# Causes for intense interannual upwelling events in the tropical Indian Ocean

*Weiqing Han*
*(ATOC, the University of Colorado at Boulder)*

*Zhang, X. and W. Han, 2019: J. Clim., accepted with minor changes*

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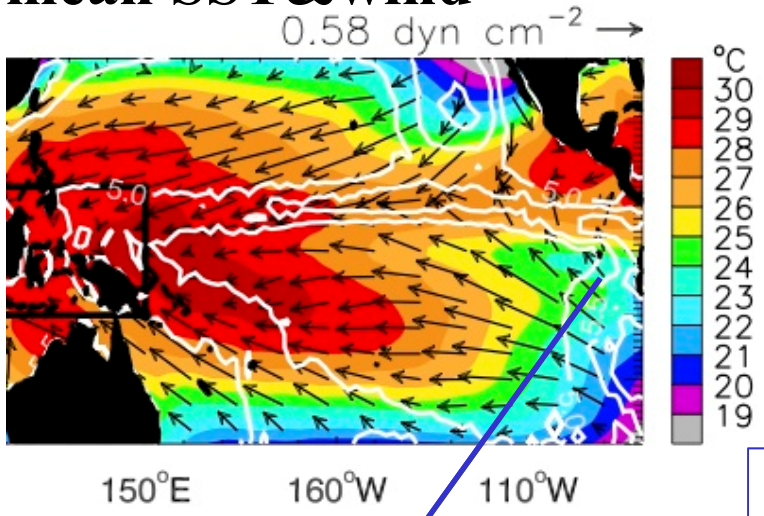
# 1. Background

**The tropical Pacific (&Atlantic):**

**mean SST&wind**

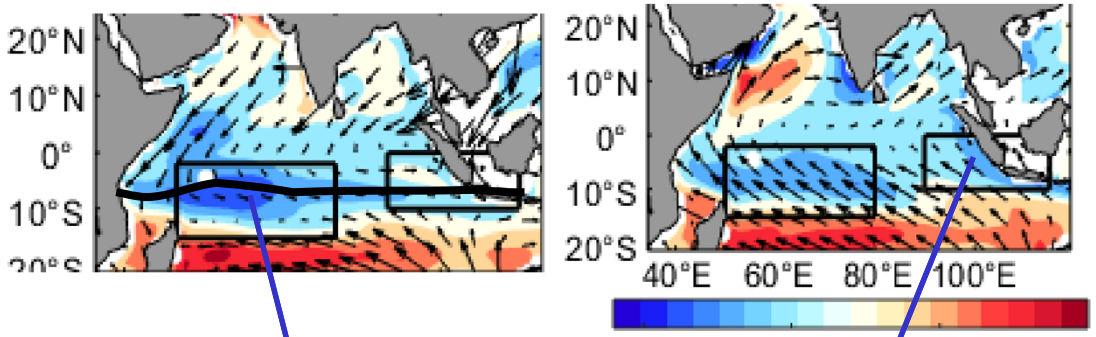



**Mean upwelling zone: eastern EQ**

**1993-2016 mean**

**a) Winter monsoon & D20**

**b) Summer-fall**




***a) Seychelles-Chagos Thermocline Ridge – mean upwelling zone in West Indian Ocean (WIO)***

***b) East Indian Ocean (EIO), Java and Sumatra – seasonal coastal upwelling: boreal summer- fall***

Ekman pumping velocity:

$$w_e = \frac{\partial}{\partial x}\left(\frac{\tau^y}{\rho f}\right) - \frac{\partial}{\partial y}\left(\frac{\tau^x}{\rho f}\right)$$

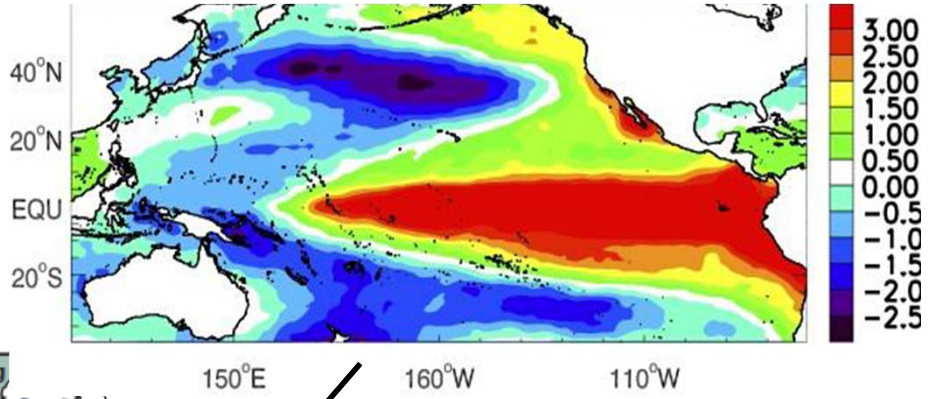
# The boreal summer-fall seasonal upwelling amplify: during positive IOD & El Nino years

