

A discrepancy between observed and OGCM-simulated trends in recent SSTs of the Indian Ocean: Apparent trends in atmospheric reanalysis data

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INTRODUCTION

It is known that the Indian Ocean SSTs have notably increased since the late 20th century (Lau and Weng, 1999) (Fig.1). The warming of the Indian Ocean is considered to contribute to climate impacts by AGCM studies with the prescribed SSTs (Hoerling et al., 2001, Watanabe and Jin, 2002).

In order to understand the warming mechanism of the Indian Ocean, it is necessary to know the surface heat balance of the Indian Ocean. However, due to the lack of long-term observation, there are few studies to examine the surface heat balance of the Indian Ocean based on observations. Under these circumstances, many studies diagnose the surface heat balance by using OGCM (ex. Murtugudde and Busalacchi, 1999, Du et al., 2005). However, it is noted that the present OGCMs give a relatively poor simulation in the Indian Ocean, compared to the central to eastern tropical Pacific (Fig.2), and the cause has not been well understood.

The aim of this paper is to elucidate the cause of the relatively poor simulation of the Indian Ocean SSTs. The knowledge obtained in this study is expected to be useful for ocean modeling studies and for understanding of climatic variability and long-term trends in the Indian Ocean.

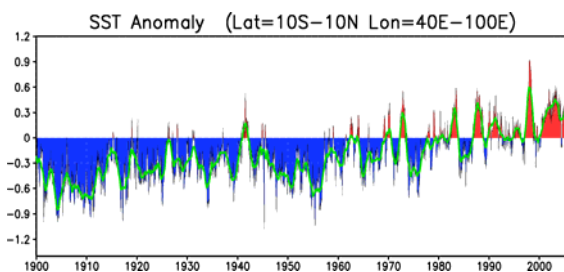


Figure 1 Time series of the observed SST anomaly averaged in the equatorial Indian Ocean (**EQIND**: 10°S-10°N, 40°E-100°E). The SST data set is based on COBE-SST. The base period is from 1971 to 2000.

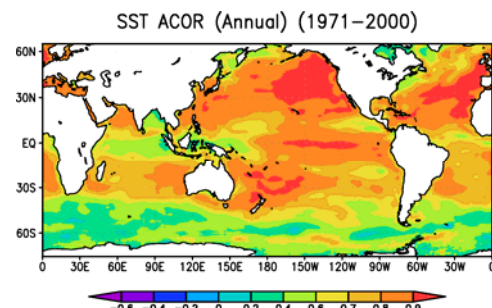


Figure 2 Annual mean anomaly correlation between the observed and the simulated SST anomalies. The OGCM was driven by atmospheric forcing based on ERA-40.

OGCM and DATA SETS

The Ocean General Circulation Model (OGCM) used in this study is a Meteorological Research Institute community ocean model (MRI.COM, Ishikawa et al., 2005). MRI.COM is a MOM-type z-coordinate model. The model domain is a near global from 75°S to 75°N. The horizontal resolution is 1° in longitude and 1° in latitude (0.3° near equator). The model has 50 levels in vertical, with 24 levels in the top 200m.

The atmospheric variables as the surface boundary condition are two sets of daily atmospheric reanalysis data: ECMWF 40 years reanalysis data (**ERA-40**: Simmons and Gibson, 2000) and Japan Meteorological Agency 25 years reanalysis data (**JRA-25**: Onogi et al., 2007). The bulk formula for the surface fluxes is based on the formulation by Kara et al. (2000). After the model was integrated for 102 years as spin-up, two experiments were conducted under two different interannual atmospheric forcings (Table 1).

Table 1. OGCM simulations

<i>Experiment Name</i>	<i>Atmospheric Forcing</i>	<i>Integration period</i>
Exp.A	ERA-40	Jan. 1961 to Dec. 2001
Exp.B	JRA-25	Jan. 1979 to Dec. 2004

The observed SST data set used here is the COBE-SST data set of in-situ measurements of sea surface temperature (Ishii et al., 2005). For comparison with the model results, we used solar radiation and precipitation data derived from JRA-25, ERA-40, in addition to two observation-based estimates: **CMA**P (Xie and Arkin, 1996) and **GPCP** (Adler et al., 2003). For comparison among the reanalyses, we also used solar radiation and precipitation data derived from NCEP/NCAR 40-years reanalysis (**NCEP1**: Kalnay et al., 1996), and NCEP-DOE AMIP-II reanalysis (**NCEP2**: Kanamitsu et al., 2002), in addition to the ISCCP (International Satellite Cloud Climatology Project) solar radiation data derived from Common Ocean-ice Reference Experiment (**CORE/ISCCP**: Large and Yeager, 2004).

