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Arabian Sea ecosystem responses to the South Tropical Atlantic teleconnection

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ABSTRACT

The aim of this work is to investigate the Arabian Sea response to changes in the South Tropical Atlantic (STA) sea surface temperatures (SSTs). A series of recent studies have shown that the atmospheric circulation and SSTs in the Indian Ocean, and particularly in the Arabian Sea, are affected by STA SST anomalies via a simple Gill–Matsuno mechanism. Here, we use a regional ocean model coupled with a nutrient–phytoplankton–zooplankton–detritus (NPZD) ecosystem model to analyze the impact of the tropical Atlantic SST anomalies on the IO circulation and ecosystem variability. The STA teleconnection to the Indian Ocean develops as follows: Cold SST anomalies in the Gulf of Guinea during boreal summer cause strengthening of the Somali Jet, upwelling favorable winds, cold SST anomalies and a shallower than usual thermocline in the Arabian Sea. The enhanced upwelling in the Arabian Sea, in turn, causes an increase in phytoplankton concentrations. The opposite sequence is verified for warm SST anomalies in the STA region. For a 1 °C STA anomaly, the increase/decrease in productivity represents by September up to 19% of the surface phytoplankton climatological values in the model, and up to 13% in the observations. The STA teleconnection contributes to the interannual variability in the Arabian Sea in boreal summer as much as the El Niño Southern Oscillation and the Indian Ocean Dipole.

1. Introduction

The Arabian Sea is home to one of the most productive ecosystem in the world (>300 g C m^{-2} $year^{-1}$, Madhupratap et al. (1996)). Both the circulation and the biological productivity in this region are characterized by strong seasonality and interannual variability, and are tightly coupled to the Indian monsoon. Sea surface temperatures (SSTs) have been shown to influence onset and strength of the monsoon (Izumo et al., 2008; Levine and Turner, 2012; Vecchi and Harrison, 2004), and the monsoonal winds drive nutrient input into the euphotic layer through upwelling, advection, and changes in mixed-layer depth (Brink et al., 1998). More recently, it has been suggested that the high productivity of the Arabian Sea in turn changes its optical properties and is responsible for SST and rainfall biases in climate models (Turner et al., 2012).

Through the year the phytoplankton biomass has two growth periods: one during summer and the other during winter, and these periods of high productivity are associated with the monsoonal wind reversals (Banse, 1987; Kone et al., 2009; Levy et al., 2007; Wiggert et al., 2005, 2006). Winds in the northern Indian Ocean (IO) generally blow from the southwest during boreal summer, and from northeast during boreal winter. The reversing of the winds triggers a seasonal reversal of the upper-ocean circulation in both coastal and open waters, including changes in vertical mixing, upwelling and downwelling patterns. These changes in the physical environment induce blooms of a varietyof phytoplankton (Lee et al., 2000; Murtugudde et al., 2007; Schott and McCreary, 2001; Shankar et al., 2002).

In the Arabian Sea the seasonal cycle has been investigated in detail by comparing Sea-viewing Wide Field-of-View Sensor (SeaWiFS) chlorophyll data with the dynamical features derived from an ocean model output in Levy et al. (2007). In early summer, the intense southwest wind associated with the onset of the monsoon enhances productivity through wind-driven mixing, Ekman pumping, and advection of nutrient-rich waters from the upwelling regions off Somalia and Arabia into the central Arabian Sea. In early winter, the northeast wind associated with the winter monsoon intensifies the northern Arabian Sea production by winter convection and injection of the nutrients to the euphotic zone by vertical mixing.

