Indian Ocean circulation, dynamics and climate variability modes

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ECCO Summer School, May 19-31, 2019, FHL, U. of Washington

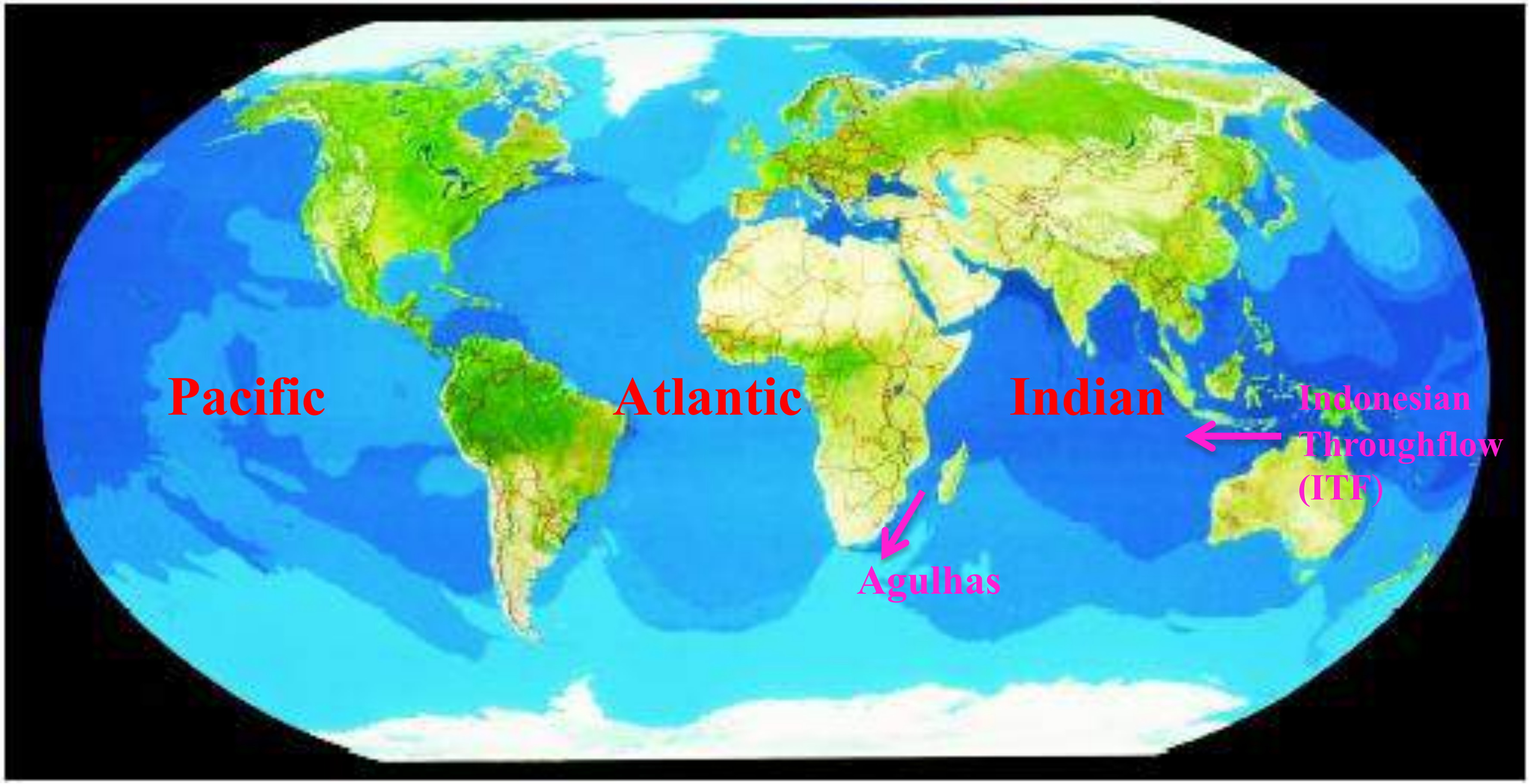
Outline

1. Monsoon and seasonal ocean circulation

2. Major climate modes

3. Influence from the Pacific

Ocean basins

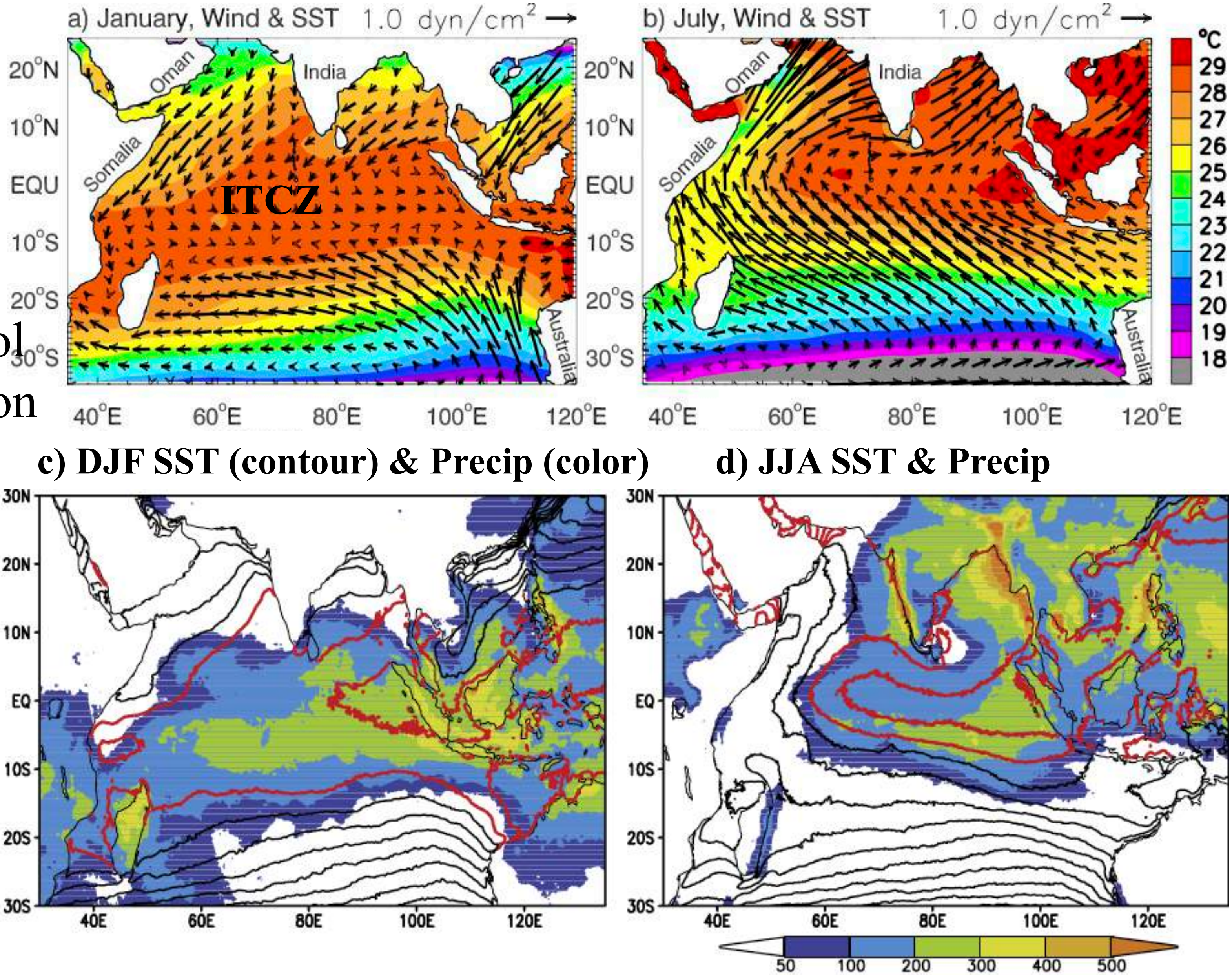


What are the unique aspects of the Indian Ocean basin, compared to that of the Pacific and Atlantic?

1. Monsoon & seasonal circulation

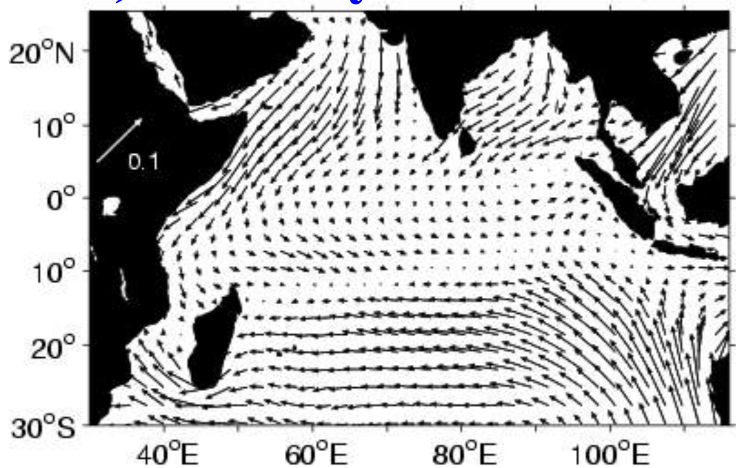
1. Monsoon Win/Sum reversing Wind;

2. Warm pool & convection

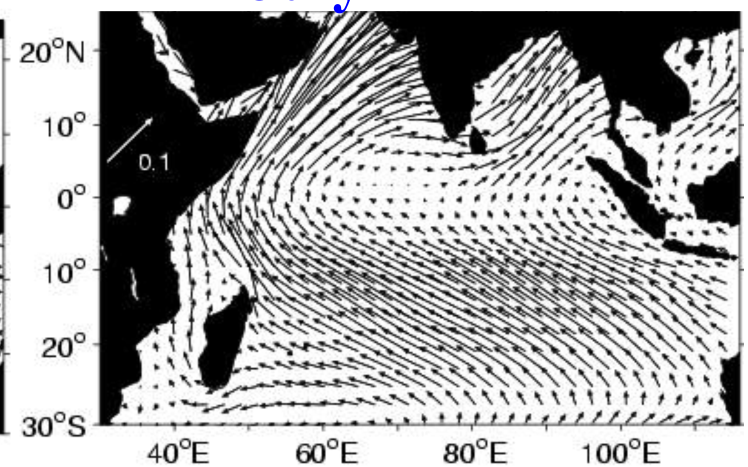


Surface wind stress: monsoon & transition

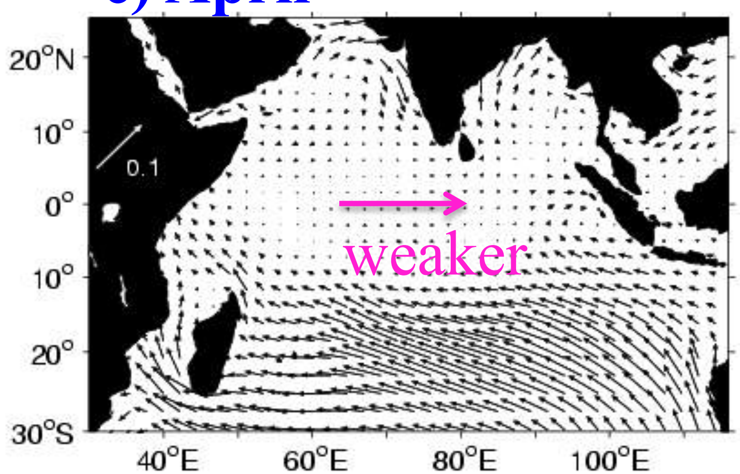
a) January



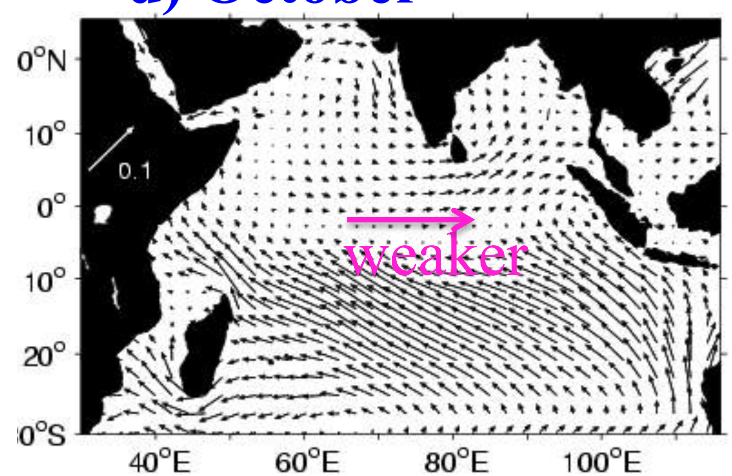
July



c) April



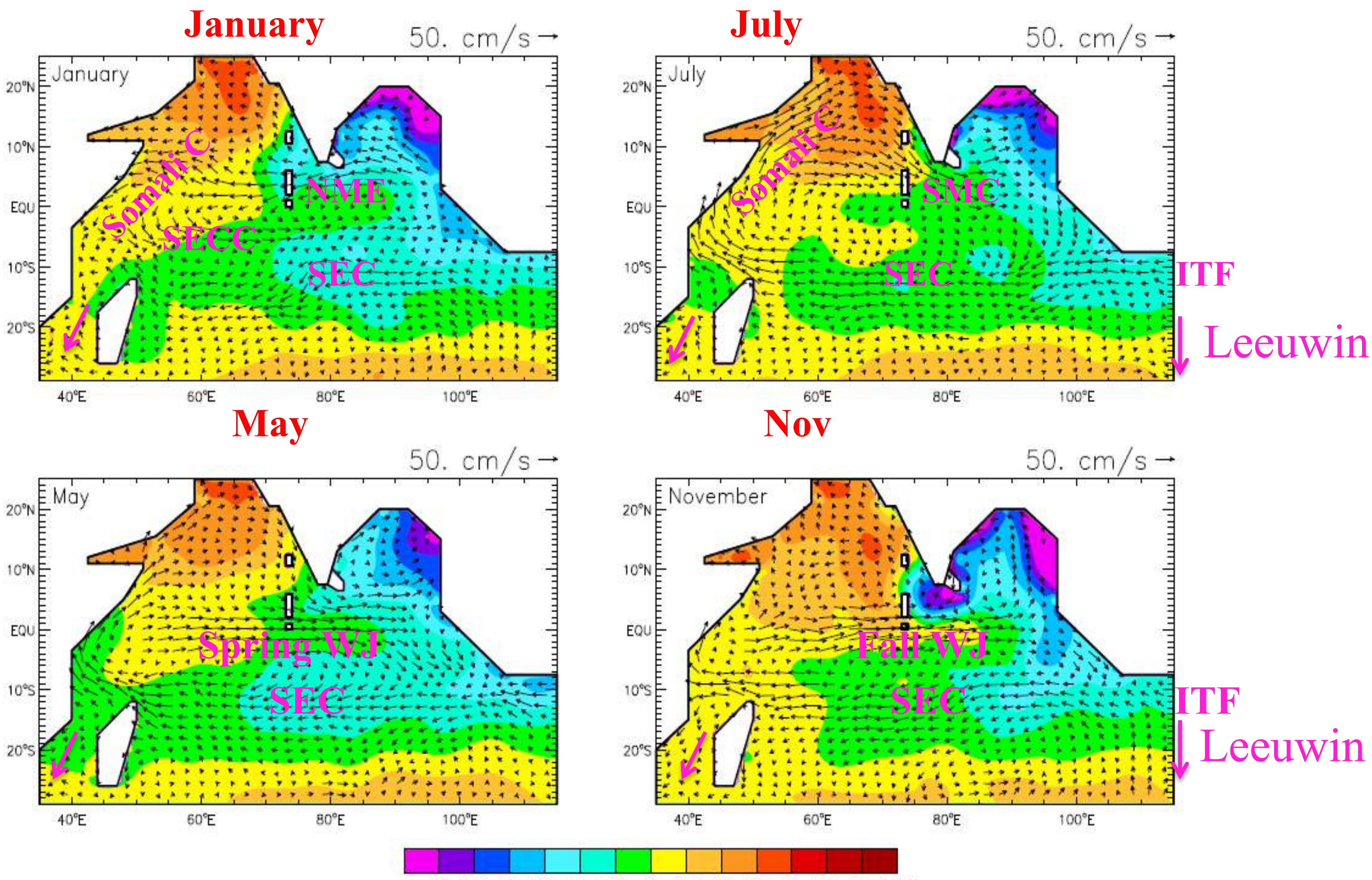
d) October



EQ: Annual mean winds are westerlies; different from the Pacific & Atlantic where EQ easterly trades prevail