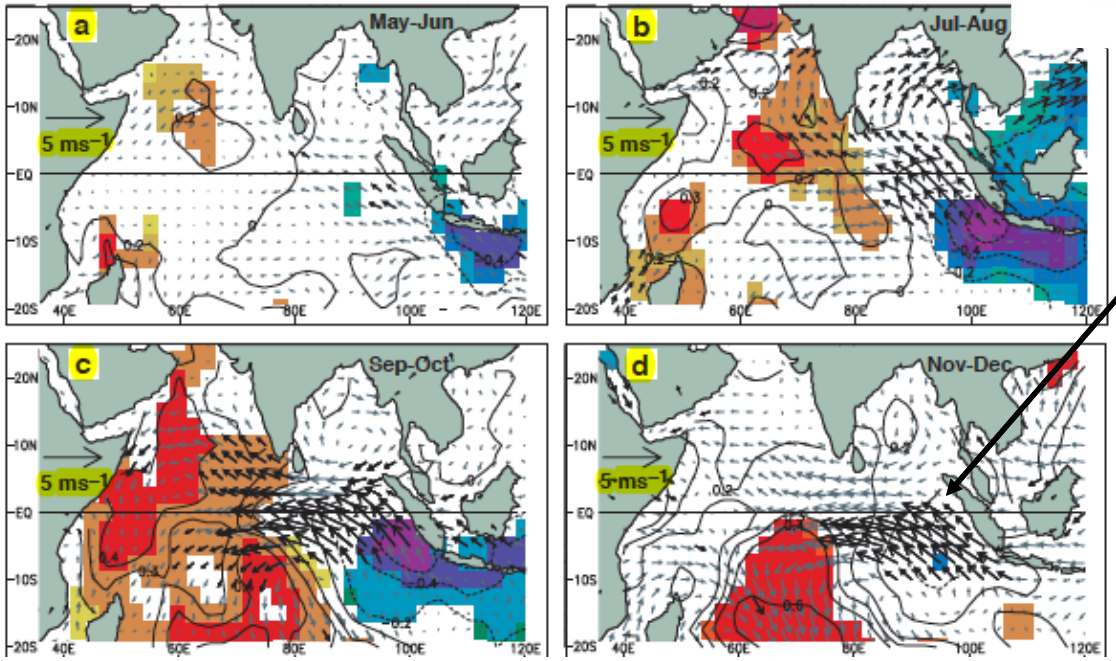
**El Nino**

**SST anomaly (SSTA)**

**Positive Indian Ocean Dipole (IOD)**

***Max: SON***




Saji et al. (1999)

