Ocean-Atmosphere Interactions associated with Indian Monsoon and its Variability

Lecture-12

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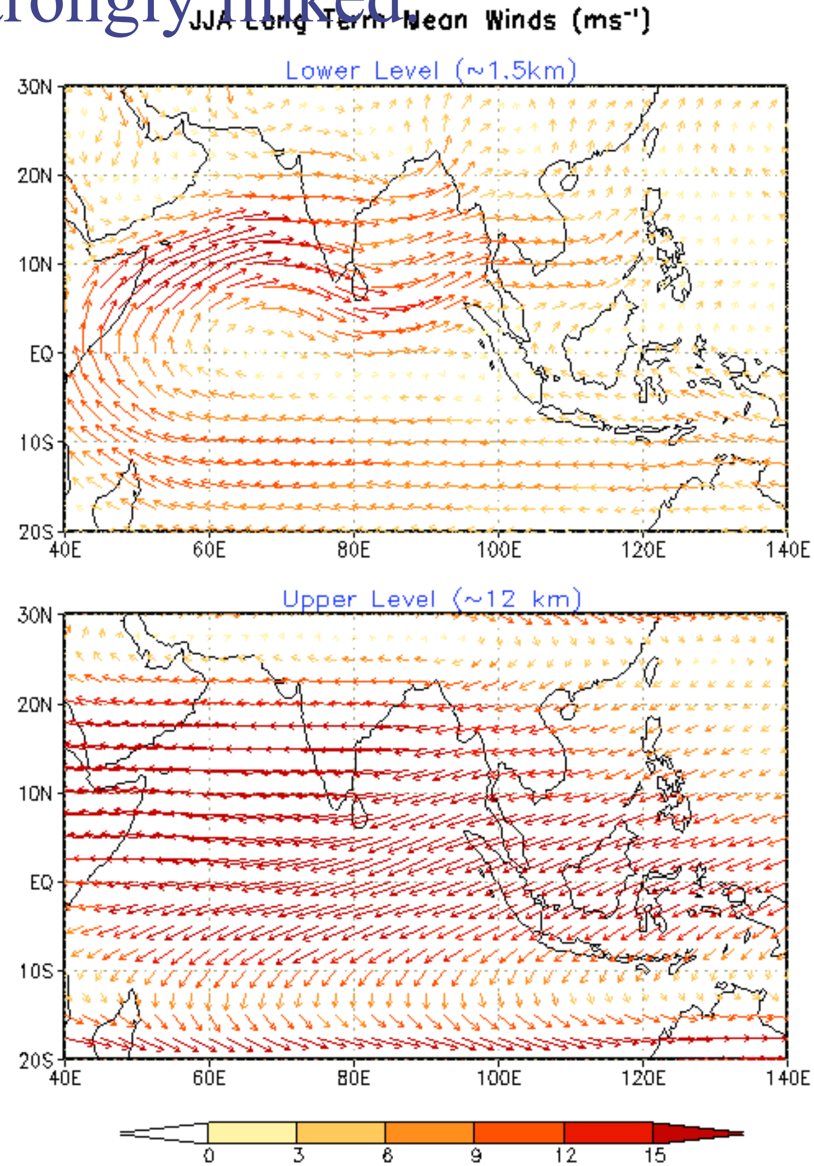
7 June, 2022

Air-Sea Interaction Associated with the Indian Summer Monsoon

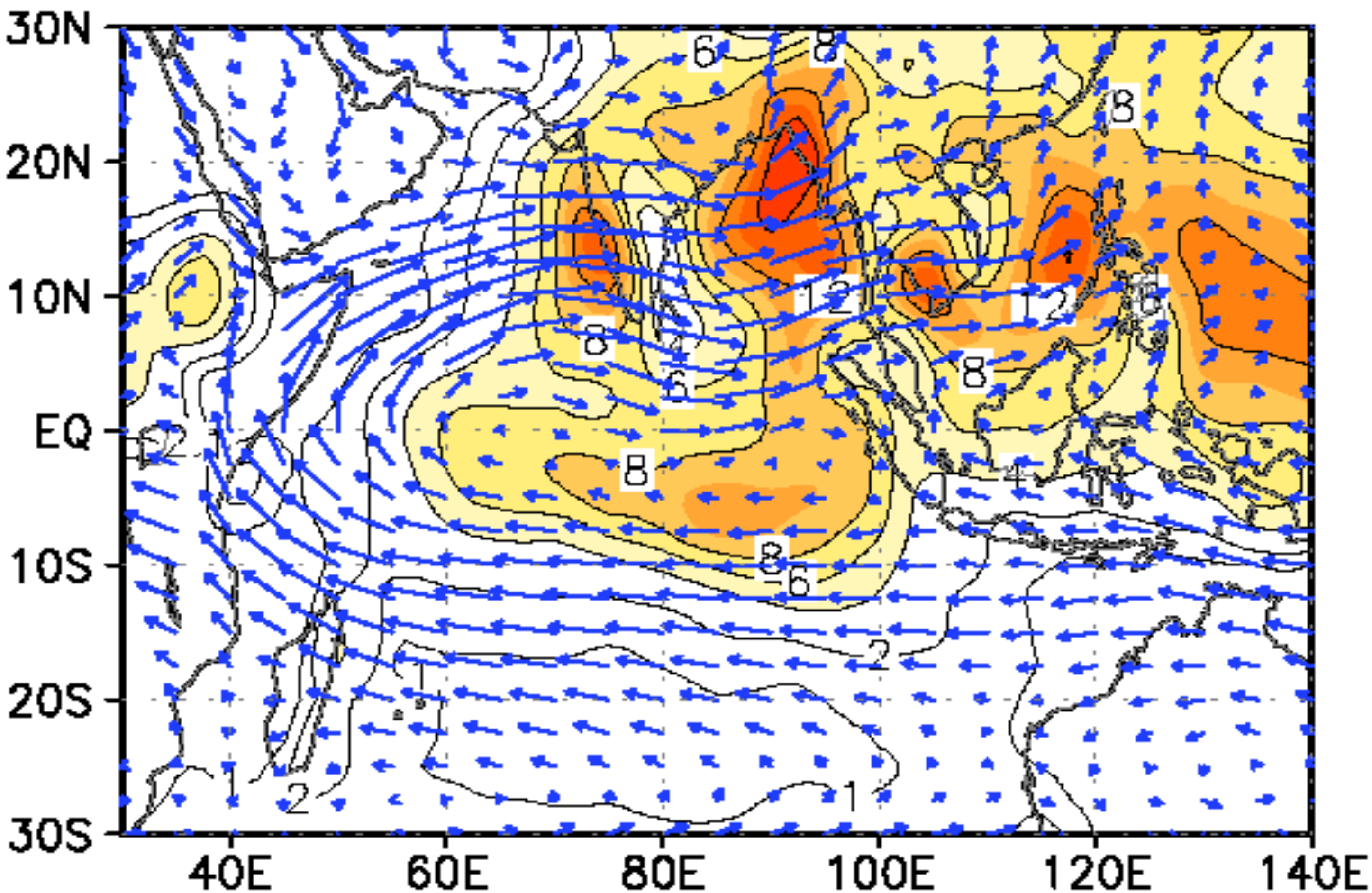
We have discussed that Indian Summer monsoon is 'Convectively Coupled phenomenon, where rainfall and winds are strongly linked.



Low level, cross-equatorial flow, south-westeries, westerly jet in Arabian sea

Upper level easteries, monsoon easterly jet

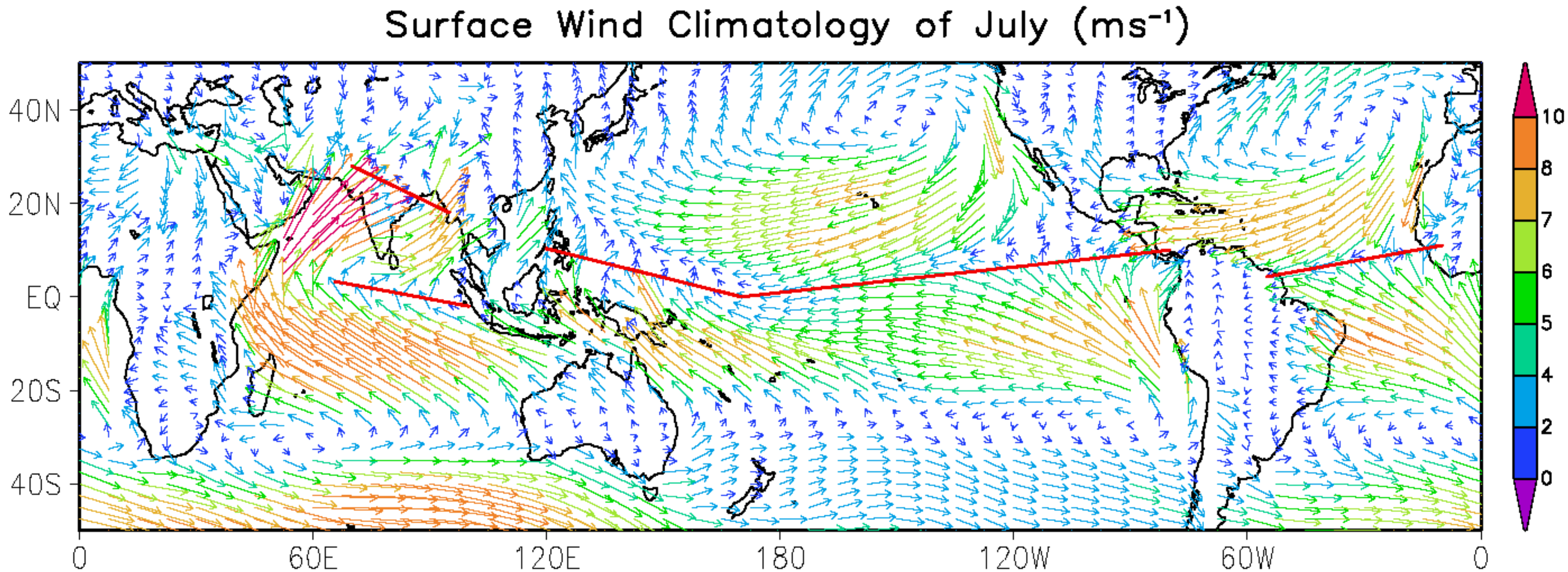
A deep baroclinic structure!

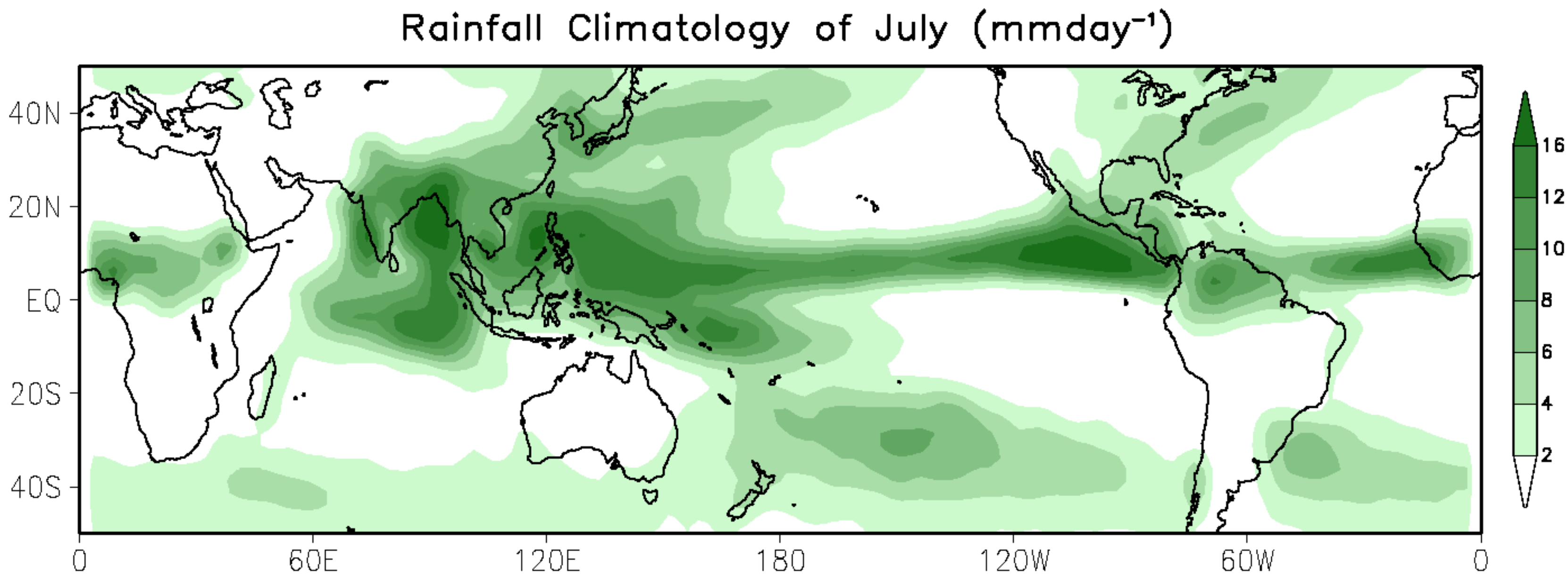


Seasonal mean precipitation (color) and 850 hPa wind vectors during JJAS over the Indian monsoon region.

➔Note that winds are attracted to the rain centers and tries to go around them in an anticlockwise manner, consistent with winds being forced by heating associated with the rain

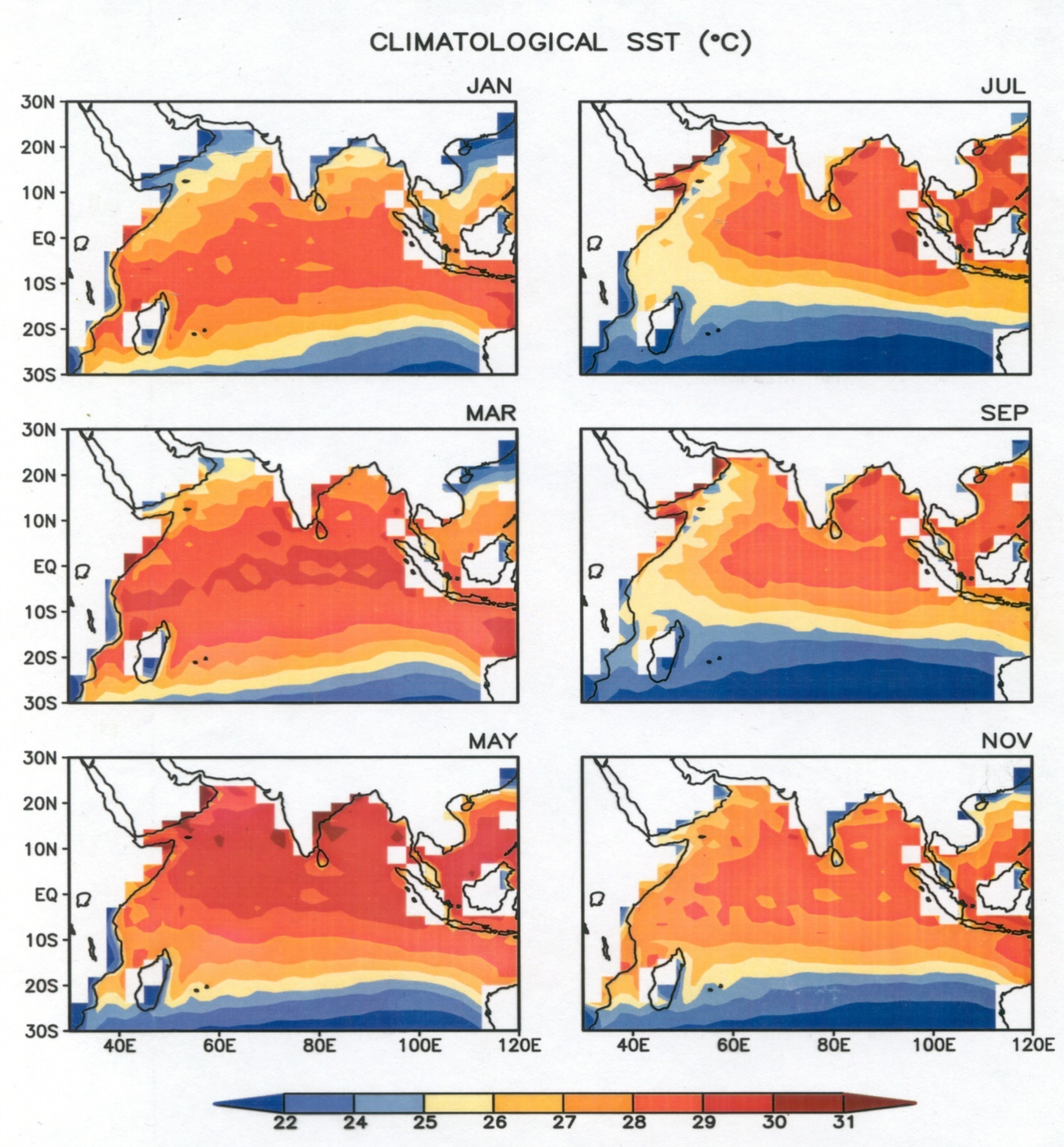
Mean July rainfall and surface wind convergence





Is Indian summer monsoon also an intrinsically Ocean-Atmosphere Coupled phenomenon? It appears so!

Why do we think so?



