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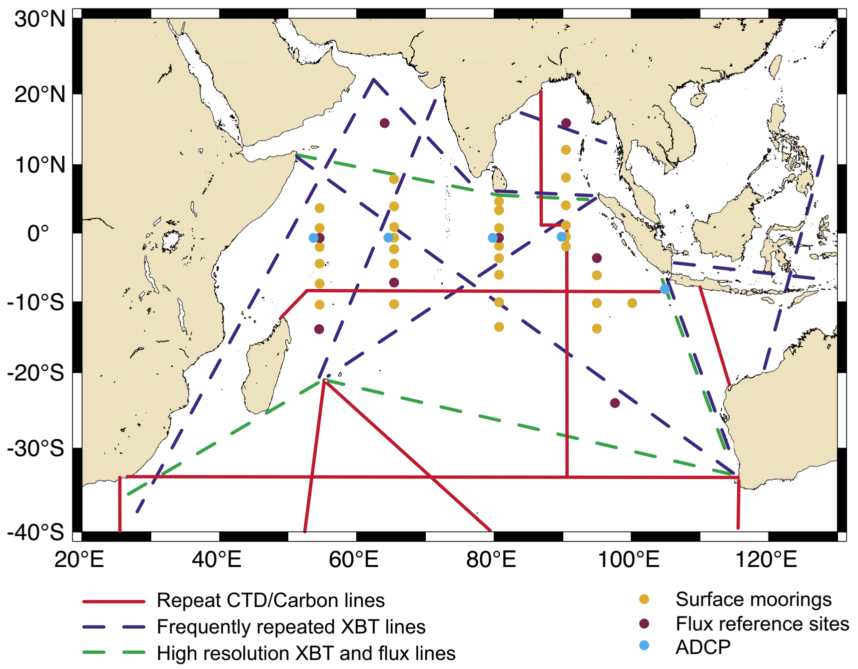
Indian Ocean Climate

From Meyers and Boscolo, page 2: The Indian Ocean Observing System (IndOOS)



Also included are the 3°x3° Argo profiling float array, 5°x5° surface drifting buoy array and a real-time and near real-time tide gauge network (20 stations in operation with ~20 planned)

CLIVAR is an international research programme dealing with climate variability and predictability on time-scales from months to centuries.

WCRP World Climate Research Programme

CLIVAR is a component of the World Climate Research Programme (WCRP). WCRP is sponsored by the World Meteorological Organization, the International Council for Science and the Intergovernmental Oceanographic Commission of UNESCO.

Editorial

As you will see, this edition of Exchanges focuses on Indian Ocean Climate. A key activity of the joint CLIVAR/IOC GOOS Indian Ocean Panel has been to develop a plan for sustained observations over the Indian Ocean region, summarized in the paper by Gary Meyers and Roberta Boscolo. As it works to encourage implementation of this plan through national agencies and international ocean observation coordination mechanisms, illustrated by the paper by Mike McPhaden et al., the panel is also seeking to develop the science of the Indian Ocean's role in climate. It will do this in particular in conjunction with CLIVAR's Asian-Australian Monsoon and Variability of the African Climate System Panels. Linking these activities to the wider role of the Pacific in the climate system and CLIVAR activities in seasonal to interannual, decadal and climate change prediction is also a key integrating role for CLIVAR overall. Papers here represent recent developments in Indian Ocean observational and modelling studies. In addition, this edition also carries reports of two CLIVAR-related workshops, one linking the International Climate of the 20th Century Project and CLIVAR efforts in seasonal to interannual prediction and the other on much longer timescales - the joint PAGES/CLIVAR Workshop on past-millennia climate variability, illustrating the breadth and range of CLIVAR. The next edition of Exchanges (January 2007) will be joint with the International Council for the Exploration of the Sea (ICES) and will focus on North Atlantic and Nordic Sea climate variability.

Howard Cattle

The Indian Ocean Observing System (IndOOS)

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The circulation and transport of heat in the Indian Ocean is unique in many respects, compared to the Pacific and the Atlantic. The Asian landmass blocks the ocean in the north so that currents cannot carry tropical heat to higher latitude as the Atlantic and Pacific do. It also receives extra heat from the Pacific via the Indonesian Throughflow. The movement of heat around the ocean and exchange with the atmosphere is highly variable in time. As a consequence, the Indian Ocean plays a unique role in the variation of regional and global climate systems.

Indian Ocean climate research has been limited in the past by a very sparse historical record of oceanographic and marine meteorological observations. Never-the-less, the research-issues that have to be addressed have been identified. The key issues are:

- Seasonal monsoon variability, in particular the role of seasonal variation in oceanic circulation and heat transport
- Intraseasonal variability, in particular air-sea interaction, and what, if any, role does oceanic dynamics play in the longer time-scales of weather prediction
- Indian Ocean zonal dipole mode, El Nino–Southern Oscillation and their mutual interactions
- Decadal variation of all of the above, and warming trends in the upper Indian Ocean
- Southern Indian Ocean, one of the most sparsely sampled regions of the world, and its role in climate variability
- The unique features of Indian Ocean circulation and their role in the global heat budget, including the Indonesian Throughflow, the shallow subtropical-tropical overturning cell that affects sea surface temperature on both sides of the equator, and the inter-ocean exchange with the Atlantic
- Biogeochemical cycling in the Indian Ocean.

The societal and economic impacts of these climate variations affect the lives of nearly hundreds of millions of the world's population. The benefit to be derived from describing, understanding, modelling and predicting the coupled ocean–atmosphere behaviour in this region is potentially huge.

The CLIVAR-GOOS Indian Ocean Panel (IOP) (http://www.clivar.org/organization/indian/indian.php) has prepared an implementation plan to collect essential data required to support research on these issues. The plan is available for download at: http://eprints.soton.ac.uk/20357/01/IOP_Impl_Plan.pdf. It provides a brief overview of each of the above research-issues, and technical details on a basin-scale, integrated observing system (Figure 1, front cover). Integration implies that we make use the technologies for in situ data collection that have proven to be sustainable and useful for climate research in the long term, as well as integration with the available satellite based measurements of sea surface temperature, sea level, wind and ocean colour. Plans for physical measurements are better developed at this stage than plans for biogeochemical measurements; however, integration across physics, chemistry and biology is also anticipated.

The technologies available for large-scale ocean monitoring are moorings (for subsurface temperature, salinity, currents, biogeochemical sensors and surface weather variables), Argo floats (for subsurface temperature, salinity and oxygen), expendable bathythermograph (XBT) lines, surface drifters (for sea-surface temperature and current) and sea-level stations.

The key new element of the observing system is a basin-scale mooring array (see McPhaden et al. this issue), which is essential to capture the seasonal monsoon variability and intraseasonal disturbances. As well as measurements of oceanic variables, the meteorological measurements at moorings provide much needed data to validate and calibrate estimates of surface fluxes from satellite data and they will be extremely valuable to data assimilation issues concerned with weather forecasting and reanalysis efforts.

The Argo Programme to measure temperature and salinity profiles to a depth of ~1500 m every 10 days is progressing rapidly in the Indian Ocean. The standard sampling pattern requires 450 floats to cover the ocean to 40°S with one float per 3°×3° latitude/longitude. Sustained monitoring will require 125 deployments per year, assuming a float lifetime of 3-4 years. As a minimum the standard Argo array in the Indian Ocean should be completed and maintained. The Argo profiles are essential for research on the role of ocean circulation in climate variability and change, from interannual to multidecadal time-scales.

The XBT network in the Indian Ocean was initiated during TOGA and WOCE, but never fully implemented. XBT lines are effective for monitoring specific ocean structures that affect climate, such as the Indonesian Throughflow and upwelling zones between Java and Australia and the thermocline ridge near 10°S, both areas of documented strong ocean-atmosphere interaction. A trans-equatorial line in the western Indian Ocean can monitor inflow to the western boundary currents. The IOP critically reviewed the TOGA-WOCE XBT lines in preparing the plan, with regard to scientific justification, potential impact on future research and feasibility of implementation. The high-priority lines were determined to be IX01, IX08, IX09N/IX10E, IX12, IX22 and PX-02 for the so-called frequently repeated (FRX) sampling mode; and IX1, IX15/IX21 for the high-density (HDX) sampling mode. The value of other lines is discussed in the report as well.

The International Buoy Programme for the Indian Ocean (IBPIO) was formally established in 1996 and has become the primary body for coordinating multinational activities to implement surface drifting buoys. The drifter array was originally designed for reduction of the bias error in satellite SST measurements, and called for one drifter per 5° square. IOP noted that a re-evaluation of the sampling density is required for direct measurement of surface current, a growing need as ocean-reanalysis products require validation.

The international response to the Indian Ocean tsunami disaster in December 2004 is the rapid development of an Indian Ocean Tsunami Warning and Mitigation System (IOTWS). This development will potentially have numerous synergies with the development of IndOOS. In particular, the network of sea level stations is being upgraded to real-time monitoring at numerous locations. The IOTWS community is working closely with the climate-community to ensure that the upgraded sea level stations will also serve the purpose of climate research.

Design of biogeochemical sampling is at an early stage compared to physical sampling. The implementation plan identifies initial ideas for Indian Ocean observations, including repeat hydrographic sections, recently developed sensors on ships of opportunity, and biogeochemical sensors on the basin-scale mooring array and Argo floats.

Clearly, full implementation of IndOOS will require a well-coordinated, international effort of large magnitude. One or just a few nations cannot carry the full investment of resources. The implementation plan includes a set of principles that is meant to encourage broad international participation and rapid transition of measurements to societal benefit. Chief among the principles is the need to distributed data openly in a timely manner. There is a preference for communication of data in real time to make it available at climate analysis and prediction centers. This is essential to demonstrate the value of IndOOS and capture the potential societal benefits.

Development of an Indian Ocean Moored Buoy Array for Climate Studies

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1. Introduction
The Indian Ocean is unique among the three tropical ocean basins in that it is blocked at 25°N by the Asian land mass. Seasonal heating over this land mass sets the stage for dramatic monsoon wind reversals and intense summer rains over the Indian subcontinent and adjoining areas of Southeast Asia. Recurrence of these summer monsoon rains is critical to agricultural production that provides life-sustaining support for hundreds of millions of people in the region. The reversing monsoon winds also generate a unique system of currents unlike those observed in the tropical Atlantic and Pacific, which are under the influence of steadier trade winds. Blocked by Asia, these currents cannot export heat to the northern subtropics. The resulting oceanic thermal structure produces feedbacks to the overlying atmosphere that affect not only the monsoon circulation and rainfall patterns, but also weather and climate in remote parts of the globe through atmospheric teleconnections.

Despite the importance of the Indian Ocean in the regional and global climate system, it is the most poorly observed and least well understood of the three tropical oceans. To remedy this situation, the Indian Ocean Panel, sponsored by the Climate Variability and Predictability Program (CLIVAR) and the Global Ocean Observing System (GOOS), has developed a plan for systematic, sustained, and comprehensive in situ observations in the Indian Ocean to complement both present and planned space-based satellite measurements. The plan (available at http://eprints.soton.ac.uk/20357/01/IOP_Impl_Plan.pdf) describes the scientific rationale, design criteria and implementation strategies for each of the observing system components. These include Argo floats, drifting buoys, tide gauge stations, ship-of-opportunity expendable bathythermograph (XBT) lines, a basin scale moored buoy array, and specialized measurement programs for the Indonesian Throughflow and western boundary currents. India also maintains a regional national buoy program in the Bay of Bengal and Arabian Sea. The totality of these efforts is referred to as the Indian Ocean Observing System (IndOOS) (Meyers and Boscolo, this issue). This article focuses on specific issues related to design and implementation of the basin scale moored buoy array component of IndOOS.

2. Scientific Rationale and Design Goals
Mooring programs have been implemented in the Indian Ocean in the past as part of CLIVAR, the World Ocean Circulation Experiment (WOCE), the Joint Global Ocean Flux (JGOFS) experiment, and various national initiatives. In most cases though, these programs were relatively short term and/or focused on a particular region. Missing until recently was a plan for a coordinated, multi-national, basin-scale sustained mooring array like the Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) in the Pacific and the Pilot Research Moored Array in the Tropical Atlantic (PIRATA).

