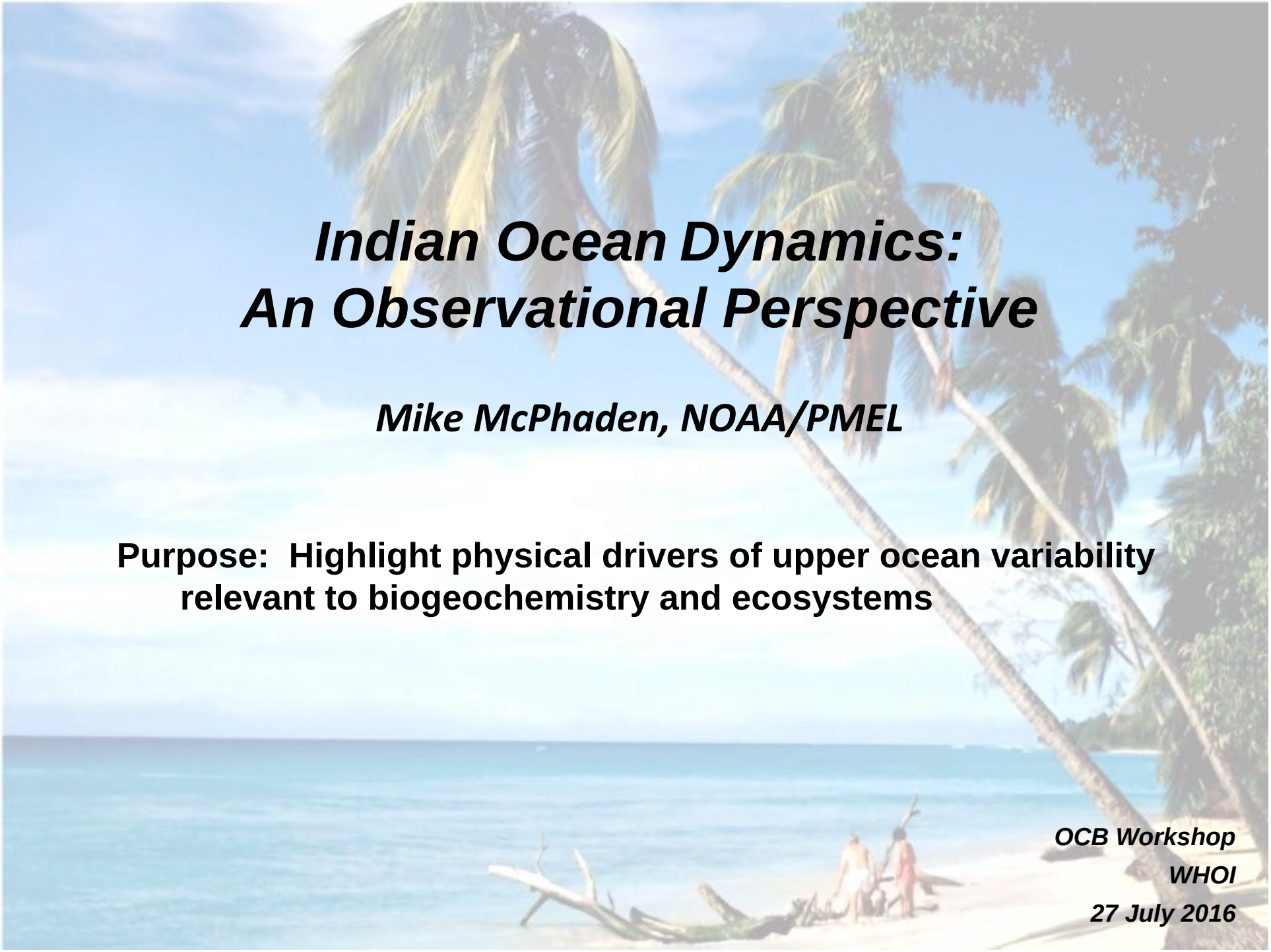


Indian Ocean Dynamics: An Observational Perspective

Mike McPhaden, NOAA/PMEL

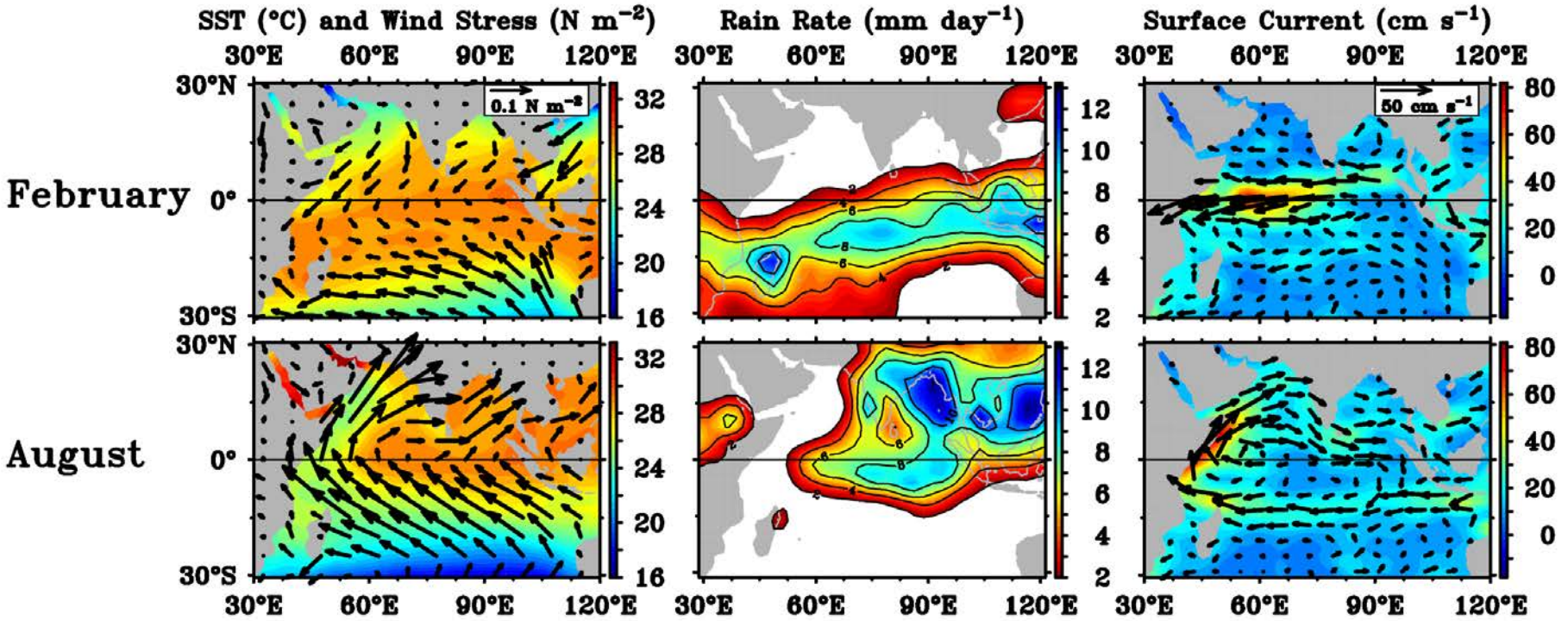
Purpose: Highlight physical drivers of upper ocean variability relevant to biogeochemistry and ecosystems

OCB Workshop

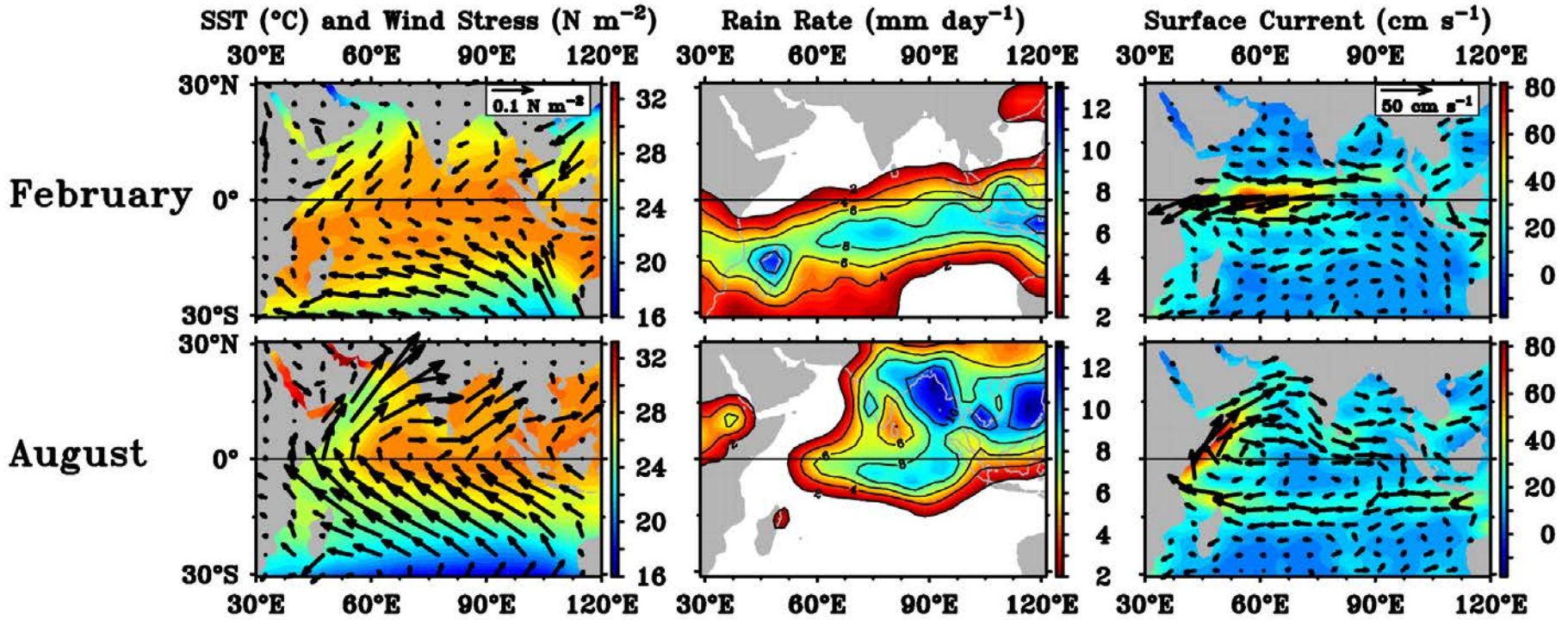
WHOI

27 July 2016

The Monsoons

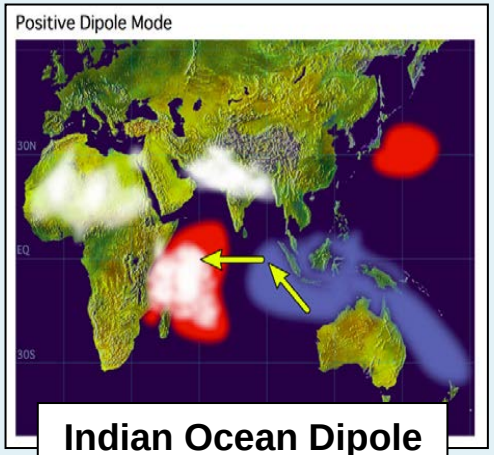


The Monsoons

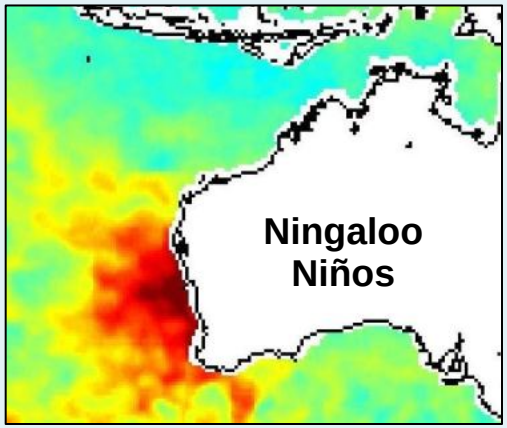


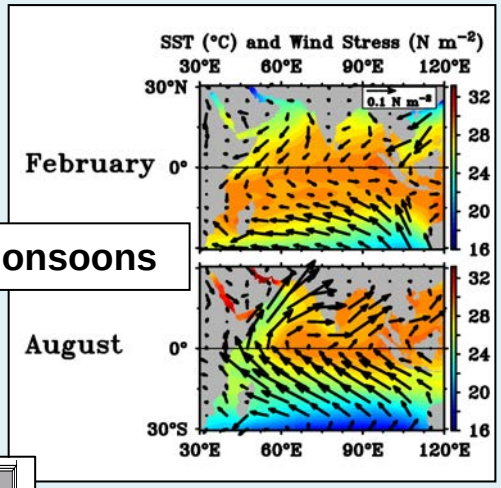
One third of the world's population depends on monsoon rainfall

Indian Ocean Science Drivers



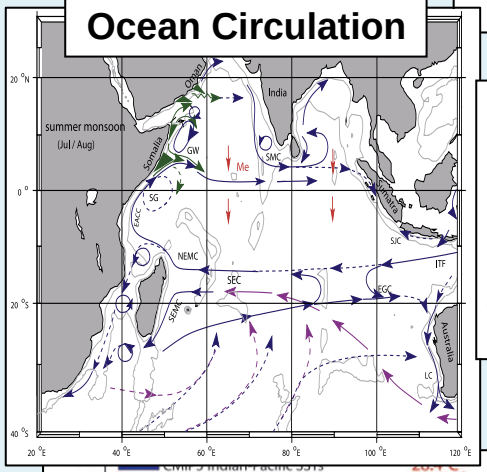
Indian Ocean Dipole

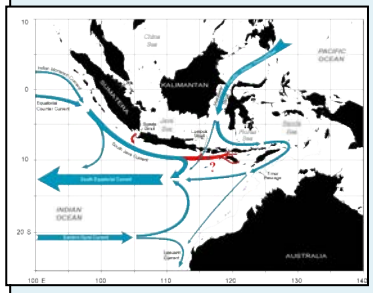


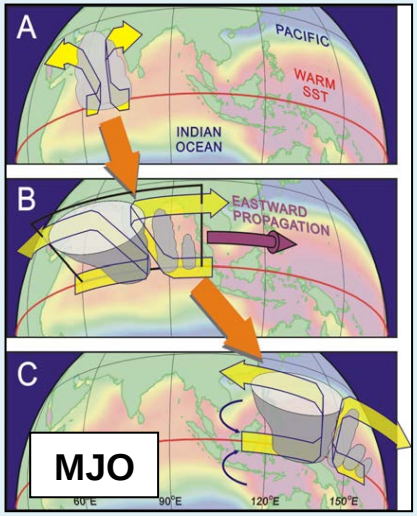


Monsoons

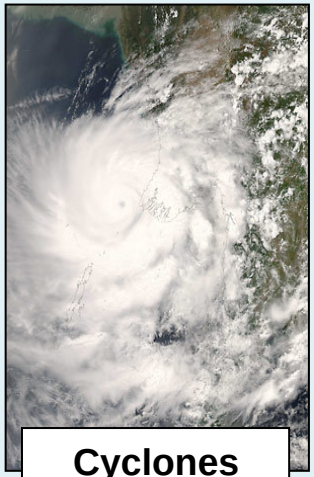
Ocean Circulation



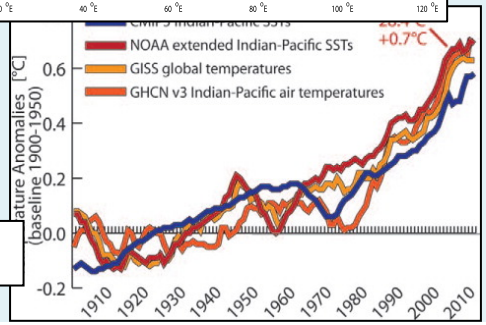




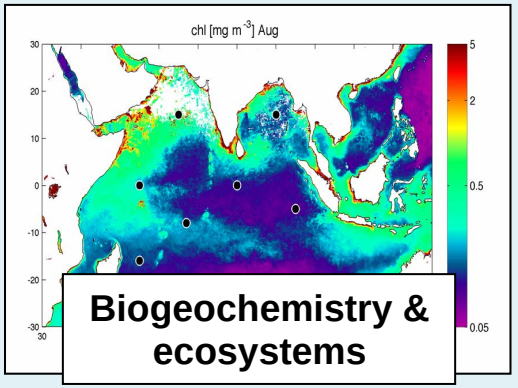
MJO



Cyclones

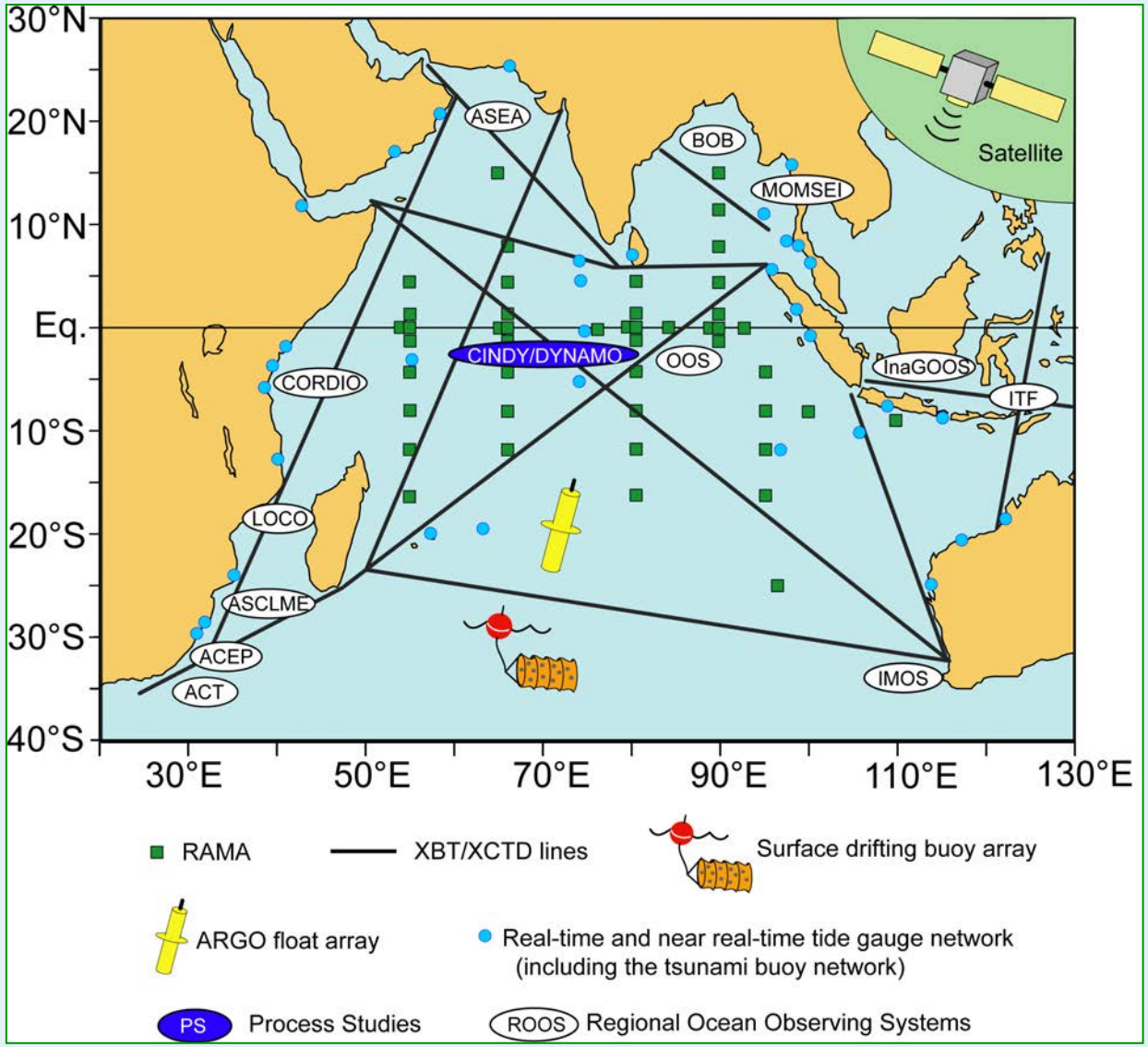


Trends



Biogeochemistry & ecosystems

Indian Ocean Observing System (IndOOS)



- Designed in 2004 by CLIVAR/GOOS Indian Ocean Panel
- *In situ* & Satellite
- Basin scale with regional elements
- Supports short term process studies
- Links to SIBER → multidisciplinary measurements

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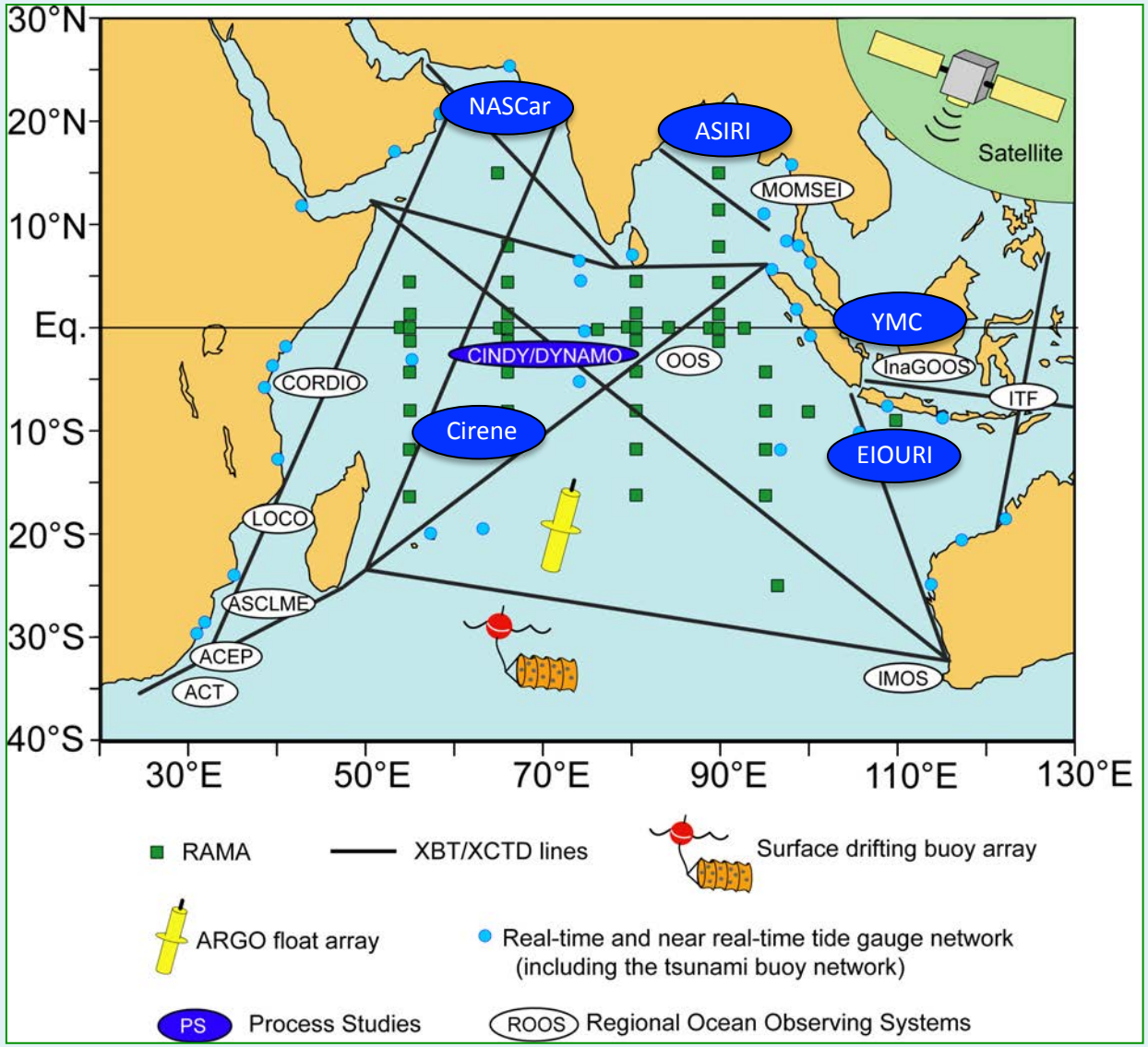