Observed ocean surface current & sea surface salinity

Heat+Salt balance: Arabian Sea & Bay of Bengal



Observed zonal surface current: spring&fall Wyrtki Jets

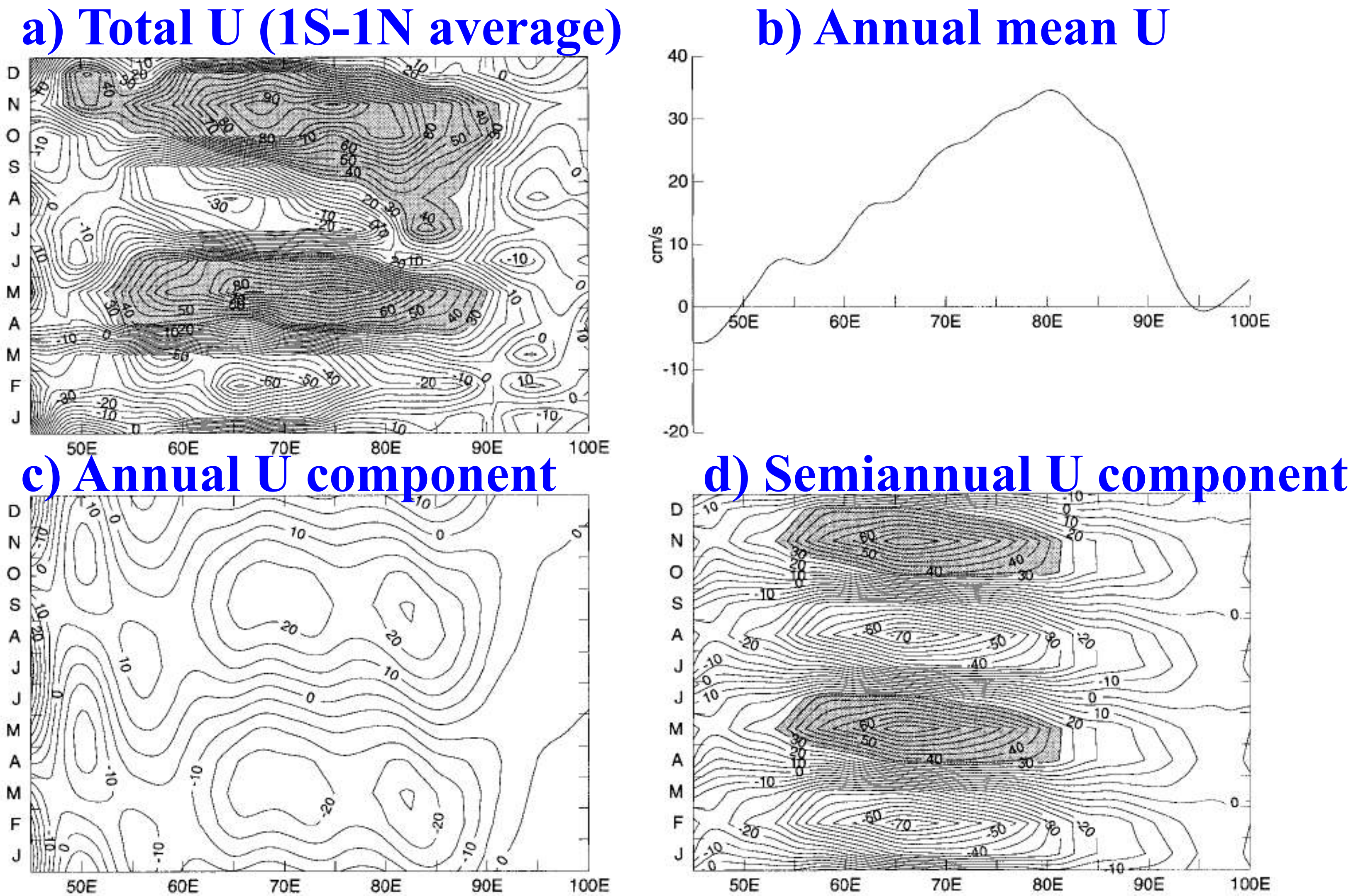
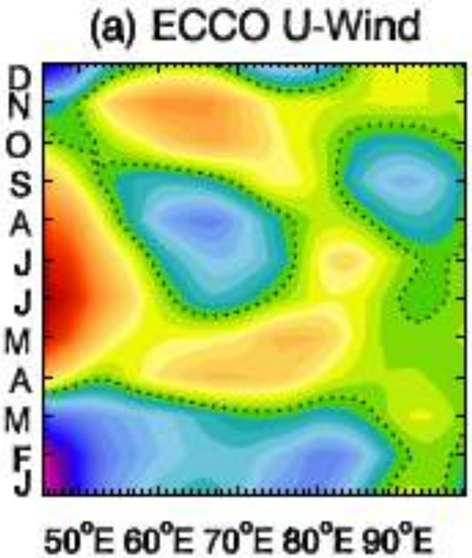


FIG. 1. Longitude–time plots of equatorial zonal currents U averaged from 1°S to 1°N, determined from the ship-drift climatology of Mariano et al. (1995): The total flow (a: top left) together with its time-averaged mean (b: top right), annual (c: bottom left), and semiannual (d: bottom right) components. The contour interval is 5 cm s^{-1}, and regions where the flow is stronger than 30 cm s^{-1} are shaded. The observations have been smoothed zonally by a 1–2–1 filter. The data is available online at ftp://playin.rsmas.miami.edu/pub/cg.

Han et al. 1999

Observed zonal surface wind along Indian Ocean EQ



Halkides & Lee 2009

a) Total taux (1S-1N mean) **b) Annual mean**

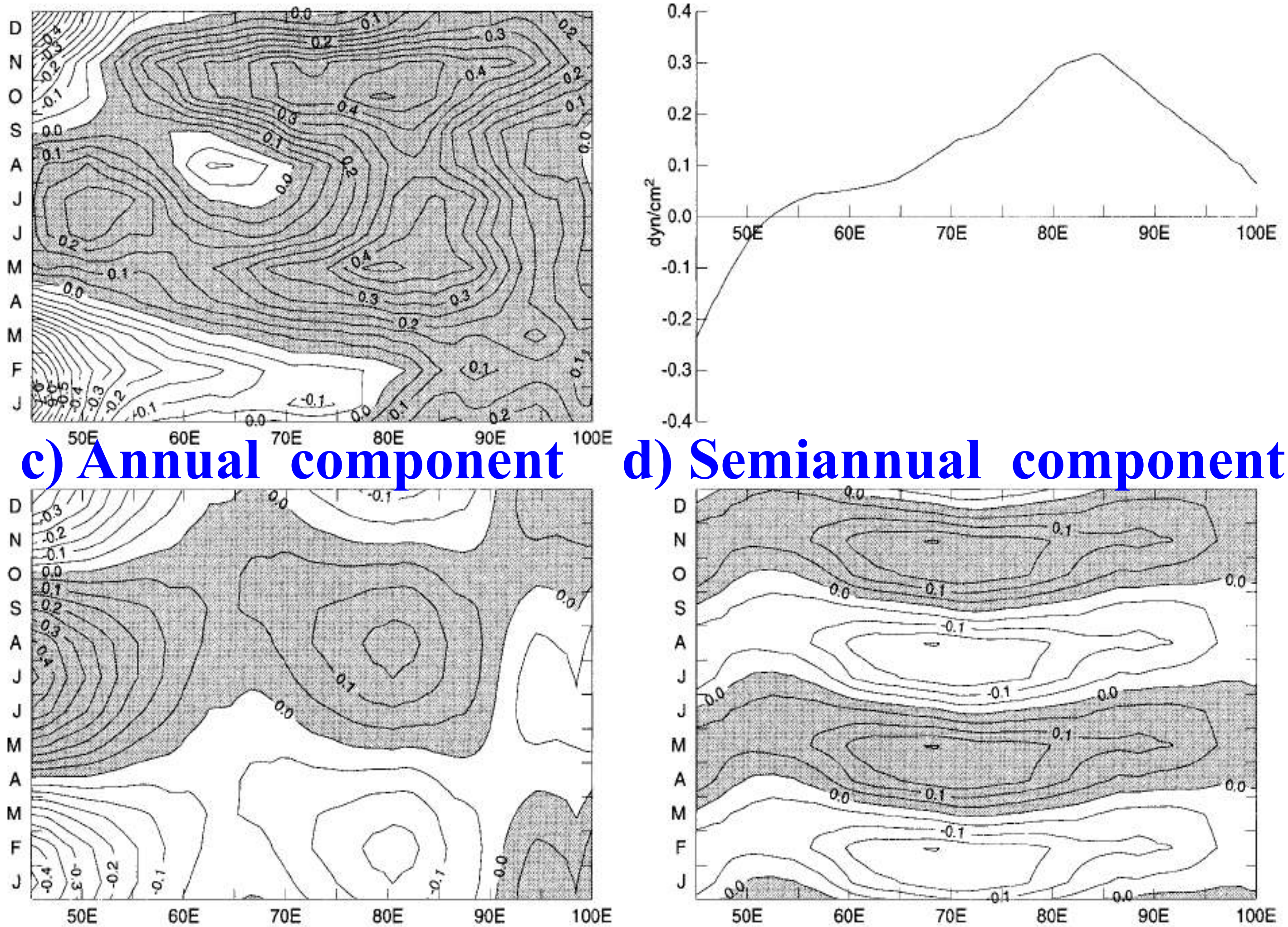
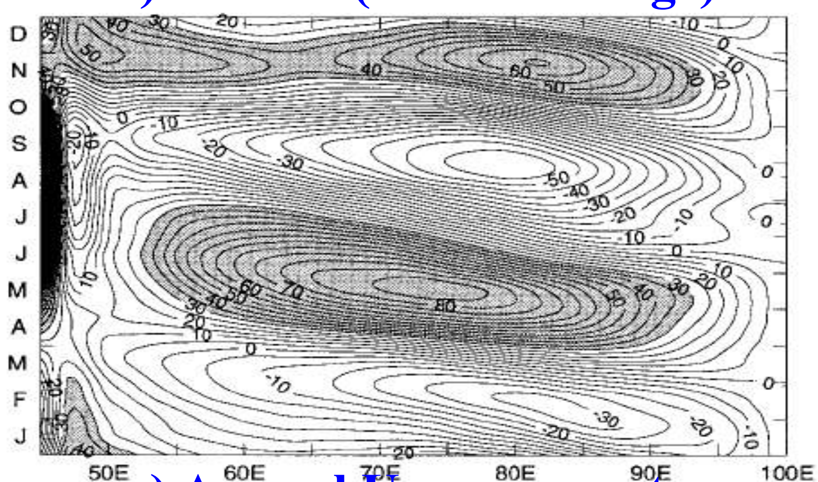


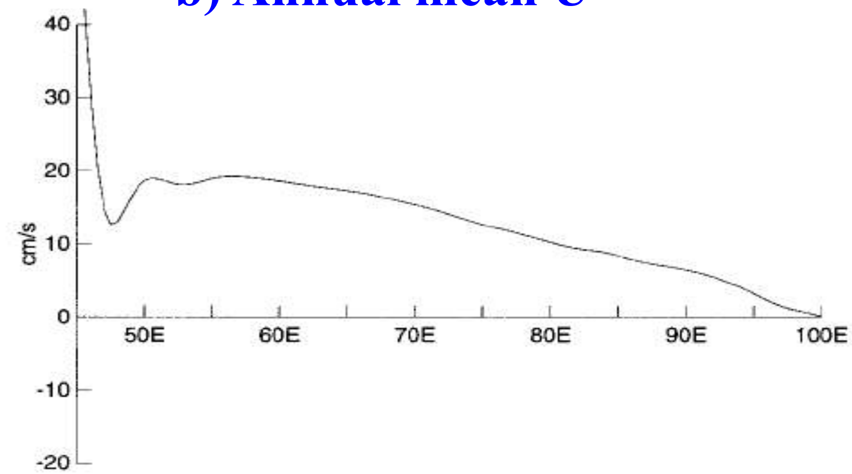
FIG. 2. Longitude–time plots of equatorial zonal wind stress τ^x averaged from 1°S to 1°N, determined from the FSU pseudostress climatology for the period 1970–96 with $\rho_a = 0.001\,175$ g cm^{-3} and $C_d = 0.0015$: The total wind (a: top left) together with its time-averaged mean (b: top right), annual (c: bottom left), and semiannual (d: bottom right) components. The contour interval is 0.05 dyn cm^{-2}, and regions of eastward winds (positive values) are shaded.

Linear 2.5-layer ocean model simulation: U at EQ

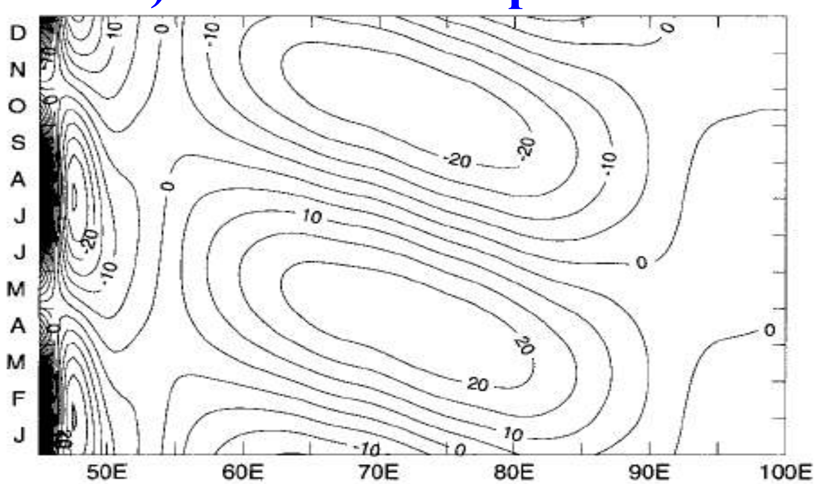
a) Total U (1S-1N average)