The CLIVAR/GOOS Indian Ocean Panel moored buoy array is designed to resolve the most energetic variations in the open ocean away from the western boundary. Like the Pacific TAO/TRITON array, it is intended to be marginally coherent in latitude and longitude for defining the evolution of large-scale intraseasonal-to-interannual wind, sea surface temperature (SST), upper-ocean temperature and salinity variations. It is essential for understanding the role of the ocean in variability related to the Madden-Julian Oscillation (MJO) and other high frequency phenomena, for understanding mixed-layer dynamics, and for understanding interactions between the ocean and atmosphere. The data will also support development of operational climate forecast models, weather and climate prediction, ocean-state estimation, reanalysis efforts, and satellite validation.

The array (Figure 1, page 15) consists of 39 surface moorings for measurement of temperature, salinity, mixed layer currents, and basic meteorological variables. Four subsurface Acoustic Doppler Current Profiler (ADCP) moorings are located along the equator where geostrophy breaks down and direct current measurements are necessary. A fifth ADCP mooring is also located in the upwelling zone off the Island of Java where the SST dipole/zonal mode first develops. This mooring is near the northern terminus of the frequently repeated XBT line IX1 between Australia and Indonesia. In addition to the 39 surface and 5 ADCP moorings, three subsurface moorings maintained by India's National Institute of Oceanography (NIO) along the equator at 77°E, 83°E, and 93°E are designed to monitor deep ocean currents.

The array is intended to cover the major regions of ocean–atmosphere interaction in the tropical Indian Ocean. These regions include the Arabian Sea, the Bay of Bengal, and the equatorial waveguide, where wind-forced intraseasonal and semi-annual current variation is prominent; the eastern and western poles of the Indian Ocean SST dipole/zonal mode; the thermocline ridge near 10°S, where wind-induced upwelling and Rossby waves in the thermocline affect SST; the southwestern tropical Indian Ocean, where ocean dynamics and air–sea interaction affect cyclone formation (Xie et al., 2002); and the southeastern basin where water masses are subducted into the upper pycnocline as part of the cross equatorial circulation cell between the subtropics and the tropics (Schott et al, 2004). Numerical model design studies have assessed the adequacy of the array to achieve its purposes in the context of other observing system components. Alternative sampling strategies have also been evaluated with the conclusion that the present array configuration is scientifically sound and cost-effective (Vecchi and Harrison, 2006; Oke and Schiller, 2006).

The entire array will contribute to the objectives of the OceanSITES program (http://www.oceansites.org/). In addition, eight specially enhanced flux reference sites will provide instrumentation to estimate all components of surface heat, moisture and momentum fluxes. These enhanced moorings are located in different climatic zones where climatologies are poorly known or where surface fluxes are critical for understanding climate variability (Yu et al, 2006).

3. Status of Implementation

The Japan Marine-Earth Science and Technology Agency (JAMSTEC) pioneered the deployment of long-term moorings for studies of ocean-atmosphere interactions in the Indian Ocean with an ADCP mooring at 0°, 90°E in 2000 (Masumoto et al, 2005) and two TRITON moorings at 1.5°S, 90°E and 5°S, 95°E in 2001 (Figure 2, page 15). Deep ocean subsurface moorings were also initiated by NIO in 2000 (Sengupta et al, 2004). These JAMSTEC and NIO moorings have been continuously maintained since then. In October-November 2004, NOAA's Pacific Marine Environmental Laboratory (PMEL) in collaboration with NIO and the Indian Department of Ocean Development (DOD) deployed 4 ATLAS moorings and 1 ADCP mooring between 80°-90°E from the Ocean Research Vessel Sagar Kanya. These five mooring sites were serviced and one additional site was initiated on a cruise of the Sagar Kanya in August-September 2006. PMEL is also working with Indonesian agencies to occupy two new locations at 4°N and 8°N along 90°E using the research vessel Baruna Jaya I in late 2006 or early 2007. The French research vessel Suroit will deploy an ATLAS mooring in the southwest Indian Ocean in January 2007. Discussions are underway between PMEL and the First Institute of Oceanography in China to jointly maintain the ADCP mooring off the coast of Java. The status of existing and planned sites for 2006-07 is shown in Figure 3 (page 15).

Securing adequate ship time to implement and sustain the array is a major issue. Making reasonable assumptions about ship speeds, carrying capacity, and ports of call around the Indian Ocean, it is estimated that a minimum of 142 days of ship time per year will be required to maintain the full array (Figure 4). This minimum assumes that cruises are dedicated only to mooring work and that other activities will not consume ship time. The minimum is likely to be exceeded, since research cruises in the region are generally multi-purpose.

A five-year implementation plan, ramping up from the current 11 sites to full implementation in 2010, is shown in Figure 4. The array will require multi-national support and a reliable, regular supply of ship time. The greatest impediment to implementation, assuming adequate financial resources and ship time can be found, is vandalism by fishing vessels. Fishing vandalism is not unique to the Indian Ocean as it also affects TAO/TRITON in the Pacific and PIRATA in the Atlantic. Unfortunately, the problem is already apparent in data and equipment losses at some of the active surface mooring sites in Figure 3.

4. Data Availability

ATLAS and TRITON mooring data are transmitted to shore in real-time via Service Argos satellite relay. Service Argos places a significant portion of these data on the Global Telecommunications System for worldwide dissemination in order to support operational climate analyses and forecasts. In addition, PMEL hosts a website where ATLAS and TRITON mooring data are freely available (http://www.pmel.noaa.gov/tao/disdel/). JAMSTEC maintains a website where TRITON mooring data are freely available (http://www.jamstec.go.jp/jamstec/TRITON/). NIO hosts a website for access to data from its deep ocean moorings (http://www.nio.org/data_info/deep-sea_mooring/oos-deep-sea-currentmeter-moorings.htm).

5. Coordination with Other Programs

The moored buoy array, in addition to being coordinated with other elements of the IndOOS, is capable of accommodating biogeochemical sensors to support programs such as the Surface Ocean Lower Atmosphere Study (SOLAS), the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER), and the International Ocean Carbon Coordination Project (IOCCP). In the wake of the Asian tsunami on 26 December 2004, discussions are also underway with organizations involved in developing the Indian Ocean tsunami warning system on how best to coordinate implementation efforts with IndOOS. It would be advantageous for example to coordinate IndOOS and tsunami mooring deployment cruises and to consider development of a multi-hazard moored buoy platform for both tsunami warnings and climate studies.

The CLIVAR/GOOS moored buoy array provides context for the development of process studies like the Mirai Indian Ocean cruise for the Study of the MJO convection Onset (MISMO; see Yoneyama et al, this issue) centered around 0°, 80°E in October-December 2006 and the French-lead VASCO-CIRENE (Duval and Vialard, 2006) project in the southwest Indian Ocean in January-February 2007. Both these process studies will examine ocean-atmosphere interactions associated with the MJO for which the high resolution moored time series data are especially valuable. VASCO-CIRENE also provides the opportunity to deploy a flux reference site mooring at 8°S, 67°E as an element of the sustained observing system. New knowledge gained from programs like MISMO and VASCO-CIRENE can feedback into design modifications to optimize the array for scientific purposes.

6. Concluding Remarks

The moored array component of IndOOS has been endorsed by CLIVAR and GOOS and is being implemented through multi-national cooperative efforts. Continued commitment of financial, human, and ship time resources from several nations

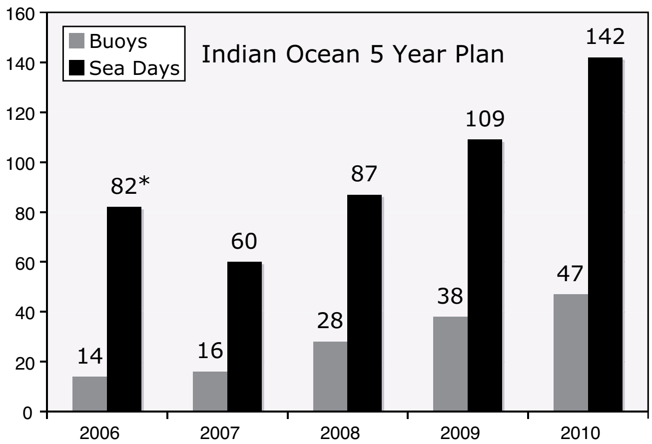

Figure 4. Implementation schedule and ship time requirements (in sea days) for establishing the moored buoy array. Ship time in 2006 (highlighted by an asterisk) is an estimate of the actual amount that will be used on mooring deployment cruises. Ship time estimates for 2007-2010 represent minimum requirements based on the assumption that cruises are dedicated solely to servicing to buoys of the array with ports of call around the Indian Ocean. In arriving at the 2007-2010 estimates, hypothetical cruise tracks were developed allowing for sufficient station time and assuming that ships typically cruise at 10 knot speeds

will be required to the fully establish this key element of the observing system over the next few years. Once completed, the array will significantly advance our understanding and ability to predict the monsoons and related climate phenomena in much the same way as TAO/TRITON and PIRATA have advanced studies of ENSO and Tropical Atlantic climate variability.

Acknowledgments

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Indian Moorings: Deep-sea current meter moorings in the Eastern Equatorial Indian Ocean

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1. Introduction

The Ministry of Ocean Development (MOD), Government of India, initiated the Ocean Observing System (OOS) programme in 1997 for long-term current measurements in the equatorial Indian Ocean. Under the OOS program, 3 locations at 93°E, 83°E and 76°E (Fig. 1) were selected along the equator for deploying the current meter moorings (Murty et al., 2002). The National Institute of Oceanography (NIO), Goa, took the responsibility of executing the project. This project started in 2002 after developing a suitable mooring design with current meters and relevant hardware. The designed I-type mooring is basically of subsurface mooring with 6 Recording Current Meters (RCMs) at six nominal depths of 100m, 300m, 500m, 1000m, 2000m and 4000m. The main objective of the project is to generate long-term time series of current data from the equatorial Indian Ocean to understand the dynamics of currents in the equatorial Indian Ocean in relation to climate variability and change. The depths of the RCMs were designed to obtain information on currents in the upper thermocline, main thermocline, intermediate, deeper and near-bottom depth ranges. The central and eastern equatorial Indian Ocean comes under the influence of the warm pool with the sea surface temperatures >28°C during most of the year (Vinayachandran and Shetye, 1991). McPhaden (1982) presented the analysis of the long-time series of current data obtained from a station near Gan Island in the equatorial Indian Ocean. Unnikrishnan et al. (1997) showed that the seasonal cycle of climatological temperature at 100 m depth in the tropical Indian Ocean is dominated by semi-annual variability in the equatorial region and annual variability elsewhere. Reppin et al. (1999) presented the analysis of time series current data from moored ADCP (Acoustic Doppler Current Profiler) and current meters at the equator and 80.5°E. Prasanna Kumar et al. (2005) in their analysis of high-resolution of Ocean General Circulation Model (OGCM) simulations showed strong seasonality (largest spatial extent during April–May, and least in December) in the time-evolution of the warm pool. These authors report that the upper ocean heat budget in the equatorial Indian Ocean is largely controlled by advection, rather than the net heat flux alone. From the theoretical considerations, Gent et al (1983) examined the semi-annual variation of zonal currents in the equatorial Indian Ocean. In this article, the authors present brief information on the Indian current meter moorings along the equator and some preliminary results.

2. Status of the data and methods of analysis

The first deep-sea current meter mooring was deployed successfully in February 2000 at the equator, 93°E on board ORV Sagar Kanya. This mooring was successfully recovered

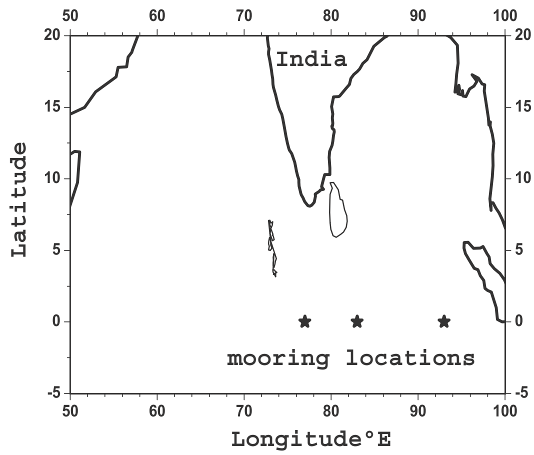

Figure 1. Study area and the locations of the Indian deep-sea current meter moorings in the equatorial Indian Ocean.

in December 2000 and data were obtained from all the RCMs. The mooring was redeployed and the second mooring was deployed at the equator, 83°E in December 2000. In March 2002, these two moorings were recovered and data were obtained. While redeploying these moorings at the same locations, a third mooring was deployed at the equator, 76°E. In October 2003, all the three moorings were recovered and redeployed for one more year, but the mooring at 76°E was shifted to 77°E. While deploying the mooring at 77°E, an upward-looking Acoustic Doppler Current Profiler (ADCP) was placed at 100 m depth on the top of the mooring. In October 2004, all the three moorings were recovered and deployed for another year. One upward-looking ADCP was placed at 100 m on top of each mooring. This project will continue till March 2007 with funding support from the MOD, and might be extended possibly for another 5 years through 2012. Though there is no human-vandalism for the moorings, we often found heaps of Tuna-fishing nets around the top current meter, particularly at the 93°E mooring location. The time-series currents data are available from the NIO website (http://www.nio.org/data_info/deep-sea_mooring/oos-deep-sea-currentmeter-moorings.htm) and are submitted to the Indian National Center for Ocean Information System (INCOIS), Hyderabad for display at INCOIS website. The moorings will be recovered in August – September 2006 and will be redeployed at the same locations for another year. Table 1 shows the status of the current data available as of July 2006.

