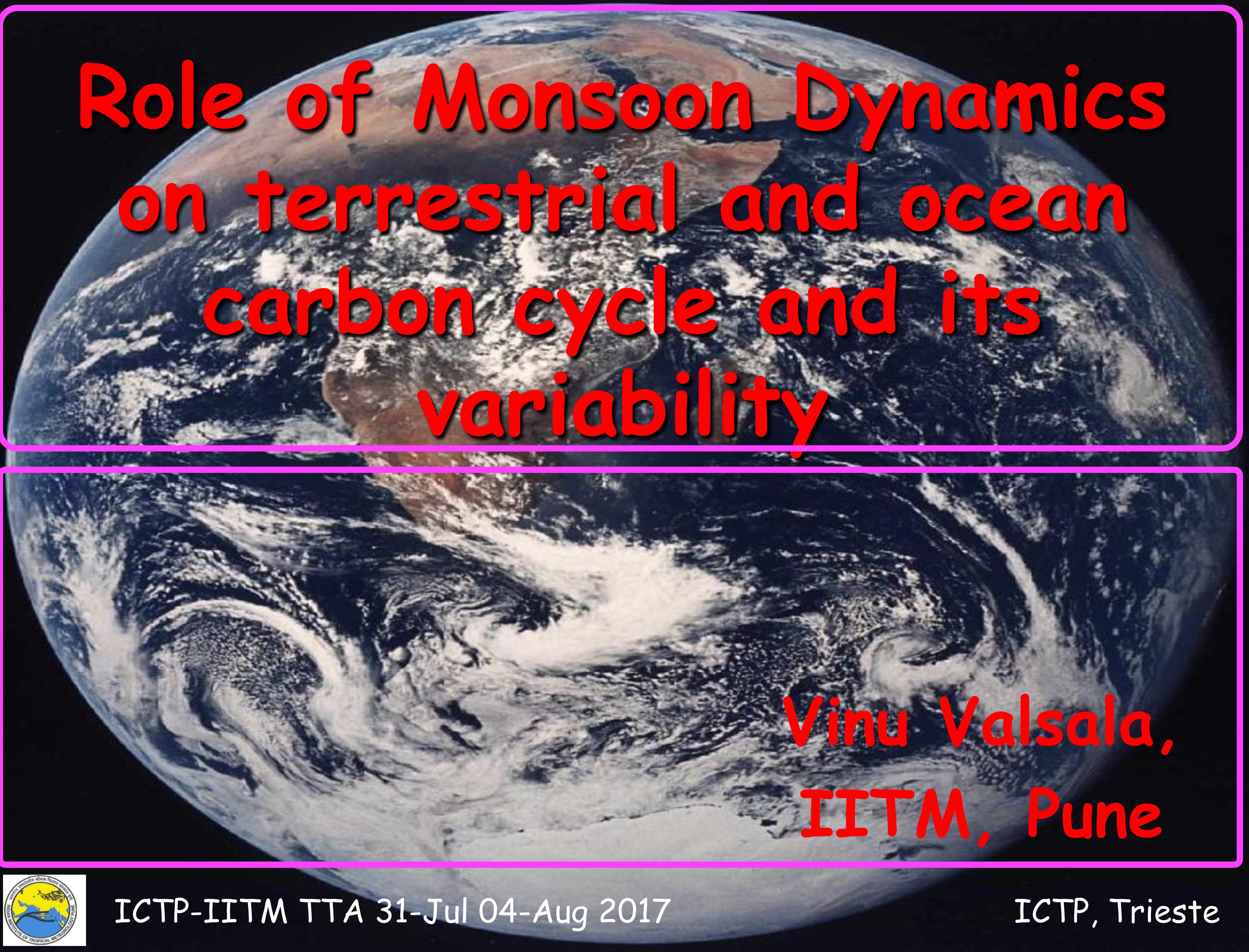


Role of Monsoon Dynamics on terrestrial and ocean carbon cycle and its variability

Vinu Valsala,
IITM, Pune

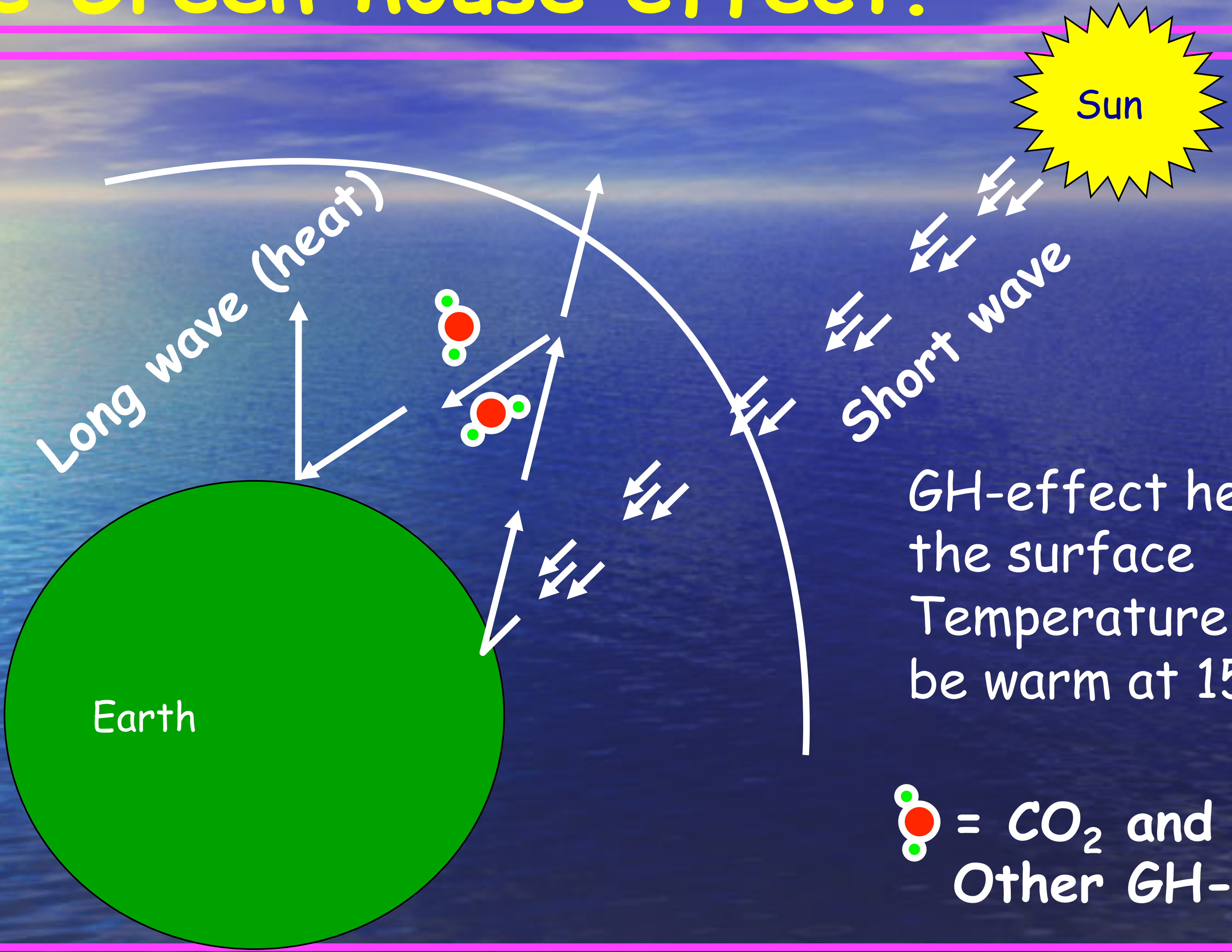
ICTP-IITM TTA 31-Jul 04-Aug 2017

ICTP, Trieste

OUTLINE

- Little bit basics on Carbon Cycle
- Linkage between Monsoon Dynamics and Carbon Cycle
- Rich spectrum of variability in carbon cycle (CO_2 and CH_4) offered by South Asian monsoon.
- Green house gases cycle → climate change → Greenhouse gases cycle change

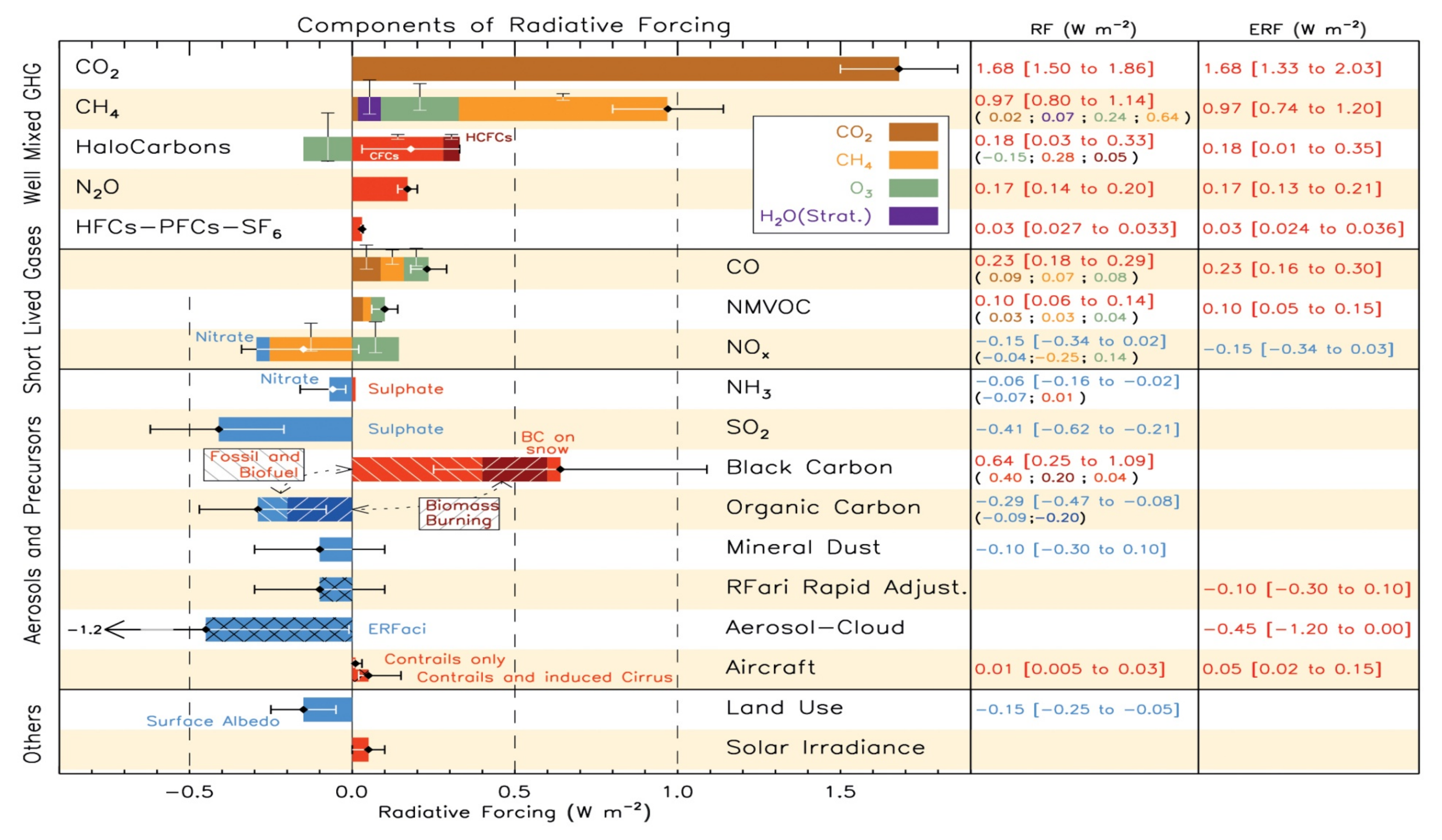
The Green house effect.



GH-effect helps the surface Temperature to be warm at 15^0C

● = CO_2 and Other GH-gases

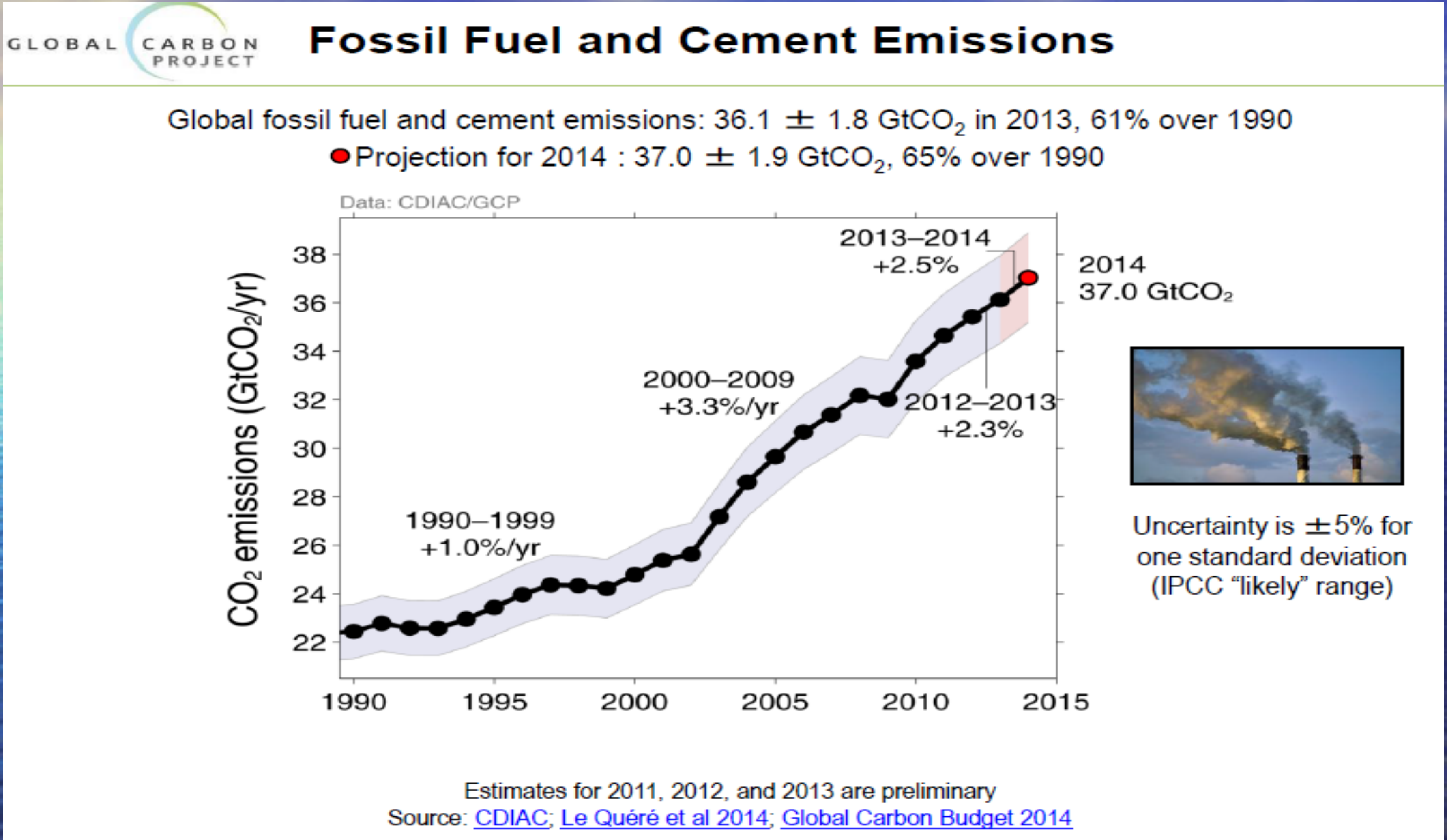
Anthropogenic radiative forcing: IPCC-AR5 WG1



		RF (W m^{-2})	ERF (W m^{-2})
Well Mixed GHG	CO_2	1.68 [1.50 to 1.86]	1.68 [1.33 to 2.03]
	CH_4	0.97 [0.80 to 1.14] (0.02 ; 0.07 ; 0.24 ; 0.64)	0.97 [0.74 to 1.20]
	HaloCarbons	0.18 [0.03 to 0.33] (−0.15; 0.28 ; 0.05)	0.18 [0.01 to 0.35]
	N_2O	0.17 [0.14 to 0.20]	0.17 [0.13 to 0.21]
	HFCs−PFCs−SF_6	0.03 [0.027 to 0.033]	0.03 [0.024 to 0.036]
Short Lived Gases	CO	0.23 [0.18 to 0.29] (0.09 ; 0.07 ; 0.08)	0.23 [0.16 to 0.30]
	NMVOC	0.10 [0.06 to 0.14] (0.03 ; 0.03 ; 0.04)	0.10 [0.05 to 0.15]
	NO_x	−0.15 [−0.34 to 0.02] (−0.04;−0.25; 0.14)	−0.15 [−0.34 to 0.03]
Aerosols and Precursors	NH_3	−0.06 [−0.16 to −0.02] (−0.07; 0.01)	
	SO_2	−0.41 [−0.62 to −0.21]	
	Black Carbon	0.64 [0.25 to 1.09] (0.40 ; 0.20 ; 0.04)	
	Organic Carbon	−0.29 [−0.47 to −0.08] (−0.09;−0.20)	
	Mineral Dust	−0.10 [−0.30 to 0.10]	
	RFari Rapid Adjust.		−0.10 [−0.30 to 0.10]
	Aerosol−Cloud		−0.45 [−1.20 to 0.00]
	Aircraft	0.01 [0.005 to 0.03]	0.05 [0.02 to 0.15]
Others	Land Use	−0.15 [−0.25 to −0.05]	
	Solar Irradiance		

Radiative forcing (RF) is a measure of the net change in the energy balance of the Earth system in response to some external perturbation, with positive RF leading to a warming and negative RF to a cooling

Anthropogenic emission of carbon



GLOBAL CARBON PROJECT

Fossil Fuel and Cement Emissions

Global fossil fuel and cement emissions: 36.1 ± 1.8 $GtCO_2$ in 2013, 61% over 1990

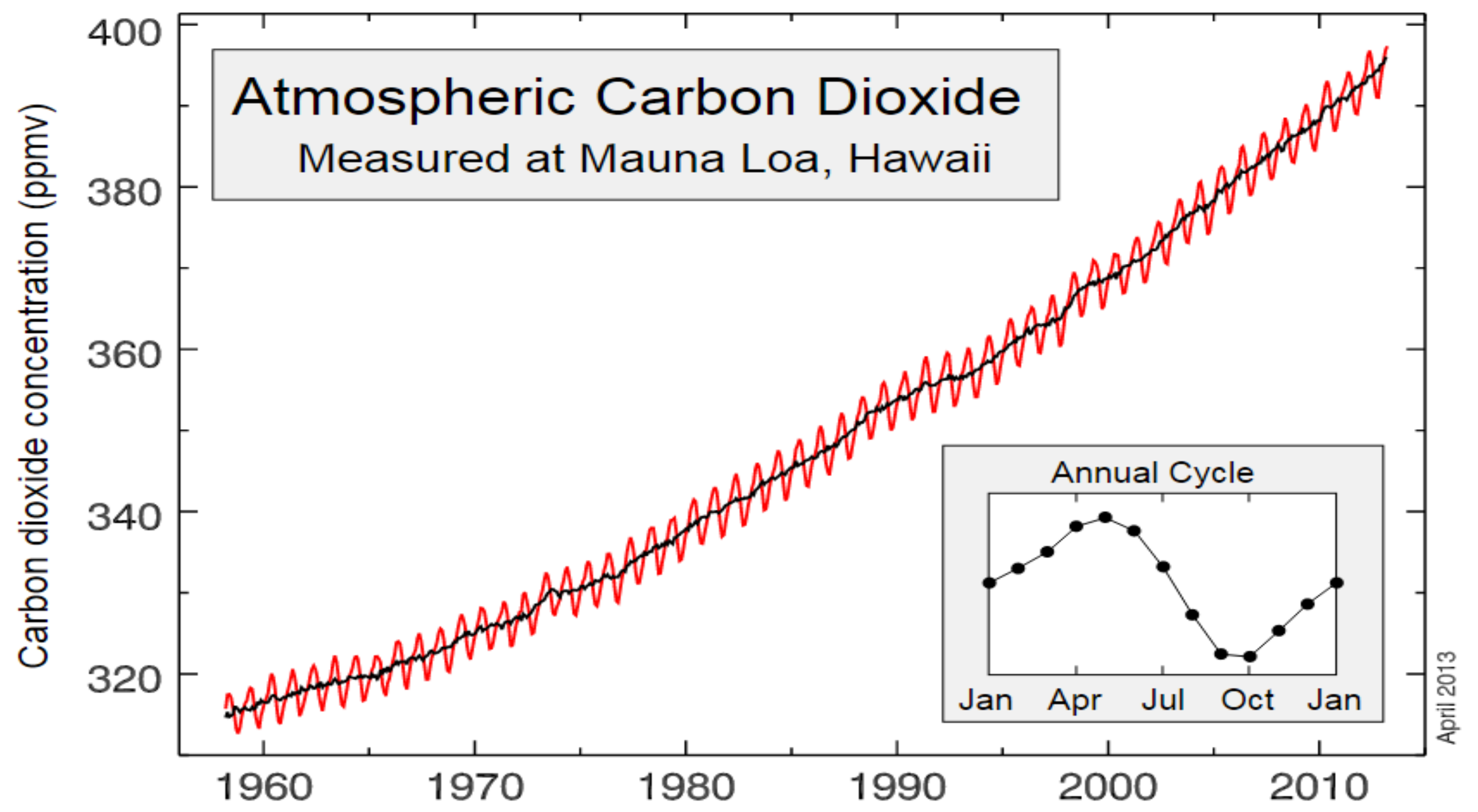
● Projection for 2014 : 37.0 ± 1.9 $GtCO_2$, 65% over 1990

Uncertainty is ±5% for one standard deviation (IPCC “likely” range)

