1

CARBON CYCLE & OCEAN MODELLING

Biogeochemical cycling of major (carbon, oxygen and nitrogen) and trace (phosphorous, silica, iron etc.) elements plays a key role in climate change. Regional estimates of the carbon and nitrogen fluxes between land, ocean and atmosphere need to be robust and accurate for acceptance by the international community in compliance to commitments. This calls for synthesis of modeling and measurements to provide robust estimates of fluxes. To continue this research at CSIR-4PI, a project titled "Carbon and Nitrogen Cycling in the Earth System (CNES)" was funded by CSIR.

Robust estimation of carbon fluxes at reasonable spatial and temporal scales is required as we try to fulfill national commitments towards controlling carbon emissions and increasing uptake by vegetation. The availability of greenhouse gases i) data of very high absolute accuracy and a ii) procedure to infer robust fluxes by ingesting this data into an inverse transport model are extremely important in this endeavor. At CSIR-4PI we have been collecting WMO-standard Greenhouse gases (GHG) data at Hanle, Pondicherry, Port Blair and Hoskote over the past few years and we have assimilated this data into a 4-dimensional variational assimilation scheme which employs the adjoint of the LMDZ model. India has been shown to be a substantial land sink.

Numerical simulations of marine biogeochemical model (TOPAZ) are carried out for climatological and interannual variations for the period 1949 to 2018 at two model resolutions and forcing with two different fluxes. Results of these model simulations are evaluated with available data. Data bases reflecting the spatial, seasonal and interannual variability of physical and biogeochemical variables and fluxes are generated which can be used to estimate the impact of climate change.

Inside

- WMO-standard GHG data collection at 4 Indian sites
- Operation of calibration facility with primary NOAA standards
- Estimation of carbon fluxes using a 4-D Variational assimilation procedure
- Evaluation of the results of three biogeochemical model simulations for spatial, seasonal and interannual variabilities
- Analysis of the results of model simulations to understand the biogeochemical processes contributing to the estimation of primary productivity, carbon flux and oxygen distribution in the ocean

1.1 Carbon cycle studies in the Indian Ocean using ocean biogeochemical model simulations and observations

In the earlier studies, numerical simulations of marine biogeochemical model (TOPAZ) were carried out by forcing with climatological and inter annual CORE fluxes at 1-degree resolution and simulation results were evaluated using data from World Ocean Atlas, cruises and satellites. At present, numerical simulations of the marine biogeochemical model (TOPAZ) (i) at a resolution of 0.25 degree forced with CORE fluxes for the period 1949 to 2009 and (ii) at a resolution of 1 degree forced with NCEP fluxes for the period 1978 to 2018 are set up in the global domain for the estimation of marine productivity, carbon and nitrogen fluxes, and hypoxia in the open ocean. The physical model is the modular Ocean Model (MOM5) and the biogeochemical model TOPAZ developed at GFDL has been coupled with MOM5. The model is spun up for 200 years with climatological forcing using bulk formulae to compute surface fluxes.