In this article, the authors present some of the results obtained from the analysis of the time series current data from the Indian deep-sea current meter moorings. Both semi-diurnal and diurnal tides were removed from the time series of zonal (u) and meridional (v) current data using a 49 hour moving average. The residual time series data were used for spectral analysis (Murty et al., 2002; Emery and Thomson, 1997). The upward-looking ADCP (300 kHz, RD Instruments Make, USA) provided data of zonal (u) and meridional (v) current velocity and pressure (at the depth of the ADCP) in the upper 100 m. Due to mooring motion there were data gaps in the first top bins. The data were acquired at 15 minute intervals at 4m bins and all data were daily averaged to obtain the daily mean profiles of u and v for the period of September 2003 to October 2004.

3. Intraseasonal variability of measured currents

Murty et al. (2002) reported the first results of the Indian current meter moorings and described the variability of current structure at 93°E. They showed that there exists considerable meso-scale variability in the measured currents, comprising of intraseasonal oscillations of period 10-20 days and 30-50 day periods. Senguta et al. (2004) modelled successfully the observed biweekly mode (10-20 day period) variability in the equatorial Indian Ocean using an Ocean General Circulation Model (OGCM) forced by the daily averaged QuikSCAT surface winds. They demonstrated that the biweekly mode is due to the propagation of Mixed Rossby Gravity (MRG) waves generated by the intraseasonal winds over the equatorial Indian Ocean, and that the energy of bi-weekly wave intensifies eastward with depth. Sengupta et al. (2004) compared the simulated u and v components with those observed at 83°E and 93°E during 2000-2001. They reported that the biweekly wave has a wavelength of about 3000 km. Reppin et al. (1999) reported the spectral peak at 15 day period in the zonal component of velocity off the equator, 80.5°E and in the meridional velocity at the equator. Figure 2 shows the vertical structure of current vectors at six depths at the equator, 93°E during February 2000 – December 2004. It should be noted that the mean depths of the data are different in each deployment year (Table 1), and there are data gaps as the moorings' recovery was carried out after 13 to 15 months of deployment. Also some RCMs did not record the data due to loss of rotors. At this location, the vectors show considerable intraseasonal variability. Figure 3 (page 8) shows the long-term temporal variability of u and v at the uppermost depth of each mooring at the equator, 93°E during 2000-2004. The zonal velocity (top panel in Figure 3) shows the dominant seasonal variation superimposed with intraseasonal variation. Figure 3 also shows the dominant intraseasonal variability in the meridional velocity of period 10-20 day (bottom panel in Fig. 3) that has been compared well with model simulated meridional velocity (Sengupta et al. 2004). At the shallowest depth level of the RCM (e.g.., 2001-2003 and 2003-04 deployments at 93°E), the zonal velocity is eastward both during April-May and September-October, coinciding with the semi-annual occurrence of equatorial Wyrtki jets (Wyrtki, 1973). During winter and summer monsoon periods, the zonal velocity is towards the west along the equator. The upward-looking ADCP-obtained meridional velocity in the upper 100 m at 77°E also clearly shows a banded structure with change of velocity at intraseasonal period of 10-20 days (Figure 4 page 15).

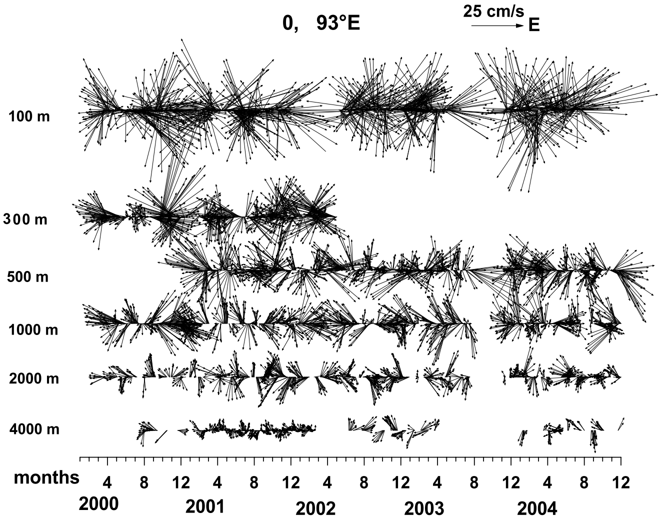

Figure 2. Long-term variability of current vectors at the nominal depths of the Indian deep-sea current meter mooring at the equator, 93°E during April 2000 – December 2004

Station No.	Mean depths of RCMs (obtained from Pressure sensors in each RCM)				
	2000	2000-02	2002-03	2003-04	2004-05
EQCM 1 [Equator, 93°E]	156, 290, 484, 991, 2004, 3995	139, 275, 470, 981, 1962, 3971	106, 344, 529, 1024, 2004, 4015	76, 312, 501, 996, 1981, 3991	To be recovered
EQCM 2 [Equator, 83°E]	----	ND, 397, 604, 1093, 2100, 4100	141, 342, 538, 1032, 2026, 4008	139, 339, 534, ND, 2022, 4000	To be recovered
EQCM 3 [Equator, 76°E]	----	----	418, 645, 821, 1314, 2311, 4122	----	----
EQCM 3A [Equator, 77°E]	----	----	-----	168, 389, 568, 1059, 2101, 4084	To be recovered

ND: No data available

Table 1. Mean depths of RCMs in the deep-sea current meter moorings during each deployment.

Each zonal velocity time series dataset is fitted with the semi-annual harmonics (thick curve in the top panel of Figure 3) obtained by the least square method. The phase of the semi-annual wave is referenced from January 1 for each time series. The amplitude of the semi-annual wave is large (14 cm/s) during the 2003-04 deployment when the mean depth of the RCM is as shallow as 106 m, and the amplitude decreases as the mean depth of the RCM increases. Table 2 presents the amplitude and phase of the semi-annual wave fitted to the time series of u and v components at 93°E, 83°E and 76°E.

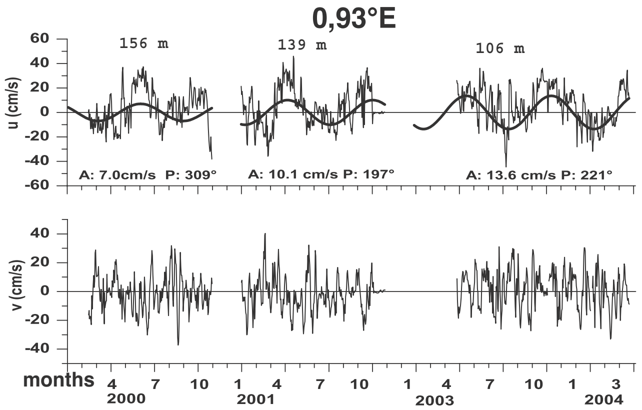

Figure 3. Long-term variability of zonal (top panel) and meridional (bottom panel) components of current velocity (cm/s) at the equator, 93°E during February 2000 – April 2004.

During the 2002-03 deployments at 83°E and 76°E locations, the amplitude of the semi-annual wave decreases with depth with highest amplitude of 29 cm/s at 141 m depth at 83°E and lowest amplitude of 10.2 cm/s at 1032 m at 83°E (Table 2). The amplitudes of the semi-annual wave are lower at the 93°E location (during all the 3 deployments), compared to those at the 83°E and 76°E locations. At the 83°E and 76°E locations, one can notice the upward increase of phase from about 800 m to towards surface, indicating the downward propagation of energy associated with the semi-annual wave. This upward phase propagation is clear at 93°E only during January – October 2001 deployment (Table 2). The amplitude and phases of the semi-annual wave fitted to the meridional velocity are also shown in Table 2. The amplitudes are in general smaller compared to the zonal velocity amplitudes, while the phases do not show any trend. The phase of the semi-annual wave fitted to the meridional velocity is almost constant for the 83°E deployment during 2002-03. For the deployment period of 2002-03, the zonal phase increased eastward from 186° at 83°E to 221° at 93°E at the uppermost depth level. This yields an eastward phase velocity of about 80 cm/s which is closer to the speed of the semi-annual Kelvin wave. The depth penetration of the semi-annual wave appears to be deeper at 76°E/77°E and 83°E locations and shallower at 93°E. Further observations and modeling studies are essential to understand this behavior of the semi-annual wave along the equator of the Indian Ocean.

The daily averaged time series of zonal and meridional velocity data at 76°E, 77°E, 83°E and 93°E locations were analysed using the Fast Fourier Transformation (FFT) technique (Emery and Thomson, 1997). Figure 5 shows the spectra of the zonal and meridional velocity at the topmost level respectively at 77°E, 83°E and 93°E from different deployment periods. The zonal velocity shows the dominant 170 day and 64 day periods at all the three locations, corresponding to the semi-annual period of Kelvin Wave and Madden-Julian oscillations respectively. The spectra for the meriodional velocity, however, show the dominant intraseasonal variability with periods between 15 and 24 day at the three locations. It may be noted that the spectra are shown for periods above 10 days.

4. Conclusions

The status of Indian deep-sea current meter moorings along the equator is presented along with the brief results. The observations showed the presence of intraseasonal variability of 10-20 day period. It is noticed that the semi-annual variability is dominant in the central equatorial Indian Ocean and penetrates to deeper depths, compared to that at 93°E. Further studies are being carried out to analyze the long-term measured current data with various model simulations to identify the variability associated with the Indian Ocean Dipole (Saji et al., 1999).

5. Acknowledgements

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Mooring duration	Mooring Location	Mean depth (m)	Zonal velocity (u) Amplitude (cm/s)	Zonal velocity (u) Phase	Meridional velocity (v) Amplitude (cm/s)	Meridional velocity (v) Phase
Jan/2000 – Dec/2000	93°E	156	7.0	309	3.5	22
		290	9.8	39	2.4	61
		991	4.6	108	1.4	20
Jan/2001 – Oct/2001	93°E	139	10.1	197	2.4	110
		275	6.7	22	1.1	86
		470	3.2	307	2.8	137
Apr/2002 – Mar/2003	93°E	106	13.6	221	1.5	290
Apr/2002 – Mar/2003	83°E	141	29.2	186	1.1	269
		342	13.2	76	2.1	245
		538	21.0	44	3.7	244
		1032	10.2	334	0.3	79
Aug/2002– Mar/2003	76°E	418	13.4	101	2.7	176
		645	17.7	97	2.5	159
		821	14.6	72	2.2	277

Table 2: The amplitude and phase of the semi-annual variation of zonal and meridional velocity at the mean depths of Recording Current Meters at 93°, 83° and 76°E during 2000-03 in the equatorial Indian Ocean. The phase is referenced from January 1.

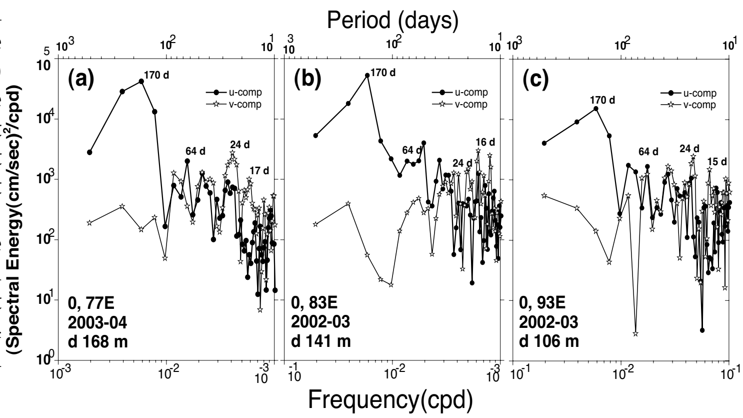

Figure 5. Spectra of zonal (filled circles) and meridional velocity (open stars) at the depths of uppermost Recording Current Meter (RCM) in the moorings at (a) 77°E, (b) 83°E and (c) 93°E. The mean-depth of RCM and the period of deployment are given in the figures. Spectra for periods below 10 days are not shown.

