# 1

# Climate and Environmental Modelling Programme (CEMP)

*Capacity to model and forecast climate and environmental processes at different spatio-temporal scales has the potential to revolutionize our approach and ability to address many issues that concern us closely. It was to address these issues in an integrated manner and to generate a capability for multi-scale forecasting that CEMP was initiated.*

## *Highlights*

*The year 2005-20056 had seen a number of significant developments in CEMP. C-MMACS is now a major participant in a national multi-institutional extended -range monsoon prediction (MI-ERMP) programme, which seeks to improve prediction of monsoon rainfall with a multi-model ensemble. C-MMACS has been also involved in a number of national and international programmes and projects.*

## *Inside*

## 1.1 Experimental Forecasts of Monsoon Rainfall for 2005: Post-Forecast Evaluation

A major research programme at C-MMACS is to improve scope and skill of monsoon forecasting. We have developed and employed a new methodology termed Multi-Grid Ensemble (MuGE). Unlike in a conventional multi-lead (ML) ensemble using initial conditions from a number of observations (days); the multi-grid (MG) ensemble uses the variations in the forecasts due to small changes in the grid structure. While ML ensemble forecasting relies on model's response (memory) to differences in initial conditions, the MG ensemble represents a dynamical (and persistent) perturbation, thus providing an alternative and attractive method for enhancing forecast skill.

Traditionally, the day of the onset of monsoon is the day on which coastal Kerala receives it first monsoon rainfall of the season. It is obvious that a unique definition of onset does not (and cannot) exist, as the definition depends on the emphasis. With our focus on rainfall and the users, we have adopted a very functional definition of the onset.

The onset of monsoon is defined as the day in May/ June period on which rainfall occurs with the following characteristics:

(a) Large-scale: should occur more or less simultaneously over a number of stations.

(b) Significant: should be above a threshold value, typically 3 mm/day.

(c) Persistent: should last a few days with characteristics intermittently (day-to-day-variation).

(d) Sustained: The first spell should be followed by another rainfall spell with a gap of no more than 10 days.

While the criteria (a)-(c) have been advocated by others, the criteria (d) is our addition; its implementation requires forecasts for days subsequent to onset.

