Iron limitation Patterns, IOD Impacts & Monsoon-Climate Connections in the Indian Ocean

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Acknowledgements: Mike Behrenfeld, Jim Christian, Birgit Gaye, Chris Measures, Nick Hardman-Mountford, Raleigh Hood, Chuck McClain, Raghu Murtugudde, Tim Rixen, Sharon Smith, Jerome Vialard, Anya Waite

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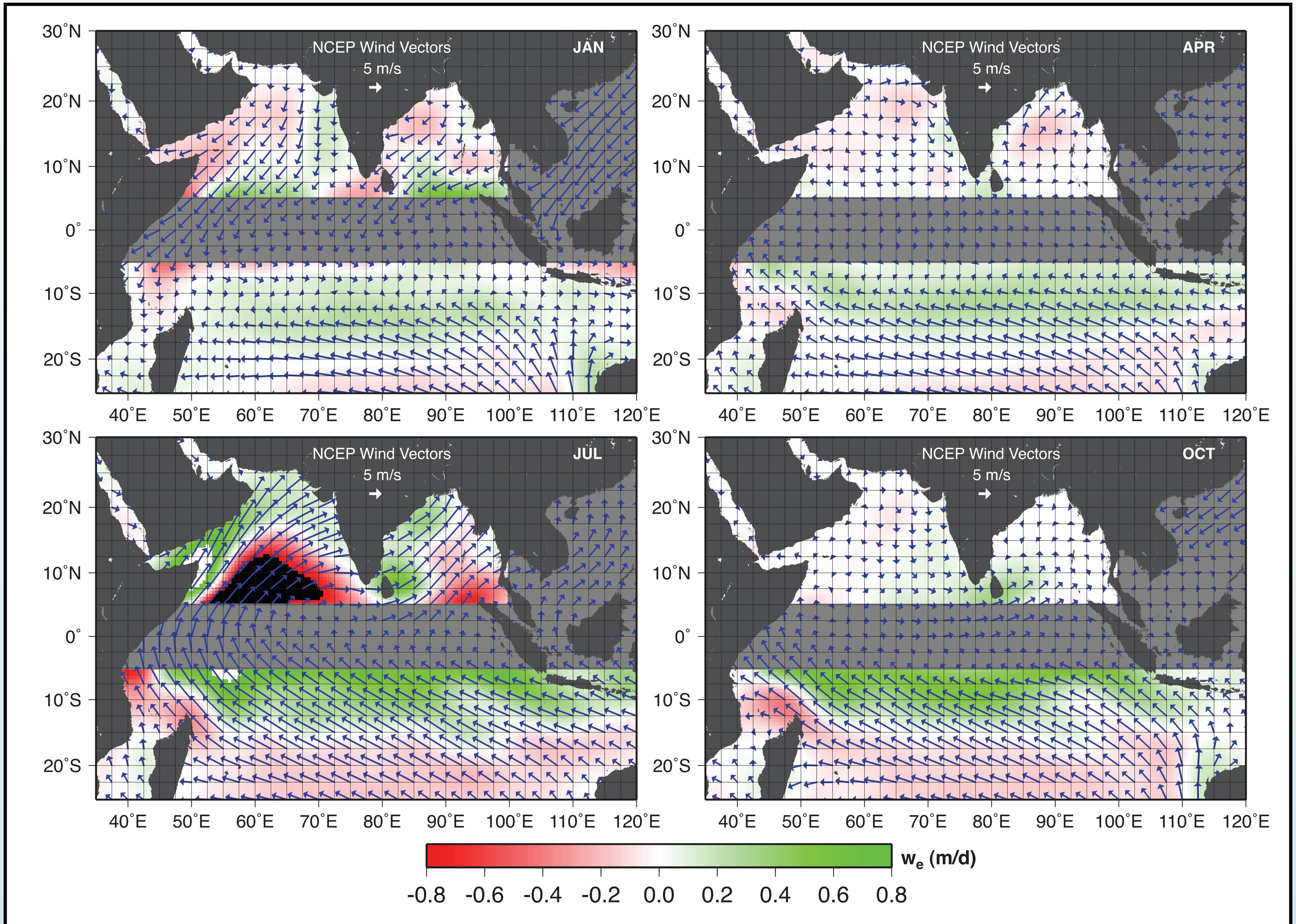
Outline

- Indian Ocean Forcing and Biological Response to Monsoon
- Iron Limitation Signatures in the Indian Ocean
- Impact of Indian Ocean Dipole on Patterns of Biogeochemical Variability
- Climate Signal in Summer Monsoon Intensity?
  - Long-term Trend or Decadal Variability?
  - Biogeochemical Implications?
- Broader Biogeochemical Implications of these Biophysical Processes?

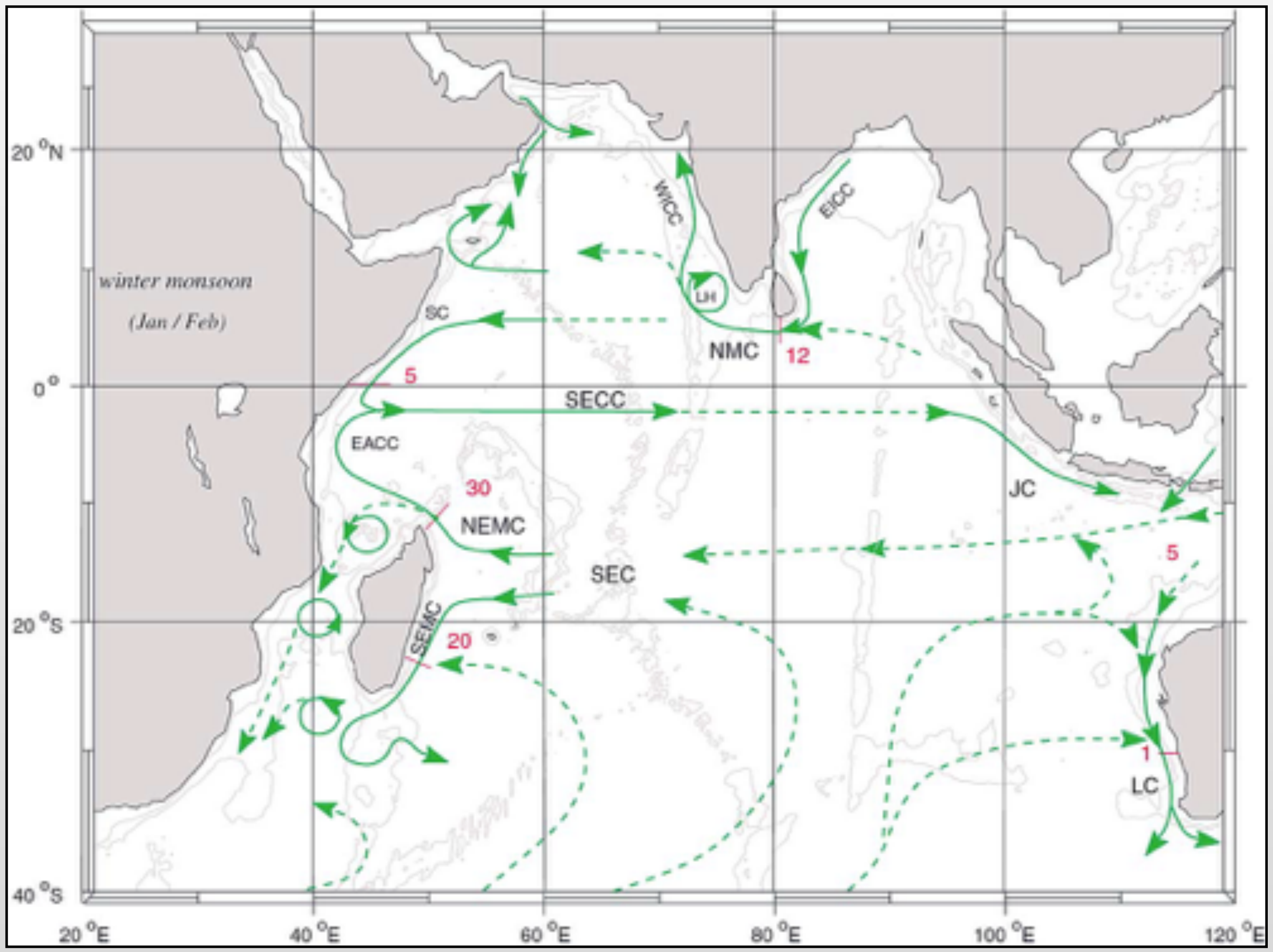
Indian Ocean Forcing & Biological Response

Monsoonal Forcing w/ Ekman Pumping
(NCEP Winds)

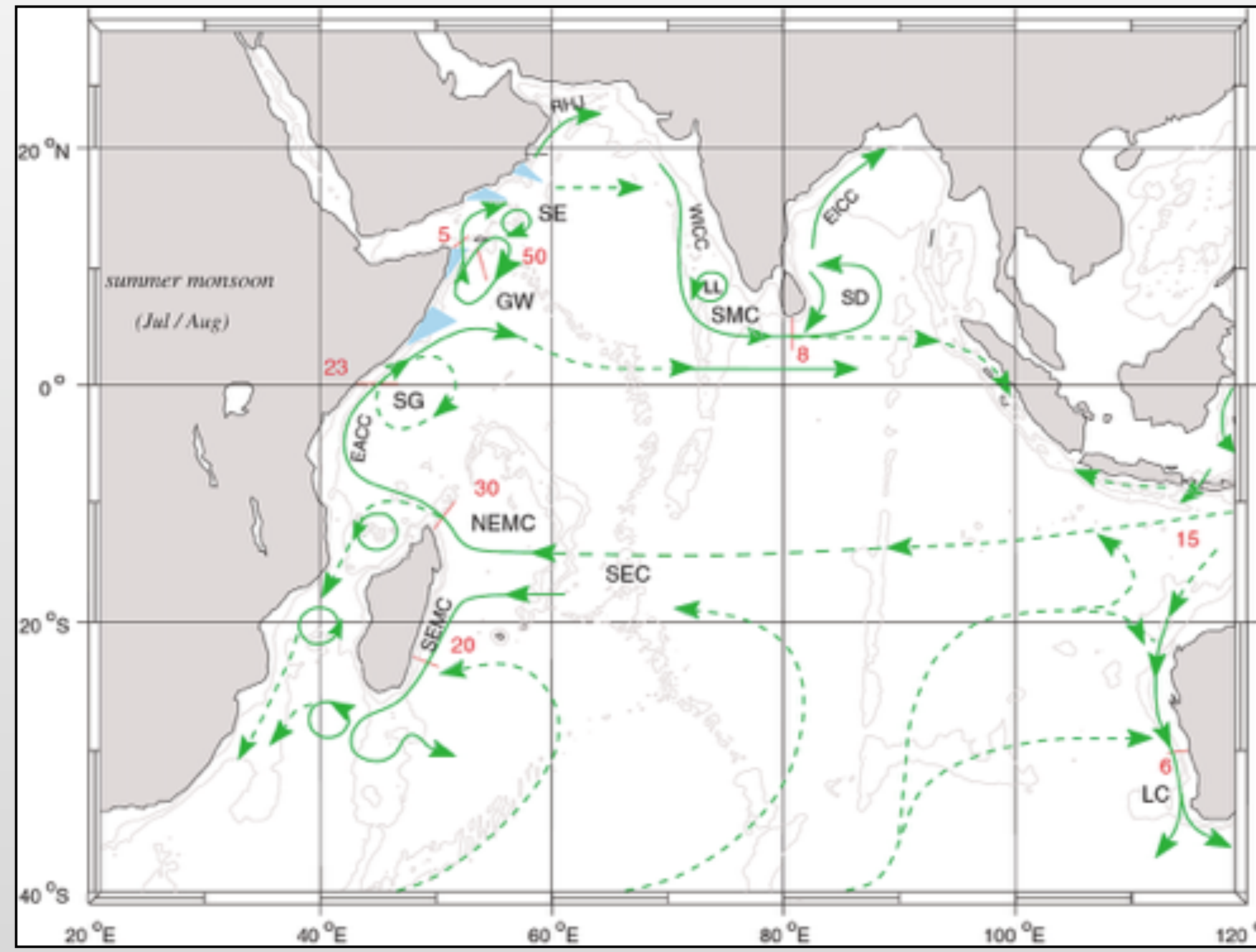


Major Ocean Currents in Indian Ocean

Winter Monsoon



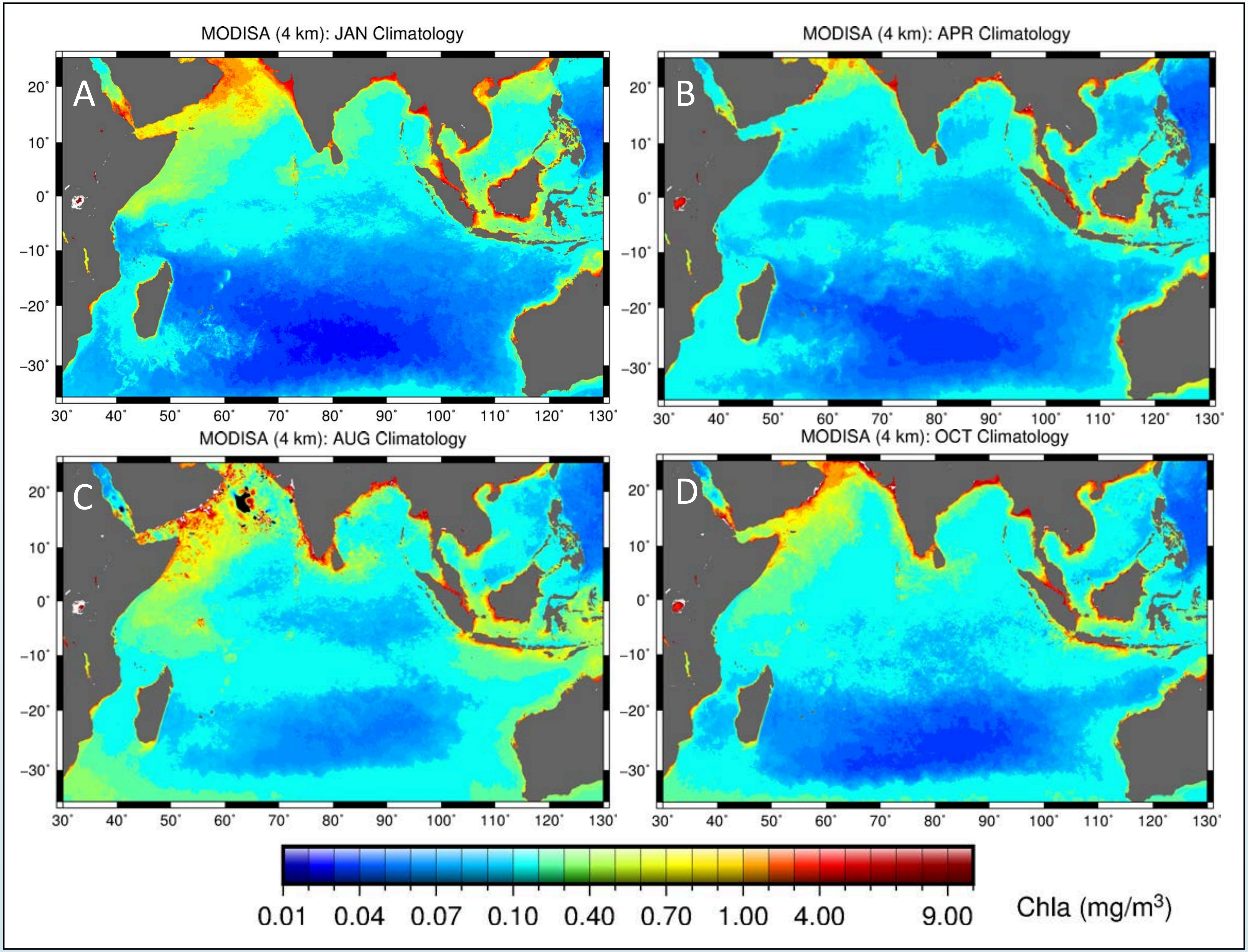
Summer Monsoon



- Major currents of the Northern Indian Ocean reverse semi-annually, due to monsoonal wind forcing

Schott and McCreary (2001), *Prog. Ocean.*, 51(1), 1-123.

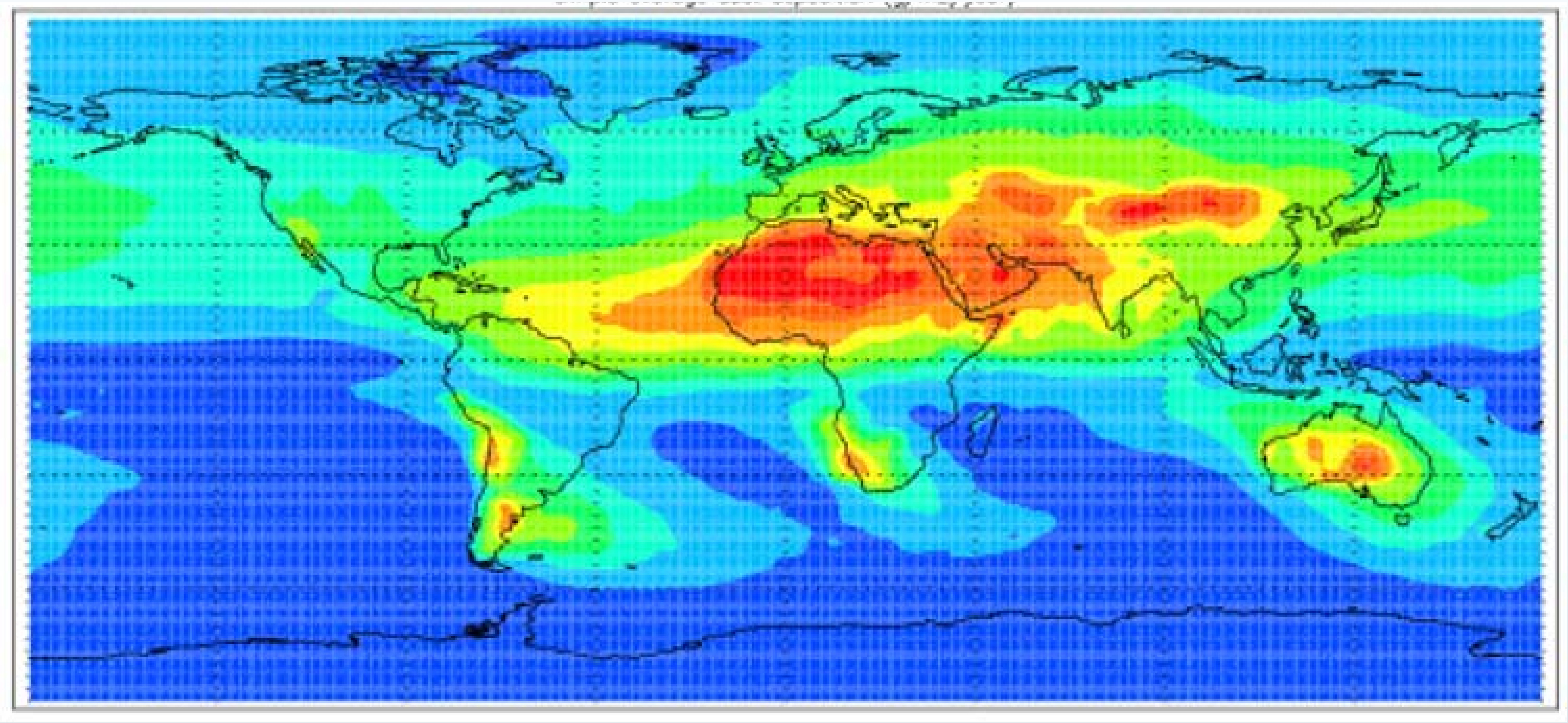
Climatological Surface Chl



Iron Limitation in the Indian Ocean

Global Desert Dust Deposition Patterns

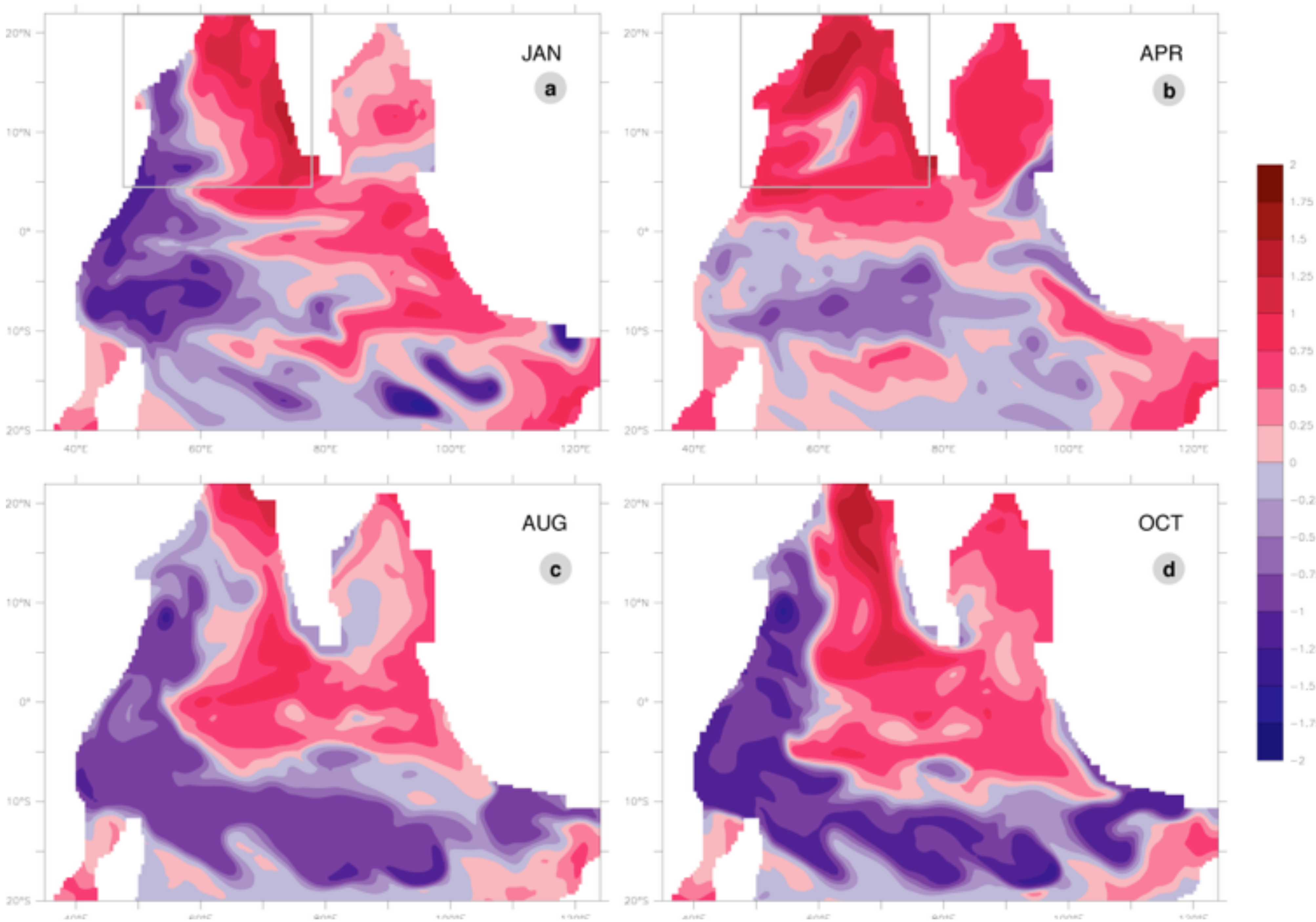
($g\ m^{-2}\ yr^{-1}$)



Arabian Sea JGOFS Planning Report - “Arabian Sea is Mother Nature’s Iron Experiment”

Mahowald et al., (2005), *Global Biogeochem. Cycles*, 19(4), doi:10.1029/2004GB002402.

