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Response of the Arabian Sea to global warming and associated regional climate shift

S. Prasanna Kumar [a,*], Raj P. Roshin [a], Jayu Narvekar [a], P.K. Dinesh Kumar [b], E. Vivekanandan [c]

[a] *National Institute of Oceanography, Dona Paula, Goa 403 004, India*
[b] *Regional Center of NIO, Kochi 682 018, India*
[c] *Central Marine Fisheries Research Institute, Kochi 682 018, India*

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ABSTRACT

The response of the Arabian Sea to global warming is the disruption in the natural decadal cycle in the sea surface temperature (SST) after 1995, followed by a secular warming. The Arabian Sea is experiencing a regional climate-shift after 1995, which is accompanied by a five fold increase in the occurrence of "most intense cyclones". Signatures of this climate-shift are also perceptible over the adjacent landmass of India as: (1) progressively warmer winters, and (2) decreased decadal monsoon rainfall. The warmer winters are associated with a 16-fold decrease in the decadal wheat production after 1995, while the decreased decadal rainfall was accompanied by a decline of vegetation cover and increased occurrence of heat spells. We propose that in addition to the oceanic thermal inertia, the upwelling-driven cooling provided a mechanism that offset the CO_2-driven SST increase in the Arabian Sea until 1995.

1. Introduction

Global warming and human-induced climate change are the immediate threats to mankind and tropical regions are the most vulnerable to them. Global warming has different manifestations, such as increase in the number and severity of tropical cyclones (Emanuel, 2005; Webster et al., 2005), changing pattern of precipitation and increase of extreme rain events (Goswami et al., 2006; Zhang et al., 2007), melting of glaciers (Oerlemans, 1994) and associated sea level rise (Church, 2001; Meehl et al., 2005). In addition to these changes in the physical climate, the terrestrial as well as the aquatic ecosystem will also experience great pressure and undergo change (Meyer et al., 1999; Cramer et al., 2001). For example, variation in the length of a season may lead to mismatches between the key elements in an ecosystem such as flowering and nesting times, feeding period of young birds (Both et al., 2006). Similarly, a warming environment driven by rapid increase in the concentration of atmospheric carbon dioxide and ocean acidification may lead to coral bleaching (Hughes et al., 2003; Hoegh-Guldberg et al., 2007), while increased land temperature may lead to an increase in the tropical vector-borne diseases (Rogers and Randolph, 2000; Hopp and Foley, 2003) thus causing concern for human health. Recent studies showed that not only are the oceans becoming warmer at the surface, but there is penetration of the human induced warming into the deeper parts of the oceans (Barnett et al., 2005). However, it is presently unclear how the Arabian Sea is responding, except that it has warmed by about 0.5 °C during 1904–1994 (RupaKumar et al., 2002). In this paper we explore the response of the Arabian Sea to global warming and its possible impact on frequency and intensity of cyclones, summer monsoon rainfall, wheat production, land vegetation cover and frequency of heat spells.

2. Material and methods

2.1. Study area

The Arabian Sea is a tropical basin situated in the western part of the northern Indian Ocean (0–25 °N and 45–80 °E) which is land locked in the north. It is forced by a semi-annually reversing wind system called monsoon. During winter (December–February), the weak (~5 m s^{-1}) northeast trade winds bring cool, dry continental air into the Arabian Sea, while during summer (June–September), the strong (~15 m s^{-1}) southwest winds brings moisture-laden maritime air into the Arabian Sea. In response to this wind reversal, the upper ocean circulation of the Arabian Sea also undergoes seasonal reversal. The Arabian Sea is biologically one of the most productive regions of the worlds' oceans (Ryther et al., 1966) due to the summer and winter blooms. The summer phytoplankton

* Corresponding author. Tel.: +91 832 2450300; fax: +91 832 2450608.
E-mail address: prasanna@nio.org (S.P. Kumar).

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bloom occurs due to wind-driven upwelling (Smith and Codispoti, 1980; Banse, 1987; Brock and McClain, 1992) along the coast of Somalia, Arabia and southern part of the west coast of India, while the winter bloom driven by winter-cooling and convective mixing (Madhupratap et al., 1996; Prasanna Kumar et al., 2001a) occurs in the northern Arabian Sea.

2.2. Data and analysis

We used a variety of multi-disciplinary data from the Arabian Sea and the adjacent landmass of India to elucidate the signature of global warming and regional climate-shift. The monthly mean sea surface temperature (SST) data in the Arabian Sea (0–25 °N and 45–80 °E) were extracted for the period 1960–2006 from three different sources: (1) the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) (Woodruff et al., 2005) (http://www.cdc.noaa.gov/cdc/data.coads.1deg.html), (2) NOAA SST data (Reynolds et al., 2002) and (3) Kaplan SST data (Kaplan et al., 1998), both provided by the NOAA/OAR/ERSL PSD, Boulder, Colorado, USA from their website http://www.cdc.noaa.gov/in (Reynolds et al., 2002). From the monthly mean SST annual mean SST anomaly was computed for further analysis. The strong El Nino years (1972–1973, 1982–1983, 1991–1992 and 1997–1998) (see http://ggweather.com/enso/oni.htm) as well as Indian Ocean Dipole (IOD) years (1961, 1963, 1967, 1972, 1982, 1994, 1997 and 2006) (see http://www.marine.csiro.au/~mcintosh/ENSO_IOD_years.htm; Thompson et al., 2005) were excluded from the analysis. We have used two kinds of solar irradiance data. The measured solar irradiance data (Frohlich, 2008) from www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant and the reconstructed solar irradiance data (Lean, 2000) from ftp://ftp.ncdc.noaa.gov/pub/data/paleo/climate_forcing/solar_variability/lean2000_irradiance.txt. The data on global CO_2 emission (Marland et al., 2007) were taken from http://cdiac.ornl.gov/trends/emis/meth_reg.htm, while the global CO_2 concentration measured at Mauna Loa (Keeling and Wharf, 2005) was from www.esrl.noaa.gov. The data on the cyclones over the Arabian Sea during 1970–1999 were obtained from the India Meteorological Department (IMD) (http://www.imd.ernet.in/section/nhac/static/cyclone-history-as.htm) while that during 2000 and 2007 were taken from the Joint Typhoon Warning Center (JTWC) https://metocph.nmci.navy.mil/jtwc/best_tracks/2001/2001sbio/bio012001.txt. The data for air temperature and rainfall over India (Fig. 1) during 1960 and 2005 (Parthasarathy et al., 1995; Kothawale and RupaKumar, 2005) were taken from Indian Institute of Tropical Meteorology (IITM) (http://www.tropmet.res.in). The monthly mean climatology of wind was obtained from NCEP/NCAR reanalysis (Kalnay et al., 1996) data (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html).