The northern IO marine ecosystem variability displays also interannual variations superimposed on the seasonal cycle. Estimates of those interannual variations require continuous observational records for a couple of decades, and they are not available at present. The global monitoring of ocean color that began with SeaWiFS in 1997 is too short and it is strongly affected by the intense cloud coverage that characterizes the Indian Ocean during the monsoon seasons. So far two modes of interannual variability have been investigated in the literature: the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD; also referred as the Indian Ocean Zonal Mode IOZM). ENSO is the leading mode in the equatorial Pacific interannual variability, and

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is teleconnected through the atmosphere and ocean to the IO, while the second is intrinsic to the IO. An overview of these modes with their climatic impacts over the IO is given by Schott et al. (2009). Both those modes induce wind and upwelling anomalies, and affect the marine ecosystem in the Arabian Sea. The goal of this paper is to introduce a third mode, associated with SST anomalies in the South Tropical Atlantic (STA), that may influence the Arabian Sea productivity in boreal summer. Before introducing the STA teleconnection mechanism to the IO, we briefly summarize what is known of the ENSO and IOD impacts on the marine ecosystem of the Arabian Sea, to give the reader a prospective of their relative importance.

During the development of El-Niño in the equatorial Pacific, a basin-wide warming is seen in the tropical IO (Behera et al., 1999; Saji et al., 1999; Venzke et al., 2000): SSTs increase over the whole basin from late boreal winter to the next spring (see, e.g., Allan et al., 2001; Huang and Kinter, 2002; Kawamura, 1994; Klein et al., 1999; Lazante, 1996; Liu and Alexander, 2007; Nicholson, 1997; Nigam and Shen, 1993; Pan and Oort, 1990; Tourre and White, 1995; Venzke et al., 2000). Observational and modeling studies show that this basin-scale warming is the first dominant mode of IO SST variability. Klein et al. (1999) found that this it is caused by ENSO-induced changes in surface heat fluxes, and in particular in the wind-induced latent heat and cloud solar radiation fluxes; those fluxes induce a suppression of the atmospheric convection over the IO, a consequent increase in solar radiation, and therefore SST warming. The suppression of convection and the reduction of upwelling winds cause a weaker than normal summer blooms. This was observed in the Arabian Sea following the 1997–1998 positive ENSO (McCreary et al., 2009). The largest ecosystem changes are however found in winter and spring. An investigation using SeaWiFS satellite images quantified a 38% decrease in surface chlorophyll on April 1998 compared to normal conditions (Sasamal and Chen, 2003). Likely this estimate represents an upper limit, given that the 1997–1998 El-Niño is the strongest recorded since SeaWiFS data have been available. An enhancement of atmospheric convection, cooler than normal SSTs, and generally higher productivity characterize the IO during La-Niña, the opposite phase of ENSO.

The IOD, on the other hand, consists of a zonal gradient in SST anomalies that develops in the tropical IO in summer and fall. A typical positive IOD event is characterized by unusually strong upwelling, a rise of the thermocline depth, and cold SSTs in the eastern equatorial Indian Ocean along the coasts of Java and Sumatra in late spring–early summer, followed by a deepening of the thermocline and warm SST anomalies in the western equatorial Indian Ocean in September–October (Saji et al., 1999; Webster et al., 1999; Vinayachandran et al., 1999; Saji and Yamagata, 2003; Bracco et al., 2005; Horii et al., 2008). Anomalies of opposite sign characterize the negative IOD phase. The IOD impact on the marine ecosystem remains uncertain. Wiggert et al. (2009) compared two positive IOD events of comparable strength and found that the central Arabian Sea was characterized by a decrease in chlorophyll and primary productivity from October 1997 to January 1998, and by a decrease in chlorophyll and an increase in primary productivity over the same months for 2006–2007. Sarma (2006) quantified a 30% decrease in primary production integrated over the euphotic zone for the 1997–1998 IOD event.

