# Interannual Variability in the Tropical Pacific


**Ingo Richter**

Application Laboratory, JAMSTEC, Yokohama, Japan


**ICTP Summer School on AMV and TBI**

**Trieste, Italy**

**2 August 2023**

# Outline

- observations
- coupled air-sea feedbacks
- negative feedbacks
- the delayed oscillator
- the recharge oscillator
- phase locking of ENSO
- flavors of ENSO
- ENSO precursors
- simulation of ENSO by climate models

# Observations

The big picture

# What is El Niño?

- anomalous warming (or cooling) in the central and eastern equatorial Pacific
- often referred to El Niño-Southern Oscillation (ENSO)
- occurs at irregular intervals (~2-7 years)
- amplitude ~ 1-3 K
- positive and negative events tend to alternate but double and even triple events do occur (not a pure oscillation)
- relies on coupled air-sea feedbacks in the equatorial region

# A selective history of ENSO

| | |
|---|---|
| 18th century or earlier | • Peruvian fisherman note unusual warming off the coast of Peru in some years around Christmas<br>• dubbed “the child Jesus” (El Niño in Spanish) |
| 1890s | Carranza and Carillo note impacts on rainfall in Peru |
| 1920s | Sir Gilbert Walker “discovers” the Southern Oscillation |
| 1950s | first evidence for coupling between Southern Oscillation and El Niño |
| 1969 | Jacob Bjerknes postulates an air-sea coupled feedback to explain ENSO growth |
| 1960s-1970s | equatorial wave theory worked out by Matsuno, Gill and others |
| 1982 | the 1982/1983 extreme El Niño catches researchers by surprise; indicates clear need for more observations |
| 1986 | Cane and Zebiak intermediate complexity model developed; first model that can predict ENSO events |

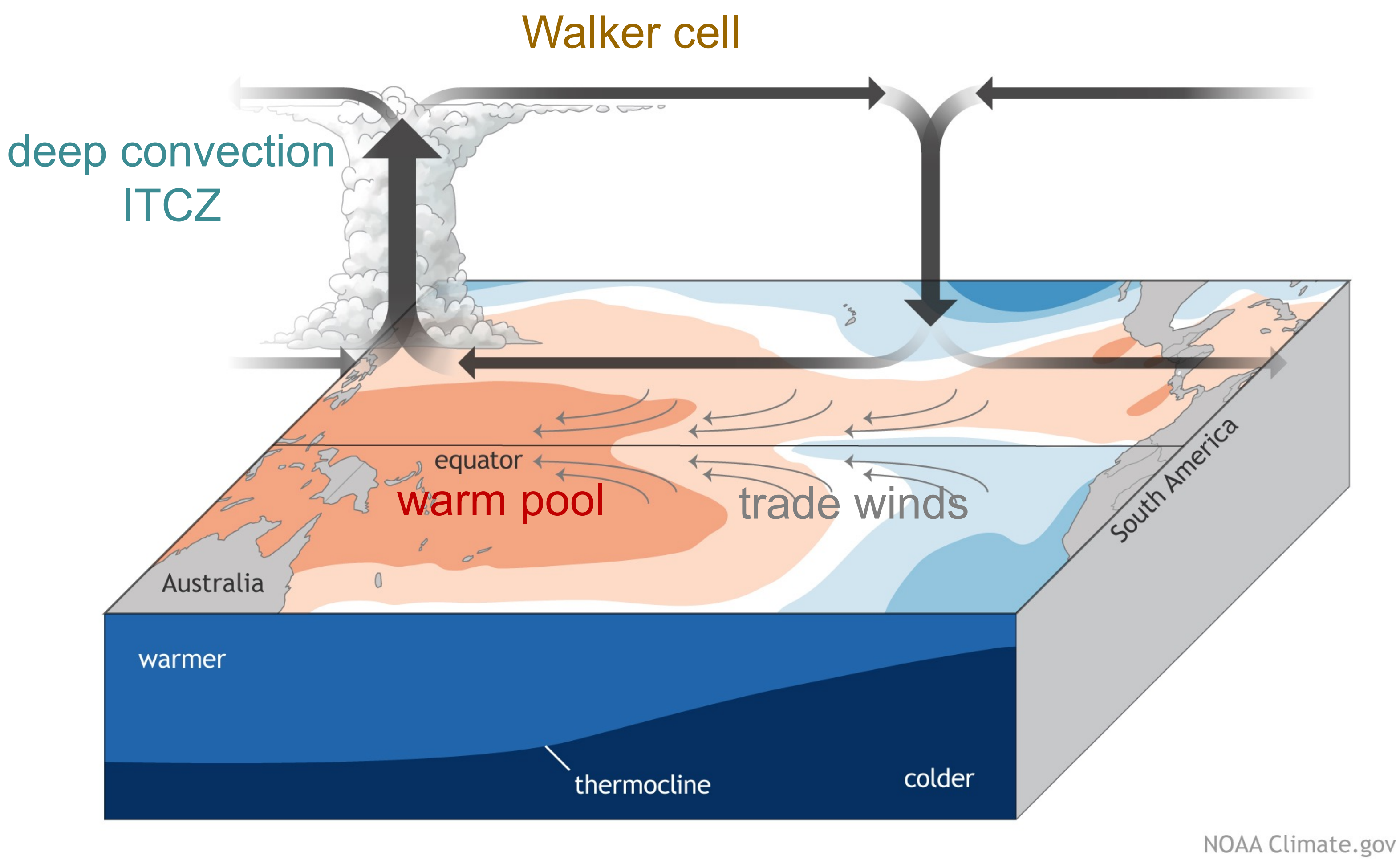
# A selective history of ENSO

| | |
|---|---|
| 1988 | Schopf and Suarez suggest delayed oscillator theory to explain ENSO phase reversal |
| 1997 | Fei-Fei Jin suggests recharge oscillator theory to explain phase reversal |
| 2003 | Vecchi and Harrison suggest mechanism for ENSO phase locking |
| 2004 | Chiang and Vimont suggest that North Pacific variability could act as an ENSO precursor |
| 2007 | Ashok et al. suggest the existence of El Niño Modoki (aka central Pacific or date line El Niño) |
| 2009 | Rodriguez-Fonseca et al. suggest that the equatorial Atlantic can act as an ENSO precursor |
| 2013 | Ham et al. suggest that the northern tropical Atlantic can act as an ENSO precursor |

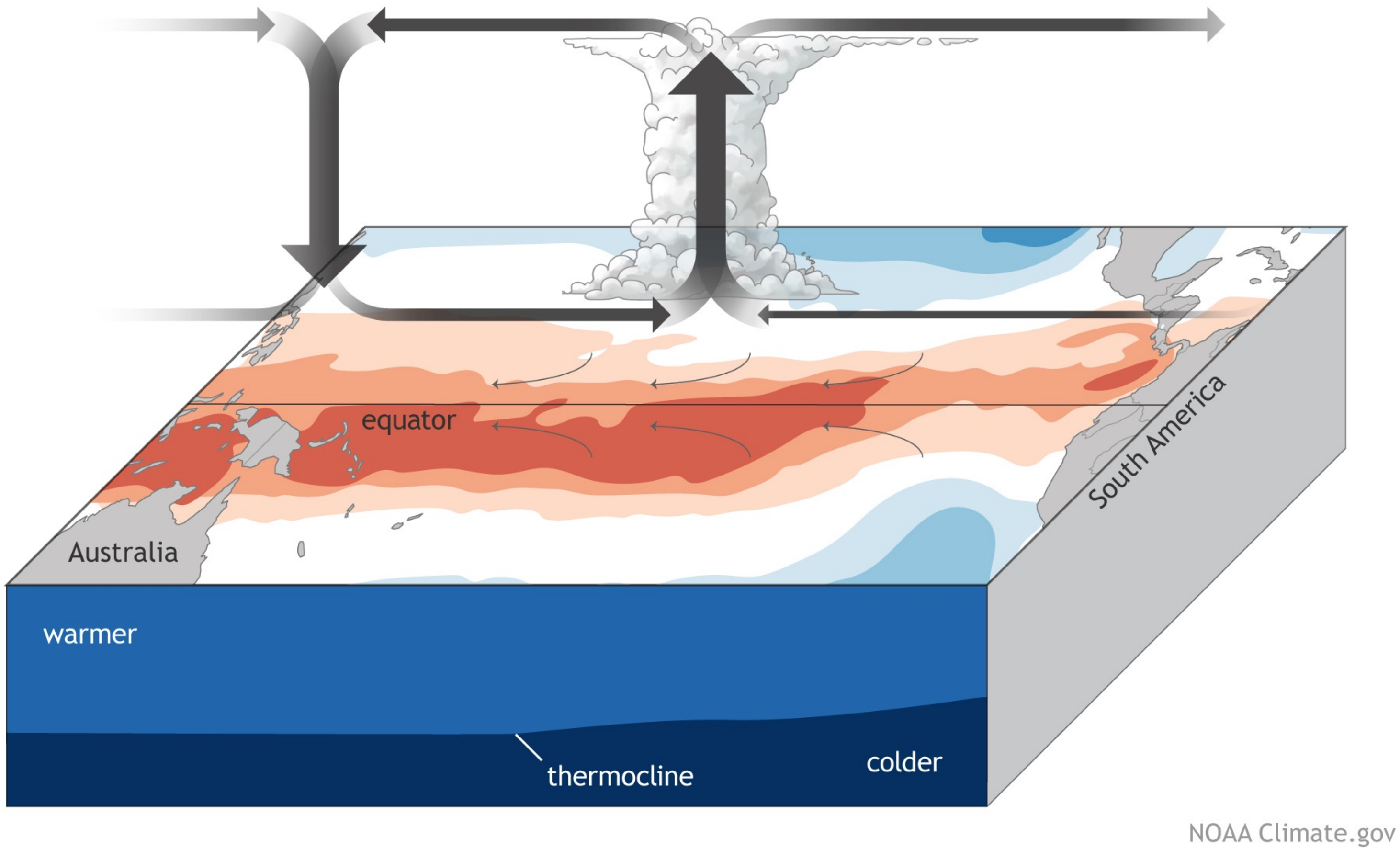
# A selective history of ENSO

| | |
|---|---|
| 2014/15 | back-to-back blockbuster Nature papers by Wenju Cai suggest more extreme El Niño and La Niña events under global warming |
| 2014/15 | everybody thinks they have a good grip on ENSO now; then the 2014/15 event fails to develop and people are scratching their heads |