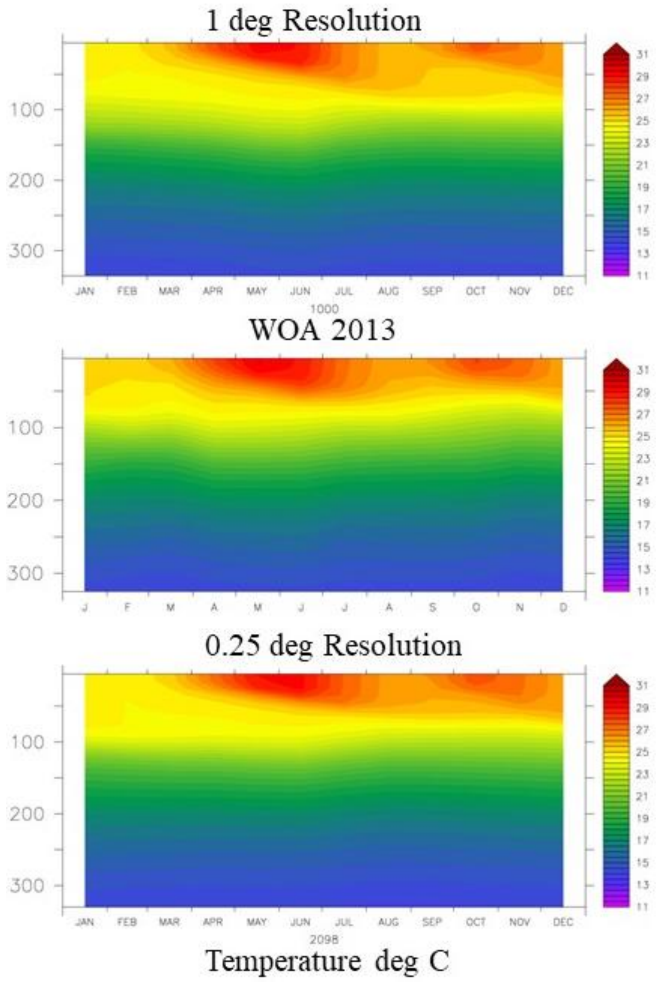

Figure 1.1a Seasonal variation of Temperature (deg C) with respect to depth from two climatological model simulations (1 degree and 0.25-degree Resolution) with World Ocean Atlas (WOA 2013) for one region in west Arabian Sea (60:65º E, 15:18º N)

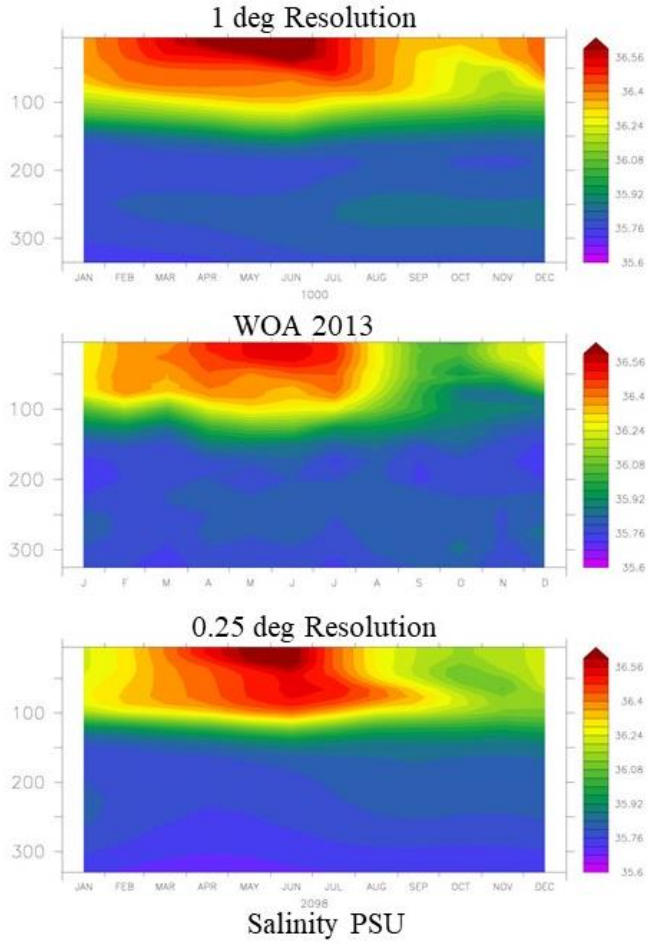

Figure 1.1b Seasonal variation of Salinity (PSU) with respect to depth from two climatological model simulations (1 degree and 0.25-degree Resolution) with World Ocean Atlas (WOA 2013) for one region in west Arabian Sea (60:65º E, 15:18º N)

Results of climatological model simulation with 0.25-degree resolution are initially evaluated for spatial and seasonal variations using data from World Ocean Atlas (WOA 2005, 2008, 2013), data from satellites (SeaWiFS and MODIS, Merged data) and cruises (US JGOFS, Indian JGOFS, BOBPS) in the Arabian Sea (AS) and the Bay of Bengal (BOB)

Seasonal variations with respect to depth for temperature and salinity from the climatological model simulations (0.25 degree and 1 degree resolution forced with CORE Fluxes) are compared with WOA 2013 for different regions in AS and BOB. Figures 1.1 (a) and (b) show the variations of temperature and salinity with respect to depth for one region in west AS from simulation results and WOA 2013. Variation of temperature from model results compare well with WOA 2013 at all depths, in particular, in the upper 100m during all seasons. Very high Salinity observed during February to August, low salinity during September-October in the upper 100m are well captured by the model results.

