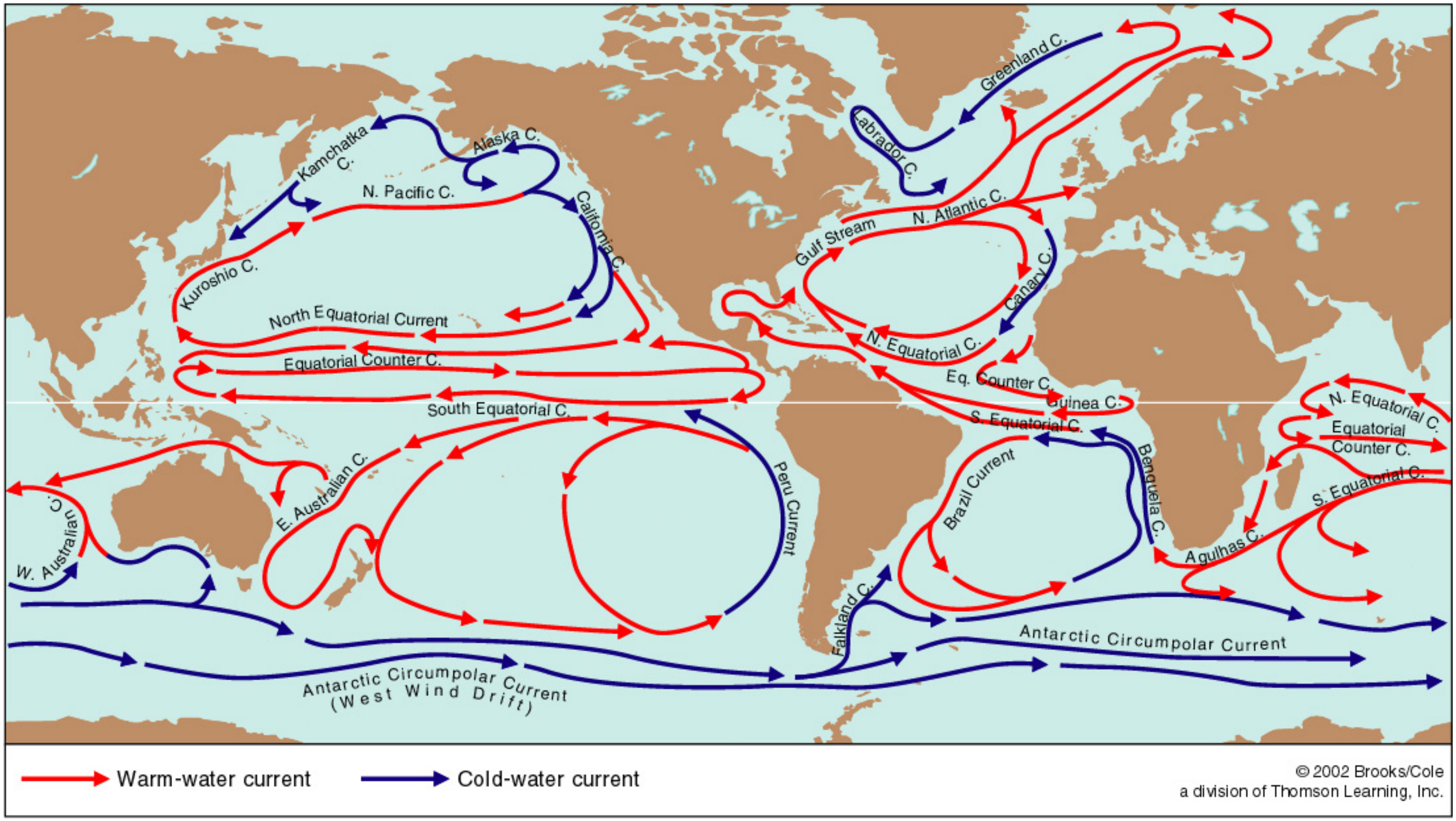
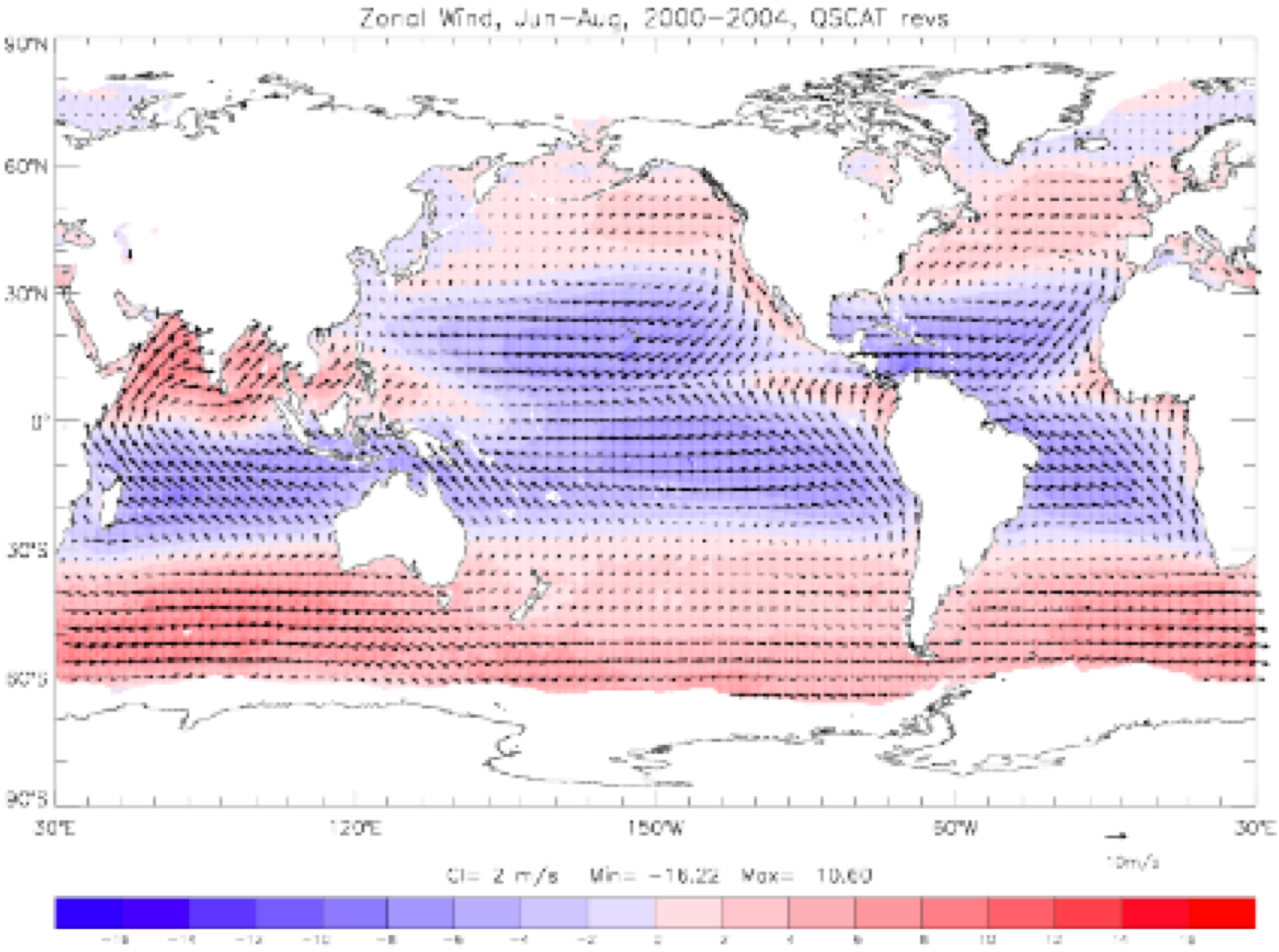
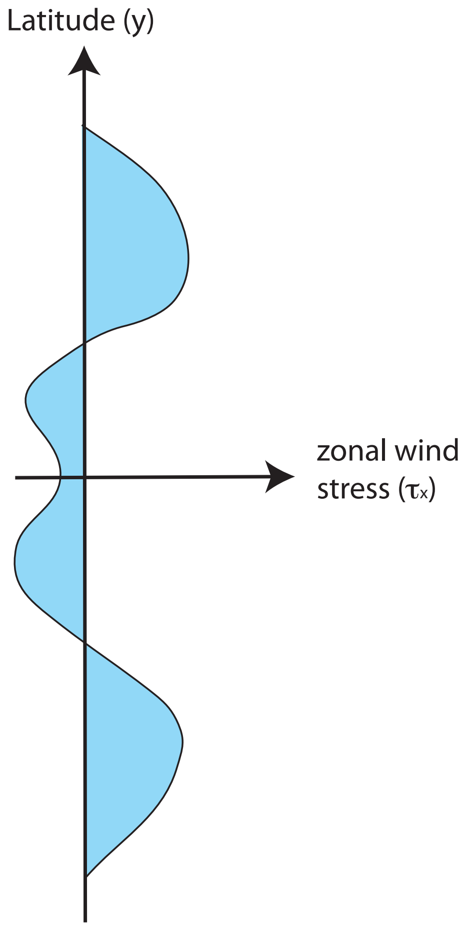
Week 14-15: Tropical Circulation and El-Nino Southern Oscillation



Observed surface wind stress

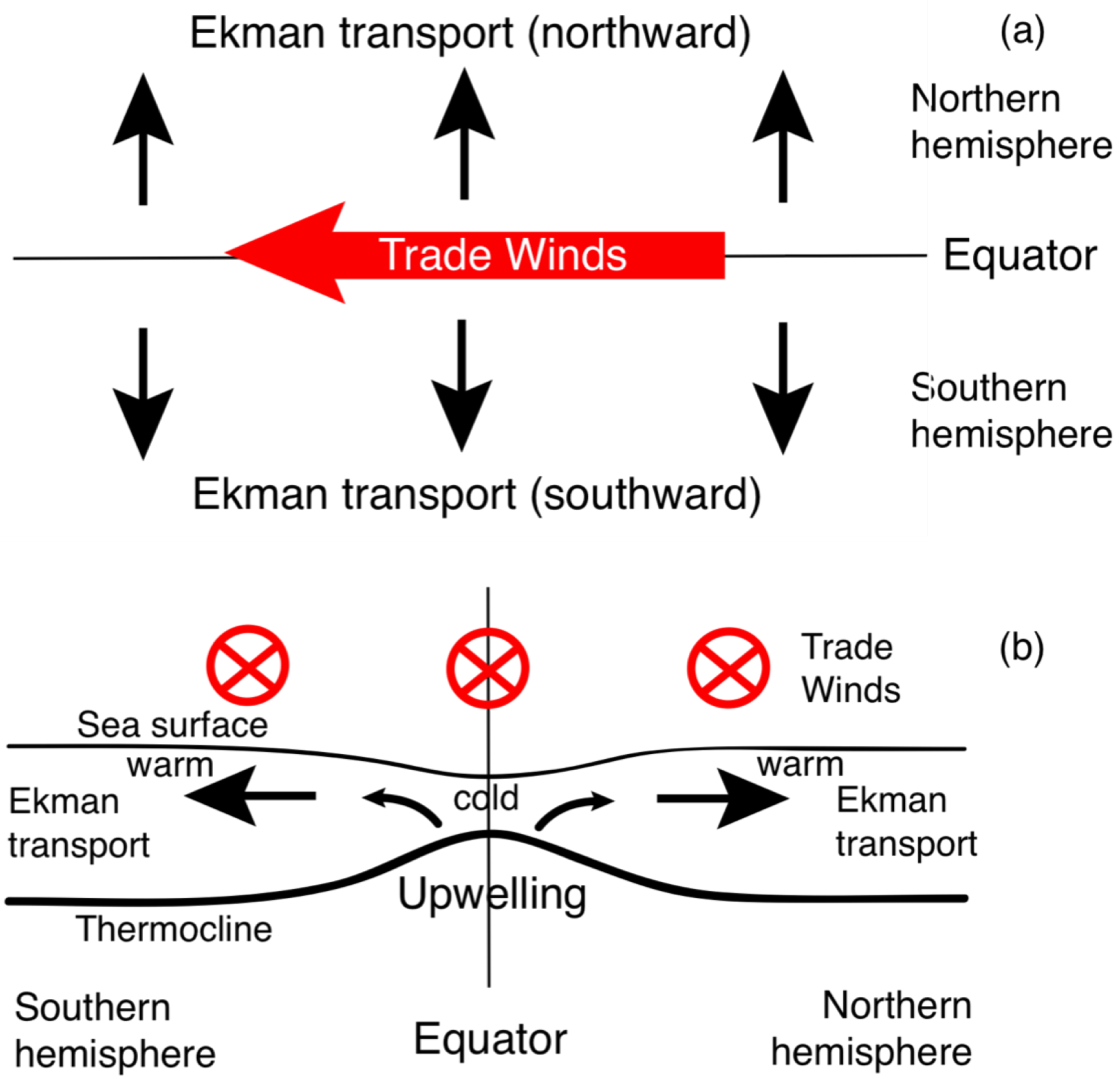




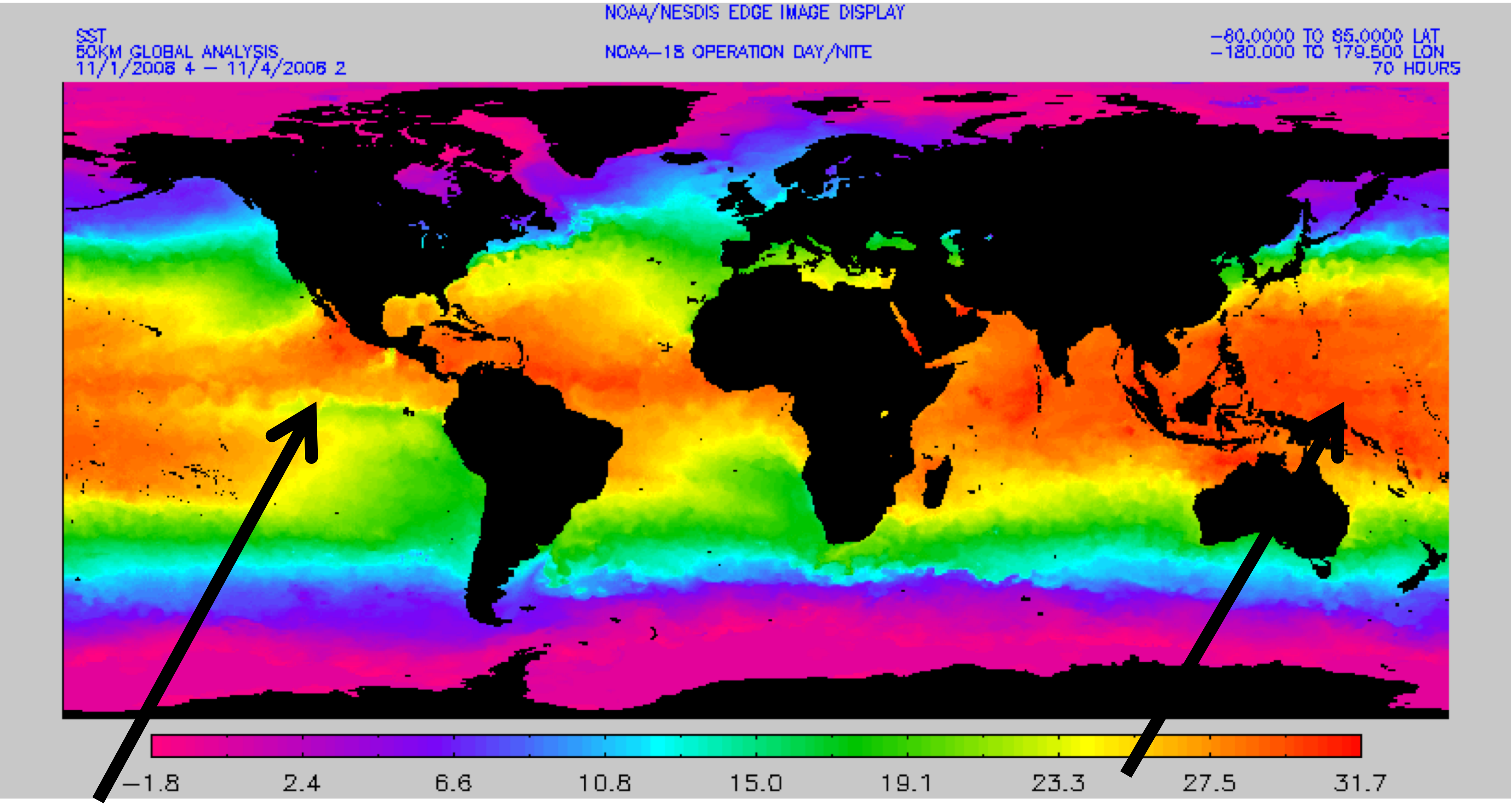
Blue = westward (trade wind)

Red = eastward (westerly wind)

Equatorial upwelling



Sea surface temperature (satellite)



Cold tongue (colder water along equator in east)

Warm pool (warmer water along equator in west)

Pacific equatorial structures: mean state

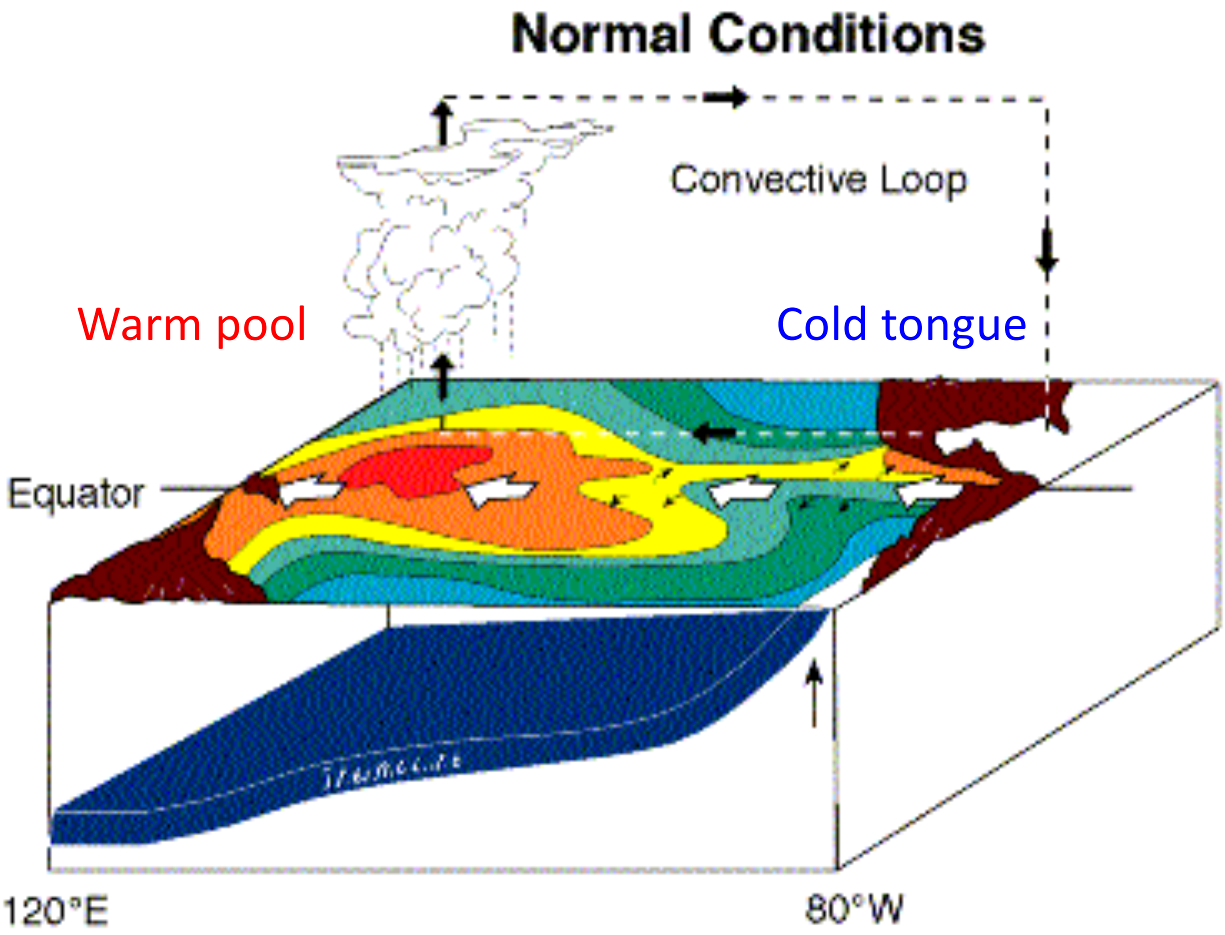


Figure credit: NOAA PMEL

1. **Trade wind** on the equator (driven by atmospheric Walker circulation)

2. **Poleward Ekman transport** creates meridional PGF, supporting westward geostrophic flow off-equator

3. **Westward surface flow** on equator by direct effect of the wind (no Coriolis effect there)

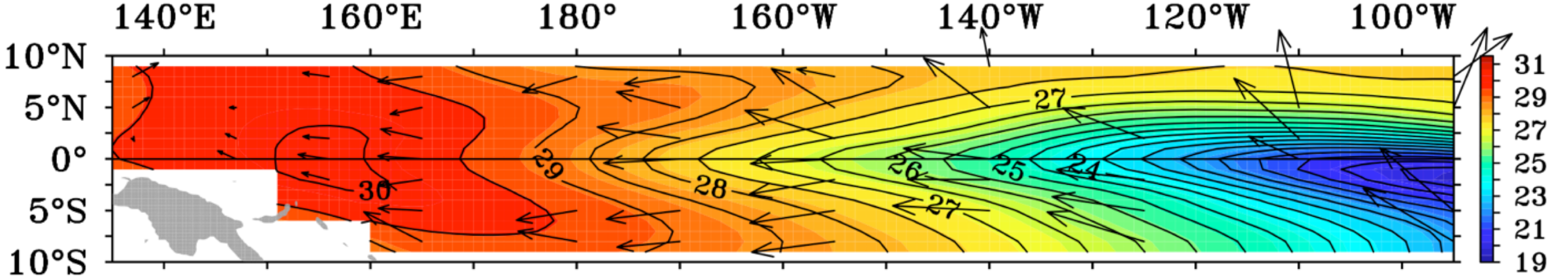
4. **Equatorial upwelling** due to (a) Ekman divergence and (b) the westward surface flow

5. As a result of (b), **thermocline is tilted:** shallower in the eastern margin

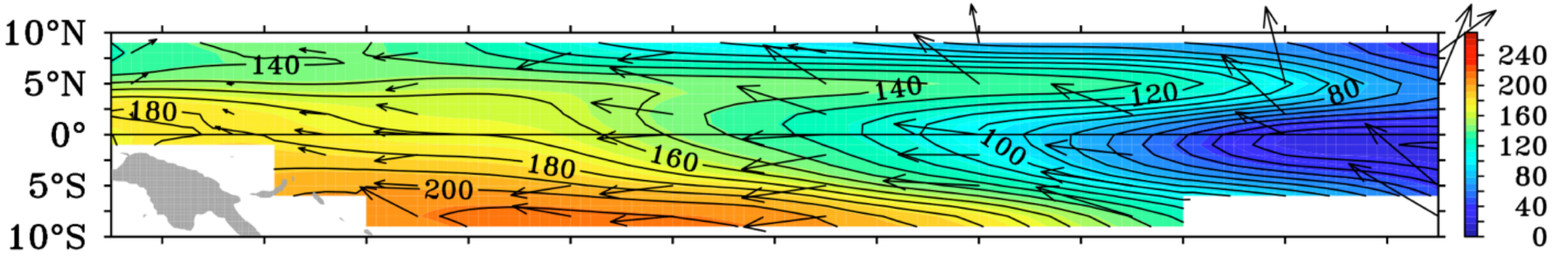
Equatorial Pacific SST, SSH and thermocline