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MISMO : MIRAI Indian Ocean cruise for the Study of the MJO-convection Onset

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1. Introduction

The Madden-Julian Oscillation (MJO, Madden and Julian 1971, 1972) is known as dominant intraseasonal variability in the tropics. The MJO is an eastward propagating disturbance, occurring primarily during the boreal winter-spring season, with strong atmospheric convection which usually appears at first in the central-eastern equatorial Indian Ocean. Influences of the MJO spread not only within the tropical region but also to the atmospheric and oceanic conditions over the world through interactions with the monsoon (e.g., Yasunari 1979), El Niño (e.g., McPhaden 1999), tropical cyclones (e.g., Maloney and Hartmann 2001), and others. Although previous studies have revealed the various aspects of the MJO, so far there is no definitive explanation on the onset of the MJO convection over the Indian Ocean and associated upper-ocean variability.

As for the atmospheric convection itself, recent studies have suggested several key components that have to be clarified by observations. For example, Johnson et al. (1999) demonstrated the trimodal cloud distribution (cumulus, congestus, and cumulonimbus) in the tropics. In particular, it was shown that congestus clouds developed during the suppressed phase of the MJO moistened the mid-troposphere and preconditioned for the active phase with deep convection (Johnson et al. 1999, Kikuchi and Takayabu 2004). Furthermore, the large diurnal cycle in the sea surface temperature in a light wind condition seems to be crucial for the initiation of shallow cumuli and congestus clouds, suggesting the important role of coupling between the atmosphere and the upper ocean in the MJO-convection onset (Slingo et al. 2003). These studies suggest that fine-scale observation from the ocean surface to the entire troposphere is required for better understanding of MJO-convection. The TOGA COARE program in the tropical western Pacific during 1992 and 1993 (Webster and Lukas 1992) was one such observational effort. There are no intensive observations, however, in the Indian Ocean, though fine-scale observations are strongly desired for the study on the initiation of the MJO convection there.

For the upper-ocean variability in the central-eastern tropical Indian Ocean, it has been well known that a strong zonal jet and associated thermocline displacement appear twice a year during the monsoon transition periods (April-May, and October-November). These are known as the Wyrtki jets (Wyrtki 1973). Using current data from an ADCP mooring at 0°, 90°E, Masumoto et al. (2005), however, demonstrate that intraseasonal disturbances with the 30-50 days period dominate the zonal current in the eastern equatorial Indian Ocean. From their coherence analysis, the intraseasonal variability of zonal currents is considered to be induced by the wind stress between 80°E and 90°E at the periods of 30-50 days. However, details of generation mechanisms for the intraseasonal variability remain unsolved. Thus, it is important to obtain fine resolution data sets to reveal the air-sea interaction processes at the intraseasonal time scale. The data will also be able to be used for validating numerical models and satellite observations, and in turn the models will help in understanding the complex physical processes.

Based on these recent areas of progress, an observational cruise by the R/V Mirai named as MISMO (Mirai Indian Ocean cruise for the Study of the MJO-convection Onset), has been designed to conduct the needed intensive atmospheric and oceanic observations. In the following sections, basic information on the MISMO project will be briefly described.

2. Objectives

The aim of MISMO is to reveal the atmospheric and oceanic features of the central-eastern equatorial Indian Ocean in November, where and when the convection in the MJO is often initiated. Special emphases are put on the following issues:

a. *Vertical structure of the atmosphere*
- Moisture convergence in the lower troposphere
- Variation of vertical profile of atmospheric parameters such as water vapor, divergence field, and clouds
- Development of cumulus convection

b. *Role of the air-sea interaction*
- Diurnal cycle of SST and its difference in behavior before/after the onset of the MJO
- Variation of ocean surface heat flux

c. *Oceanic responses to the MJO*
- Variation of ocean surface currents accompanied with westerly wind bursts
- Evaluation of warm water and salinity transports

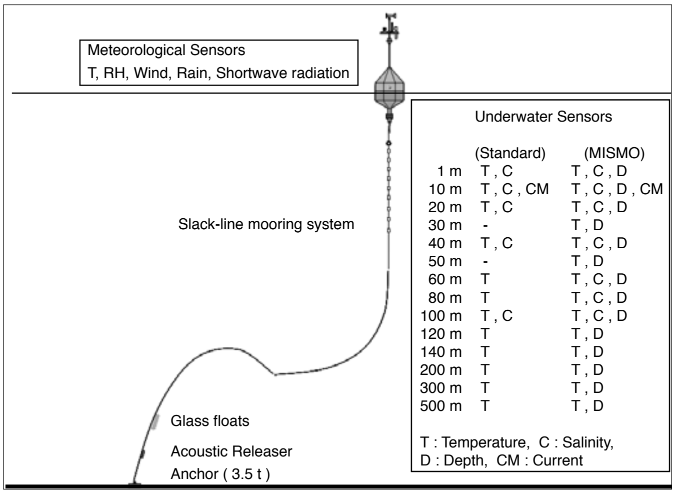

Figure 2.Basic configuration of the small-size-TRITON buoy. A few more depth sensors will be added as standard.

- Heat budget in the upper-ocean mixed layer

3. Observations

Based on previous studies on the dominant season and location of convective activity in the MJO (e.g., Kemball-Cook and Weare 2001, Zhang and Dong 2004), the intensive observation period and sites will be in October/November and around 80.5°E on the equator, where an ATLAS buoy has been deployed as the intensive flux site by PMEL/NOAA. A proposed observation network during the MISMO is shown in figure 1 (page 16), while a brief summary is as follows.

3.1 R/V Mirai

The main missions of the R/V Mirai are to conduct intensive observations around (0, 80.5°E) for one month and to deploy a mooring buoy array. Since many institutes have been approved to join the cruise through the public invitation process in addition to JAMSTEC and their cooperative institutes, various observations will be carried out during the cruise. Observation items and participating institutes are summarized in Tables 1 and 2.

3.2 Mooring buoy array

A buoy array, consisting of surface and sub-surface moorings, is a major part of the experiment, as it will provide basic upper-ocean conditions as well as ocean surface fluxes. During the MISMO period, newly designed two small-size-TRITON buoys (Fig. 2) will be deployed at (0°, 79°E) and (0°, 82°E), and four sub-surface ADCP moorings will be deployed at (0°, 79°E), (0°, 82°E), (1.5°N, 80.5°E), and (1.5°S, 80.5°E). In addition to these one-month-long moorings, three ATLAS buoys at (1.5°N, 80.5°E), (0°, 80.5°E), (1.5°S, 80.5°E) and a sub-surface ADCP mooring will be replaced before the MISMO cruise by PMEL/NOAA and NIO. The squared buoy array will enable us to calculate the surface heat flux, warm water convergence/divergence, and, hence, the heat budget in the upper ocean.

3.3 Argo floats

In addition to the standard Argo float 10-day interval sampling from 2000m depth, ten specially programmed Argo floats, which park at 500 m depth and sample once a day, will be deployed along the 80°E line from 8°S to 3°N, to capture the oceanic response to the MJO.

3.4 Land-based sites

To construct the large-scale atmospheric flux array, meteorological measurements will be carried out at three islands, Gan (0.7°S, 73.2°E), Kadhdhoo (1.9°N, 73.5°E) and Hulhule (4.2°N, 73.5°E), in the Republic of Maldives under the cooperation with the Department of Meteorology, Maldives. In addition to the standard surface meteorological measurements, radiosonde observations (2 or 4 times / day) will be conducted at Gan and Hulhule Islands. Furthermore, Doppler radar will be operated at Gan Island.

4. Schedule

The planned schedule of the MISMO cruise (Leg-1 and Leg-2) is as follows. These dates may be subject to change due to various reasons such as weather conditions.

a. *Year 2006*
- Oct. 4, Depart Sekinehama, Japan
- Oct. 15 – 16, Call at Singapore
- Leg-1, Deployment of ADCP moorings, small-size-TRITON buoys, and Argo floats
- Oct. 26 - Nov. 24, Stationary intensive observations at (0, 80.5°E)
- Recovery of ADCP moorings and small-size-TRITON buoys
- Nov. 27 – 28, Call at Male, Maldives
- Leg-2, Recovery/Deployment of TRITON, small-size-TRITON, and ADCP in the Indian Ocean
- Dec. 13 – 14, Call at Singapore
- Leg-3, Recovery / Deployment of TRITON in the western Pacific Ocean

b. *Year 2007*
- Jan. 16, Arrive at Sekinehama, Japan

5. Concluding remarks

Table 1. Measurement systems on-board the R/V MIRAI

INSTRUMENTS	PARAMETERS
5.3-GHz scanning Doppler radar	3-d reflectivity and Doppler velocity
Radiosonde	temperature, humidity, and wind (8 times/day during IOP)
Ceilometer	cloud base height
Total sky imager	cloud images/fraction in daytime
Surface meteorological station	pressure, air/sea temperature, humidity, wind, rain, radiation
Infrared SST Autonomous Radiometer	skin sea surface temperature
Turbulent flux measurement system	surface turbulent flux of momentum and latent/sensible heat
Wind profiler	vertical wind profile in the lower troposphere
Mie Scattering Lidar	vertical profiles of aerosols and clouds
95-GHz Cloud radar	vertical profiles of clouds and rain
Sky radiometer	solar radiation (optical thickness)
Videosonde	images of precipitation and cloud particles within clouds
Radiosonde with hygrometer/ozone sensor	vertical profile of water vapor and ozone
Rain sampler	rain sampling for stable isotope measurement
Surface water monitoring system	sea surface temperature, salinity, DO, chlorophyll, and pCO2
75-kHz Acoustic Doppler Current Profiler	current vector profile in the upper ocean
CTD with water sampler and fluorometer	vertical profile of temperature, salinity, DO, chlorophyll, pH and nutrients (4-8 times /day during IOP

Table 2. Participating institutes for the R/V Mirai cruises

JAPAN	JAMSTEC National Institute for Environmental Studies Hokkaido Univ. Tohoku Univ. Kyoto Univ. Toyama Univ. Osaka Prefecture Univ. Okayama Univ. Yamaguchi Univ. Global Ocean Development Inc. Marine Works Japan Ltd.
U. S.	Univ. of Miami RMR Co. International Pacific Research Center
INDIA	National Institute of Oceanography

During the one-month intensive observation period of MISMO, various atmospheric and oceanic measurements will be carried out at the stationary site and the nearby regions. The data obtained may add new insights to the MJO related variability in both the atmosphere and the ocean and they will be open to the scientific community within a certain period (one or two years). Further information and updates of this experiment can be found at the MISMO web site at http://www.jamstec.go.jp/iorgc/mismo/

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The first 1.5 years of INSTANT data reveal the complexities of the Indonesian Throughflow

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The major ocean basins are connected by passages of varied widths and depths. These passages allow for interocean exchange of water properties, which tend to reduce, though not remove, the thermohaline differences between the oceans. Such interocean exchange influences the heat and freshwater budgets of each ocean basin and in so doing represents an important part of the climate system. Most of the interocean exchange routes are at high latitudes, allowing for the establishment of the Antarctic Circumpolar Current and for low salinity surface water flow into the Arctic Sea by way of the Bering Strait. At mid-latitudes there is leakage of subtropical Indian Ocean thermocline water into the South Atlantic around the southern rim of Africa. The Indonesian seas alone allow for an interocean exchange of tropical waters in what is referred to as the Indonesian Throughflow (ITF): a transfer of warm, relatively low salinity Pacific waters into the Indian Ocean. The ITF affects both oceans, though perhaps more so the thermohaline stratification of the smaller Indian Ocean. While the literature of the last 45 years offers a very wide range of annual mean transport values for the ITF, from near zero to 25 x 10^6 m^3/sec, the more recent estimates narrow the range to 10 ± 5 x 10^6 m^3/sec with large seasonal and intraseasonal variability (Wijffels and Meyers, 2002; Gordon, 2005).

