Decadal variability of the Indian Ocean dipole
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Received 26 August 2004; revised 14 October 2004; accepted 19 November 2004; published 23 December 2004.

[1] Using the Simple Ocean Data Assimilation (SODA), NCEP/NCAR reanalysis and the GISST datasets from 1950–1999, and an atmosphere-ocean coupled general circulation model, we explored the possible existence of decadal Indian Ocean Dipole (IOD) variability for the first time. We find that there are strong decadal IOD events, and that the time series of the decadal IOD and decadal ENSO indices are not well correlated. The simulated decadal signal of the IOD index is highly correlated with the 20°C isotherm depth anomaly, indicating that ocean dynamics is involved in the decadal IOD. It is also associated with the zonal wind anomaly. We suggest that the decadal IOD in the tropics is interpreted as decadal modulation of the interannual IOD events. INDEX TERMS: 9340 Information Related to Geographic Region: Indian Ocean; 4504 Oceanography: Physical: Air/sea interactions (0312); 4522 Oceanography: Physical: El Nino; 4215 Oceanography: General: Climate and interannual variability (3309); 1620 Global Change: Climate dynamics (3309). Citation: Ashok, K., W.-L. Chan, T. Motoi, and T. Yamagata2004, Decadal variability of the Indian Ocean dipole, Geophys. Res. Lett., 31, L24207, doi:10.1029/2004GL021345.

1. Introduction
[2] The Indian Ocean Dipole (IOD) is a phenomenon that occurs interannually owing to basin-wide ocean-atmosphere coupled dynamics [Saji et al., 1999; Webster et al., 1999; Yamagata et al., 2003]. The IOD has vast impact on climate conditions in many regions of the world [Ashok et al., 2003a, 2004; Guan and Yamagata, 2003; Saji and Yamagata, 2003]. Some studies discussed the decadal modulation of the IOD events and their changing impact on the climate in surrounding areas. For example, Ashok et al. [2001] have shown that the frequent occurrence of the IOD events in the last two decades of the twentieth century has reduced the impact of the El Niño/Southern Oscillation (ENSO) on the Indian summer monsoon rainfall. Behera and Yamagata [2003] have shown that these frequent IOD events have even weakened the link between El Niño and the Southern Oscillation by influencing the sea-level pressure at Darwin. To understand these long-term climate variations and those related to the recent global warming trend, it is important to discuss details of the decadal modulation of IOD as well as ENSO.

2. Methodology
[3] It is known that interannual ENSO events are associated with a decadal manifestation known as decadal ENSO [Nitta and Yamada, 1989]. Several theories have been proposed for this decadal ENSO (see Zhang et al. [1997] and Luo et al. [2003] for details and references). Recently, Kripalani and Kumar [2004] found decadal epochs in seasonally stratified IOD index. In this context, we here examine the possibility of the existence of a decadal IOD using observed data sets and a coupled general circulation model (CGCM).

[4] We use the GISST 2.3b data set [Rayner et al., 1996] to compute the IOD mode index (IODMI) defined as difference of the area-averaged SSTA between the regions 50°E–70°E, 10°S–10°N and 90°E–110°E, 10°S-equator [Saji et al., 1999], and NINO3 index (area-averaged SSTA over 150°W–90°W, 5°S–5°N) to represent ENSO. The NCEP/NCAR reanalyzed zonal winds are also used [Kalnay et al., 1996]. The 20°C isotherm depth (D20) from the Simple Ocean Data Assimilation (SODA) dataset [Carton et al., 2000] represents thermocline variations. Although these subsurface hindcast data have quality problems because of sparsity of observations, they are the only available dataset for describing subsurface variations for the longest period, starting from 1950. Our analysis period for observations is from 1950 to 1999. We also use the GFDL CGCM [Manabe et al., 1999] to understand the decadal variability of the model-simulated IOD. This model comprises of an atmospheric general circulation model (AGCM) and an ocean general circulation model (OGCM) coupled through momentum, heat and water exchanges once daily. The AGCM has 9 vertical levels and rhomboidal spectral truncation at wave number 15 (~4.5° latitude by 7.5° longitude). The OGCM has a grid spacing of approximately 4.5° latitude by 3.75° longitude and 12 vertical levels. Realistic geography and smoothed topography are included and flux adjustment of heat and water is carried out to avoid climate drift. The model has been integrated for 5,000 years starting from the final ocean and atmosphere conditions of a 10,000 year integration carried out at GFDL, which are at equilibrium with each other [Chan and Motoi, 2003]. We analyze the last 1,000 years of the integration.

3. Results
[5] The IODMI has a primary peak of variability at quasi-biennial frequency followed by a quasi-pentadal frequency [Ashok et al., 2003b]. Interestingly, there is also a quasi-decadal peak at 125 months significant at 90% confidence level [Ashok et al., 2003b]. In Figure 1, we show the time series of the observed decadal IODMI and NINO3 index, and here only decadal signals (8–25 years) are retained by...
using a band pass filter [Murakami, 1979]. Although strong
(amplitude larger than one standard deviation of about
0.12°C) decadal IOD episodes are found in the 1950s, early
1960s and 1990s, no consistent phase relationship with the
NINO3 index is seen. Actually, the correlation is only 0.01.