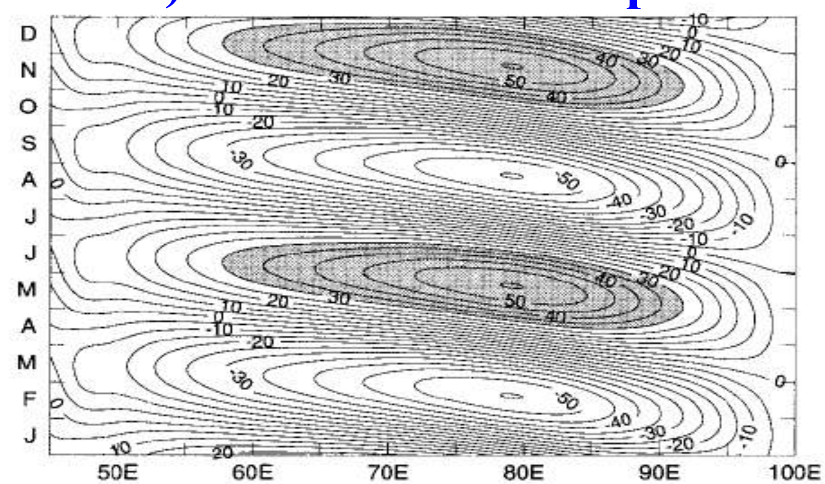
b) Annual mean U



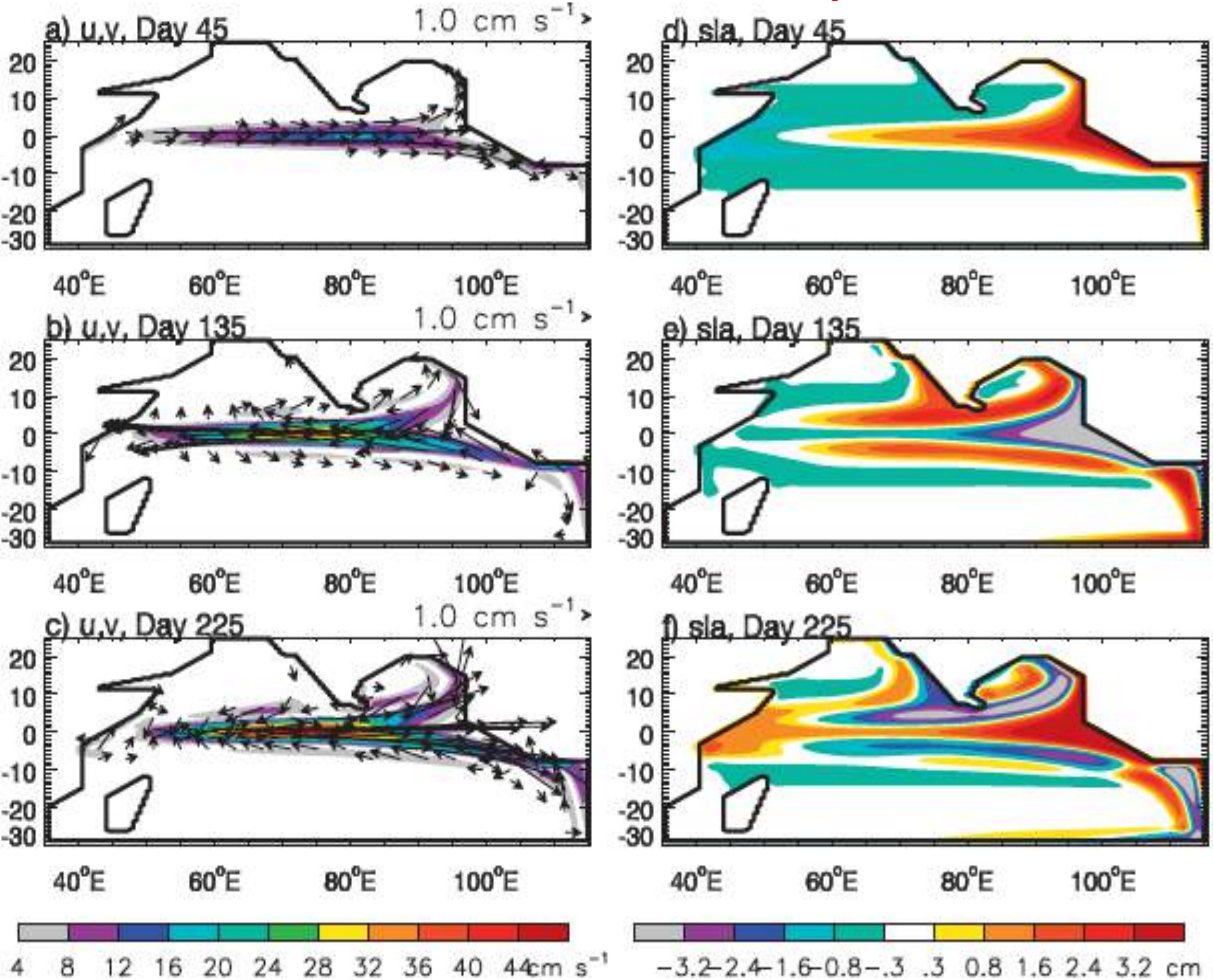
c) Annual U component



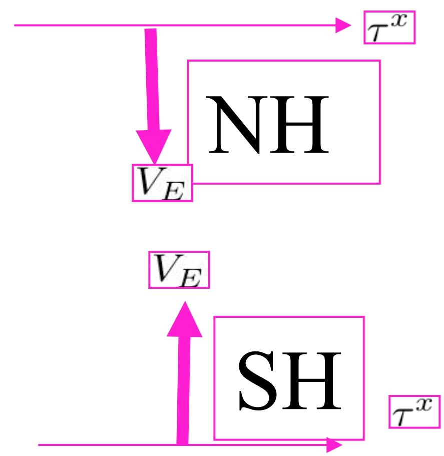
d) Semiannual U component



Linear ocean model: forced by semiannual zonal wind



Ekman transport



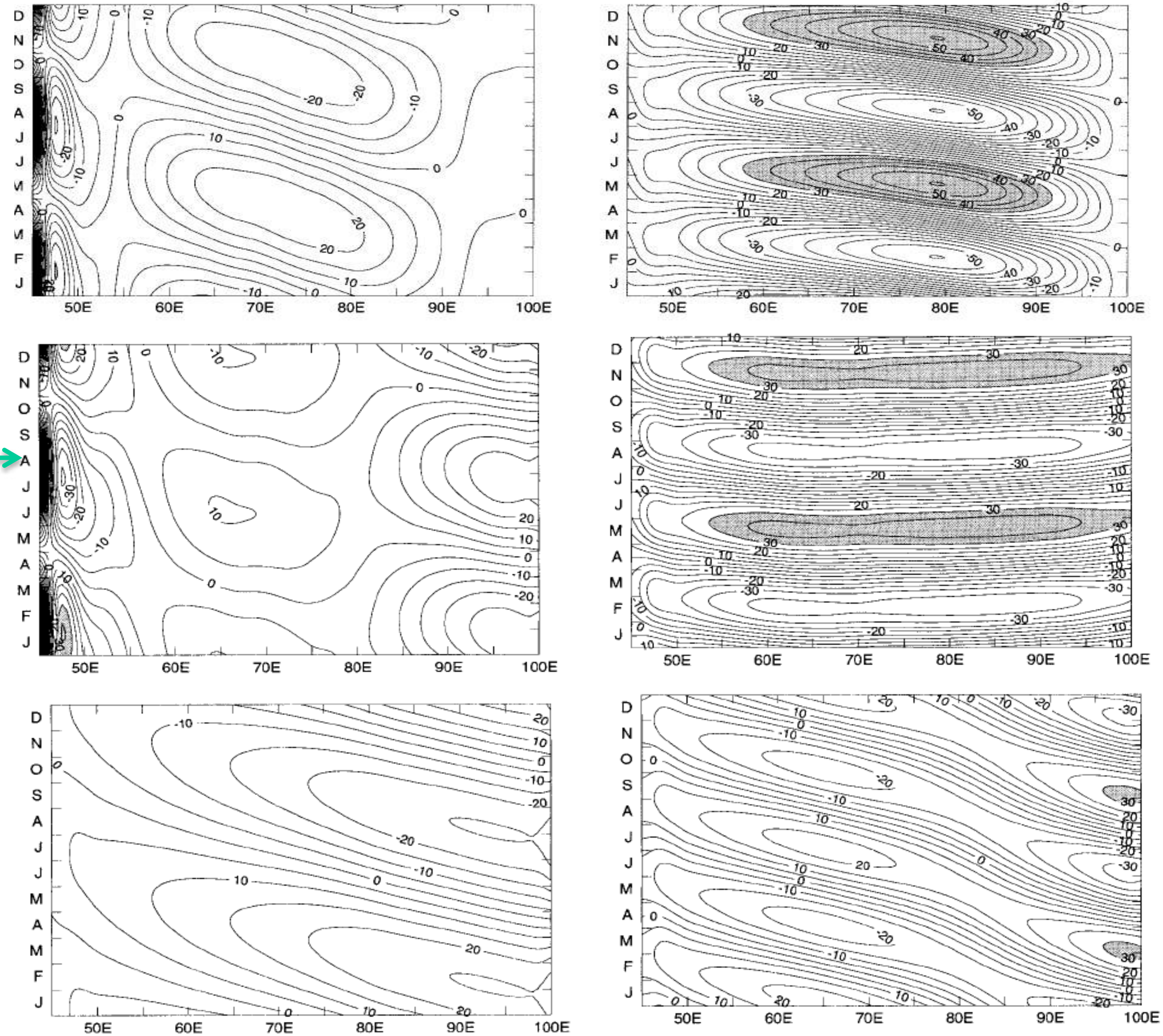
Han et al. 2011

Linear 2.5-layer ocean model simulation: EQ U

Annual U **Semiannual U**

Directly Forced
no reflected RW

Reflected RW from eastern boundary



$$T = \frac{4L}{mc_n},$$

L: Indian Ocean Zonal width

m=1,2,…

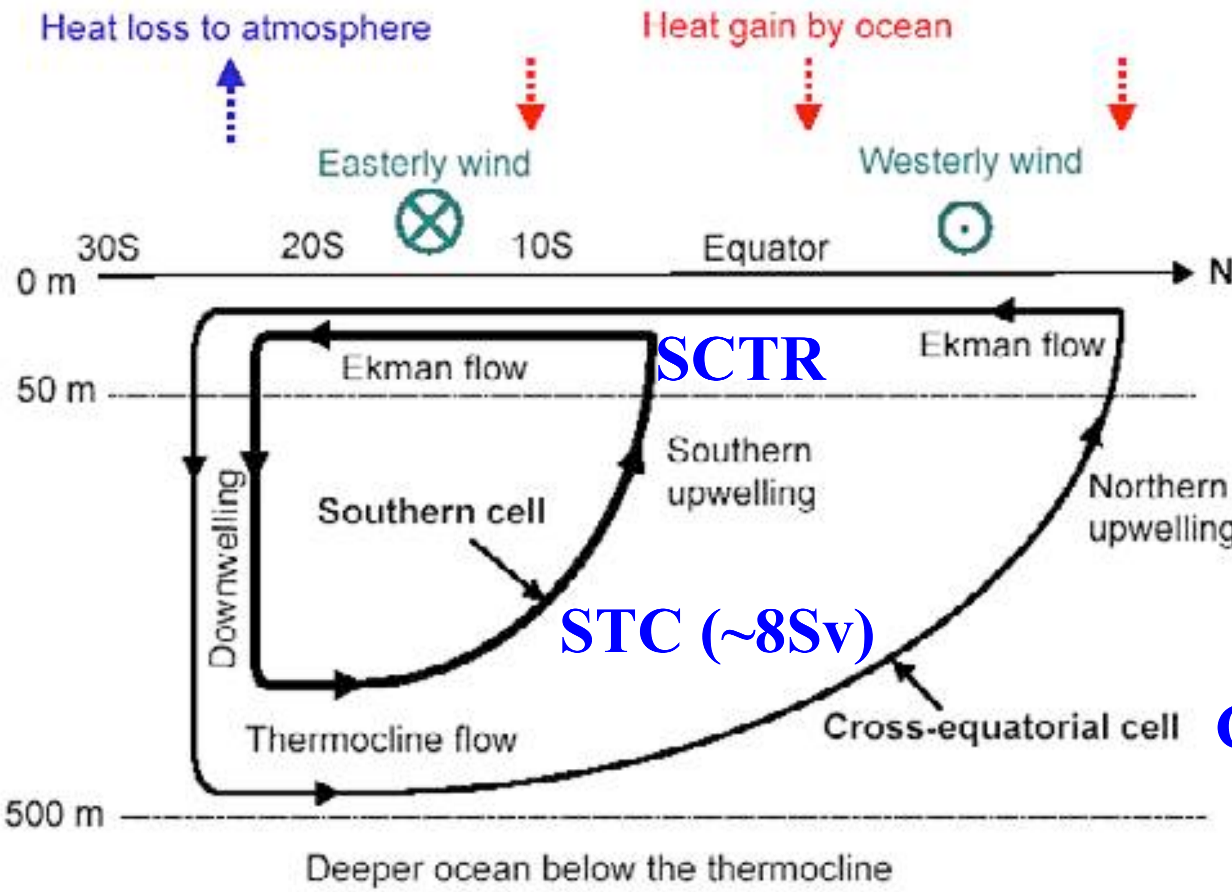
C_n: baroclinic mode speed

T: Forcing period (e.g., semiannual=180days)

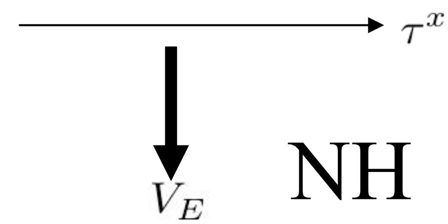
Basin resonance in the EQ Indian Ocean:

EQ Indian Ocean L: C_2~170cm/s, T=180

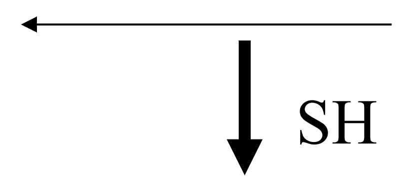
Wind-driven shallow meridional overturning cells



Lee 2004



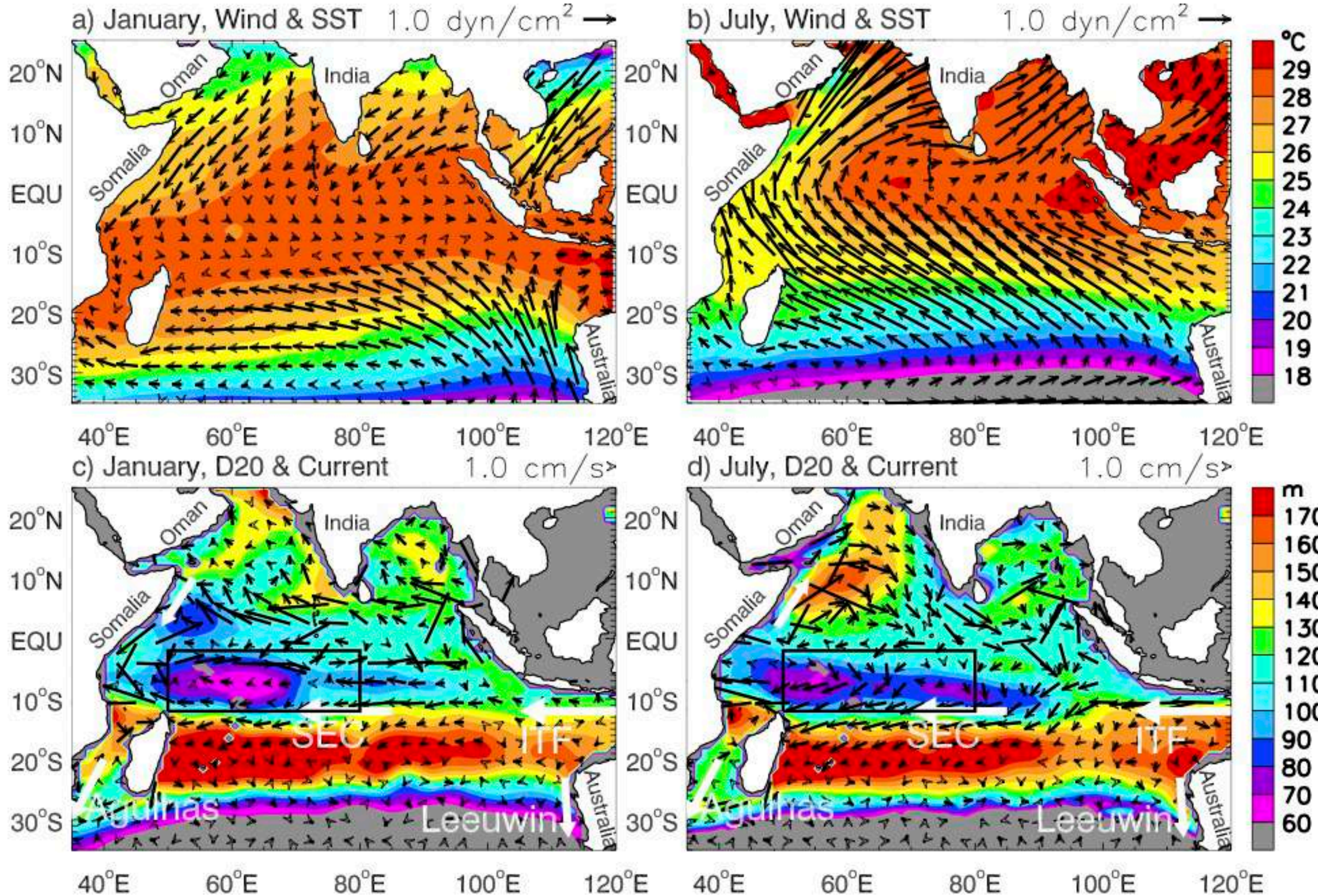
$$V_E = \int_{-H_E}^{0} v_E \, dz = -\frac{\tau^x}{\rho_0 f}$$