The February temperature in northwestern India and western Himalayas (see Fig. 1 for the geographic location) was computed by averaging the air temperature from that region in February, while all India monsoon rainfall was computed by averaging for the months June to September. The 5-year running mean anomaly and integrated anomaly over the decade were calculated from the monsoon rainfall data. The wheat yield data of India during 1965 and 2005 were taken from the Statistics Division of the Food and Agriculture Organization (FAO) (http://faostat.fao.org). The normalized difference vegetation index (NDVI) (Tucker, 1979) for the homogeneous Indian rainfall region (Fig. 1) was taken from advanced very high resolution radiometer (AVHRR) for the period 1982–2002 (http://apdrc.soest.hawaii.edu). The data on the number of heat spells over India from 1978 to 2005 were taken from disastrous Weather Events published yearly by the IMD.

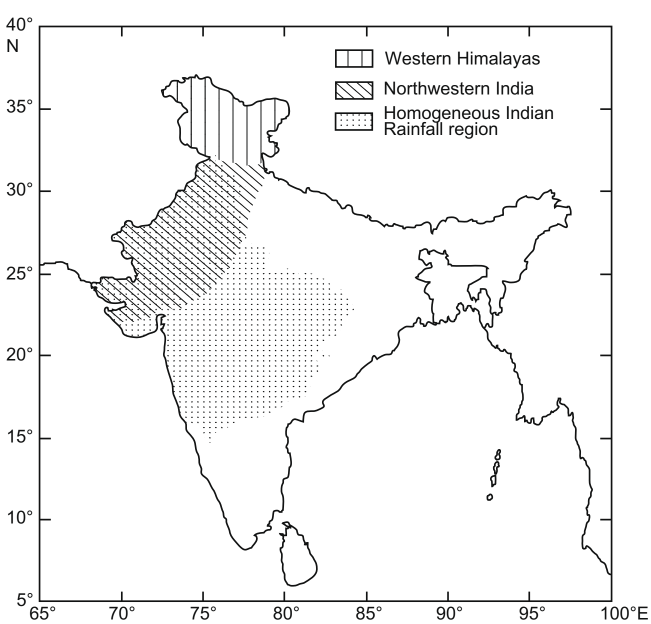

Fig. 1. Map showing geographical regions used in the study for computing spatial averages of various parameters. Region with vertical lines represent Western Himalayas and slanting lines represent the northwestern Indian region over which winter temperature data were used. The dotted region indicates the homogeneous rainfall region. The data on normalized difference vegetation index (NDVI) were used for the homogeneous rainfall region.

3. Results and discussion

The analysis of all the three basin-averaged annual mean SST (ICOADS, NOAA and Kaplan) anomaly of the Arabian Sea (0–25 °N and 45–80 °E) showed dominant decadal scale variability during the period 1960–1995 (Fig. 2) with a slow warming trend. Beyond 1995, a disruption in the natural decadal cycle of SST anomaly was noticed. Since the natural decadal cycle is known to arise from solar activity (White, 2006) we examined the measured as well as reconstructed solar irradiance. It showed a smooth decadal cycle without any abrupt change during the study period (Fig. 2). The decadal cycle seen in the SST anomaly closely followed the solar irradiance cycle until the year 1995, which underscored the importance of the decade after 1995. Note that when the solar activity was declining after the year 2000, and subsequently was at its lowest (Fig. 2), the SST anomaly did not show any decreasing trend.

On the contrary, SST anomaly was the highest. This indicated that the solar activity was not responsible for the deviation of the natural decadal cycle in SST anomaly after 1995. To understand this, we examined the atmospheric CO_2 concentration measured at Mauna Loa, Hawaii, and global CO_2 emission. The correlation of atmospheric CO_2 concentration with all the three basin-averaged SSTs (ICOADS, NOAA and Kaplan) in the Arabian Sea was larger and highly significant during the period 1960–2006 compared to the period 1960–1995 (Table 1). Note that the Kaplan SST did not show significant correlation with atmospheric CO_2 concentration prior to 1995. Similarly, though the correlation of all the three SSTs with global CO_2 emission was not significant during the period 1960 and 1995, a stronger and significant correlation was noticed during the period 1960 and 2006 (Table 1).

Both these results indicated the role of human-induced warming in the disruption of natural decadal cycle and subsequent secular warming of SST after 1995. It may be noted that the CO_2 driven radiative forcing during 1995 and 2005 showed a 20% increase, the largest change for any decade in at least the last 200 years (IPCC, 2007). The observed disruption of the natural decadal cycle of SST after 1995 can thus be attributed to intrinsic ocean response, in the form of regional climate-shift, to external forcing by greenhouse gases.