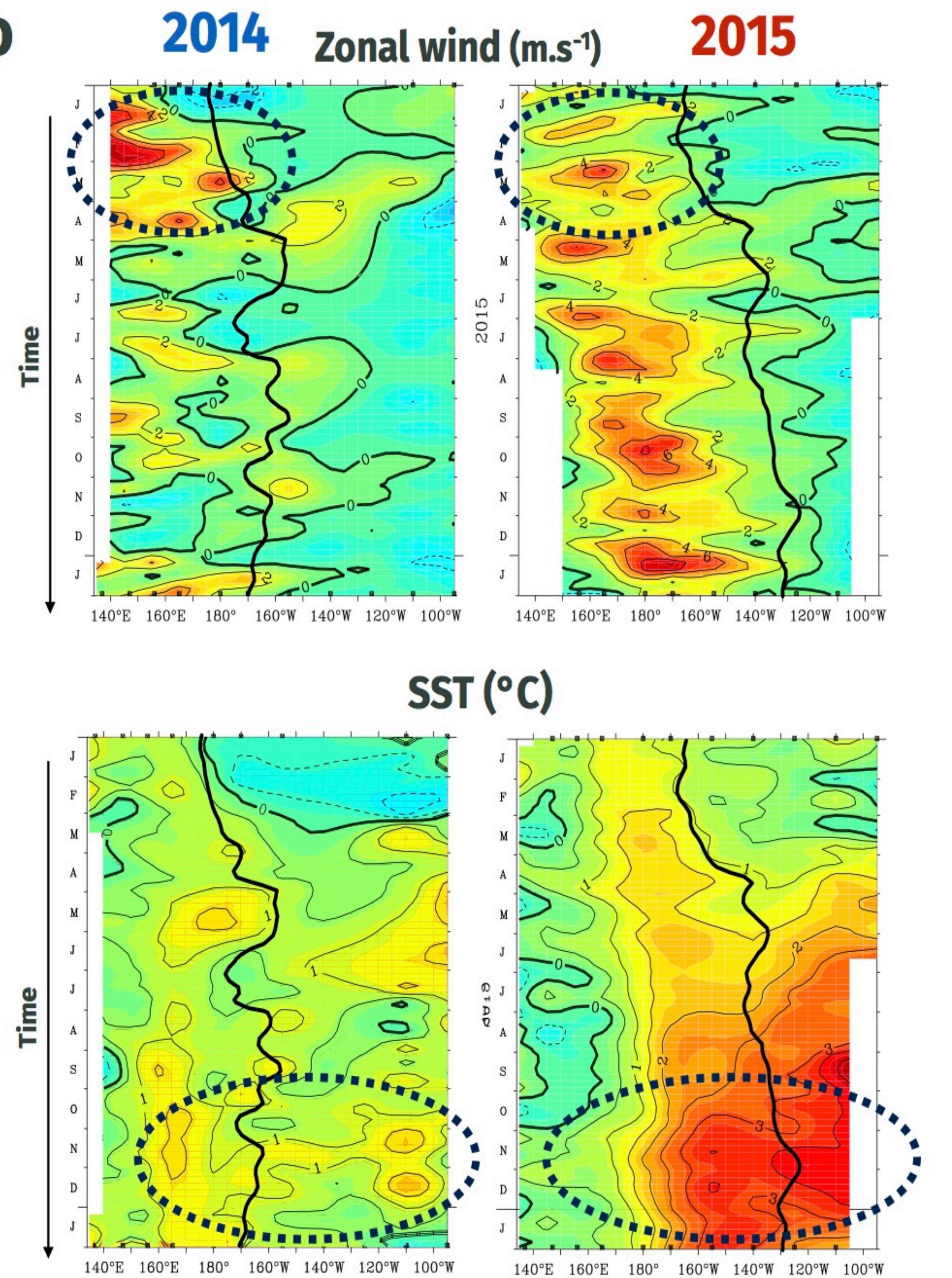
All WWEs don't have an impact on El Niño

- Similar favorable conditions for El Niño in **2014** et **2015** :
  - Recharged equatorial Pacific (anomalous heat content)
  - Strong WWE in JFM

- **Why such a different evolution between 2014 and 2015 ?**

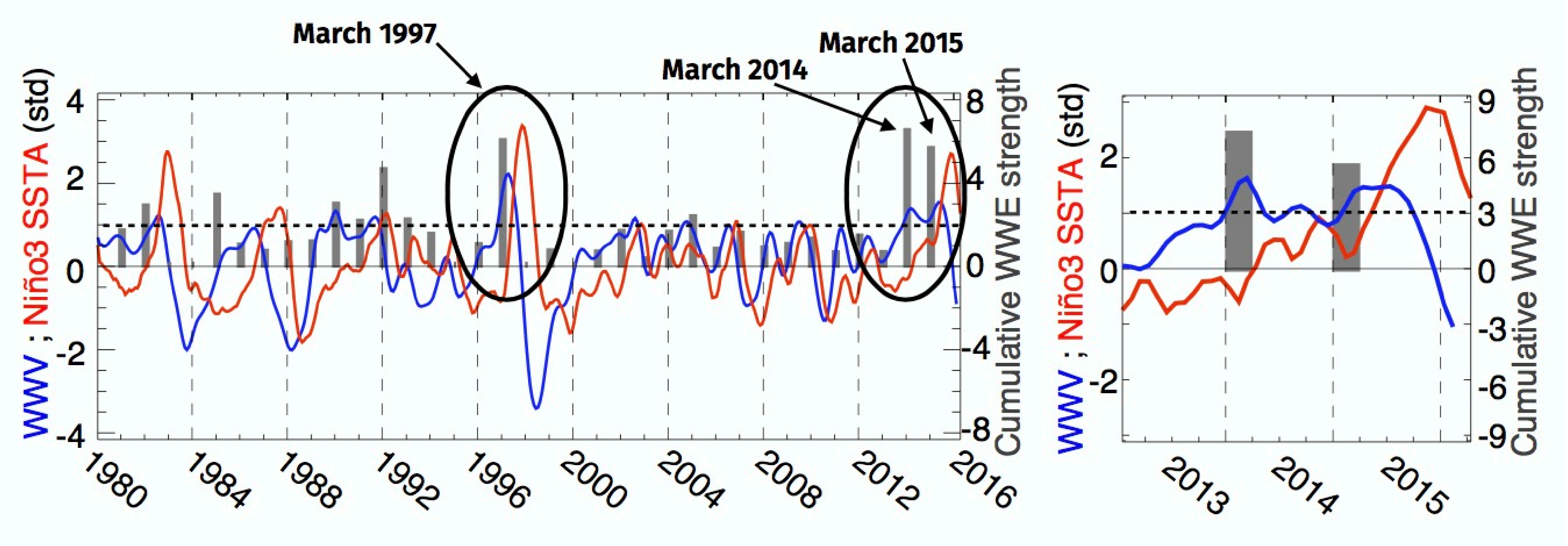
- **No WWE in summer/fall 2014**

- **Can this difference be attributed to the WWEs?**



El Niño precursors: heat recharge and westerly wind event

Well documented El Niño precursors in Spring :