Estimates for 2011, 2012, and 2013 are preliminary

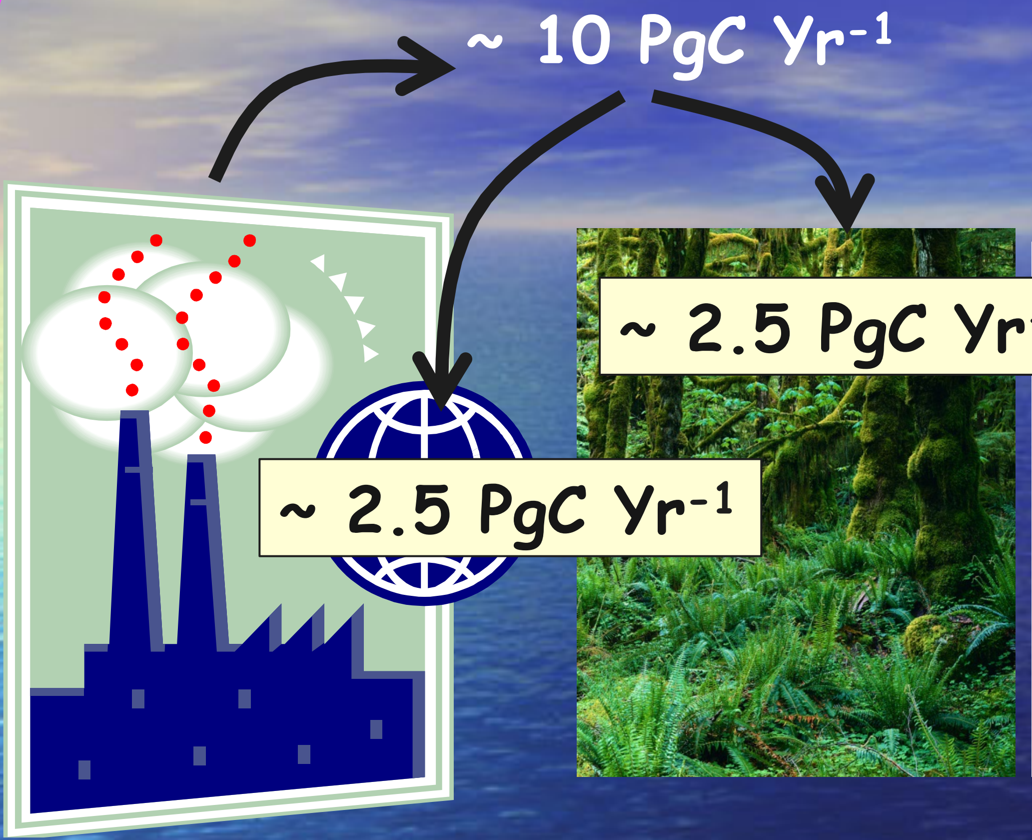
Source: CDIAC; Le Quéré et al 2014; Global Carbon Budget 2014

Anthropogenic accumulation of CO_2 in recent past



Keeling Curve

Contemporary carbon budget: The Partitioning

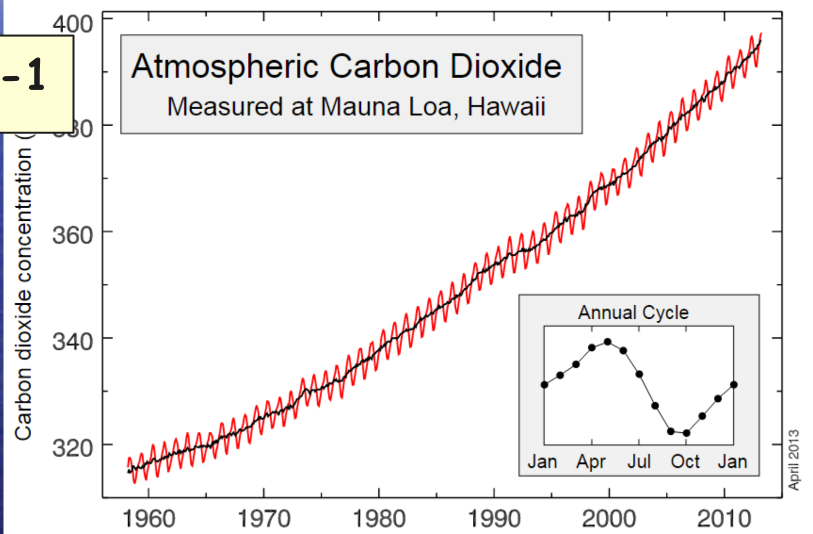


~ 10 PgC Yr^{-1}

~ 2.5 PgC Yr^{-1}

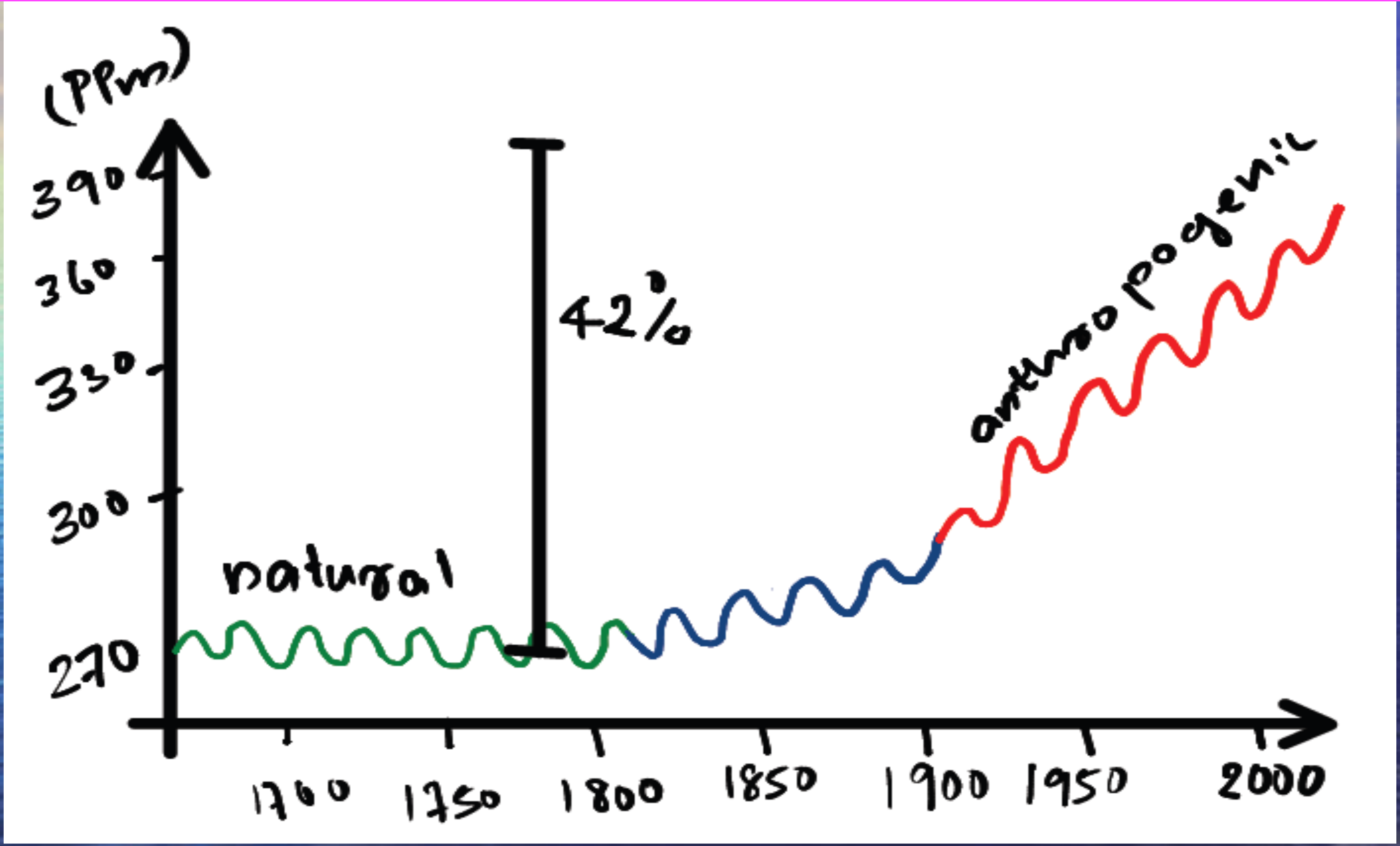
~ 2.5 PgC Yr^{-1}

Atmospheric CO$_2$ since 1950

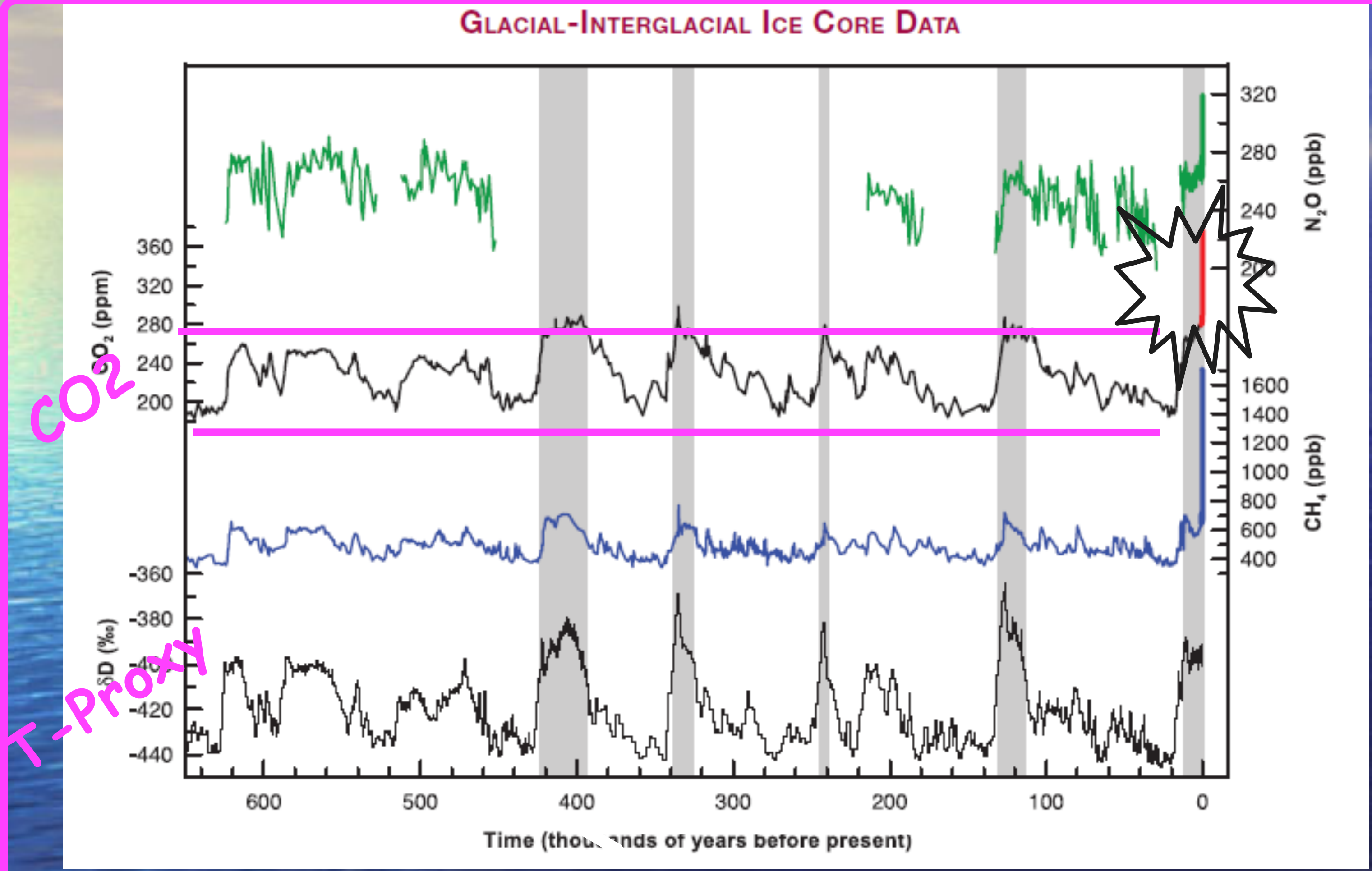


Ocean and land absorbs ~ 50% of global total CO$_2$ emission (numbers are from GCP, 2014 budget)

Atmospheric CO_2 from 1700 to 2010



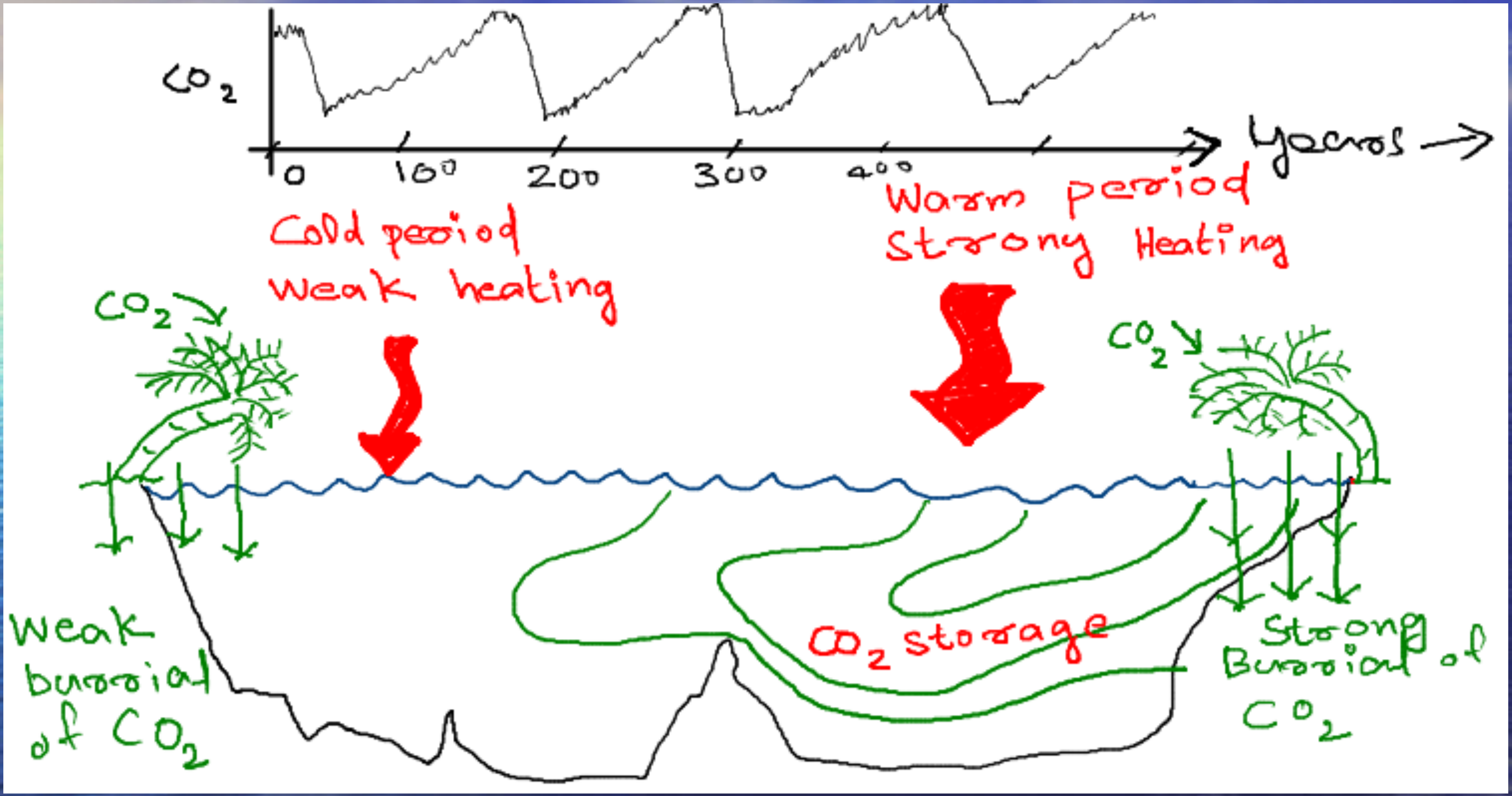
Atmospheric CO_2 record since 700-k Yr B.P.



Petit et al, 1999, Nature

700-k 500-k 300-k 100-k 0 Kilo-years

Milankovitch Cycle and Carbon Feedbacks within Earth System



How do we estimate these carbon exchanges (or fluxes) ?

Bottom-up approach

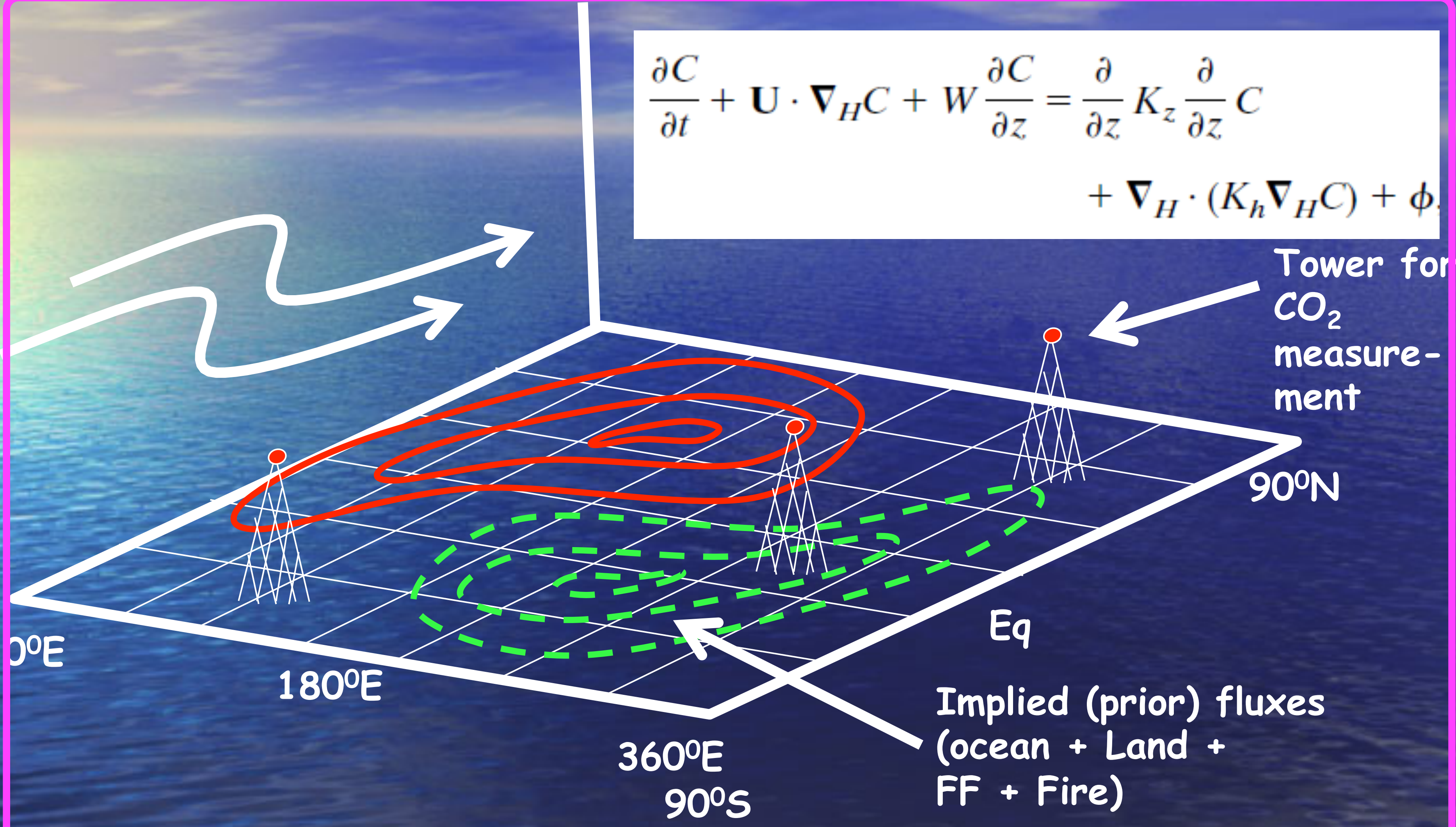
Process based modeling, ground based observations, Eddy covariance, Inventories, data assimilation etc.

Top-down approach

Inverse inferring of the fluxes by atmospheric concentrations of CO_2 and transport functions.

Top-down estimates of CO$_2$ fluxes:

$$\frac{\partial C}{\partial t} + \mathbf{U}\cdot\nabla_H C + W\frac{\partial C}{\partial z} = \frac{\partial}{\partial z}K_z\frac{\partial}{\partial z}C + \nabla_H\cdot(K_h\nabla_H C) + \phi$$



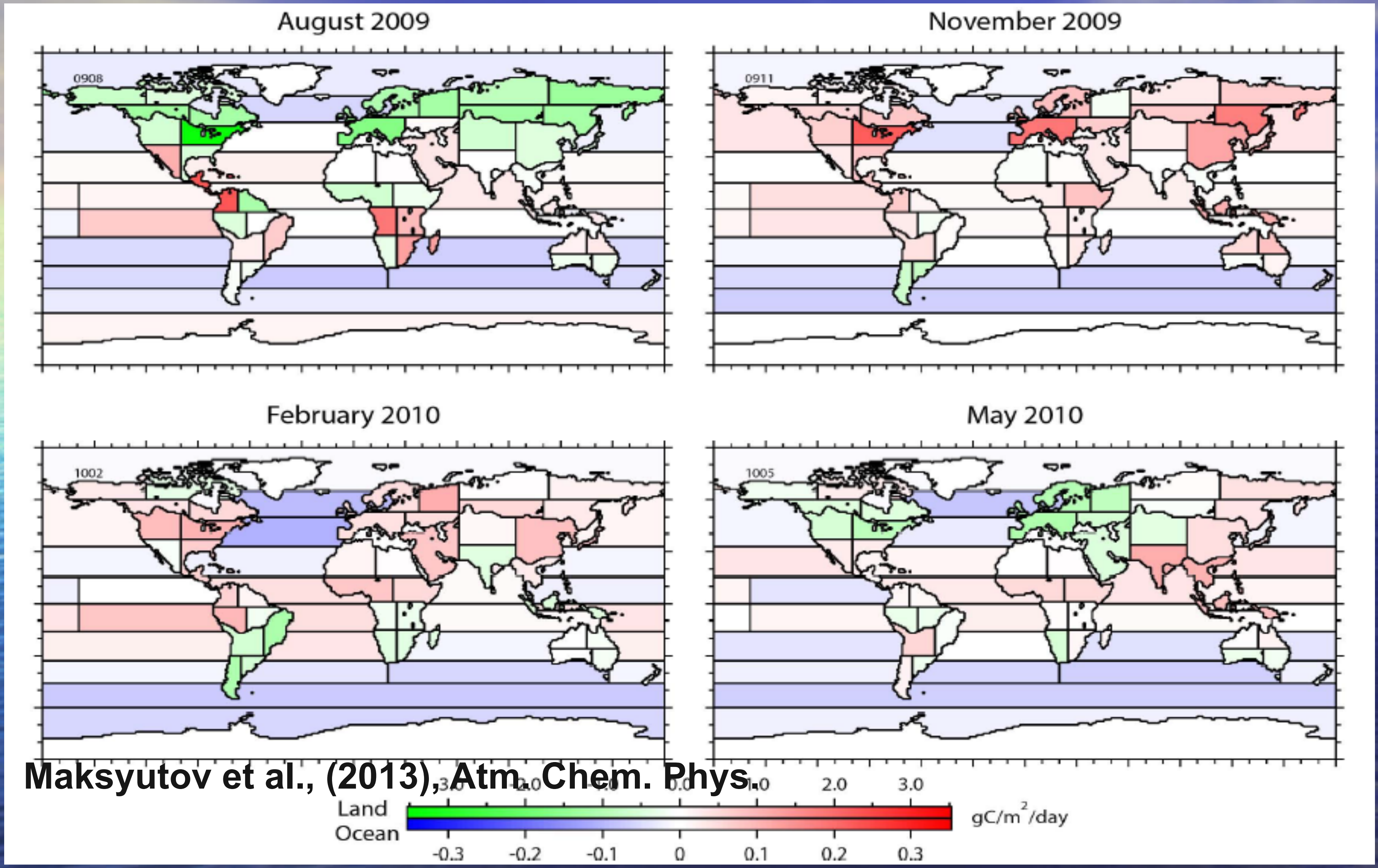
Model and observation errors.