The ITF stream is fed from the North Pacific thermocline waters, though within the lower thermocline and deeper levels the waters are drawn directly from the South Pacific. The primary inflow passage is Makassar Strait, with the Lifamatola Passage east of Sulawesi the dominant deep-water route. During residence in the Indonesian seas the inflowing Pacific stratification is modified by mixing, with energy derived from dissipation of the powerful tidal currents within the rugged sea floor topography, and by buoyancy flux across the sea-air interface. This results in a unique Indonesian tropical stratification—one of a strong, though relatively isohaline, thermocline. The Indonesian water is exported into the Indian Ocean via the three major passages within the Sunda archipelago: Timor Passage, Ombai Strait and Lombok Strait. The waters of the ITF are apparent within the thermocline as a cool, low-salinity streak across the Indian Ocean near 12°S (Gordon, 2005) and at intermediate depths as a band of high silicate (Talley and Sprintall, 2005). These ITF waters have no choice but to exit the Indian Ocean within the poleward-flowing western boundary Agulhas Current, though not before mixing and recirculating with ambient Indian Ocean thermocline water and interacting with the monsoonal atmosphere. The ITF acts to flush the Indian Ocean thermocline waters to the south by boosting transport of the Agulhas Current, increasing both the southward ocean heat flux across 20-30°S and the sea-air heat fluxes within the Agulhas Retroflection, over the no-ITF condition (Gordon, 2005).

The ITF is a fundamental component of the climate system and affects the marine ecosystems of the Indonesian seas, yet it is poorly observed and simulated in ocean and climate models. The main throughflow passages have been monitored but over different years and for varied lengths of time, making it impossible to assemble a simultaneous picture of the multiple corridors of the ITF. The International Nusantara Stratification and Transport (INSTANT) program (Sprintall et al, 2004) will do much to develop a far more quantitative appreciation of the Throughflow phenomena. INSTANT is a multi-national (Indonesia, United States; Australia, The Netherlands, France) program to measure the velocity, temperature and salinity of the Indonesian Throughflow within all of the primary inflow and outflow passages simultaneously (Fig. 1, page 16), a feat never before accomplished.

The objectives of INSTANT are: 1. To determine the full depth velocity and property structure of the Throughflow and its associated heat and freshwater flux; 2. To resolve the annual, seasonal and intraseasonal characteristics of the ITF transport and properties; 3. To investigate the storage and modification of the ITF waters within the internal Indonesian seas, from their Pacific source characteristics to the Indonesian Throughflow water exported into the Indian Ocean; and 4. Contribute to the design of a cost-effective, long-term monitoring strategy for the ITF.

The initial deployment of ten INSTANT moorings was in December 2003 to January 2004 (the 11th, an Ombai mooring, was deployed in August 2003). Approximately 1.5 years later, in June/July 2005, the moorings were recovered and redeployed to acquire an additional 1.5 years of data. The final recovery is scheduled for November/December 2006. A glimpse of the first 1.5 years of INSTANT data is afforded with a composite view of the de-tided along channel speeds for a select mooring and depths within each passage (Fig. 2, page 16).

The along-channel flow within various depth intervals reveals much variability across a wide range of temporal scales, marked with month long periods of significant imbalance between the inflow and export implying substantial convergence and divergence within the interior seas. Makassar Strait along channel speeds are relatively large, with a velocity maximum near 140 m. The southward thermocline speeds are greater towards the latter half of the southeast and northwest monsoons. The estimated Makassar transport is 8 to 9 Sv, about the same or maybe a bit larger than that observed in 1997 during the Arlindo program (Susanto and Gordon, 2005). The highest speeds within the deep water, shown on the >700 m panel of Fig. 2, are in Lifamatola Passage at a current meter ~300 m above the sill depth of ~1940-m. There speeds as high as 0.5 m/sec mark the overflow and descent of Pacific water into the depths of the Seram and Banda Seas. Lombok and Ombai are particularly rich in intraseasonal fluctuations; Makassar and Timor are fairly steady in comparison. Flow into the Indonesian seas is observed within the Lombok and Ombai Straits in late May 2004: a likely cause is a downwelling coastally trapped Kelvin wave propagating eastward along the archipelago as a consequence of a Wyrtki Jet in the equatorial Indian Ocean as was also observed in December 1995 (Molcard et al, 2001) and in May 1997 (Sprintall, et al., 2000). There is a hint of its presence at the Makassar Strait, with a similar 5 day delay as observed in Ombai after northward flows appear in Lombok. In the 350-450 m interval the Makassar flow exhibits the strongest Indian Ocean bound flow, but is matched by westward flow within Ombai within two periods, June-September 2004 and December 2004 to February 2005, coinciding with the peak times of the two monsoon phases.

The first 1.5 years if INSTANT measurements coincide with a weak El Niño, but since the redeployment a weak La Niña phase has ensued. As the ITF is thought to be reduced in El Niño and increased during La Niña, it will be interesting to compare the first 1.5 year record with the final 1.5 year record (though the swing in ENSO phase may not be sufficient to impact of the ITF transport).

Analysis of the INSTANT data in addressing the objectives listed above is a challenge we savor. Each time series is information rich and comparing and interpreting the phase differences between the passages and their varied spectra is an exciting prospect. In particular, comparison of these observations to model results will be a most challenging and interesting exercise. We all look forward to acquiring the full 3 year INSTANT record.

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From Xie et al, next page.

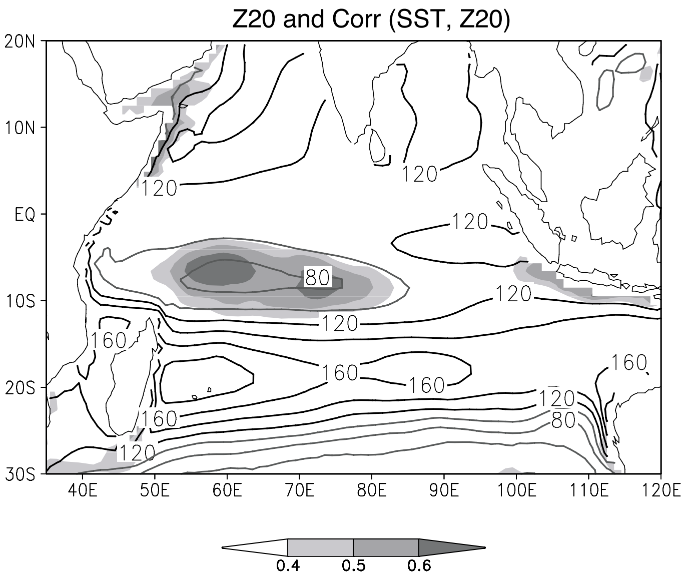

Fig. 1. Annual-mean depth of the 20°C isotherm (Z20; contours in m), and correlation between SST and Z20. From Xie et al. (2002).

Thermocline dome and climate variability over the tropical South Indian Ocean

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1. Thermocline dome

This article discusses the recent progress in studying intraseasonal to interannual variability over the South Indian Ocean. The southwest tropical Indian Ocean emerges as a region important for climate variability with high predictability owing to a unique thermocline dome. The dome is centered around 8°S in response to the Ekman pumping between the southeast trades to the south and weak equatorial westerlies to the north. The shallow thermocline in the dome enables subsurface variability to affect sea surface temperature (SST), as manifested by their high cross-correlation (Fig. 1, page 11). In fact, this thermocline feedback is so strong that Klein et al. (1999) "were unable to match SST anomalies in the southwestern Indian Ocean to any local anomalies in cloud cover or latent heat flux". The collocation of the mean thermocline dome with the Indian Ocean intertropical convergence zone (ITCZ) suggests that the resultant SST anomalies further influence atmospheric convection. Their collocation is also critical to the formation of the thermocline dome as the intense latent heat release in the Indian Ocean ITCZ generates positive vorticity in the lower troposphere, maintaining an Ekman pumping south of the equator.

2. Interannual Rossby waves

Basin-scale ocean Rossby waves of large amplitudes are observed in the tropical South Indian Ocean (Masumoto and Meyers 1998) in response to El Nino/Southern Oscillation (ENSO) and/or the Indian Ocean dipole (IOD). Propagating into the thermocline dome in the western half of the basin, these subsurface waves induce SST anomalies. Figure 2 shows correlations of Indian Ocean thermocline depth and SST anomalies with an El Nino index. Toward the El Nino's mature phase (December), wind anomalies in the eastern half of the tropical Indian Ocean excite downwelling Rossby waves in the ocean with characteristic westward propagation. Anomalous winds are easterly on the equator, lifting the thermocline in the east on the equator and on the eastern boundary. Embedded in a basin-wide warming that peaks in February-April following the El Nino, SST anomalies display a positive core that co-propagates with the ocean Rossby waves. These Rossby wave-induced SST anomalies increase local precipitation and tropical cyclone activity, and are collocated with a cyclonic anomalous circulation in the lower troposphere (Xie et al. 2002). Thus, ocean subsurface waves produce a strong response in SST, precipitation, and atmospheric circulation over the thermocline dome. Such atmospheric response to Rossby wave-induced SST anomalies has recently been reproduced in an atmospheric general circulation model (GCM); Annamalai et al. 2005.

While earlier studies emphasize the forcing by ENSO, recent partial correlation analyses indicate that the forcing mechanisms for Rossby waves in the tropical Indian Ocean may vary in latitude. Rao and Behera. (2005) and Yu et al. (2005) show that the IOD and ENSO are the major Rossby wave forcing north and south of 10°S, respectively. Yu et al. (2005) suggest that this variation in Rossby wave forcing is due to the differences in the meridional scale of wind anomalies associated with the IOD and ENSO. The former wind anomalies are more narrowly trapped near the equator than the latter, forcing near-equatorial Rossby waves.

The transit time for these ocean waves across the basin is about one year (Fig. 2), a delay that gives rise to enhanced predictability in a broad region over the tropical South Indian Ocean. Recent seasonal forecast experiments (e.g., Luo et al. 2005) identify the tropical South Indian Ocean as a region of high skills as measured by correlation between the forecast and observations. Figure 3a shows the skills at nine-month lead in the tropical South Indian Ocean of Luo et al.'s (2005) dynamical forecast system based on a fully coupled GCM. Useful skill scores (say, correlation > 0.5) are found across the basin during February-May, and persist in the western basin as late as August. Using the persistence as a baseline, we evaluate the benefits of using a dynamical forecast system. The dynamical system increases the forecast skills over most of the region (Fig. 3b) partly due to an improved ENSO forecast compared to persistence. In the tropical South Indian Ocean, the skill improvements peak in the central basin during February-April and then show a tendency of westward propagation that is characteristics of ocean Rossby waves in Figure 2. Thus, the slow propagation of remotely forced Rossby waves is an important source of predictability.

Modeling the South Indian Ocean Rossby waves and their effects on SST and atmospheric variability remains a challenge. In 17 coupled GCMs submitted for the IPCC fourth assessment report, only a few simulate the ENSO-forced Rossby waves and even fewer capture the co-propagating SST anomalies (Saji et al. 2006a). Forced with observed SST in the tropical Pacific, Huang and Shukla (2006) show that in their coupled model of the Indian Ocean, ENSO-forced Rossby waves exert a discernible influence on SST and the atmosphere as late as during June-August in the year after ENSO peaks. The failure of most IPCC models to simulate this Rossby wave effect may be due to the poor simulation of ENSO, its teleconnection, or the thermocline dome in the South Indian Ocean. This contrasts with the general success of these models in simulating the mean state of the equatorial Indian Ocean, the IOD, and its relationship with ENSO (Saji et al. 2006a).