All data was converted to monthly means before further analysis. Monthly mean data for ERA-40 surface flux was produced by using the daily mean data based on 36 hour forecast data at each 12UTC initials.

RESULTS

a. Cause of Poor Simulation in the Indian Ocean

The simulated SST anomaly averaged in the tropical Indian Ocean (10°S - 10°E , 40°E - 100°E) exhibits a trend toward negative values gradually since the late 1990s, which is commonly found in Exps. A and B (Fig.3). This implies that the poorly simulated SST in the Indian Ocean is the result of the cooling trend, which is inconsistent with the warming trend in the observed SSTs. The cooling of the model Indian Ocean after 1990 is found not only at the surface but also at the subsurface, resulting in the deepening of the surface mixed layer (Fig.4). This simulated cooling trend in the upper ocean differs from the observed trend of Levitus et al. (2005), where significant warming near the surface accompanies with cooling in the upper thermocline (Han et al., 2006). It is suggested that the deepening of the surface mixed layer altered the heat balance in the model.

The sea surface heat fluxes over the Indian Ocean in Exp.A display a significant decreasing trend in solar radiation (Fig.5). Similar decreasing trend in solar radiation is also found in Exp. B.

In order to clarify the role of the reanalyzed solar radiation on the cooling trend in the simulated SSTs, we made an additional experiment (Exp.C), where the atmospheric forcing is the same as Exp. A, except that solar radiation

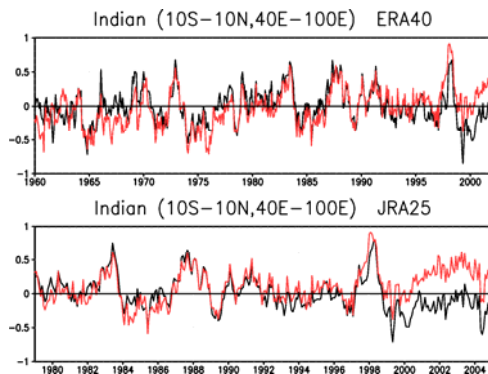


Figure 3 Time series of the SST anomalies averaged in EQIND for the observed (red) and the simulated (black) in (a) Exp.A and (b) Exp.B.

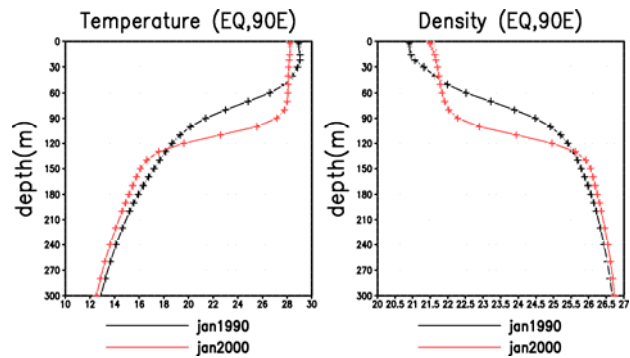


Figure 4 Vertical profiles of temperature (left) and potential density (right) in the equatorial Indian Ocean in Exp.A on Jan. 1990 (black) and on Jan. 2000 (red).

includes only seasonal variations, neither interannual nor longer variations. The simulated SST anomalies in Exp. C displays better agreement with the observed than in Exp. A (Figure 6 upper). It is also found that the warming of the Indian Ocean in the 1990s is roughly captured in Exp. C. The sea surface flux anomalies (Figure 6 lower) shows that increases in long wave radiation have contributed to the simulated warming of the Indian Ocean in the 1990s in Exp. C.