$$J = (Hx - x_0)C_d^{-1}(Hx - x_0) + (\Phi - \Phi_0)C_\Phi^{-1}(\Phi - \Phi_0)$$

In least square theory, the Bayesian inversion suggest that the model and observational misfit are minimized if the fluxes are implied by

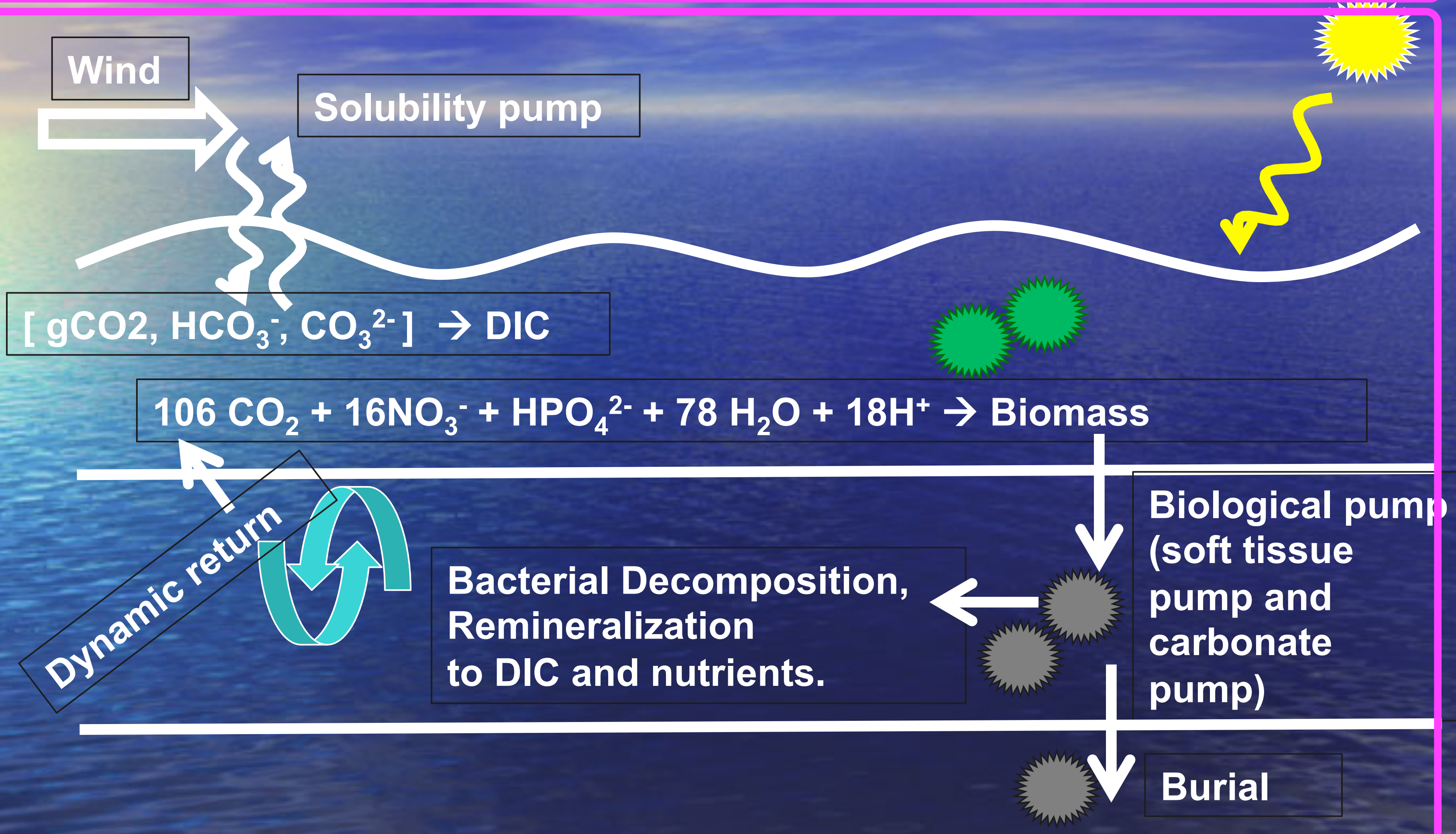
$$\Phi = \Phi_0 + \left(G^T C_d G^{-1} + C_\Phi^{-1}\right)^{-1} G^T C_d^{-1}(D - G\Phi_0)$$

Inverted CO_2 fluxes in a global inversion of 64 regions



Maksyutov et al., (2013), Atm. Chem. Phys.

Bottom-up approach: Process based modeling of Carbon fluxes: An oceanic view



Wind

Solubility pump

[gCO2, HCO_3^-, CO_3^{2-}] → DIC

$106\ CO_2 + 16NO_3^- + HPO_4^{2-} + 78\ H_2O + 18H^+ \rightarrow$ Biomass

Dynamic return

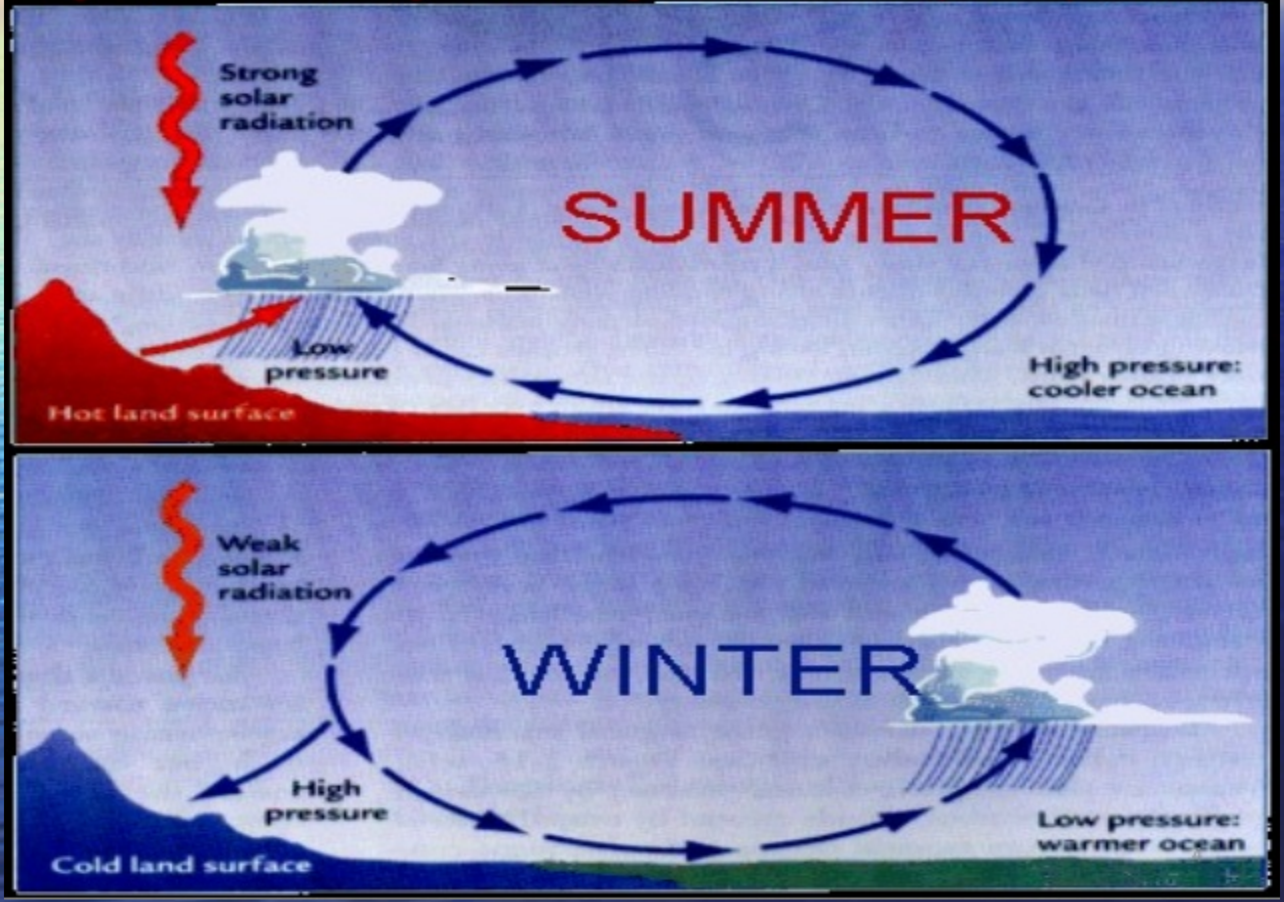
Bacterial Decomposition,
Remineralization
to DIC and nutrients.

Biological pump (soft tissue pump and carbonate pump)

Burial

South Asian Monsoon Dynamics and it's role in carbon cycle

Fig-1:Thermal concept of the origin of monsoon by Halley (1686)



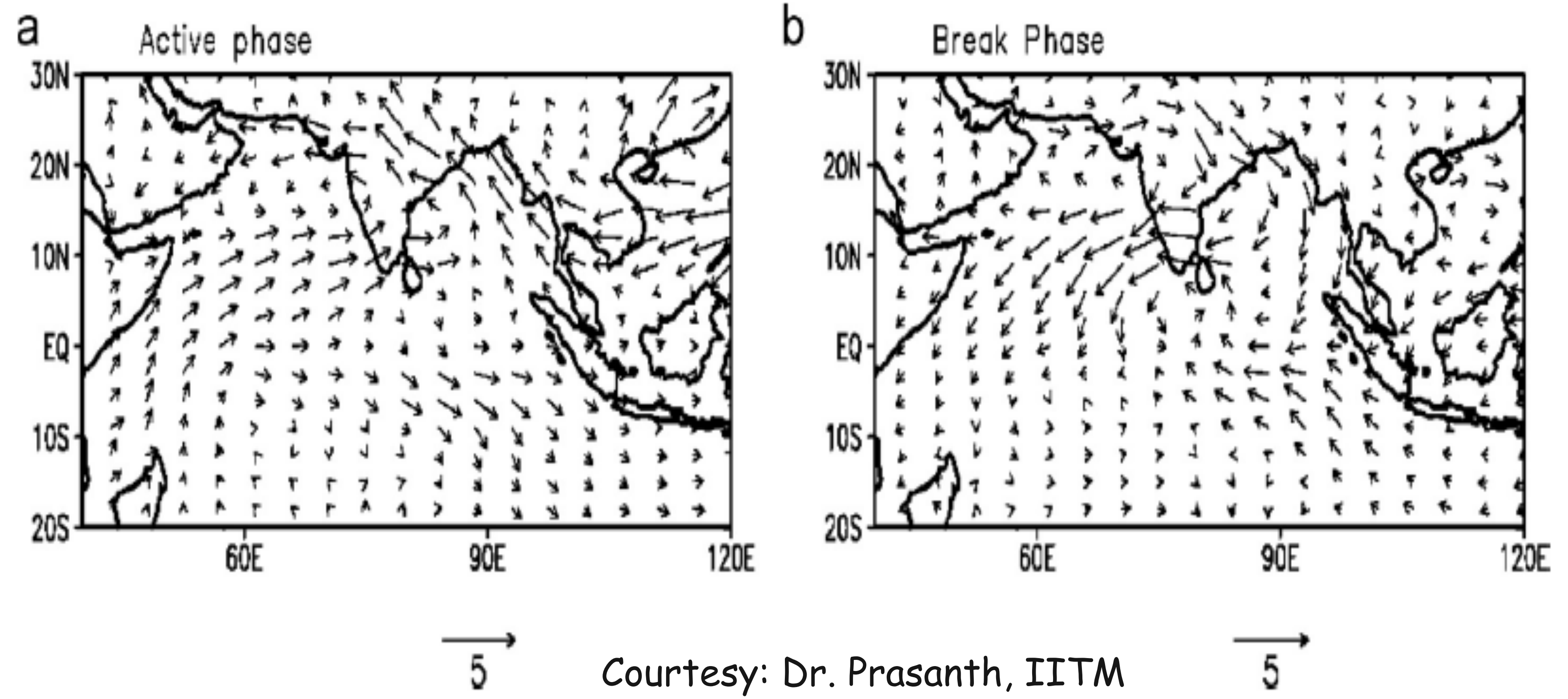
©https://blog.extension.uga.edu/climate/2015/06/monsoon-returns-late-to-india/

Monsoon Dynamics and it's role in carbon cycle (Biospheric, Oceanic CO_2 and CH_4)

- **Intra-seasonal scales**
- **Mean and Seasonal cycle**
- **Inter-annual and Decadal**

Indian Summer monsoon comes with systematic oscillatory nature in Monsoon Dynamics at intra-seasonal scales (20-60 days)

Sikka and Gadgil (1980), Goswami et al., (2006)



Courtesy: Dr. Prasanth, IITM

June to September CO_2 Net Ecosystem Exchange (NEE) in mole m^{-2} yr^{-1}.

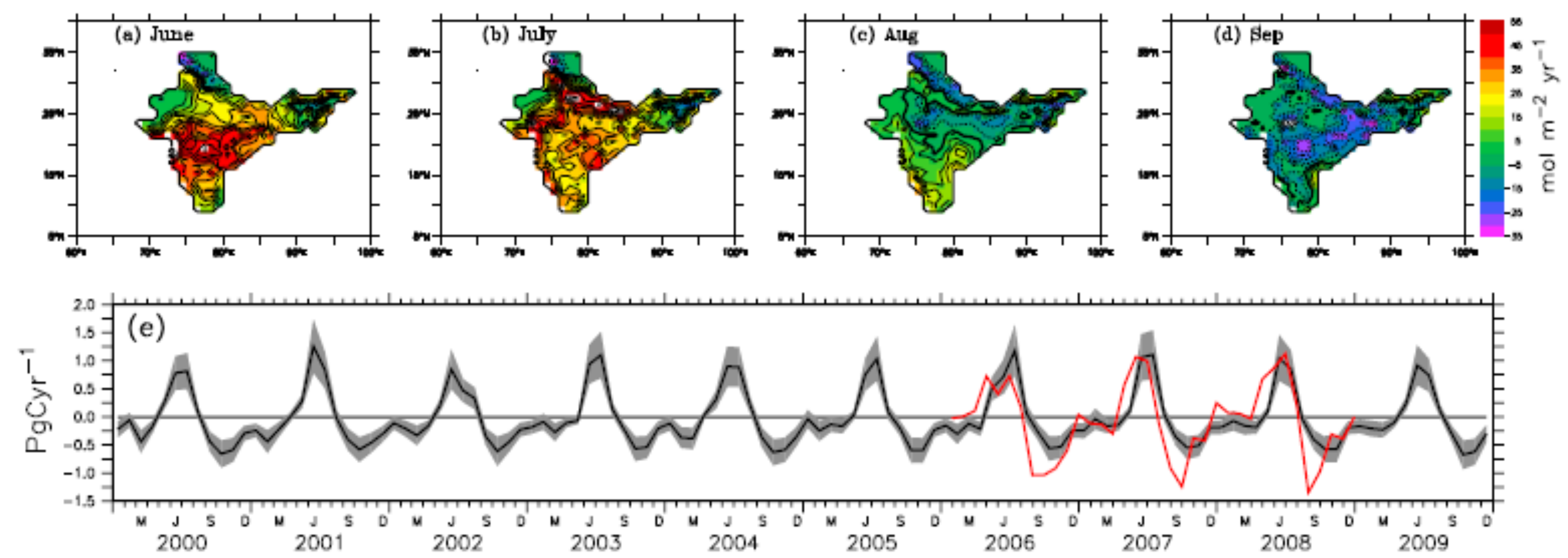


Figure 2. Monthly mean CO_2 fluxes over continental India during (a) June, (b) July, (c) August, and (d) September derived for 2000 to 2009 from CT data are shown. The anomalous years 2002 and 2004 are not included in the mean. The transition of CO_2 source to sink during summer monsoon rainfall is highlighted in Figures 1a–1d. Positive values show CO_2 sources. Units are in mol $m^{-2}yr^{-1}$. (c) Seasonal cycle (line) and daily standard deviations during each month (shades) of area-integrated land-air CO_2 fluxes from 2000 to 2009.

(Boundary shown is the grid cell boundaries at 2.5x2.5 degrees)

June to September CO2 Net Ecosystem Exchange (NEE) in mole m^{-2} yr^{-1}.

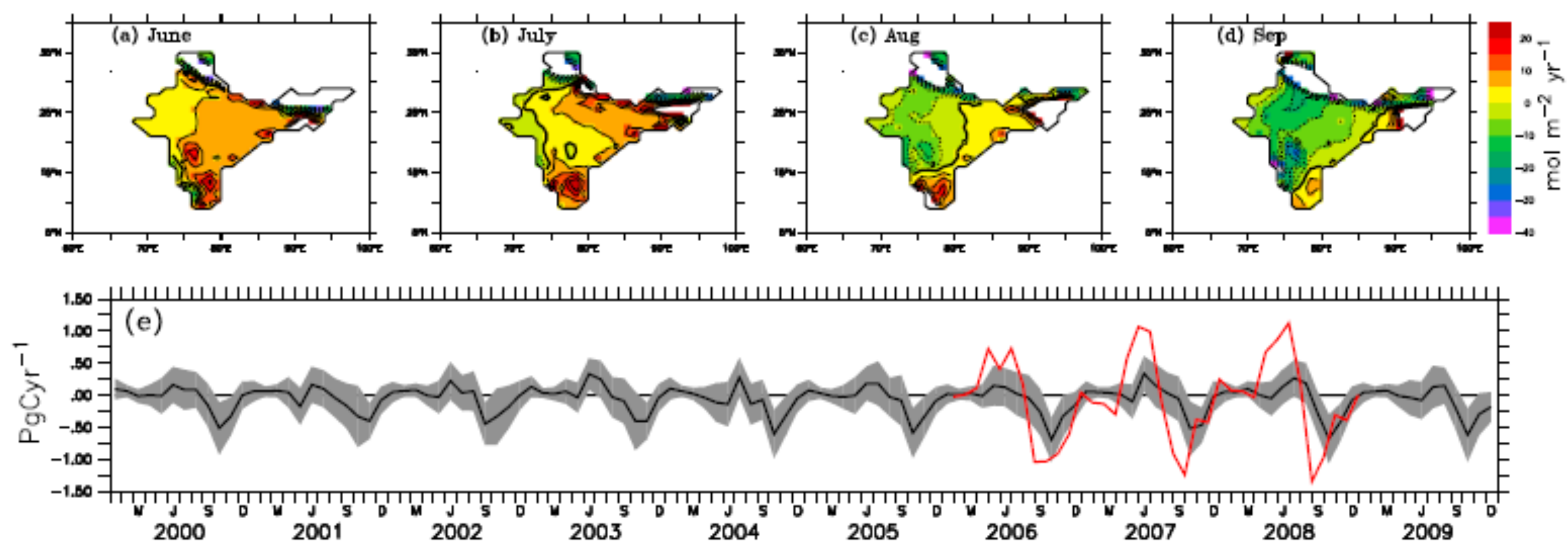


Figure 3. Same as Figure 2 but from VISIT data.

Data Source:

- Carbon tracker data from NOAA (previous page)
- VISIT NEE Processes based model (this page)
- Red lines (Inversion estimates)

(Boundary shown is the grid cell boundaries at 2.5x2.5 degrees)

Spatial pattern of dominant periodicity within 30-60 day scale of NEE oscillations (scale in days)

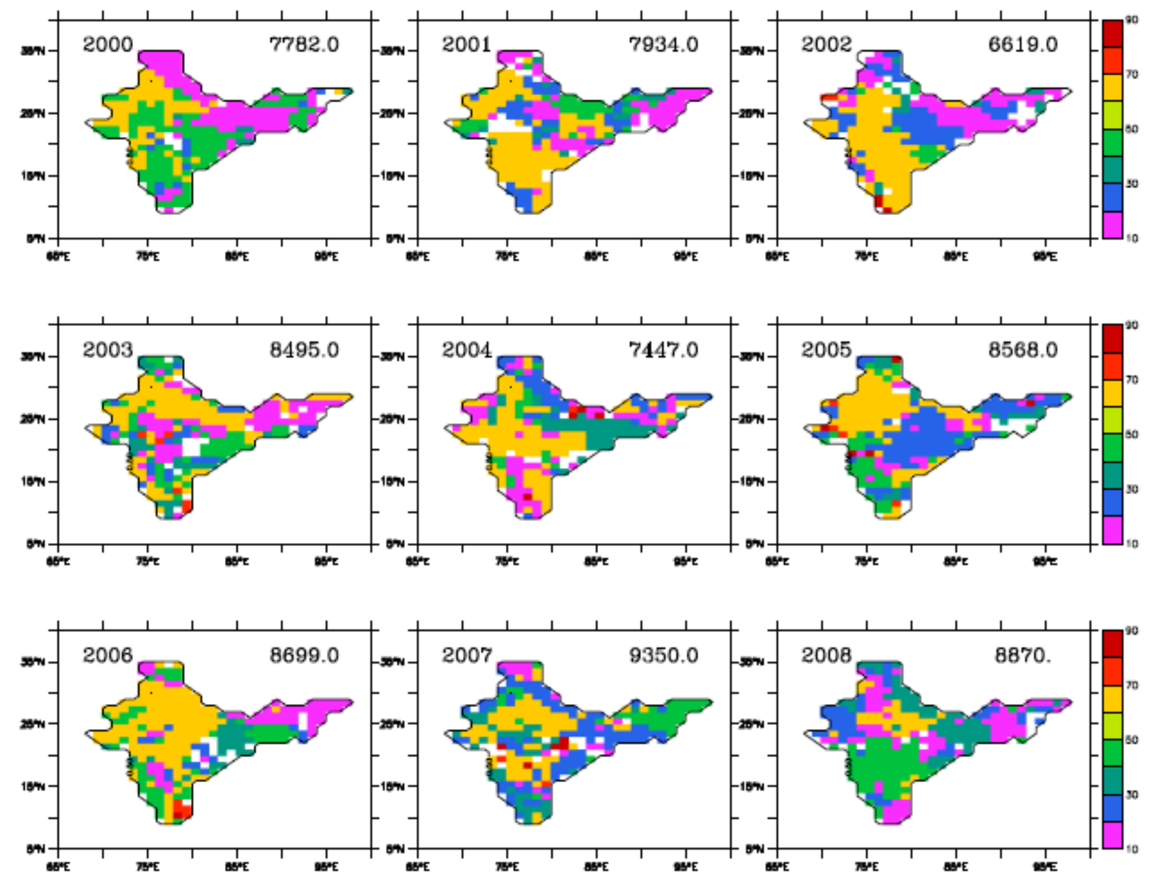


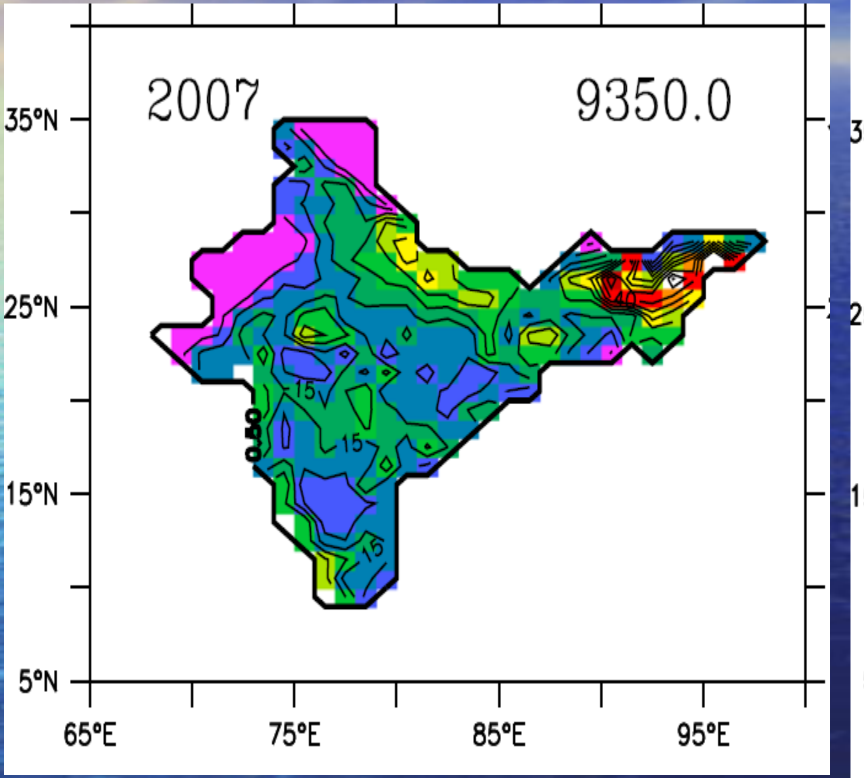
Figure 4. Spatial pattern of periodicity (in days) of maximum power of variability of daily fluxes for the four summer monsoon months from June to September. Patterns are shown for each year separately. The annual mean rainfall for each year is shown on top right of each panel.