Spatial variations of Sea Surface Chlorophyll (Chl) and net Primary Productivity (PP) from climatological model simulation for four seasons in the north Indian Ocean are compared with ocean colour data (merged) from satellites. It is noted that significant features of seasonal and spatial variations are captured well by the model simulations.

Spatial variation of nitrate in the upper 50 m during four seasons shows that nitrate is higher in the west AS and southern coast of India during south-west monsoon (SWM) and fall intermonsoon (FIM) and low in central AS and whole of BOB during all seasons, both in WOA 2013 and model simulation results. It is noted that nitrate obtained from model simulations is higher in the west AS during northeast monsoon (NEM) and spring inter-monsoon (SIM) compared to WOA 2013. Spatial and seasonal variations in silicate, ammonium, pCO_2, dissolved inorganic carbon and carbon flux between ocean and atmosphere are also analysed in detail.

Generation of databases and detailed analysis of physical, biogeochemical variables and fluxes using numerical simulations of models and data from observations, reflecting seasonal and inter-annual variability of primary productivity, macro and micro nutrients, carbon flux and oxygen in the north Indian Ocean which can be used to estimate the impact of climate change, are under progress.

1.2 Suboxic Zone in the Arabian Sea and Bay of Bengal

Spatial variation of annual mean concentration of Oxygen (m Mol/ m^3) in the world ocean at 200m depth obtained from model simulation compares well with data from World Ocean Atlas (WOA 2013) and all the Oxygen Minimum Zones (OMZ) in the world ocean are captured by results of the model simulation. Spatial variation of Oxygen in the upper 50 m in the north Indian Ocean from the model simulation compares well with WOA 2013 during four seasons in the north Indian Ocean. Significant features like (i) low oxygen concentrations observed (WOA 2013) in the west and north AS, and coastal regions of India during southwest monsoon (SWM) and fall intermonsoon (FIM) (ii) higher oxygen concentration observed in the west AS and BOB during NEM and SIM are well captured by the model simulation results.

Monthly variation of chlorophyll integrated over euphotic zone, sea surface temperature (SST) and mixed layer depth (MLD) during 1996 to 2009 from the model simulations (Figure 1.2) forced with CORE fluxes at 1-degree resolution, show that Chlorophyll is high, SST is low and MLD is deeper in the regions of OMZ compared to regions in non-OMZ. Significant interannual variabilities are observed during 1996-1998, 2002-2004 and 2006-2008 which correspond to ENSO events.

Interannual variation of Oxygen with respect to depth for one of the regions from two model simulations (forced with CORE and NCEP fluxes) for the years 1996-99 is shown in the figure 1.3. It can be observed that extent of OMZ is less for simulations forced with NCEP fluxes compared to CORE fluxes since primary productivity is less for simulations forced with NCEP fluxes in the region considered.