Note that during northern summer,

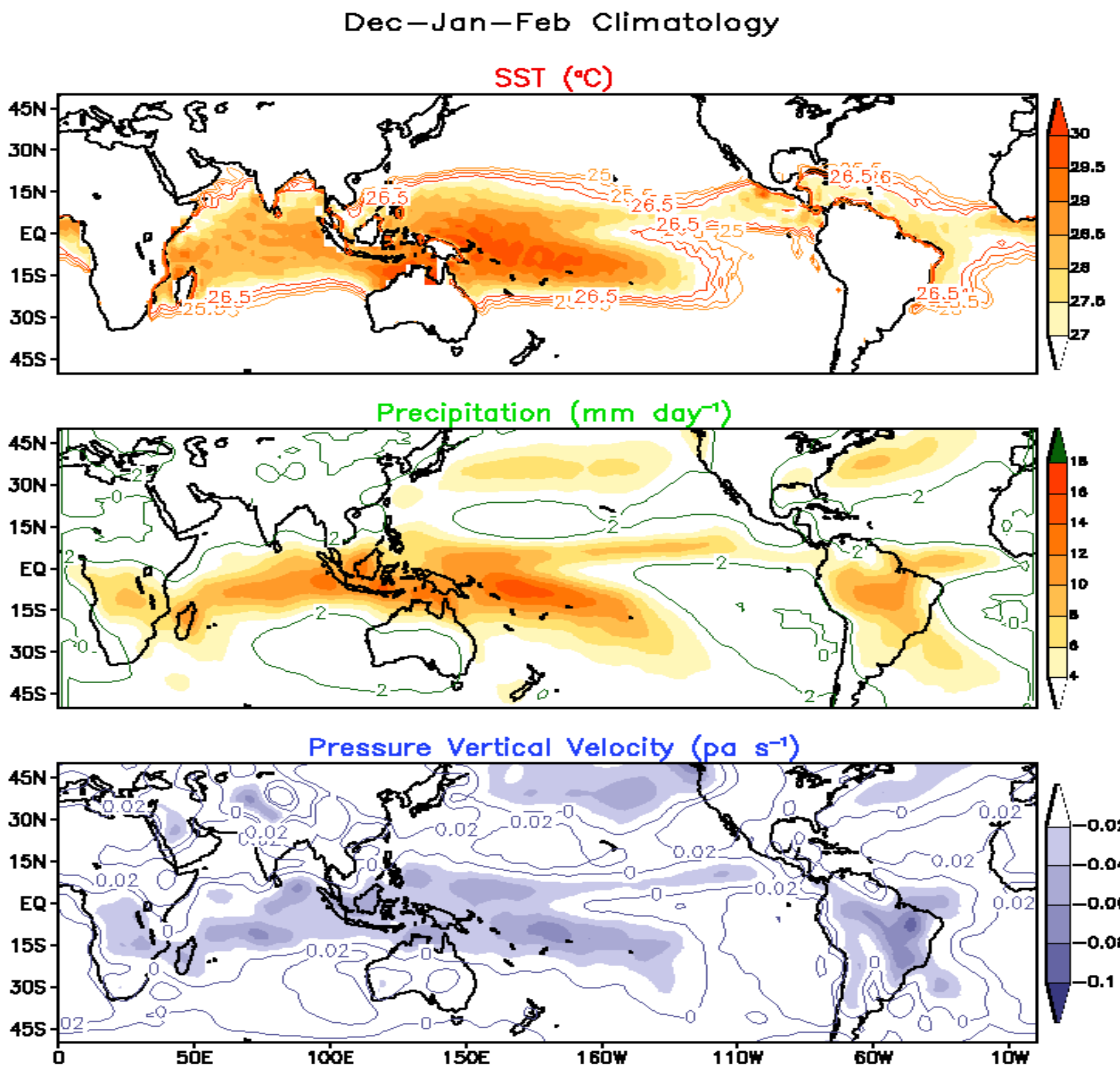
Eastern IO➔Warmer

Western IO➔ Cooler

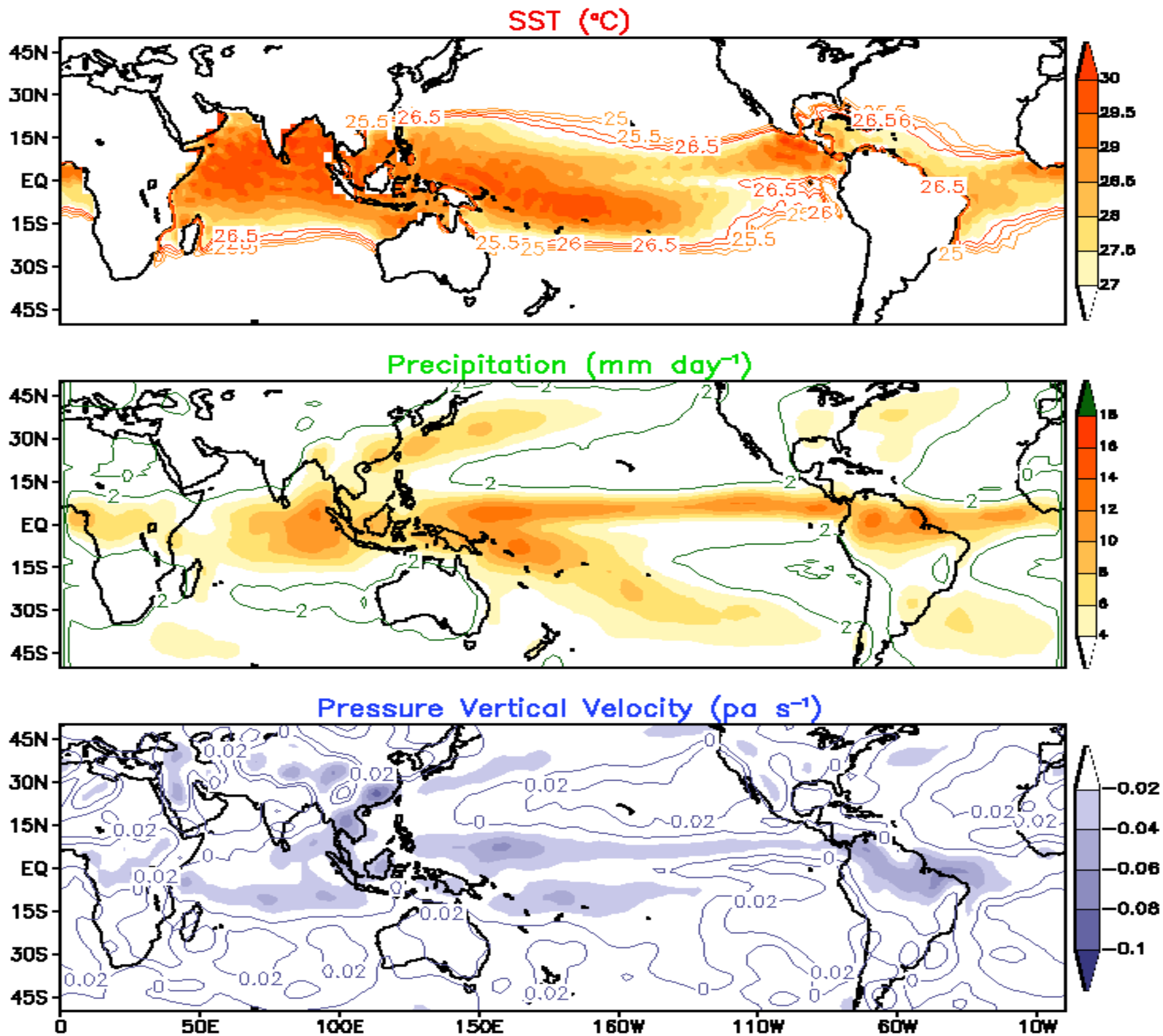
Most of IO is very warm sst > ~27^{O}C

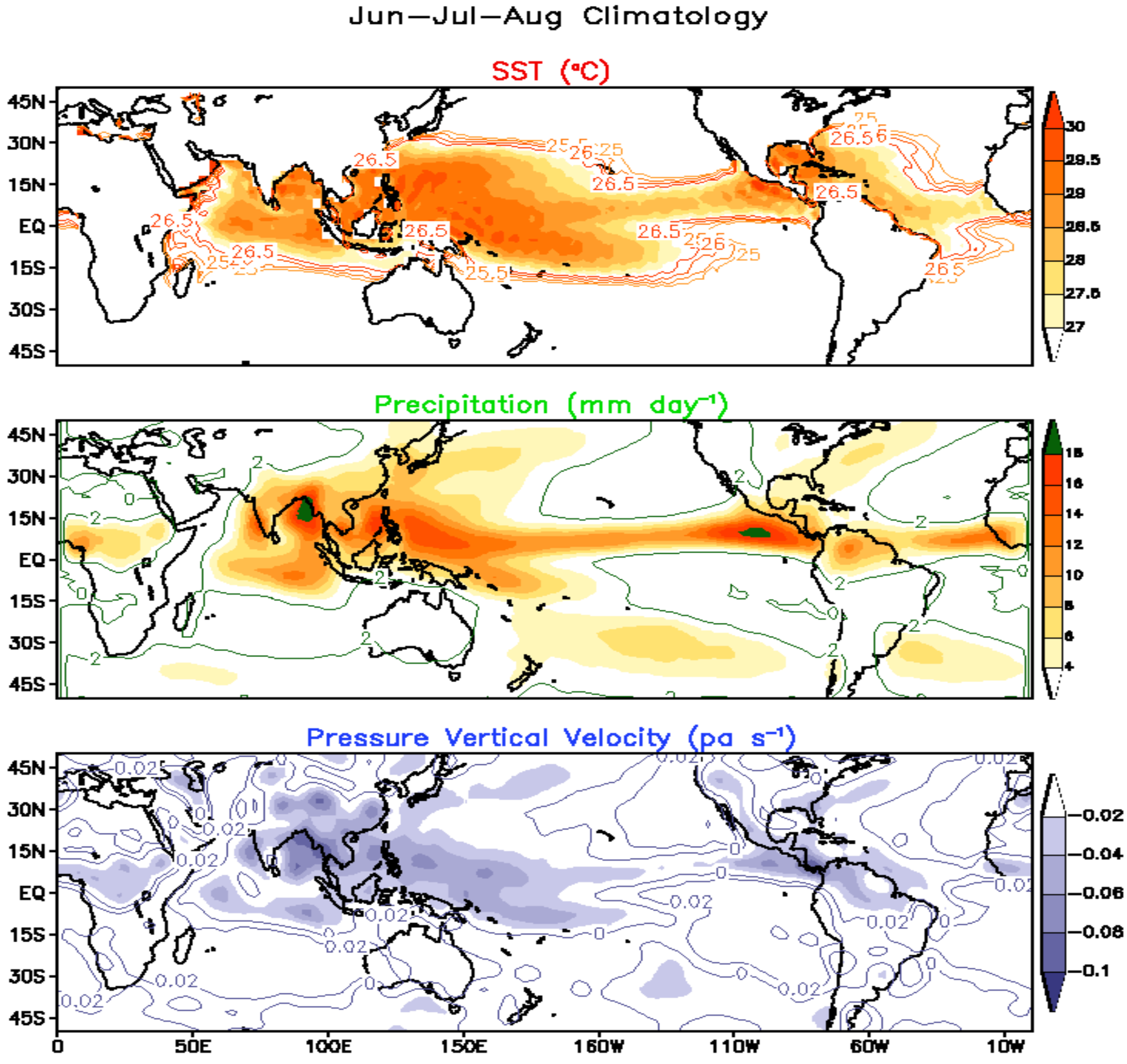
➔ Source of abundant moisture for Indian monsoon

ITCZ➔Indian monsoon. The annual cycle of ITCZ ➔strongly linked with the annual cycle of SST globally

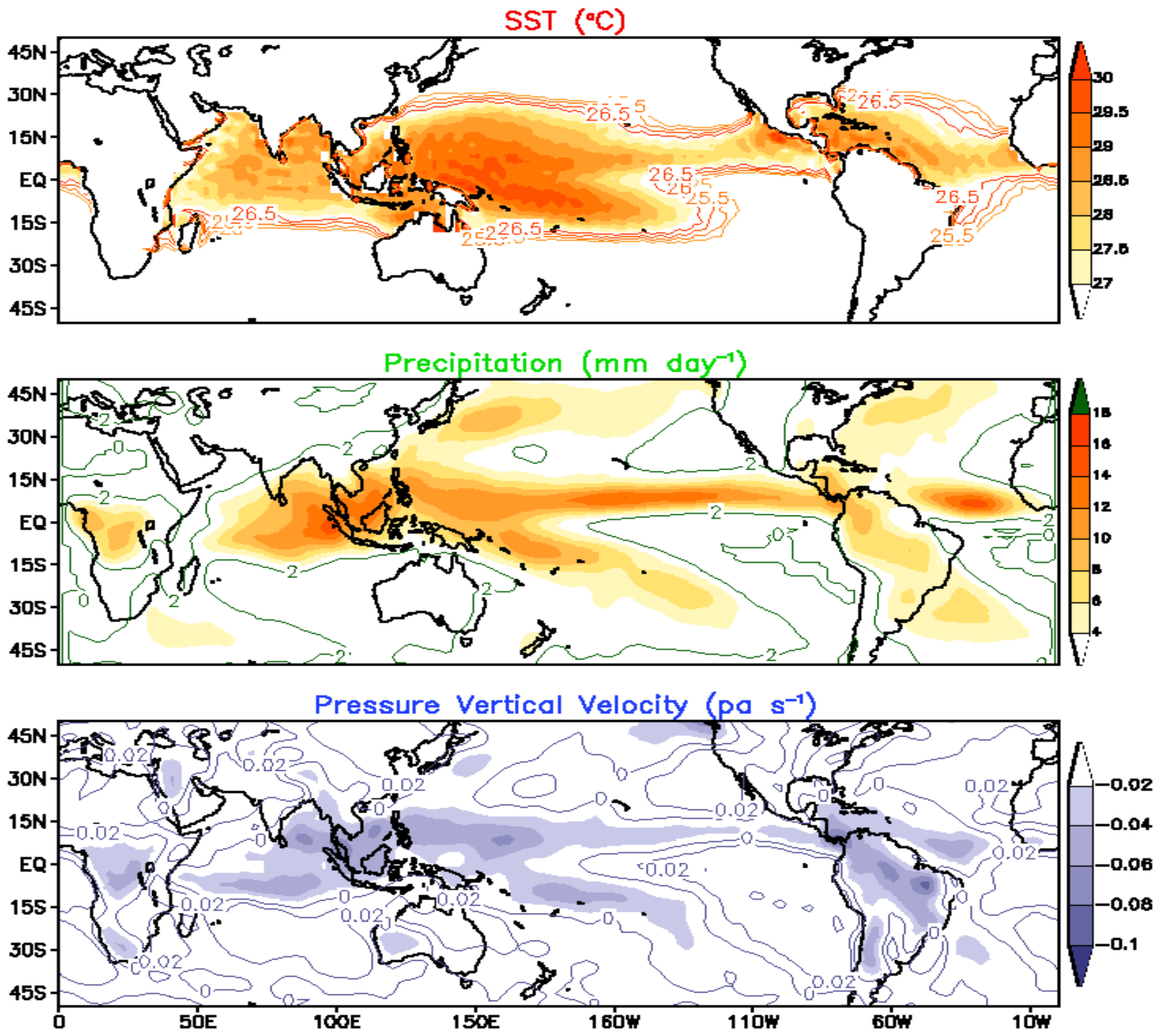


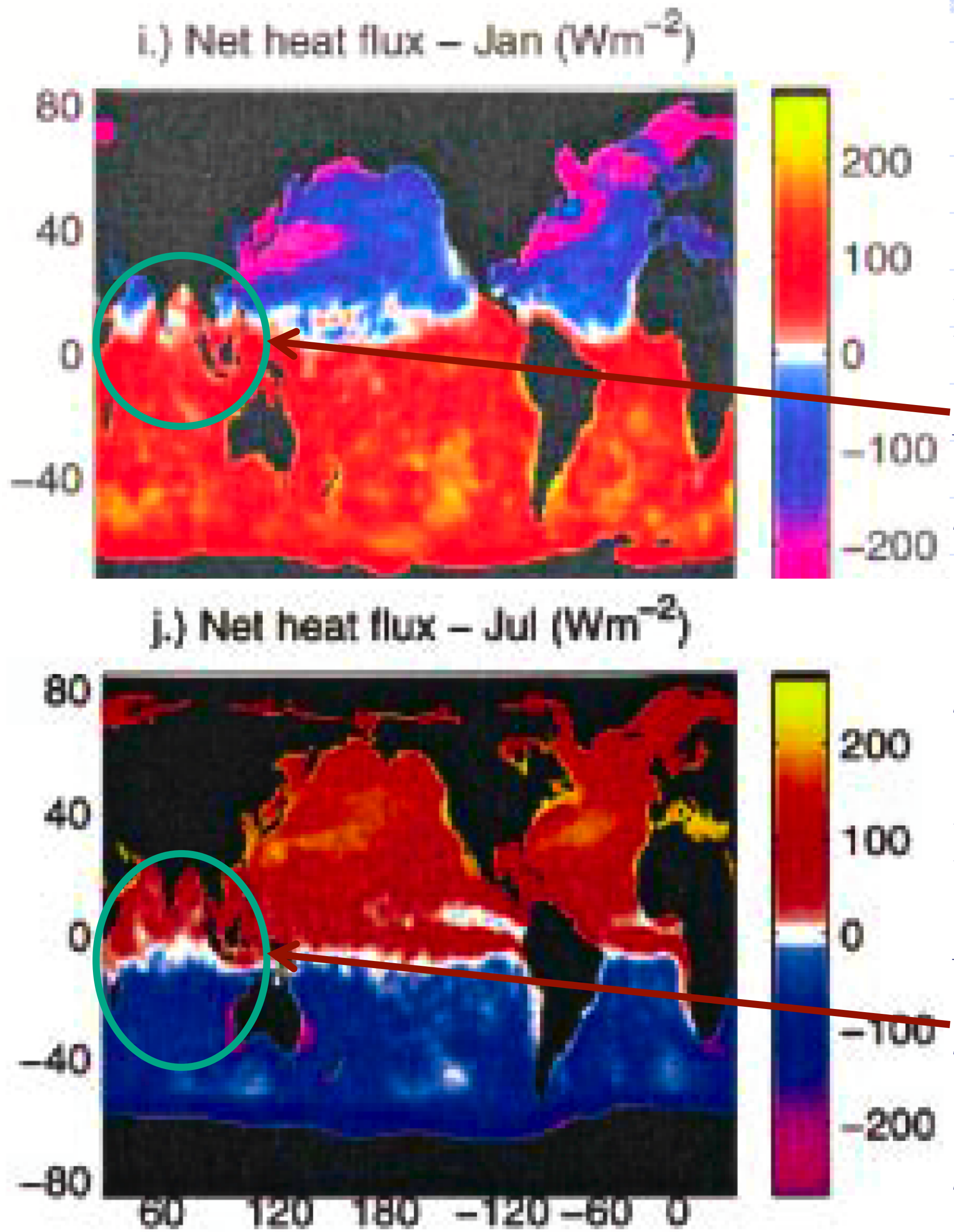
April–May Climatology




Jun–Jul–Aug Climatology
SST (°C)
Precipitation (mm day⁻¹)
Pressure Vertical Velocity (pa s⁻¹)
45N
30N
15N
EQ
15S
30S
45S
0
50E
100E
150E
160W
110W
60W
10W

Oct–Nov Climatology





Importantly,

Please Note,

During northern Summer,
NIO has negative Qnet ~100 W/m^2

SIO has positive Qnet ~100 W/m^2

During northern winter,

NIO has positive Qnet ~100 W/m^2
SIO has negative Qnet ~100 W/m^2

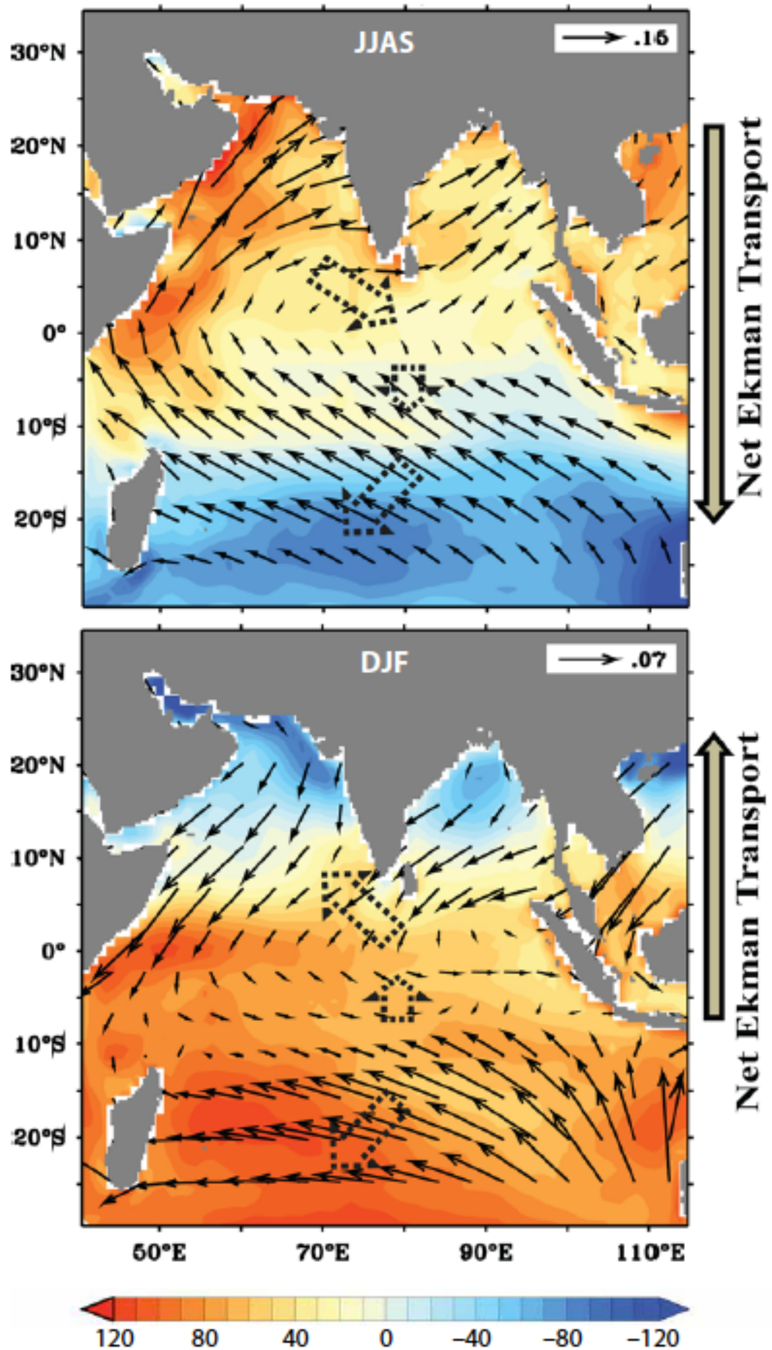


FIGURE 2. Objectively analyzed surface net heat flux in W m^{-2} (shading) and European Centre Reanalysis (Uppala et al., 2005)) surface winds stress in N m^{-2} (vectors) during the months of June, July, August, September (JJAS) and December, January, February (DJF) over the tropical Indian Ocean. The big arrows indicate implied Ekman flow in the ocean.

Goswami et al.,2016: Oceanography, vol. 29(2) 18-27

It implies..

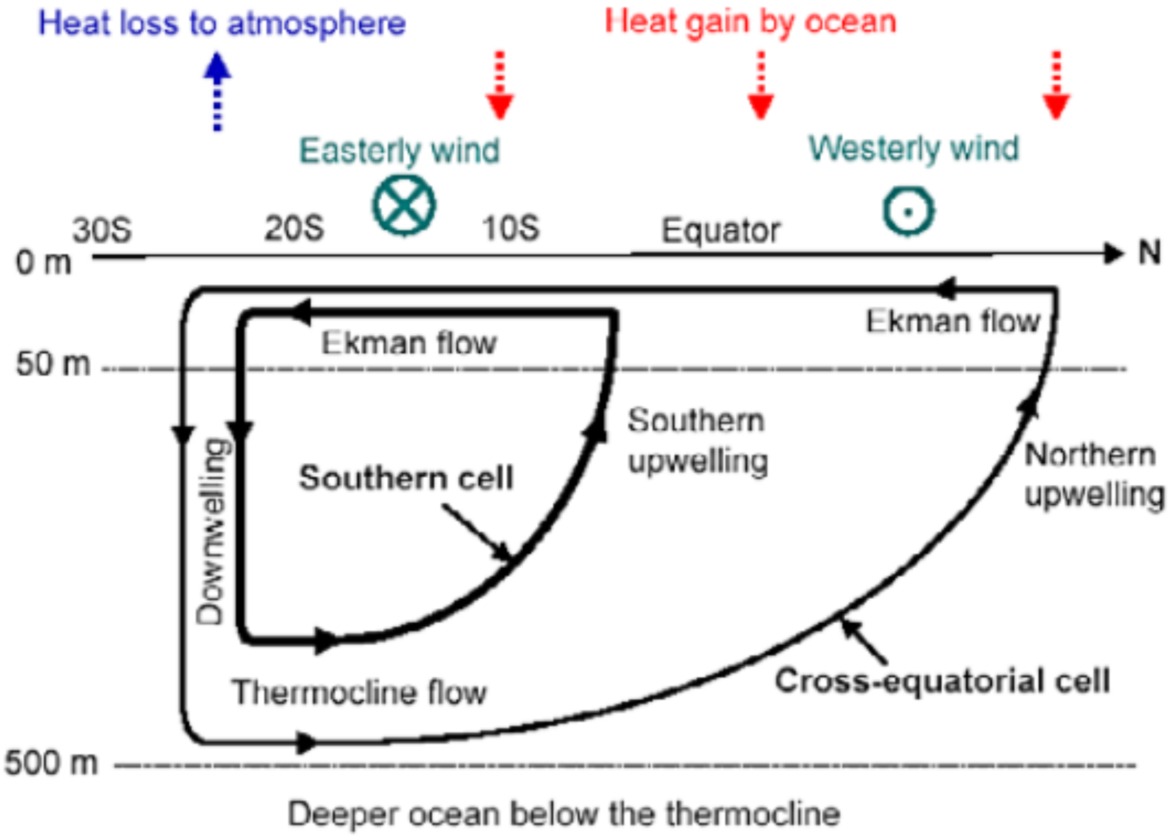


Figure 1. Conceptual illustration of the time-mean meridional overturning circulation of the upper Indian Ocean that consists of a southern and a cross-equatorial cell. The time-mean zonal wind and surface heat flux are also shown schematically. The Indonesian throughflow that carries water from the Pacific Ocean into the Indian Ocean near the latitudes of 10°–15°S [*Gordon*, 1986] is not shown. This flow is believed to partially supply the cross-equatorial thermocline flow [*Schott et al.*, 2002].