Normal / La Nina condition

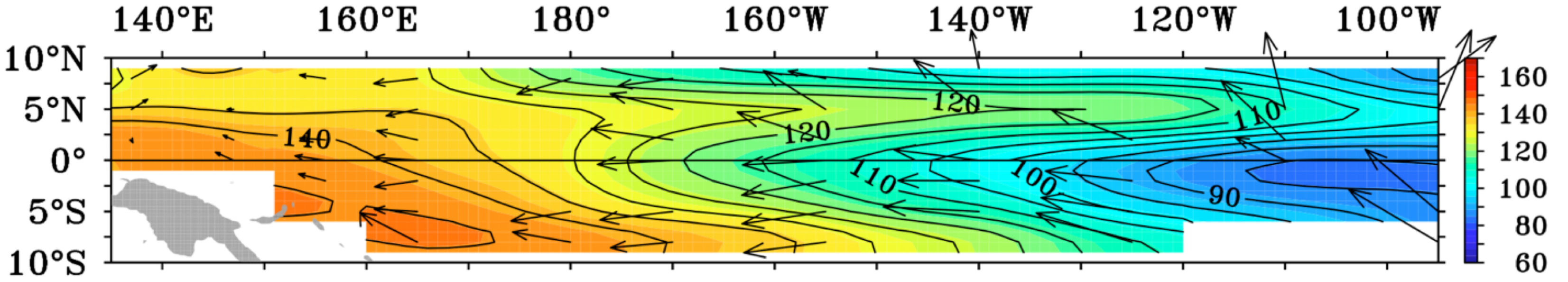
TAO/TRITON Monthly Data August 2007



(a) SST (°C) and Wind

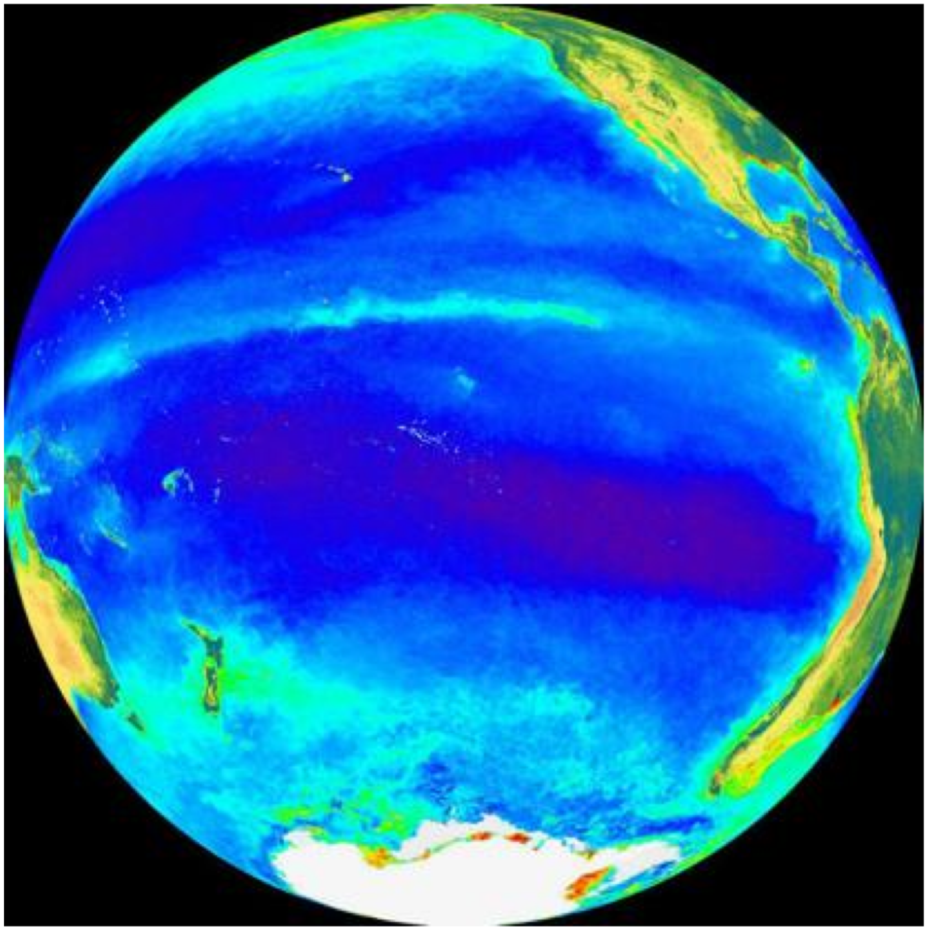


(b) 20°C isotherm depth and Wind

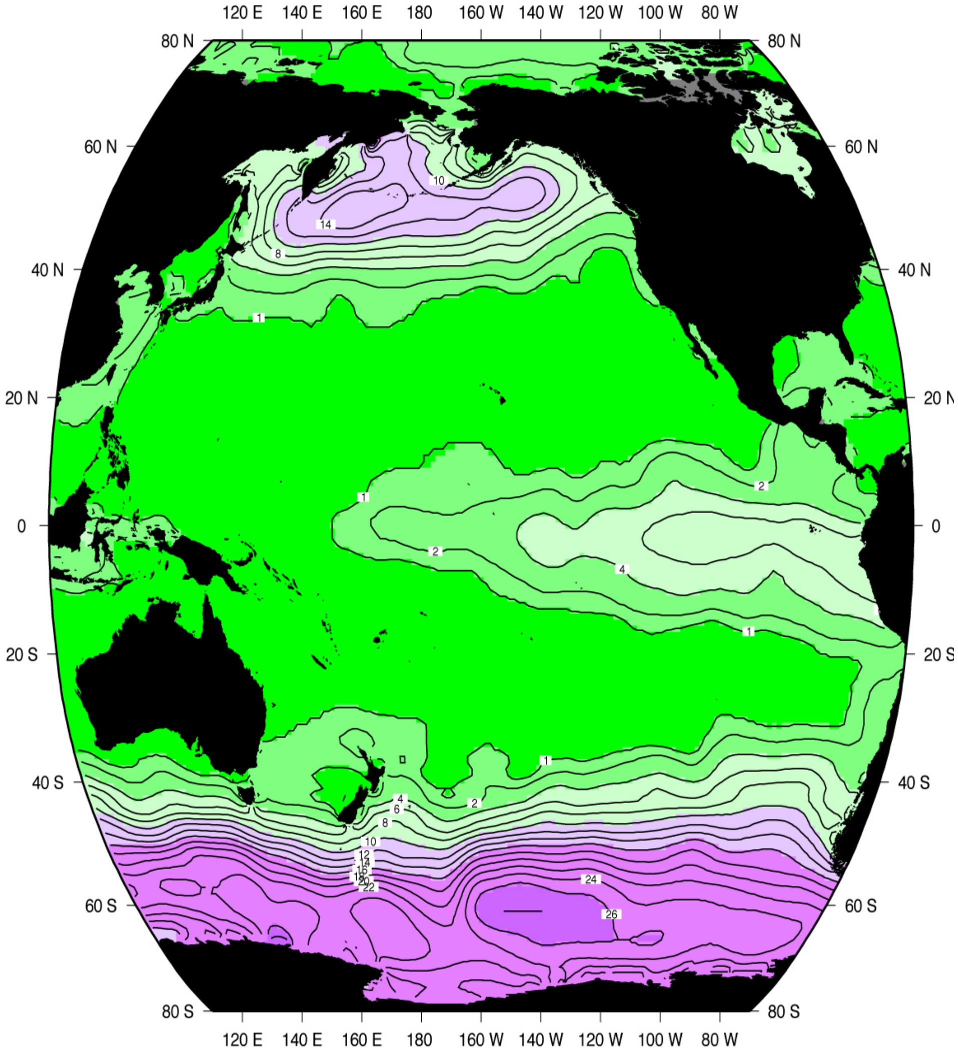


(c) Dynamic height (dyn cm rel. to 500 dbar) and Wind

Effects on surface nutrients and productivity



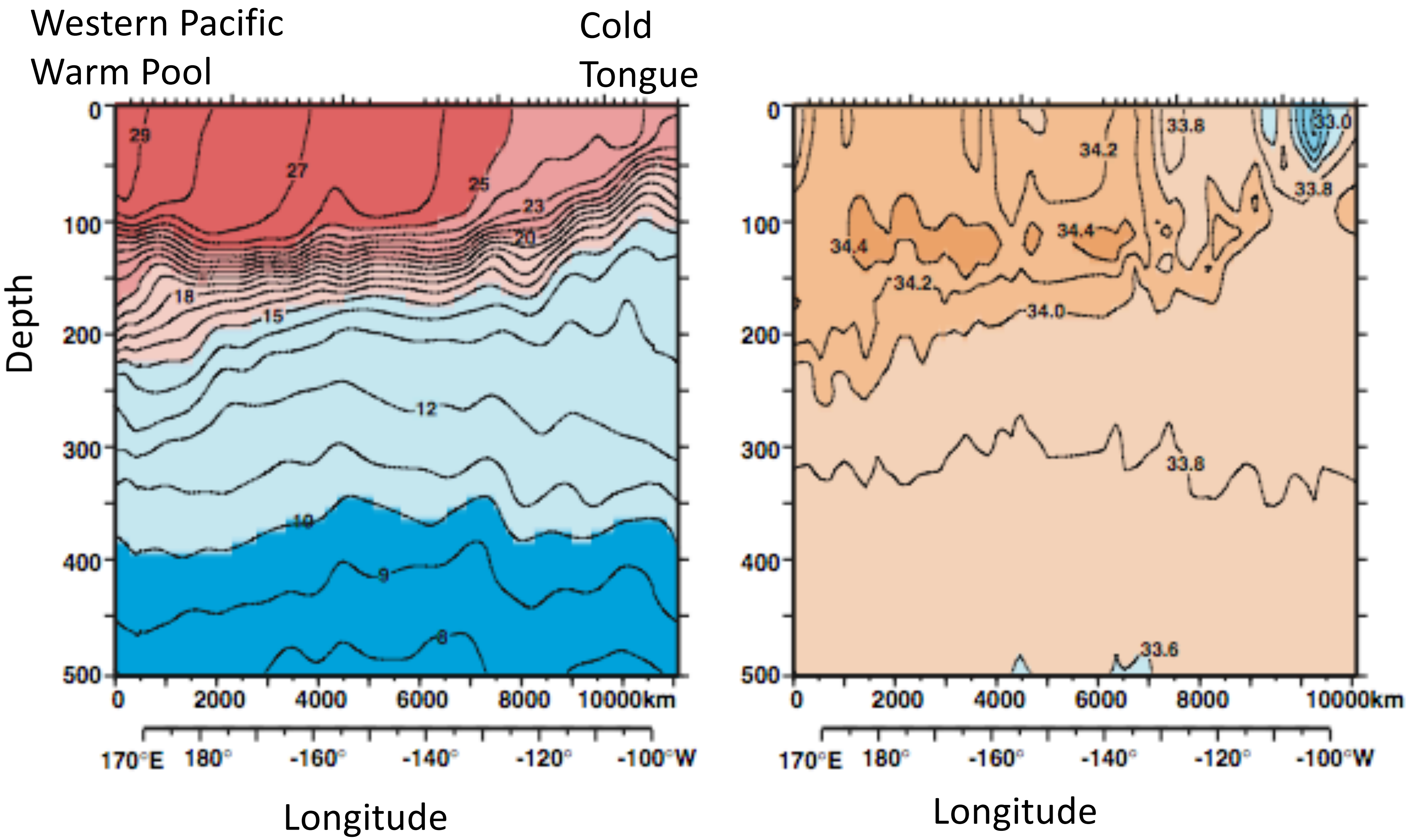
Ocean color: chlorophyll



Nitrate at 10 m depth

Equatorial upwelling brings nutrients to sea surface, enhanced in cold tongue

Vertical structure of the equatorial currents

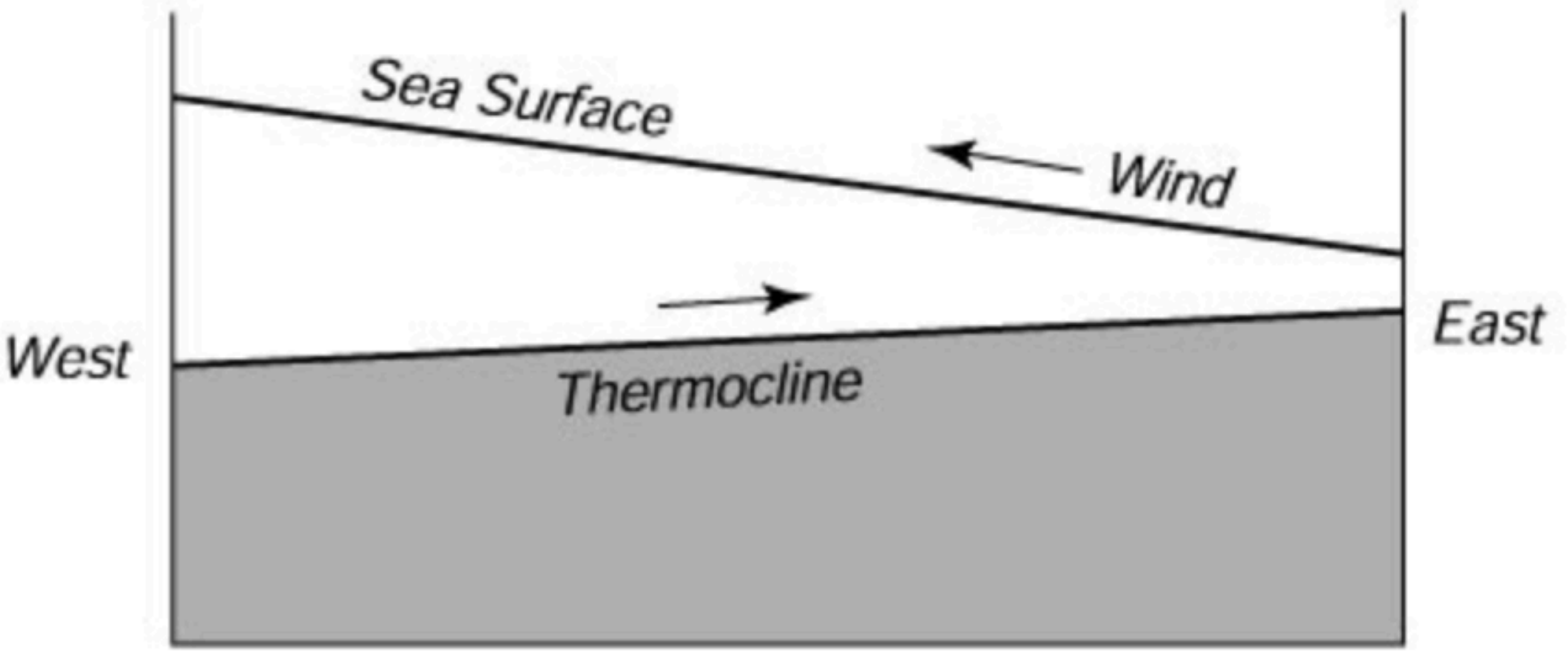


Temperature

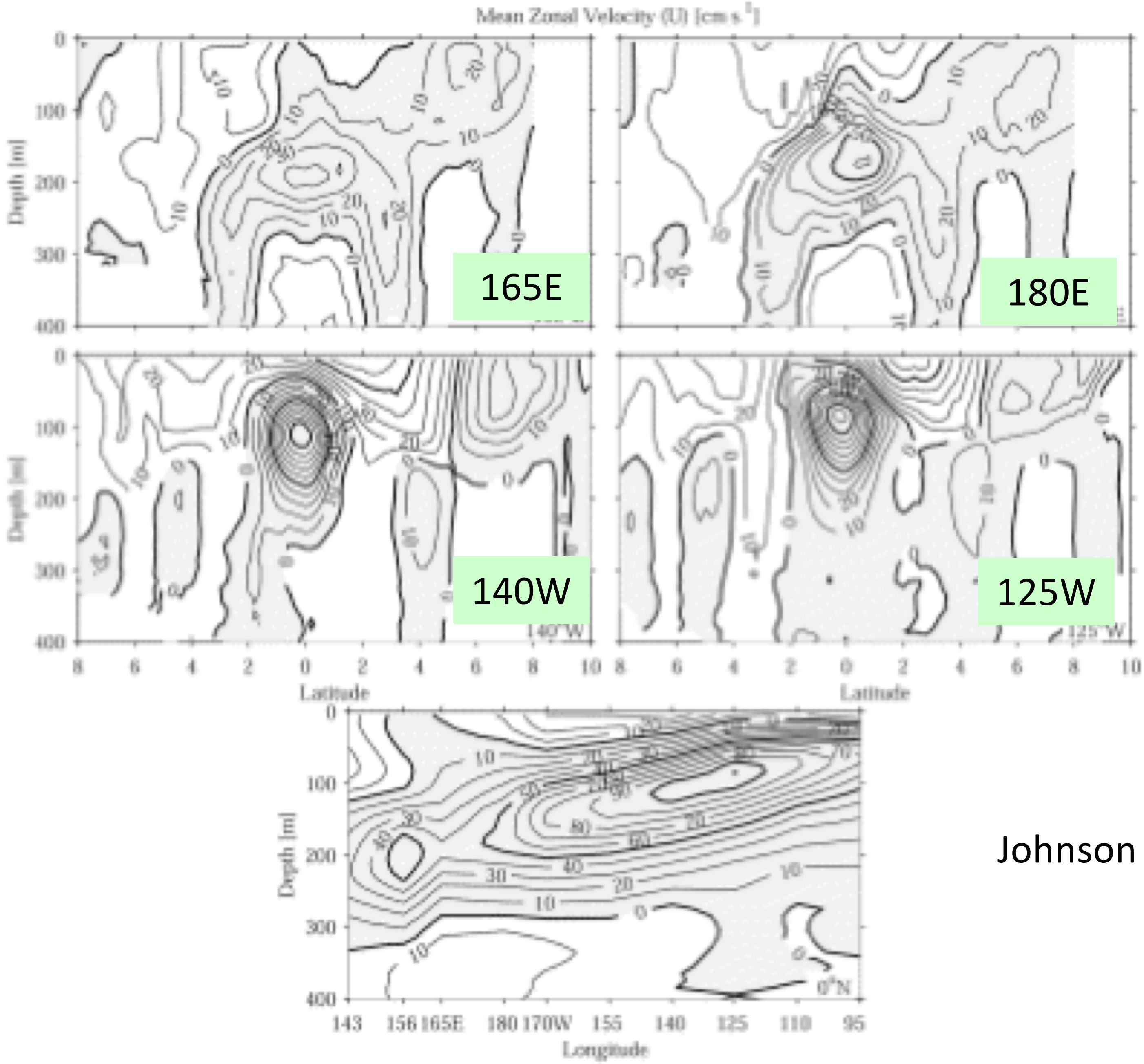
Salinity

Equatorial Undercurrent (EUC)

Down-gradient flow driven by the equatorial PGF: causes eastward flow along the equator. This is called the Equatorial Undercurrent. The strongest current in the global ocean > 150 cm/sec, but very thin and restricted to very close to the equator.



Section across the EUC



North-South
Section across the
equator

Shading indicates
the direction of the
flow:

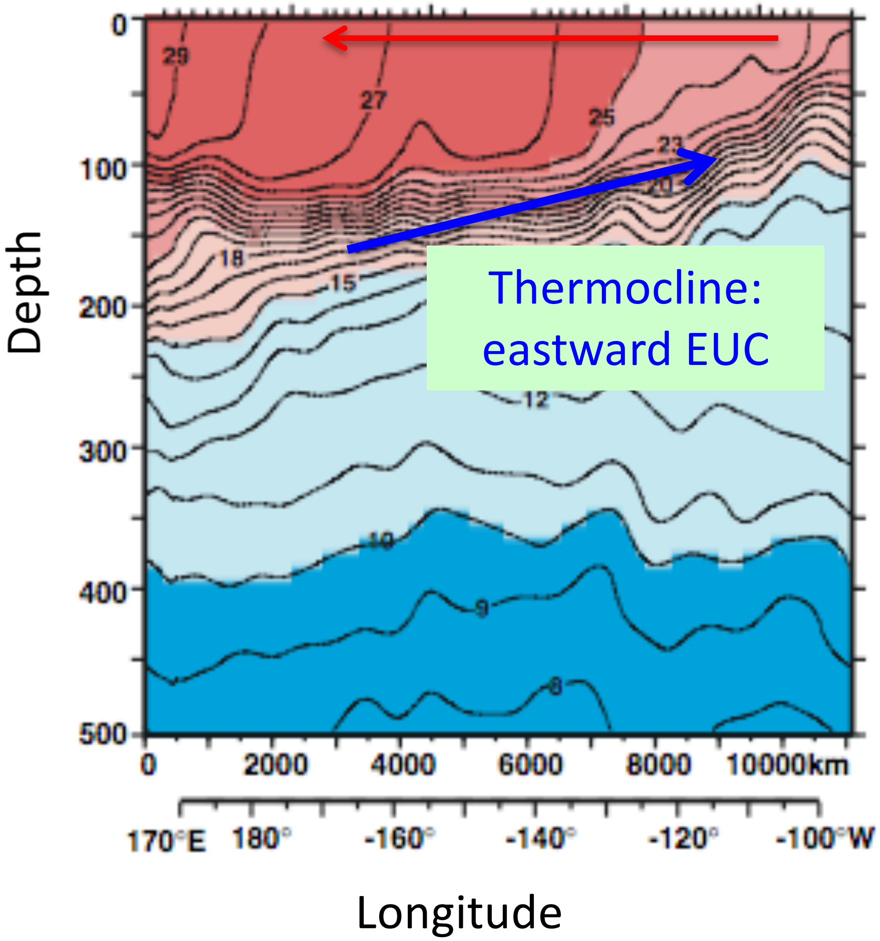
White = westward
Gray = eastward

Johnson et al., (2002)

Vertical structure of the equatorial currents

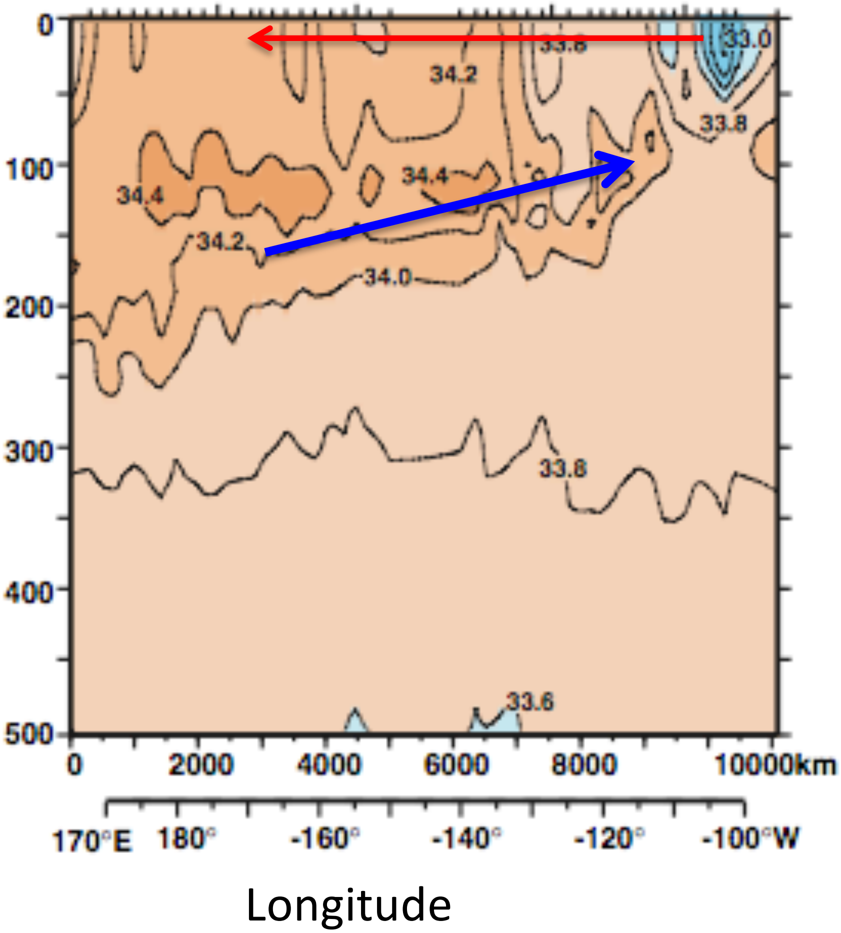
Temperature

Surface: westward
Equatorial current

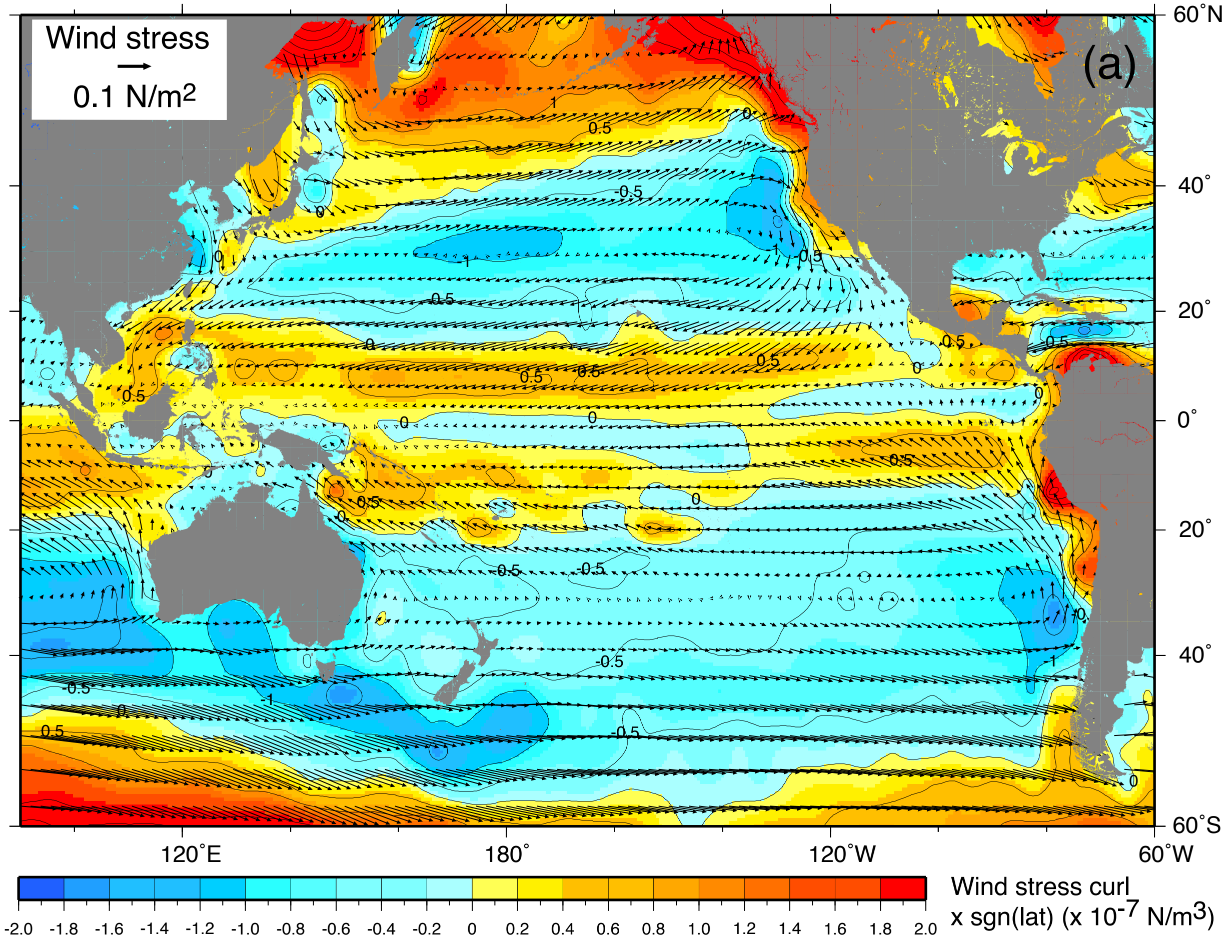


Thermocline:
eastward EUC

Salinity



Atmospheric wind and its curl

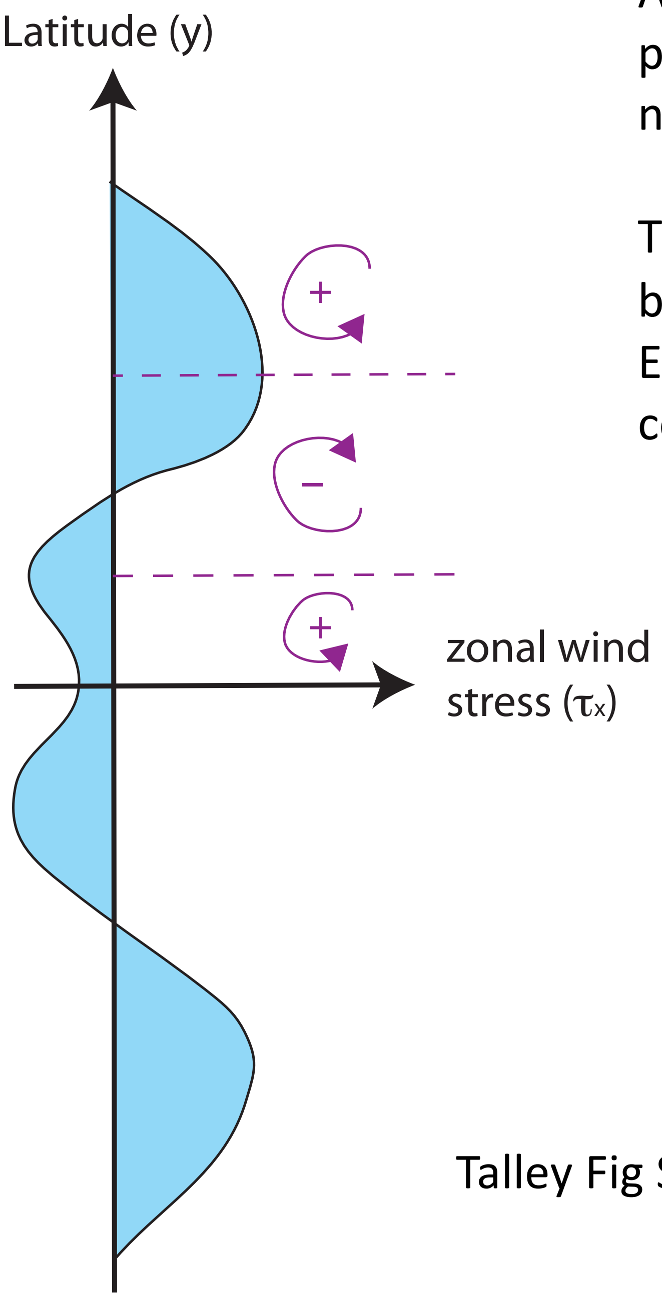


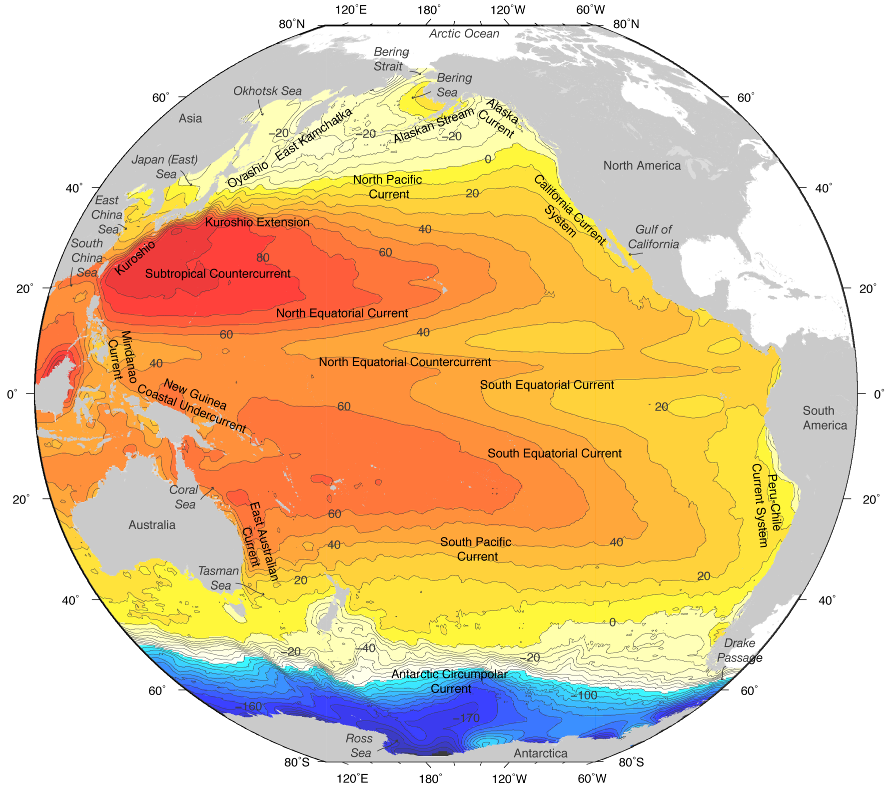
- Right on the Equator, the wind stress curl is very small. There is a band of positive wind stress curl at about 10ºN (under ITCZ)
- Positive curl → Ekman upwelling just below the surface
  → Poleward Sverdrup transport

Sverdrup circulation off the Equator

At slightly north (south) of the Equator, there is a positive (negative) wind stress curl, leading to a northward (southward) Sverdrup flow.

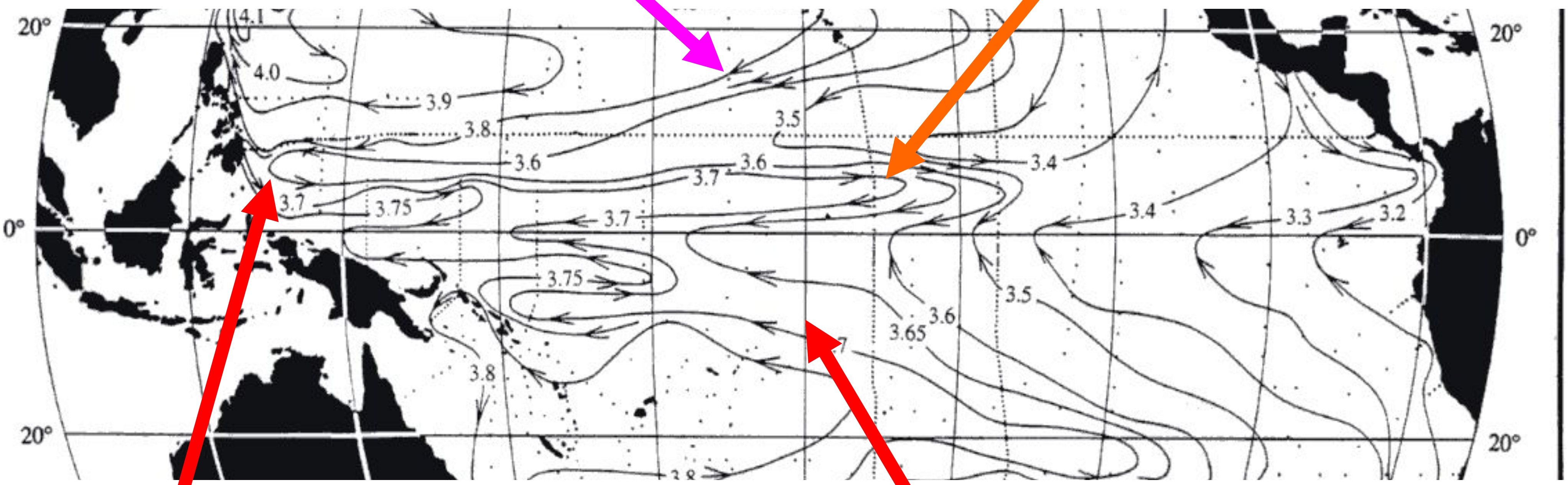
This circulation must close through the western boundary current (Mindanao current/North Equatorial current/North Equatorial countercurrent)





Talley Fig S10.1

Equatorial current system (Reid, 1997)



North Equatorial Current (westward)

North Equatorial Countercurrent (eastward)

Mindanao Current (western boundary current for the NEC/NECC cyclonic circulation)

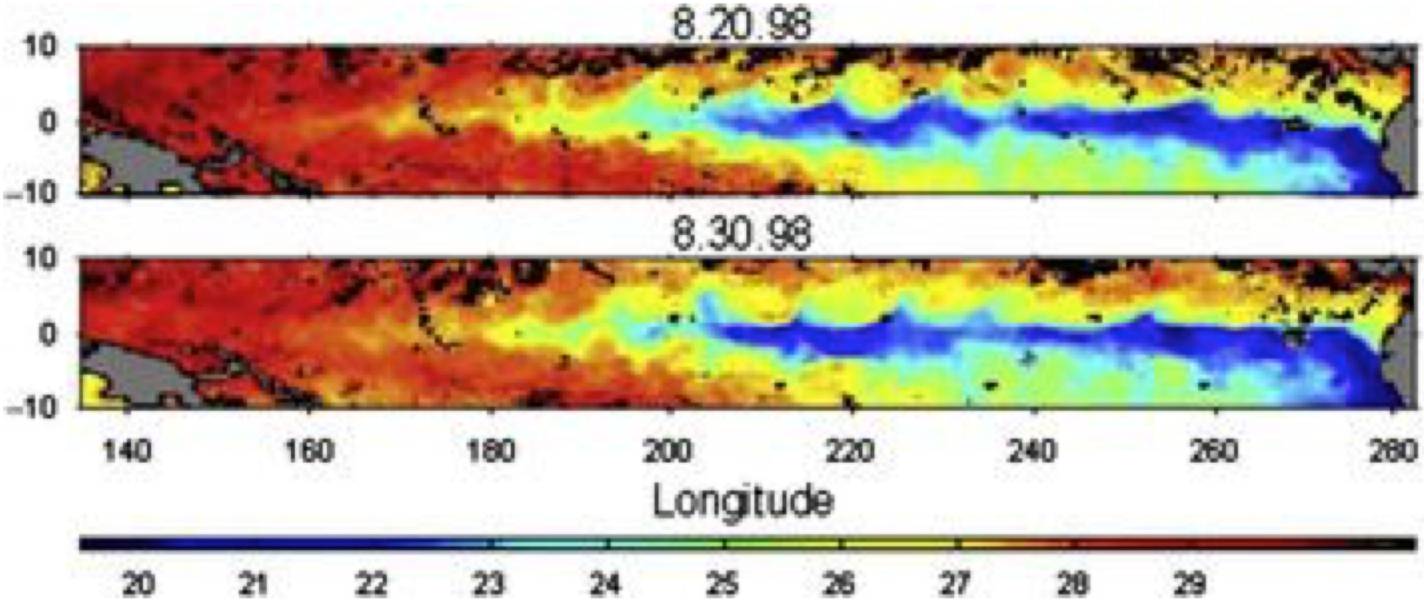
South Equatorial Current (westward)

NOTE: The mean surface flow on the equator is westward

(Talley Fig. 10.1)

Tropical ocean variability

- **Tropical Instability Wave** (TIW) are oscillation of SST in the equatorial oceans. Its spatial scale is of the order of 1,000km with periods of 20-40 days. The equatorial currents are unstable and spontaneously produce meanders and waves. They form at the edge of the cold tongue, and the pattern propagates westward at the speed of 0.2-0.5 m/s.