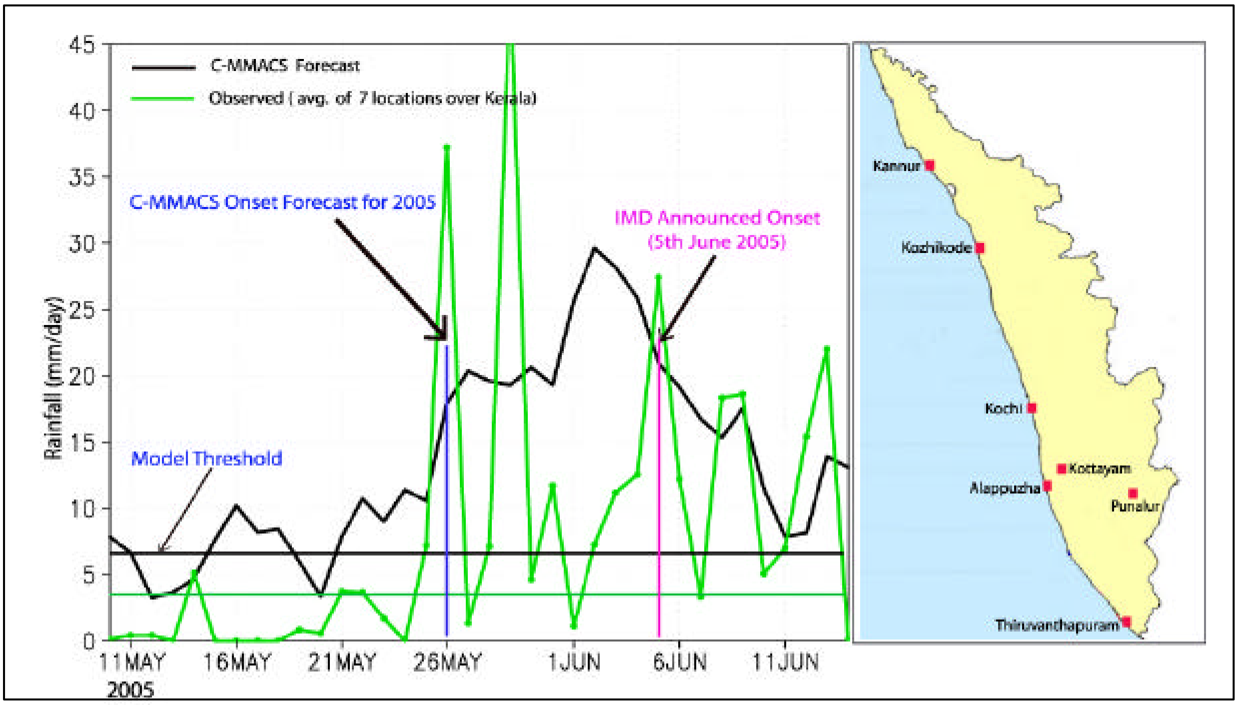


**Figure 1.1 Time series of area-averaged (75-77E; 8-12N) daily rainfall over coastal Kerala. Day 1 corresponds to 1st May 2005.**

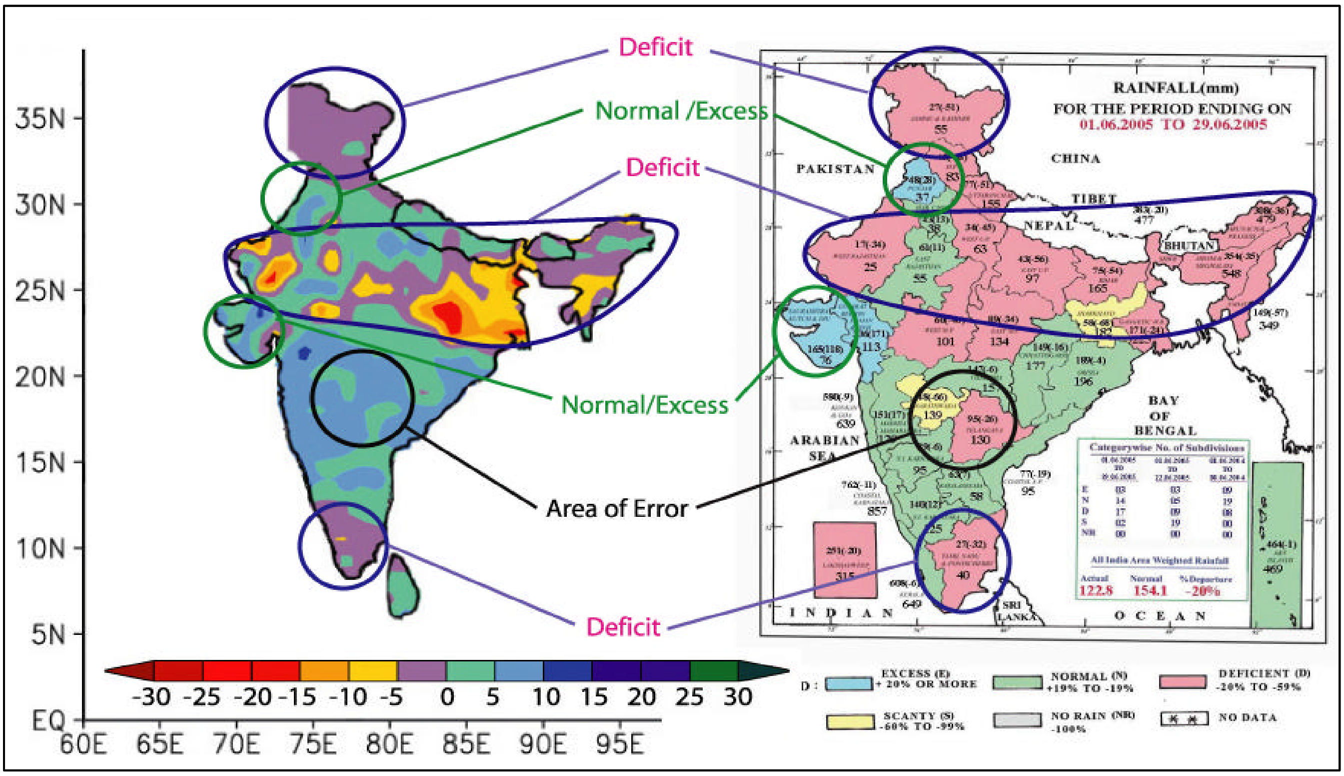


**Figure 1.2 Comparison of anomalies in monthly rainfall for June, 2005 from C-MMACS experimental forecasts and observations (www.imd.ernet.in). The forecast anomalies are with respect to 15 year model climatology.**

The adopter definition has a number of advantages:

(a) It automatically takes into account a larger time windows, recognizing that nature is not likely to oblige with any fixation of our regarding the likely period of onset.