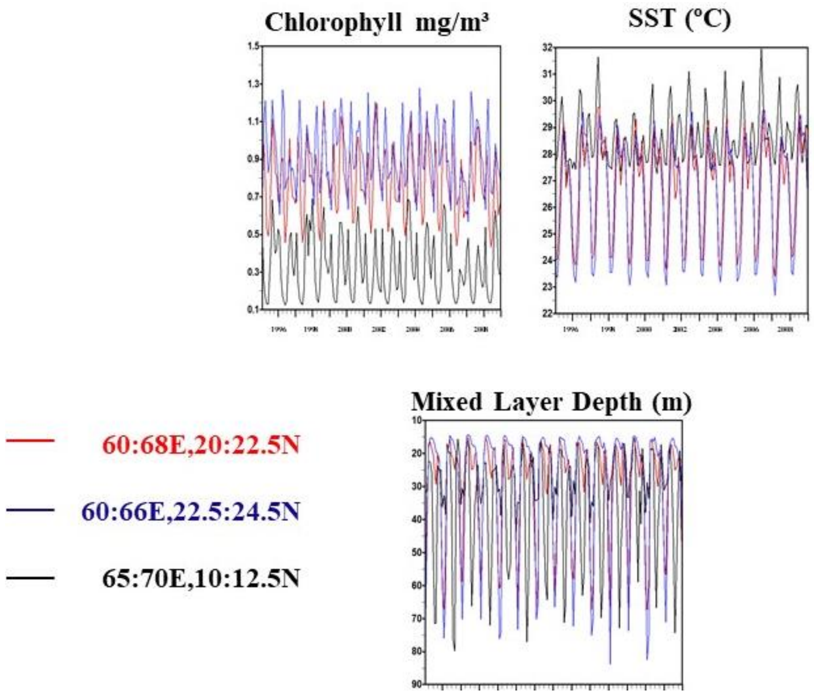

Figure 1.2 Monthly variation of Chlorophyll integrated over euphotic zone (mg/m^2), Sea Surface Temperature (SST: degree C) and Mixed Layer Depth (m) during 1996 to 2009 for the regions of Oxygen Minimum Zone (OMZ: Red and Blue) and non-OMZ (Black) in the Arabian Sea from the model simulations

Detailed analysis of the source and sink terms of the oxygen equation in the model is being carried out to understand the contribution of various biogeochemical processes to spatial, seasonal and interannual variations of oxygen concentration in the AS and BOB.

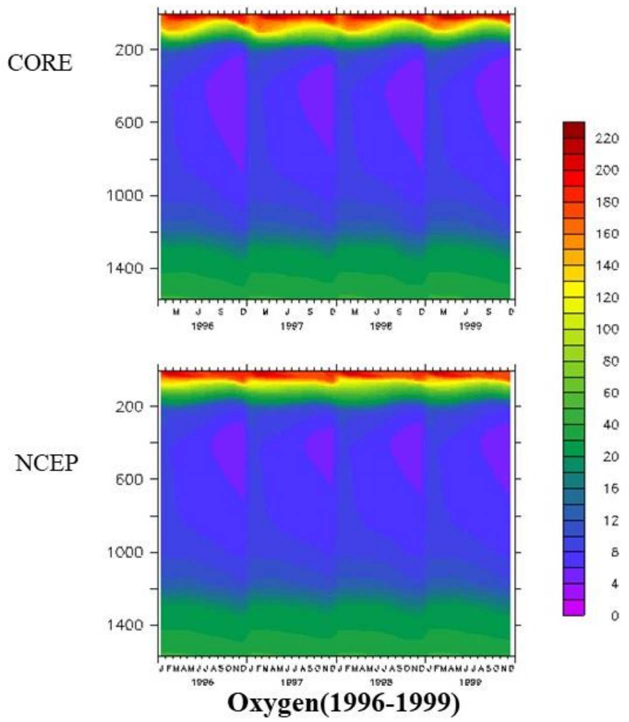

Figure 1.3 Interannual variation of Oxygen (mMol/m^3) with respect to depth in one of the regions of OMZ from two model simulations (forced with CORE and NCEP fluxes at 1-degree resolution) for the years 1996-99.

1.3 Measurements and analysis of Greenhouse gases (GHG): Data collection and analysis

Measurements of carbon dioxide and methane at Hanle, Hoskote and Pondicherry continued through the year. The daily means of carbon dioxide along with a smooth curve consisting of a constant, linear, quadratic and 4 harmonics (Thoning 1988) terms for Hanle is also shown in figure 1.4. There is a small deviation between the data and the curve indicating that the site is quite clean and can serve as a background station. The yearly change between 2018-19 and 2019-20 is roughly 2.6 ppm. Assuming that Hanle measurements are indicative of global well-mixed concentrations, a difference of 2.6 ppm indicates a global atmospheric loading of 5.5 Gigatonnes of carbon. A similar figure for Hoskote is shown in figure 1.5. The data is noisy due to local effects unlike Hanle but the year-to-year increase is nearly the same as Hanle. Similar analysis has been done for methane. Unlike carbon dioxide, methane reacts vigorously with Hydroxide (OH) and it is not straightforward to estimate the atmospheric loading.

