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Influence of oceanic Rossby waves on phytoplankton production in the southern tropical Indian Ocean

Jinfeng Ma [a,b], Yan Du [a,*], Haigang Zhan [a], Hailong Liu [b], Jia Wang [c]

[a] *State Key Laboratory of Tropical Oceanography (LTO), South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China*
[b] *State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences, Beijing 100029, China*
[c] *Great Lakes Environmental Research Laboratory (GLERL), NOAA, Ann Arbor 48105, USA*

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ABSTRACT

Using Sea-viewing Wide Field-of-view Sensor (SeaWiFS) ocean color data, we investigated the biological responses to oceanic Rossby waves in the southern tropical Indian Ocean (TIO) during 1997–2007. The findings indicate that, during the developing phase of El Niño/La Niña events, usually in boreal fall, and triggered by anomalous anticyclonic/cyclonic wind circulations in the southeast TIO, downwelling/upwelling Rossby waves form and then propagate westward. After a few months, downwelling/upwelling Rossby waves interface with the thermocline dome in the southern TIO, and suppress/enhance the upwelling. Correspondingly, less/more nutrient-rich waters enter the mixed layer and result in lower/higher chlorophyll concentrations. Due to the asymmetric effects on the thermocline dome between downwelling and upwelling Rossby waves, higher chlorophyll concentrations appear earlier and in the eastern part of the dome, whereas lower chlorophyll concentrations appear later and in the central part of the dome. Moreover, when El Niño/La Niña–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) events coincide, the biological responses are stronger.

1. Introduction

The upwelling in the southwest tropical Indian Ocean (TIO) at around (55°E–80°E, 4°S–12°S) is important for climate variation (Schott et al., 2002; Xie et al., 2002) and biological processes (McCreary et al., 2009). During boreal winter, the southeasterly winds to the south of the region and westerly winds to the north result in an open-ocean upwelling and thermocline shoaling (McCreary et al., 2009; Xie et al., 2002). The rising thermocline increases the concentration of surface phytoplankton either by bringing more nutrients or by taking more phytoplankton from the subsurface (McCreary et al., 2009; Wiggert et al., 2006). Relatively high chlorophyll concentrations are evident from satellite observations (Fig. 1a).

Changes in thermocline depth can be attributed to local winds, or can occur via the oceanic long waves. For example, oceanic Rossby waves have a significant impact on the thermocline and even the sea surface temperature (SST) in the 4°–12°S region of the Indian Ocean (Hermes and Reason, 2008; Xie et al., 2002; Yu et al., 2005). Rossby waves also have a significant influence on primary production (Cipollini et al., 2001; Uz et al., 2001). Kawamiya and Oschlies (2001) studied the effect of Rossby waves at around 12°S in the Indian Ocean using a coupled biological–physical model. They found that the enhancement of surface chlorophyll in boreal summer is due to Rossby-wave-induced upwelling that lifts the deep chlorophyll maximum (DCM) into the surface mixed layer. Other model studies (Jayakumar and Gnanaseelan, 2012; Wiggert et al., 2006) have indicated that both local Ekman pumping and remotely forced Rossby waves favor the movement of nutrients into the euphotic zone in the southern TIO.

With its thin mixed layer (ML) and shallow thermocline, the southwestern TIO (SWIO) is considered to be a sensitive region in terms of its response to climatic variations, e.g. El Niño/La Niña–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) events. ENSO is regarded as the dominant forcing for the interannual variability in the southern TIO thermocline (Xie et al., 2002). During the mature phase of El Niño, changes in the atmospheric Walker circulation induce anomalous anticyclonic winds over the southern TIO, which forces a downwelling oceanic Rossby wave. The Rossby wave deepens the thermocline and raises the SST as it propagates westward (Chakravorty et al., 2013; Chowdary and Gnanaseelan, 2007; Du et al., 2009, 2013; Schott et al., 2009; Xie et al., 2002). During the boreal winter of a La Niña event, an upwelling cold Rossby wave propagates westward and results in cold SST anomalies (Chowdary et al., 2006; Hermes and Reason, 2009; Singh et al., 2013).

In response to the thermocline variability, phytoplankton production experiences significant interannual variability. Wiggert et al.

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* Corresponding author at: State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, 164 West Xingang Road, Guangzhou 510301, China.
E-mail address: duyan@scsio.ac.cn (Y. Du).