(b) It is functional; the onset date signifies the beginning of a large-scale, significant, persistent rainfall episode regardless of its mechanism. This is the critical requirement for initiating agricultural activity.

(c) It is holistic: It recognizes that the monsoon is not a monolith in terms of its circulation system but is a composite of many scales: global to local, all of which determine the amount and distribution of rainfall.

In short, our definition somewhat deviates from (or redefines) a pure academic definition. In our definition, a widespread, significant rainfall episode initiated by, say, a tropical cyclone on May 20th and subsequently merging with rainfall due to westerly flow would result in a date of onset as May 20.

With this definition, the onset date for 2005 was predicted as May 26, based on an ensemble of 12 simulations based on initial conditions during the period 01 February to 30 April, 2005.

A quick comparison of anomalies in monthly rainfall from observations and forecasts for June 2005 reveal the following features:

Successes:

a) The north-west part of India was characterized by a strong spatial variation: while Gujrat recorded an excess, the neighboring west Rajasthan experienced a strong deficit, Punjab, neighboring WR on the other hand, experienced an excess rainfall in June. These features are well captured in forecast.

b) The forecasts captured well the belt of severe deficit extending from east to wet, including the severe deficit over ….

c) The forecasts also captured well the normal to excess rainfall over the south-central India.

d) The forecasts indicated deficit rainfall over the north-eastern states as observed.

e) The forecasts correctly indicated deficit rainfall over the peninsular India.

Failures:

a) The amplitudes of the anomalies in the forecasts are smaller than those observed in some cases.

b) The forecasts couldn't capture the severe deficits over Marathawada and Telengana, although they indicated relatively weaker rainfall.

c) The forecasts failed to capture the severe deficits over eastern and western Uttar Pradesh.

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## 1.2 A Comparison of Interpolated NCEP (I-NCEP) Rainfall with High-Resolution Satellite Observations

Large-scale long-period analyses like NCEP Reanalysis have become invaluable for generating robust statistics for model validation and carrying-out comprehensive diagnostics. This study evaluates daily NCEP rainfall as a high-resolution analysis through comparison with high-resolution rainfall based on satellite and GTS gauge observations. We use daily composite rainfalls over the Indian summer monsoon domain for the period 2001-2005 from satellite observations available at 10-km resolution and 10-km Interpolated NCEP rainfall (I-NCEP). Figure 1 compares all-India daily rainfall values (mm/day) from satellite data (red line) and NCEP (blue line) for five years (2001-2005).

It is clear from both the Figure 1.3 that the I-NCEP rainfall follows the temporal variations in the high-resolution satellite data quite well. As expected, the I-NCEP rainfall does not always match the high amplitudes of certain episodes in the satellite data; however, the broad features of temporal variations are comparable.