# Importance of upwelling

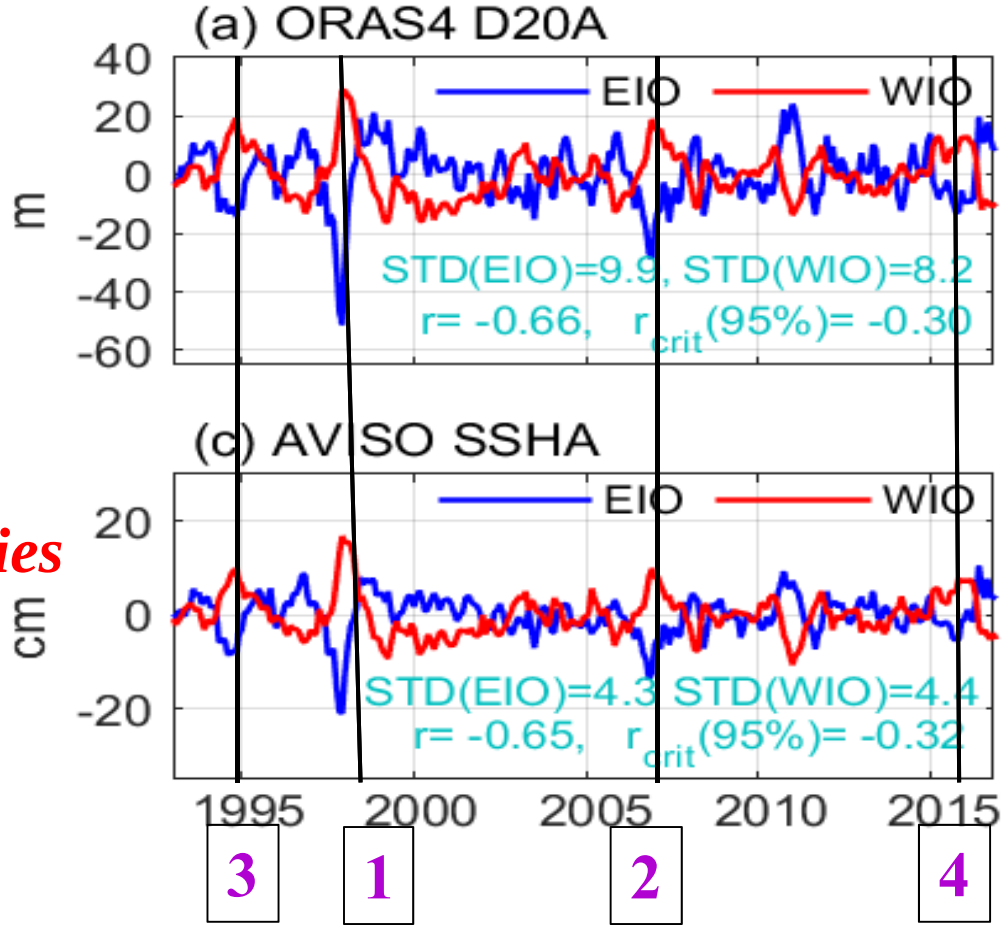
1) **Biological activities & fishery (http://www.fao.org);**
2) **Indicator of upwelling: Sea level change:**

Baroclinic response to wind forcing dominates tropical ocean:

***Upwelling: shallow thermocline (D20) & sea level fall,***
***sea level anomalies (SLAs) mirror thermocline anomaly (D20A)***

***WIO: Seychells-Chagos islands***
***(mean sea level: 0m)***
**Tide gauges: ~0.3m**

***EIO: Sumatra & Java coasts***
***directly affect coastal communities***
***& island nations***



## Questions:

1) **Why are the WIO and EIO upwelling anomalies (SLA&D20A) out of phase?**
2) **Why are the upwellings so strong in the EIO during 1997-98, 2006-07, 1994-95 & 2015-16?**

## 2. Approach

### (a) Bayesian Dynamical Linear Model (DLM):

$$SLA(t) = b_0(t) + b_1(t) * ENSO(IOD) + \varepsilon(t), \quad (1)$$

$$b_i(t) = b_i(t-1) + w_i(t), \quad (2)$$

where $\varepsilon(t) \sim N(0, V(t))$, $w_i(t) \sim N(0, W_i(t))$.