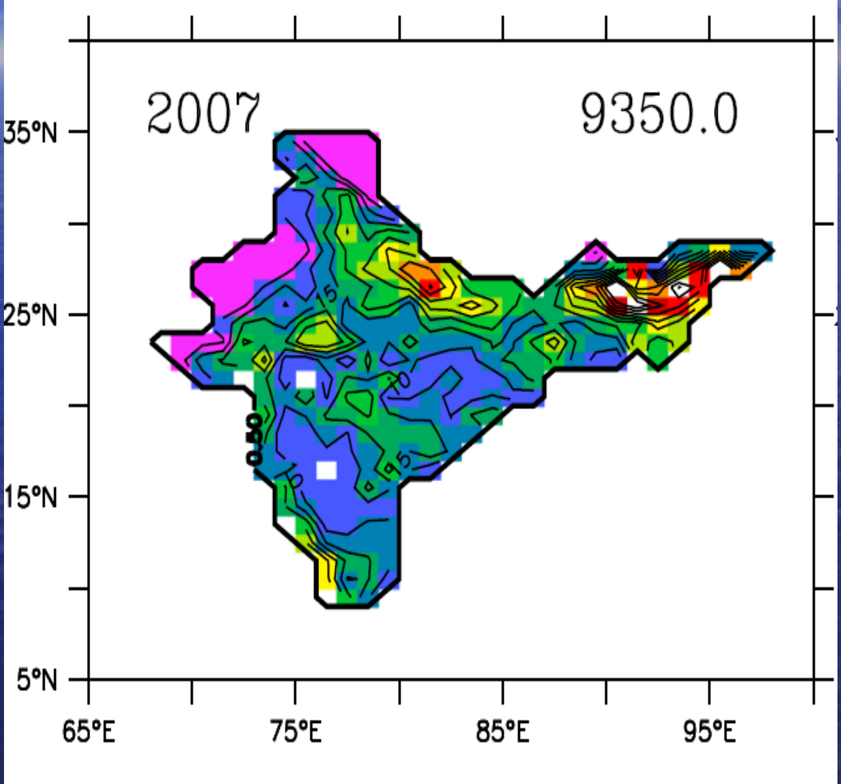
Year 2000 to 2008 are shown.

A dry monsoon year generally comes with a longer periodicity in NEE short term variability
Valsala et al., (JGR, 2013)

(Boundary shown is the grid cell boundaries at 2.5x2.5 degrees)

Spatial pattern of composite NEE (emission, left) and absorption, right) at ISO scale





(Boundary shown is the grid cell boundaries at 2.5x2.5 degrees)

Coherent structures of NEE CO_2 and key atmospheric variables at ISO scale

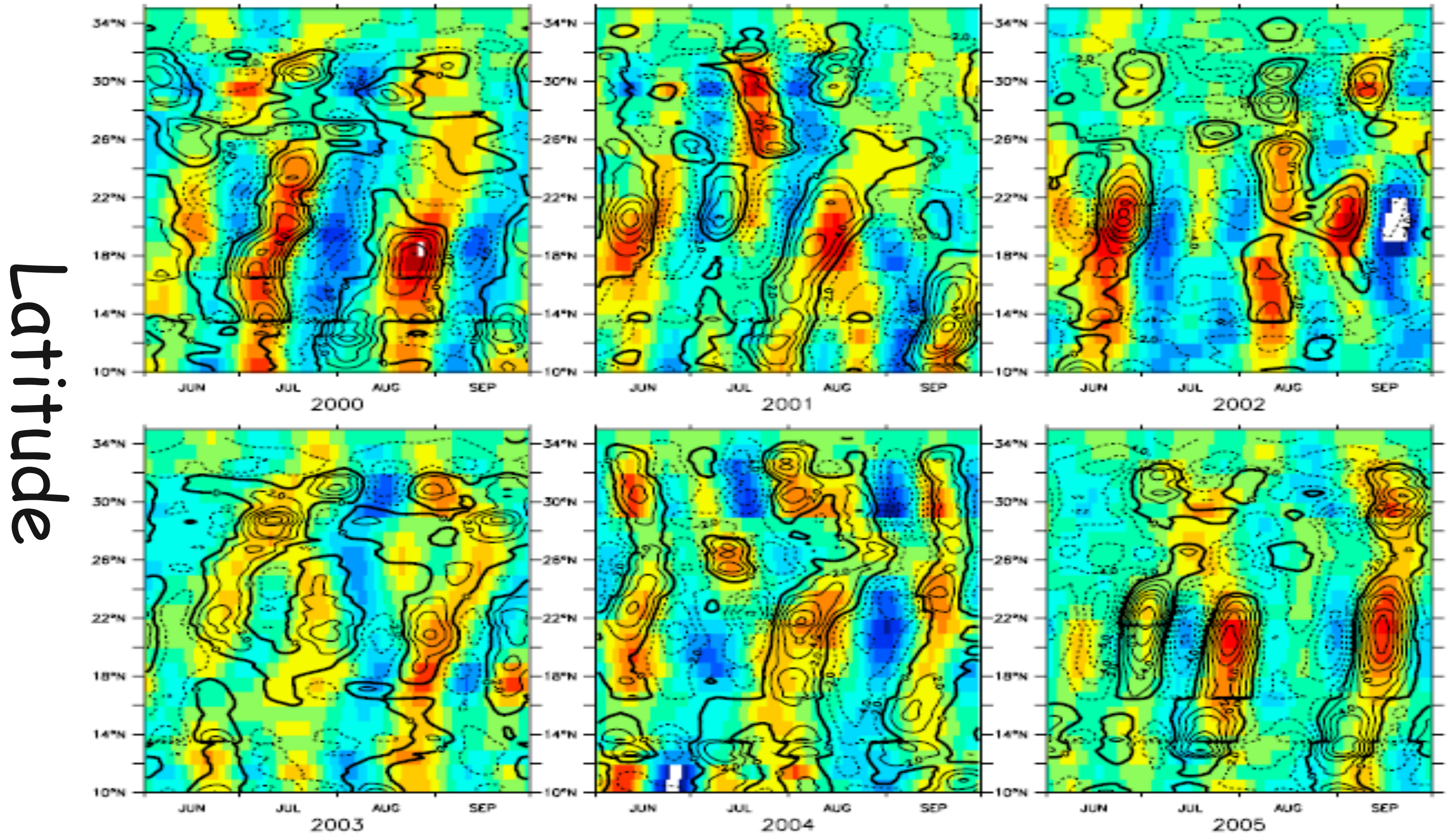
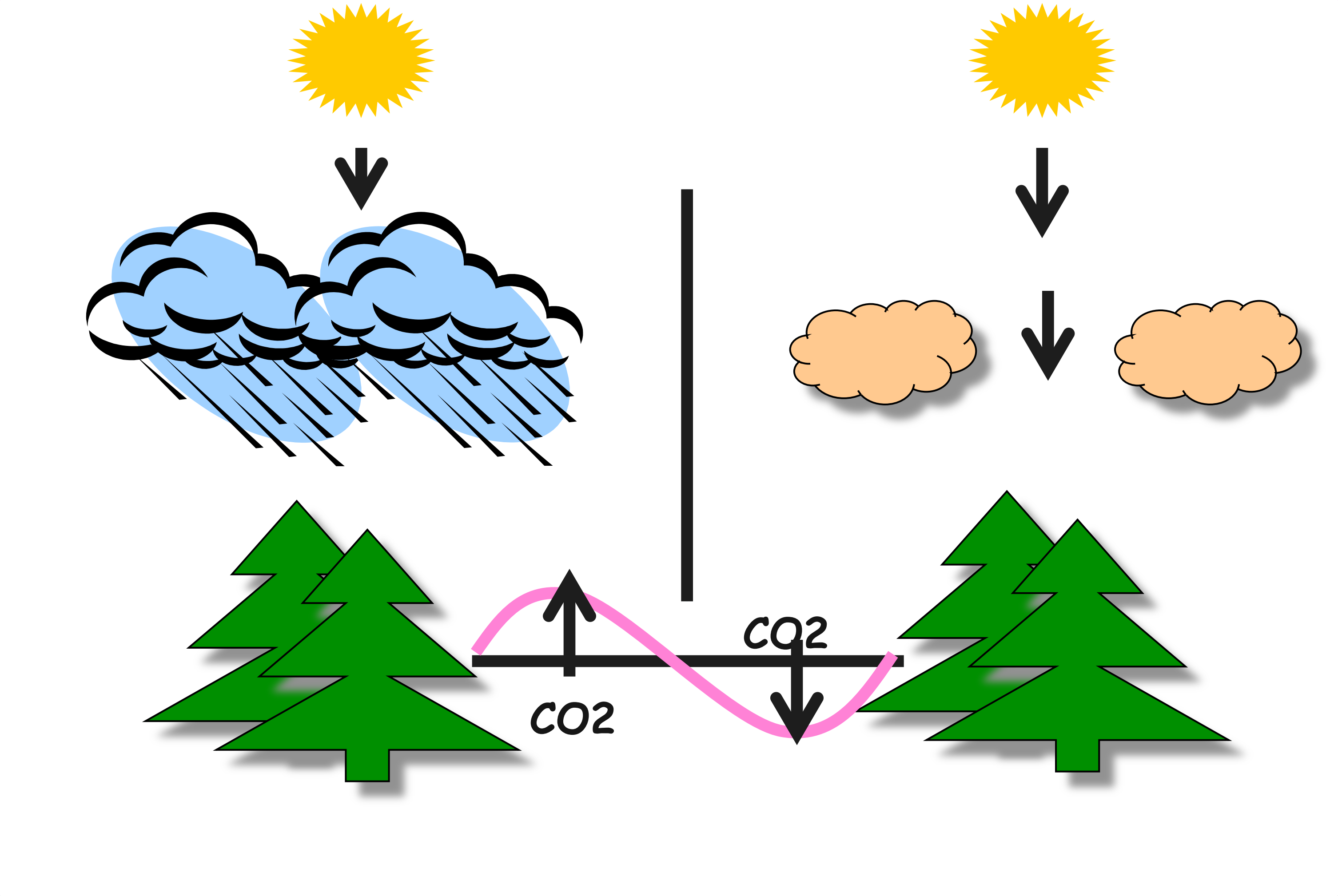


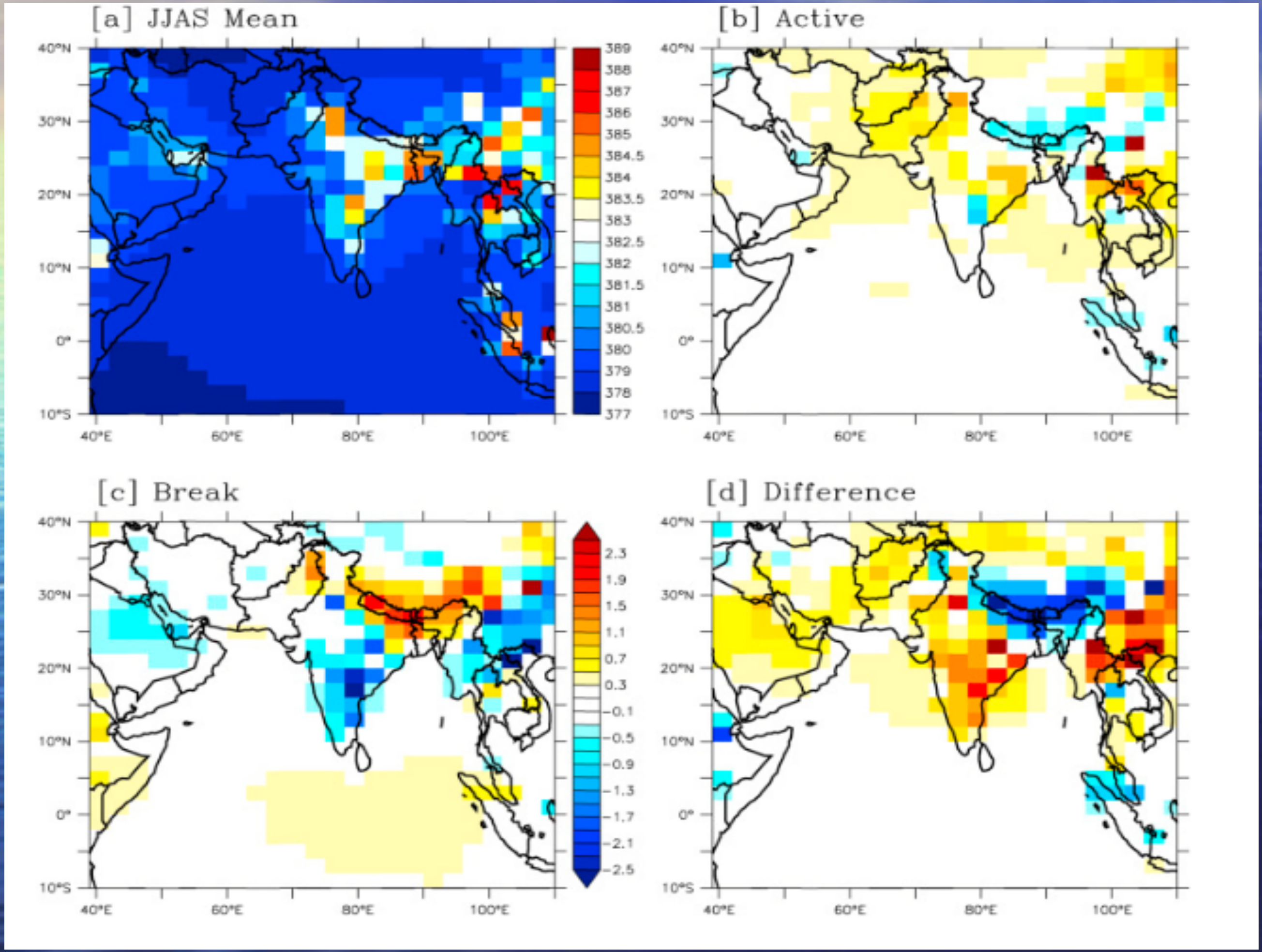
Figure 10. The 30–60 day filtered and zonally integrated (over 65°E-95°E) CO_2 fluxes (shades) and daily rainfall (contours).

Composite evolutions of biospheric CO_2 and atmospheric variables during active-break-active cyclae of monsoon



2013)

Composite evolutions of atmospheric CO_2 concentrations during active and break cycle of monsoon



AIRIS satellite XCO_2 data based analysis.

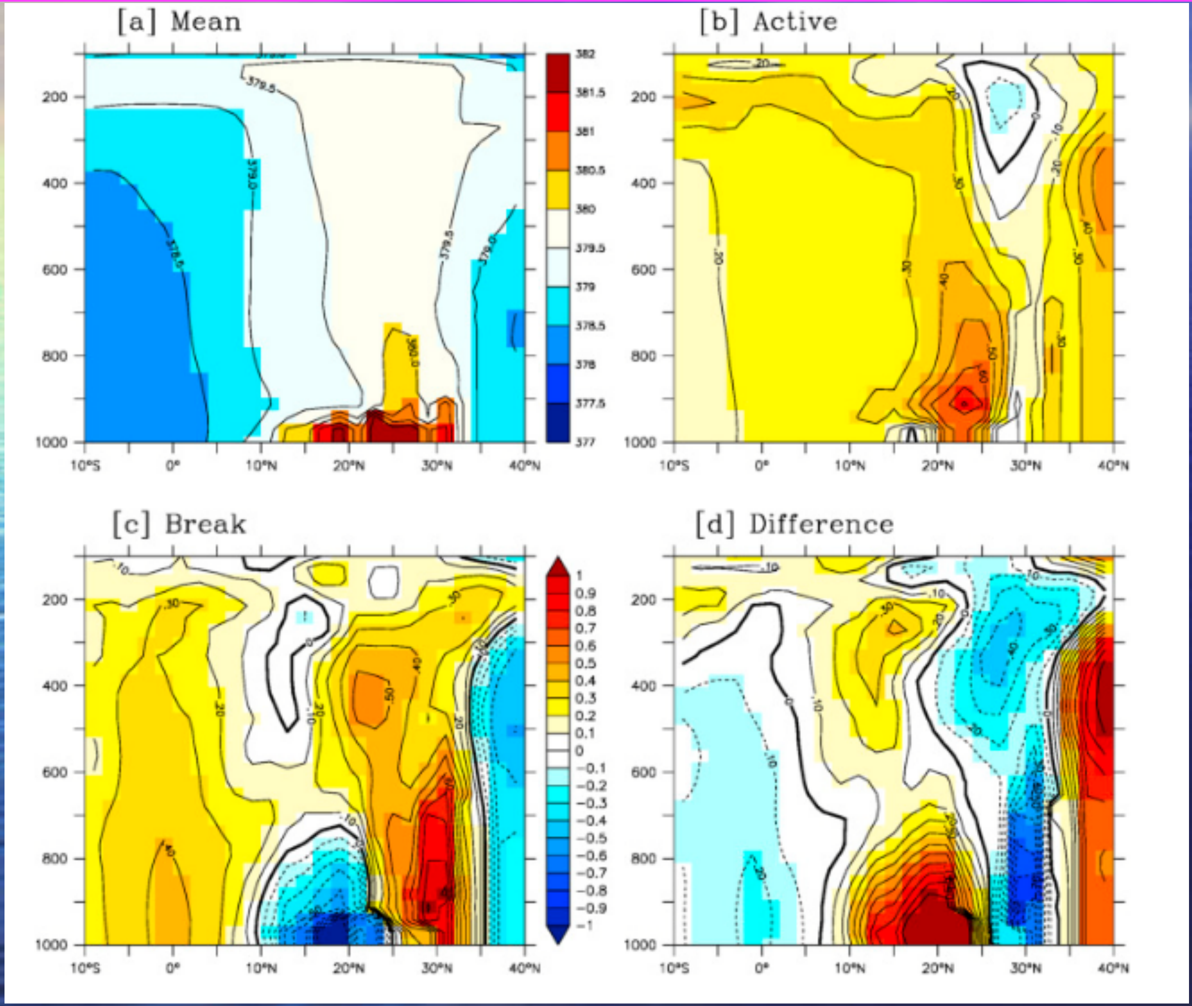
Active phases shows positive XCO_2 anomalies.

Break phases shows negative XCO_2 anomalies.

They are driven by Biosphere-Monsoon interaction.

Ravikumar et al., (Atm. Env., 2016)

Composite evolutions of atmospheric CO_2 concentrations active and break cycle of monsoon



Model XCO_2 based analysis.