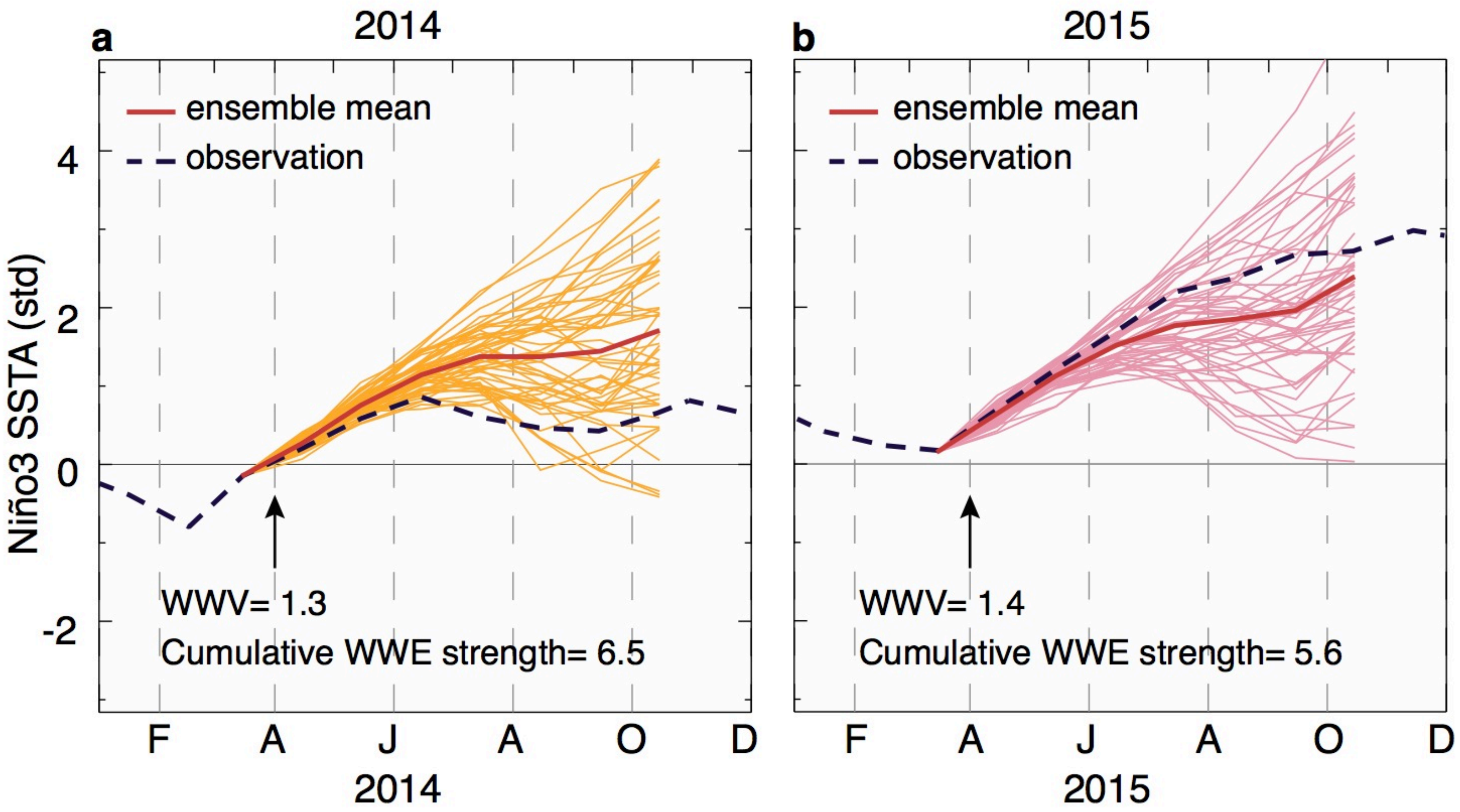


- Similar precursors in March 2014 and 2015 :
  - Equatorial Pacific recharge *(WWV ~1.5 std)*
  - Strong WWE *(WWE Strength ~ 6 std)*

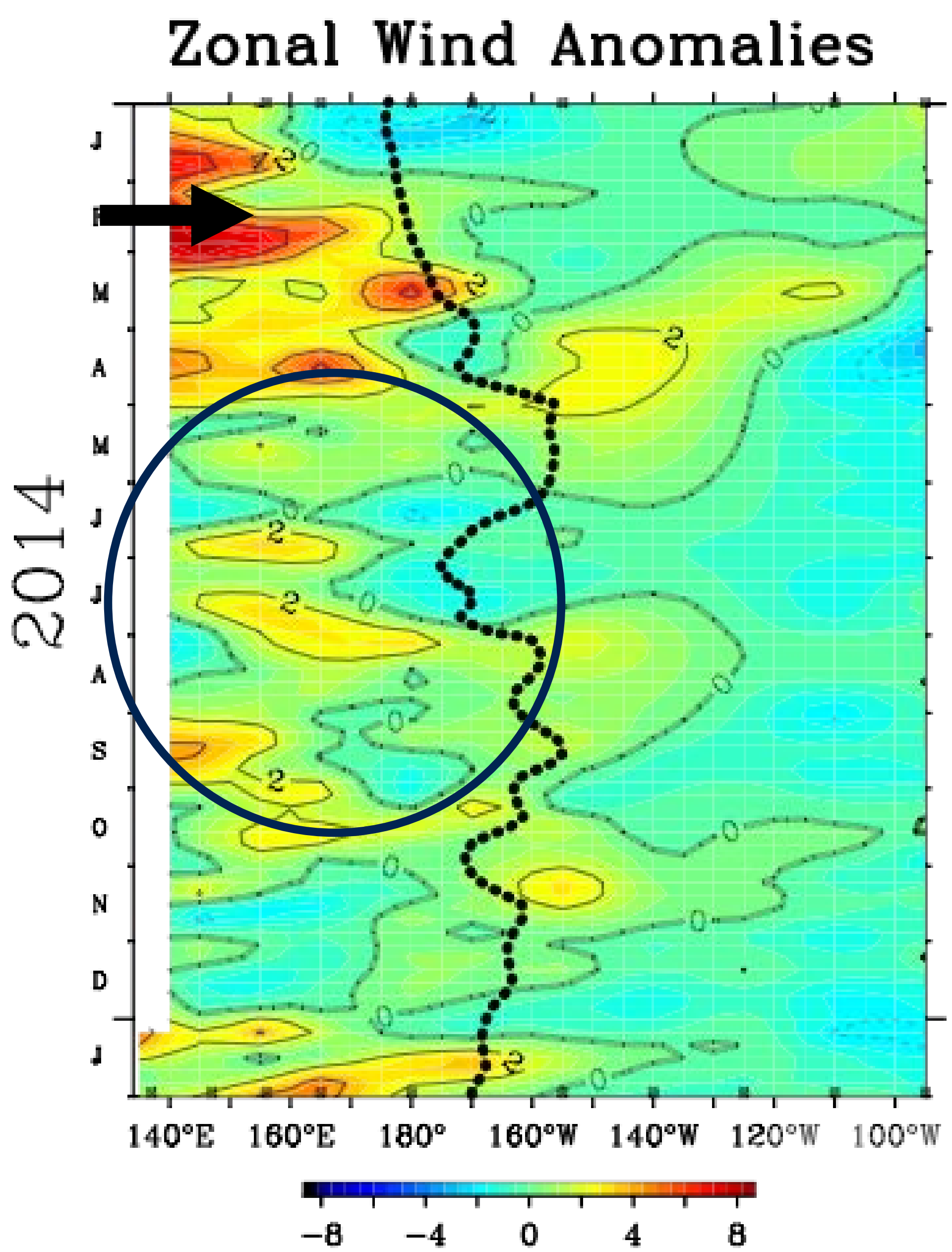
Puy et al 2017

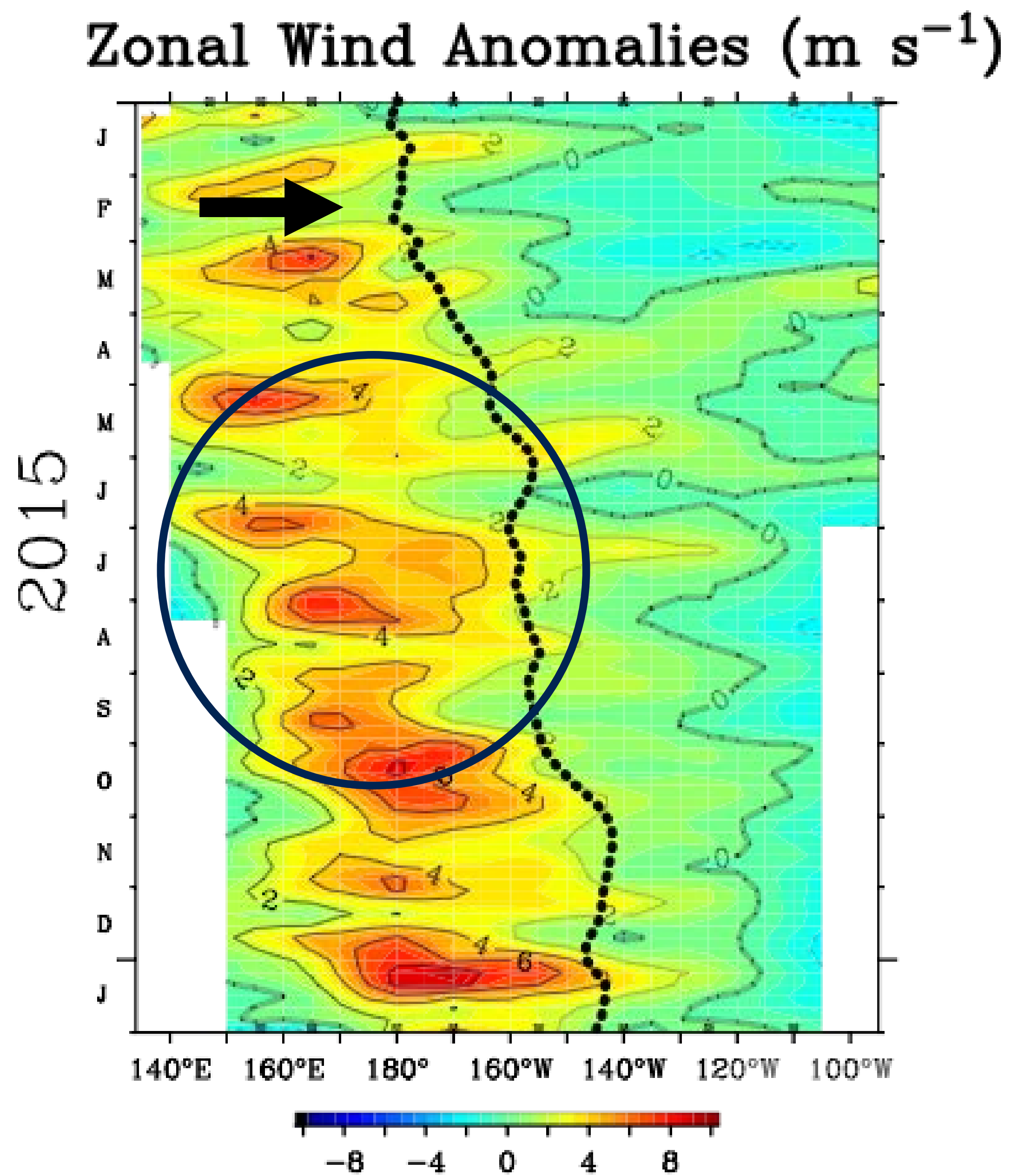
Similar subsurface and WWEs initial conditions ~ similar forecasts