T. Li, 2004: GRL

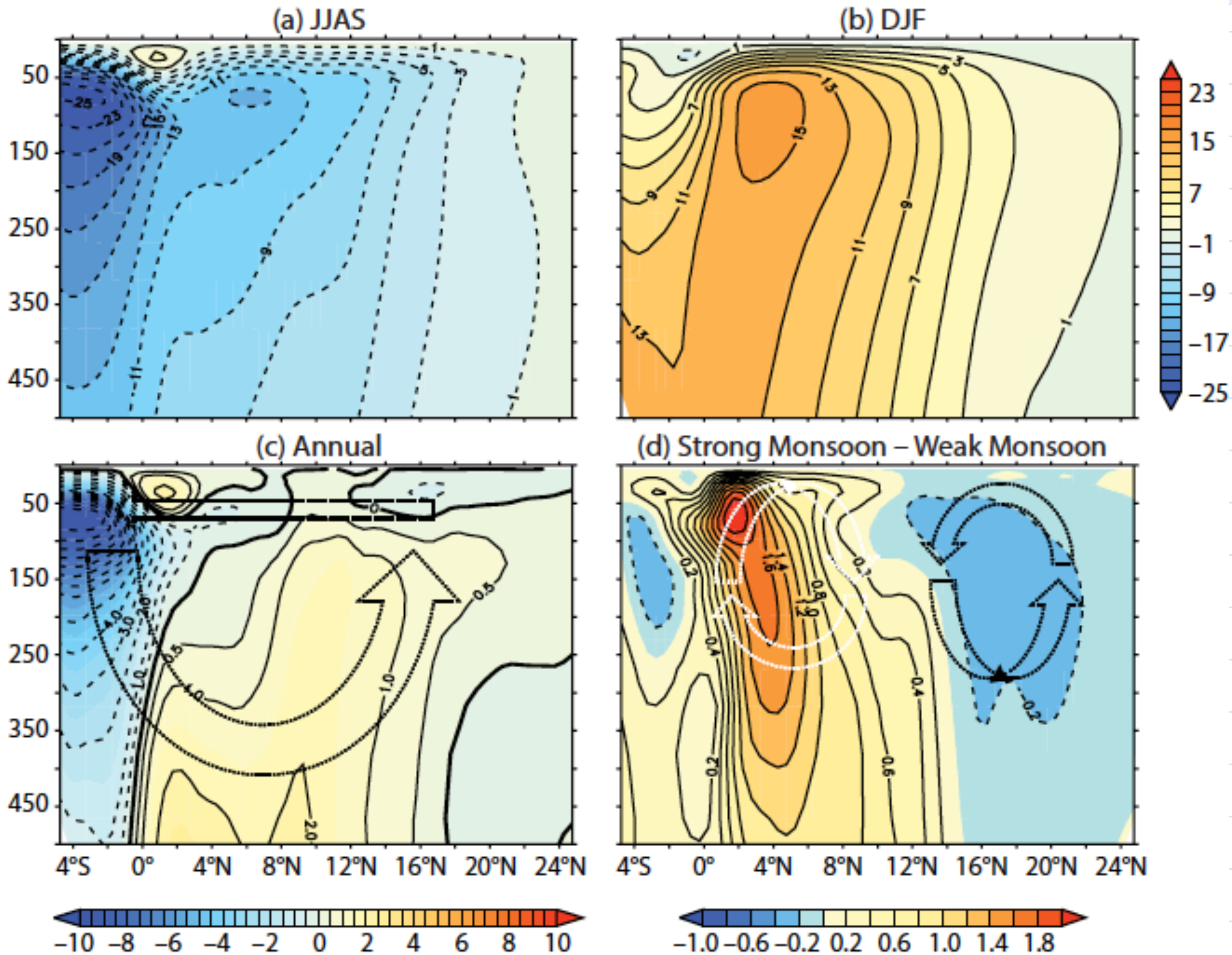


FIGURE 3. Climatological mean meridional stream function in the tropical Indian Ocean during (a) JJAS, (b) DJF, and (c) annual mean calculated from the velocity field of the Simple Ocean Data Assimilation (SODA) analysis (Carton and Giese, 2008). (d) Composite difference in the meridional stream function between strong and weak monsoons.

The shallow meridional circulation is a result of Ocean-atmosphere interaction.

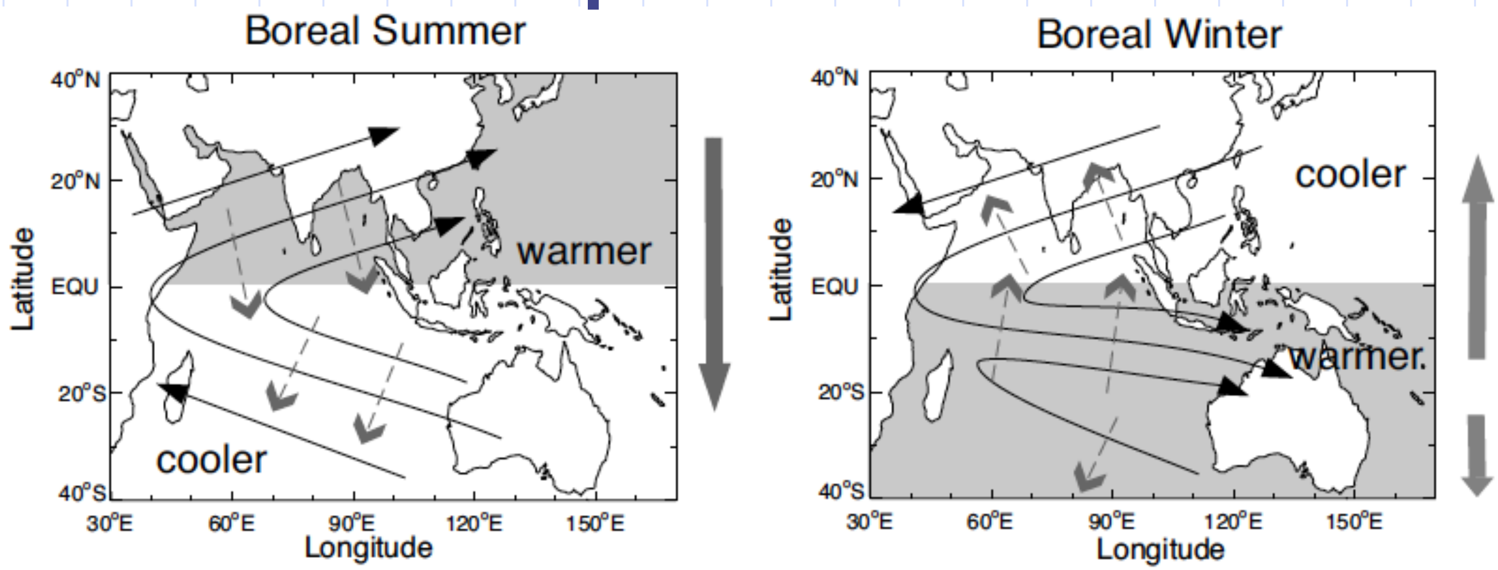
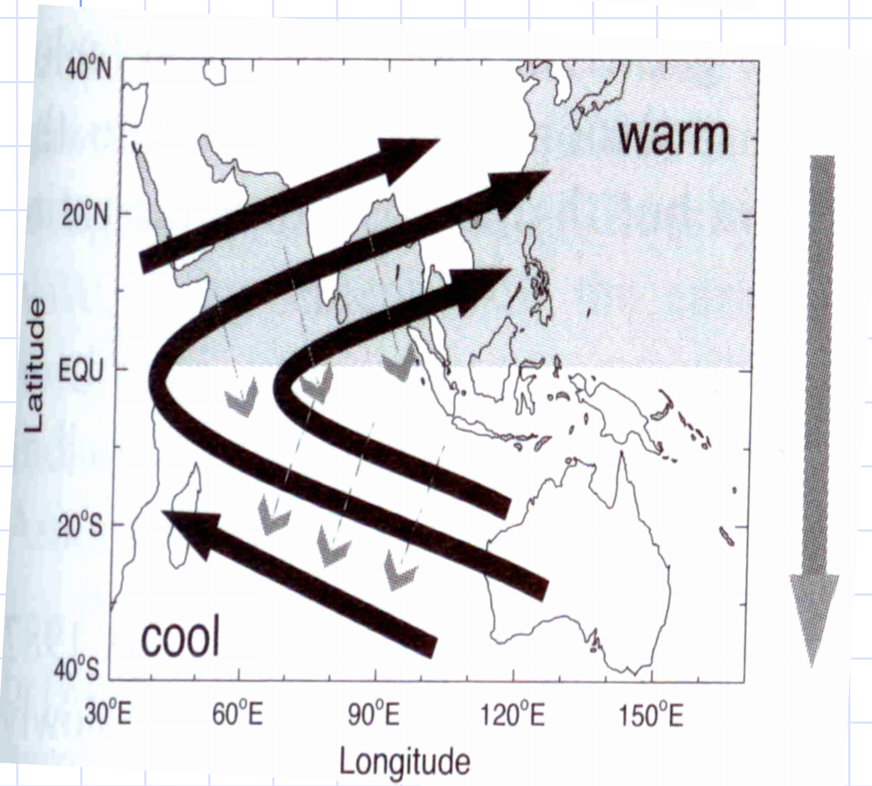


Figure 1.15. Schematic of regulation of the seasonal cycle of the Indian Ocean for (a) the boreal summer (June–September) and (b) the boreal winter (December–February). Curved solid lines indicate near-surface winds forced by the large-scale pressure gradients associated with the cross-equatorial heating gradient denoted by 'warm' and 'cool' (cf., Figure 1.10). Small gray arrows denote wind forces, Ekman drift, and the direction of the associated heat flux. The large vertical arrow denotes the sense and magnitude of the net zonally averaged heat flux reverses. Overall, the wind-driven southward flux of heat in the summer tends to cool the north Indian Ocean, while the northward flux during the winter tends to heat the north Indian Ocean, thereby reducing the SST gradient at all times of the year. The coupled ocean–atmosphere interaction described in the figure imposes a strong negative feedback on the system regulating the seasonal extrema of the monsoon.

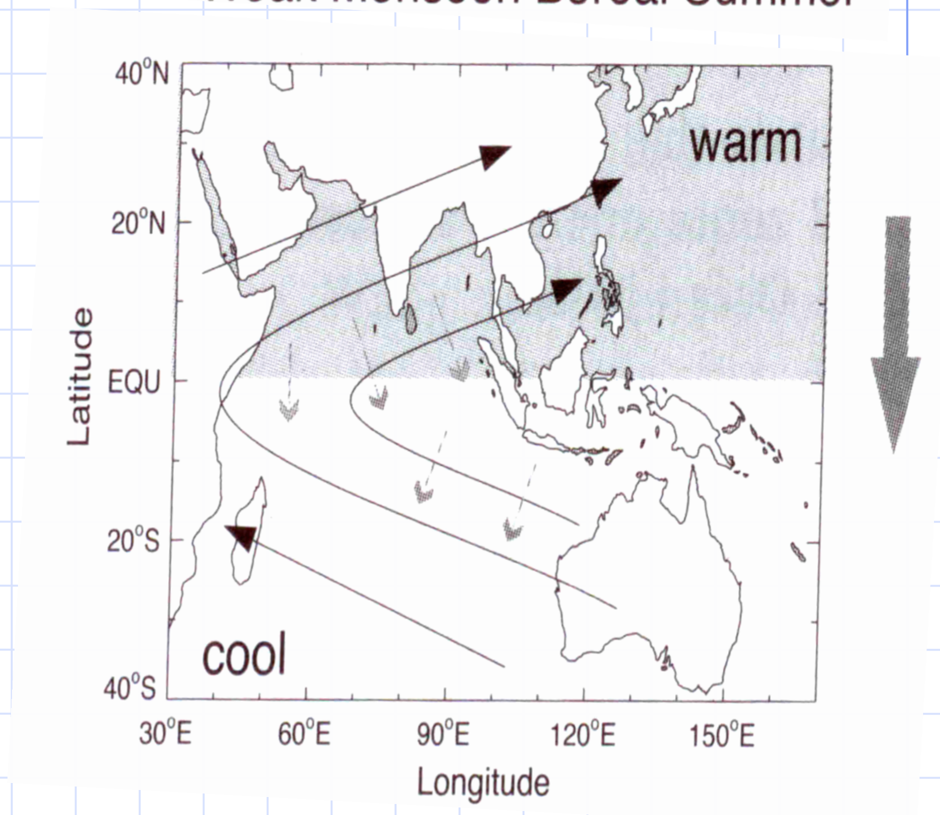
Webster, P.J., 2006: The Coupled Monsoon System, in The Asian Monsoon, Bin Wang (Ed.), Praxis

The transport by the meridional circulation in IO has the potential to produce a biennial oscillation of the Indian monsoon.

- Strong Monsoon Boreal Summer



Weak Monsoon Boreal Summer



- Do we have air-sea interaction in the Indian Ocean-monsoon region on inter-annual time scales similar to those over the Pacific?

- We have discovered a mode of variability in the Indian Ocean, known as the **'Indian Ocean Dipole Mode'** that involves local air sea interaction similar to ENSO.

(Saji, Goswami, Vinayachandran and Yamagata, 1999, Nature, **401**, 360-363,

Webster et. al., 1999, Nature, **401**, 356- 360)

SST anomaly pattern associated with a canonical El Nino

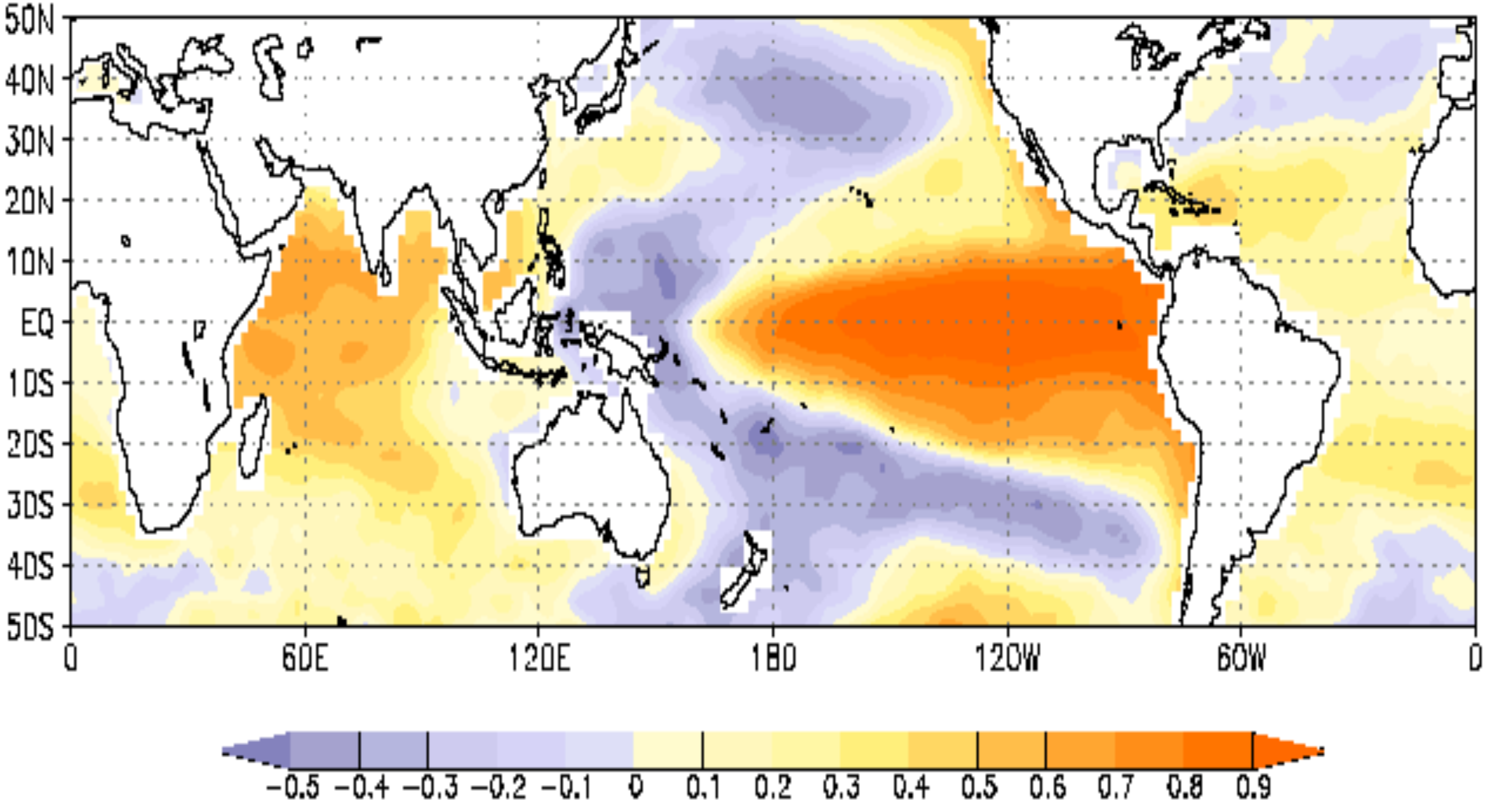


Figure 1: One point correlation between monthly SST anomalies over the NINO3 area (150W-90W, 5S-5N) and monthly SST anomalies elsewhere. Trend and oscillations with period greater than 7 years were removed from the SST anomalies. The period used was January 1949 to December 1998. Large part of tropical IO fluctuates coherently with eastern Pacific SST variations.

Amplitude of inter-annual variation of June-September SST over the IO

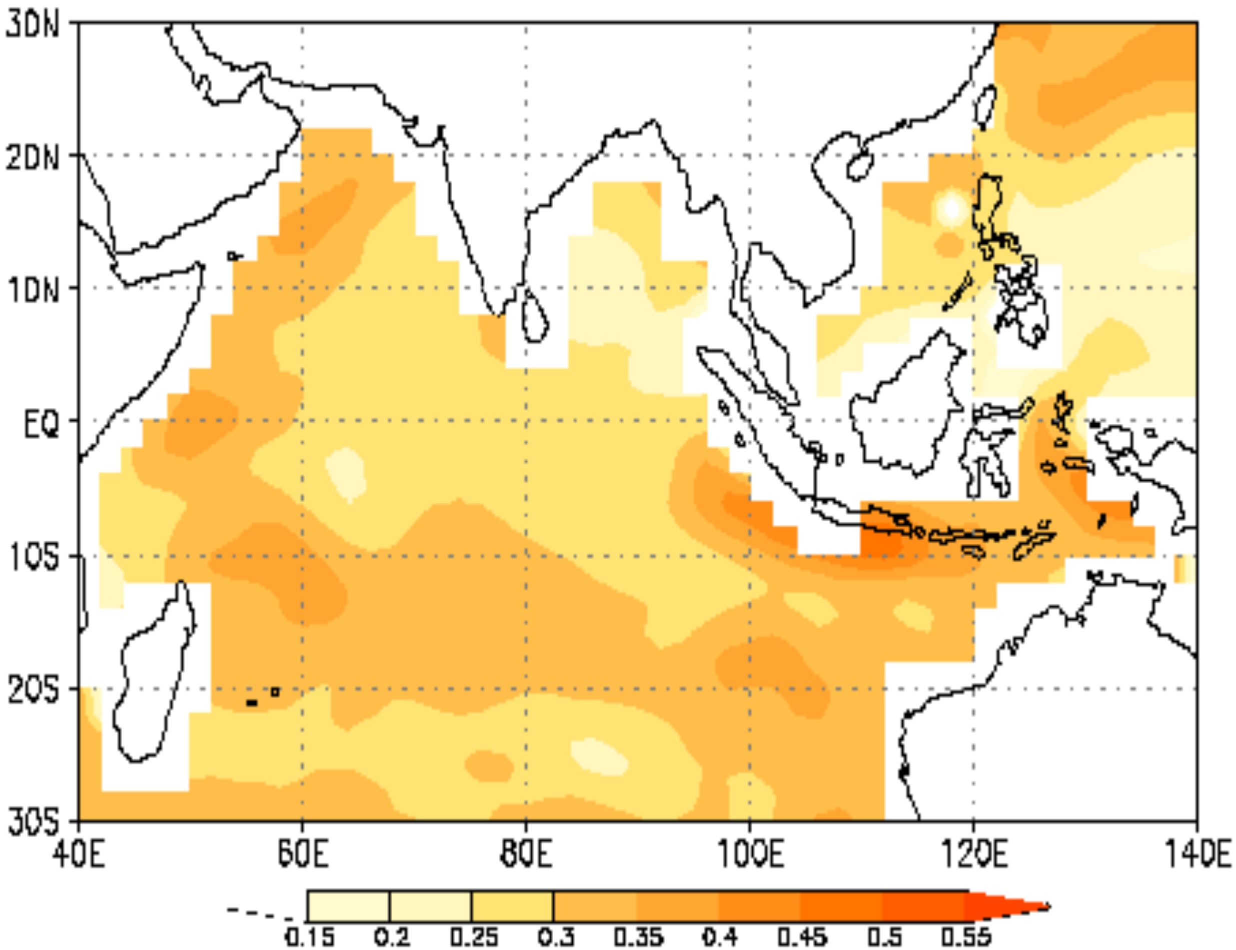


Figure 3: Standard deviation of SST anomalies for June-September (in degrees C). Trend and long period oscillations have been removed from the monthly anomalies. The period used was January 1949 to December 1998.