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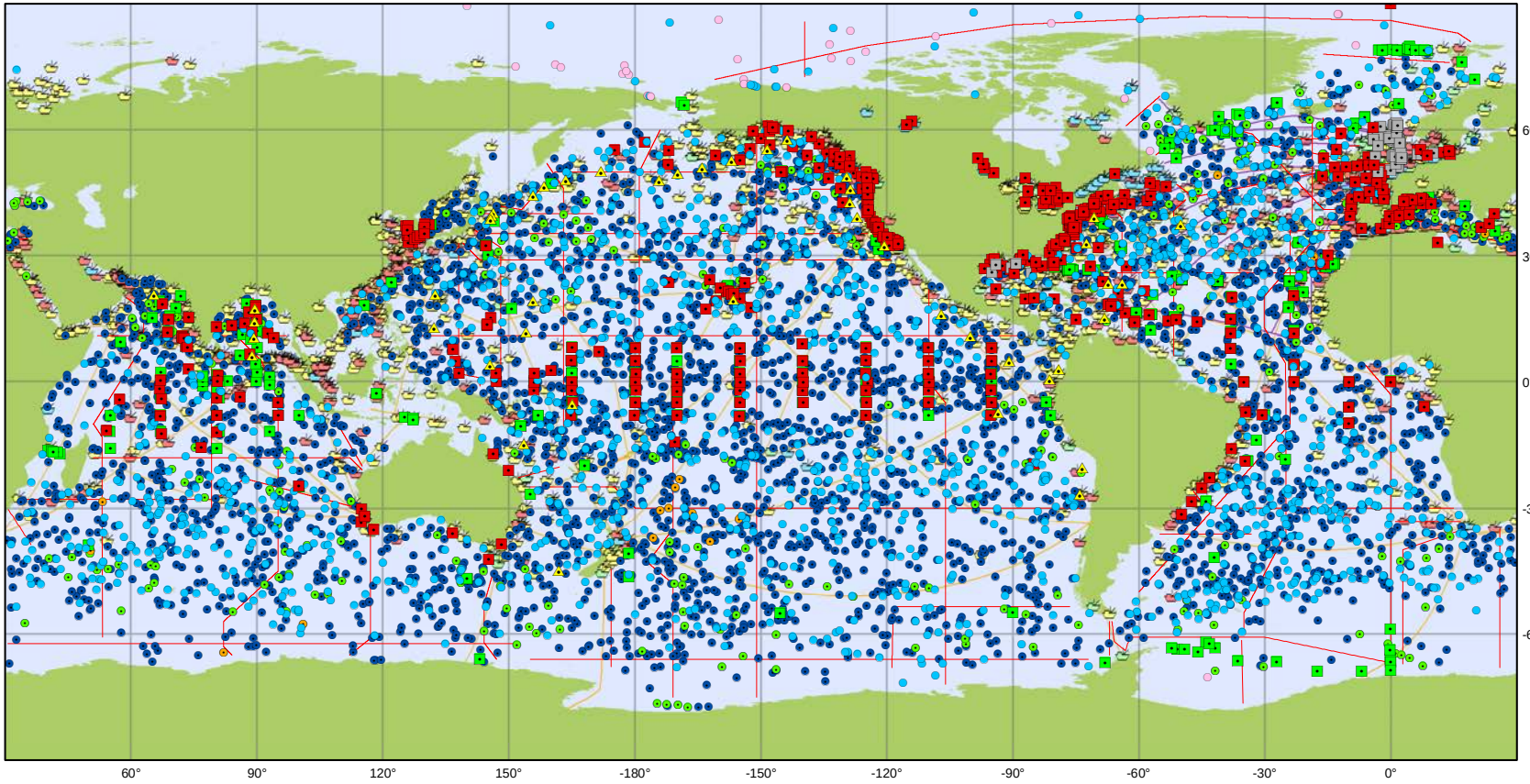
Current Status: In Situ Observing System



Main in-situ Elements of the Global Ocean Observing System **June 2016**

Argo
- Argo (3758)
- Deep-Argo (16)
- Bio-Argo (275)

DBCP
- Surface Drifter (1442)
- Fixed Platform (104)
- Ice Buoy (29)
- Moored Buoy (474)
- Tsunameter (46)

OceanSITES
- Platforms (331)

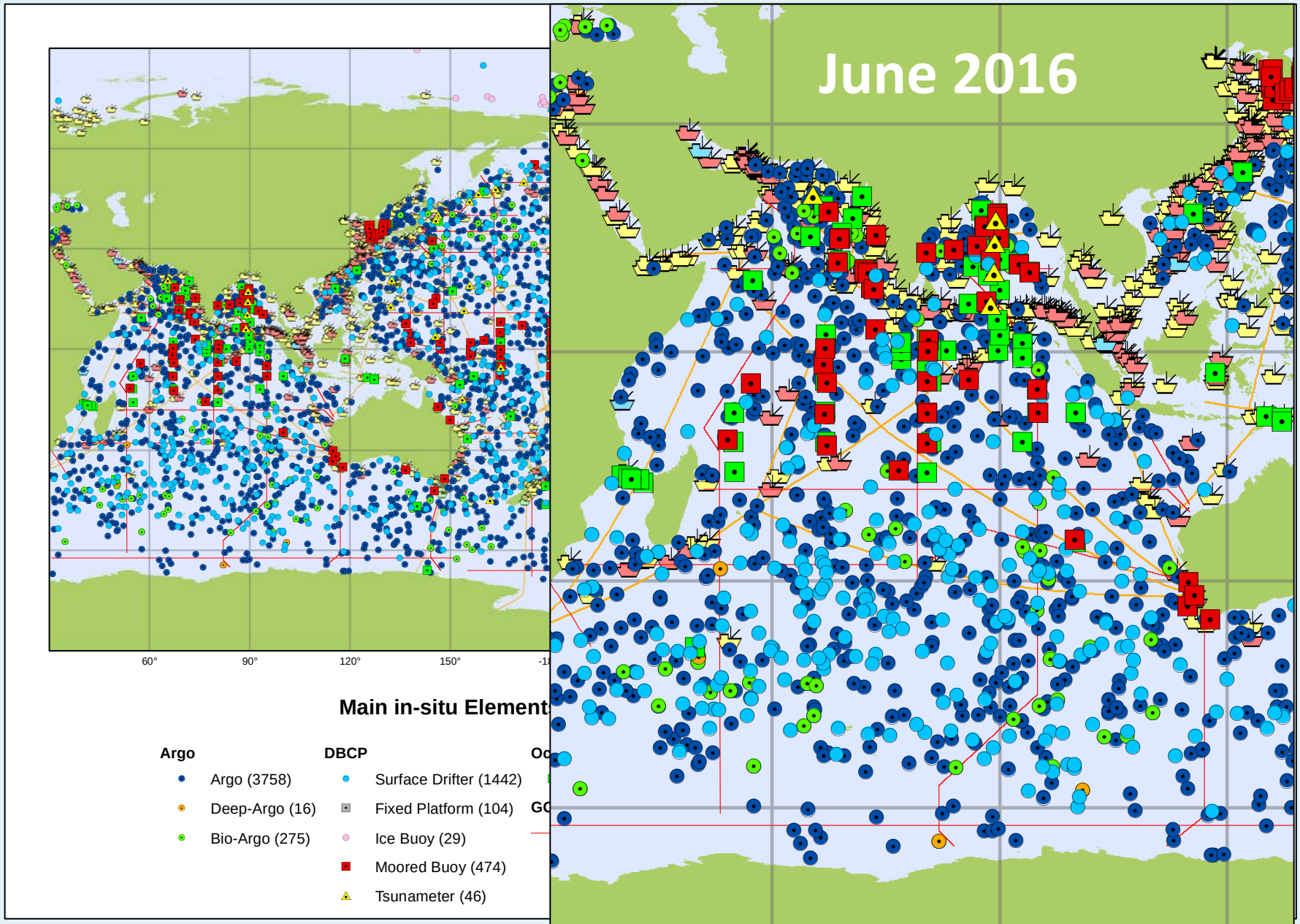
GO-SHIP
- GO-SHIP (61)

SOT
- VOSClim-Automated (103)
- VOSClim-Manned (354)
- VOS-Automated (147)
- VOS-Manned (1161)

- ASAP Radiosondes (7)
- SOOP XBTs (46)

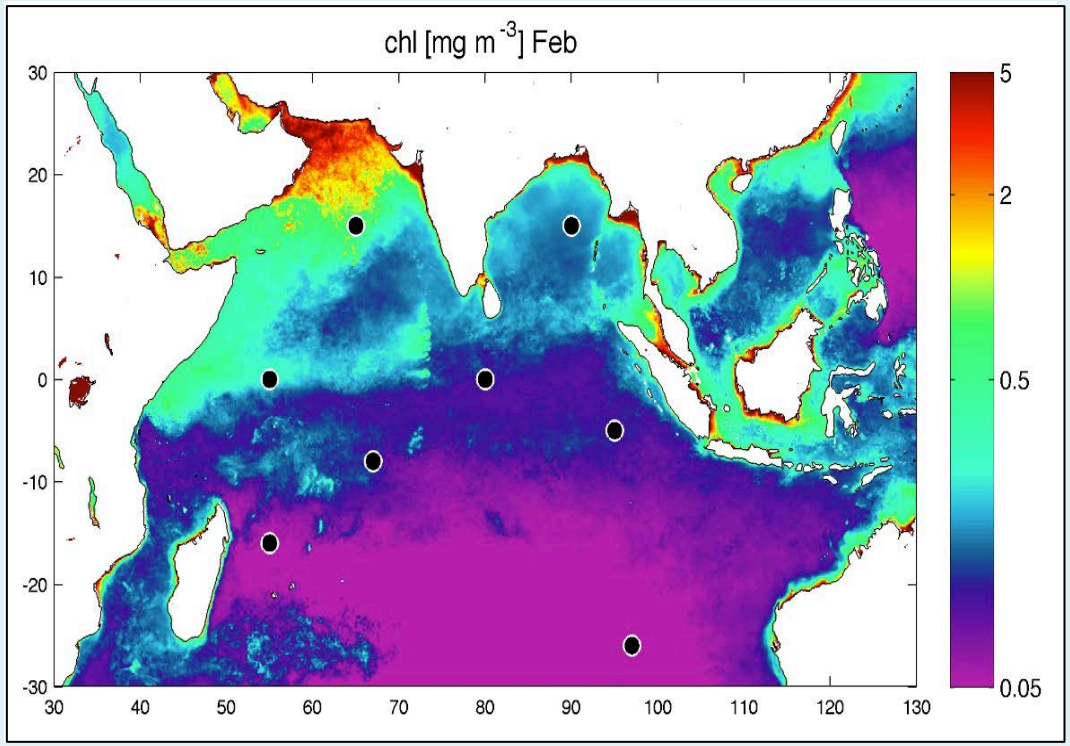
Generated by www.jcommops.org, 07/07/2016

Current Status: In Situ Observing System



Planned Biogeochemical Measurements:
A SIBER-RAMA Initiative

August Seawifs Chl-a Concentrations
(Solid Dots are RAMA Flux Reference Sites)



Objectives: To provide data for

A) Defining biogeochemical variability in key regions of the Indian Ocean and for improved understanding of processes;

B) Developing models of ocean-atmosphere-biosphere interactions;

C) Assessing the impacts of climate change on ocean uptake of CO_2 and primary productivity.

Key Measurements: CO_2, pH, Fluorescence, Particle Backscatter, O_2,….

**SIBER=Sustained Indian Ocean Biogeochemical and Ecosystem Research Program*

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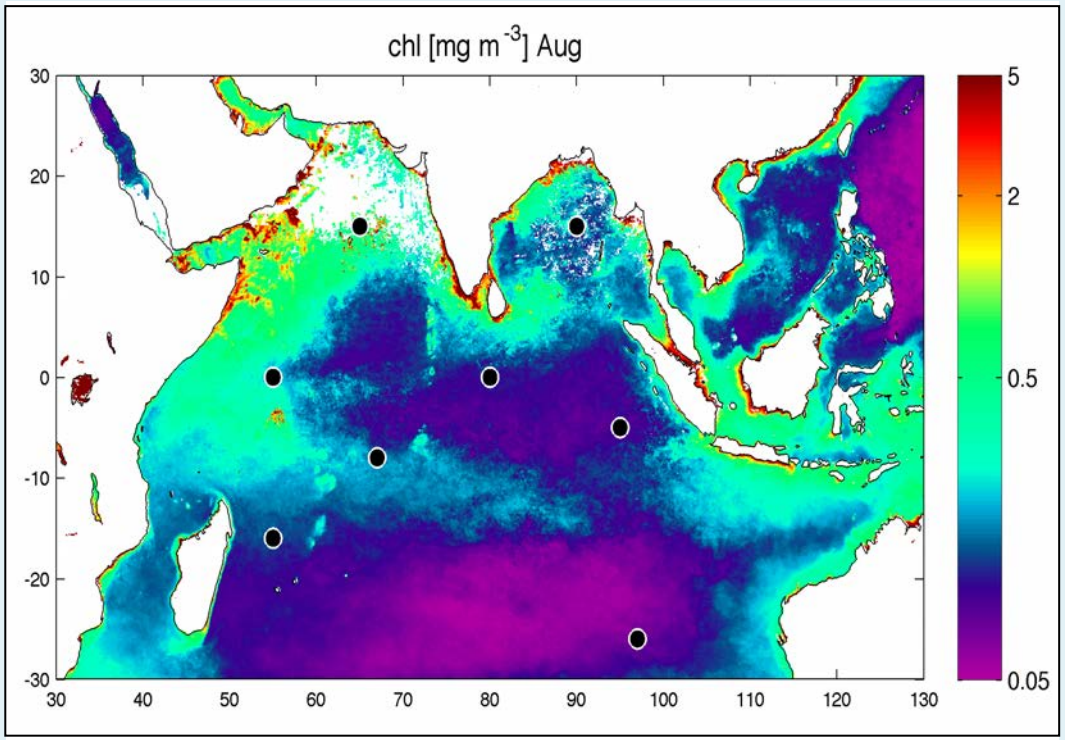

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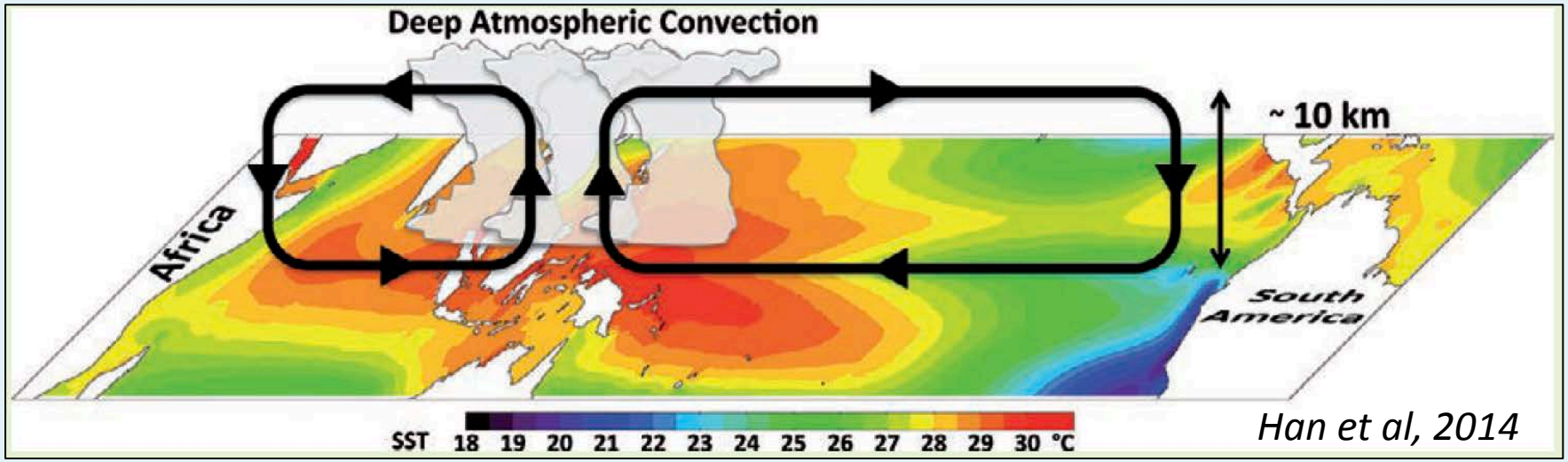
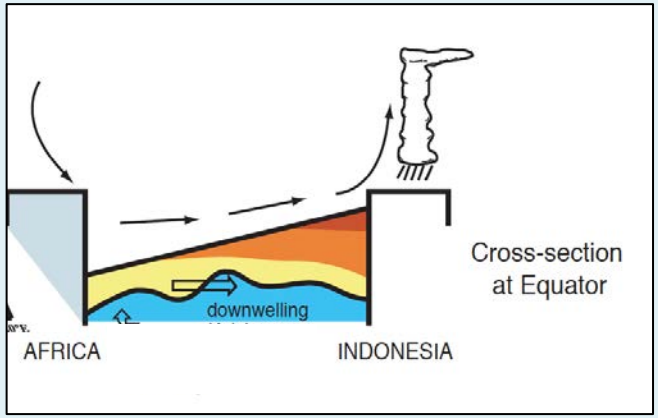
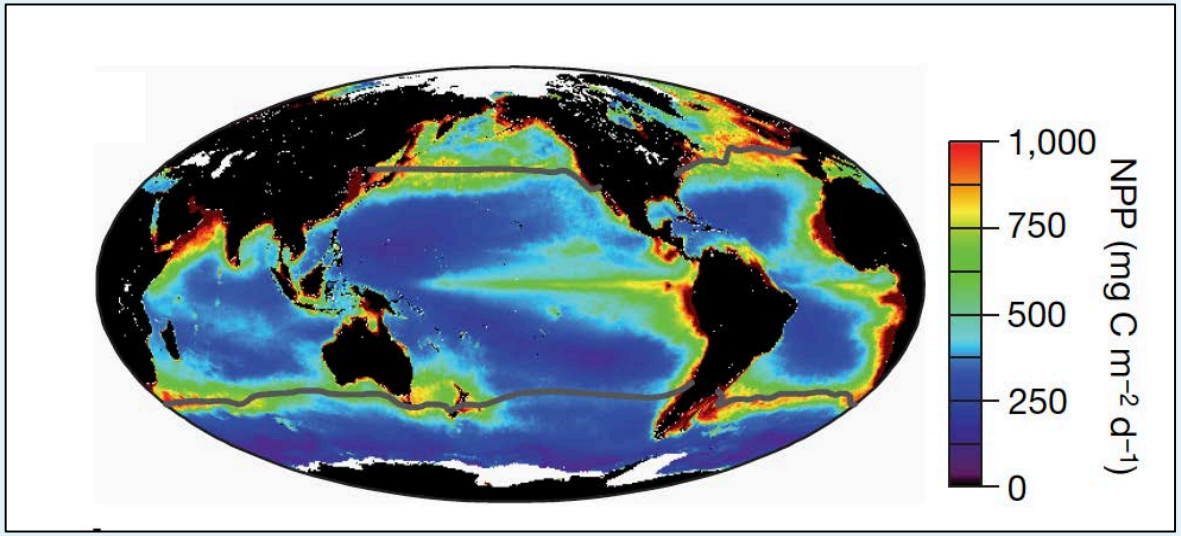
Climatological Mean



Han et al, 2014

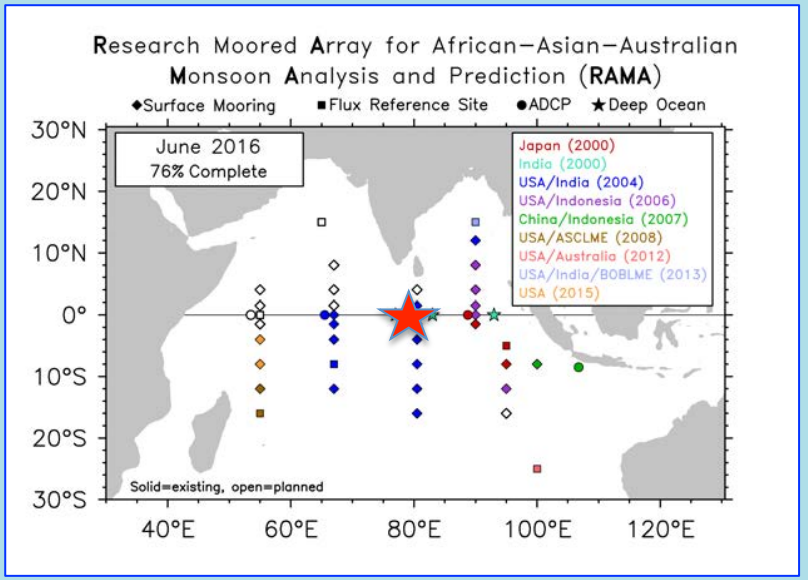


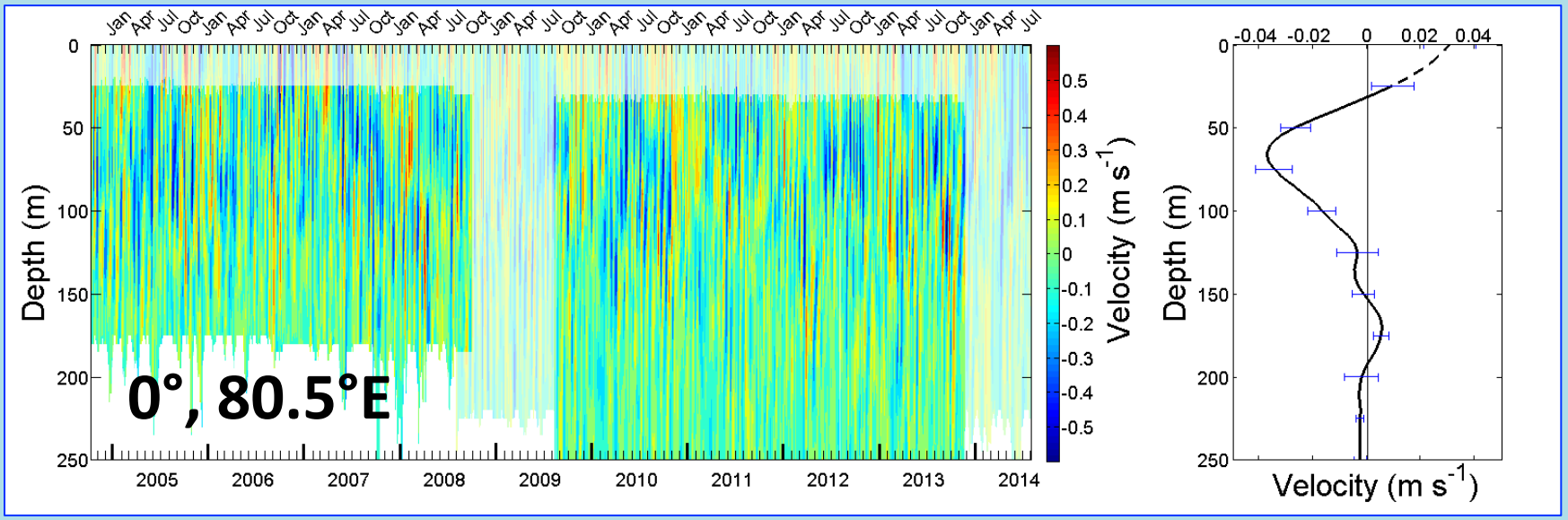
Webster et al, 1999



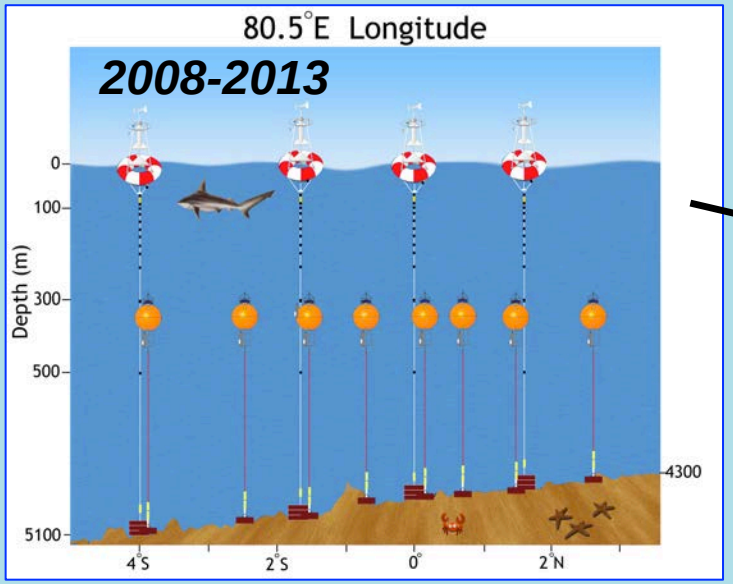
Behrenfeld et al, 2006

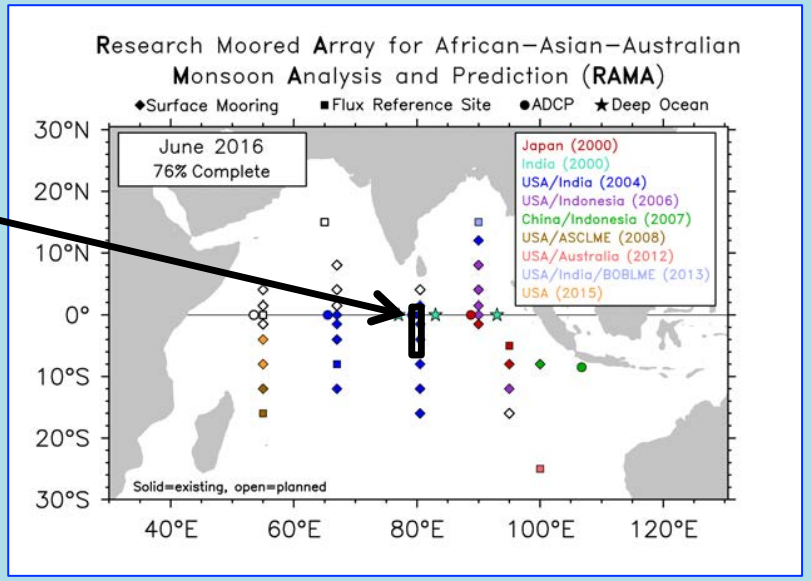
ADCP Data


Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA)
◆Surface Mooring ■Flux Reference Site ●ADCP ★Deep Ocean
June 2016
76% Complete
Japan (2000)
India (2000)
USA/India (2004)
USA/Indonesia (2006)
China/Indonesia (2007)
USA/ASCLME (2008)
USA/Australia (2012)
USA/India/BOBLME (2013)
USA (2015)
Solid=existing, open=planned
30°N
20°N
10°N
0°
10°S
20°S
30°S
40°E
60°E
80°E
100°E
120°E


