Interannual Variability in the Tropical Indian Ocean

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Outline

1. Asian-Australian monsoon, wind-driven shallow meridional overturning circulation & its feedback to monsoon

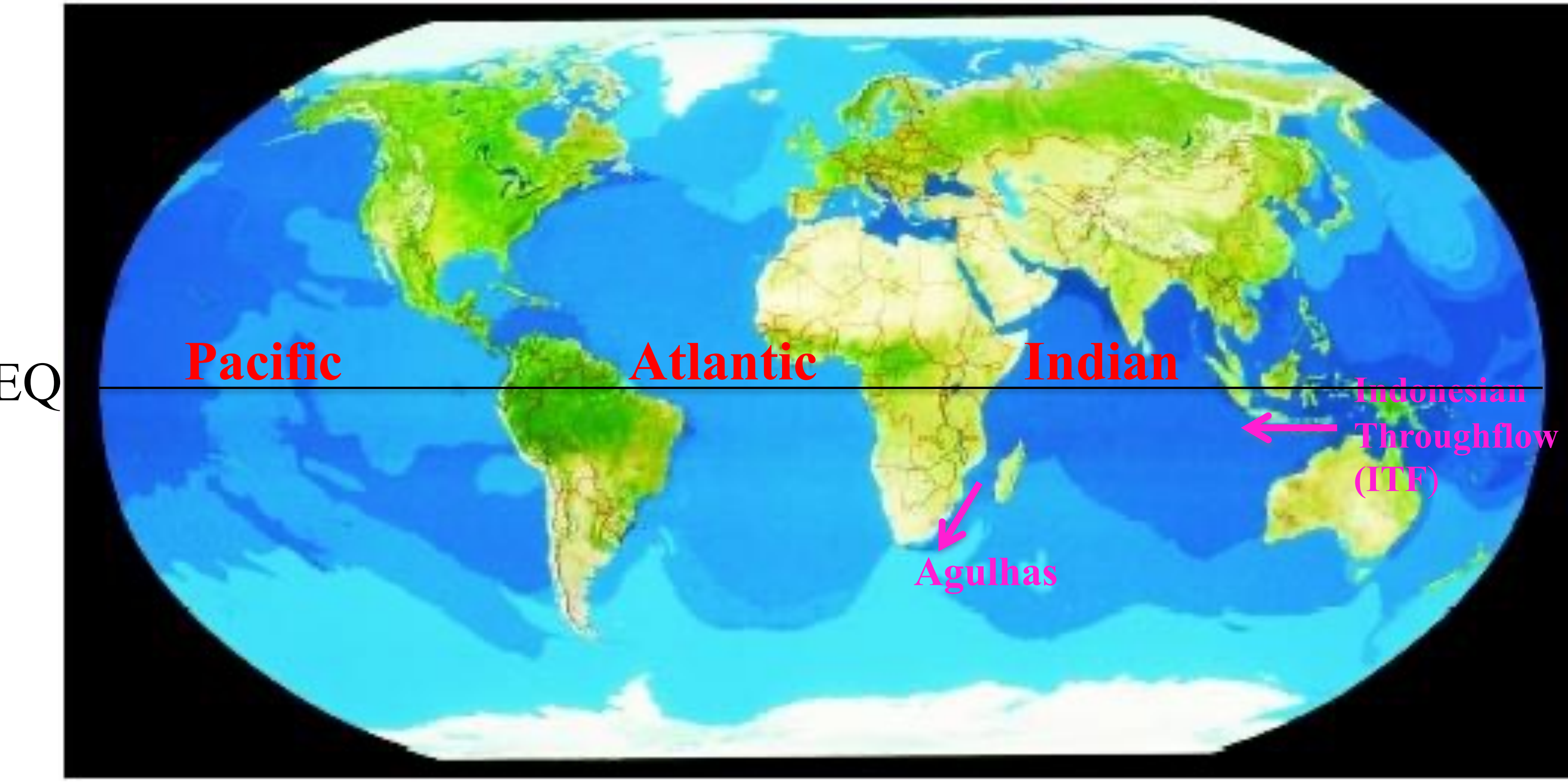
2. Tropical Biennial Oscillation (TBO)

3. Indian Ocean Dipole (IOD)

4. TBO-IOD-ENSO relations

5. ENSO impact: brief introduction

Uniqueness of the Indian Ocean basin



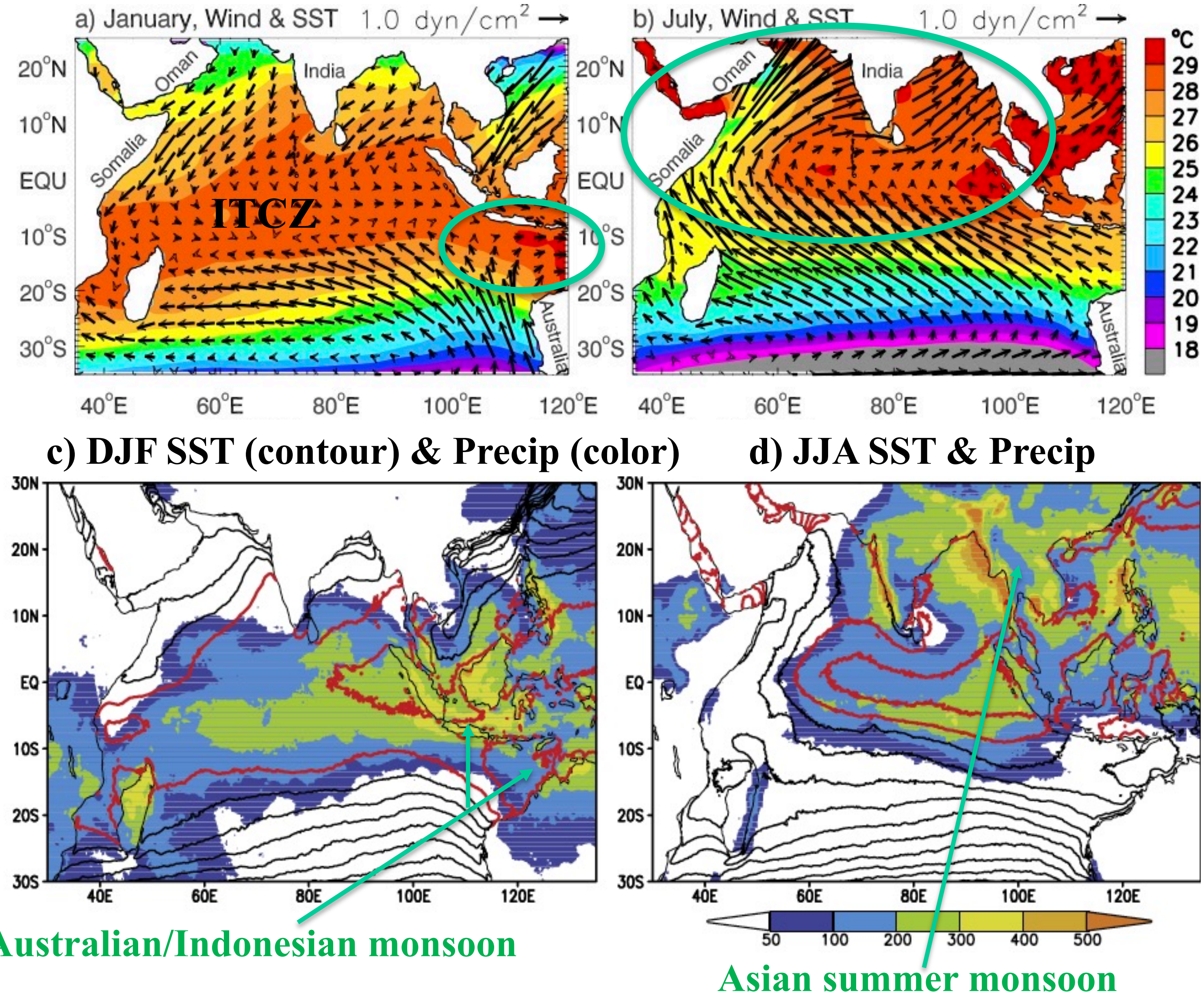
Is bounded to the north by Asian subcontinents

- **Asian-Australian monsoons: winds & rainfall**
- **Net heat gain (Qnet>0) in tropical Indian Ocean – transported southward across the equator by wind-driven shallow MOC**

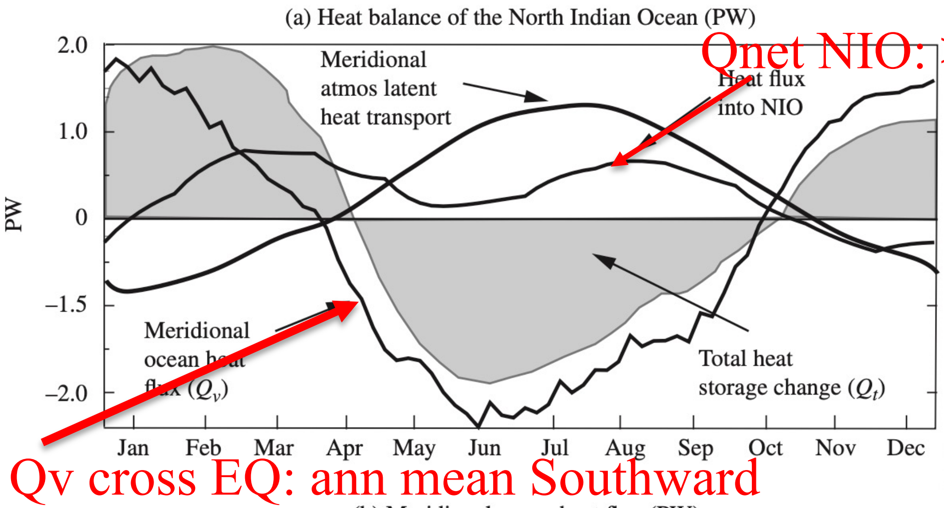
1. Monsoon, shallow MOC & feedback to monsoon

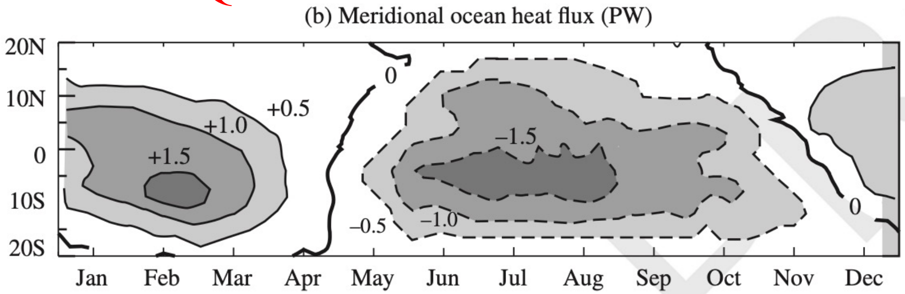
(a) Asian-Australian monsoon: Seasonal reversing **winds &** associated **rainfall**

(b) Net heat gain (Qnet>0) in tropics – transported southward



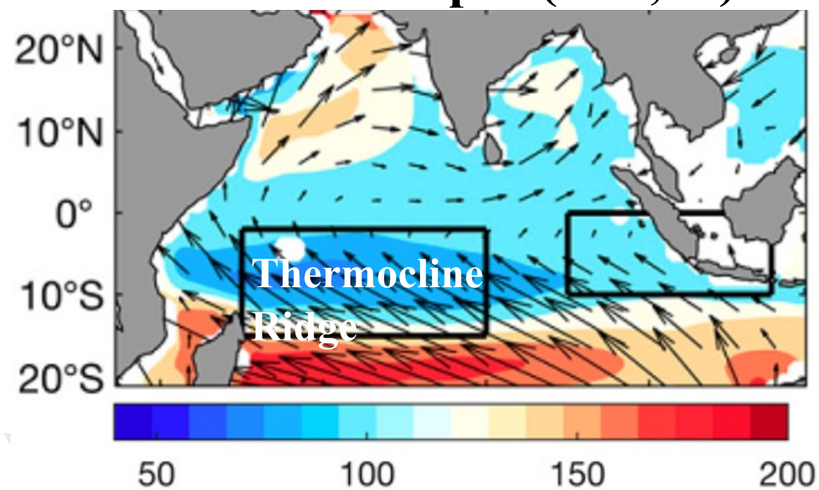
Wind-driven shallow meridional overturning cells



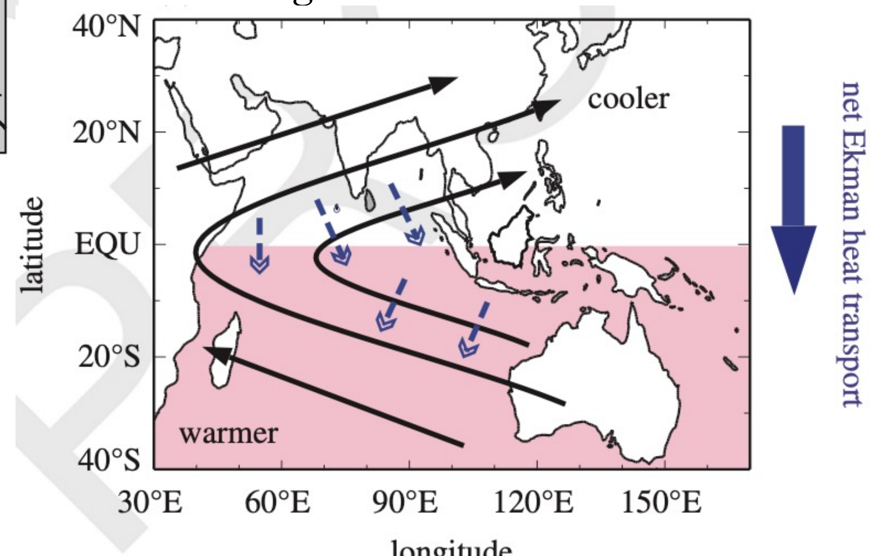


Webster, 2020: Dynamics of The Tropical Atmosphere and Oceans, EMS (book)

Ann. Mean wind & thermocline depth (D20, m)

