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SIGNATURES OF GLOBAL WARMING AND REGIONAL CLIMATE SHIFT IN THE ARABIAN SEA

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Human-induced global warming has different manifestations in different ocean basins (Barnett *et al*., 2005; Webster *et al*., 2005; Goswami *et al*., 2006; Zhang *et al*., 2007). Among them the most alarming response is the increase in the occurrence of extreme events (Emanuel, 2005; Goswami *et al*., 2006; Zang *et al*., 2007) and melting of glaciers (Oerlemans, 1994) which has implication to global hydrological cycle apart from the concern of sea-level rise (Church, 2001; Meehl *et al*., 2005). Though there exist considerable amount of information on the global warming and climate change in the Pacific and Atlantic oceans, we do not have yet much information about the Indian Ocean. Rupakumar *et al*. (2002) was the first to show the warming of Indian Ocean by about 0.5°C based on data analysis during 1904 to 1994. Recently, based on a suite of remote sensing as well as in situ data, Prasanna Kumar *et al*. (2009) showed that the decadal cycle of sea surface temperature (SST) in the Arabian Sea was disrupted after 1995 and linked it with the increased occurrence of severe cyclones in the Arabian Sea. They also showed that the warming of winter after 1995 has affected the wheat production of India. In this paper we use the data presented by Prasanna Kumar *et al*. (2009) and analyze their results in the context of increased marine phytoplankton biomass and fish-catch (oil-sardine) in the Arabian Sea. We also use the Eurasian snow cover data to see if there is any link between the declining monsoon rainfall after 1995.

Material and methods

The monthly mean sea surface temperature (SST) for the Arabian Sea (0-25°N and 45-80°E) extracted from the International

Comprehensive Ocean Atmosphere Data Set (ICOADS) for the period 1960-2005 (http://www.cdc.noaa.gov/cdc/data.coads.1deg.html) was used for computing 5-year running mean. The Sunspot number was obtained from http://www.ngdc.noaa.gov/stp/SOLAR/ftpsunspotnumber.html. Global CO_2 emission data was from http://cdiac.ornl.gov/trends/emis/meth_reg.htm while global CO_2 concentration data measured at Mauna Loa was obtained from www.esrl.noaa.gov.

The rainfall over India was from Indian Institute of Tropical Meteorology (http://www.tropmet.res.in). The all India monsoon rainfall was computed by averaging for the months June to September. The integrated anomaly over the decade was calculated by removing the mean from the all India average summer-monsoon rainfall. The chlorophyll pigment concentration and aerosol optical depth at 865 nm was obtained from SeaWIFS (ftp://oceans.gsfc.nasa.gov/SeaWiFS/Mapped/Monthly). The monthly mean winds were obtained from NCEP/NCAR reanalysis data (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html).

The oil Sardine catch data along the west coast of India (eastern Arabian Sea) was collected from Central Marine Fisheries Research Institute, Kerala, India while that along the Yemen coast (western Arabian Sea) was obtained from FISHSTAT, FAO

(http://www.fao.org/fi/statist/FISOFT/FISHPLUS.asp).

Results and discussion

The analysis of basin-averaged 5-year running mean of the Arabian Sea (0-25°N and 45-80°E) SST (Woodruff *et al.,* 2005) showed a strong decadal scale variability riding over a gradual linear warming trend for the period 1963 to 1995 (Fig.1). The natural decadal cycle of SST, however, was disrupted after 1995. It is well established that the natural decadal cycle arise from solar activity (White, 2006). An examination of the sunspot activity did not show any abrupt change during the study period (Fig.1). The correlation of sunspot activity and SST during 1963-2005 (r2=0.18) was lesser than that during 1963-1995 (r2=0.34), which underscored the importance of the decade after 1995. Though the sunspot activity declined after the year 2000 (Fig.1) the SST did not show any decreasing trend. This indicates that the sunspot activity was not responsible for the disruption of the natural decadal cycle in SST after 1995. We examined the atmospheric CO_2 concentration measured at Mona Loa, Hawaii and global CO_2 emission

(Marland *et al*., 2007) to understand the human-induced effect. The correlation of atmospheric CO_2 concentration and Arabian Sea SST is larger during 1963-2005 (r2=0.78) (Fig.2b) than during the period 1963-1995 (r2=0.58) (Fig.2a) and also a stronger correlation was noticed between SST and CO_2 emission during 1963-2005 (r2=0.72) (Fig. 2d) compared to the period 1963-1995 (r2=0.53) (Fig. 2c). From the above results it is evident that human-induced warming plays an important role in the disruption of natural decadal cycle and subsequent secular warming of SST after 1995.

