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Sea surface salinity variability in the tropical Indian Ocean

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ABSTRACT

Argo profiles of temperature and salinity data from the north Indian Ocean have been used to address the seasonal and interannual variability of Sea Surface Salinity (SSS) and SSS Anomaly (SSSA) in 2 boxes from the eastern Equatorial Indian Ocean (EIO: 5°S–5°N, 90°–95°E) and Southeastern Arabian Sea (SEAS: 5°–9°N, 72°–76°E) and to compare with the HYbrid Coordinate Ocean Model (HYCOM) simulated SSS for the period from January 2002 to February 2007. The observational period covered one strong negative Indian Ocean Dipole Zonal Mode (IODZM) event in 2005 and a strong positive IODZM event in 2006. The Argo profiles in each box captured the impact of these IODZM events with a larger impact in the EIO box showing salting (positive SSSA, +0.9) during negative IODZM (November 2005) and freshening (negative SSSA, −0.6) during positive IODZM (November 2006). A band of positive (negative) SSSA occurs in the central EIO during negative (positive) IODZM event in 2005 (2006) under the influence of IODZM dynamics. The impact of IODZM event in the SEAS is more evident during boreal winter months. The observed anomalous eastward (westward) surface current contributed to the observed intense salting (freshening) during negative (positive) IODZM event in the EIO. Following the IODZM events, the East India Coastal Current (EICC) gets modulated through the propagation of downwelling/upwelling Kelvin Waves and further lead to the freshening/salting in the SEAS during boreal winter. These are well corroborated with the HYCOM simulations of SSS and currents. This study emphasizes that the HYCOM simulated salinity fields would be useful to provide rapid checks revealing either problems or successes in the satellite retrievals of salinity from the Soil Moisture and Ocean Salinity (SMOS) and Aquarius missions.

1. Introduction

There are many well-documented studies on the seasonal and interannual variability of Sea Surface Temperature (SST) in the tropical Indian Ocean from *in situ* observations, satellite measurements, and model simulations [see the elaborate reviews by Schott and McCreary (2001); Annamalai and Murtugudde (2004); Schott et al., 2009 and the numerous references therein]. The interannual variability in SST anomalies (SSTA) is interesting in the Equatorial Indian Ocean (EIO) wherein anomalous cooling (negative SSTA) occurs by October–November off the Sumatra coast in the eastern EIO and warming occurs in the western/central EIO, a phenomenon widely known as the positive IODZM event (Saji et al., 1999; Webster et al., 1999). During the negative IODZM event, the eastern EIO shows anomalous warming while the central/western EIO has negative SST anomalies (Saji et al., 1999 and Rao et al., 2002). Murtugudde and Busalacchi (1999); Murtugudde et al. (2000) and Rao et al. (2002) showed that the dynamics and thermodynamics and the associated circulation and subsurface variability are affected during the IOD years in the tropical Indian Ocean.

Compared to temperature measurements, salinity observations are sparse both temporally and spatially in the tropical oceans as there are no satellite salinity measurements as of now. However, based on the climatological salinity data (Conkright et al., 2001) and sparse Sea Surface Salinity (SSS) data collected along Ships of Opportunity shipping lanes, the seasonal cycles of SSS have been studied to some extent in the tropical Indian Ocean (Donguy & Meyers, 1996; Rao & Sivakumar, 2003; Murty et al., 2004 and Delcroix et al., 2005). Modelers also used the available information on SSS variability for assessing numerical model performance (Murtugudde & Busalacchi, 1998) and for understanding climate variability (Murtugudde et al., 2000).

