Indian Ocean circulation, dynamics and climate variability modes

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Outline

1. Monsoon and seasonal ocean circulation
2. Major climate modes
3. Influence from the Pacific
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

January

May

July

Nov

Heat + Salt balance: Arabian Sea & Bay of Bengal
Observed zonal surface current: spring&fall Wyrtki Jets

a) Total U (1S-1N average)  b) Annual mean U

c) Annual U component  d) Semiannual U component

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

(a) ECCO U-Wind

- a) Total taux (1S-1N mean)
- b) Annual mean
- c) Annual component
- d) Semiannual component

Halkides & Lee 2009

Fig. 2. Longitude–time plots of equatorial zonal wind stress $\tau_x$ averaged from 1°S to 1°N, determined from the FSU pseudostress climatology for the period 1970–96 with $\rho_u = 0.001 \ 175 \ g \ cm^{-3}$ 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

Han et al. 2011
Linear 2.5-layer ocean model simulation: EQ U

Directly Forced
no reflected RW

Reflected RW
from eastern boundary
L: Indian Ocean Zonal width
m=1,2,...
$C_n$: baroclinic mode speed
T: Forcing period (e.g.,
  semiannual=180 days)

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

Basin resonance in the EQ Indian Ocean:
EQ Indian Ocean L: $C_2 \sim 170 \text{cm/s, } T=180$
Wind-driven shallow meridional overturning cells

- Heat loss to atmosphere
- Heat gain by ocean
- Easterly wind
- Westerly wind
- 0 m to 50 m
- 50 m to 500 m
- Southern cell
- Northern cell
- Southern upwelling
- Northern upwelling
- Ekman flow
- Thermocline flow
- Cross-equatorial cell
- Deeper ocean below the thermocline

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

SCTR

STC (~8Sv)

CEC (~6Sv)

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

Lee 2004
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)

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

zonal wind dominates

Subtropical Cell (STC)
Miyama et al. 2003; Schott et al. 2009
Wind-driven shallow meridional overturning cell: STC

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) 1.5, (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

Saji et al. 1999

(1) Summer-Fall: seasonal phase locked with Sumatra-Java upwelling;
(2) fall Wyrtki Jet is extremely weak or disappears
Webster et al. 1999
ECCO budget analysis

Net SSTA tendency; $Q_{net}$

Hori. Advection; Subsurface ~ mainly upwelling + z mixing
The Madden-Julian Oscillation (MJO): intraseasonal var.

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

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
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%, $Q_{sen}+Q_{lat}$ (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

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
 increases 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

**Schematic for ITF**

**r for SSHA at Fremantal: La Nina**

**r with SSTA & wind at x location**

_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**

(a) SSHA (64.3%) & ($\tau^X, \tau^Y$) & We

(b) PRECIP (49.6%) & ($\tau^X, \tau^Y$) & We

(c) OLRA (64.0%) & ($\tau^X, \tau^Y$) & We
El Niño: reduced the ITF;
La Niña: enhanced ITF, Leeuwin current & warming

2011 La Niña: SSTA during Feb and Mar 2011

SSHA & wind associated with La Nina

Feng et al. 2013
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
Wind-driven shallow meridional overturning cells

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

But zonal wind dominates
Miyama et al. 2003

Schott et al. 2009