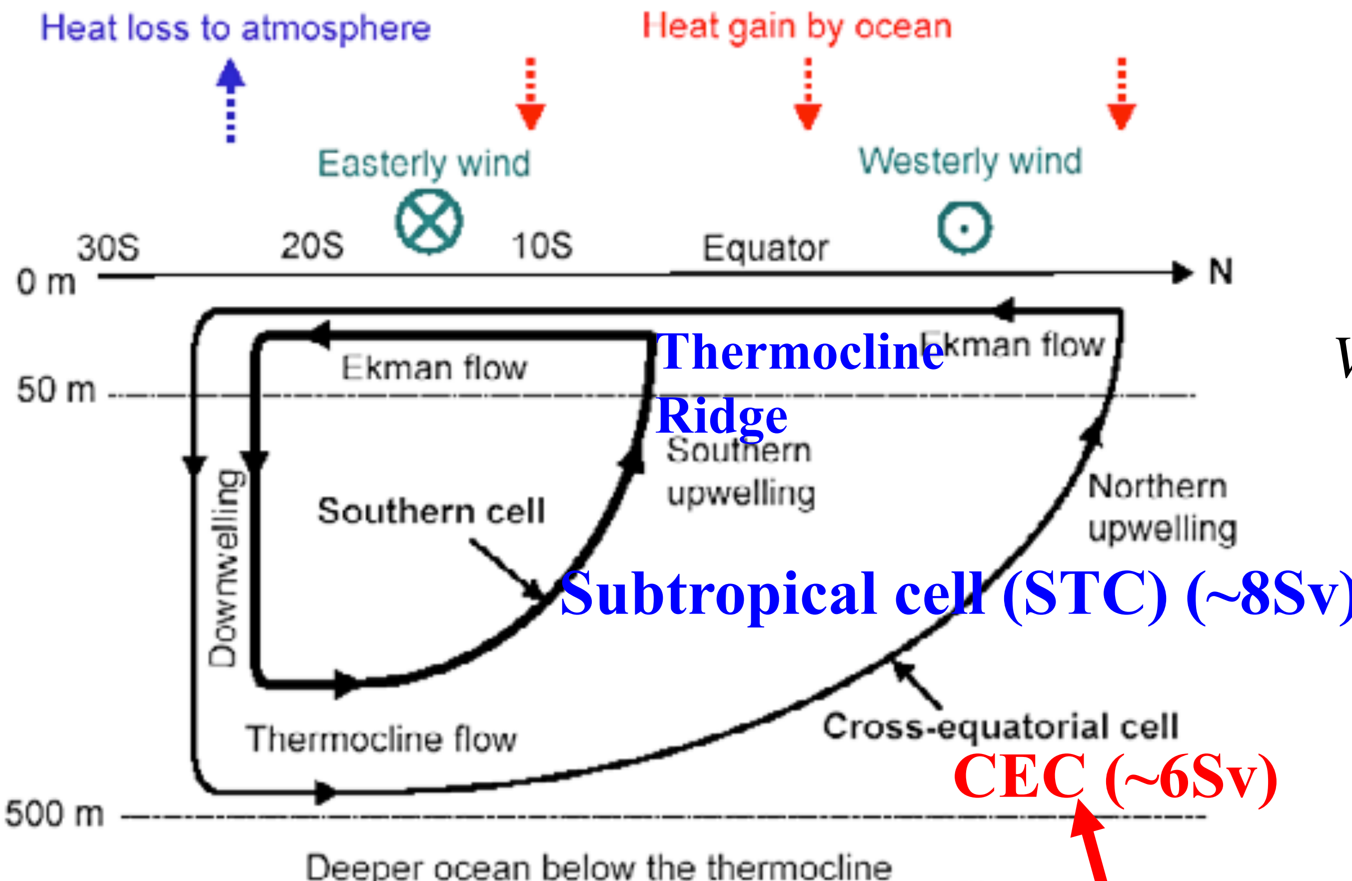


Zhang and Han 2020

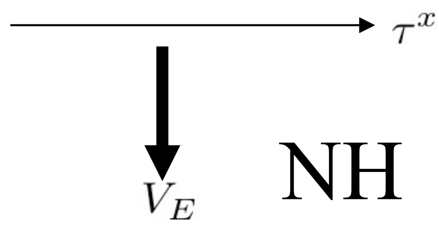


Webster, 2020

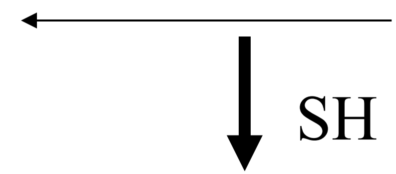
Wind-driven shallow meridional overturning cells



Lee 2004



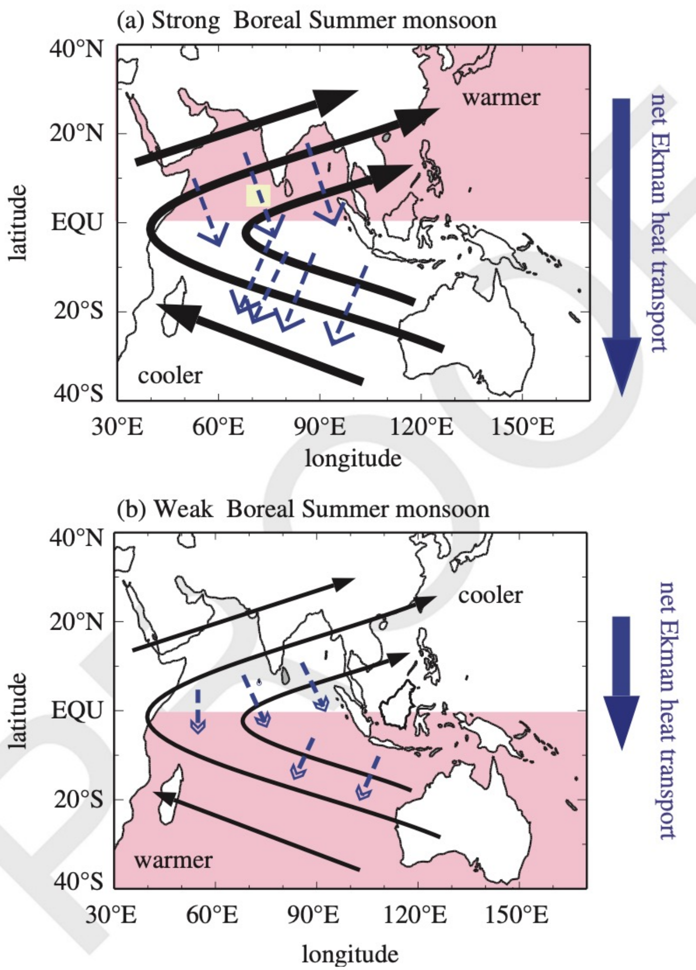
$$V_E = \int_{-H_E}^{0} v_E \, dz = -\frac{\tau^x}{\rho_0 f}$$



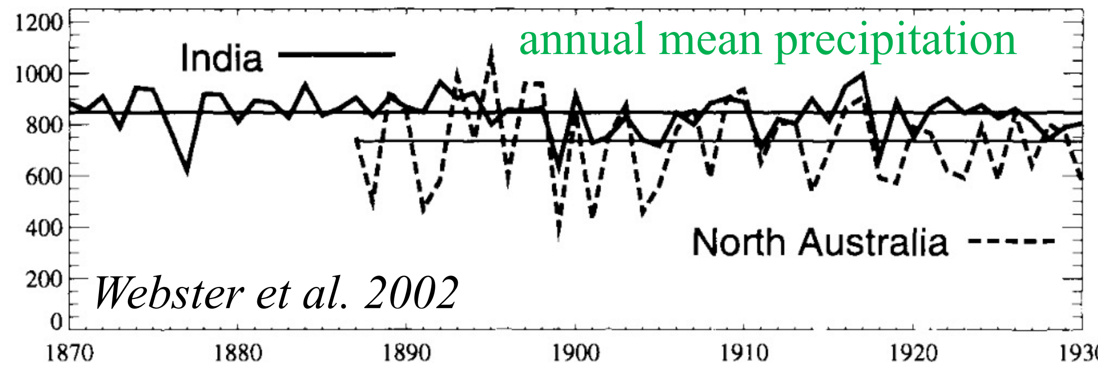
$$M(y) = \frac{1}{\beta}[\tau^y(x_w, y) - \tau^y(x_e, y)] - \frac{1}{\beta}\int_{x_w}^{x_e} \tau_y^x \, dx$$

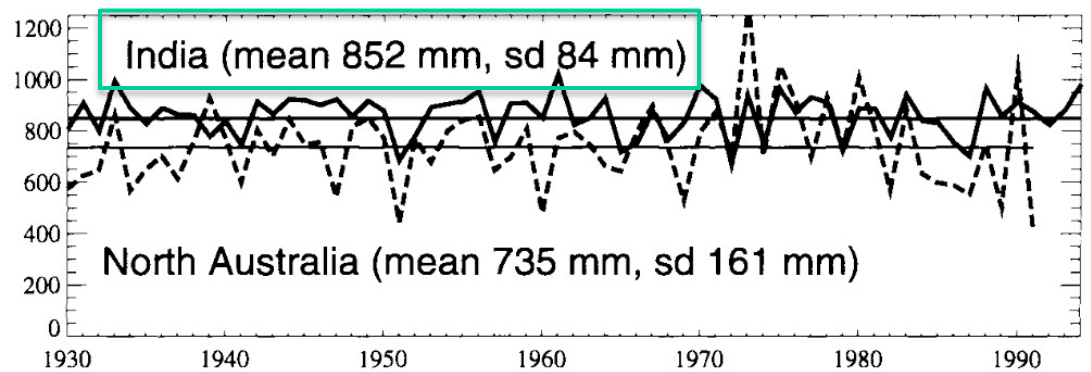
Miyama et al. 2003;Schott et al. 2009

Negative feedback of CEC heat transport - small interannual variability amplitude of Indian summer monsoon



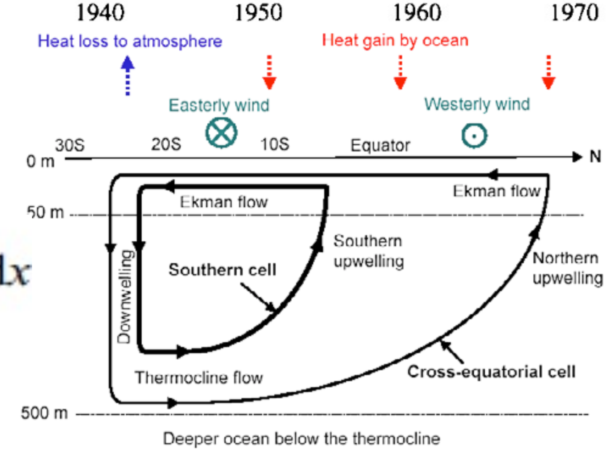
Webster et al. 2002





$$M(y) = \frac{1}{\beta}[\bar{\tau}^y(x_w, y) - \bar{\tau}^y(x_e, y)] - \frac{1}{\beta}\int_{x_w}^{x_e} \bar{\tau}_y^x \, dx$$

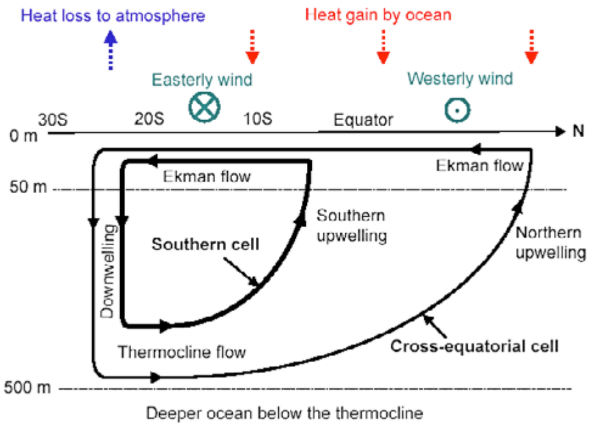
Miyama et al. 2003



Summary 1

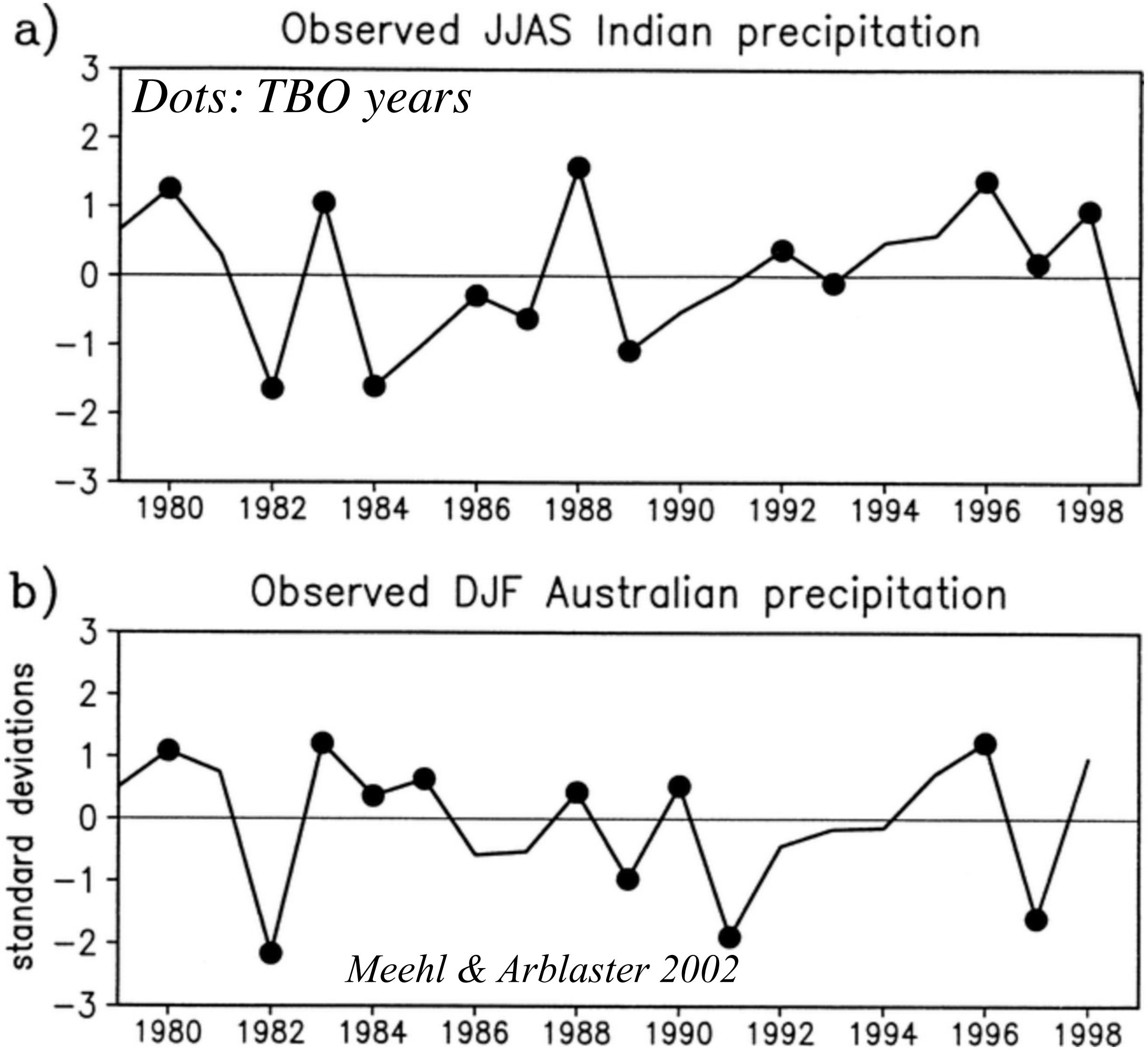
- **Land/Ocean heating contrast generates seasonally reversing Asian-Australian monsoon winds that prevail the tropical Indian Ocean (IO)** & associated **monsoon rainfall over lands;**