Notable,

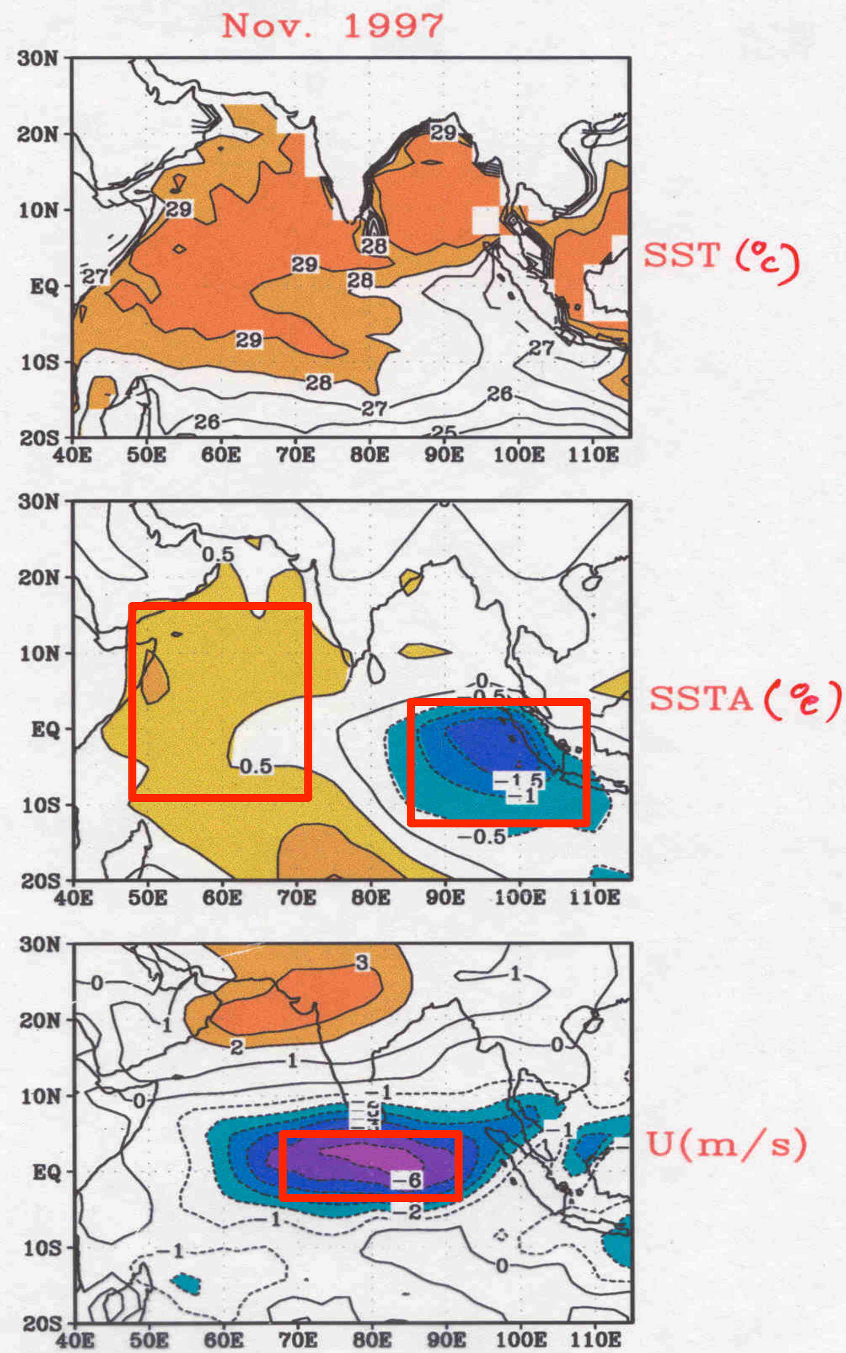
In contrast to Cental/Eastern Pacific where amplitude is ~1.0^{O}C, over the IO, it is smaller ~0.45

In 1997, something unusual happened!

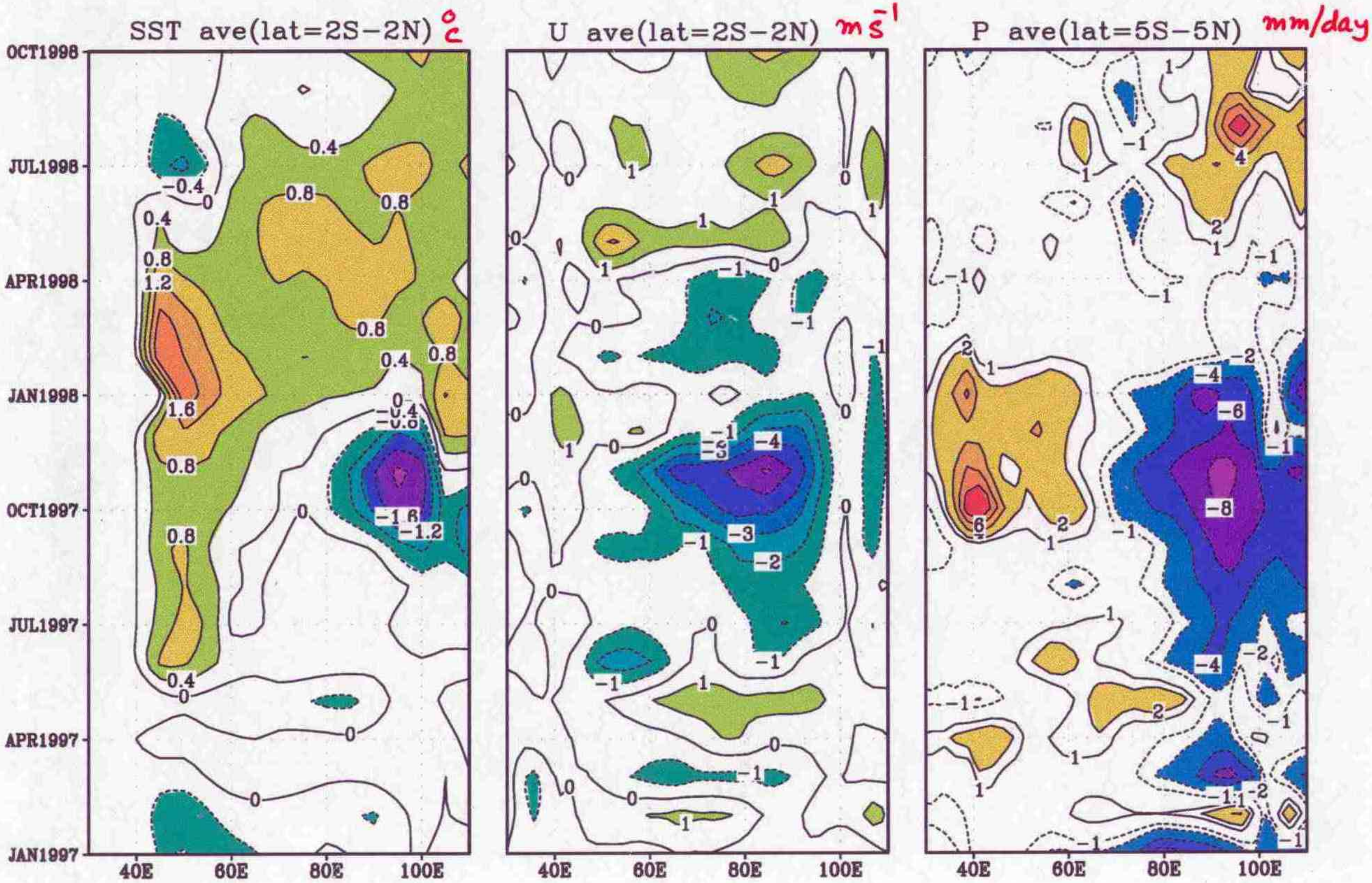
- In fall of 1997 the east-west SST gradients reversed in the tropical Indian Ocean.

- A strong east-west dipole type pattern of SST anomalies (cold east and warm west) together with strong easterly surface wind anomalies in the central equatorial IO were seen.

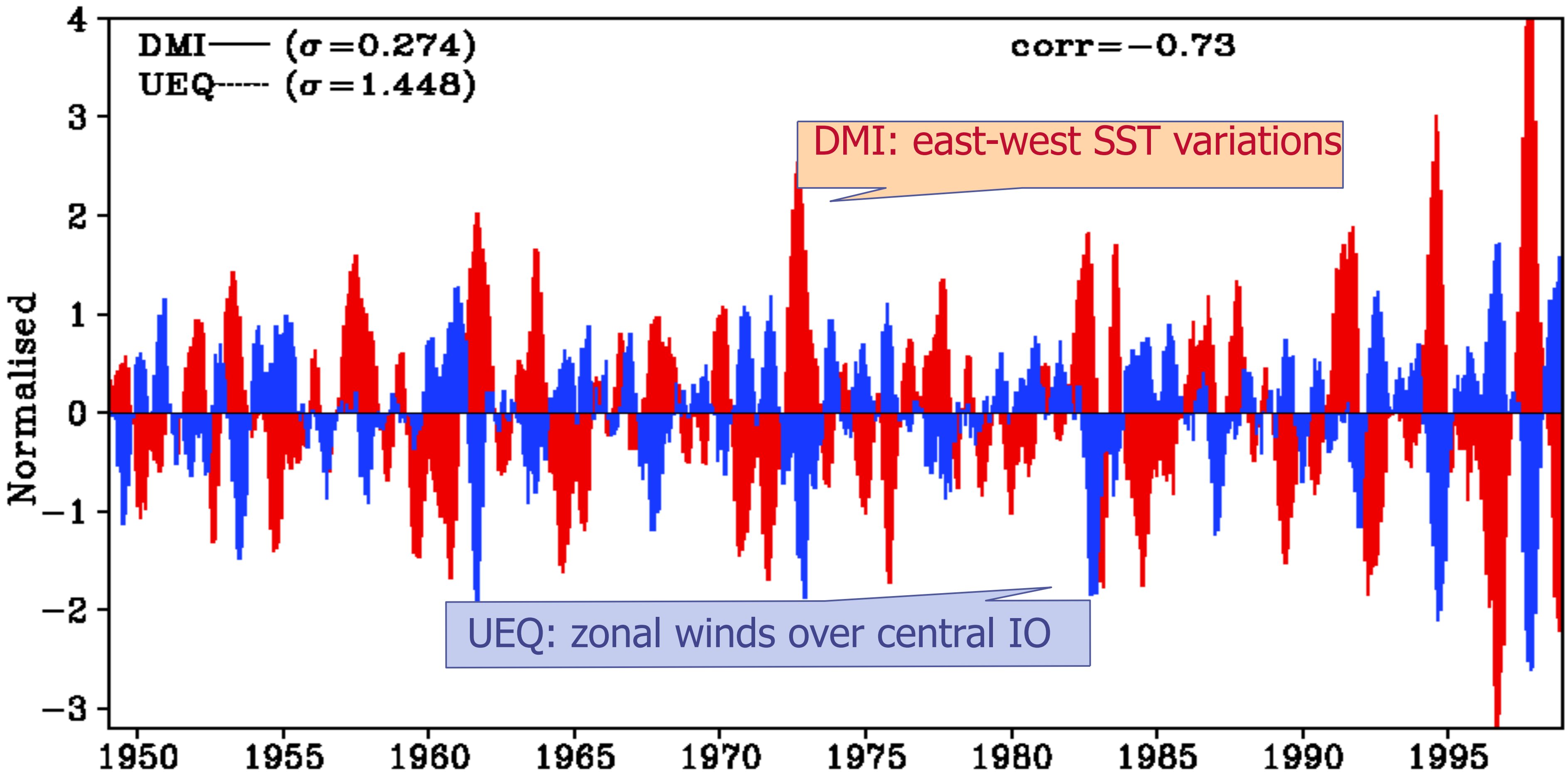
- Anomalous SST surface winds were indicative of unstable air-sea interactions



THE 1997-98 SPECIAL EVENT IN THE IO



Indication of air-sea interaction in the Indian Ocean

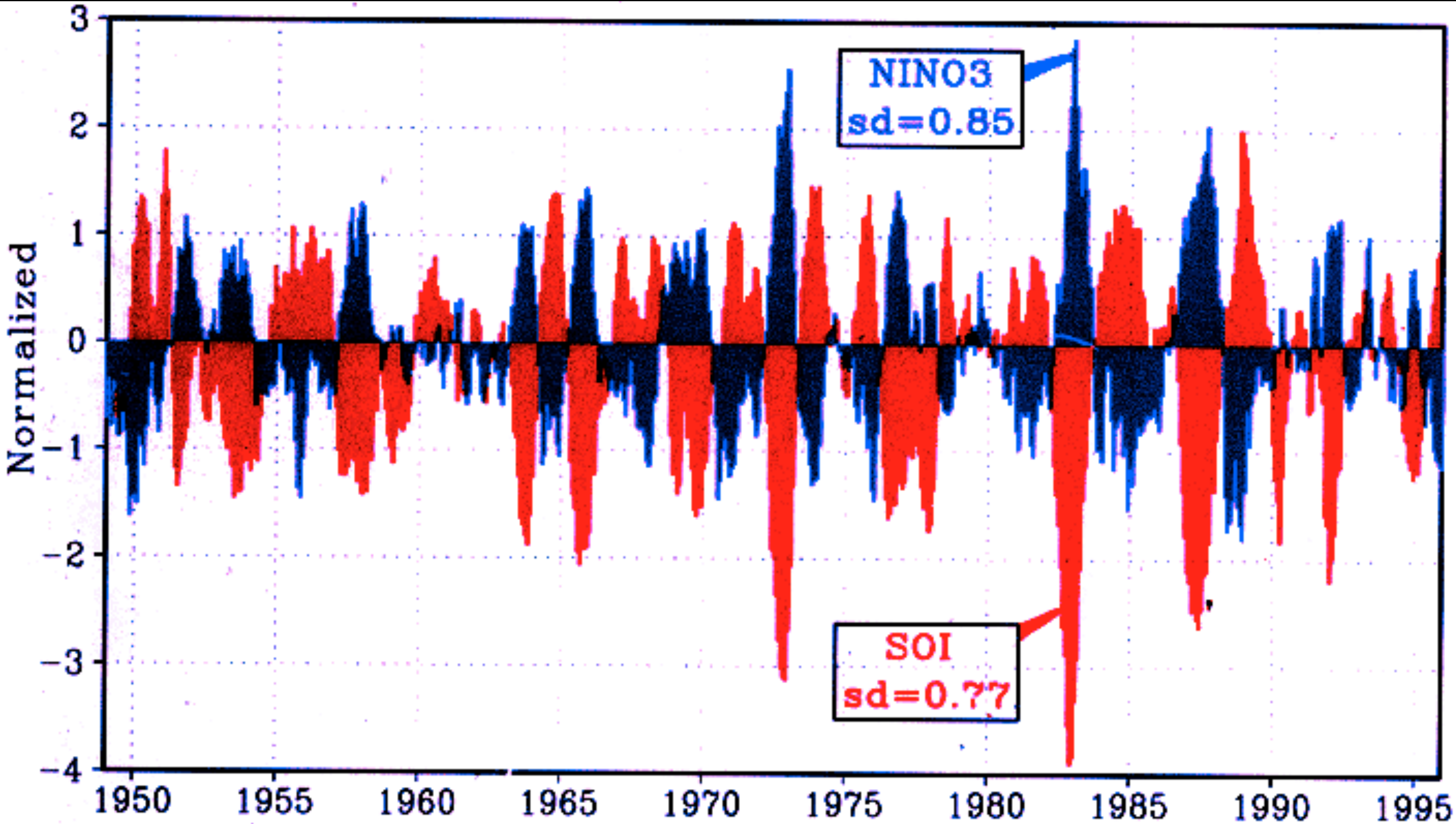


Relation between Dipole Mode Index (DMI) and Equatorial Zonal Winds.

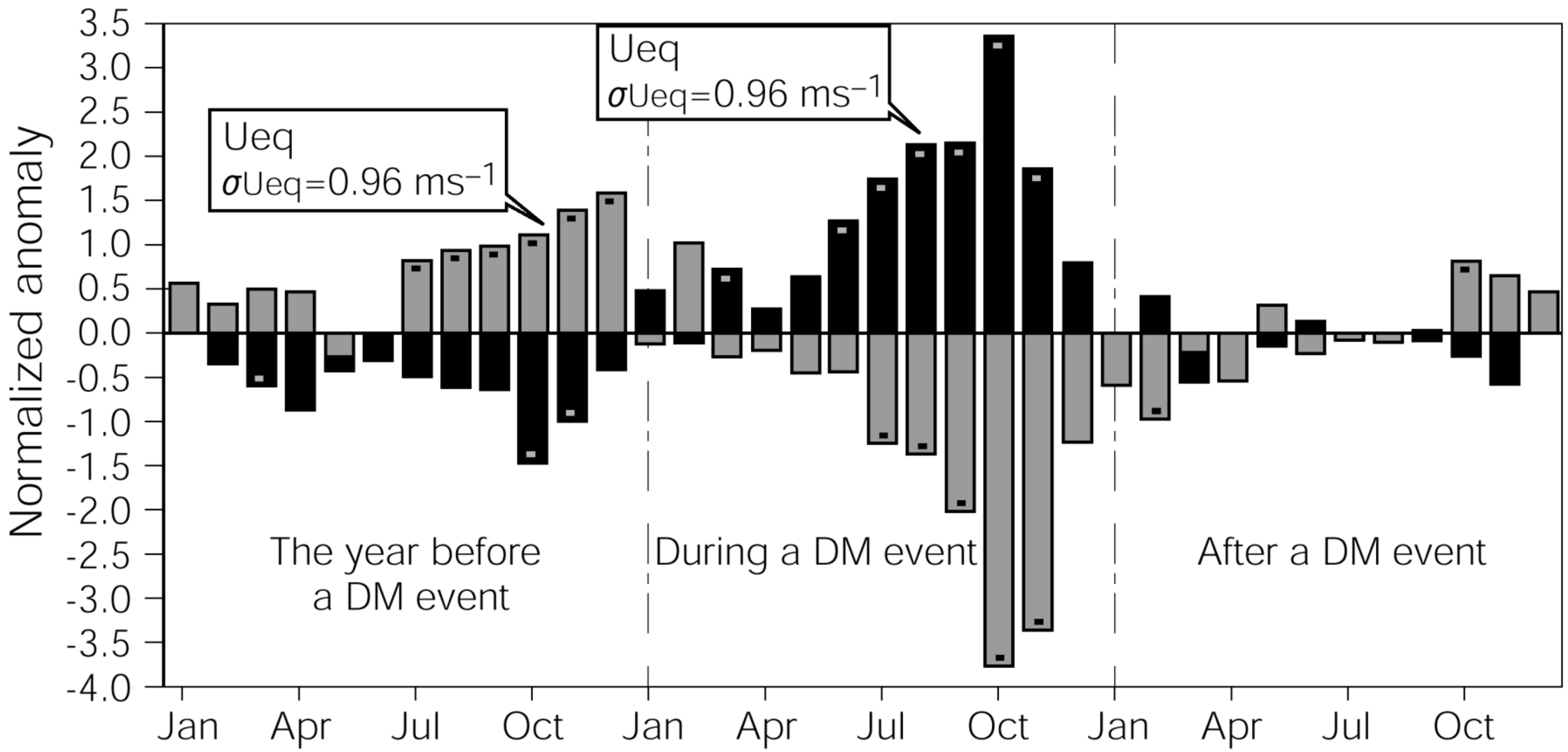
DMI: SSTA ave (50E-70E,15S-15N)-SSTA ave (90E-110E,15S-EQ), UEQ: U ave (70E-90E,5S-5N)

➔ Strong correlation between URQ and DMI indicates Ocean Atmosphere coupling

Time series of Nino3 and SOI

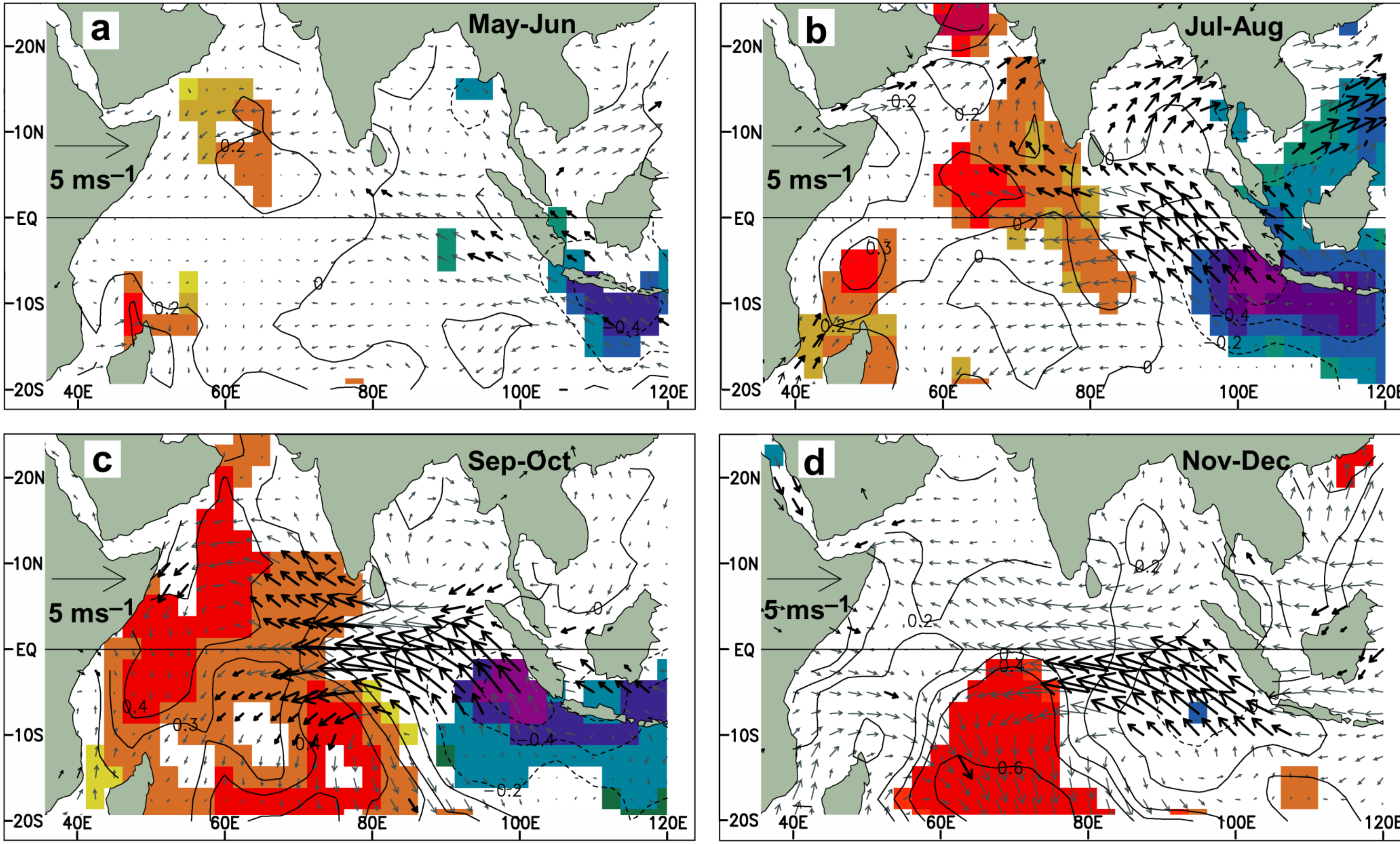


The similarity of the association between Nino3 and SOI and that between DMI and UEQ is notable.