- ECMWF El Niño (Niño3-SSTA) forecasts initialized Apr, 1st 2014 and 2015



Lack of subsequent WWEs

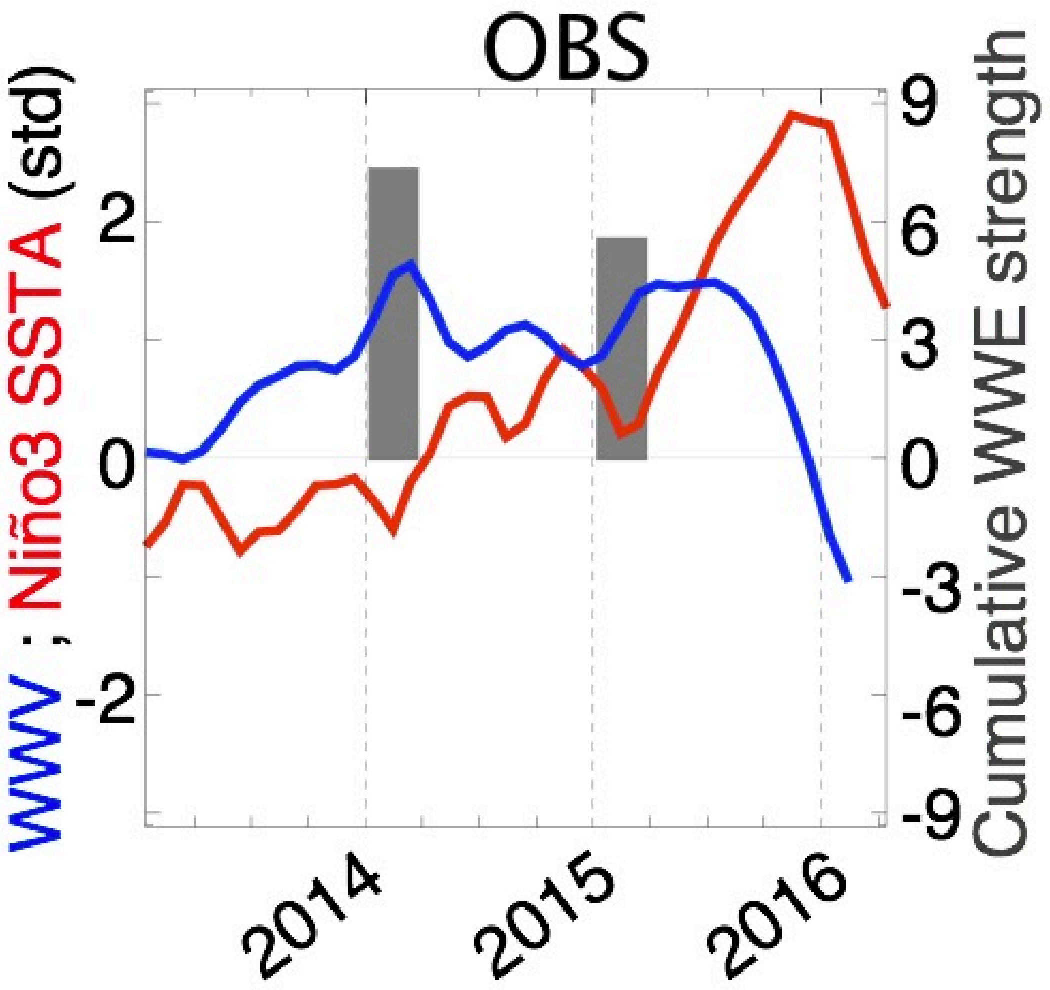


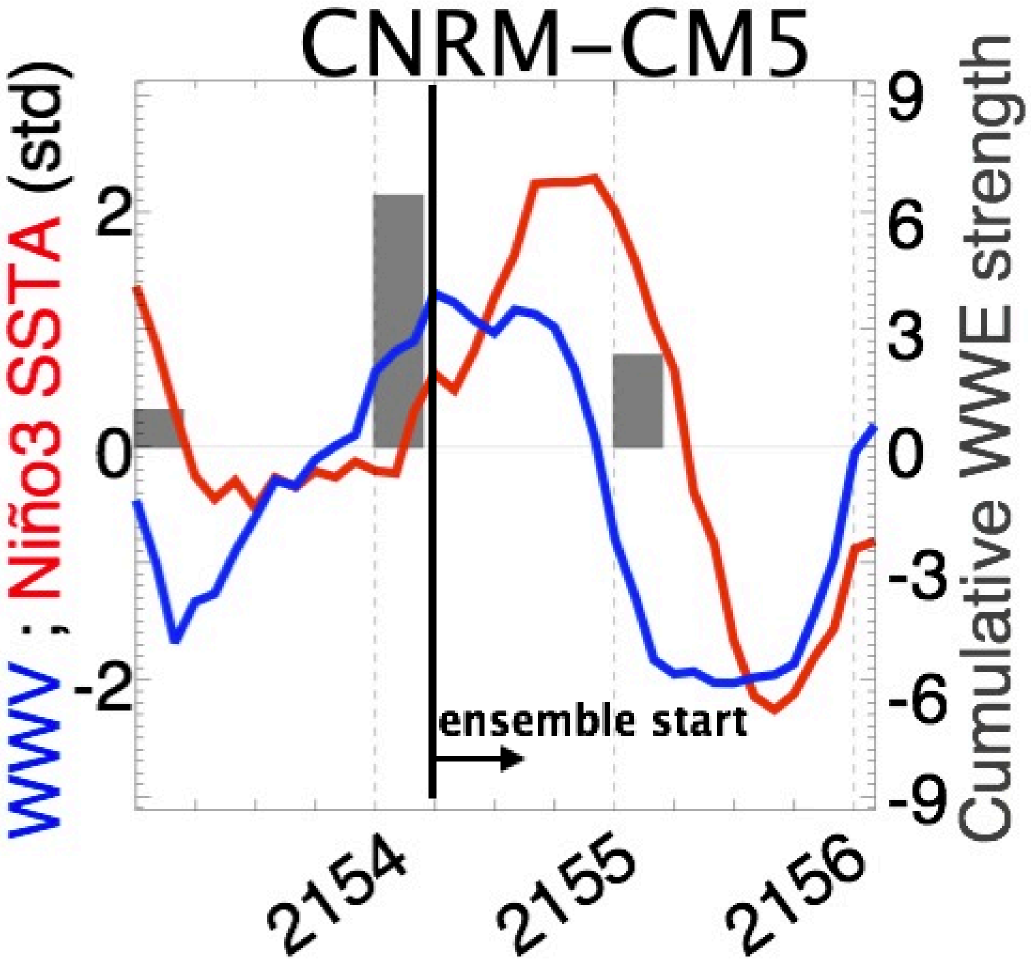


- Forced oceanic simulations: Lack of subsequent WWEs in summer could explain the weak El Niño amplitude in 2014
  (Menkes et al 2014)

Model analog to March 2014 and 2015 preconditioning

- 150 years control run using the CNRM-CM5 coupled model.