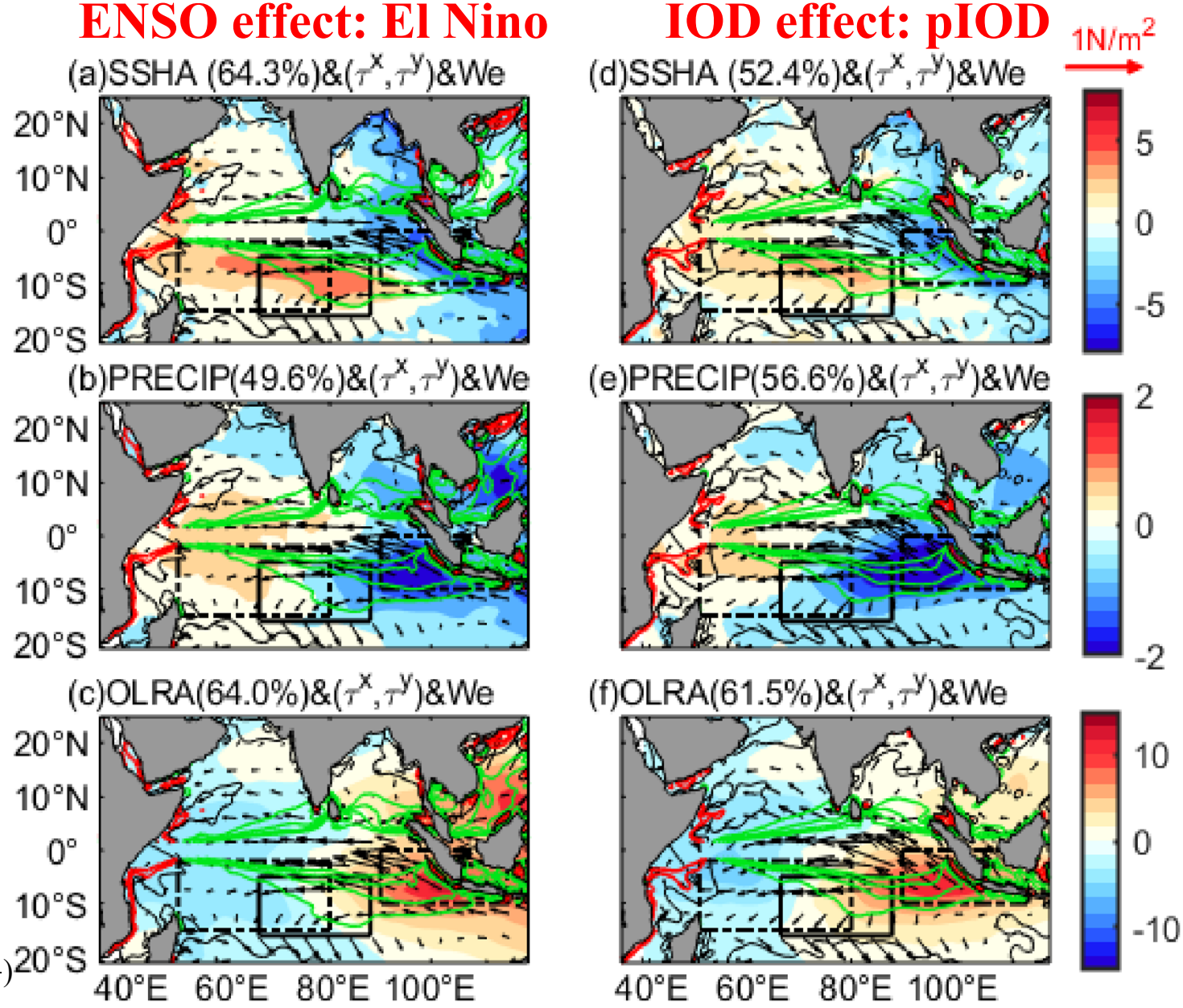
### (b) Wind-driven, linear continuously stratified ocean model (LOM):

