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CARBON CYCLE & OCEAN MODELLING

Fluxes of greenhouse gases (GHG) between different compartments of the earth system – atmosphere, land and ocean – need to be quantified robustly before we can close the carbon budget of the planet. It is essential that we do this at good spatial and temporal scales because it is the cornerstone of our efforts to mitigate climate change by controlling anthropogenic emissions. There are two approaches to this effort and CSIR-4PI has made important contributions to both.

The bottom-up approach models all the processes of the marine carbon, nitrogen and oxygen cycles essential to get basin-wide estimates of the air-sea fluxes as well as the estimation of oxygen minimum zones which have a large impact of the marine ecosystem. We do this by combining a state of the art biogechemical model (TOPAZ) with an advanced 3D ocean circulation model (MOM). Climatalogical and interannual simulations of the carbon, nitrogen and oxygen cycles in the ocean have captured several observed phenomena-existence of subsurface chlorophyll maxima, biological productivity, temperature and salinity profiles, presence and extent of oxygen minimum zones - in the Indian Ocean, especially the Arabian Sea. Sensitivity experiments with parameters that control iron-limitation yielded some insights into the processes which control biological productivity.

The top-down approach inverts very accurate GHG measurements to yield robust fluxes. Data from three stations, Hanle, Pondicherry and Port Blair have been collected and analysed. A fine resolution model to simulate the transport of GHG is under development. A new GHG station with primary standards is under commissioning at Hosakote near Bangalore

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1.1 Modelling of marine biogeochemical cycles in the north Indian Ocean

Oceans have a large capacity to absorb CO_2, thus reducing the amount of CO_2 in the atmosphere. The physical and dynamical properties of the ocean influence the distribution of nutrients and carbon, which in turn affects life in the oceans. The physical and biogeochemical processes which influence nutrient availability, biological productivity and carbon cycle are essential in inferring anthropogenic changes. Modelling studies along with insitu and remote sensing data are useful in the study of significant processes like mixed layer depth variability, uptake dynamics for different nutrients, regeneration/ remineralization processes, new production etc. Synthesis of mathematical models of different complexity and data from various sources is required to understand the effect of climate variability and feedbacks on the estimation of primary productivity and carbon flux. Since long time series observations on marine ecosystem variables are very few in the Indian Ocean, use of mathematical models would help us to improve our ability to understand the marine ecosystem.

In the present study, a three dimensional coupled physical-biogeochemical model TOPAZ is used to study carbon cycle in the Indian Ocean. The coupled model is forced with CORE data to carry out climatological and interannual model simulations in the global domain.

The focus of this study is to understand the spatial and temporal variations of physical and biogeochemical components which influence the distribution of primary productivity, oxygen, carbon flux across the air-sea interface; and evaluating the model simulation results with observations from various sources on different scales.

It is noted from model evaluation studies that simulationswith climatological forcings are able to capture many of the significant features of the spatial and seasonal variations of Sea Surface Temperature (SST), mixed layer depth (MLD), surface Chlorophyll (Chl), primary productivity (PP) integrated over the euphotic zone, Nitrate (NO_3) and partial pressure of CO_2 (pCO_2) at the surface when compared with data from satellites (TMI, MODIS, SeaWiFS) and World Ocean Atlas (WOA) in the north Indian Ocean. Also, the depth profiles of temperature, salinity, nitrate, dissolved inorganic carbon (DIC), oxygen, chlorophyll and primary productivity (PP) from the climatological model simulations are evaluated using the cruise data from US JGOFS, Indian JGOFS and BOBPS at many (more than 15) locations in the Arabian Sea and Bay of Bengal for different seasons.