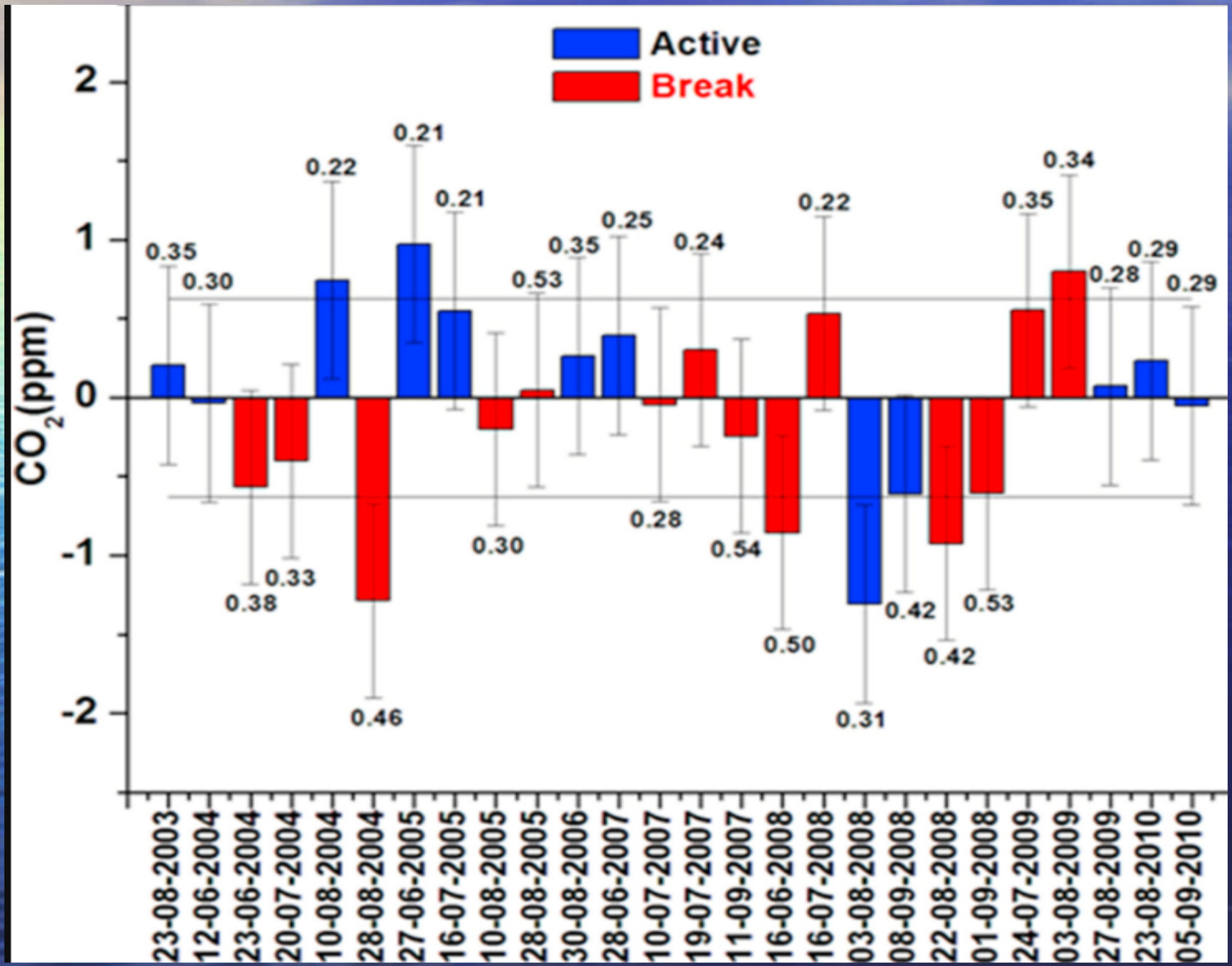
Active phases shows positive XCO_2 anomalies.

Break phases shows negative XCO_2 anomalies.

They are driven by Biosphere-Monsoon interaction.

Ravikumar et al., (Atm. Env., 2016)

Composite evolutions of atmospheric CO_2 concentrations active and break cycle of monsoon



AIRIS satellite XCO_2 data based analysis

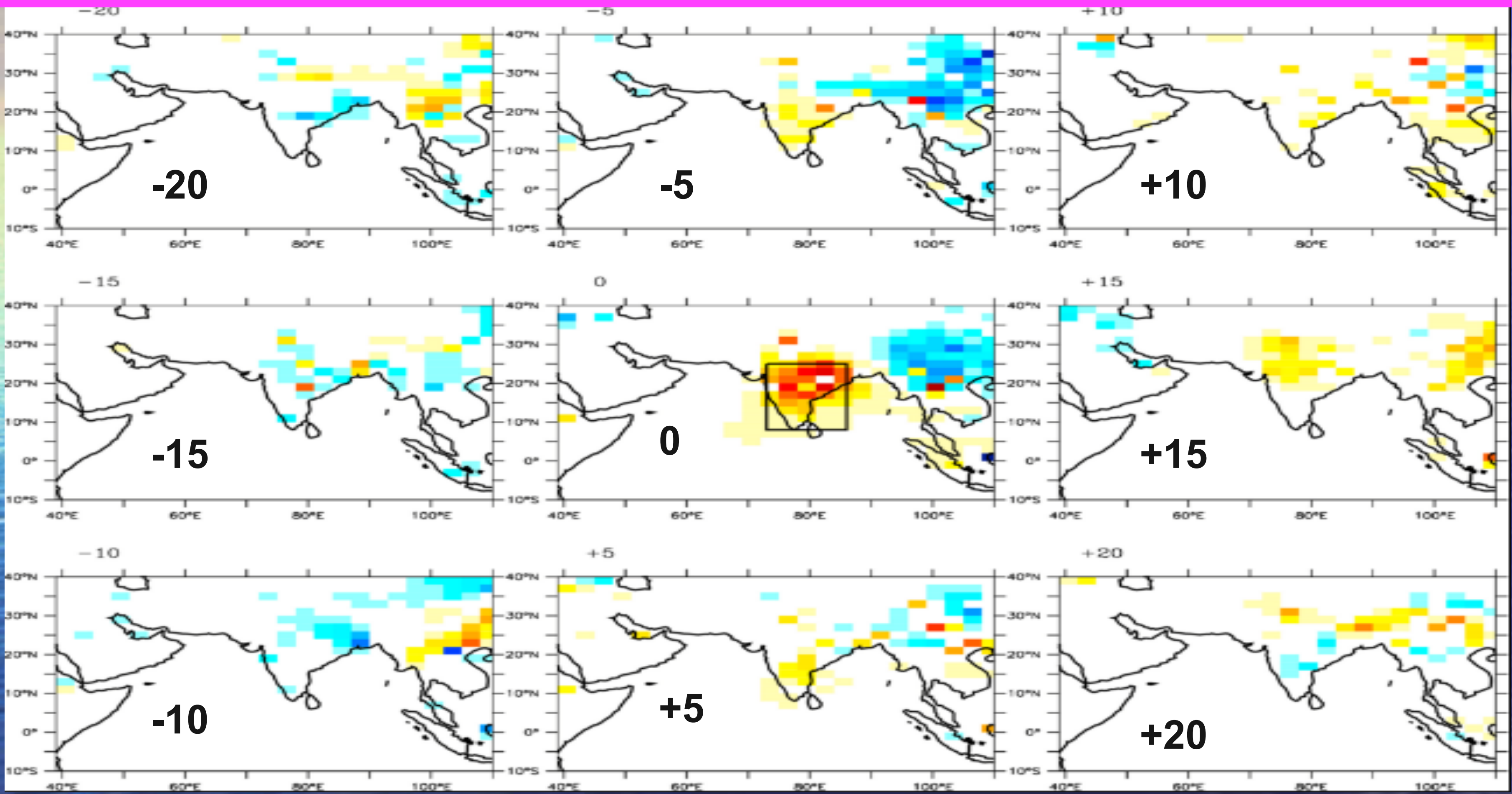
Active phases shows positive XCO_2 anomalies

Break phases shows negative XCO_2 anomalies.

They are driven by Biosphere-Monsoon interaction.

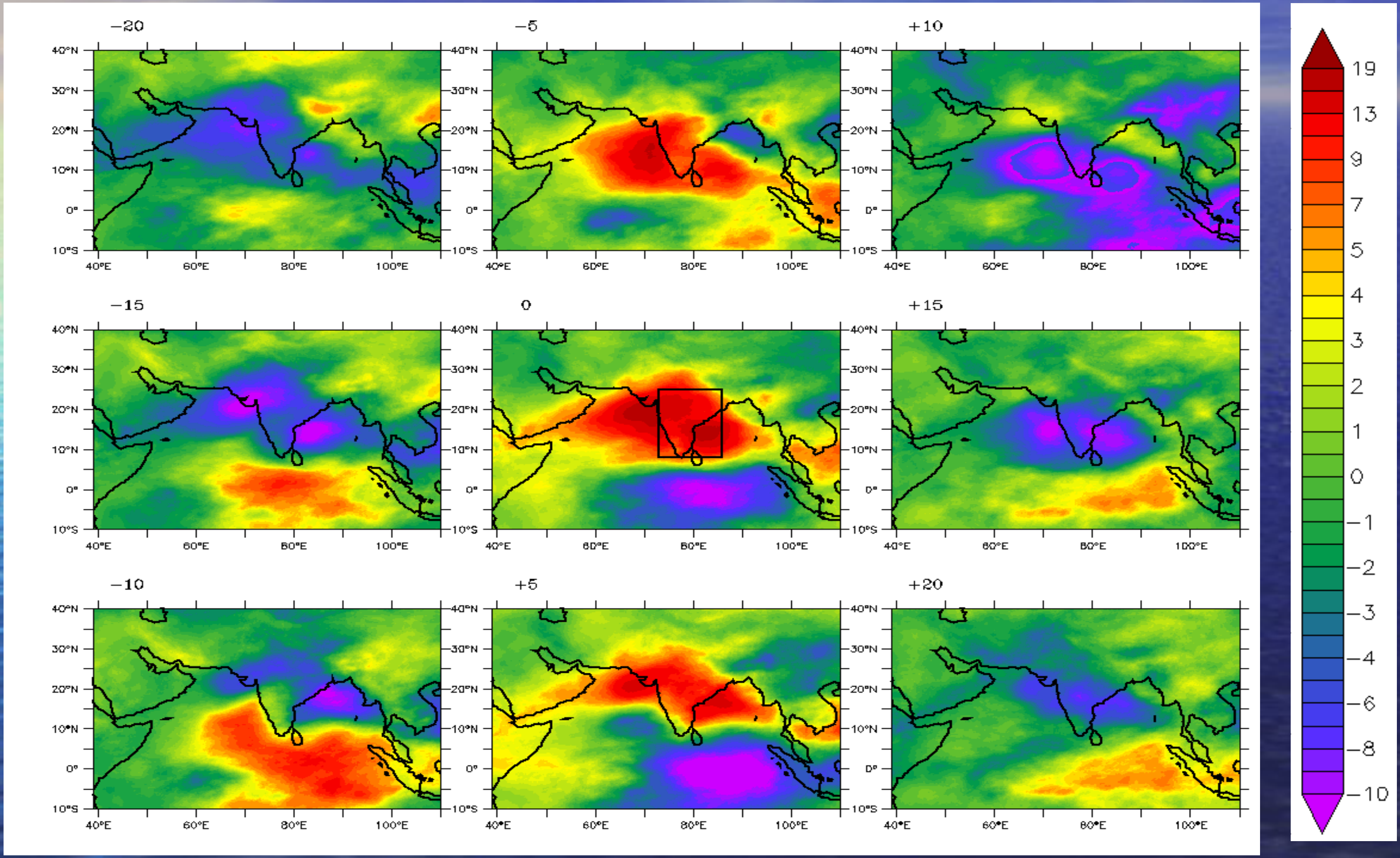
Ravikumar et al., (Atm. Env., 2016)

XCO$_2$ anomalies, however, doesn't get highlighted in the propagation because the NEE source/sink dominates the atmospheric CO$_2$ signal.



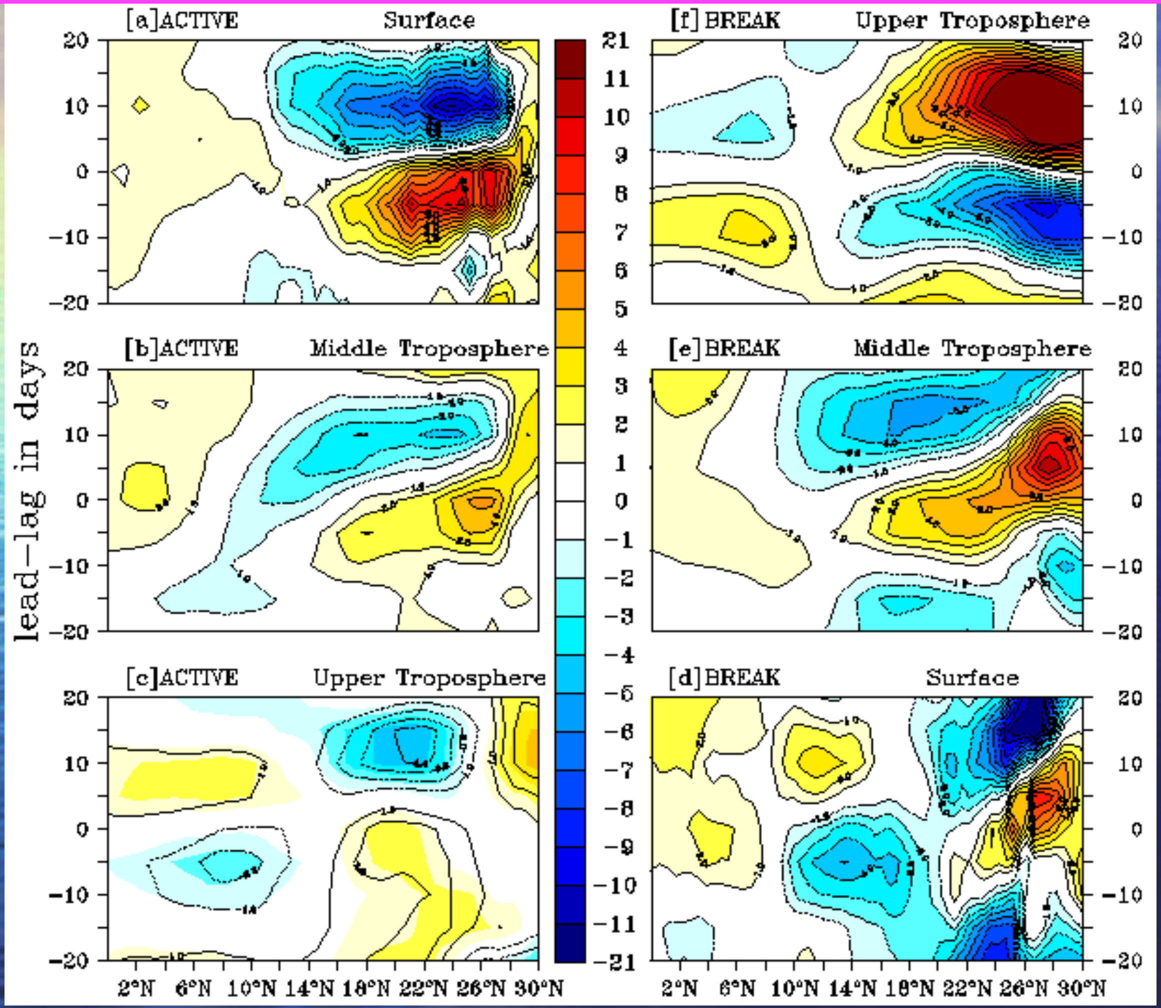
Ravikumar et al., (Atm. Env., 2016)

XCH_4 anomalies, on the other hand, get highlighted in the propagation because the CH_4 source/sink does not dominate in the atmospheric CH_4 signal.



Tania et al. (Manuscript, 2017)

Role of monsoon active/break cycles in atmospheric CH_4 anomalies over India.



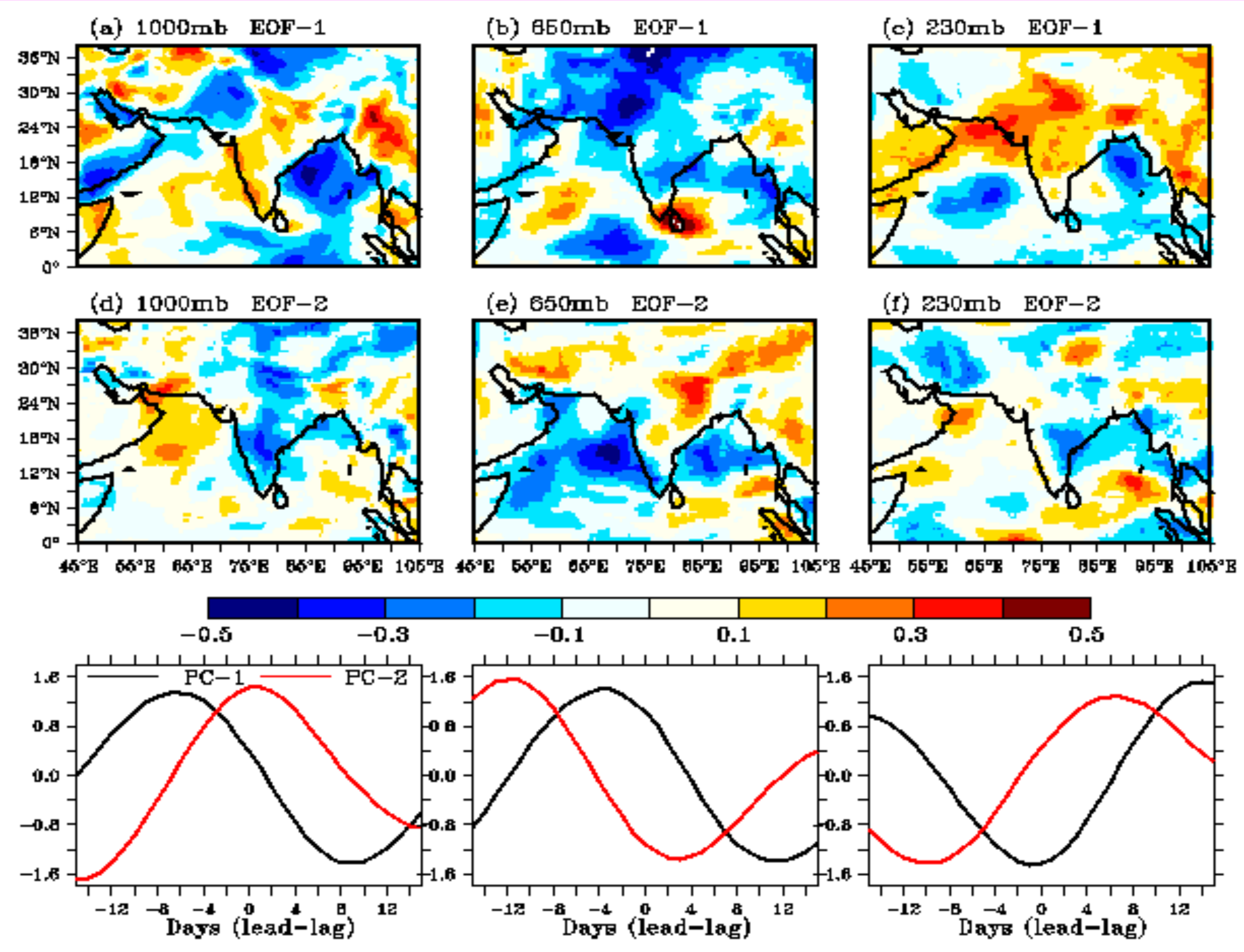
Unlike CO_2, the CH_4 anomalies have very systematic spatio-temporal structures in the ISO scale in all levels of the atmosphere.

The reason is that, the terrestrial source/sink of CH4 does not vary vigorously with monsoon

Therefore the atmospheric CH4 passively transported/ convected in the atmosphere.

Tania et al., (2017)

Role of monsoon active/break cycles in atmospheric CH_4 anomalies over India

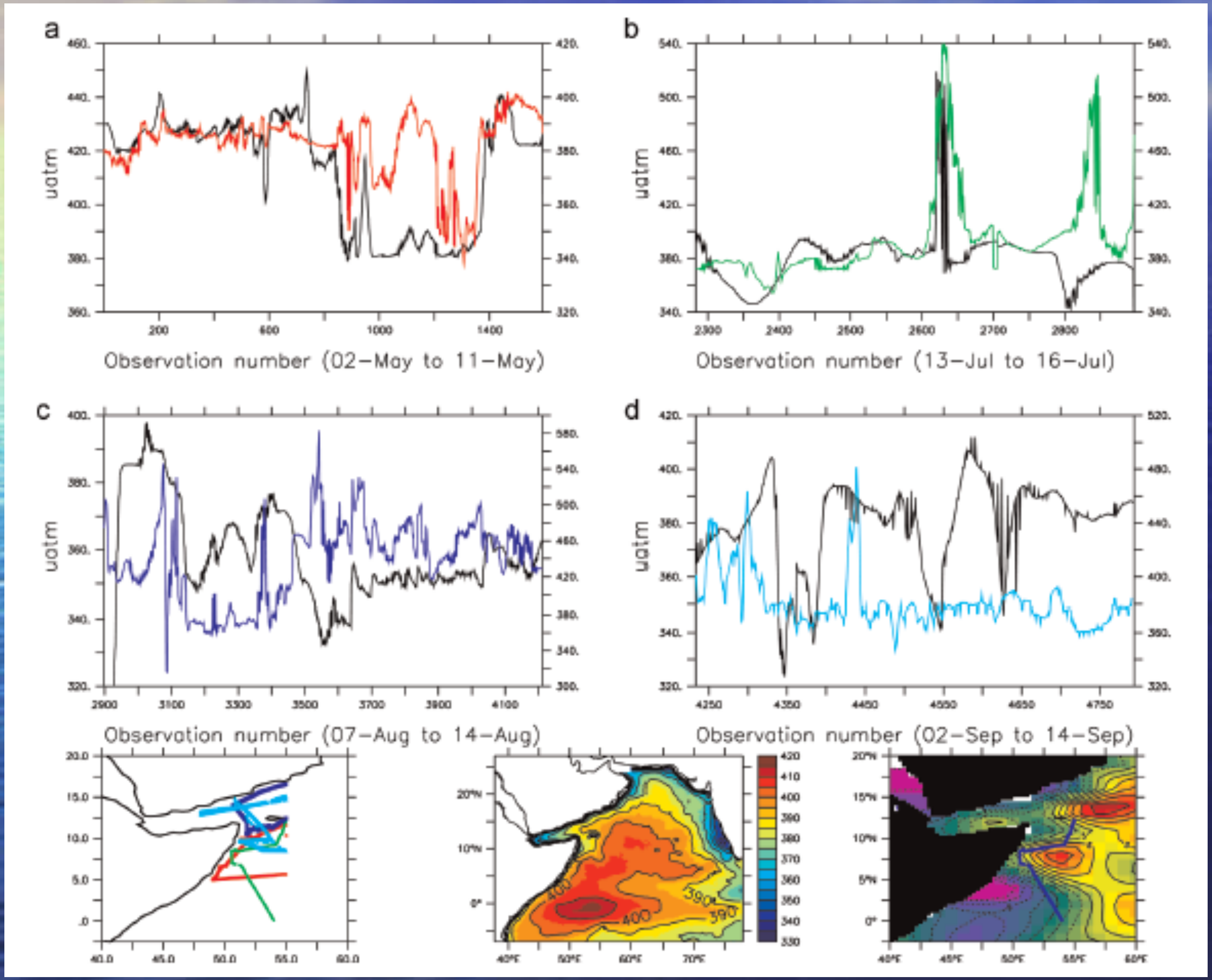


Dominant modes of lead-lag correlations between CH4 anomalies and convection anomalies.

They do have much complex structure

However the CH4 column variability in the atmosphere has little impact in radiative forcing of convection at ISO scales.

Ocean pCO_2 also varies intra-seasonally:
Atmospheric forced
Oceanic instabilities and eddies.



