Low-Frequency Coupled Atmosphere–Ocean Variability in the Southern Indian Ocean

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ABSTRACT

The low-frequency atmosphere–ocean coupled variability of the southern Indian Ocean (SIO) was investigated using observation data over 1958–2010. These data were obtained from ECMWF for sea level pressure (SLP) and wind, from NCEP/NCAR for heat fluxes, and from the Hadley Center for SST. To obtain the coupled air-sea variability, we performed SVD analyses on SST and SLP. The primary coupled mode represents 43% of the total square covariance and is featured by weak westerly winds along 45°–30°S. This weakened subtropical anticyclone forces fluctuations in a well-known subtropical dipole structure in the SST via wind-induced processes. The SST changes in response to atmosphere forcing and is predictable with a lead-time of 1–2 months. Atmosphere–ocean coupling of this mode is strongest during the austral summer. Its principle component is characterized by mixed interannual and interdecadal fluctuations. There is a strong relationship between the first mode and Antarctic Oscillation (AAO). The AAO can influence the coupled processes in the SIO by modulating the subtropical high. The second mode, accounting for 30% of the total square covariance, represents a 25-year period interdecadal oscillation in the strength of the subtropical anticyclone that is accompanied by fluctuations of a monopole structure in the SST along the 35°–25°S band. It is caused by subsidence of the atmosphere. The present study also shows that physical processes of both local thermodynamic and ocean circulation in the SIO have a crucial role in the formation of the atmosphere–ocean covariability.

Key words: southern Indian Ocean, SST, SLP, Antarctic Oscillation


1. Introduction

Natural climate variability of low-frequency time scales from interannual to decadal has been the focus of numerous studies. These climate variations are believed to arise from atmosphere–ocean interactions. The dynamics of both systems are thus coupled via exchange processes at their common interface. Coupled variability of the system occurs when the atmosphere responds to forcing from the ocean and when the ocean responds to forcing from the atmosphere. To understand and determine the mechanisms governing these climatic variations, it is vital to study the common variability of both the ocean and the overlying atmospheric systems and to characterize the large-scale interactions between them. While a vast number of studies have been devoted to SST and sea level pressure (SLP) fluctuations and their coupled variability over the northern Atlantic and the northern Pacific Oceans (e.g., Deser and Blackmon, 1993; Kushnir, 1994; Latif and Barnett, 1996; Mann and Park, 1996), the Southern Hemisphere has received little attention, except for a few studies on the southern Atlantic (e.g., Venegas et al., 1997, 1998; Sterl and Hazeleger, 2003; Fauchereau et al., 2003). Related research on the southern Indian Ocean has been rare (Allan et al., 1995; Reason, 1999;
Reason, 2001; Fauchereau et al., 2003). However, the southern Indian Ocean is bounded by the Antarctic circumpolar current to the south and receives oceanic water mass transport or throughput from the Pacific Ocean via the Indonesia throughflow. The location, shape, and topography of the subcontinent make SST highly sensitive to circulation changes in the Indian Ocean (Fauchereau et al., 2003). The southern Indian Ocean not only plays an important role in the surrounding climate of continents like Africa (Reason and Godfred-Spenning, 1998), but it is also a main region where the Asian monsoon water originates. Moreover, the study by Liu et al. (2006) showed that the Indian Ocean Dipole (IOD) in the tropical Indian Ocean responds to the southern high latitude climate almost instantaneously, suggesting that the IOD signal exists in the Southern Hemisphere. Nan et al (2009) pointed out that the Indian Ocean SST has an important bridging role in the Antarctic Oscillation (AAO)—East Asian Summer Monsoon relationship. Therefore, atmosphere–ocean interaction in the southern Indian Ocean may have implications for other areas, especially the northern Indian Ocean and Asia.

Most studies on Indian Ocean variability have only considered the tropical area north of 30°S. If the southern boundary of the domain is situated farther south, additional SST anomalies in the southern Indian Ocean emerge in a subtropical dipole mode, which is phase-locked to the austral summer (Behera and Yamagata, 2001; Reason, 2001; Reason, 2002). Huang and Shukla (2007) also discussed a subtropical dipole mode in the southern Indian Ocean; however, that study still emphasized the tropical region. As is generally known, the ex-tropical southern Indian Ocean is dominated by the lower tropospheric subtropical high. It is quite likely that atmospheric forcing has a crucial role in the evolution of the subtropical dipole (Hermes and Reason, 2005). Previous studies have shown that this SST anomaly pattern is correlated with rainfall in various regions of southern Africa (e.g., Rocha and Simmonds, 1997a, b; Goddard and Graham, 1999; Reason, 1999; Reason and Mulenga, 1999; Behera and Yamagata, 2001). Surface heat flux, especially the latent heat variability, is strongly implicated in forming these SST anomalies (Behera and Yamagata, 2001; Suzuki et al., 2004; Hermes and Reason, 2005; Huang and Shukla, 2008). It has been suggested that modulations of the subtropical atmospheric anticyclone are responsible for this latent heat flux variability, although the link between atmospheric variability and SST variability has not been precisely determined. Although the formation mechanism of the subtropical SST anomalies is different from that in the tropics, the SST anomalies may also be ultimately driven by coupled atmosphere–ocean interaction. Concerning decadal variability, Allan et al. (1995) presented the long-term fluctuations in the mean state of the climate system over the Indian Ocean during austral summertime, showing the strengthening and weakening of oceanic and atmospheric variables on the multidecadal time scale. However, the interactions and feedback mechanisms between the evolving SST and atmosphere–ocean circulations are not well understood. Knowledge of temporal and spatial covariability between ocean and atmosphere in the southern Indian Ocean remains inadequate.

In this study, we aimed to develop a preliminary insight into how the southern Indian Ocean system varies. Our first aim was to identify the principal modes of the SST and the overlying atmospheric circulation, providing insight into the variability of the southern Indian Ocean coupled atmosphere–ocean system on low-frequency time scales. Our secondary goal was to determine whether the southern Indian Ocean modes of variability are connected to Antarctic Oscillation. Notably, the AAO is the dominant pattern of nonseasonal tropospheric circulation variation south of 20°S, and it is characterized by pressure anomalies of one sign centered in the Antarctic and anomalies of the opposite sign centered around 40°–50°S. The recent trend in the Southern Hemisphere circulation is consistent with a systematic bias toward the high-index polarity of the AAO (Thompson and Solomon, 2002). In this study, it was also aimed to offer comprehensive insights into the southern Indian Ocean atmosphere–ocean coupled variability and to help the modeling studies associated with these programs.

The paper is organized as follows. A brief description of the datasets and methods is given in section 2. Section 3 introduces the main southern Indian Oceanic and atmospheric features. Section 4 presents the principal modes of behavior of the SST and the overlying atmospheric circulation in the southern Indian Ocean obtained from EOF analyses. The results pertaining to the atmosphere–ocean coupling based on the singular value decomposition (SVD) analysis are discussed in section 5, focusing on subtropical and mid-latitude regions. Finally, section 6 contains a summary and a discussion of the main results obtained from this study.

2. Data and methodology

2.1 Data

We used SST data from the Hadley Center. Sea level pressure, 850 hPa vector wind date were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF); heat fluxes were de-