0°, 80.5°E
Depth (m)
Velocity (m s-1)
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
-0.04 -0.02 0 0.02 0.04

ADCP Data


80.5°E Longitude
2008-2013
Depth (m)
0
100
300
500
5100
4300
4°S
2°S
0°
2°N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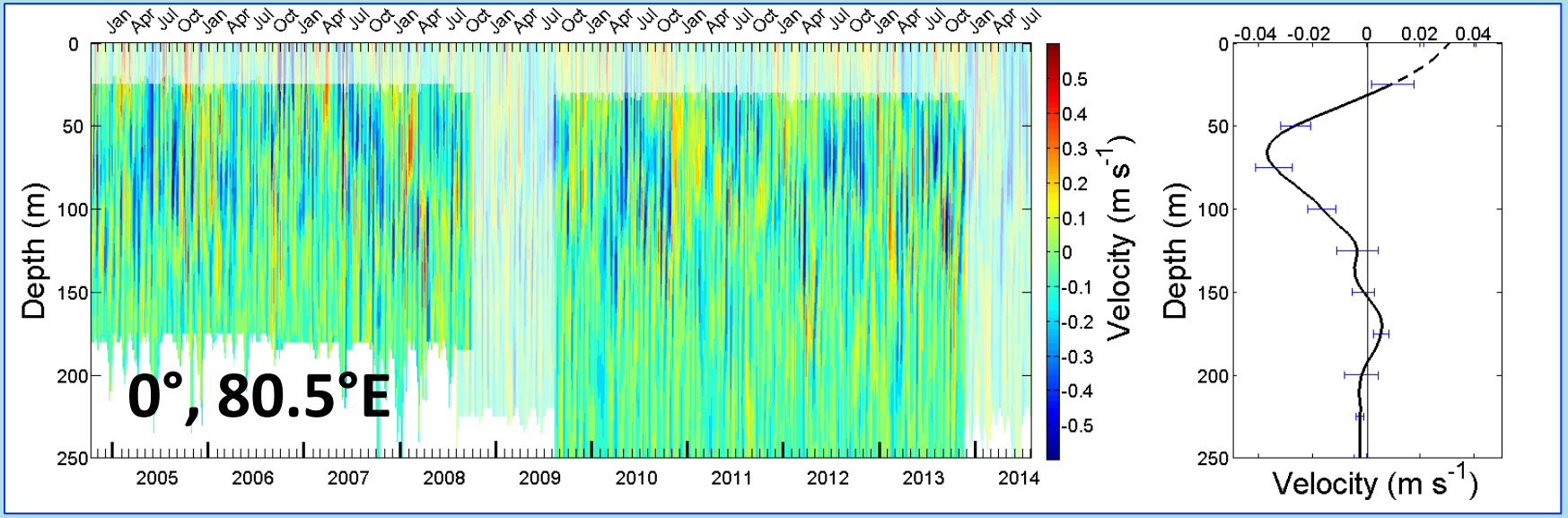
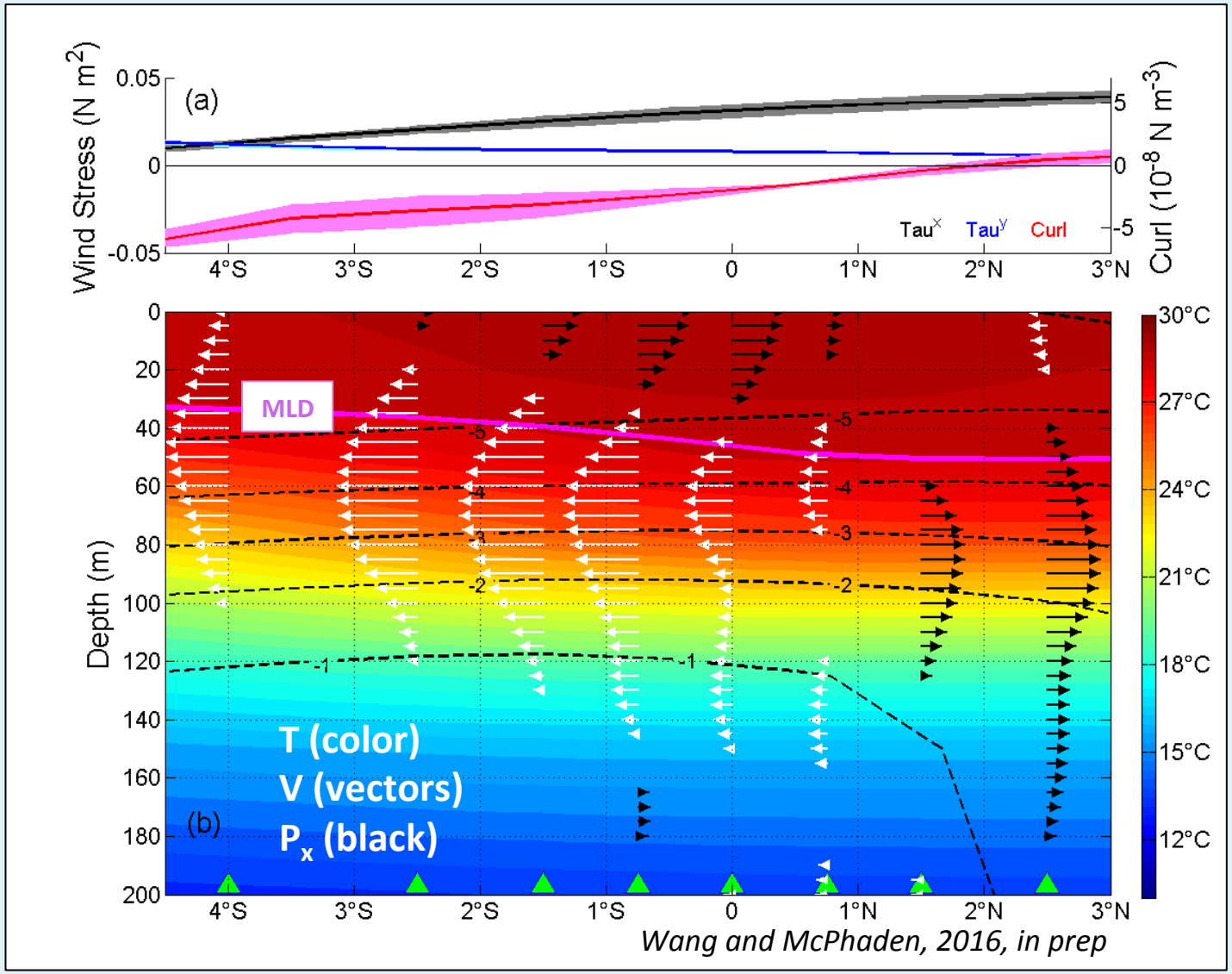
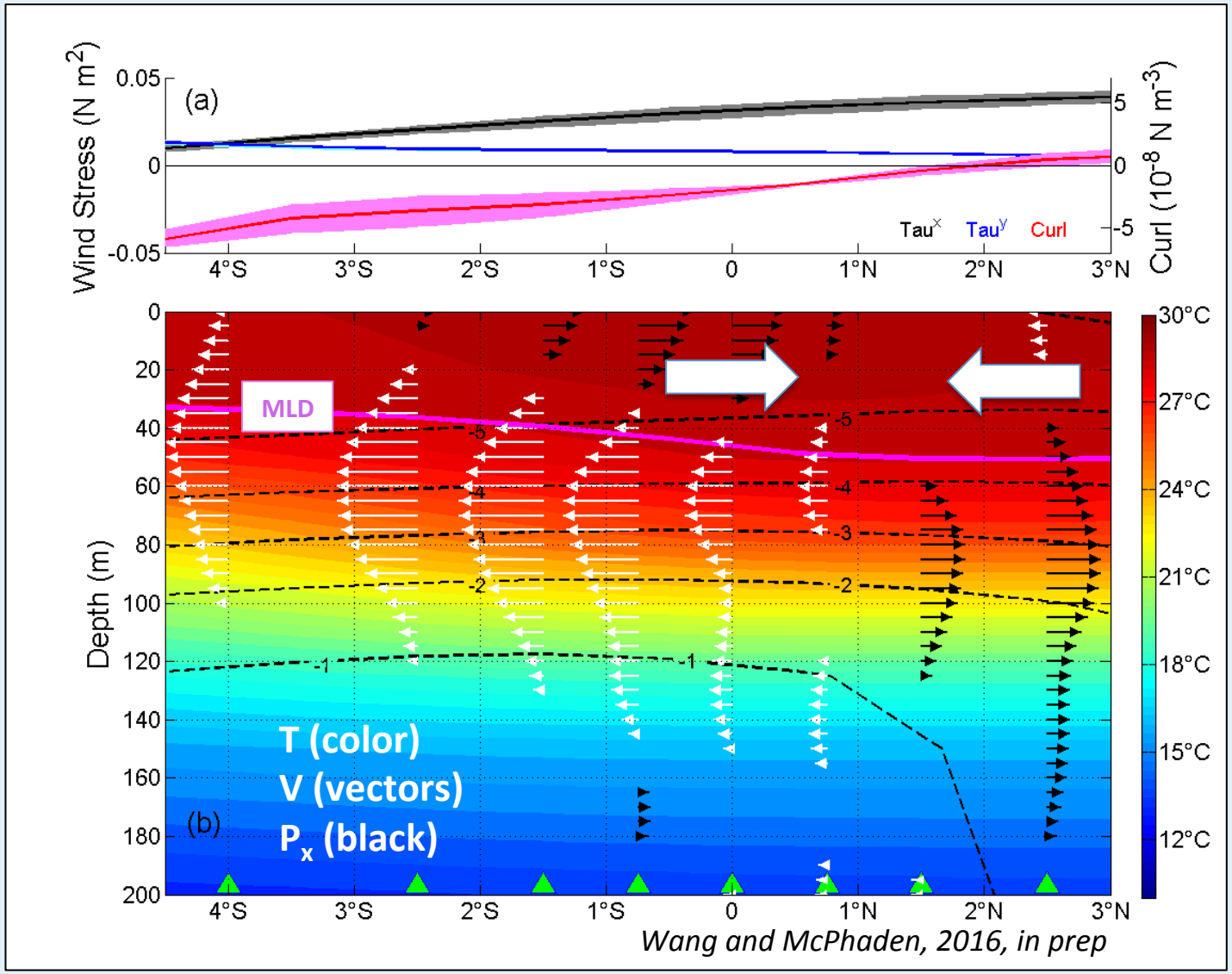
120°E


Jan Apr Jul Oct
Depth (m)
0
50
100
150
200
250
0°, 80.5°E
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Velocity (m s-1)
-0.04 -0.02 0 0.02 0.04
Depth (m)
Velocity (m s-1)

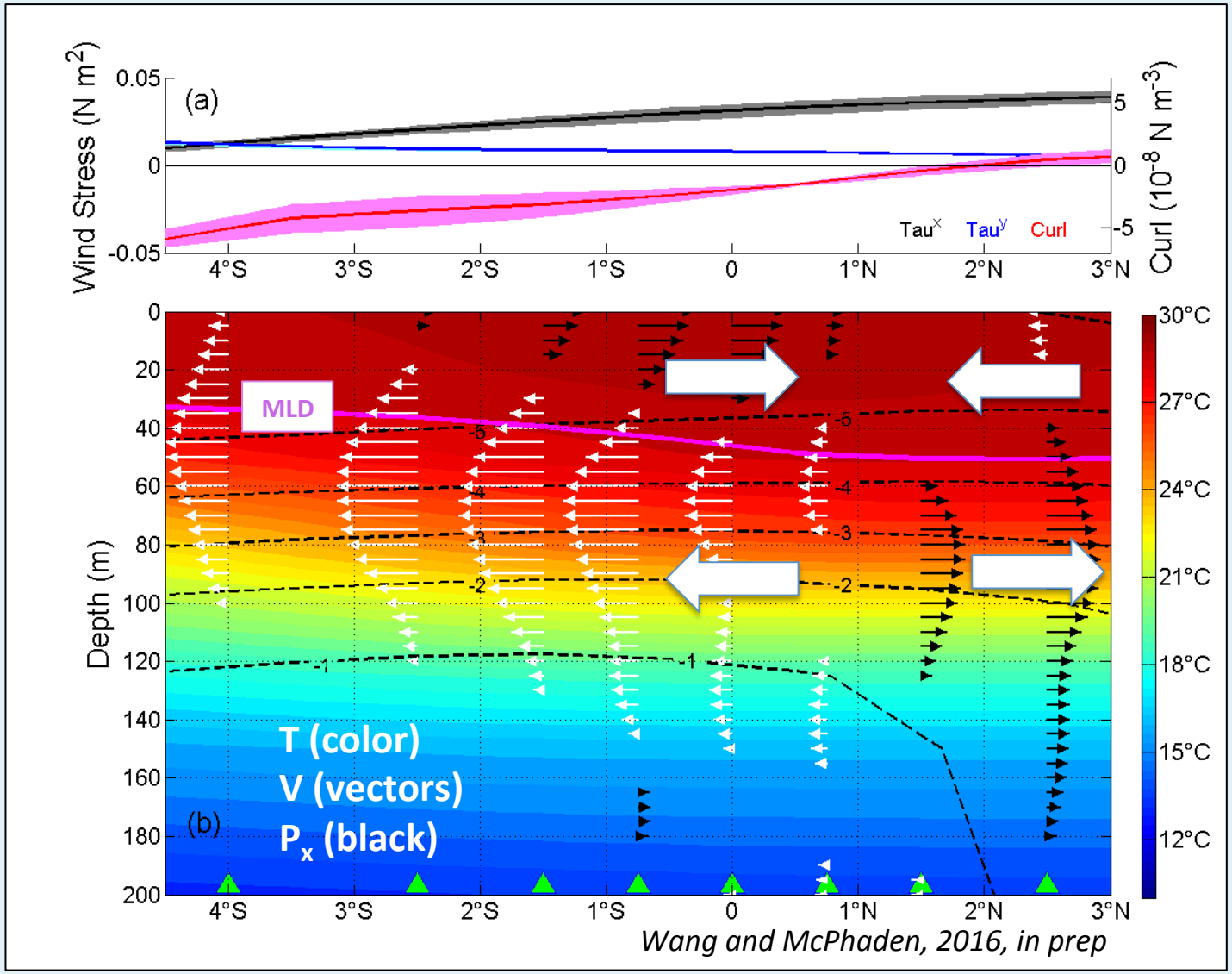
Mean Meridional Circulation along 80.5°E 2008-2013



Mean Meridional Circulation along 80.5°E 2008-2013



Mean Meridional Circulation along 80.5°E 2008-2013



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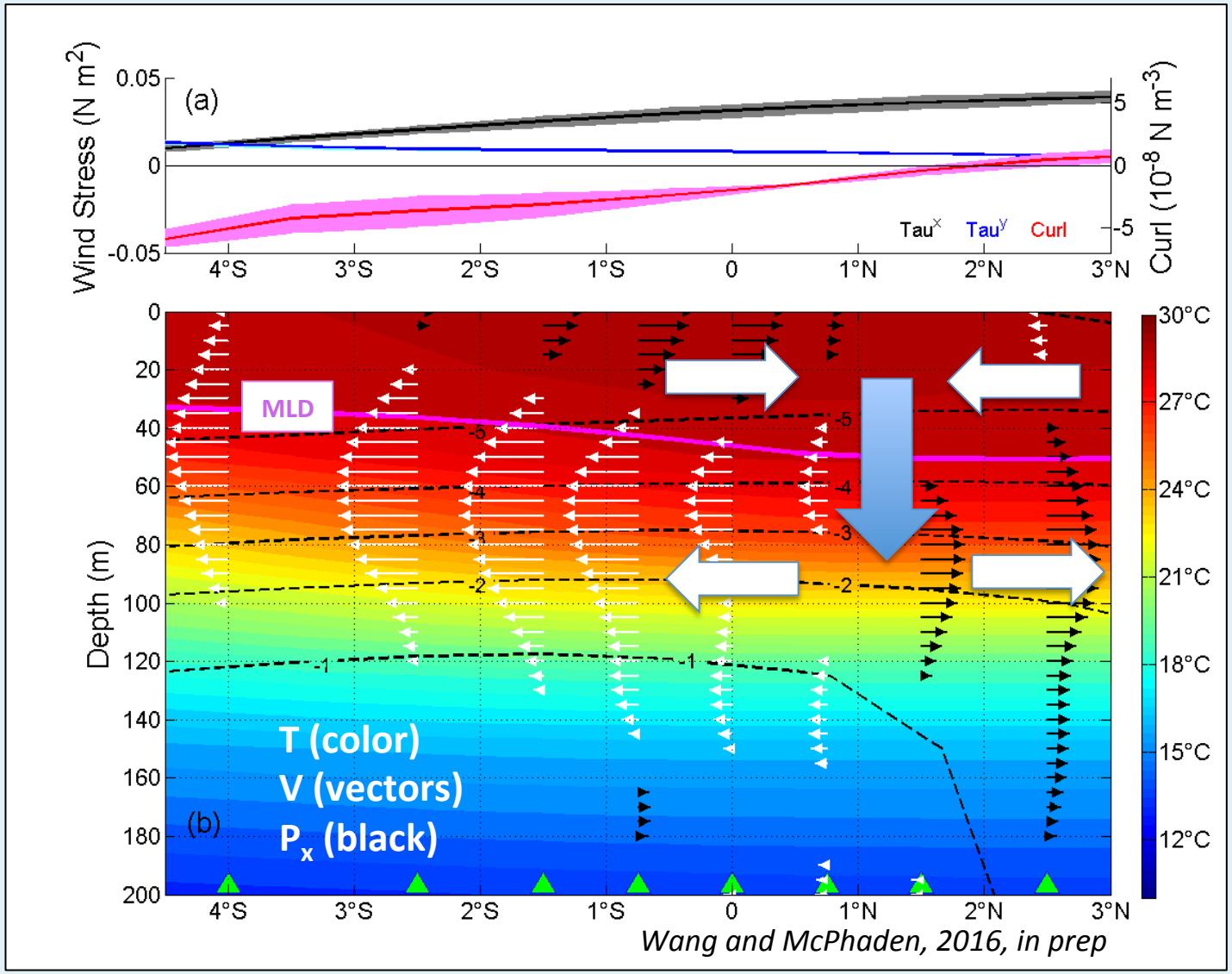