3. Intraseasonal variability

Nearly free of cloud interference, the Tropical Rain Measuring Mission (TRMM) satellite's microwave imager (TMI) improves the spatio-temporal sampling of SST observations dramatically over the cloudy tropical Indian Ocean. TMI observations reveal, previously unknown, large intraseasonal SST variability over the tropical South Indian Ocean (Harrison and Vecchi 2001). These intraseasonal anomalies of SST are nearly zonally uniform and occasionally exceed 3°C in range over a large area (Fig. 4a, page 17). They are preceded by increased atmospheric convective activity and westerly wind anomalies. Analysis of multi-year TMI observations indicates that such intraseasonal SST variability is most pronounced in the tropical South Indian Ocean between 10°S and 5°S over the thermocline dome/ridge, and peaks in December-March (Fig. 4a) when the ITCZ is overhead and the mean wind is westerly (Saji et al. 2006b). Thus the decreased solar radiation and intensified westerly winds associated with increased convection both work in the same direction to reduce SST over the region of a shallow thermocline. Based on an ocean GCM study, Duvel et al. (2004) suggest that solar radiation and latent heat flux variability contribute about

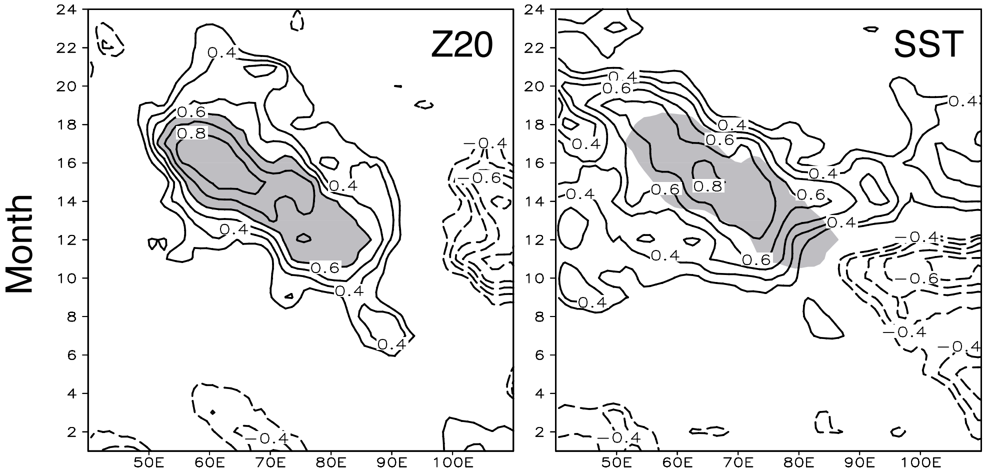

Fig. 2. Correlation of the depth of the 20°C isotherm (Z20) and SST in the Indian Ocean, both averaged over 12-8°S, with October-December (months 10-12) eastern Pacific SST as a function of longitude and calendar month.

equally to intraseasonal cooling events in 1999 while horizontal advection and mixing with thermocline water are secondary in importance. Horizontal advection is small because background SST gradients are weak during December-March on and south of the equator in the tropical Indian Ocean. Recent observations using Argo floats reveal large variability in the mixed layer depth, which is negatively correlated with the intraseasonal SST anomalies over the tropical South Indian Ocean (W. Yu, pers. comm.).

During November-April, the Madden-Julian Oscillation (MJO), considered to be an intrinsic mode of atmospheric convection and circulation, displays pronounced eastward propagation along the equator, especially in the Indo-western Pacific sector. The fact that atmospheric anomalies lead those of SST indicates the importance of atmospheric forcing (by wind and surface radiation). An important question is whether intraseasonal SST anomalies feed back onto the atmospheric MJO at all. The power spectrum of outgoing longwave radiation (OLR) suggests two modes of OLR variability (Fig. 4b, page 17): the equatorial mode centered on the equator with periods of 30-50 days, and a lower-frequency southern mode with large power between 10°S and the equator and periods longer than 50 days. Noting that the southern mode displays higher coherence with SST in the tropical South Indian Ocean, Saji et al. (2006b) suggest that the interaction with the ocean may have slowed down the timescale of the southern mode and displaced its center toward the Southern Hemisphere where the thermocline is shallow and SST variability is large. More research is necessary to clarify the mechanisms for intraseasonal SST variability, and its role in modulating the atmospheric MJO.

4. Conclusions

The doming thermocline in the South Indian Ocean makes SST there sensitive to subsurface variability and atmospheric forcing. On interannual timescales, remotely forced ocean Rossby waves induce SST anomalies over the southwest Indian Ocean dome, affecting precipitation and atmospheric circulation. The slow propagation of ocean Rossby waves gives rise to considerable predictability of SST anomalies up to nine-month lead. On intraseasonal timescales, SST variability is high again over the shallow thermocline in the South Indian Ocean during December-March when the ITCZ moves overhead.

Few in-situ observations exist in the tropical South Indian Ocean. The planned CIRENE field experiment in early 2007 is very timely to observe intraseasonal variability in the ocean and atmosphere as well as the processes by which subsurface anomalies influence SST over the thermocline dome. The formation of the barrier layer under the ITCZ and surface heat flux, for example, are likely important for intraseasonal SST variability.

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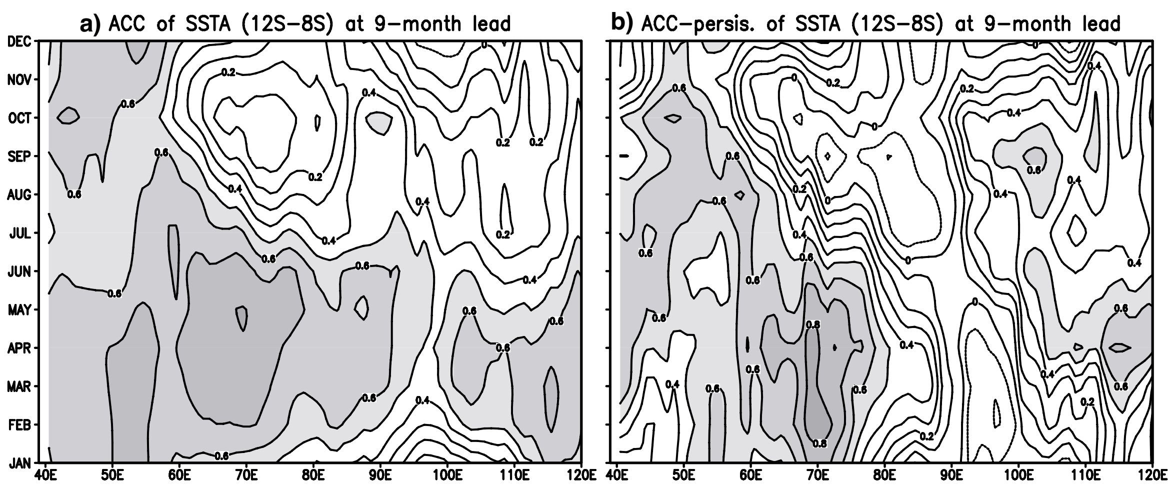

Fig. 3. (a) Skills of SST forecast at nine-month lead in the Luo et al. (2005) model as measured by correlation between observations and forecast for a 23-year period of 1982-2004. (b) Skill differences from the persistence.

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The Active Role of South West Indian Ocean

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1. Introduction

During an El Niño event, the tropical Indian Ocean, witnesses a basin-wide warming in boreal winter (January – March) with a local maximum over southwest Indian Ocean (SWIO; 15°S-0°, 50°-80°E). These regional SST anomalies (Fig. 1a, page 17) peak in spring and persist into early summer. Xie et al. (2002). Huang and Kinter (2002) demonstrated that much of SWIO SST variability is not locally forced but is due instead to oceanic Rossby waves that propagate from the east. More details on the role of ocean dynamics causing SWIO SST variations are available in Xie (this issue). The present article summarizes the author's recent research that explored the possible role of SWIO SST on: (a) the intensity of convective anomalies over the tropical West Pacific – Maritime Continent and East Asian Winter Monsoon (EAWM), (b) the onset of the Indian Summer Monsoon (ISM), and (c) the intensity of the circulation anomalies over the Pacific-North American (PNA) region.

During the boreal winters of El Niño years, negative convective anomalies over the tropical West Pacific – Maritime Continent force an anticyclone in the lower atmosphere over the South China Sea – Philippine Sea region that in-turn influences the EAWM (Wang et al. 2000). Using different atmospheric general circulation models (AGCMs), Wang et al. (2000) and Lau and Nath (2000) showed that the Philippine Sea anticyclone is forced by El Niño. These AGCM studies, however, did not consider the effect of SWIO SST anomalies. Forcing a linear model with Indian Ocean SST anomalies, Watanabe and Jin (2003) noted that an increase in precipitation over the western Indian Ocean is accompanied with a precipitation decrease over the tropical West Pacific, an encouraging result that needs to be verified with AGCMs.

In their correlation analysis between the ISM onset date and SST anomalies in the preceding winter and spring, Joseph et al. (1994) identified significant positive correlations with SST over SWIO. Based on this observational result, they proposed that SWIO SST anomalies could cause the interannual variability of the ISM onset through affecting the timing of the northwestward movement of the equatorial convective maximum, a hypothesis to be tested with AGCMs. Since the effect of oceanic Rossby waves on SWIO SST variations is felt in early summer, we expect for an active role of these spatially well-organized SST anomalies (Fig. 1a) on the ISM onset.

One of the outstanding issues in the tropical-extratropical linkage is to understand if the SST anomalies beyond the equatorial central-eastern Pacific feed back onto the PNA pattern (Kumar and Hoerling 1998). Using an NCEP AGCM, Barsugli and Sardeshmukh (2002) pointed out that there is a nodal line in the sensitivity at about 100°E longitude, with warm SST anomalies in the Indian Ocean resulting in a negative value of the PNA index. On noting low correlation between basin-wide indices of Indian Ocean SST and precipitation some AGCM studies (Kumar and Hoerling 1998) have disallowed the Indian Ocean as a source of predictability.

The motivation for the present research stems from two aspects: (i) SWIO SST anomalies are forced by ocean dynamics, and (ii) significant local SST-precipitation association exists there. Since these SST anomalies co-occur with those in the tropical Pacific it is difficult to quantify their effects separately from observations. However, experiments with a realistic AGCM forced with SST anomalies in each ocean basin (Fig. 1a) offer a means to separate their effects. By performing multi-member ensemble simulations with ECHAM5 AGCM the sensitivity of SWIO SST anomalies on the above aspects of the climate system is tested by comparing and contrasting model solutions in which SST anomalies for combined (Tropical Indo-Pacific: TIP), and individual (Tropical Pacific Only – TPO; Tropical Indian Ocean – TIO) oceans are prescribed as boundary forcing. Here, we highlight the salient results but more details are available in Annamalai et al. (2005; 2006).

2. Results

2.1 Convective anomalies over the tropical West Pacific – Maritime Continent and EAWM:

Figure 1b shows the simulated precipitation anomalies from TIO integrations. One notes an increased precipitation over the western Indian Ocean is accompanied with a substantial decrease in precipitation (4-5 mm/day) over the TWP – Maritime Continent. The interpretation for this notable difference is that in the TIO solutions warm SST anomalies increase the convection over SWIO and the resultant heat source forces low-level (upper-level) easterly (westerly) wind anomalies

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From McPhaden et al, Page 3: Development of an Indian Ocean Moored Buoy Array for Climate Studies

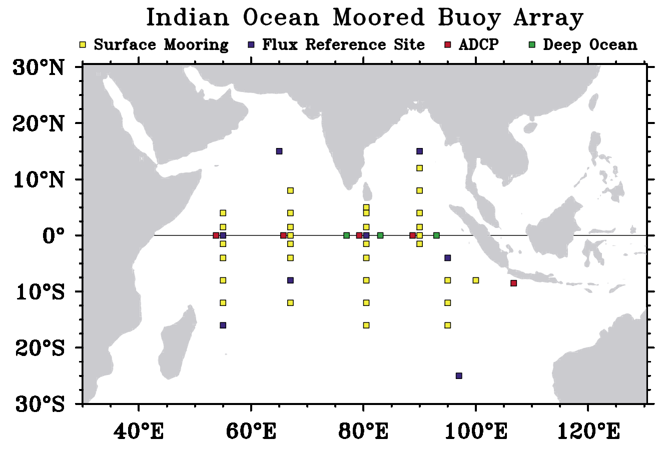


Figure 1. Plan for an Indian Ocean moored buoy array as part of a sustained and integrated ocean observing system.