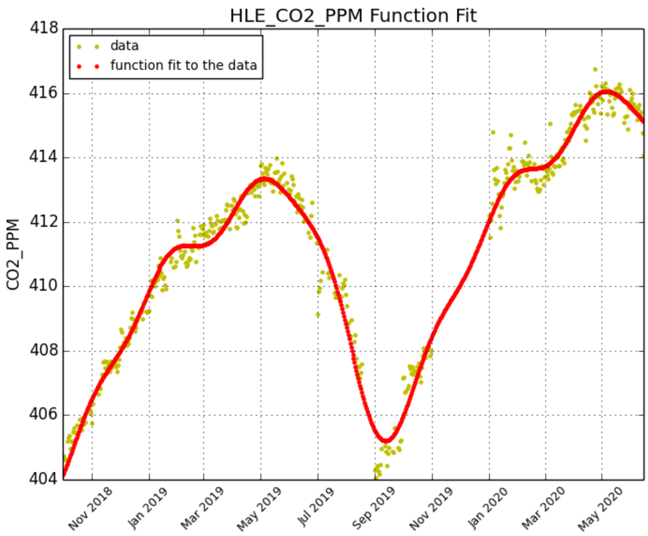

Figure 1.4 Daily mean carbon dioxide and smooth curve in Hanle

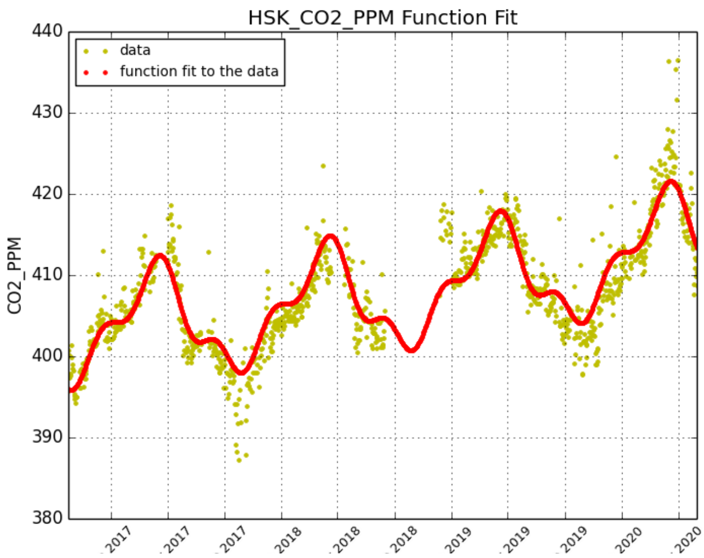

Figure 1.5 Daily mean carbon dioxide and smooth curve in Hoskote

1.4 Diurnal Variation at Hoskote

The monthly mean diurnal variation of carbon dioxide, methane in the months of March 2020 are shown figures 1.6. Notice that the winds at Hoskote in April are mostly from the south-east while it shifts to more southerly and south-westerly in April and May. The reduction in concentrations during daytime (5-11 UTC) due to both vigorous vertical mixing and photosynthesis for carbon dioxide and mixing alone for methane can be clearly seen.

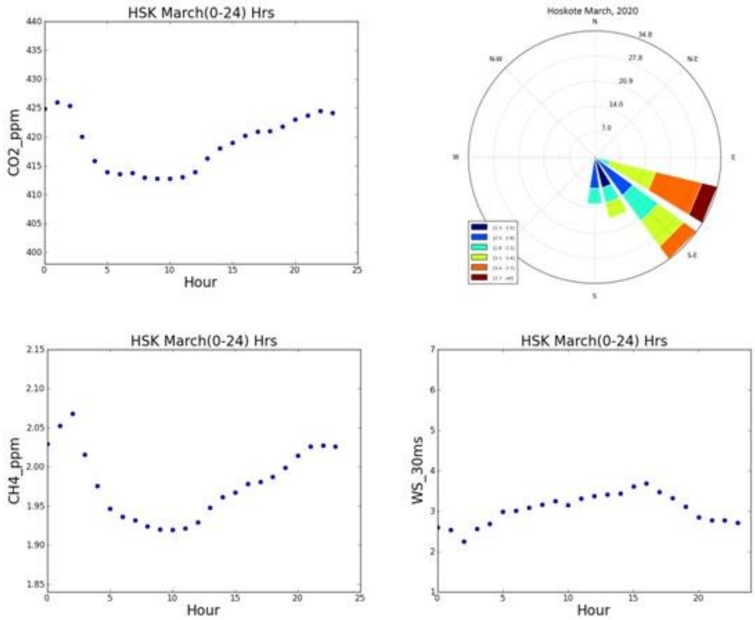

Figure 1.6 Diurnal variation of carbon dioxide (upper left), methane (lower left), wind speed(lower right) and rose plot of wind direction (upper right) at Hokote in March 2020

National Atmospheric Research Laboratory (NARL), Tirupathi brought its Picarro instrument for repeat primary calibration in Dec 2019. All our instruments and secondary cylinders were recalibrated with primary NOAA cylinders at the same time.