These results strongly suggest that the cooling of the simulated Indian Ocean SSTs is primarily caused by the atmospheric reanalysis data used as the surface boundary condition.

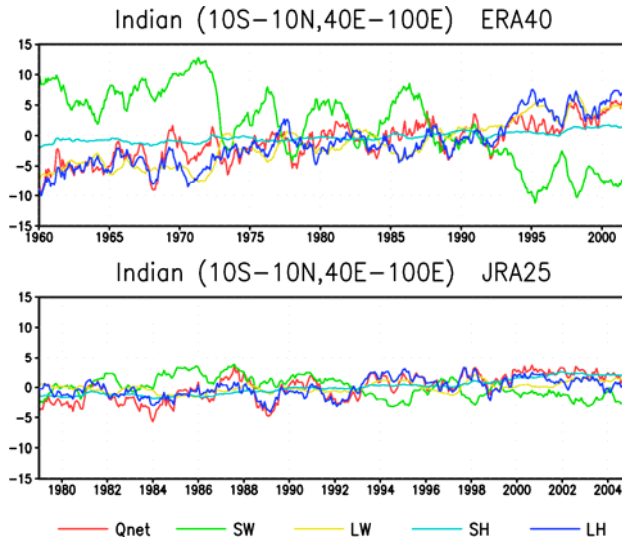


Figure 5 Time series of the sea surface flux anomalies in Exp.A (a) and in Exp.B (b) averaged in EQIND for net surface heat flux (red), solar (green) and long wave (yellow) radiation, sensible (aqua) and latent (blue) heat flux.

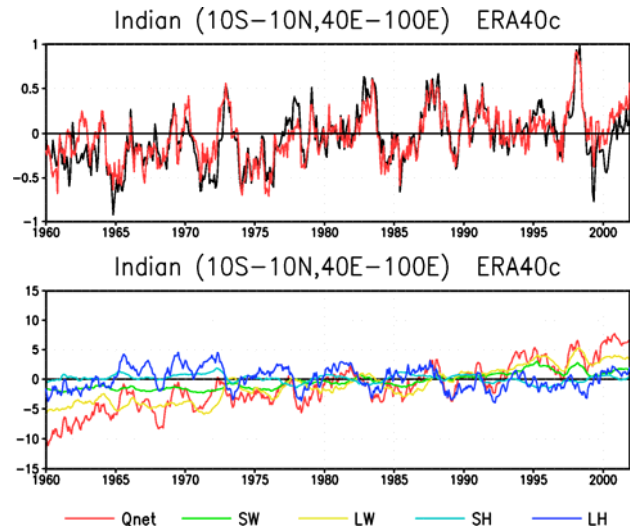


Figure 6 Time series of the simulated (black) and observed (red) SST anomalies (upper) and sea surface flux anomalies (lower) averaged in EQIND in Exp. C, where the atmospheric forcing is the same as Exp. A except that solar radiation includes only seasonal variations. Each line in the sea surface flux anomalies is the same as Fig. 5.

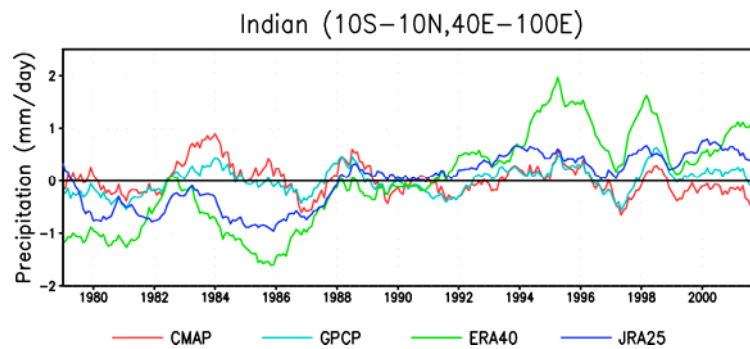


Figure 7 Time series of precipitation anomalies averaged in EQIND. Red line denotes CMAP, aqua GPCP, green ERA-40, and blue JRA-25.

b. Apparent Trends in Atmospheric Reanalysis Data

Next, we examine why the atmospheric reanalysis products display the decreasing trends in solar radiation. The decrease is considered to come from the increase in cloud amount, deduced by precipitation (Fig.7). On the other hand, the observed precipitation (CMAP or GPCP) exhibits no significant increasing trend over there, so may not be the observed cloud amount.