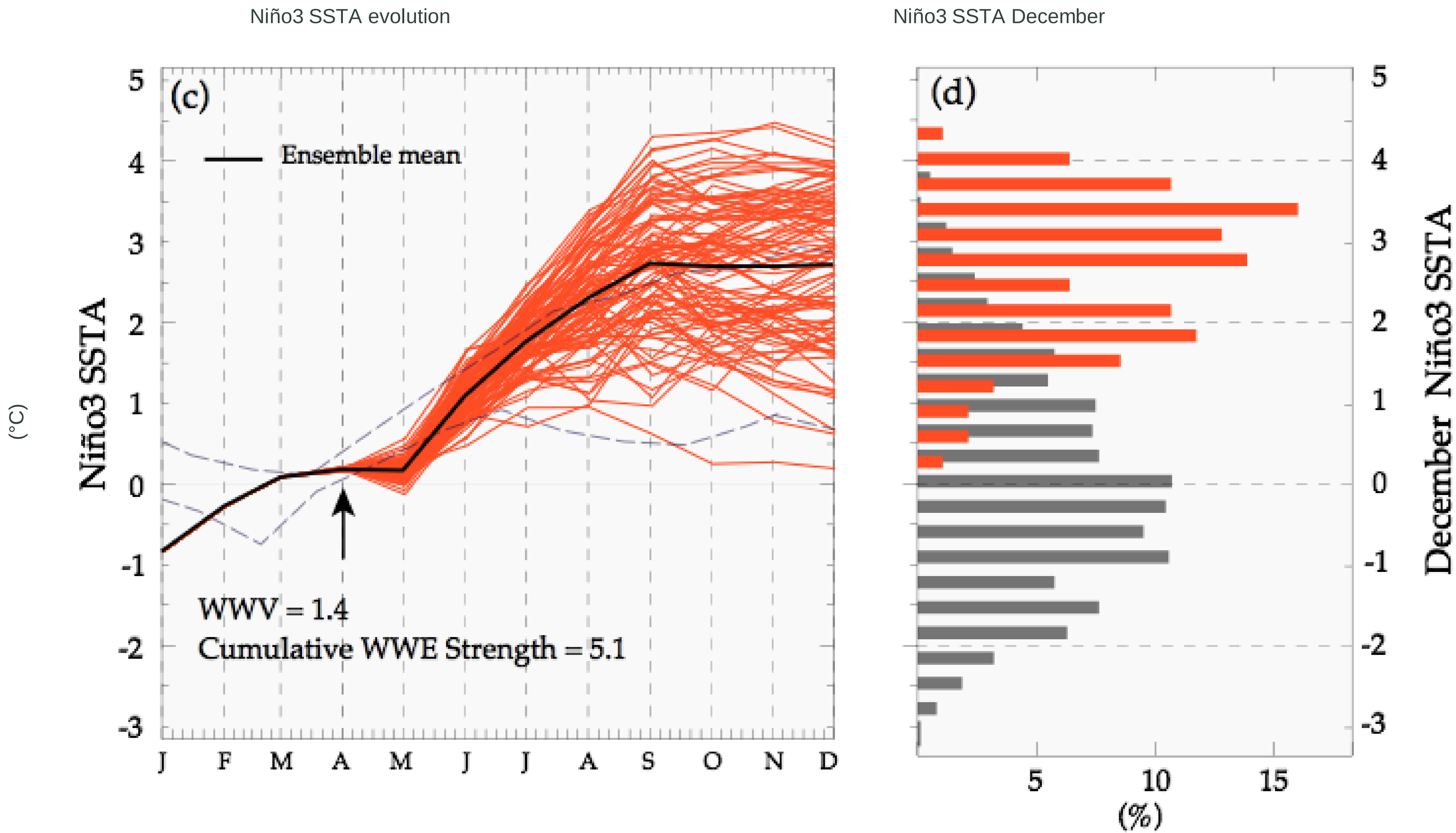




- March 2154 in model has preconditioning similar to March 2014 and 2015:
  - *WWV ~1.5 std / WWE ~6 std*
- 100-members ensemble simulation starting on the 1st April 2154

Puy et al 2017

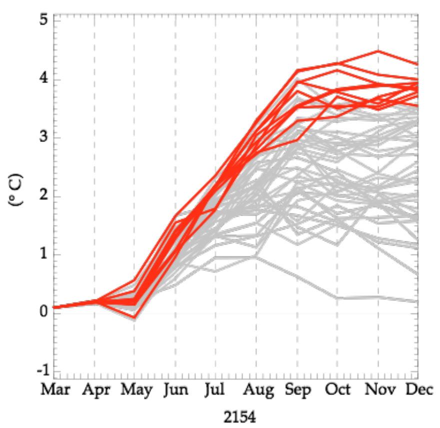
Control ensemble simulation



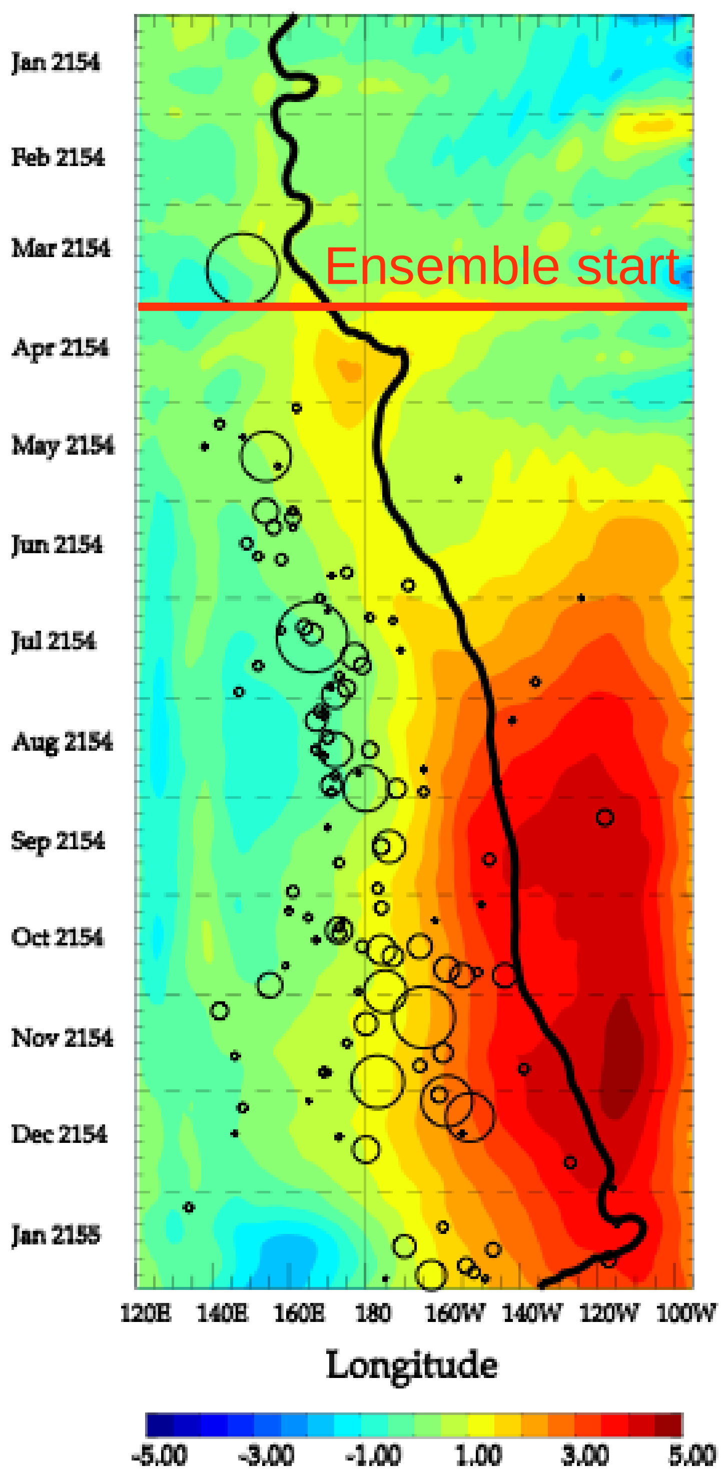
- Impact of the initial conditions : no Niña
- Large warming diversity [0 - 4 °C]