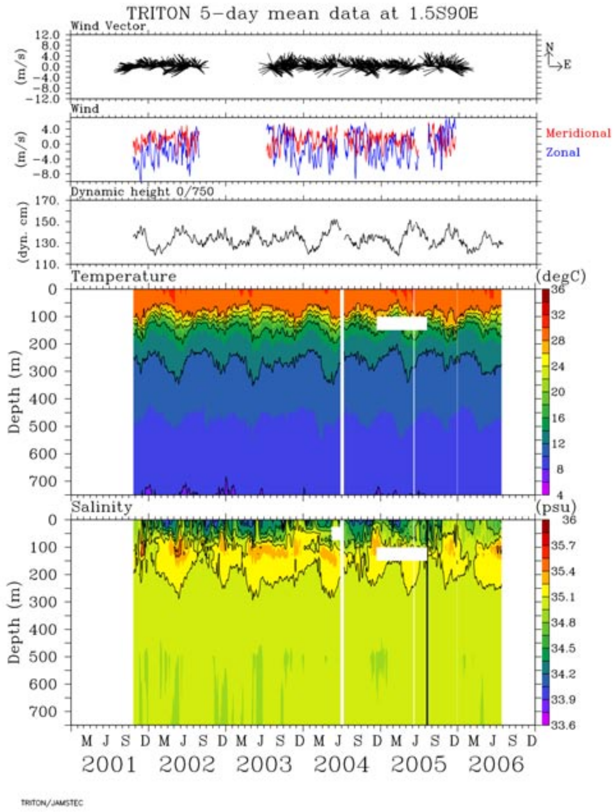


Figure 2. TRITON time series at 1.5°S, 90°E for the period October 2001 to July 2006. Five-day averages of vector surface winds, wind components, dynamic height, upper ocean temperature and salinity are shown

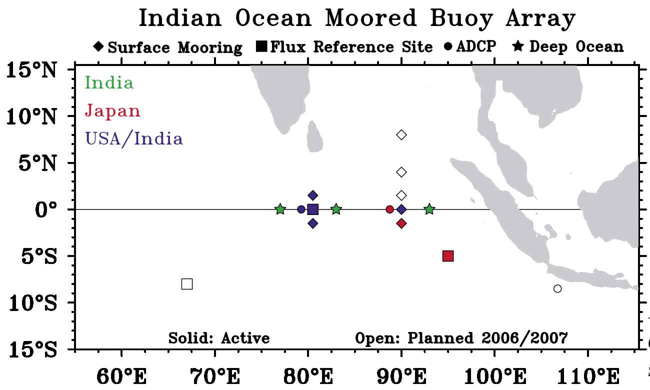
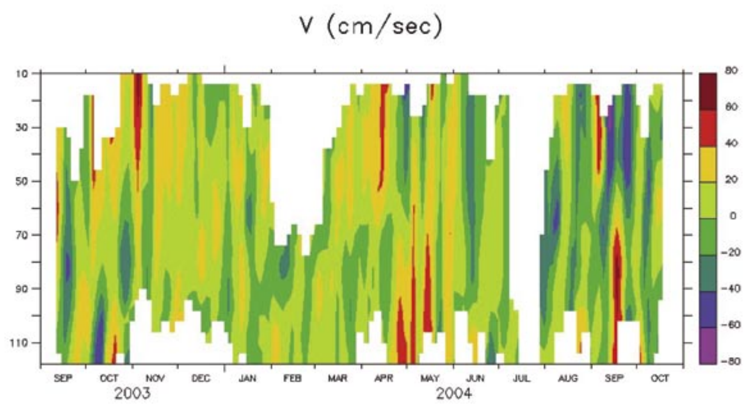


Figure 3. Status of the moored buoy array in 2006-07. Existing sites as of 1 August 2006 are shown as solid symbols and planned sites as open symbols. The planned sites along 90°E should be deployed in the latter half of 2006; the sites off Java and at 8°S, 67°E should be deployed in 2007.

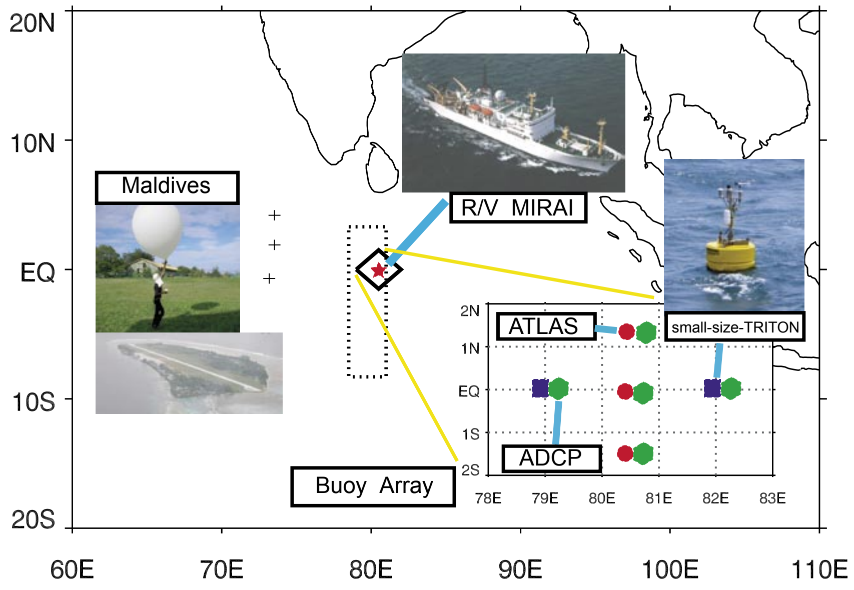
From Murty et al, page 5: Indian Moorings: Deap-sea current meter moorings in the Eastern Equatorial Indian Ocean.

Figure 4. Depth-time structure of ADCP measured meridional velocity (cm/s) in the upper 120 m at the equator, 77°E during September 2003 – October 2004.



From Yoneyama et al, page 8: MISMO : MIRAI Indian Ocean cruise for the Study of the MJO-convection Onset

Figure 1.Observation network for MISMO. Argo floats will be deployed within dotted rectangle. Stationary observations at (0, 80.5°E) will be conducted from Oct. 26 to Nov. 24, 2006.



From Gordon et al, page 10: The first 1.5 years of INSTANT data reveal the complexities of the Indonesian Throughflow

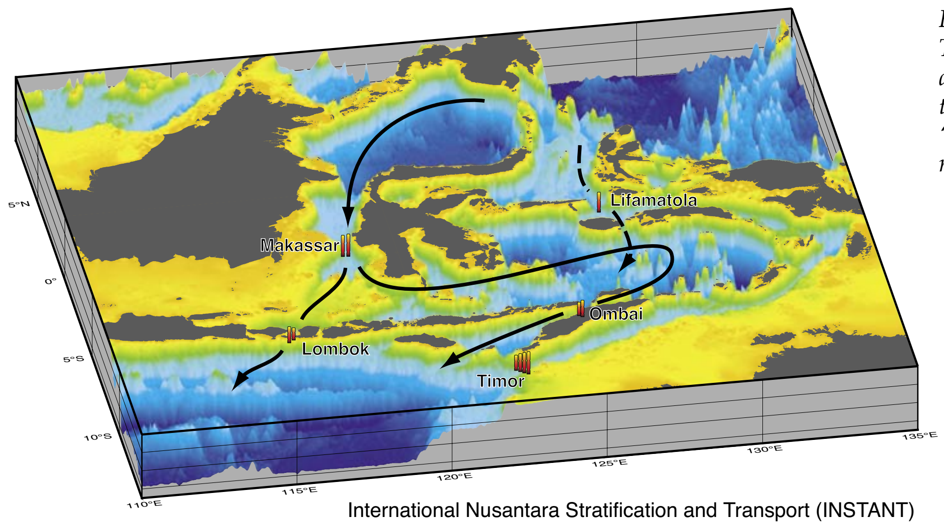


Figure 1. The array of INSTANT moorings. The black arrows show the ITF pathways. The dashed arrow in Lifamatola Passage represents the overflow across the 1940 m sill. The red "poles" mark the positions of the INSTANT moorings.

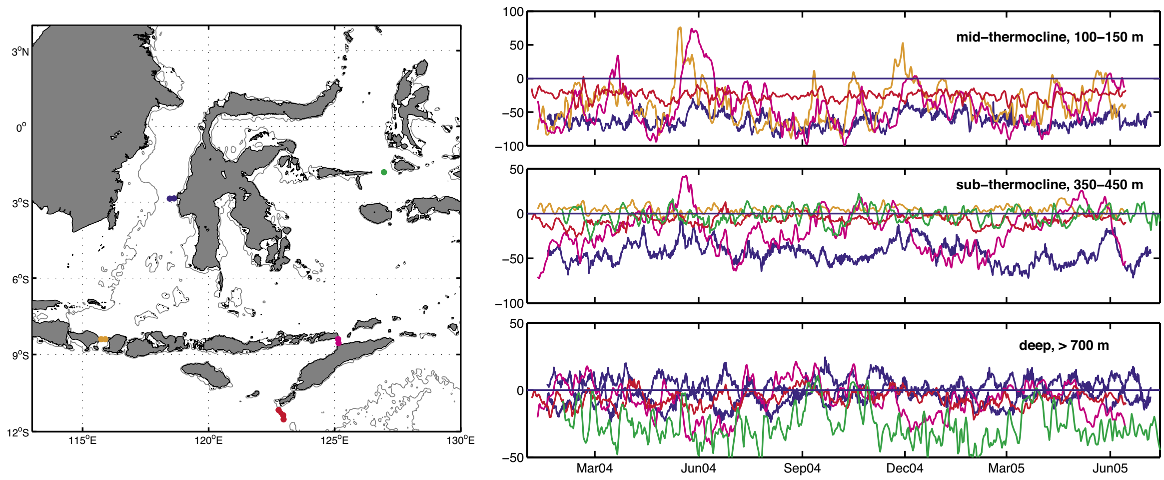


Figure 2. A composite view of the along-axis speeds [cm/sec; tides removed] from select moorings within each passage as measured during the first 1.5 years of INSTANT. Negative speeds are towards Indian Ocean. Color coding: Blue: Makassar; Green: Lifamatola; Orange: Lombok; Purple: Ombai; Red: Timor.

From Xie et al, page 12: Thermocline dome and climate variability over the tropical South Indian Ocean

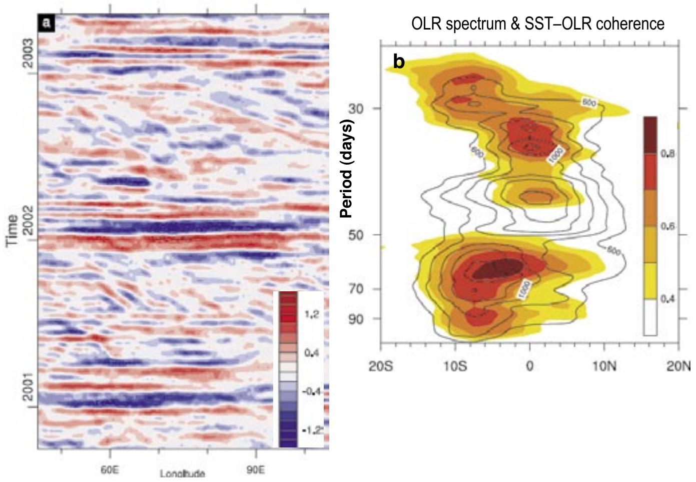


Fig. 4. (a) Longitude-time section of band-passed (30-90 days) SST anomaly averaged in 10-5°S (°C). (b) OLR power spectrum (W^2m^{-4}) and SST-OLR coherence squared (shaded) and as a function of latitude and frequency for data averaged in 60-90°E during DJF. From Saji et al. (2006b).

From Annamalai et al, page 14: The Active Role of South WEst Indian Ocean

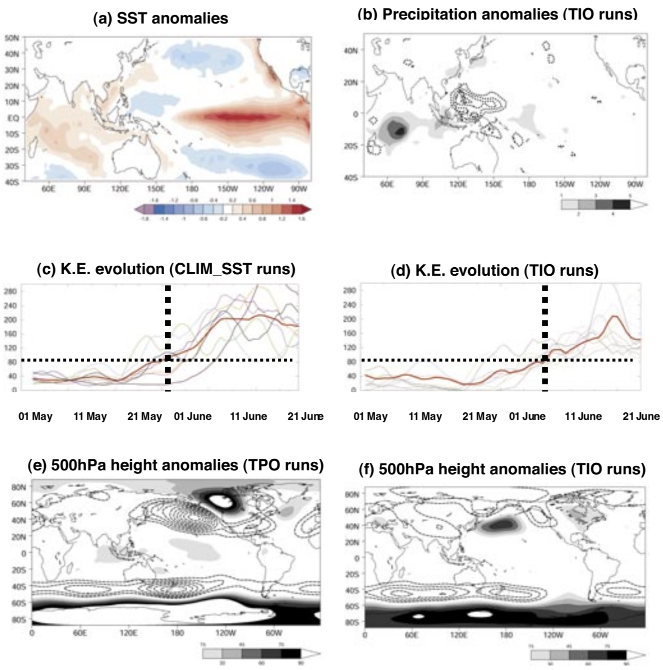


Figure 1: (a) Observed SST (°C) anomalies during El Nino years; (b) anomalous precipitation (mm/day) from the TIO solutions; Time series of kinetic energy (K.E in m^2/s^{-2}) averaged over the Arabian Sea (50E-70E, 5N-12N) from (c) CTL, and (d) TIO runs; (e) 500hPa geo-potential height anomalies (m) from the TPO solutions; and (f) same as (e) but from TIO runs. In (a) and (b) results are shown for seasonal averages (December through May), while in (e) and (f) they are for January through March. In (b, e, f) positive values are shaded progressively while negative values are shown as contours. The contour interval in (b) is 1.0 mm/day while that in (e) and (f) is 15m. In (c) the kinetic energy from the individual years as well their mean (thick red line) are shown. In (d) the kinetic energy from the individual members as well the ensemble-mean (thick red line) are shown, and the vertical line corresponds to onset in CTL run. Anomalous fields shown are obtained by subtracting the model's climatology from the ensemble mean. CTL refers to model run where monthly climatological SST is used as forcing