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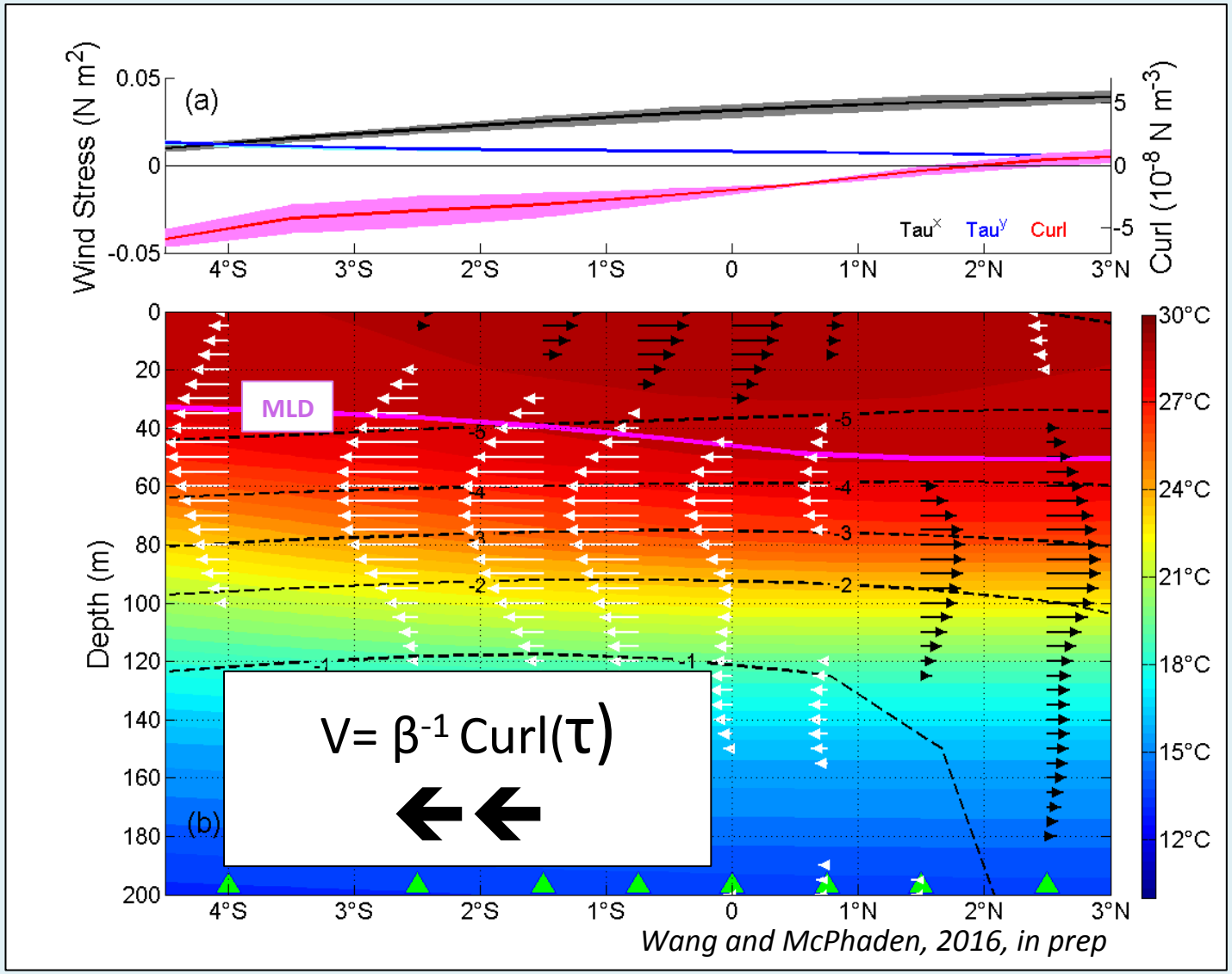
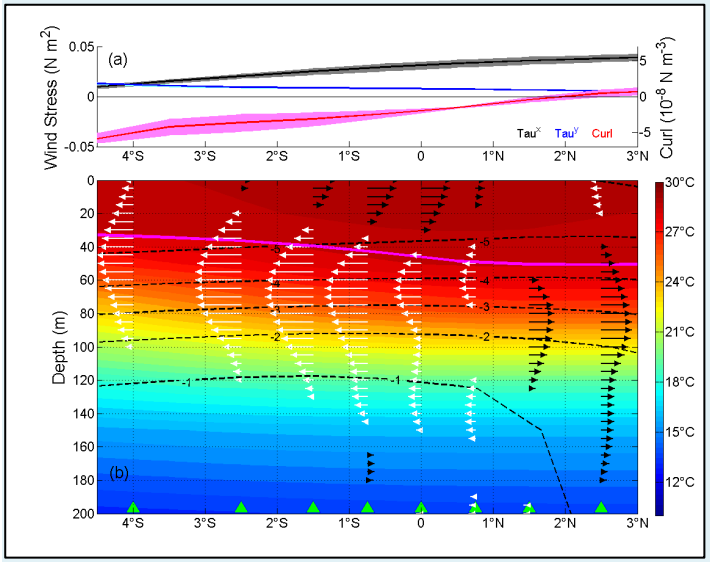
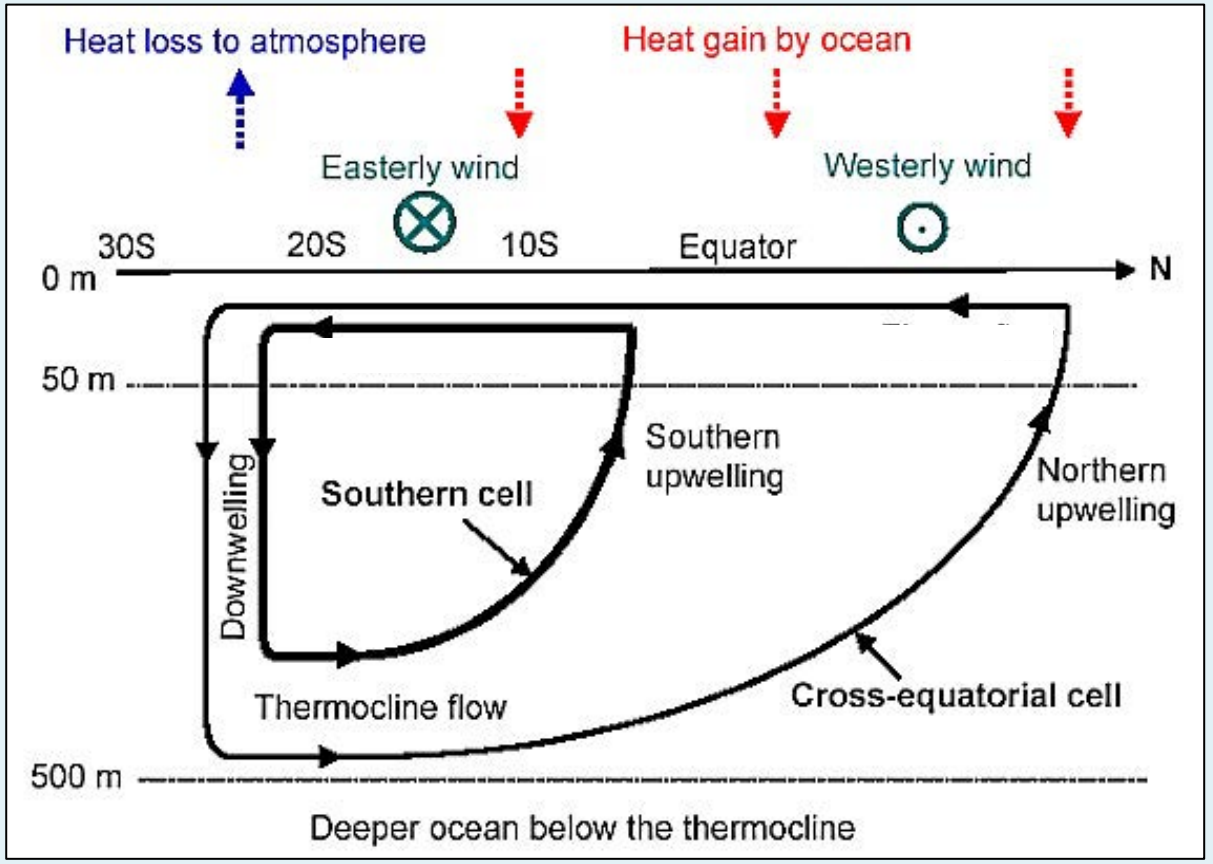


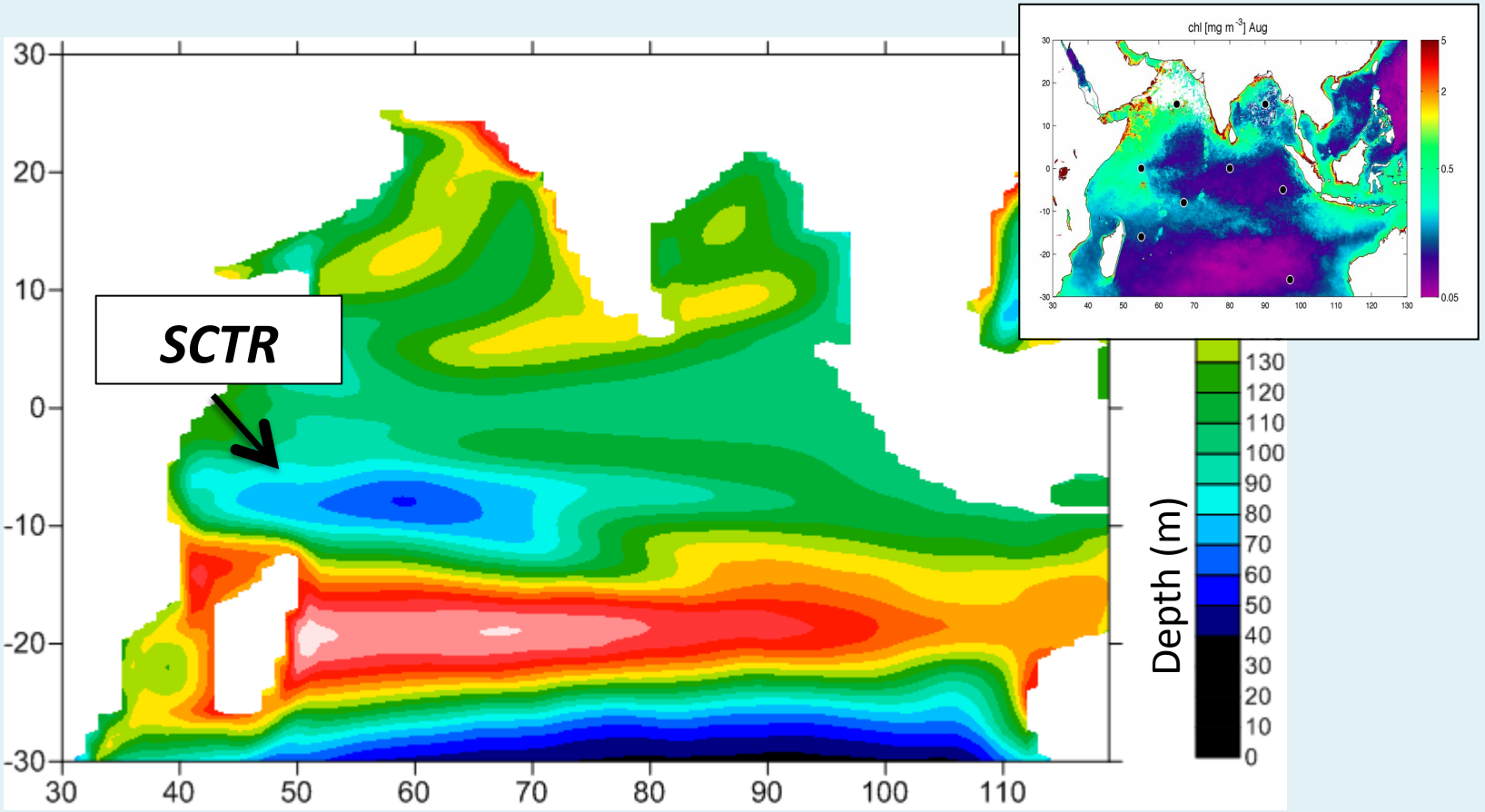
Mean Cross-Equatorial Southward Flow





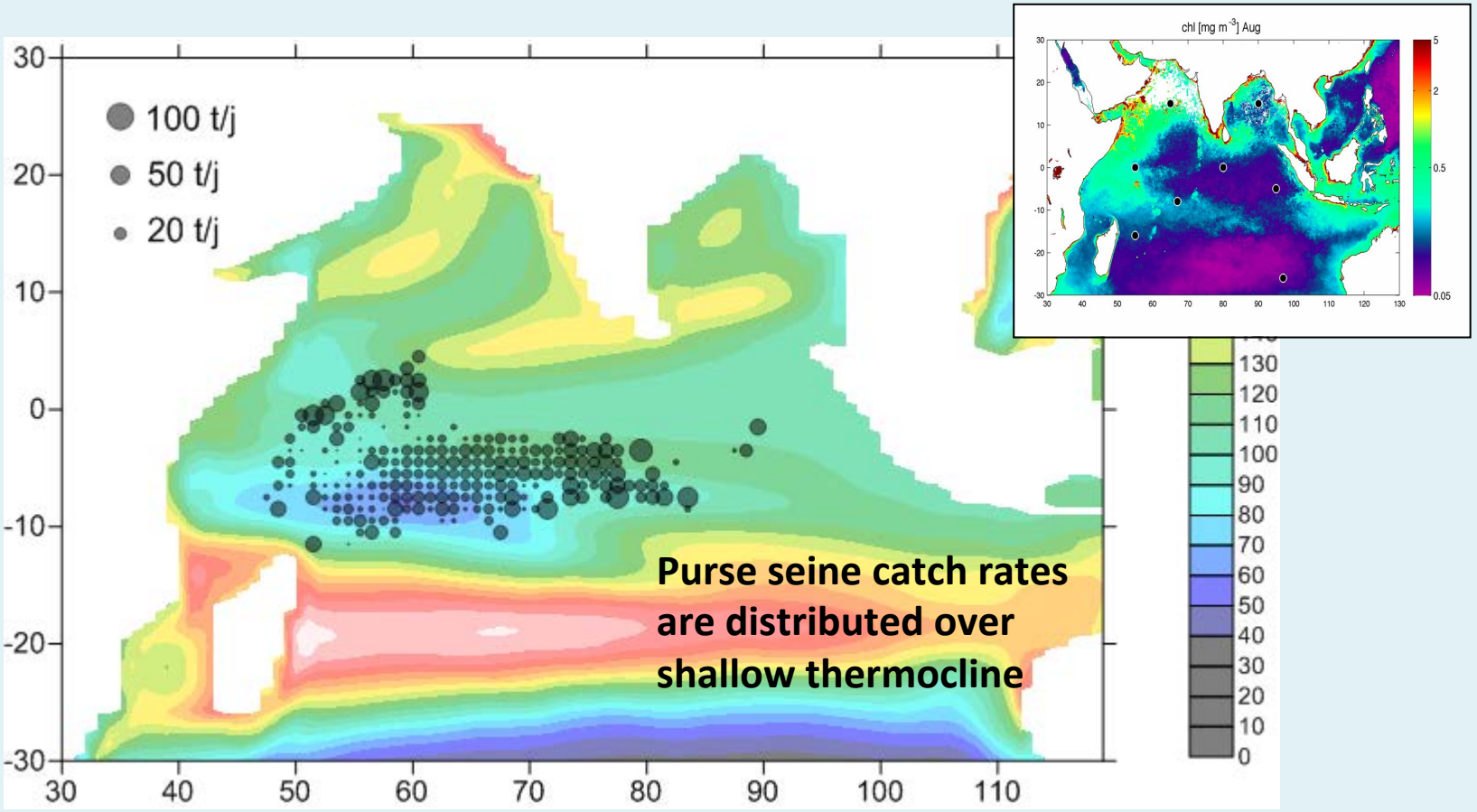
Lee, 2004, JGR

Seychelles Chagos Thermocline Ridge (SCTR)



Distribution of 20°C depth

Seychelles Chagos Thermocline Ridge (SCTR)

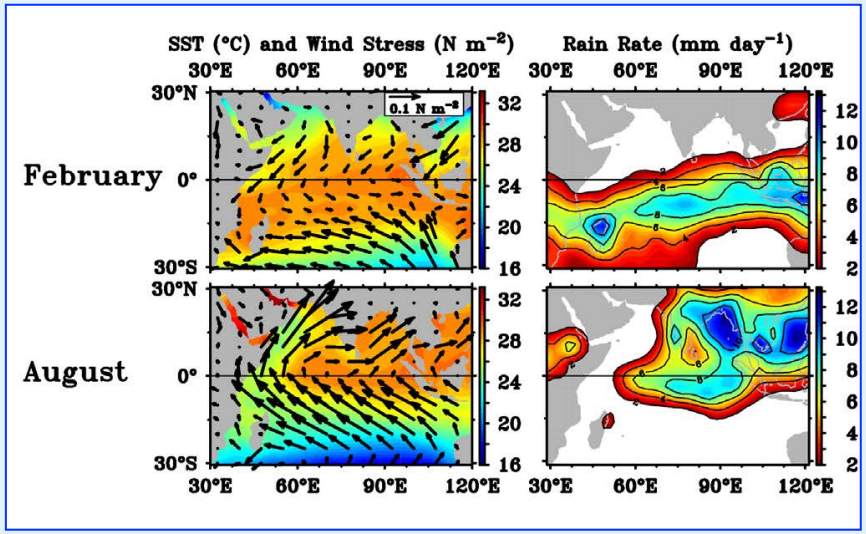


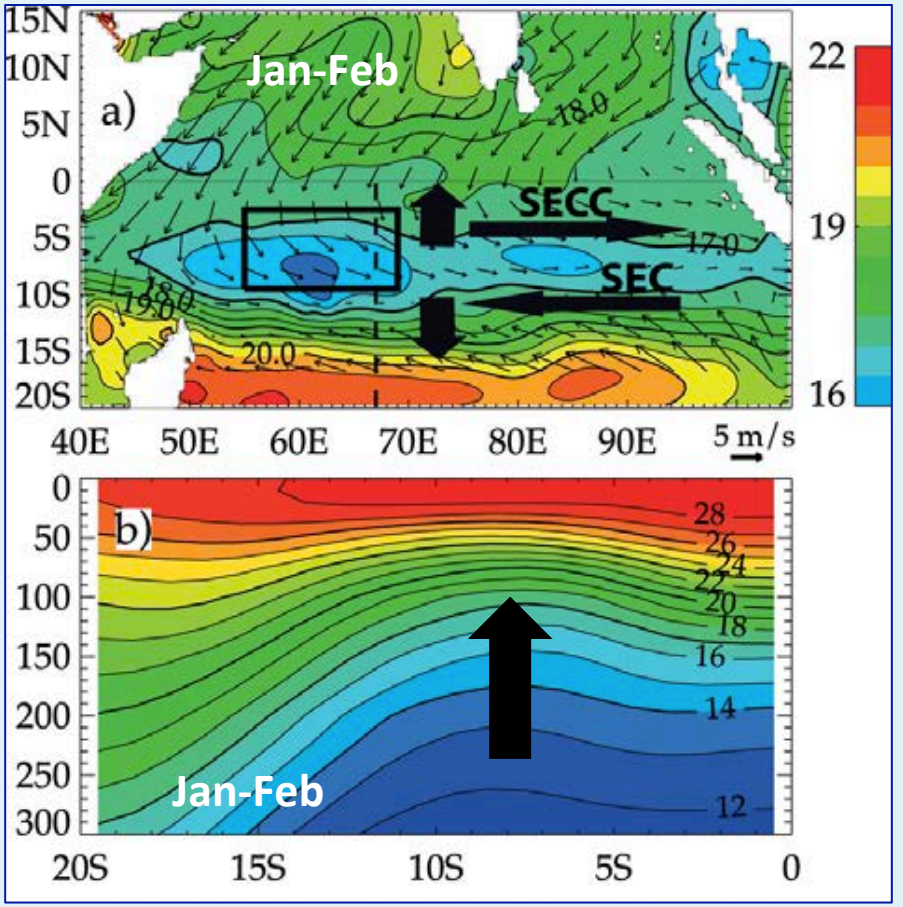
Distribution of 20°C depth
with average PS tuna catch rates in Jan (1991-2002) (circles)

Courtesy of F. Marsac, IRD

Seychelles Chagos Thermocline Ridge (SCTR)

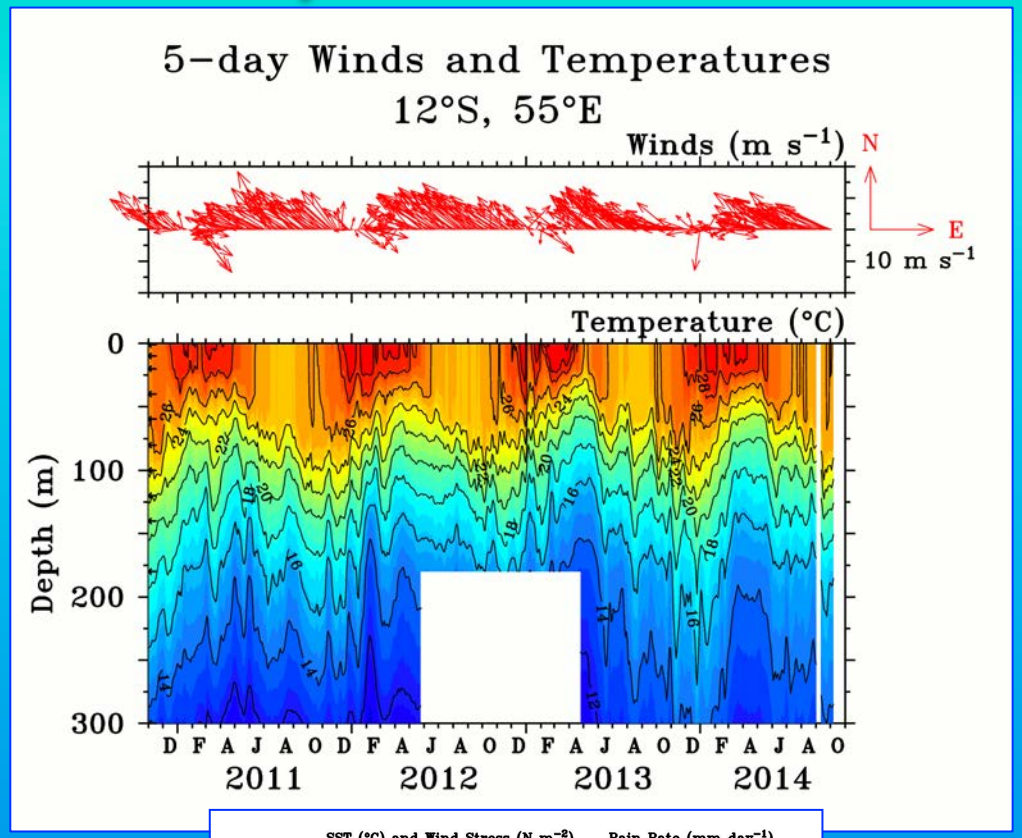
Strong seasonality variations in SCTR region

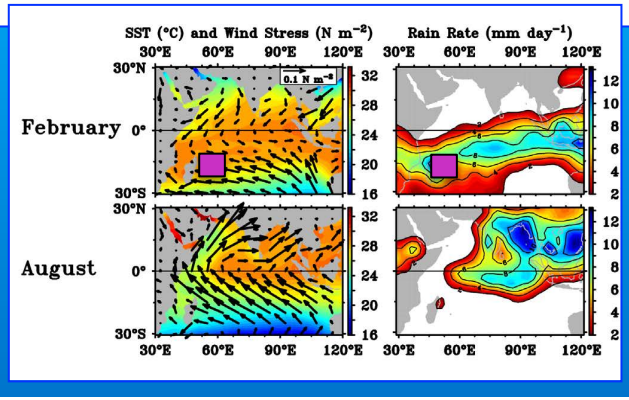


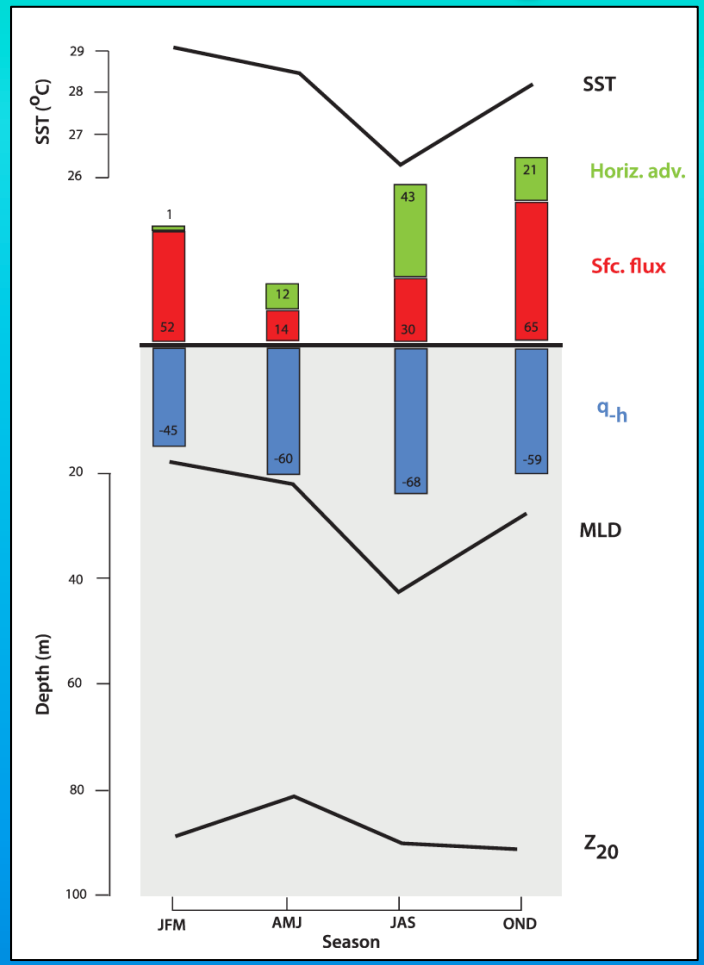


Vialard et al, 2009, BAMS

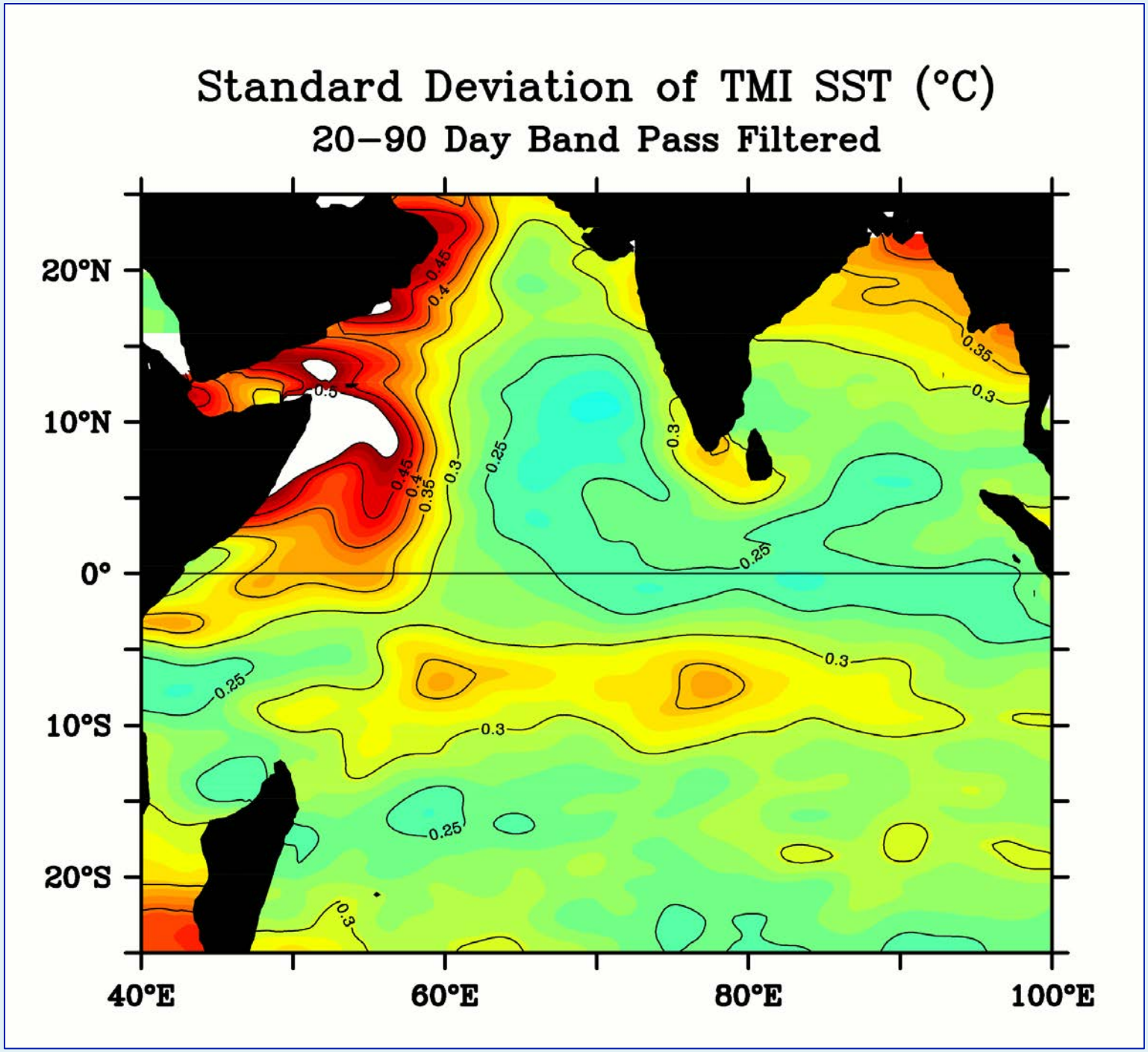
SCTR Seasonal Heat Balance: Importance of Vertical Turbulent Mixing