Unique to the Indian Ocean: CEC & off-EQ upwelling

Ekman pumping velocity:

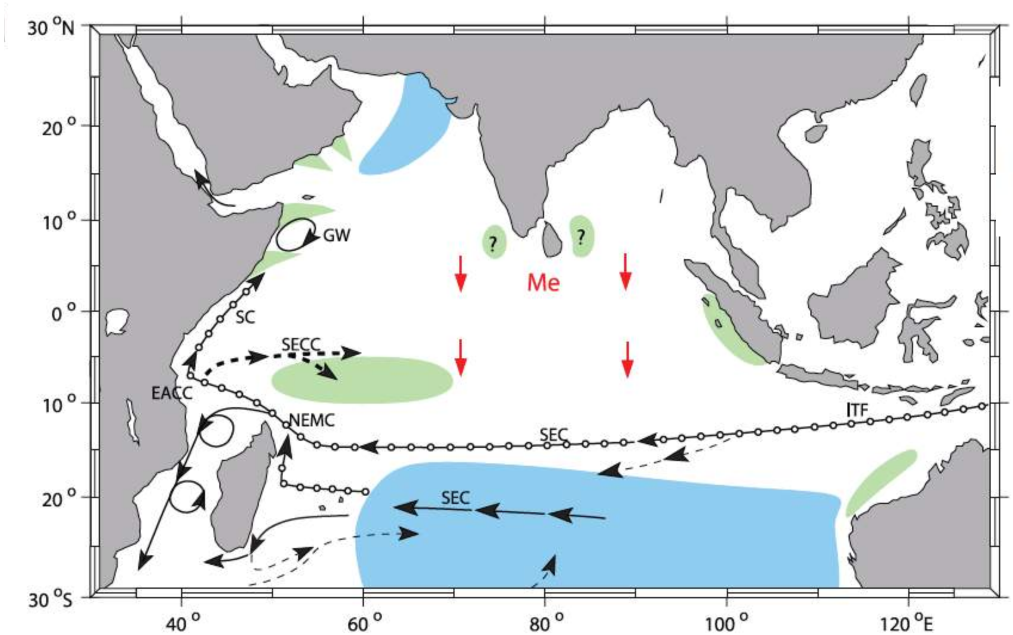
$$w_e = \frac{\partial}{\partial x}\left(\frac{\tau^y}{\rho f}\right) - \frac{\partial}{\partial y}\left(\frac{\tau^x}{\rho f}\right)$$



a) Seychelles-Chagos Thermocline Ridge (SCTR) – mean upwelling zone

b) Somali & Oman, West Indian & east EQ, Java and Sumatra - coastal upwelling areas during boreal summer & fall

3D: Wind-driven shallow meridional overturning



Cross-EQ Cell (CEC)

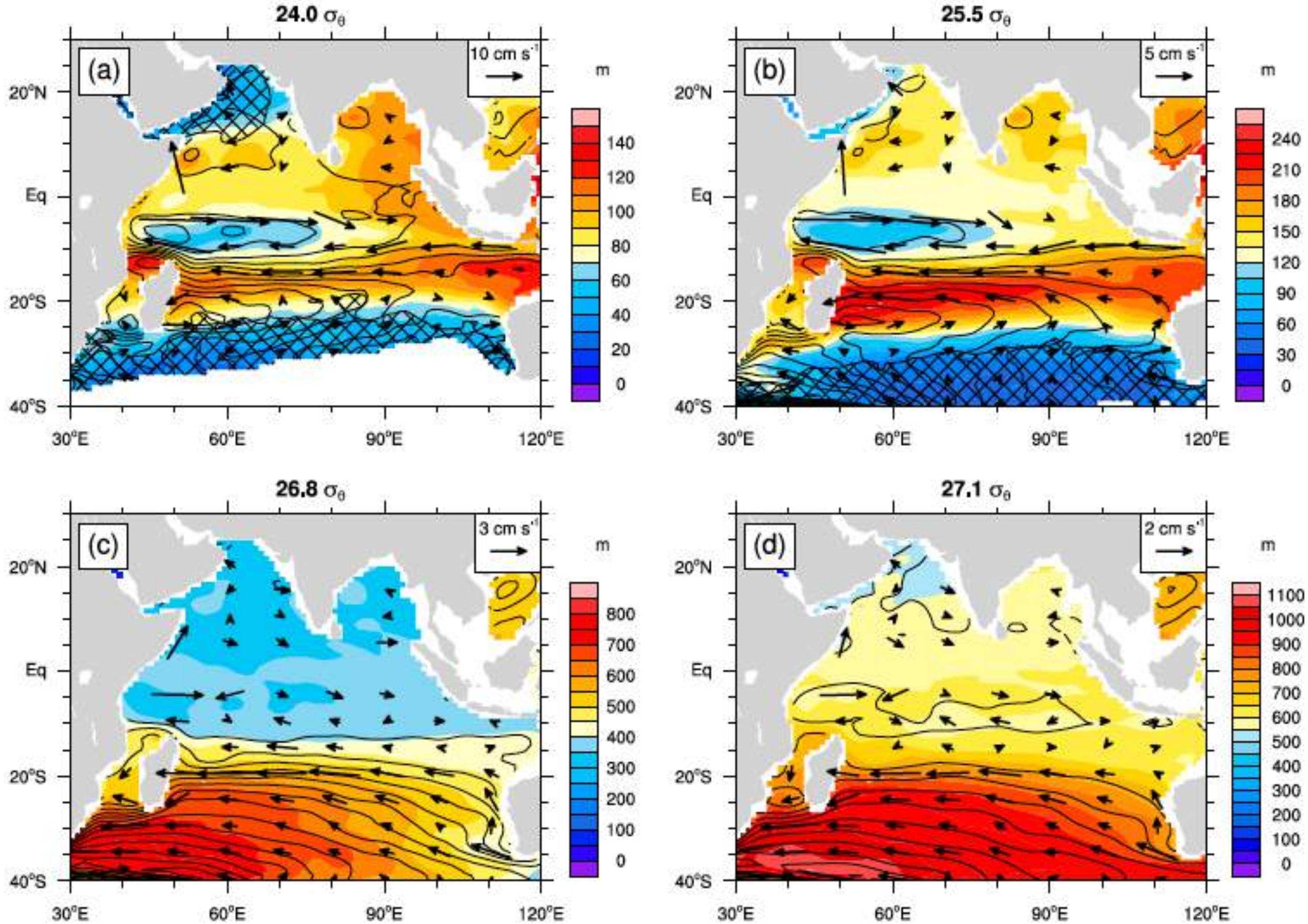
$$M(y) = \frac{1}{\beta}[\bar{\tau}^y(x_w, y) - \bar{\tau}^y(x_e, y)] - \frac{1}{\beta}\int_{x_w}^{x_e} \bar{\tau}_y^x \, dx$$

zonal wind dominates

Subtropical Cell (STC)

Miyama et al. 2003;Schott et al. 2009

Wind-driven shallow meridional overturning cell: STC



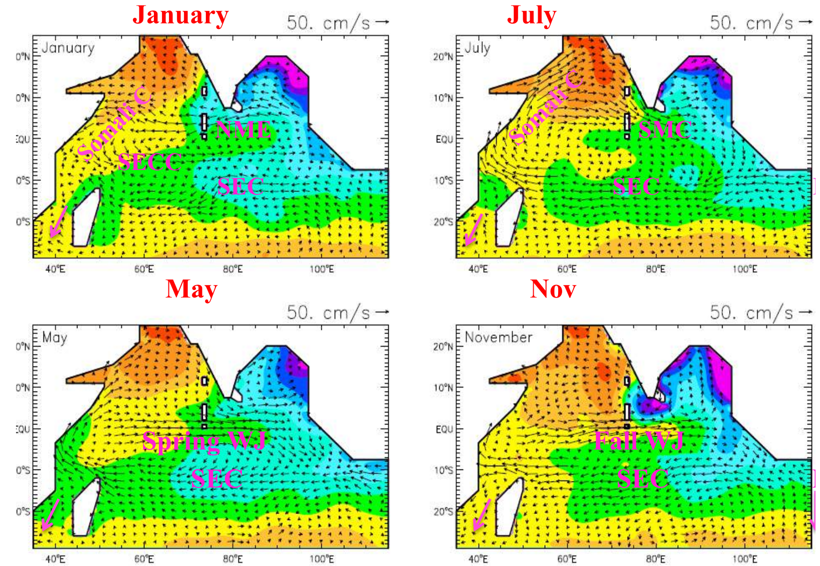
Nagura & McPhaden 2018

FIG. 5. Mean depth of isopycnals (colors), absolute velocity (vectors), and streamlines for absolute velocity (contours) obtained from in situ observations. (a) $24\sigma_\theta$, (b) $25.5\sigma_\theta$, (c) $26.8\sigma_\theta$, and (d) $27.1\sigma_\theta$. Contour intervals for streamlines are (a) 0.5, (b) 0.5, (c) 0.3, and (d) $0.3 \times 10^4\ m^2\ s^{-2}$. Hatching shows outcropping regions, where the annual mean depth of the isopycnal is shallower than the wintertime MLD. The MLD is defined from potential density as the depth where density is higher than the 10-m value by $0.03\ kg\ m^{-3}$ following de Boyer Montégut et al. (2004).

Summary 1

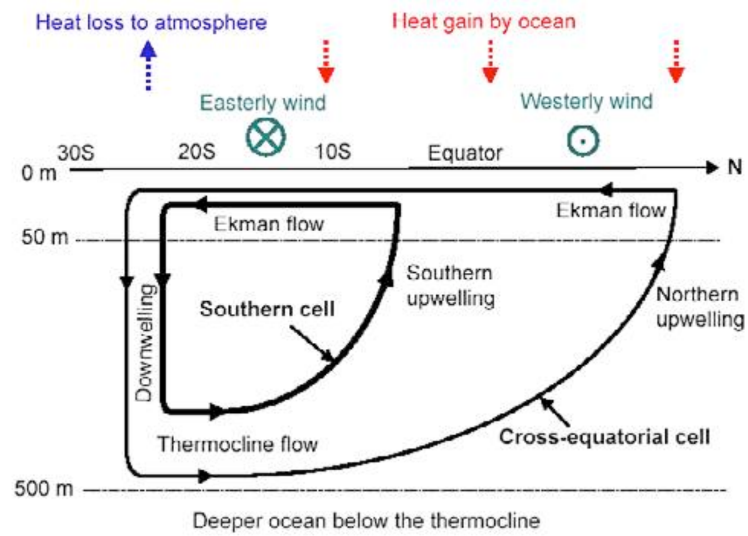
(1) Land-ocean heating contrast:

Monsoon & Indian Ocean seasonal circulation: Spring & Fall Wyrtki Jets: Forced KW+RW & Reflected RW – East-west salt balance



(2) North Indian Ocean: net heat gain:

CEC & STC
Heat balance



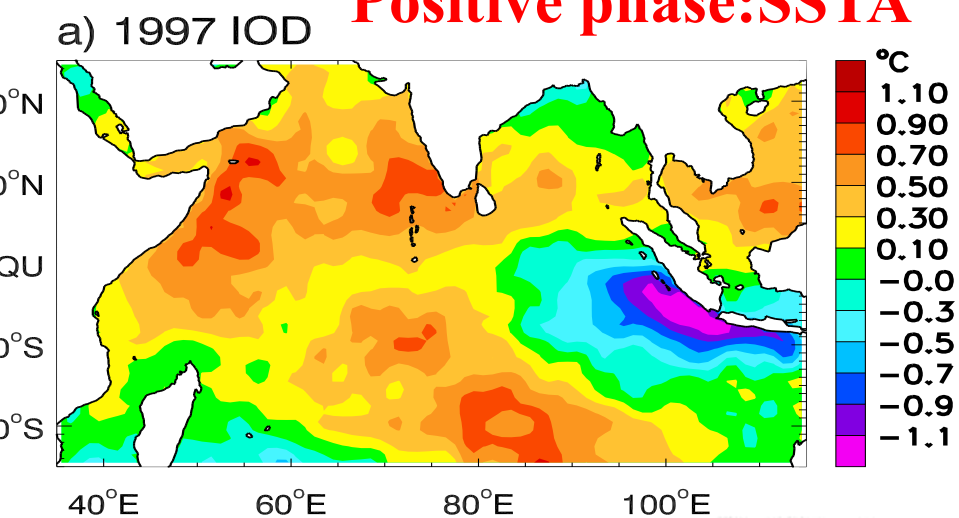
2. Major Climate modes of variability

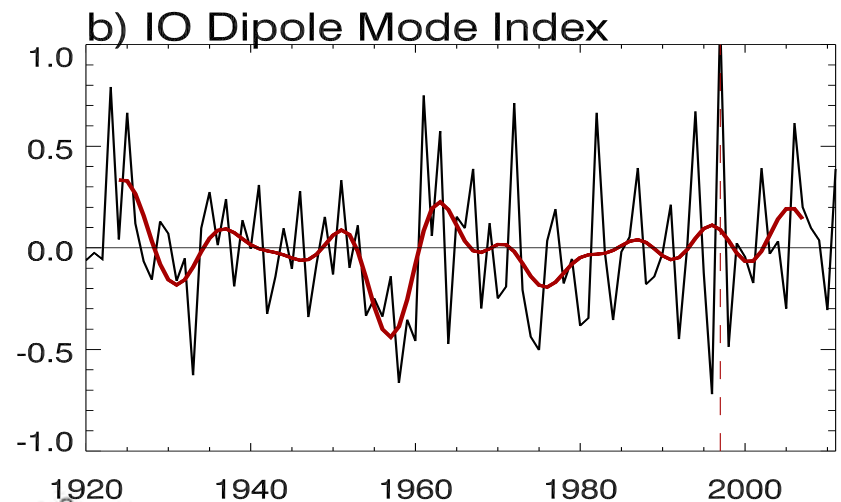
Tropical Indian Ocean: *interannual* climate mode:

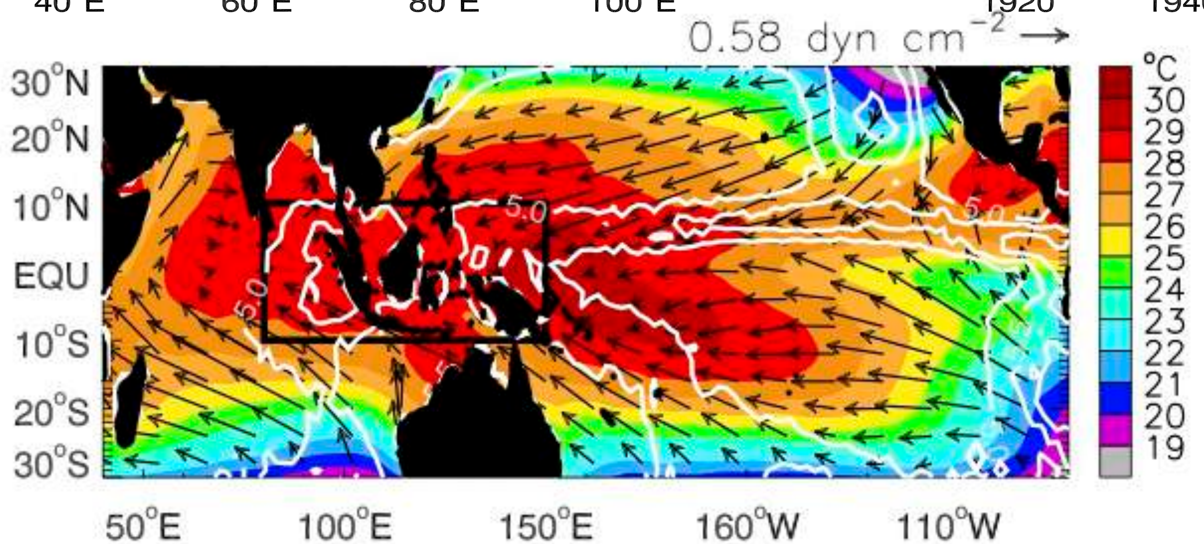
The Indian Ocean Dipole (IOD) (*Saji et al. 1999, Webster et al. 1999)*

(Subtropical IOD: discussed here)

Positive phase:SSTA



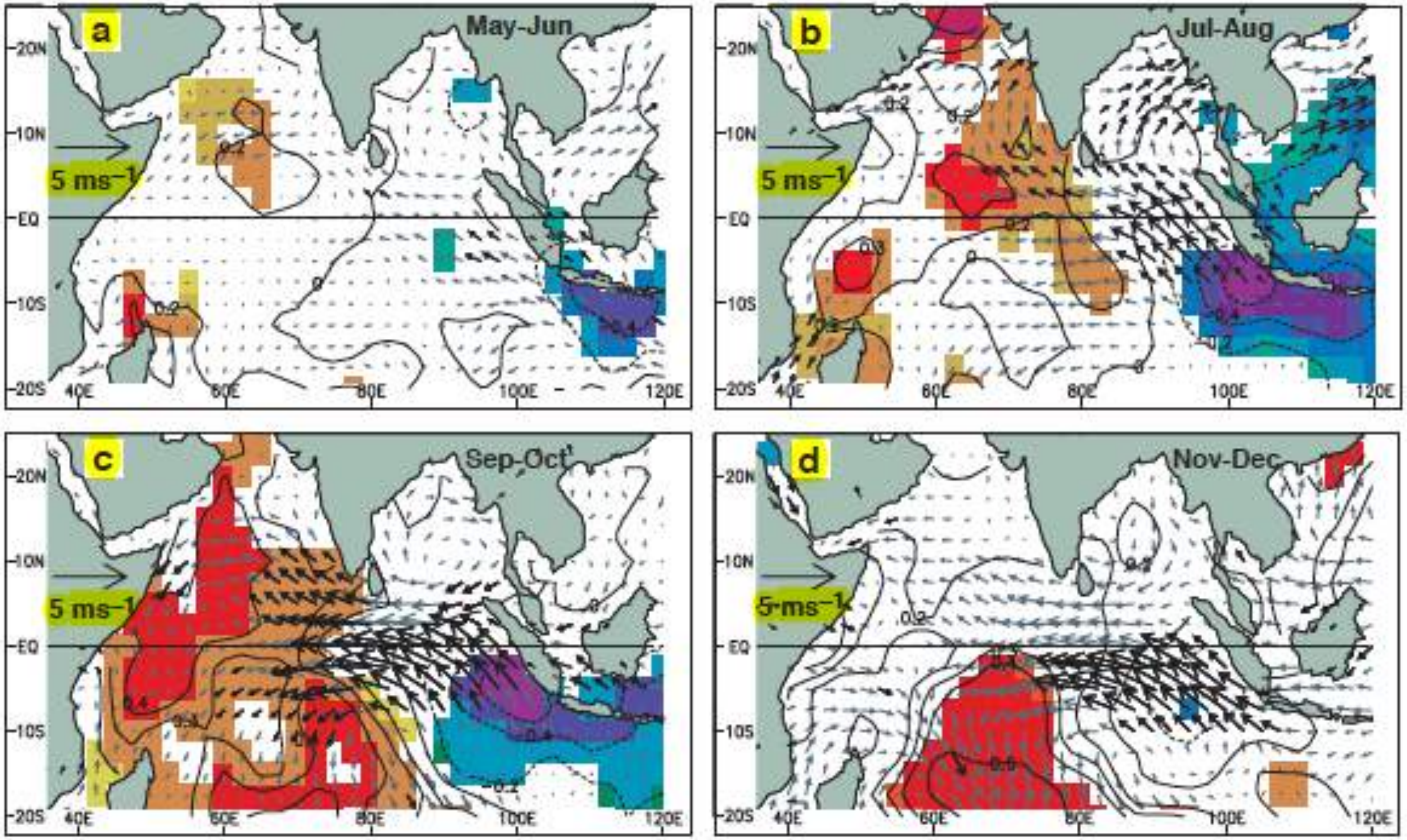




Climate impacts:

Indonesia drought & East African floods; affect El Nino & likely Indian summer monsoon

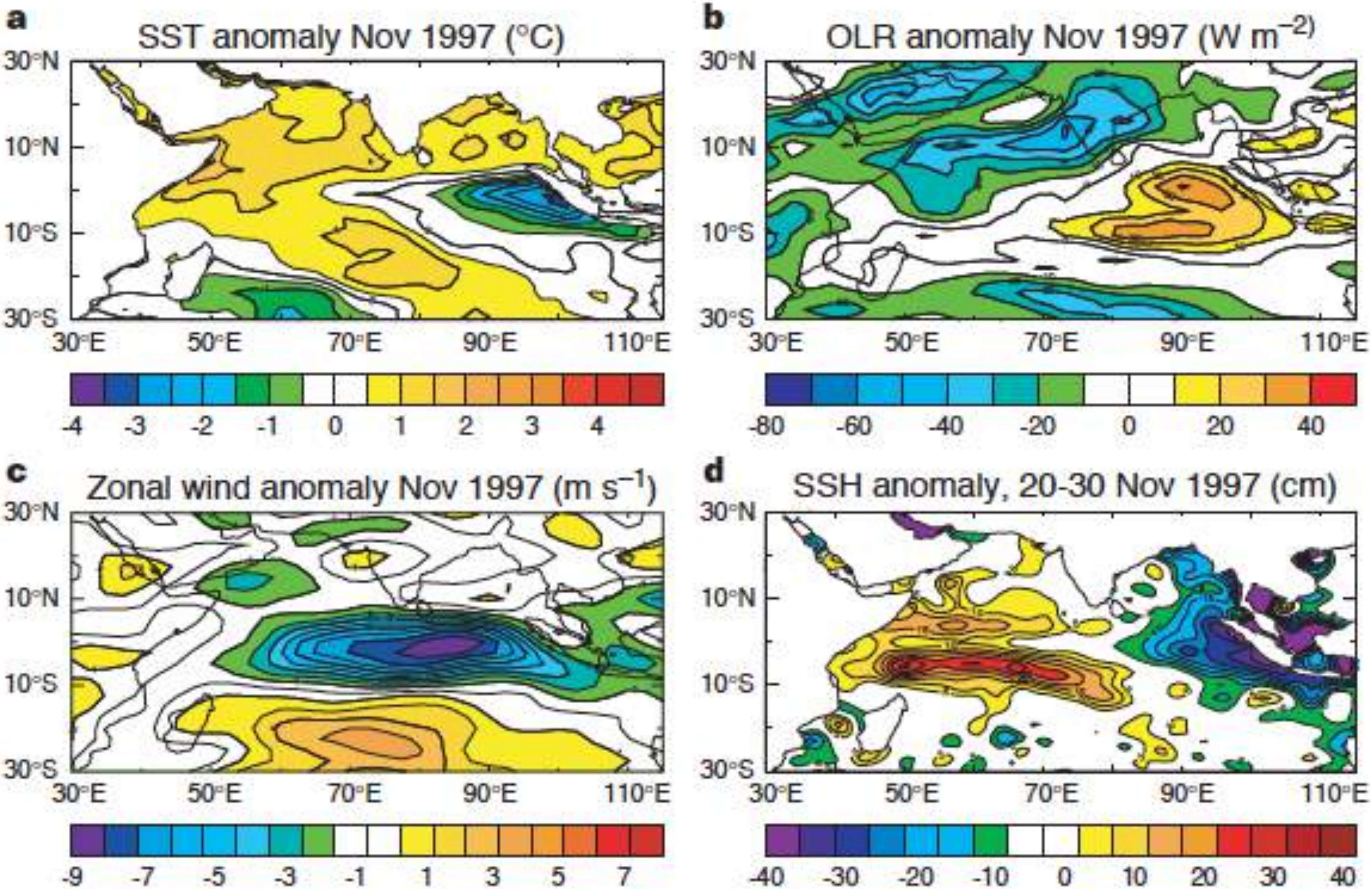
The coupled ocean-atmosphere mode: IOD evolution



(1) Summer-Fall: seasonal phase locked with Sumatra-Java upwelling;

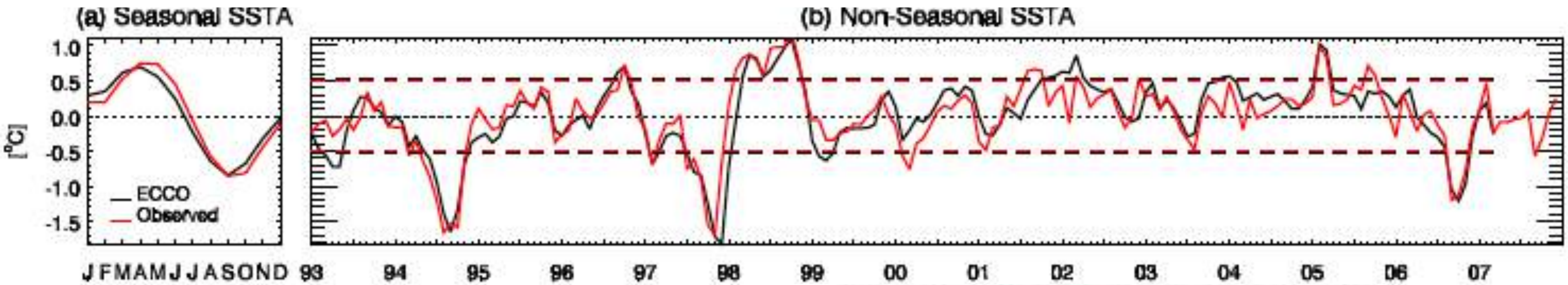
(2) fall Wyrtki Jet is extremely weak or disappears

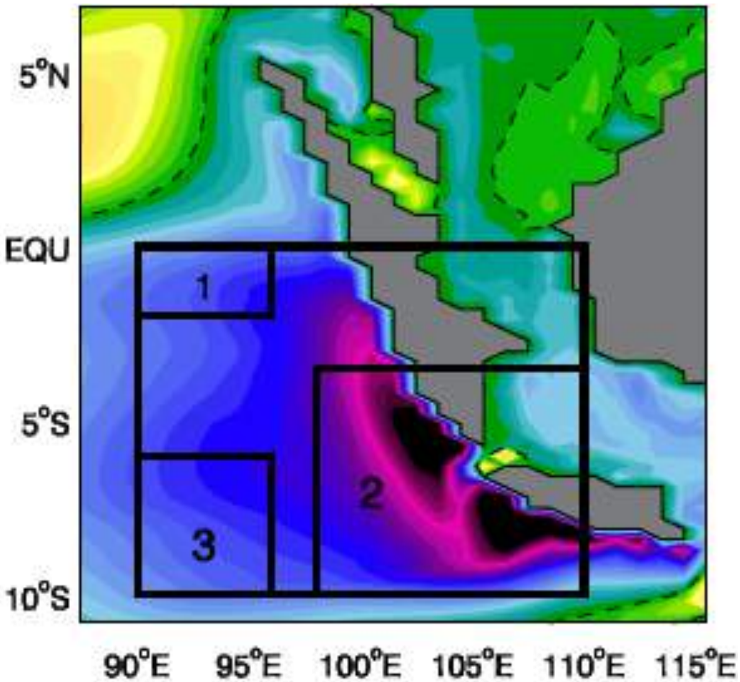
Saji et al. 1999

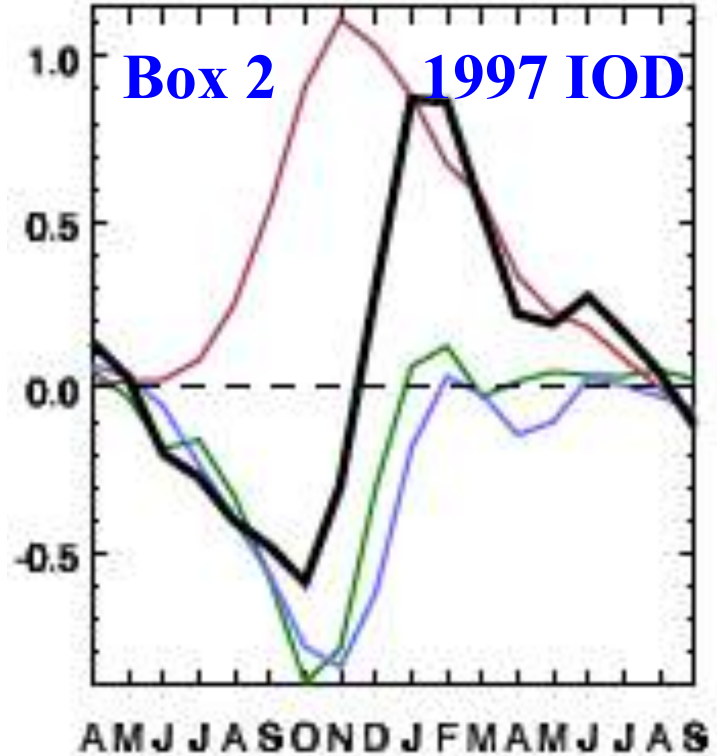


Webster et al. 1999

ECCO budget analysis





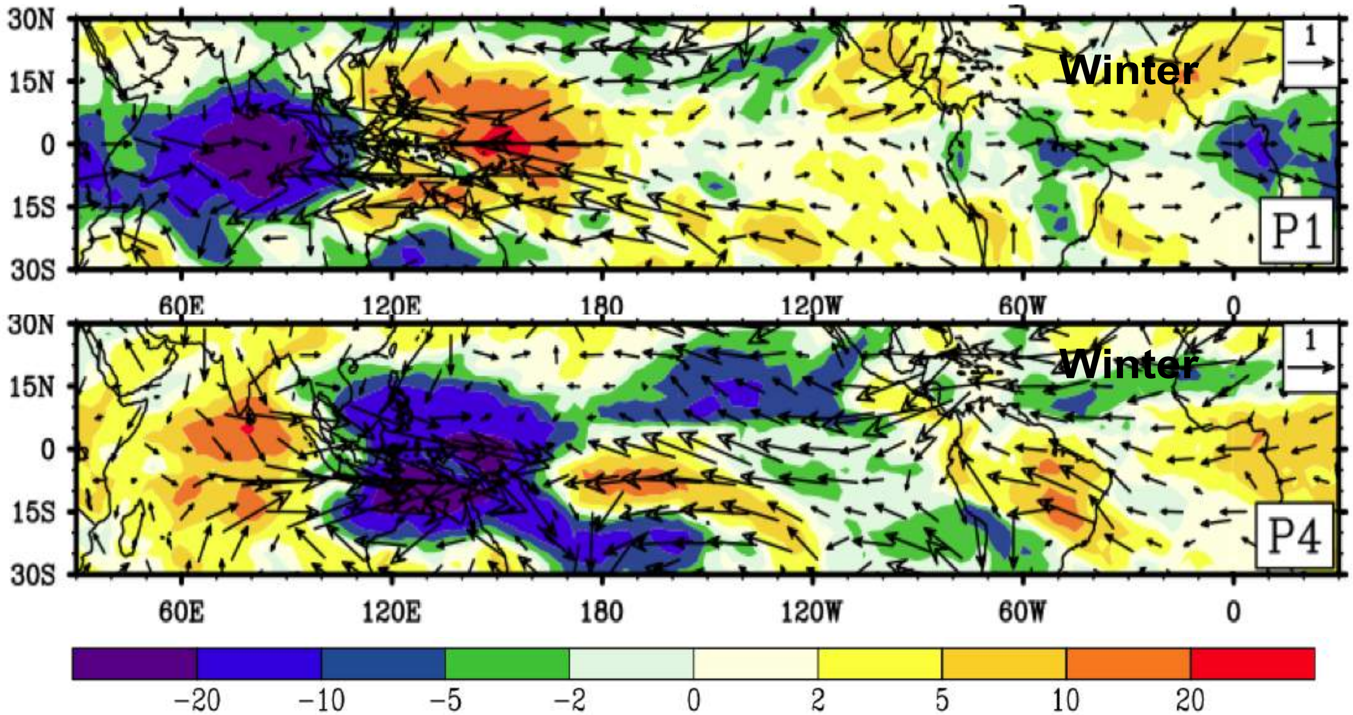


Halkides and Lee 2009

Net SSTA tendency; Qnet
Hori. Advection; Subsurface ~ mainly upwelling + z mixing

The Madden-Julian Oscillation (MJO):intraseasonal var.