To understand the physical-biological-chemical processes responsible for the seasonal and interannual variability of biogeochemical variables in different regions in the Arabian Sea and Bay of Bengal, detailed analysis of Sea Surface Temperature (SST), Mixed Layer Depth (MLD), Depth-integrated Chlorophyll & Primary Productivity, Nitrate, Oxygen, Surface pCO_2, Carbon Flux, etc. is carried out, for the period 1997 to 2009 using the results of model simulation and available satellite data. It is noticed that SST, MLD, PP, Chl, pCO_2, Carbon flux show interannual variations in the regions west of 65^o E & north of 12^o N (Figure 1.1) and spatial extent of suboxic zone (Oxygen < 6 m Mol/m^3) shows significant interannual variability (Figure 1.2). This kind of analysis of model simulation results on various biogeochemical components and fluxes is carried out to relate the interannual variability of spatial extent of suboxic zonesand carbon flux at the air-sea interface to SST, MLD, PP, Chl, nutrients etc. in different regions of AS and BOB.

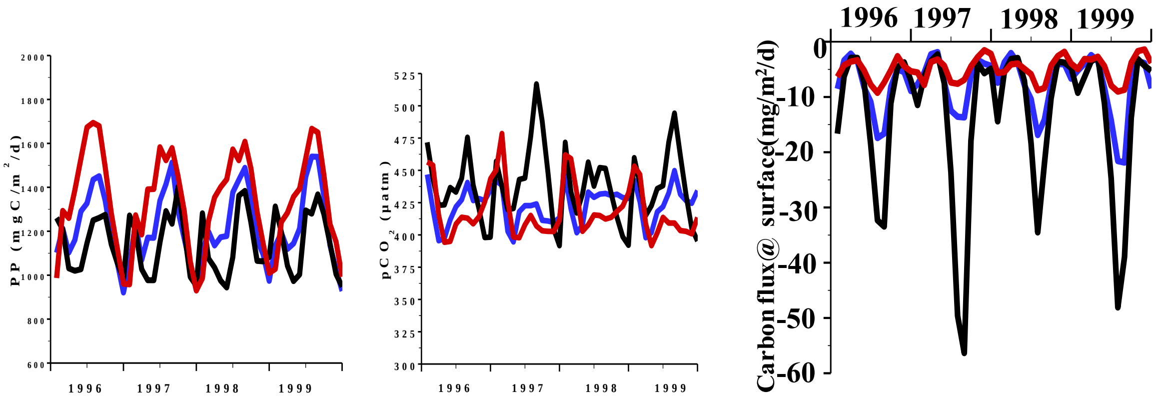


Figure 1.1 Comparison of PP, pCO_2 and Carbon Flux at the air-sea interface for different regions