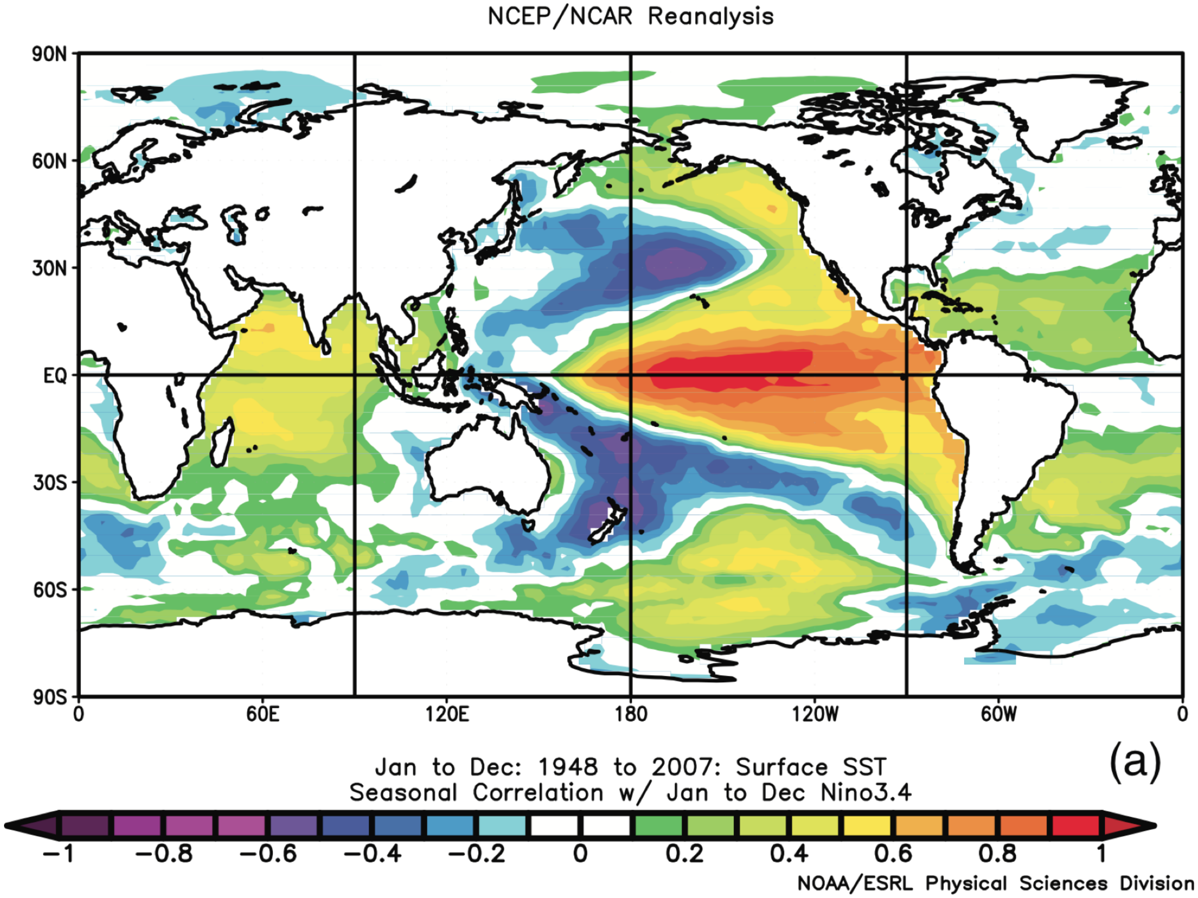


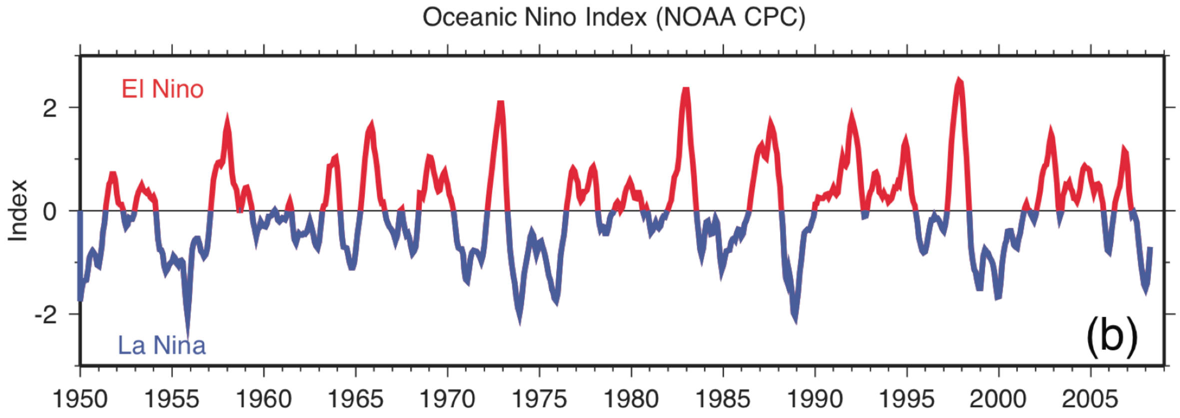
Tropical ocean variability

- **Equatorial waves** generally include three types of waves. **Inertia-gravity waves** (fast), **Kelvin wave** (eastward propagating, fast) and **Rossby wave** (westward propagating, slow). Due to the vanishing effect of the Coriolis effect, the equator acts as a wave guide, supporting these waves only in the vicinity of the equator. These waves exist both in the atmosphere and oceans. The width of the equatorial wave guide is determined by the Equatorial deformation scale (L_β). Kelvin wave can travel across the Pacific ocean in about 1-2 months, whereas Rossby wave is much slower (about 6 months).

- Equatorial waves are important component of the El-Nino Southern Oscillation.

El-Nino Southern Oscillation (ENSO)





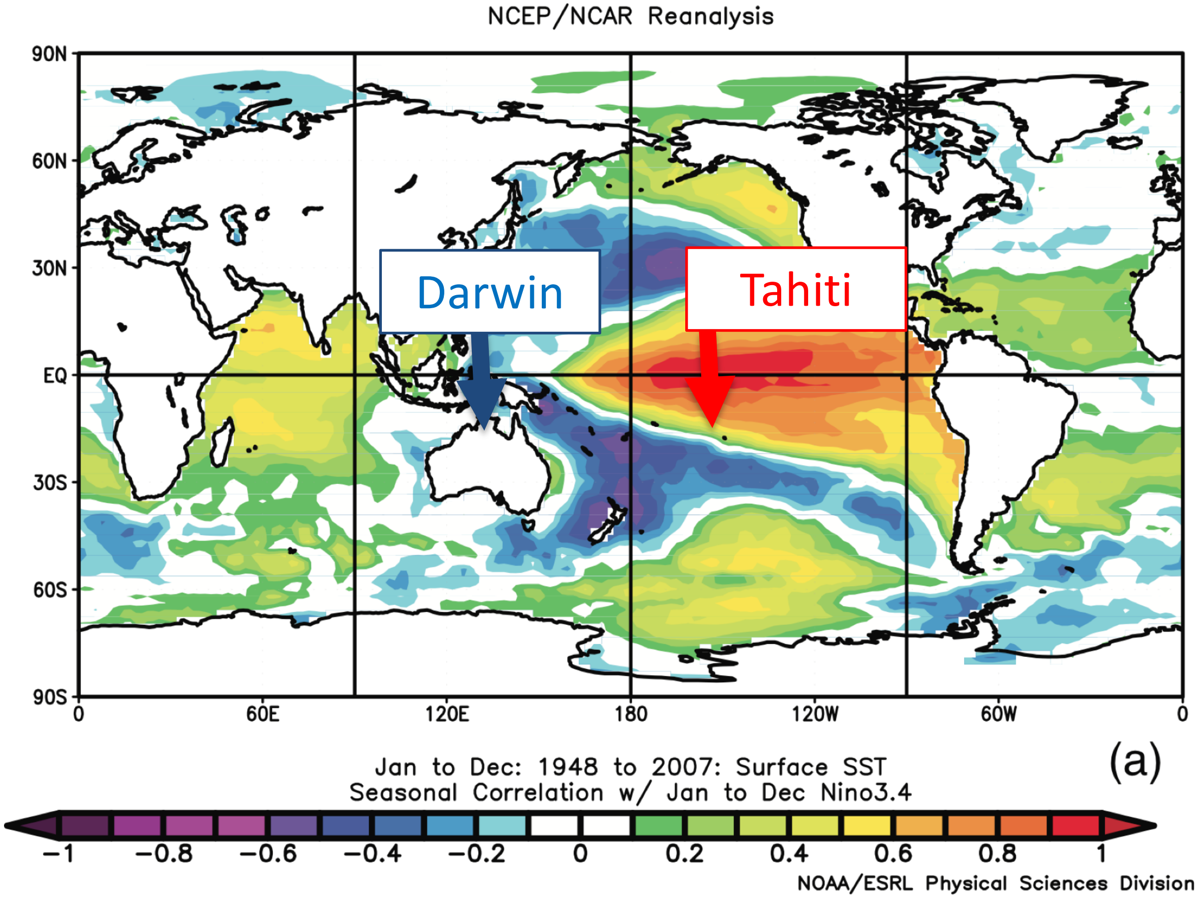
Correlation of SST with El Niño index (“Nino3.4” index = Eastern Equatorial Pacific SST, will discuss later)

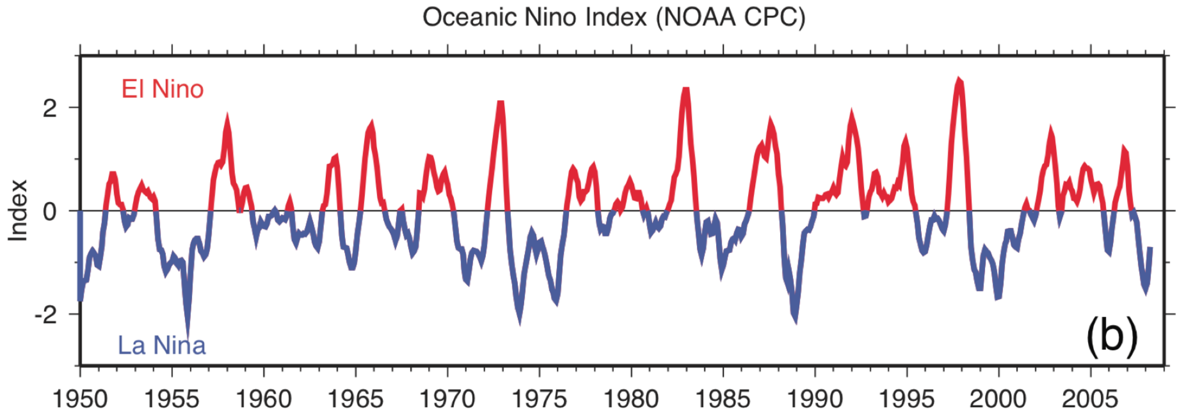
El-Nino event = Warming of eastern tropical Pacific (>28C)

La-Nina event = Cooling of eastern tropical Pacific (<25C)

*named by Peruvian fisherman, dating back to 1600s, as the ocean warms (cools) always around Christmas in the El Nino (La-Nina) year. Also, the warming is accompanied by the massive loss in ocean productivity.

El-Nino Southern Oscillation (ENSO)



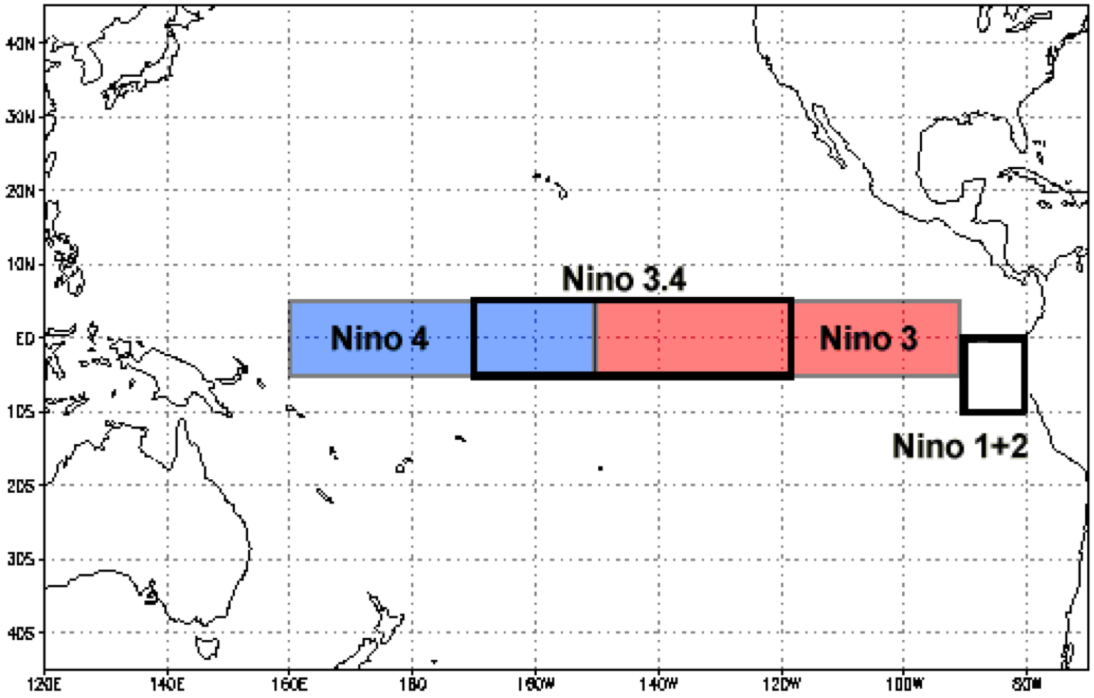


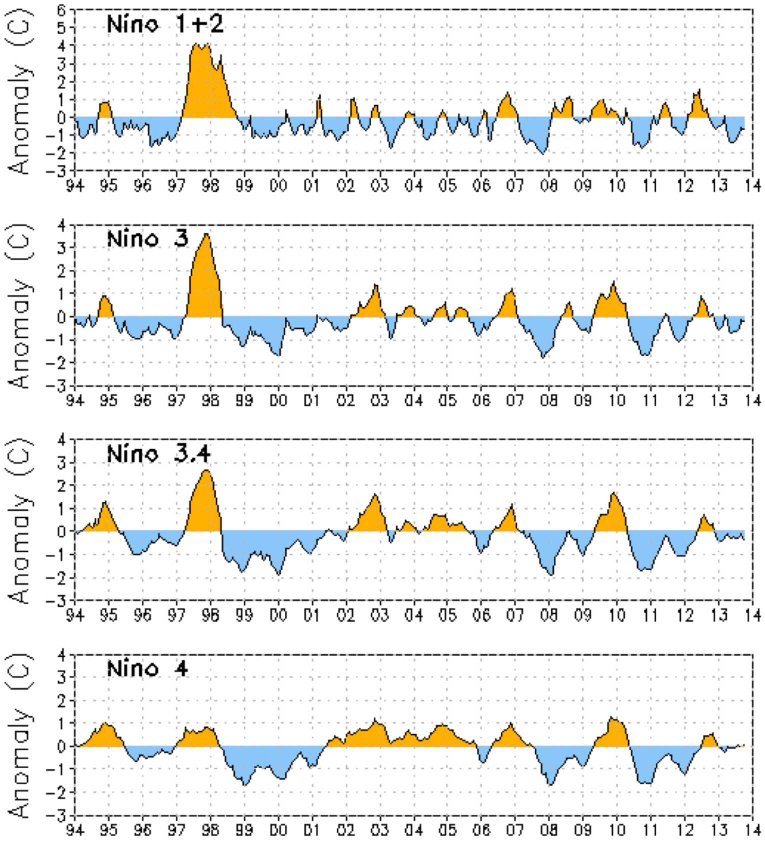
Atmospheric counterpart is the **Southern Oscillation Index**, defined as the sea level pressure (SLP) difference between Darwin and Tahiti.

The SOI (that is based on SLP) is closely related to the El Nino – La Nina events (that is based on SST). Since southern oscillation is a part of the same phenomenon that causes El Nino events, we now call them ENSO (El-Nino Southern Oscillation) as a single climate pattern.

Nino indices for tropical SST

Nino 3.4 is most commonly used for its wide coverage of cold tongue SST. If it exceeds the mean by 0.5 degree C, it is operationally classified as El-Nino condition





Data updated through October 2013

What controls what?

Cold tongue – Warm pool is sustained by the tropical trade wind

Walker circulation (whose surface expression is the tropical trade wind) is sustained by the heat from the Warm pool

If trade winds weaken, then

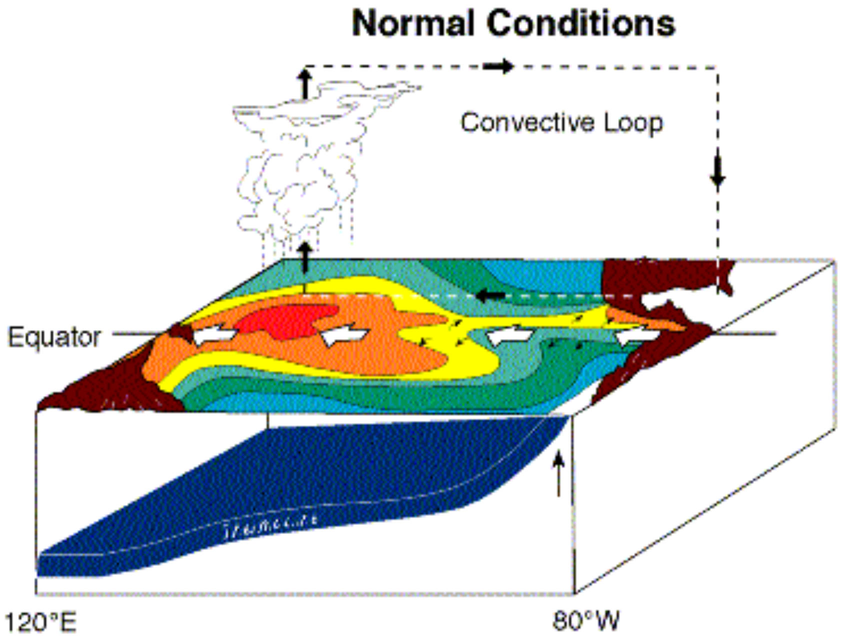
(1) Equatorial current weakens, allowing western Pacific warm waters to move eastward

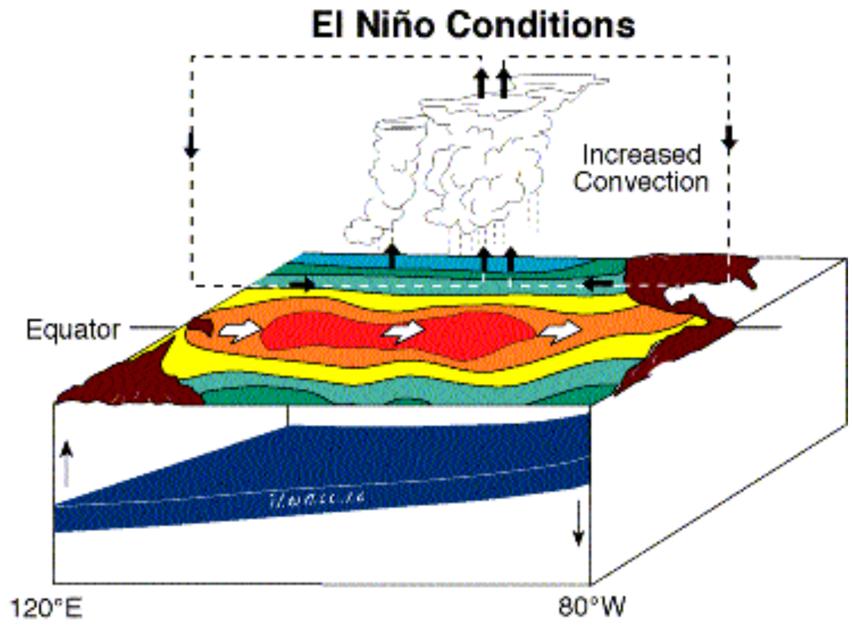
(2) Warm pool cools down, cold tongue warms up

(3) Convection shifts to the central Pacific

(4) Walker cell (this trade wind) weakens, reinforcing the original weakening of the wind

(5) This then becomes the El Nino condition.





NOAA/PMEL/TAO

***Bjerknes Feedback** (La Nina)

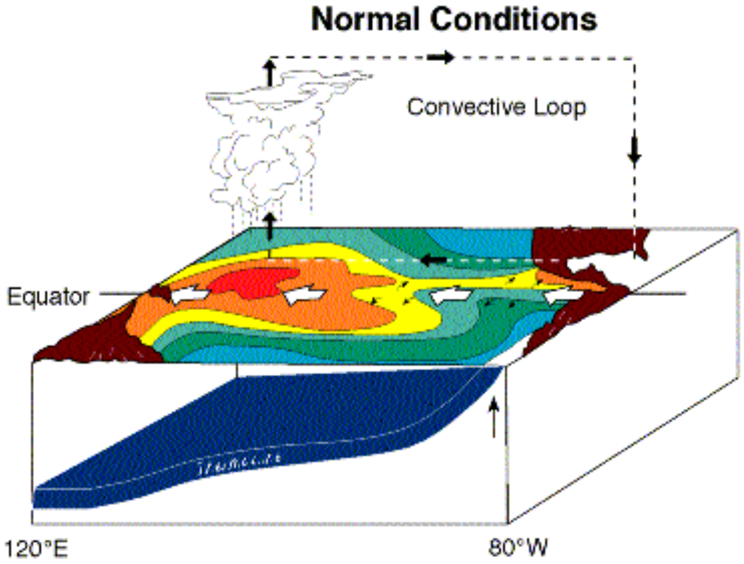
If trade winds strengthen, then

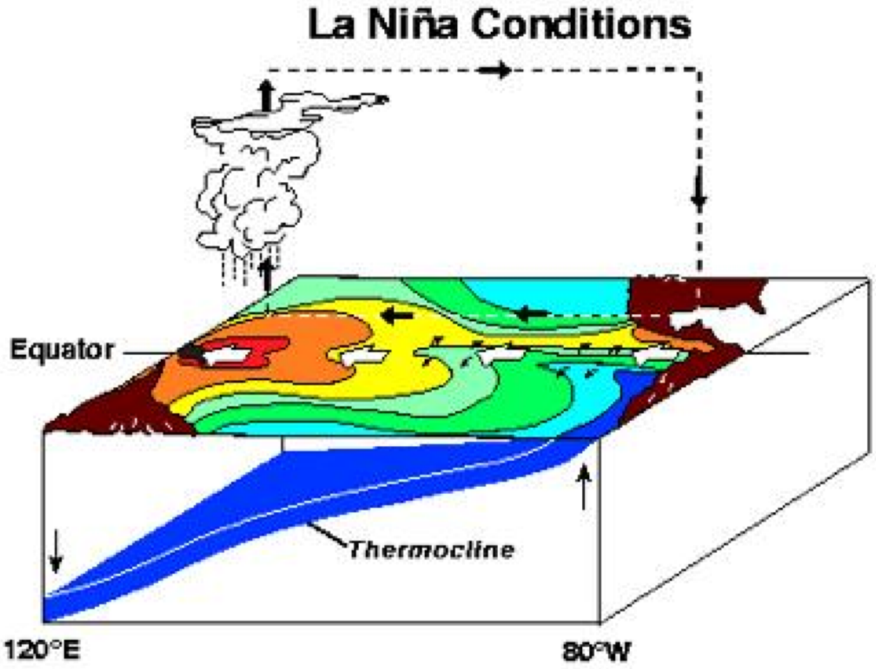
(1) Equatorial current strengthens, warm pool stays in west

(2) Upwelling in the east sustains cold SST there

(3) Convection over the warm pool is sustained, thus trade wind is reinforced

(4) This then becomes the La Niña condition.


Normal Conditions


La Niña Conditions

Atmospheric convection preferentially occurs over the warmest SST.

***Jacob Bjerknes**, a Norwegian-American meteorologist who founded UCLA's Atmospheric Science Department, and also is the son of **Vilhelm Bjerknes**, a Norwegian physicist and early meteorologist, establishing Bergen school of Meteorology, whose students included Ekman and Rossby.

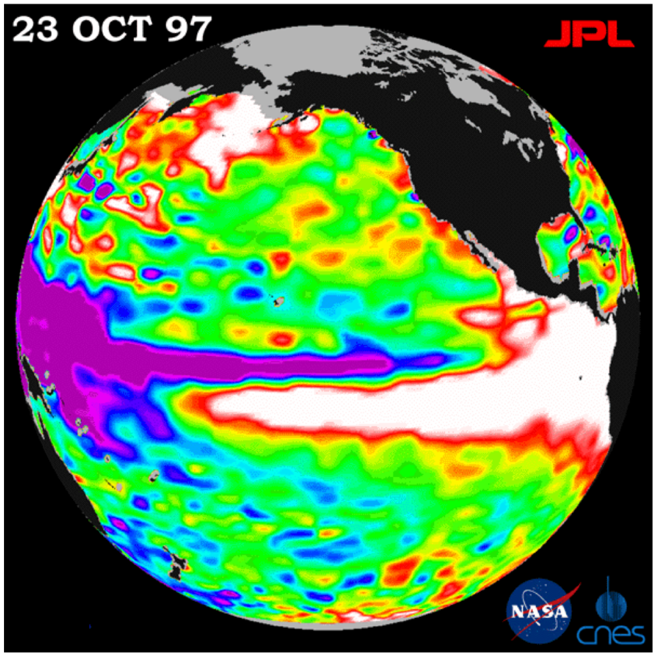
Expressions of ENSO

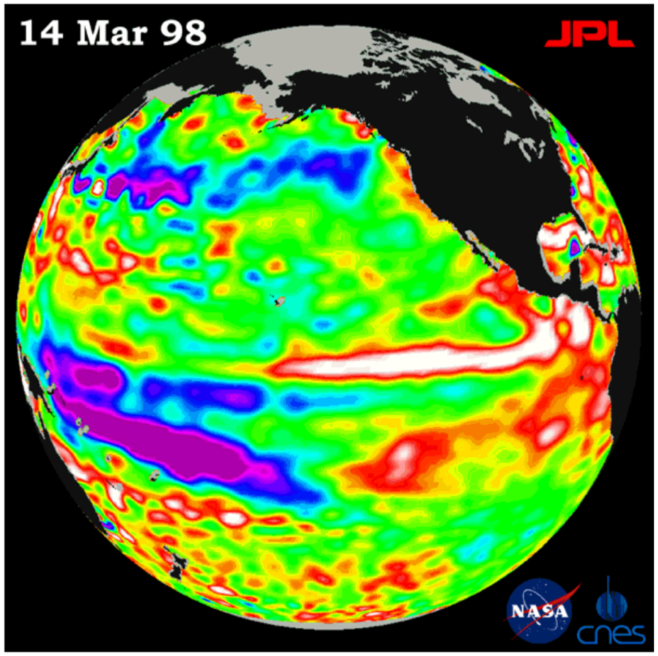
What are the typical metric for El-Nino?