In order to further decipher the impact of the climate shift on the adjacent landmass, we analyzed the integrated. All-India summer-monsoon (June to September) rainfall decadal anomaly showed a decline of 70.9 mm during 1995-2004 (Fig. 3a). This decline was much higher than those during 1965-1975 (39.5 mm) and 1985-1995 (7.5 mm) periods in spite of having only 1 drought years since 1995. Note that during 1965-1975 and 1985-1995 there were 5 and 3 drought years respectively. Since it has been shown that the Eurasian snow cover during winter was inversely related to Indian summer-monsoon rainfall (Dickson, 1984; Sankarrao *et al*., 1996), we examined the Eurasian snow cover during 1967-2006. Winter snow cover showed a decreasing trend until 1995 and thereafter showed a distinct increase (Fig. 3b). Thus, the decrease in the rainfall after 1995 is linked to the increase in the Eurasian winter snow cover. Since more than 80% of the rainfall over India occurs during summer-monsoon, it is expected to have a major influence on the vegetation cover. Based on the analysis of normalized difference vegetation index (NDVI) Prasanna Kumar *et al*. (2009) showed a decline of vegetation after 1995.

To explore the impact of climate shift on the marine phytoplankton we analyzed the satellite-derived chlorophyll pigment concentration in the Arabian Sea during 1998 to 2006. The annual mean chlorophyll pigment concentration showed an increasing trend (Fig.4a) which arises due to a substantial increase in the pigment concentration during September (Fig. 4b), followed by October and to a lesser extent in winter (Fig. 4c). However, no perceptible trend was discernible during summer (Fig. 4b). An examination of the basin averaged annual mean winds from NCEP/NCAR reanalysis (Kalaney *et al*., 1996) showed a decline (Prasanna Kumar *et al*., 2009). Thus, the increased pigment concentration in the Arabian Sea which occurs during late summer-fall transition and to a lesser extent in winter was not driven by the strengthening of summer-monsoon winds as hypothesized earlier (Goes *et al*., 2005). Further, instead of Eurasian warming (Goes *et al*., 2005) we found an increase in the Eurasian snow cover during winter-spring after 1995 (Fig.5). Thus, based on the above we conclude that the observed increase in the Arabian Sea productivity is not driven by the strengthening of the upwelling due to strengthening monsoon winds as hypothesized by Goes *et al.* (2005) and that other mechanisms need to be explored. One such mechanism could be dust-induced iron-fertilization. The observed declining monsoon rainfall after 1995 has the potential to increase the aridity of the land mass and the dust production. The continuous build up of macronutrients in the Arabian Sea during the summer-monsoon due to upwelling may lead to subsequent iron limitation (Wiggert *et al*., 2007) which in turn limits the phytoplankton growth. We hypothesize that the observed increase in the phytoplankton during fall and winter is triggered by the dust-induced iron-fertilization.

The chlorophyll pigment concentration indicates the biomass of phytoplankton standing stock. Increase in phytoplankton standing stock will be potentially transferred into higher trophic levels. The oil Sardine, *Sardinella longiceps*, which is the most abundant finfish in the Arabian Sea, feed on phytoplankton (Devraj *et al*., 1997). Oil Sardine catch (CMFRI, 2006) along the eastern (west coast of India) and western (Yemen coast) Arabian Sea showed an increasing trend after 1995 (Fig.6). Considering catch as a surrogate of abundance, we conclude that one of the reasons for increase in the biomass of oil Sardine is the increase of phytoplankton biomass. Since fish can be considered as an indicator of climate change (McFarlene *et al*., 2000), we attribute the increase in sardine landings after 1995 to the increase in primary productivity that is tightly-coupled with the climate-shift.

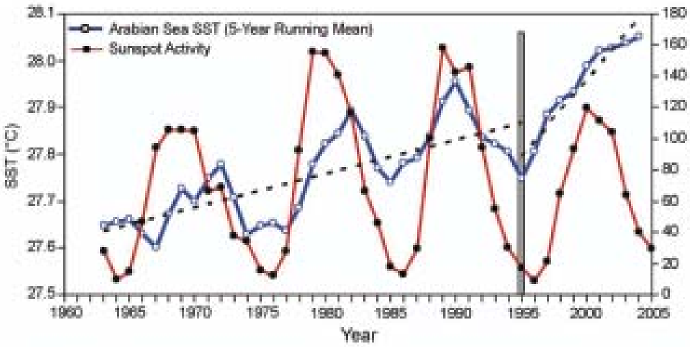


Figure 1. Five-year running mean of sea surface temperature (SST, °C) of the Arabian Sea (hollow circles) averaged over the basin (0°-25°N, 45°-80°E) and the sunspot activity (dark circles). Broken-line is the trend line of SST.