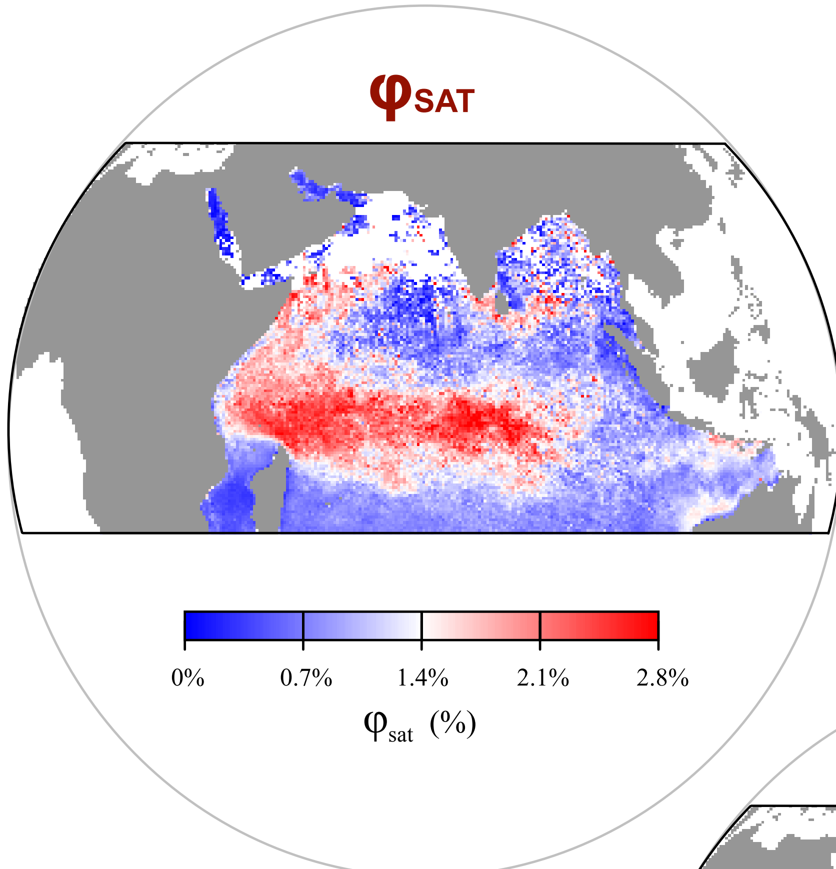
Bio-availability of Dissolved Iron

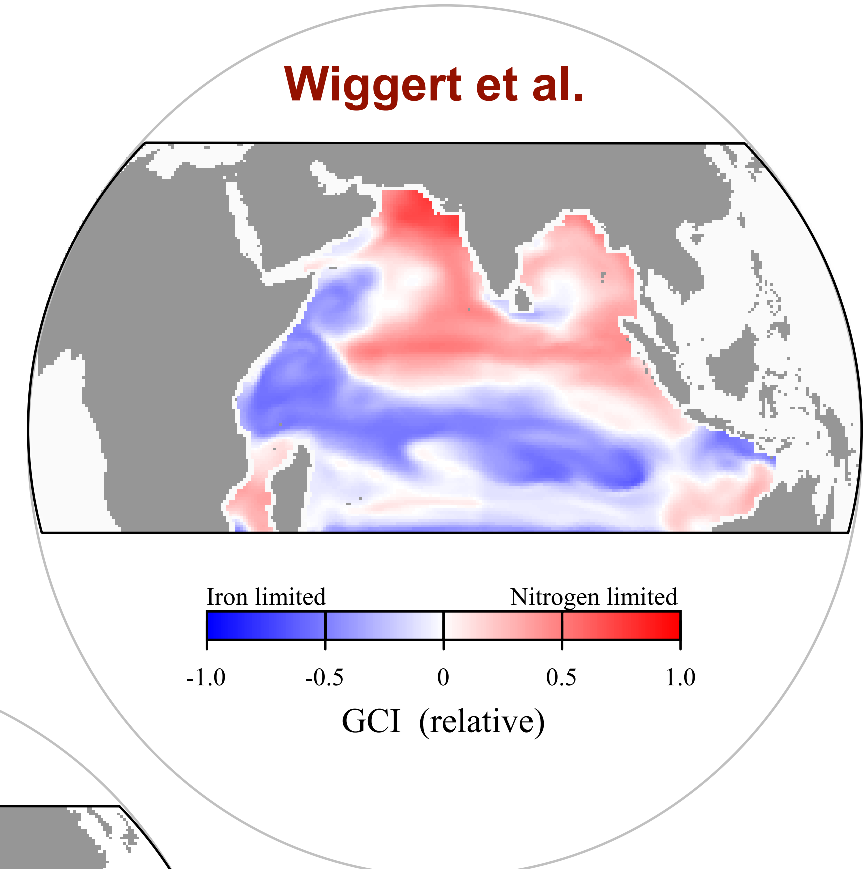


- Iron limitation develops w/ upwelling of higher N:Fe waters and/or lack of nearby terrigenous sources
- Western Arabian Sea exhibits pronounced seasonal variation
- Bay of Bengal is iron replete except for Sri Lanka Dome during SWM
- Southern Tropics primarily iron limited
- Western Equatorial Band always iron limited

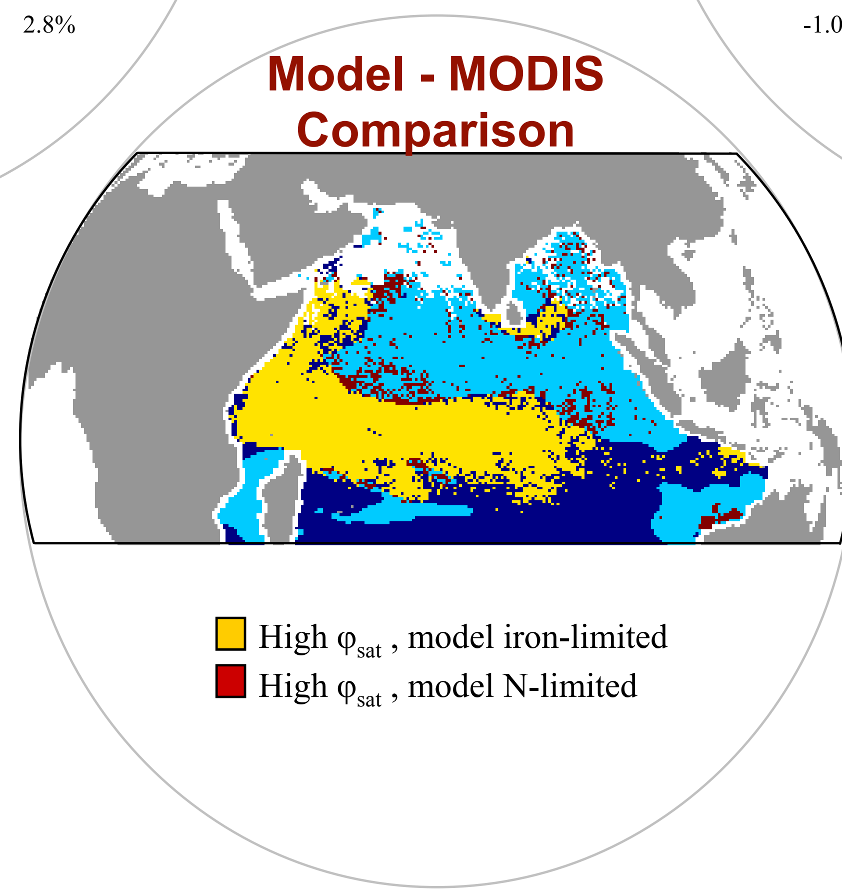
Wiggert et al., (2006), *Deep-Sea Res. II.*, 53(5-7), 644-676.

MODIS-Based Phytoplankton Fluorescence (φ_{SAT}) & Ocean GCM Iron Limitation Distributions (JUN-AUG)

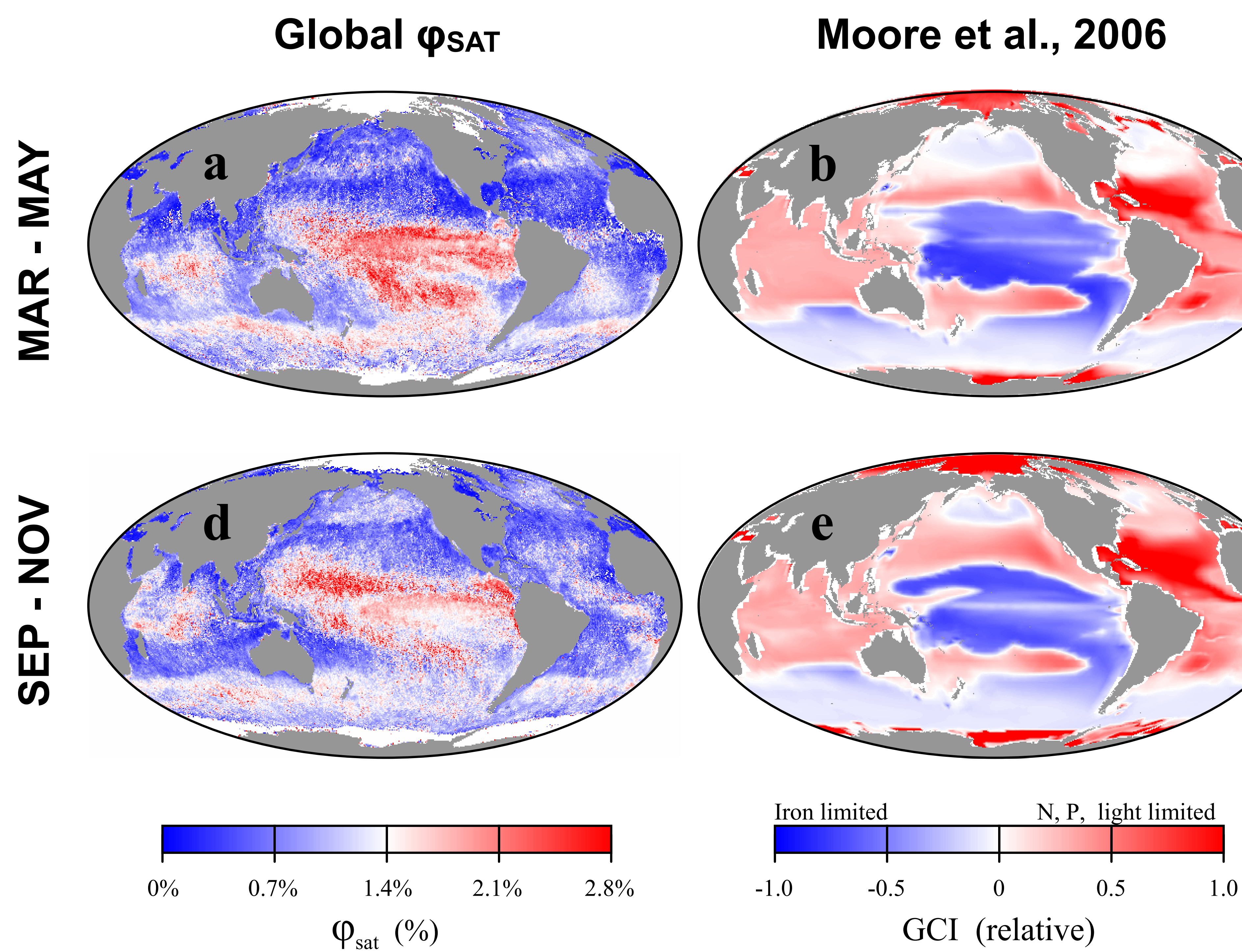




φ_{SAT} > 1.4% -> Nutrient Stress

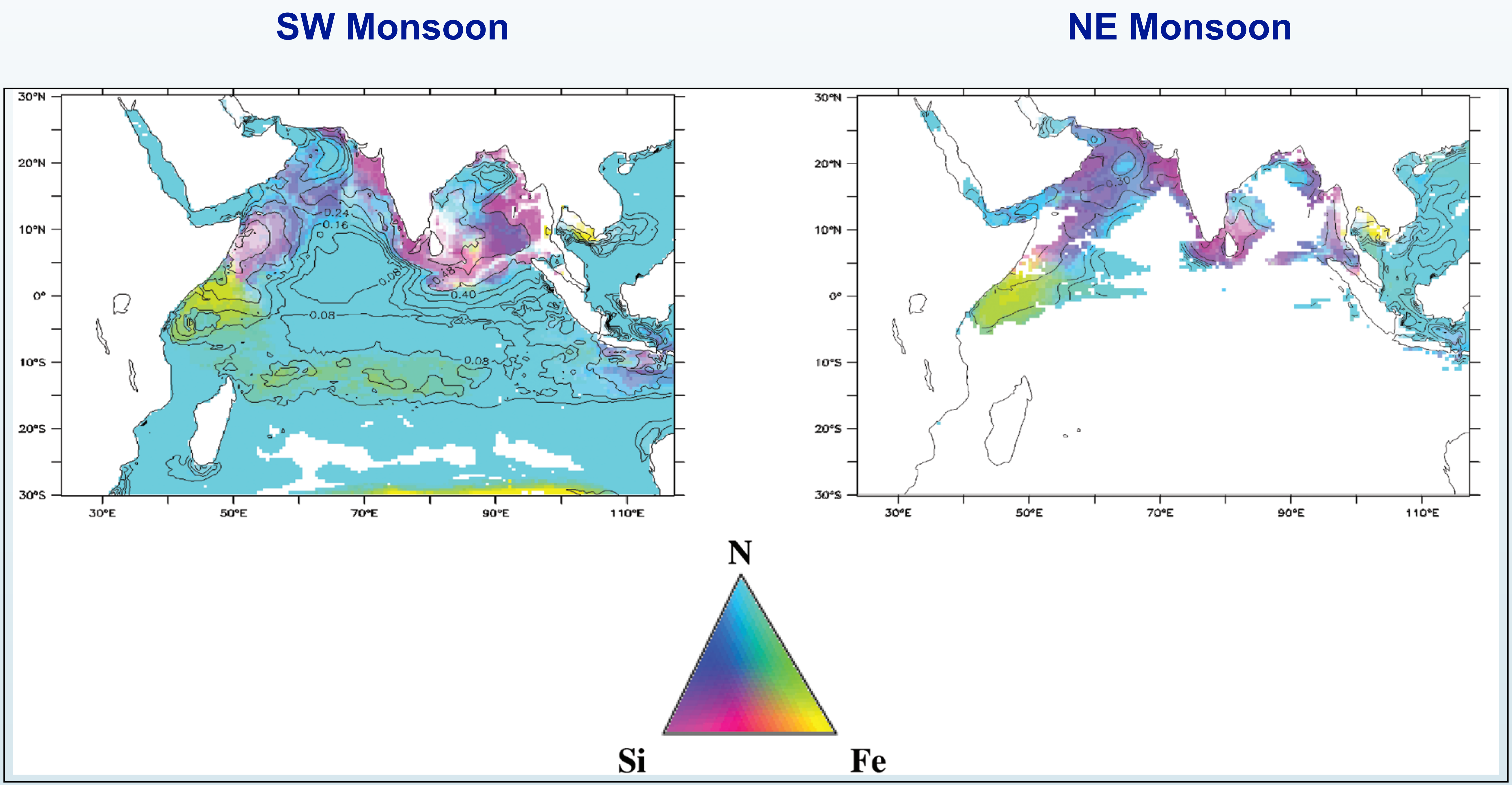


MODIS-Based Phytoplankton Fluorescence (φ_{SAT}) & Ocean GCM Iron Limitation Distributions



Moore et al., (2006), *Tellus, 58(5), 560-572.*

Nutrient co-Limitation (Diatoms) from PISCES Model



Koné et al., (2009), AGU Monograph 185.

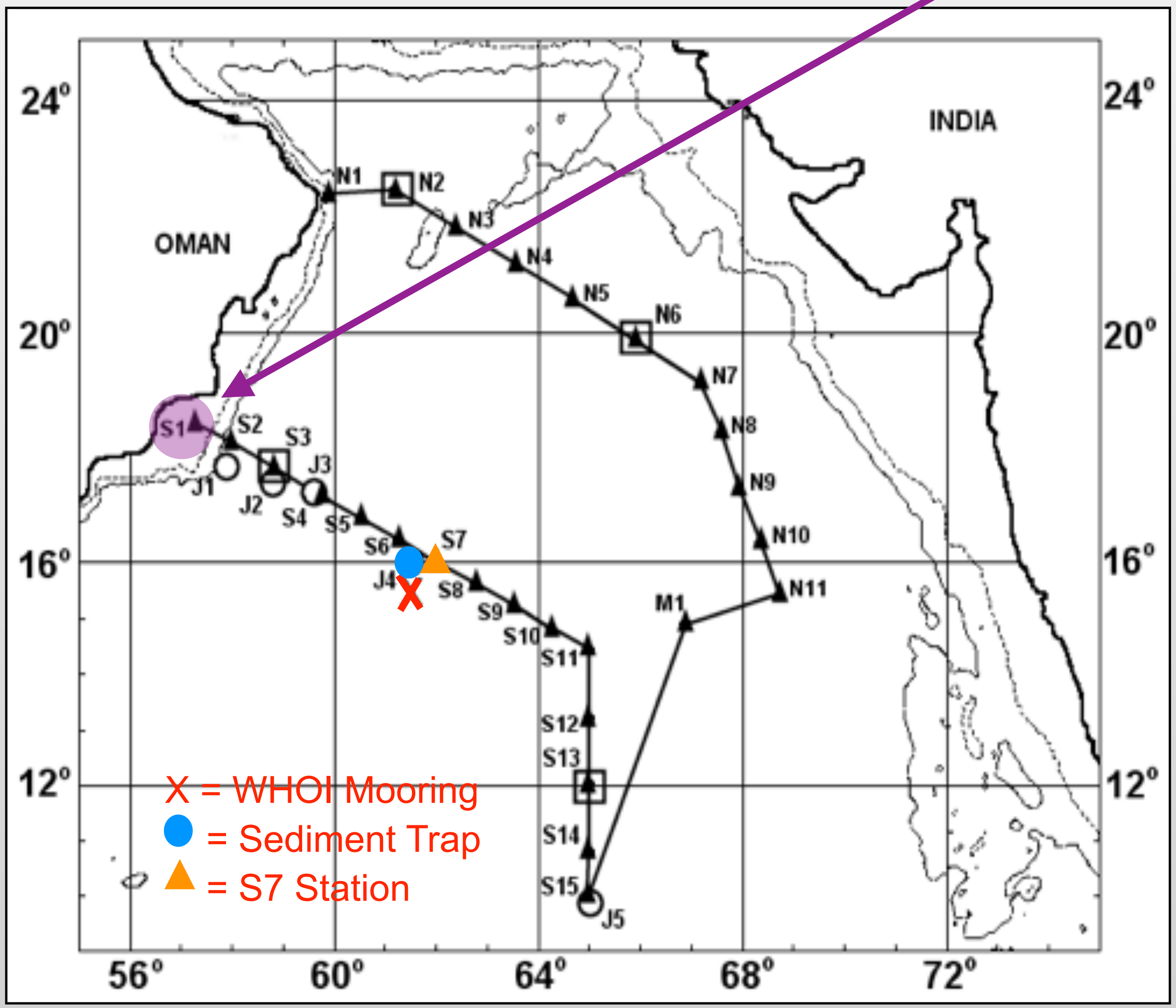
Model Guidance on Arabian Sea Iron Limitation