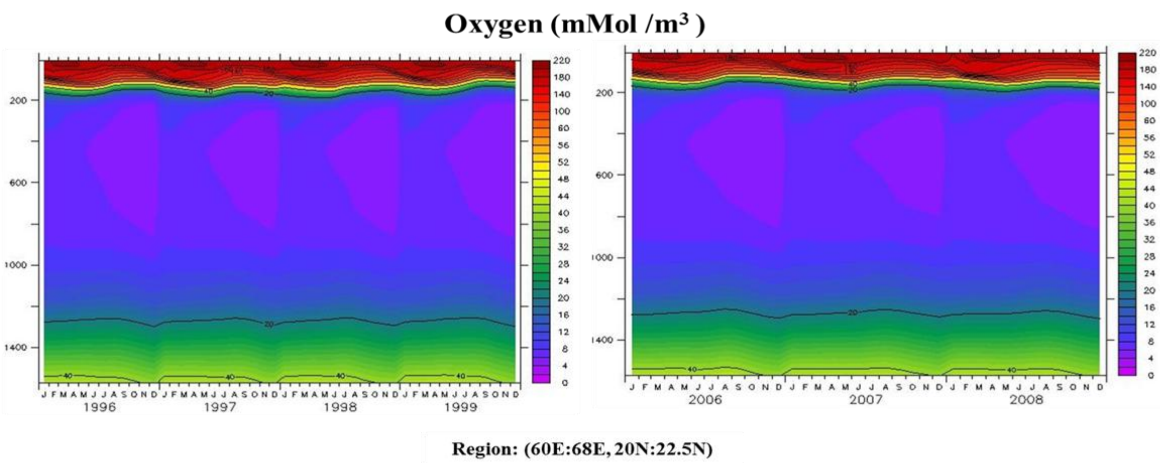


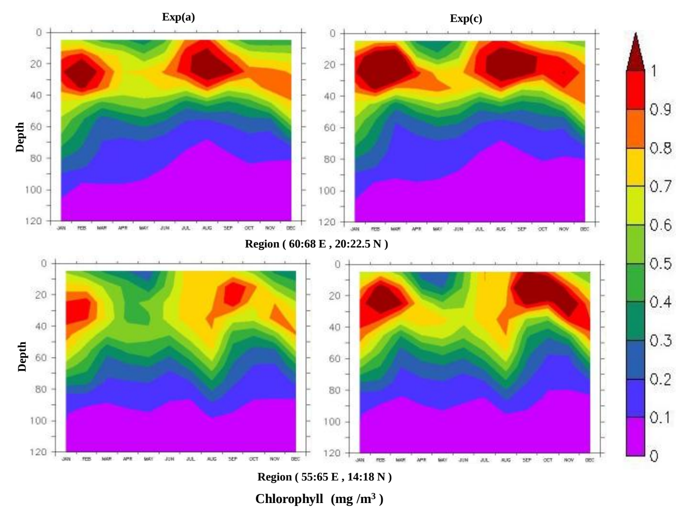
Figure 1.2 Interannual variation of Oxygen(mMol/m^3) with respect to depth during 1996 to 1999 and 2006 to 2008

Detailed analysis of model results on some of the biogeochemical variables, subsurface processes, values of model parameters is being carried to relate the interannual variability of Carbon Flux at the air-sea interface and extent of Oxygen Minimum Zone with Primary Productivity, pCO_2, MLD, SST, ENSO events etc.

Denitrification flux in the Arabian Sea

It is assumed in the model simulations that denitrification process will occur in the Oxygen Minimum Zone (OMZ) when the oxygen concentration is below 5 m mol/m^3. The dependence of denitrification on the volume of OMZ, amount of primary productivity and the ENSO events (El Nino and La Nina) are studied by analyzing the model simulation results.

(a)



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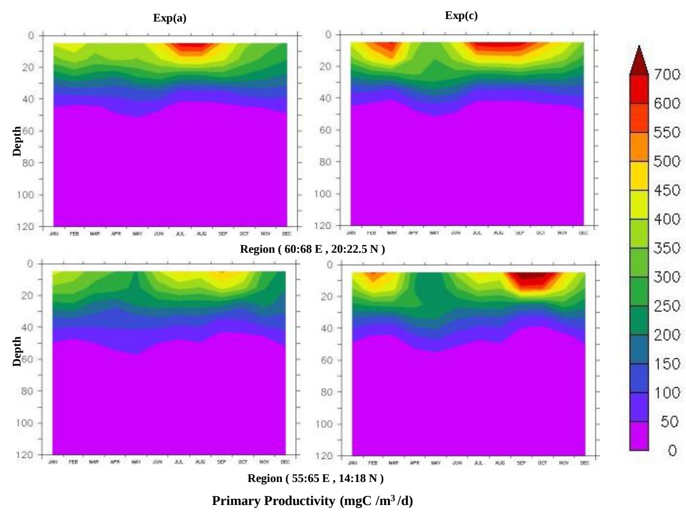

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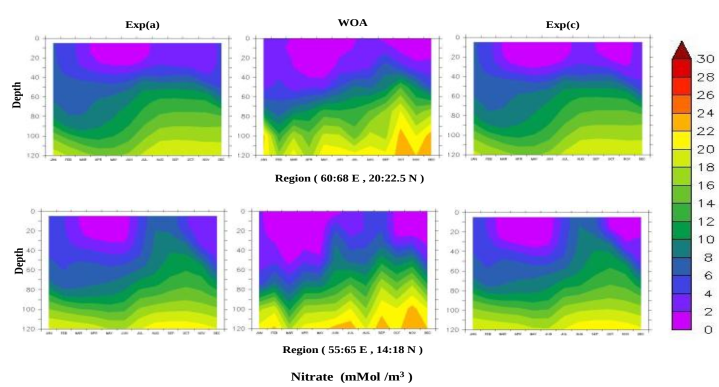