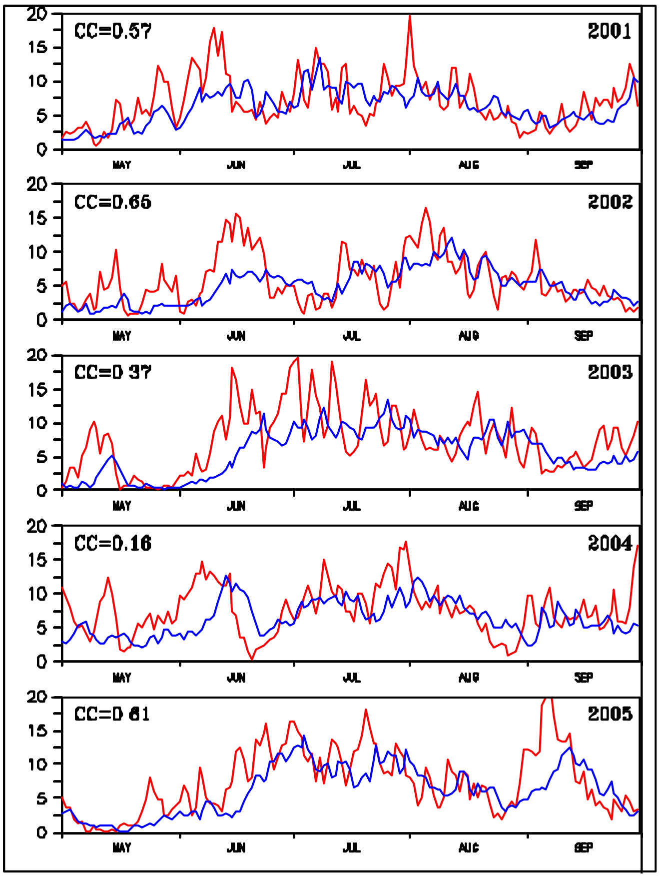


**Figure 1.3 All-India daily rainfall values from satellite derived data (red line) and I-NCEP reanalysis (blue line). The x-axis shows time (days) for the June-September period while the y-axis shows rainfall in mm.**

The correlation coefficients (Table 1.1) between daily (D) and weekly (W) rainfall values from the two data sets for different domain averages are significant for the degrees of freedom involved, especially at weekly scale. The correlation coefficients, however, show significant variations from domain to domain in the same year from year to year for the same domain, a point that needs further investigation.

The spatial correlation between observed and I-NCEP daily rainfall, reveals three features are discernible: i.e.,

(a) The correlation coefficient is generally non-

**Table 1.1 Correlation coefficient between daily (D) and weekly (W) rainfall values for different domain averages**

| Year | All India | | North India | | South India | | Central India | |
|---|---|---|---|---|---|---|---|---|
| | W | D | W | D | W | D | W | D |
| 2001 | 0.80 | 0.57 | 0.79 | 0.60 | 0.49 | 0.32 | 0.86 | 0.65 |
| 2002 | 0.81 | 0.65 | 0.78 | 0.61 | 0.61 | 0.41 | 0.68 | 0.50 |
| 2003 | 0.64 | 0.37 | 0.40 | 0.12 | 0.58 | 0.38 | 0.56 | 0.28 |
| 2004 | 0.27 | 0.16 | 0.59 | 0.46 | 0.50 | 0.31 | 0.38 | 0.11 |
| 2005 | 0.82 | 0.61 | 0.62 | 0.51 | 0.81 | 0.40 | 0.79 | 0.48 |

negative over the continental Indian domain.

(b) The correlation coefficient is significant (for the degrees of freedom involved) over northern and southern India, while it is insignificant over certain locations, such as parts of eastern India and parts of central India.

(c) The correlation coefficient exhibits significant interannual variations, however; there is no discernible trend in the spatial distribution.

The agreement between rainfall anomalies fromsatellite data and I-NCEP analysis is further quantified in terms of phase synchronization, defined as

$$h = \frac{n - n`}{n}$$

where n is the total number of events (122 in daily scale, 17 for weekly scale) and n` is the number of cases for which the two anomalies have opposite signs (out of phase). Thus η is equal to zero if all the anomalies from the two sets are out of phase while η=1 when all of them are in phase. The values of η (%) for four domains and the five years are given in Table 1. 2. For each domain, and for each of the five years, the phase synchronization is quite high, and considerably higher at weekly (W) scale as expected. Thus the two anomalies are in the same direction most of the time.

The correlation coefficient and phase synchronization, shows that the I-NCEP rainfall provides a good representation of high-resolution observations even at meso-scales and provides a good long-period, high-resolution data set for model

**Table1.2 Phase synchronization (%) between daily rainfall anomalies of Satellite and NCEP datasets different domain averages.**

| Year | All India | | North India | | South India | | Central India | |
|---|---|---|---|---|---|---|---|---|
| | W | D | W | D | W | D | W | D |
| 2001 | 83.3 | 66.1 | 83.3 | 76.9 | 66.7 | 67.8 | 77.8 | 68.6 |
| 2002 | 83.3 | 71.1 | 83.3 | 76.0 | 88.9 | 73.6 | 77.8 | 71.1 |
| 2003 | 83.3 | 64.5 | 66.7 | 54.6 | 83.3 | 68.6 | 83.3 | 62.8 |
| 2004 | 83.3 | 57.9 | 83.3 | 63.6 | 72.3 | 57.9 | 77.8 | 49.6 |
| 2005 | 72.2 | 70.2 | 88.9 | 68.6 | 72.3 | 63.6 | 71.8 | 68.6 |

validation and evaluation. This in turn implies that the I-NCEP Reanalysis can be used for validation and diagnostics of high-resolution rainfall forecasts over a number of years. These conclusions need to be checked for other variables, seasons and other regions. There are, however, certain caveats and issues that need further exploration.