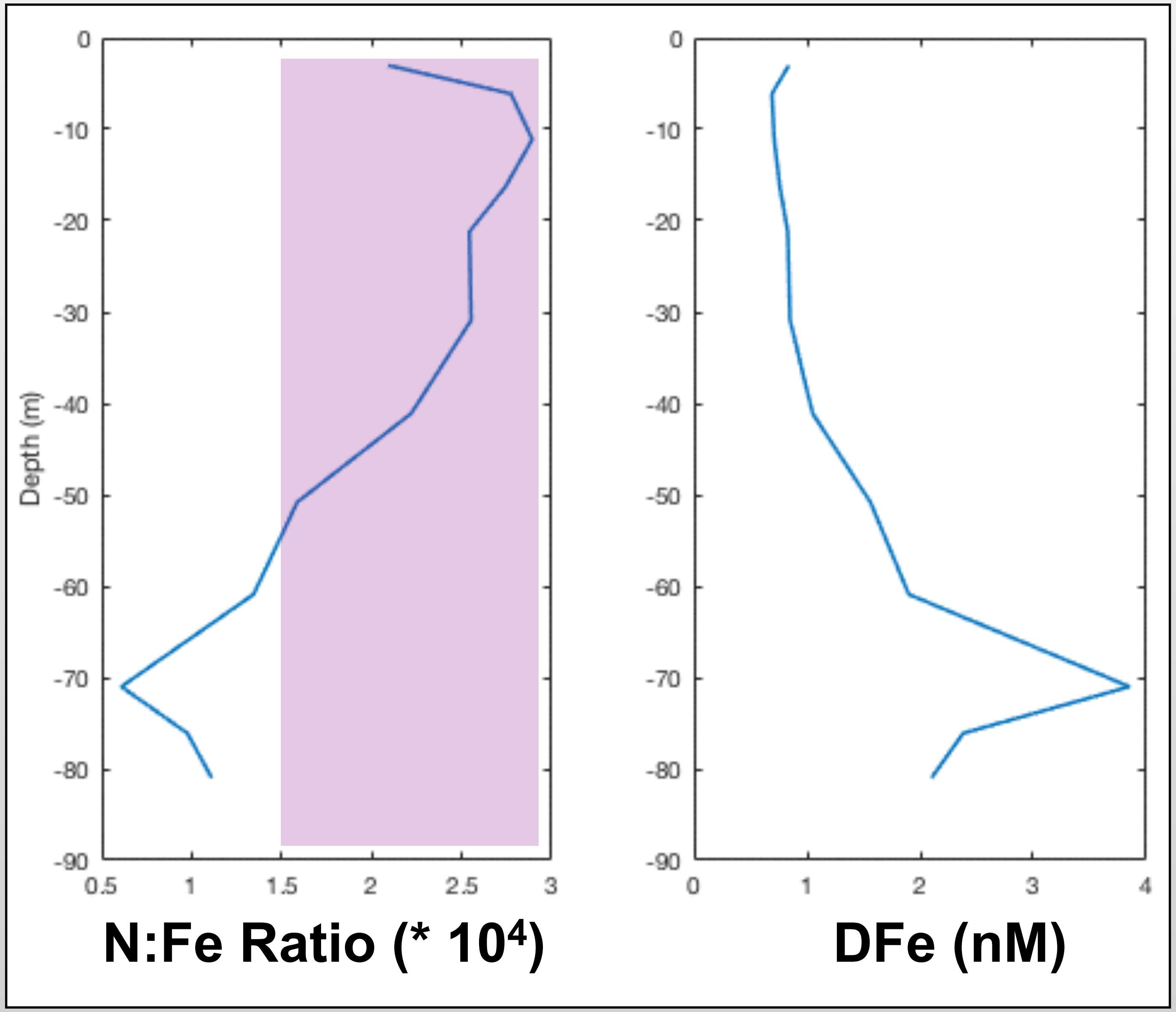
- Wiggert et al. 2006
  - 2 Photo (Large, Small)
  - Tracked Nutrients / Micro-nutrients
    - NO3, NH4, Fe
  - Western Arabian Sea exhibits Fe limitation, particularly during summer monsoon upwelling off Oman; Iron replete during SIM
- Moore et al., 2006
  - 2 Phytoplankton (Large, Small), 1 Diazotroph
  - Tracked Nutrients / Micro-nutrients
    - NO3, NH4, Fe, P, Si
  - Western Arabian Sea primarily N-limited, also some light, P (DIAZ) and Si limitation
- Kone et al., 2009
  - 2 Phytoplankton (Large, Small)
  - Tracked Nutrients / Micro-nutrients
    - NO3, NH4, Fe, P, Si
  - Western Arabian Sea shows a mix of Si, N and Fe limitation. Omani upwelling Si - N co-limited; Somalia (Great Whirl) Si - Fe co-limited

Observation Guidance on Arabian Sea Iron Limitation

- Arabian Peninsula Upwelling Site
- ASPS Iron Data: S1 - TN050

JGOFS Arabian Sea Process Study Stations

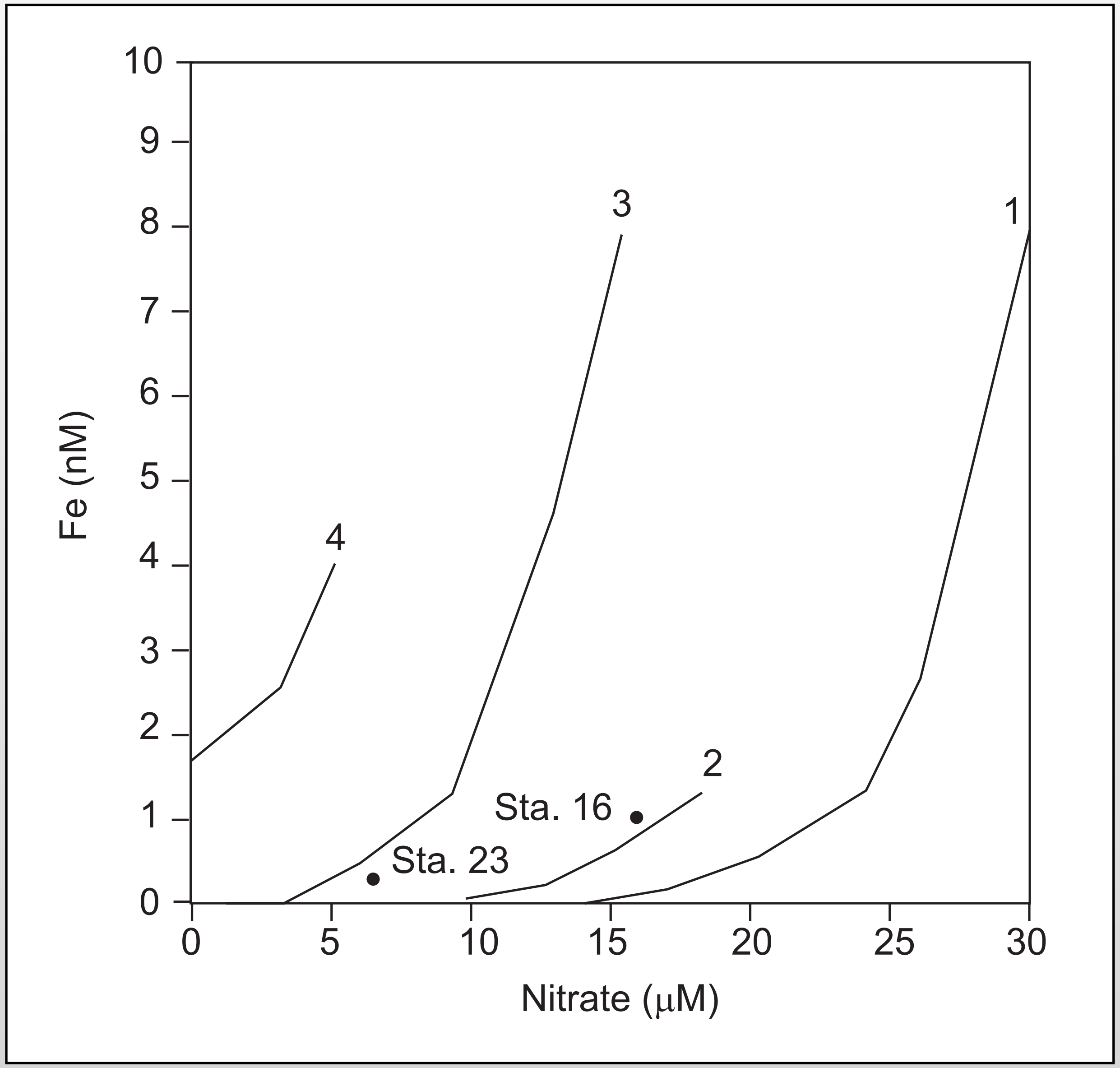




N:Fe > 15,000 → Prone to Fe Limitation (Measures and Vink, (1999), DSR-II, 46(8-9), 1597-1622.)

TN050 is late SWM Cruise

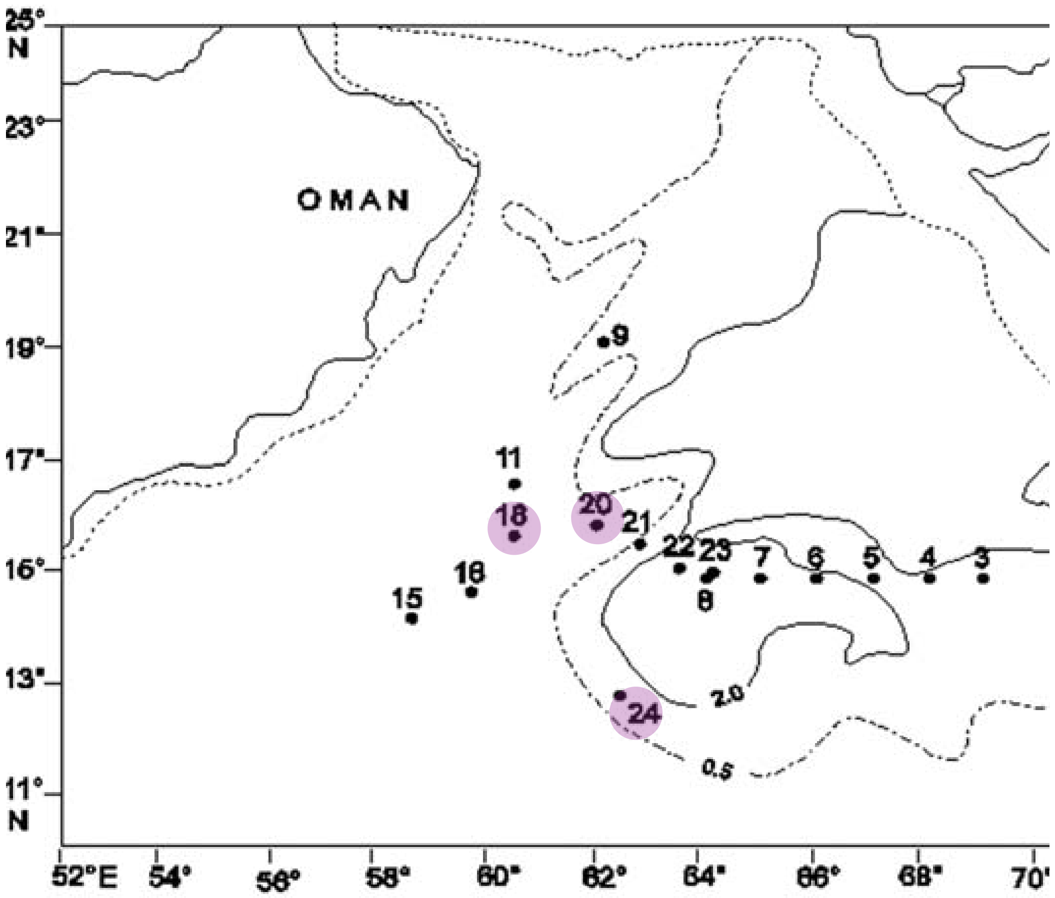
Observation Guidance on Arabian Sea Iron Limitation



- Curves 1-4 are nutrient draw-down experiment results from Bruland et al., 2001 for coastal waters in California upwelling system
  - Cases 1 - 3 represent eventual Fe limitation
- Sta 16 (near S1) and Sta 23 (near S9) data points from Arabian Sea suggest similar tendency toward Fe limitation

Naqvi et al., (2010), *Biogeosci.*, 7(7), 10.5194/bg-7-2091-2010, 2091-2100.

Observation Guidance on Arabian Sea Iron Limitation



Station	Date	Lat(N)	Lon(E)	[Fe] (pmol L^{-1})	ILI
8	29 Aug 2007	15.00	64.00	165	4.0
10	3 Sep 2007	17.83	61.21	377	1.3
12	5 Sep 2007	16.21	59.68	440	3.7
12 mol L^{-1}	5 Sep 2007	15.88	59.47	238	2.4
13	6 Sep 2007	15.00	58.65	205	4.3
14	6 Sep 2007	14.29	57.54	242	1.4
15	7 Sep 2007	14.26	58.67	60	2.8
16	8 Sep 2007	14.74	59.76	179	3.2
17	9 Sep 2007	15.75	60.23	280	6.0
18	10 Sep 2007	16.75	60.50	229	0.9
19	10 Sep 2007	16.43	61.25	213	1.5
20	10 Sep 2007	16.00	62.00	288	0.4
22	11 Sep 2007	15.20	63.50	522	1.5
23/8R	12 Sep 2007	15.00	64.00	192	2.5
24	13 Sep 2007	13.13	62.60	150	1.1

Data marked with * were within a low temperature filament.

- Iron limitation index (ILI) = 1.0 indicates no difference realized in iron amended experiments. As ILI exceeds 1.0, progressively greater degree of Fe limitation is indicated (Firme et al., 2003)
- Locations with ILI ≤ 1.3 are highlighted
- Of 15 stations reported in table, 4 have ILI ≤ 1.3
- Cruise time frame is late SW Monsoon

Moffett et al., (2015), *Limnol. Oceanogr.,* 60(5), 10.1002/lno.10132, 1671-1688.

Iron Limitation Summary

- Models disagree on whether iron limitation plays a role in nature of primary production in the Arabian Sea
  - Mechanism that operates in the Wiggert et al. model is N:Fe ratio in upwelled coastal waters that is > 15,000 (i.e., prone to Fe limitation)
  - Models that include broader set of nutrients suggest complex co-limitation patterns among N, Fe, Si, P
- Observational evidence is growing that during the summertime, waters upwelled in the western Arabian Sea and within offshore propagating filaments are inherently prone to Fe limitation

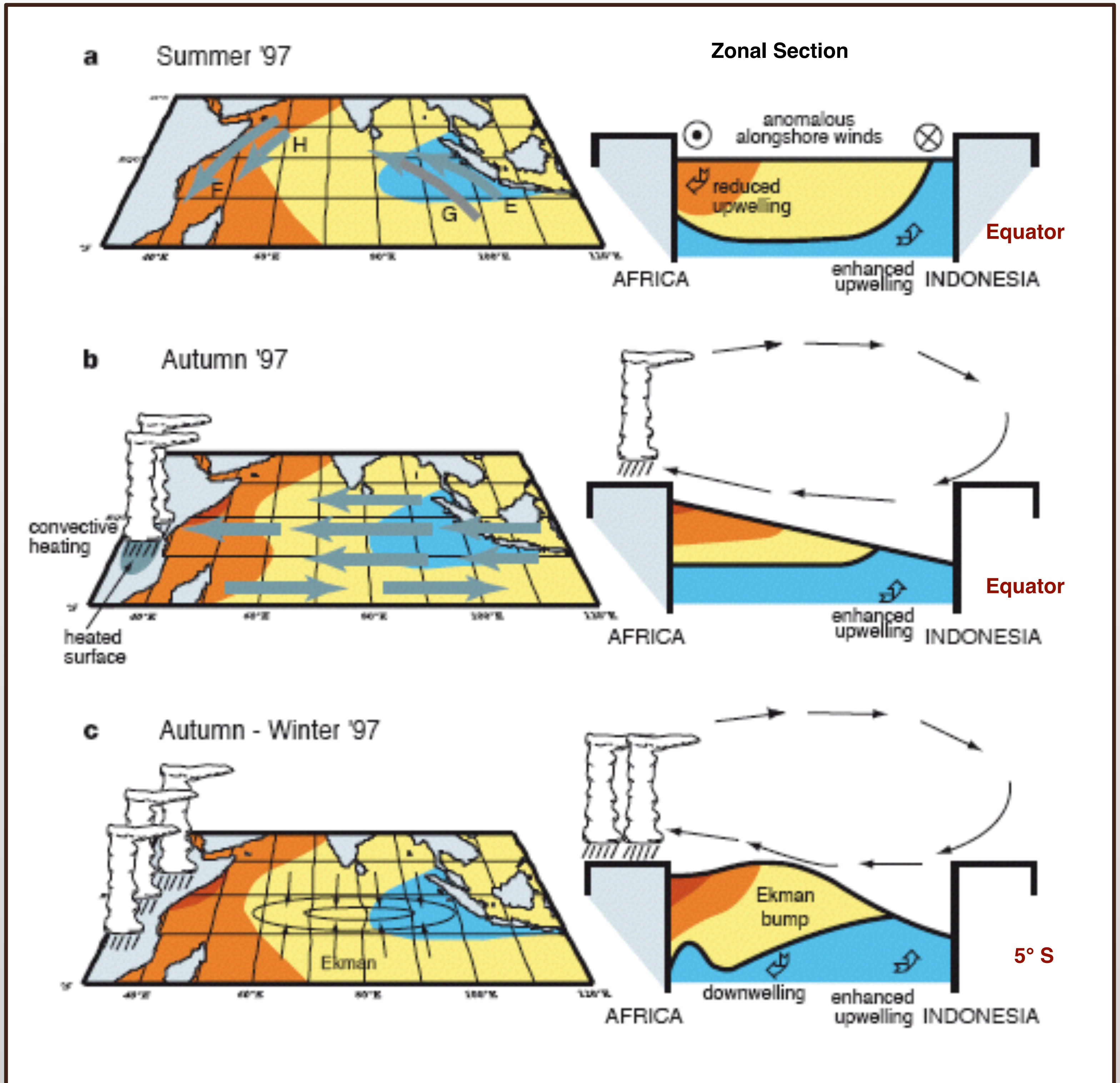
- This despite:
  - Heavy dust deposition loadings
  - Benthic remineralization in near-coast waters
  - Open ocean OMZ, with elevated DFe conditions

Iron Limitation Summary

- Models disagree on whether iron limitation plays a role in nature of primary production in the Western Indian Ocean and Southern Tropical Indian Ocean (STIO)
  - Wiggert model indicates year-round iron limited conditions
  - Behrenfeld MODIS (FLH) - based φ_{SAT} results indicate nutrient stress over a spatial domain during JUN - AUG time frame that is remarkably consistent with Wiggert model
  - Moore model does not indicate a nutrient limitation condition
  - Koné model (SWM Period) indicates Fe limitation off African coast; Fe - N co-limitation across the STIO
  - Koné model (NEM Period) indicates Fe limitation off African coast; No limitation across the STIO

Indian Ocean Dipole (IOD) Impacts on Basinwide Biogeochemical Processes

Indian Ocean Dipole (IOD)

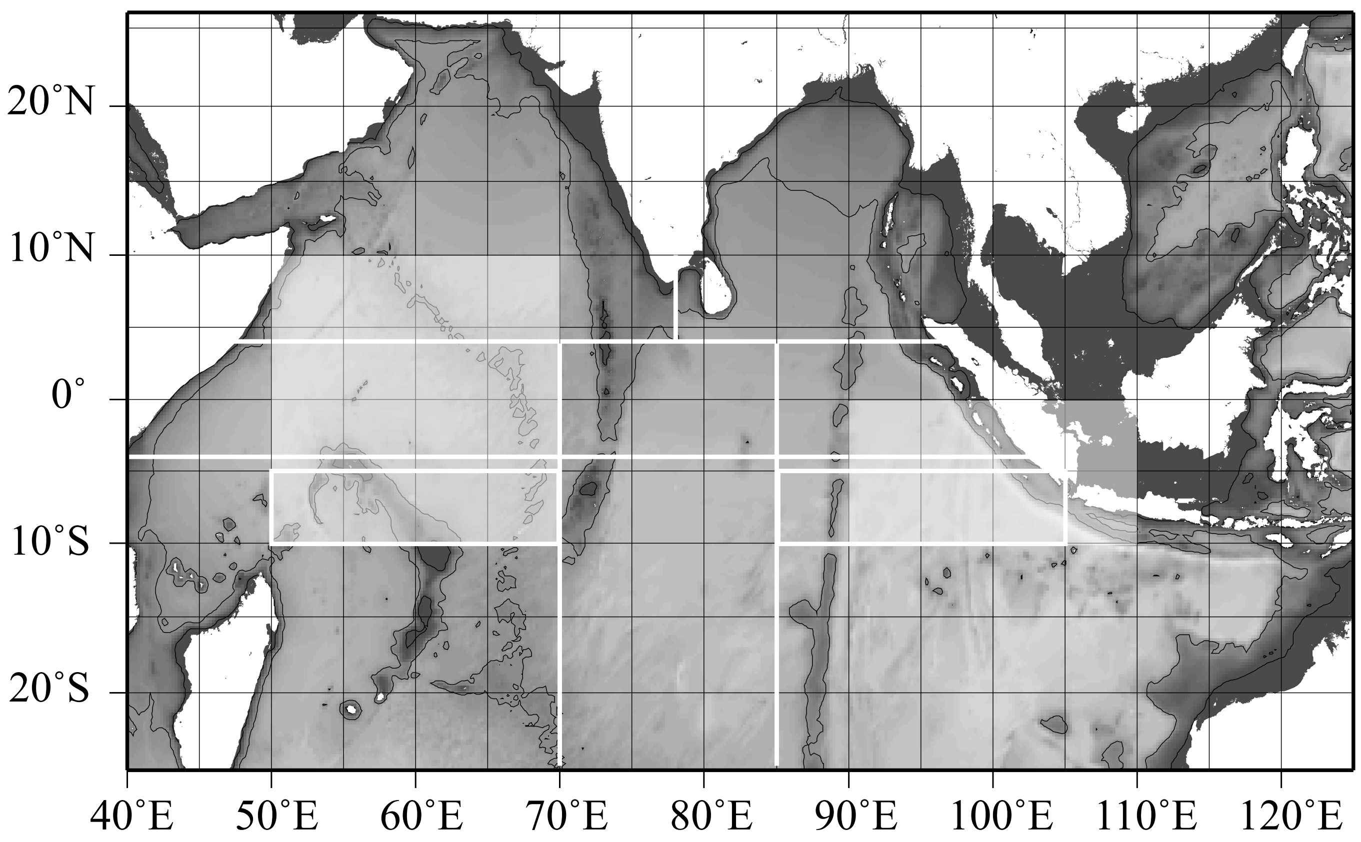


- Anomalous coastal winds drive upwelling in the east and reduces upwelling in the west (climatological: E, F; IOD: G, H)
- Anomalous convection over eastern Africa -> Anomalous equatorial easterlies & reduced/absent fall Wyrtki Jet
- Anomalously deepened thermocline along 5° S in the west