Figure 1.3 a & b: Comparison of Chlorophyll (mg/m^3) and Primary Productivity (mg C/m^3/d) with respect to depth for two model simulations with different iron limitation parameter (Exp (a) & (c)), Figure c: Comparison of Nitrate (m Mol/m^3) with respect to depth for two model simulations with different iron limitation parameter (Exp (a) & (c)) and the WOA

It is noted that denitrification flux in the AS from the simulation results varies between 20 and 40 TgN/year which is comparable with the estimates based on calculations of nitrate deficit. The interannual variation of annual average of denitrification flux in the AS and processes in the OMZ are studied during 1949 to 2007. It is clear from the simulation results that denitrification flux depends on the PP and the volume of OMZ. Also, lower values of denitrification flux, volume of OMZ and PP correspond to El Nino years and higher values correspond to La Nina years. Consumption of oxygen below the euphotic zone depends on the amount of dissolved and particulate organic matter and remineralisation processes. If PP is high (low), the concentration of organic matter is high (low) and consumption of oxygen for remineralization processes is high (low). Hence, higher (lower) PP leads to the increase (decrease) in the volume of OMZ and higher (lower) denitrification flux.

Parameter sensitivity study

Numerical simulations of TOPAZ are carried out for three different values of a parameter related to iron limitation namely, $(Fe:N)_{irr}$. Initially the model results are evaluated for some of the biogeochemical components using data from World Ocean Atlas-05 (WOA-05). Monthly, seasonal and interannual variations of PP and Chl integrated over the euphotic zone and sea surface pCO_2 and Carbon flux are analysed in detail to understand the sensitivity of the two different $(Fe:N)_{irr}$ values and also physical processes in various biogeochemical provinces in the Arabian Sea (AS). It is noted that (i) the model simulation with lower iron limitation increases PP and Chl in the west and central AS especially during North-East monsoon (NEM) and Fall Inter-monsoon (FIM)seasons and hence reduce pCO_2 (ii) model results show that iron limitation has significant influence on PP, Chl, nitrate (Figures 1.3a, b & c)as well as pCO_2 in the west and north-west regions of the AS but not in the east AS. (iii) There is no significant change in the Carbon Flux due to change in iron limitationacross the air-sea interface in the Arabian Sea implying that interannual variability in carbon flux may be associated with physical processes.

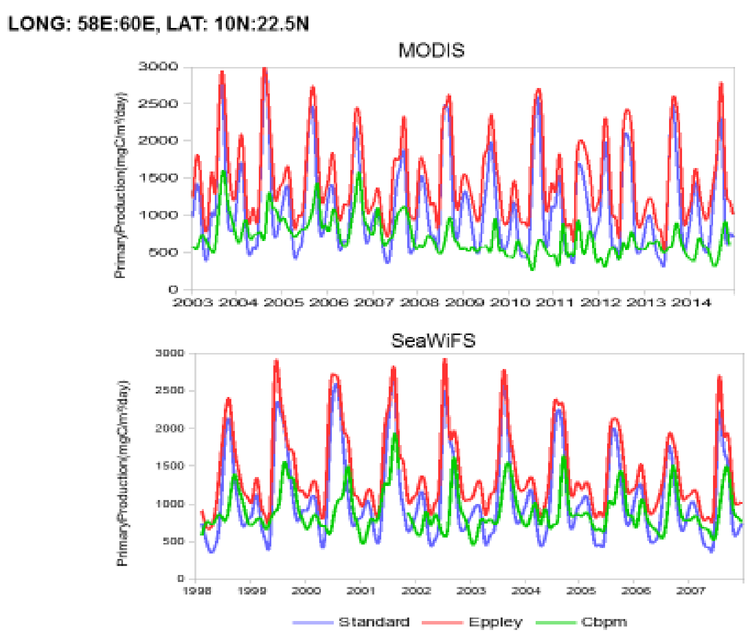

Figure 1.4 Comparison of Interannual Variation of Primary Productivity derived using three different algorithms for MODIS and SeaWiFS satellites in the West Arabian Sea