Wintertime MJO OLR & 850mb wind: Phases 1 & 4

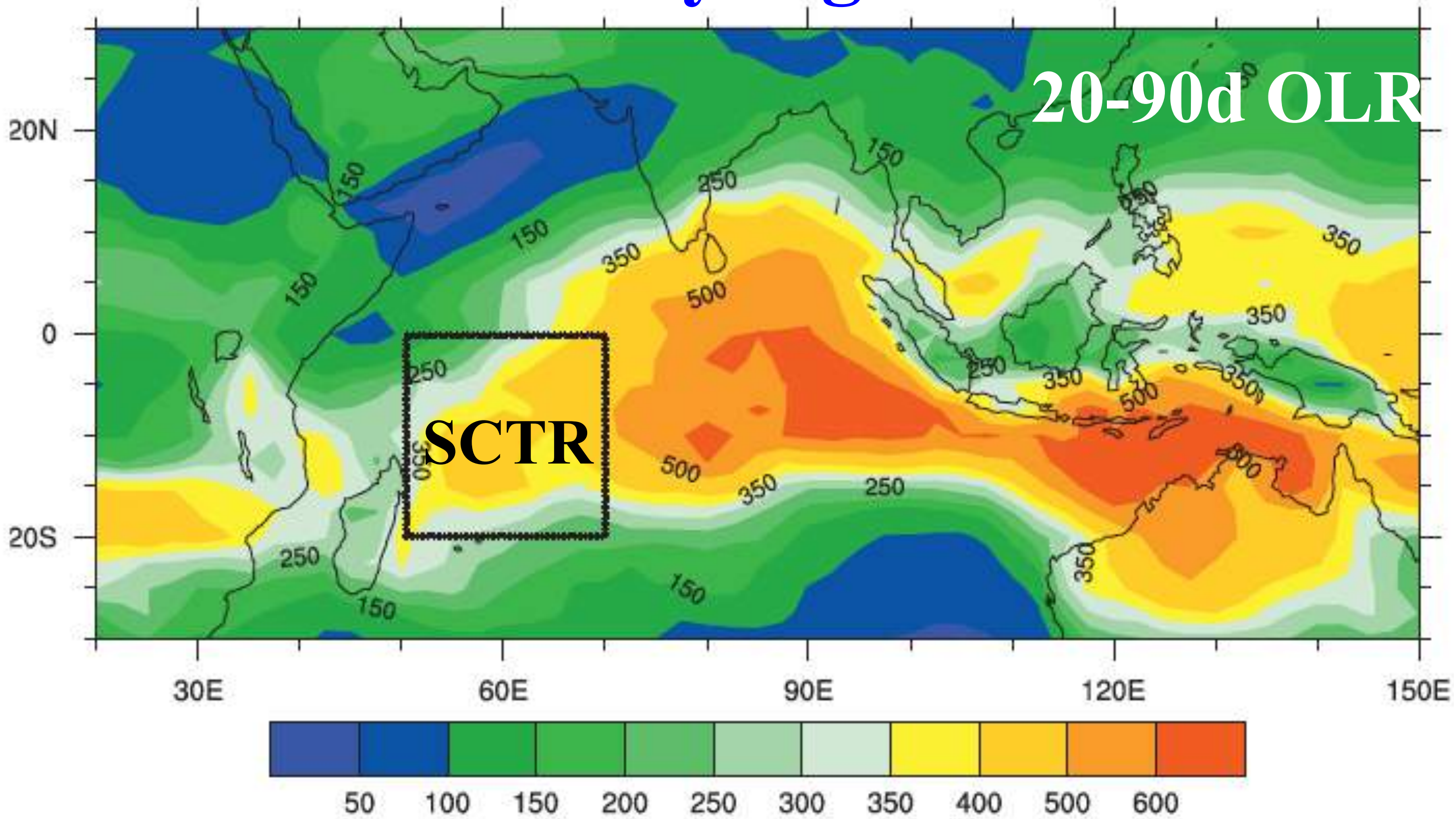


10-90d

Large impacts on weather and climate: affecting ENSO, Hurricane in Caribbean Sea & Australian monsoon in northern winter; Asian summer monsoon in northern summer

The MJO: Many initiate in the Indian Ocean *(e.g., Zhang et al. 2013; Yoneyama et al. 2013)* – **field campaigns: DYNAMO & YMC**

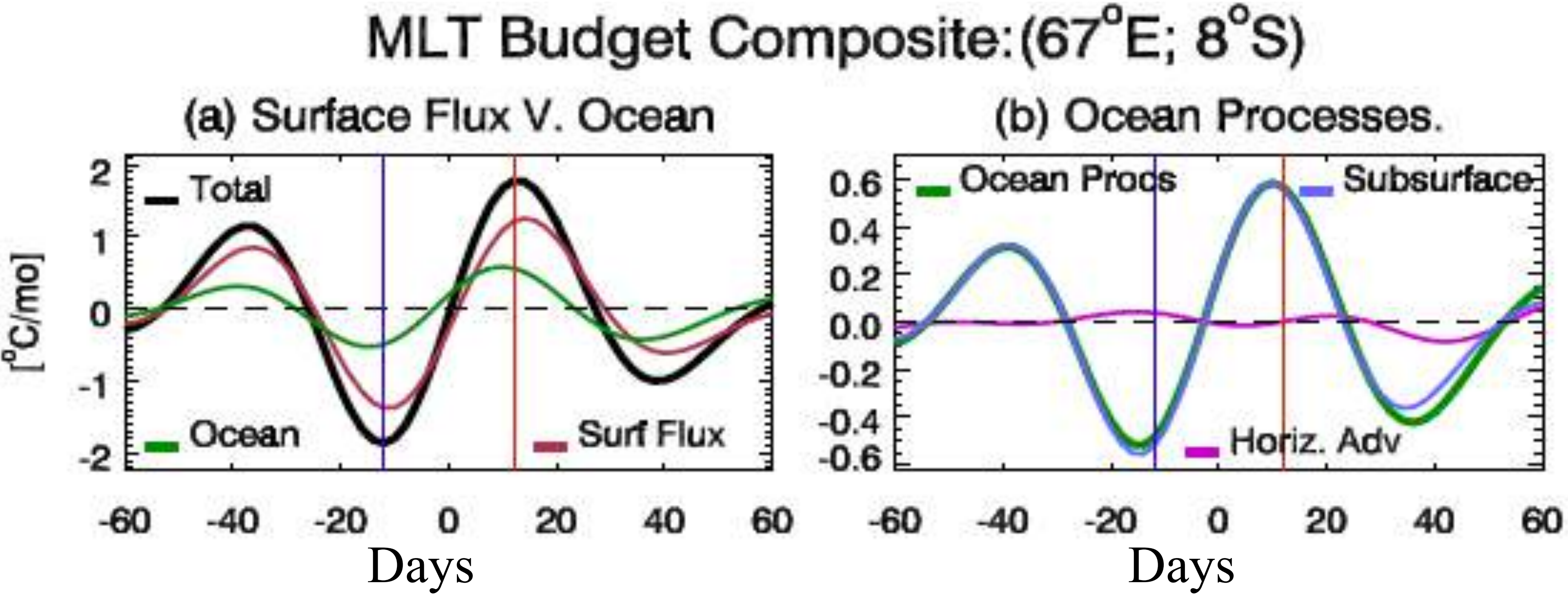
SCTR: one of the key regions for the MJO Initiation



Zhao et al. 2013

The role of ocean dynamical processes in initiating the MJO: not well understood; budget analysis using ECCO shows that ocean dynamical processes (i.e., D20a associated with Rossby waves) – important for inducing SSTA

Mixed-layer heat budget using ECCO reanalysis



~70% SWR + turbulent heat fluxes; ~30% ocean processes
(Halkides, Waliser, Lee, Menemenlis & Guan 2015)

Consistent with OGCM experiments: *Li et al. (2014):*

SWR 31%, Qsen+Qlat (wind) 39%, Ocean dyn. (wind stress) 23%

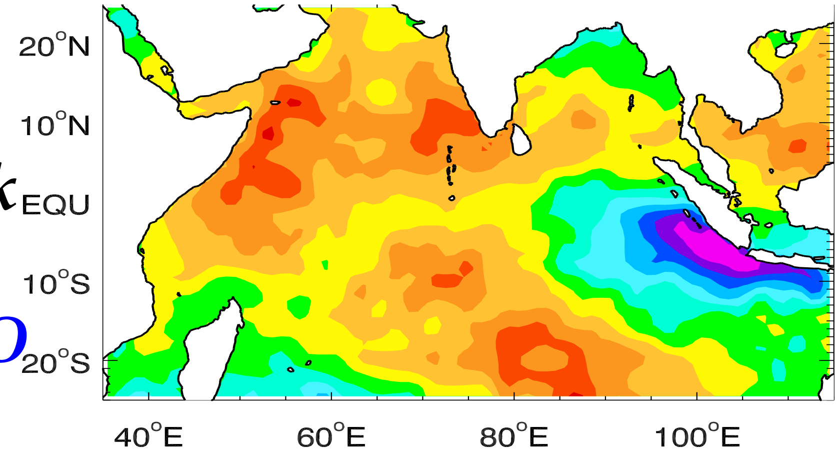
McPhaden and Foltz 2013:Budget analysis using RAMA at (80.5E, 0N)

Summary 2

Interannual climate mode: the IOD: *coupled ocean-atmosphere Mode that involves Bjerknes feedback & surface heat fluxes*

Climate impact: drought, flood, ENSO monsoon

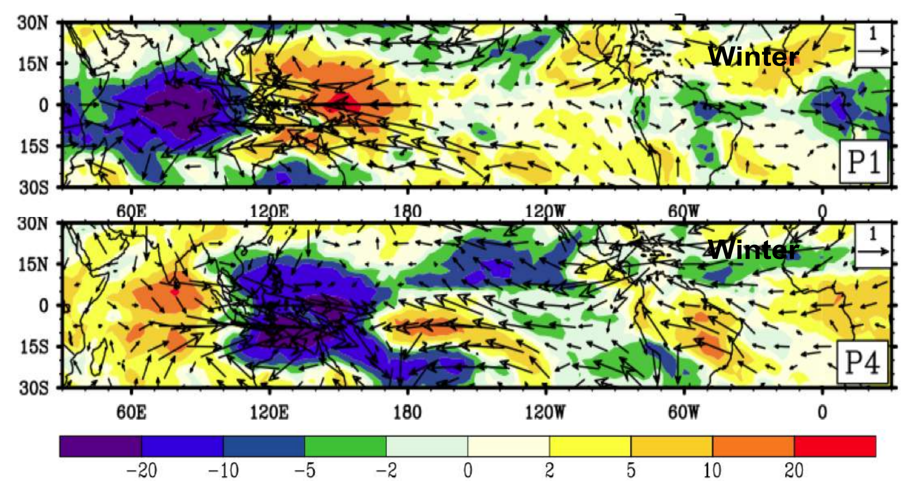
Positive phase:SSTA



The MJO – large climatic impacts

ECCO budget analysis & OGCM experiments: Ocean dynamical processes contributes ~1/3 of intraseasonal SSTA over SCTR mean upwelling region;