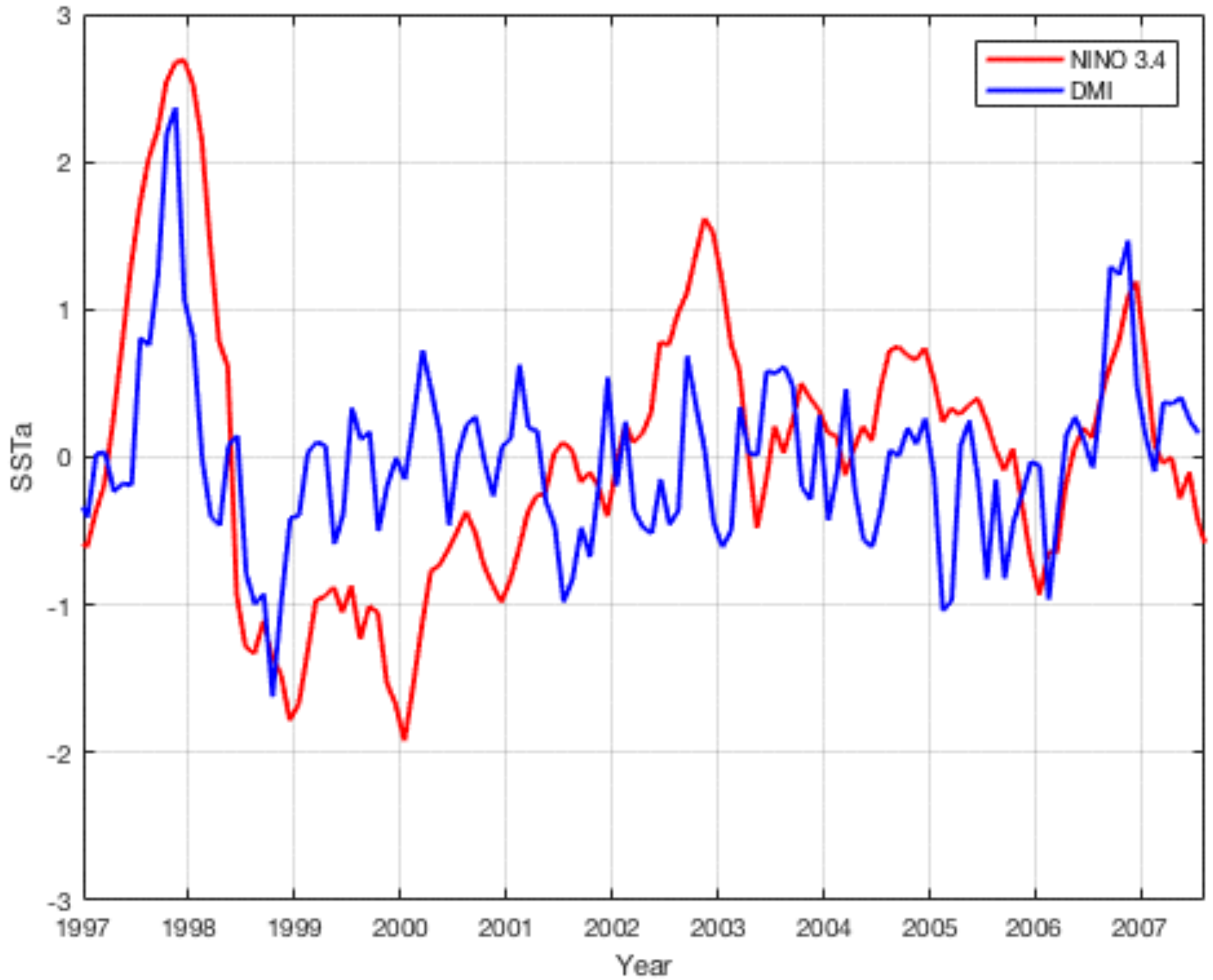
Webster et al., (1999), *Nature,* 401(6751), 356-360.

Regional Definitions and DMI Definition

Indian Ocean Bathymetry (NGDC)



DMI & NINO 3.4 during SeaWiFS Era



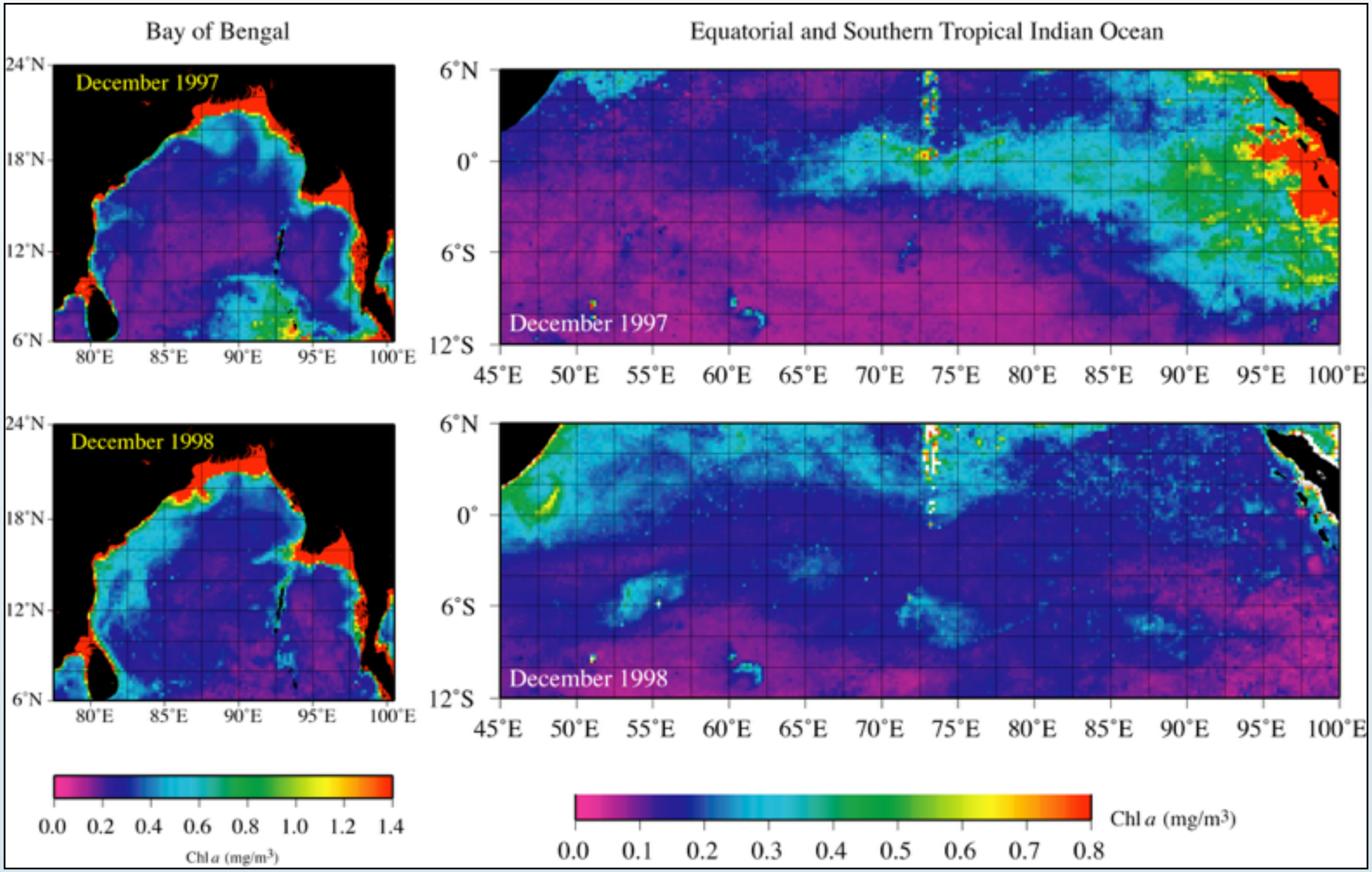
- White lines depict regional boundaries for Arabian Sea, Bay of Bengal, W/E Equatorial Band, W/E STIO, W/E SCTR
- Opaque regions demark areas used to calculate DMI
- In general, + IOD correlates with El Niño
- During SeaWiFS era, two + IODs occur (97/98, 06/07)
- Over the course of this time series, frequency of notable IOD events indicated in historical record (~2/decade) bears out over 10+ years shown here

Chlorophyll Response to IOD in Eastern IO

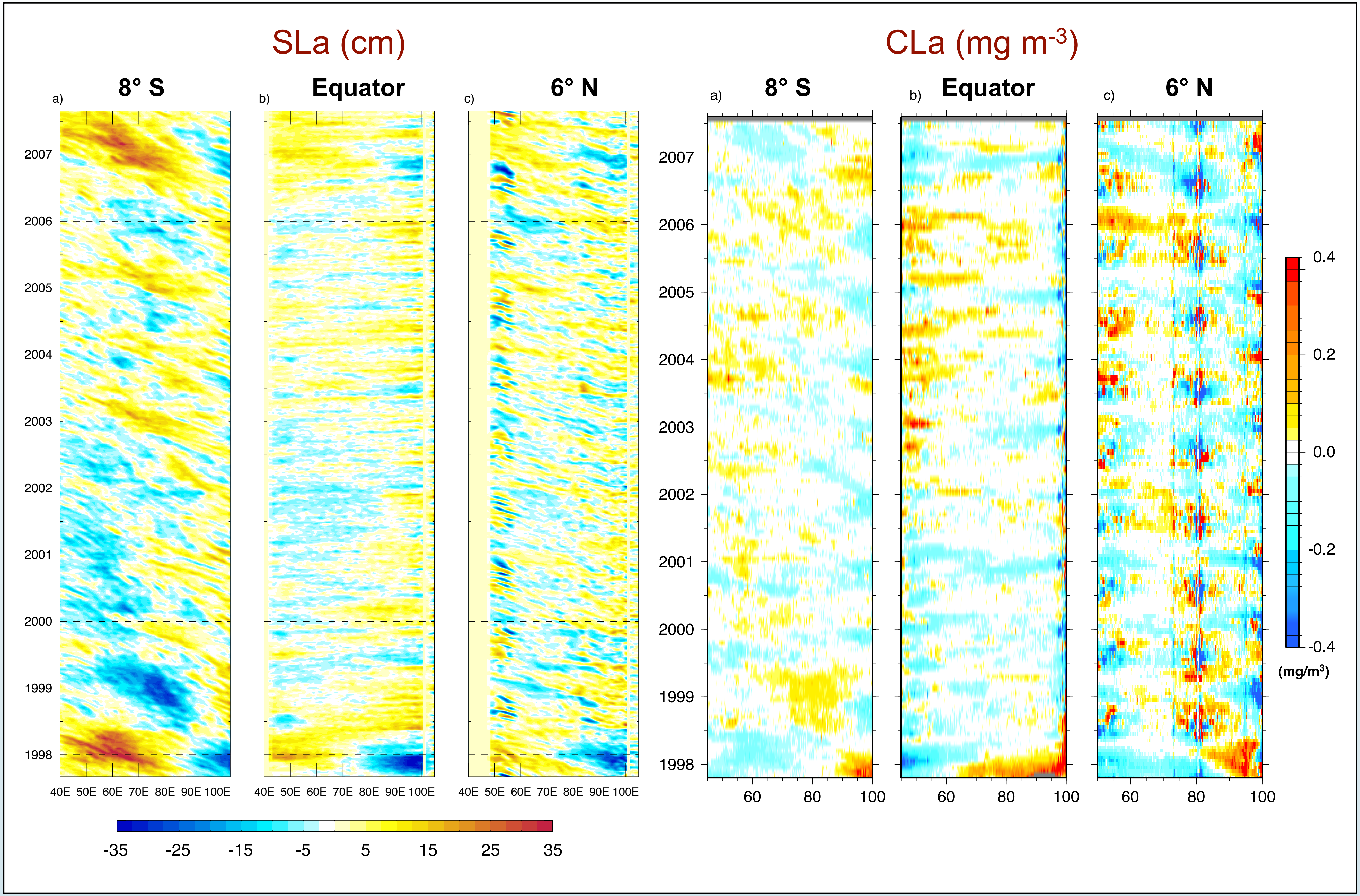
Dec (NE Monsoon)

IOD

Typical

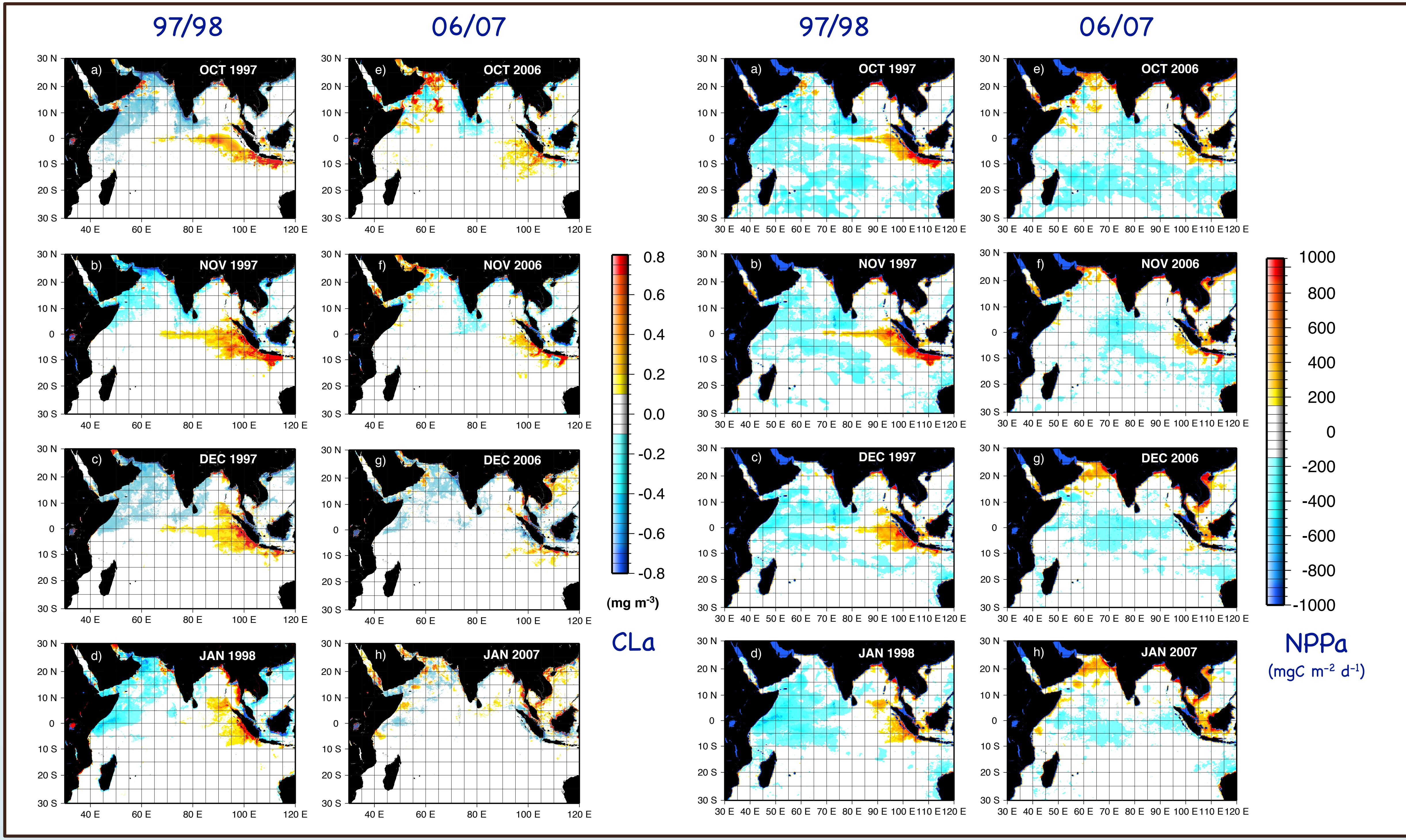


Sea Level & Chlorophyll Anomaly



Wiggert et al., (2009), AGU Monograph 185.

Monthly Biological & Carbon Flux Anomaly



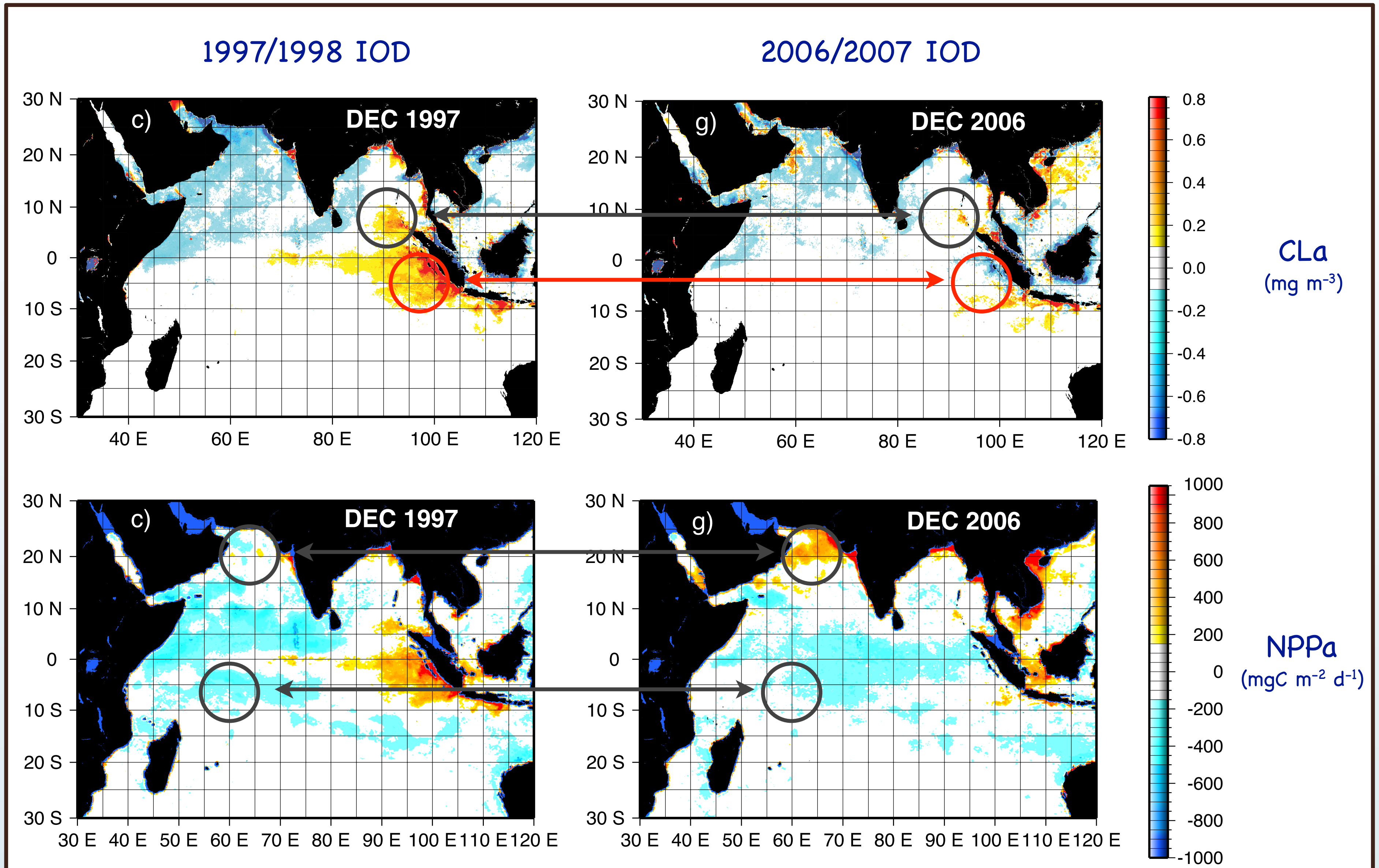
- Broadly consistent but less prominent CLa signatures during 06/07 event (eEQ, AS, sBB)
- CLa prominent into Jan '98 but largely dissipated in Jan '06

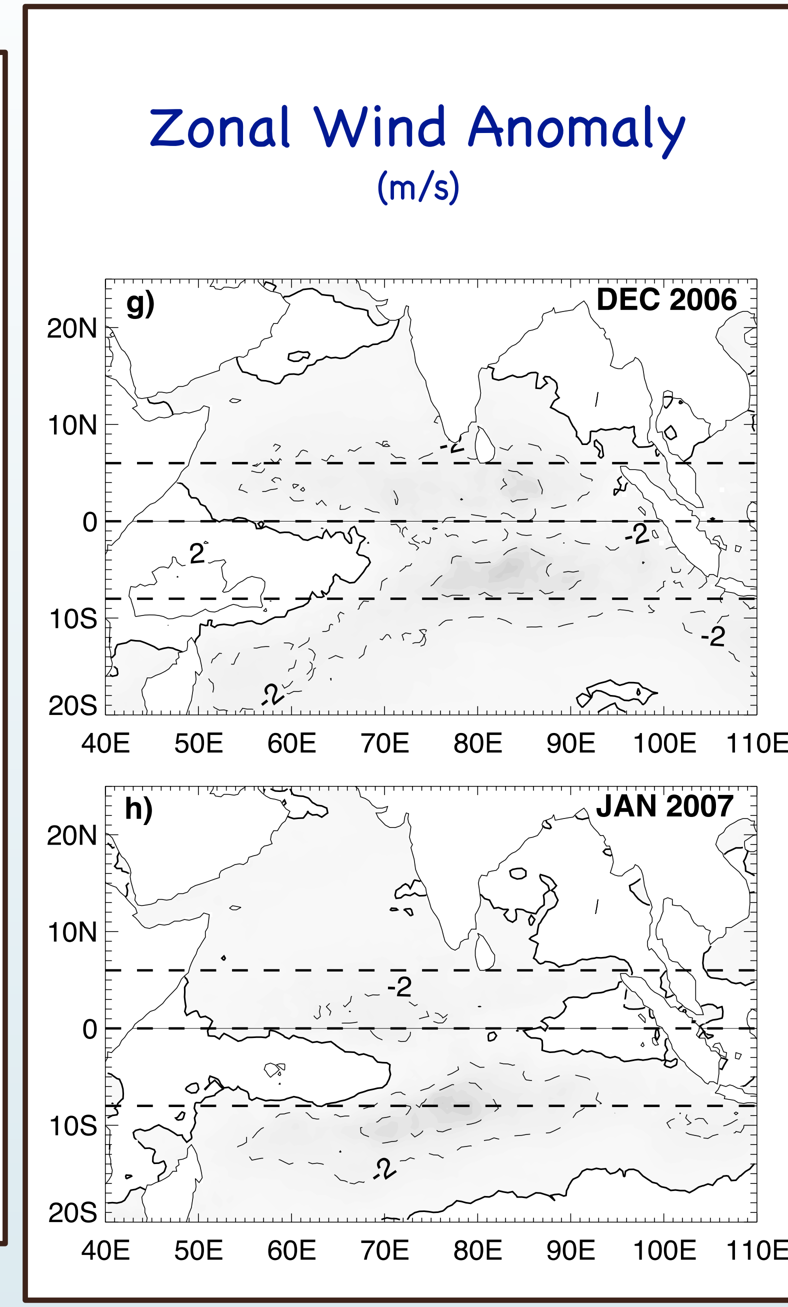
- NPPa calculated from CBPM-based NPP distributions (Behrenfeld et al., 2005)

- Generally, +/- NPPa coincides w/ +/- CLa

Wiggert et al., (2009), AGU Monograph 185.