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## 1.3 Coupled air-sea interactions in the tropical Indian Ocean and impending monsoon droughts

Monsoon droughts over the Indian subcontinent arise due to failures in the seasonal (June-September) summer monsoon rainfall and rank among the foremost of natural disasters affecting mankind and society. For example, monsoon drought of 2002, which resulted in economic losses of billions of dollars, is a striking example of a large-scale catastrophic event. The question as to how the tropical Indian Ocean and the monsoon circulation dynamically interact on the intraseasonal time-scale still remains unresolved. One of the key issues, in this context, is the role of ocean sub-surface processes in contributing to the maintenance of anomalous atmospheric circulation and convection patterns over the monsoon region. In this study, we demonstrate, from an analysis of a suite of observed datasets, that ocean-atmosphere coupling on the intraseasonal time-scale, in the tropical Indian Ocean, is pivotal in forcing long-lasting breaks in the monsoon rainfall and causing droughts over the subcontinent. The monsoon drought witnessed in 2002 also was related to near equatorial precipitation anomalies; however for the first time advances in the ocean observing system allow characterization of subsurface properties. The striking contrast in the rainfall activity between the equatorial Indian Ocean and the Indian landmass during July 2002 is evident. The suppression of monsoon precipitation over the Indian landmass during July 2002 resulted due to anomalous subsidence over the subcontinent induced by strong upward motions over the equatorial Indian Ocean which weakened the so-called monsoon Hadley circulation.

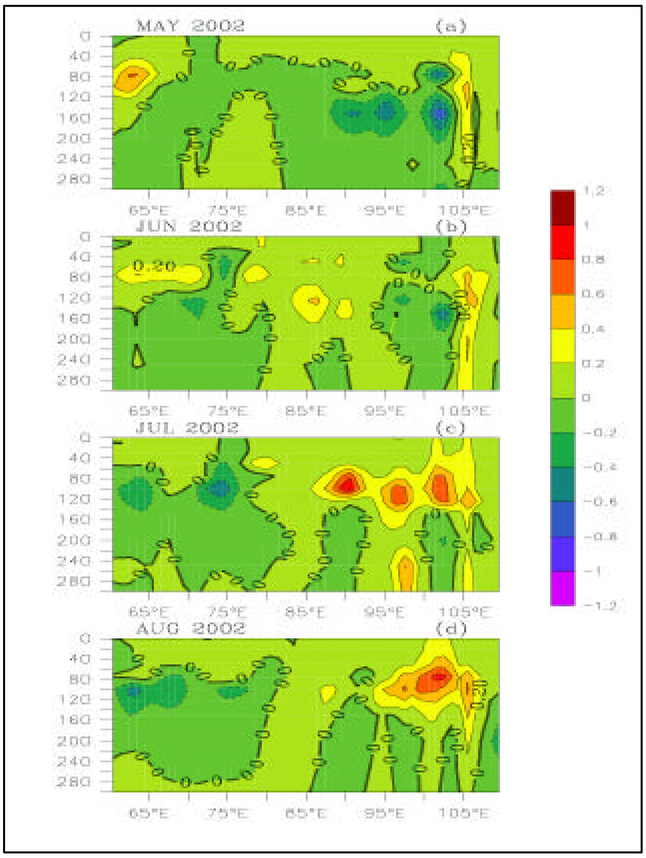


**Figure 1.4 Longitude-depth sections of monthly temperature anomalies averaged between 10oS-5oN during May-August, 2002 shown in (a-d). The subsurface temperature anomalies are relative to the climatological World Ocean Atlas 2001 - database.**

The dynamical link between the wind field and sea-level anomalies can be interpreted as downwelling Kelvin waves, forced by westerly winds over the equator, which propagate to the eastern boundary (Sumatra) and are reflected as Rossby waves that increase the heat content in the Bay of Bengal, as well as the eastern Indian Ocean as far south as Java. Furthermore, the occurrence of anomalous sub-surface warming, by as much as 0.8oC during July and August 2002, in the EEIO (Figure 1.4 c-d) corroborates the increase in oceanic heat content in the region. The warm sub-surface anomalies in the EEIO together with the cold anomalies of about 0.4oC in the equatorial western Indian Ocean (Figure1.4b-d) represent an anomalous intensification of the near-equatorial zonal temperature gradient.