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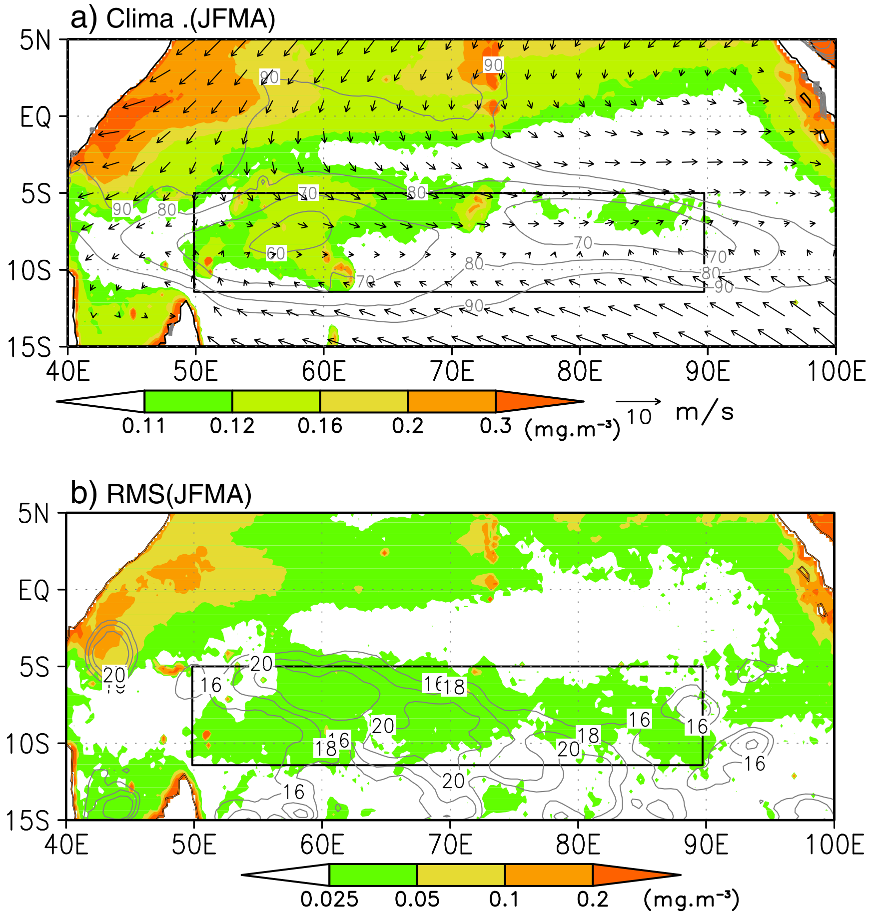

Fig. 1. (a) Climatologically mean of SeaWiFS chlorophyll concentration (color shade in $\text{mg}\cdot\text{m}^{-3}$), SODA 22 °C isothermal depth (contours in m) and sea surface wind (vectors in $\text{m}\cdot\text{s}^{-1}$) and (b) Root Mean Square (RMS) variance of chlorophyll concentration anomalies (color shade in $\text{mg}\cdot\text{m}^{-3}$) and 22 °C isothermal depth anomalies (contours in m) during Jan–April. Seasonal cycle is removed for the RMS computation. The rectangular box shows the study area (50°E–90°E, 5°S–12°S).

(2009) studied the biogeochemical processes of the Indian Ocean during the positive phase of two recent IOD events, which coincided with El Niño events. They reported reduced chlorophyll concentrations during November 1997 to January 1998 and November 2006 to January 2007. During January and February 2007, corresponding to the positive IOD and El Niño events, the Cirene oceanographic cruise observed that both the thermocline and subsurface chlorophyll maximum deepened. At the same time, the catch rate of tuna decreased in the SWIO region (Vialard et al., 2009).

There were four ENSO events between 1997 and 2007, and two IOD events that coincided with ENSO events in 1997–1998 and 2006–2007. The present study focuses on the similarities and differences of the biological responses to different El Niño and La Niña events in the southern TIO. We examine the differences when ENSO and IOD events coincided, and when ENSO occurred alone. The biological responses to the upwelling Rossby waves caused by La Niña events in the southern TIO are discussed.

The remainder of the paper is organized as follows. Section 2 describes the data. Section 3 analyzes the interannual variability of the biological and physical parameters and their relationships. Section 4 discusses the different mechanisms for the different biological responses to the El Niño and La Niña events. Section 5 summarizes the key findings of the study.

2. Data and methods

The chlorophyll data are 9-km monthly mean Sea-viewing Wide Field-of-view Sensor (SeaWiFS) L3 products from September 1997 to December 2007, provided by the Distributed Active Archive Center (DAAC) of the Goddard Space Flight Center (GSFC), NASA. The data are reprocessed to a resolution of 0.25° × 0.25°. Sea surface height (SSH) data are the merged product of the TOPEX/Poseidon (T/P), Jason, ERS-1, ERS-2, and ENVISAT satellites at a resolution of 1/3° from October 1992 to December 2007. Sea surface temperature (OISST) data are from the Climate Diagnostics Center (CDC, NOAA). The spatial resolution of the data is 0.25°. The temperature and salinity data are from the Simple Ocean Data Assimilation (SODA), version 2.1.6 (Carton and Giese, 2008). Sea surface wind (SSW) is combined by SSM/I (January 1997 to July 1999), from the Jet Propulsion Laboratory (JPL, NASA), and QuikSCAT (August 1999–December 2007), from the French Institute of Research for the Exploitation of the Sea (IFREMER). Ekman pumping velocity (EPV) is calculated using the equation $W = -Curl(T * \rho^{-1} * f^{-1})$ (Stewart, 2002), where W is EPV; and T, ρ, and f are wind stress, seawater density, and the Coriolis parameter, respectively. T is calculated using the method of Large and Pond (1981).

The mixed layer depth (MLD) is defined by the depth of a specified potential density from surface salinity and a specified temperature difference, ΔT, from SST. We select $\Delta T = 0.8$ °C as the criterion (Du et al., 2005; Kara et al., 2000). The salinity and temperature data use SODA reanalysis. Linear vertical interpolation is used to estimate the MLD. The 22 °C isothermal depth (hereafter, D22) is also calculated from SODA reanalysis. We use D22 as a proxy for thermocline depth.

Both the Niño-3.4 index and IOD index are computed from OISST. Niño-3.4 index is the sea surface temperature (SST) anomalies averaged over the eastern tropical Pacific (170°–120°W, 5°S–5°N) (Trenberth, 1997), and the IOD index is the SST difference between the western