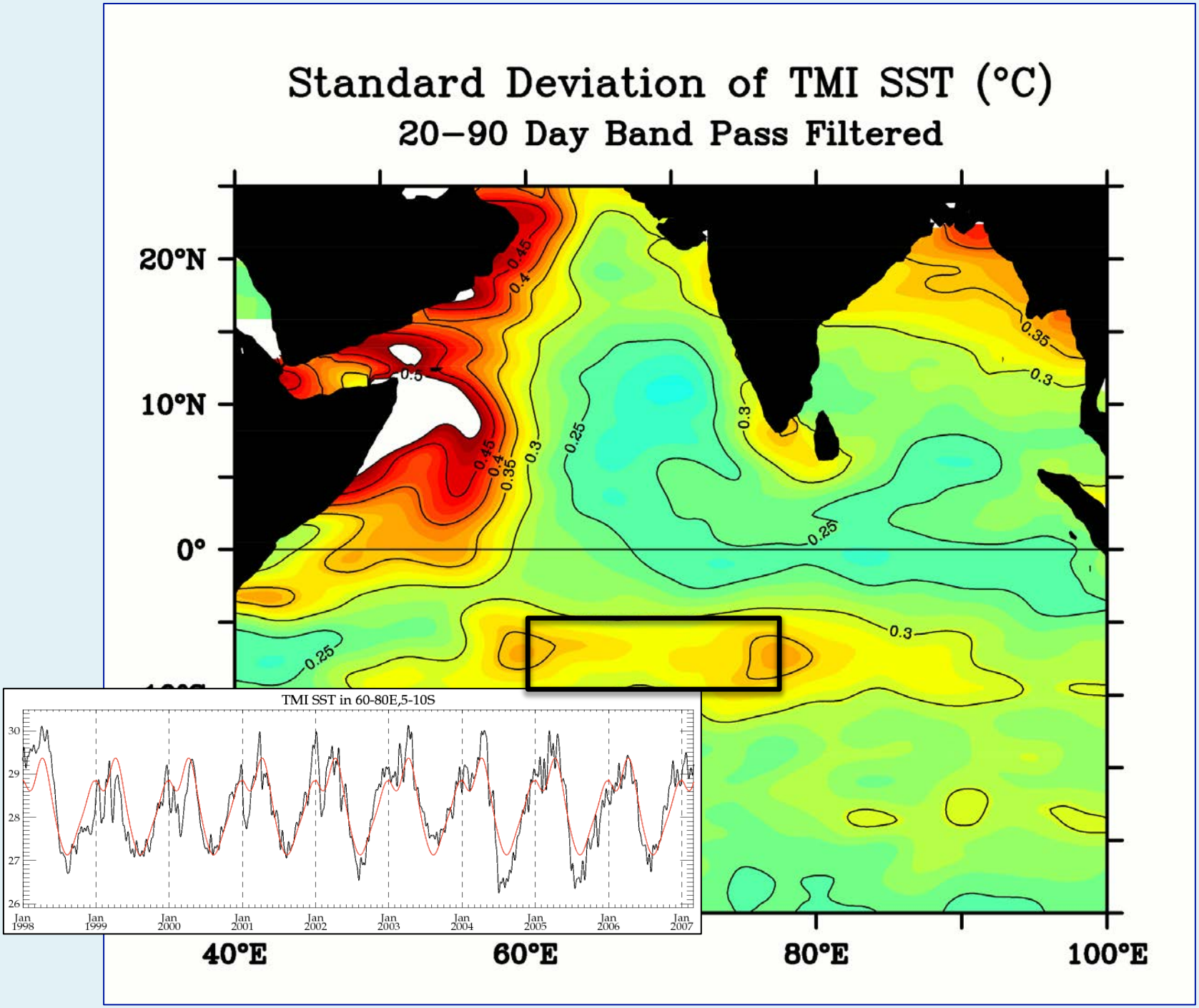






Foltz et al, 2010. J. Climate


Standard Deviation of TMI SST (°C)
20–90 Day Band Pass Filtered
20°N
10°N
0°
10°S
20°S
40°E
60°E
80°E
100°E
0.5
0.45
0.4
0.35
0.3
0.25


Standard Deviation of TMI SST (°C)
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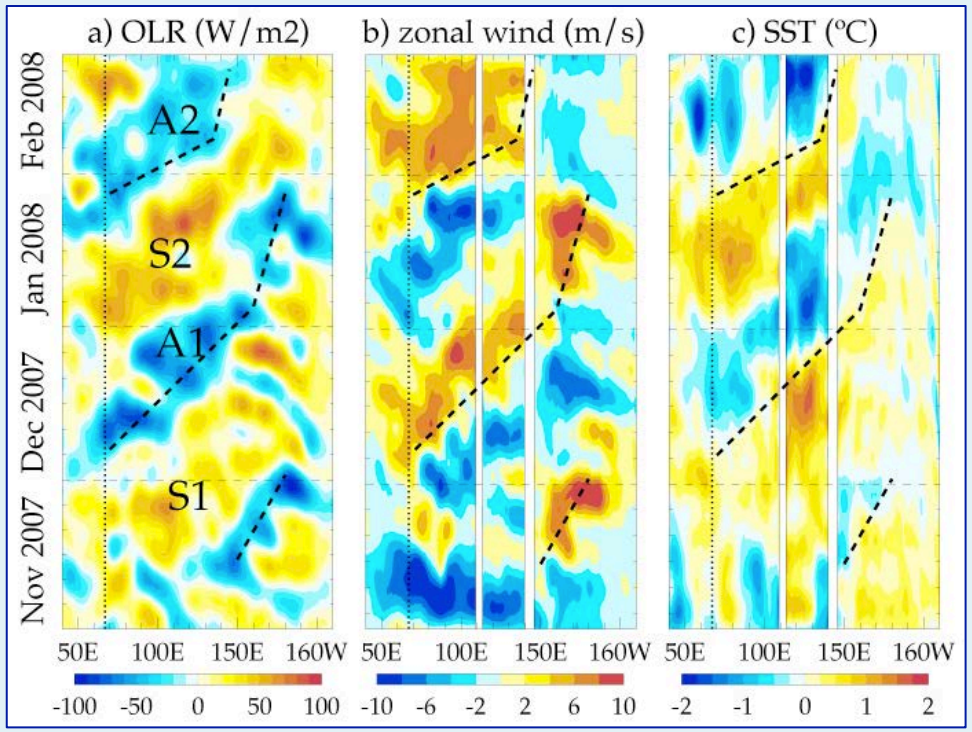
20°N
10°N
0°
40°E
60°E
80°E
100°E
0.5
0.45
0.4
0.35
0.3
0.25
TMI SST in 60-80E,5-10S
30
29
28
27
26
Jan 1998
Jan 1999
Jan 2000
Jan 2001
Jan 2002
Jan 2003
Jan 2004
Jan 2005
Jan 2006
Jan 2007

SCTR SST Variations Related to MJO

Along 8°S in the Indian Ocean

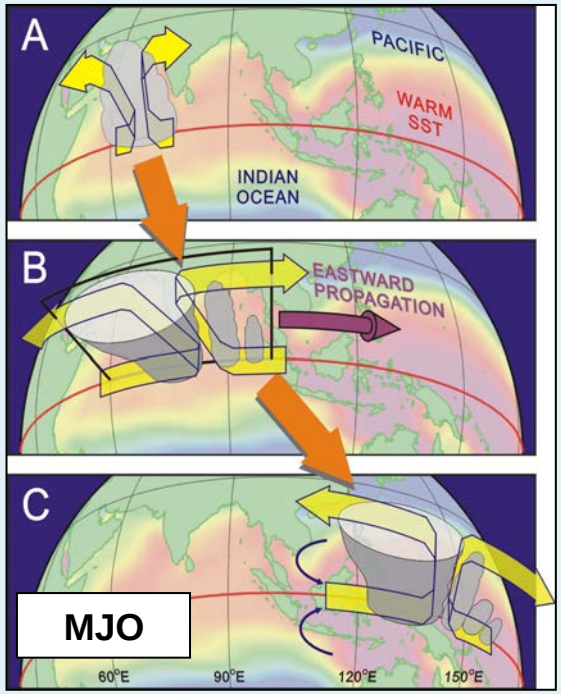


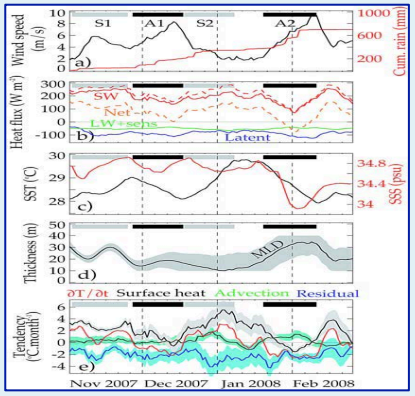
"…atmospheric fluxes dominate the upper ocean heat balance at the MJO timescale…but MJO-induced variations of subsurface processes may also contribute to the cooling...."