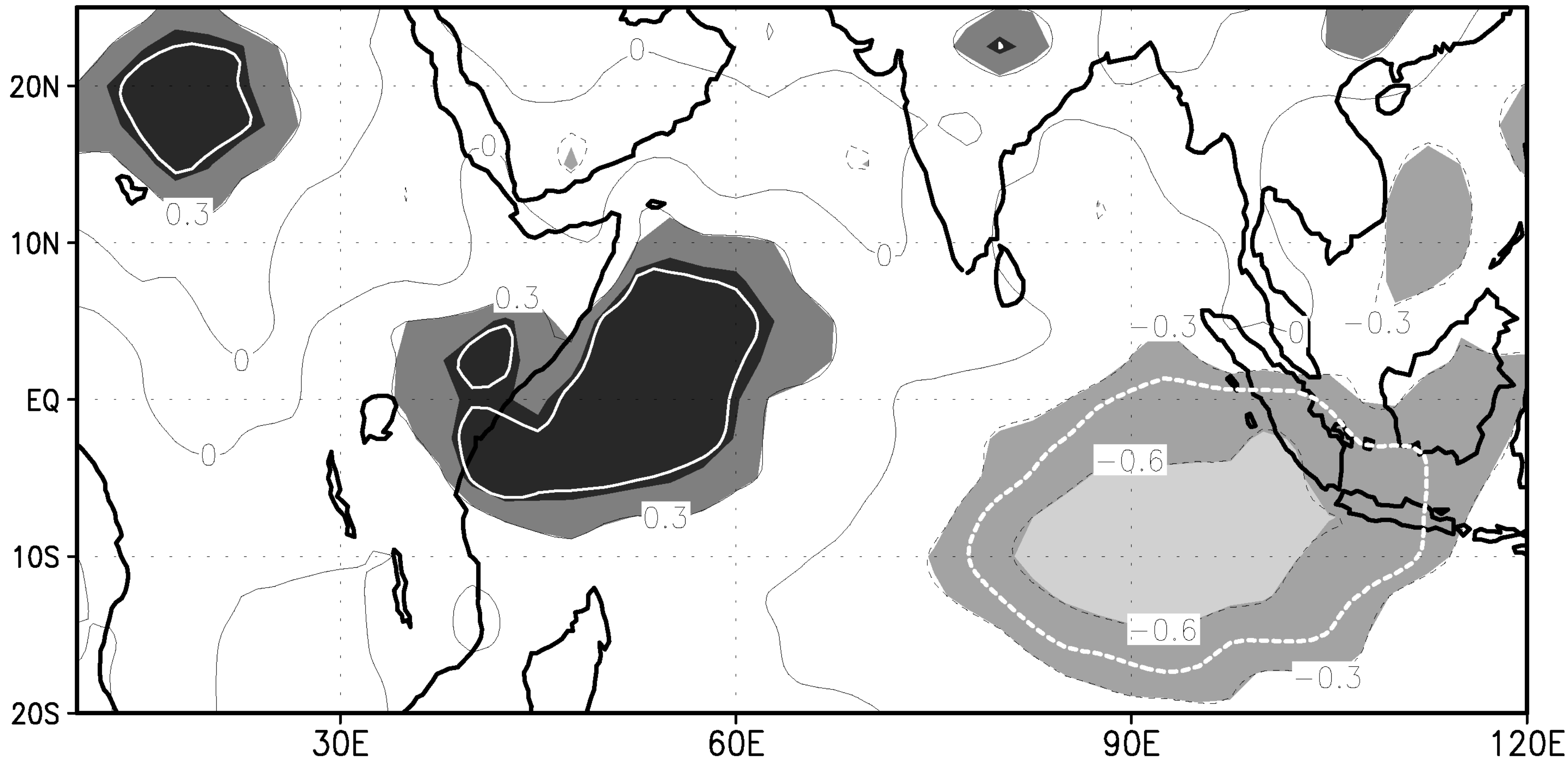
Strong coupling of SST dipole intensity to Ueq . Shown is the co-evolution of intensity of the dipole mode (DMI, black bars) and strength of equatorial zonal winds anomalies (Ueq , grey bars) from the year before, to the year following a typical dipole mode event. Bars indicating significant anomalies (estimated by a two-tailed t-test) exceeding a 90% confidence level are marked with spots.

➔ Indicates a quasi-biennial periodicity of IOD



Composite evolution of anomalous winds & SST during a typical DM event (based on average of six events). Coherent evolution of east-west dipole structure of SST and equatorial winds indicate that it is an ocean-atmosphere coupled mode.

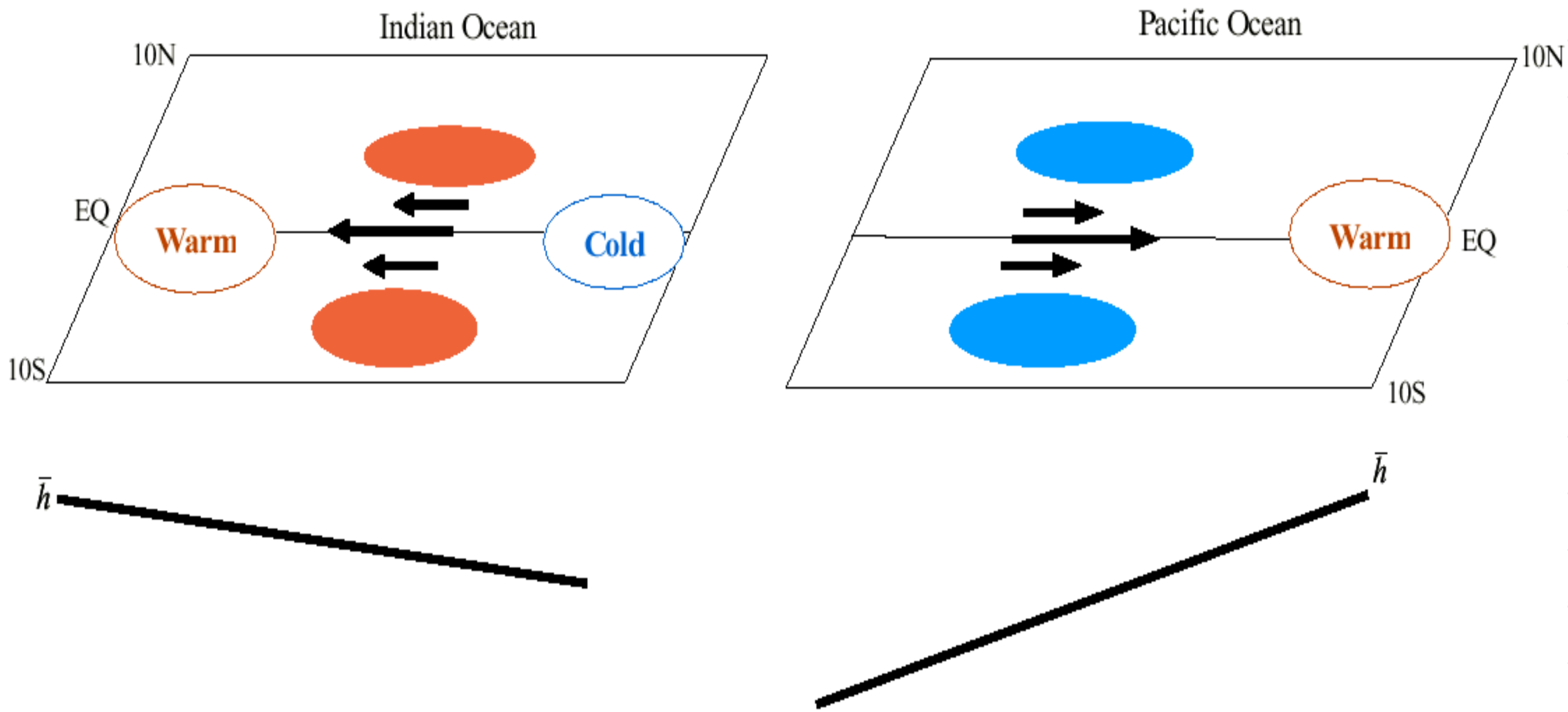
East west see saw of Precipitation associated with Dipole Mode Events



Simultaneous Correlation b/w DMI and Precipitation using data from 1974-1998. The precipitation data is from Xie-Arkin (1996).

The precipitation pattern, the SST dipole and the equatorial zonal winds are all consistent with a coupled evolution of the DM events

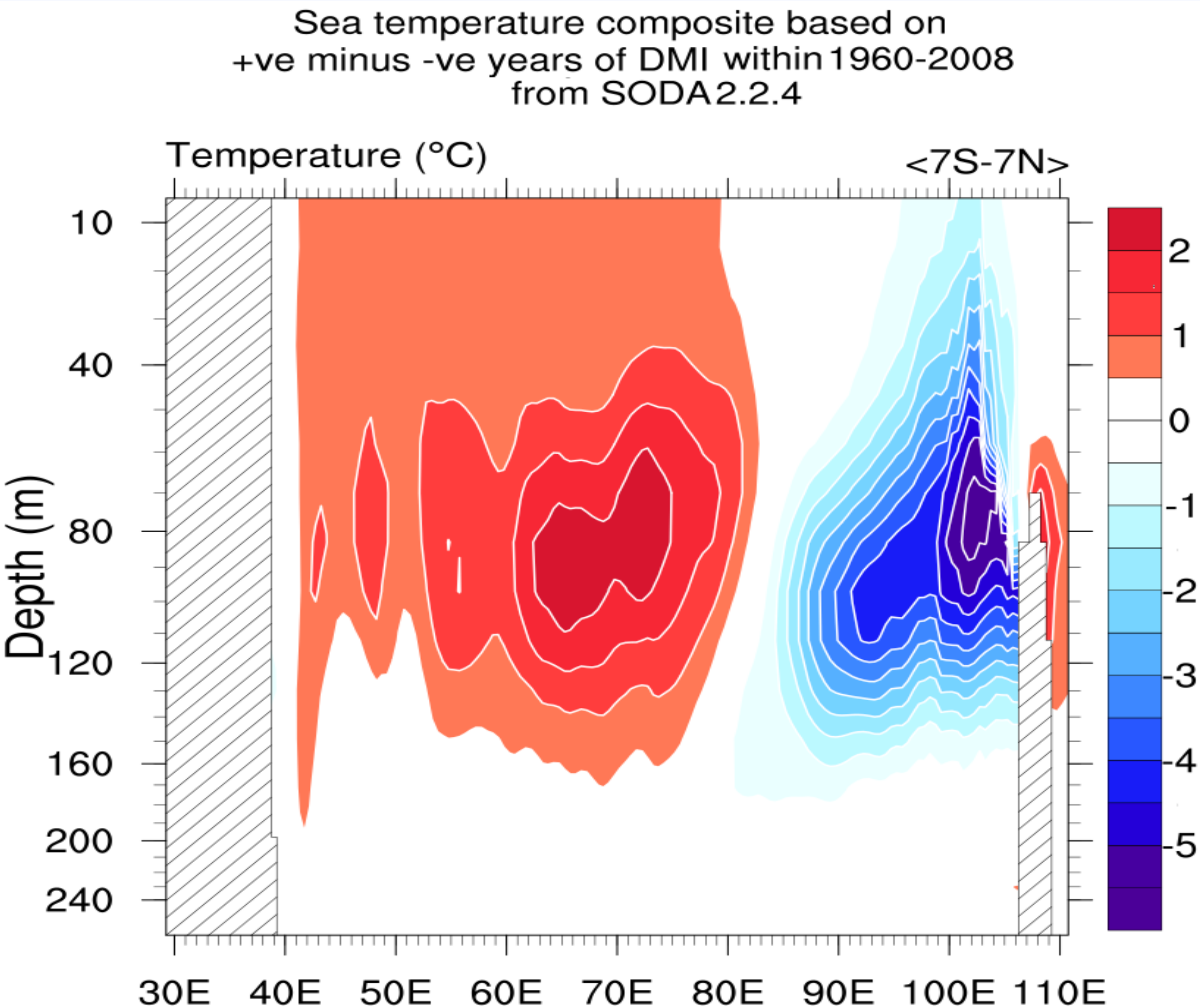
Bjerknes Feedback in the Indian Ocean



Easterly anomaly around the eq. in the IO leads to depression (shoaling) of thermocline in the west (east) and warming (cooling)

Westerly anomaly around the eq. in the Pacific leads to depression (shoaling) of thermocline in the east (west) and warming (cooling)

Evidence of Bjerknes Feedback in the Indian Ocean



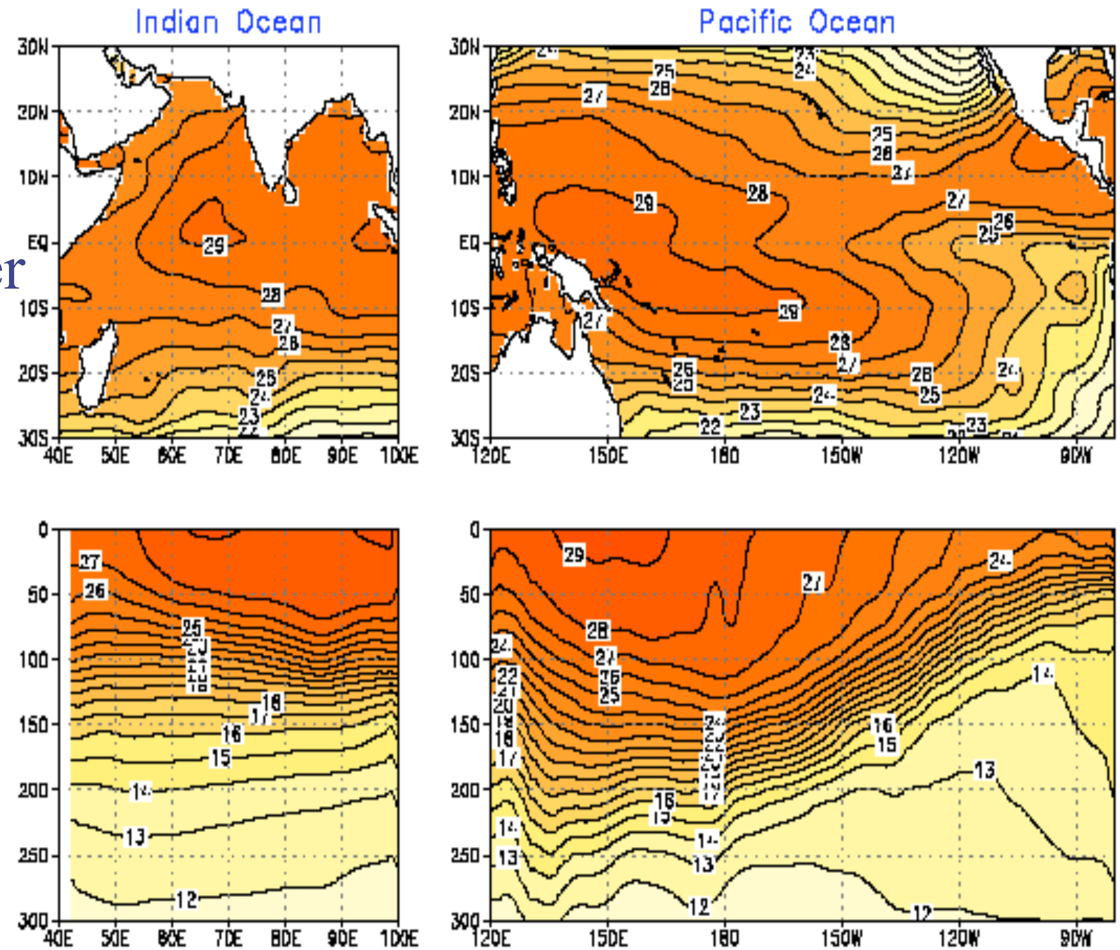
Courtesy: Prolay Saha

Difference in Mean conditions between IO and Pacific:

(Required to understand differences in air-sea interactions in the two basins)

Indian

East➔Warm
West➔Cooler



Pacific

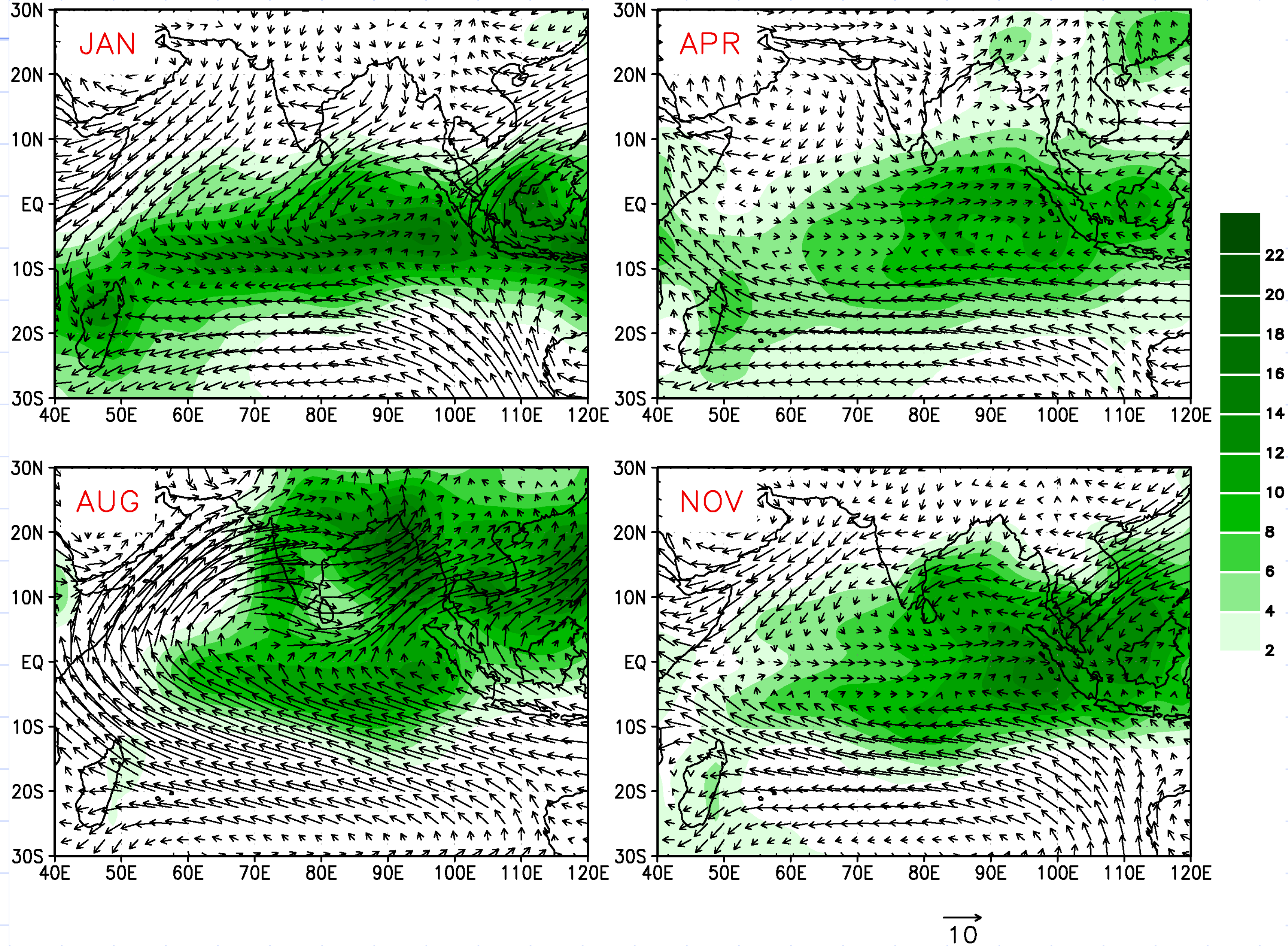
East➔Cooler
West➔Warm

Thermocline ➔ increases depth from west to east

Thermocline ➔ increases depth from east to west

Figure 4: (Top) Annual mean SST over the Indian and Pacific oceans. (bottom) height-longitude section of SST averaged around the equator between 2S and 2N showing the east west orientation of the thermocline.

During Boreal Summer, off equatorial Indian monsoon heat source can influence equatorial winds and ocean-atmosphere interaction over Indian Ocean basin. There is nothing like that over the Pacific basin.