how the SSTA affects the MJO initiation is an active research



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

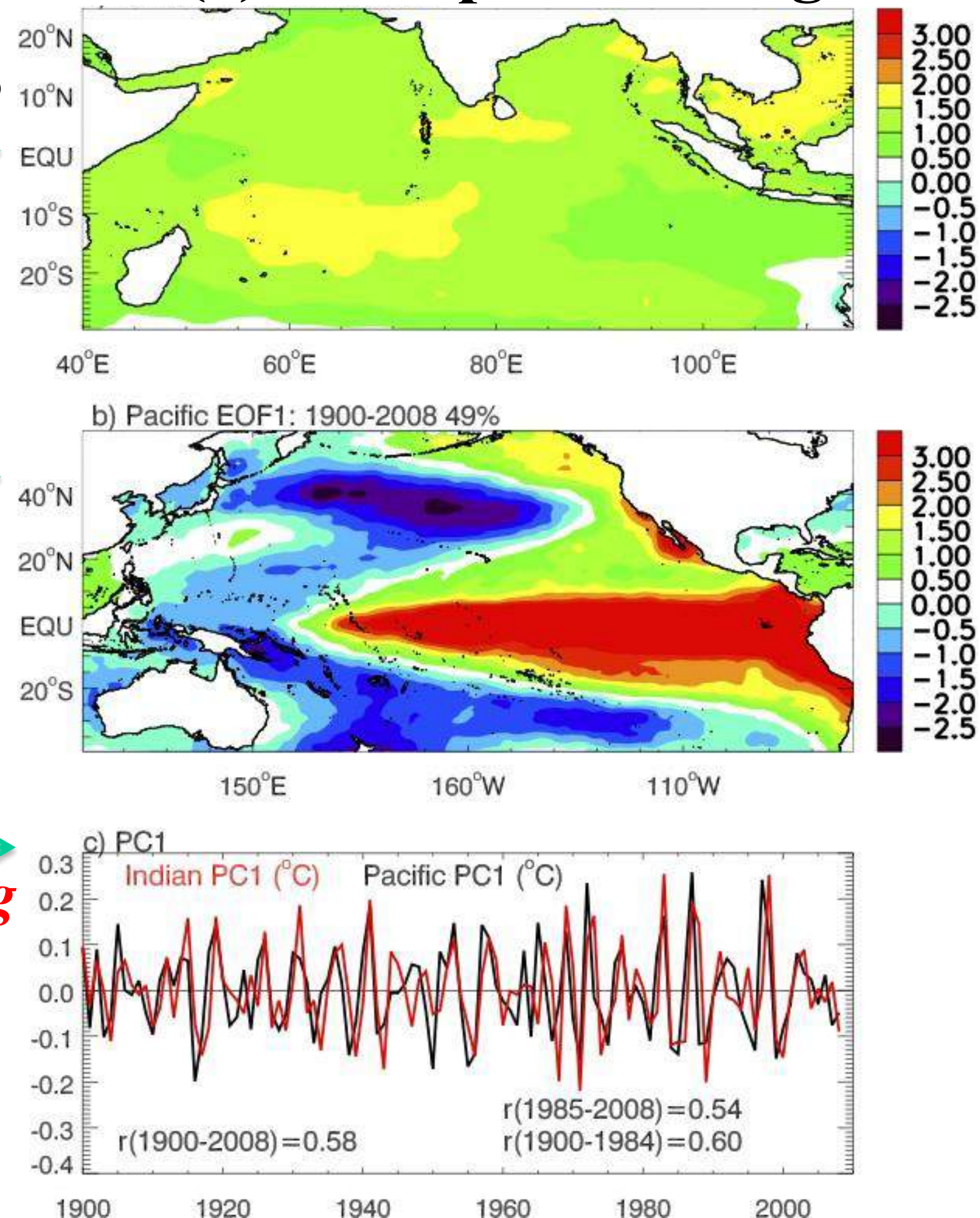
Indian SSTA EOF1 45%

Pacific SSTA EOF1:49%

PC1

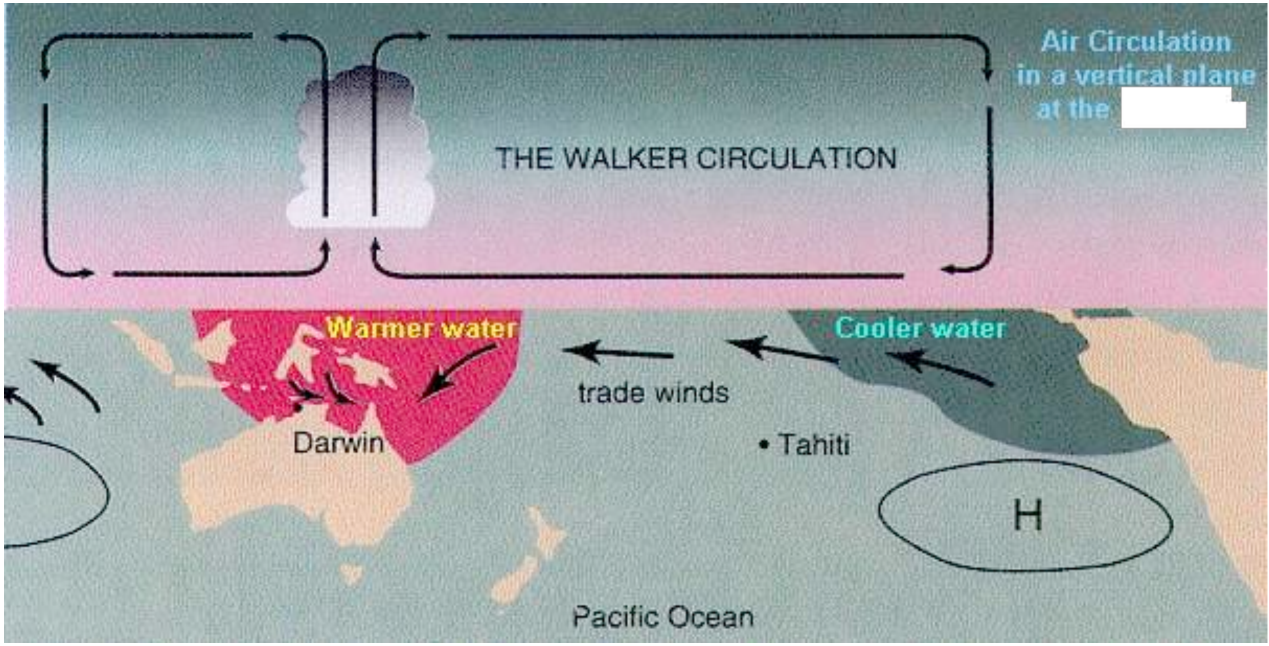
El Nino: Indian Ocean warming

La Nina: Indian Ocean cooling

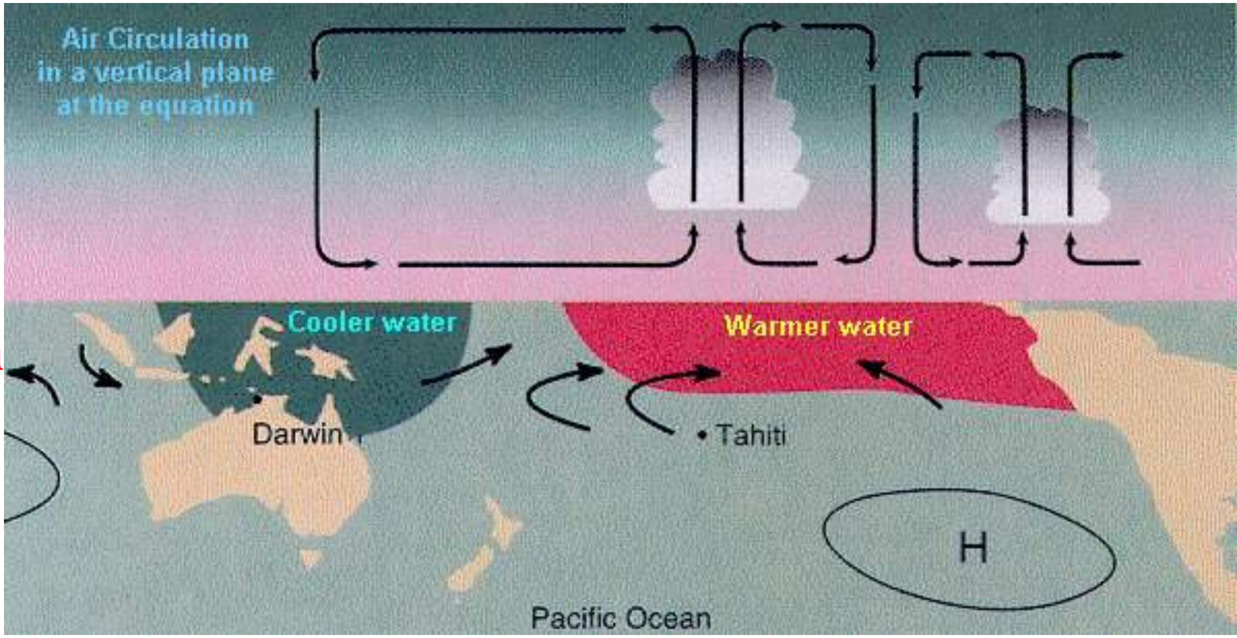


Pacific influence: atmospheric bridge - Walker Circulation

Normal Condition →



El Nino →

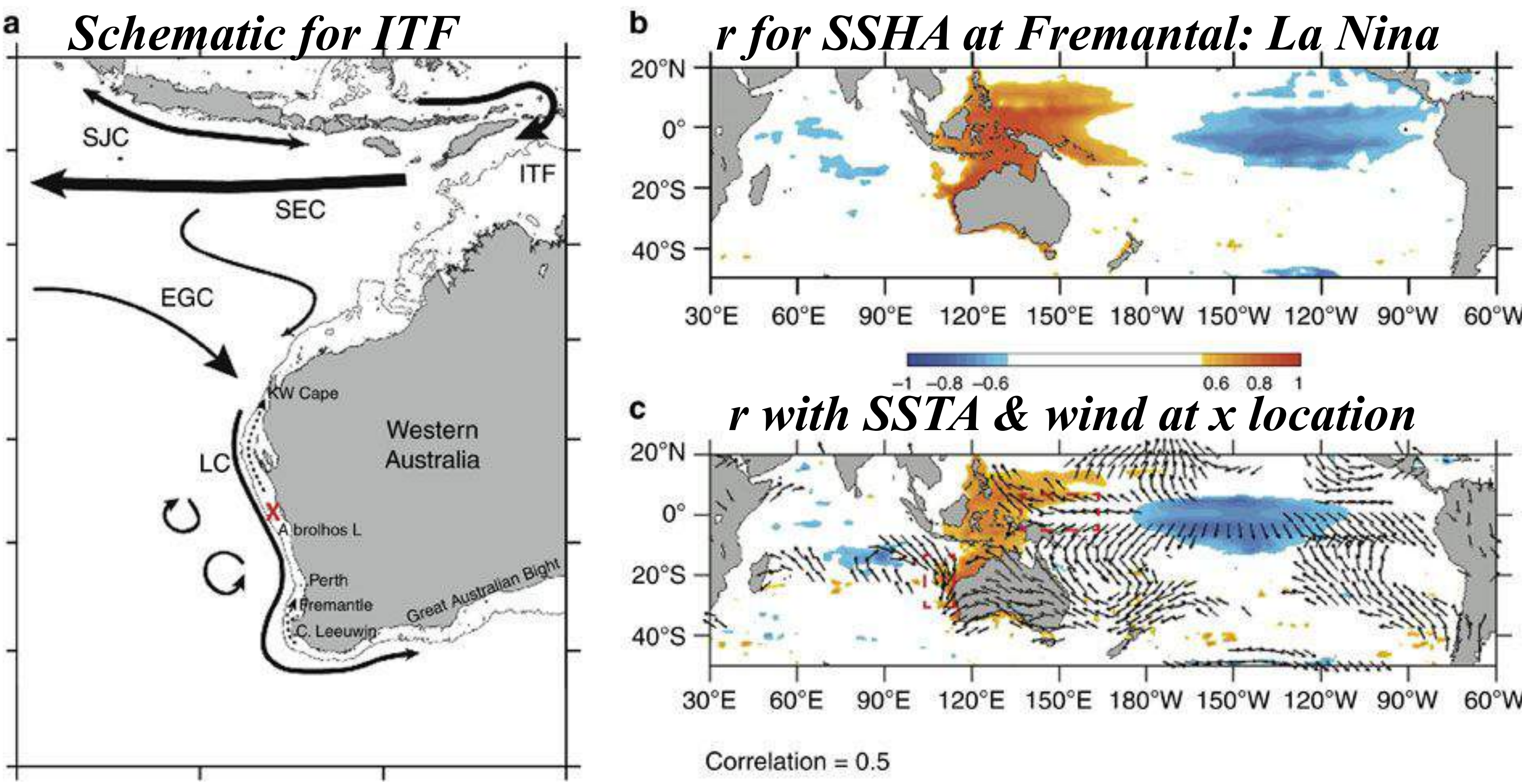


Increases atmospheric
-subsidence
-reduces convection
-increase solar radiation
-warming

Klein et al. 1999

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

Summary 3

Influence from the tropical Pacific ENSO:

Atmospheric bridge – basin wide warming/cooling

Oceanic connection: ITF – strongest influence in Southeast IO

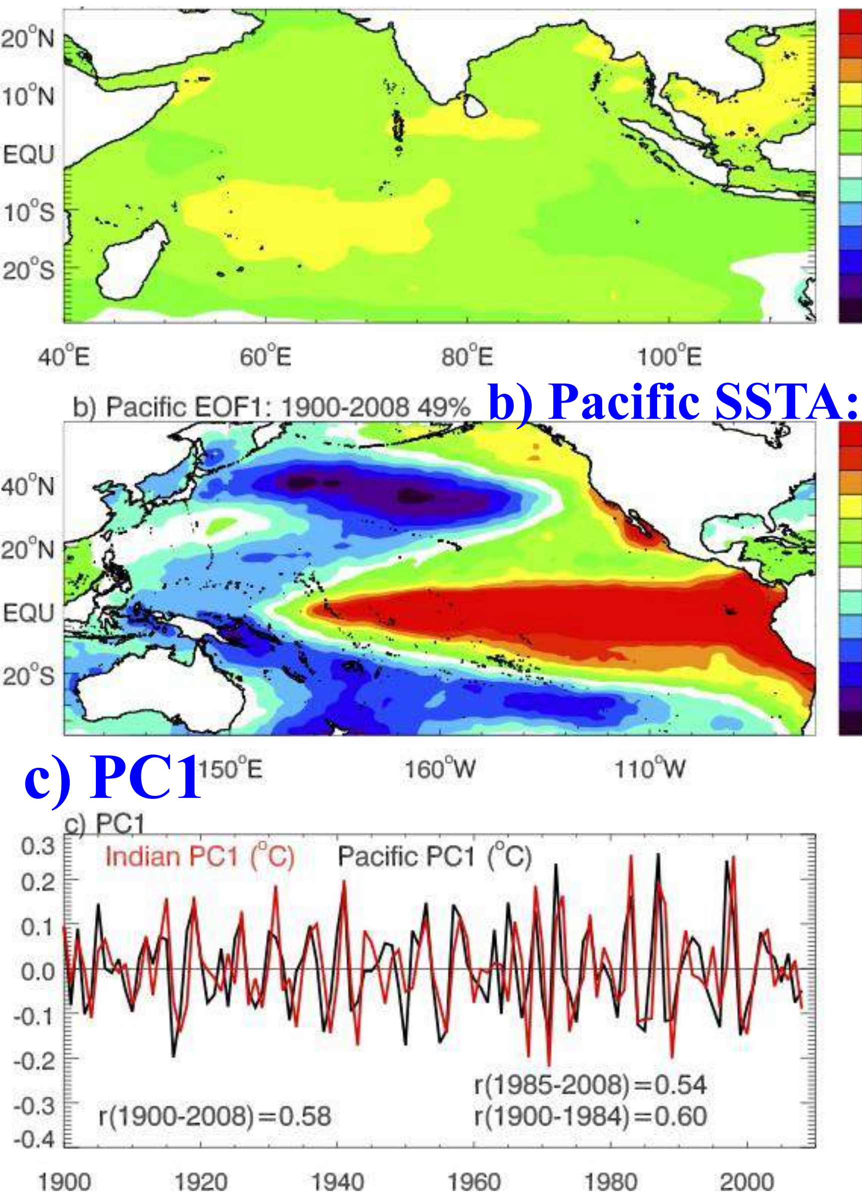
Thank you!