Puy et al 2017

Role of summer WWEs in control ensemble spread

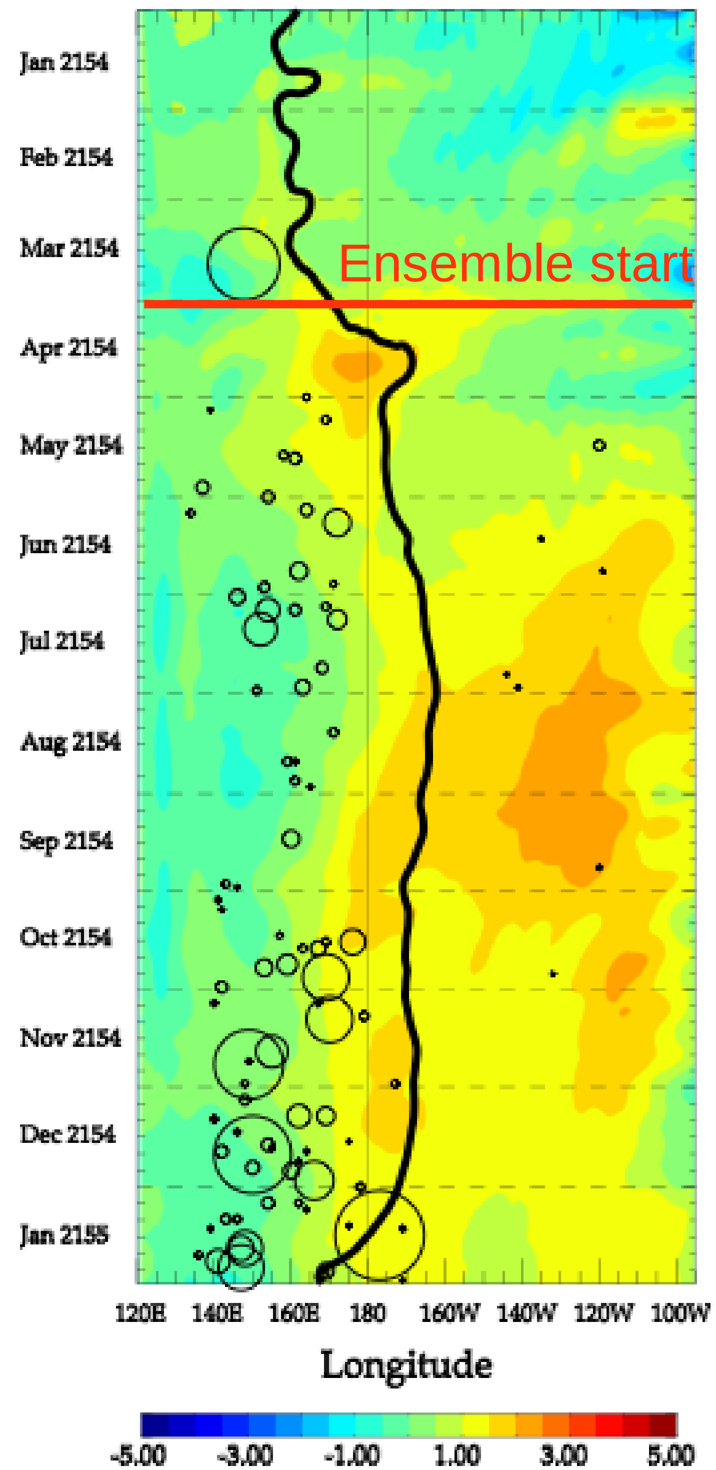


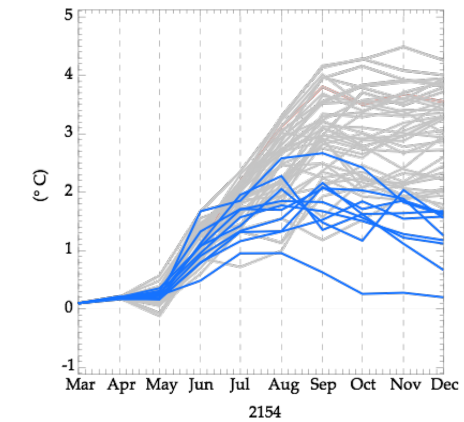
10 warmest El Niño SSTA composite



SSTA evolution similar to 2015

10 coolest El Niño SSTA composite

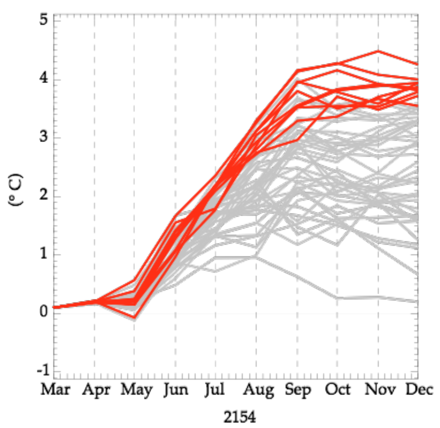




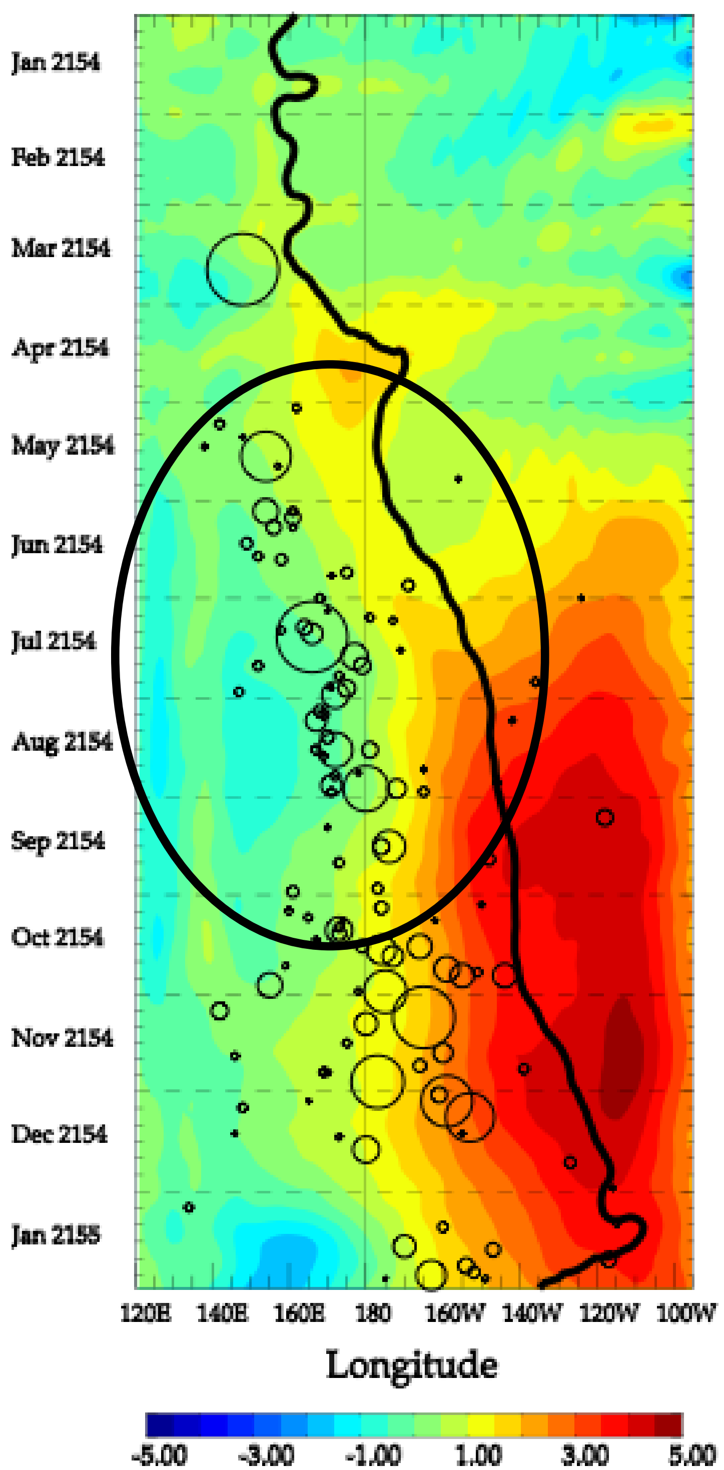
SSTA evolution similar to 2014

Puy et al. 2017

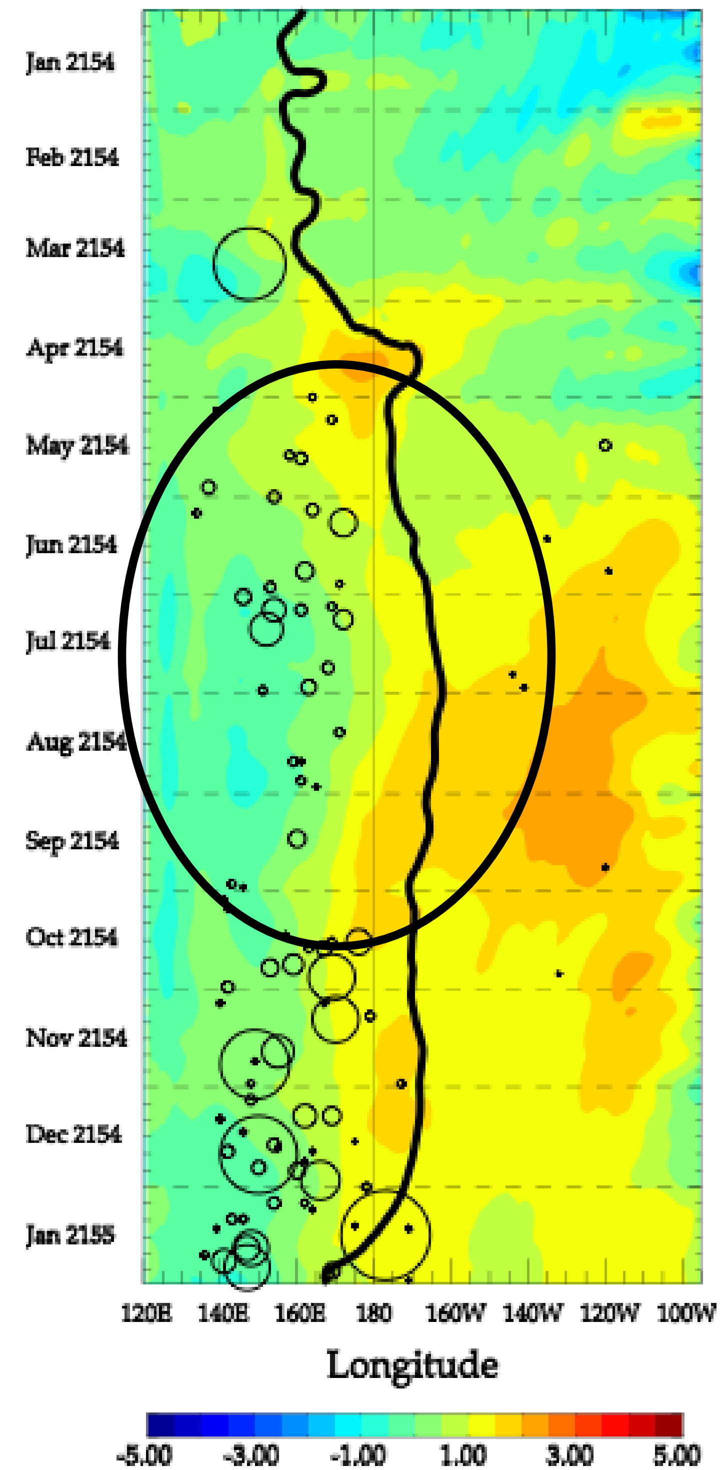
Role of summer WWEs in control ensemble spread