Because of the shorter time span of available datasets,
particularly in the subsurface, it would be beneficial to use
the CGCM outputs to understand mechanisms behind the
decadal IOD evolution. We have carried out empirical
orthogonal function (EOF) analysis on the simulated model
SST during the September–October–November (SON)
season over the tropical Indian Ocean. EOF1 (figure not
shown) captures a basin-wide monopole mode similar to
observed EOF1 that is related to ENSO. The magnitude of
the variability explained by the simulated EOF1 is 10.6% as
compared to 30% in the observed data [Saji et al., 1999].
This is because the ENSO-like variability in the model is
relatively weak as compared to that in the observations.
Although the model ENSO is weaker than the observed,
particularly in the eastern Pacific, its life cycle is qualita-
tively similar to those from many other high resolution
models. The simulated EOF2 pattern shows a dipolar
structure with both poles centered in the equatorial Indian
Ocean (figure not shown), similar to the EOF2 of the
observed SST; the variance explained by this simulated
EOF2 is 9%, close to the observed value of 12% [Saji et al.,
1999]. Based on this distribution, we define an index for
model IOD variations as the difference between the area-
averaged SST anomalies over the tropical west Indian
Ocean bounded by 40°E–60°E, 15°S–10°N, and the tropical
southeastern Indian Ocean bounded by 90°E–110°E,
15°S-equator. The standard deviation of the simulated
IODMI is 0.44°C, which is close to observations. We filter
out all signals outside the decadal range (8–31 years) from
the simulated anomalies for IOD and D20. The partial
correlation between these decadal signals is presented in
Figure 2a. NINO3.4 index is the second predictor whose
influence has been removed through the partial correlation
technique; since the model simulated NINO3 SST is weak,
a NINO3.4 type index defined as the area-averaged SST
over 7°N–7°S, 172.5°E–120°W has been used for climate
studies with this model [Knutson et al., 1997; Knutson and
Manabe, 1998]. The dipolar correlation pattern is highly
significant, indicating strong coupling between the surface
and subsurface variations at the decadal timescale. This
pattern is similar to that obtained from the correlation
between the decadal (8–25 year) component of the
GISST-derived IODMI and D20 anomalies from SODA
dataset (figure not shown), though the loadings in the latter
are weaker in the east. We have also calculated 31-year
moving correlations of the simulated IODMI with the
equatorial Indian Ocean zonal wind anomalies to examine
the ocean-atmosphere coupled dynamics [cf. Saji et al.,
1999]. While the CGCM is able to simulate the observed
tight relationship between the zonal wind anomalies and
IODMI throughout the time series, the simulated correlation
between the D20 variations in the Indian Ocean and the
NINO3.4 index is very weak (figure not shown).

[7] Understanding the mechanism of the simulated
decadal IOD-like variations is useful for interpreting obser-
vations. We have composited twenty simulated decadal IOD
episodes. During the fall of the first year, decadal D20
anomalies show a dipolar structure indicating a shoaled
thermocline in the east, in harmony with the anomalous
zonal easterlies (Figure 2b). After about 4 years, we see
similar but weakened conditions (figure not shown); the
equatorial anomalous easterlies over the eastern pole of the
IOD weaken during this transition phase, and the negative
D20 anomalies are simulated much further west. After
another 2 years (Figure 2c), we see anomalous equatorial
westerlies with a reversed thermocline structure relative to
Figure 2b. About eleven years after the beginning of the
decadal IOD episode, the system returns back to the original
positive IOD-like conditions; the whole process similar to
that of the interannual IOD [Saji et al., 1999; Rao et al.,
2002] except for the much longer timescale. This situation
reminds us of such similarity between delayed oscillator
theory for the interannual ENSO [Schopf and Suarez, 1988]
and that for the decadal ENSO [Knutson and Manabe,
1998]. However, the phase speed (of about 0.08 m.s
−1) of simulated decadal Rossby waves is smaller than
the theoretical prediction of 0.18 m.s
−1. This may be due to
their coupling with the overlying atmosphere, as suggested
by White et al. [2003] in the context of slower tropical
Pacific decadal waves. Indeed, the model simulated decadal
Webster-Yang index [Webster and Yang, 1992], a zonal
wind index defined as June–August (JJA) zonal wind shear
between 850–200 hPa area-averaged over 40°E–110°E,
equator-20°N (henceforth WYI), is well correlated to the
decadal D20 fall anomalies (Figure 3a) after removal of
ENSO component through partial correlation technique; the
peak correlations with (reversed sign) occur with 5 years

![Figure 1](image1.png)

**Figure 1.** Normalized observed decadal (8–25 year signals) time series of NINO3 index (dashed) and IODMI (solid).

![Figure 2](image2.png)