Analysis of satellite data on primary productivity

Data on Net Primary Productivity derived from Chlorophyll from SeaWiFS and MODIS satellites using VGPM (Vertically Generalized Production Model) have been analysed for Arabian Sea (AS) and Bay of Bengal (BOB) for spatial, monthly, seasonal and interannual variabilities.Net primary production obtained from three algorithmsare compared in different regions in the AS for monthly variations (Figure 1.4). It can be noticed that NPP values obtained from Cbpm is much less than standard and Eppley VGPM in all the regions of AS. NPP values from Eppley VGPM is more than Standard VGPM in many regions in AS.

Data on Net Primary Productivity, Surface Chlorophyll, Sea Surface Temperature from different satellites have been analysed in detail for climatological and interannual variations in different regions of the AS and BOB. Model simulation results are being evaluated using these data.

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1.2 Greenhouse gas measurements

One of the outstanding research tasks in Climate Change Research remains the reduction of uncertainties in the current estimates of Carbon fluxes exchanged between the atmosphere and the underlying oceans/land surface, especially in India and Asia and the surrounding seas. Current uncertainties in estimates of CO_2 fluxes are of the order of 0.5 GTC (Giga Ton of Carbon) or larger in regions of poor data coverage (Asia, Africa etc.). We need to reduce this substantially before we can use these estimates in treaty negotiations.

The problem is to infer estimates of CO_2 sources and sinks using observations of CO_2 concentrations from a network of stations. To do this well, we need a good coverage of stations, high quality measurements, a good temporal coverage, a good transport model and a robust inversion procedure.

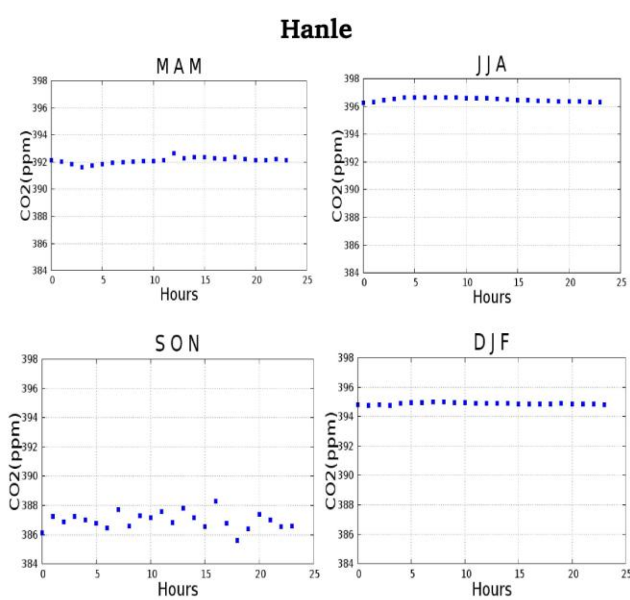

Figure 1.5 Seasonal variations of CO_2 in Hanle

This will require the establishment of high precision CO_2 measurement stations based on WMO protocols and a careful network design for locating stations optimally, in addition to the already functional stations. Measurements have to be made at relatively clean sites which are reasonably far away from large local sources such as major cities. Coastal locations are preferred as both continental and oceanic air masses are sampled. Keeping all the points made above in mind three continuous measurement stations for GHGs (greenhouse gases) are set up in Port Blair, Pondicherry and Hanle where the data is collected every 5 seconds for CO_2 and CH_4 and downloaded at CSIR-4PI for analysis and modelling. At Port Blair we have another instrument measuring N_2O and CO also. These are the national facilities and have to continue working for long time to come and the data from these instruments will be invaluable for India's policy makers.

