INTRODUCTION

Special Issue on Indian Ocean Climate*

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In the past, great advances in Indian Ocean research have emerged after expeditions by research vessels such as the *Discovery* in the 1930s or international cooperative observational programs such as the International Indian Ocean Expedition (1960–65) and ship surveys during the World Ocean Circulation Experiment in the mid-1990s.

However, Saji et al. (1999) and Webster et al. (1999), in two letters to *Nature*, with an introduction by Anderson (1999), used existing observational data to bring attention to an air–sea interaction phenomenon across the tropical Indian Ocean. It involved abnormally high sea surface temperatures in the west during the southwest monsoon, and large cold anomalies off Sumatra and associated easterly equatorial wind anomalies that last through the fall. This La Niña–like pattern tends to make the Indian Ocean SST pattern be more like the pattern in Pacific Ocean and Atlantic Ocean tropical regions. The terms Indian Ocean dipole (IOD) mode or Indian Ocean zonal mode (IOZM) have been used for this climate event, and the extent to which this mode is independent from ENSO quickly became controversial. In spite of the controversy, or rather perhaps because of it, the IOD/IOZM discovery has generated an unprecedented interest in Indian Ocean air–sea interaction. The 24 papers in this special issue reflect this revival of interest in the Indian Ocean region. Many of these papers are based on presentations given at the Climate Variability and Predictability Studies (CLIVAR) workshop hosted by the International Pacific Research Center in Honolulu, Hawaii, from 29 November to 3 December 2004.

The first group of papers addresses the decadal and interannual variability in the Indian Ocean and its relation to El Niño and La Niña. Part of the controversy as to which extent IOD and ENSO are related depends on the definition of these events. Meyers et al. propose a new method to classify El Niño, La Niña, and positive and negative IOD events and use that method to identify independent and co-occurring events from 1876 to 1999, setting the stage for the subsequent papers in this group. In the paper by Tozuka et al., a 200-yr run of a coupled ocean–atmosphere model is analyzed for decadal variations of sea surface temperature anomaly (SSTA) and heat content over the Indian Ocean. Modulation of an El Niño–like basin-scale SSTA pattern and an independent interannual IOD pattern are found. In the following paper by Song et al., a similar decadal modulation is seen. They explore the feedbacks between oceanic heat content and the atmosphere in a 250-yr-long coupled atmosphere–ocean model over the Indian Ocean with emphasis on composite El Niño and IOD events. Co-occurrence of IOD and El Niño results in particularly strong anomaly patterns. Huang and Shukla, in two papers, use ensemble coupled ocean–atmosphere model runs to determine the link between remote and regional forcing in the Indian Ocean. It is

* International Pacific Research Center Contribution Number 430 and School of Ocean and Earth Science and Technology Contribution Number 7108.

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DOI: 10.1175/JCLI4286.1

accomplished by using a globally coupled model and a model in which SST is prescribed outside the Indian Ocean. The dominant external forcing of a tropical Indian Ocean mode is due to ENSO, leading to longer-lasting thermocline anomalies in the southwest Indian Ocean compared to the regional forced case. A subtropical mode with an IOD pattern and independent of ENSO is also identified. Finally, the last paper in this group by Drbohlav et al. uses reanalysis data, observed SST, and ocean data assimilation products to analyze the differences in wind patterns and SST during IOD events in El Niño years and during non–El Niño years, and provides a detailed discussion of the role of advection and heat flux.

The two following papers address the response of the Indian Ocean. Using an Indian Ocean model driven with composite winds, Jensen finds that the annual clockwise cross-equatorial circulation of the upper Indian Ocean on average is slowed down during La Niña years, allowing Bay of Bengal water to enter the Arabian Sea. Conversely, the circulation is intensified during El Niño, and in particular during IOD. Valsala and Ikeda are identifying the major pathways of water from the Indonesian Throughflow using particle trajectories, passive tracers, temperature, and salinity from an OGCM. They found three main routes: A clockwise circulation cell in the thermocline confined to the south of the equator, a near-surface branch entering the Arabian Sea via the Somali Current, and a cross-equatorial subsurface branch at depths between the two other pathways.

Intraseasonal oscillations have been identified as playing a central role in terminating IOD events. From a coupled atmosphere–ocean model Rao et al. find that model IOD events are terminated by 20–40-day intraseasonal disturbances, which prevents sustained cool SSTs in the eastern Indian Ocean beyond the boreal fall. It is also found that intraseasonal disturbances during the boreal summer at times prevent full development of IOD events.

In the work by Sengupta et al. observations in the equatorial Indian Ocean show large intraseasonal variability of winds and currents on time scales of 10–60 days. The authors investigate the zonal momentum balance for currents and equatorial jets associated with this variability in an OGCM forced by Quick Scatterometer (QuikSCAT) winds. In the third paper in this group, Duvel and Vialard investigate the relations between intraseasonal variability of sea surface temperature, outgoing longwave radiation, heat flux, surface wind, and mixed layer depth from observations and reanalysis data over the Indian Ocean region.