- **Monsoon winds drive shallow MOCs (CEC & STC), which transport annual mean net heat gain southward from tropical to subtropical IO;**



- **Variability of southward heat transport provides negative feedback to Indian Summer monsoon (ISM) rainfall, reducing the amplitude of ISM interannual variability.**

2. Tropical Biennial Oscillation (TBO)



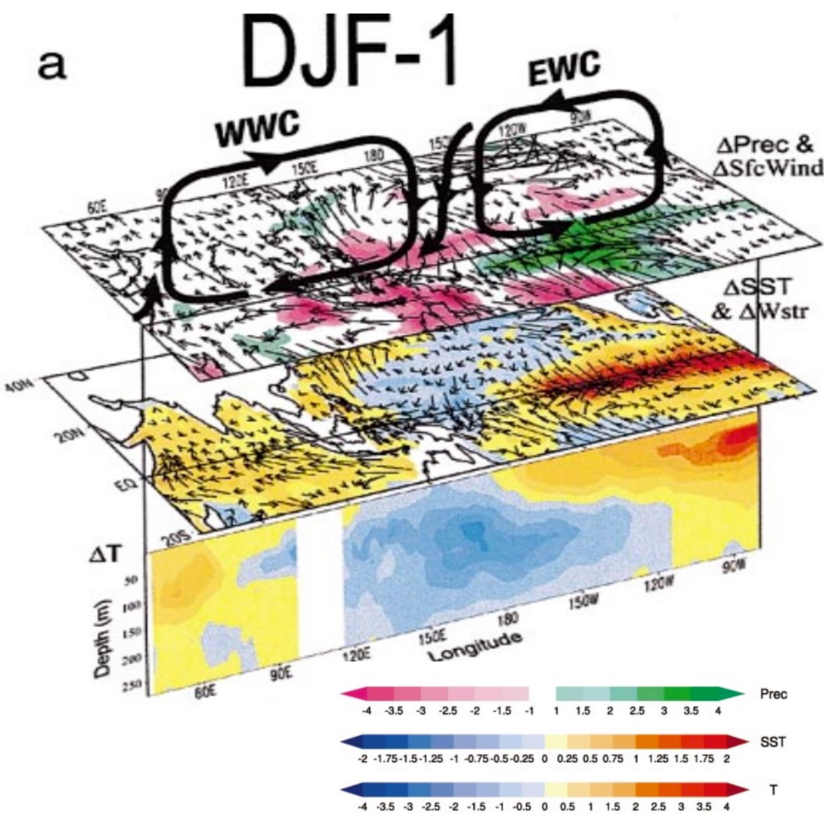
Spectral peak: 2-3yrs

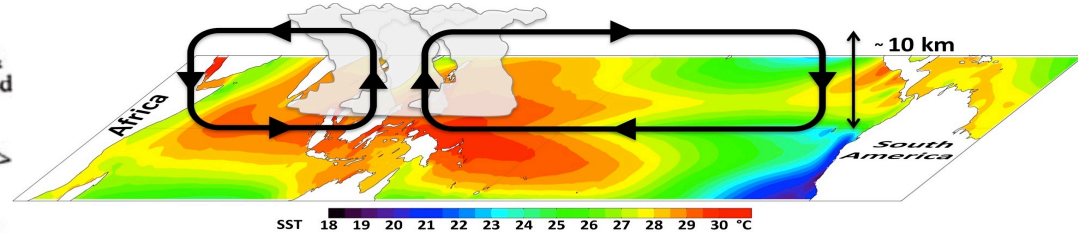
Asian–Australian monsoon rainfall: ***tendency for a relatively strong monsoon to be followed by a relatively weak one, and vice versa – defined as the TBO***

TBO synthesis coupled interactions

The TBO *transitions* *(e.g., strong to weak)* occur in ***NH spring*** for the ***south Asian/ Indian summer monsoon*** & ***NH fall for the Australian monsoon***

Situation for a weaker Australian monsoon in DJF, prior to a stronger Indian Summer Monsoon (ISM)

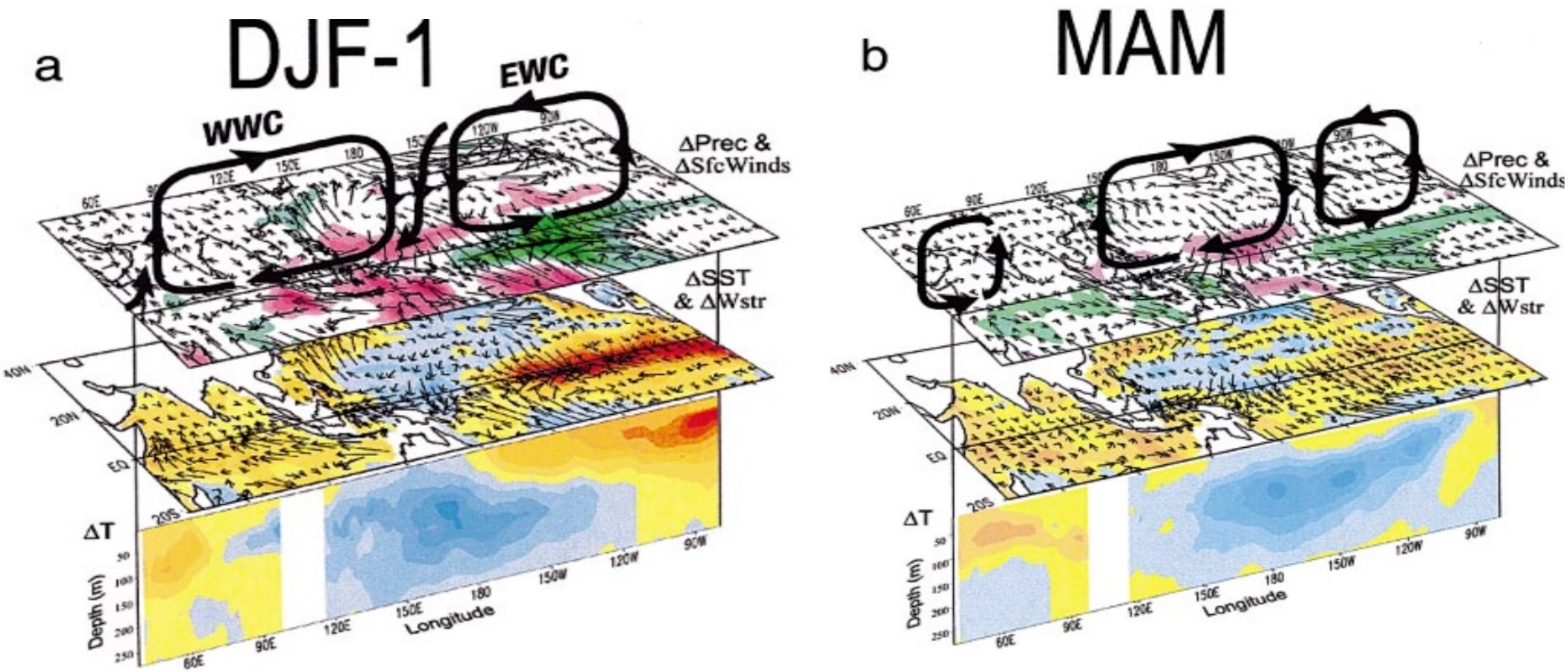




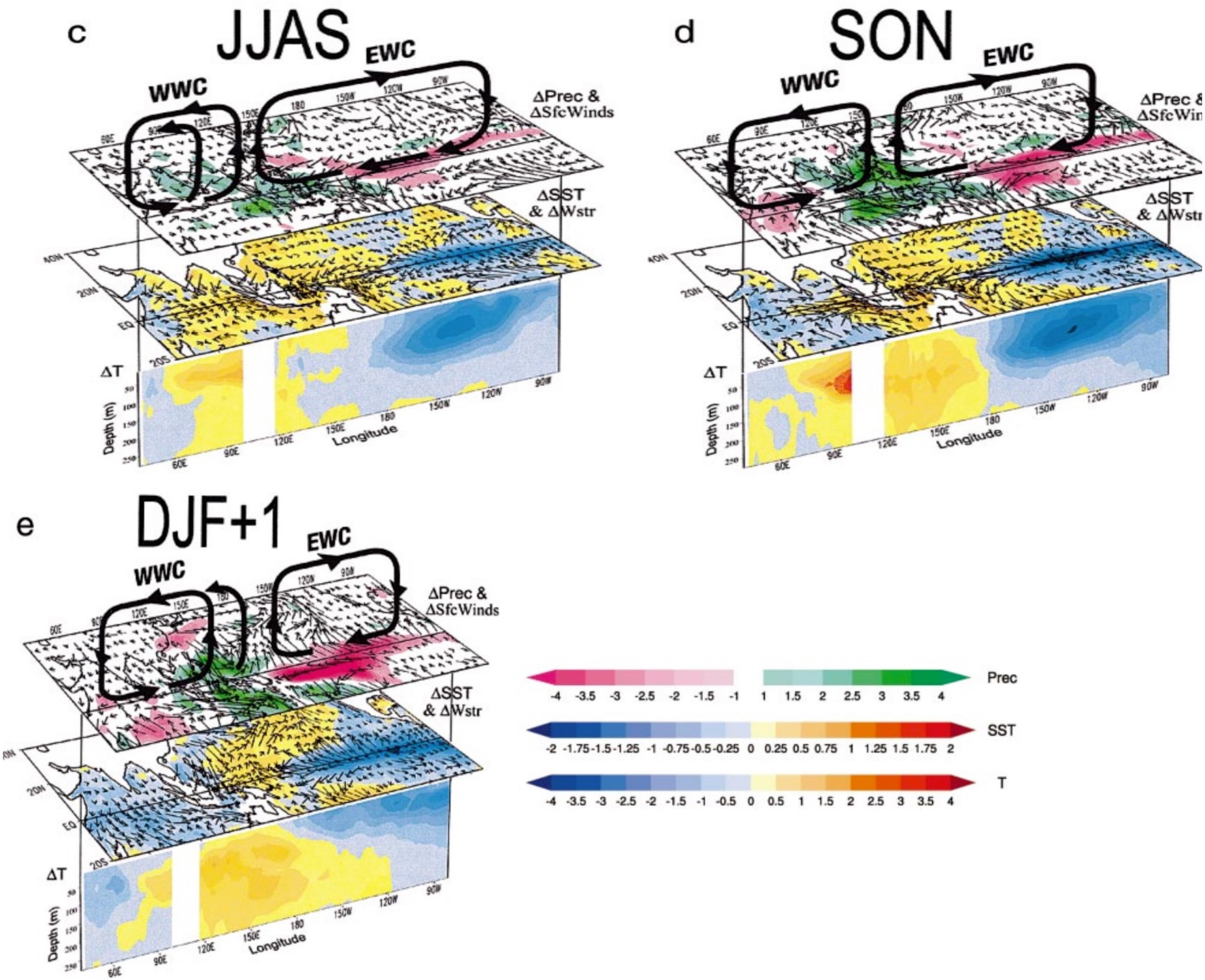
Mean Walker Cells & SST

TBO synthesis coupled interactions

MAM: transition season to a stronger Indian Summer Monsoon



- **DJF:** EQ easterly/southeasterly EIO & WP – upwelling, shoal (deepen) thermocline in warm pool (western IO);
- downwelling Rossby waves south of EQ propagate westward, favoring a warm western Indian Ocean in MAM;
- **MAM:** Convection anomaly in western IO drives EQ westerlies in April – deepen thermocline & EQ KW eastward – favor +SSTA in east IO – increased convection drives EQ easterlies in PO – shoal thermocline – propagate eastward – cold eastern EQ Pacific – precondition stronger easterly & Asian monsoon.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-4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5 3 3.5 4

Summary 2

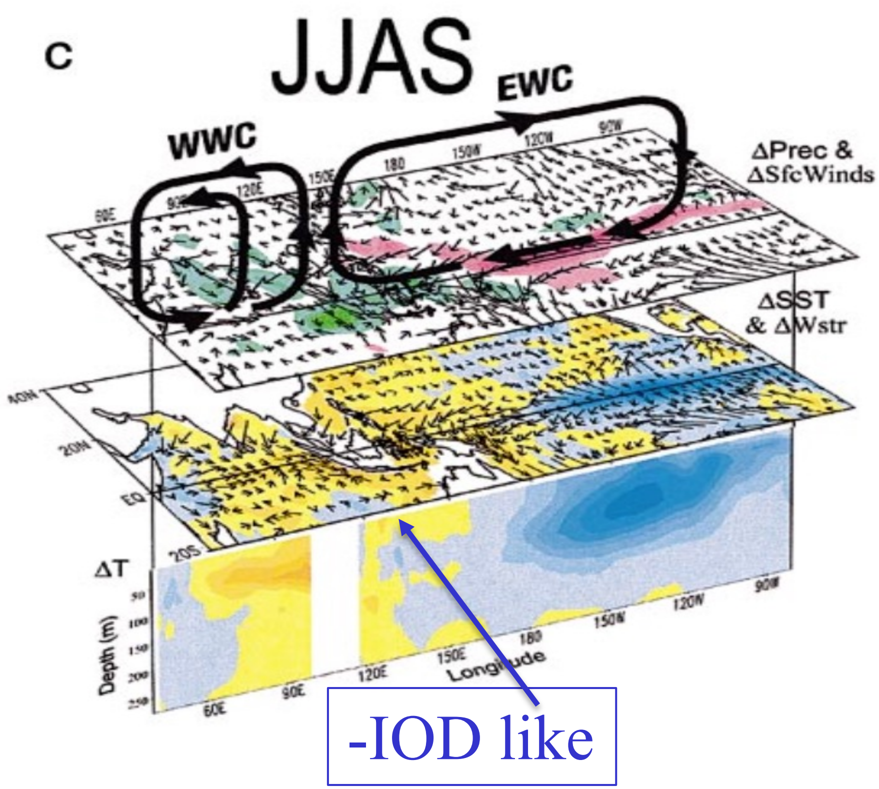
- The TBO involves **coupled atmosphere–ocean-land processes over a large area of the Indo-Pacific region;**