**Figure 2.** Simulated decadal (8–31 year signals) (a) partial correlations between the IODMI and anomalies of D20 (b) composite D20 anomalies (cm) during 1st year of the cycle; in contours, and significant surface winds (cm s
−1) (c) same as Figure 2b, but in 6th year. Shaded values are significant at 90% confidence level, obtained from 10,000
Monte Carlo simulations in Figure 2a (and also in Figure 3), and from 2-tailed t-test in Figures 2b and 2c.
lead (Figure 3b), suggesting that decadal atmospheric variability modulates and possibly forces decadal wave-like processes in the tropical Indian Ocean. Similar partial correlations between the NCEP-based WYI and SODA-derived D20 anomalies during fall are also qualitatively similar (Figures 3c and 3d), supporting the proposed mechanism; we note that the peak lead-time is 6 years in this case, comparable with the 5 years from the CGCM.

The wavelet analysis [after Torrence and Compo, 1998] on the model-simulated IODMI shows significant decadal peaks (8–13 years) spaced at centennial intervals (Figure 4a). Also seen are significant interannual peaks spread at decadal intervals, indicating that the model interannual variability is associated with the decadal modulation. This reminds us of similar observations by Saji et al. [1999]; the intense and frequent IOD events in the 1960s returned again in the 1990s. To understand this decadal modulation of the interannual IOD variability, we have carried out power spectrum analysis on the time series of simulated IODMI. The most dominant interannual peak is seen at about 2.2 years that is significant at 95% confidence level from red noise spectrum (not shown) and is consistent with the observation of the strong biennial nature of IOD events [cf. Meehl et al., 2003; Loschnigg et al., 2003], followed by another two significant peaks around 3.5 and 6 years, respectively. Interestingly, the model IODMI power spectrum has a decadal peak centered around 9 years, which is significant at 90% confidence level in agreement with the observations. There are also some significant multi-decadal peaks. The decadal modulation of the interannual IOD variability appears to be a key to understand the decadal IOD in the model [cf. Arblaster et al., 2002]. Indeed, most of the interannual IOD peaks from the wavelet analysis appear to be associated with some significant decadal peak at 8–32 year periodicity (Figure 4a). The correlation between the scale-averaged variance of 2–8 (5–8) year band with that of 8–32 years is 0.23 (0.34), which is significant at 99.9% confidence level. This important aspect will be reported in more detail using a high-resolution coupled GCM.

4. Summary and Discussion

The present study is summarized as follows. The occurrence of strong decadal IOD signals in the late 1950s and 1960s and again from the late 1980s to 1990s is consistent with the power spectrum of the observed IODMI, which shows a significant decadal peak. The correlations between the decadal components of D20 from SODA data and GISST-derived IODMI for the period from 1950 through 1999 demonstrate the importance of subsurface ocean dynamics in the decadal IOD.

The wavelet analysis on the model simulated IODMI indicates that the decadal IOD episodes may be related to decadal modulation of the interannual IOD, as observed during the second half of the 20th century. The present coupled model simulates a similar decadal IOD. This gives credulity to our observation-based finding of the decadal IOD, which is vulnerable to criticism due to sparse subsurface measurements. The CGCM study suggests that the turnabout of the decadal IOD events is similar to that for interannual IOD events, but the evolution of the former is much slower than the latter possibly due to oceanic Rossby waves coupled to the atmosphere. However, we cannot exclude involvement of other factors such as tropical and extratropical interactions associated intrinsically with the interannual events [Lu and McCreary, 1996; Gu and Philander, 1997]. T. Tozuka et al. (personal communication, 2004) have recently suggested that decadal asymmetric occurrence of positive and negative IOD events may lead
us to a decadalIOD-like picture because of linear statistical analysis methods. Such simulated association between the asymmetric interannual fluctuations of SST over the western pole of the IOD and its decadal component is presented in Figure 4b as an example (methodology similar to Figure 1a of Fedorov and Philander [2000] except that apart from the removal of seasonal cycle and high frequency components, multidecadal and centennial signals also have been removed). The prospective role of the occurrence of asymmetric interannual events in such “decadal regime shifts” is a topic that has to be explored further.

[11] The present analysis is limited by the coarse resolution of the model as well as the sparse datasets. Given the potential importance of the decadal IOD in global climate change, it is important to understand decadal IOD using much higher resolution coupled models.

[12] Acknowledgment. The authors thank Dr. S. Manabe for many helpful suggestions during the course of this work, Drs. S. K. Behera, J-J. Luo, Y. Masumoto, S. Masson, A. S. Rao, and T. Tozuka for their kind support, Dr. H. Yih for his contribution in setting up the program, Dr. C. Luo, Y. Masumoto, S. Masson, A. S. Rao, and T. Yamagata (2003), The Asian monsoon, the tropospheric biennial oscillation and the Indian Ocean dipole in the NCAR CSM, J. Clim., 16, 2138–2158.


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