# Neutral conditions

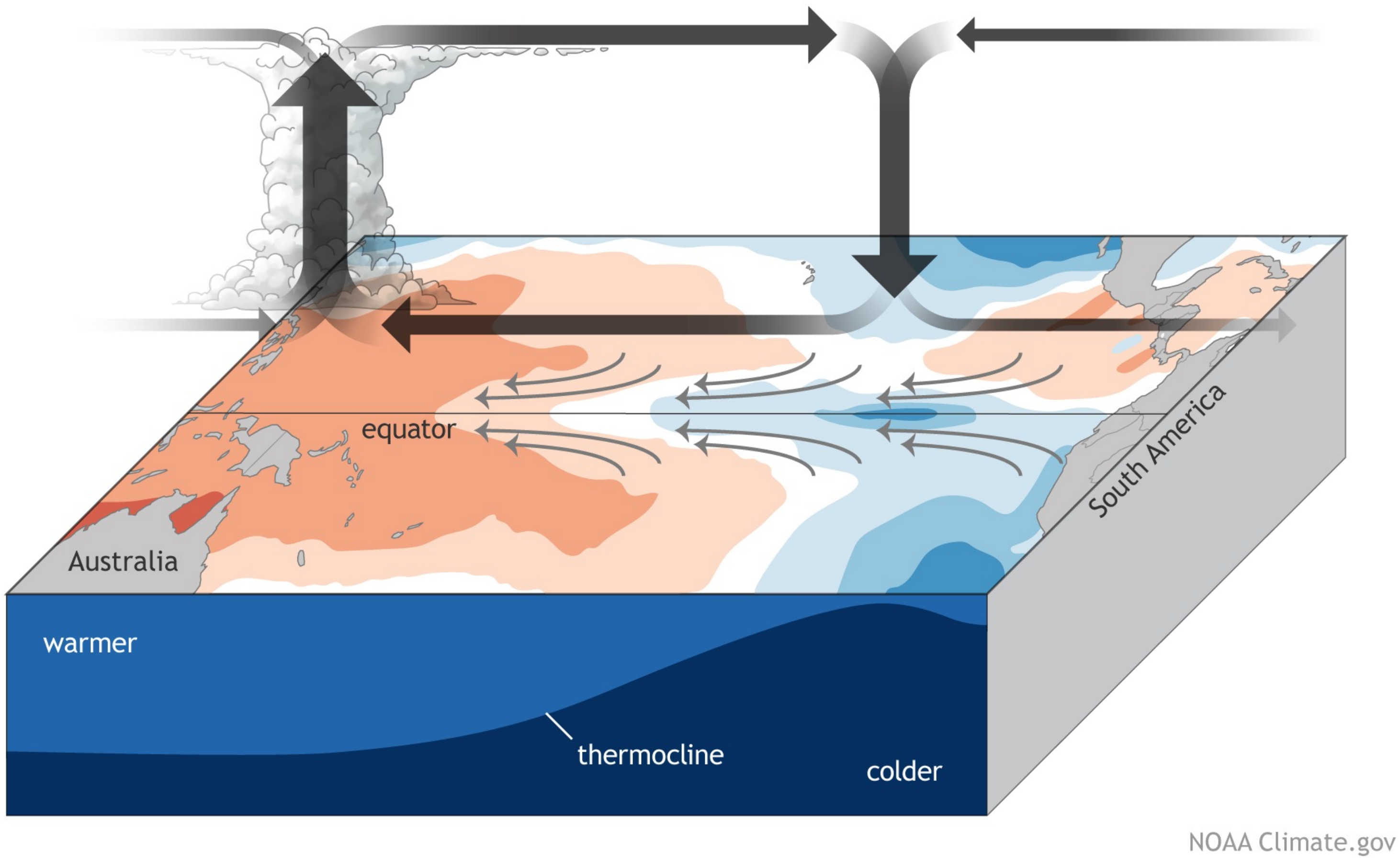


# El Niño



equator
Australia
South America
warmer
thermocline
colder
NOAA Climate.gov

# La Niña



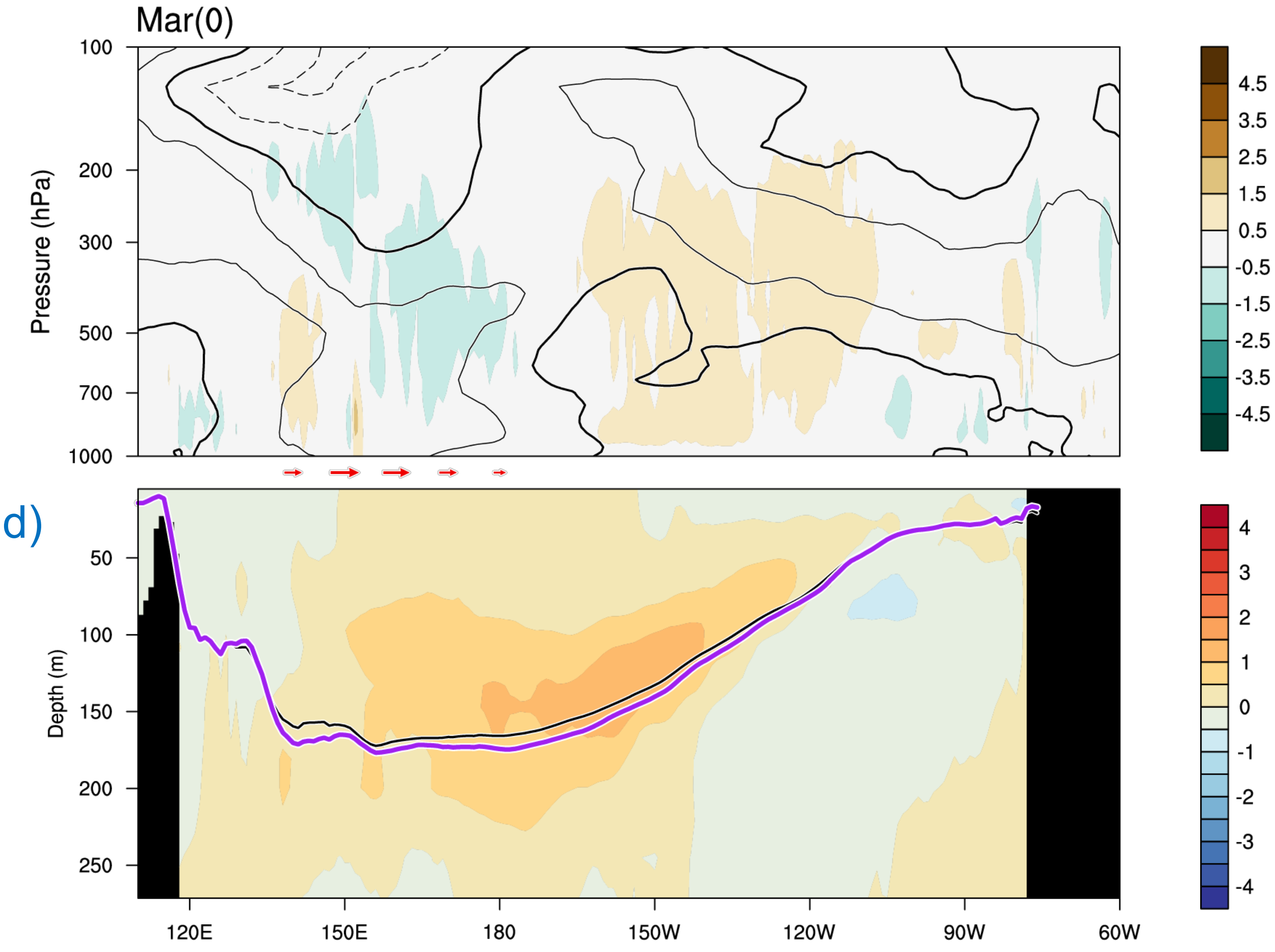
equator
Australia
South America
warmer
thermocline
colder
NOAA Climate.gov

# El Niño composite – yr0 March

## ERA-5 omega (shd) and u (cnt) and ORAS-5 temp

vertical pressure velocity (shading; negative means upward)
zonal wind (contours)

ocean temperature (shd)
Z20 (purple line)
climatological Z20 (green line)



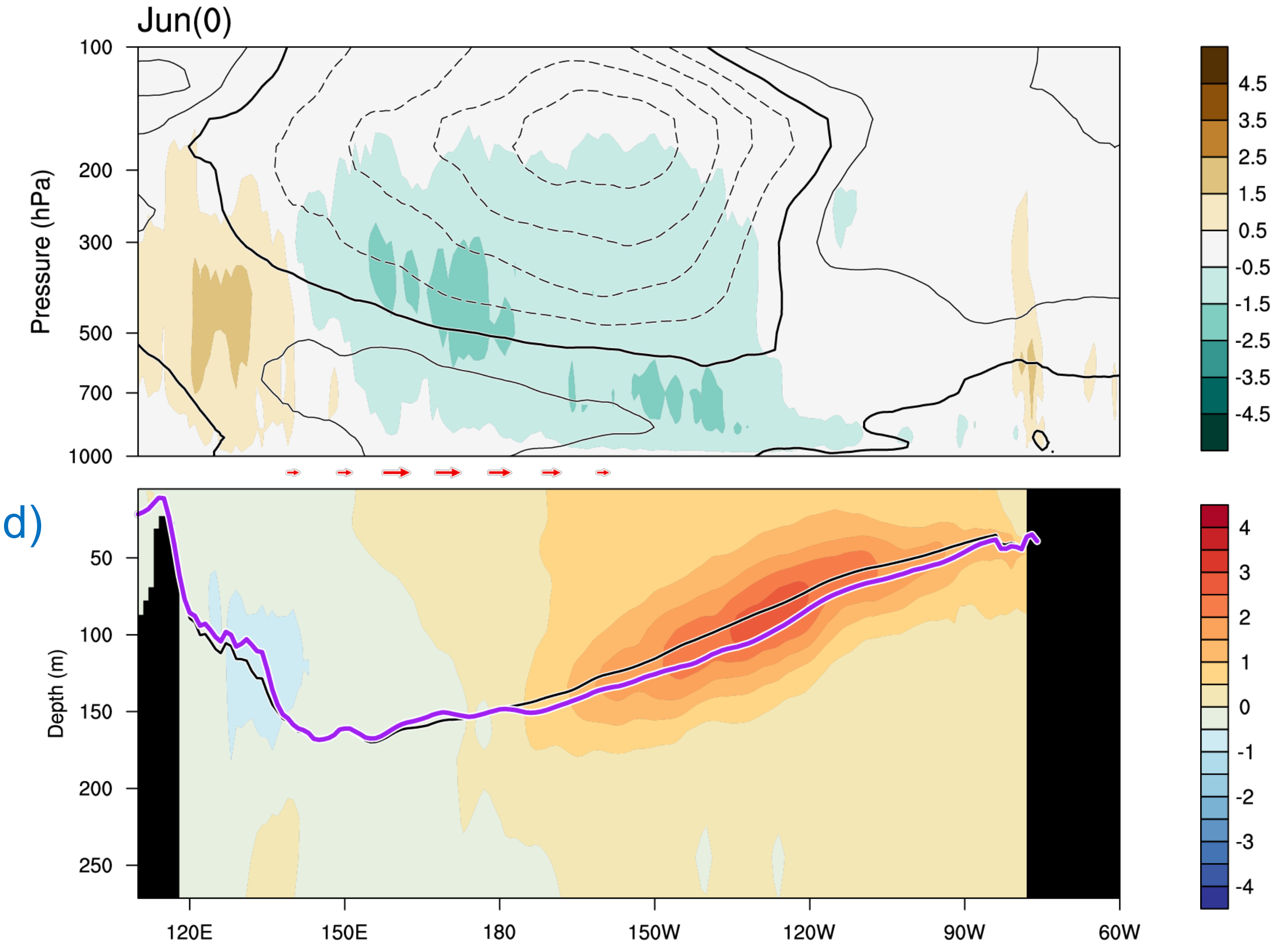

*provided by Hiroki Tokinaga; Kyushu University*

# El Niño composite – yr0 June

ERA-5 omega (shd) and u (cnt) and ORAS-5 temp

vertical pressure velocity (shading; negative means upward)
zonal wind (contours)

ocean temperature (shd)
Z20 (purple line)
climatological Z20 (green line)



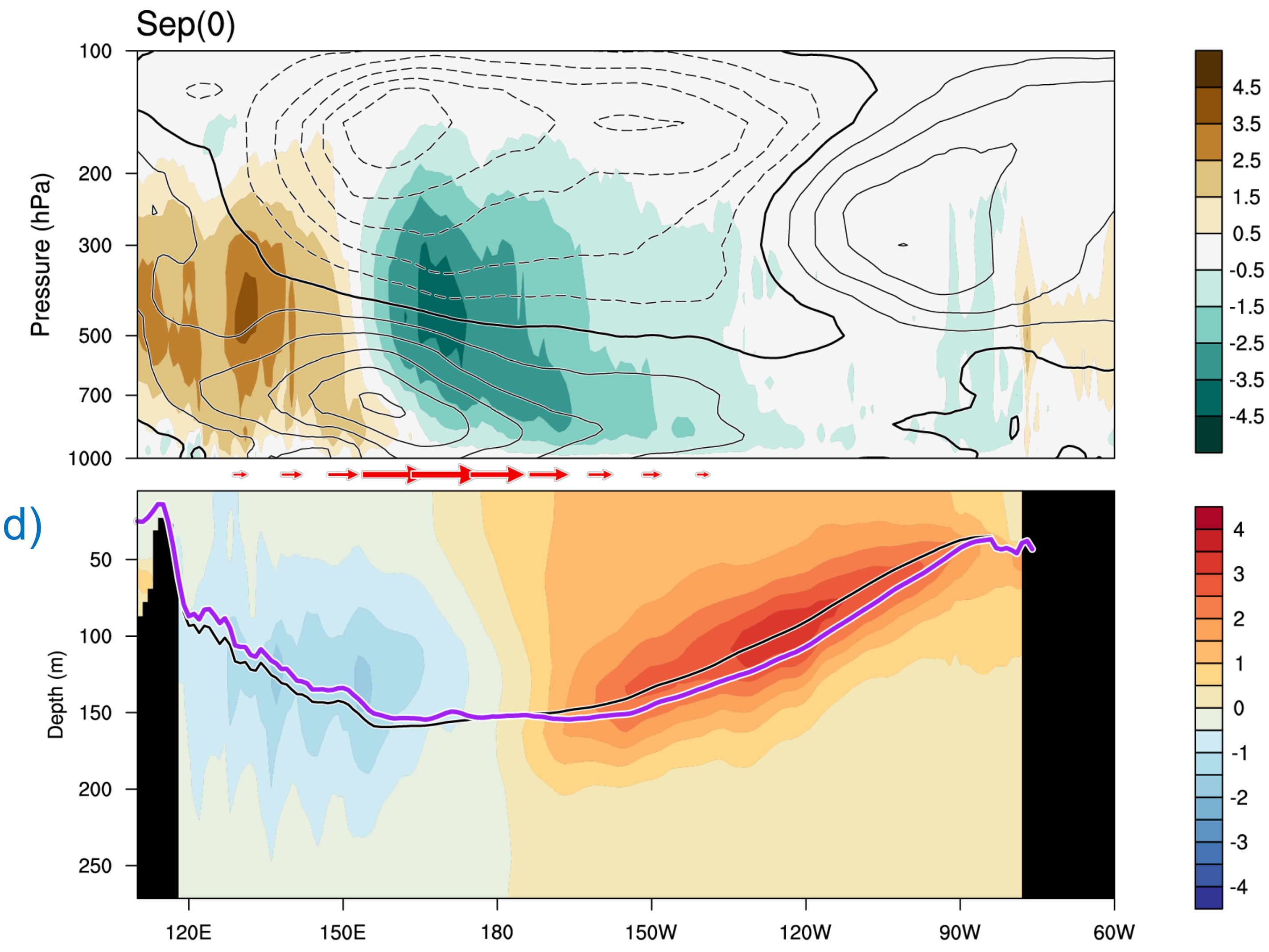

*provided by Hiroki Tokinaga; Kyushu University*

# El Niño composite – yr0 September

## ERA-5 omega (shd) and u (cnt) and ORAS-5 temp

vertical pressure velocity (shading; negative means upward)
zonal wind (contours)

ocean temperature (shd)
Z20 (purple line)
climatological Z20 (green line)



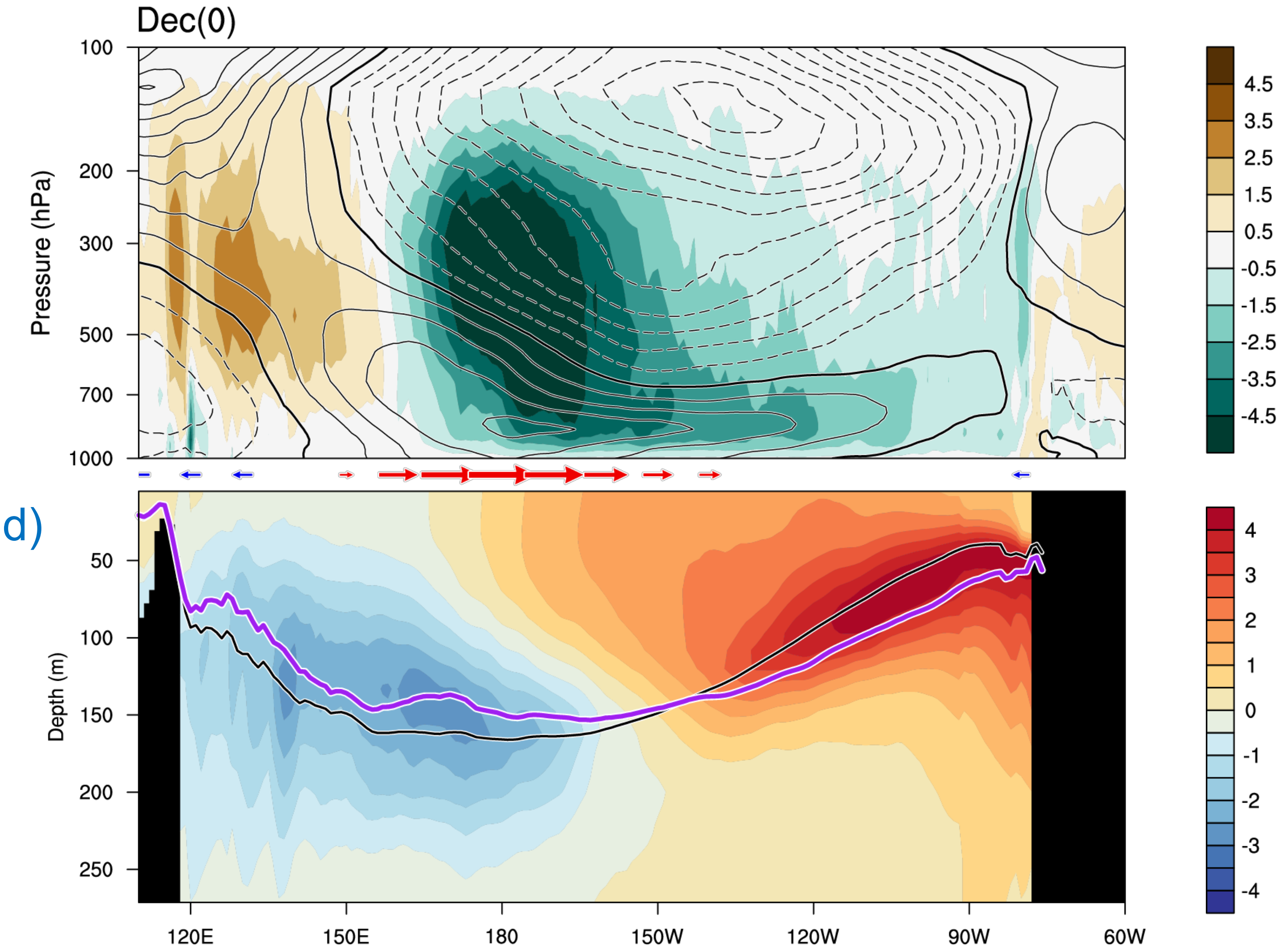

*provided by Hiroki Tokinaga; Kyushu University*

# El Niño composite – yr0 December

## ERA-5 omega (shd) and u (cnt) and ORAS-5 temp

vertical pressure velocity (shading; negative means upward)
zonal wind (contours)

ocean temperature (shd)
Z20 (purple line)
climatological Z20 (green line)