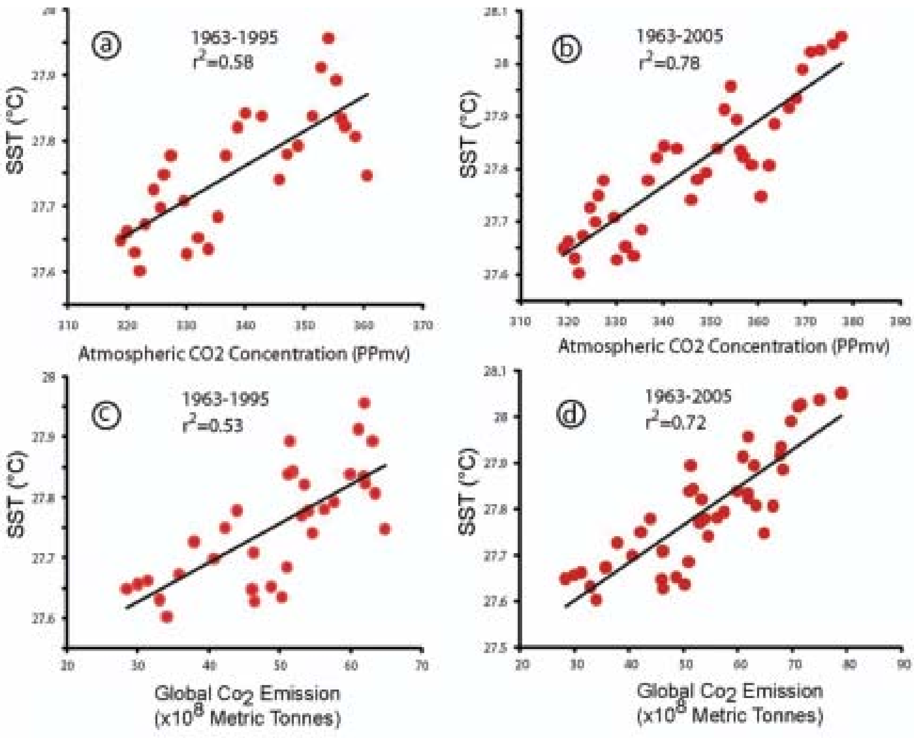
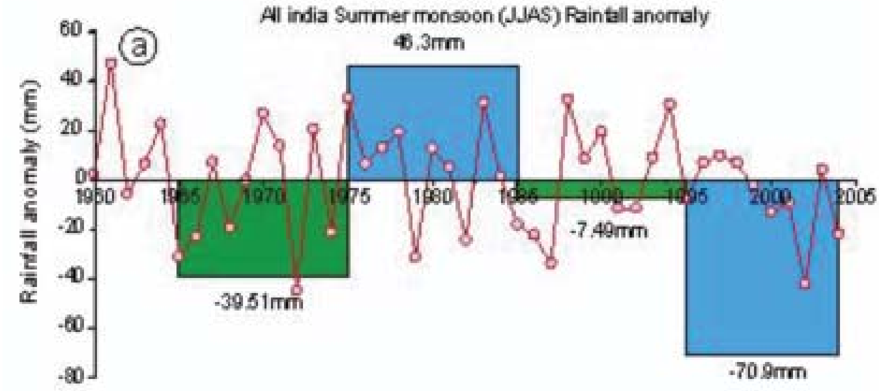


Figure 2. Correlation between Arabian Sea SST and Atmospheric CO_2 concentration during (a) 1963-1995, (b) 1963-2005, and between Arabian Sea SST and Global CO_2 emission during the period (c) 1963-1995 and (d) 1963-2005.