Diurnal variation of CO_2 in 4 seasons at Hanle and Pondicherry are shown in Figure 1.5 and 1.6, respectively. It can be seen that Hanle, on account of its lack of vegetation does not have a noticeable diurnal cycle while Pondicherry has a very pronounced one with a range of nearly 30 ppm. Besides vegetation, the onset of the sea breeze has a significant impact in lowering the CO_2. The variation across seasons is about 8 ppm at Hanle between SON and MAM season while it is lowest during SON at Pondicherry as well. The variation for CH_4 is quite similar to CO_2 at both stations (Figures 1.7 and 1.8).

A fourth GHG (greenhouse gas) station is being installed near Bangalore in the IIA campus in Hosakote for continuous measurement of CO_2, CH_4, N_2O and CO as seen in the picture Figure 1.9. This station is also equipped with the primary standards of gases for calibration of the instruments as prescribed by WMO for precise measurements of GHGs. This can be treated as a reference station for all the GHG stations making precise measurements of GHGs presently in India.

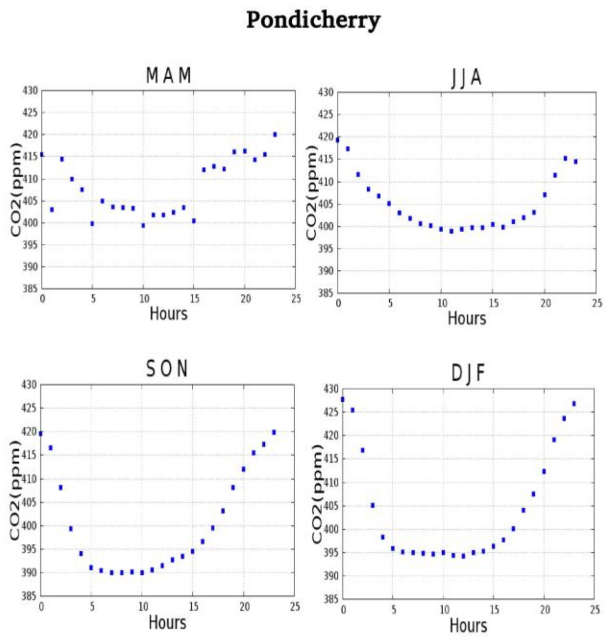

Figure 1.6 Seasonal Variations of CO_2in Pondicherrv

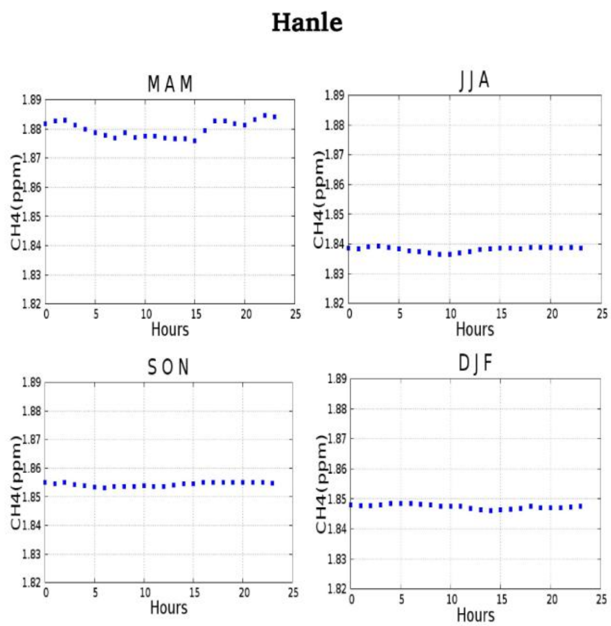

Figure 1.7 Seasonal Variations of CH_4 in Hanle

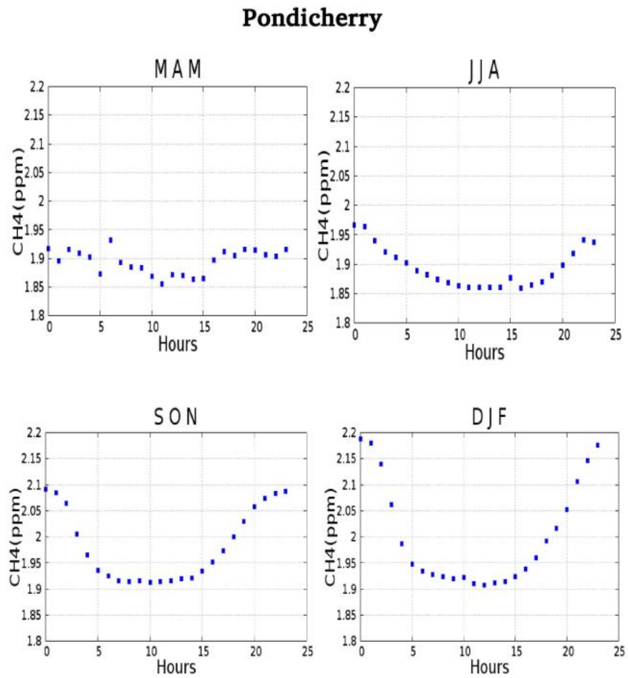

Figure 1.8 Seasonal Variations of CH_4in Pondicherry

Figure 1.9 GHG Instruments and tower at Hosakote

We have recently completed 5 years of flask measurements, conforming to WMO-standards, of carbon dioxide, methane, carbon monoxide, nitrous oxide, sulphur hexafluoride, and hydrogen from clean background sites, Hanle (32.78 °N, 78.96 °E, 4517 m a.s.l., HLE), Pondicherry (12.01 °N, 79.86 °E, 20 m a.s.l, PON) and Port Blair (11.65 °N, 92.76 °E, 20 m a.s.l., PBL) and the results have been published in Atmospheric Chemistry and Physics.