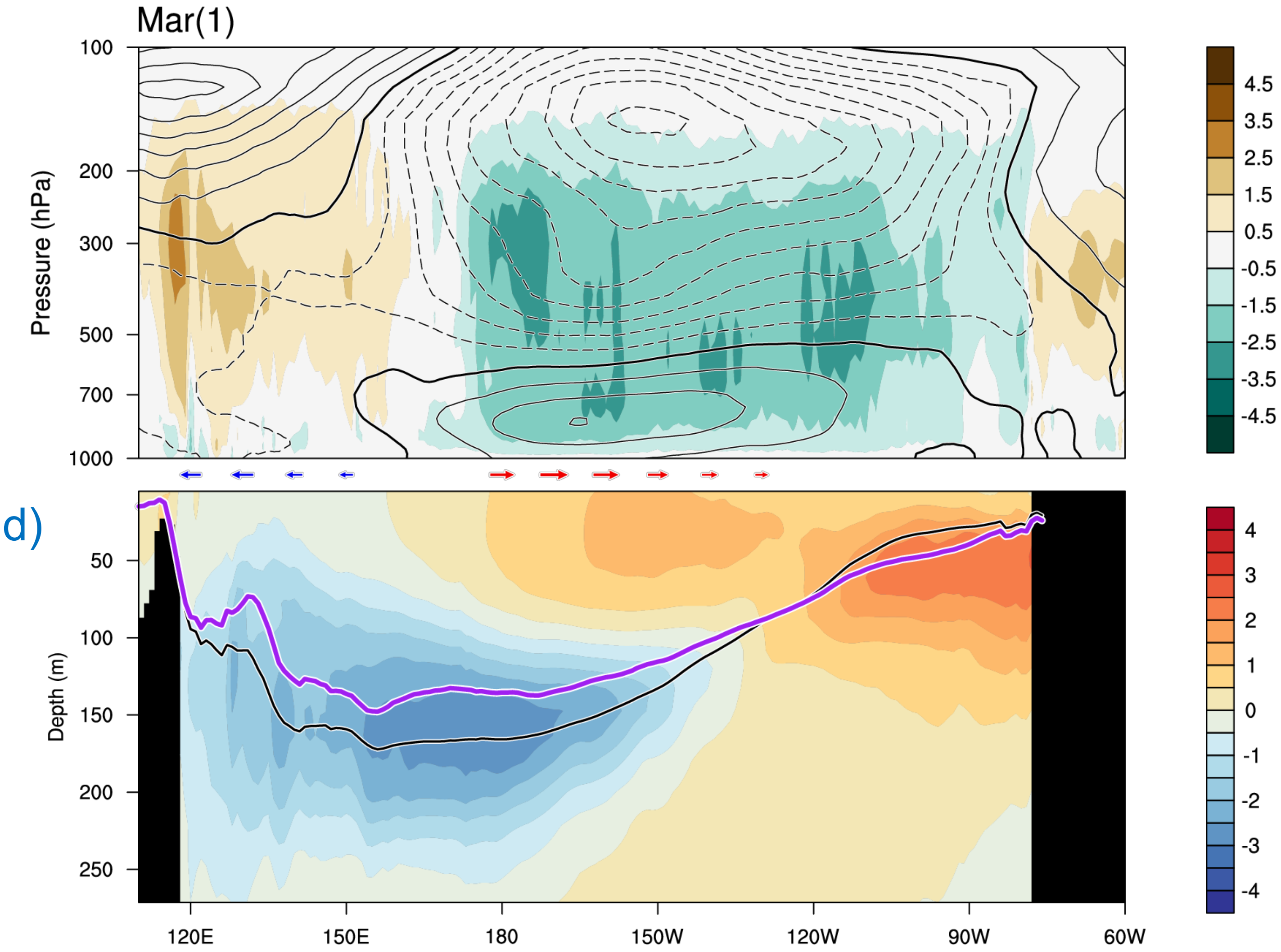

*provided by Hiroki Tokinaga; Kyushu University*

# El Niño composite – yr1 March

## ERA-5 omega (shd) and u (cnt) and ORAS-5 temp

vertical pressure velocity (shading; negative means upward)
zonal wind (contours)

ocean temperature (shd)
Z20 (purple line)
climatological Z20 (green line)

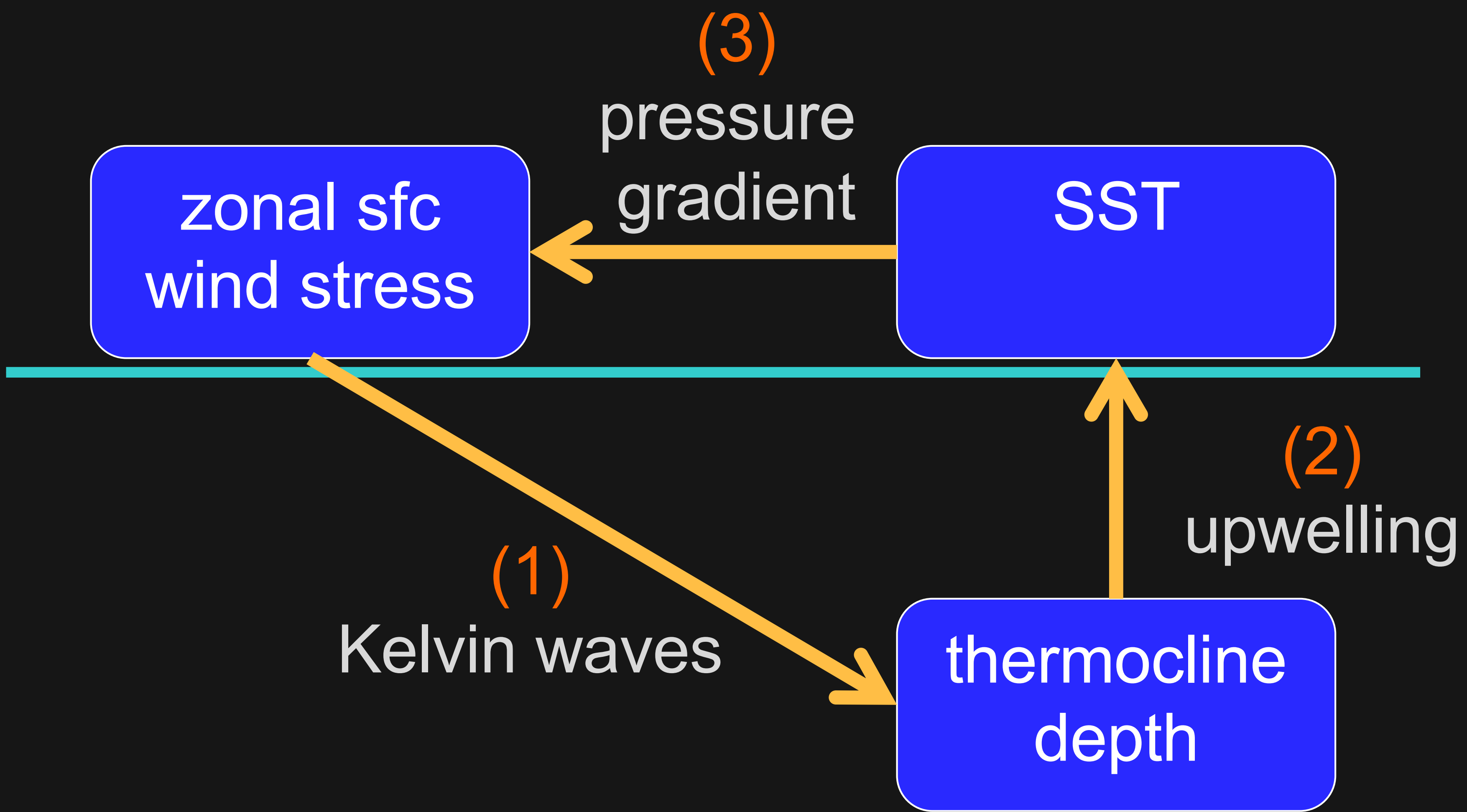



*provided by Hiroki Tokinaga; Kyushu University*

# Coupled air-sea feedbacks

Enter Bjerknes

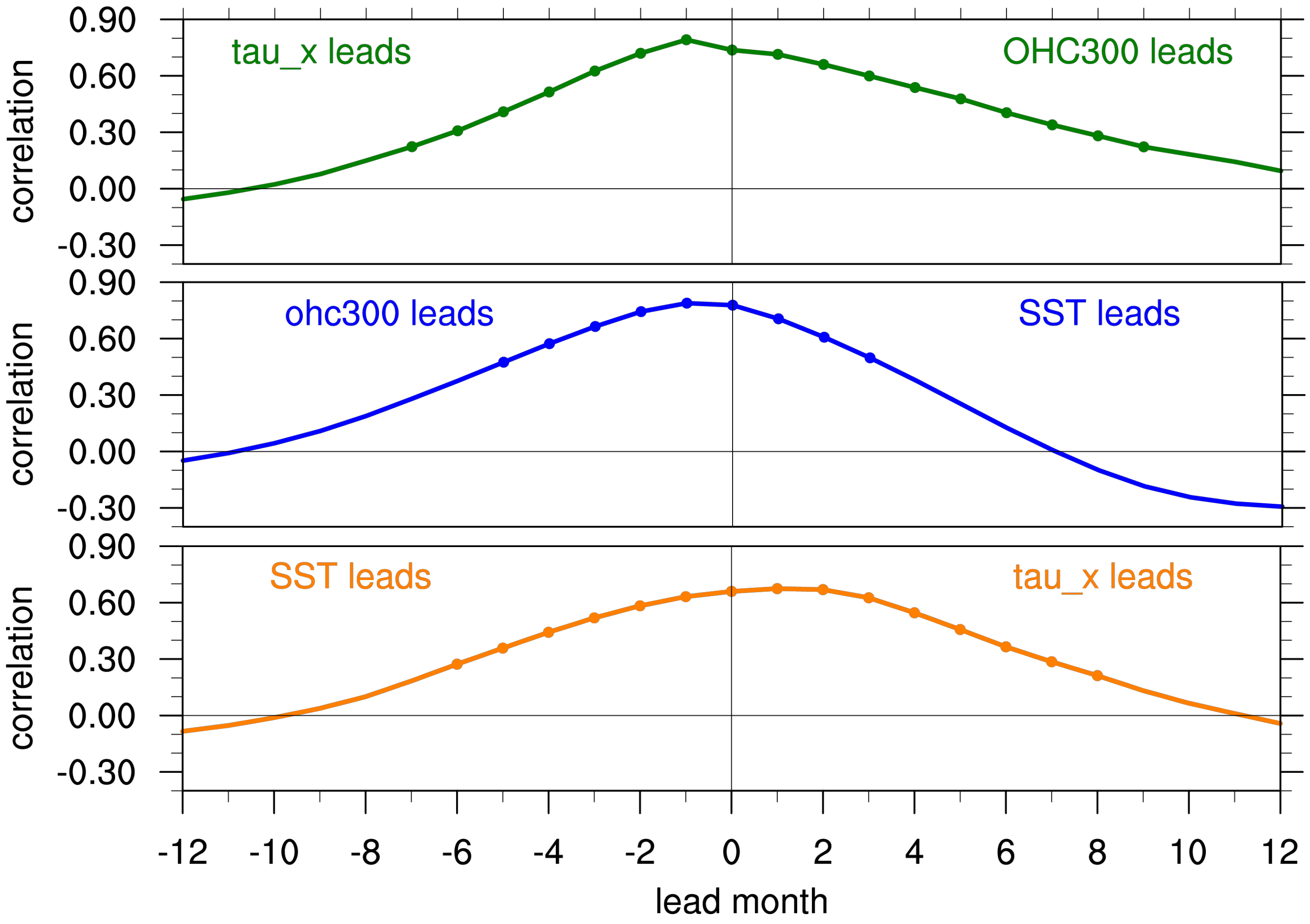
# Bjerknes Feedback



# The Bjerknes positive feedback loop

1) westerly wind stress in the western equatorial Pacific triggers Kelvin waves
2) thermocline deepens in the eastern equatorial Pacific
3) upwelling becomes less efficient in cooling eastern equatorial Pacific
4) SSTs warm in the east
5) zonal surface pressure gradient weakens
6) zonal wind stress weakens -> back to 1)

# Bjerknes feedback components



# Limitations of the Bjerknes feedback

- role of convection not fully explained
- eastern equatorial Pacific usually too cold to support deep convection
- can explain the growth of ENSO events, but what about the decay?

# Negative feedbacks

Where is the brake?