IOD Comparison Highlights Mechanisms
Equatorial IO



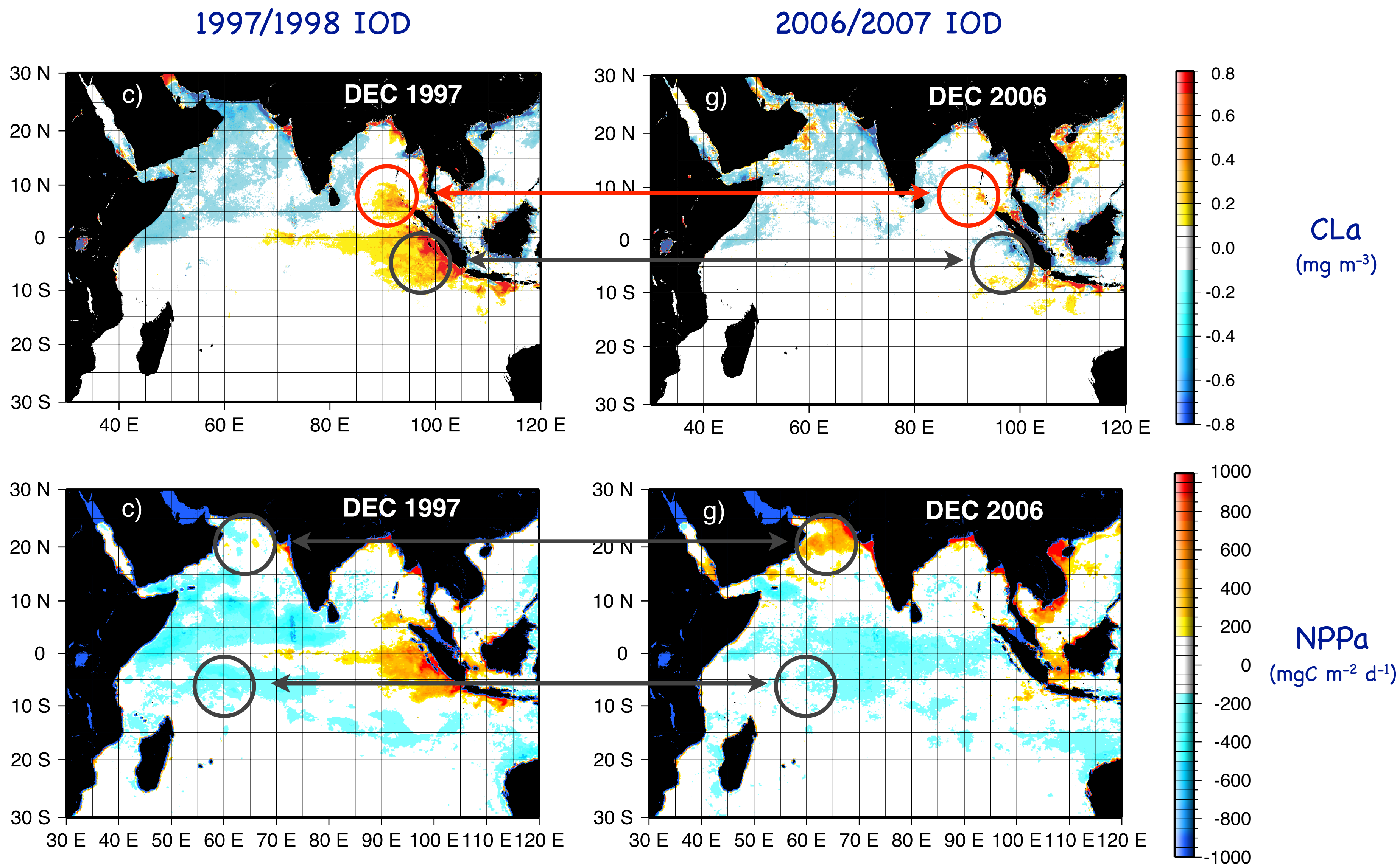


- The 97/98 biological response is pronounced +CLa and +NPPa; These result from persistent, anomalous upwelling winds offshore of Indonesia and weak or absent Wyrtki Jet impingement in Fall '97, both of which promote nutrient enrichment of surface waters
- Clear difference in magnitude & spatial extent of CLa off Java/Sumatra; By Jan '06 +CLa off Java remains; But -CLa off Sumatra!
- Result of weakening easterlies in Dec '06 and equatorial westerlies that manifest in Jan '07

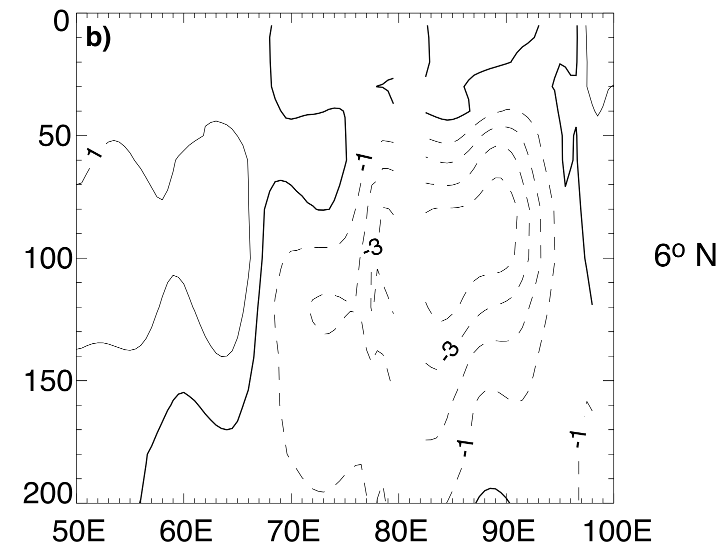
Wiggert et al., (2009), AGU Monograph 185.

IOD Comparison Highlights Mechanisms

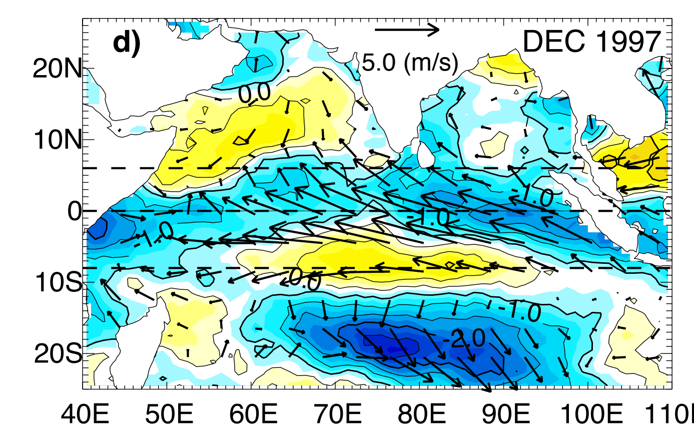
SE Bay of Bengal



ARGO Temp. Anomaly
(JAN 2007)



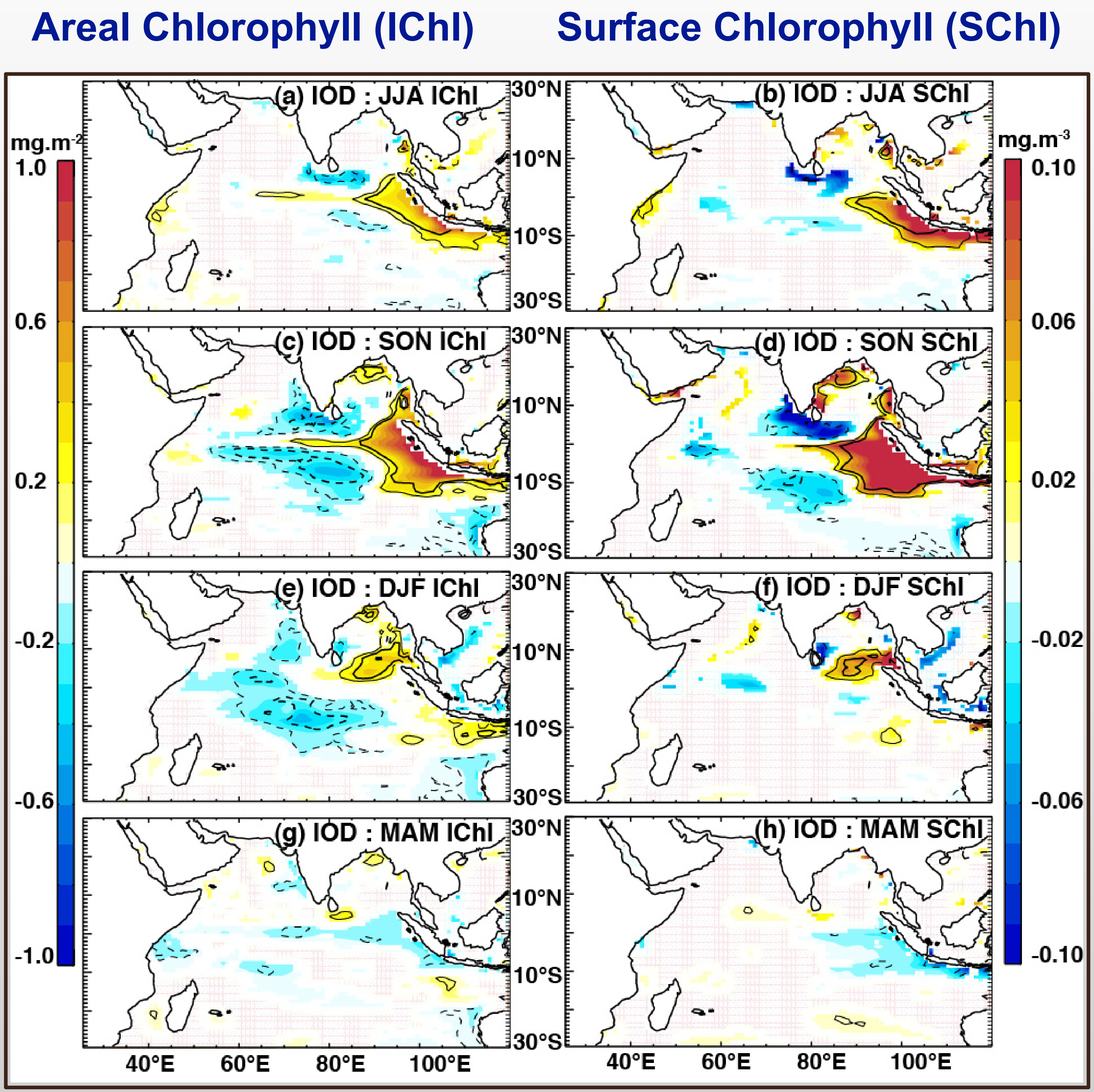
ERS Wind Anomaly
(m/s)



- Prominent +CLa in SE Bay of Bengal in 1997; also appears in 2006 (though weaker)
- Subsurface - Temperature Anomaly in ARGO data suggest pool of elevated nitrate below 50 m in Dec 2006
- Associated with -SLa feature along 6 °N, which exhibits upwelling RW nature
- Similar conditions existed in Dec 1997; difference appears to be elevated wind mixing (anomalous easterlies) during earlier IOD, which overcomes near surface density structure (i.e., overlying freshwater) that inhibits nutrient injection

Wiggert et al., (2009), AGU Monograph 185.

Seasonal IOD Impact on Areal and Surface Chl



- Chlorophyll from 40-year interannually forced biophysical model
  - Surface forcing from ERA40 reanalysis
- Regressions computed for the period 1961–2001
- SON: Strongest regression in SChl
  - Positive in Eastern EqIO
  - Negative off Equator (N & S)
- DJF:
  - Positive in Southern BoB (SChl & IChl)
  - Negative in SE Arabian Sea & SCTR (IChl)

Currie et al., (2013), *Biogeosci.,* 10(10), 6677-6698, doi:10.5194/bg-10-6677-2013.

Basinwide Impact of IOD on Annual NPP (TgC)

Production (TgC) by Region (SEP - APR)

	Basin	AS	BoB	wEQ	eEQ	wSTIO	eSTIO	wSCTR	eSCTR
CLIM	4420	909	485	336	167	1004	953	146	131
97/98 IOD	4460	831	556	267	247	927	1101	115	184
06/07 IOD	4656	1041	544	328	182	992	1031	134	153

% Change by Region

	Basin	AS	BoB	wEQ	eEQ	wSTIO	eSTIO	wSCTR	eSCTR
97/98 IOD	1	-9	15	-20	48	-8	15	-21	40
06/07 IOD	5	15	12	-2	9	-1	8	-8	17

- Basinwide impact on NPP by IOD is increase of 1% (97/98) and 5% (06/07) (i.e., essentially zero-sum)
- Significant +/- effects are realized regionally; thus a significant remapping of NPP (& export & C-flux) is indicated
- Most prominent impact in equatorial band during 97/98 IOD (48% increase eEQ, 20% decrease wEQ)
- AS shows -9% (97/98) but +15% (06/07); **Sole region to show inconsistent impact!**
- For both IOD wSCTR shows 8-21% decrease while eSCTR shows 17-40% increase **(however NPP magnitude is low)**

This underscores clear need for better understanding of IOD-modified export flux, and therefore knowledge of IOD-driven phytoplankton speciation

IOD Impacts Summary

- Redistribution of NPP
  - Eastern Equatorial IO (+48%)
  - Western Equatorial IO (-20%)
  - Southern Bay of Bengal (+15%)

- Basinwide NPP only increased by 1-5%, but there is a clear remapping of NPP distribution

- Re-distribution of NPP related to both the anomalous atmospheric forcing (local) and atypical Wyrtiki jet behavior and Rossby wave field (remote)

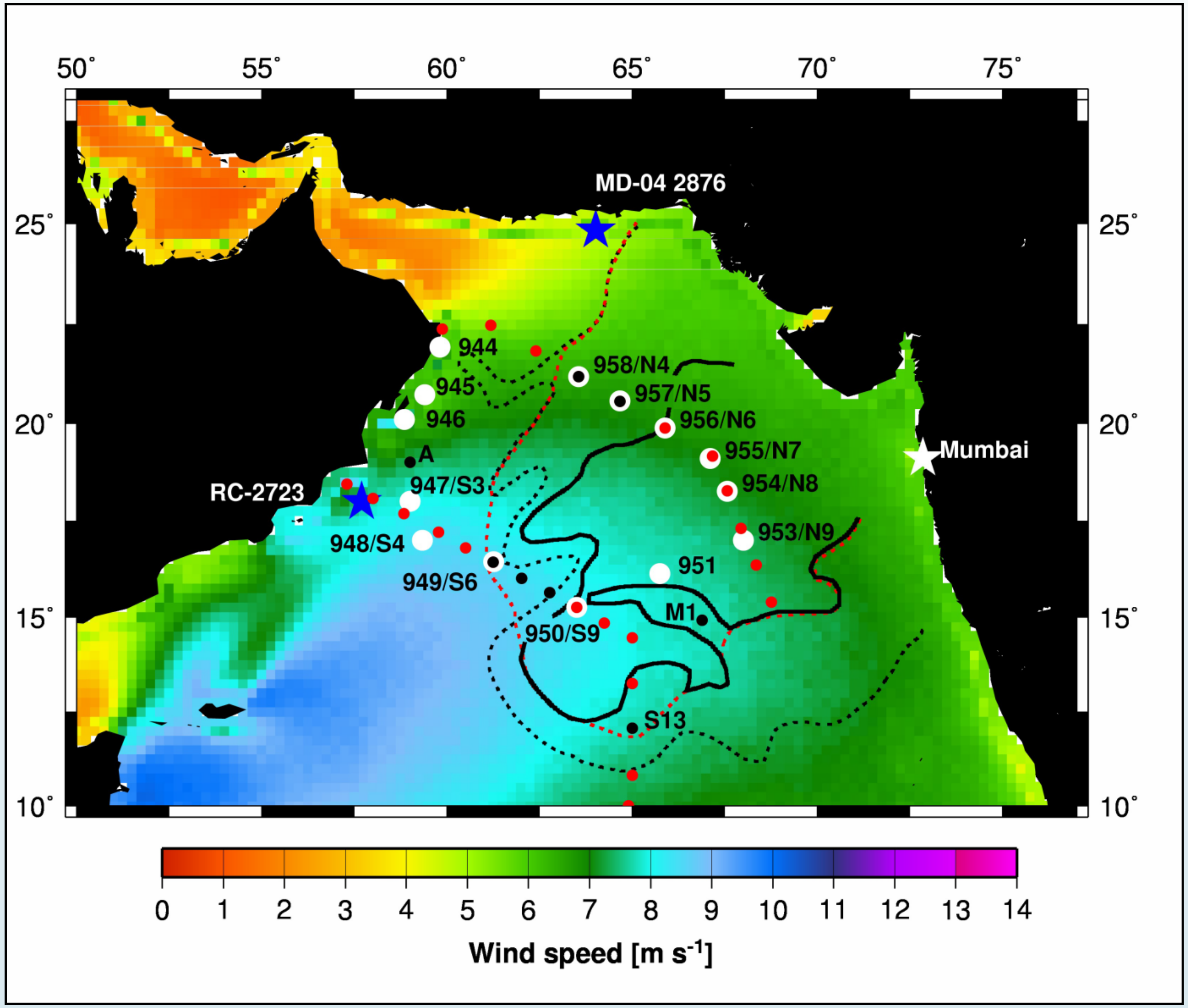
- Model-based IOD response apparent in Areal Chl (IChl) in SE Arabian Sea, SCTR
  - Timing indicative of Rossby Wave association

Climate Signal in Monsoon Intensity?

Monsoon Bloom Implications?

Linkage to Deoxygenation?

Extent of Denitrification Maximum in AS



Secondary Nitrite Maximum (SNM)

Naqvi and Shailaya 1996:

- ········· NO_2 > 0.5 µM
- ——— NO_2 > 2 µM

Rixen et al. 2014:

- ········· NO_2 > 2 µM

SNM area increased by 63% since JGOFS time frame

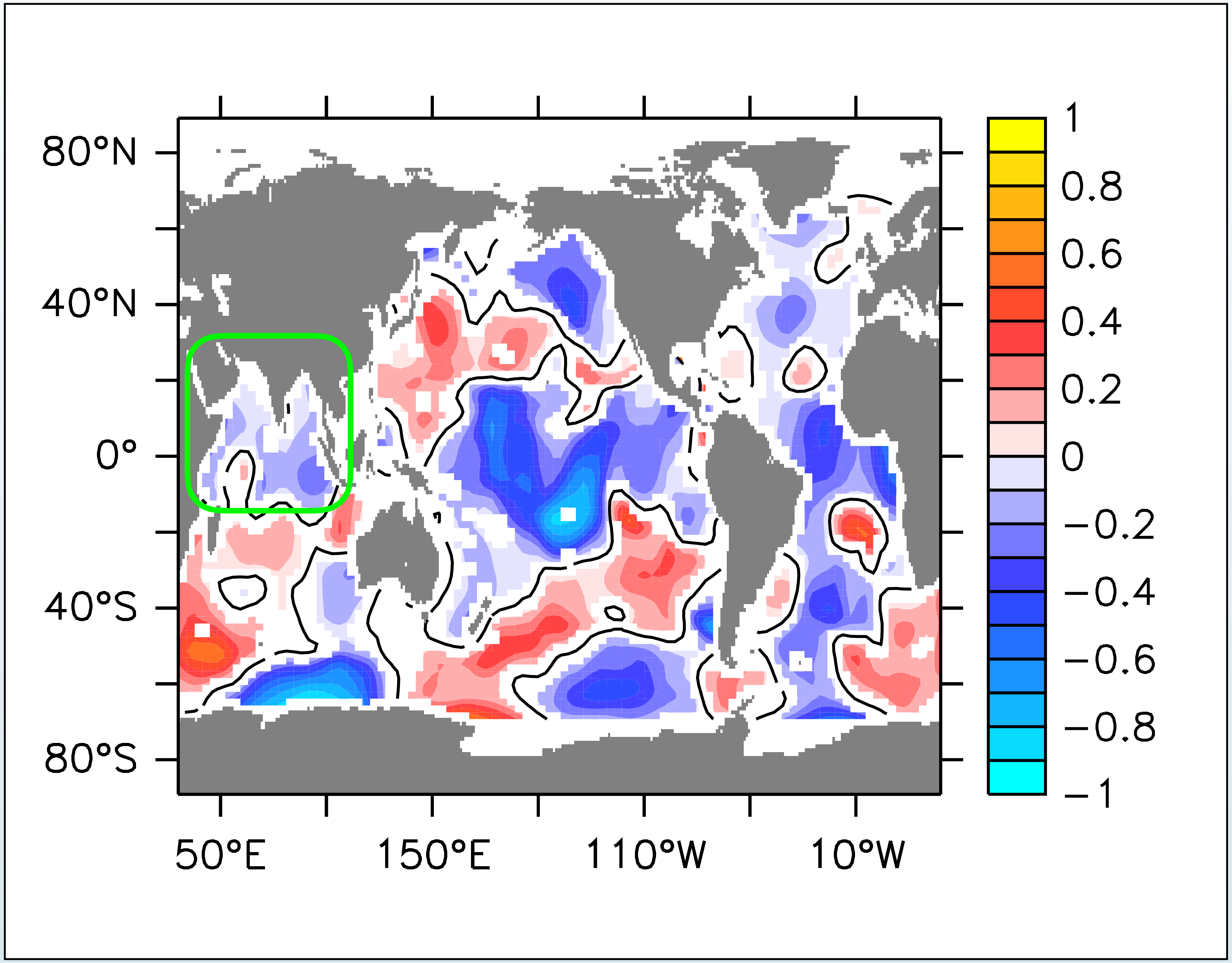
SWM Mean Wind Speed

Black/Red Circles: AS JGOFS (1995)

White Circles: R/V Meteor (2007)

Rixen et al., (2014), *Biogeosci.*, 11(20), 5733-5747.