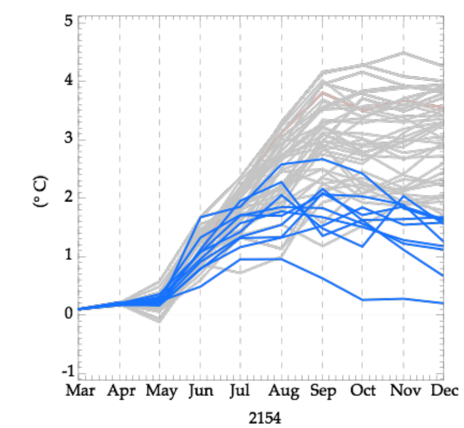


10 warmest El Niño SSTA composite



10 coolest El Niño SSTA composite





SSTA evolution similar to 2015

6 WWEs / member

SSTA evolution similar to 2014

3 WWEs / member

Puy et al. 2017

El Niño Magnitude linearly related to Summer/Fall WWEs activity

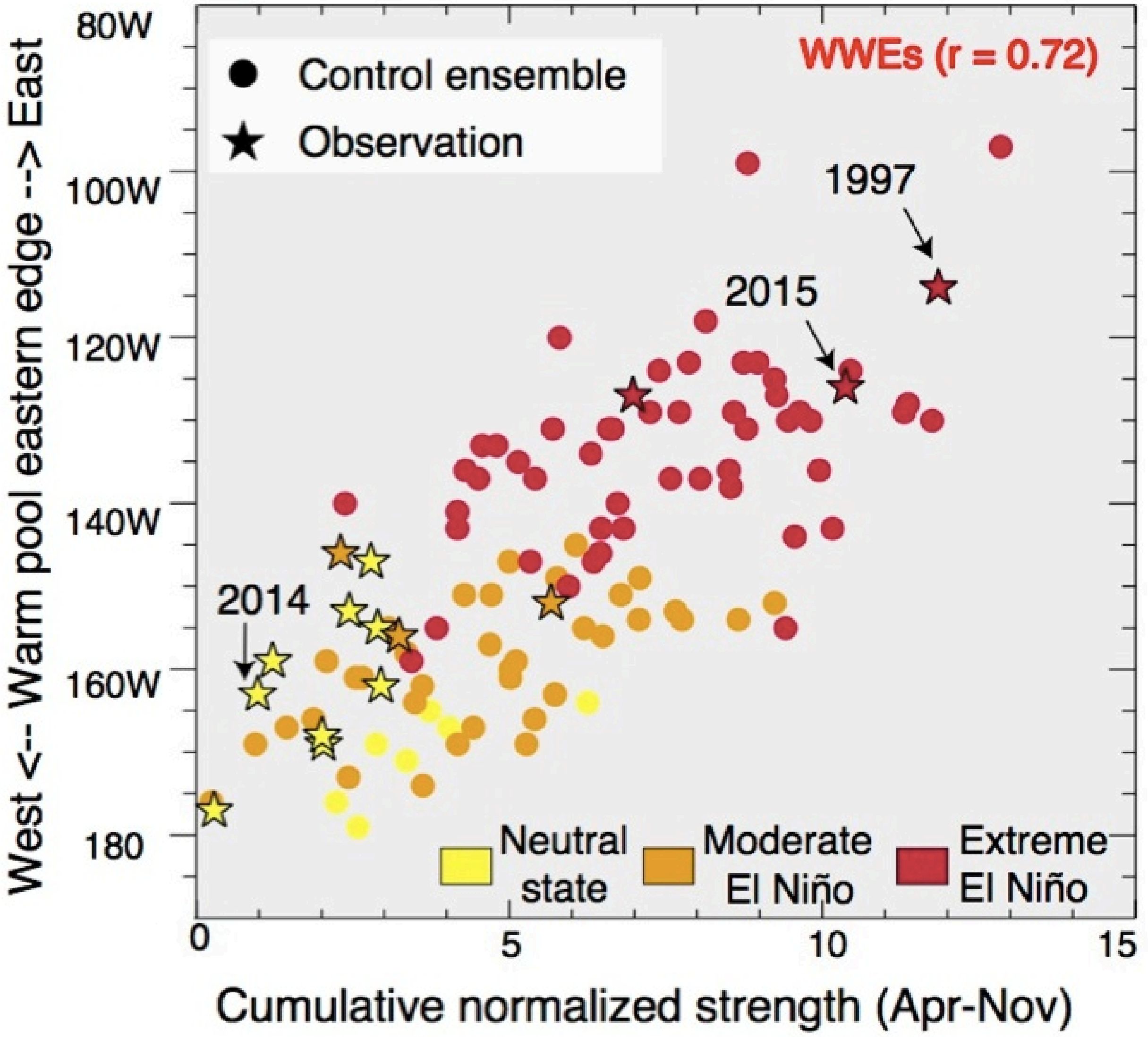
Statistics for 50 members

- Cumulative WWE Strength from April to November

WWE - Warm Pool Eastern Edge (WPEE) position

East

West



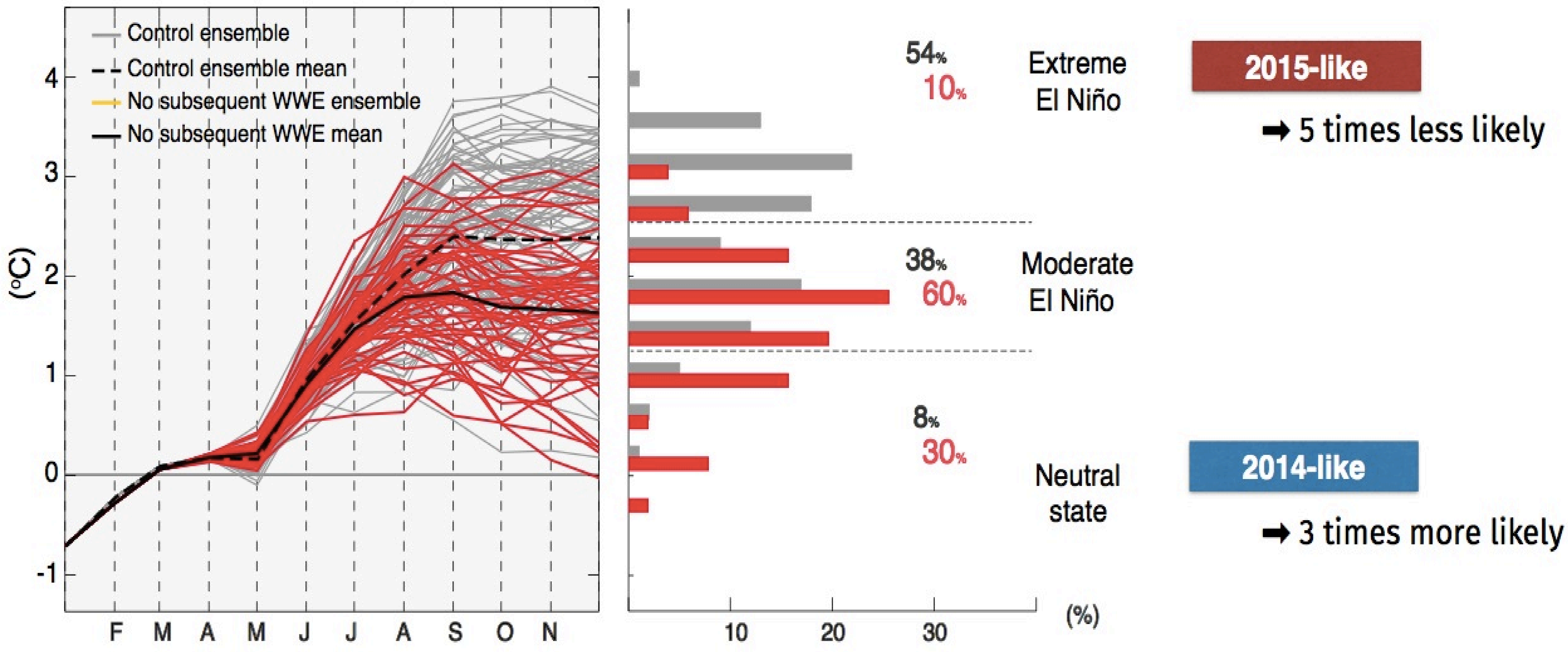
Correlation = 0.72

- **Do summer WWEs passively respond to El Niño or do they actively participate to its magnitude?**

Puy et al 2017

Removing Summer WWEs weakens El Niño ensemble mean

- Sensitivity experiment : April to November WWEs have been removed



- **Summer / fall WWEs strongly impact final El Niño magnitude**

Puy et al. 2017