# What limits ENSO growth?

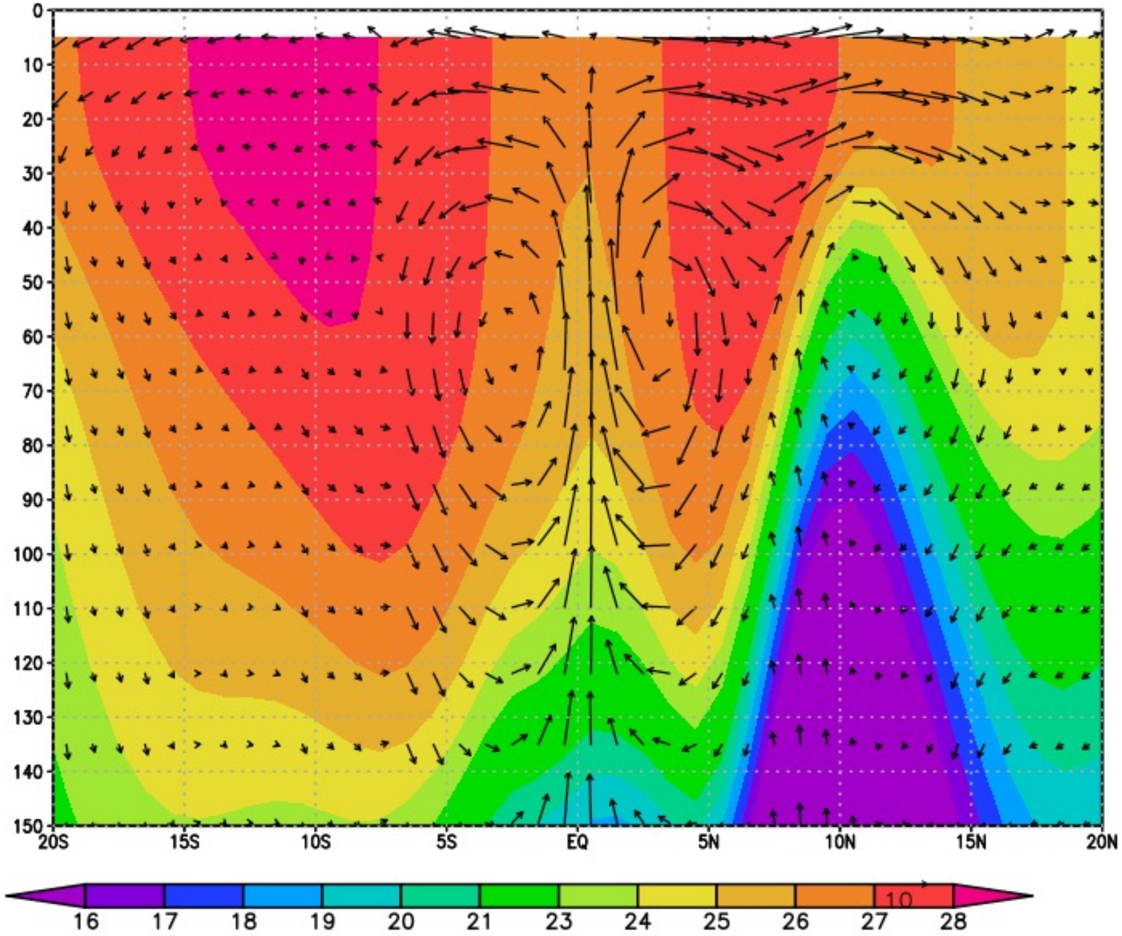
- surface heat flux damps SST anomalies
- equatorial Pacific is leaky
  - coastal Kelvin waves carry energy poleward at eastern boundary
  - mean upwelling continuously cools SST
  - mean divergence carries water poleward
  - wind stress curl leads to poleward Sverdrup transport (see recharge oscillator)
- destructive wave interference (see delayed oscillator)