1.6 Development of a Database for GHG and AWS measurements

We have developed a database to archive all the GHG and Automatic Weather Station (AWS) measurements till date using MySQL, PHP and Python. The measurements are catalogued according to stations, type and instruments and can be queried using a web interface and python to display any parameter of interest.

1.7 Maintenance of GHG stations

All the stations set up at four different locations are regularly maintained for the smooth functioning of the GHG instruments AWS sensors. AMCs for power, cooling system and the sensors with the tower are in place. All the data generated from these instruments are downloaded regularly at CSIR-4PI.

1.8 Four-Dimensional Variational Data assimilation of GHG data

The rate of exchange of carbon dioxide between atmosphere, land and ocean is a key component of the global carbon budget. It is extremely important to quantify these both on a spatial and temporal basis as it can identify sources and sinks of anthropogenic carbon which are important in setting goals for country-wise emissions and uptake. Carbon dioxide data from three stations from India (Hanle, Pondicherry and Port Blair) along with 100 global stations for 2006-2011 have been ingested into a 4-D variational assimilation scheme involving the forward and adjoint models of LMDZ. The grid point-wise results are aggregated into larger regions representing India, China, USA, Western Europe and the Rest of the World (ROW) to reflect the quantification of sources and sinks in these regions.

Table 1.1 Fossil Fuel Emission totals in **Gigatonnes of Carbon (GTC)**

Year	Global , GTC	India	China	USA	W Europe	ROW
2006	8.388	0.406	1.693	1.681	1.424	3.184
2007	8.581	0.431	1.796	1.687	1.408	3.260
2008	8.763	0.459	2.007	1.583	1.407	3.308
2009	8.662	0.453	1.983	1.564	1.391	3.270
2010	9.180	0.481	2.102	1.658	1.474	3.466

The residual land flux after assimilation of data is shown below in figure 1.7.