1. Eastern Tropical SST
2. High SSH in central and eastern equatorial Pacific and low SSH anomaly over the Warm Pool
3. Deep thermocline depth in the east, shallow thermocline in the west
4. Winds: weakened trade wind
5. Atmospheric pressure anomalies (measure of the walker circulation, Southern Oscillation Index)

Sea surface height images

http://topex-www.jpl.nasa.gov/elnino/index.html



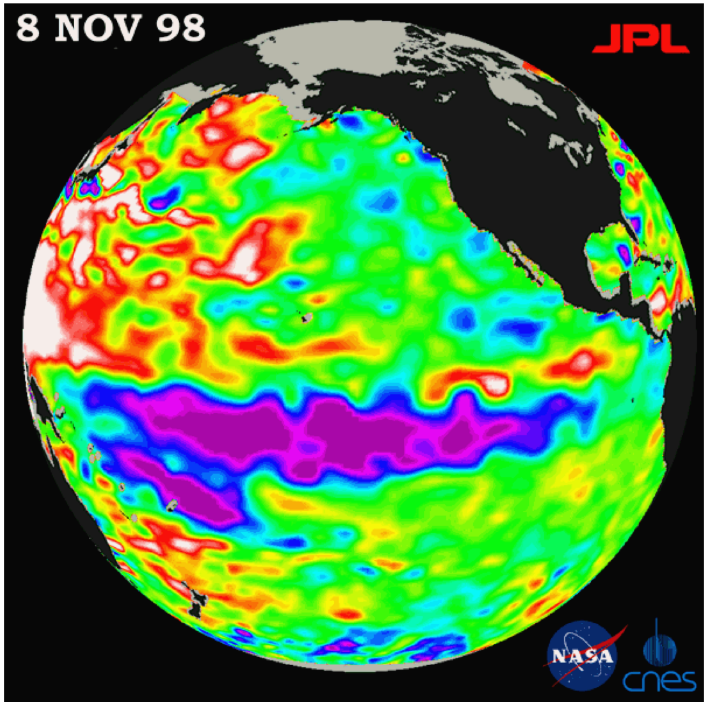


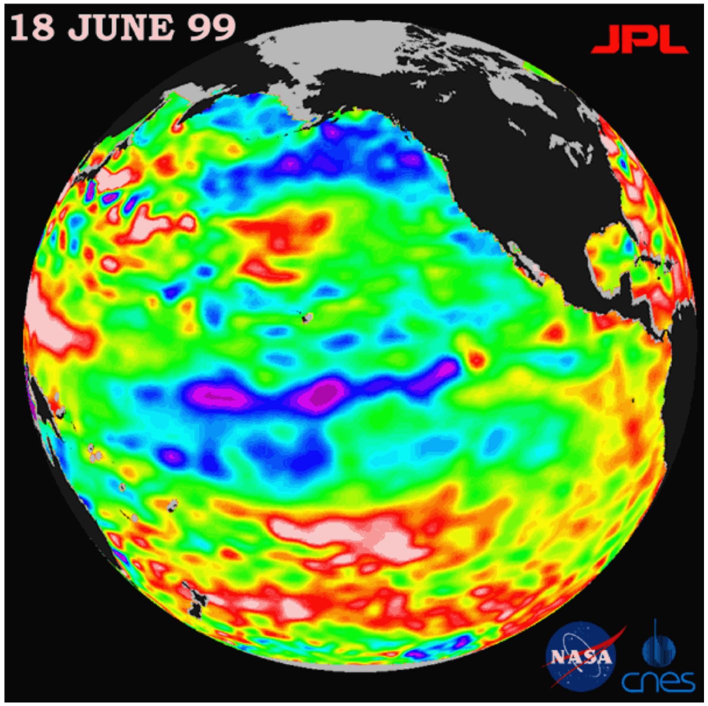
(top left) Full El Niño condition

(top right) El Niño retreating

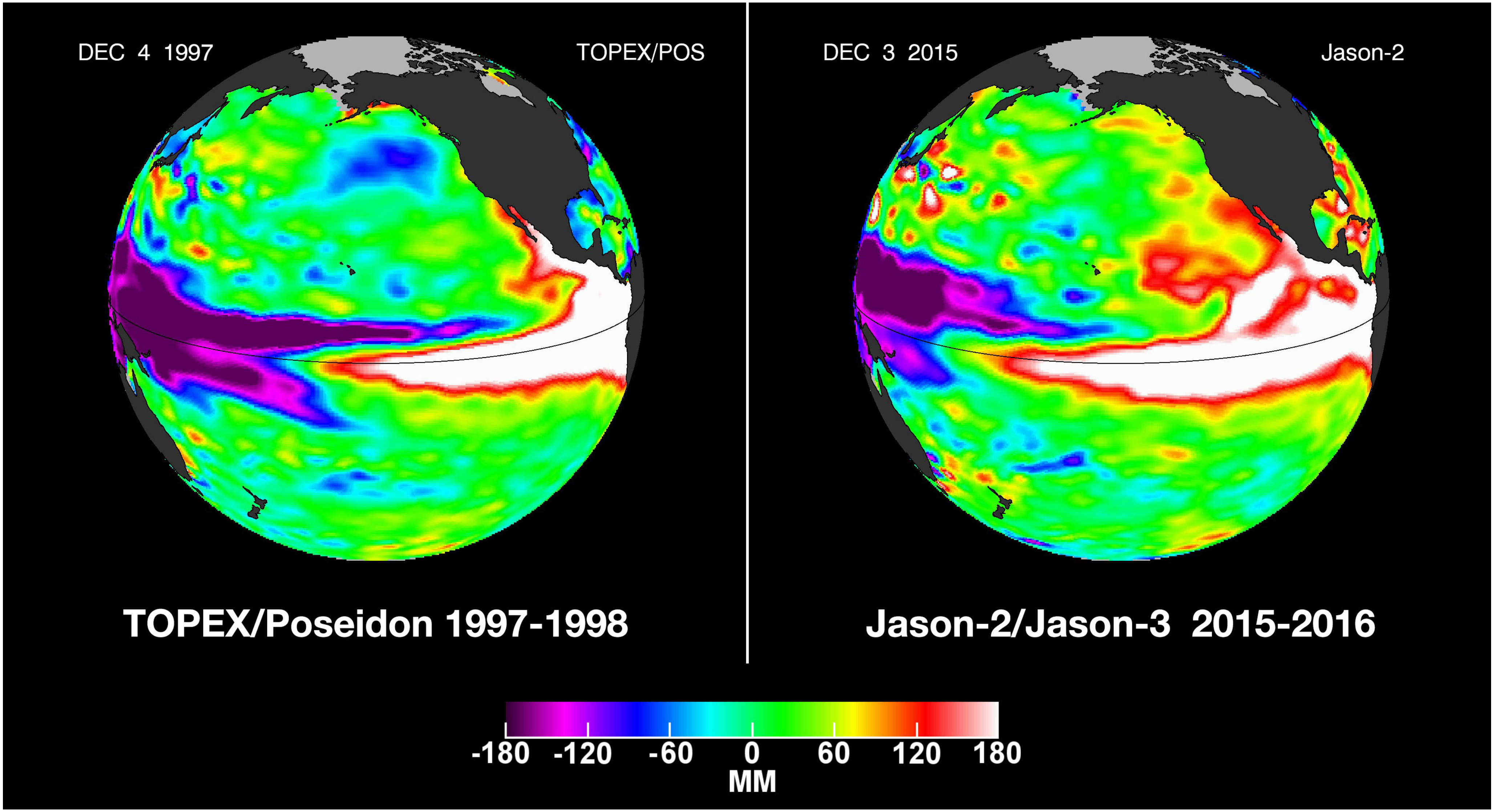
(bottom left) Full La Niña condition

(bottom right) La Niña fading

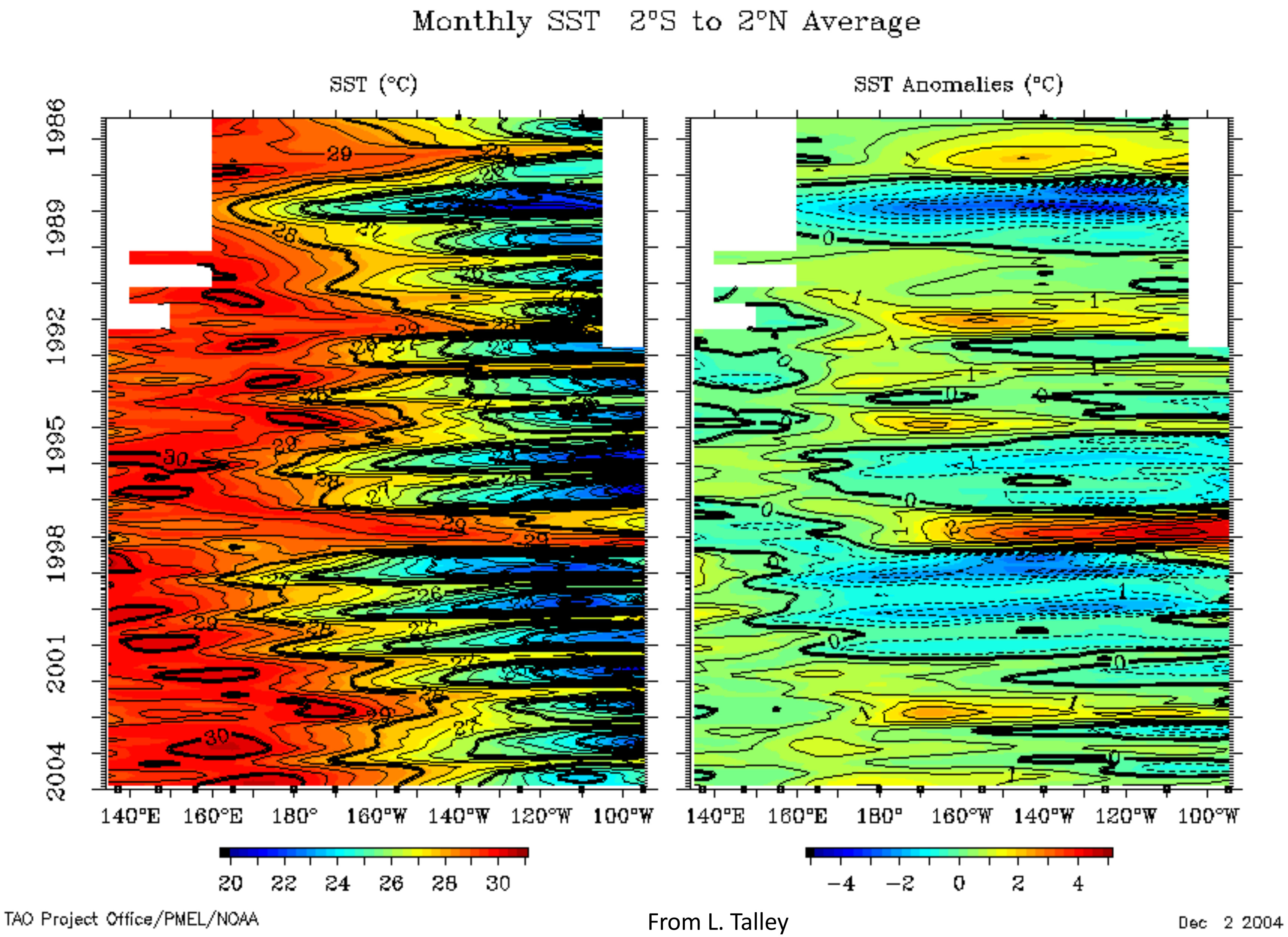




1997-1998 vs 2015-2016

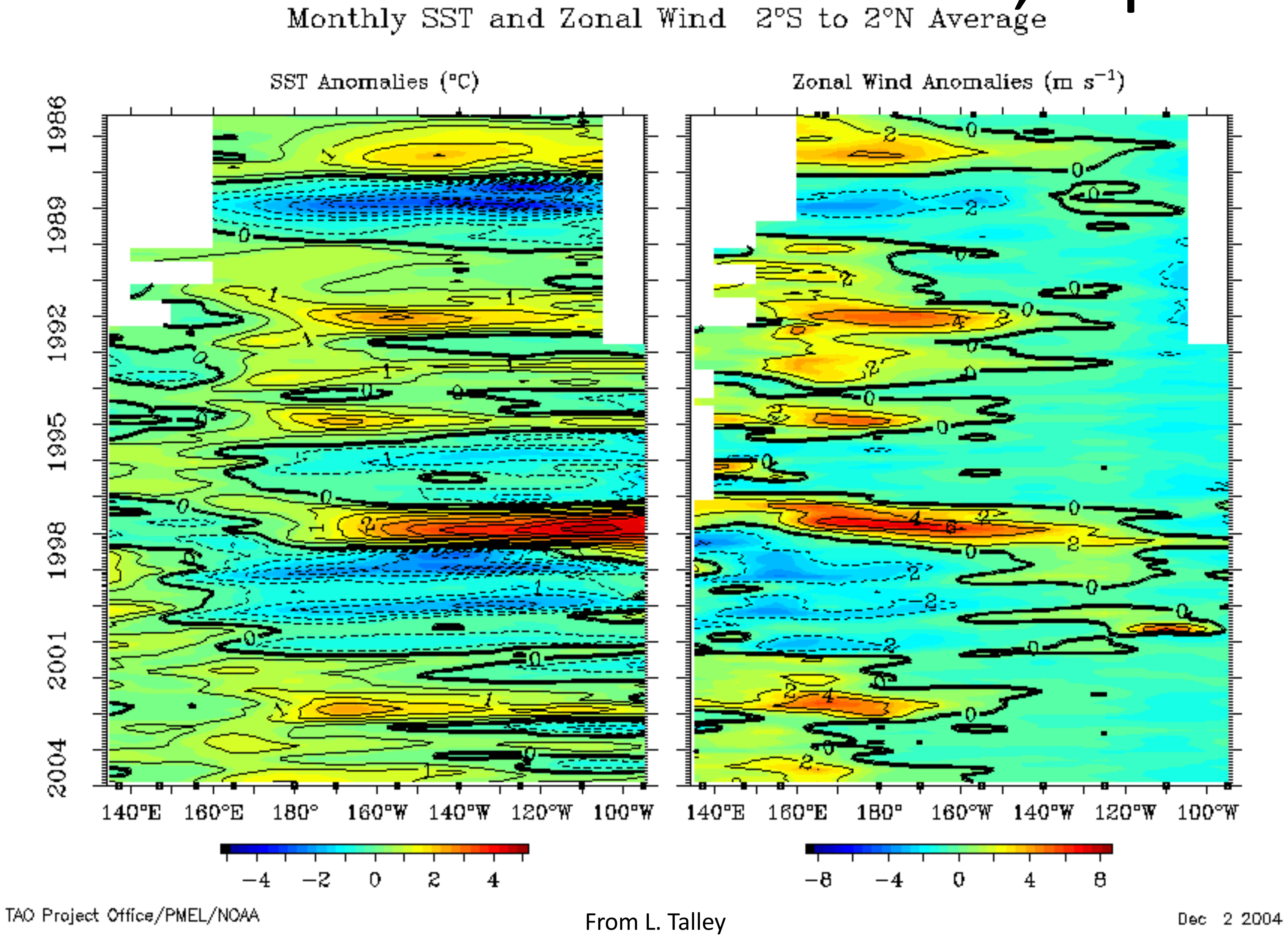


Time series: SST at equator



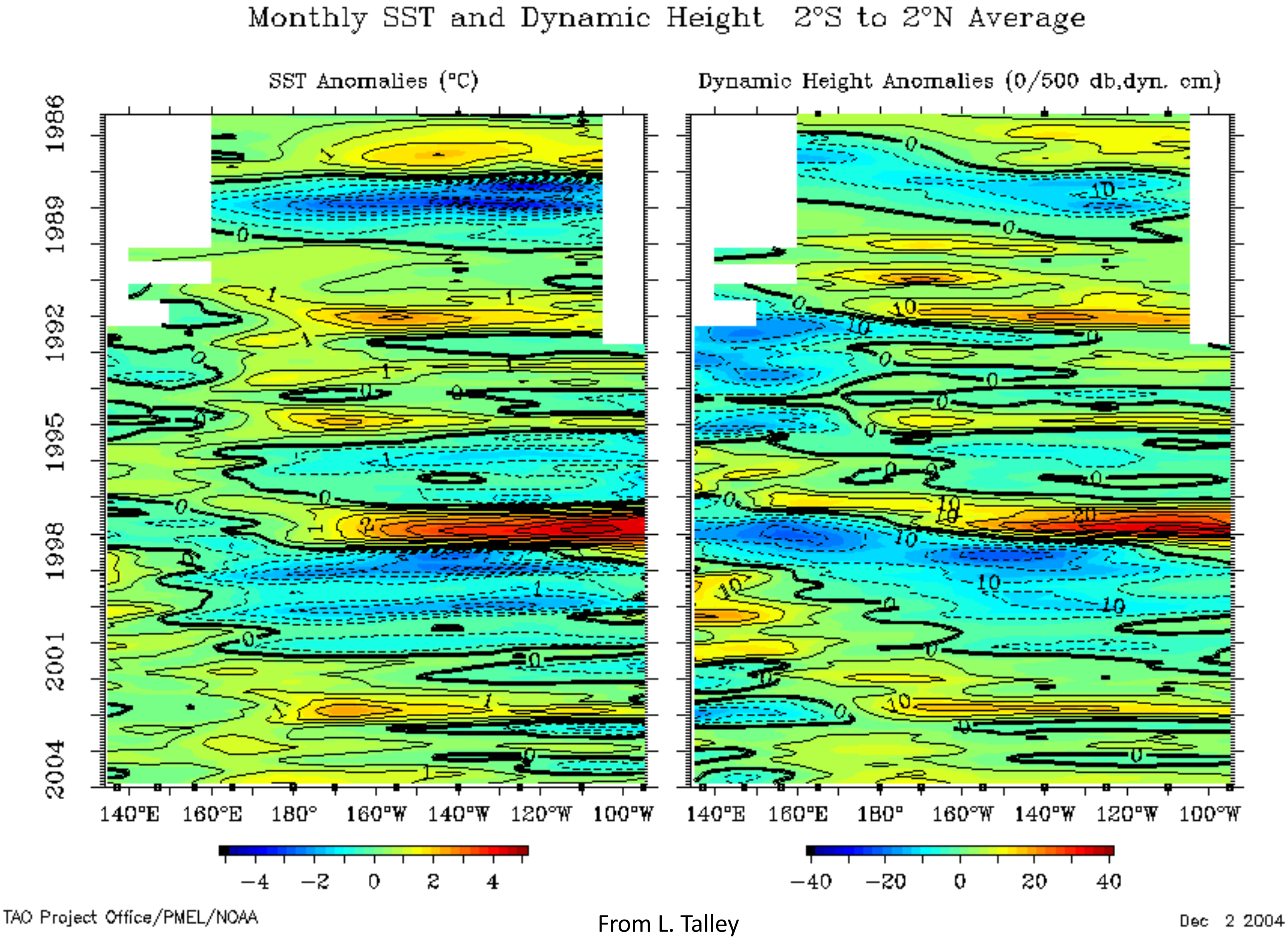
From L. Talley

SST and zonal wind anomalies, equator



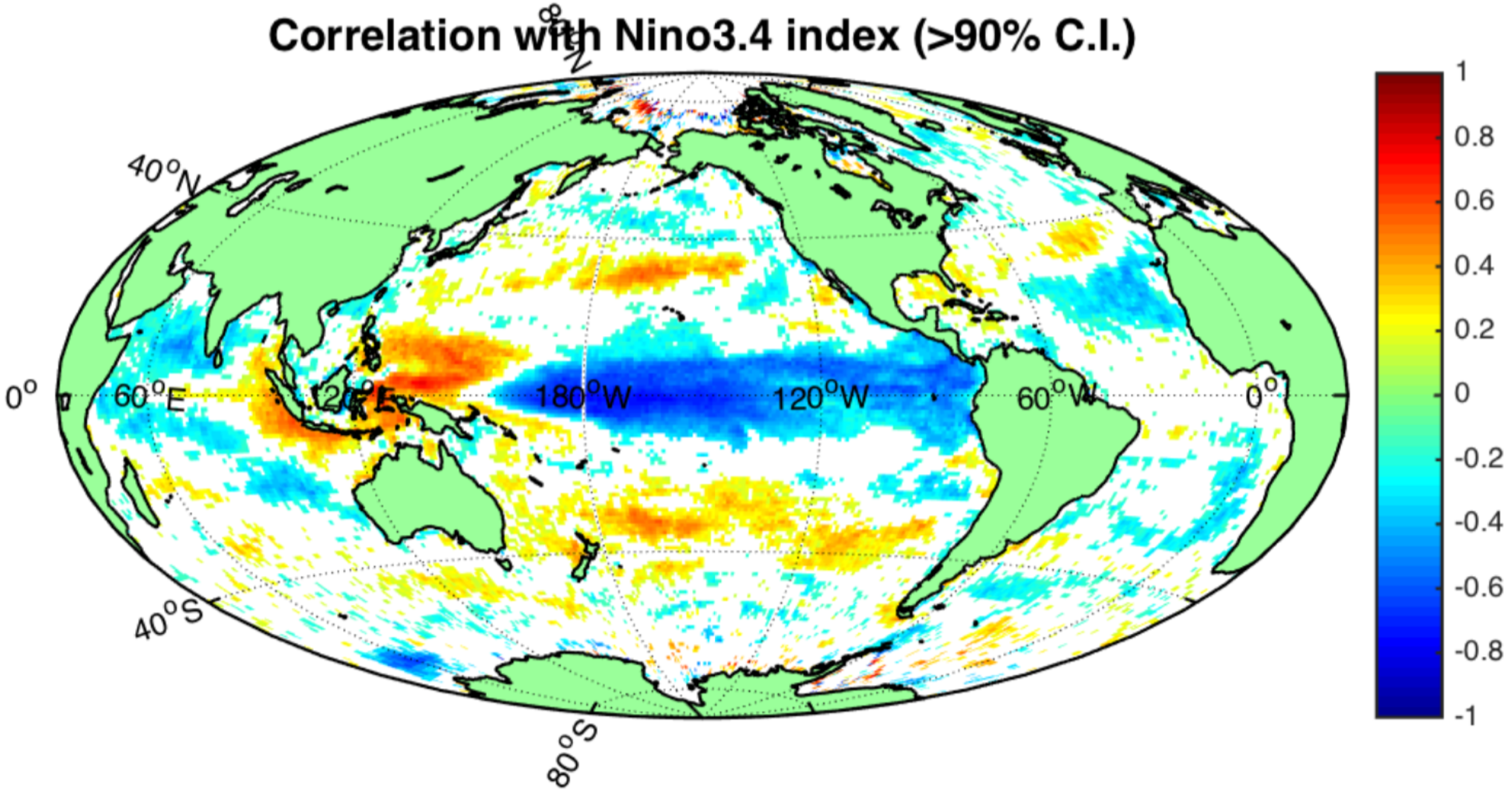
From L. Talley

SST and dynamic height anomalies,



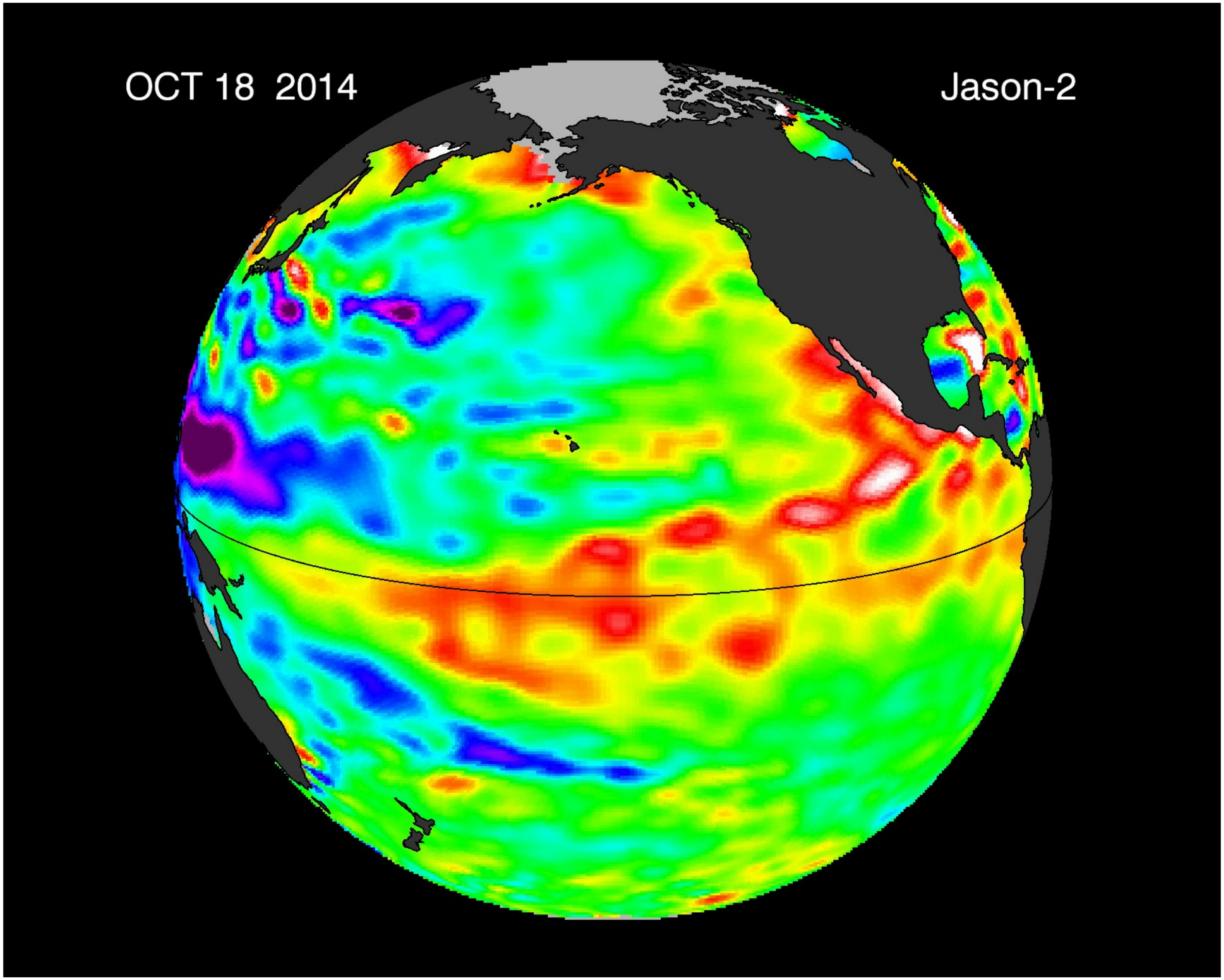
From L. Talley

Biogeochemical impacts

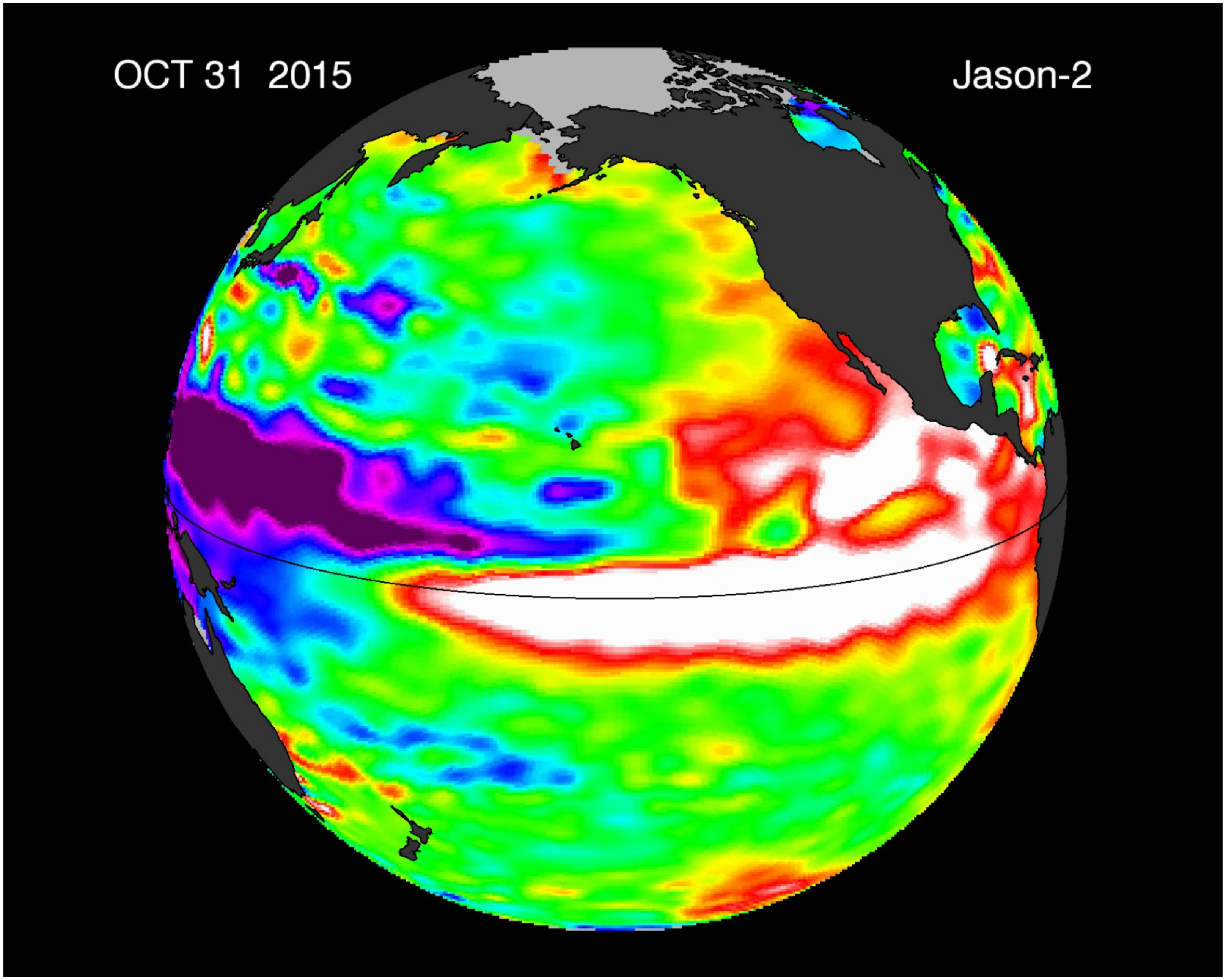


Deseasonalized, detrended Chlorophyll-a anomalies (1998-2010) from SeaWiFS satellite negatively correlates with Nino3.4 index