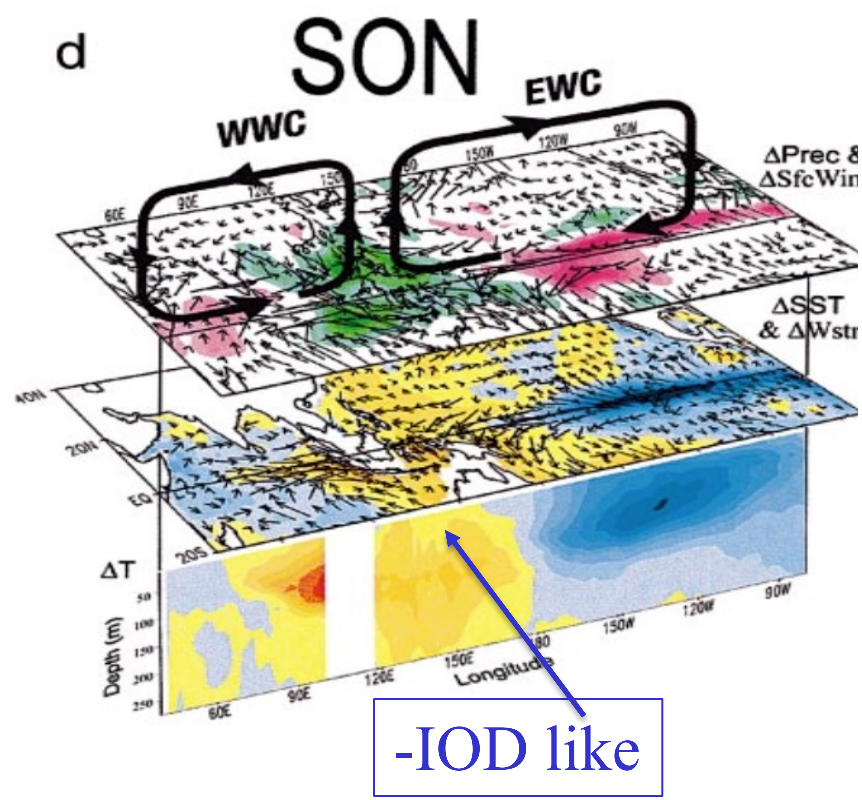
- Slowly **eastward-propagating** equatorial ocean heat content anomalies, **westward-propagating** ocean Rossby waves south of the equator, and **anomalous cross-EQ ocean heat transports** (via the shallow MOCs) contribute to the HCA and consequent SSTA.

3. The Indian Ocean Dipole (IOD)

***interannual* climate mode of variability in tropical Indian Ocean**

TBO:

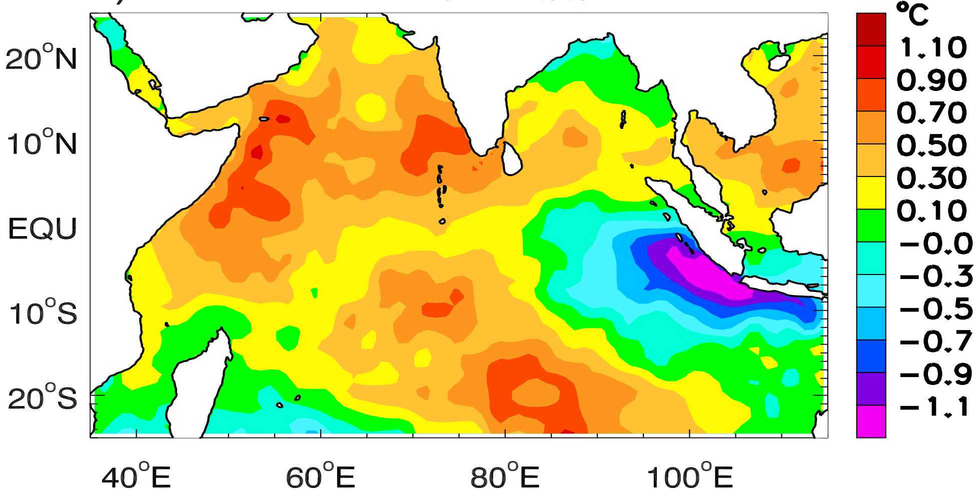




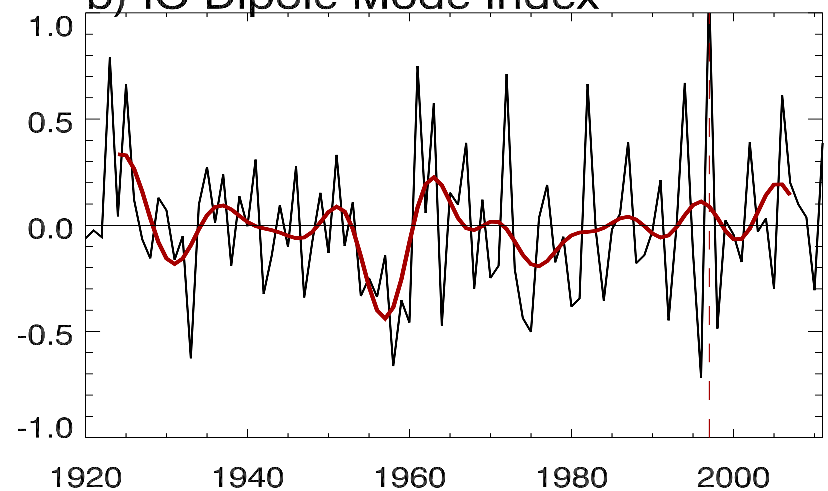
The Indian Ocean Dipole (IOD)

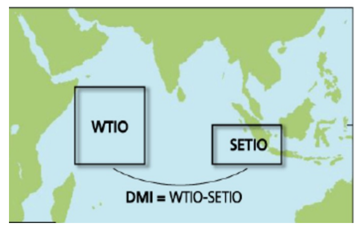
interannual climate mode of variability in tropical Indian Ocean

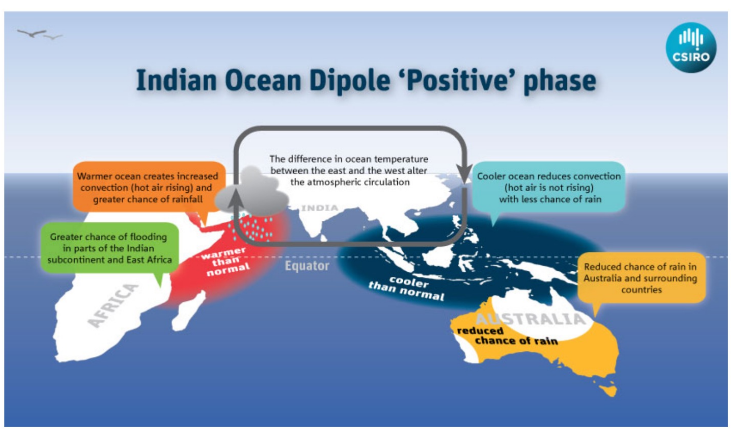
a) 1997 IOD **+IOD: SSTA**



b) IO Dipole Mode Index

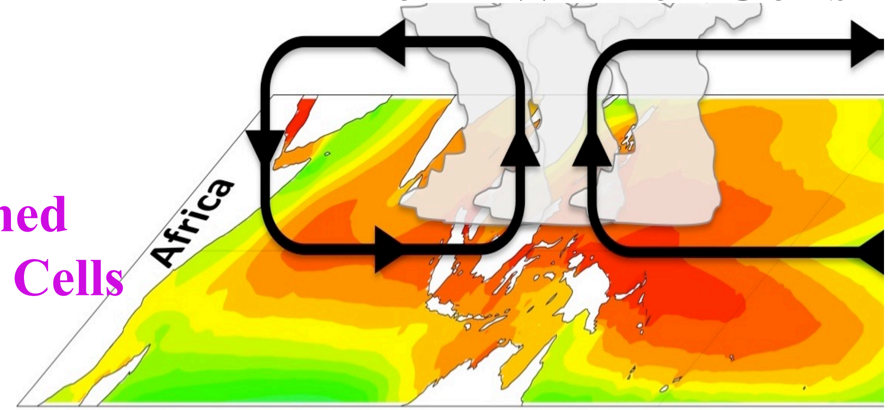






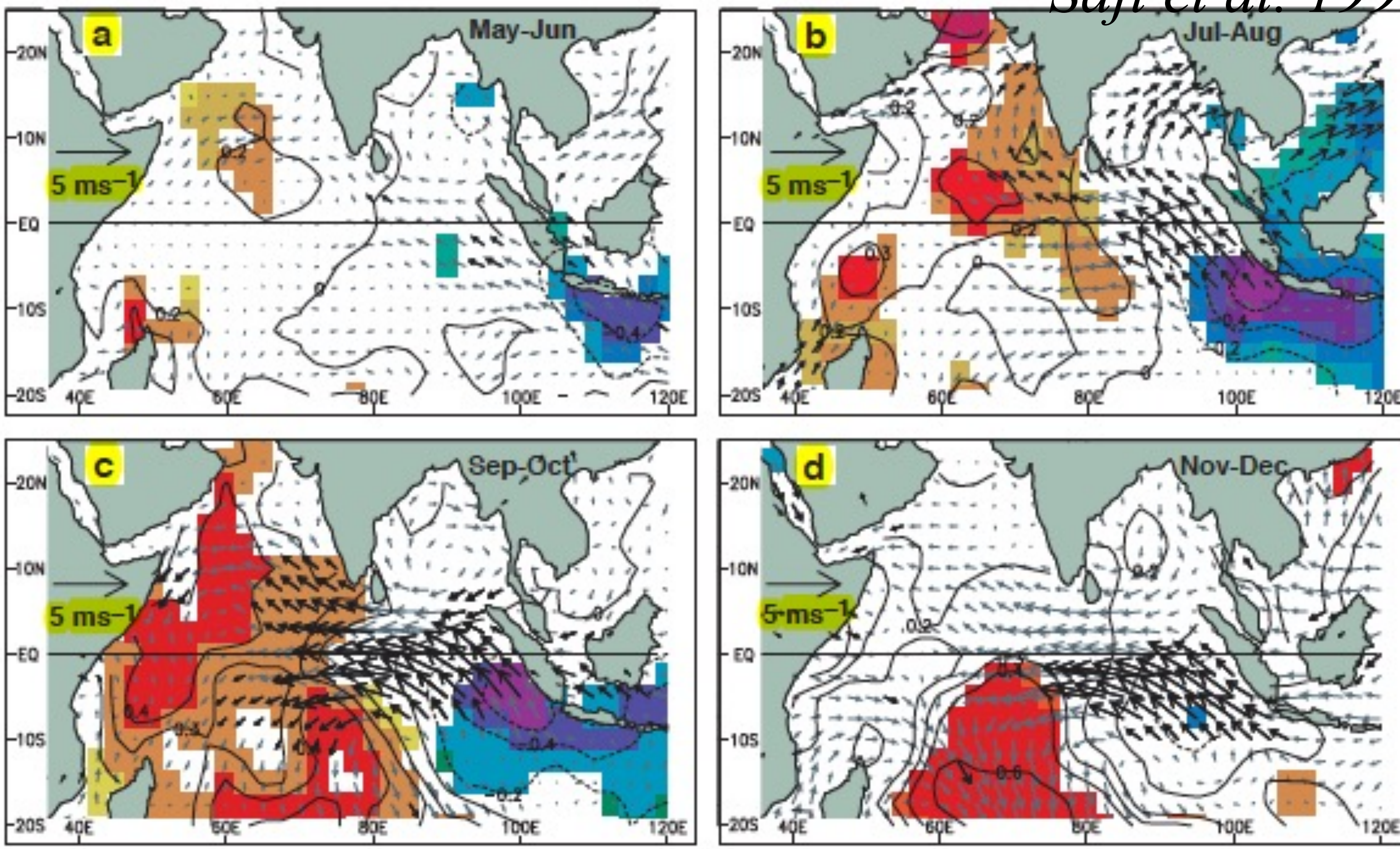
+IOD: Weakened Walker Cells

Mean Walker Cells



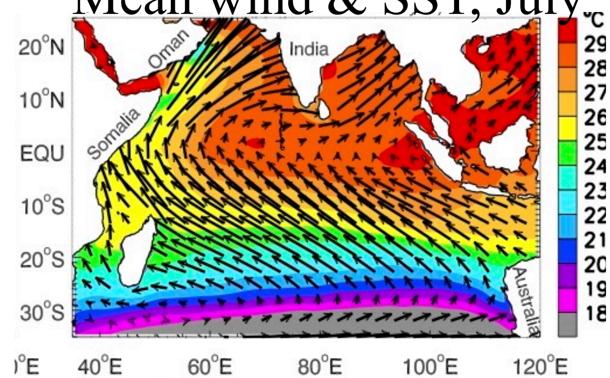
The coupled ocean-atmosphere mode: IOD evolution