***Main Run (MR*: complete solution/obs)**

***DAMP Run:* *absorbs* EQ &Coastal Kelvin waves**

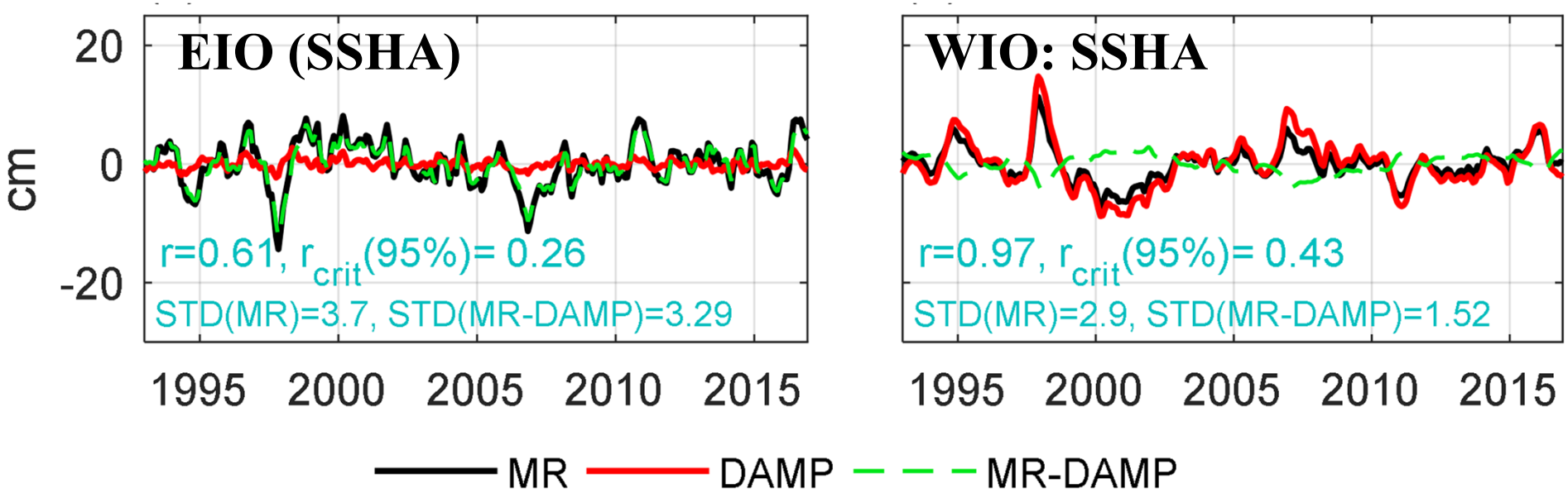
# 3. Results: Bayesian DLM

**ENSO effect: El Nino** **IOD effect: pIOD**




$$w_e = \frac{\partial}{\partial x}\left(\frac{\tau^y}{\rho f}\right) - \frac{\partial}{\partial y}\left(\frac{\tau^x}{\rho f}\right)$$

# Results: Wind-driven LOM



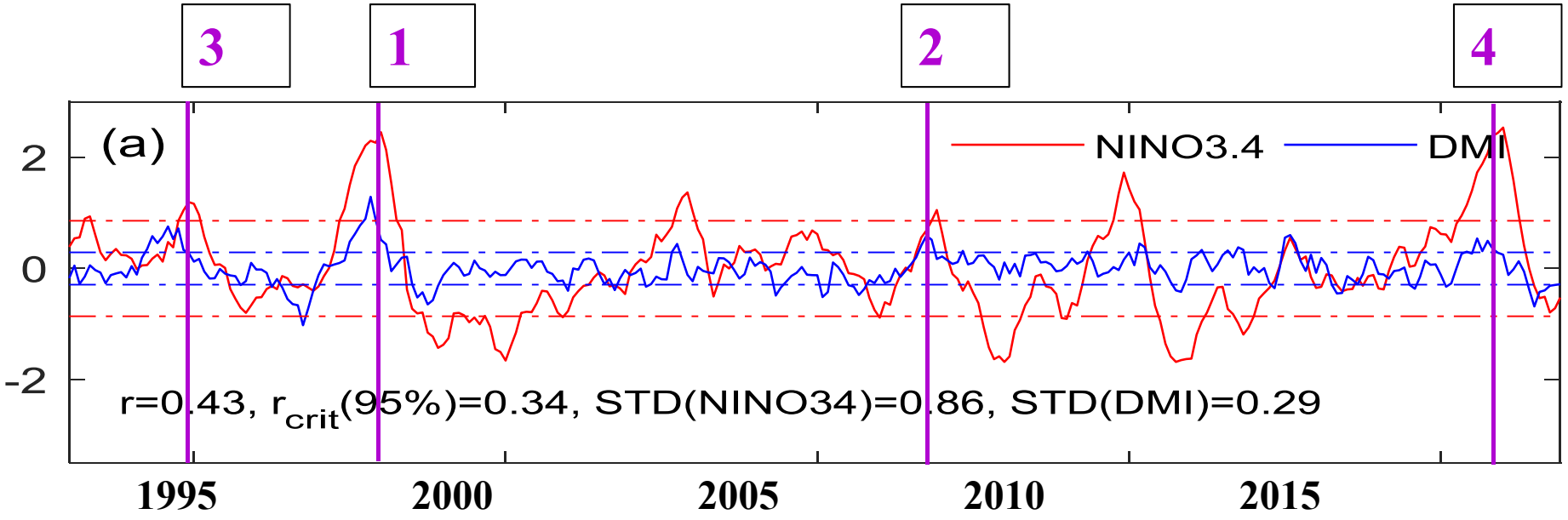

**1) Why are the WIO and EIO upwelling anomalies (SLA&D20A) out of phase?**

*Easterly wind anomalies associated with El Nino & pIOD drive EIO upwelling via exciting EQ & coastal KWs; downward Ekman pumping velocities associated with wind stress curls force downwelling Rossby Waves propagating westward, reducing the mean upwelling in WIO (Seychelles- Chagos).*