Implications for El Niño predictability

- **Strong WWEs likely to impact El Niño are associated with the MJO**

    Better MJO predictability could lead to better WWEs predictability

- **WWEs are modulated by ENSO (deterministic component of the WWEs)**

    WWEs more likely to occur when the warm pool is shifted eastward

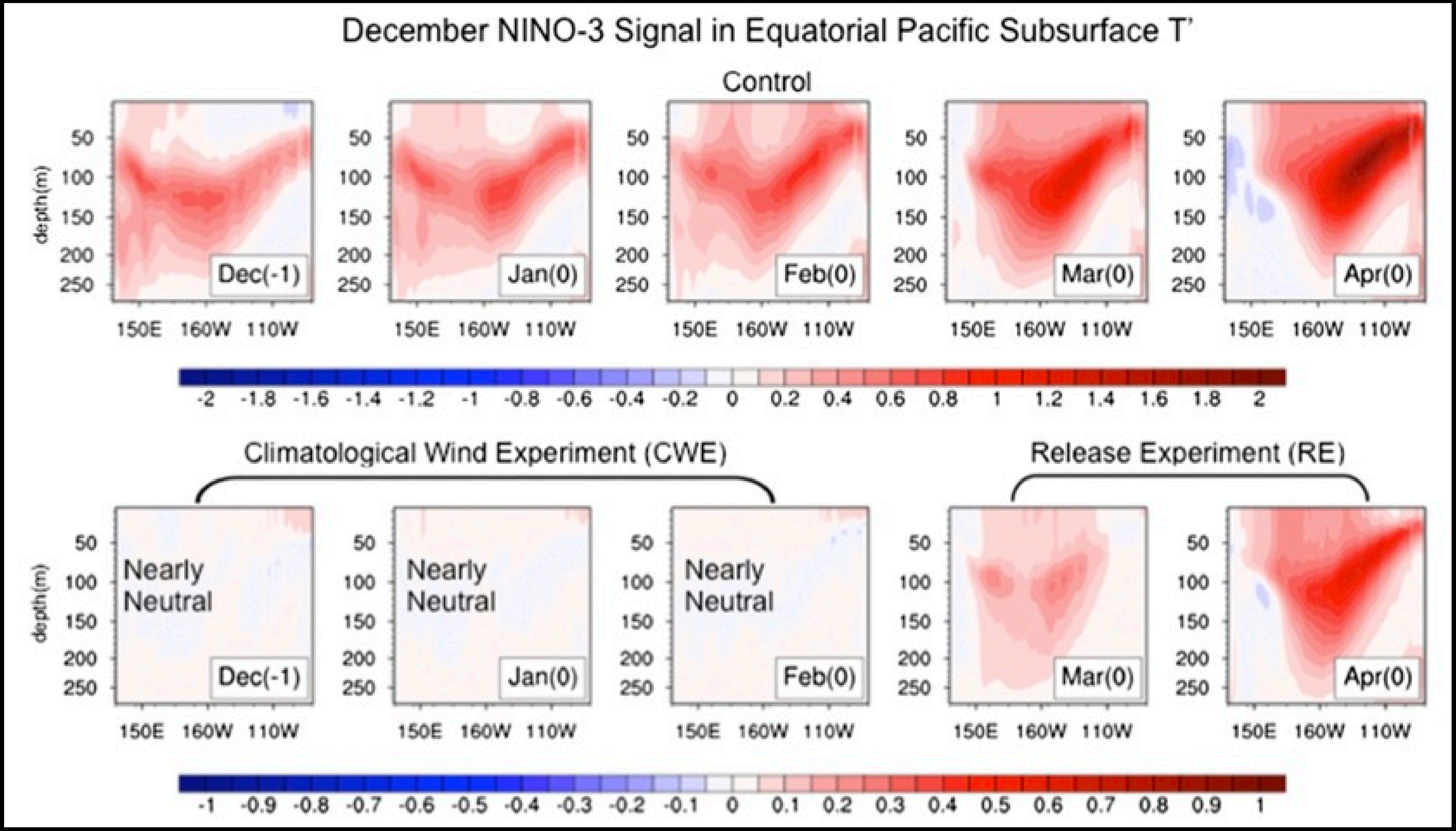
➡ **Even during favorable conditions for El Niño, the inherent stochasticity of the WWEs limits El Niño predictability**

Puy et al. 2017

ENSO predictability

Large scale precursors vs. stochasticity and error growth

Simulation protocol to isolate coupled instability induced SST error growth in the ENSO region



Larson and Kirtman (2015)

ENSO occurence similar without large-scale precursor

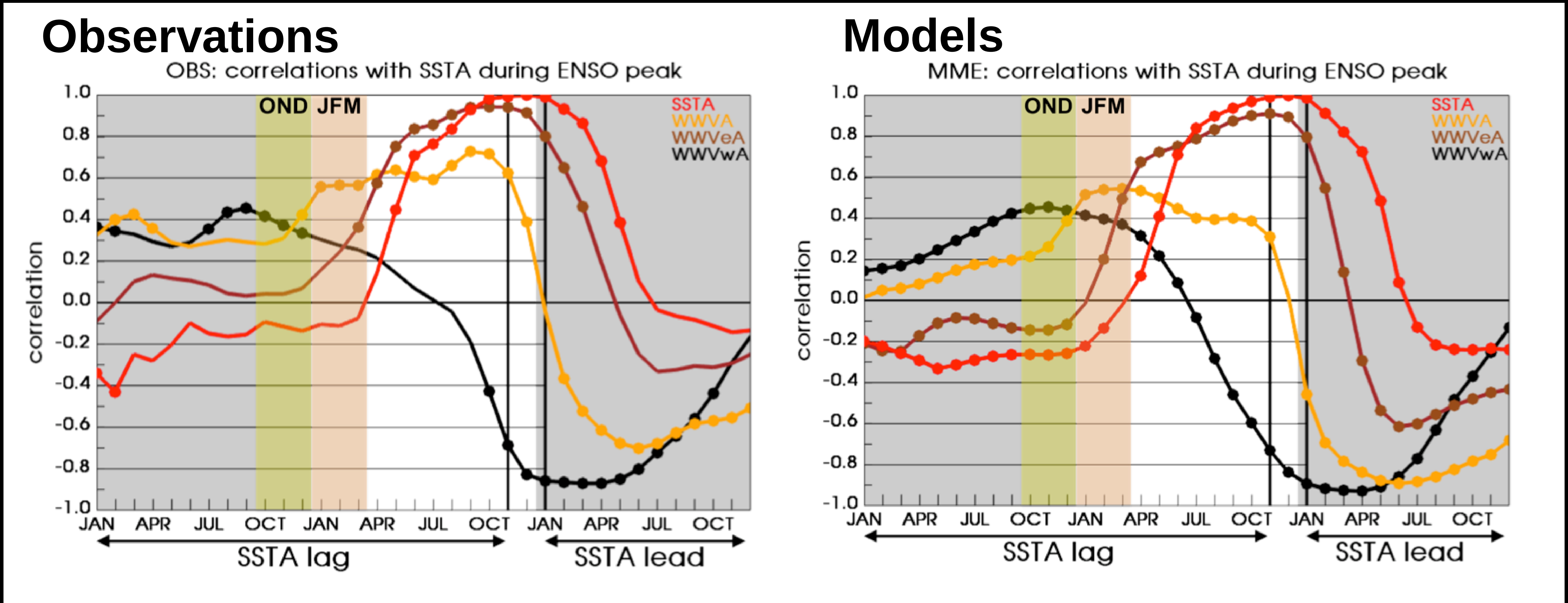
Amplitude weaker (cannot get the large El Niño events)