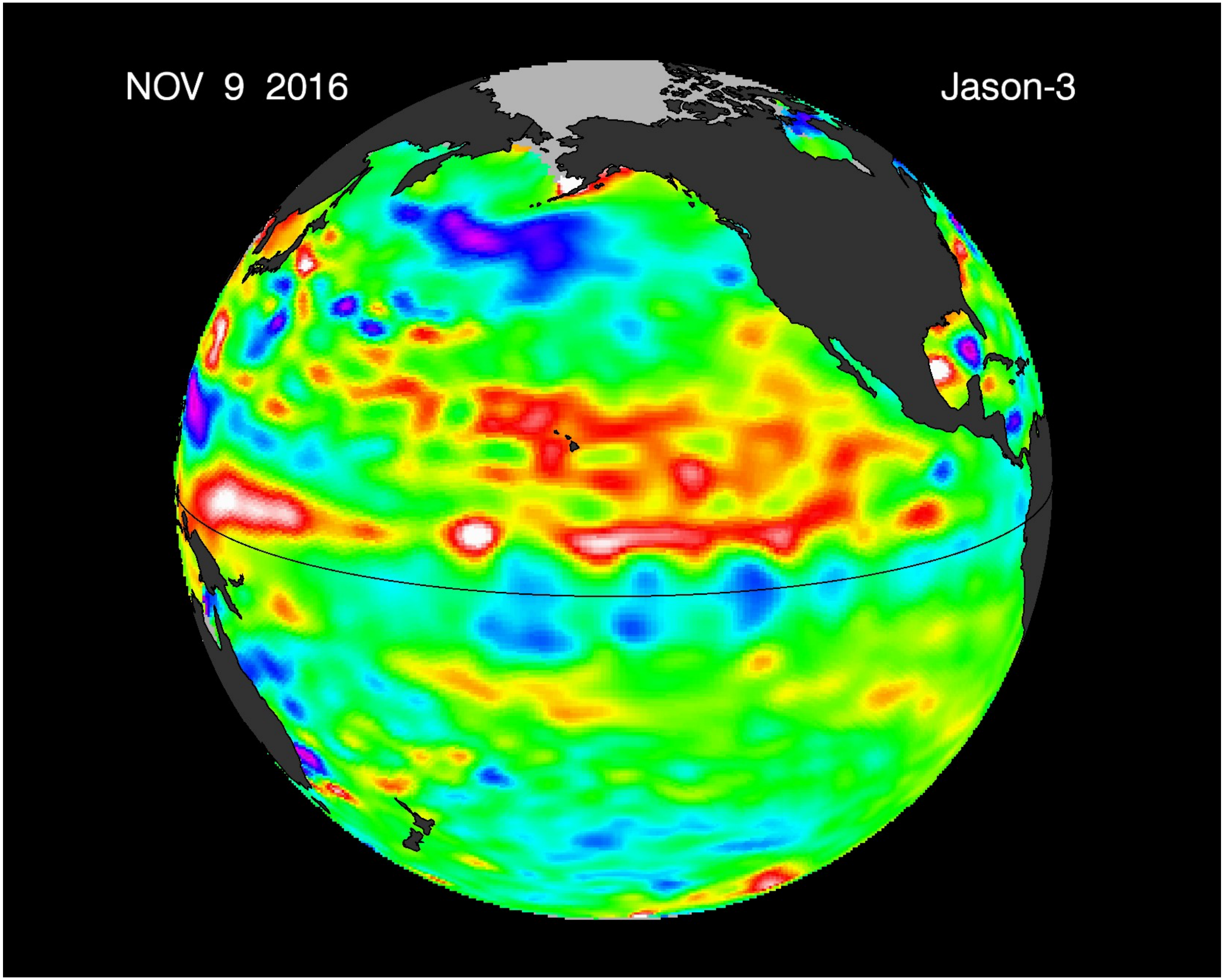
2014: Pacific SSH from satellite obs



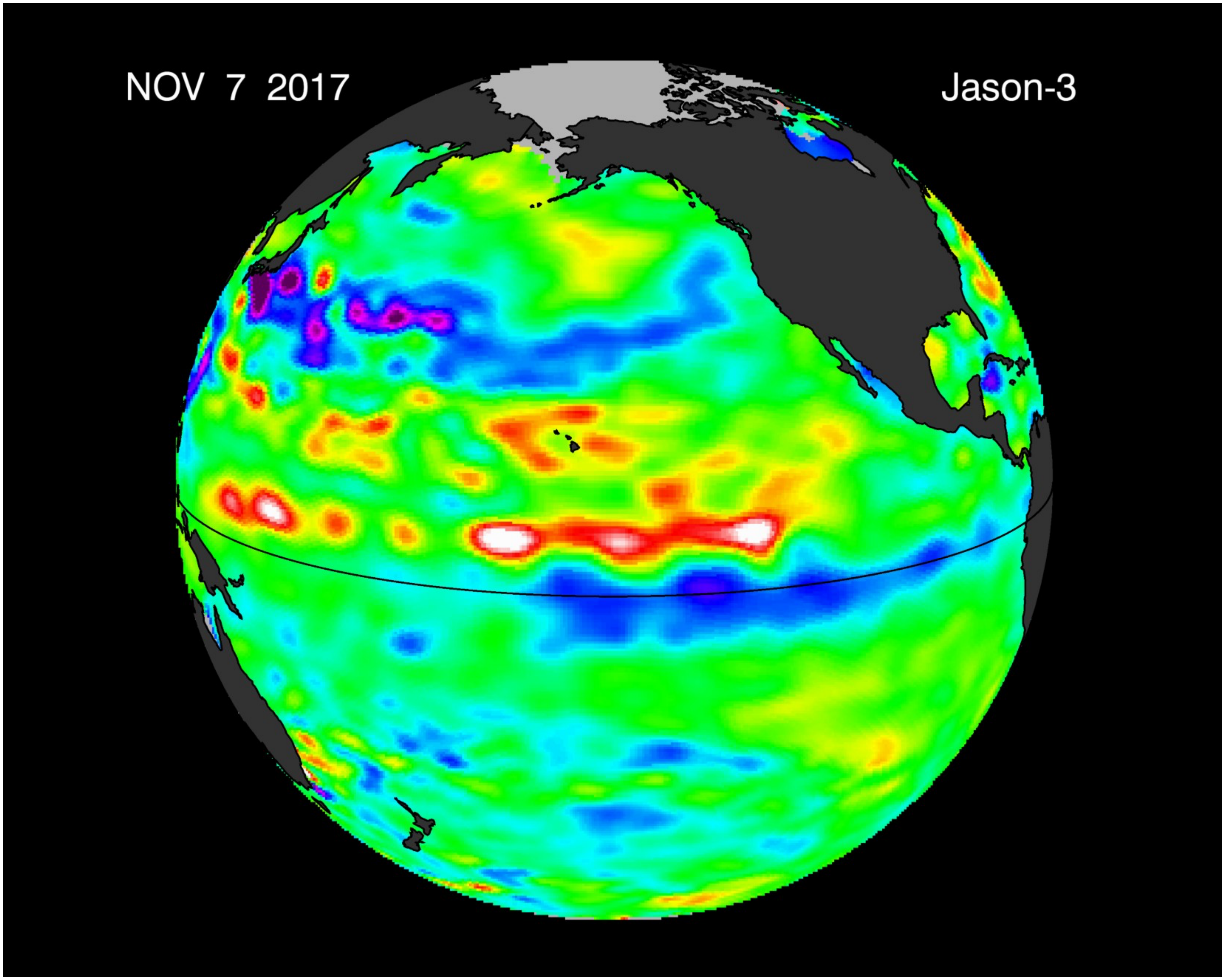
2015: Pacific SSH from satellite obs



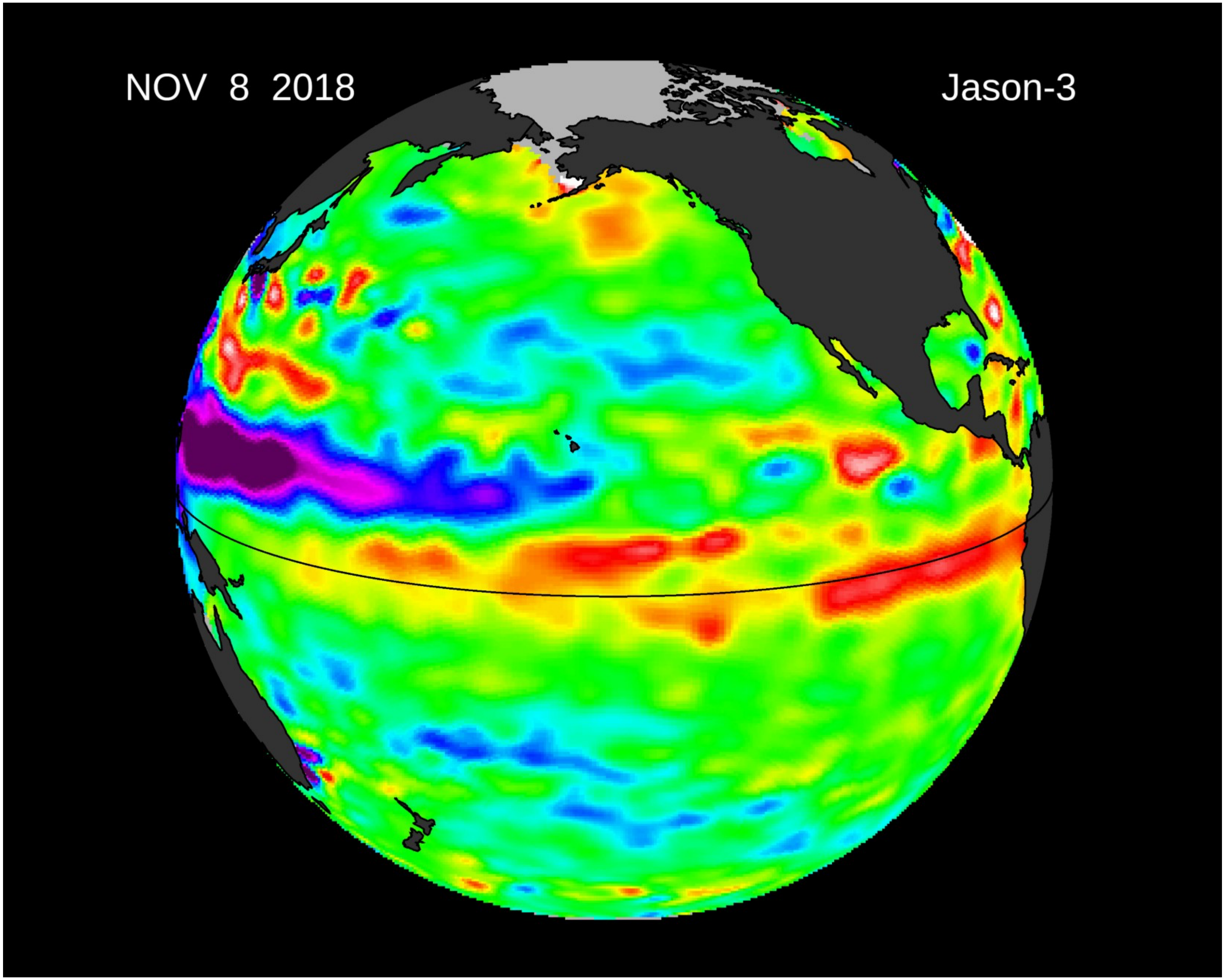
2016: Pacific SSH from satellite obs



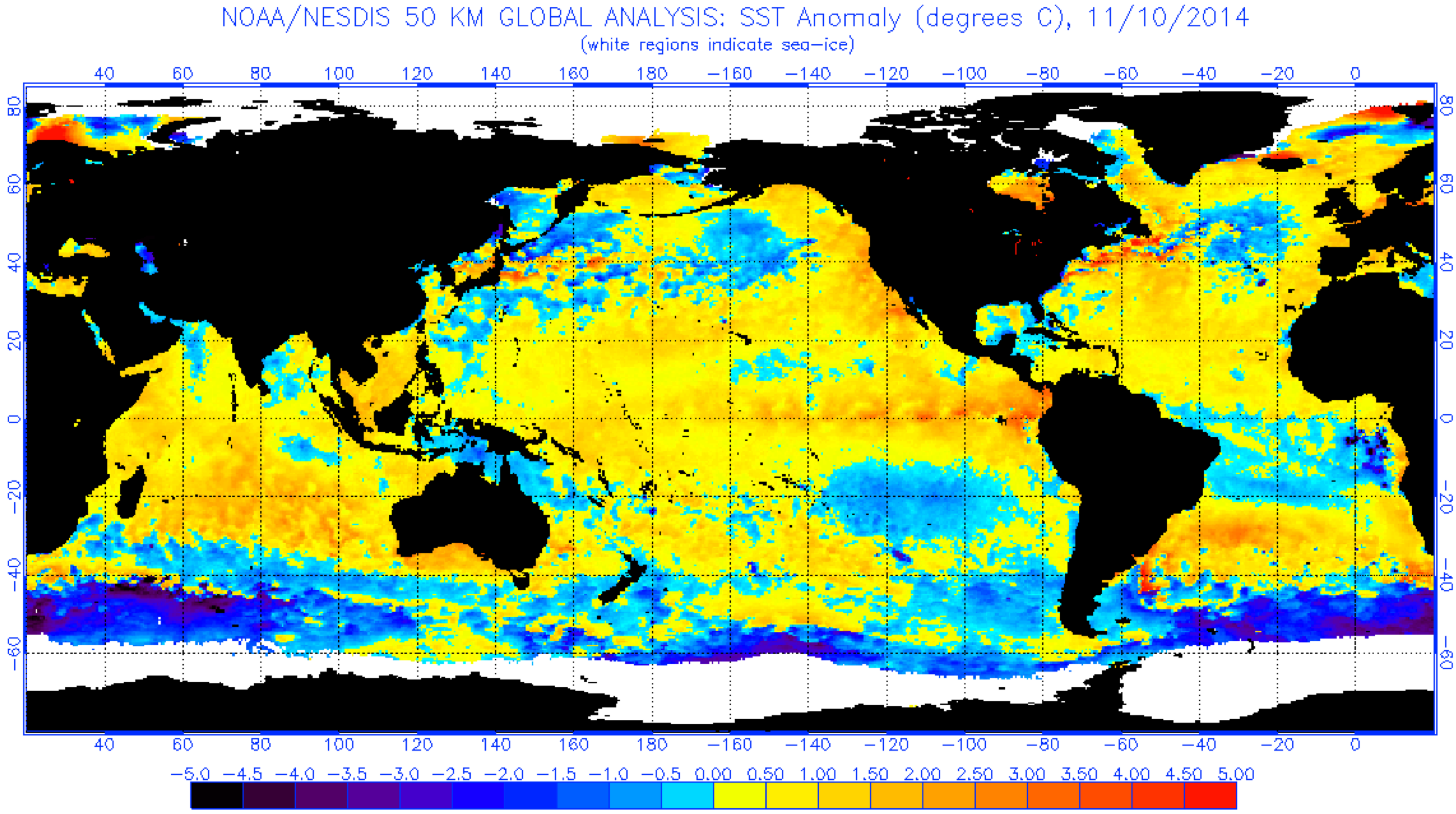
2017: Pacific SSH from satellite obs



2018: Pacific SSH from satellite obs

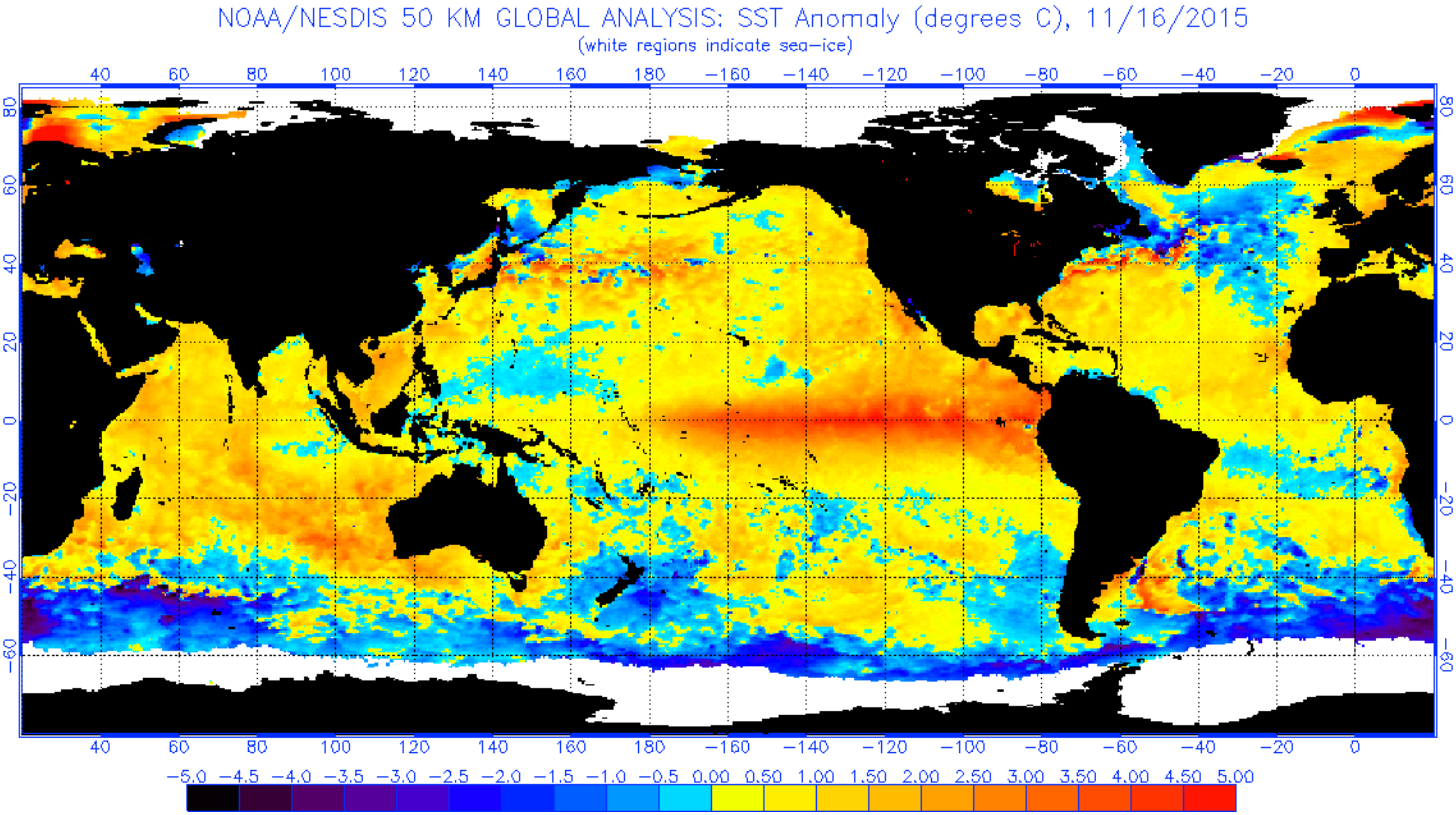


2014: SST anomaly



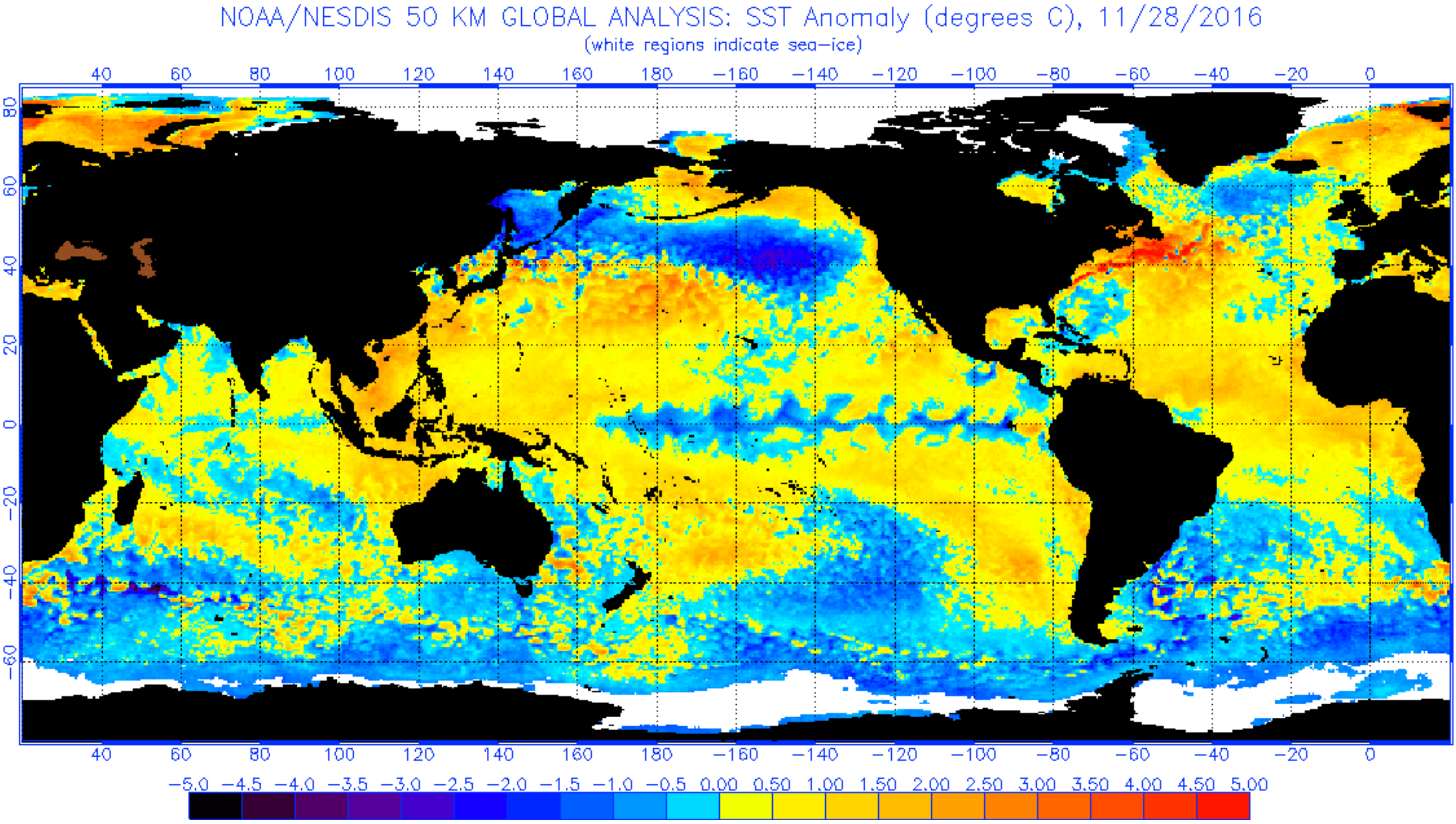
At that time, the prediction was that 58% chance of El Niño during the Northern Hemisphere winter (NOAA Climate Prediction Center)

2015: SST anomaly



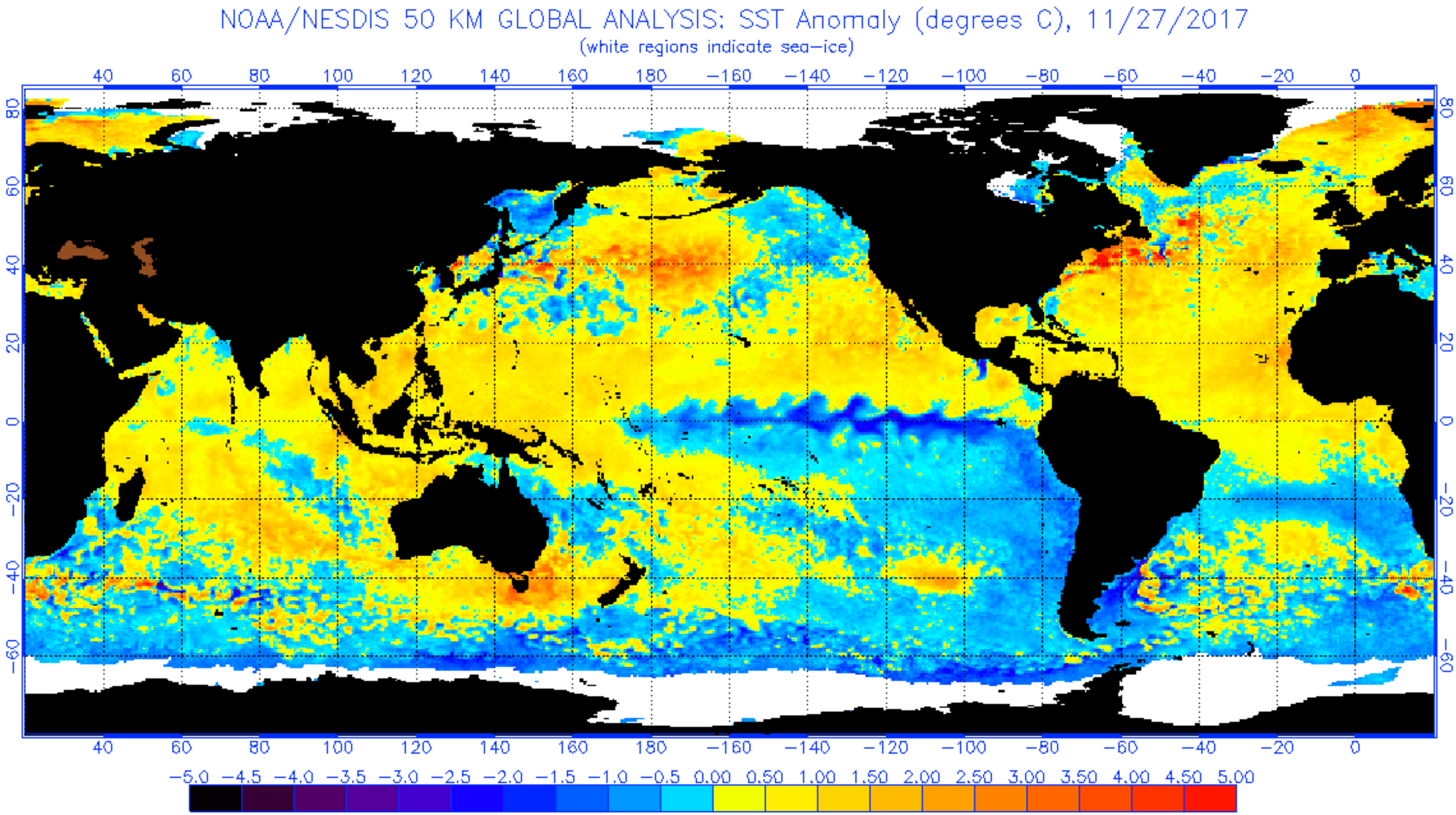
Much stronger SST anomaly in 2015 compared to 2014, expected to peak in the winter of 2015-2016.

2016: SST anomaly



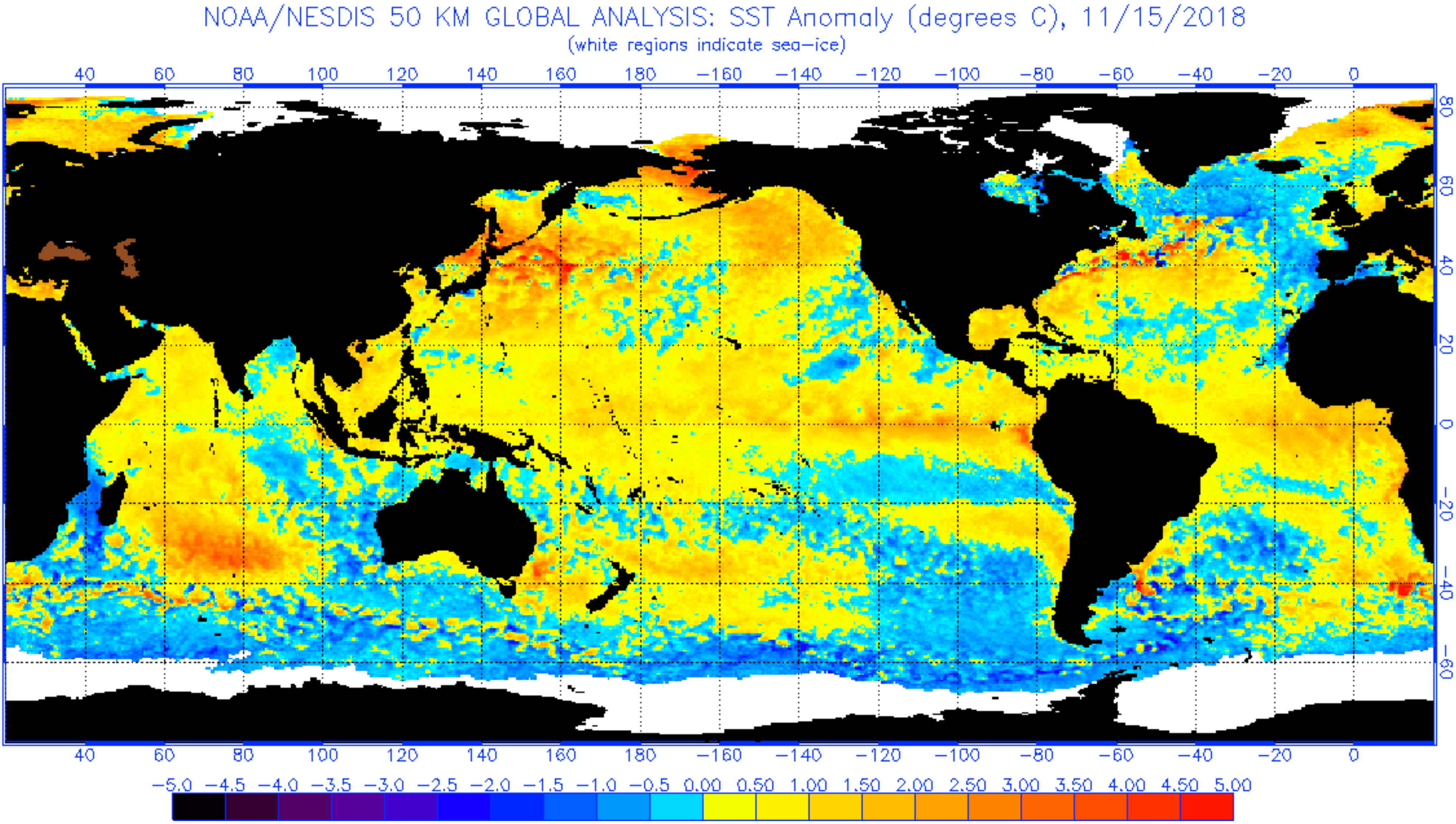
The 2015-2016 El Nino has ended. We are heading towards La Nina.

2017: SST anomaly



Cold SST establishing in the tropical Pacific. 2017-2018 is La Nina.

2018: SST anomaly


NOAA/NESDIS 50 KM GLOBAL ANALYSIS: SST Anomaly (degrees C), 11/15/2018
(white regions indicate sea–ice)

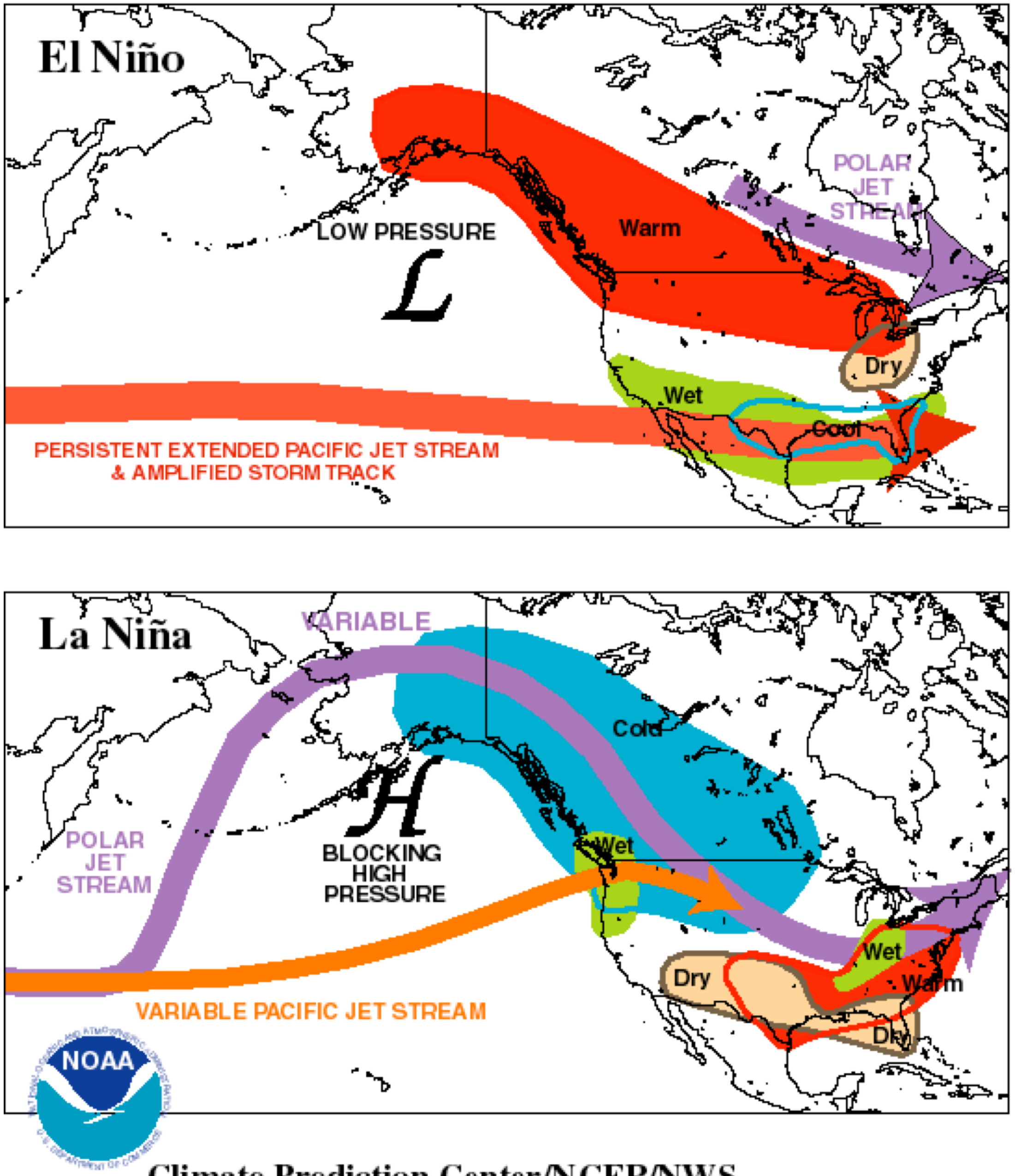
Mild El-Nino state developing in Nov 2018.