# Damping through upwelling

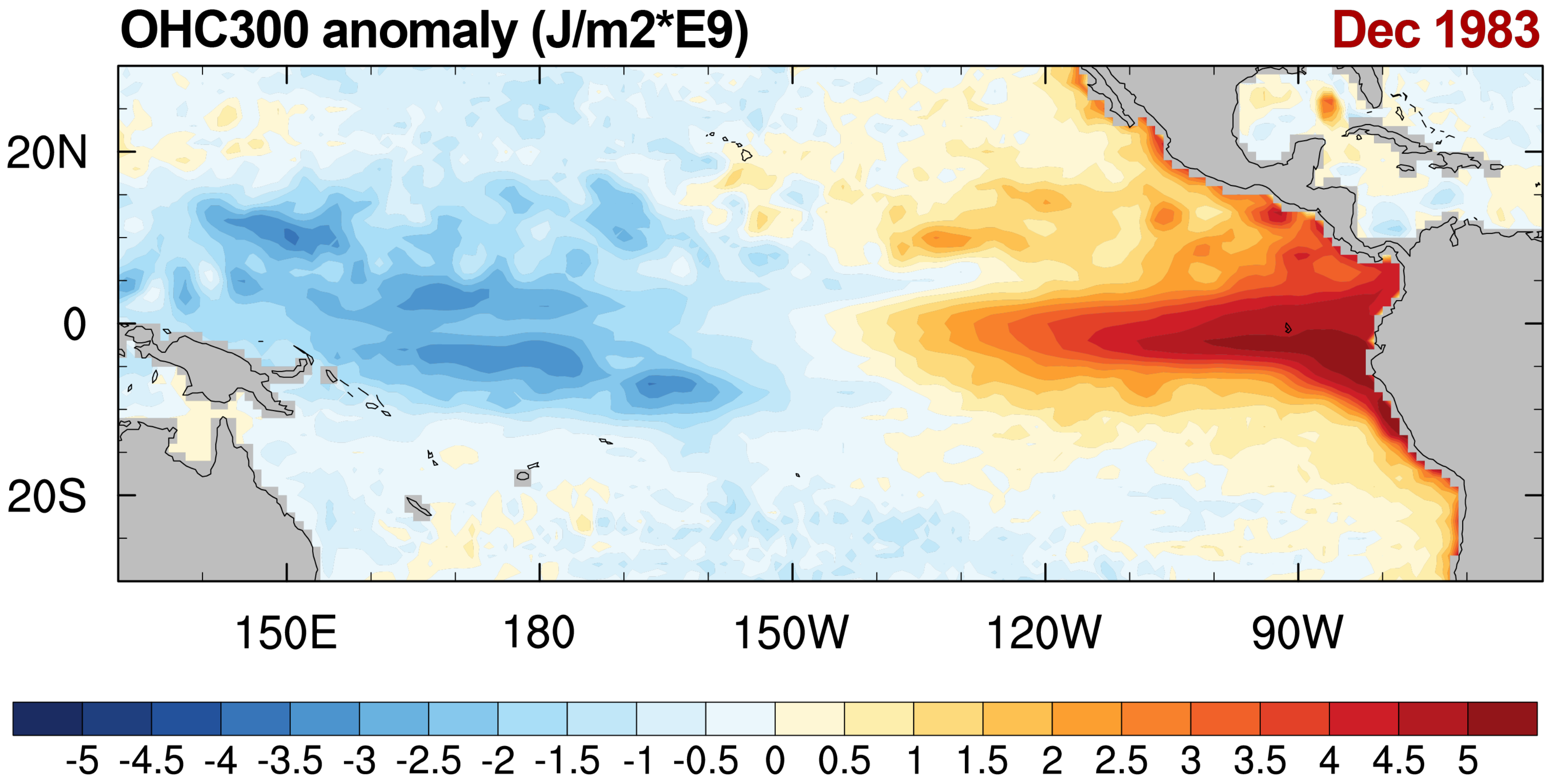
ORAS5 cliamatology in December

latitude-depth section, ave 180-120W

shd: ocean temperature; arrows: currents

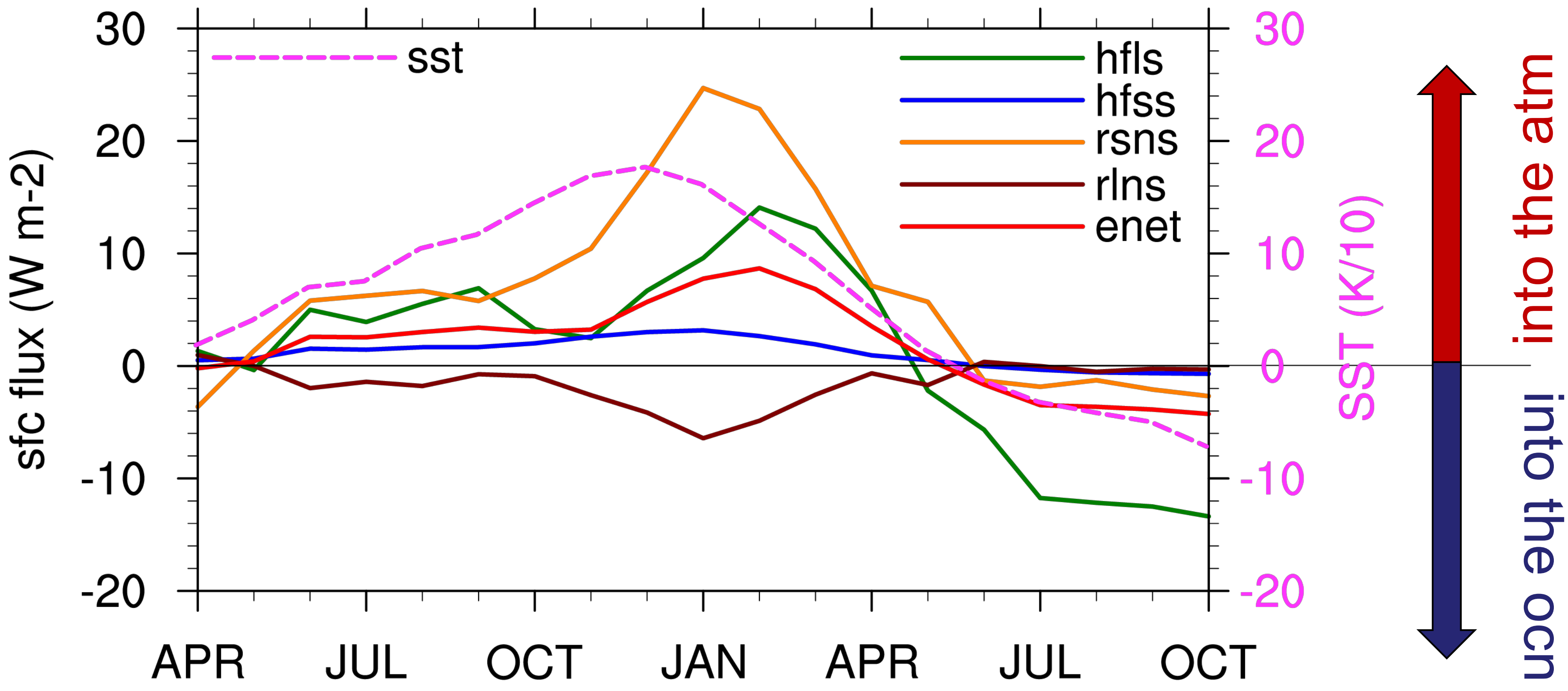


# Warm water leakage into the coastal waveguide



# Surface heat flux damping

El Niño composite from ERA5



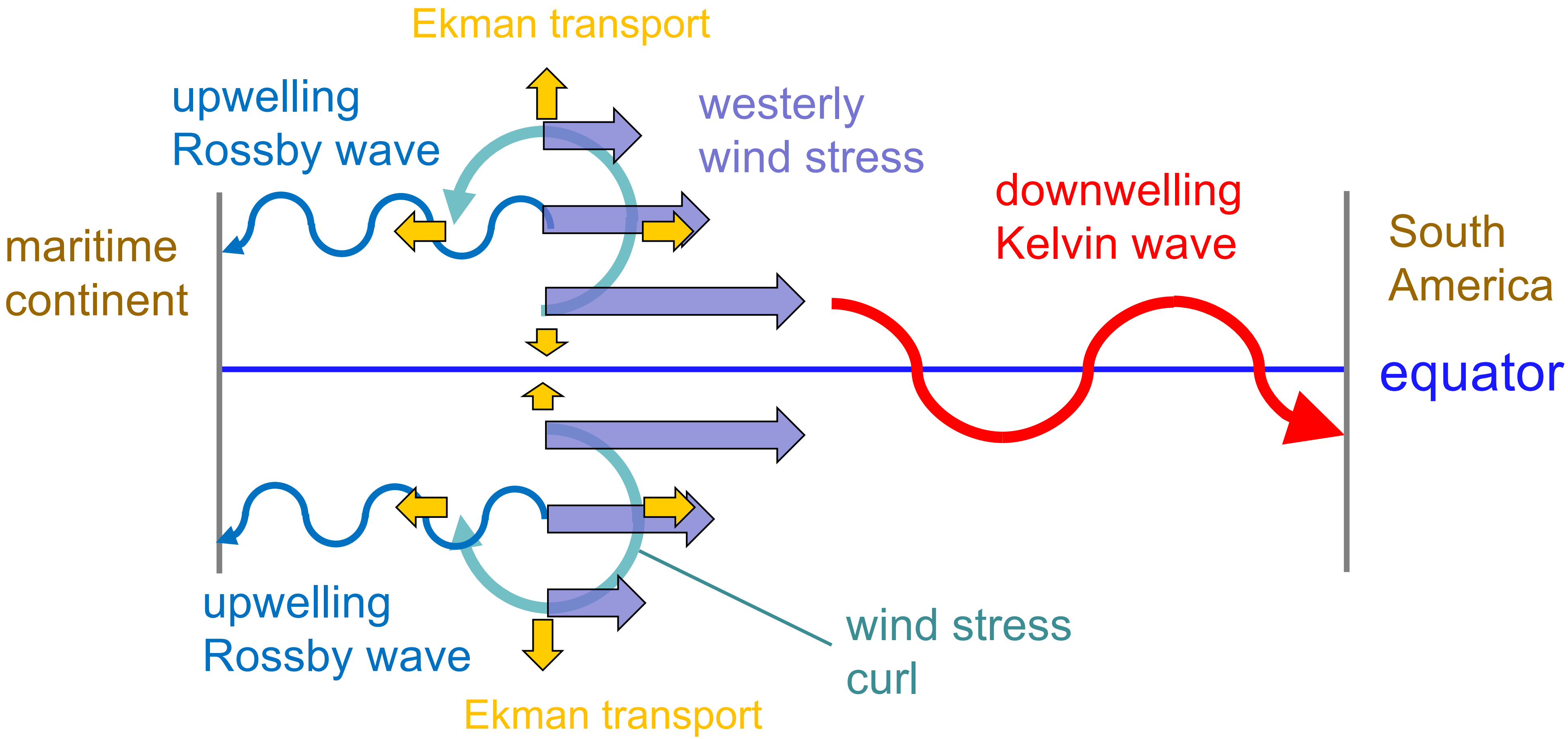
# The delayed oscillator

The revenge of the reflected Rossby wave

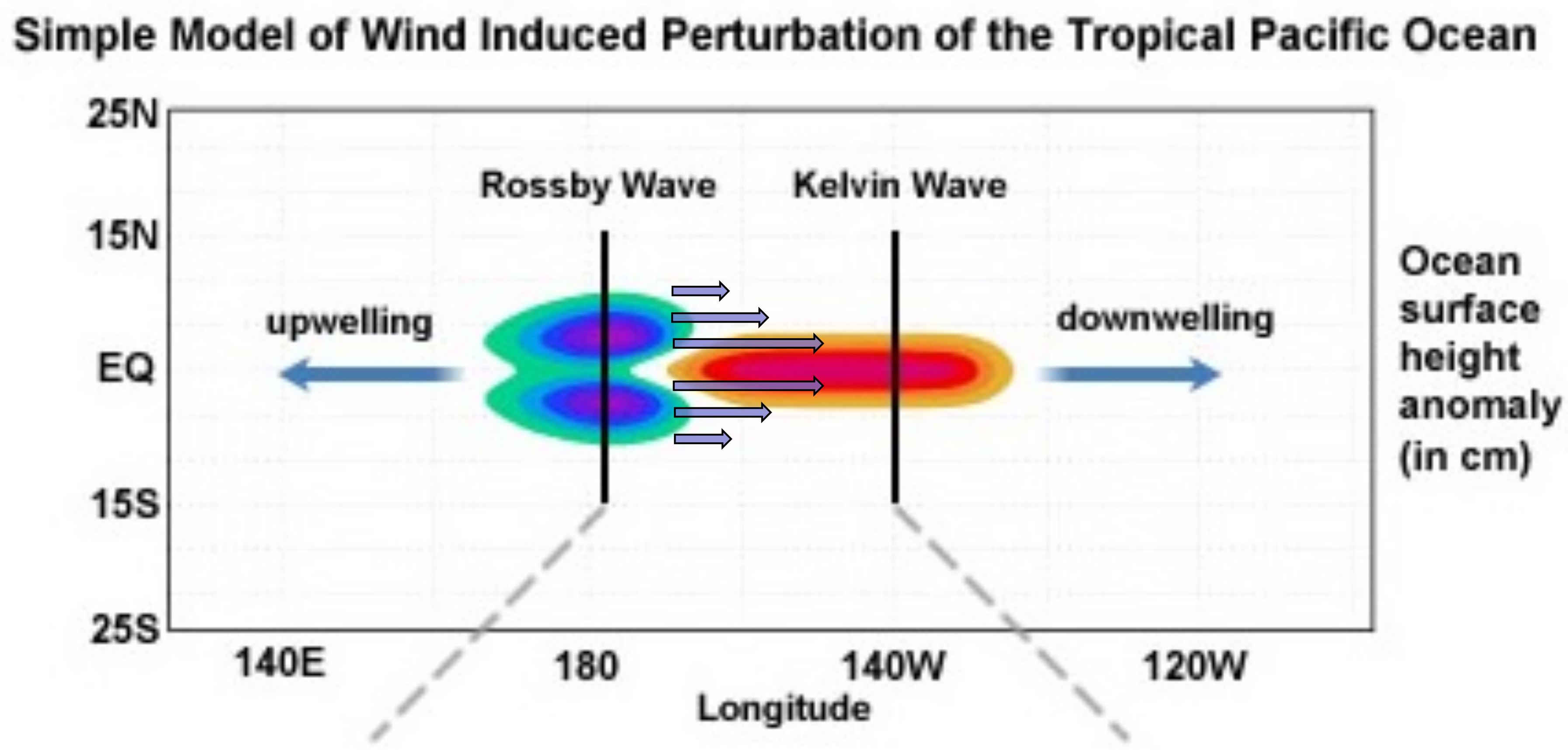
# The importance of wave dynamics

- westerly wind stress forcing over the western equatorial Pacific excites two kinds of ocean waves
  1) downwelling ("warm") Kelvin waves that travel eastward at ~ 2 m/s
  2) upwellling ("cold") Rossby waves that travel westward at ~ 0.6 m/s
- why downwelling Kelvin waves but upwelling Rossby waves?

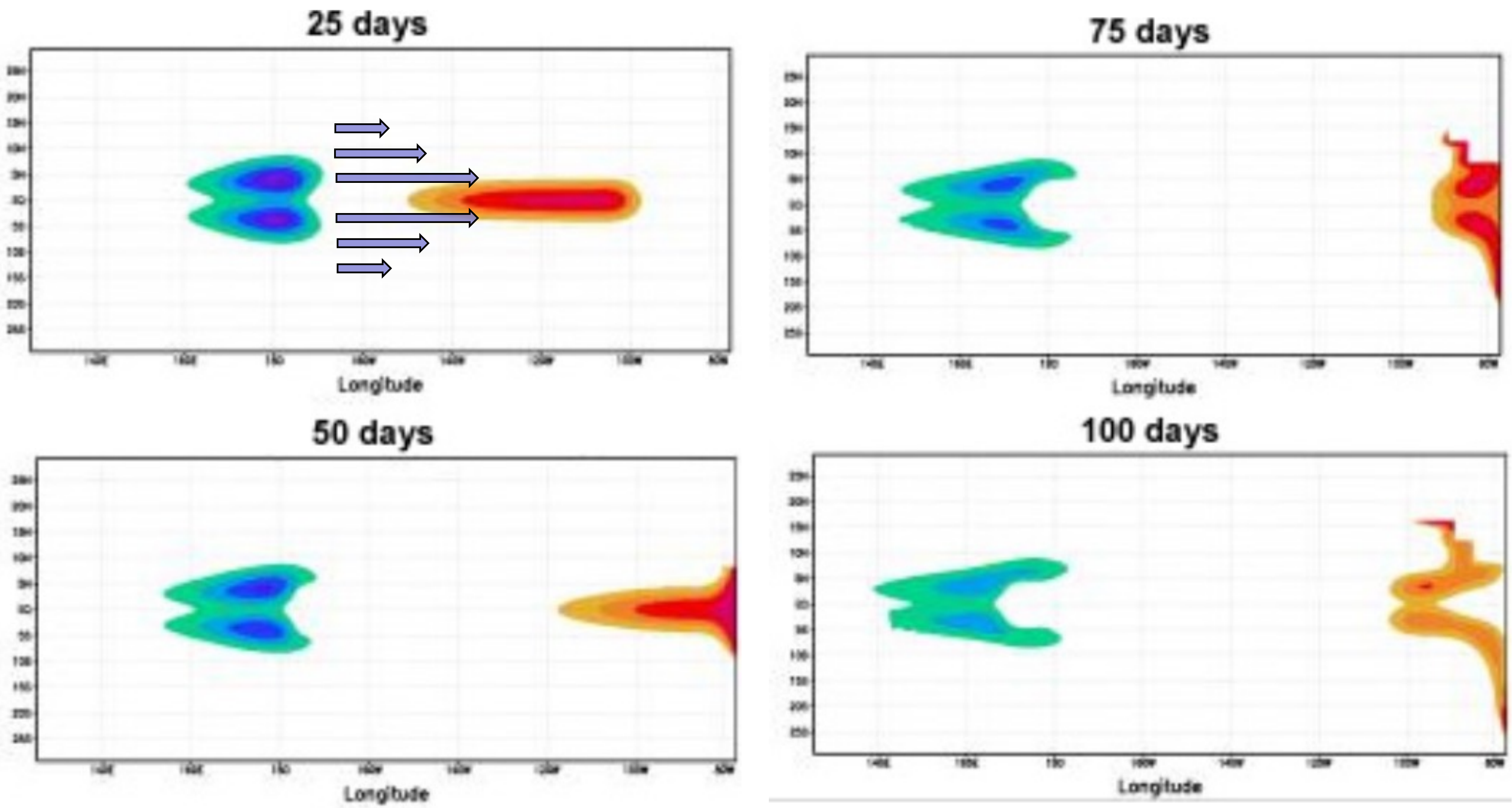
# The ocean response to the wind stress and its curl



# The delayed oscillator mechanism

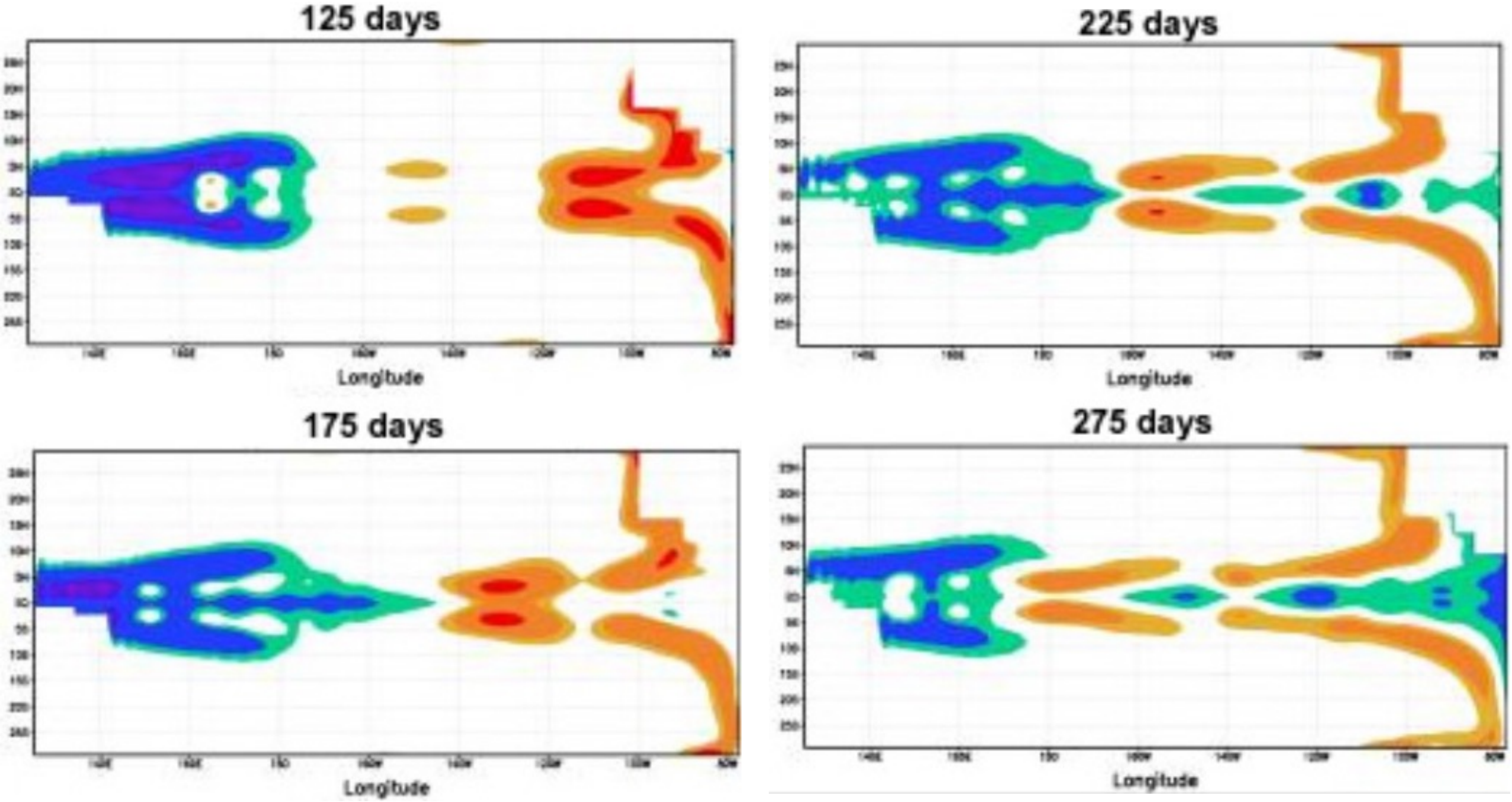


# The delayed oscillator mechanism




International Research Institute for Climate and Society

# The delayed oscillator mechanism



# Delayed oscillator summary

- westerly wind stress excites both downwelling Kelvin wave and upwelling Rossby wave
- Rossby wave travels more slowly
- eventually reflected into upwelling Kelvin wave
- travels to the eastern Pacific and terminates the event
- eventually leads to cold event -> phase reversal

# Limitations of the delayed oscillator

- produces very periodic behavior, unlike observed ENSO
- air-sea interaction in the western Pacific
- wave reflection at the eastern boundary not considered
- cannot explain phase locking

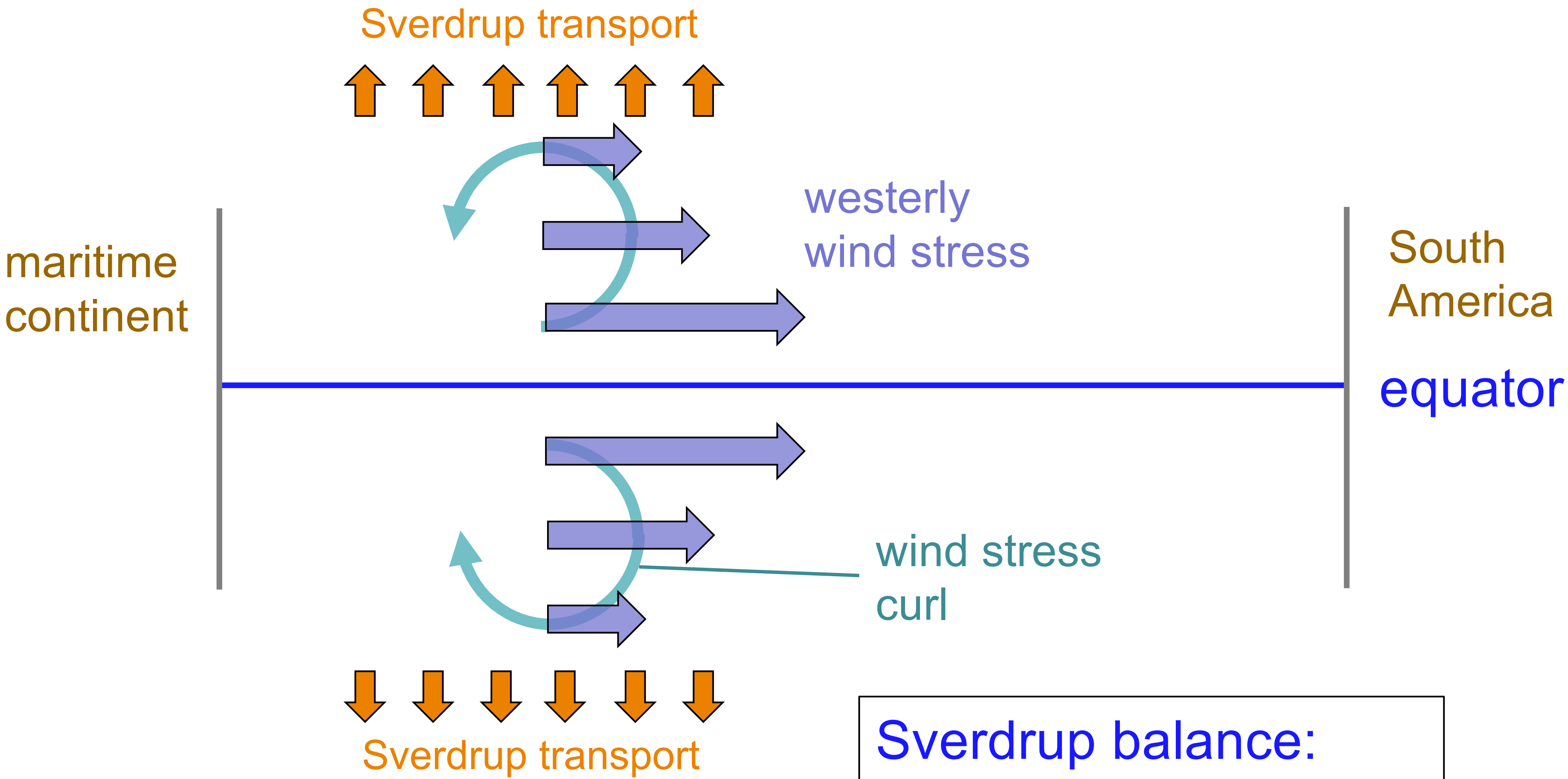
# The recharge oscillator

The importance of wind stress curl

# RO basic idea

- westerly wind anomaly has two effects
  - in-phase adjustment of the thermocline tilt: shoaling in the west, deepening in the east
    -> due to zonal wind stress
  - out-of-phase response of the equatorial heat content: poleward discharge of heat
    -> due to wind stress curl
- the second response proceeds slowly and ultimately leads to the demise of the event (and its phase reversal)