--Vialard et al, 2008, JGR

70% surface heat flux (SW) , wind driven 20% entrainment…

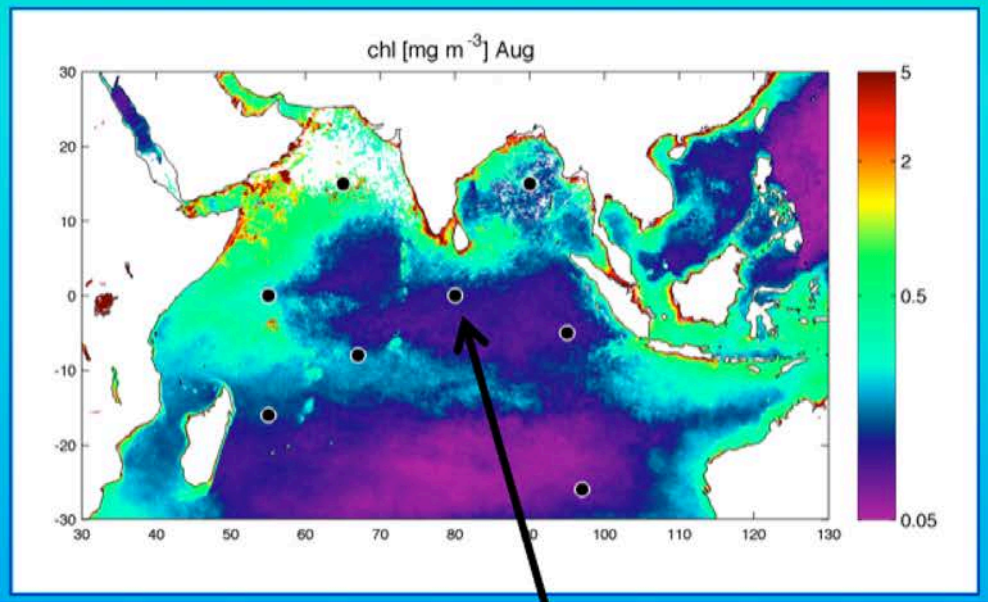
--Jayakumar et al, 2011, Clim Dyn

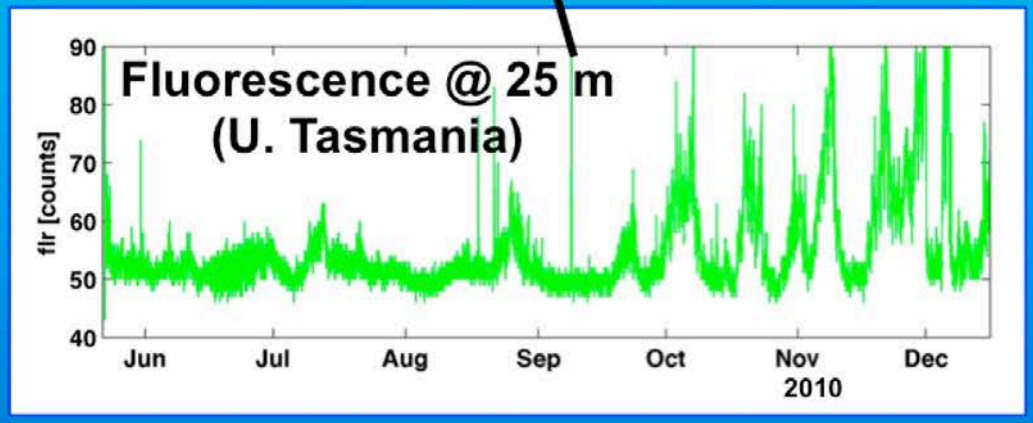




Heat Balance @ 8°S, 67°E

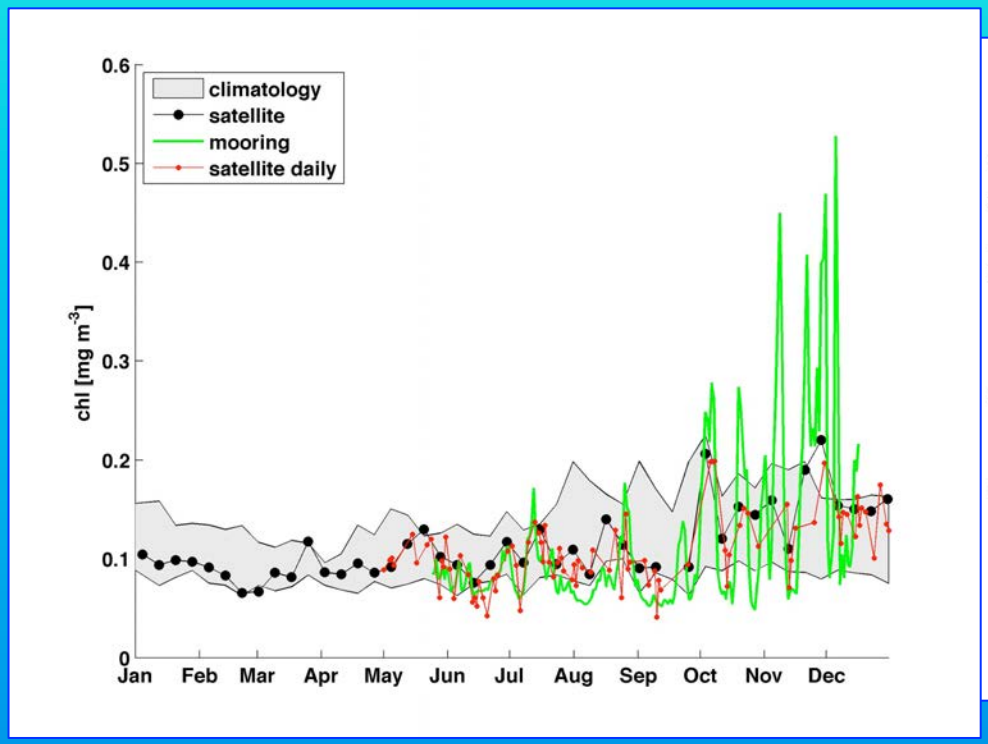
RAMA Bio-optical Measurements

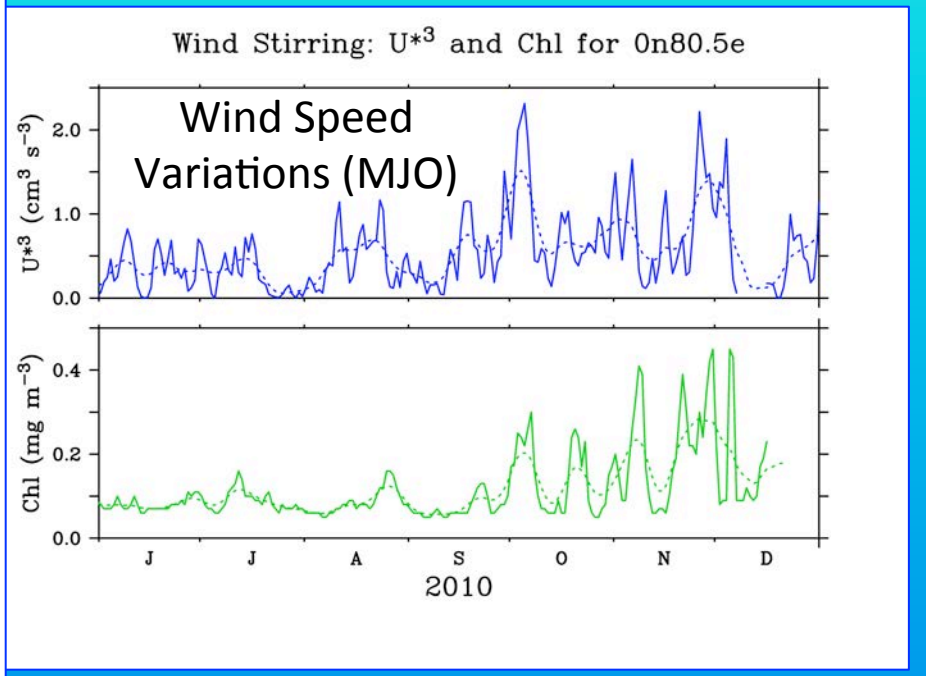




Deployment of fluorometer on an ATLAS mooring

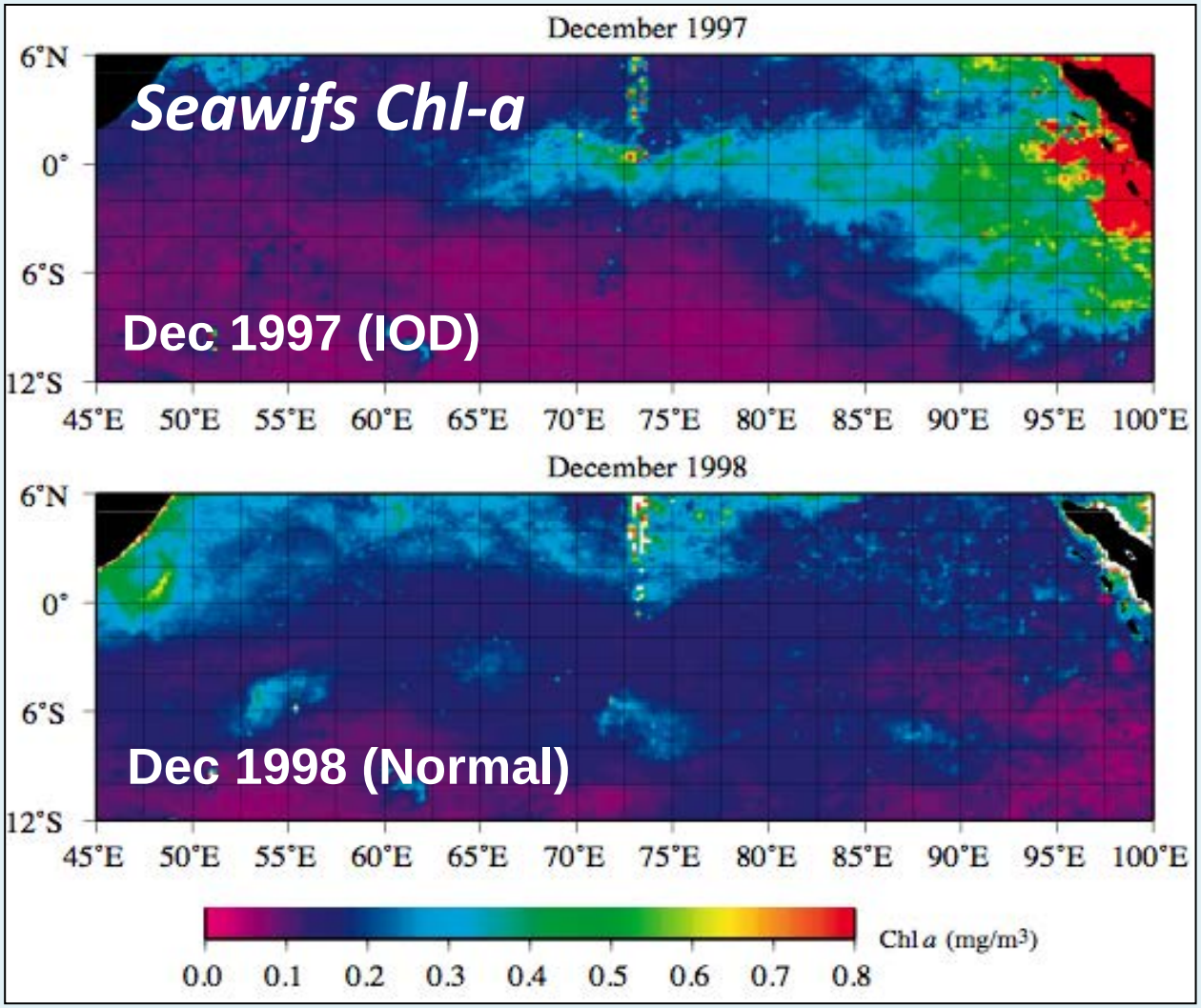
RAMA Bio-optical Measurements

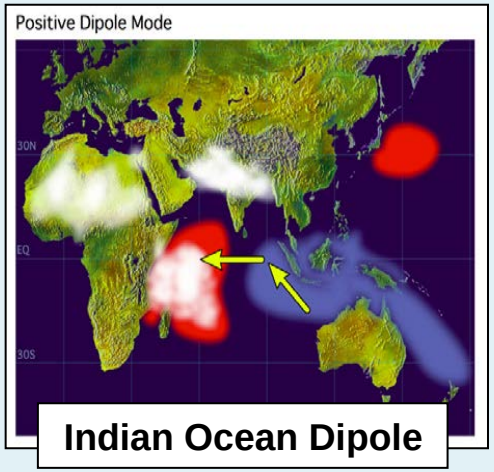




Strutton et al, 2015, Biogeosciences

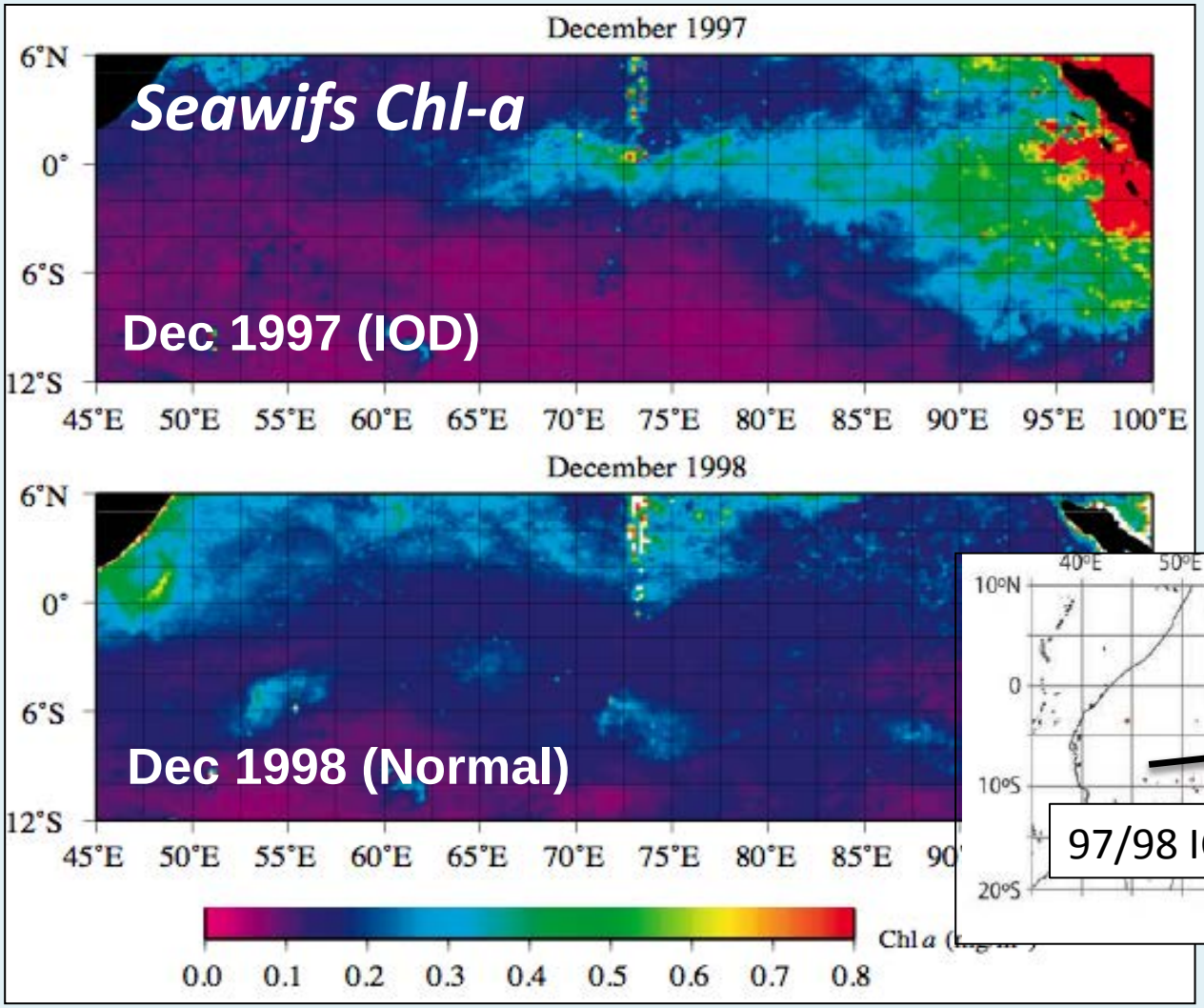
IOD Biophysical Interactions



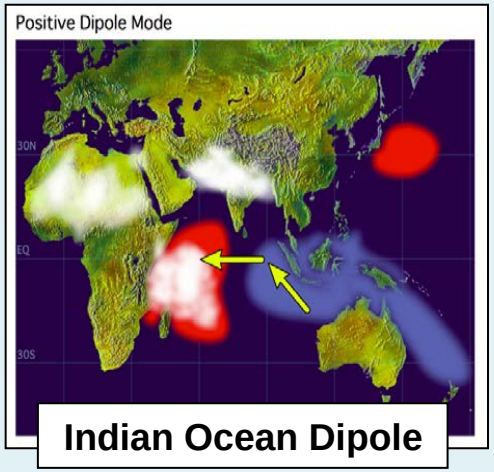


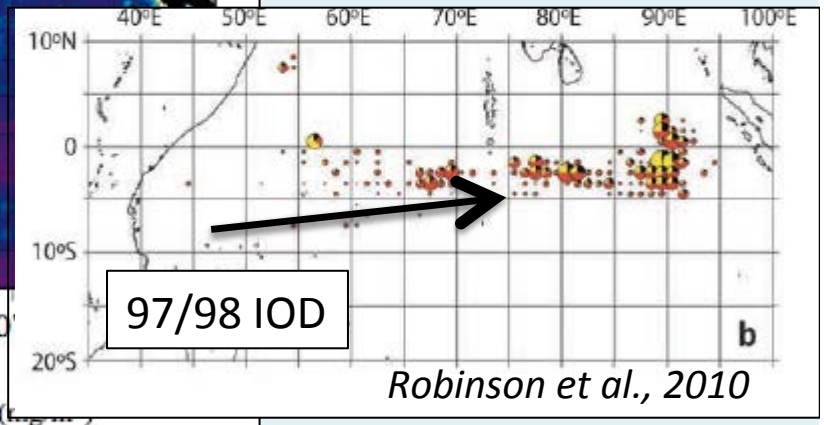
Wiggert et al, 2009

IOD Biophysical Interactions

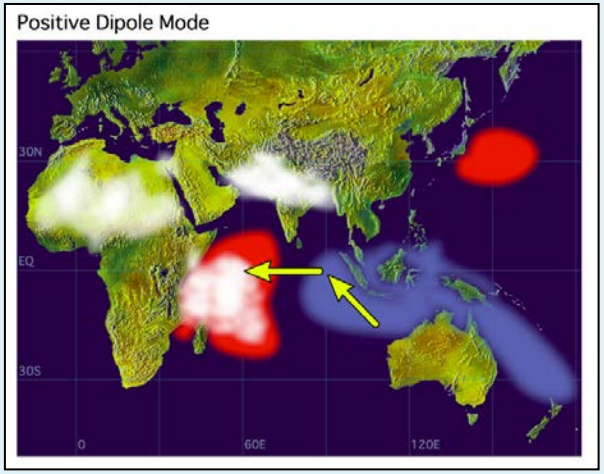


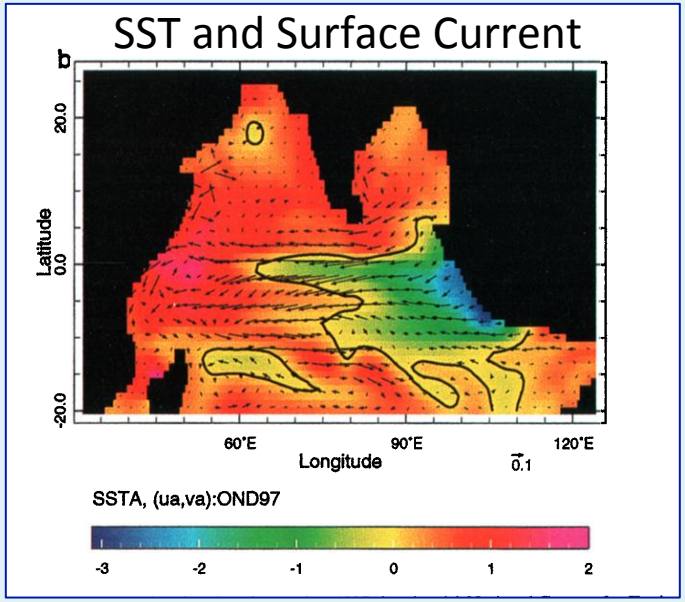
Wiggert et al, 2009





Ocean Circulation and IOD Development



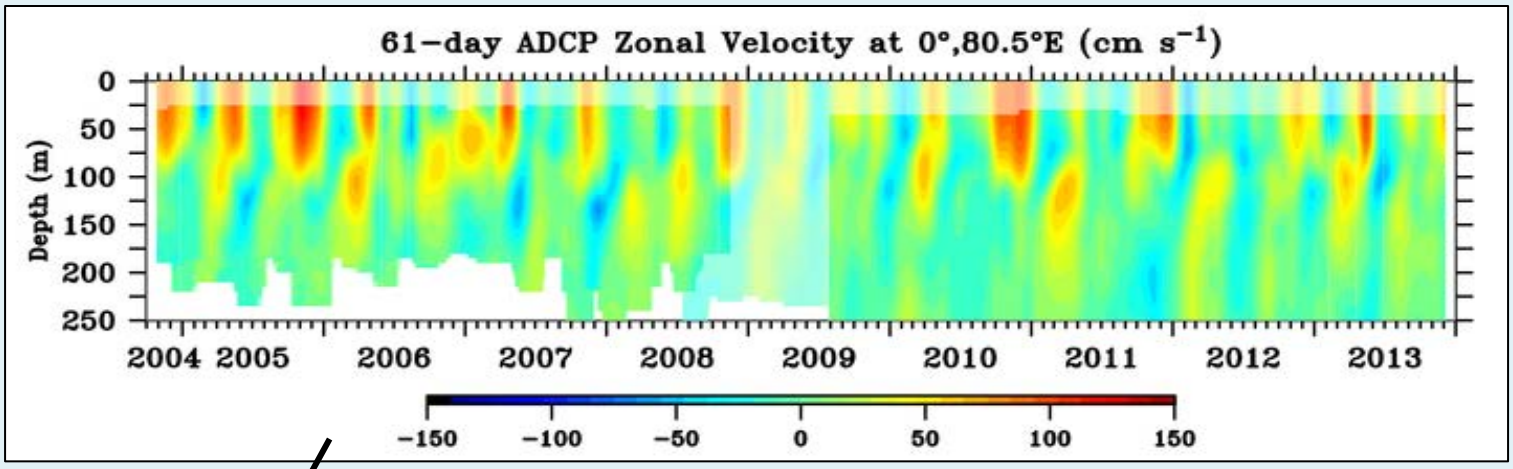


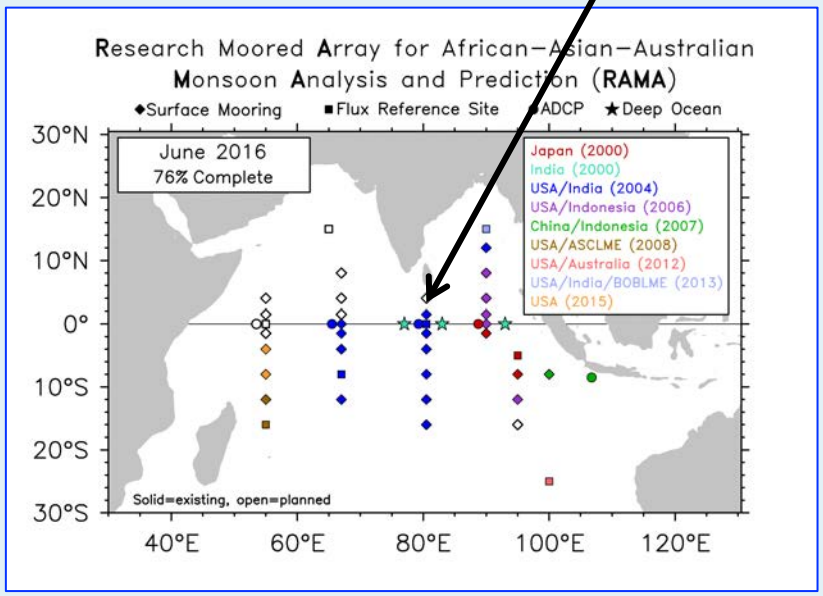
In models, ocean currents (and in particular, the Wyrtki Jets) play a key role in the evolution of the Indian Ocean Dipole by changing thermocline depth → upwelling → SST (also biogeochemistry and ecosystems)

Murtugudde et al, 2000

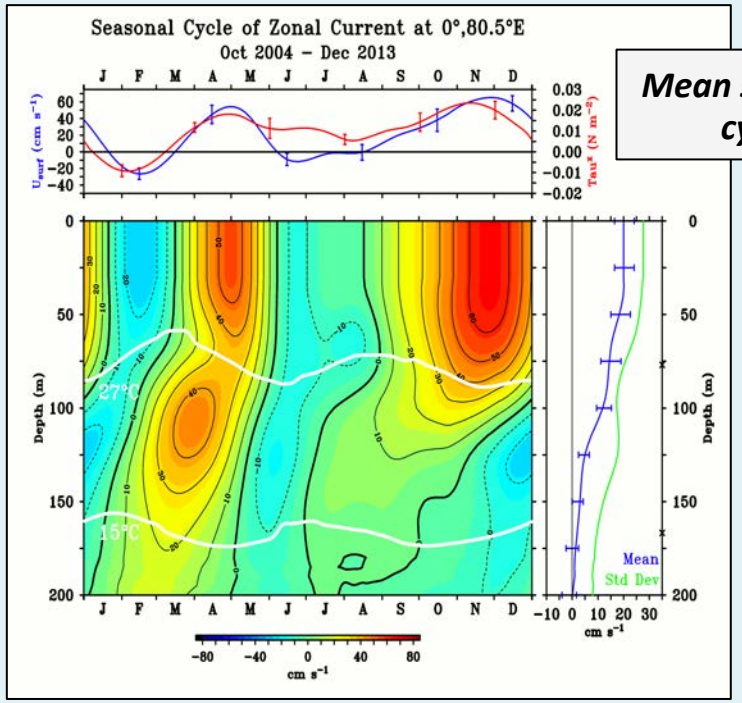
Equatorial Indian Ocean Circulation: Wyrtki Jets

Wyrtki Jets advect mass, heat, and salt along the equator on seasonal to interannual time scales, dynamically affecting the development of Indian Ocean Dipole events



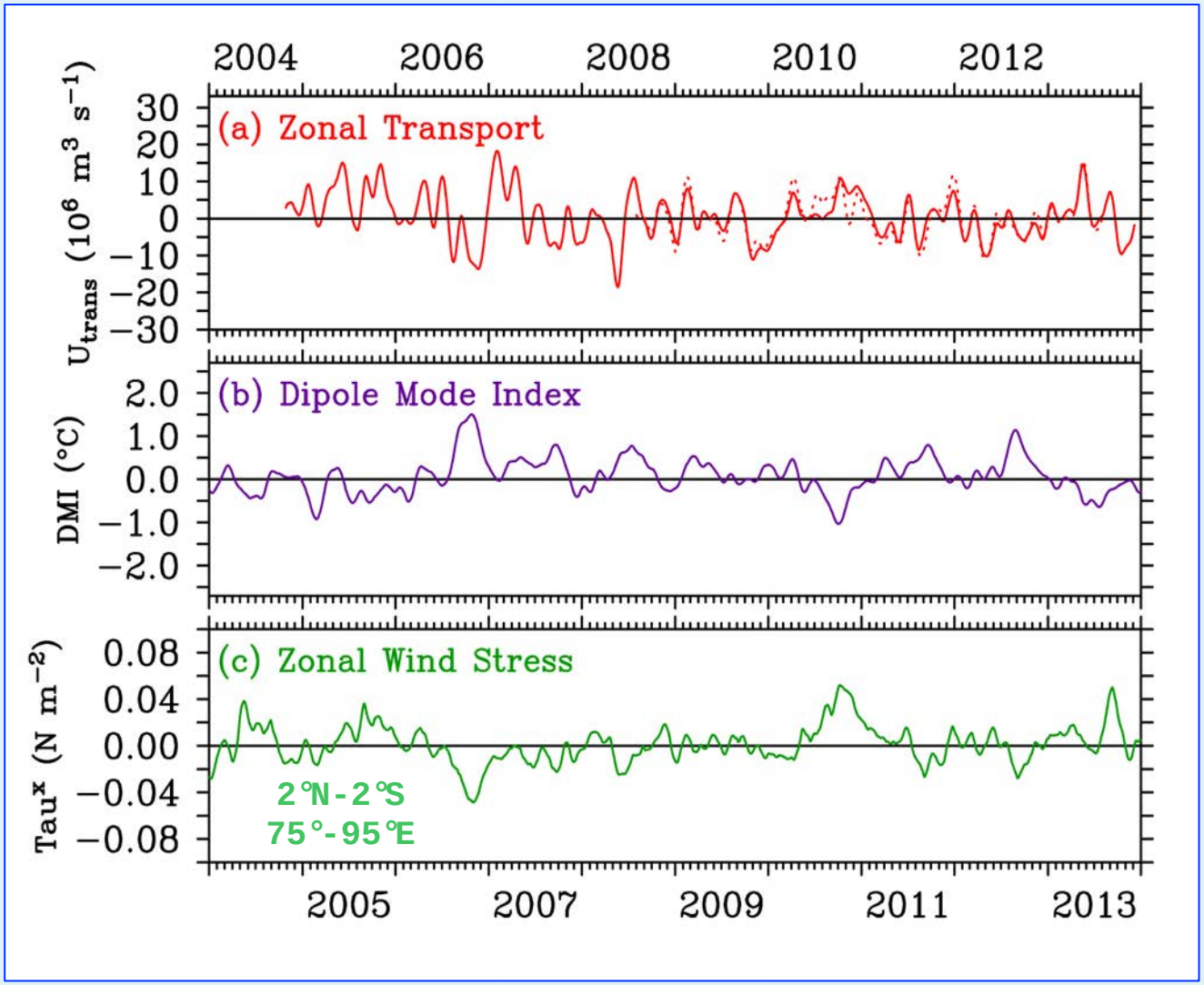


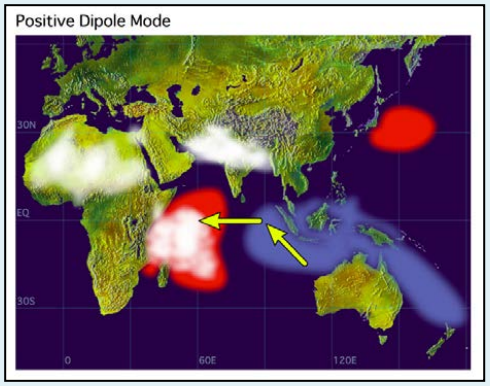
McPhaden et al, 2015, JGR

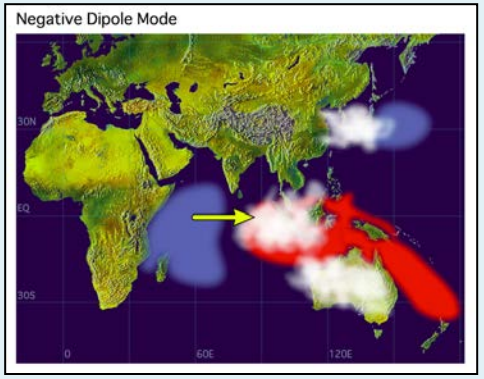


Mean seasonal cycle

Interannual Variations: Dipole Mode Index, Zonal Wind Stress & Zonal Transport (0-80 m)







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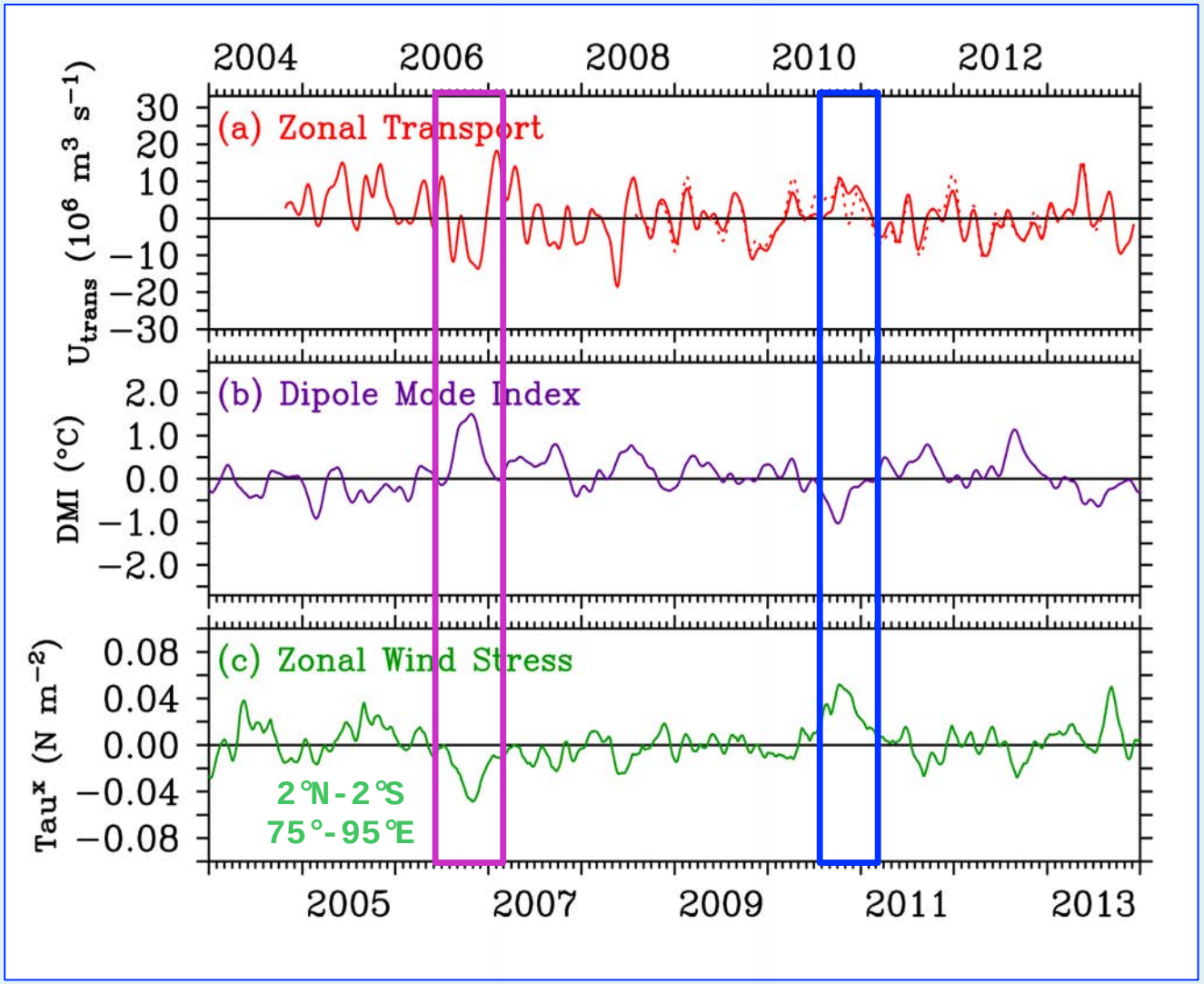
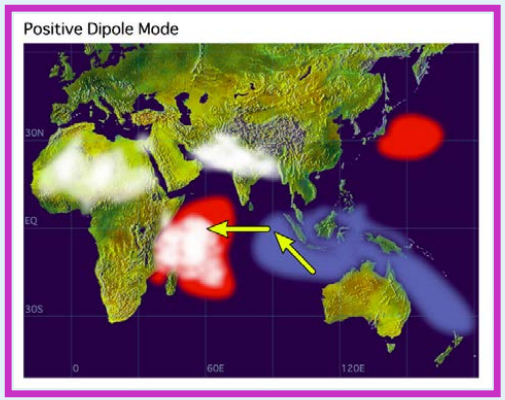
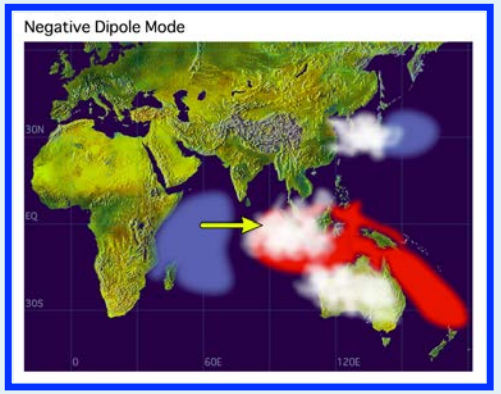
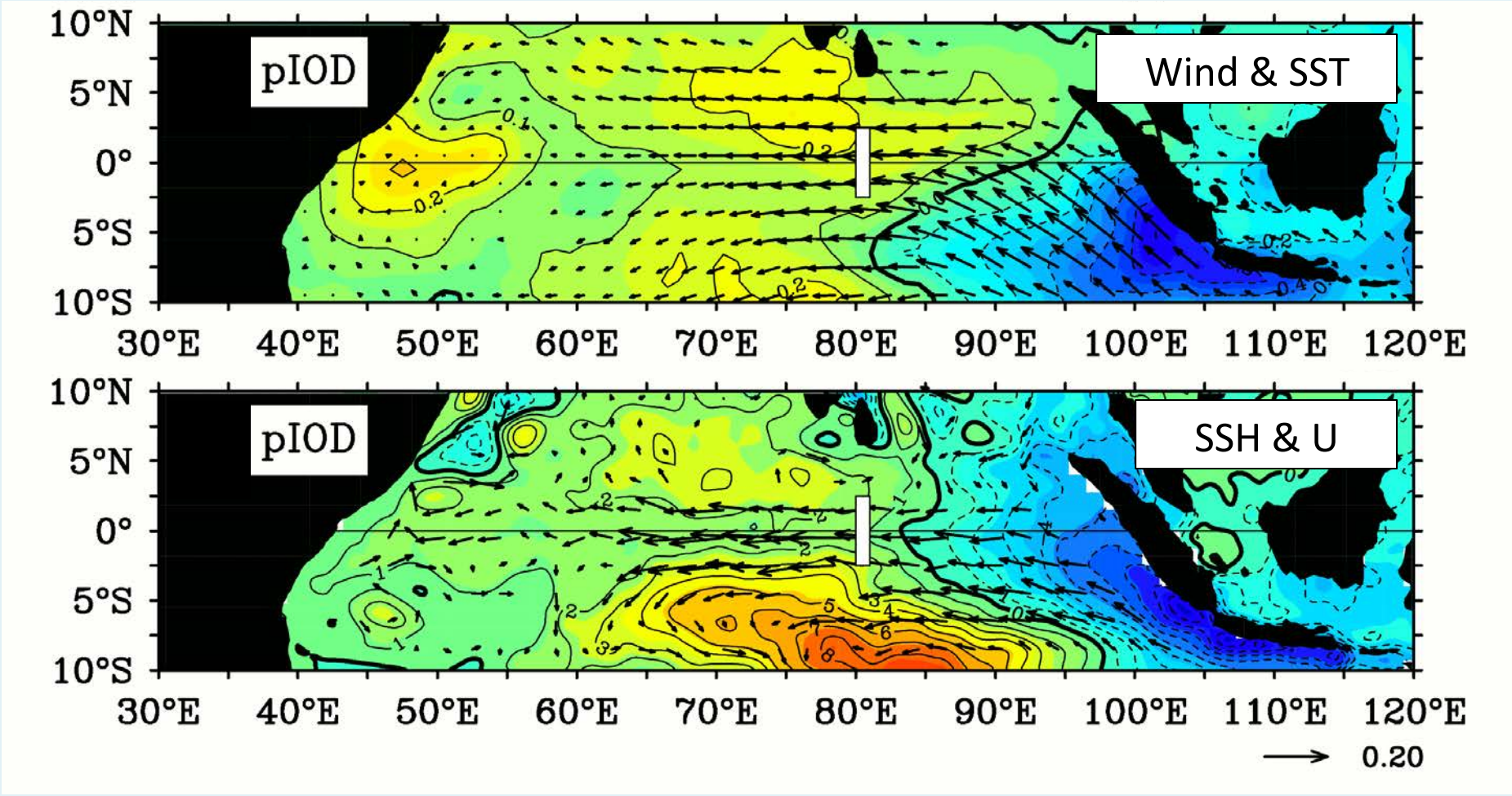