ENSO anomaly effects

"warm episode" = El Niño condition

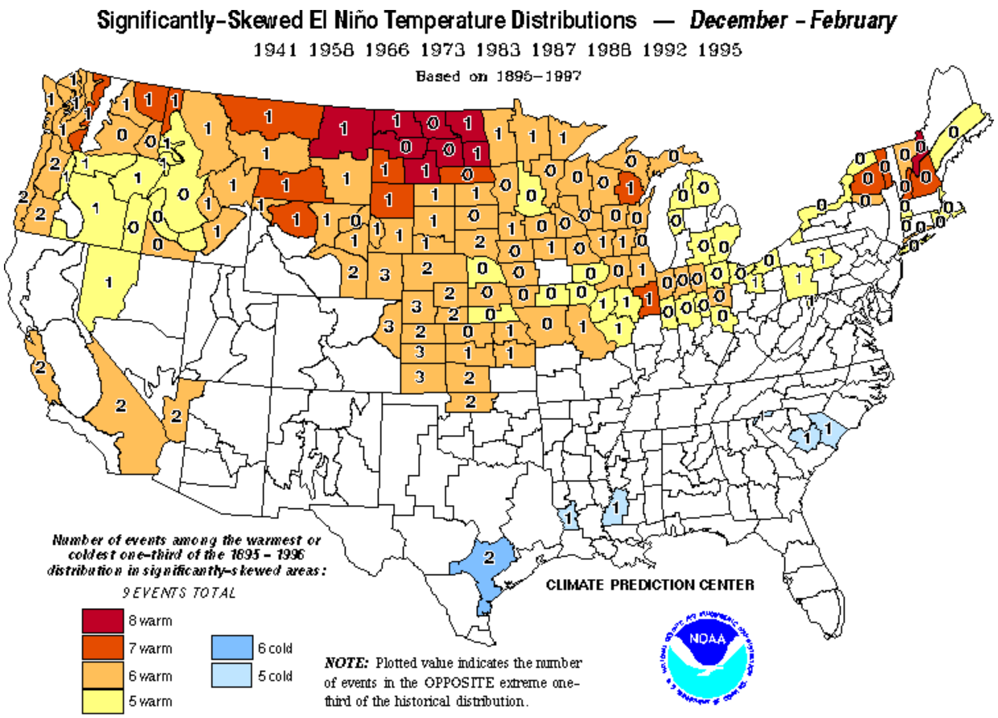
Related to shift in winds, especially the Walker circulation and its "teleconnections" to mid-latitude winds

TYPICAL JANUARY-MARCH WEATHER ANOMALIES
AND ATMOSPHERIC CIRCULATION
DURING MODERATE TO STRONG
EL NIÑO & LA NIÑA


El Niño

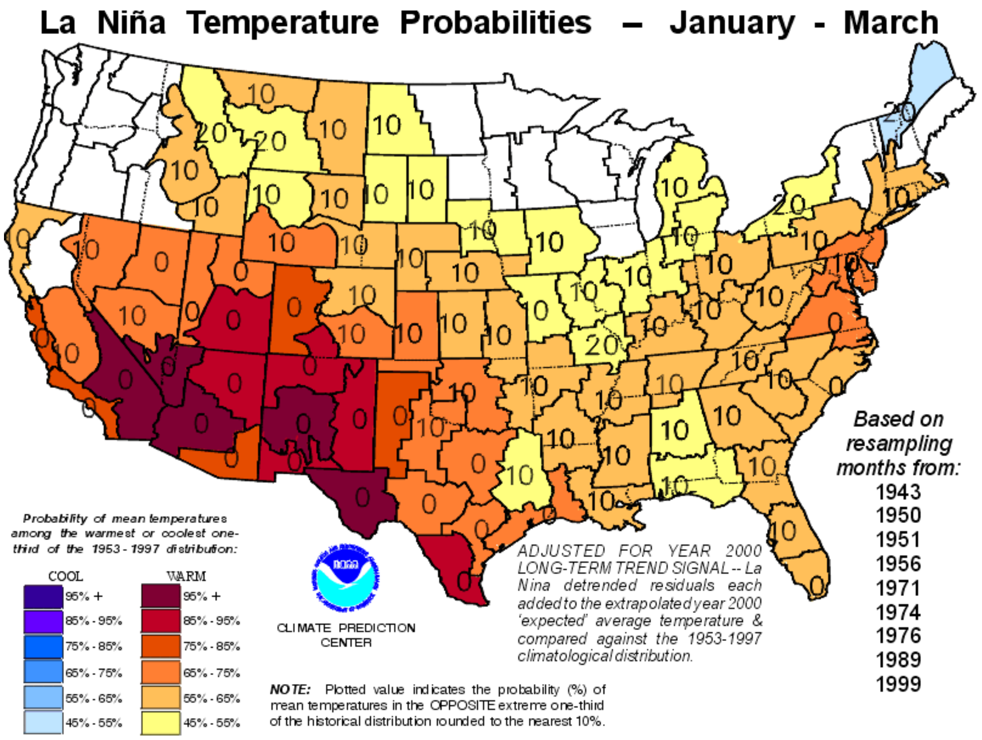
La Niña

Climate Prediction Center/NCEP/NWS



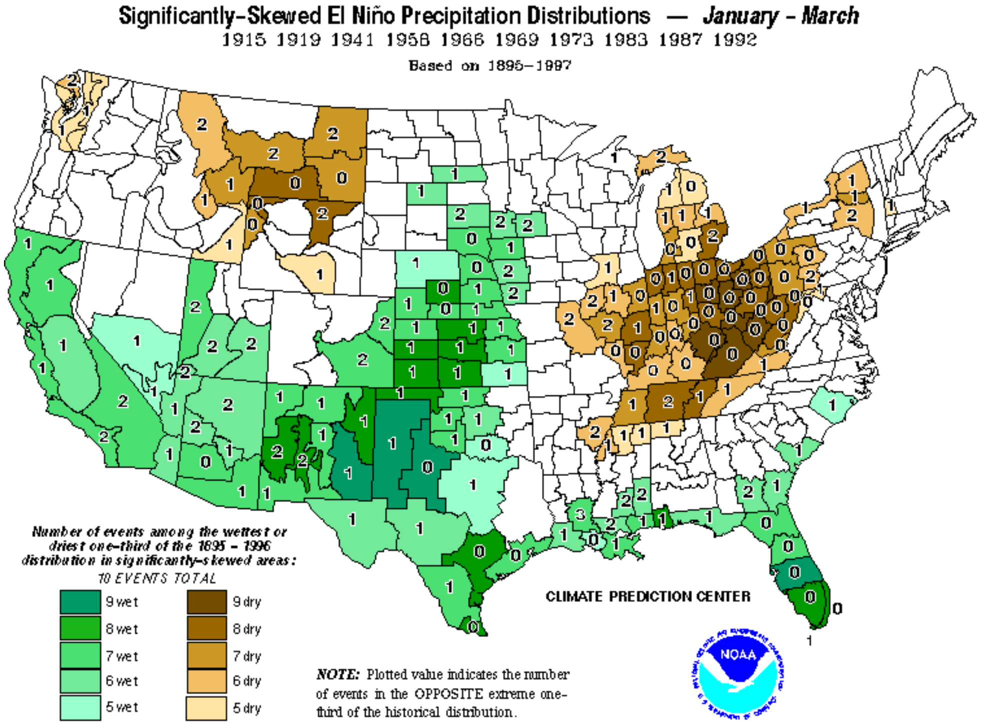
USA impacts of El Niño and La Niña: temperature

El Niño winter T anomaly



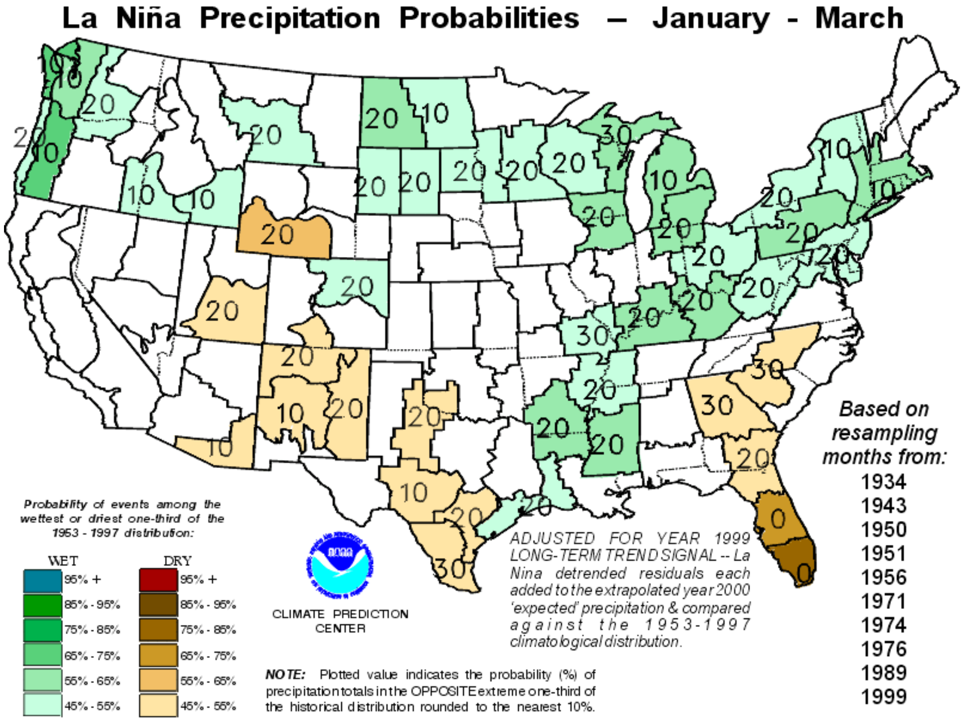
La Niña winter T anomaly

USA impacts of El Niño and La Nina: precipitation



NOTE: Plotted value indicates the number of events in the OPPOSITE extreme one-third of the historical distribution.

El Niño winter precip anomaly



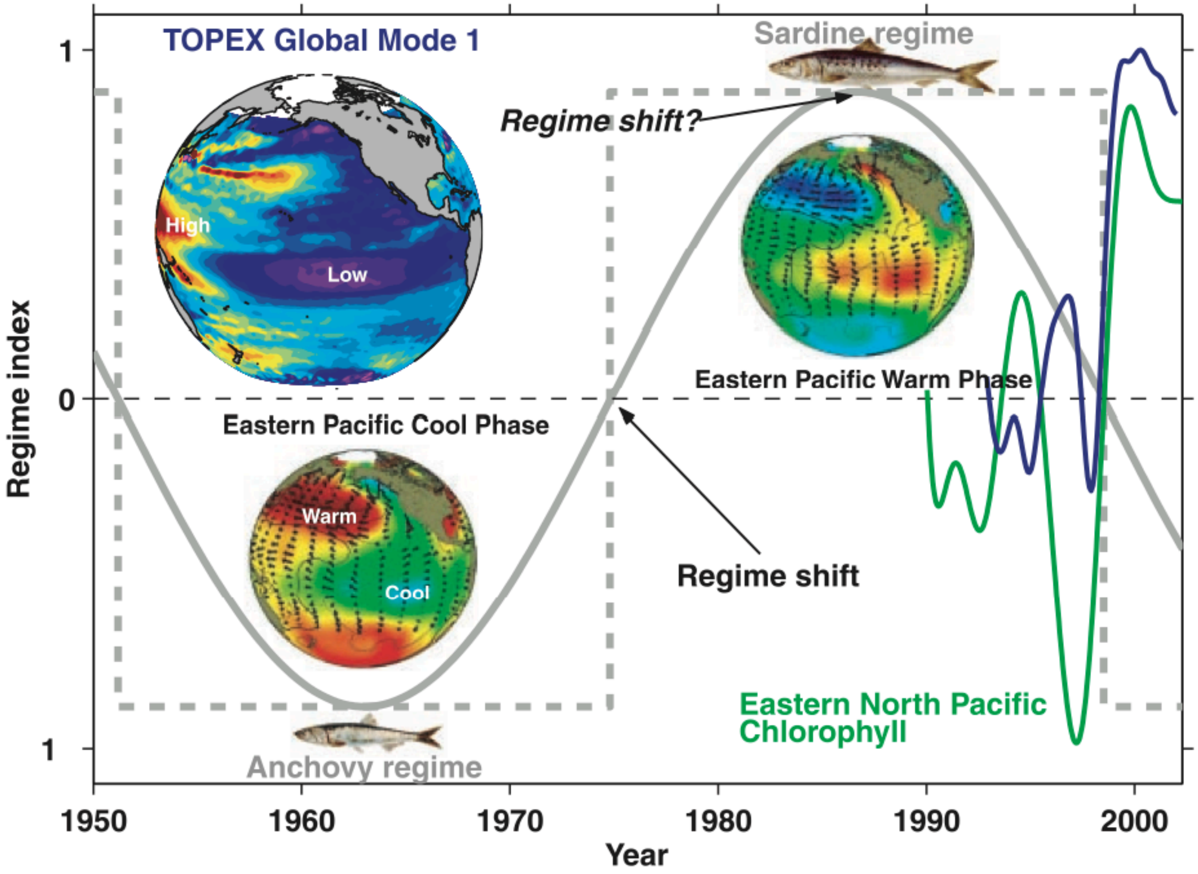
ADJUSTED FOR YEAR 1999 LONG-TERM TREND SIGNAL -- La Nina detrended residuals each added to the extrapolated year 2000 'expected' precipitation & compared against the 1953-1997 climatological distribution.

NOTE: Plotted value indicates the probability (%) of precipitation totals in the OPPOSITE extreme one-third of the historical distribution rounded to the nearest 10%.

La Niña winter precip anomaly

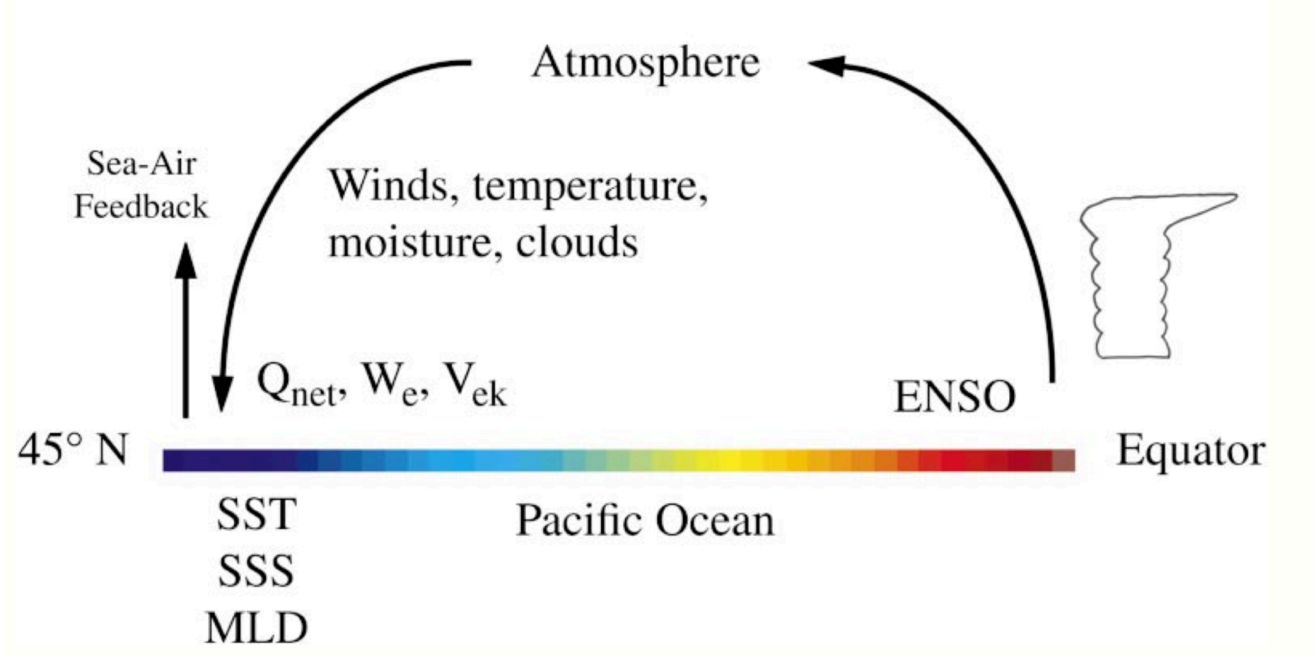
Decadal scale changes in the Pacific

- ENSO cycle timescale : 3-7 years
- PDO (Pacific Decadal Oscillation) is a decadal scale, ENSO-like changes : ~ 25 years?!
- Chavez paper



Mechanisms for PDO

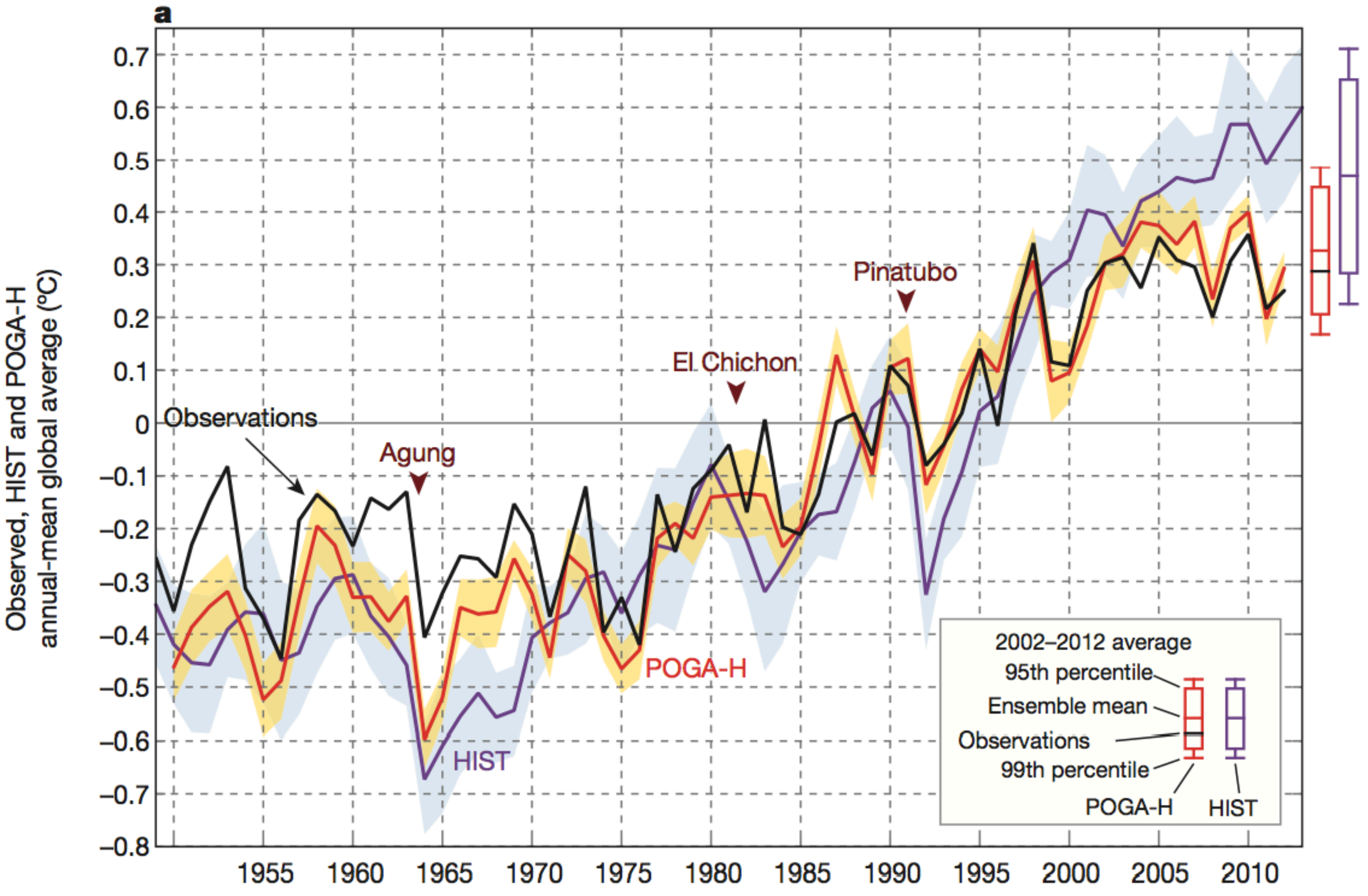
- To date, no self-sustaining oscillatory mechanism is found on the decadal timescale
  - PDO may be driven by ENSO and atmospheric variability (Aleutian low etc)
- The link between ENSO and mid-latitude climate is established through "atmospheric bridge"
  - So the SST pattern somewhat looks alike between ENSO and PDO



Alexander et al., (2002); Newman et al., (2003)

Global warming vs PDO

Global mean surface temperature has not increased since ~2000 while the greenhouse gas concentration has been rising steadily. Climate modelers instructed their model to have observed SST in the eastern tropical Pacific (i.e. cool SST during 2000s due to PDO). They were able to reproduce the global mean T hiatus (stagnant T after 2000).



PDO has a global influence

Future change in PDO may accelerate global warming…

Kosaka and Xie (2013)

Review question

- 2018-2019 is going to be a El Nino year. Will the biological productivity of the tropical Pacific be higher or lower than normal condition?

  – 1. Higher due to warmer sea surface temperature
  – 2. Higher due to higher nutrient supply
  – 3. Lower due to colder sea surface temperature
  – 4. Lower due to lower nutrient supply

ENSO theory: oscillation

- **Bjerknes feedback** (Bjerknes, 1969) Weakened trade wind causes warm SST in the eastern tropical Pacific. The warm SST slows down the atmospheric, Walker circulation keeping the trade wind weak → the "El-Nino" state

- **How does it switch between El-Nino and La-Nina?**
- In another words, what is the mechanism behind the oscillation of the tropical climate?

- Hypothesis 1 : Delayed oscillator theory (equatorial waves)
- Hypothesis 2 : Recharge oscillator theory (heat content)

Zebiak and Cane (1987)

- Developed coupled ocean-atmosphere model of equatorial waves.
- Without external forcing, this model spontaneously oscillates, and it reproduces many features of ENSO cycles (SST, trade wind, themocline depth)

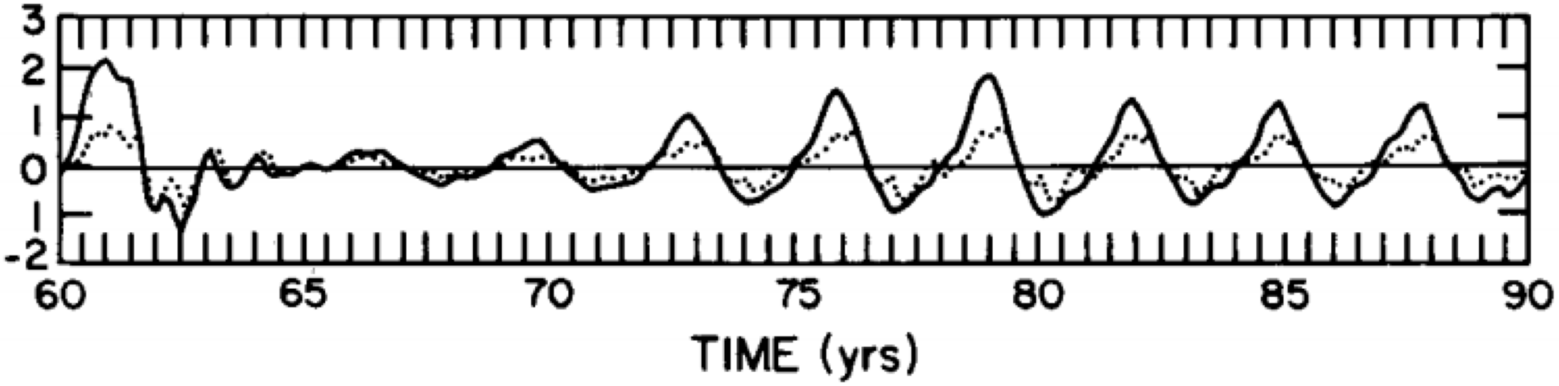
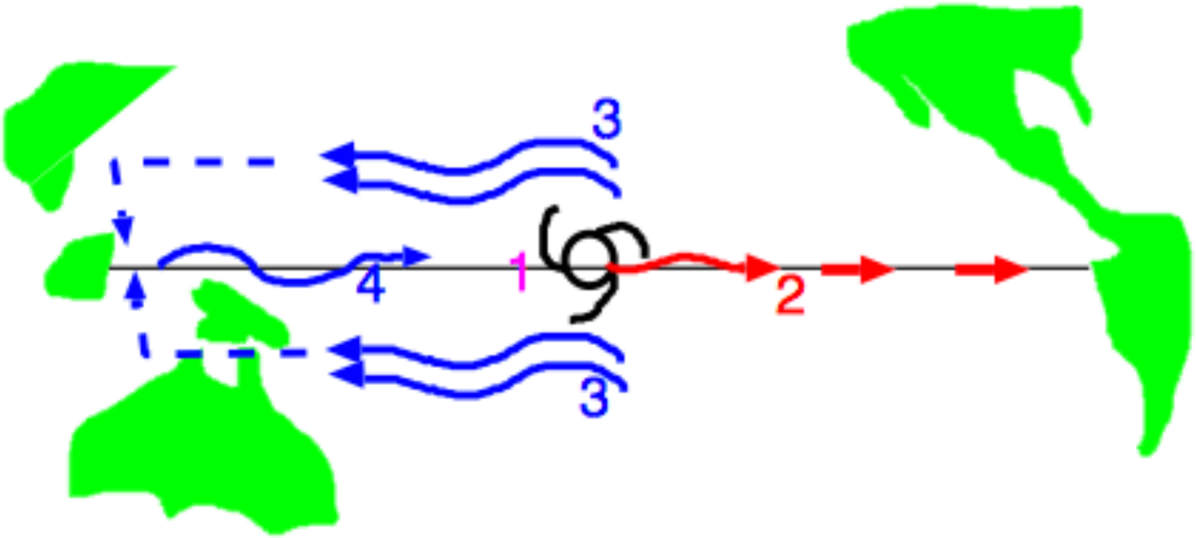


FIG. 1. Area-averaged SST anomalies for the 90-year model simulation. The solid line is NINO3 (5°N–5°S, 90°–150°W), and the dotted line is NINO4 (5°N–5°S, 150°W–160°E).

Mechanism: Equatorial waves (Schopf, 1987; Battisti 1988)

- There are two waves that are crucial. Kelvin and Rossby waves.
- It starts with the weakened trade wind in the central Pacific. It triggers El-Nino.
- But it also seeds two Rossby waves that eventually destroy the El-Nino state



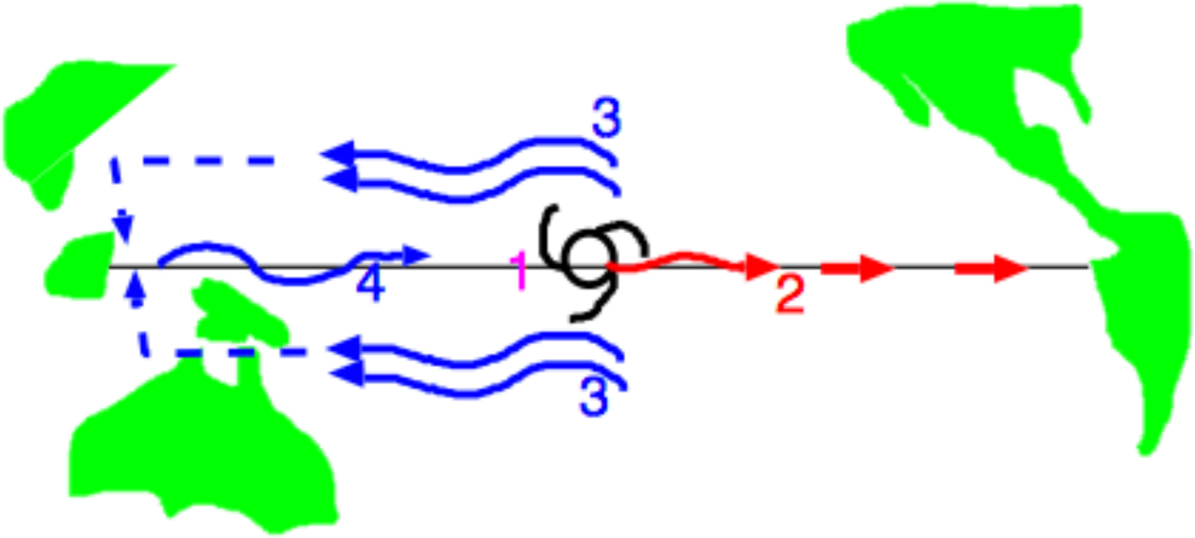
1. Weaker trade wind excites Kelvin wave

2. Within 1-2 months, the eastern Pacific warms up

3. Weaker trade wind also excites cold Rossby wave

4. Rossby wave reflects at the western boundary as cold Kelvin wave, then it takes 6 months to reach the eastern Pacific, terminating the El-Nino event → “**Delayed Oscillator Theory** (Schopf, 1987; Battisti 1988)”

Delayed oscillator model: tropical wave



1. Weaker trade wind excites Kelvin wave
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4. Rossby wave reflects at the western boundary as cold Kelvin wave, then it takes 6 months to reach the eastern Pacific, terminating the El-Nino event → "**Delayed Oscillator Theory** (Schopf, 1987; Battisti 1988)". The following simple equation was used to illustrate the point by Suarez and Shopf (1988)

$$\frac{dT(t)}{dt} = T(t) - \alpha T(t - \delta_T) - T^3(t).$$

Non-linear effect (leads to decay)

Bjerknes feedback (leads to growth)

Wave effect (leads to decay)

$$\frac{dT(t)}{dt} = T(t) - \alpha T(t - \delta_T) - T^3(t).$$

- Suarez and Shopf (1988)
- Delayed, negative feedback = Rossby wave

- Stability analysis/numerical calculation show that the typical period is several times the delay.

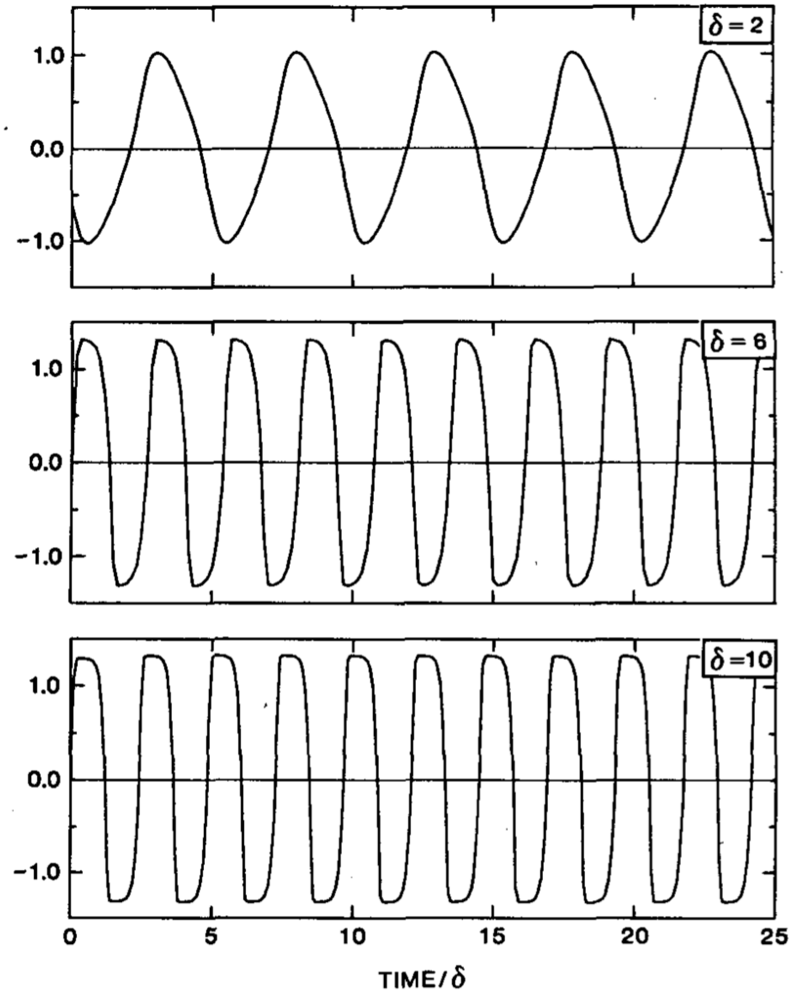
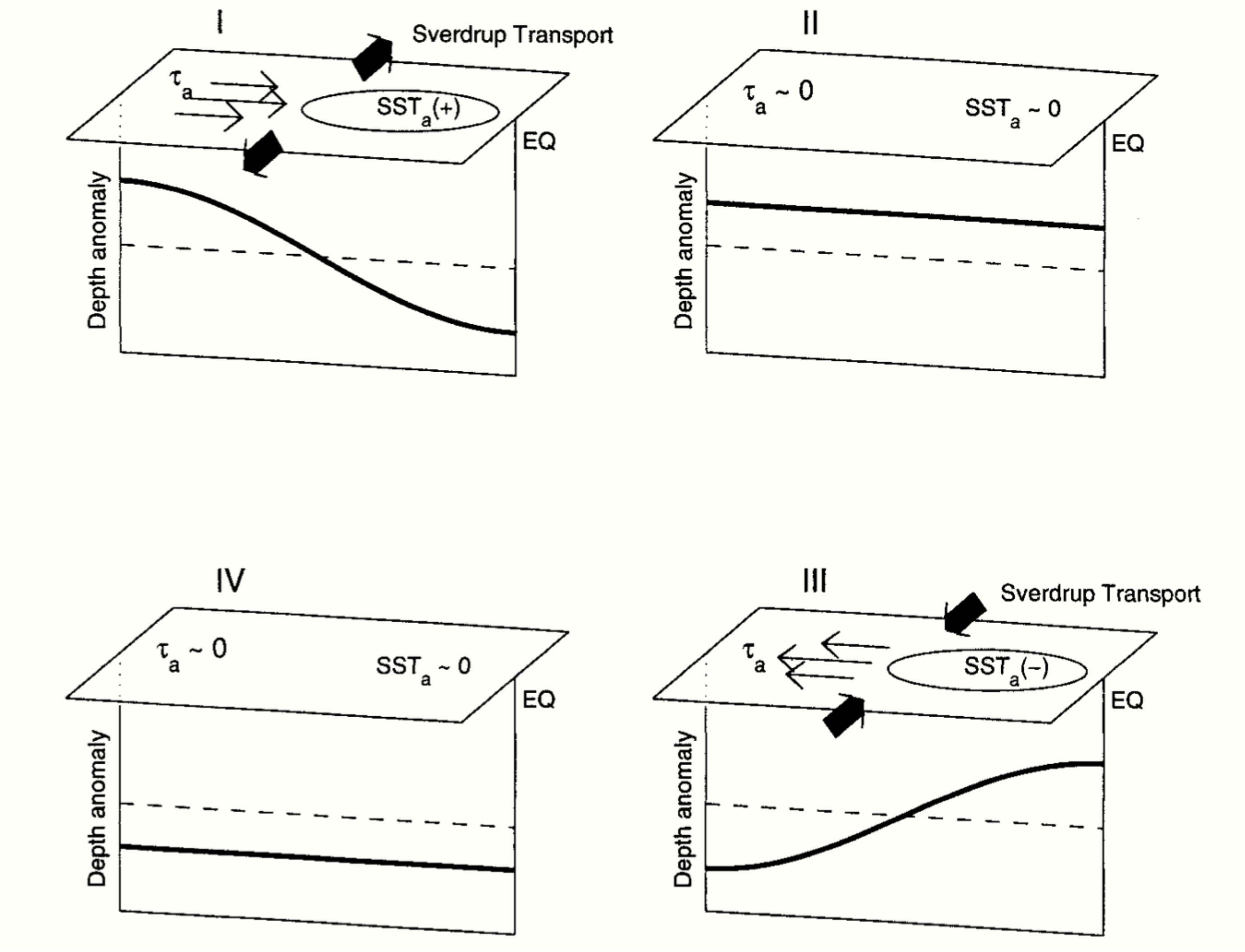


FIG. 4. Behavior of the nonlinear oscillator. (a) $\alpha = 0.75$, $\delta = 2$, (b) $\alpha = 0.75$, $\delta = 6$, and (c) $\alpha = 0.75$, $\delta = 10$. The time axis is scaled in units of the delay.