Here we demonstrate, from the above analysis of a suite of observed datasets, that ocean-atmosphere coupling on the intraseasonal time-scale, in the tropical Indian Ocean, is pivotal in forcing long-lasting breaks in the monsoon rainfall and causing droughts over the subcontinent. This coupling involves a self-sustaining feedback between the monsoonal flow and the thermocline depth in the equatorial eastern Indian Ocean (EEIO), in which an anomaly of the monsoon circulation induces downwelling in the EEIO and maintains a deeper-than-normal thermocline and higher-than-normal ocean heat content. The warm ocean favours enhanced precipitation locally over the EEIO and weakens the monsoon circulation by inducing subsidence over the subcontinent. The antecedents of an ensuing monsoon drought are evident from ocean heat content evolution starting from the preceding spring season. Our analysis conclusively shows that the intraseasonal evolution of the tropical Indian Ocean coupled system holds the key to unlocking and understanding the dynamics of monsoon droughts.

A question arising at this stage is regarding the termination of the positive feedback process. Our preliminary understanding indicates that the termination can be influenced by processes contributing to SST cooling - such as cloud-radiative effects associated with convective anomalies over the EEIO region; heat loss from the ocean due to increase in latent and sensible heat fluxes over the warm equatorial region. Further studies will be required to resolve this issue. The present findings take on added significance in view of the antecedents that are initiated during the spring months preceding the summer monsoon drought (as in 2002), when enhanced eastward currents in the equatorial Indian Ocean cause accumulation of warm waters in the east. If indeed the coupled interactions among the Indian Ocean dynamics, monsoon circulation and the MJO activity hold the key to the evolution of the tropical intraseasonal oscillations, the implications of these coupled interactions on the regional and global climate warrants careful consideration.

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## 1.4 Mathematical Modelling of Biogeochemical Cycles in the Indian Ocean

A central problem in large-scale biogeochemical modeling is determining how well biological models can simulate observed variability in different ocean environments. The key questions are: Which model formulations work best for a given region? How transferable are models specifically designed for one region to other regions? Answering such questions is one of the central goals of the U.S. JGOFS Synthesis and Modeling Project (SMP). Since biogeochemical models are sensitive to the physical framework in which they are embedded, different models have to be run under the same physical conditions to enable quantitative model intercomparisons. To promote intercomparison studies, the U.S. JGOFS SMP has formed a working group to provide 1-D test beds, which allow researchers to run a variety of biogeochemical models in a specific physical context. This testbed for the central Arabian Sea at 15.5 N, 61.5 E, the site of the WHOI mooring uses environmental fields obtained from a 3-D physical model (McCreary et al., 2000) to run biogeochemical models offline in 1-D.

The objective of this study is to understand the effect of five kinetic relations for ammonium inhibition on nitrate uptake by phytoplankton and two light models on the state variables of a seven-component ecosystem model in the 1-D physical framework given in AS Testbed. This marine ecosystem model is evaluated by using US JGOFS data and buoy data. Figure1.5 shows the profiles of chlorophyll