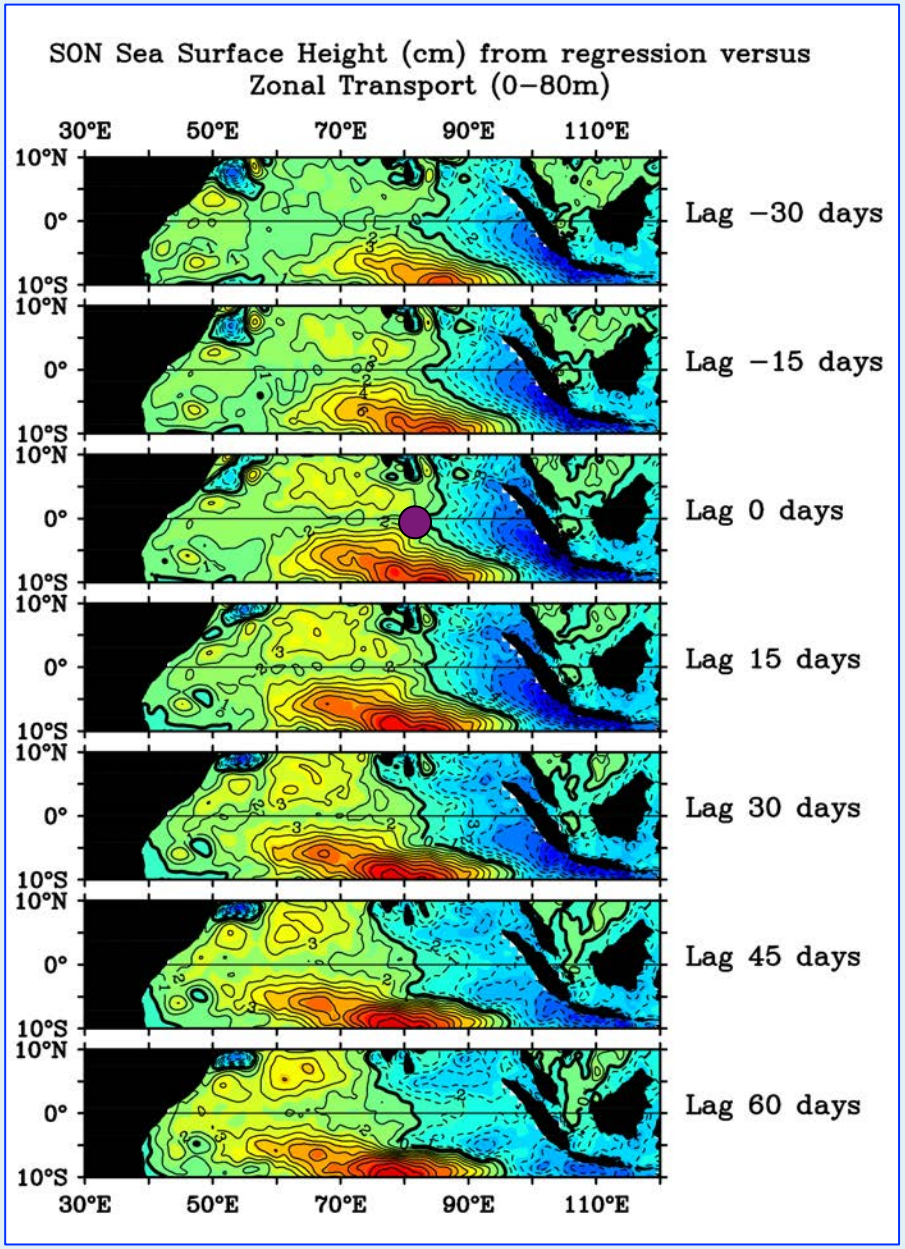


IOD conditions in SON

SST, Wind Stress, Surface Currents, SSH from Regression



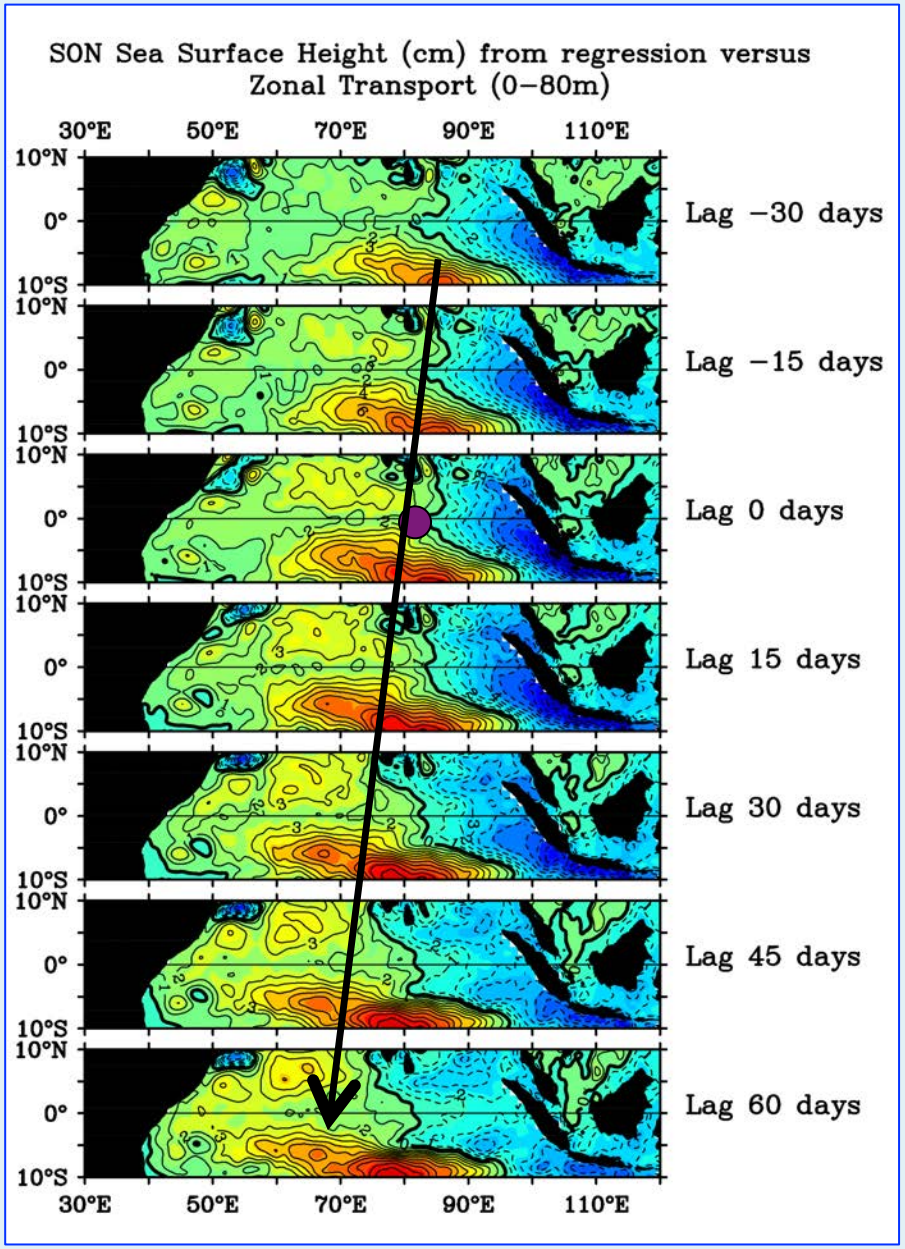
SSH Evolution Associated with IOD



Transport variations of the Wyrtki Jets are dynamically linked to wind forced equatorial Kelvin and Rossby waves and eastern boundary generated Rossby waves

Nagura & McPhaden, 2010
McPhaden & Nagura, 2014

SSH Evolution Associated with IOD



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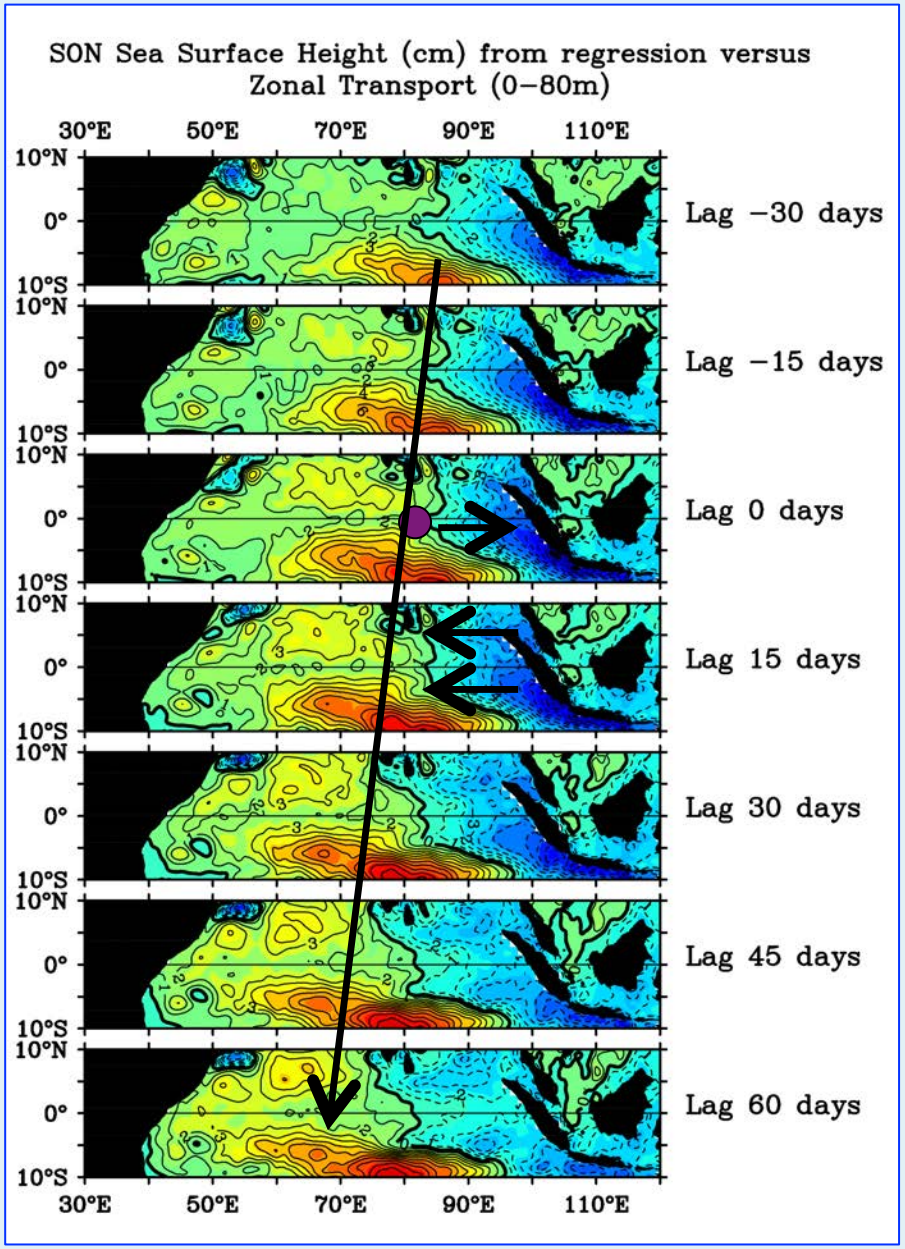

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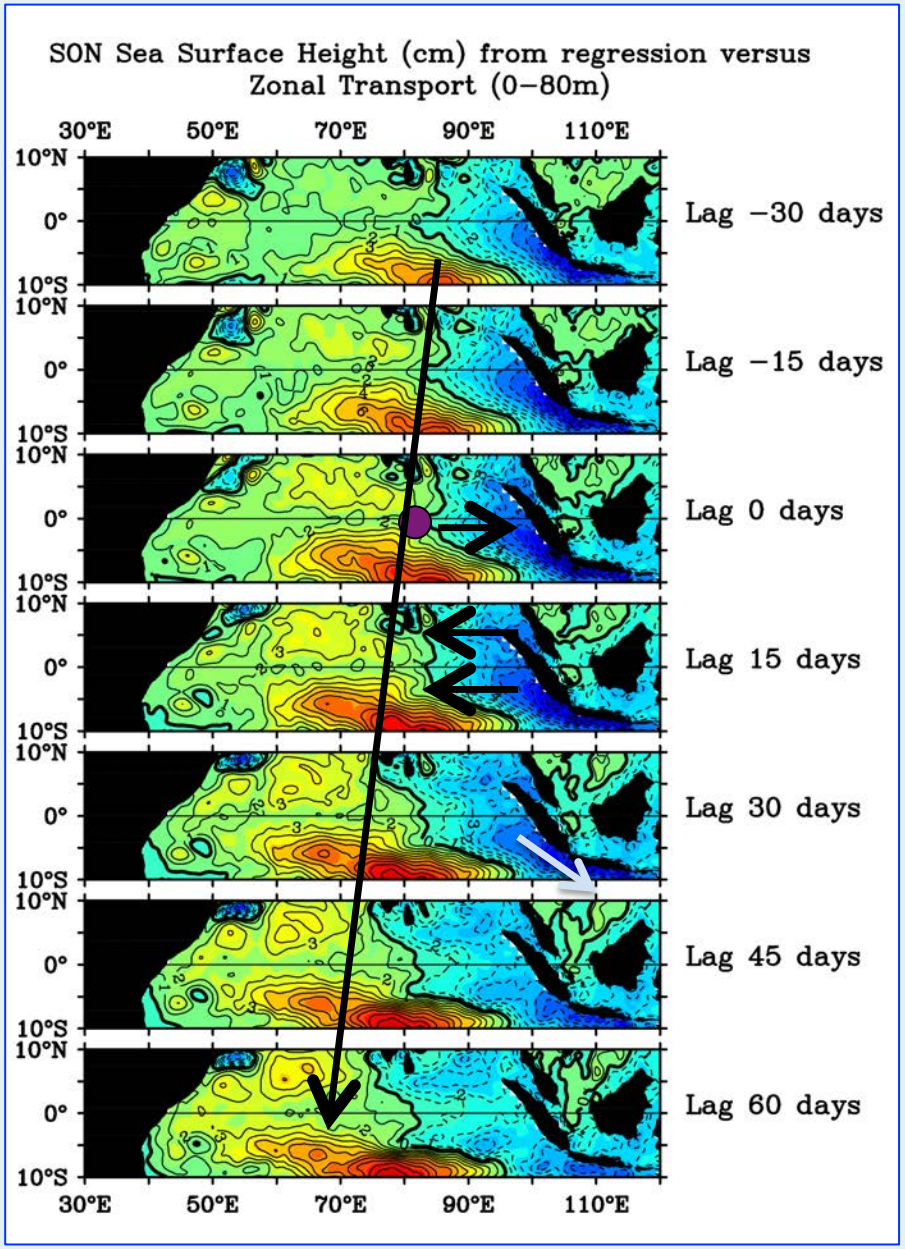

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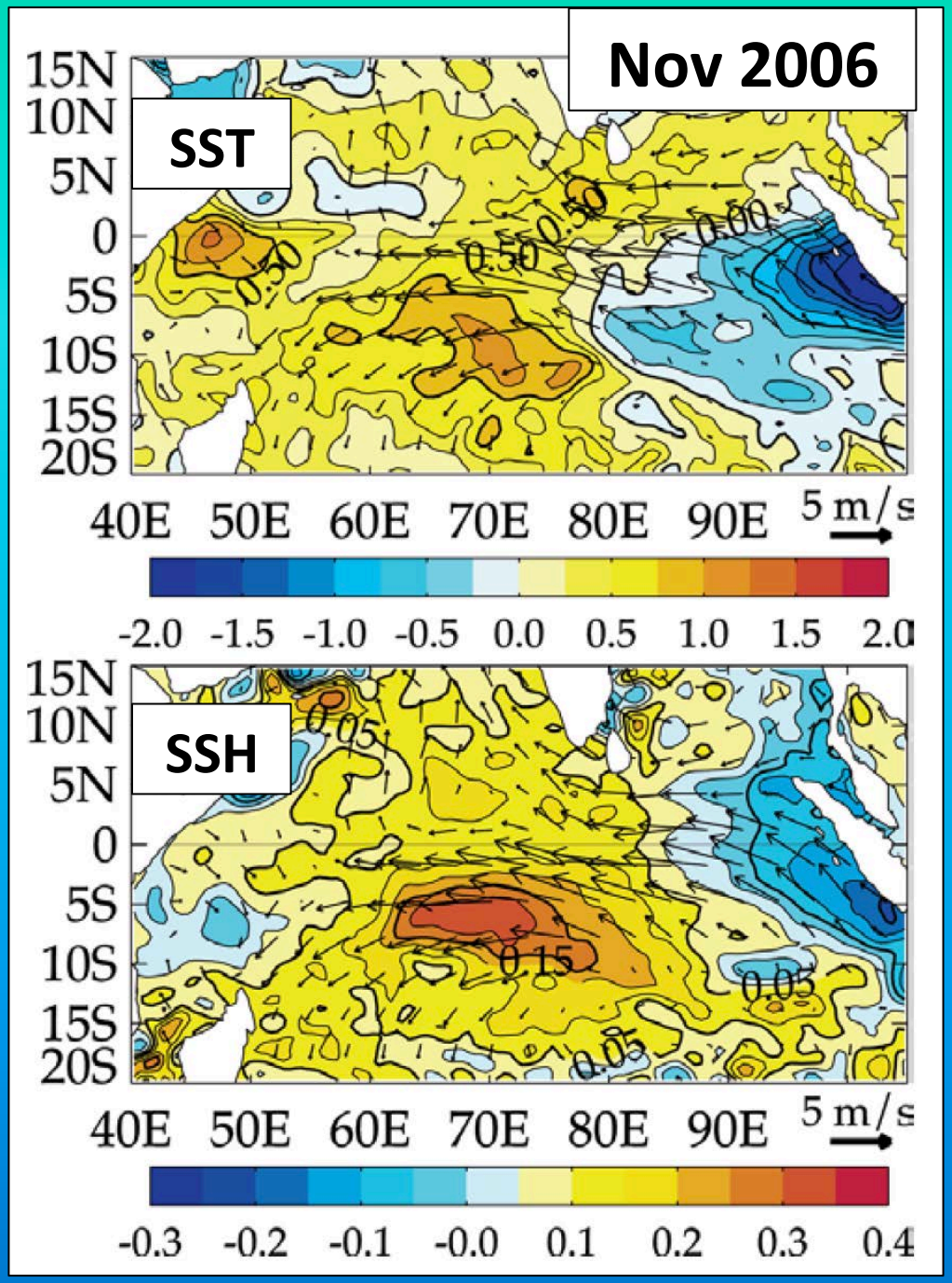
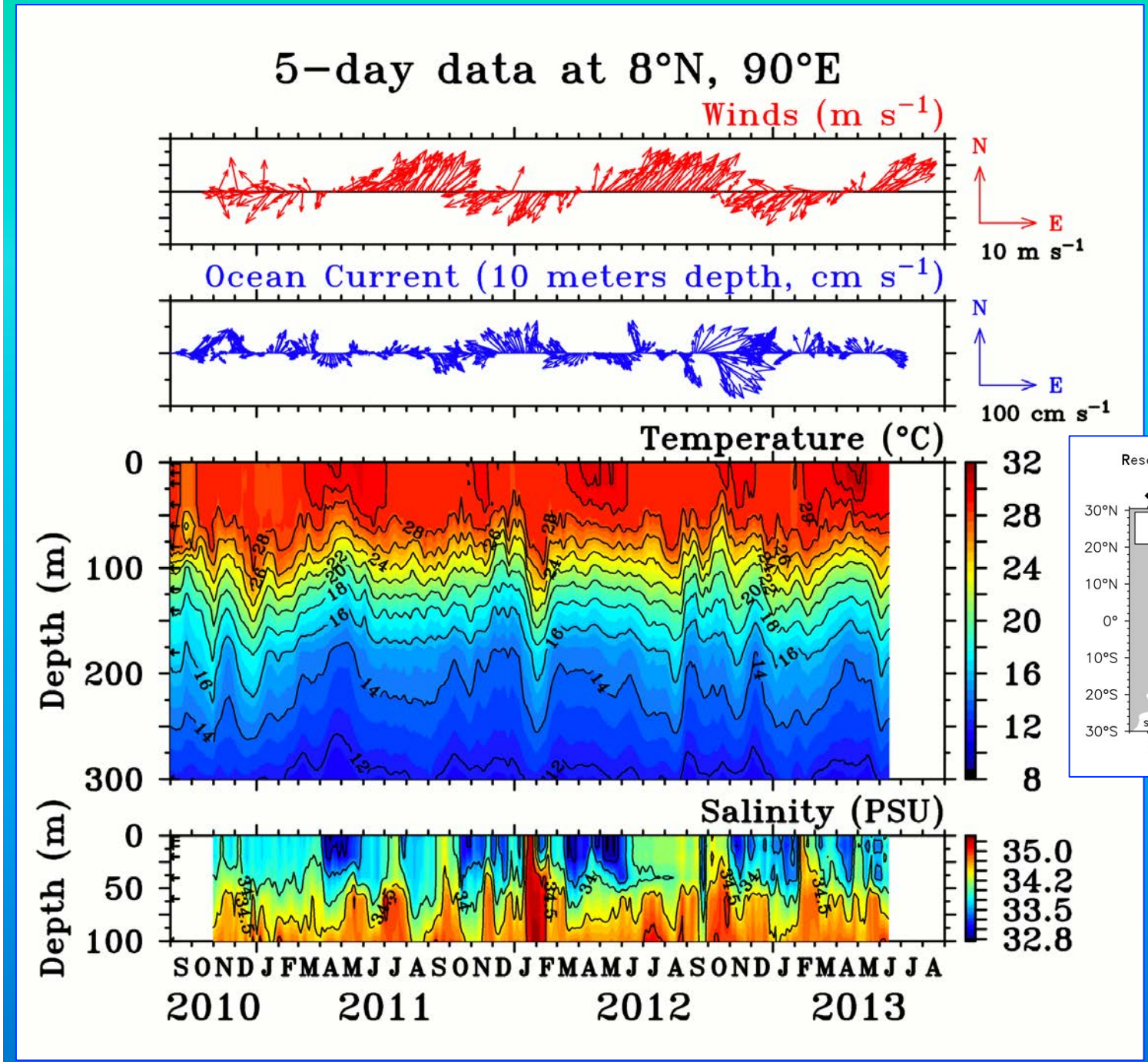
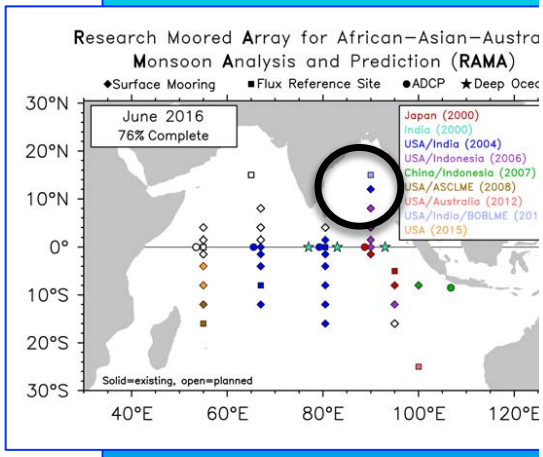