# Why does wind stress curl lead to poleward heat transport?



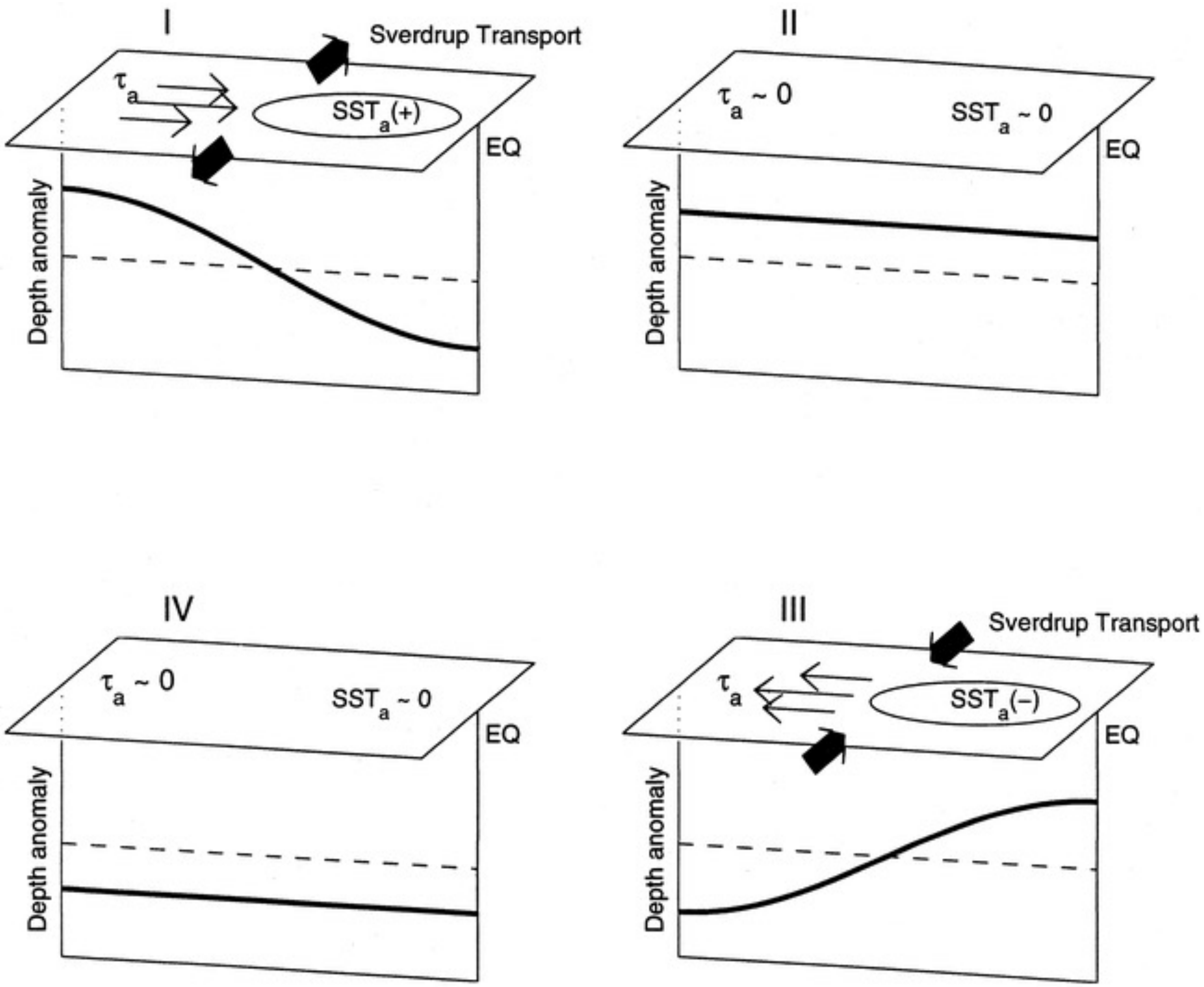

Sverdrup balance:

$$\beta V = curl(\tau)/\rho$$

$V$=depth integrated meridional current

# The RO mechanism

(from Meinen and McPhaden 2001)



# Limitations of RO

- cannot explain El Nino/La Niña asymmetry (same heat content anomaly leads to different amplitude in SST response)
- phase transition 4->1 not well supported by observations
- phase locking not explained

# Phase locking of ENSO

Why this fixation on Christmas?

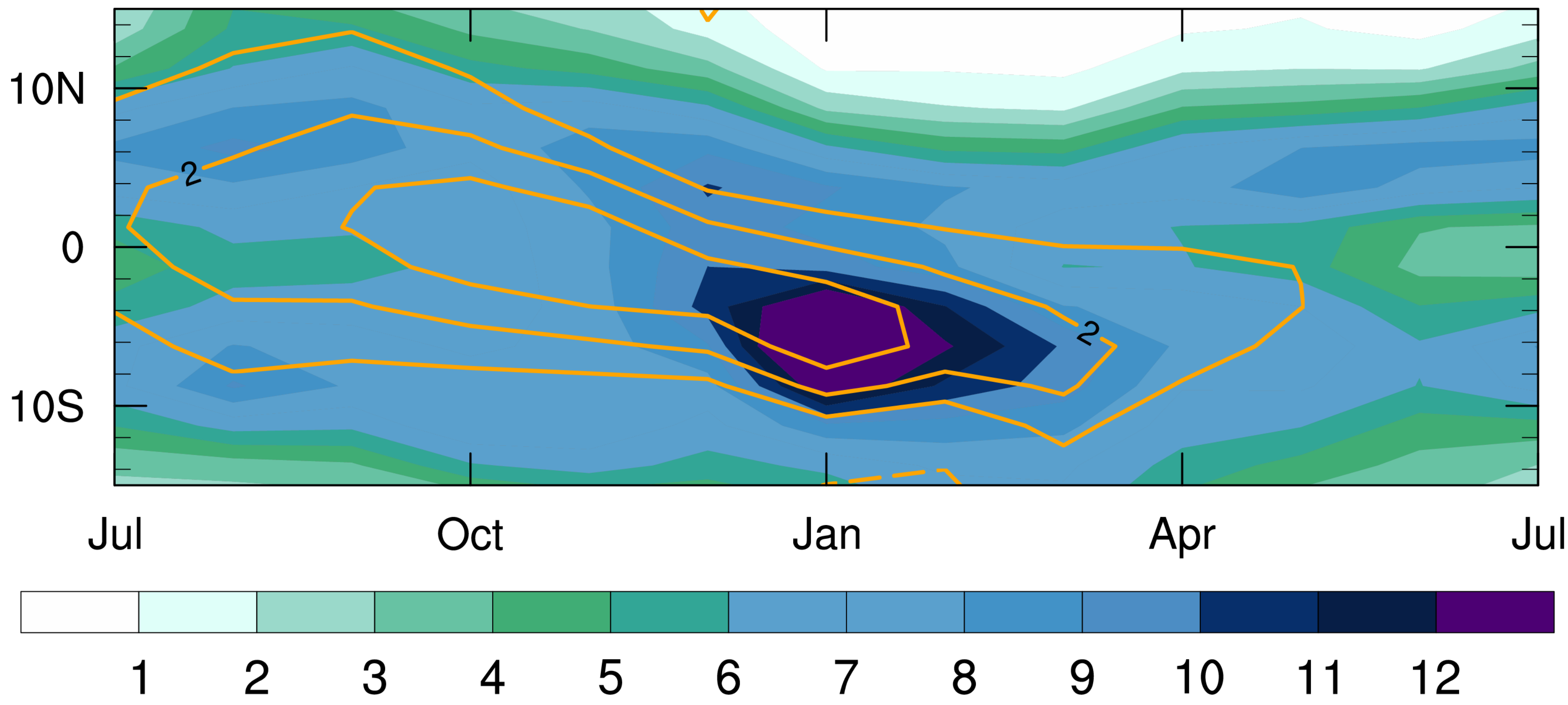
# Mechanisms for phase locking

- still an area of active research
- anomaly models not enough to explain seasonality of ENSO -> annual cycle of full fields must play a role
- two lines of thought
  - frequency entrainment: non-linear dynamics modulate ENSO variability (e.g., Chang et al. 1994, Tziperman et al. 1995)
  - mean state changes modulate the coupling strength (e.g., Harrison and Vecchi 1999, Lengaigne et al. 2006, McGregor et al. 2012)

# Composite lat-time section of El Niño

precip (shd; mm/d) and sfc zonal wind (cnt; m/s)