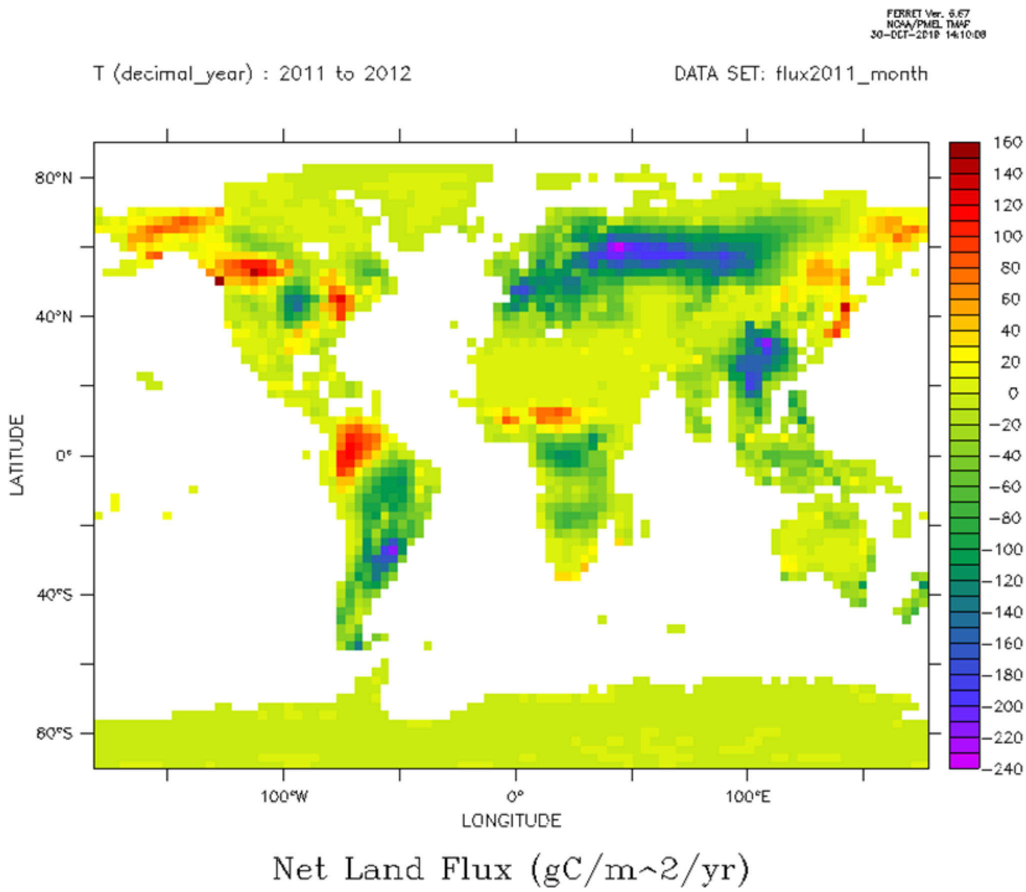

Figure 1.7 Net land flux of carbon dioxide after assimilation

The aggregated net fluxes are given in Table1.2. India and China are substantial sinks of carbon.

Table 1.2 Aggregated fluxes over continental regions in GTC

Year	Global FF GTC	India	China	USA	W Europe	ROW	Ocean	Atm	Atm GR ppm	Atm GR NOAA
2006	8.39	-0.274	-0.357	0.203	-0.045	-2.471	-1.575	3.868	1.83	1.75
2007	8.58	-0.258	-0.317	-0.252	0.160	-1.373	-1.415	5.126	2.42	2.09
2008	8.76	-0.261	-0.587	-0.340	-0.190	-2.314	-1.602	3.469	1.64	1.78
2009	8.66	-0.232	-0.598	-0.122	-0.334	-2.060	-1.517	3.798	1.79	1.61
2010	9.18	-0.148	-0.204	-0.059	-0.729	-0.861	-1.664	5.517	2.60	2.43
2011	9.18	-0.078	-0.449	0.017	-0.639	-2.595	-2.015	3.421	1.61	1.70

The final fit to Hanle data after inversion is shown in figure 1.8. The inverse model is able to fit the observation very well.

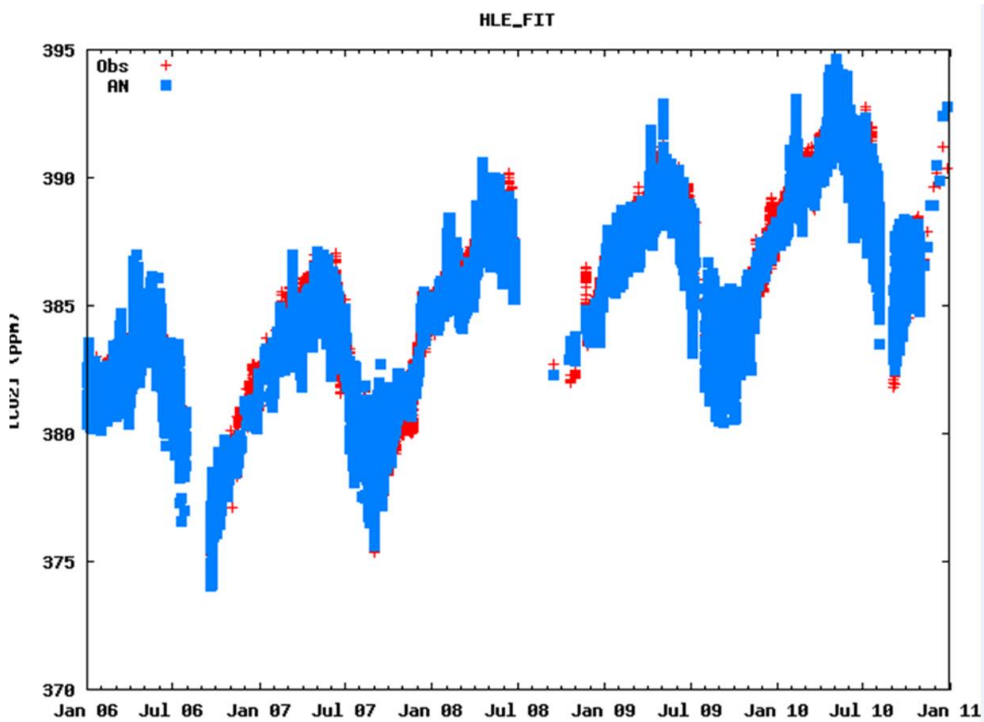

Figure 1.8 Observations and fit to Hanle carbon dioxide measurements