Indira N K, Swathi P S, Prashant Meti, Nagaraj Naik, Akash Choudhury, Natesh S, Smrutishree Lenka, Sambit Kumar Panda, Nunna Bala Ankaiah, Ramonet M and Delmotte M, LSCE

1.3 Fine resolution modelling of GHG transport in Asia.

The increasing availability of atmospheric measurements of GHGs from surface stations can improve the retrieval of fluxes at higher spatial and temporal resolutions by inversions, provided that chemistry transport models are able to properly represent the variability observed locally at different stations. Asia, especially, South and Southeast Asia (SEA) is a region with large and uncertain emissions of the two main anthropogenic greenhouse gases, carbon dioxide (CO_2) and methane (CH_4).

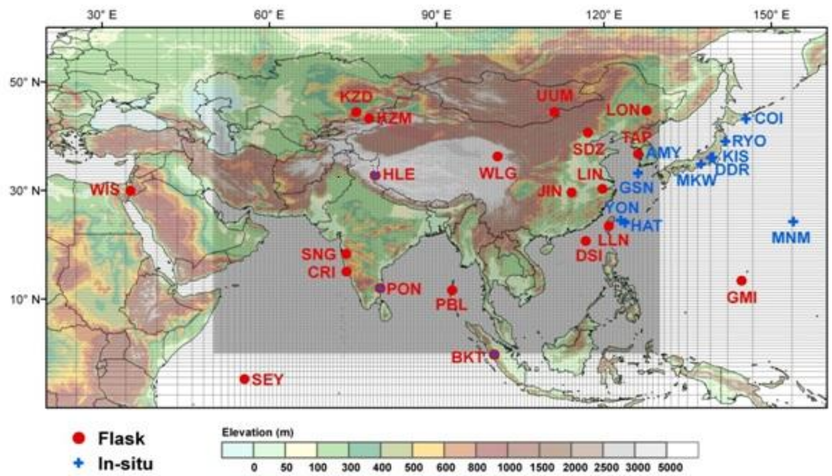

Figure 1.10 Horizontal grid with a zoom over Asia. Locations of GHG stations are also shown.

Monitoring networks have expanded in SEA during the past decade and this can contribute significantly to the robust estimation of GHG fluxes. In this study, we simulate concentrations of CH_4 and CO_2 using a zoom version (ZASIA) of the global chemistry transport model LMDzINCA during the period 2006–2013 along with uniform resolution (REG) of coarser resolution (2.5^o in longitude and 1.27^o in latitude). The ZASIA model (see Figure 1.10) has a high horizontal resolution of ~0.66° in longitude and~0.51° in latitude over SEA and a coarser resolution elsewhere. Both models have 19 sigma pressure levels in the vertical. The models are forced by surface fluxes which vary from interannual to climatological.The performance of the models is evaluated for annual gradients between sites, seasonal, synoptic and diurnal variations by comparing data from 20 flask and 13 continuous surface stations over SEA and adjacent regions.