data: GPCP and ERA-Int; ave 160W-170E

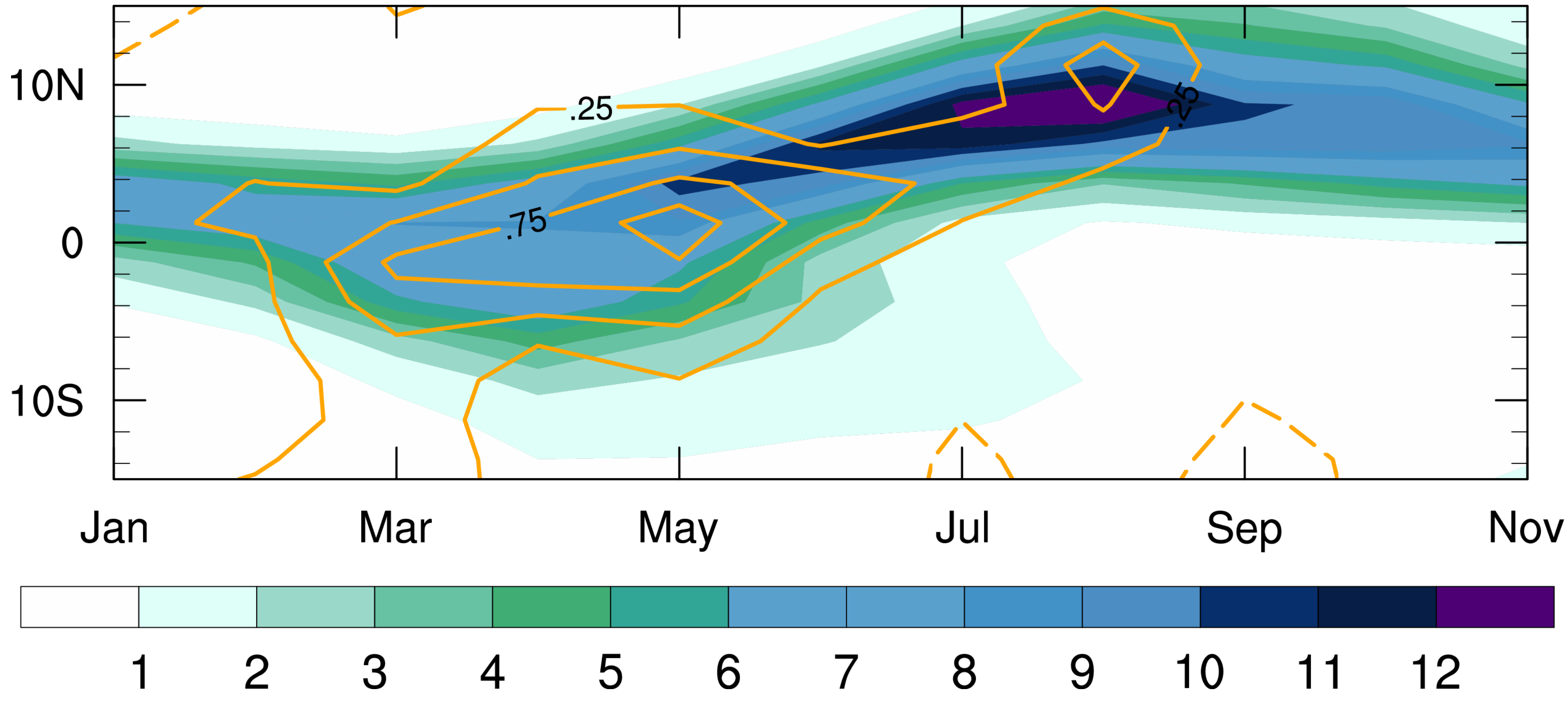



*adapted from Richter et al. (2017)*

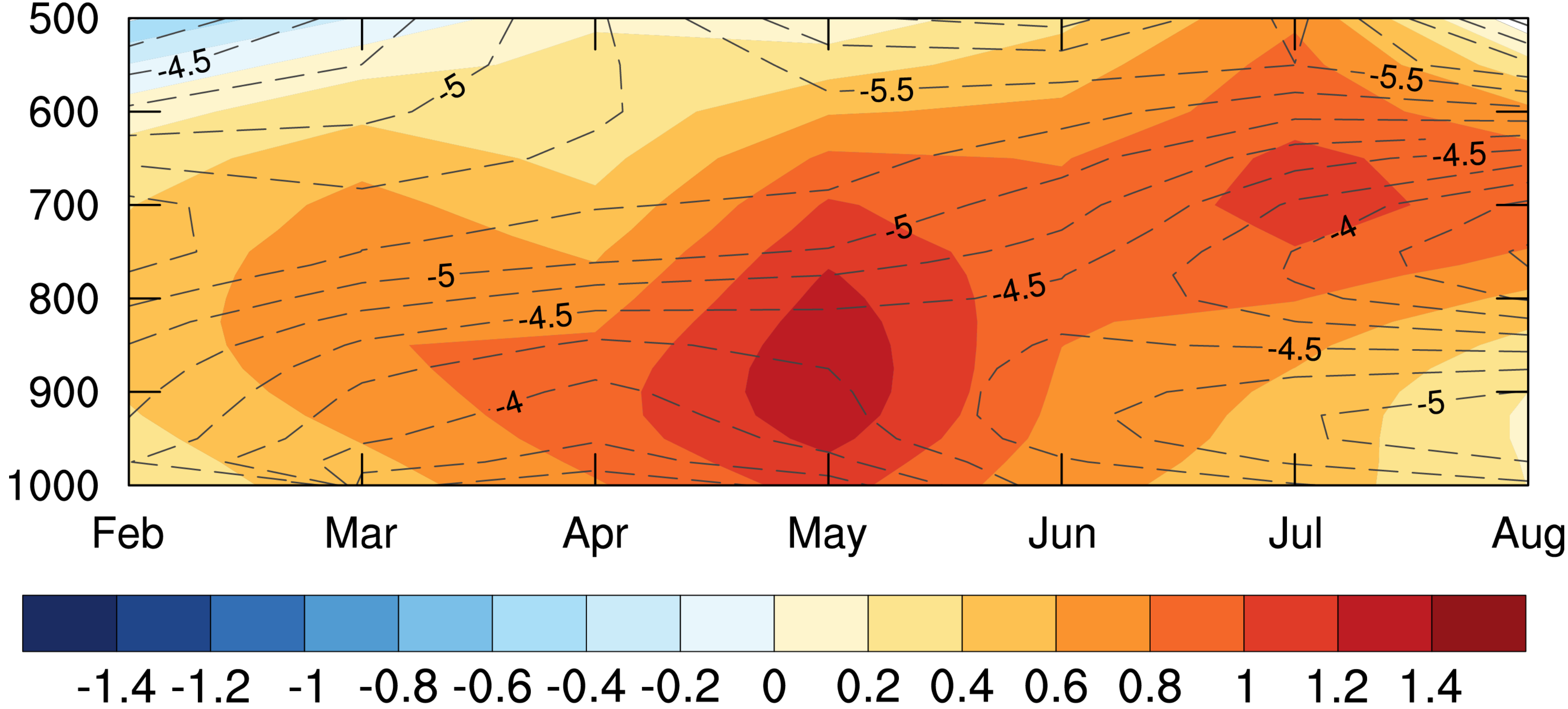
# Composite lat-time section of Atl Niño

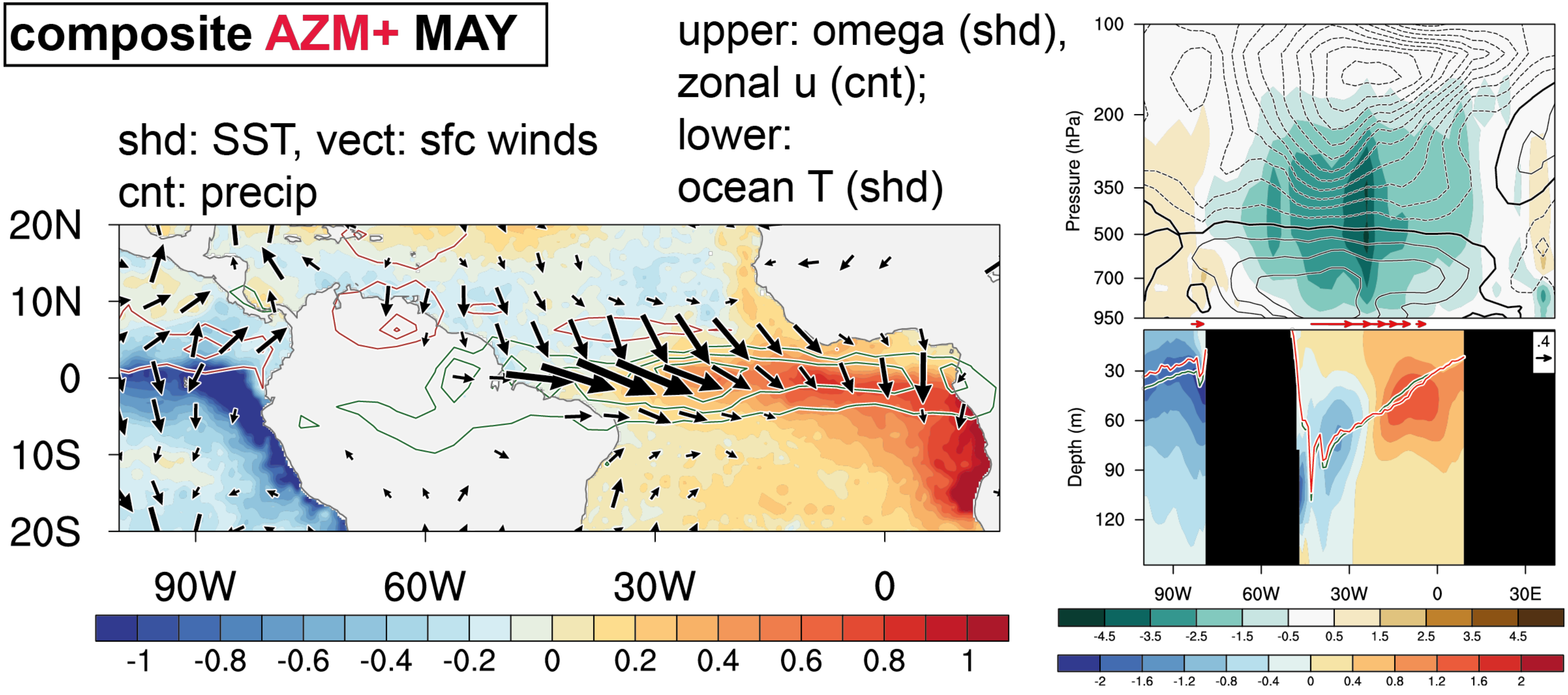
precip (shd; mm/d) and sfc zonal wind (cnt; m/s)

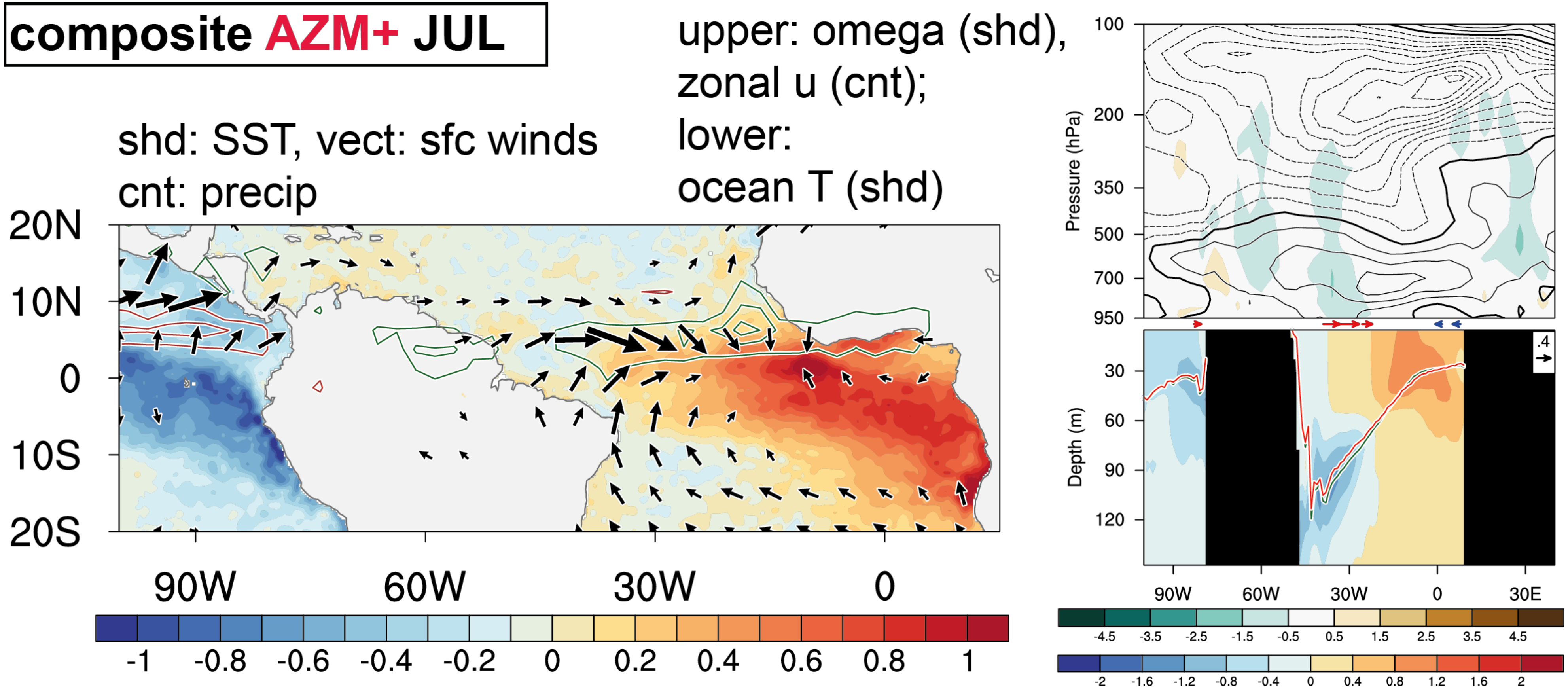
data: GPCP and ERA-Int; ave: 40-10W



# Composite time-height section
# 40-20W, 2S-2N




composite AZM+ MAY
shd: SST, vect: sfc winds
cnt: precip
upper: omega (shd),
zonal u (cnt);
lower:
ocean T (shd)
20N
10N
0
10S
20S
90W
60W
30W
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Pressure (hPa)
100
200
350
500
700
950
Depth (m)
30
60
90
120
.4
90W
60W
30W
0
30E
-4.5
-3.5
-2.5
-1.5
-0.5
0.5
1.5
2.5
3.5
4.5
-2
-1.6
-1.2
-0.8
-0.4
0
0.4
0.8
1.2
1.6
2


composite AZM+ JUL
shd: SST, vect: sfc winds
cnt: precip
upper: omega (shd),
zonal u (cnt);
lower:
ocean T (shd)
20N
10N
0
10S
20S
90W
60W
30W
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Pressure (hPa)
100
200
350
500
700
950
Depth (m)
30
60
90
120
.4
90W
60W
30W
0
30E
-4.5
-3.5
-2.5
-1.5
-0.5
0.5
1.5
2.5
3.5
4.5
-2
-1.6
-1.2
-0.8
-0.4
0
0.4
0.8
1.2
1.6
2

# ENSO diversity

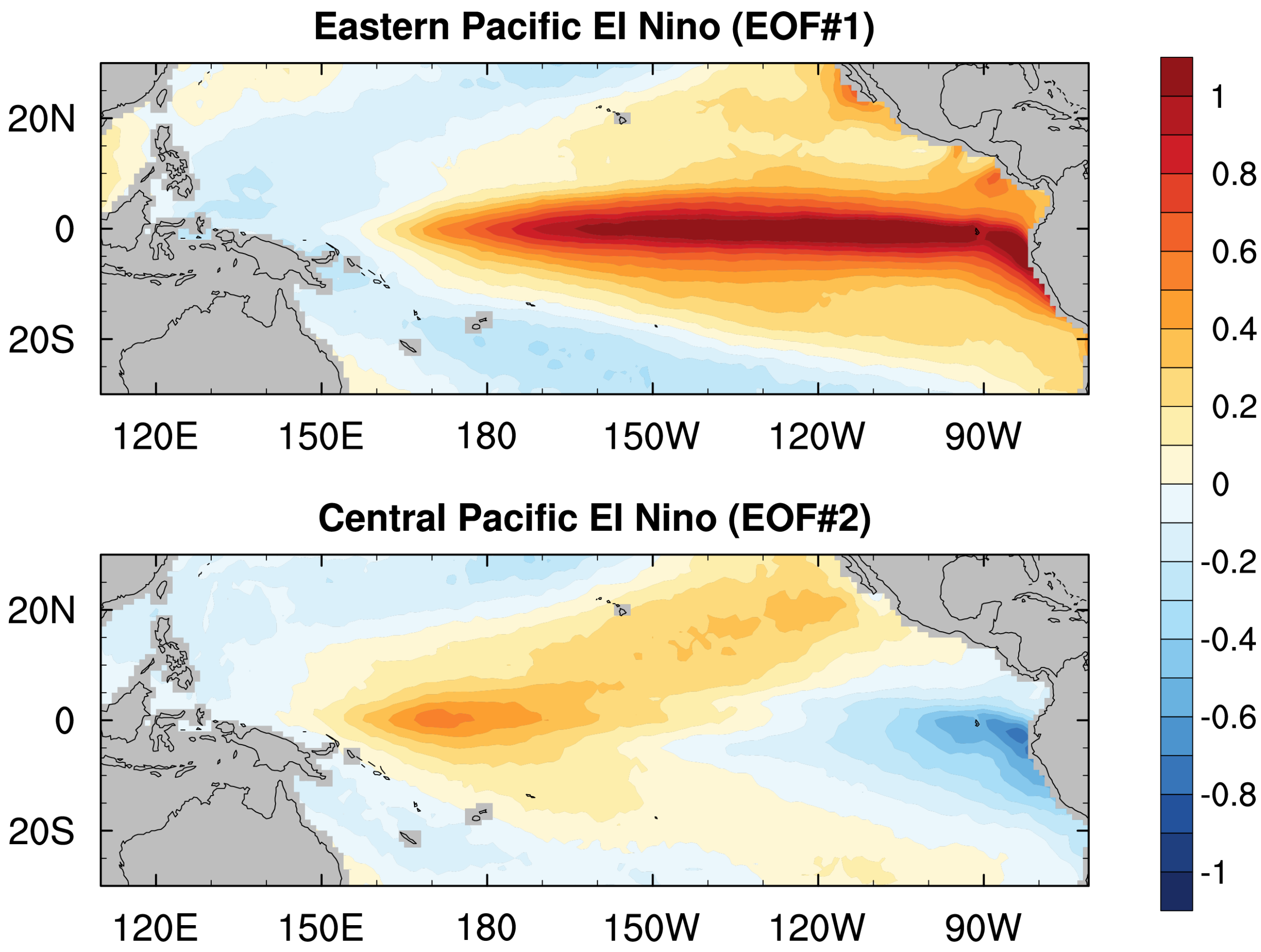
Dateline Niño demands equal rights

# A different type of El Niño (?)

- warming occurs further west, around the date line
- first noted by Larkin and Harrison (2005)
- different terminologies
  - date line Niño (Larkin and Harrison 2005)
  - El Niño Modoki (pseudo Niño; Ashok et al. 2007)
  - warm pool Niño (Kug et al. 2009) -> WP vs. CT
  - central Pacific Niño (Kao and Yu 2009) -> CP vs. EP
- Modoki terminology suggests a phenomenon whose outward appearance is that of ENSO, but whose mechanisms are different
- still an open question to what extent this holds true
- is ENSO “on a spectrum”? (e.g. Takahashi et al. 2010)