Figure 8 shows average trends during the period 1979 to 2001 in the atmospheric reanalysis products (JRA-25, ERA-40, NCEP1, and NCEP2) with the prescribed SSTs for the reanalyses, in addition to the CORE/ISCCP solar radiation and the CMAP precipitation. The reanalysis products exhibit decreasing trends in solar radiation over the Indian Ocean, and their spatial patterns are almost reverse to the precipitation patterns. This feature is generally found in all of the reanalysis products, though it seems more pronounced in JRA25 and ERA40 than in NCEP1 and NCEP2. The increasing trend in precipitation roughly corresponds to the increasing trend in SSTs prescribed as the lower boundary condition for the reanalyses. Hence, it is suggested that the decrease in solar radiation is associated with increases in precipitation directly over the region of most rapidly warming SST. By contrast, an increasing trend in solar radiation over the Indian Ocean is not recognized in the CORE/ISCCP data. Also, the CMAP data shows no increasing trend in precipitation, or even a decreasing trend over the southern Indian Ocean.

Several problems in the atmospheric reanalyses may have caused this spurious increasing trend in precipitation. One may come from the bias in the assimilation. For example, it is known that ERA-40 has rainfall problems over tropical oceans from the early 1990s, associated with the bias of satellite radiance corrupted by the Pinatubo