Hypothesis 2: Recharge oscillator theory

- Jin (1997) put forward the theory, Meinen and McPhaden (2000) showed it with observation

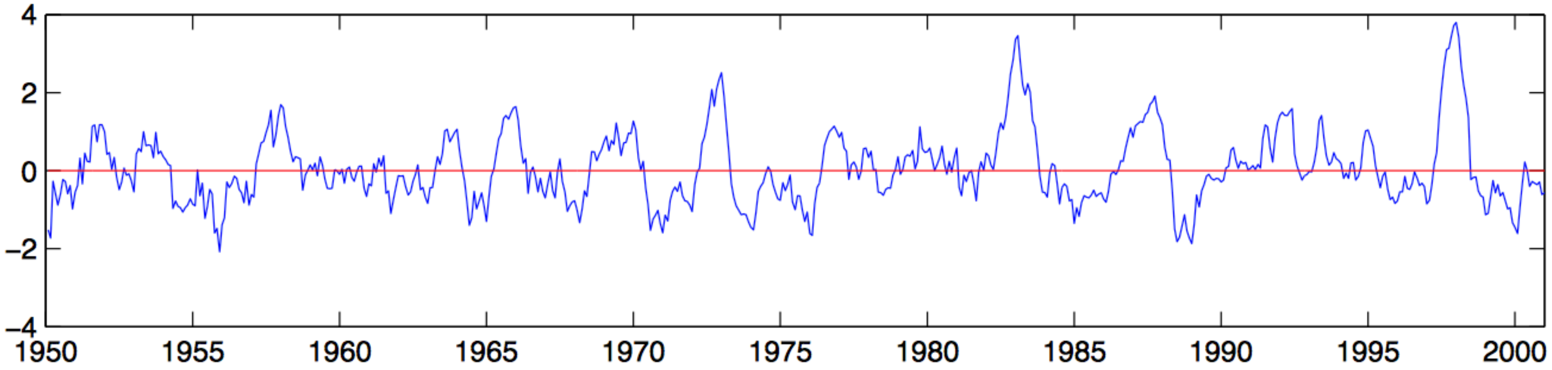


Recharge oscillator theory

- 1. During the El-Nino condition, trade wind is weaker (equivalent of anomalous westerly wind)
- 2. Sverdrup circulation gradually discharges warm water under the equator to off-equatorial regions
- 3. Ocean heat content decreases under the equator, leading to a shallower thermocline depth → cooler SST
- 4. Cooler SST initiates La Nina condition. Stronger trade wind.
- 5. Sverdrup circulation gradually recharges warm water under the equator from off-equatorial regions → deeper thermocline
- 6. Deeper thermocline → Warmer SST → El Nino returns.

On irregularity

- Data (e.g. Nino3.4) shows that ENSO irregular



On average, El-Nino event occurs every 3-7 years, and each event lasts 12-18 months. But the ENSO cycles are irregular and difficult to predict. Simple theory predicts self-sustained oscillation (e.g. delayed oscillator/recharge oscillator theory) with a consistent amplitude and periodicity. Reality is not.

Issues with coupling mechanism

- Atmospheric trade wind driven by SST
- Thermocline tilt driven by the trade wind
- SST change driven by the thermocline tilt
- Generation of propagation of the equatorial waves

- Simple models (delayed oscillator, recharge oscillator) assumes strong, consistent coupling to reproduce the oscillatory behavior. If any one of couplings becomes weak, oscillation may dampen and the system may require external energy input ← source of irregularity. Also the coupling strength may change seasonally.

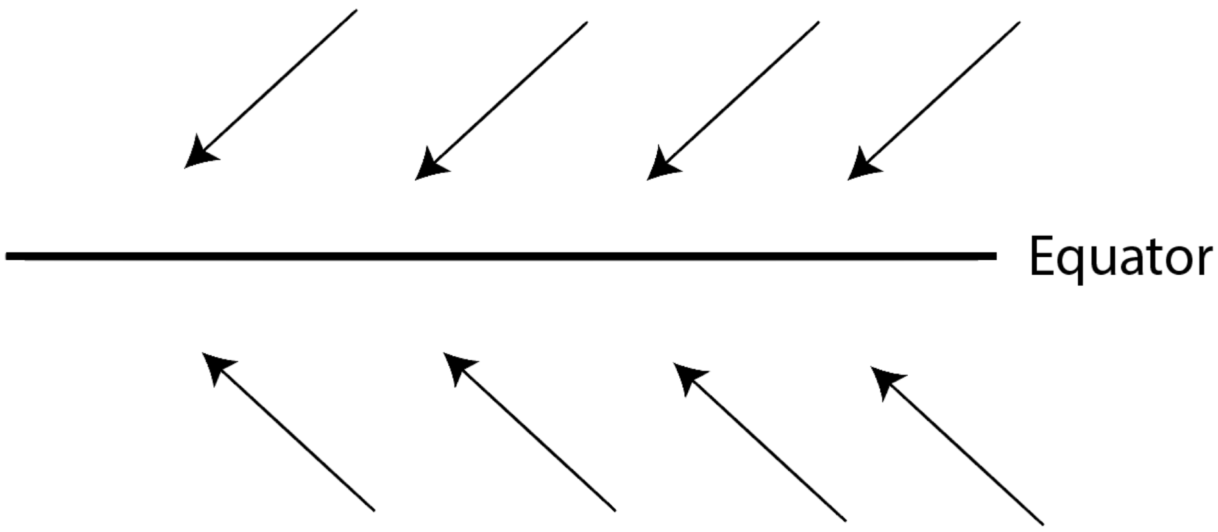
ENSO theory: feedback

- Besides the Bjerknes feedback, what other climate feedbacks are there?
- In another words, what is the mechanism behind the tropical climate variability and ENSO cycles?

- WES feedback (Wind-Evaporation-SST feedback)
- Cloud Feedback

WES feedback

- Wind – Evaporation – SST (WES) feedback, Xie and Philander (1994)
    - Thermodynamic coupling; exists in Atlantic and Pacific
    - Weaker wind → Less evaporation → Warmer SST
    - Stronger wind → More evaporation → Cooler SST



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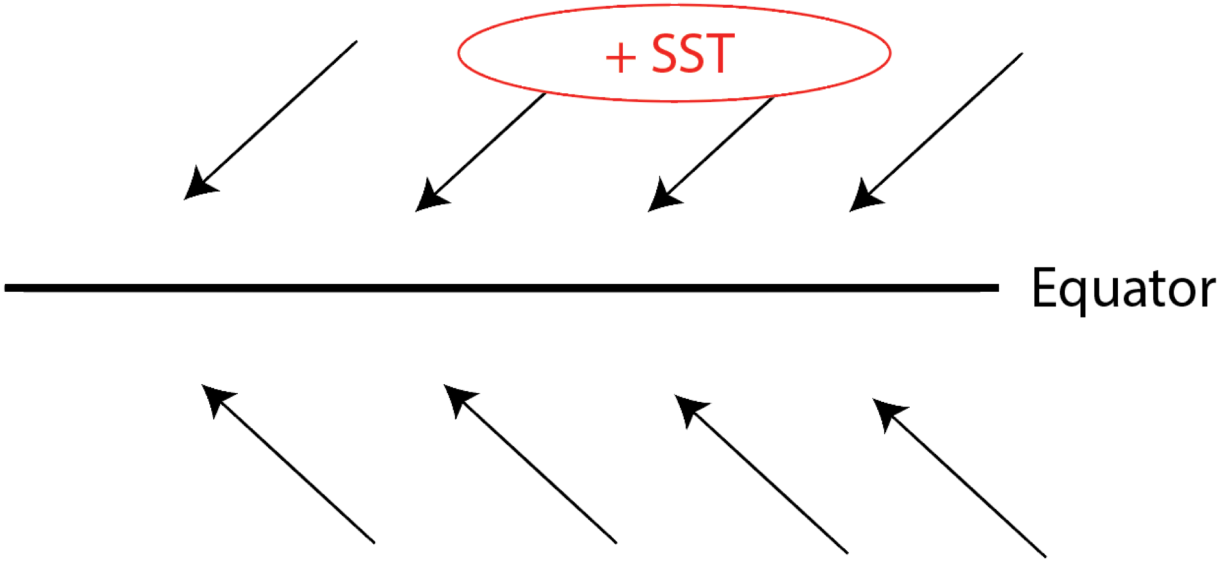

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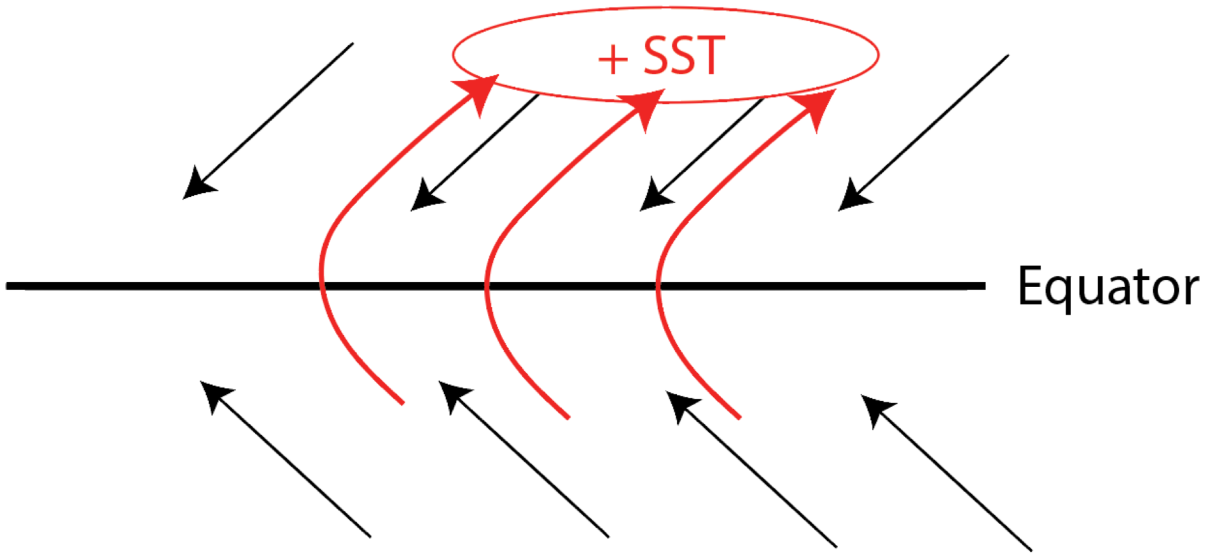
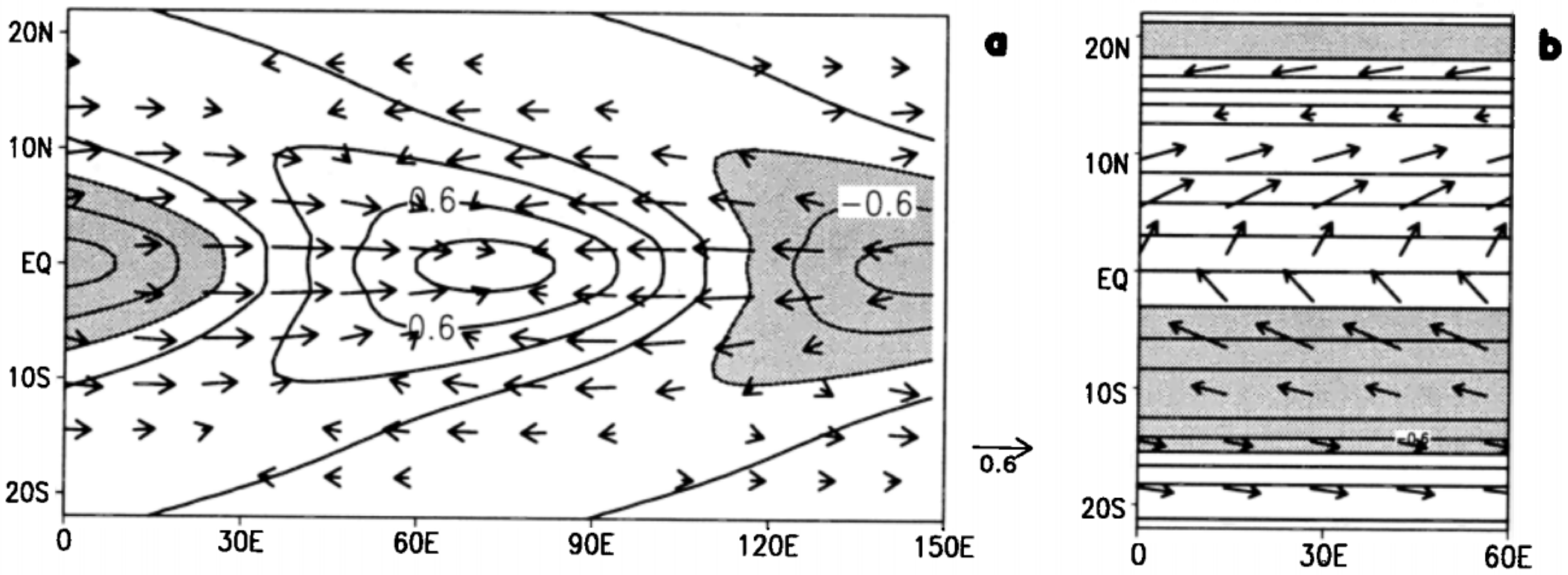


“Zonal Mode” and “Meridional Mode”

- **Zonal Mode** refers to the SST variability associated with ENSO, primarily reflecting the Bjerknes feedback
- **Meridional Mode** refers to the SST variability associated with the WES feedback


Zonal Mode

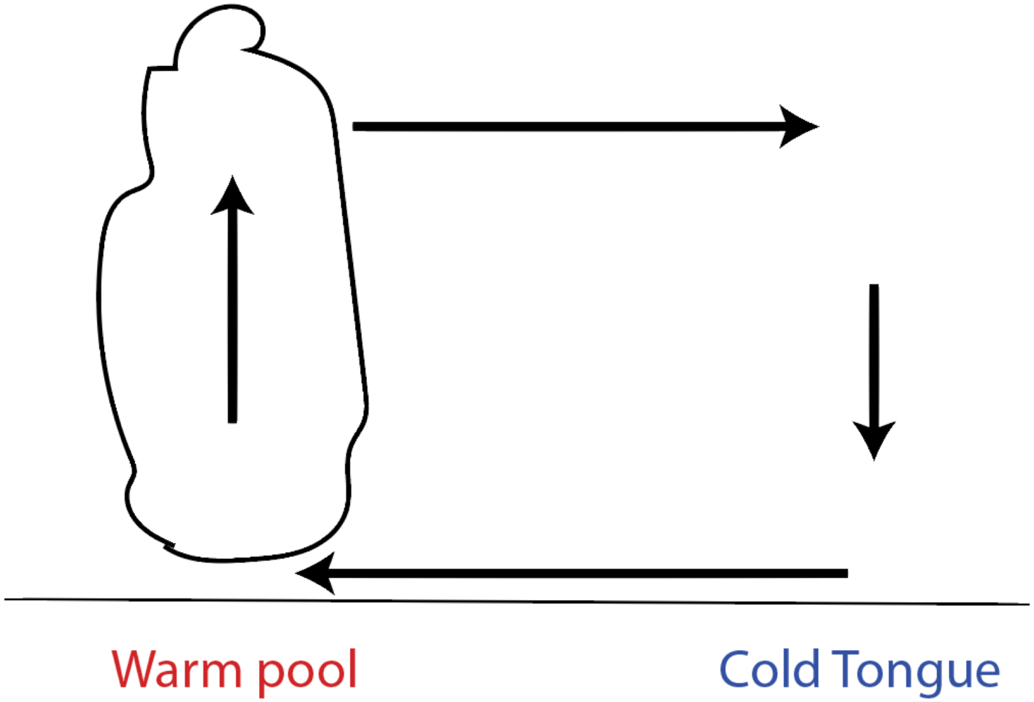
Meridional Mode

Figure 3 Dominant modes at **a**, the Pacific and **b**, the Atlantic wavelengths in the coupled model. SST in contours (<-0.3°C shaded) and surface wind velocity (m/s) in vectors.

Xie (1999) GRL

Cloud feedback

- In the tropics, deep convection (cumulonimbus clouds) generally occurs over warm SST (>27C), and cloud cover increases with SST → Dense cloud cover reflects sunlight, cooling the SST (negative feedback).



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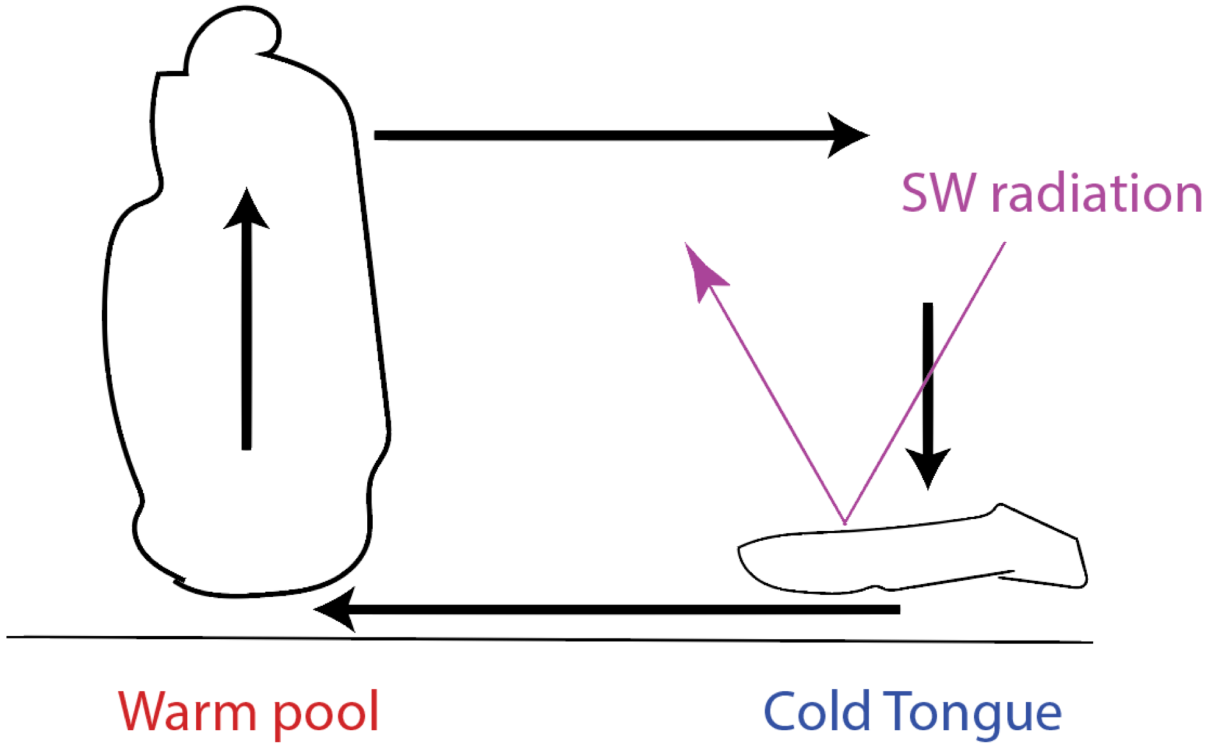
- Over the cold tongue region, dense shallow (stratus) clouds dominates. Cloud cover decreases with SST. (positive feedback)



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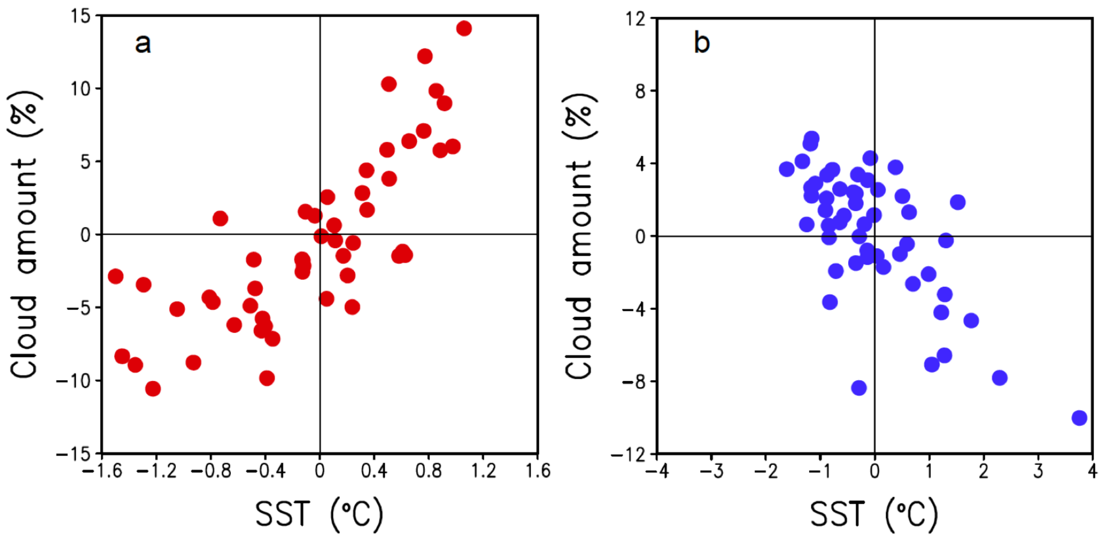
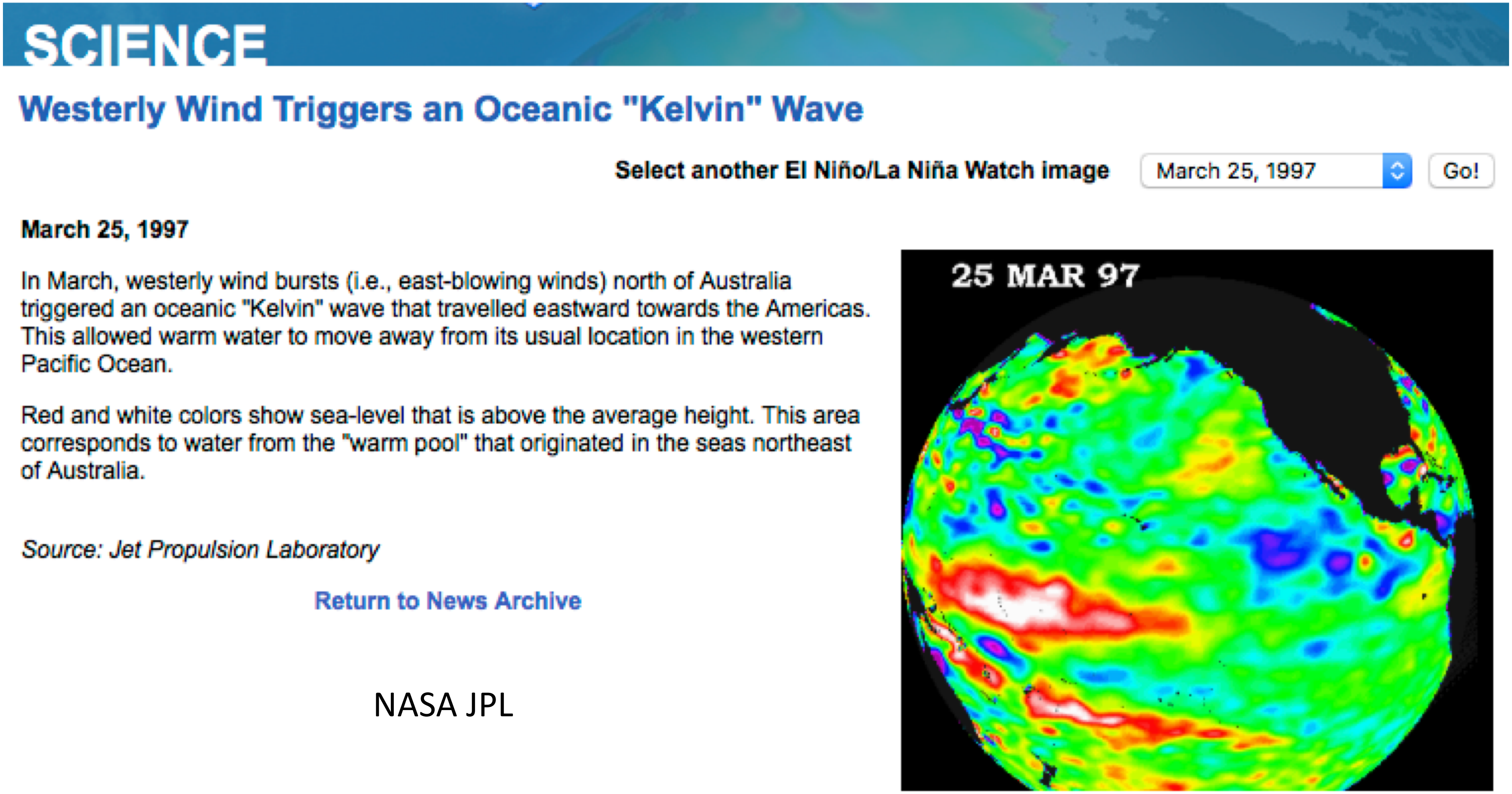


Figure 5. Scatter diagrams between SST and cloudiness for (a) the central equatorial Pacific (150°E – 140°W, 5°S-5°N) and October-January; and (b) the southeastern tropical Pacific (100 – 80°W, 10°S-0) and June-November, based on ship observations for 1950-2000. Deep convective and low clouds prevail in the respective regions. Correlations are 0.79 for (a) and -0.69 for (b).

ENSO theory: triggers

- Are there any events that can cause the onset of an El-Nino event?
- **Westerly wind burst (WWB) =** a westerly wind anomaly over the central Pacific. It starts a warm Kelvin wave that initiates an El-Nino event.
- **Madden Julian Oscillation (MJO)** = tropical intra-seasonal variability.
- **Extratropical influences** = influences from the subtropics. Seasonal footprinting mechanism (Vimont 2003). Meridional Mode.

1997-1998 El Nino



Westerly Wind Triggers an Oceanic "Kelvin" Wave

March 25, 1997

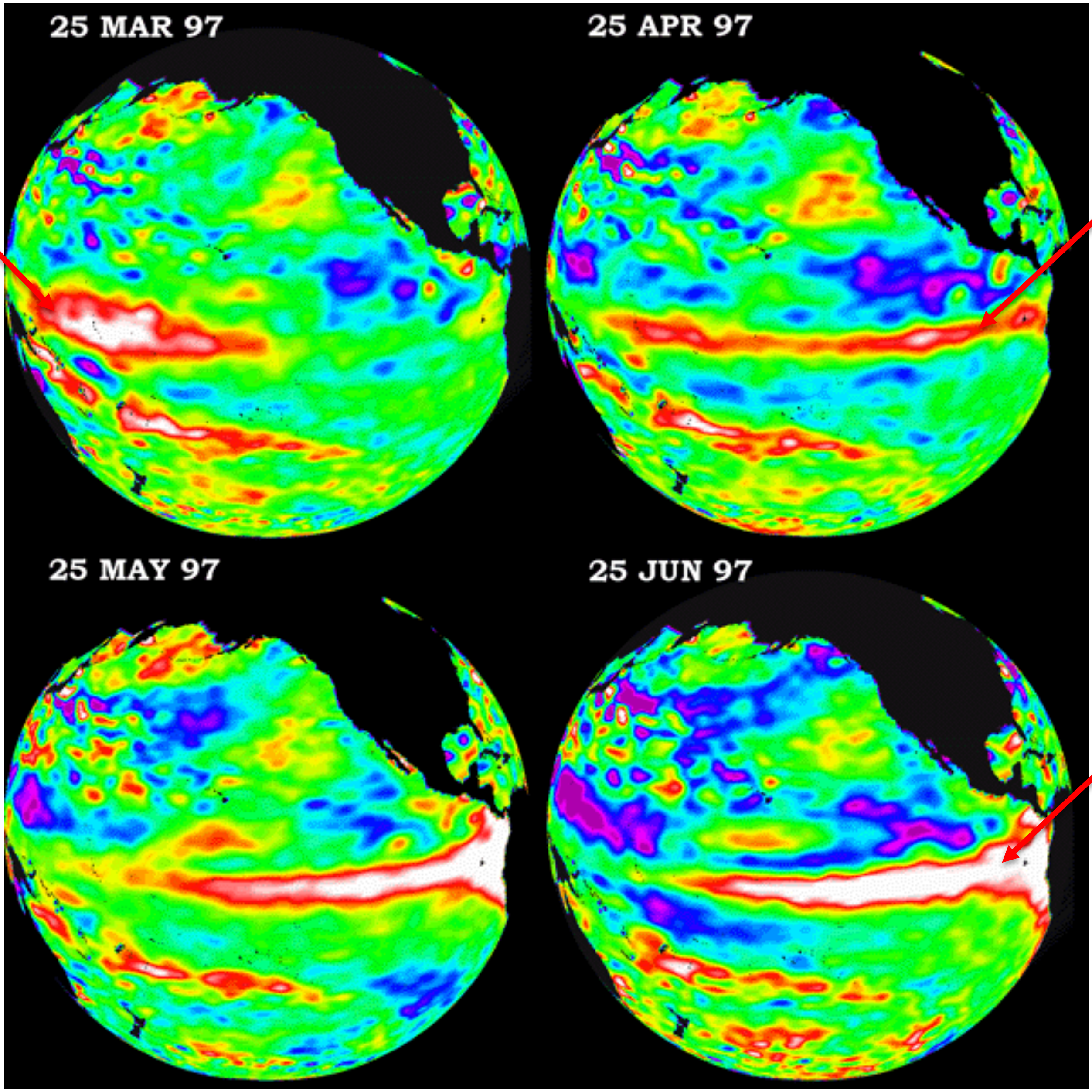
In March, westerly wind bursts (i.e., east-blowing winds) north of Australia triggered an oceanic "Kelvin" wave that travelled eastward towards the Americas. This allowed warm water to move away from its usual location in the western Pacific Ocean.