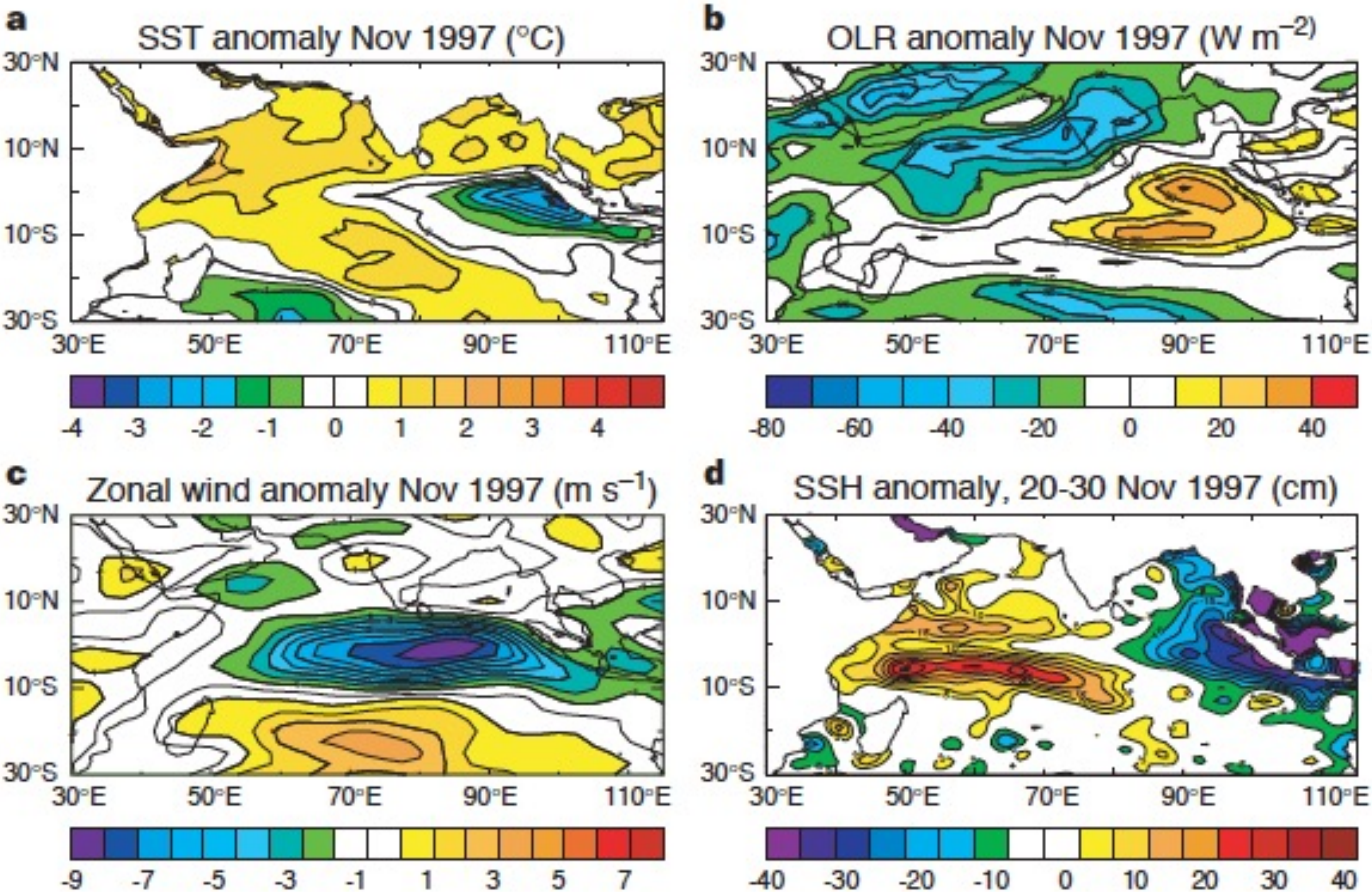
Saji et al. 1999



Summer-Fall: seasonal phase locked with Sumatra-Java upwelling

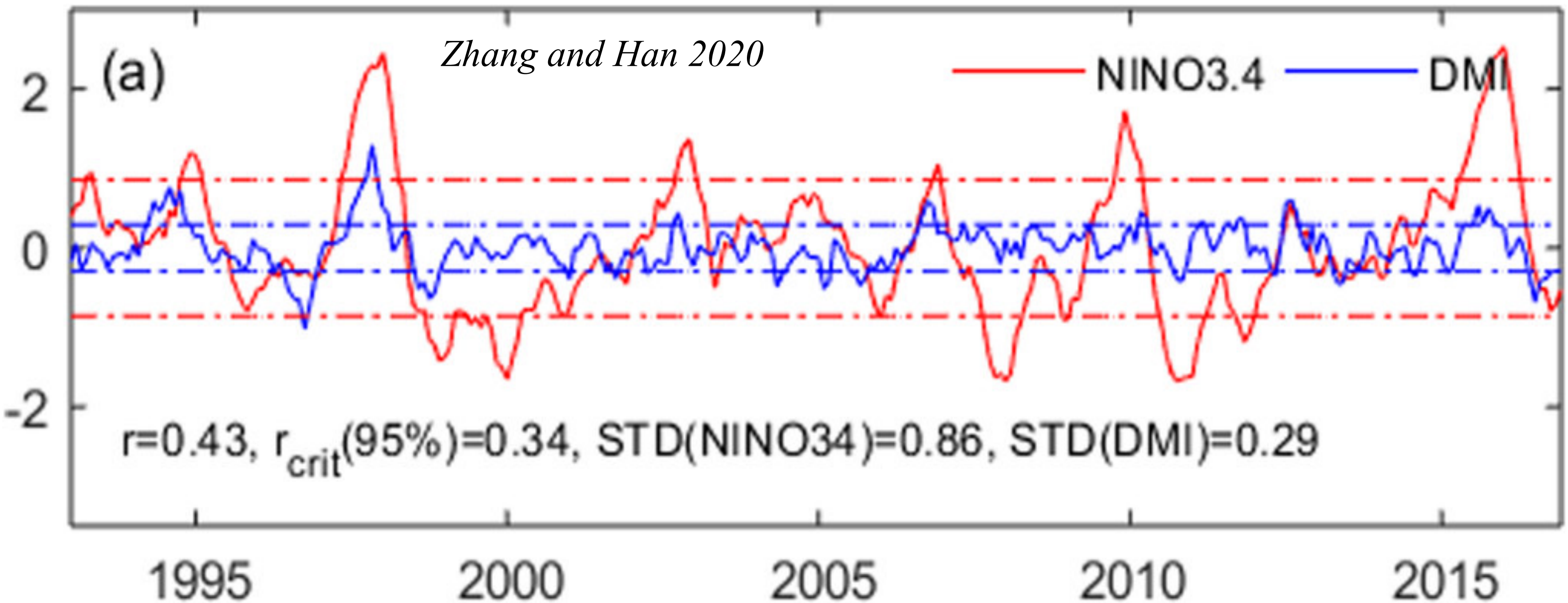
Mean wind & SST, July





Webster et al. 1999

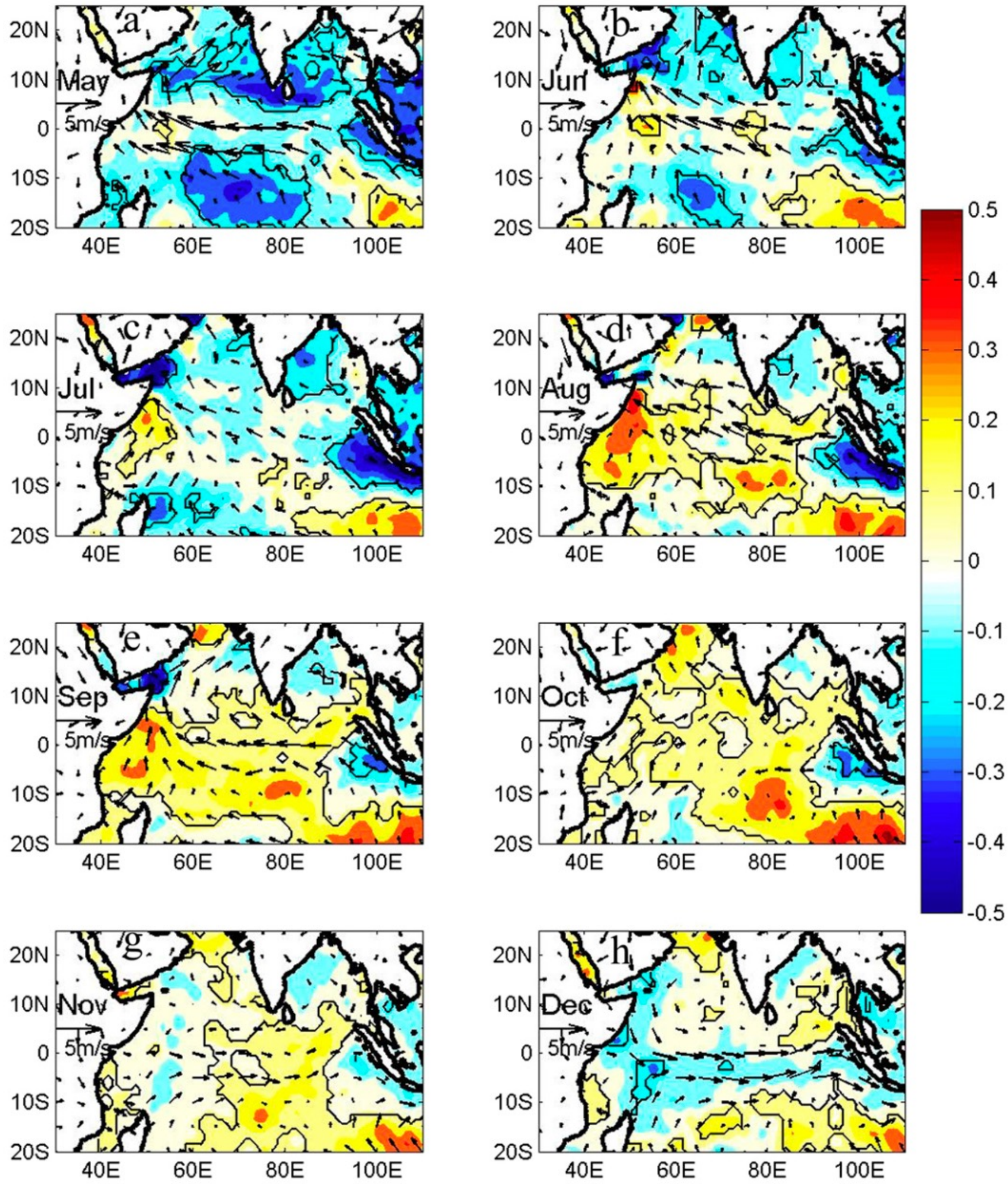
IOD & ENSO correlated: monthly DMI/Nino3.4 index



r is higher for SON mean

Independent IOD: IOD can exist without ENSO

Wind- show monsoon wind pattern: monsoon circulation is linked to IOD initiation. Begins early & demises early.



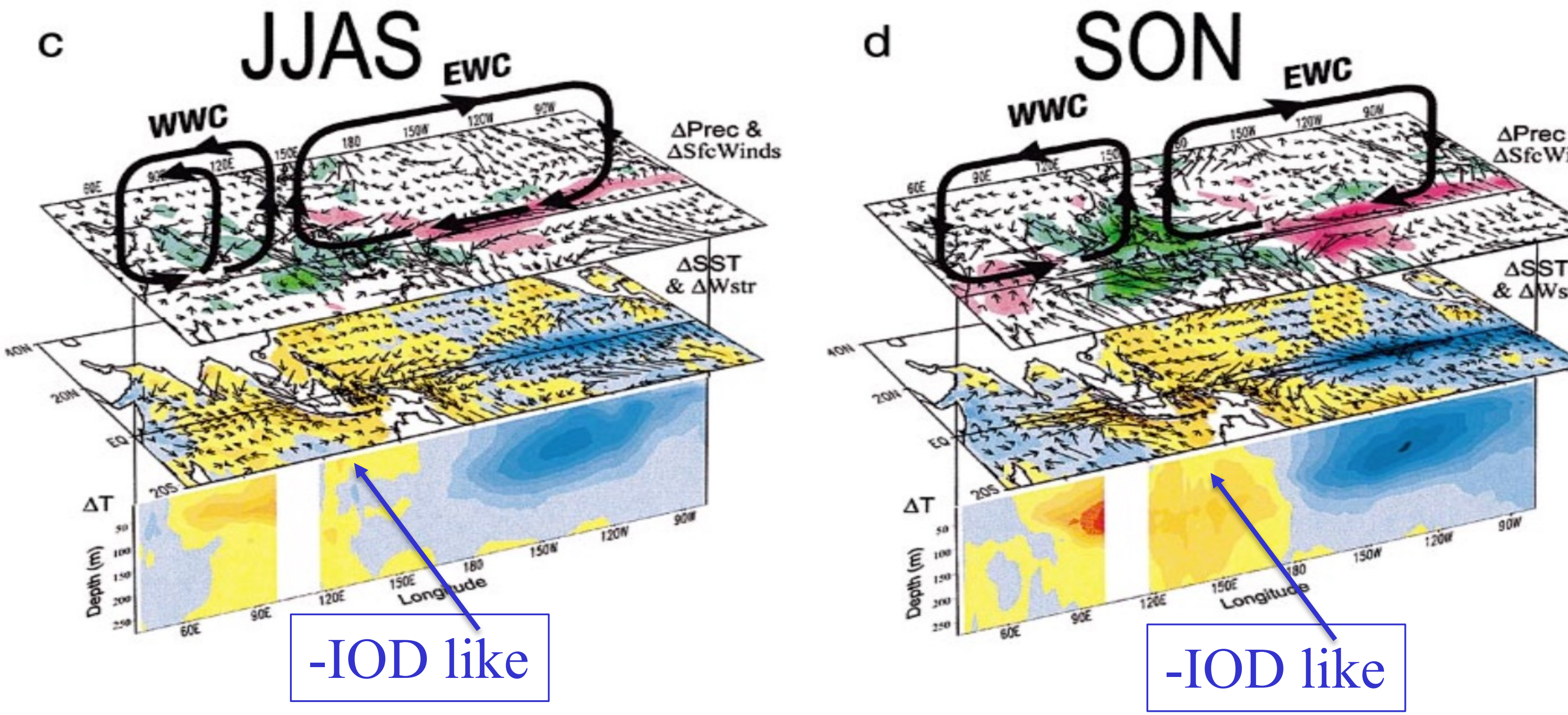
Sun et al. 2015

Summary 3

- **The IOD is a coupled ocean-atmosphere climate mode of variability in the tropical Indian Ocean at interannual timescale;**
- **The IOD generally develops in boreal summer, peaks in SON, and demises in December;**
- **The IOD is affected by ENSO, with El Nino being associated with +IOD; however, IOD can exist independently: it starts in May, peaks in boreal summer and decays in October-Nov (linked to Indian summer monsoon).**