With the launch of the Argo (Array for Real-time Geostrophic Oceanography) program, the number of temperature and salinity profiles repeated with 5/10 day cycles increased considerably in the tropical Indian Ocean (Anonymous, 2001) (visit http://www.incois.gov.in for more information). The Indian National Center for Ocean Information System (INCOIS), Hyderabad is the regional nodal agency for archiving the Argo profiles data gridded into 10-day cycles and 3°×3° boxes for the user community. Ravichandran et al. (2004) discussed the first results of India's Argo observations from SEAS highlighting the annual cycle of Argo SSS with lower SSS occurring in January–February and higher SSS during July–November. Shenoi et al.

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(2005) documented the evolution of SSS during March 2002–April 2003 in the SEAS and reported that lower SSS waters first appeared in the eastern part of the SEAS during February–March 2003. Vinayachandran et al. (2005) noticed the bifurcation of EICC off east coast of Sri Lanka in non-IOD years and proposed that the low salinity waters from the Bay of Bengal may reach the SEAS through the Winter Monsoon Current (WMC). Gopalakrishna et al. (2005) studied SSS variability during 2002–2005 and reported the occurrence of very low salinity waters in SEAS (the south box in their Fig. 3c) during December 2003–February 2004. The continued SSS observations in the SEAS till June 2007 (Gopalakrishna, personal communication) showed considerable interannual variation in SSS with very low SSS (<33.0) in January–February 2004 and 2006 and relatively higher SSS (33.5–34.5) in February–March of 2003, 2005, and 2007. Phillips et al. (2005) examined the interannual variability of upper ocean salt content in the southeast Indian Ocean. Thompson et al. (2006) reported the Indian Ocean circulation and SSS variability during IODZM events, using different OGCM (Ocean General Circulation Model) simulations and assimilated data sets of SODA (Simple Ocean Data Assimilation) and ECCO (Estimating Climate and Circulation of the Ocean). They noted significant negative salinity anomalies in the central equatorial Indian Ocean (0–5°N; 75–90°E) during the positive IOD events. However, due to the lack of observations of long-term time-series salinity data in the tropical Indian Ocean, the interannual variability of salinity during the IODZM events is not completely documented.

The availability of long-term Argo profiles data motivated us to study the seasonal and interannual variability of observed Argo SSS and SSSA in relation to the IODZM events in two 5° × 5° boxes selected in the eastern EIO and SEAS (Fig. 1) during January 2002–February 2007. The two selected boxes are located in the region of higher SSS variability in the eastern tropical Indian Ocean and help link the equatorial dynamics associated with the IODZM events and the observed interannual variability of SSS in the eastern EIO and SEAS. The Dipole Mode Index (DMI) data (http://www.jamstec.go.jp) for the study period suggests the occurrence of 2 positive IODZM events with cooler eastern EIO in the years 2003 and 2006. Rao and Yamagata (2004) mentioned that the IODZM event in 2003 was intense in the June–September period and terminated early due to intraseasonal disturbances. The year 2005 was identified as a negative IODZM event with warm SSTs in the eastern EIO. Horri et al. (2008) reported that the year 2006 was a very strong positive IODZM event, with highest anomalous cooling (up to ~2 °C) off southern Java coast in November 2006. Yoneyama et al. (2008), based on the MISMO (Mirai Indian Ocean cruise for the Study of the MJO-convection Onset) field Experiment in the central EIO (0°, 80.5°E) and the eastern EIO during October–December 2006, highlight the presence of low salinity waters at 10 m depth in the central EIO (80.5°E) and their westward advection from the eastern EIO during the positive IODZM event in 2006 (Vinayachandran et al., 2007). Anilkumar et al. (2007) also reported low salinity (<34.2) waters in the upper 40 m in the central EIO (77°–93°E) and their westward spread along the equator during September–October 2006, the period of positive IODZM event. McPhaden (2008) reported positive rainfall anomalies in the central EIO (80.5°E) in November 2006 in association with the positive IODZM 2006 event.