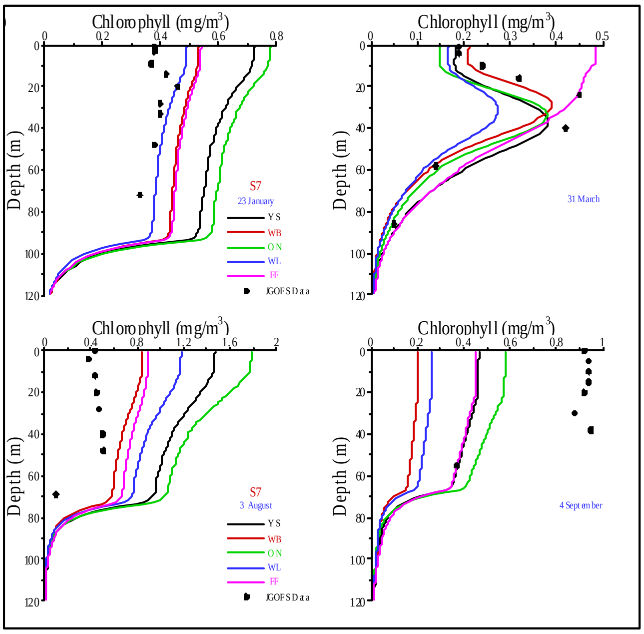


**Figure 1.5 Profiles of Chlorophyll (mg Chl/m3) from five simulations of 1-D coupled physical-biological model compared with the US JGOFS data from five cruises at (15.5  N, 61.5  E).**

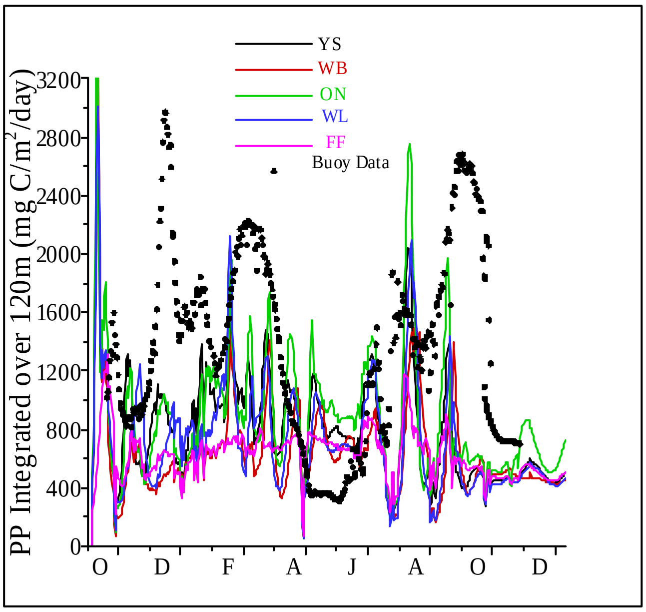


**Figure 1.  Seaonal variation of depth integrated primary productivity values (mg C/m2/day) from five simulations of 1-D coupled physical-biological model compared with the buoy data at (15.5  N, 61.5  E).**

from five model simulations, compared with the data from US JGOFS cruises. It is noticed that deep chlorophyll maximum observed during the spring inter monsoon is captured by the four models and high values of chlorophyll observed during the fall inter monsoon is not obtained from any model simulations. The seasonal variation of  depth integrated values of primary productivity is compared with the buoy data (Figure 1.6**).** The peak values of depth integrated primary productivity obtained from some model simulations during both monsoons agree well with the buoy data.

This kind of study helps in identifying the appropriate relation(s) for the ammonium inhibition on nitrate uptake and relevant light model to be incorporated in the 3D coupled physical-biological-chemical model used for the study on biogeochemical cycles in the Indian Ocean.

Spatial and temporal variations of carbon flux across the air-sea interface on the regional scale have evoked considerable interest in view of the ocean's capacity to take up anthropogenic carbon. The present models of ocean biogeochemical cycles incorporate several key biological processes whose parameter values are assumed. The major challenges in marine biogeochemical modeling can be addressed by model-data comparisons and data assimilation studies. As a part of these studies, climatological simulations of a 3D coupled physical-biological-chemical model are performed at C-MMACS. We focus on the effect of biology on the carbon cycle in the North Indian Ocean. However, since this effect depends on the assumed values of biological parameters, parameter sensitivity analysis becomes prerequisite. In the present study, simulations were carried out for several sets of values of five parameters governing nutrient recycling. One set of parameter values was selected on the basis of comparison of the simulation results with biological and chemical observations from cruises and satellite. Figure 1.7 shows the profiles of primary productivity obtained from the selected simulation compared with the US JGOFS data from five cruises at S7 (16  N, 62  E). The simulation results agree well with the data during northeast monsoon.