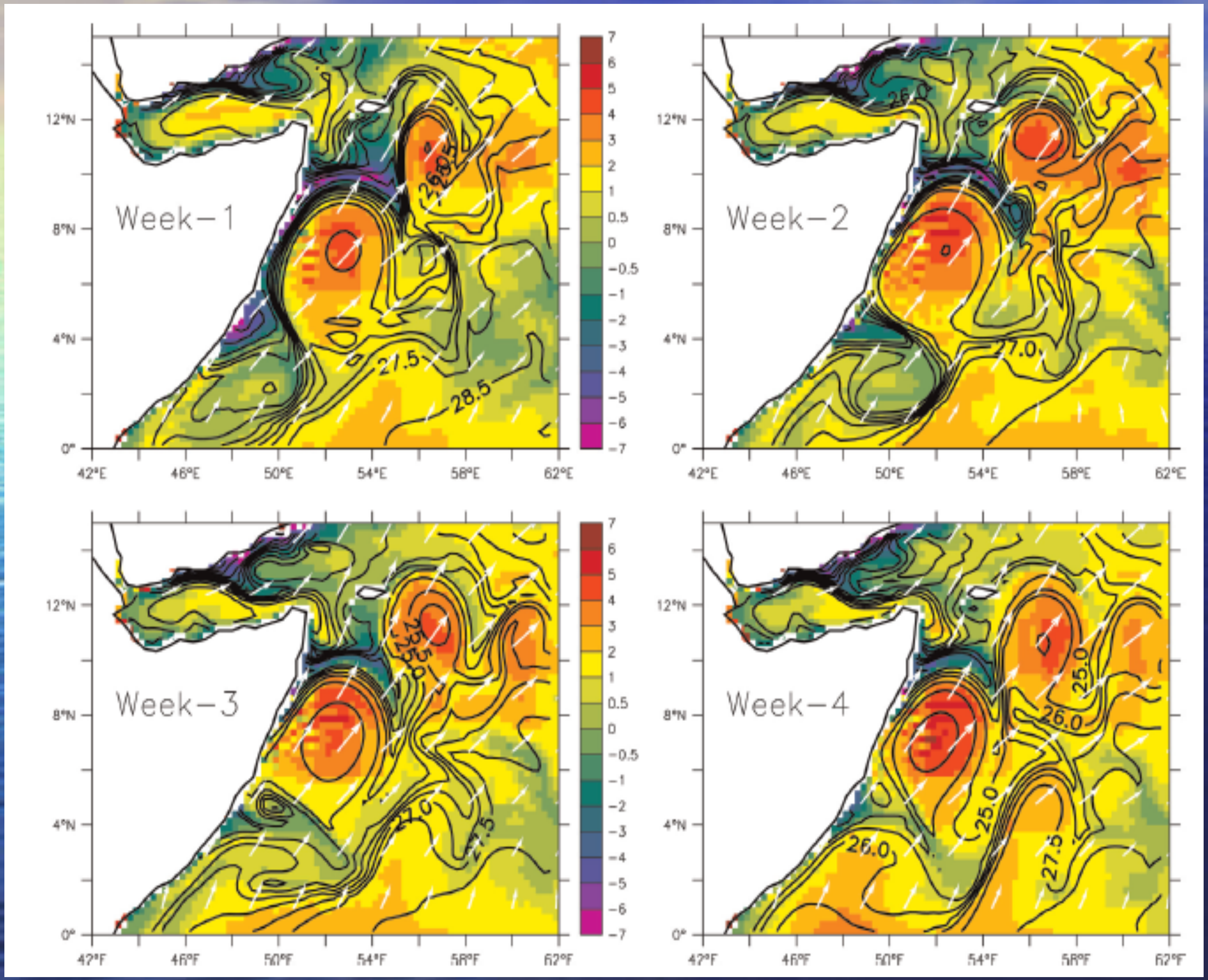
Three difference tracks of ocean pCO_2 by ships and model.

Strong variability at short time-space scale.

Key role of air-sea interaction and oceanic eddies both forced by monsoon dynamics.

Valsala et al., (DSR-I. 2015)

Ocean pCO_2 also varies intra-seasonally:
Atmospheric forced
Oceanic instabilities and eddies.

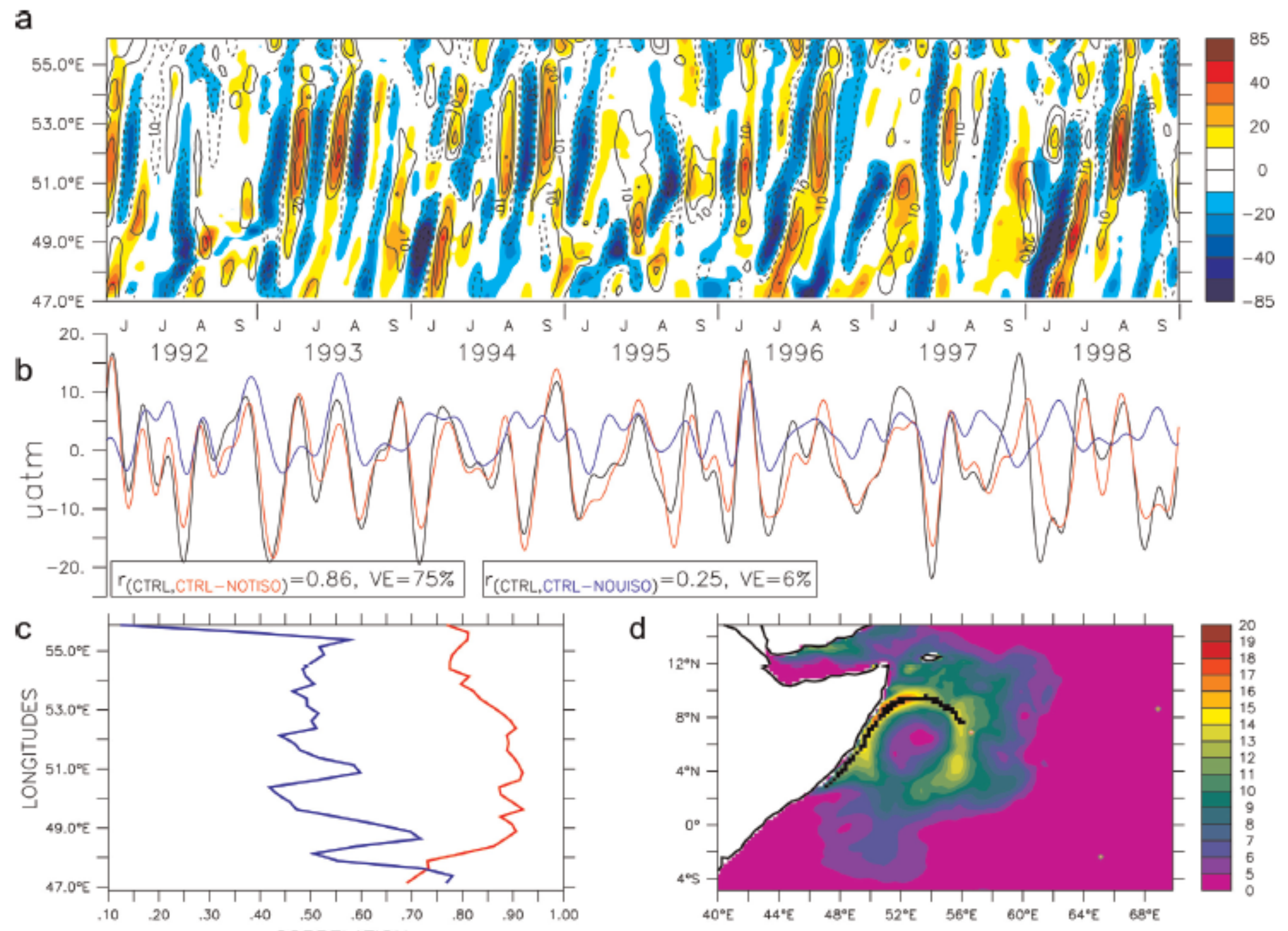


Air-sea CO_2 fluxes (red is emissions, blue is absorption)

Eddies, cold SST wedges, oceanic pCO_2 and air-sea interaction are linked.

Valsala et al., (DSR-I. 2015)

Ocean pCO_2 also varies intra-seasonally:
Atmospheric forced
Oceanic instabilities and eddies.



Coherent structures of SST, pCO_2 and air-sea CO_2 flux all brought by Monsoon Dynamics.

Therefore monsoon ISOs are integral part of carbon cycle variability.

Valsala et al., (DSR-I. 2016)

Monsoon Dynamics and it's role in carbon cycle (Biospheric, Oceanic CO_2 and CH_4)

- Intra-seasonal scales
- **Mean and Seasonal cycle**
- Inter-annual and Decadal

Biosphere responses to mean monsoon and seasonality.

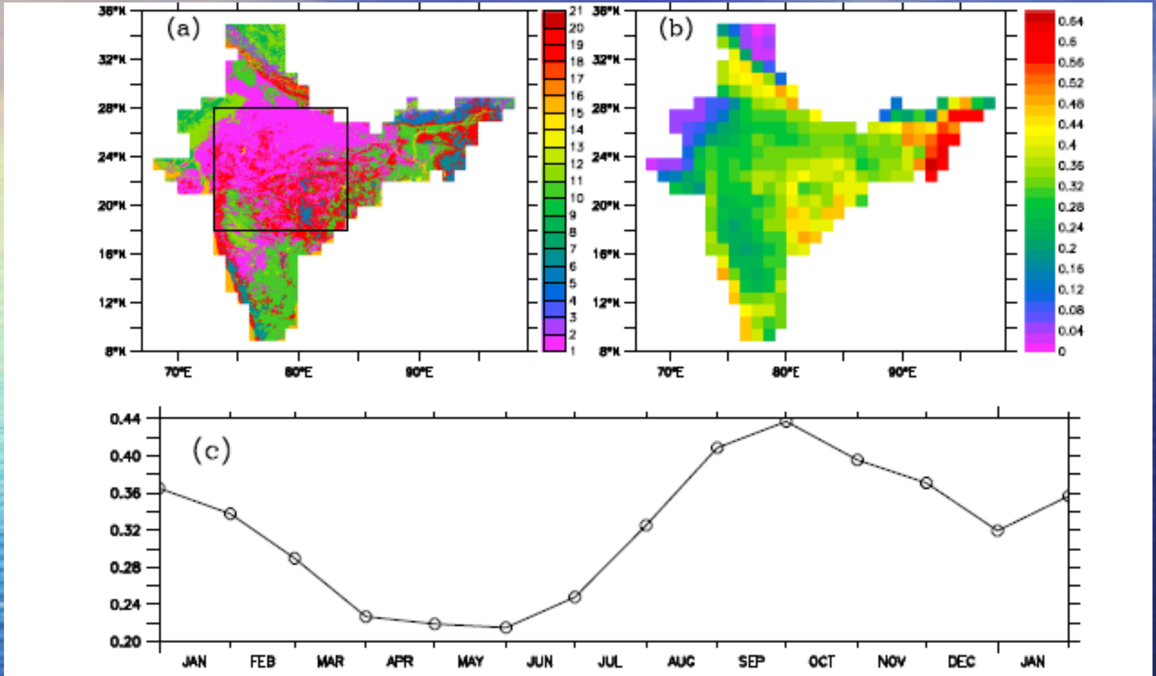
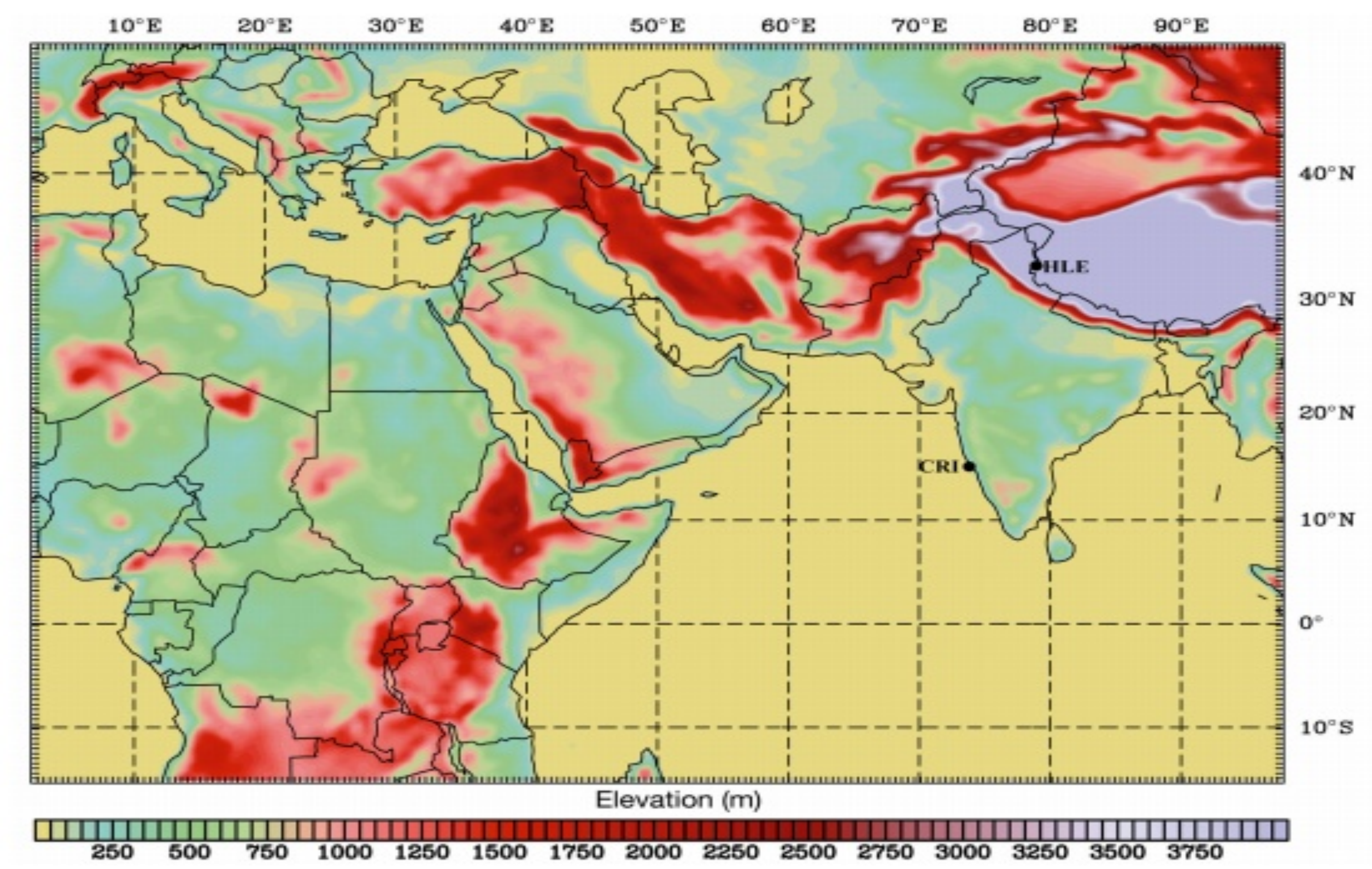


Figure 1. (a) Annual land use data over India from Global Land Cover Characterization (GLCC) data sets as derived from the 1 km Advanced Very High Resolution Radiometer (AVHRR) data spanning April 1992 to March 1993. The vegetation types are defined by biosphere atmosphere transfer scheme (BATS). The 20 vegetation types shown here are (1) crop/mixed farming, (2) short grass, (3) evergreen needle leaf tree, (4) deciduous needle leaf tree, (5) deciduous broad leaf tree, (6) evergreen broad leaf tree, (7) tall grass, (8) desert, (9) tundra, (10) irrigated crop, (11) semi-desert, (12) ice cap/glacier, (13) bog or marsh, (14) inland water, (15) ocean, (16) evergreen shrub, (17) deciduous shrub, (18) mixed woodland, (19) forest/field mosaic, and (20) water and land mixture. (b) Annual mean normalized difference vegetation index (NDVI) obtained from 1982 to 2000 satellite data. (c) The seasonal cycle of climatological NDVI over Indian subcontinent. The red line indicates the data from *Niwa et al.* [2012] but the amplitude is scaled by half.

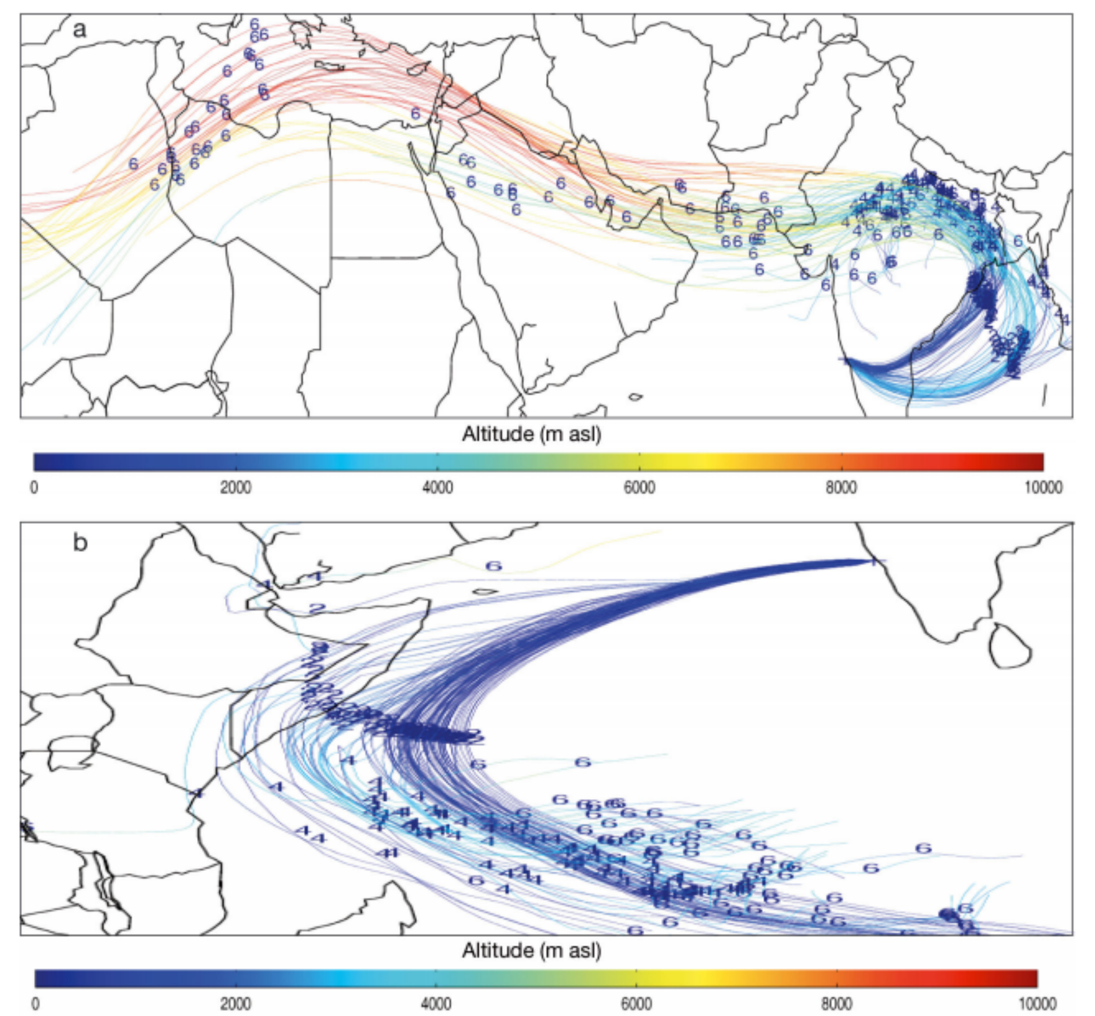
Normalized Difference Vegetation Index (NDVI) seasonality

Biosphere growth in response to Monsoon Rain

Seasonality of xCO2 over Indian region is influenced by monsoon dynamics



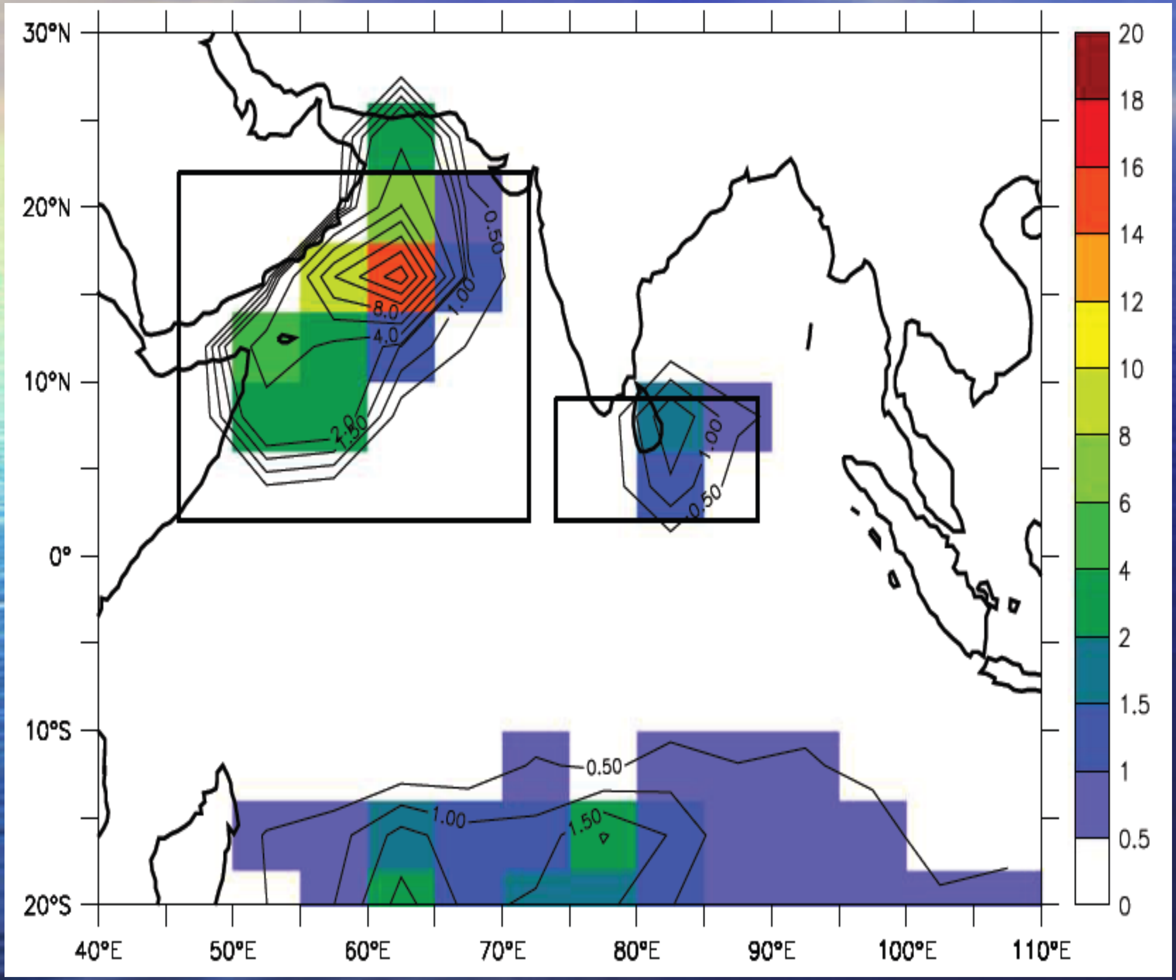
Monsoon offers a unique characteristics of air arriving over India from two difference sources



Winter (top) and Summer (bottom) back trajectories for 10 days showed for each height.