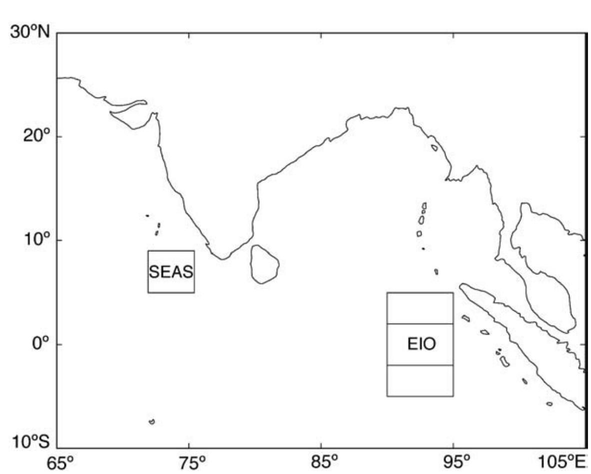

Fig. 1. Study area showing the boxes in the Equatorial Indian Ocean (EIO: 5°S–5°N and 90°–95°E) and Southeastern Arabian Sea (SEAS: 5°–9°N, 72°–76°E). The EIO box is further divided into EIO-north box, EIO-equator box and EIO-south box.

In this study, we have used the archived gridded Argo products (http://www.incois.gov.in, http://www.coriolis.eu.org) of temperature and salinity data in 3° × 3° boxes and 10 day cycles for 5 year long-duration in the previously selected boxes to understand the seasonal and interannual variability of SSS. This study has also prompted us to look into the performance of the high-resolution HYbrid Coordinated Ocean Model (HYCOM) simulations of SSS and currents in comparison with Argo SSS data during the IODZM events. River input and precipitation are also considered in the HYCOM simulations.

As the interannual variation of SSS is affected by the rainfall over the oceans, we have also examined the rainfall data (Adler et al., 2003) obtained from Global Precipitation Climatology Project (GPCP) [http://ftp.ncdc.noaa.gov/pub/data/gpcp/pentad/data] in the selected boxes.

Section 2 gives a brief methodology of Argo data analysis and descriptions of HYCOM simulations. Section 3 describes results of the multi-year mean seasonal cycle and interannual variation of SSS and SSSA both from Argo and HYCOM data sets in each box. Section 4 provides discussion on the interrelationships between the SSSA variability in the two boxes and the linkage between the IODZM dynamics and the observed SSSA variability in the two boxes through the anomalous surface circulation derived from HYCOM simulations. Conclusions are given in Section 5.

It is expected that this study of comparison of Argo observed SSS with the HYCOM SSS fields would provide the necessary background to use the high resolution and wide-scale modeled salinity fields as a tool to compare and validate the satellite retrievals of SSS from the Soil Moisture and Ocean Salinity (SMOS) mission launched by the European Space Agency (ESA) and the *Aquarius* mission to be launched by the National Atmospheric and Space Administration (NASA) and the Space Agency of Argentina (Comisión Nacional de Actividades Espaciales, CONAE). These missions would provide the first-ever global maps of sea surface salinity and offer the possibility of comprehensive SSS measurements (Lagerloef et al., 1995).

2. Argo floats data and model simulations

2.1. Argo float data

Argo is a pilot programme of the Global Ocean Observing System. These data were collected and made freely available by the INCOIS and Coriolis project and the national programmes that contribute to it. The Argo Float mission was implemented in 1999 under the joint auspices of Climate Variability (CLIVAR) and Global Ocean Data Assimilation Experiment (GODAE), to produce unprecedented broad-scale measurements of temperature, salinity, and ocean circulation for climate and other applications. There are about 3175 Argo floats worldwide and 506 active floats in the Indian Ocean as of August, 2008 (http://www-argo.ucsd.edu/). Each Argo float is equipped to take salinity and temperature vertical profiles up to the parking depth of 2000 m. After 5/10 days of repeat cycle the float returns to the surface to transmit its position and data to a satellite, then returns to depth. The Argo salinity data in the upper 100 m from EIO box and SEAS box are compared