# Q2: Why are the upwellings so strong (weak) in the EIO (WIO) during 1997-98, 2006-07, 1994-95 & 2015-16?

## El Nino + pIOD co-occur!

**NINO3.4 index & Dipole Mode Index (DMI)**



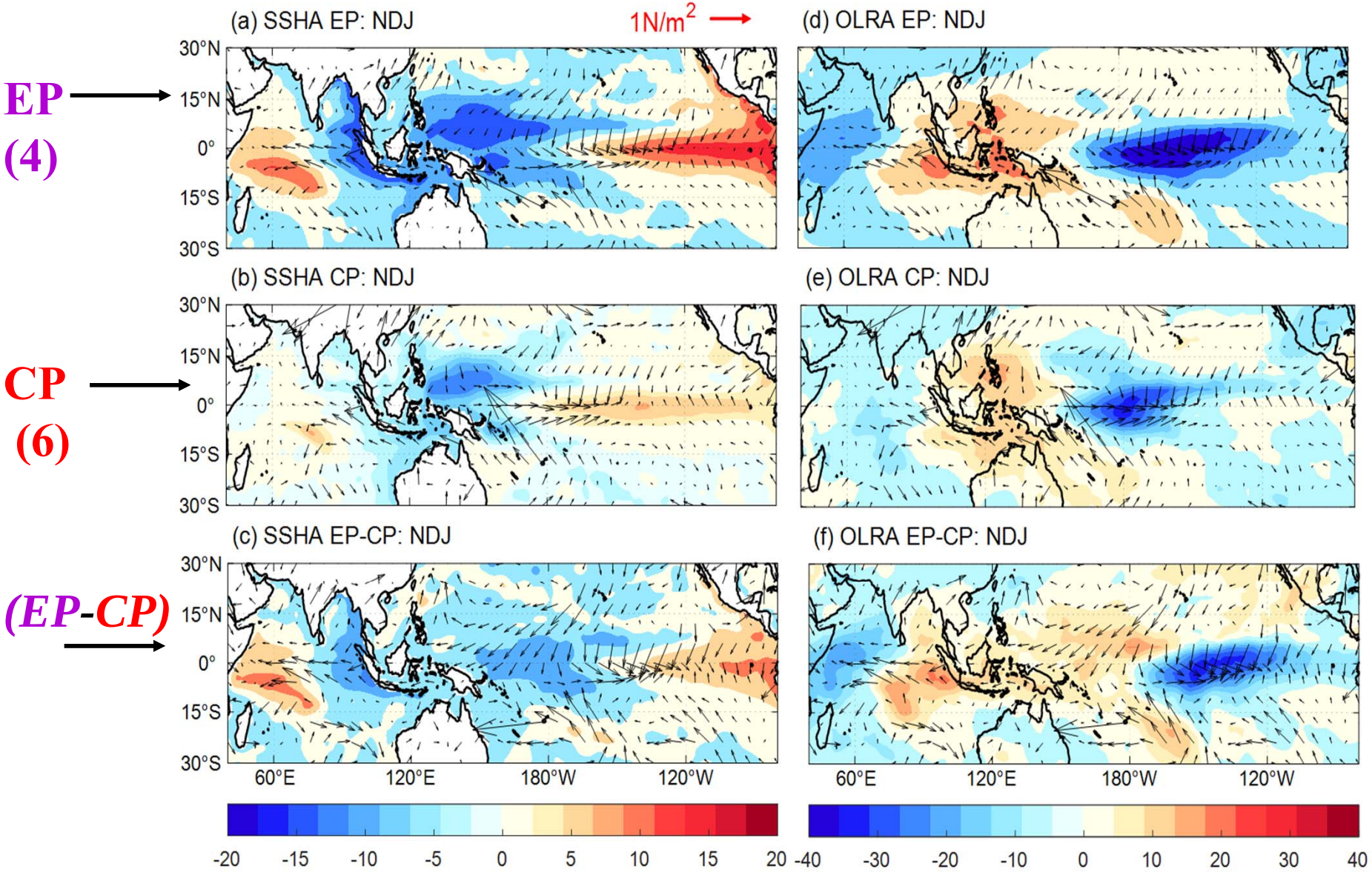
## Eastern Pacific (EP) versus Central Pacific (CP) El Nino events

| Years of Events | ENSO | IOD |
|---|---|---|
| 1982 | EP | pIOD |
| 1983 | | pIOD |
| 1986 | EP | |
| 1987 | CP | |
| 1991 | CP | |
| **1994 (3)** | **CP** | **pIOD** |
| **1997 (1)** | **EP** | **pIOD** |
| 2002 | CP | |
| 2004 | CP | |
| **2006 (2)** | **EP** | **pIOD** |
| 2009 | CP | |
| 2012 | | pIOD |
| **2015 (4)** | **‘Hybrid”** | **pIOD** |