Tiwari et al., (2013)

Seasonal variances in oceanic pCO_2 is linked to Ocean Seasonal Dynamics in Indian Ocean.



Western Arabian Sea and Sea East of Sri-Lanka has largest seasonal amplitudes of pCO_2.

They are driven by large scale upwelling forced by monsoonal winds.

A clear example of role of Monsoon Dynamics and Ocean pCO_2 variability.

Valsala and Maksyutov (2013), Ocean Dynamics

Seasonal variances in oceanic primary production is linked to corresponding scale Ocean Dynamics forced by monsoon.

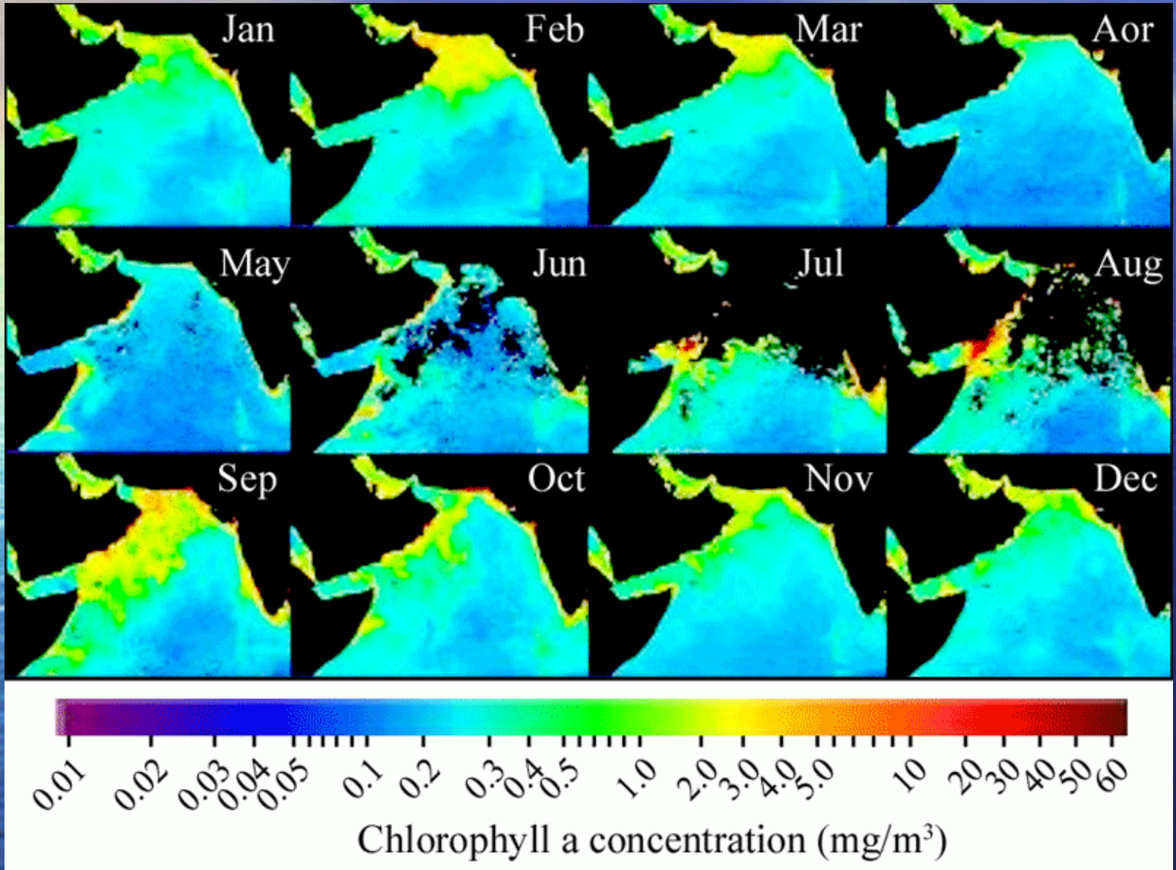
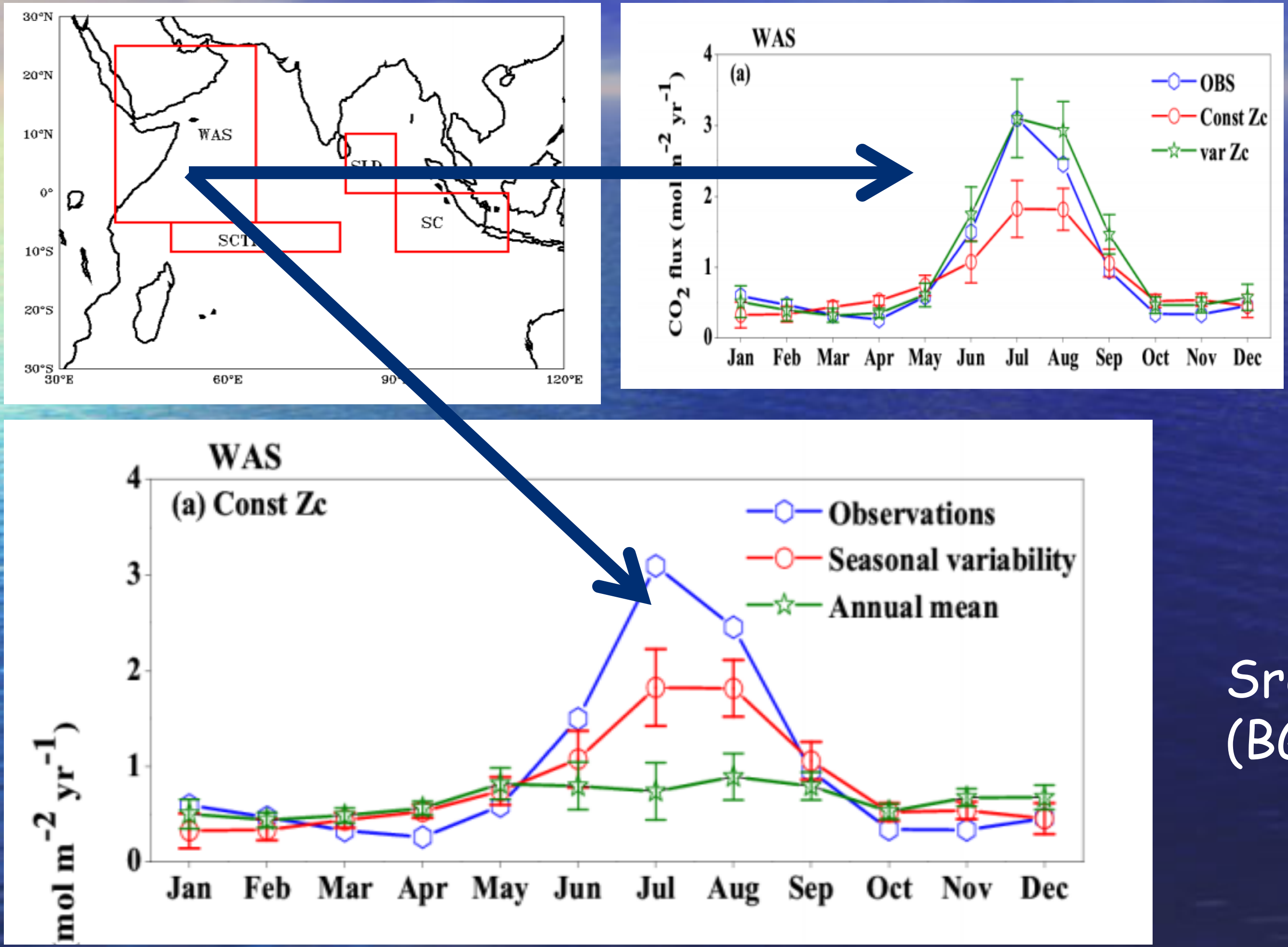


Figure 2 Typical annual distribution of the chlorophyll-a concentration in the Arabian Sea derived from SeaWiFS

Satellite chlorophyll-a concentrations shows the seasonality of primary production in the Arabian Sea.

Monsoon Dynamics (winds, nutrient upwelling and dust input) influence the seasonal cycle of primary production in the ocean.

Seasonal Dynamics of the Indian Ocean is the key driver of the seasonality of Carbon cycle in the Indian Ocean.

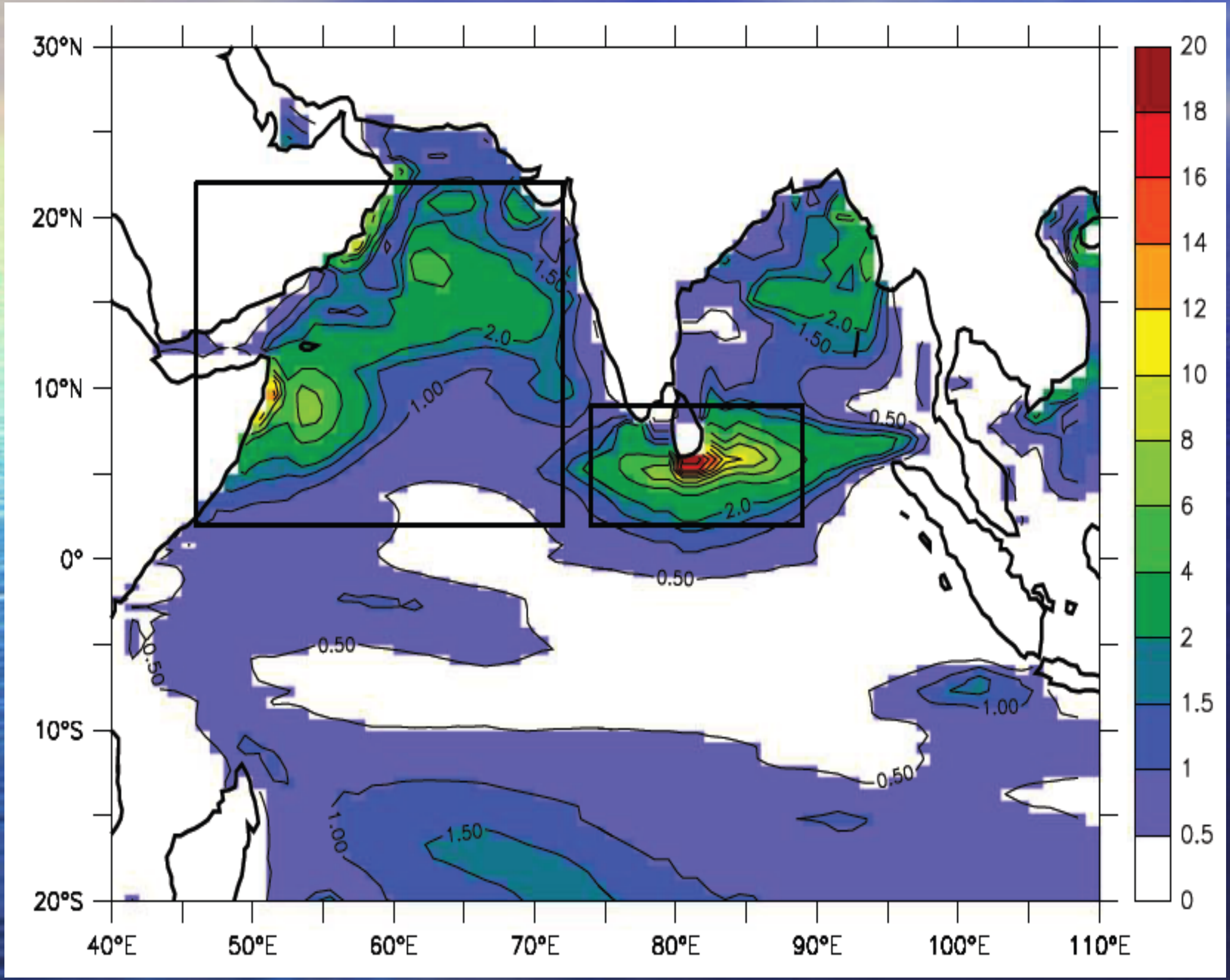


Sreeush et al., (BGD, 2017)

Monsoon Dynamics and it's role in carbon cycle (Biospheric, Oceanic CO_2 and CH_4)

- Intra-seasonal scales
- Mean and Seasonal cycle
- **Inter-annual and Decadal**

Interannual variances of Indian ocean carbon cycle variability is close to where largest seasonal amplitudes are located

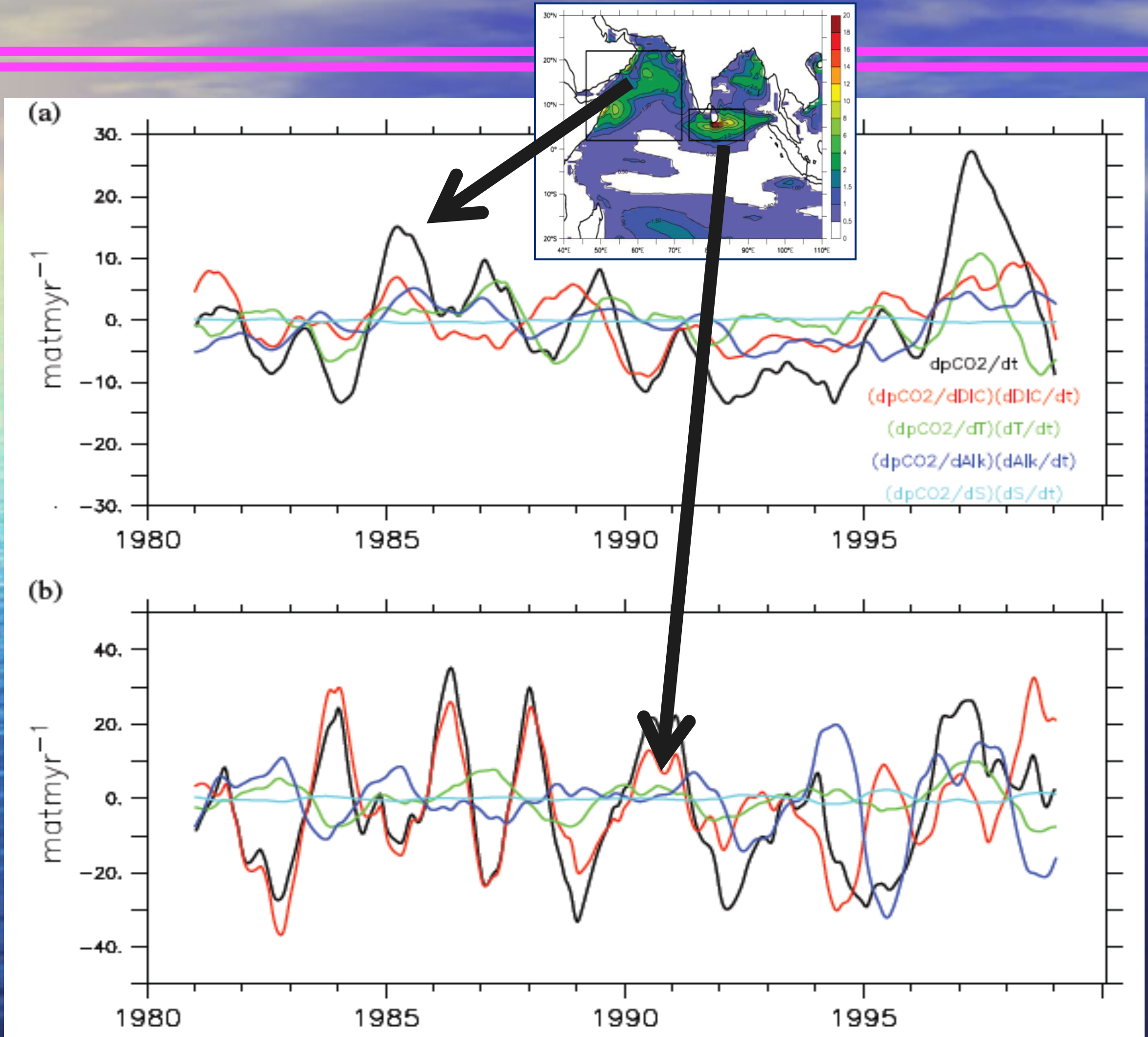


pCO_2 inter-annual variance from a model.

Variability are more in the Arabian Sea and the south of Sri-Lanka where upwelling is dominent

Valsala and Maksyutov (2013).

Inter-annual variances of Indian ocean surface carbon cycle variability is close to where seasonal amplitudes are located



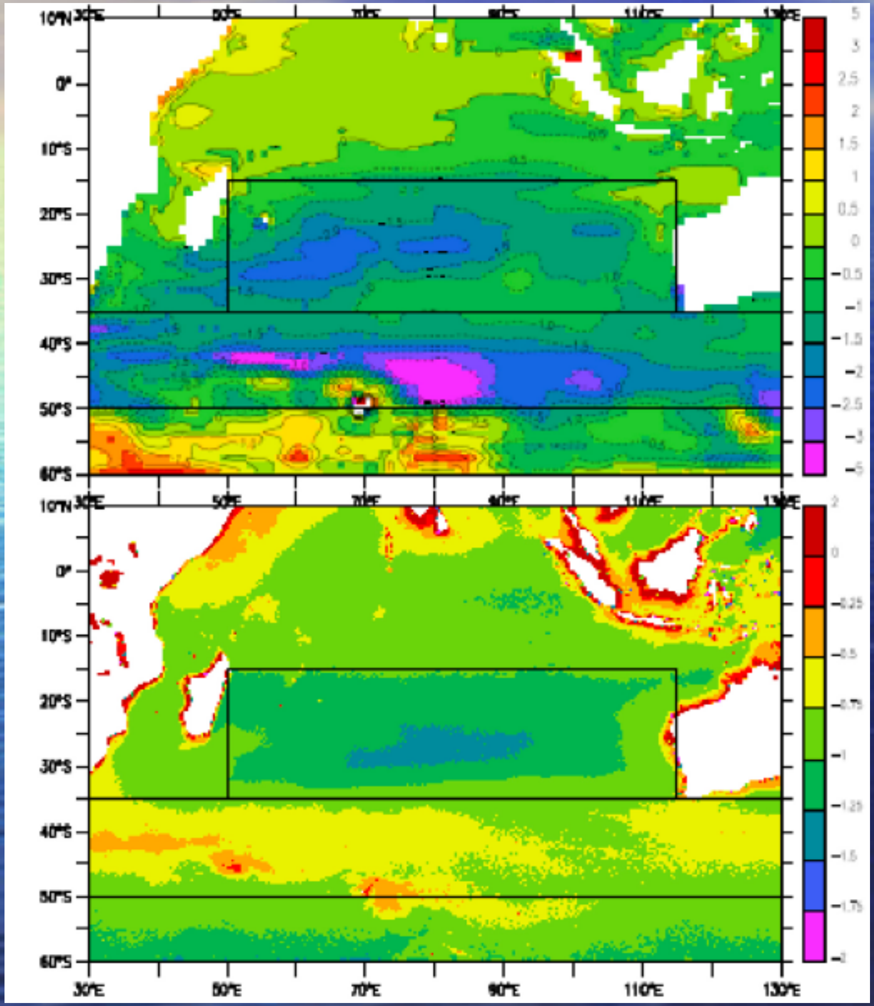
$$\frac{dpCO_2}{dt} = \frac{\partial pCO_2}{\partial \mathrm{DIC}}\frac{d\mathrm{DIC}}{dt} + \frac{\partial pCO_2}{\partial T}\frac{dT}{dt} + \frac{\partial pCO_2}{\partial \mathrm{ALK}}\frac{d\mathrm{ALK}}{dt} + \frac{\partial pCO_2}{\partial S}\frac{dS}{dt}$$

pCO_2 inter-annual variance from a model.

Variability are more in the Arabian Sea and the south of Sri-Lanka where upwelling is dominant

Valsala and Maksyutov (2013).

Large scale monsoon forcing and its variability inducted by ENSO, SAM, IOD etc. contribute to the carbon cycle variability of Indian Ocean.



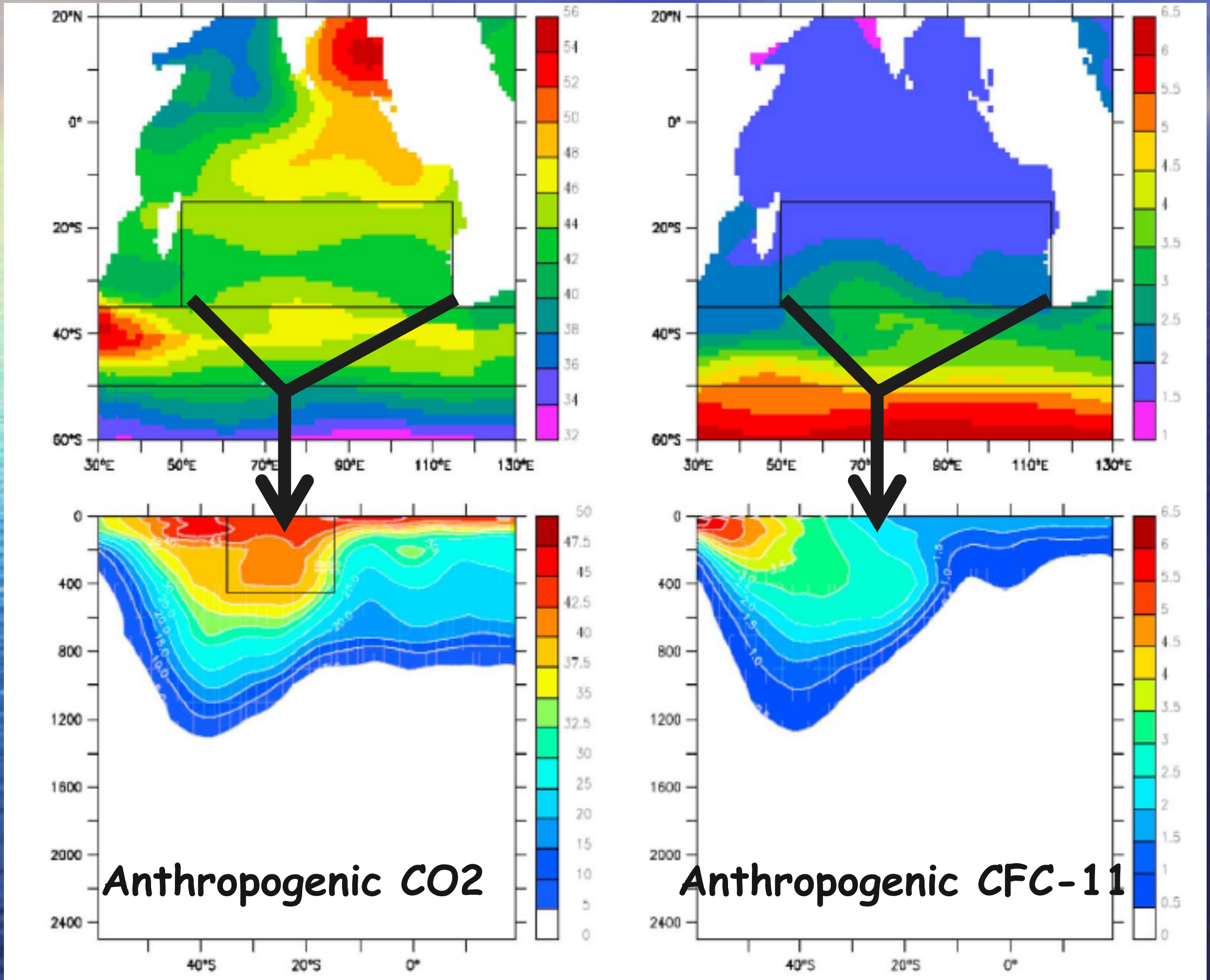
Sea-to-Air CO_2 fluxes in subtropical Indian Ocean.