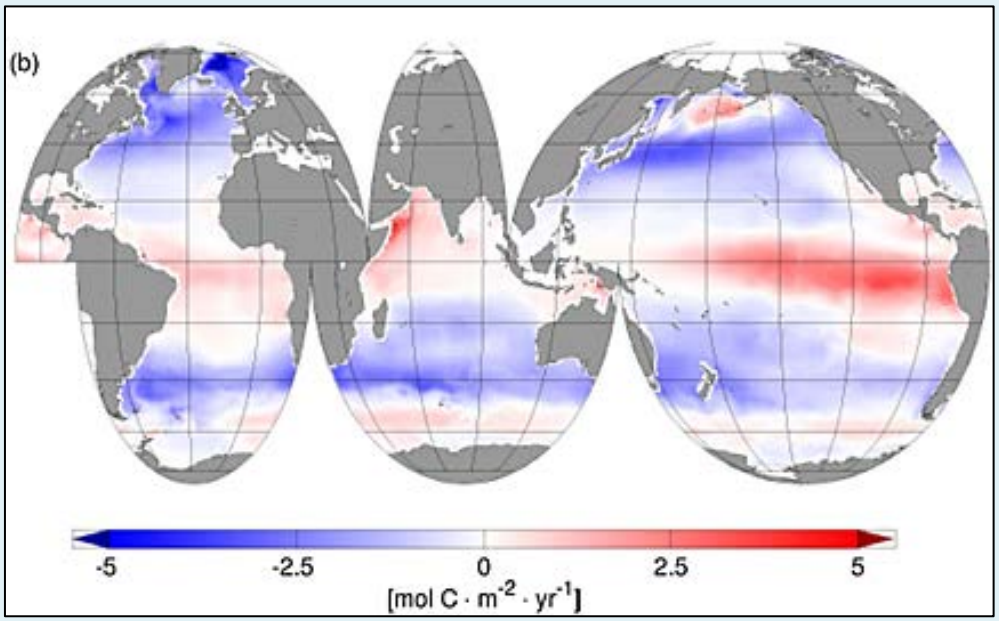
Java-Sumatra Upwelling and SCTR Downwelling Linked During IOD Events

Bay of Bengal

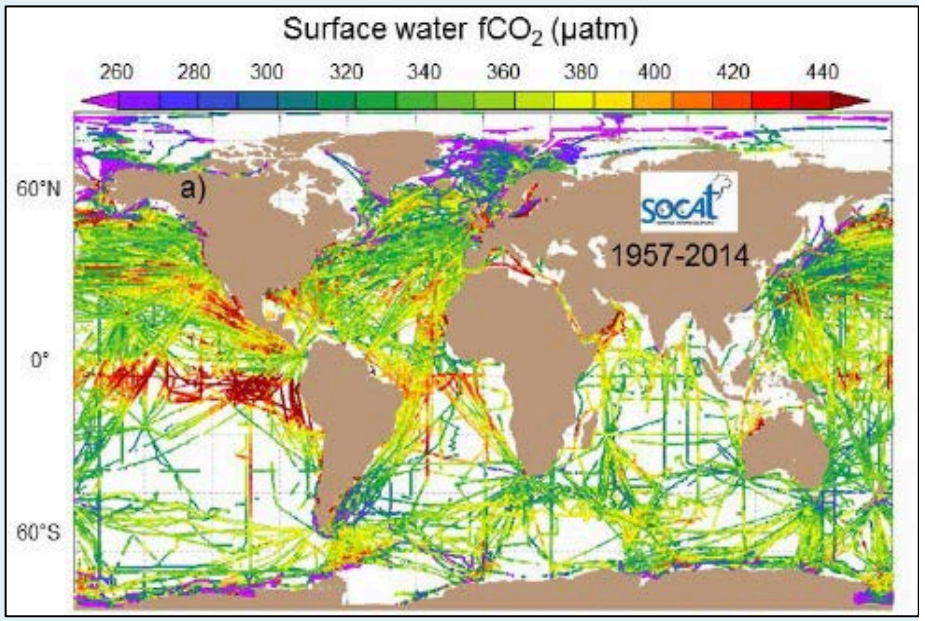




Bay of Bengal CO_2 Fluxes

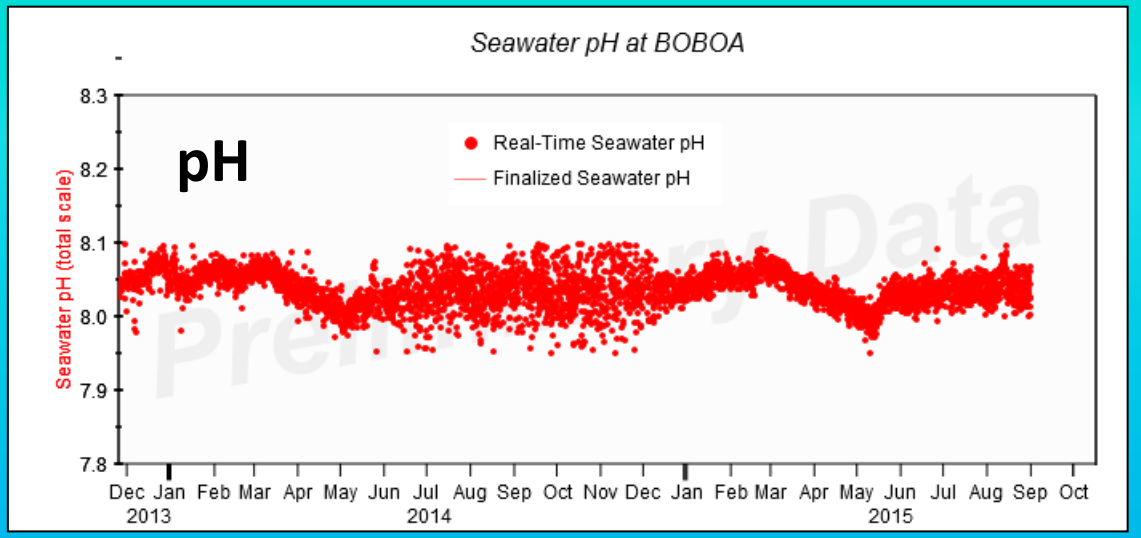


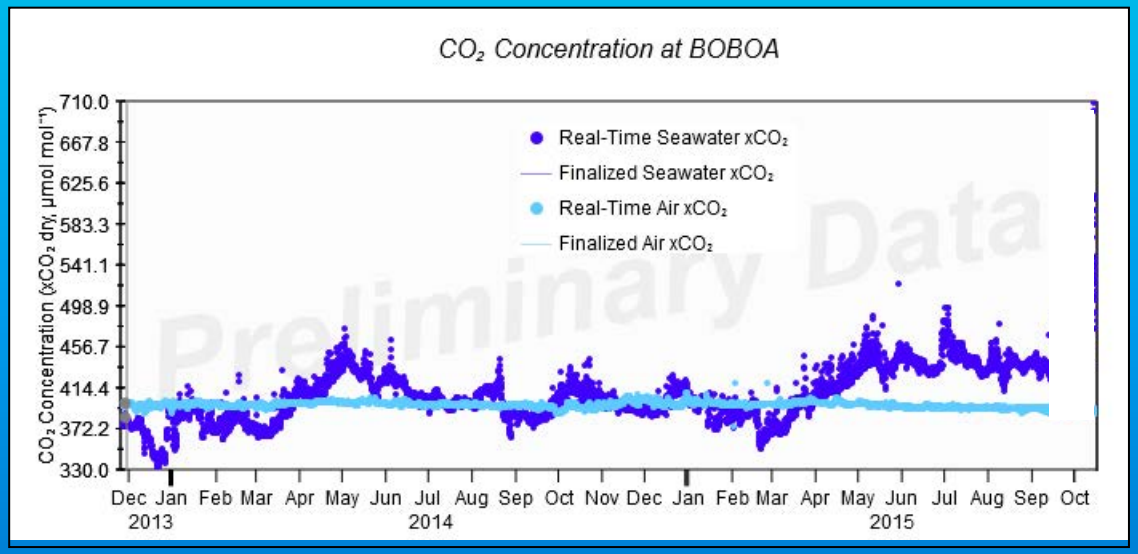
Landschützer et al, 2014, GBC



Bakker et al, 201, ESSD

BoB Ocean Acidification Mooring





BOBLME
OA System @ 15°N, 90°E
Deployed 23 Nov 2013

Second International Indian Ocean Expedition (IIOE-2)
2015-2020

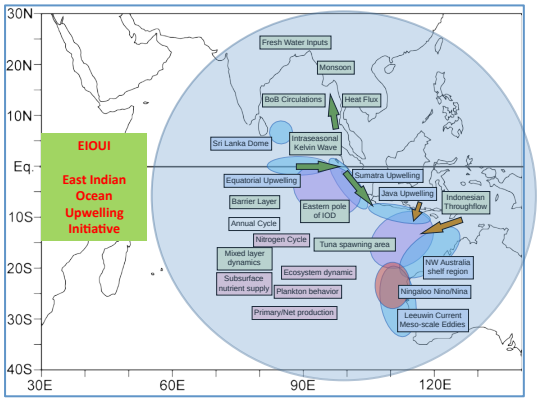
The overarching goal of IIOE-2 is to advance our understanding of interactions among geological, ocean and atmospheric processes that give rise to the complex physical dynamics of the Indian Ocean region, and to determine how those dynamics affect climate, extreme events, marine biogeochemical cycles, ecosystems and human populations.

Scientific themes:

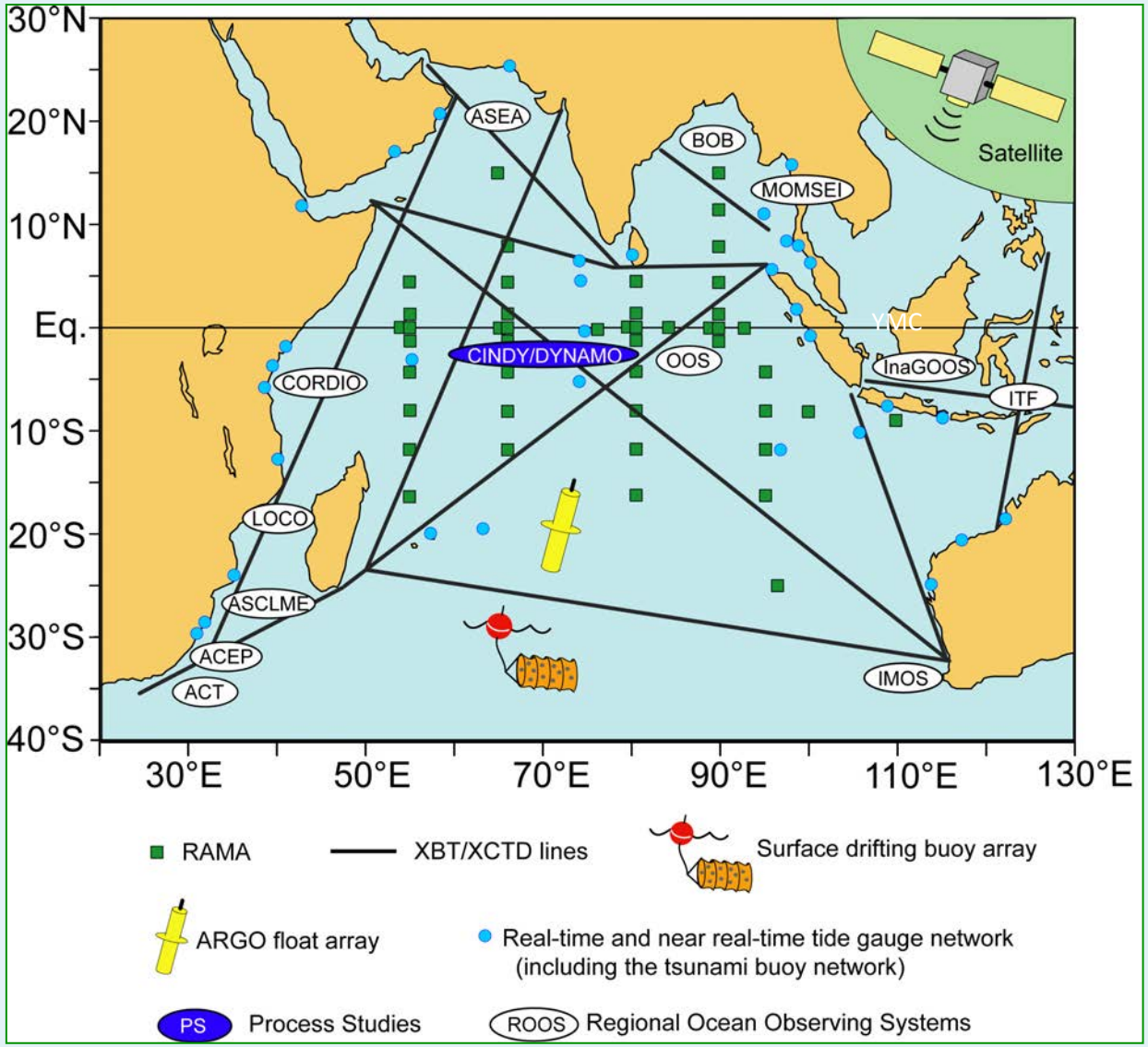
Theme 1: Anthropogenic Impacts
Theme 2: Boundary current dynamics, upwelling variability and ecosystem impacts
Theme 3: Monsoon variability and ecosystem response
Theme 4: Circulation, climate variability and change
Theme 5: Extreme events and their impacts on ecosystems and human populations
Theme 6: Unique geological, physical, biogeochemical and ecological features of the Indian Ocean

Implementation Strategies:

1) **Leverage off and coordinate existing nations/international programs**
2) **Develop and coordinate new initiatives. The first of these is the Eastern Indian Ocean Upwelling Research Initiative (EIOURI)**

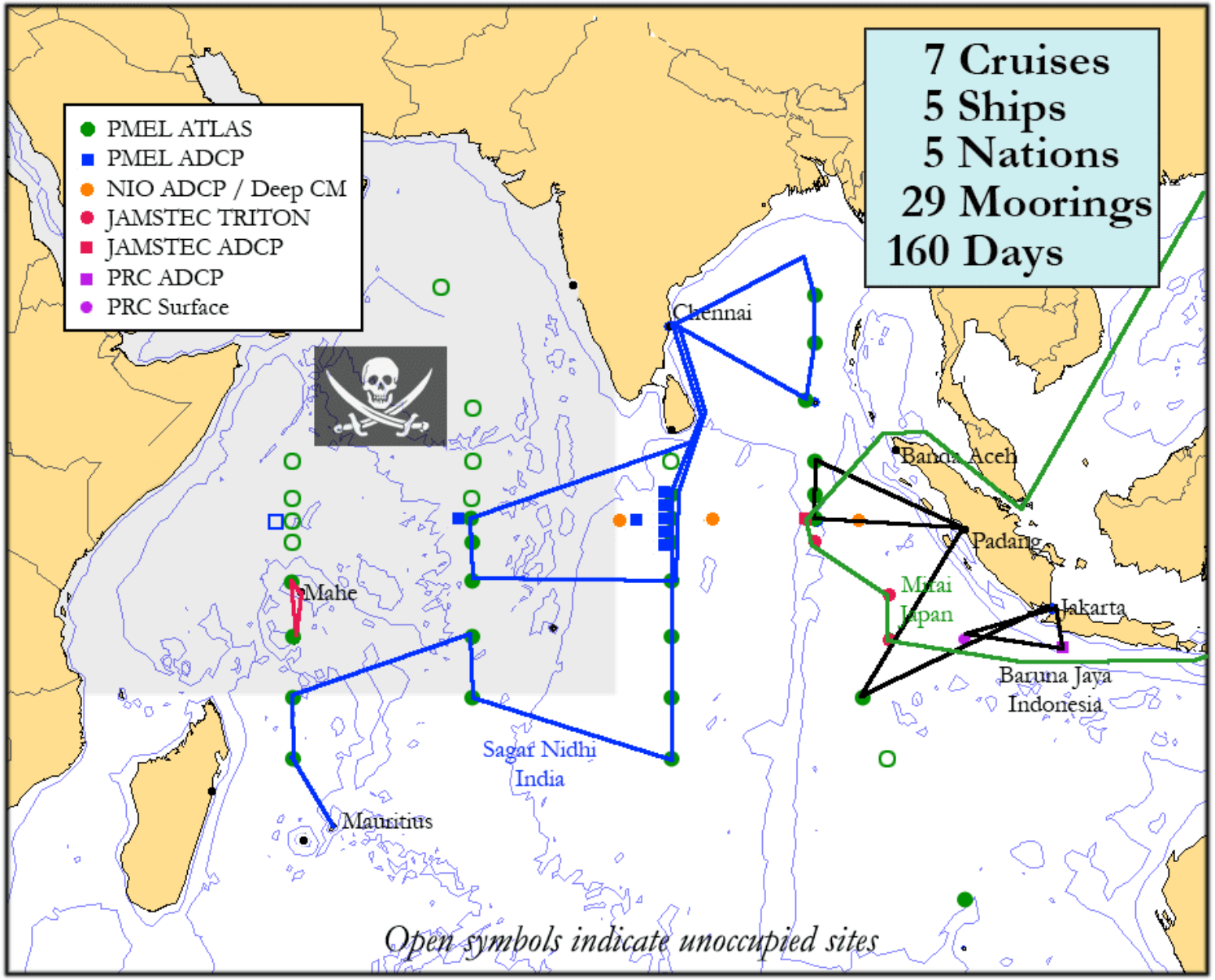


Review of IndOOS in 2017



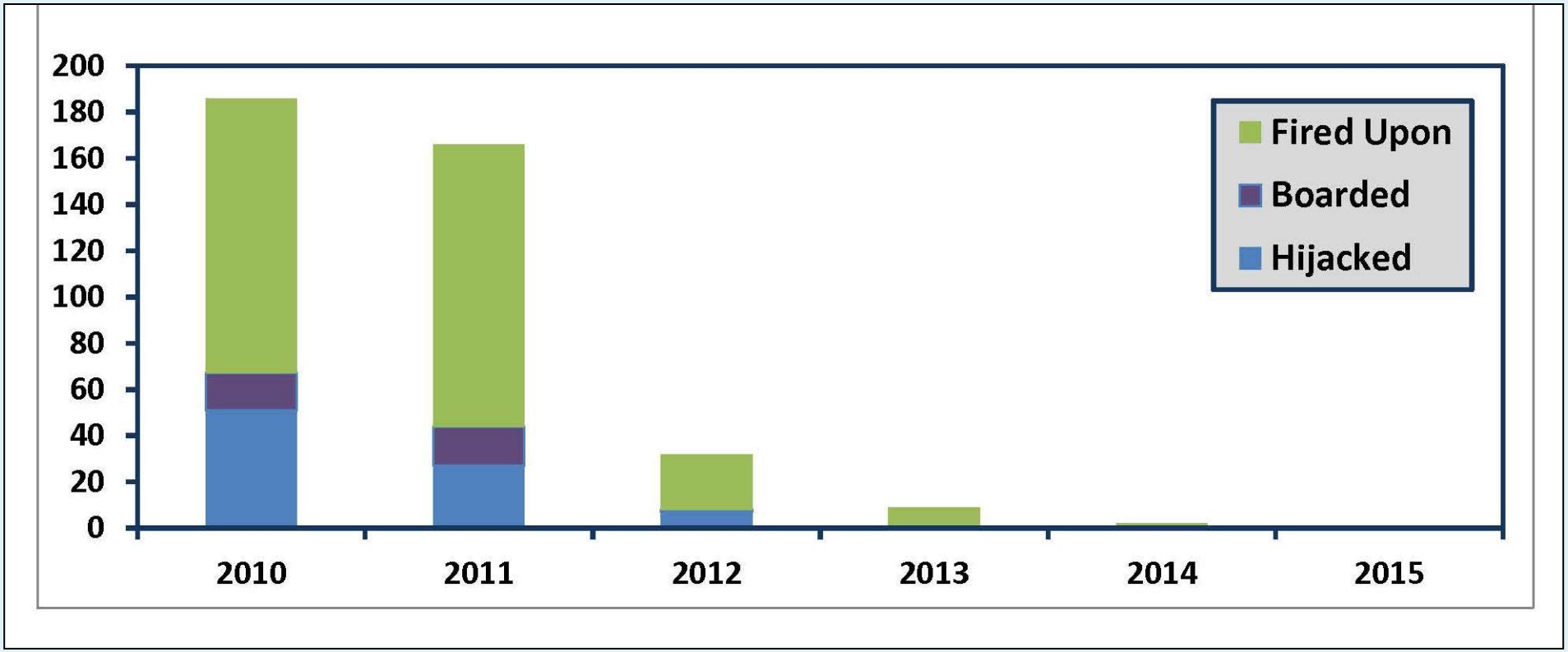
- Convened by CLIVAR/ GOOS Indian Ocean Panel (responsible for original design)
- Sponsored by CLIVAR, GOOS, IMBER, …
- Focus *in situ* components
- Adjust and enhance
- Introduce new technologies
- Expand multi-disciplinary measurements

Planned 2016 RAMA Cruises



Piracy on the Decline

Number of Indian Ocean Incidents



http://www.oni.navy.mil/Intelligence_Community/piracy.htm

Summary

Establishment of the Indian Ocean Observing system has enabled major advances in our understanding of the Indian Ocean's role climate variability and change in the past 10 years.

There is great potential for more *in situ* biogeochemical measurements as part of IndOOS

The next 5 years promise to be particularly exciting time for Indian Ocean research with the establishment of the Second International Indian Ocean Expedition (IIOE-2).