Recent works have explored the influence of Indian Ocean variability on the Asian monsoon and the extratropics. In the paper by Cherchi et al. the relationship between the Indian summer monsoon and tropical Indian Ocean (TIO) SST is investigated. A new method, the coupled manifold, is applied to separate the part of TIO SST variability that is independent from Pacific SST variability and to estimate the amount of Indian rainfall due to TIO SST. Murray et al. use an OGCM to model the observed subsurface cooling of mode water and intermediate waters at 32°S from 1965 to 1987 and the subsequent warming/continued cooling of those water masses until 2002. In another model study, Hermes et al. find that the recirculation in the southwest Indian Ocean subgyre is a major contributor to variation in the Agulhas Current transport on annual and interannual time scales. Going farther poleward, in their analysis Ashok et al. separate the remote influence of ENSO and positive IOD events on the Southern Hemishere winter storm tracks and the associated reduced rainfall over southern Australia and New Zealand. Annamalai et al. are using ensemble calculations from two AGCMs to show that during El Niño the SSTA in the southwestern Indian Ocean opposes the effects of SSTA in the tropical Pacific over the Pacific–North American region.

The next four papers address the heat flux and heat transport in the tropical Indian Ocean. In the first paper, Yu et al. discuss the difficult problems that face researchers in assessing models against observations and data assimilation products. The authors analyze six products of the mean, annual cycle, and interannual variability of net surface heat flux into the Indian Ocean. Biases of several tens of watts per meter squared are found for the mean net heat flux, while the seasonal and interannual flux products are more consistent. In the works by Godfrey et al. and Hu and Godfrey, it is shown that the annual mean heat flux in the tropical Indian Ocean, and consequently southward oceanic heat transport, is too low in OGCMs compared to estimates from observations. This is an indication that the subsurface geostrophic northward flow is too warm in the models. Using idealized and realistic model geometries, it is hypothesized that the main reason is that diapycnal mixing in models are too weak in the upwelling and downwelling regions near the western boundary and the Great Whirl. The diapycnal mixing was found to be due to horizontal diffusion, spurious convective overturning, and mixing due to the numerical scheme rather than due to realistic processes. In the fourth paper, Montegut et al. investigate the heat budget of the Arabian Sea and the Bay of Bengal. They find that penetrative solar radiation leads to heat storage during monsoon breaks. Stratification due to freshwater plays a major role for the storage in the Bay of Bengal.

As the CLIVAR acronym implies (CLIVAR Scientific Steering Group 1995) observation of variability and prediction are central to the program. The next three papers aim to improve mooring design in the Indian Ocean using models as a tool. Optimal mooring array configurations for the observation of the depth of the 20°C isotherm on interannual time scales and the mixed layer depth on intraseasonal time scales are presented and explored by Oke and Schiller. The optimal array designs for the two different time scales differ, so a consolidated array is proposed. Ballabrera-Poy et al. use data assimilation based on Kalman filters of subsampled observed SSH and SST to reconstruct the complete observed fields. The optimized locations for observing stations agree quite well with those proposed for CLIVAR, although some redundancy in stations is identified near the equator. Vecchi and Harrison simulate an in situ Indian Ocean Observing System (IOOS) with ARGO floats, repeated XBT lines, and moorings using a high-resolution OGCM. Their results show that a system using a 10-day sampling interval for floats combined with moored arrays is capable of capturing interannual and subseasonal variability in this region.

The final paper addresses the important issue of predictability and forecasting. Wajsowicz investigates the predictability and potential predictability of SSTA in the regions of the two IOD index regions using coupled ocean–atmosphere ensemble forecasts. A late spring predictability barrier is identified for SSTA in both regions, but with higher predictability potential for the western pole.

The efforts of many people have gone into this special issue. As editor, I would like to thank the authors who patiently have waited to see their work in print, the reviewers who have substantially improved many of the manuscripts, editorial assistant Stacey Yamasato at the University of Hawaii at Manoa, and the staff at AMS who made it all possible.

REFERENCES

Anderson, D., 1999: Extremes in the Indian Ocean. *Nature,* **401,** 337–339.

CLIVAR Scientific Steering Group, 1995: CLIVAR—A study of climate variability and predictability: Science plan. WRCP 89, WMO/TD 690, World Climate Research Programme, Geneva, Switzerland, 170 pp.

Saji, N. H., B. N. Goswami, P. N. Vinayachandran, and T. Yamagata, 1999: A dipole in the tropical Indian Ocean. *Nature,* **401,** 360–363.

Webster, P. J., A. M. Moore, J. P. Loschnigg, and R. R. Leben, 1999: Coupled ocean-atmosphere dynamics in the Indian Ocean during 1997-98. *Nature,* **401,** 356–359.