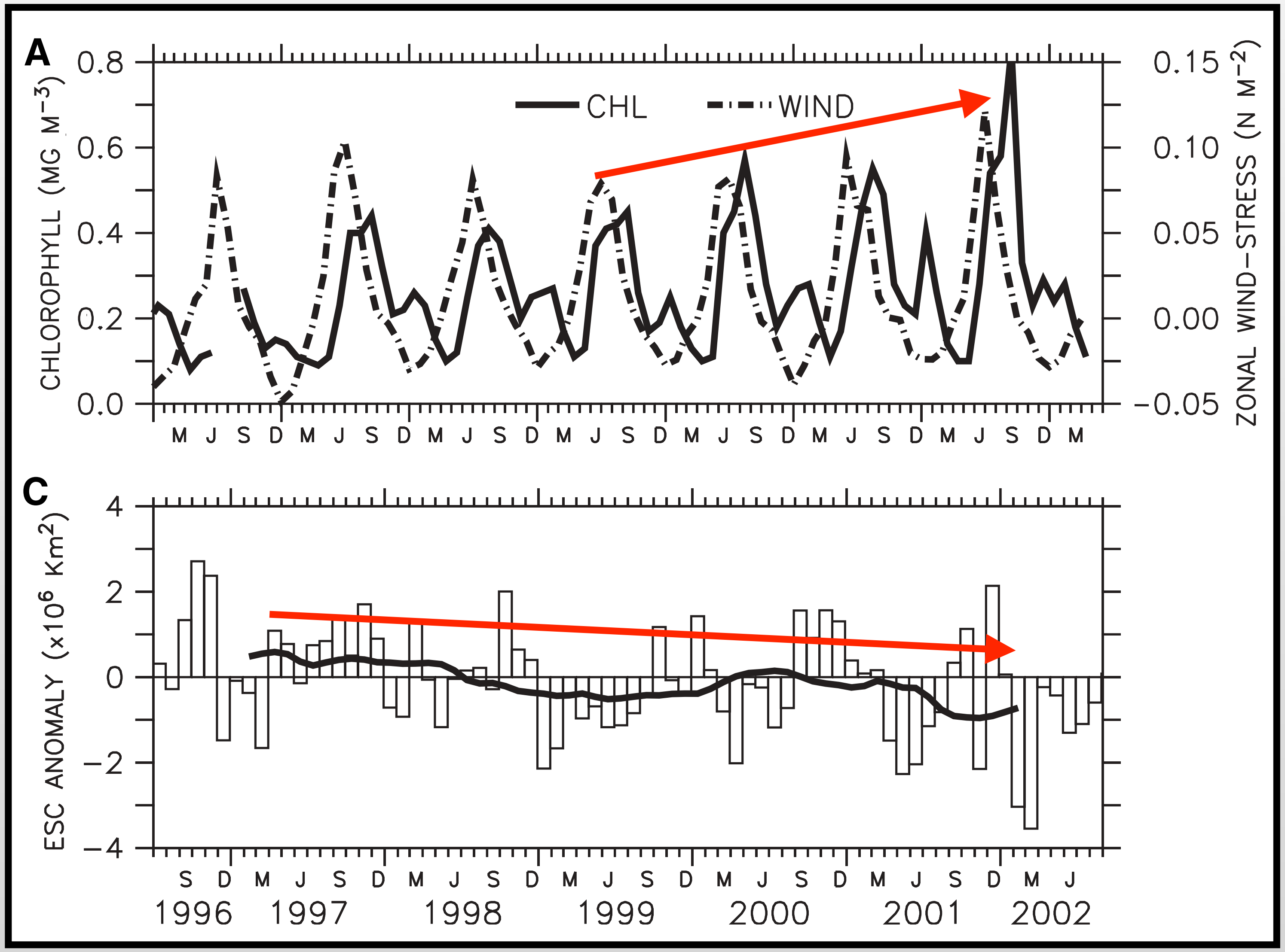
Deoxygenation in the N. Indian Ocean (1960 ⇒ 2010)



Changes in Dissolved Oxygen (DO) at 300 dbar (μmol kg^{-1} yr^{-1}) for the period 1960 - 2010

RED - DO increase
BLUE - DO decrease
WHITE - DO changes not Statistically Significant

Snow Cover Impact on Arabian Sea Production



- Time series of CHL (OCTS, SeaWiFS) and zonal wind stress are extracted from region off NE Somali Coast (47-55 °E; 5-10 °N)
- European Snow Cover (ESC) Anomaly
  - Solid line (−) is 14-month moving average
- Relationship Identified for SWM:
  - ⇣ Eurasian Snow Cover (ESC); ⇡ τx; ⇣ SST; ⇡CHL

Reported Causal Link:

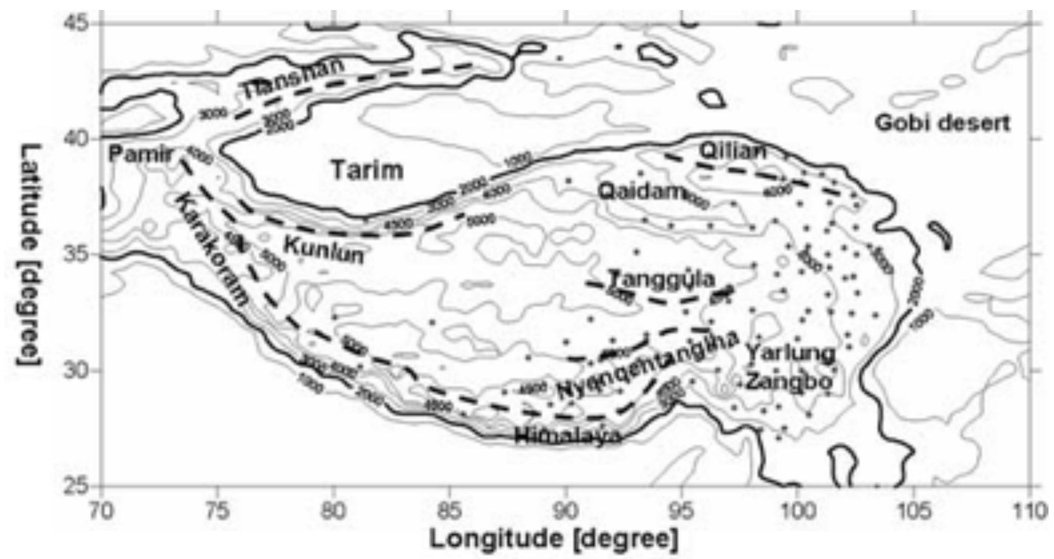
Global Warming → Reduced Snow/Ice Cover → Stronger Summer Monsoon & Higher CHL (proxy for Phytoplankton Biomass & Primary Production)

Goés et al., (2005), *Science*., 1308(5721), 545-547.

Data Sets

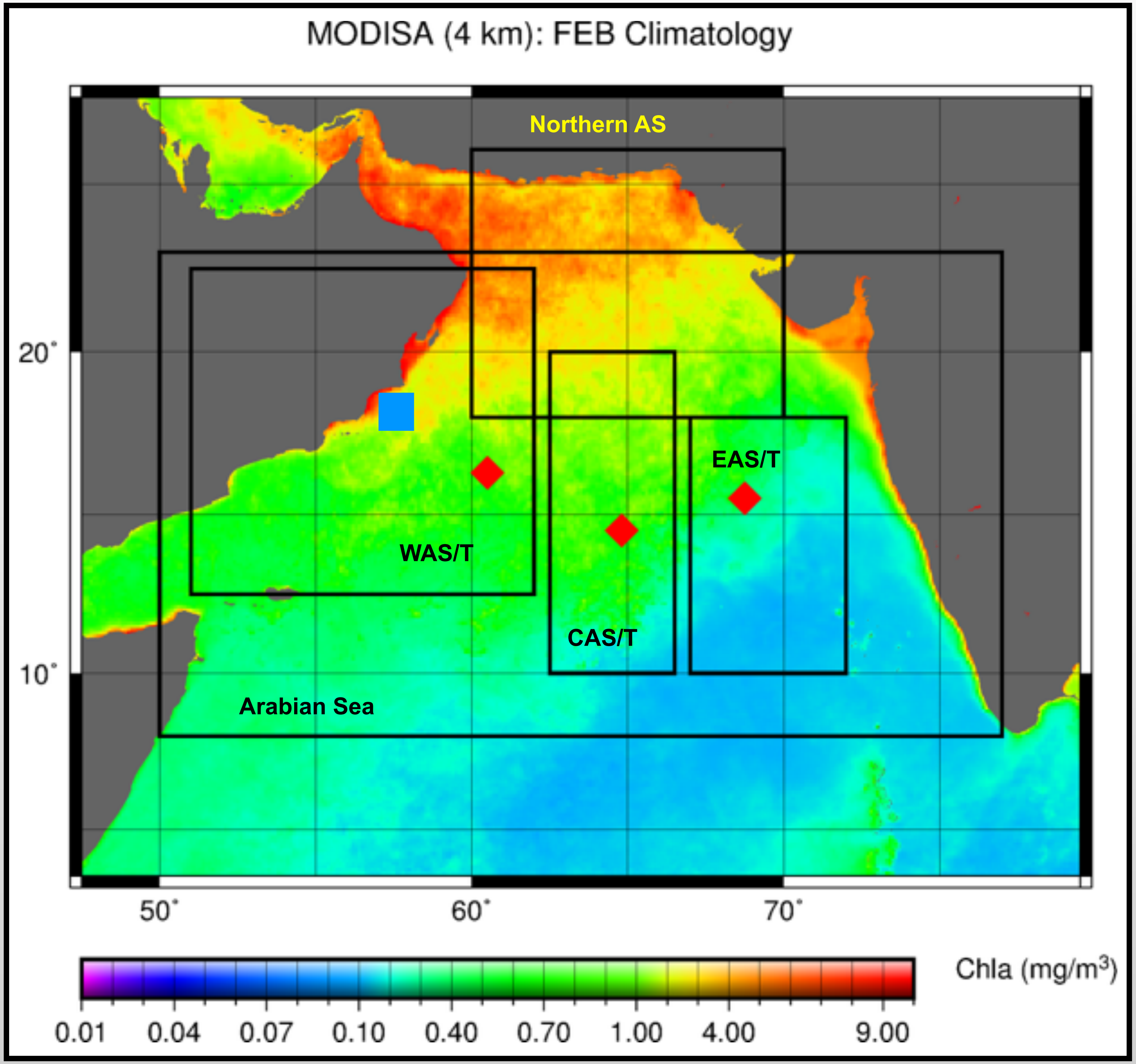
- Chlorophyll
  - Platform: SeaWiFS (1998 - 2002), MODIS - Aqua
    - Arabian Sea (AS), Western AS (WAS), Central AS (CAS), Eastern AS (EAS), Northern AS (NAS)
- Winds
  - CCMP: Level 4 Product; Monthly; Extends through 2011 (Atlas et al. 2010)
    - Wind Speed
    - Upwelling Index (57–58 °E. 17–18 °N; (Ras ash Sharbatat)
      - Rotated w.r.t. Arabian Peninsula Land Boundary
- Sediment Trap:
  - WAST: (60.5 E, 16.3 N)
  - CAST: (64.8 E, 14.5 N)
  - EAST: (68.75 E, 15.5 N)
- Snow Cover
  - Platform: MODIS - Terra, MODIS - Aqua
    - Snow Cover Fraction (SCF)
    - 70–110 °E. 25–45 °N (Tibetan Plateau)
  - NCDC: Eurasian Snow Cover (ESC) Anomaly
    - https://www.ncdc.noaa.gov/snow-and-ice/

Tibetan Plateau



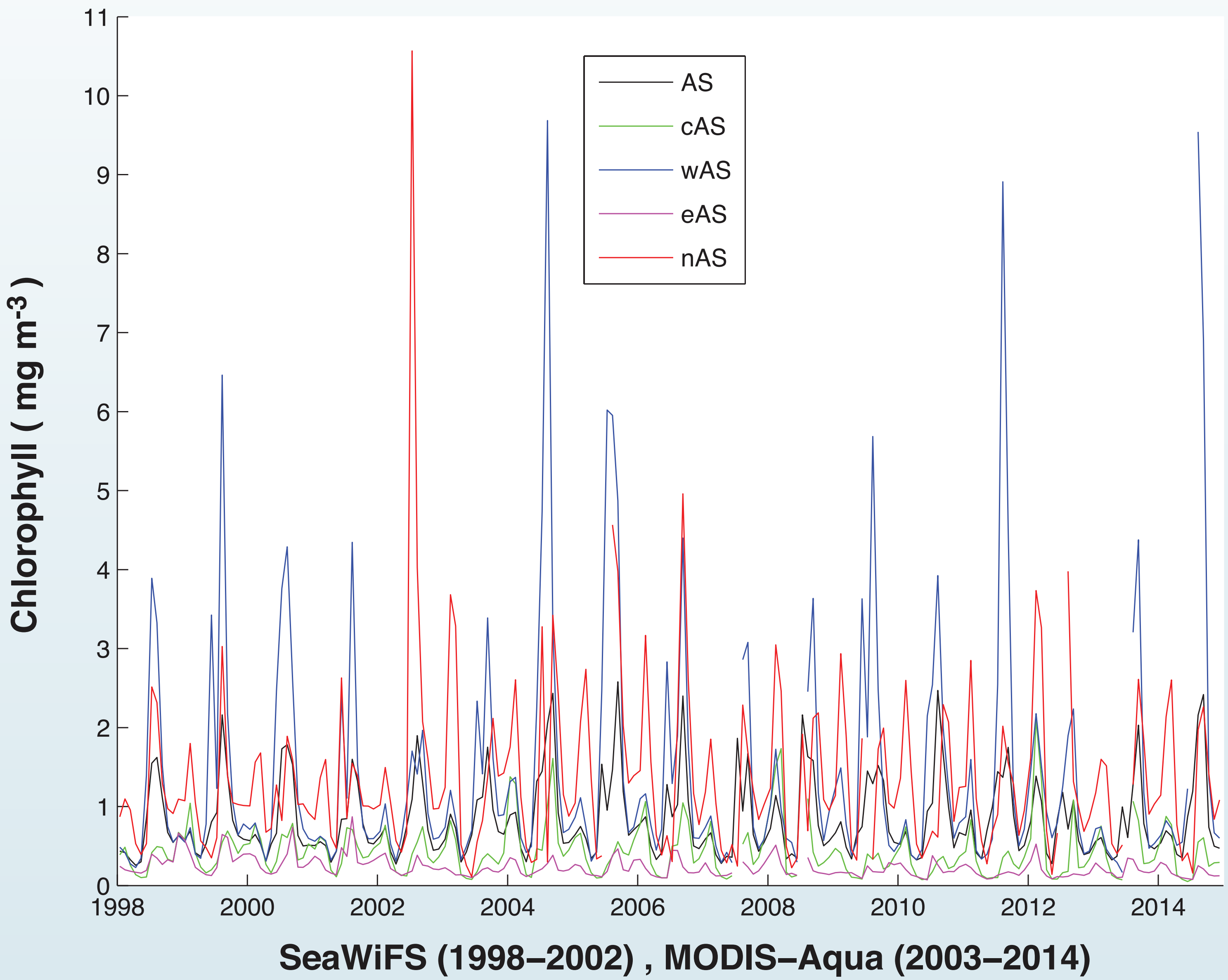
Pu et al. (2007), GRL, doi:10.1029/2007GL029262

Regional Partitioning

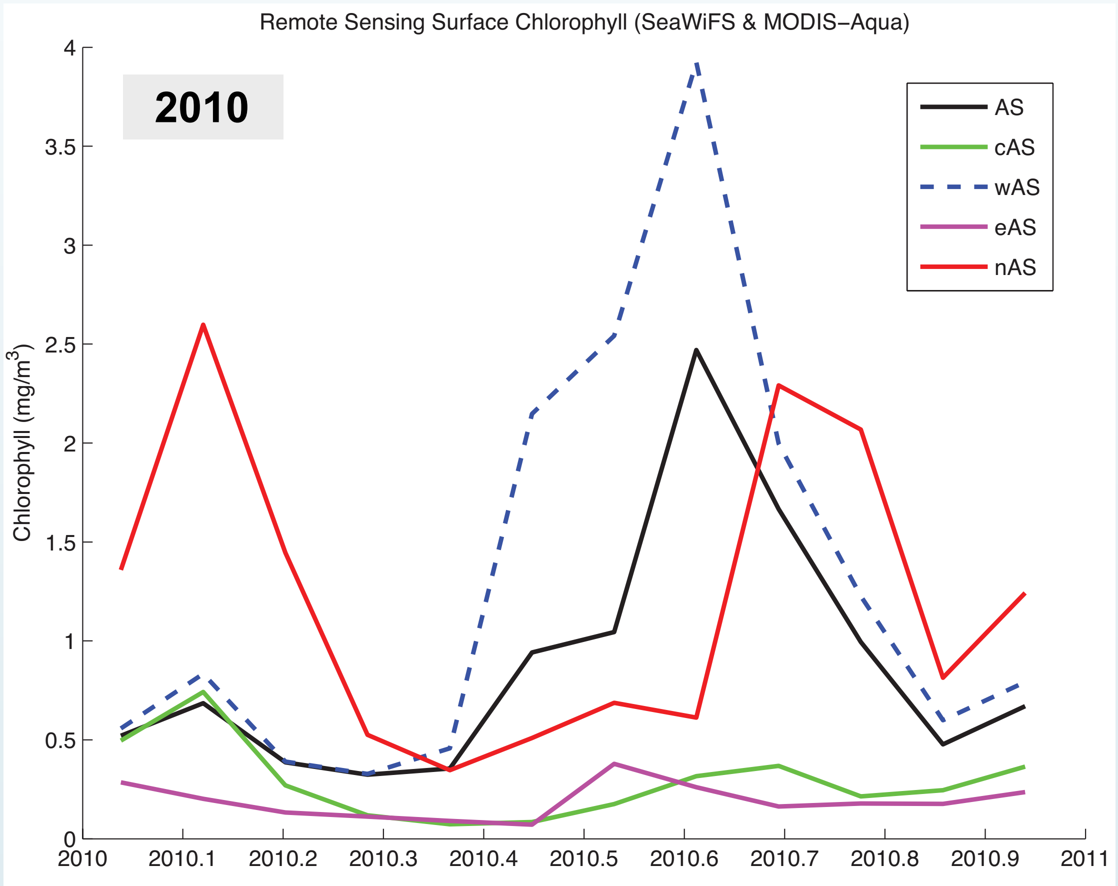


- Regional subsets for extraction of remote sensing chlorophyll *a* time series (Black Boxes)
  - Arabian Sea, Western AS, Central AS, Eastern AS, Northern AS
- Sediment Trap Locations
  - WAST, CAST, EAST (◆)
- Regional subset for extraction of CCMP level 4 wind product
  - Area off Ras ash Sharbatat (■)
- Image backdrop is MODIS - Aqua 4 km chlorophyll a climatology for February