# EP vs. CP El Niño

## EOFs #1 and #2 of tropical Pacific SST (ERA5)



# Central Pacific Niño characteristics

- thermocline tilt does not change much
- heat content recharge/discharge plays less of a role -> more difficult to predict
- little shift in convection
- zonal advective feedback more important
- may have become more prevalent after 2000
- may have different teleconnections

# ENSO precursors

## Outside influences

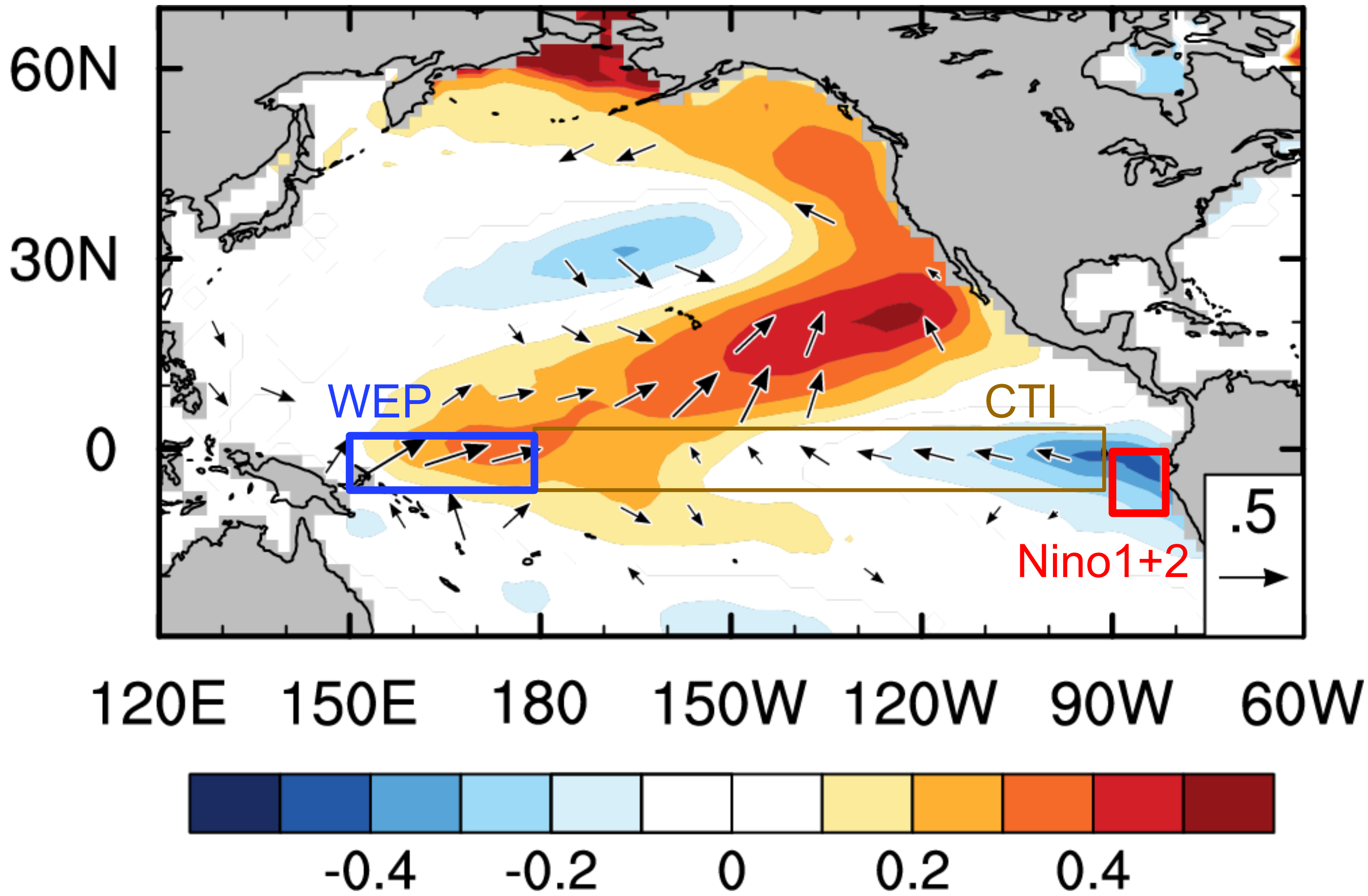
# Precursors

- may enable to extend skillful ENSO predictions, particularly across the spring predictability barrier
- two examples
  - the Atlantic zonal mode (aka Atlantic Niño) peaks in JJA and <u>may</u> trigger an ENSO event of the opposite sign 6 months later
  - the North Pacific Meridional Mode may trigger ENSO events

# The PMM pattern

Regression of PMM index on SST, u10, v10

CTI removed



# Considerations

- PMM develops in boreal winter and may trigger development of El Niño, particularly the CP type
  however, high lag-0 correlation of PMM with CP ENSO -> usefulness as predictor (Stuecker 2018; Richter et al. 2022)
- importance of tropical Atlantic influences on ENSO still under debate

# Simulation of ENSO by climate models

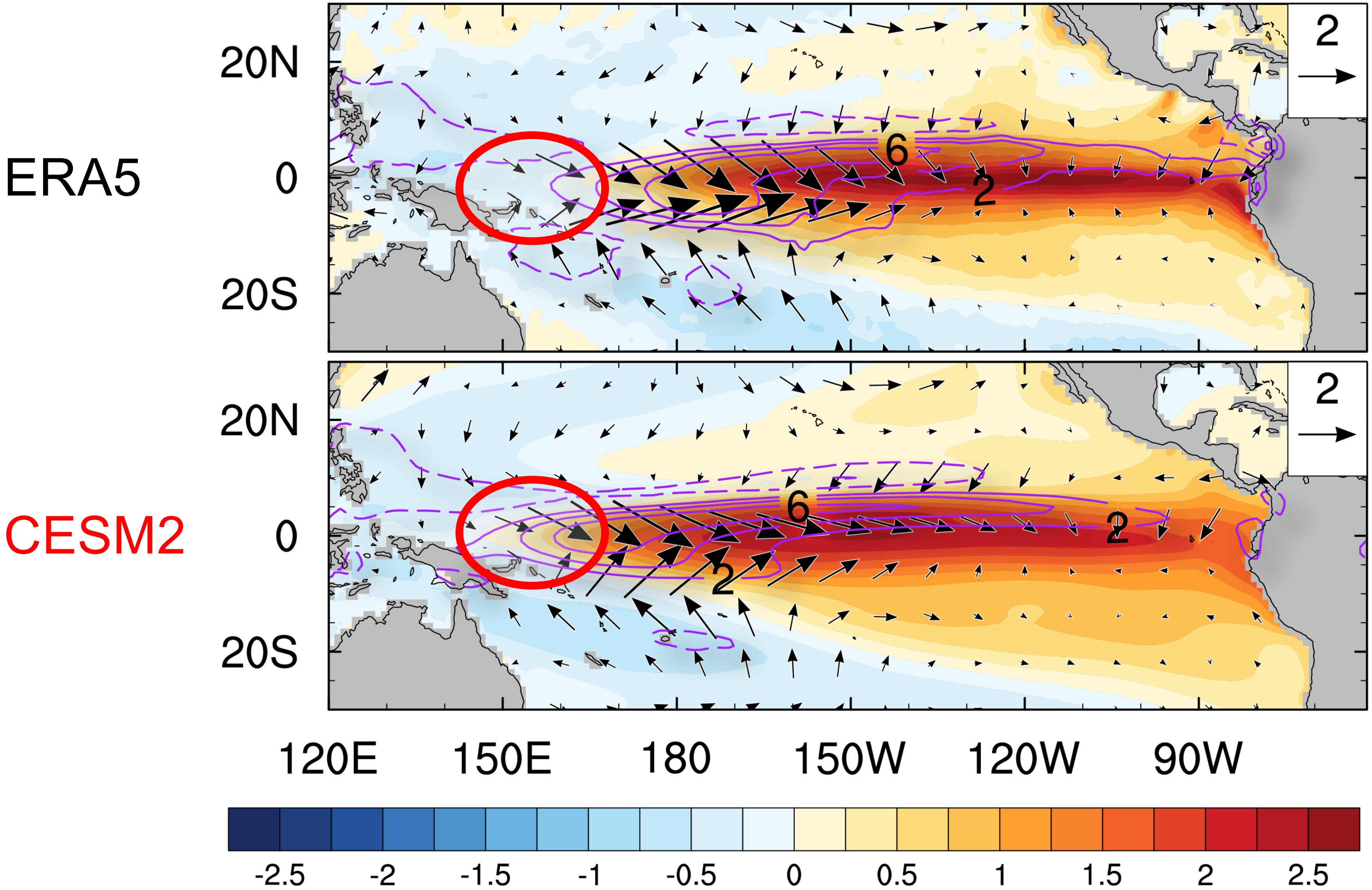
How good is good enough?

# How well do global climate models simulate ENSO?

- overall quite realistically…

# Can you spot the ”fake”?

NDJ composite; SST (shd), wind (arrows), precip (cnt)

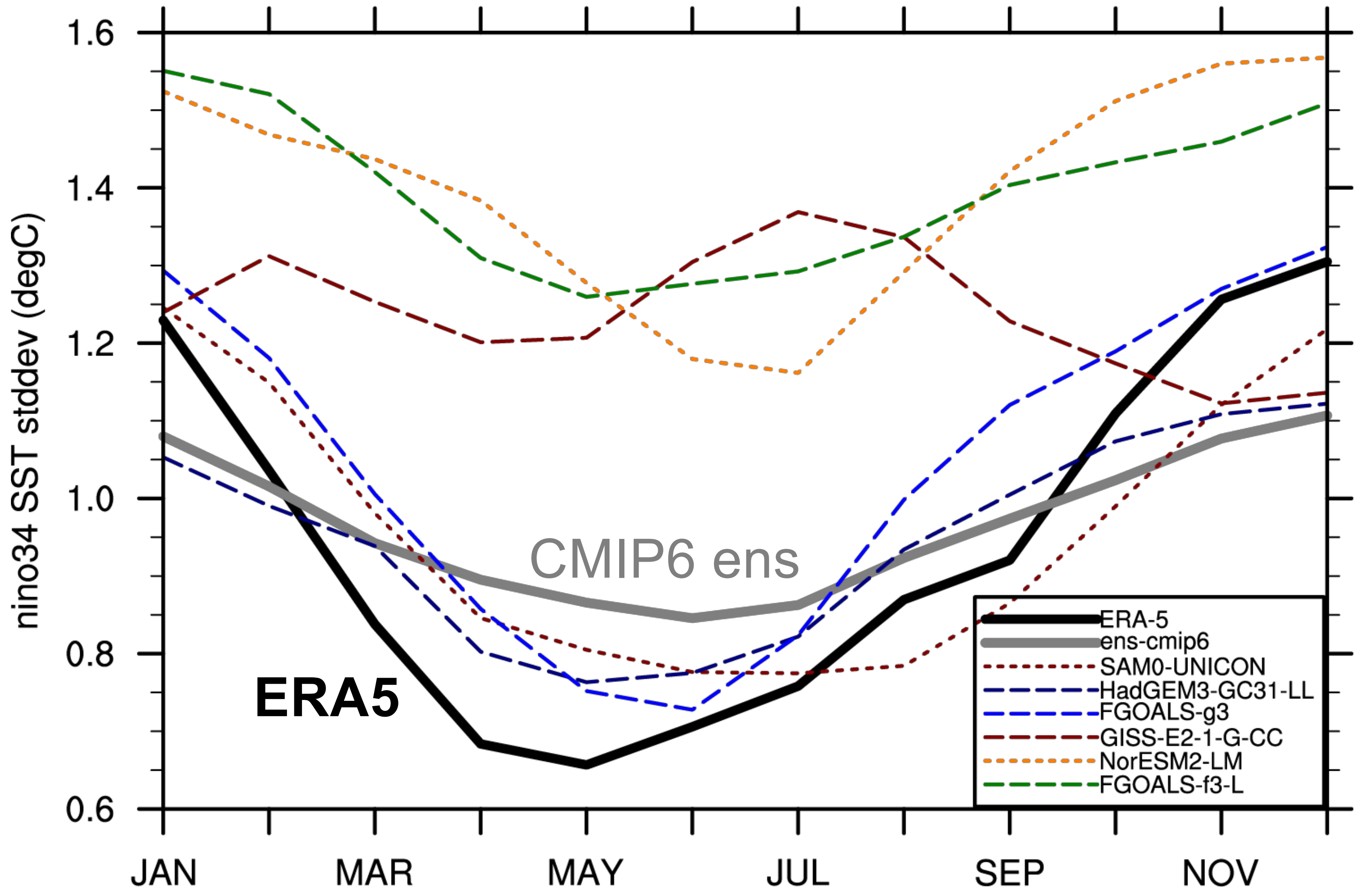


# How well do global climate models simulate ENSO?

- overall quite realistically
- some common problems
  - SST pattern extends too far west
  - weak phase locking

# Phase locking

## stddev of Niño 3.4 SST



# How well do global climate models simulate ENSO?

- overall quite realistically
- some common problems
  - SST pattern extends too far west
  - weak phase locking
  - low-frequency variability too weak
  - ENSO asymmetry not well represented

# Final remarks

- understanding of ENSO has advanced considerably since the 1980s
- some open questions remain, such as phase locking mechanism, and the role of influences from outside the tropical Pacific
- climate models have also improved considerably, and are useful tools for improving our understanding