4. IOD, ENSO & TBO relations

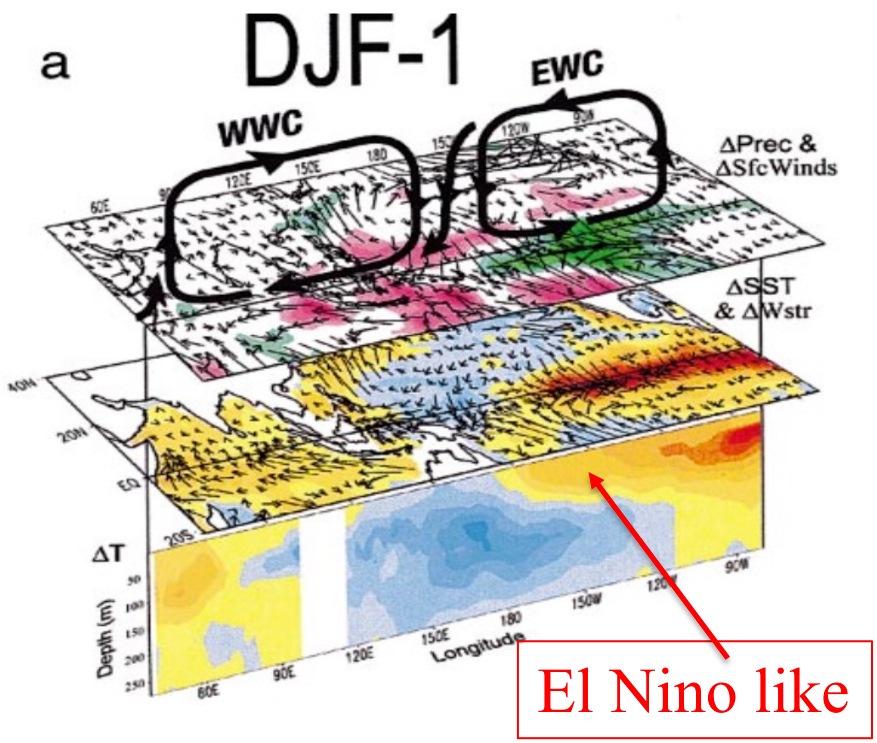
Stronger Asian monsoon & -IOD pattern



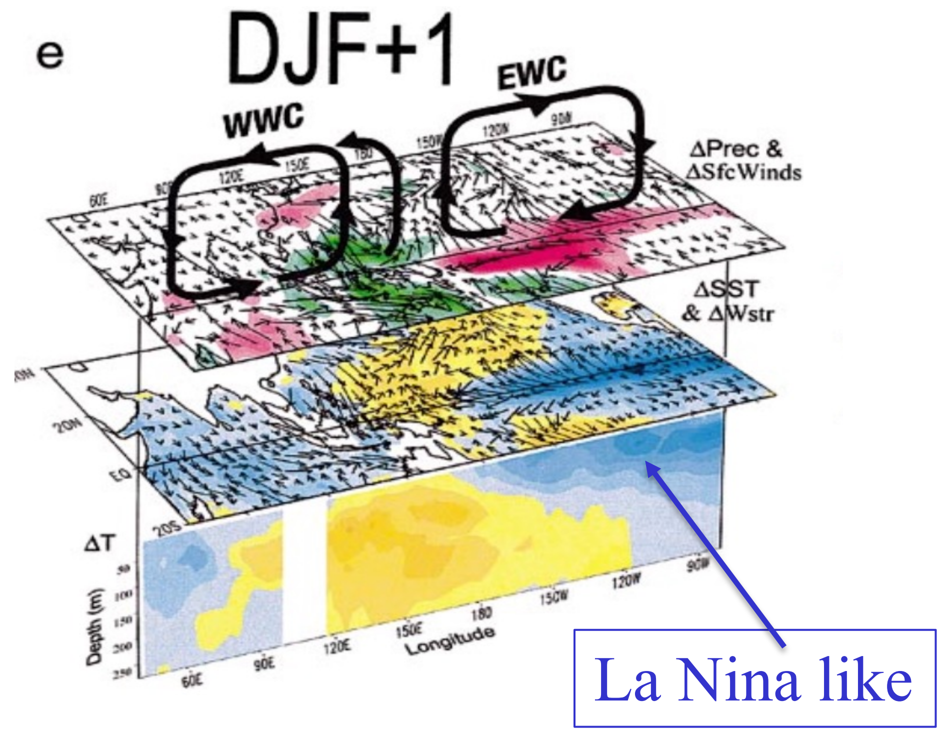
Different from Sun et al. (2015) & empirical studies discussed above: +IOD -> stronger ISM rainfall (*e.g., Ashok et al. 2004; Ashok & Saji 2007; Prajeesh et al. 2022*)

ENSO & TBO

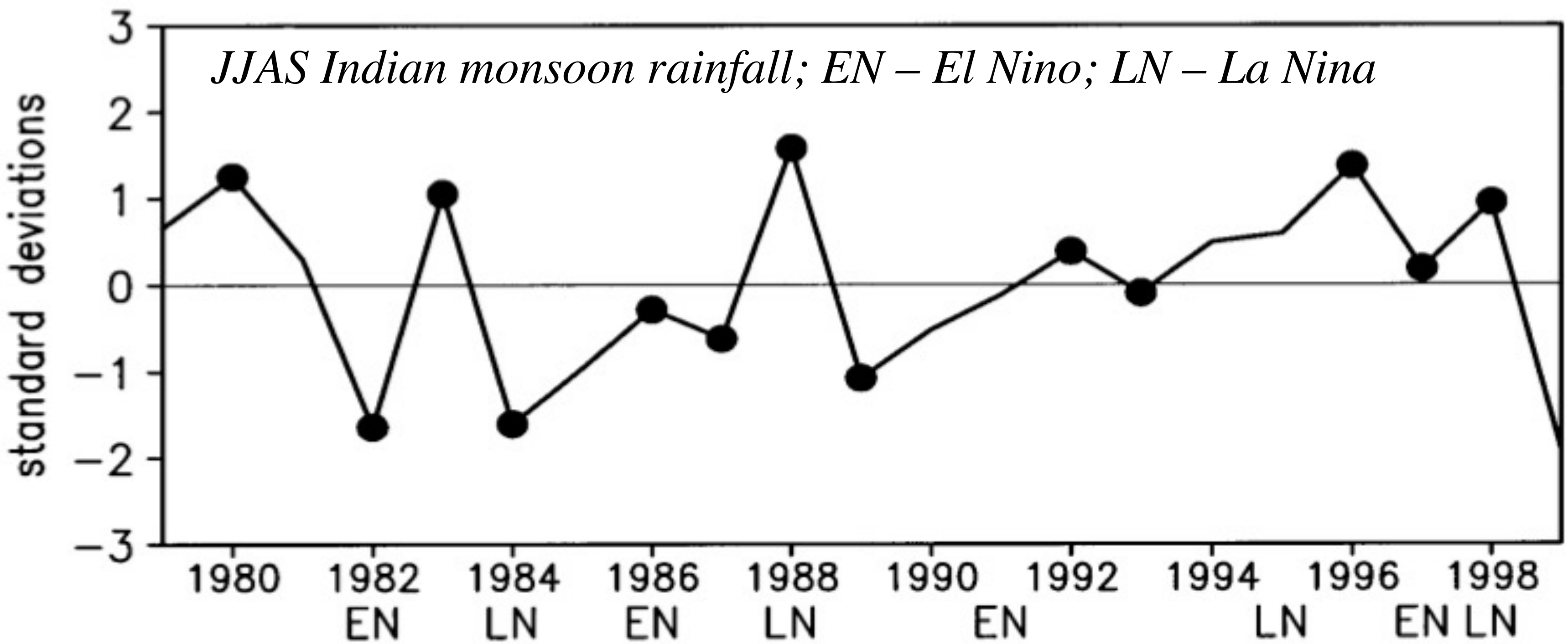
Weaker Australian monsoon



Stronger Australian monsoon

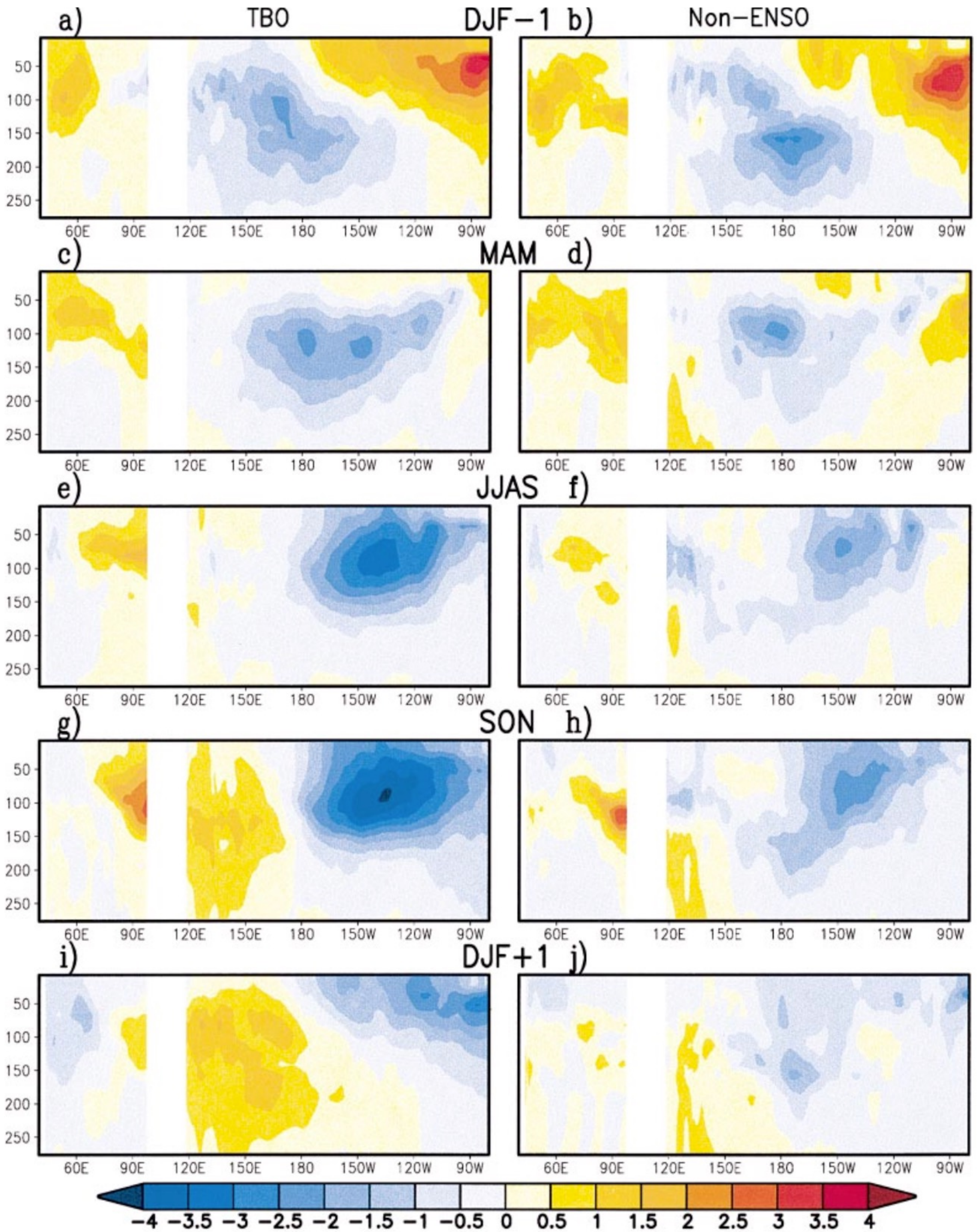


ENSO & Tropical Biennial Oscillation (TBO)



ENSO and IOD events are often **large-amplitude** excursions of the TBO in the tropical Pacific and Indian Oceans, respectively, associated with anomalous eastern and western Walker cell circulations, coupled ocean dynamics, and upper-ocean temperature and heat content anomalies.

Other years with similar but **lower- amplitude signals** also contribute to the TBO.

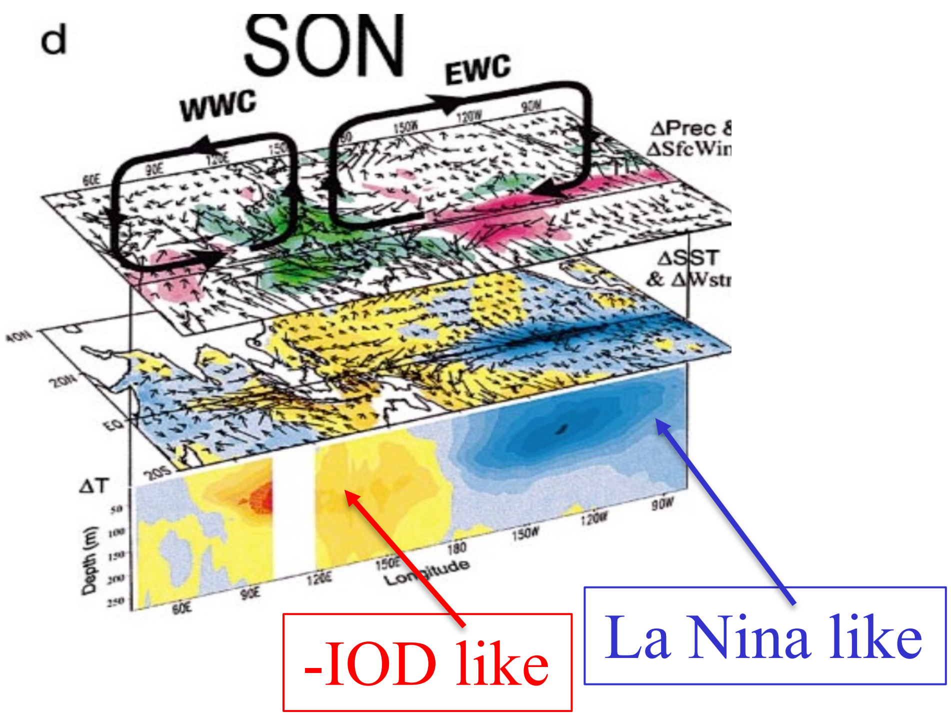


Positive minus negative TBO Indian monsoon years' composites:
(a) Equatorial upper-ocean T(z) for all TBO years and (b) non-ENSO onset TBO years for DJF prior to the Indian monsoon; (c) all TBO years and (d) non-ENSO onset TBO years for MAM prior to the Indian monsoon; (e) all TBO years and (f) non-ENSO onset TBO years for JJAS Indian monsoon season; (g) all TBO years and (h) non-ENSO onset TBO years for SON after the Indian monsoon; (i) all TBO years and (j) non-ENSO onset TBO years for DJF after the Indian monsoon. Positive anomalies are shaded; contour interval is 0.5C.