Red and white colors show sea-level that is above the average height. This area corresponds to water from the "warm pool" that originated in the seas northeast of Australia.

Source: Jet Propulsion Laboratory

NASA JPL

1997-1998 El Nino



WWB
trigger

Kelvin
wave

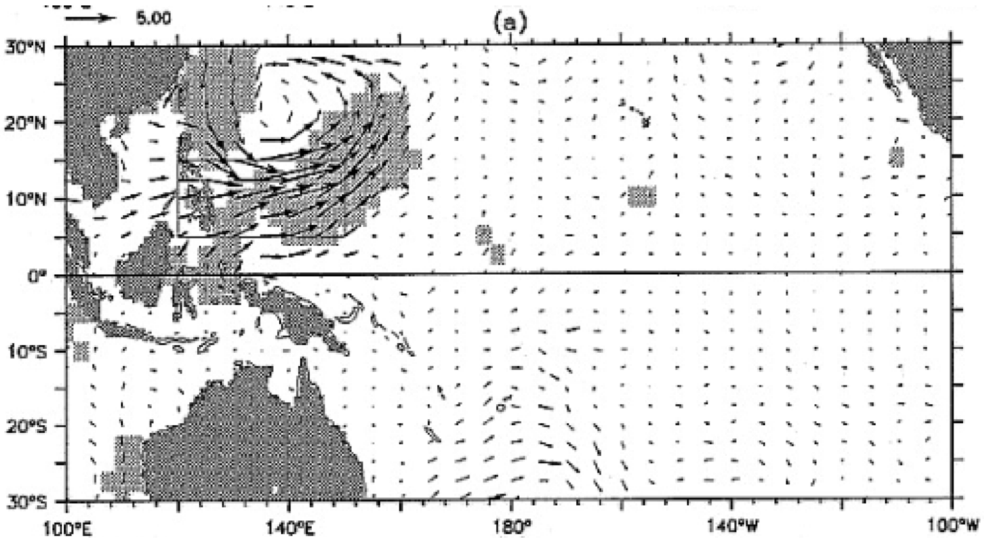
Build-up of
warm water

NASA JPL: sealevel.jpl.nasa.gov

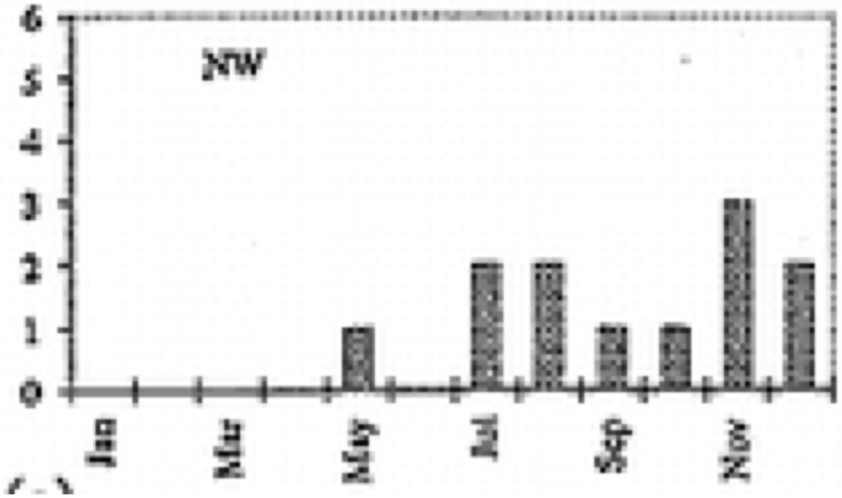
Westerly wind burst

- Are there different types of WWB?
- Harrison and Vecchi (1997) categorized WWBs by their geographic locations

NE pattern



Occurrence of extreme event



Westerly wind burst

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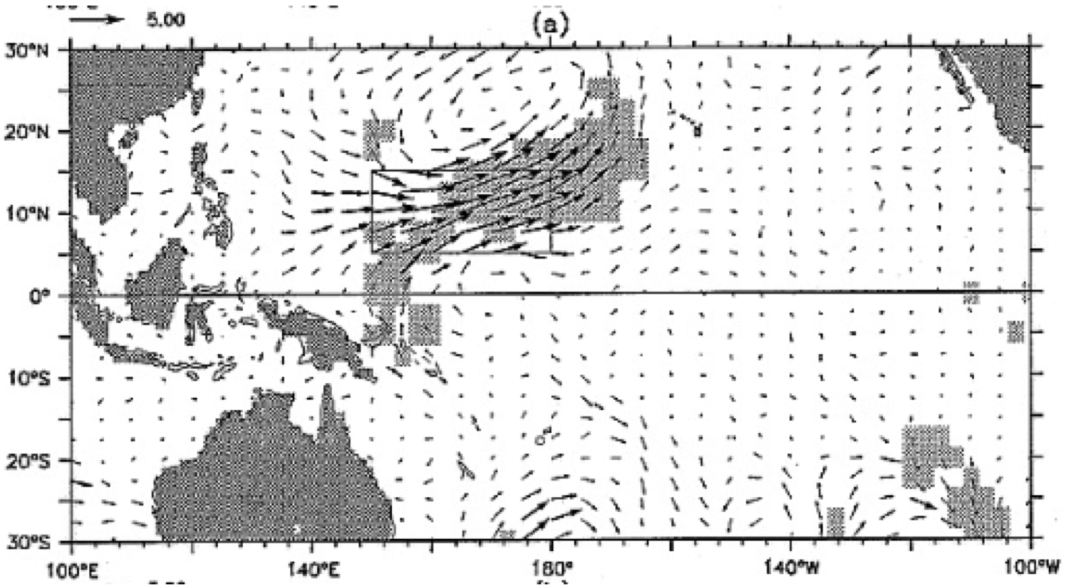
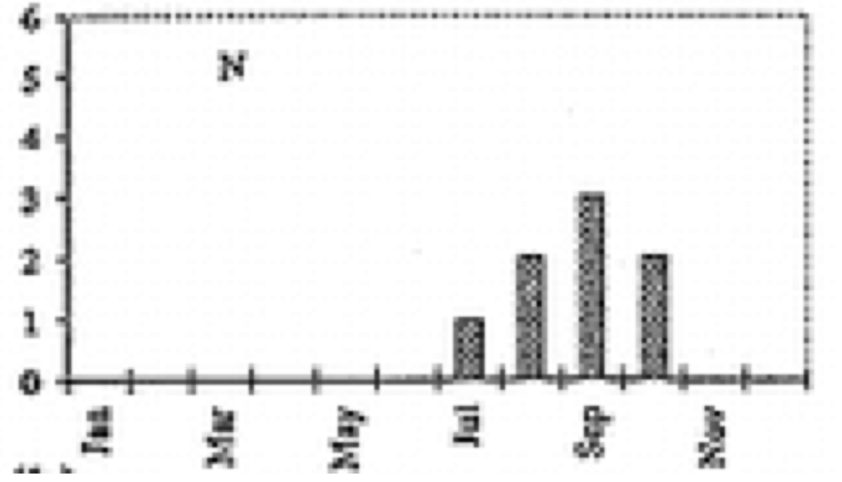
N pattern



Occurrence of extreme event



Westerly wind burst

- Are there different types of WWB?
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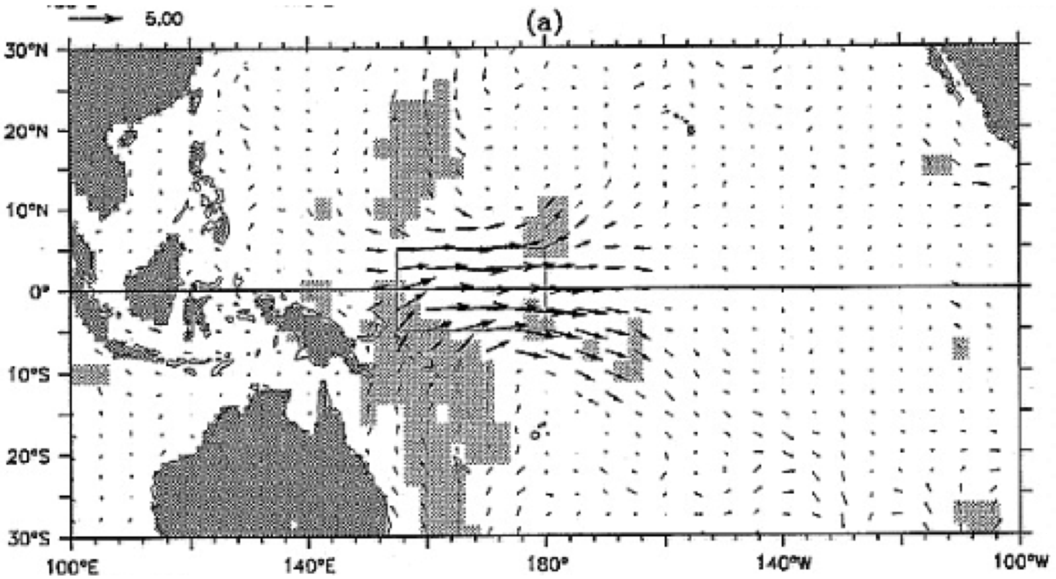
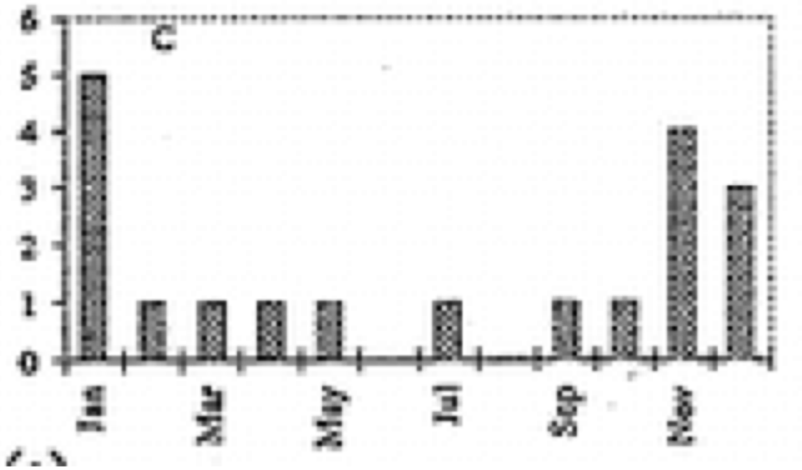
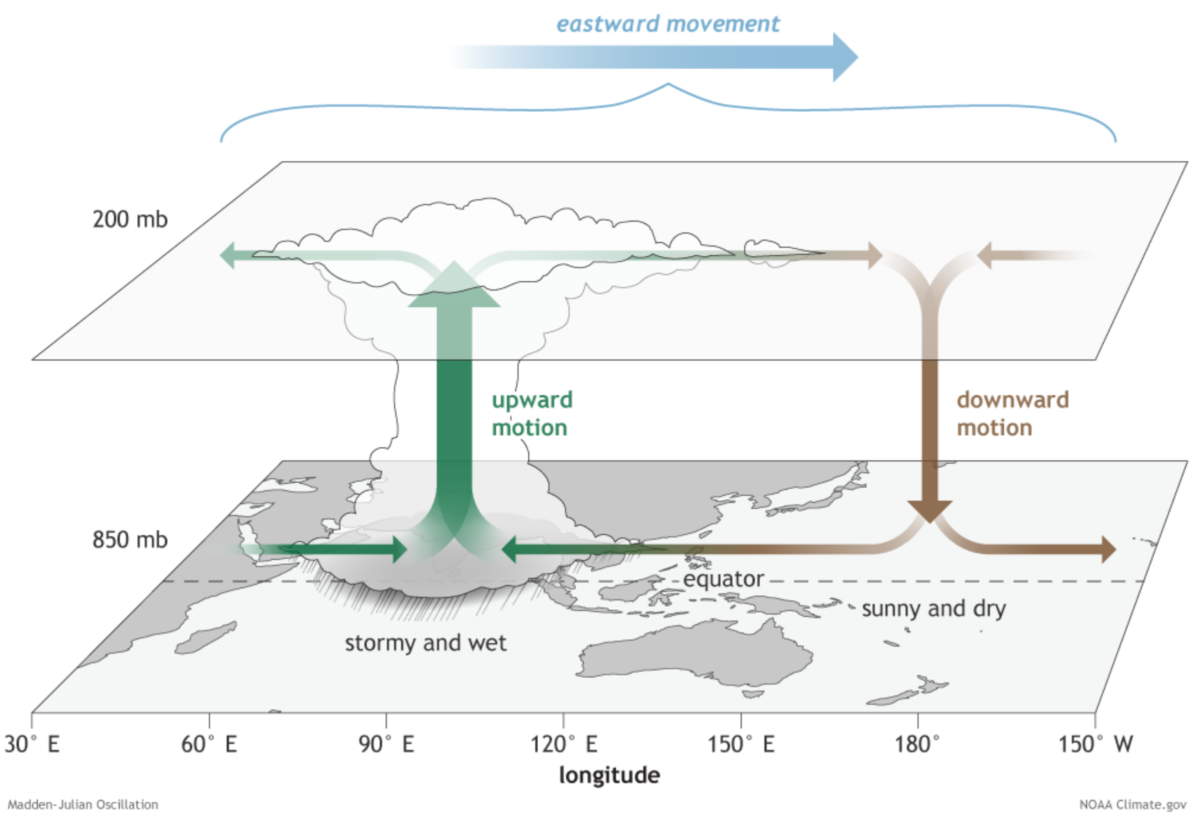
C pattern



Occurrence of extreme event



- WWB are known to initiate the El Nino events. What atmospheric processes can cause WWBs?
  - Madden Julian Oscillation (MJO) is the major fluctuation in tropical weather on weekly to monthly timescales.



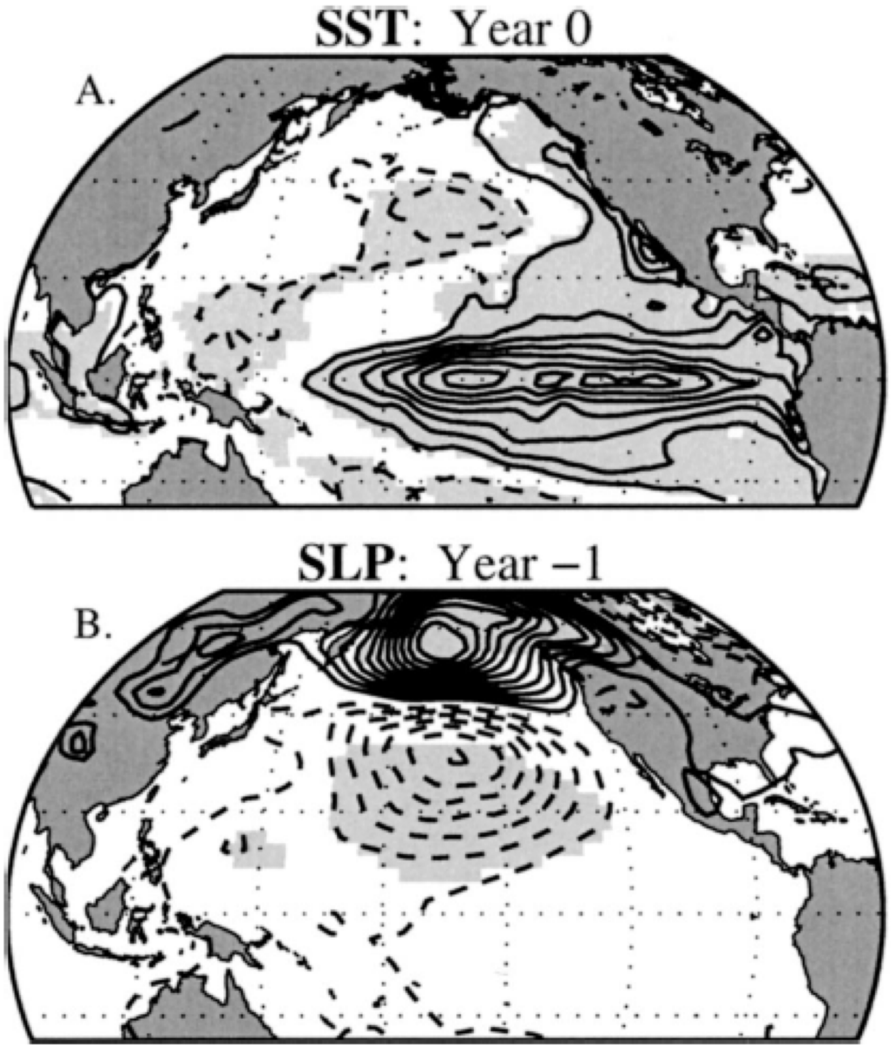
Madden and Julian (1971)

- Atmospheric process
- Eastward propagating tropical wind/precipitation anomaly
- 30-60 days cycle
- Affects monsoons, tropical cyclones, WWB and ENSO, mid-latitude weather over continental US

Image from NOAA

Influence from subtropics

- Seasonal footprinting mechanism (Vimont 2003),



Looking for a pattern of sea level pressure (SLP) one year before El-Nino event

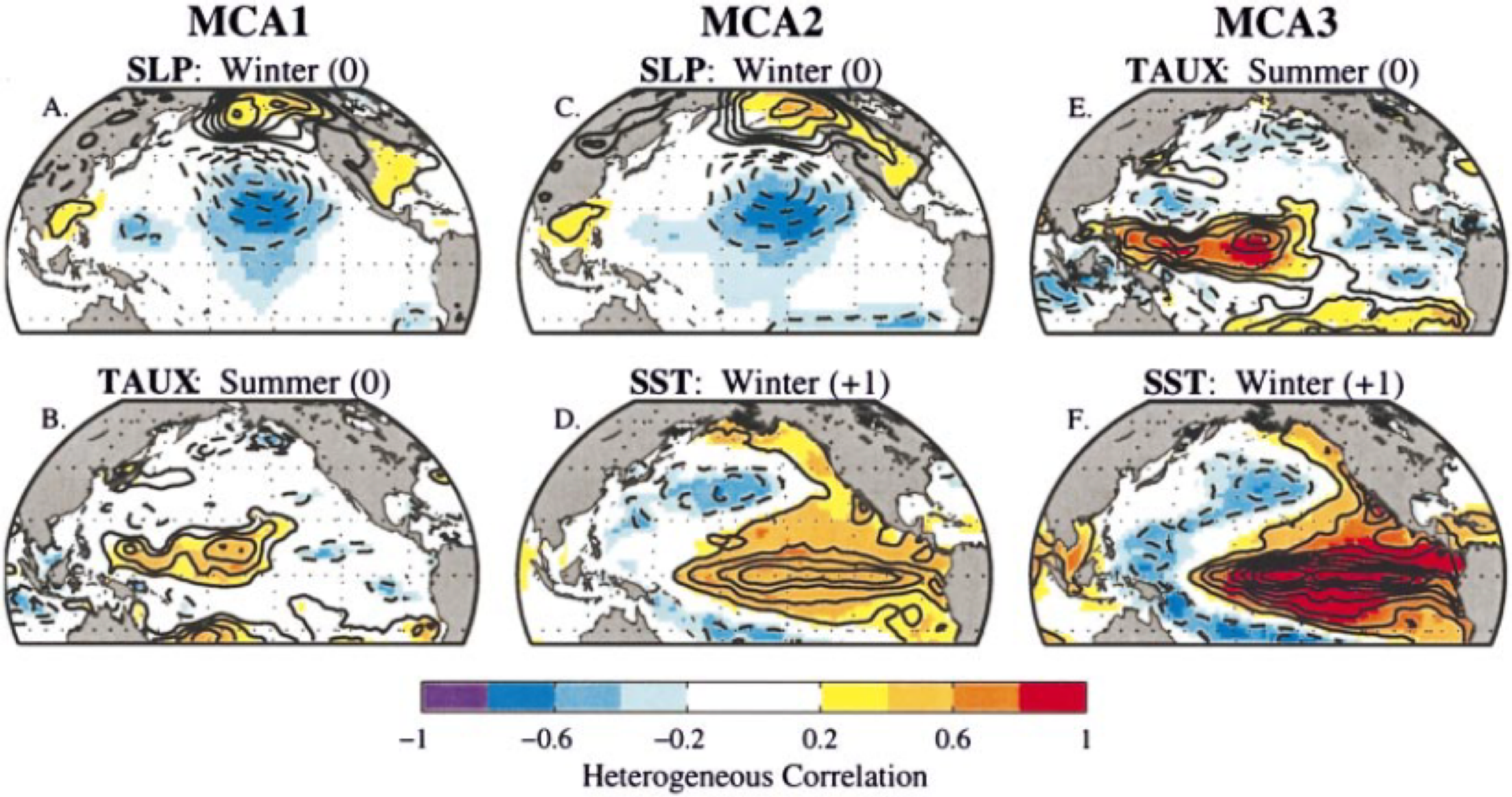
(top) SST associated with El-Nino.

(bottom) SLP associated with the following year’s El-Nino

When this SLP pattern occurs, there is an increased chance that an El-Nino event develops in the following year.

Influence from subtropics

- Seasonal footprinting mechanism (Vimont 2003),



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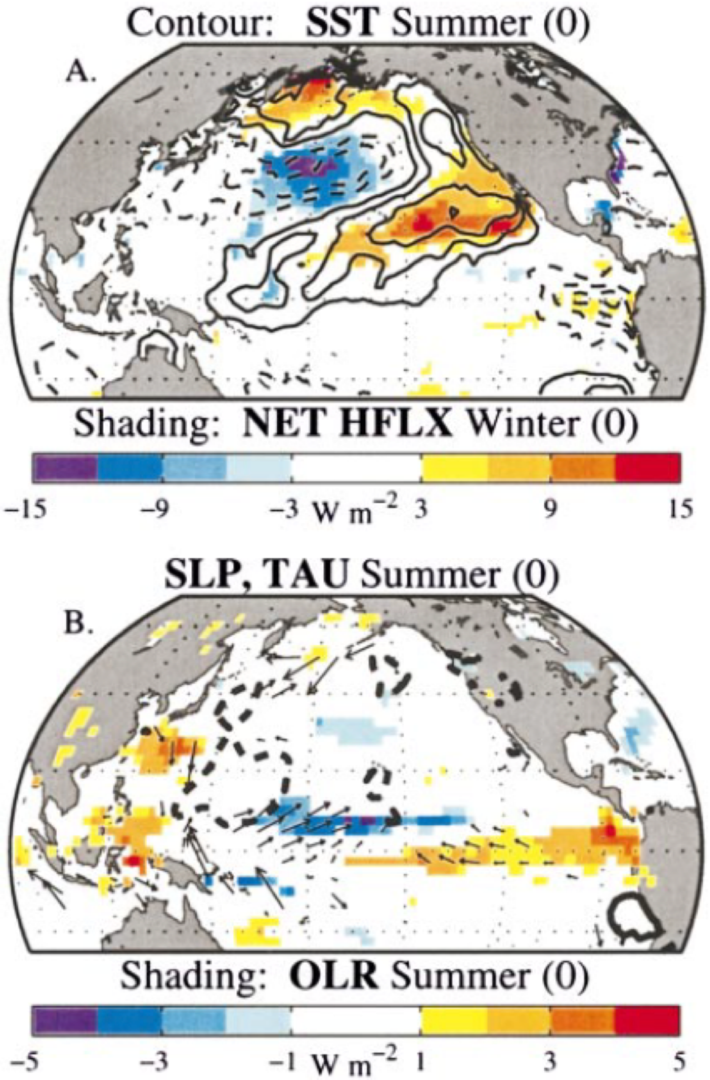

- There is a winter-time SPL pattern associated with WWB event in the summer and with El-Nino in the following winter.

- This summer-time WWB is in turn related to the summer-time SST pattern…

- This is shown to be related to the Meridional Mode and the WES feedback (Chang et al 2007)

WES feedback and MM

- Wind – Evaporation – SST (WES) feedback, Xie and Philander (1994)
  - Thermodynamic coupling; exists in Atlantic and Pacific
  - Weaker wind → Less evaporation → Warmer SST
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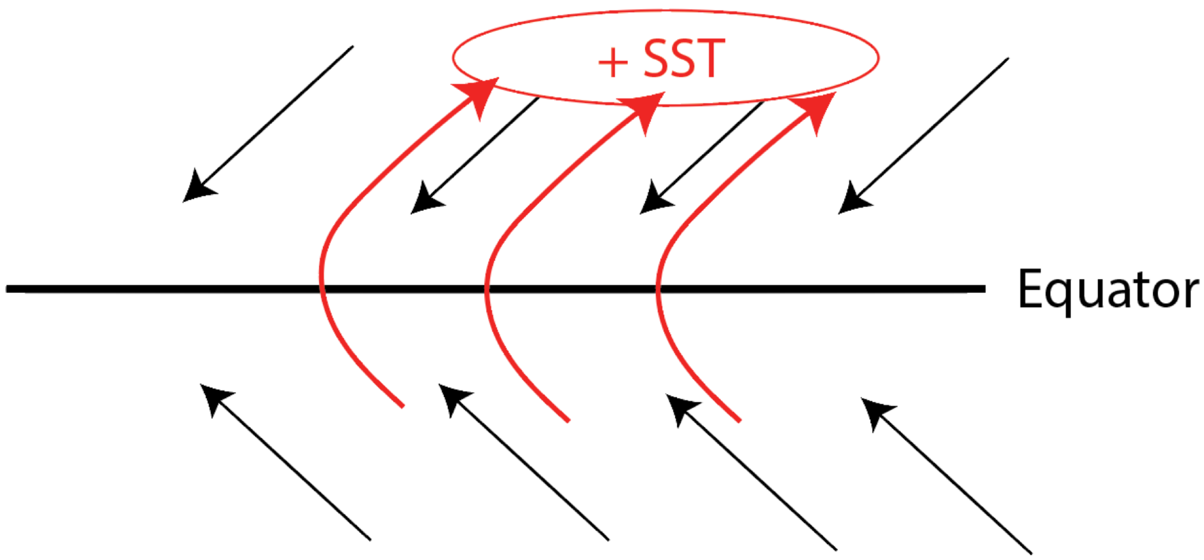
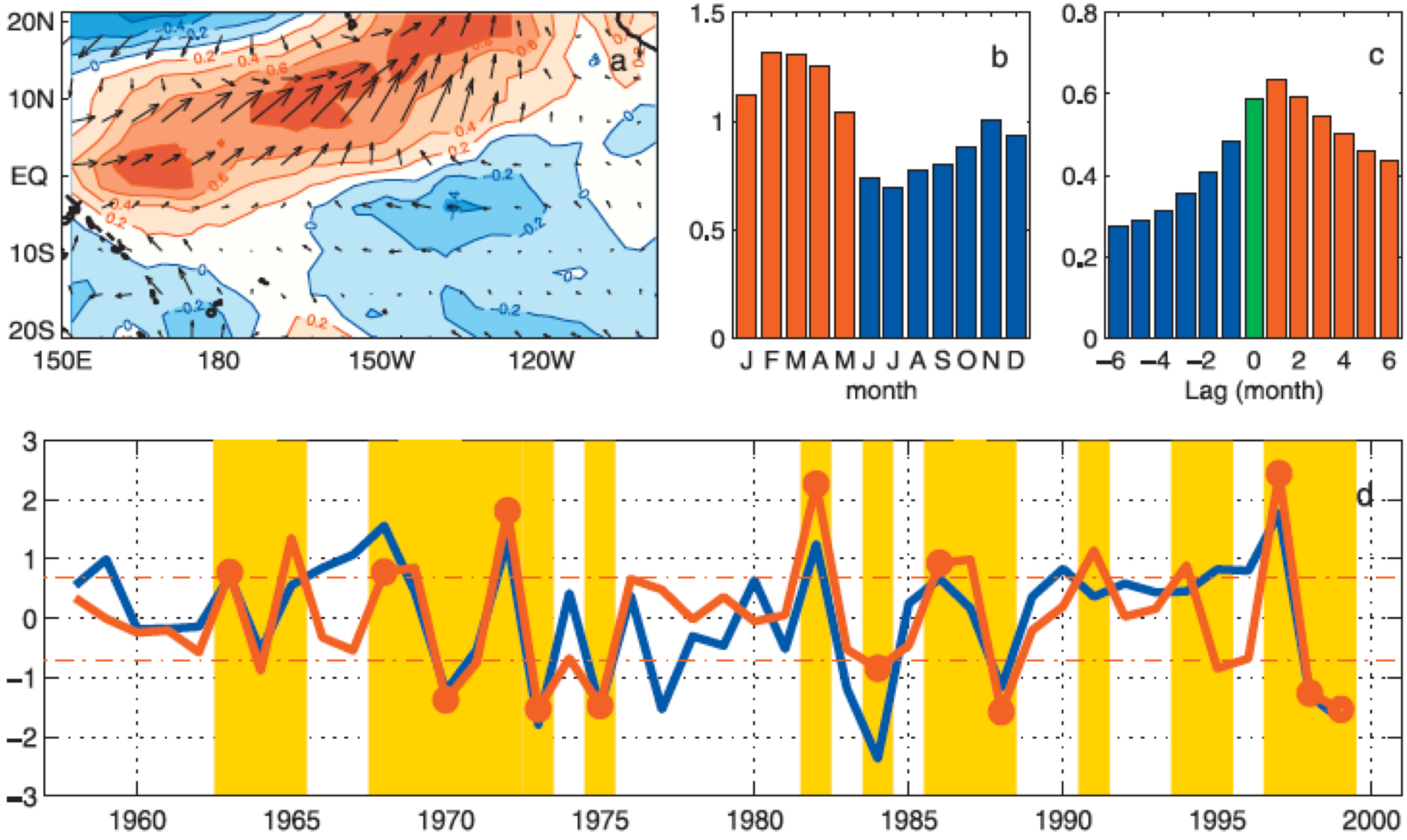


Influence from subtropics

- Meridional Mode and ENSO (Chang et al 2007)



a. MM pattern of SST and winds **b. MM seasonal amplitude**

d. Blue = spring-time MM index, Red = ENSO index

Summary

- ENSO is a manifestation of the strong ocean-atmosphere coupling with impacts on global weather, biogeochemistry, fishery, agriculture, …
- The ENSO cycle is irregular because of complex interplay between many processes, feedbacks and triggers.
- An ENSO event lasts 12-18 months every 3-7 years.
- ENSO is triggered by WWBs which in turn depends on atmospheric weather, MJO, and the subtropical MM.
- PDO is an ENSO-like climate fluctuation on the timescale of 10s of years, influencing the global surface temperature