In the last few years a number of studies have pointed to the SST variability in the South Tropical Atlantic (STA) as another remote source of interannual modulation of the atmospheric and oceanic circulation over the IO in summer (Barimalala et al., 2011; Kucharski et al., 2007, 2008; Losada et al., 2010; Wang et al., 2009). Heating anomalies in the Gulf of Guinea in early summer have been shown to induce a Gill–Matsuno-type response in the atmosphere, with baroclinic Kelvin waves propagating toward Africa and into the IO basin (Kucharski et al., 2009). Such mechanism has been investigated by analyzing reanalysis data and the output of an atmospheric general circulation model (AGCM). A cold anomaly in the STA region induces low-level westerly wind anomalies in the western tropical IO that trigger a strengthening of the Somali Jet, and an increase in evaporation and ocean upwelling along the coast of North-East Africa. The opposite response is found for warm STA SST anomalies. As shown in (Kucharski et al., 2007, 2008), the South Tropical Atlantic SST can also effectively modulate the strong and quasi-linear relationship between ENSO and the Indian Summer monsoon.

According to the studies mentioned earlier, the ecosystem variability in the northern IO is strongly affected by atmospheric forcing, being driven predominantly by coastal upwelling and Ekman pumping. It can be expected that the STA remote forcing will play a significant, but so far unexplored, role on the Arabian Sea productivity. The goal of this work is to investigate such role using the Regional Ocean Modeling System (ROMS) coupled with a nutrient–phytoplankton–zooplankton–detritus (NPZD) ecosystem model and configured in the northwestern IO. By comparing two integrations, one forced by winds and heat fluxes representative of monthly climatological conditions, and the other forced by fluxes representative of the STA teleconnection, we find that cold STA anomalies enhance upwelling along the East-African coast, in the Somali Jet region and also in the western Arabian Sea. We then quantify the impact of those circulation changes on the marine ecosystem.

The remainder of this paper is organized as follows: in Section 2, we describe the experimental design along with the validation of the modeled circulation. The analysis of the ecosystem response follows in Section 3. Section 4 provides a summary and conclusions.

2. Data and model description

2.1. Data

In this paper we use the HadISST data set (Rayner et al., 2003) from 1950 to 2007 and at a 1° × 1° resolution as proxy for observed SST. AVISO satellite data provide maps of observed sea surface height (SSH) anomalies and geostrophic currents from January 1993 to December 2007. AVISO data are merged from TOPEX/POSEIDON or JASON-1 + ERS-1/2 and Envisat satellites to produce sea level anomalies at a 0.33° × 0.33° resolution (http://www.jason.oceanobs.com). SeaWiFS images at 9 km × 9 km horizontal resolution from 1998 to 2010 are used as a proxy for observed surface chlorophyll-a (Chl-a, the dominant photosynthetic pigment in phytoplankton) concentrations (http://oceancolor.gsfc.nasa.gov/SeaWiFS/).

We extend the SeaWiFS analysis to 2010 to increase as much as possible its statistical significance. As mentioned, Chl-a during the summer monsoon is very sparsely sampled by SeaWiFS due to generally intense cloud coverage. Additionally, images for July 2008, May 2009 and September 2009 are missing. Thus, for most cases 8-day composites do not provide full coverage of the eastern Indian basin, and monthly means for July and August have large areas always covered by clouds centered in the Arabian Sea. We preferred SeaWiFS over the Coastal Zone Color Scanner (CZCS) data that span the time period 1978–1986 due to the availability of AVISO only during the SeaWiFS mission, and to the significant underestimation of chlorophyll concentrations in the CZCS data due to calibration and algorithm problems (Conkright and Gregg, 2002).

In the appendix, we also compare our model output with in-situ data from the 1994–1996 US Joint Global Ocean Flux Study (US JGOFS) Arabian Sea Process Study (ASPS) (http://usjgofs.whoi.edu/jg/dir/jgofs/arabian) covering the months of July to September 1995 from the TN049 and TN050 cruises. In-situ data from the Arabian Sea, unfortunately, do not offer sufficient temporal coverage to investigate the interannual variability of the basin. The percentage of 1° × 1° squares in the north Indian Ocean which contain some in situ chlorophyll measurements from 1957 and 1998, including both coastal and open ocean waters, is comprised between 5.4% and 8.8% depending on season, according to the analysis by Conkright and Gregg (2002).