Monthly Chlorophyll a Time Series



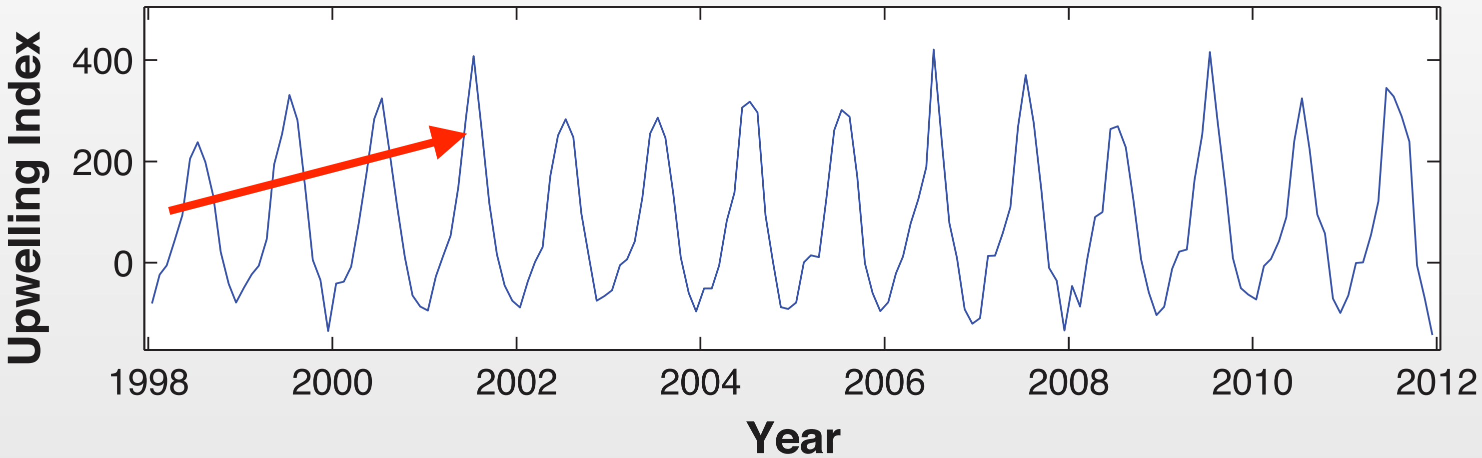
- Interannual Variability
  - 5 of 6 peaks are from wAS
  - Highest CHL in nAS during 2002 SWM
  - No apparent trend



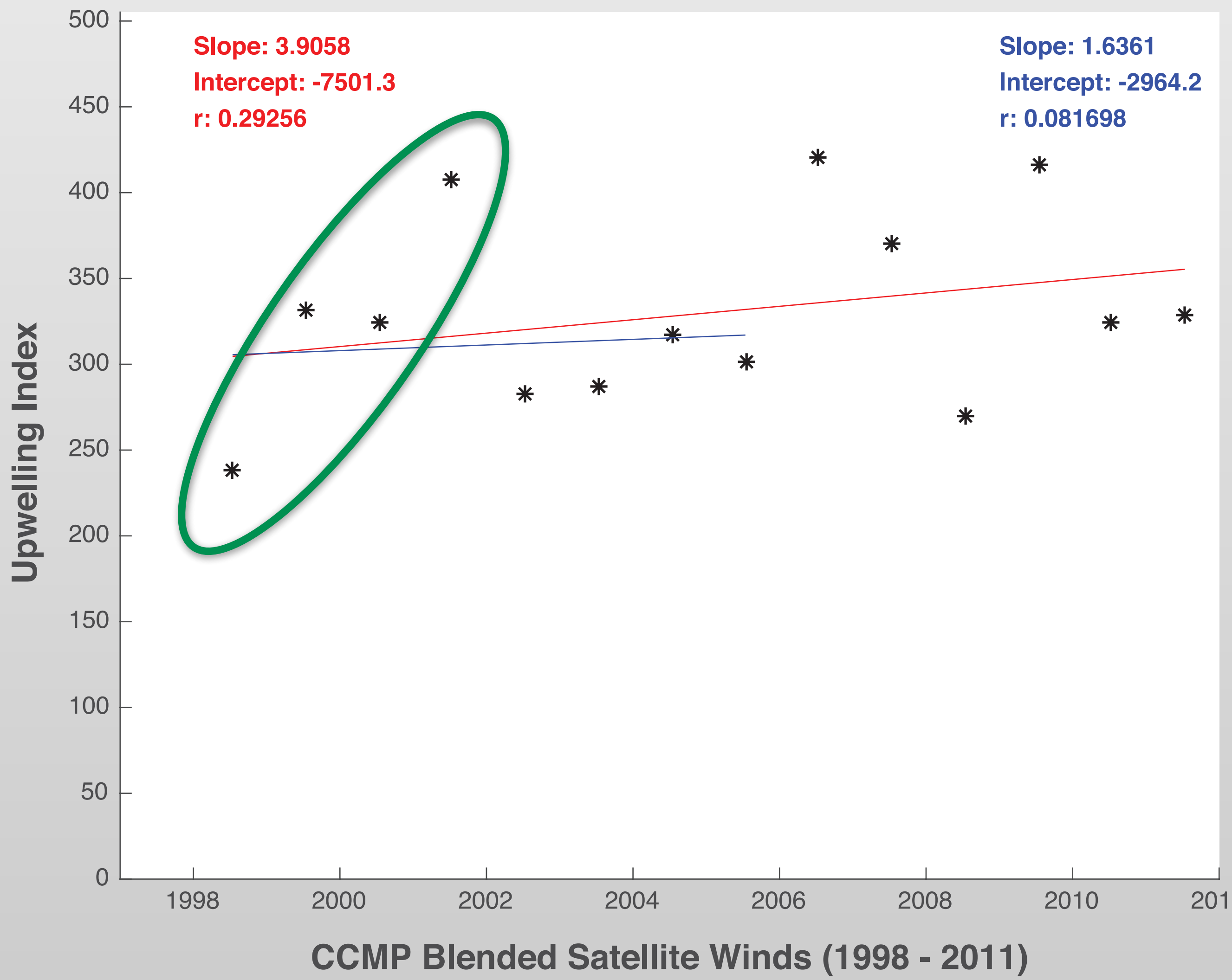
- Seasonal Cycle (2010)
  - Winter and Summer Blooms are present for all regions
  - nAS has strongest NEM bloom and delayed SWM bloom
  - wAS has the strongest SWM bloom

Upwelling Index off Ras ash Sharbatat

Arabian Sea Winds: Blended Satellite Winds (CCMP, 1/4°) – Monthly

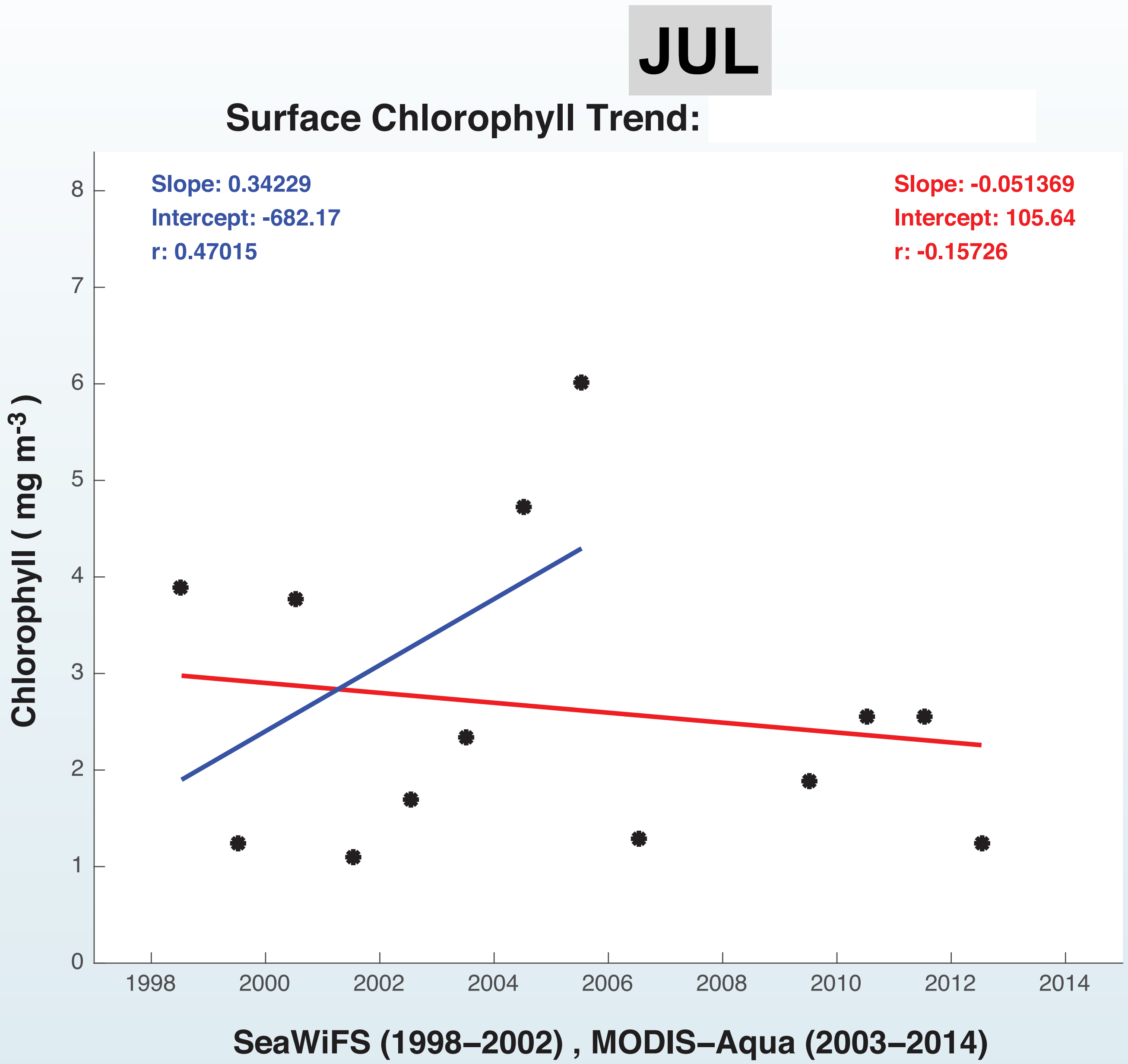


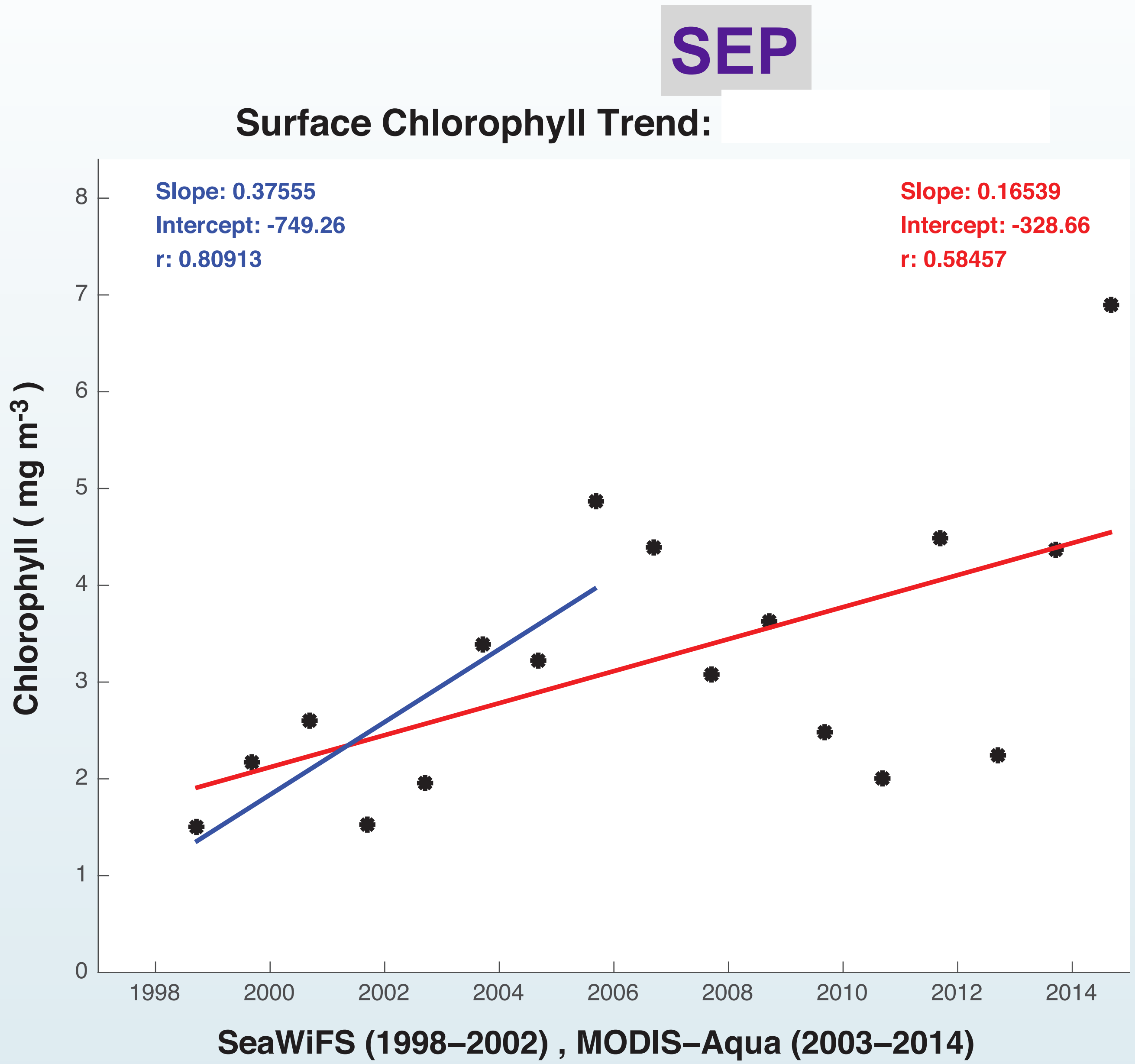
UI Trend: Arabian Peninsula - JUL



- Trend in wind speed and upwelling index (UI) through 2001 SWM is consistent with the wind stress trend reported by Goes et al.
- Longer term: Clear persistent trend in SWM winds is not apparent

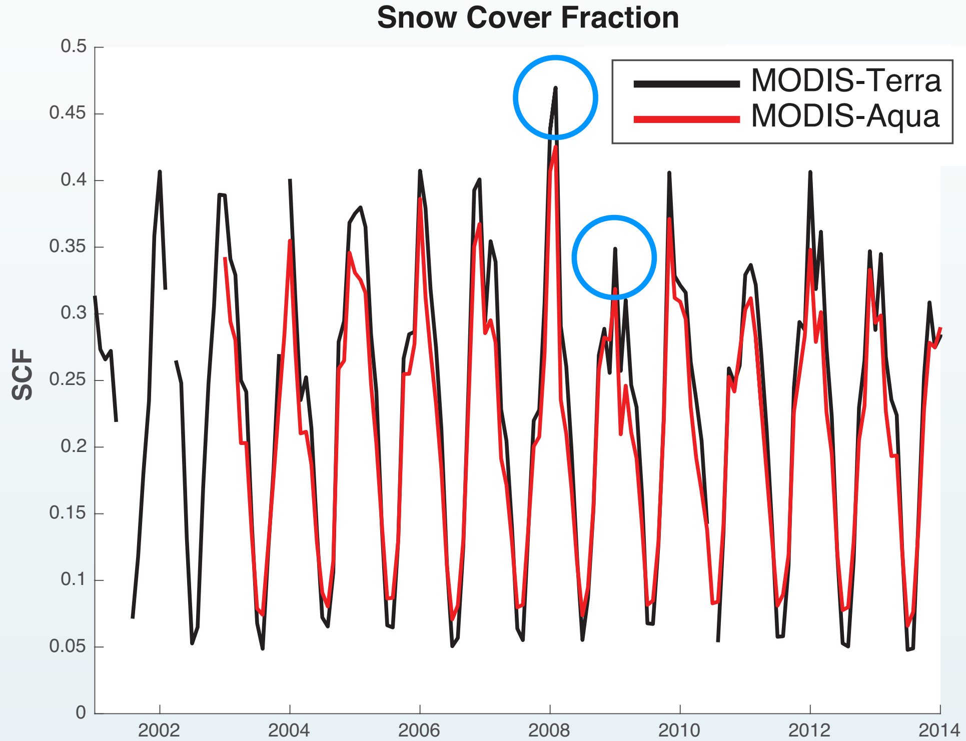
SWM Chlorophyll Trend - Western AS

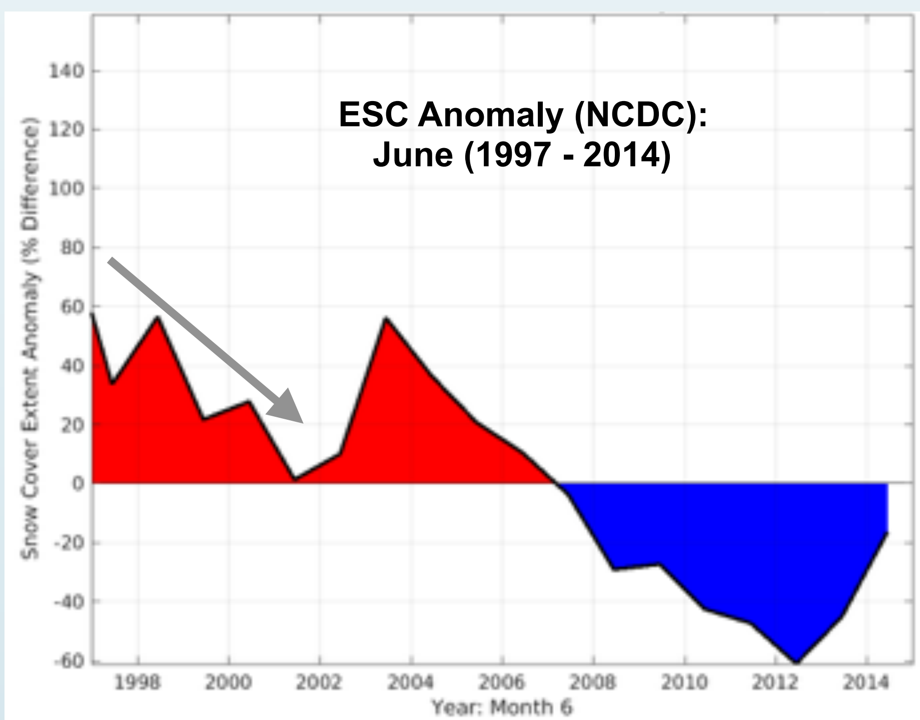


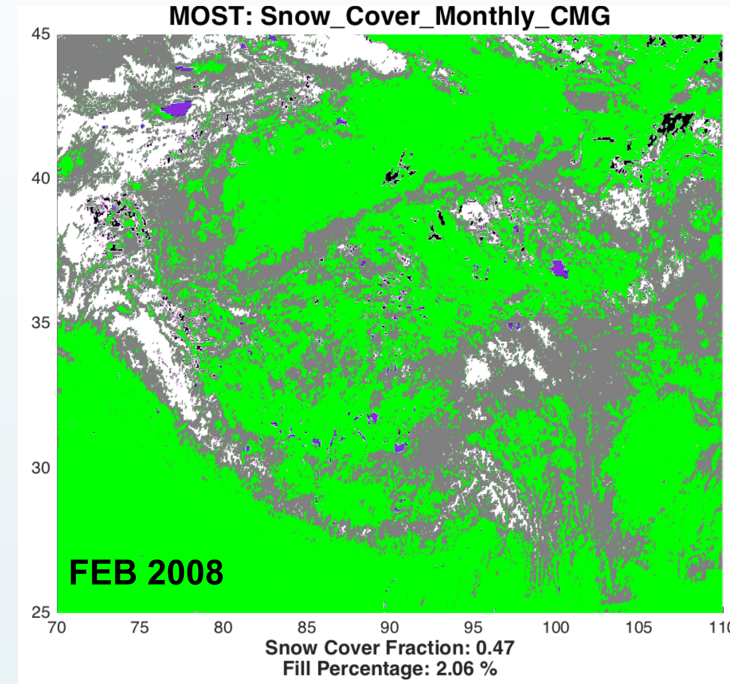


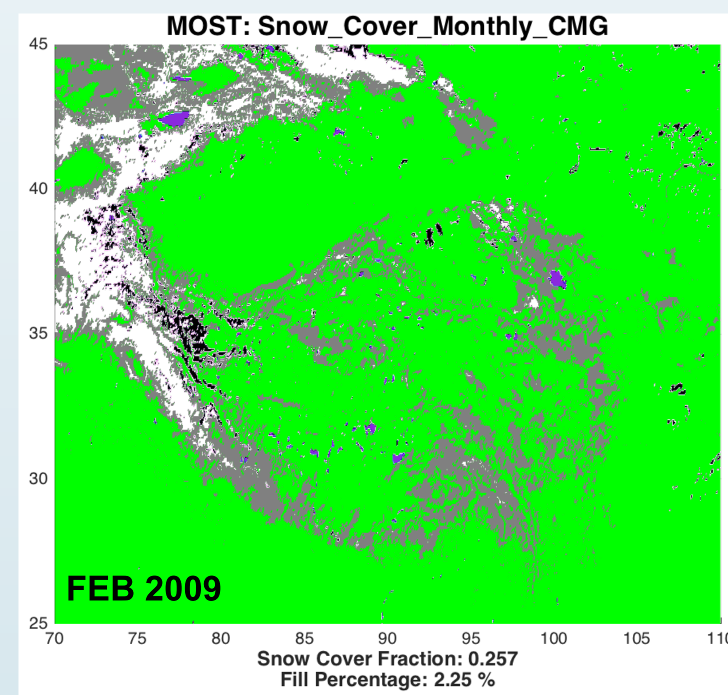
- 7-year trend (1998 - 2004) in Western AS
  - In both JUL and SEP, chlorophyll show a positive trend.
  - For SEP, trend is statistically significant
- 17-year trend (1998 - 2014) in Western AS
  - Trend remains positive, though less statistically significant, during SEP
  - Trend is negative for JUL and is not statistically significant