Meehl et al. 2003

Summary 4

- ENSO and IOD events are often **large-amplitude** excursions of TBO in the tropical Pacific and Indian Oceans
- ENSO and IOD make the TBO more biennial; without ENSO and IOD, TBO amplitudes are weaker



5. ENSO impact: (a) atmospheric bridge

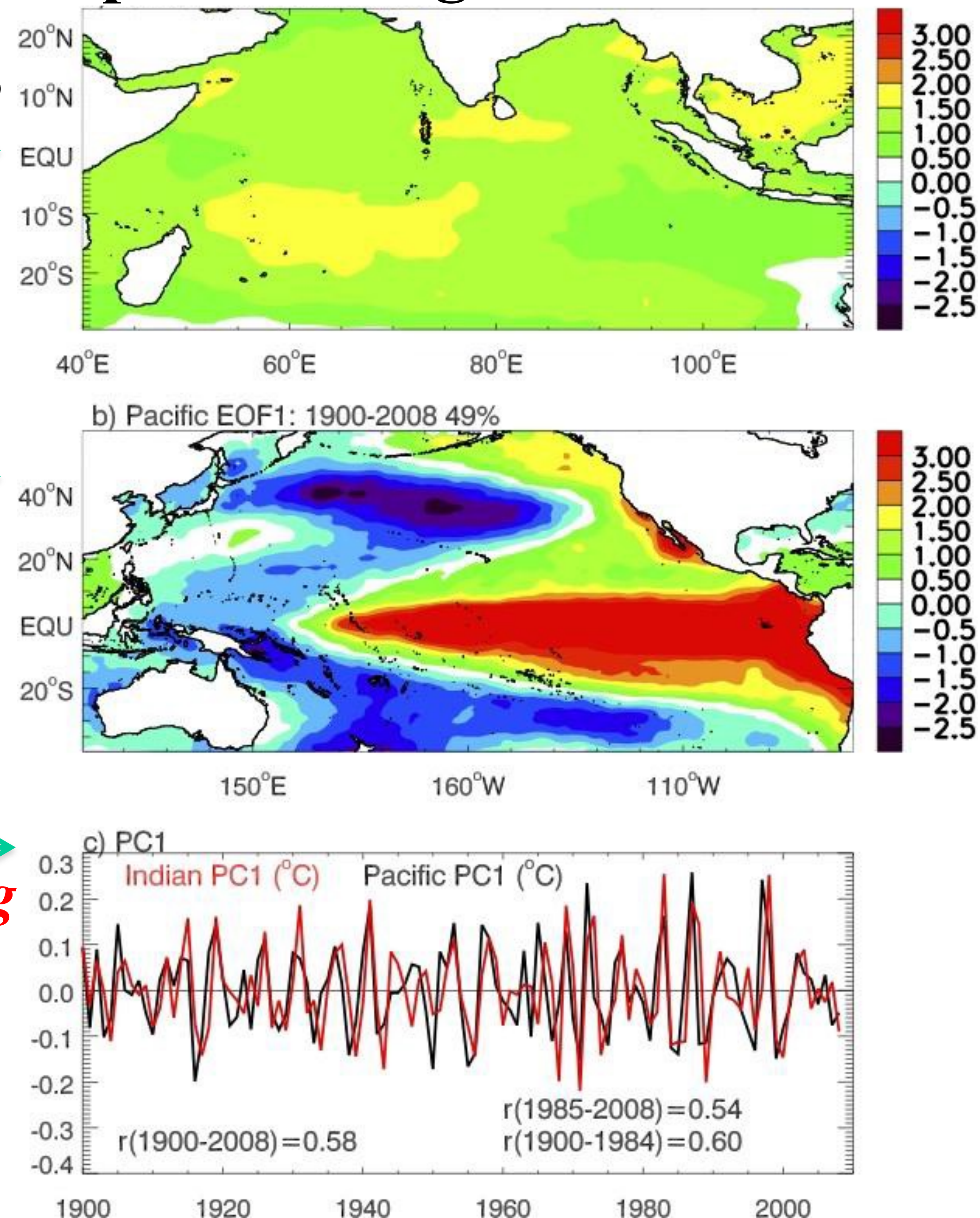
Indian SSTA EOF1 45%

Pacific SSTA EOF1:49%

PC1

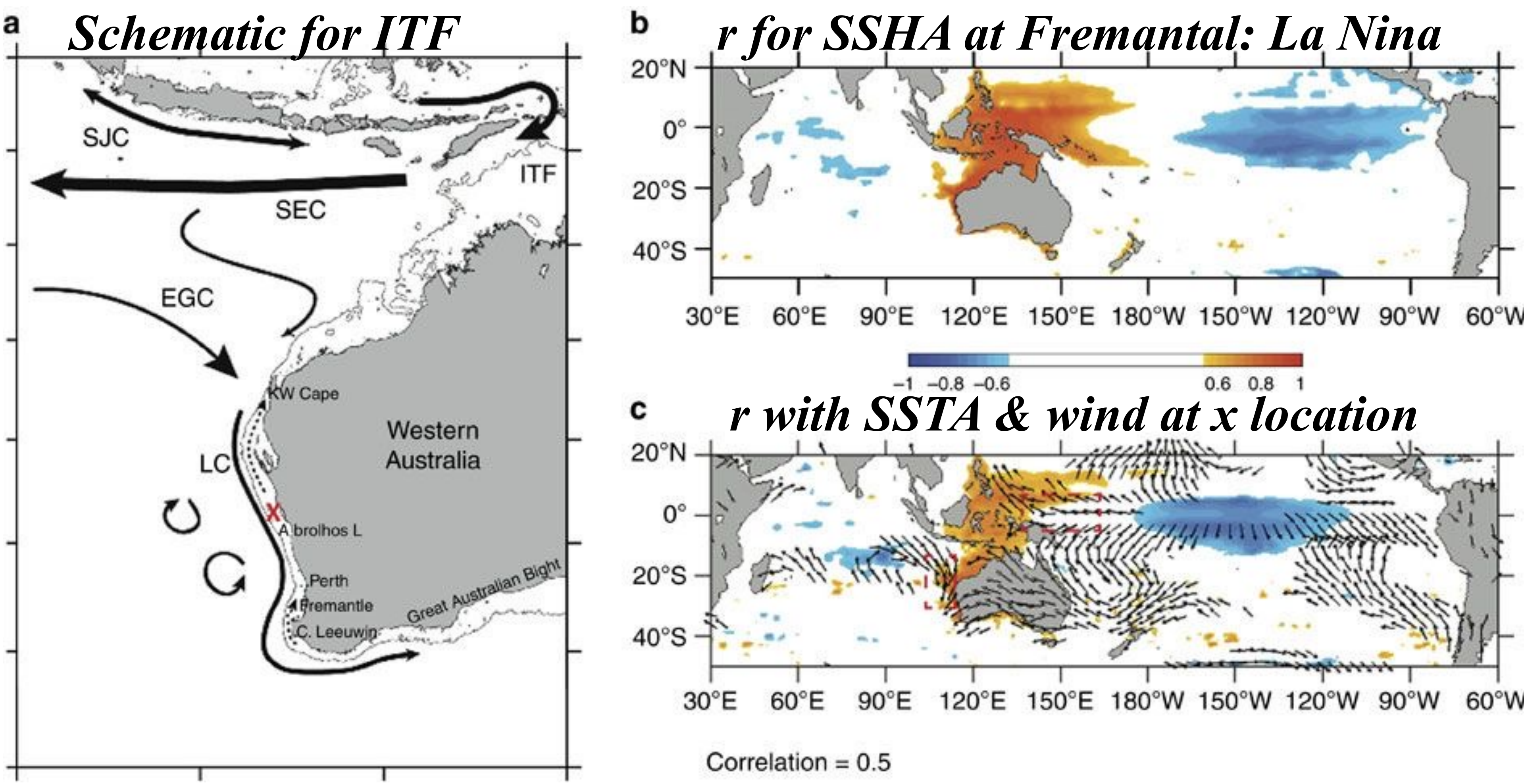
El Nino: Indian Ocean warming

La Nina: Indian Ocean cooling



Influence from the Pacific:
(b) oceanic connection – the Indonesian Throughflow (ITF)

El Nino: reduced the ITF; La Nina: enhanced ITF, Leeuwin current & warming along West Australian coast

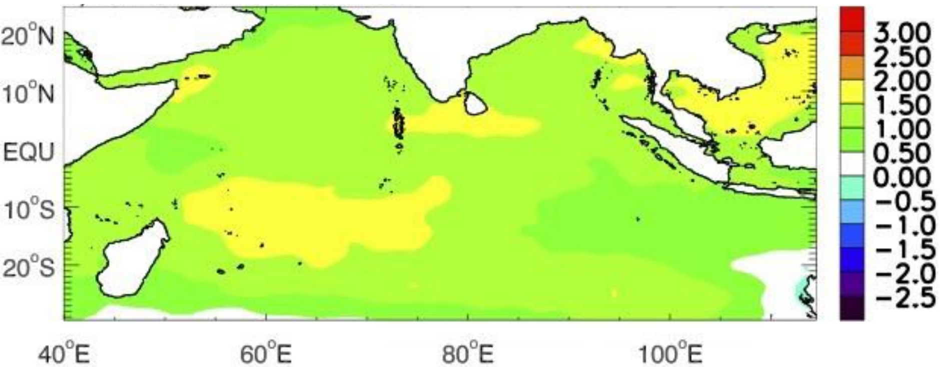


Feng et al. 2013; Zinke et al. 2014

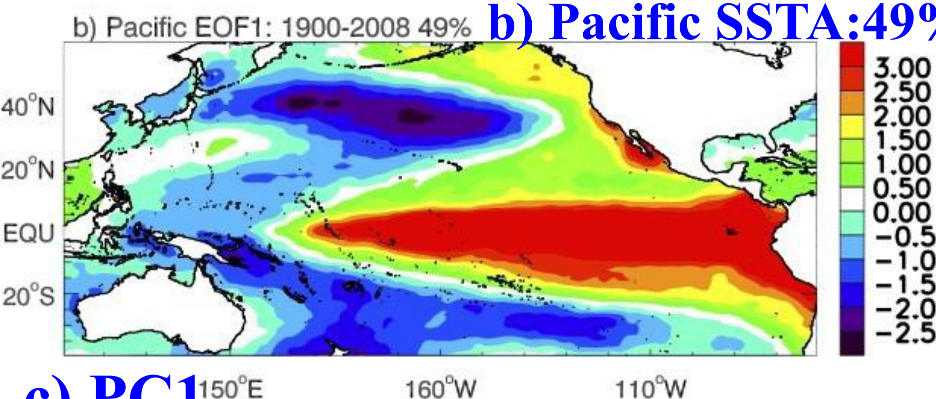
Thank you for your attention!