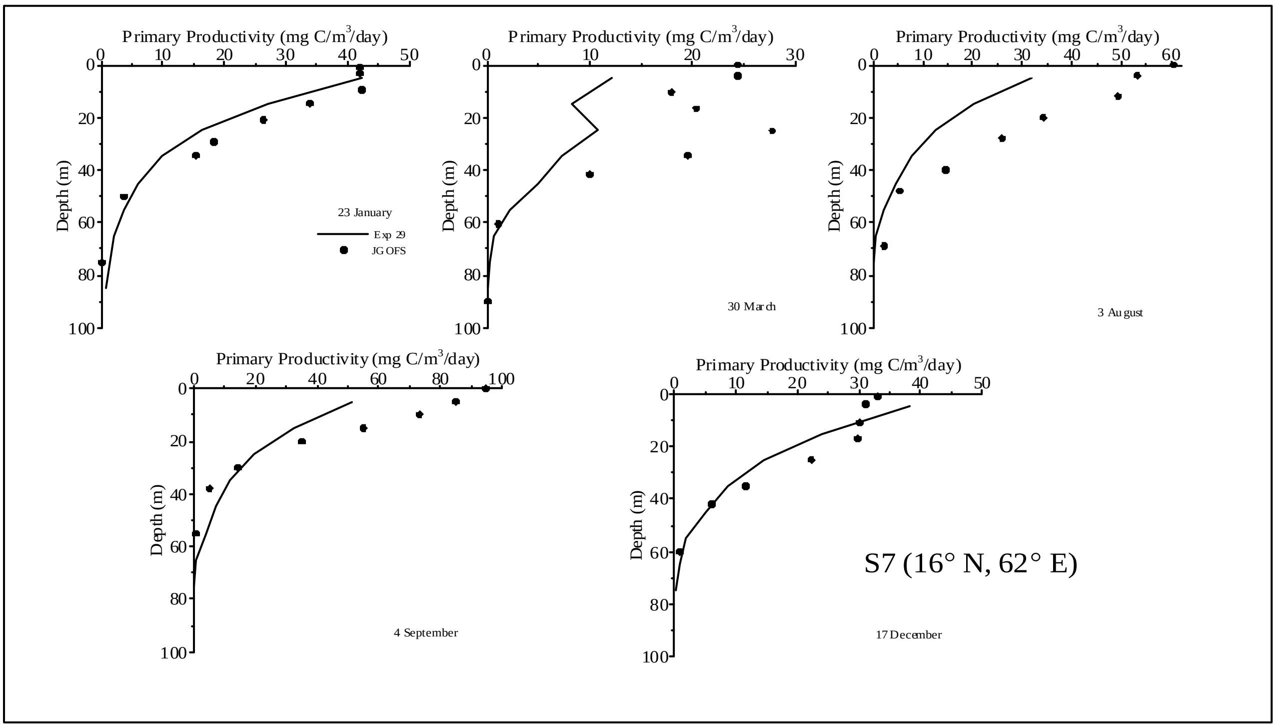


**Figure 1.7 Profiles of Primary Productivity (mg C/m3/day) from 3-D coupled physical-biological (Selected experiment) model compared with the US JGOFS data from five cruises at (16 N, 62 E).**

The results of the selected simulation give fresh insight into the mechanisms and the extent to which biology contributes to the spatio-temporal variability of pCO2, dissolved inorganic carbon and alkalinity in the upper layers of the Indian Ocean. Comparison of this simulation with the corresponding abiotic simulation reveals the effect of the biological pump. The contribution of the biological pump in north Indian Ocean (above the equator), AS (west of 750 E) and BOB (east of 750 E) in the annual carbon budget is given in Table 1, where carbon flux from the ocean to the atmosphere indicates the magnitude of outgassing over a year. While the biological pump decreases outgassing by 20% in AS, it increases in BOB by 12%, the absolute magnitude of the effect being much smaller in BOB than AS. The effect of the biological pump over the entire north Indian Ocean on a year is decrease of outgassing by 13%. This explains the unexpected effect of biological pump increasing the outgassing which is due to the dominance of regeneration over carbon fixation in large parts of the north Indian Ocean. It is also noteworthy that the carbon flux in AS is nearly two and half times that in BOB.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Table 1 Carbon Flux from Ocean to Atmosphere over an year (Pg C/Year)** | | | | | | |
| | | | | | | | |
| | **Region** | **Abiotic** | **Biotic** | **% Difference** | **Takahashi** | | |
| | | | | | | | |
| | Basin | 0.262 | 0.228 | -13 | 0.119 | | |
| | AS | 0.204 | 0.163 | -20 | 0.0761 | | |
| | BOB | 0.058 | 0.065 | 12.1 | 0.0135 | | |

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