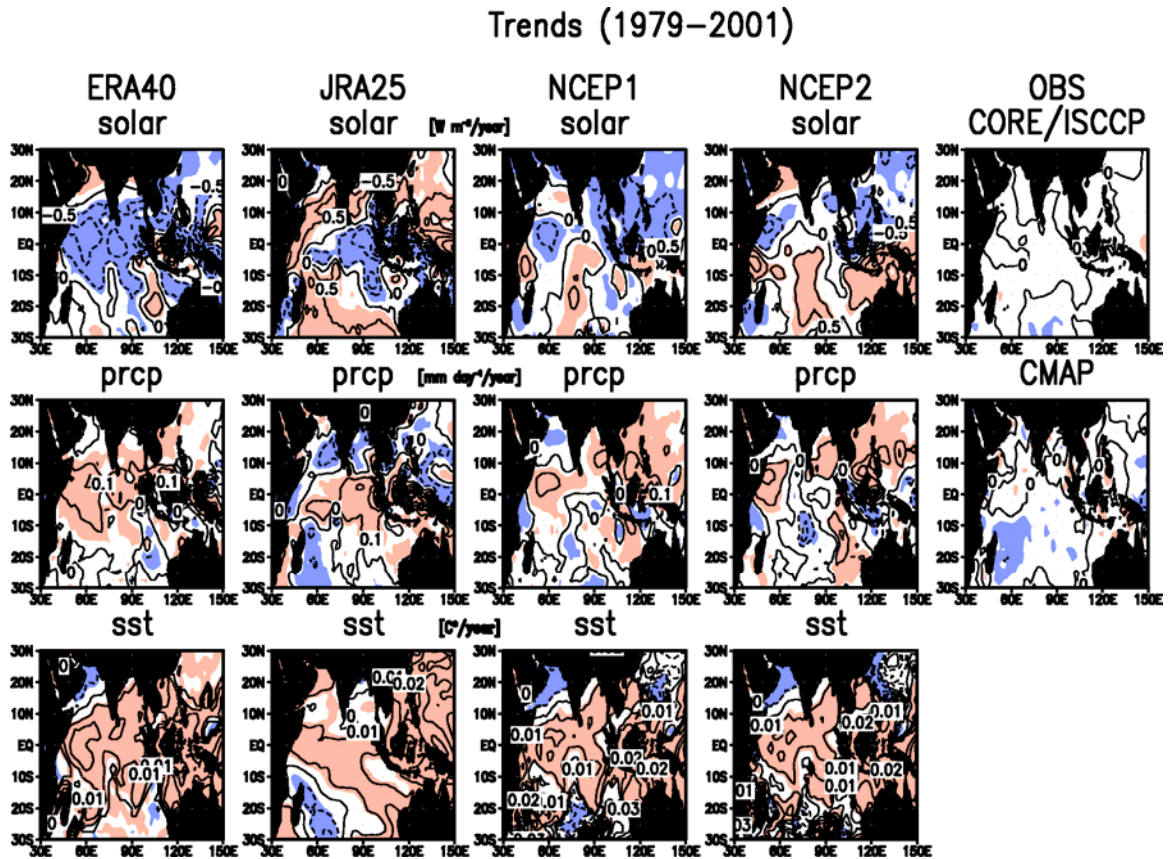


Figure 8 Average trends during the period 1979 to 2001 in the reanalysis products (JRA-25, ERA-40, NCEP1, and NCEP2) and observed data (CORE/ISCCP and CMAP) for solar radiation (upper), precipitation (middle), and the prescribed SSTs for the reanalyses (lower) over the Indian Ocean. The contour interval is $0.5 \text{ W m}^{-2}/\text{yr}$ for solar radiation, $0.1 \text{ mm day}^{-1}/\text{yr}$ for precipitation, and $0.01 \text{ }^{\circ}\text{C}/\text{yr}$ for SST. Red and blue shaded areas denote where the rate of the change is significant with positive and negative values, respectively.

eruption (Dee et al., 2008), and that JRA-25 has major discontinuous changes associated with transition from TOVS to ATOVS in November 1998 (Tsutsui and Kadokura, 2008). Another may come from the bias in the model. Over tropical oceans where in-situ observations are infrequent and sparse, it is known that a reanalysis dataset would be equivalent to AGCM outputs where SST is given as the lower boundary condition (Arakawa and Kitoh, 2004). Hence, responding to the warming of the Indian Ocean, AGCM tends to enhance convective activities and thus to result in the enhanced increases in precipitation and cloud amount.

As a result, the decrease in the solar radiation caused the cooling trend of the simulated SSTs in the Indian Ocean, inconsistent with the observed SSTs (Fig.1). This is supported by the fact that the area with a relatively low skill of the simulated SSTs in the tropical Indian Ocean (Fig.2) approximately corresponds to the area with the decreasing trend in the solar radiation (Fig.8).

SUMMARY and DISCUSSIONS

We investigated the cause of the poor simulation of the Indian Ocean SST, and found that this is due to the atmospheric reanalysis data (ERA-40 and JRA-25) used as the surface boundary condition for OGCM, which include decreasing trends in solar radiation over there. The decreasing trend in solar radiation is related to the increasing trend in precipitation over the Indian Ocean, which is in part a response to local warming of the SSTs. Thus, a caution is needed when one uses the atmospheric reanalysis data as surface boundary conditions for OGCMs.

Recently, Copsey et al. (2006) reported a rise in sea surface pressure, as a proxy for precipitation, over the Indian Ocean between 1950 and 1996. Deser and Phillips (2006) concluded no significant increase in precipitation over the Indian Ocean, based on the analysis of the cloud amount and wind convergence over the ocean. Norris (2005) suggests a negative trend in upper level cloud cover in the equatorial Indian Ocean between 1952 and 1997. These studies suggest that no increase or even decreases in precipitation may occur over the Indian Ocean. Further study based on the observation is needed to elucidate the long-term trend of precipitation in the Indian Ocean.

The apparent trends in the atmospheric reanalysis products are a crucial problem for long-term ocean modeling studies because surface flux data based on the atmospheric reanalysis products are widely used as the surface boundary conditions for OGCMs. One approach to avoid the unrealistic cooling of the model Indian Ocean is the use of the CORE/ISCCP solar radiation, which displays no significant decreasing trend (Fig.7). However, it should be kept in mind that the CORE/ISCCP data include no interannual variations before the mid-1983 because of the limited availability of the satellite data.

Nevertheless, it is no doubt that the atmospheric reanalysis products have greatly contributed to ocean modeling studies and thus have been indispensable. From a standpoint of ocean modeling, further progress on the reanalysis including air-sea interaction processes, which is lacking in the current atmospheric reanalyses, is expected to improve sea surface fluxes.

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