Equatorial Indian Ocean mean winds are dominated by a SEMI ANNUAL Cycle

Annual mean around Equator is weak easterly (westerly)~ ± 1 m/s

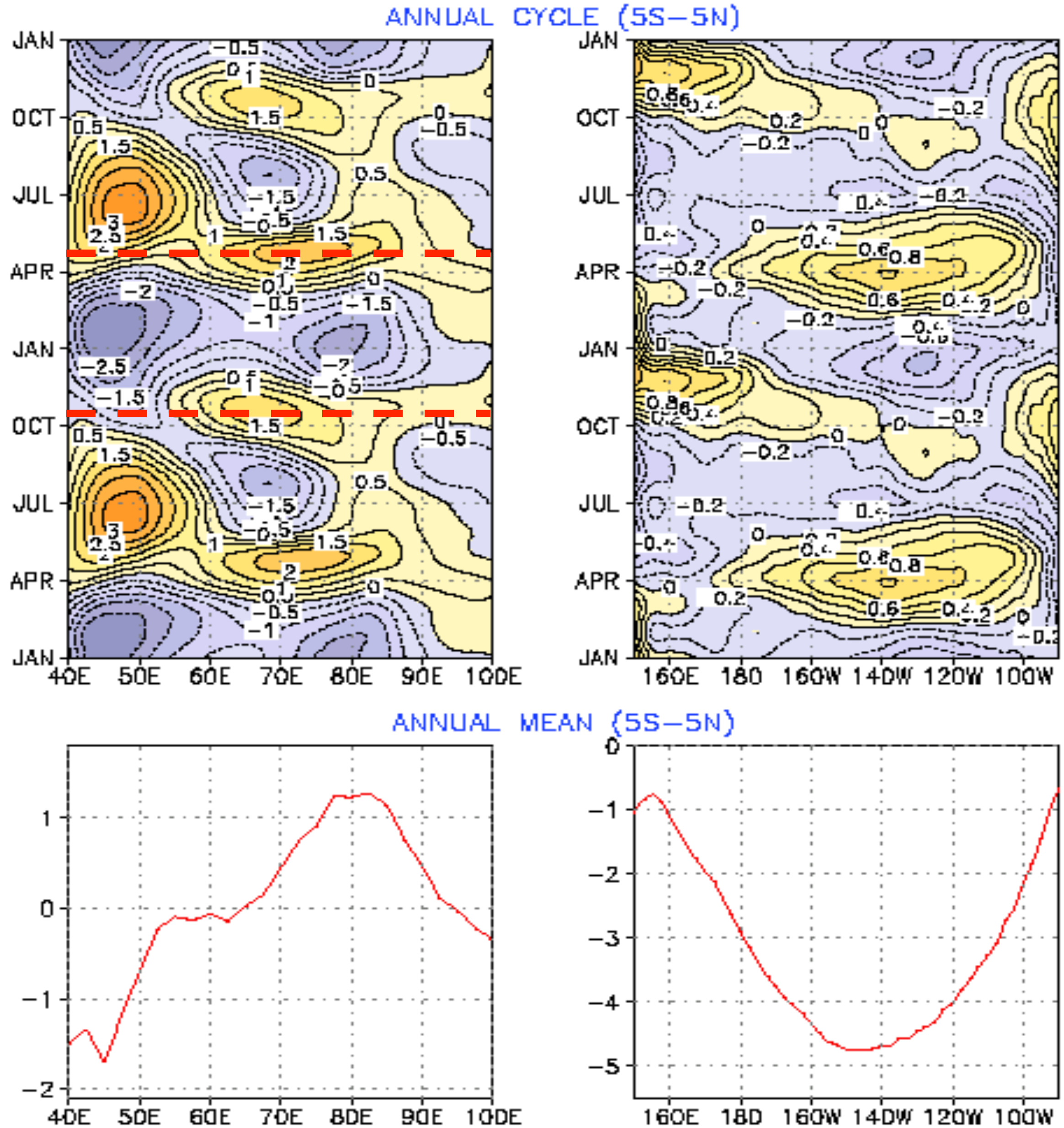


Figure 5: The annual cycle (top) and the annual mean (bottom) of zonal winds (m/s) around the equator in the Indian and Pacific Oceans.

Equatorial Pacific mean winds are dominated by a ANNUAL Cycle

Annual mean around Equator is Always Strong Easterly

The Wyrtki Jet in Equatorial Indian Ocean

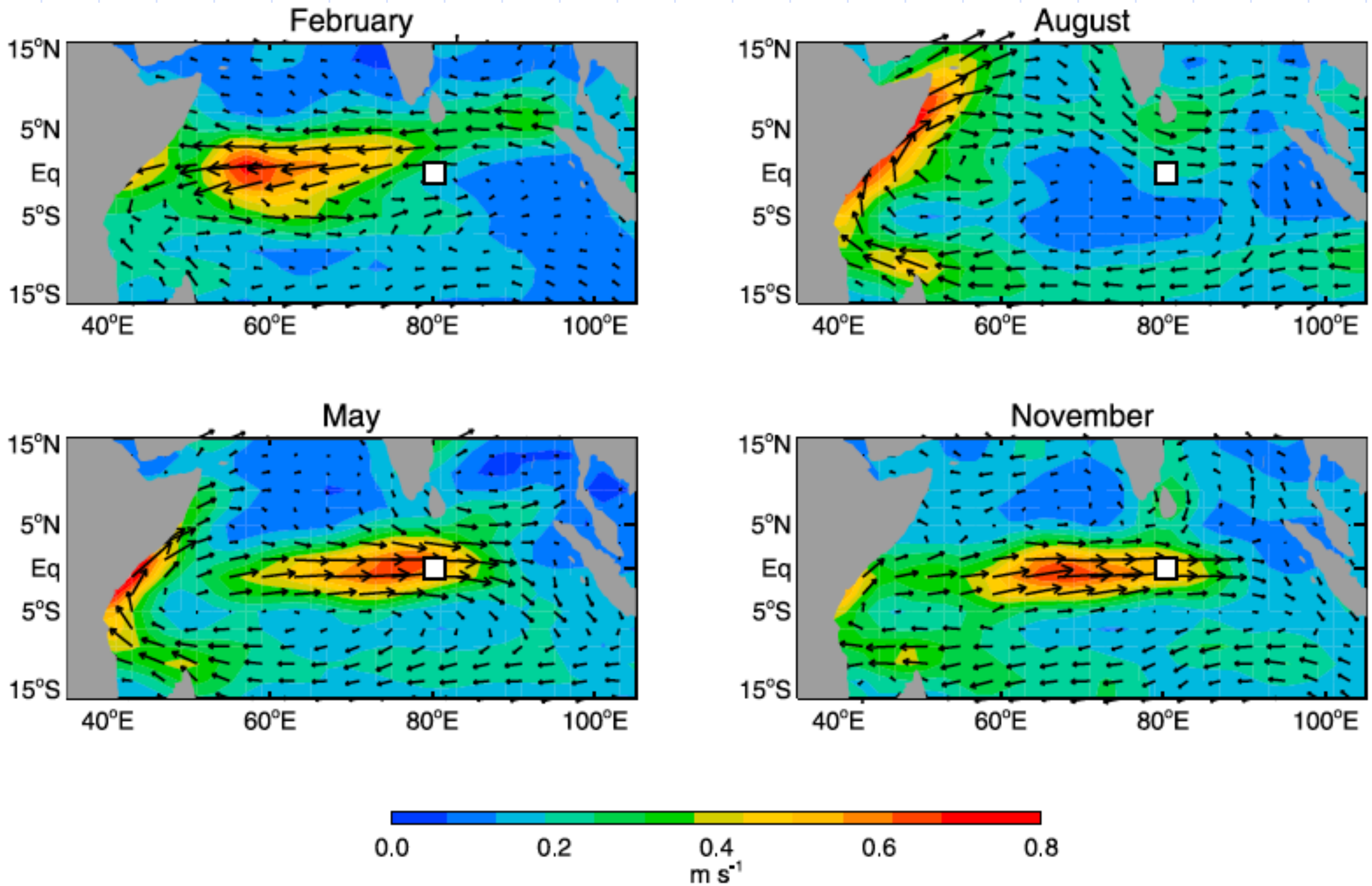
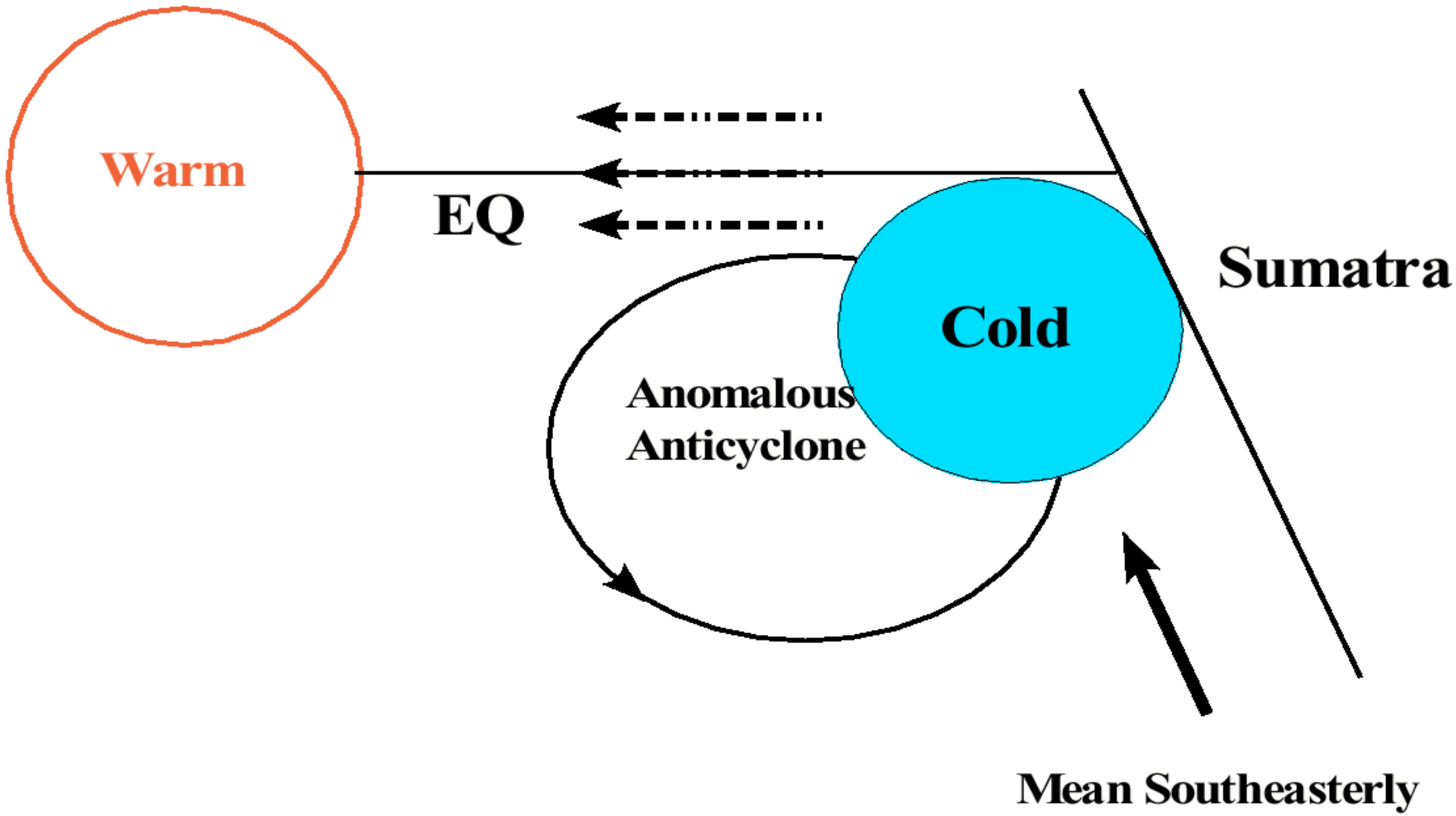


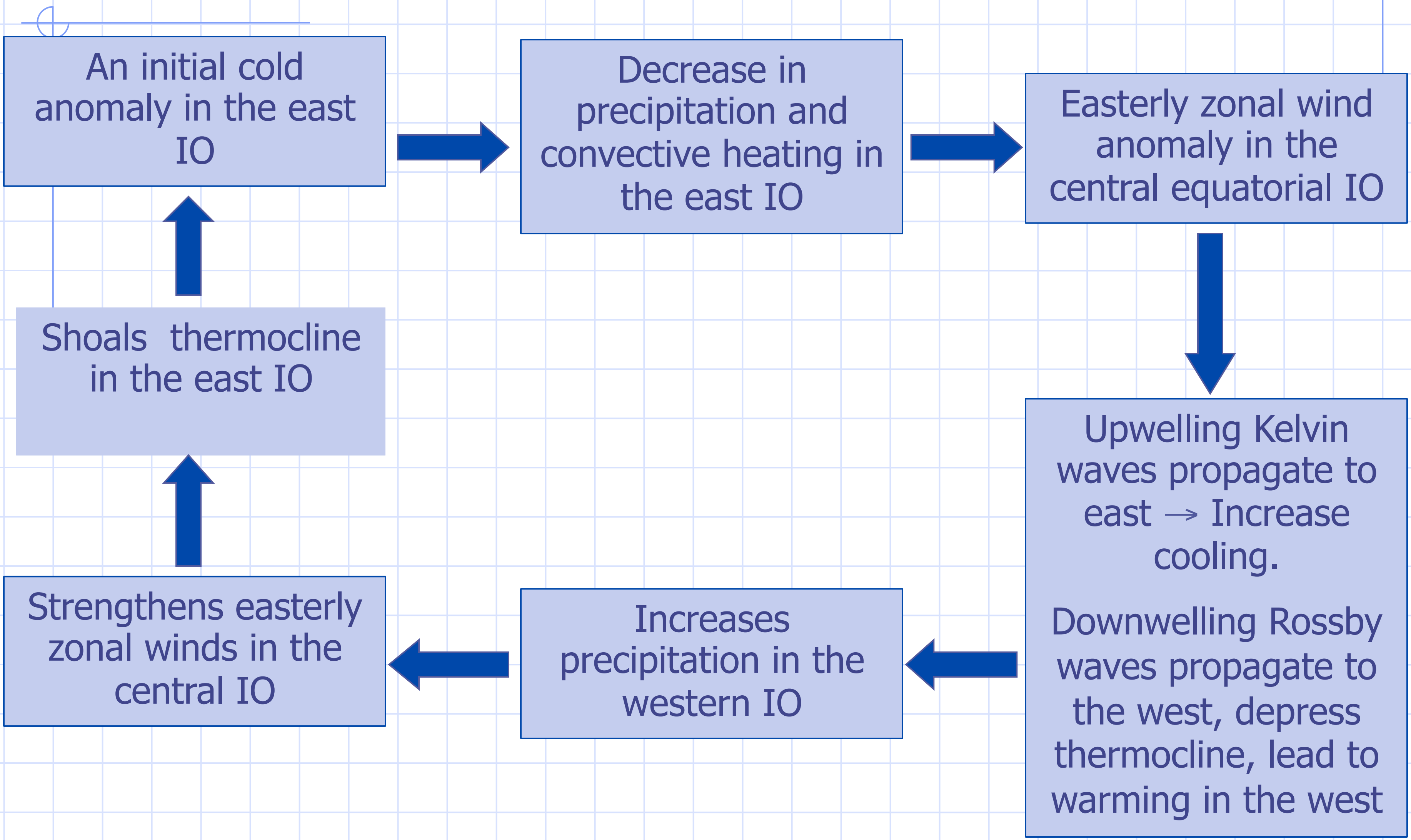
Figure 1. Monthly climatologies of surface velocity (vectors) and scalar speed (color shading) from ship drift observations for February, May, August, and November [*Cutler and Swallow*, 1984]. The white box at 0°, 80.5°E indicates the position of RAMA ADCP observations.

Nagura and McPhaeden, 2010: LGR,115, doi:10.1029/2009JC005922.

A Positive Air-Sea Feedback off Sumatra in Summer



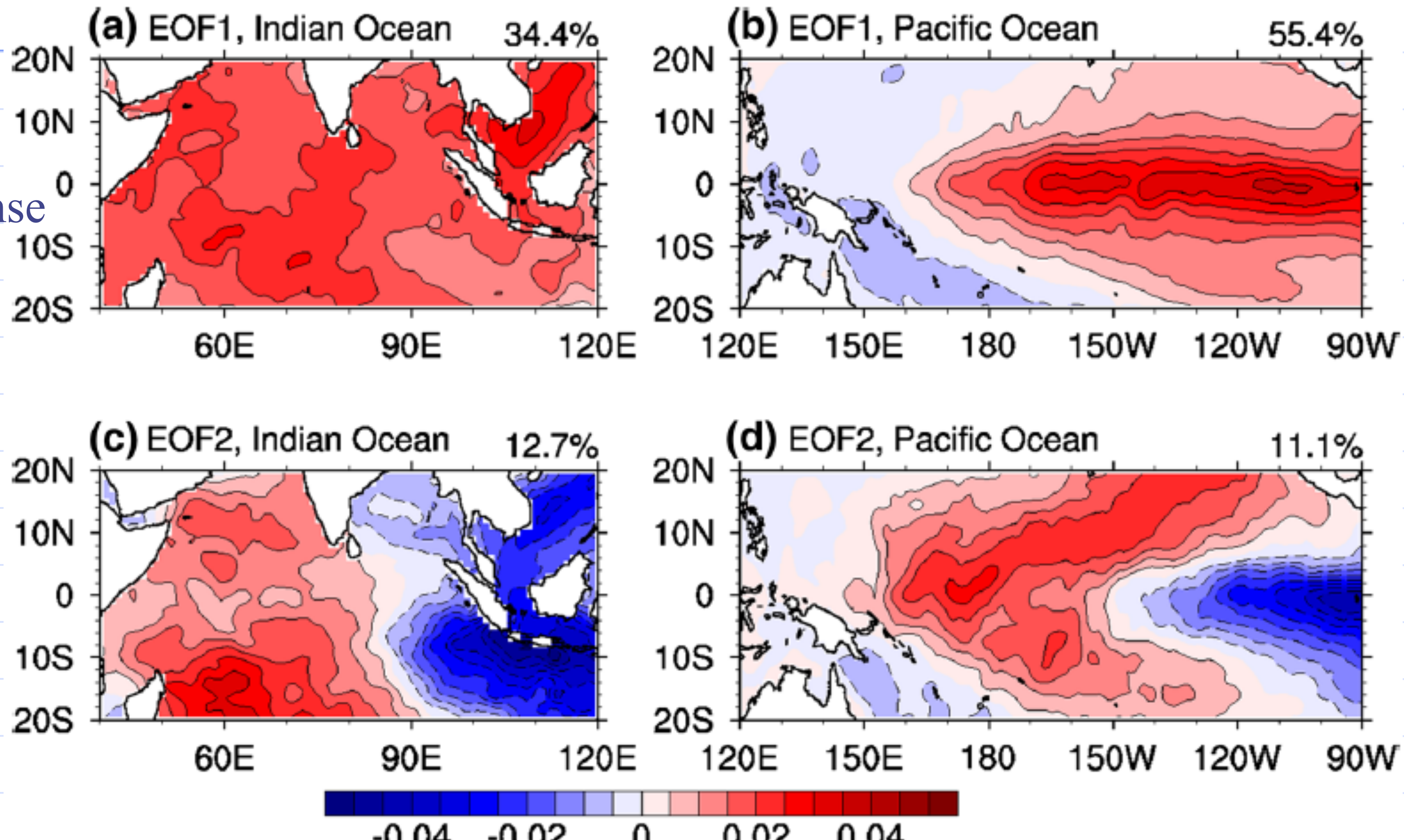
The air-sea coupled feedback associated with DM



While the IOD mode is a important mode of variability of the Indian Ocean sustained by local air-sea interactions, it is not the ‘dominant mode’ of variability in the IO

ENSO Response

IODM



First two leading modes of monthly sea surface temperature (SST) anomalies over a, c tropical Indian Ocean and b, d Pacific Ocean during the period 1950–2010 (Ha et al., 2017, Climate Dynamics)

How does the IODM influences Indian Monsoon?

A Positive IOD ➔ weaker ascending motion in eastern IO + warm western IO ➔ strengthening the Indian monsoon

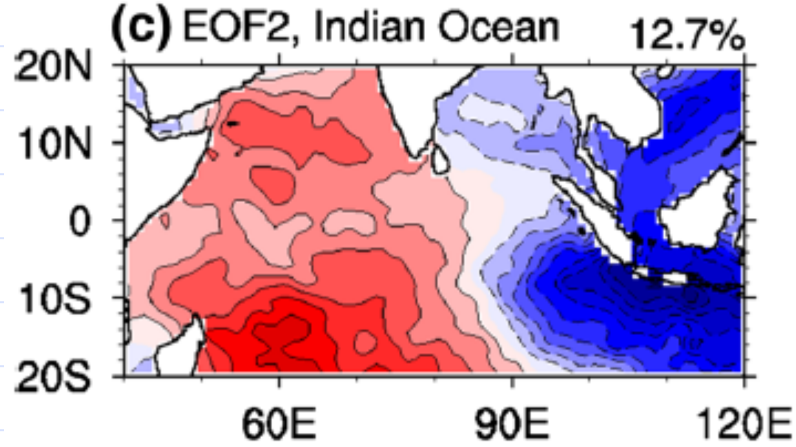
Ashok et al., 2001, GRL

When ISMR-ENSO is strong, ISMR-IOD is weak

Currently, both seem to contribute to the ISMR variability.