# Composite analysis

## SSHA & wind

## OLRA & wind



# 4. Summary

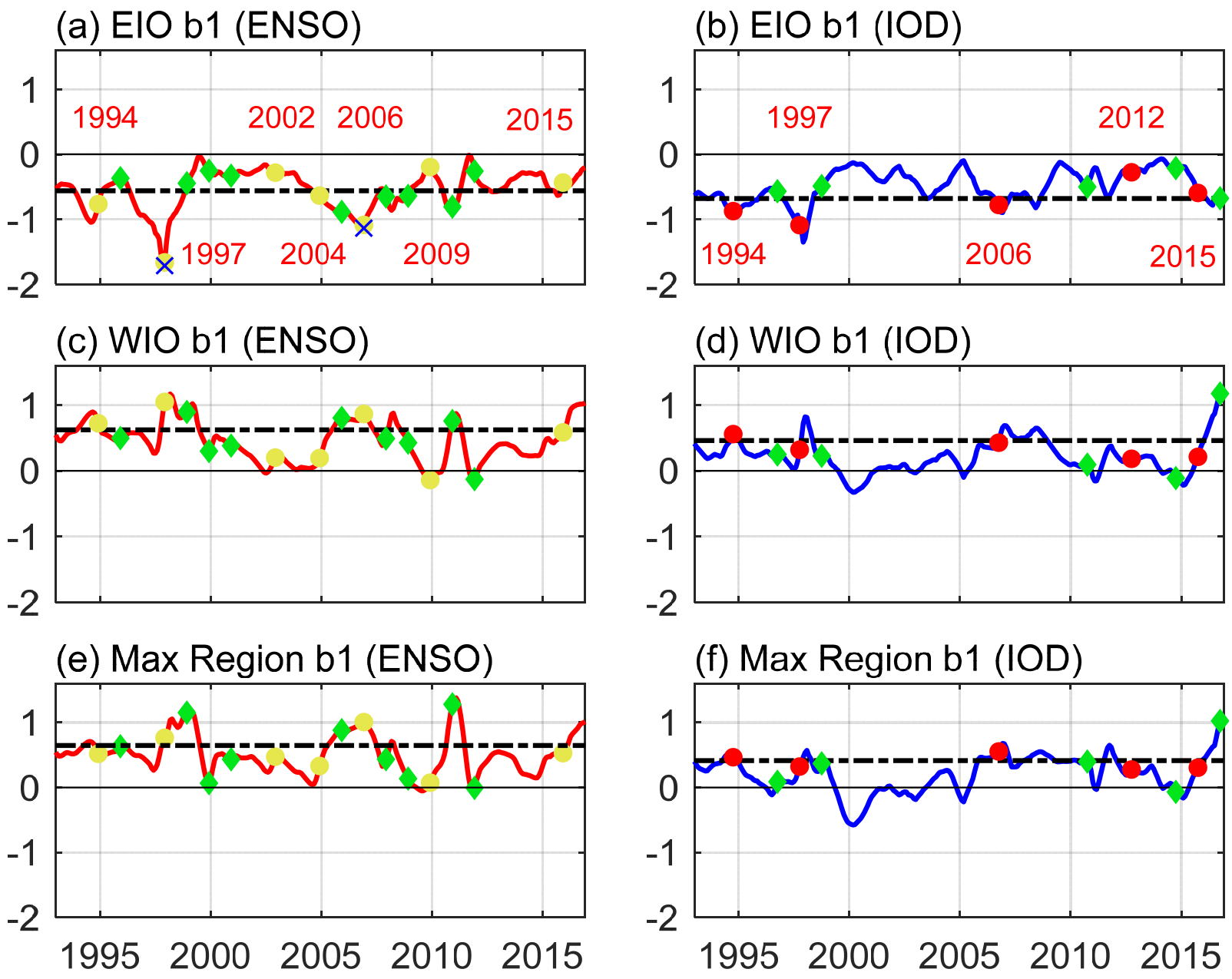
1) **Why are the WIO and EIO upwelling anomalies (SLA&D20A) out of phase?**

