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

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OUTLINE

• Little bit basics on Carbon Cycle

• Linkage between Monsoon Dynamics and Carbon Cycle

• Rich spectrum of variability in carbon cycle \((\text{CO}_2\text{ and } \text{CH}_4)\) offered by South Asian monsoon.

• Green house gases cycle \(\rightarrow\) climate change \(\rightarrow\) Greenhouse gases cycle change
The Green house effect.

- GH-effect helps the surface temperature to be warm at 15°C
- $\text{CO}_2$ and other GH-gases

Long wave (heat)

Short wave

Earth

Sun
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

**Fossil Fuel and Cement Emissions**

Global fossil fuel and cement emissions: 36.1 ± 1.8 GtCO₂ in 2013, 61% over 1990

- Projection for 2014: 37.0 ± 1.9 GtCO₂, 65% over 1990

Data: CDIAC/GCP

- 2000–2009: +3.3%/yr
- 2012–2013: +2.3%
- 2013–2014: +2.5%
- 2014: 37.0 GtCO₂

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

Atmospheric Carbon Dioxide
Measured at Mauna Loa, Hawaii
Contemporary carbon budget: The Partitioning

Ocean and land absorbs ~ 50% of global total CO$_2$ emission (numbers are from GCP, 2014 budget)
Atmospheric CO$_2$ from 1700 to 2010

The diagram shows the concentration of CO$_2$ in the atmosphere from 1700 to 2000. The concentration has increased significantly from around 270 parts per million (ppm) in 1700 to approximately 420 ppm in 2000. The natural CO$_2$ level is indicated by the green line, while the anthropogenic CO$_2$ level is indicated by the red line, which shows a noticeable increase from the late 19th century onwards.
Atmospheric CO$_2$ record since 700-k Yr B.P.

Petit et al, 1999, Nature

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Milankovitch Cycle and Carbon Feedbacks within Earth System

![Diagram showing carbon dioxide levels and climate periods]

- **Cold period**: Weak heating, weak burial of CO₂
- **Warm period**: Strong heating, strong burial of CO₂, CO₂ storage

*Years*
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.

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Top-down estimates of CO$_2$ fluxes:

\[
\frac{\partial C}{\partial t} + \mathbf{U} \cdot \nabla_h C + W \frac{\partial C}{\partial z} = \frac{\partial}{\partial z} K_z \frac{\partial}{\partial z} C + \nabla_h \cdot (K_h \nabla_h C) + \phi
\]

Tower for CO$_2$ measurement

Implied (prior) fluxes (ocean + Land + FF + Fire)
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


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

\[ [gCO_2, HCO_3^-, CO_3^{2-}] \rightarrow DIC \]

\[ 106 \text{ CO}_2 + 16\text{NO}_3^- + \text{HPO}_4^{2-} + 78 \text{H}_2\text{O} + 18\text{H}^+ \rightarrow \text{Biomass} \]

Bacterial Decomposition, Remineralization to DIC and nutrients.

Dynamic return

Solubility pump

Wind

Biological pump (soft tissue pump and carbonate pump)

Burial

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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)

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\(^{-1}\).

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) 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)

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.
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

Valsala et al., (JGR, 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.

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

AIRIS satellite $XCO_2$ data based analysis

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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)
$\text{XCH}_4$ anomalies, on the other hand, get highlighted in the propagation because the $\text{CH}_4$ source/sink does not dominate in the atmospheric $\text{CH}_4$ signal.
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 CH$_4$ does not vary vigorously with monsoon.

Therefore the atmospheric CH$_4$ 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 $CH_4$ anomalies and convection anomalies. They do have much complex structure. However the $CH_4$ 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 its 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.

Normalized Difference Vegetation Index (NDVI) seasonality

Biosphere growth in response to Monsoon Rain

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.
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.

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.

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

Valsala and Maksyutov (2013).
Inter-annual variances of Indian ocean surface carbon cycle variability is close to where seasonal amplitudes are located. 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 $\text{CO}_2$ fluxes in subtropical Indian Ocean.

Chlorophyll mean picture of Subtropical Indian Ocean.

The ‘blue’ area shows a lot of sink of $\text{CO}_2$

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 induced 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.

Sreeush et al., (2017)
Acidity (pH) trends in last 50 years only due to the SST warming. Acidity trends affects the marine biota.

\[
\frac{d\rho CO_2}{dt} = \frac{\delta p CO_2}{\delta DIC} \frac{dDIC}{dt} + \frac{\delta p CO_2}{\delta T} \frac{dT}{dt} + \frac{\delta p CO_2}{\delta ALK} \frac{dALK}{dt} + \frac{\delta p CO_2}{\delta S} \frac{dS}{dt}
\]

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.

Roxy et al., (2016)

Praveen et al., (2016)
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.