Concerns: IOD is second dominant mode IOD peaks only after the monsoon season

IODM



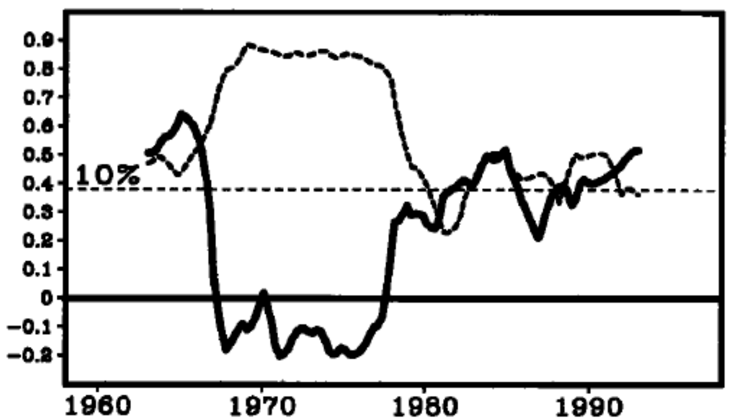
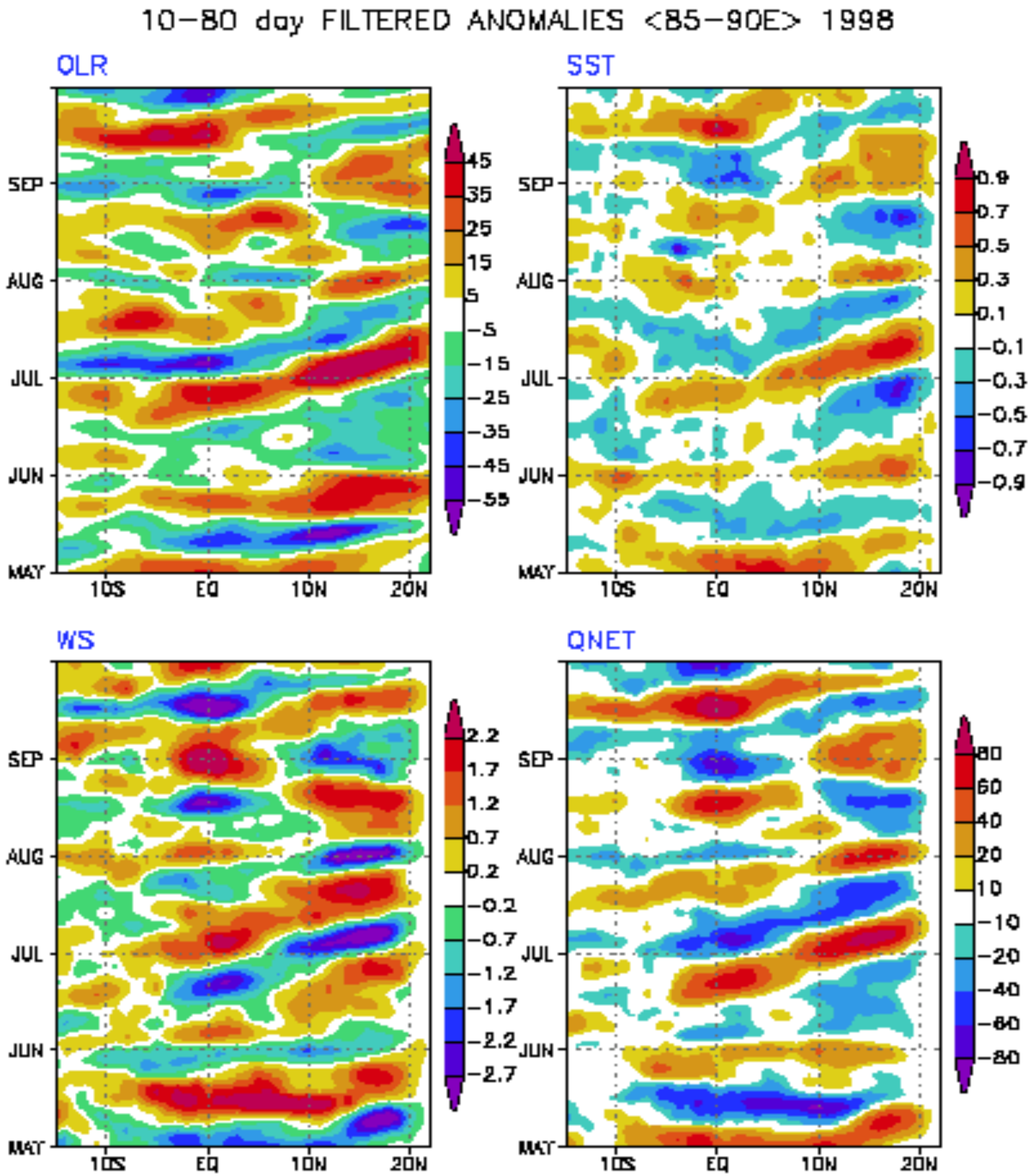


Figure 1. The 41-month sliding correlation coefficients between ISMR and IODMI (solid), and those between monthly ISMR and NINO3 SST (dashed; to be multiplied by −1) during 1958-1997. The significant correlation value at 90% confidence level is 0.38 (verified by 1,000 randomized time series, using the Monte-Carlo simulations)

Cooperation between the atmosphere and the ocean makes the earth’s climate unique and makes it possible for life to exist.

Interaction between the atmosphere and the ocean also produce fascinating variations of the climate and makes it interesting.

Air-Sea Interactions on Intraseasonal Time Scale



Indication of air-sea interaction MISO time scale

SST → clouds, winds, fluxes, → Q_{net} → drives SST

Time-latitude section around 85-90E of OLR, Surface wind speed, SST and Surface net heat flux (QNET)

Sengupta,Senan & Goswami . 2001, GRL

Air-Sea Interaction associated with MISO (30-60 day mode)

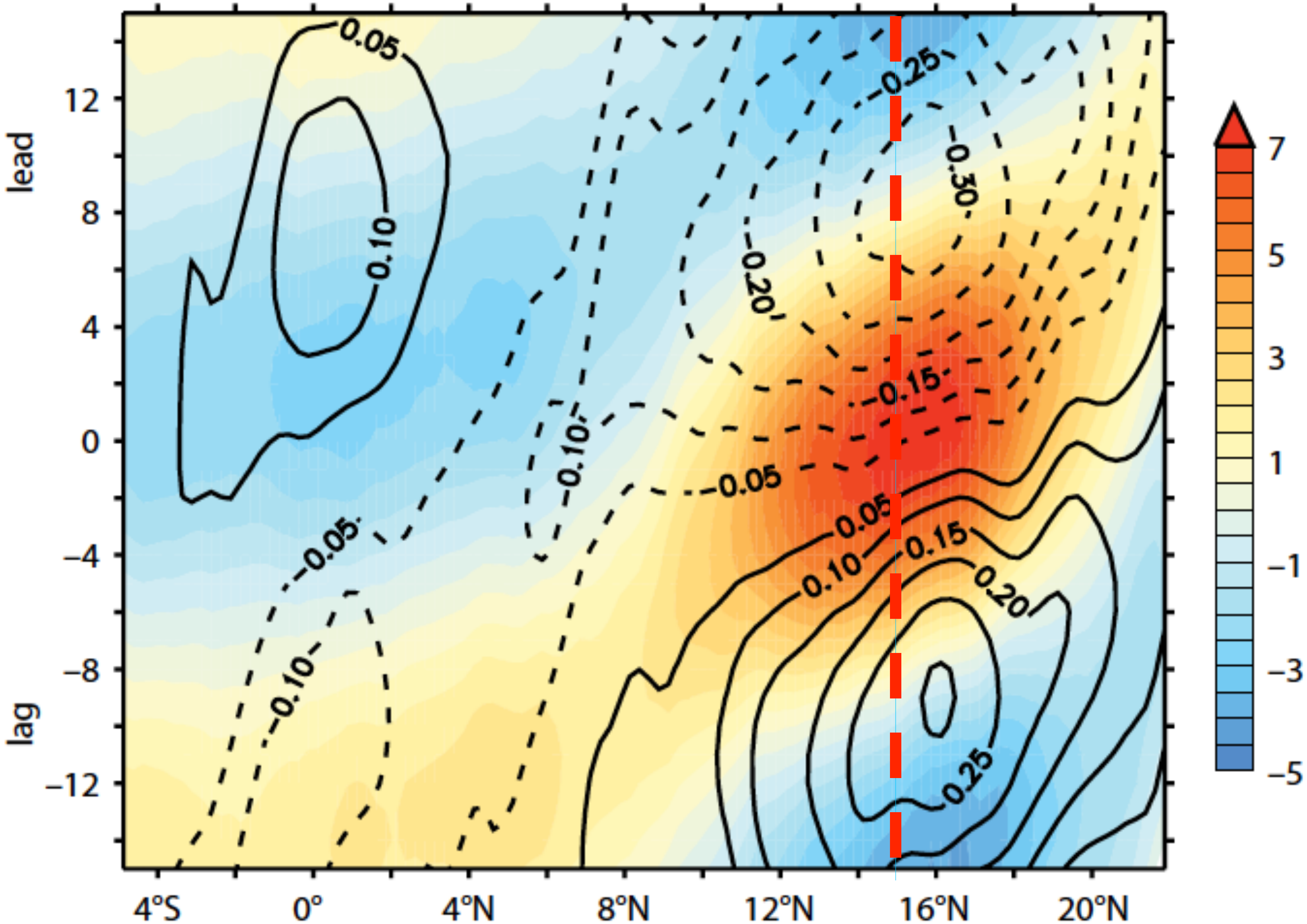


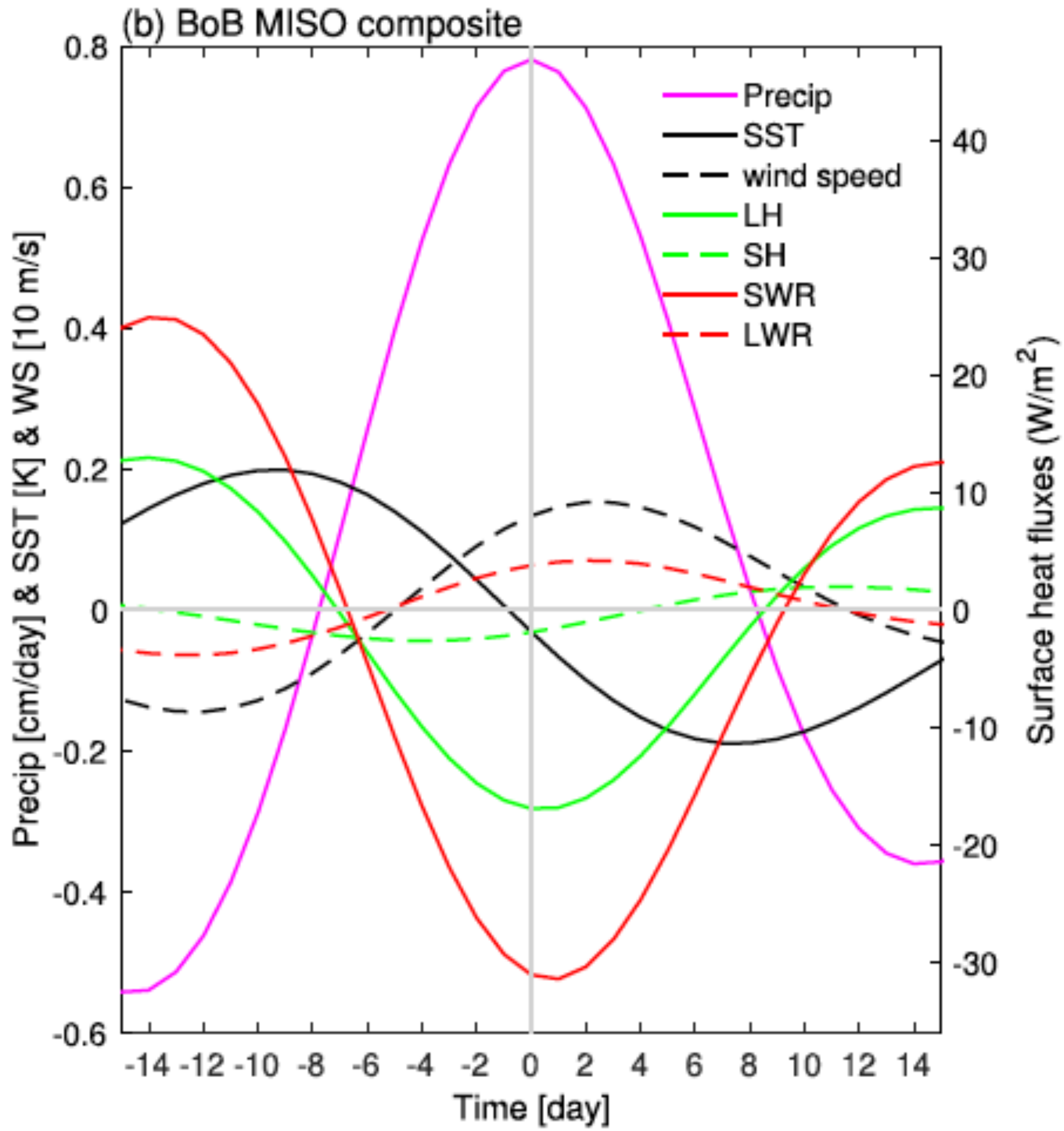
FIGURE 5. Regression of TRMM precipitation (shaded) and Optimum Interpolation Sea Surface Temperature (contours) with respect to a time series of MISO filtered (20–100 days) precipitation averaged over a 5° × 5° box around 85°E and 15°N as a function of lead or lag (days).

Lead-lag relation between precipitation and SST over Bay of Bengal

Fu, Wang and McCreary, 2003, J.A.S

Air-Sea Interaction associated with MISO (30-60 day mode)

Lead-lag composites of 20-90 day filtered fields w.r.t. precipitation over a box in north BoB



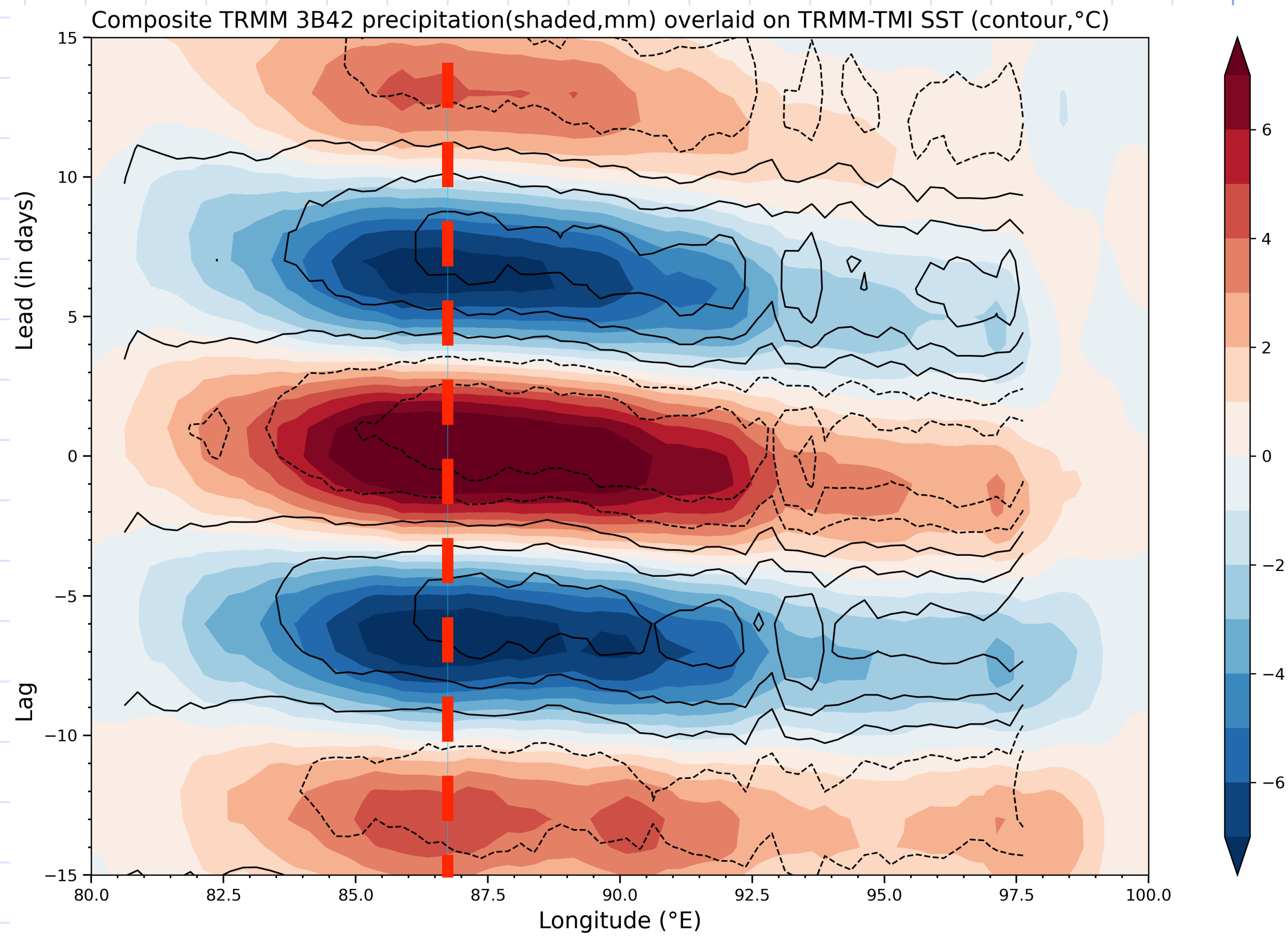
Zhang, Han and Li, 2018: J. Climate, 31(9)

DOI:10.1175/JCLI-D-17-0691.1

Air-Sea Interaction associated with the QBM (10-20 day mode)

Ocean & atmosphere are coupled even on 10-20 day time scales.

Lead-lag composites of 10-20 filtered rainfall and SST averaged between 85^{o}E-95^{o}E



Courtesy: Prolay Saha

Air-Sea Interaction associated with the QBM (10-20 day mode)

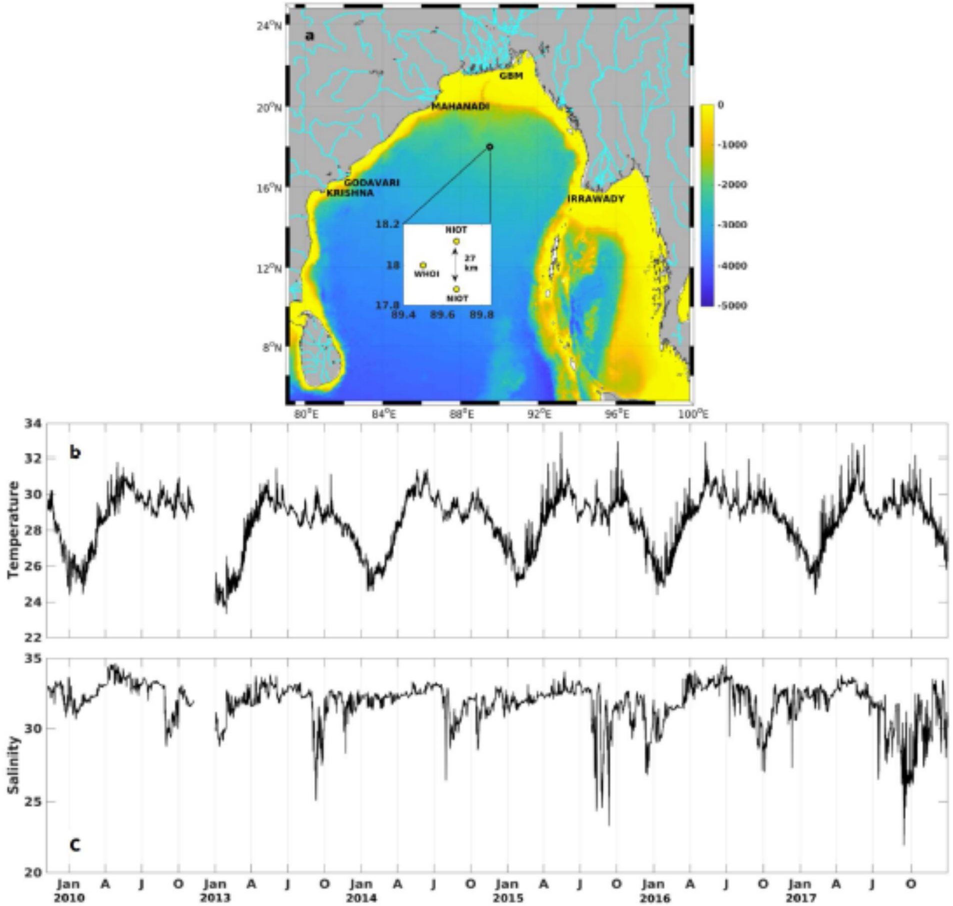


Figure 1: (a) Bay of Bengal bathymetry from ETPO2 (color; m); Ganga-Brahmaputra-Meghna (GBM), Irrawady, Mahanadi and other major rivers (cyan), and locations of the 18ºN INCOIS/WHOI and NIOT moorings (inset). Hourly time series of (b) surface temperature (ºC) and (c) surface salinity (psu) from the INCOIS mooring (18ºN 89.5ºE), WHOI mooring (18.01ºN 89.45ºE) and NIOT mooring BD08 (18.12ºN 89.67ºE). The record extends from November 2009 to November 2010, and January 2013 to December 2017. The shallowest depth at which measurements are available is 1 m in 2010, 2013 and 2015; 4 m in 2014, and 5 m in 2016-17. A mooring deployed in 2011-12 was lost.