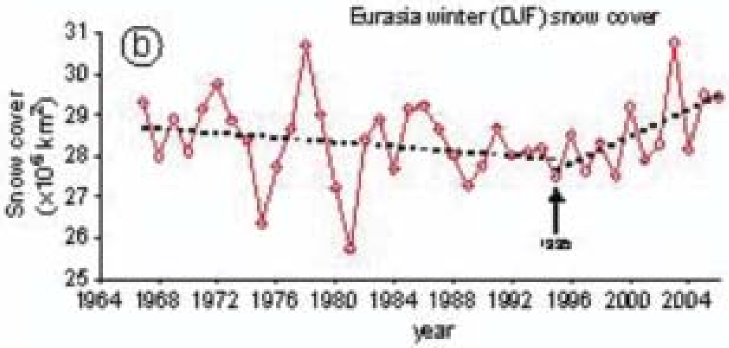
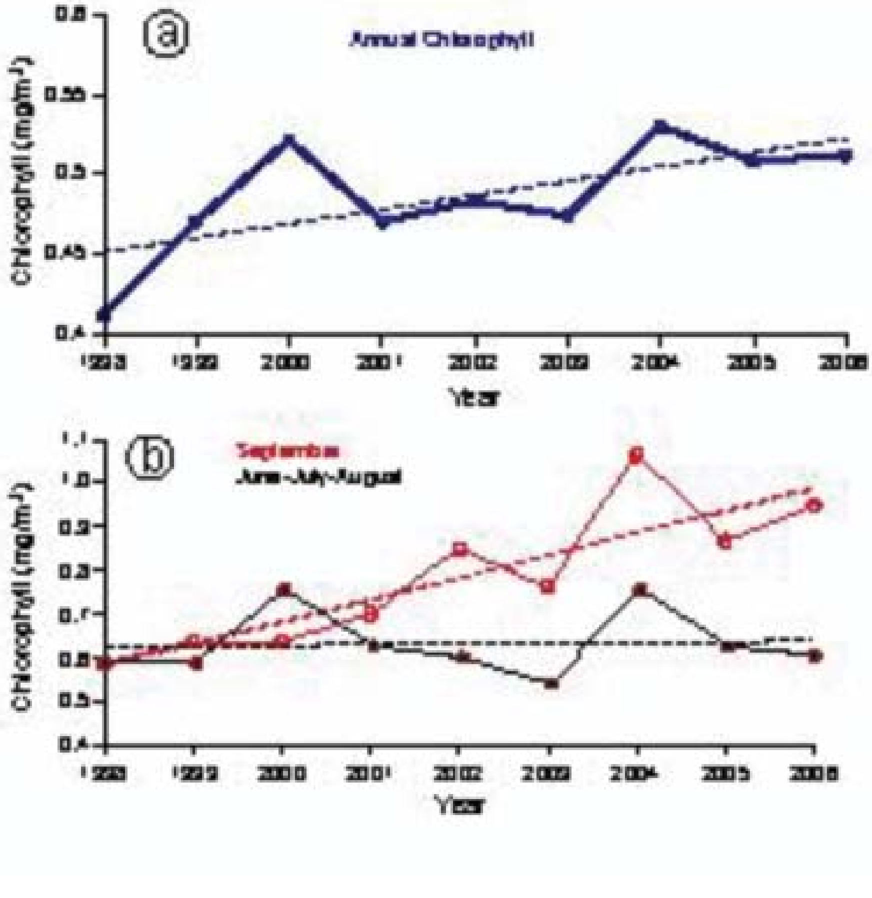


Figure 3.(a) All India summer-monsoon rainfall anomaly (red curve) and integrated decadal rainfall anomaly (bar diagram), (b) Eurasian winter snow cover



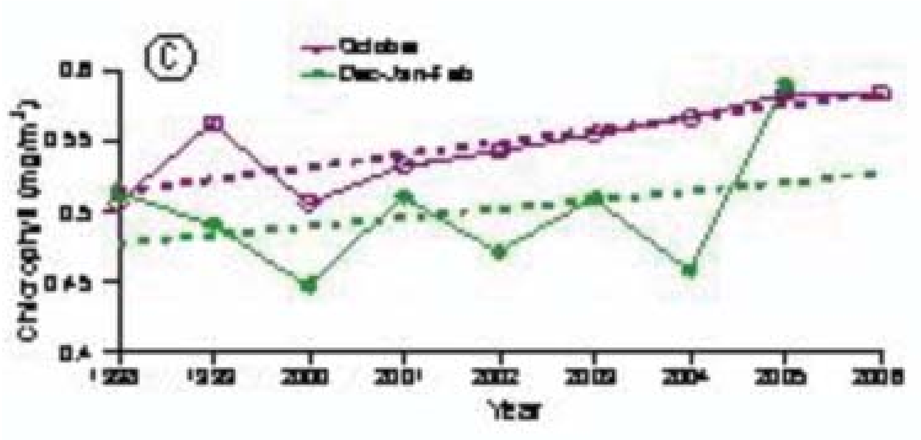


Figure 4. *Basin-averaged chlorophyll pigment concentrations (mg/m^3) derived from sea WiFS (a) annual mean during 1996 to 2006 (b) summer mean (averaged for June to August, JJA) black line) and September (red line), and (c) October (purple line) and winter mean (averaged during December to February, DJF) (green line), the dashed line in all the diagrams indicates the linear trend line.*

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