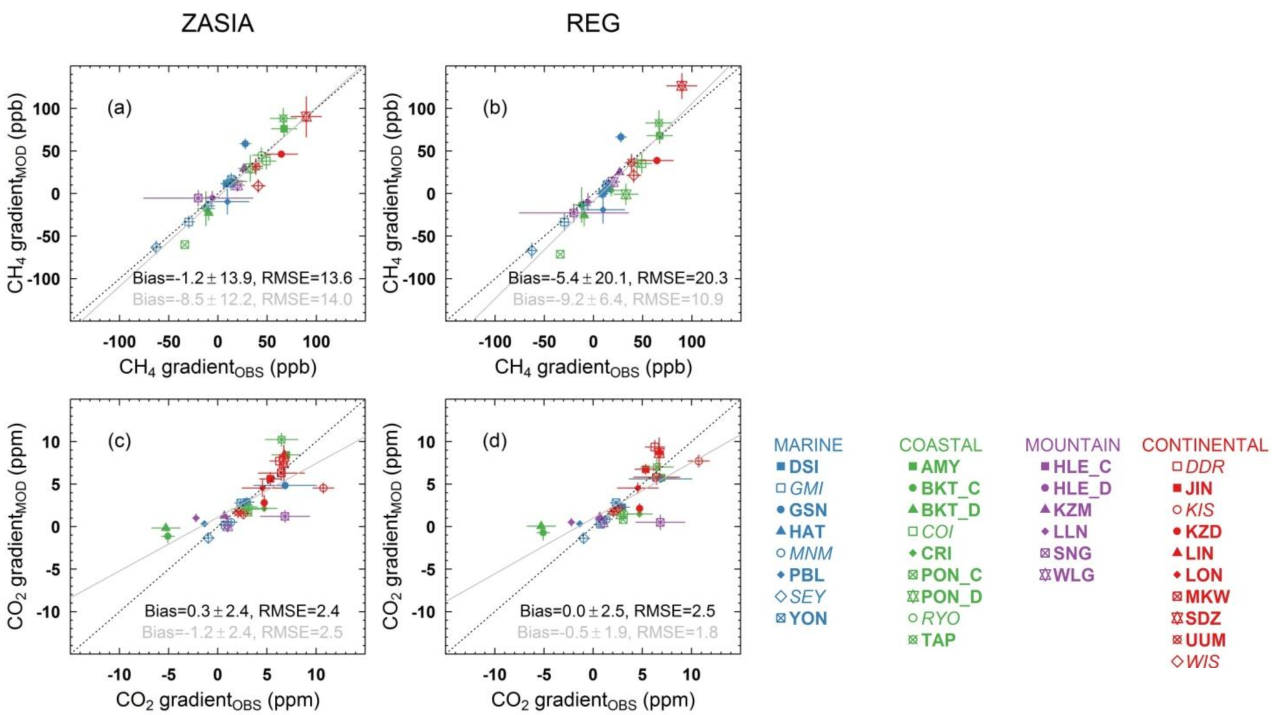

Figure 1.11 Scatter plots of simulated and observed mean annual gradients of CH_4 (a, b) or CO_2 (c, d) between HLE and other stations. For both tracers, the simulated gradients are based on simulations from ZASIA (a, c) and REG (b, d). In each panel, the black dotted line indicates the identity line, whereas the grey solid line indicates the linear line fitted to the data. The italic type and open symbols in the legend denote stations outside the zoomed region.

Figure 1.11 shows the mean annual gradients between Hanle (HLE) and other stations in the world shown in the same figure. The performance of the zoomed model is seen to be better than the unzoomed version for CH_4 while there is not much difference between the two for CO_2.

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