SreeLekha, D. Sengupta et al., 2020, JGR doi: 10.1029/2020 JC016271

Air-Sea Interaction associated with the QBM (10-20 day mode)

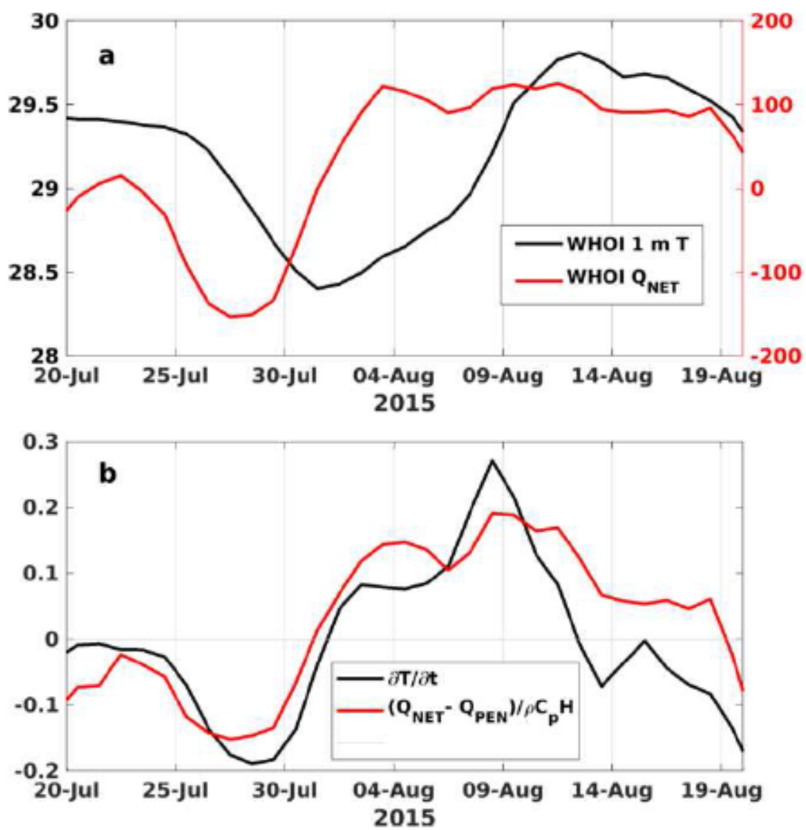


Figure 12: (a) Five-day running mean net heat flux (Q_{net}; W/m^2; red) and temperature at 1 m depth (ºC; black) from the WHOI mooring (18.01ºN 89.45ºE), 20 July–20 August 2015. (b) Temperature tendency $\frac{\partial T}{\partial t}$ (ºC/day; black) and forcing $\frac{Q_{net}-Q_{pen}}{\rho C_p h}$ (ºC/day; red). Mixed layer depth h is defined as the depth where the potential density exceeds the 1 m density by 0.125 kg/m^3.

SreeLekha et al., 2020, JGR doi: 10.1029/2020JC016271

Air-Sea Interaction associated with the QBM (10-20 day mode)

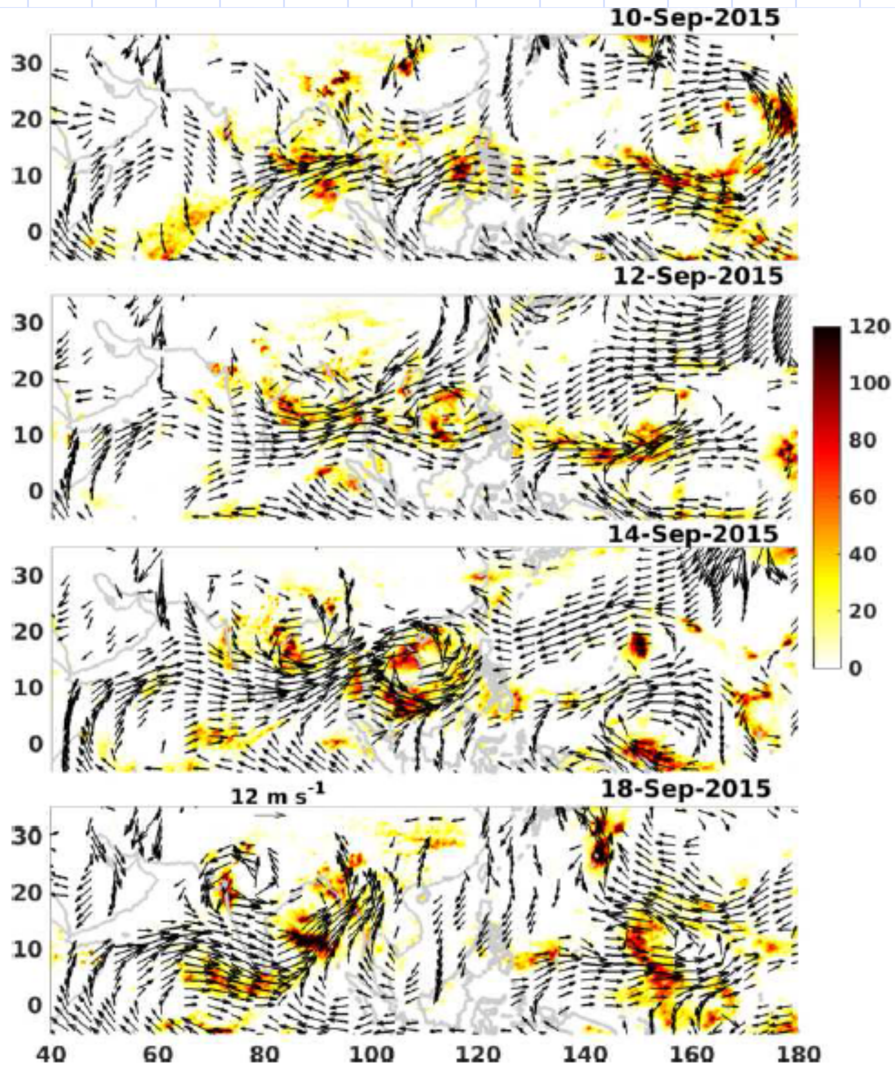
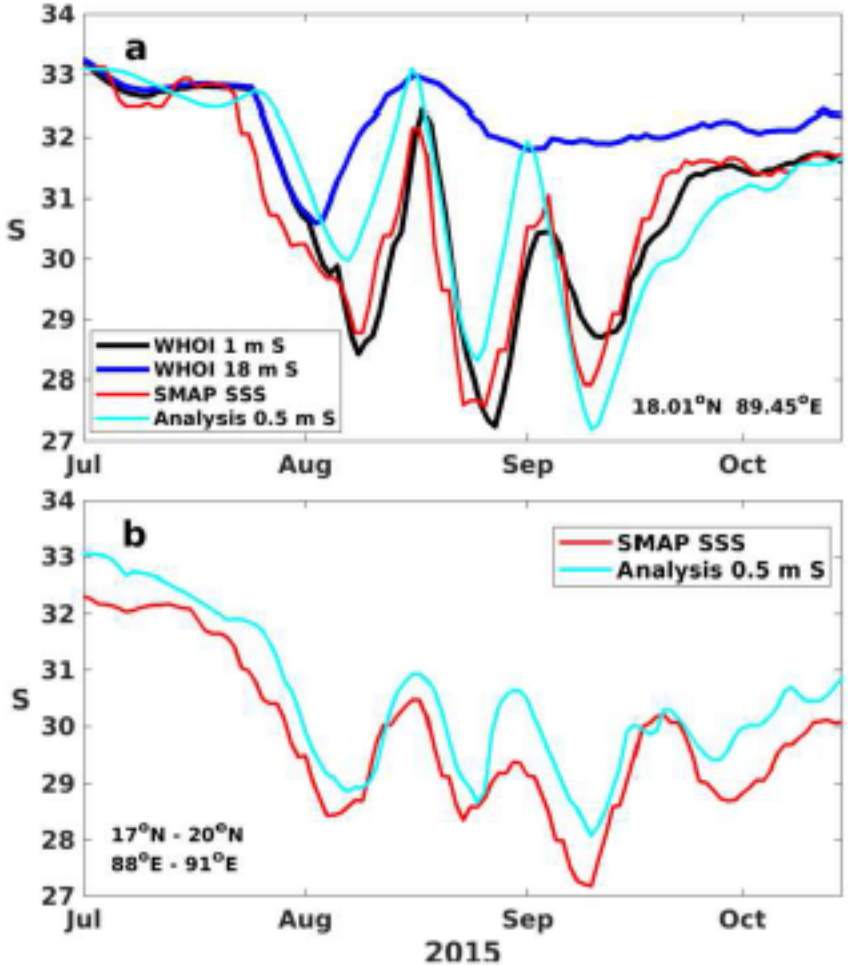


Figure 6: Daily TRMM rainfall (mm/day; colour) and MERRA2 850 hPa winds (m/s; vectors) on selected days: 10, 12, 14 and 18th September 2015. Wind vectors with magnitude less than 5 m/s are not shown. A 12 m/s reference vector is shown in bottom panel.

SreeLekha et al., 2020, JGR doi: 10.1029/2020JC016271



- Biweekly oscillation of salinity at the WHIO mooring

- Freshwater layer is very shallow.
- Strong oscillation at 1-m, none at 18-m

Figure 7: (a) 8-day running mean salinity (psu) at 1 m (black) and 18 m (blue) depth from the WHOI mooring (18.01ºN 89.45ºE) observations; SMAP gridded sea surface salinity (SSS; red), and salinity at 0.5 m depth from the ocean analysis (cyan) interpolated to the mooring location during 1 July-10 October 2015. (b) SMAP SSS (psu; red) and salinity at 0.5 m depth from ocean analysis, spatially averaged over 17–20ºN 88-91ºE, 1 July - 10 October 2015.

The salinity QB oscillations at the WHIO mooring is due to shallow freshwater from Ganga –Brahmaputra discharge being carried by ocean currents forced by atmospheric winds associated with atmospheric QBM.

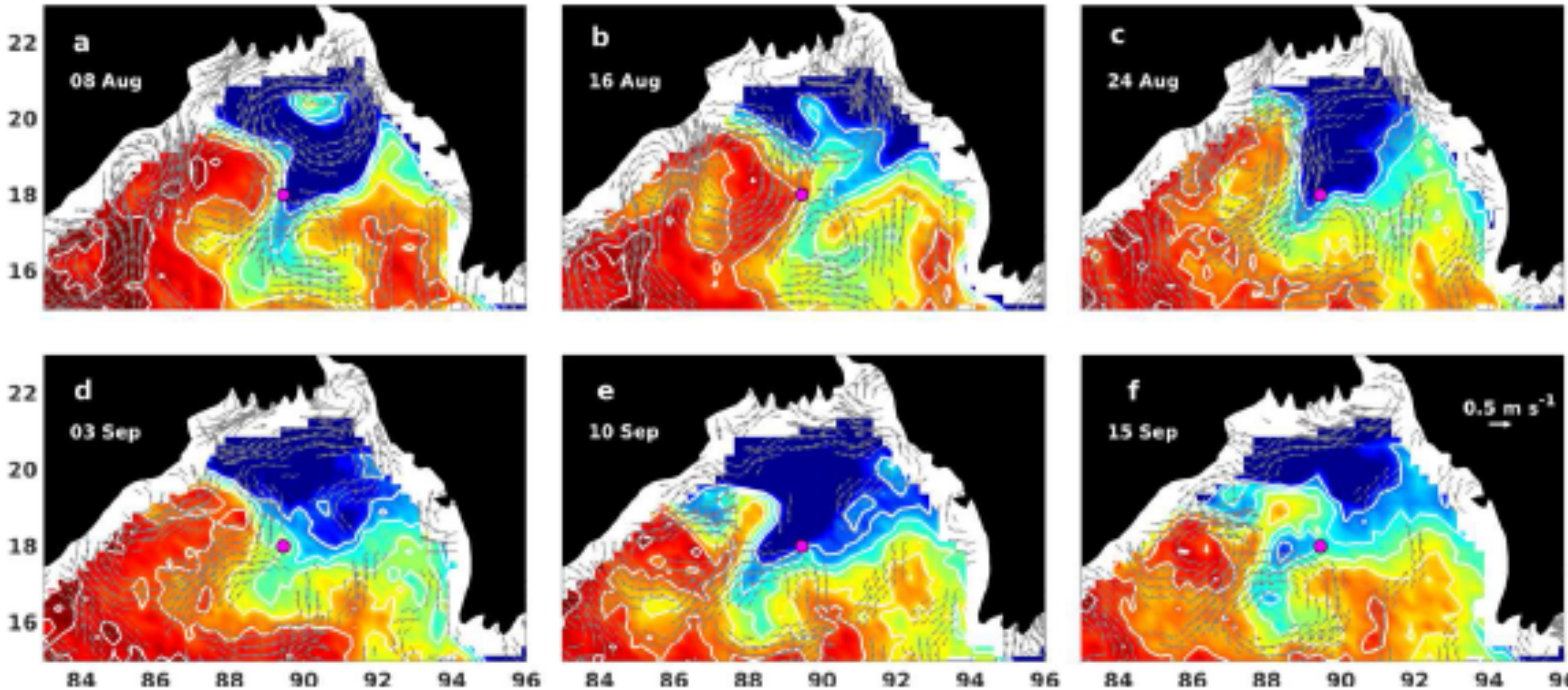


Figure 8: (a-f) SMAP SSS (psu; colour and contours) and AVISO geostrophic ocean current vectors on selected days during the three freshening and salting periods. The WHOI mooring is marked by a red dot; 29, 30 and 31 psu SSS contours are in white; dates are in top left of each panel; a reference current vector is in panel (f). Current vectors with magnitude less than 0.1 m/s are not shown.

Air-sea Interaction associated with Weather disturbances: Tropical Cyclones (TC)

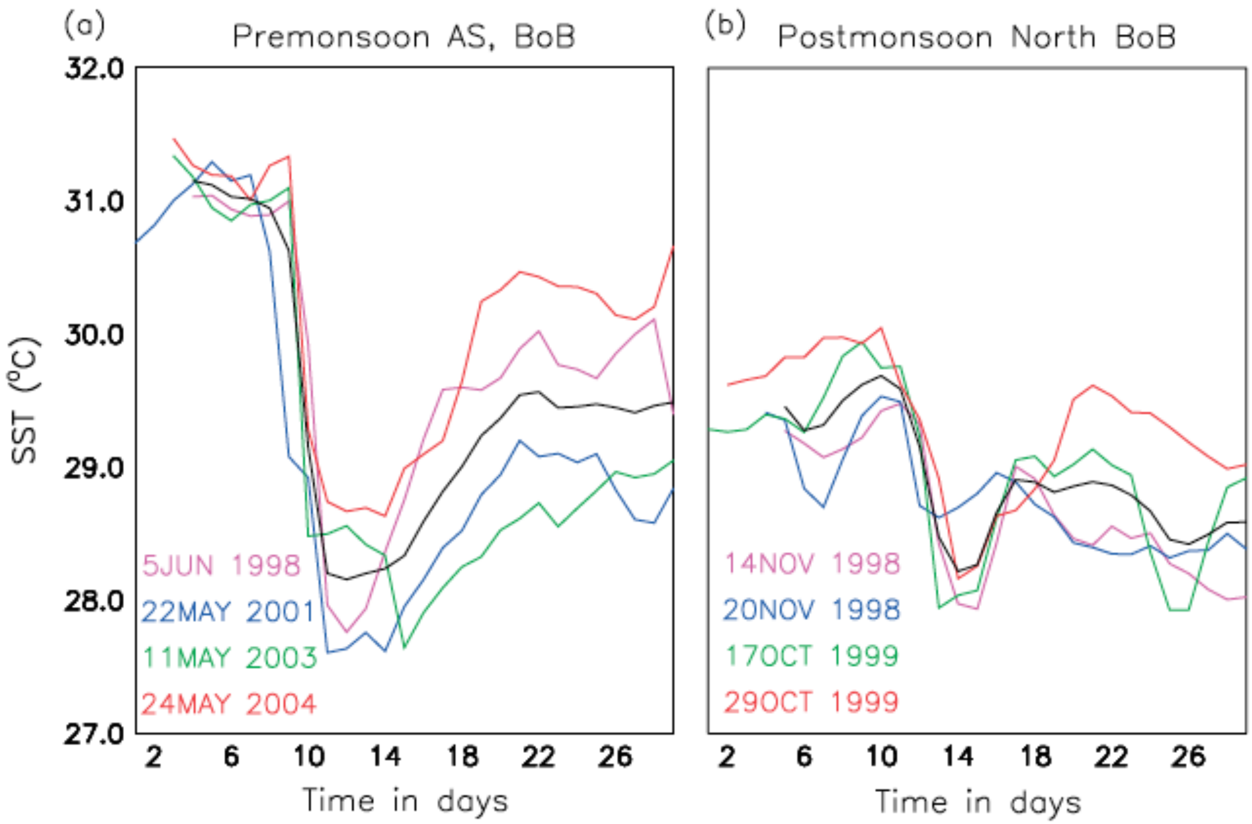


Figure 1. SST cooling due to tropical cyclones in the (a) pre-monsoon Arabian Sea and Bay of Bengal and (b) post-monsoon north Bay of Bengal. Three-day TMI SST is averaged over a 1°-wide strip along the track of each cyclone; start dates of the TCs (left bottom in each panel) have been moved so that periods of SST cooling coincide. Average SST cooling is shown in black.

Sengupta et al., 2008: Atmospheric Sci. Letts. Atmos. Sci. Lett. 9 : 1–6 (2008)DOI: 10.1002/asl.162

Air-sea Interaction associated with Tropical Cyclones (TC)

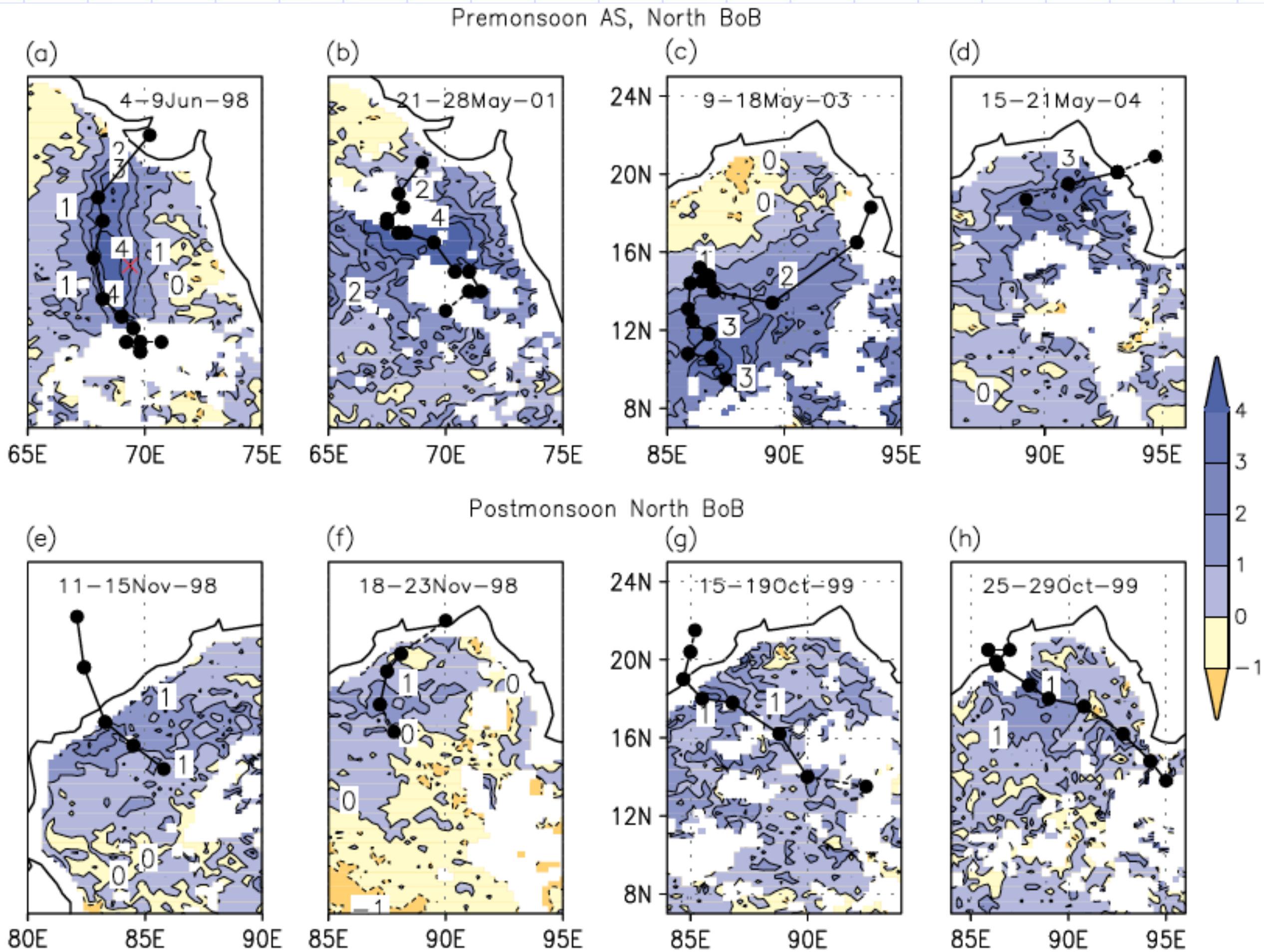


Figure 2. SST cooling due to tropical cyclones in the pre-monsoon Arabian Sea and Bay of Bengal (top, panels a–d), and post-monsoon north Bay of Bengal (bottom, panels e–h). Dots mark storm location every 12 h (from JTWC). Net SST cooling (blue shades) is the difference between pre-storm and post-storm SST (dates on top), e.g. 4–9 Jun 1998 denotes 4 June 1998 SST minus 9 June 1998 SST. The location of mooring DS1 is marked by the red cross in panel (a).

Sengupta et al., 2008: Atmospheric Sci. Letts. Atmos. Sci. Lett. 9 : 1–6 (2008)DOI: 10.1002/asl.162

In Conclusion

- Indian monsoon region with the continent surrounded by warm Ocean on three sides is a region where vigorous convective activity flourish making Indian monsoon a convectively coupled system.

- For the same reason, it is also a region where vigorous ocean-atmosphere interactions flourish shaping monsoon variability at All time scales.

(We shall discuss ocean-atmosphere interaction on multi-decadal time scales in another Lecture)

Thank You

net heat flux (Wm−2)