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

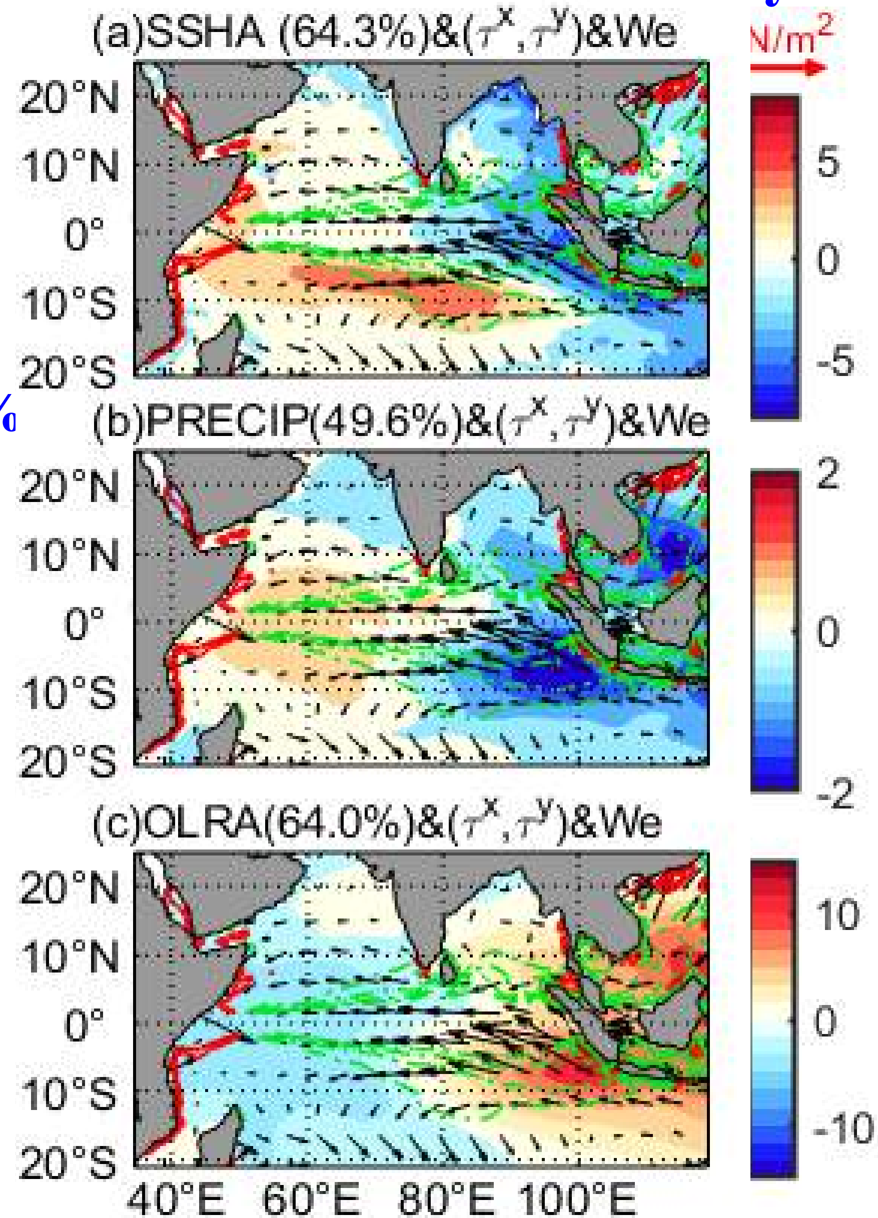
a) Indian SSTA EOF1 45%

b) Pacific SSTA:49%

c) PC1

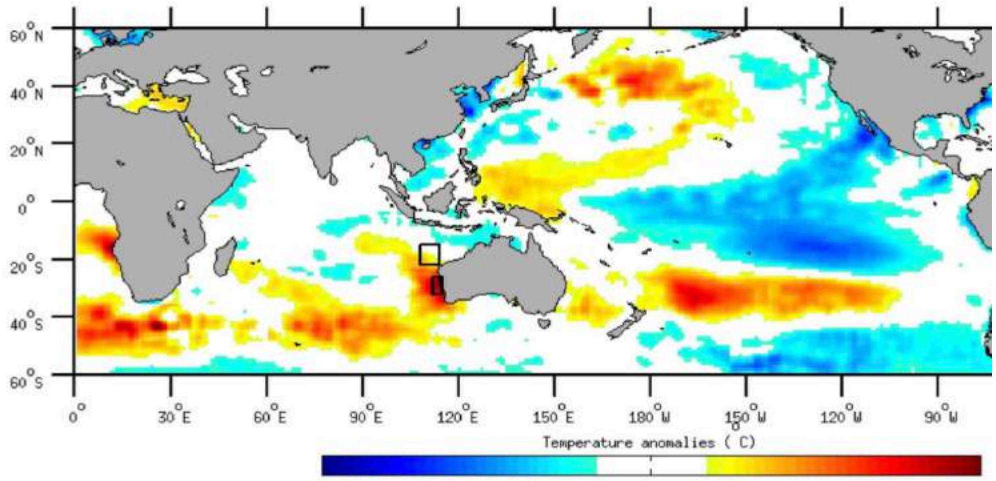


ENSO-induced variability

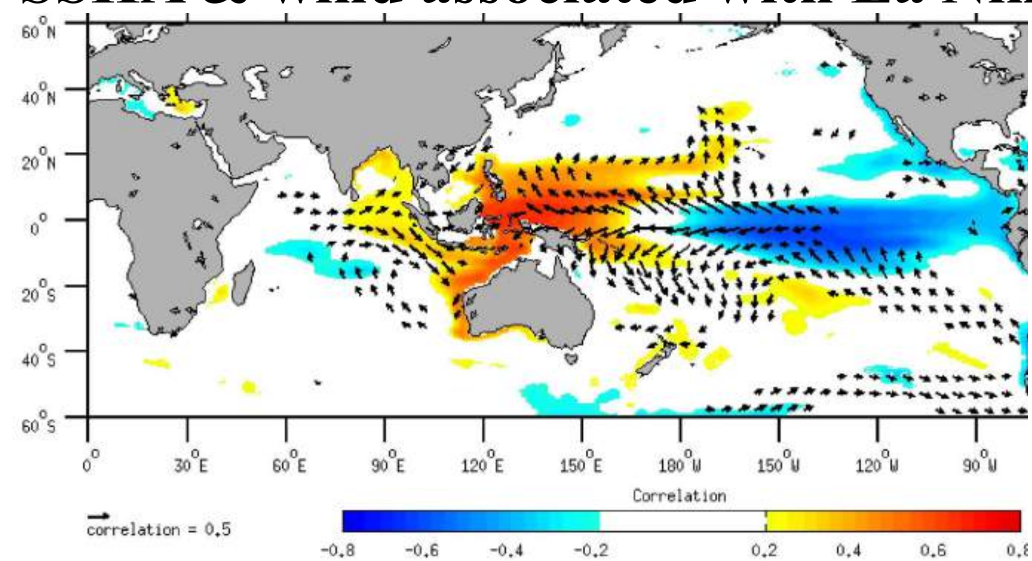


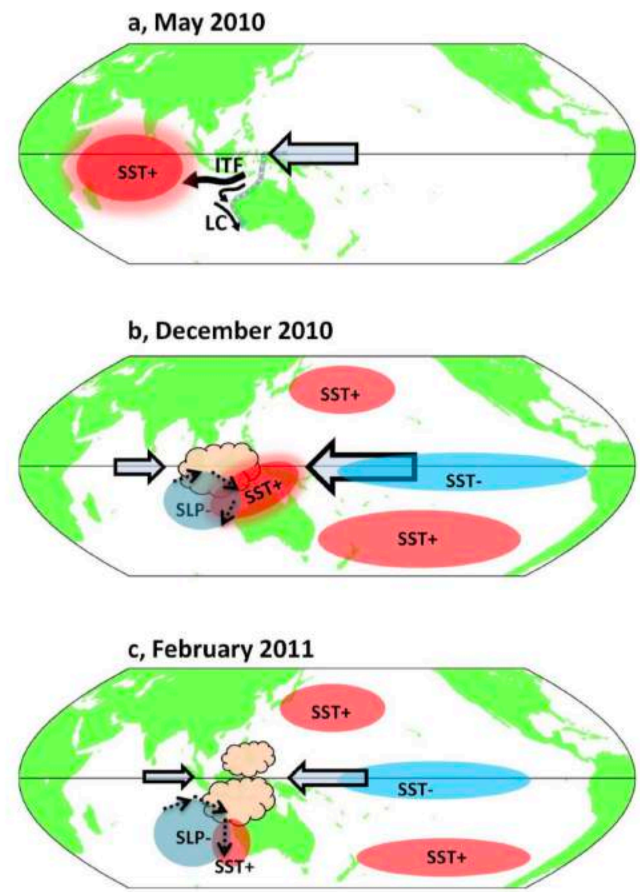
El Nino: reduced the ITF;
La Nina: enhanced ITF, Leeuwin current & warming

2011 La Nina: SSTA during Feb and Mar 2011



SSHA & wind associated with La Nina





Feng et al. 2013

El Nino: reduced the ITF;
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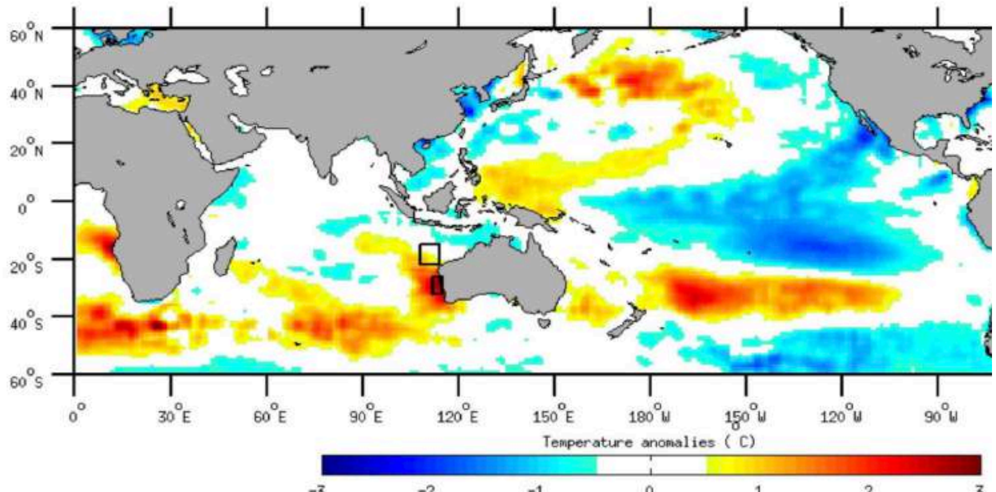
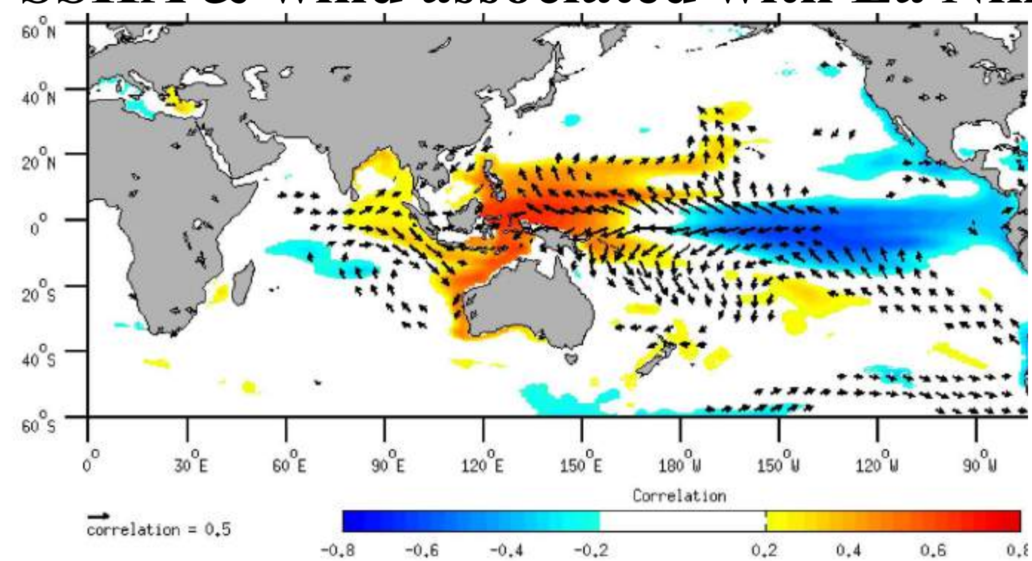
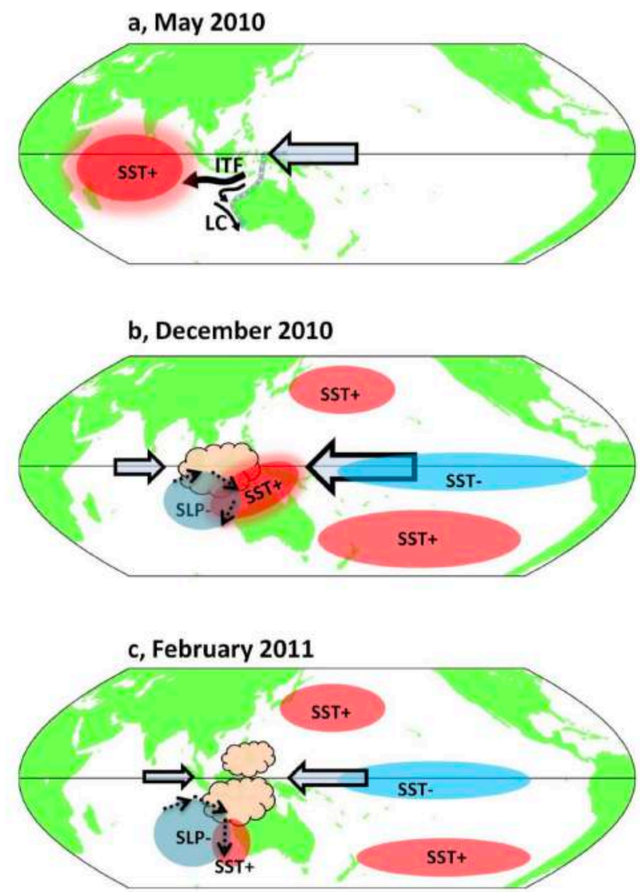


SSHA & wind associated with La Nina





Feng et al. 2013

Wind-driven shallow meridional overturning cells

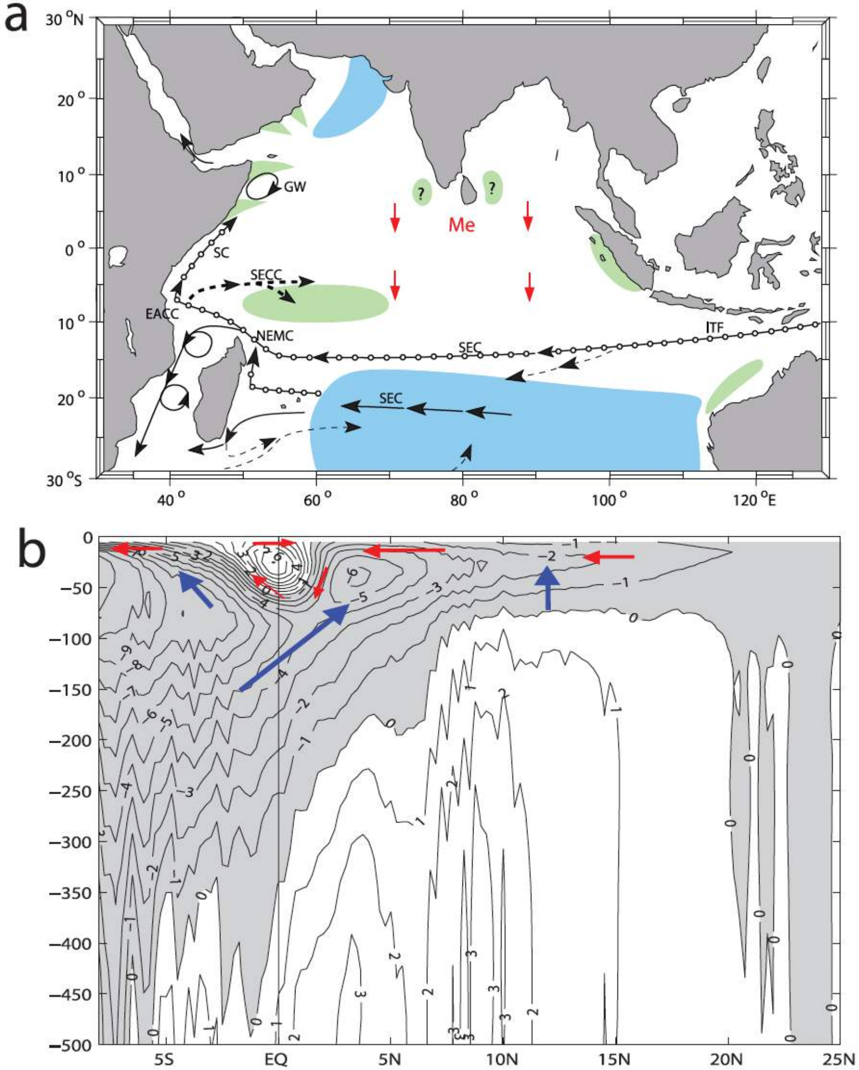


Figure 6. (a) Schematic representation of the Indian Ocean cross-equatorial cell (CEC) (light dashed stream paths for upper layer inflow into subduction zone (blue), dotted for thermocline Somali Current supply, and solid for Southern Hemisphere thermocline flow) and of the subtropical cell (STC) (heavy 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.

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

But zonal wind dominates
Miyama et al. 2003

Schott et al. 2009