3. Influence from the Pacific: (a) atmospheric bridge

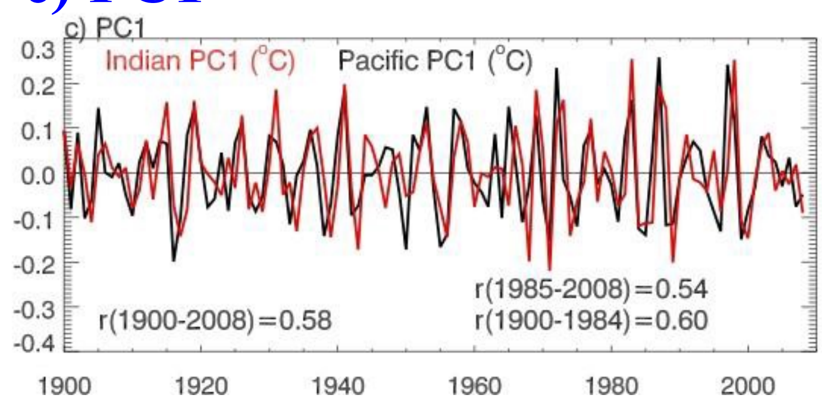
a) Indian SSTA EOF1 45%



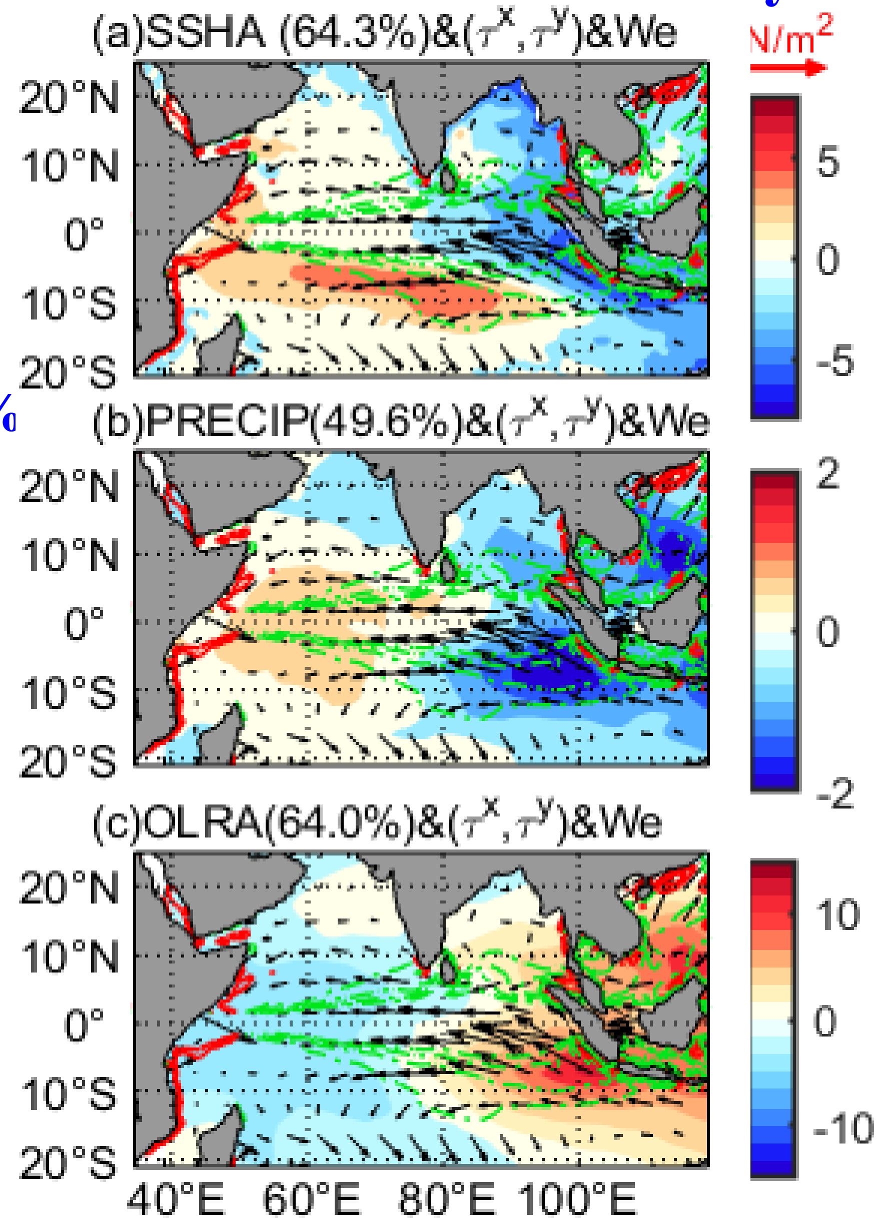
b) Pacific SSTA:49%



c) PC1

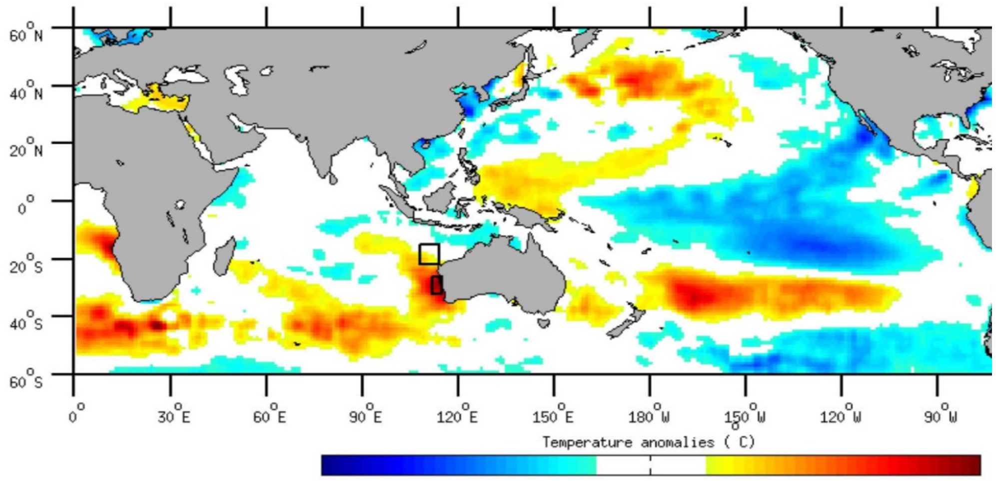


ENSO-induced variability

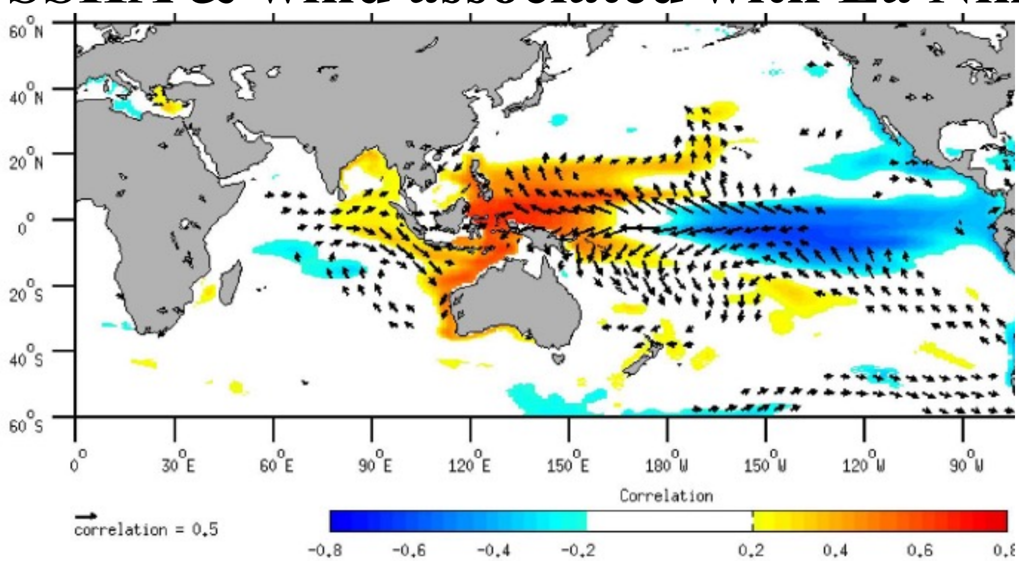


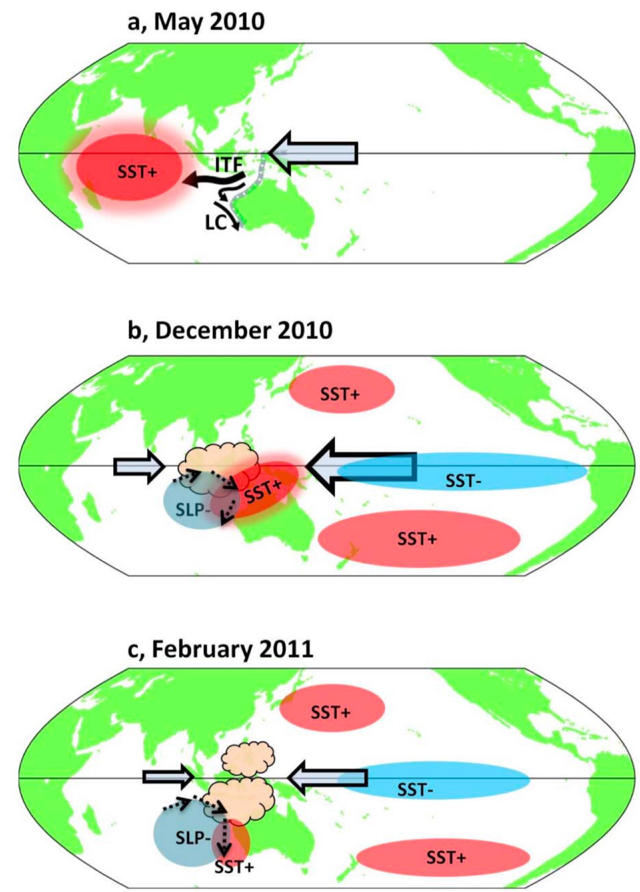
El Nino: reduced the ITF;
La Nina: enhanced ITF, Leeuwin current & warming

2011 La Nina: SSTA during Feb and Mar 2011



SSHA & wind associated with La Nina





Feng et al. 2013

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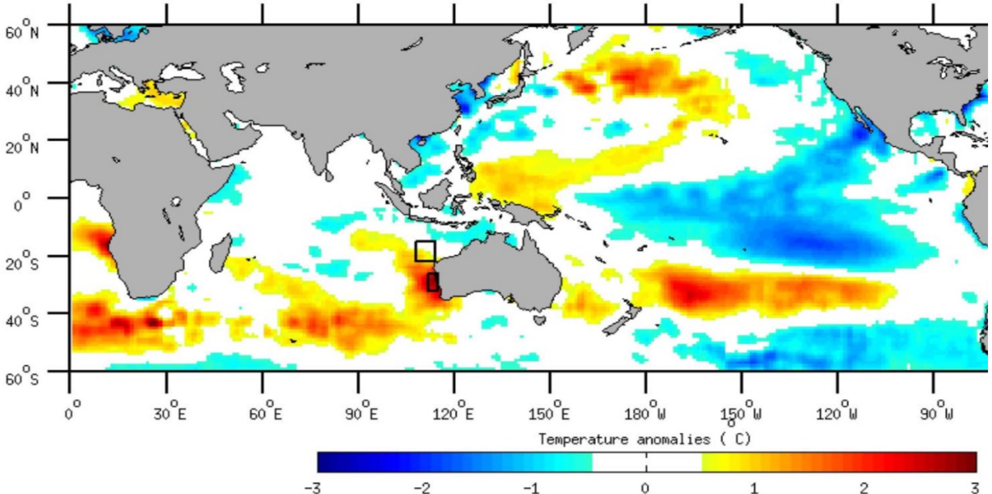
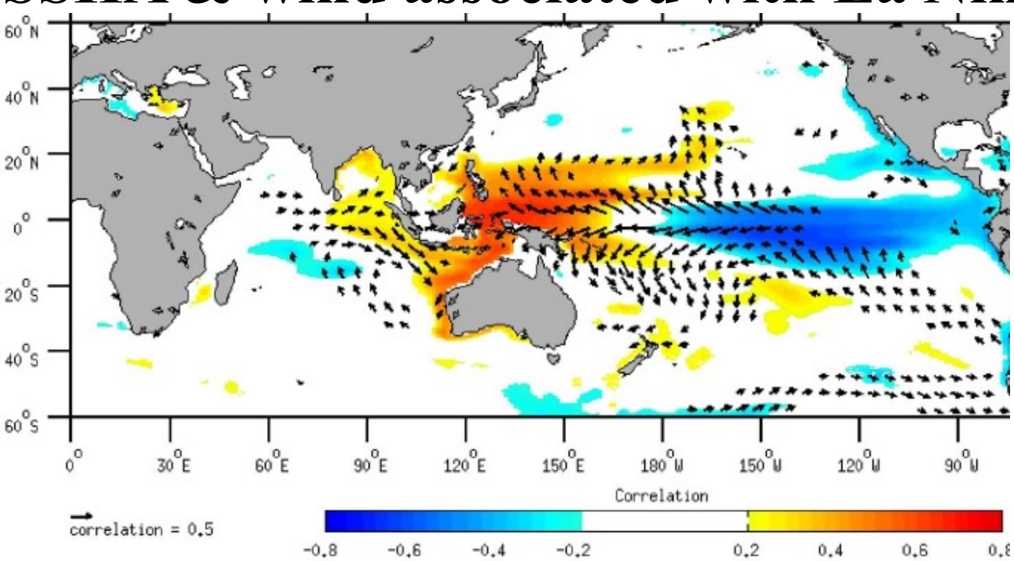
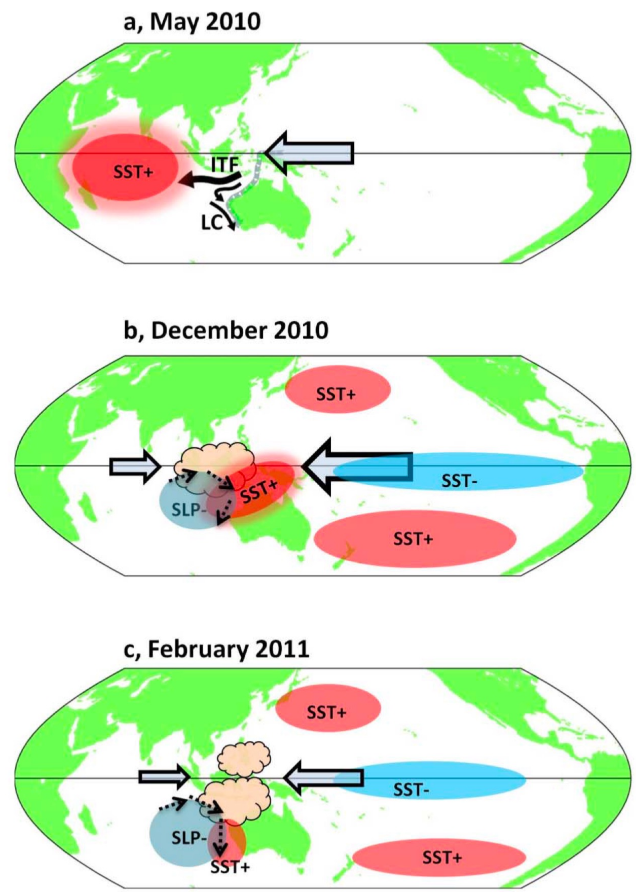


SSHA & wind associated with La Nina





Feng et al. 2013

Wind-driven shallow meridional overturning cells

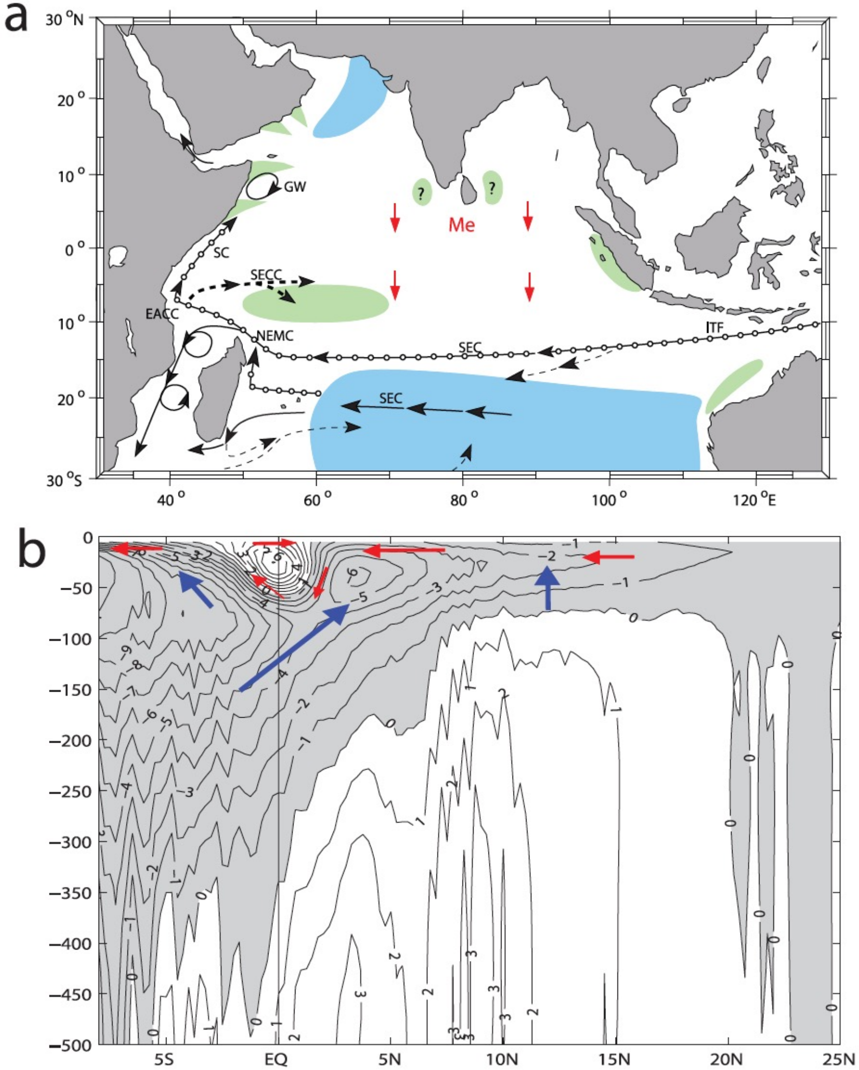


Figure 6. (a) Schematic representation of the Indian Ocean cross-equatorial cell (CEC) (light dashed stream paths for upper layer inflow into subduction zone (blue), dotted for thermocline Somali Current supply, and solid for Southern Hemisphere thermocline flow) and of the subtropical cell (STC) (heavy dashed supply route via SECC) along with upwelling zones (green) that participate in the CEC and STC. See Figure 3 for circulation names (based on *Schott et al.* [2004]). (b) Mean overturning stream function (units in Sv) of model used by *Miyama et al.* [2003] showing southward near-surface warm water flow by Ekman transports (red vectors), which have to "dive underneath" the equatorial roll, and upwelling (blue) supplying coastal upwelling regimes off Somalia and Arabia at 5–20°N and open ocean upwelling at 3–12°S.

$$M(y) = \frac{1}{\beta}[\bar{\tau}^y(x_w, y) - \bar{\tau}^y(x_e, y)] - \frac{1}{\beta}\int_{x_w}^{x_e} \bar{\tau}_y^x \, dx$$

But zonal wind dominates
Miyama et al. 2003

Schott et al. 2009