Understanding extreme El Niño events

- **Understanding ENSO diversity is a hot topic**
- **Some classifications proposed (EP/CP) but debate as very few events**
- **Experts agreement on a "continuum"**
- **ENSO impacts influence by location of heating anomaly**
- **El Niño extremes stand out – but only 3 well observed**
- **Can we use models ?**

Understanding extreme El Niño events in CMIP5

Lag-correlation of potential El Niño precursors

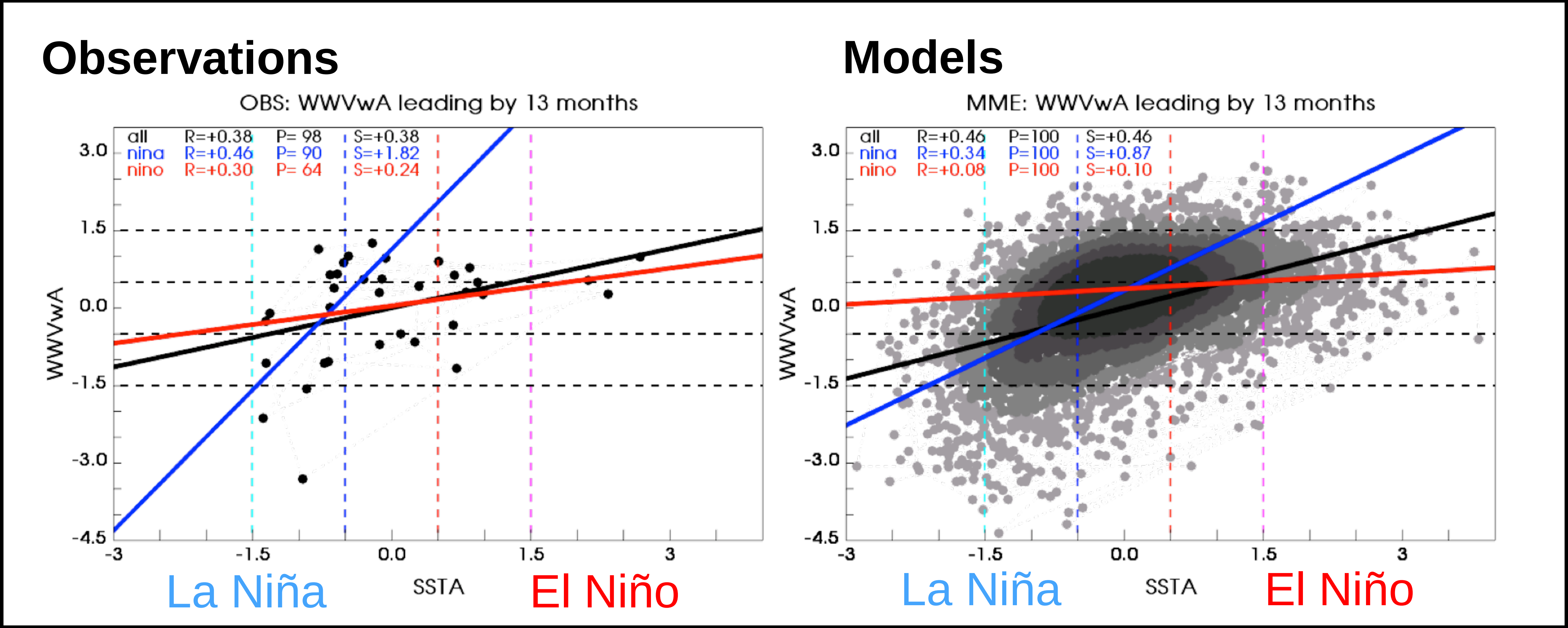


10 selected models using criteria on amplitude, seasonality and skewness

Warm water volume in West Pacific (WWV_w) best precursor up to one year in advance

Planton et al. in prep

Understanding extreme El Niño events in CMIP5



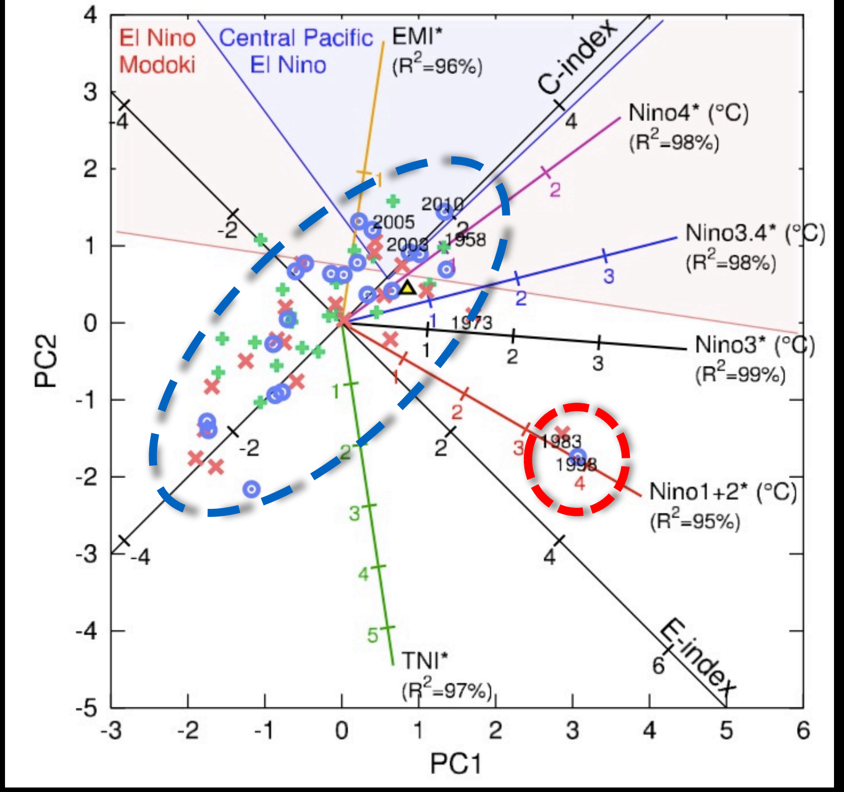
- SSTA - WWV_w relationship asymmetric between El Niño and La Niña
- WWV_w better precursor for La Niña strength but not for El Niño strength
- Can we predict extreme El Niño events before the Spring predictability barrier ?

Planton et al. in prep

Conclusions

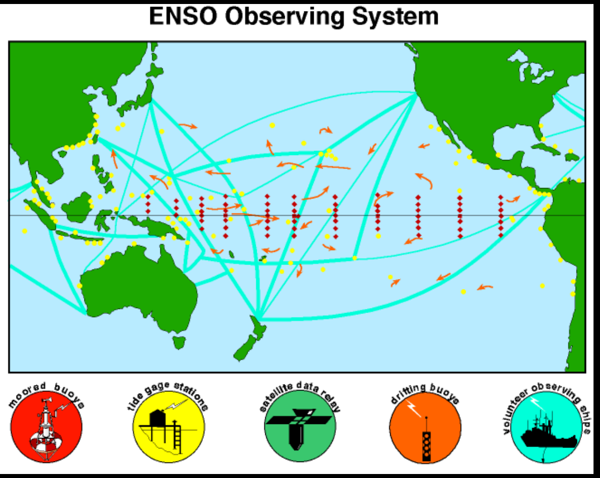
- **ENSO is complex phenomena with many interacting processes**
- **Occurrence forecast is now possible after the Spring barrier**
- **But understanding – and predicting – ENSO diversity, including extremes, is a challenge as observations lacking**
- **Models are choice tools but need process-based assessment**

Current El Niño challenges



Takahashi et al. 2011

- Diversity and extremes
- Role of intraseasonal variations
- Evaluation of ENSO in GCMs
- Interpretation/synthesis of paleo records
- Next generation observation system: TPOS



Tropical Pacific Observing System