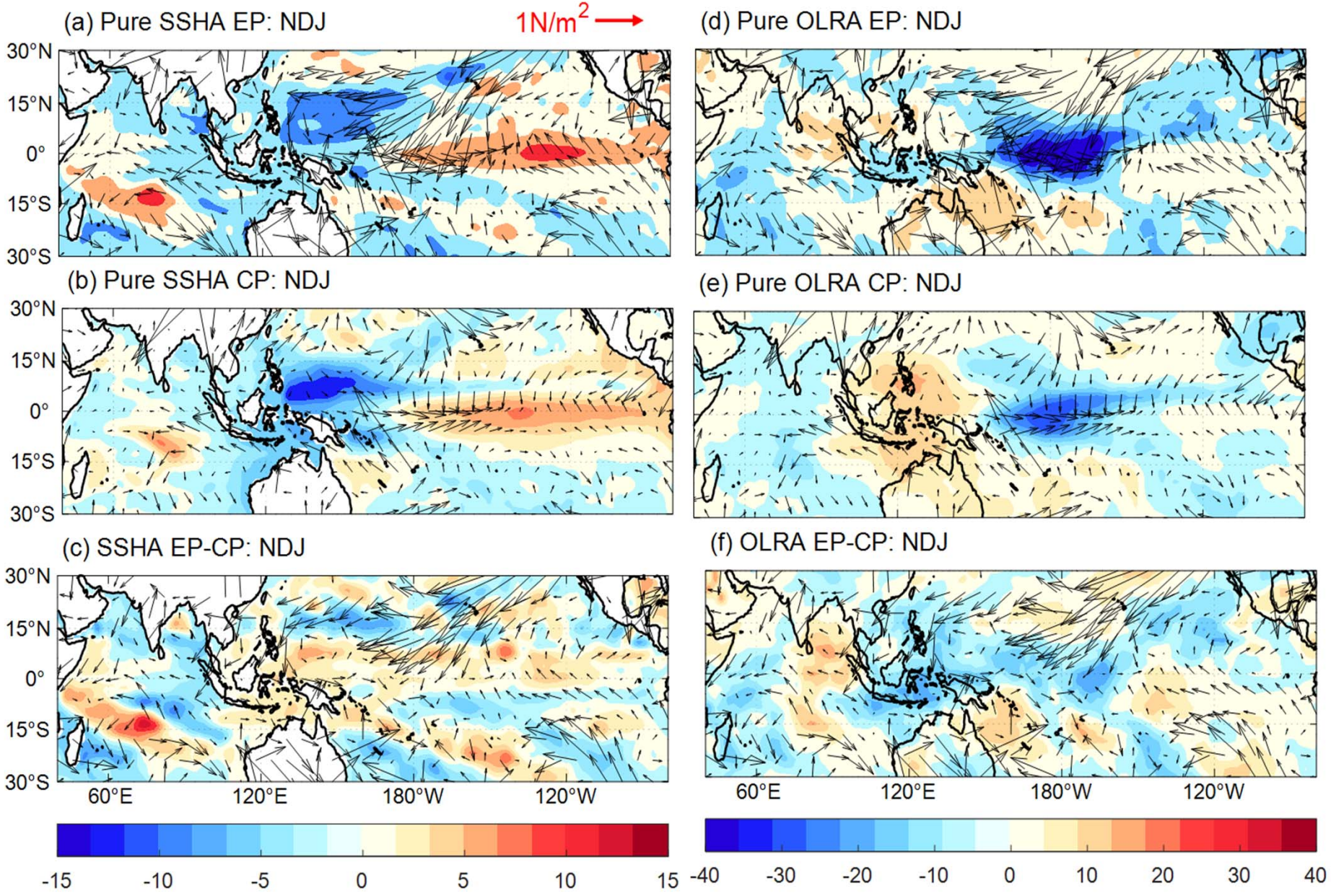
*Easterly wind anomalies associated with El Nino & pIOD drive upwelling in EIO (EQ & coastal KWs); negative Ekman pumping velocities South of EQ drive westward-propagating downwelling Rossby Waves, reducing the mean upwelling in WIO (Seychelles-Chagos).*

2) **Why are the upwellings so strong (weak) in the EIO (WIO) during 1997-98, 2006-07, 1994-95 & 2015-16?**

*El Nino & pIOD co-occurrences intensify EIO & WIO upwelling; Compared to CP El Nino, EP El Nino has stronger impacts on Indian Ocean convection, surface wind and thus upwelling for 1993-2017 altimetry period (also 1979-2017).*

**Thank you!**


(a) EIO b1 (ENSO)
1994
2002
2006
2015
1997
2004
2009
(b) EIO b1 (IOD)
1997
2012
1994
2006
2015
(c) WIO b1 (ENSO)
(d) WIO b1 (IOD)
(e) Max Region b1 (ENSO)
(f) Max Region b1 (IOD)
1
0
-1
-2
1995
2000
2005
2010
2015


(a) Pure SSHA EP: NDJ
1N/m2
(d) Pure OLRA EP: NDJ
(b) Pure SSHA CP: NDJ
(e) Pure OLRA CP: NDJ
(c) SSHA EP-CP: NDJ
(f) OLRA EP-CP: NDJ
30°N
15°N
0°
15°S
30°S
60°E
120°E
180°W
120°W
-15
-10
-5
0
5
10
15
-40
-30
-20
-10
0
10
20
30
40