Chlorophyll mean picture of Subtropical Indian Ocean.

The 'blue' area shows a lot of sink of CO_2

Valsala et al., (2012, GRL)

Large scale monsoon forcing and its variability inducted by ENSO, SAM, IOD etc. contribute to the carbon cycle variability of Indian Ocean.

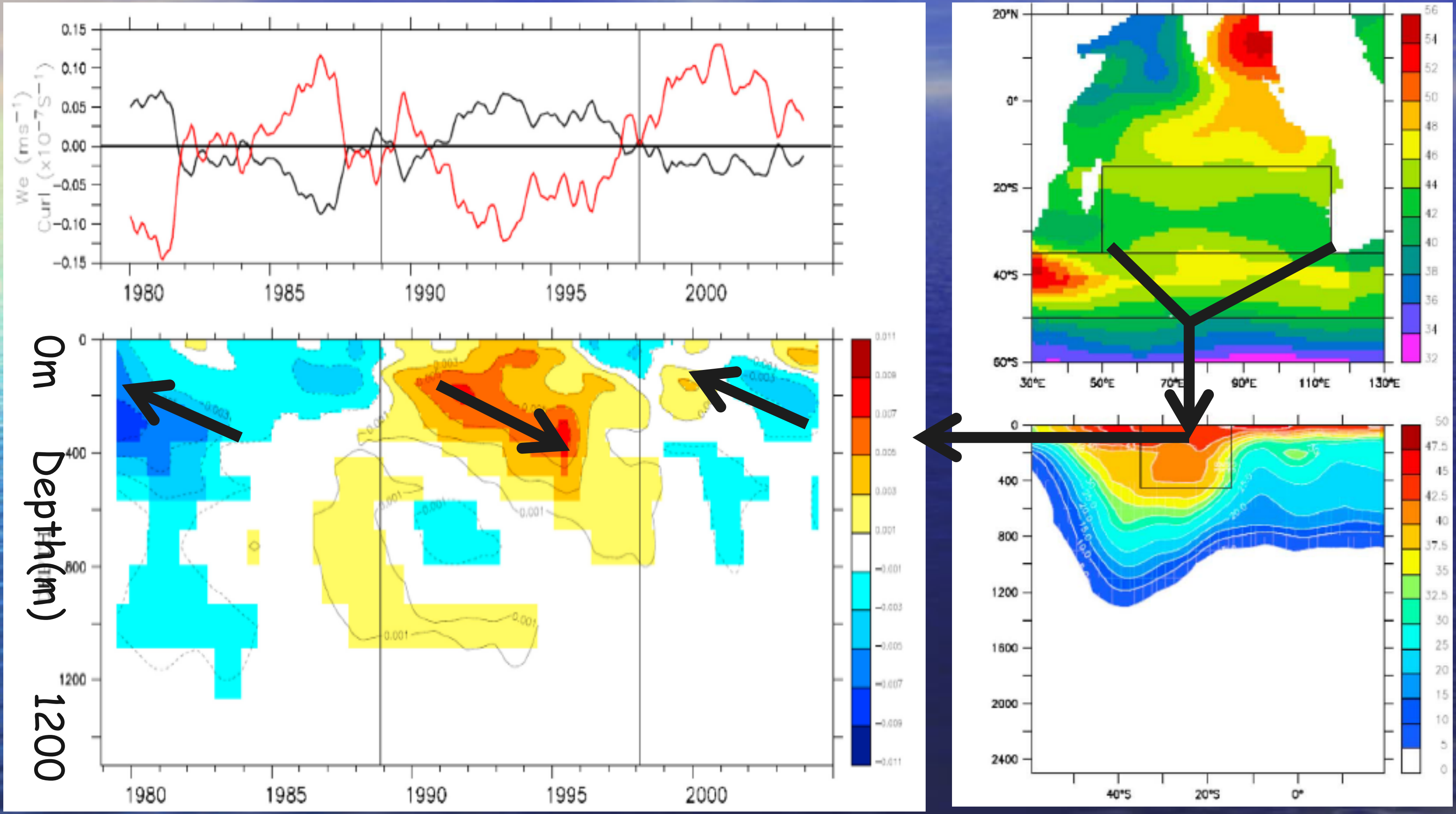


Biological active Carbon (CO_2) has more sink in this zone.

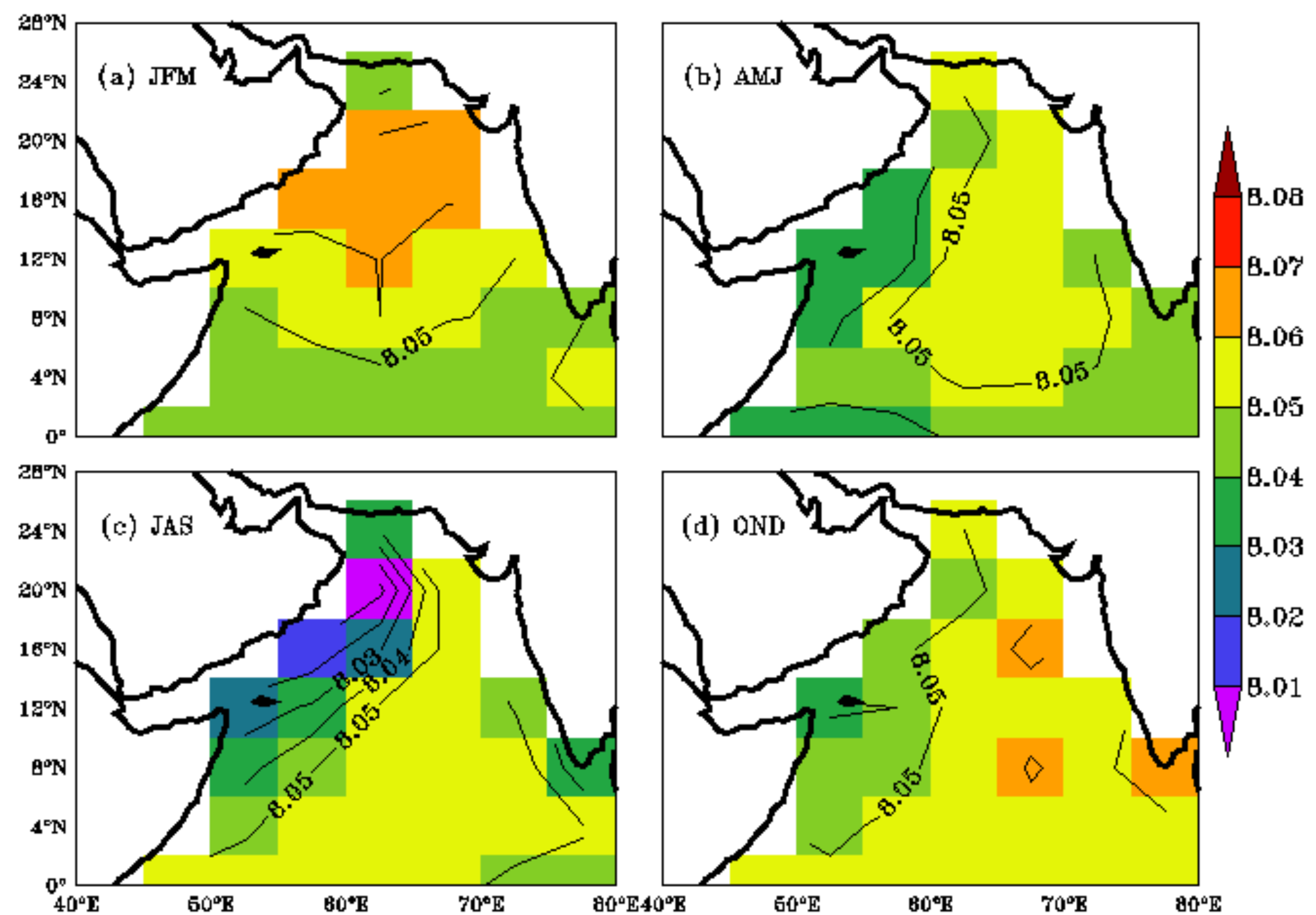
Biologically inactive Carbon (CFC-11) have less sink in this zone.

Valsala et al., (2012, GRL)

Large scale monsoon forcing and its variability inducted by ENSO, SAM, IOD etc. contribute to the carbon cycle variability of Indian Ocean.



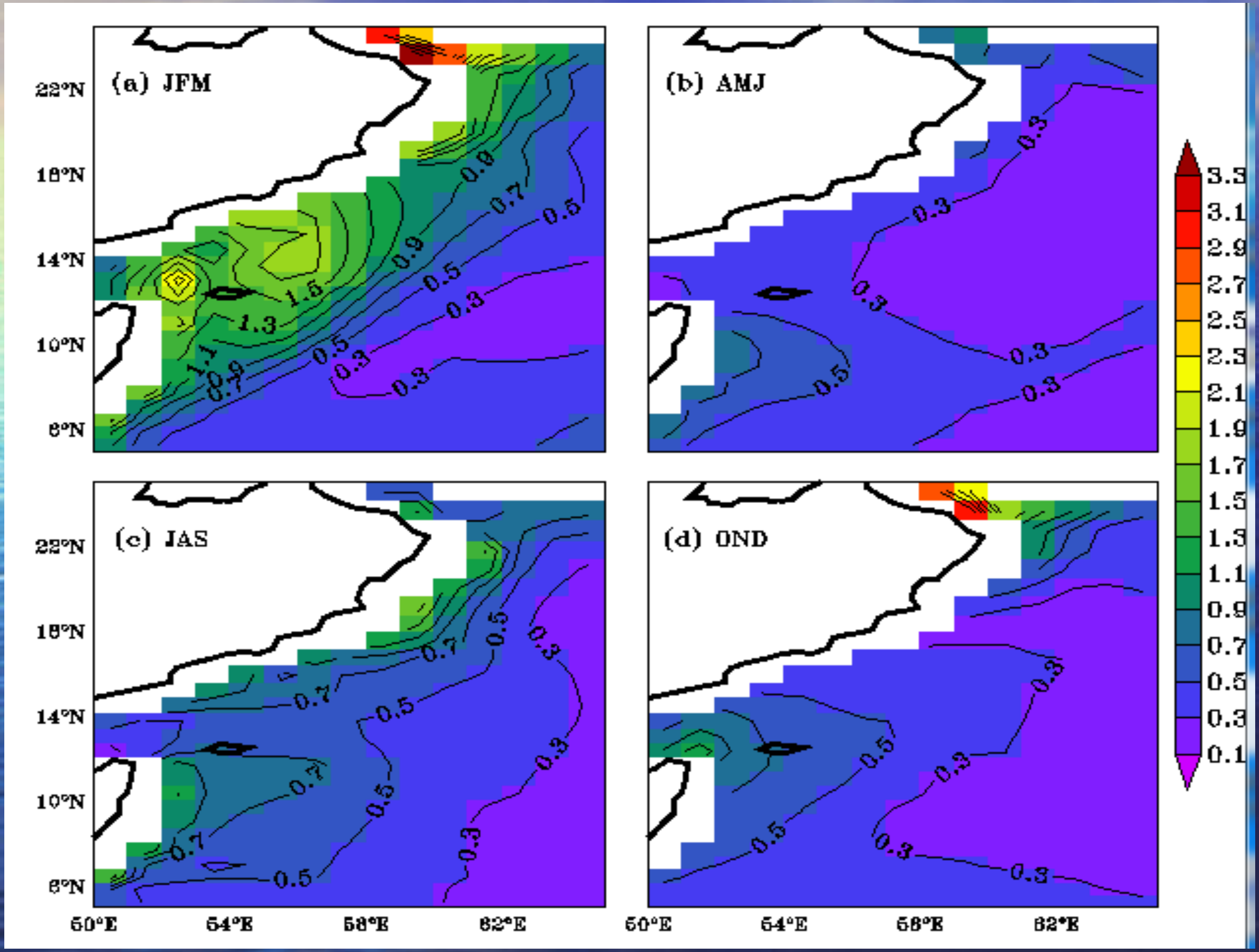
Acidity and long term trends: Another challenge in Carbon Cycle which is modified under changes in climate dynamics.



Acidity (pH) of the surface ocean.

Sreeush et al., (2017)

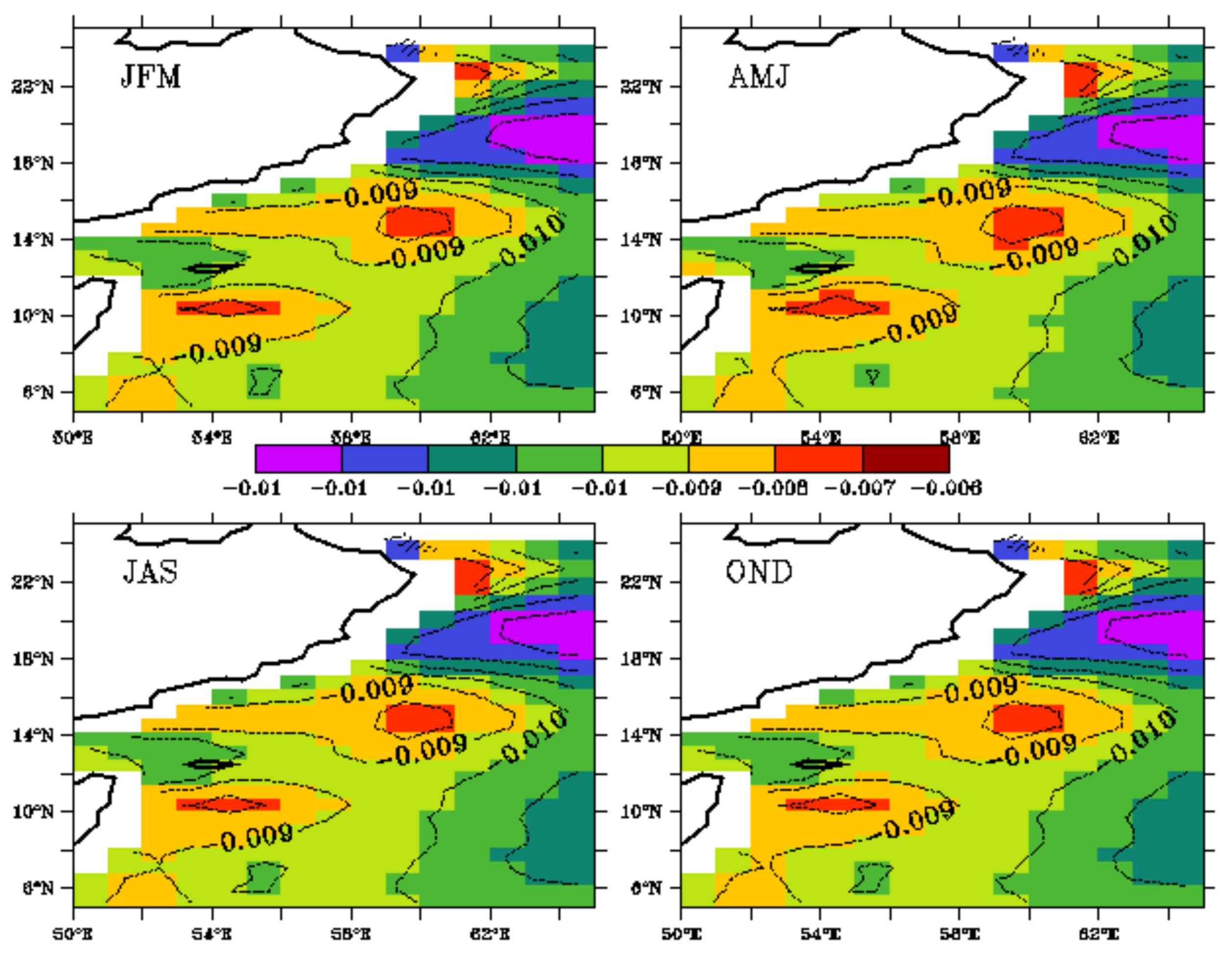
Acidity and long term trends: Another challenge in Carbon Cycle which is modified under changes in climate dynamics.



Acidity (pH) seasonal variability of the surface ocean.

Sreeush et al., (2017)

Acidity (pH) trends in last 50 years only due to the SST warming. Acidity trends affects the marine biota.

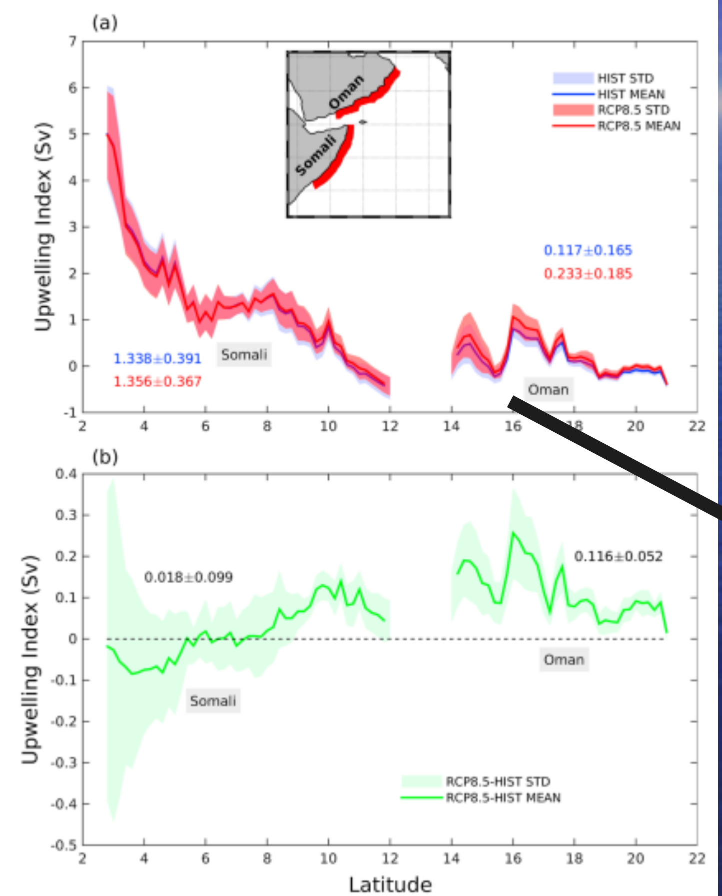


$$\frac{dpCO_2}{dt} = \frac{\partial pCO_2}{\partial \mathrm{DIC}}\frac{d\mathrm{DIC}}{dt} + \frac{\partial pCO_2}{\partial T}\frac{dT}{dt} + \frac{\partial pCO_2}{\partial \mathrm{ALK}}\frac{d\mathrm{ALK}}{dt} + \frac{\partial pCO_2}{\partial S}\frac{dS}{dt}$$

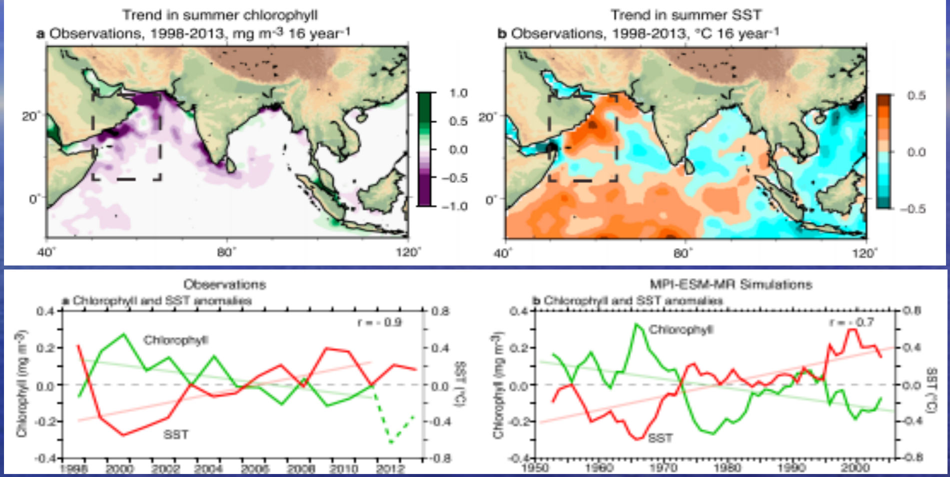
Indian Ocean warming has unique influence in ocean Acidification

Sreeush et al., (2017)

Trends in Marine productivity. Climate change may have counteracting impact on marine productivity.



Praveen et al., (2016)



Roxy et al., (2016)

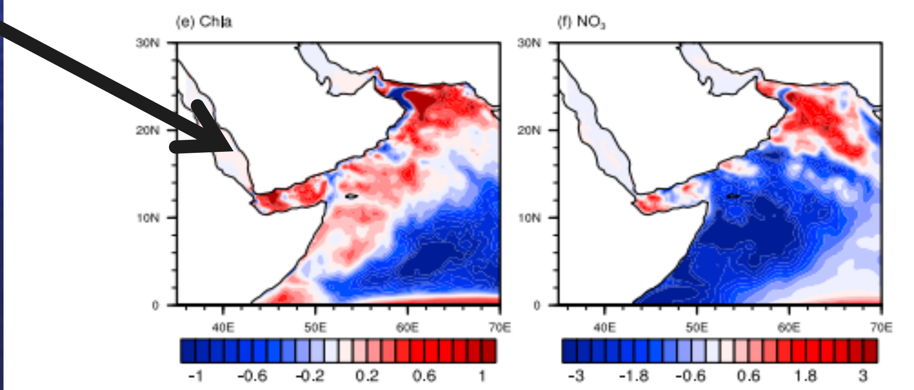


Figure 4. Difference between ROMS_RCP8.5 and ROMS_HIST ensemble mean simulations for (a) SST (°C), (b) SSS, (c) SSH (m), (d) currents (m s^{-1}), (e) Chl *a* concentration (mmol m^{-3}), and (f) NO$_3$ concentration (mmol m^{-3}).

Conclusion

- South Asian Monsoon offers a wide verity of forcing to terrestrial and ocean carbon cycle of the monsoon region.
- It may appear the carbon cycle is passive to monsoon dynamics, however, on the long term climate regulations and anthropogenic forcing controls the monsoon.
- Therefore they are highly coupled and is a potential area for further research.