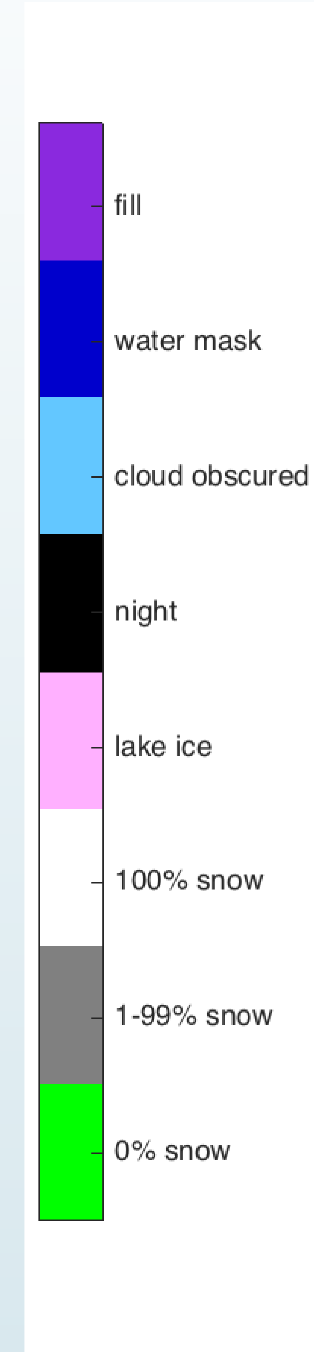
Snow Cover Fraction (SCF) - MODIS







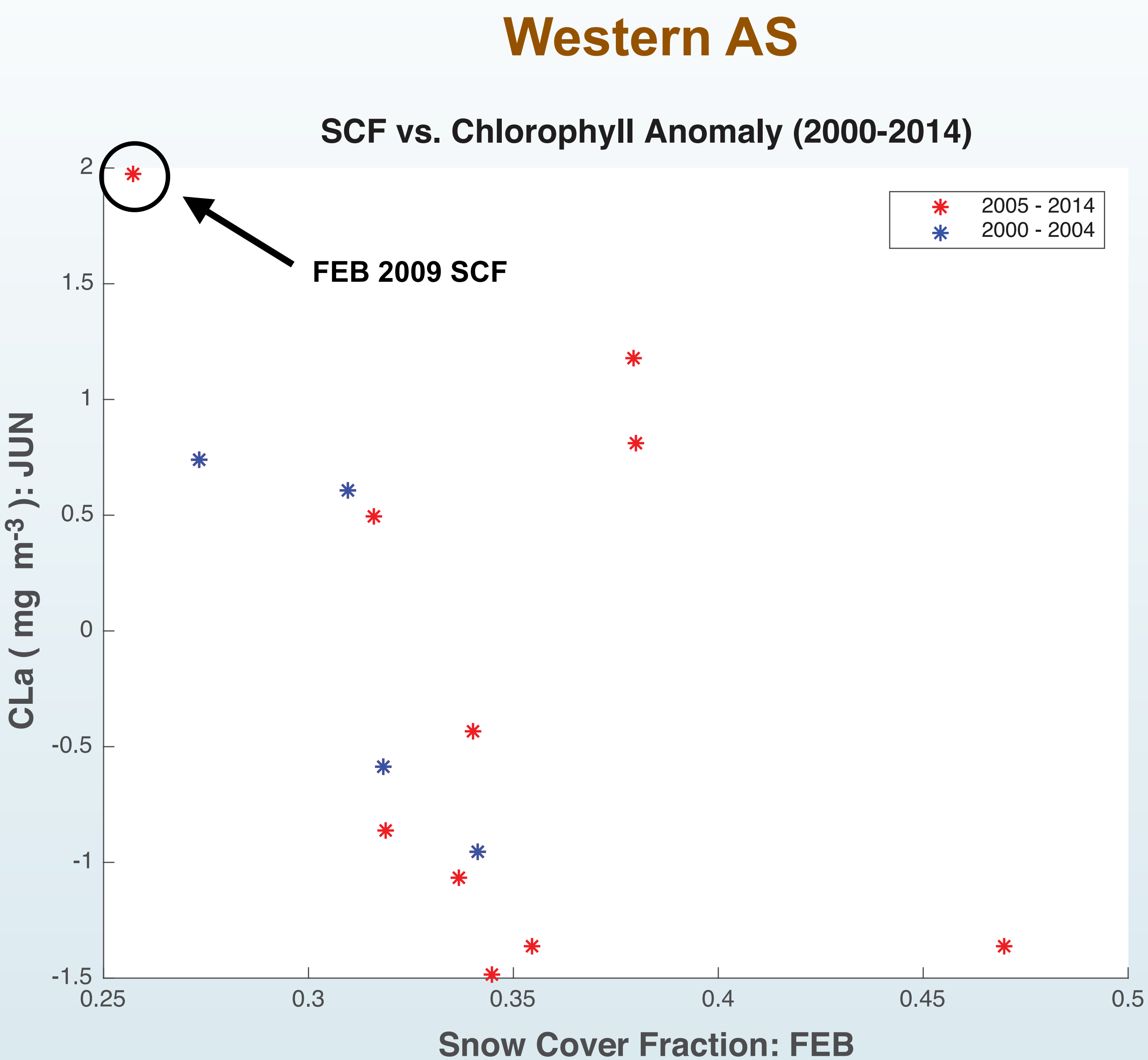


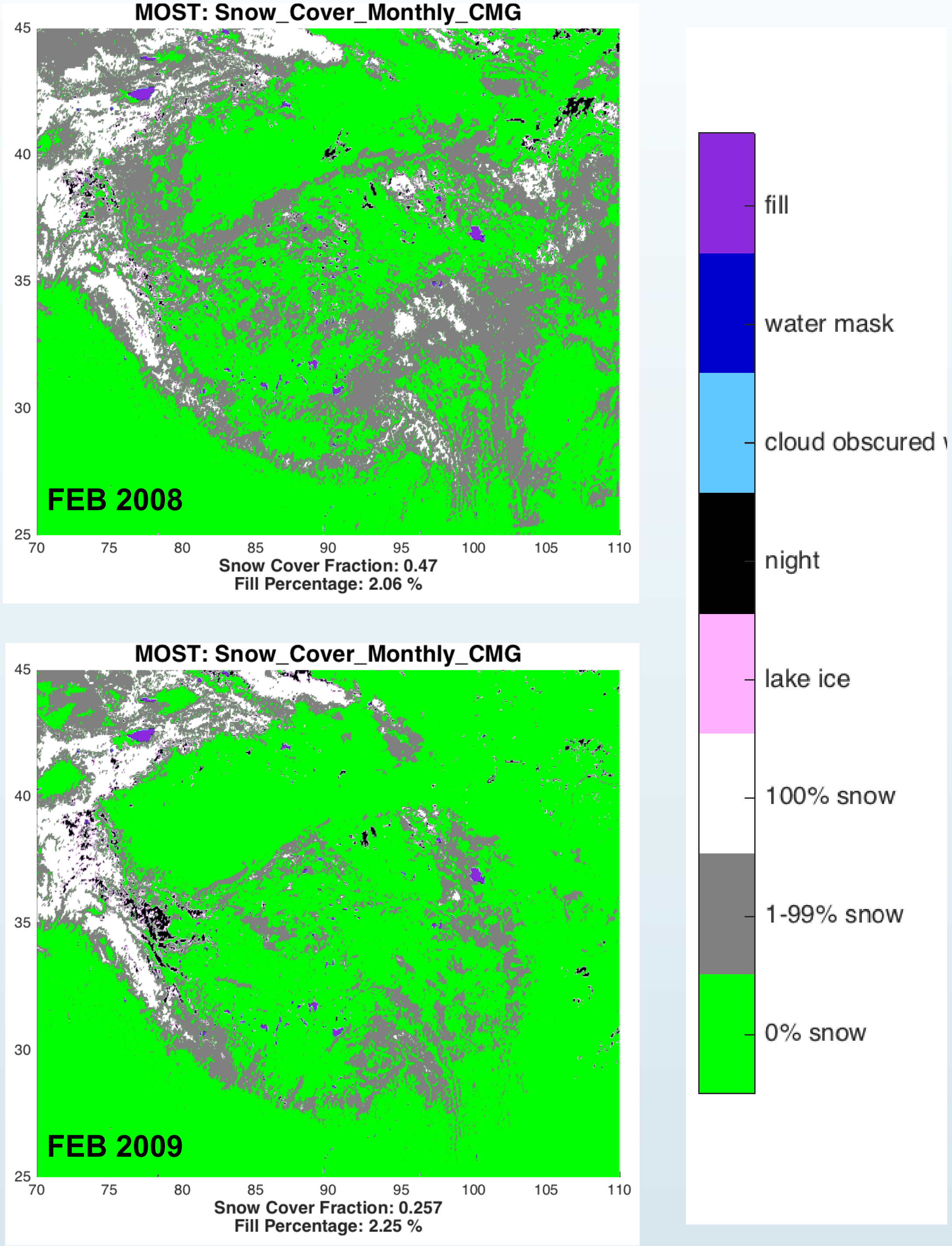


- European Snow Cover Anomaly (JUN)
  - Decreasing through 2002, but positive long-term anomaly
  - Appropriate spatial extent for SW Monsoon impact?

- Snow Cover Fraction
  - Exhibits interannual variation but no IA trend

Trend in CLa vs. SCF? - Western AS



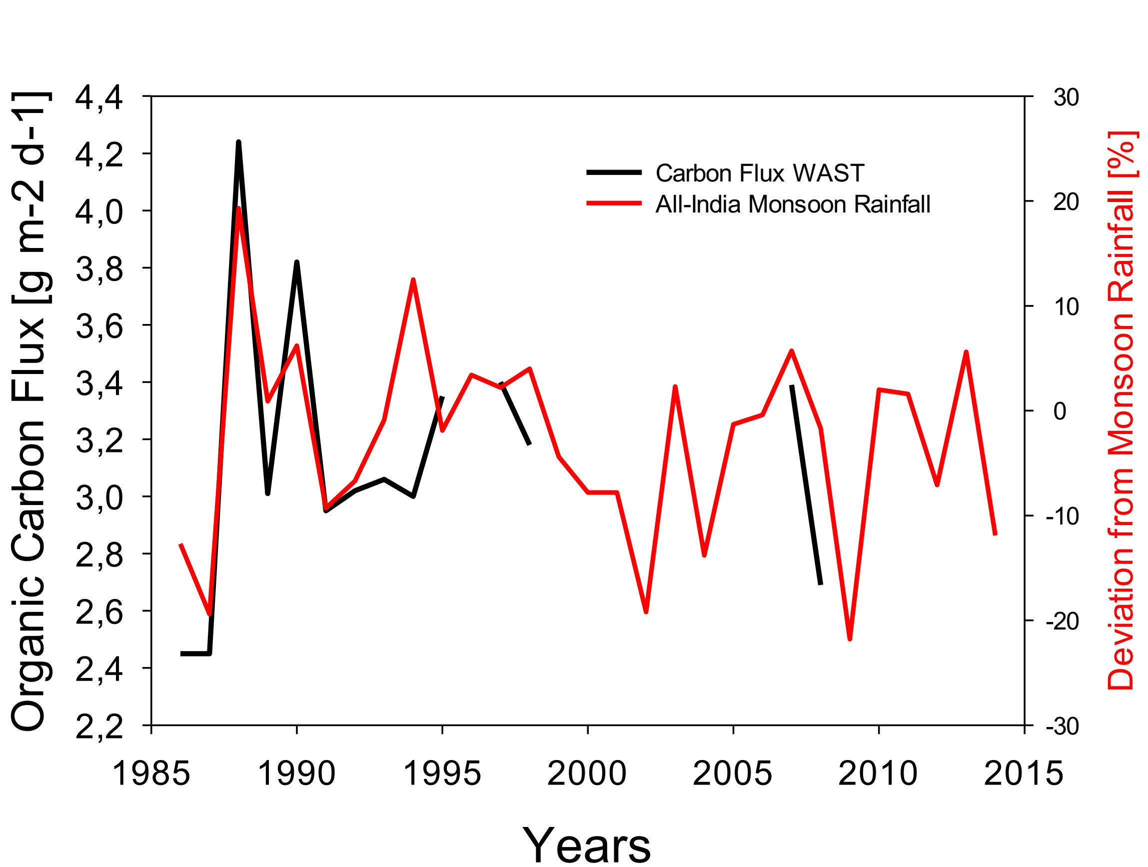


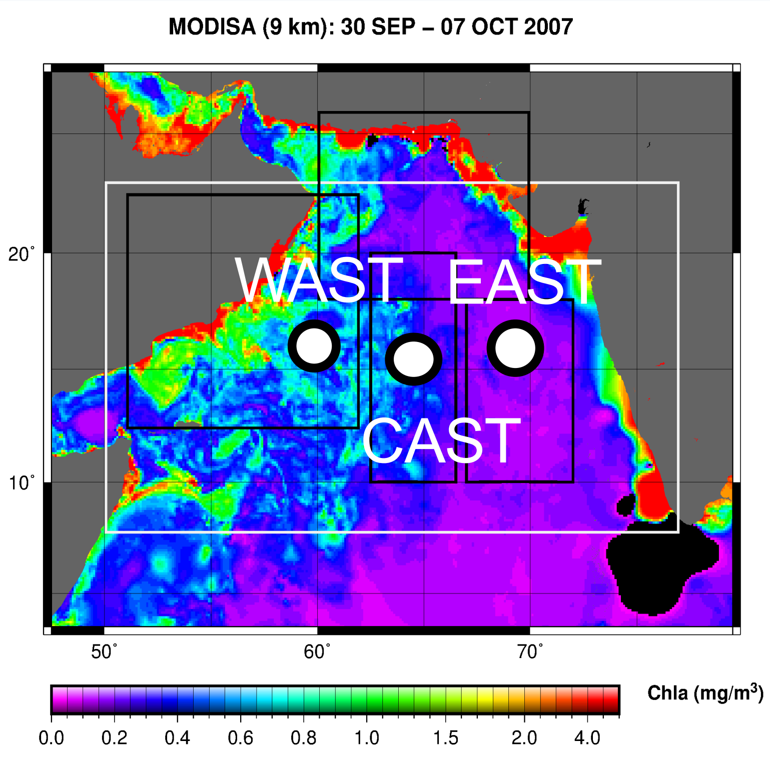
- Trend in Chlorophyll Anomaly (JUN) vs. SCF (FEB)?
  - Western Arabian Sea Region:
  - Outside of several years, a trend consistent w/ Warming ➔ Increased Biomass is indicated

- Snow Cover Fraction
  - 45% Reduction for FEB 2009 vs. FEB 2008

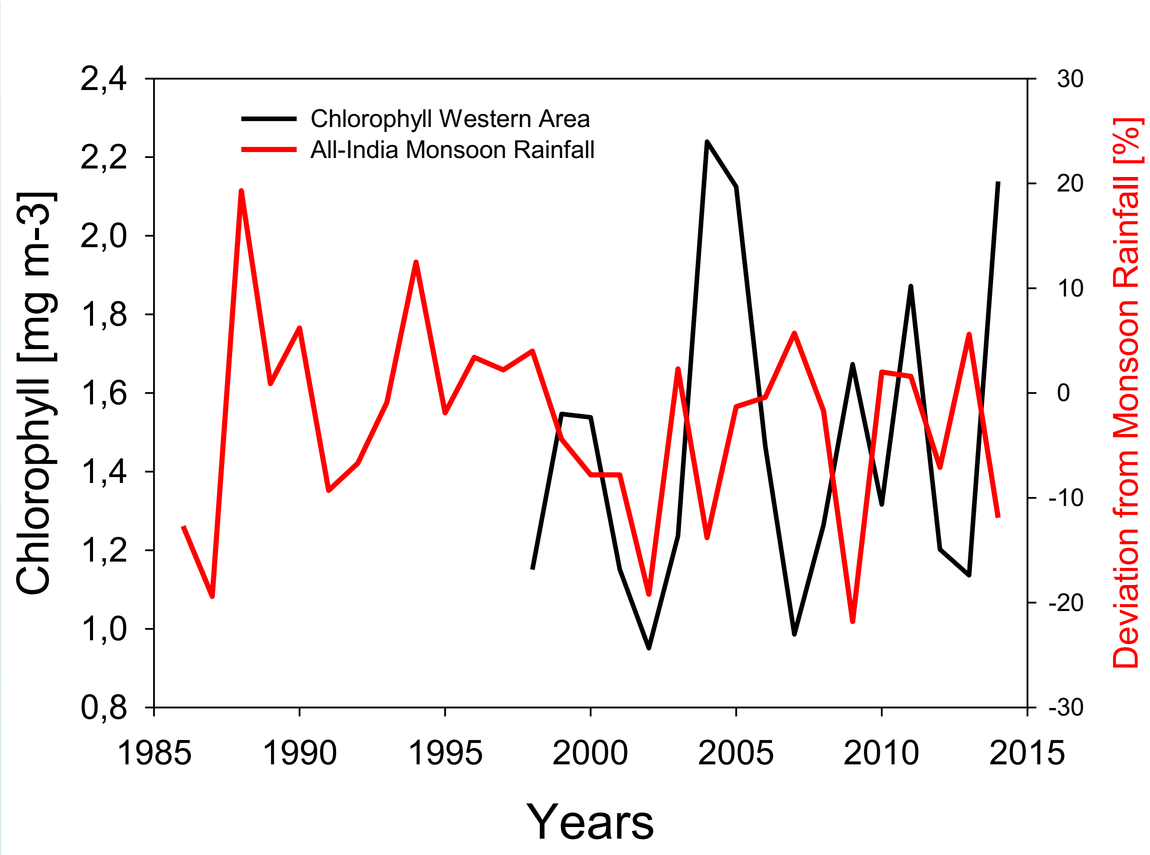
CHL - Particle Flux Link: Western AS

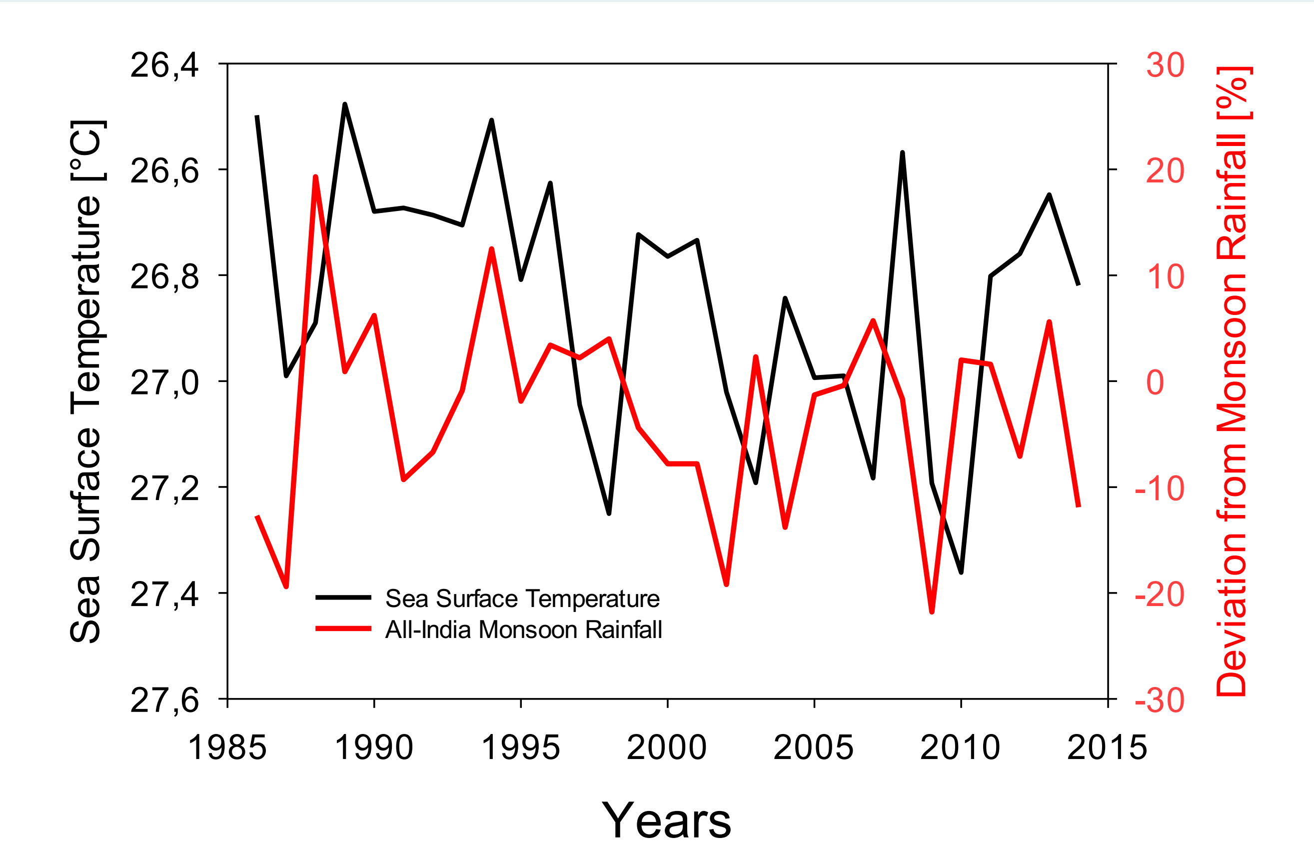
Track All-India Rainfall (AIR) Index?





- Sediment trap organic carbon fluxes and monsoon strength (AIR) correlate
- Chlorophyll and SST show no relationship w/ monsoon index





Climate - SWM Bloom Linkage Summary

- Are long term trends noted in early SeaWiFS era continuing?
  - **NO:** 17-yr ocean color record indicates decadal variability is playing a role
- Are causal links suggested in previous studies indicated?
  - ↓ Snow Cover ➔ ↑ Chlorophyll ?
    - **YES**: Chlrorophyll a during SW monsoon onset time frame tracks w/ SCF for February
  - ↑ Monsoon Strength ➔ ↑ Production ?
    - **YES**: Sediment trap particle fluxes correlate with All-India Monsoon Rainfall

Climate Linkages to Basin Deoxygenation?

- Iron Limitation in Arabian Sea
  - Transition to HNLC regime during latter SW Monsoon in Arabian Sea has been postulated (Naqvi et al., 2010)
  - Dustier conditions (higher deposition loads) under future climate conditions → Relief of HNLC tendency?
  - Connectivity of Arabian Sea OMZ to Iron Availability / Cycling and Maintenance / Evolution of OMZ
- Frequency of IOD Manifestation
  - Under climate change can expect more frequent IOD w/ associated high export flux condition occurring in Eastern IO
  - Further expansion of low oxygen regions in Eastern IO
- SW Monsoon Intensification
  - Stronger upwelling → increased production & export flux
  - Increased delivery of organic matter offshore to OMZ region

Thank You