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From Ruitjer et al, page 20: Observations of the variability in the southwest Indian Ocean

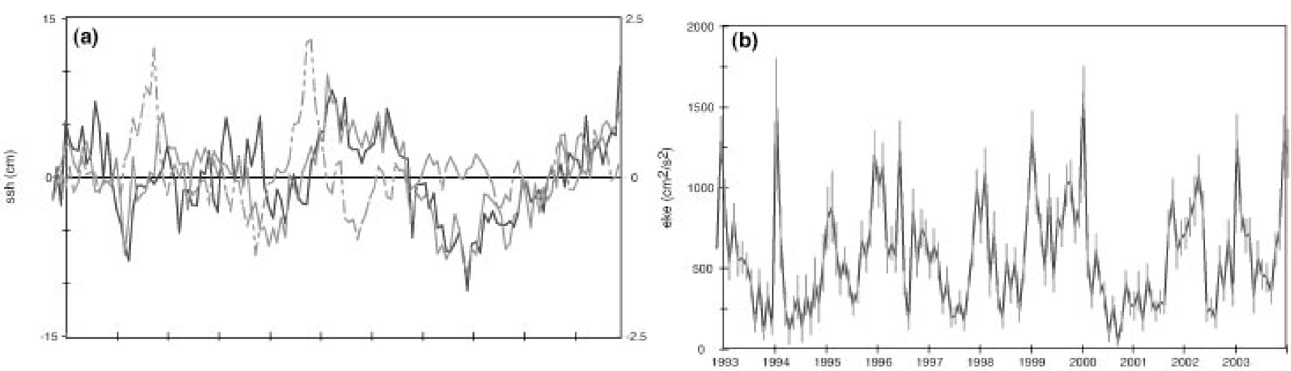

Fig 1. a) Time series of averaged SSH anomalies in a region North of Madagascar (gray line) and central Mozambique Channel (black line). The dash-dot line denotes the IOD index of Saji et al. (1999) b) EKE time series in the central Mozambique Channel. Error bars for each monthly EKE estimation are shown with gray segments. Errors are available as percentage of the signal variance for each weekly SSH field.

From Hood et al, page 24: Carbon cycling and biogeochemical variability in the Indian Ocean

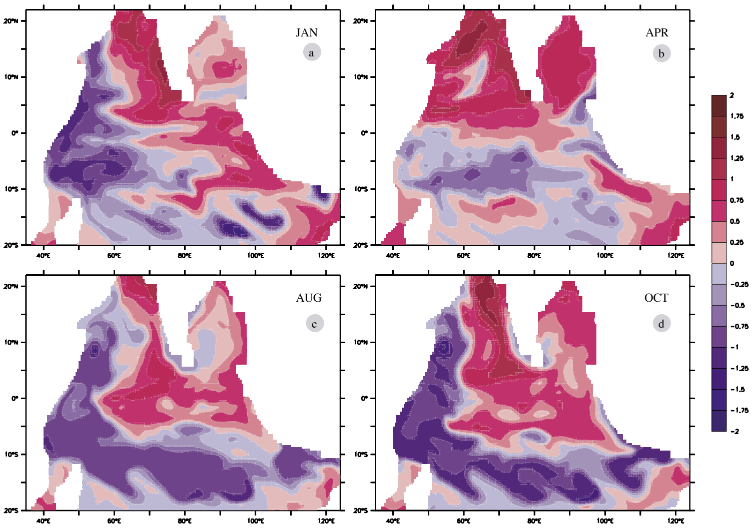

Figure 1. Seasonal evolution of most limiting surface nutrient for netplankton, with blue (red) indicating Fe (N) limitation (reproduced with permission from Wiggert et al., 2006, copyright 2006, Elsevier).

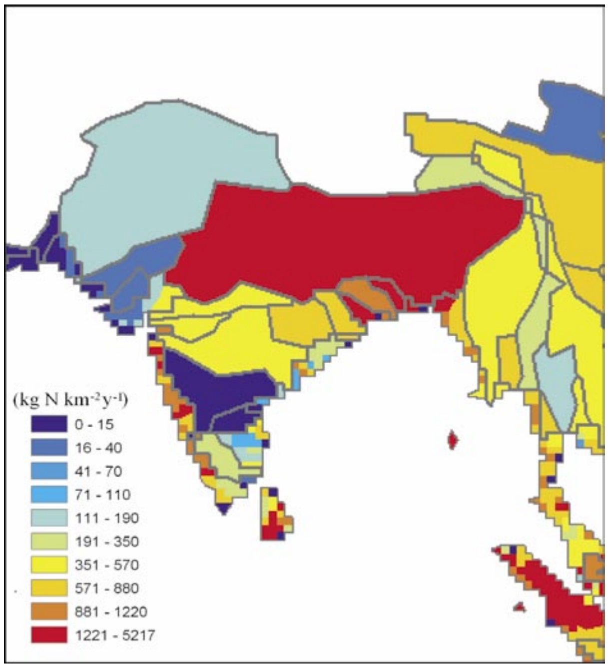

Figure 2. NEWS-DIN model predicted river export (kg N/km²/y) of DIN for the IO region (modified and reproduced with permission from Dumont et al. 2005, copyright 2005 American Geophysical Union).

From England et al, page 28: Indian Ocean variability controls interannual rainfall extremes over southwest Western Australia

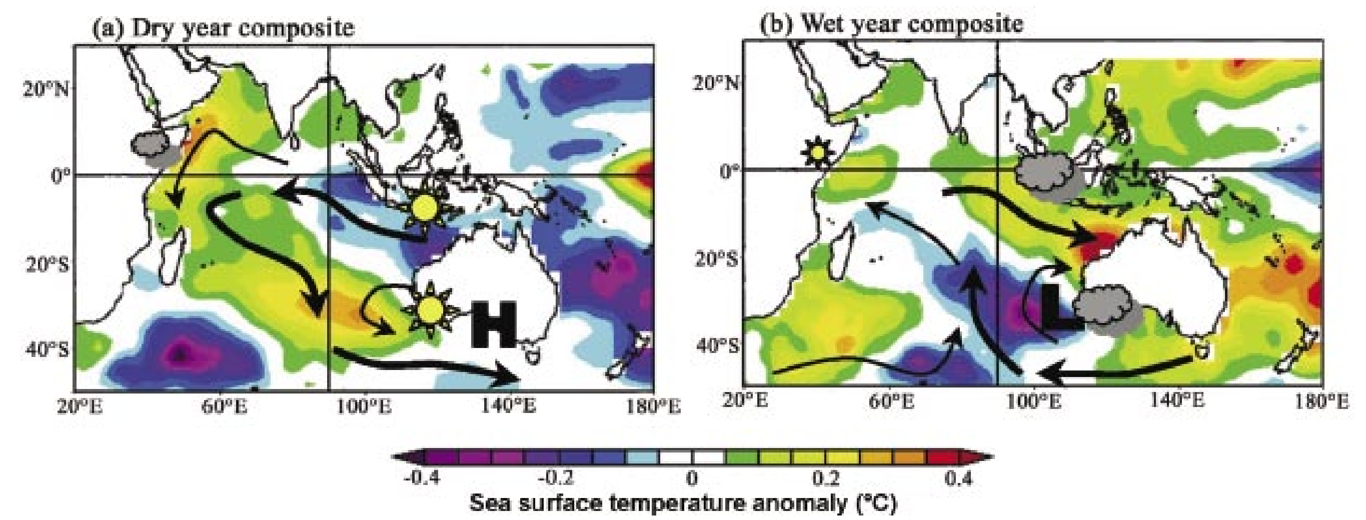

Figure 1. Schematic diagram showing the connection between Indian Ocean climate variability and (a) dry, (b) wet years over southwest Western Australia. Sea surface temperature anomalies are shown as actual observed composite fields (colour shaded in °C). Wind anomalies are shown as bold arrows, pressure anomalies by H (high) and L (low), and rainfall anomalies by sun/cloud symbols.

Continued from page 14

over the equatorial eastern Indian Ocean and west Pacific as a Kelvin wave response (not shown). Consistent with Watanabe and Jin (2003) our model results suggest that the changes in the Indian-Ocean Walker Circulation induce subsidence and reduce the precipitation over the TWP – Maritime Continent. The net result is the intensification of the rainfall along the EAWM front (Fig. 1b). Our model results indicate that more than 50% of the total precipitation anomalies over the TWP – Maritime Continent is forced by SWIO SST anomalies, offering an additional mechanism for the Philippine Sea anticyclone apart from Pacific SST.

2.2 Onset of the Indian Summer Monsoon

Traditionally, the India Meteorological Department declares the ISM onset based on rainfall over the southern tip of India. Approximately 3-5 days prior to the rapid increase in rainfall over southern India there is a dramatic rise in the kinetic energy over the Arabian Sea. During the onset, the axis of the Findlater jet lies around 5-12°N, and therefore the kinetic energy averaged over the region (50°E-70°E, 5°N-12°N) and exceeding a threshold of 80 m^2/s^2 is referred to as the dynamical onset here. Figures 1c-d show the temporal evolution of the kinetic energy from the CTL and the SWIO sensitivity runs, respectively. In the CTL run, the seven year-mean kinetic energy (thick red line) gradually rises around 22nd May with an abrupt increase around 3 June. In contrast, in years when warm SST anomalies persist over the SWIO the mean dynamical onset (thick red line) occurs at about 7 June (Fig. 1d), one week later than in the CTL run. In the TIO runs, the onset is earlier only in 2 cases, and the solutions from the majority of the ensemble members converge towards a systematic delay. Such a clear sensitivity in the ISM onset to tropical Pacific SST anomalies is not apparent in the TPO integrations (Annamalai et al. 2005).

2.3 Circulation anomalies over the Pacific-North American (PNA) region

The strength of the circulation anomalies over the PNA region is influenced by SWIO SST anomalies through the associated heating field that excites stationary Rossby waves. Figure 1e shows the simulated 500hPa geopotential height anomalies from TPO runs, and consistent with many other previous studies, tropical Pacific SST forces the well-known PNA pattern. One salient result in the TIO runs (Fig. 1f) lies in the vicinity of the central North Pacific where the model captures positive height anomalies there in contrast to negative anomalies simulated by TPO solutions (Fig. 1e). To a good approximation, similar out-of-phase features between TIO and TPO solutions are also noted over the other main centers of action over the PNA region. It is suffice to say that the height anomalies forced by SWIO SST anomalies "oppose" and "destructively interfere" with those forced by tropical Pacific SST anomalies over the PNA region. When validated against the reanalysis, the root-mean-square-error (RMSE) of the 500hPa height anomalies over the PNA region simulated in runs where only the tropical Pacific SST anomalies are specified are significantly reduced (about 42%) when tropical Indian Ocean SST anomalies are also prescribed. Therefore, our solutions suggest that for accurate seasonal prediction over North America it is imperative that contributions from regional SST anomalies are considered.

3 Summary

Recently, there is renewed interest in all aspects of the coupled system in the tropical Indian Ocean and its role on local and remote climate variability (Yamagata et al. 2004; Annamalai and Murtugudde 2004). Our model results indicate that these regional SST anomalies act as additional source of seasonal predictability. These preliminary results need to be verified with other AGCMs. If the results are reproducible, then, it is important that these regional SST anomalies are realistically reproduced in coupled models used for seasonal prediction. The possible effect of SWIO SST on South African rainfall and the seasonal climate over Hawaiian Islands are being examined. Finally, we urge that accurate observation of SST over the tropical Indian Ocean is of urgent need.

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Observations of the variability in the southwest Indian Ocean

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Satellite altimeter observations of the SSH variability of the southwest Indian ocean show a region of maximum variability in the Agulhas retroflection and Return Current that is connected to the north with the variability in the Mozambique Channel and that around the southern tip of Madagascar. Continuing upstream it connects east of Madagascar to the two zonal bands of enhanced variability across the Indian Ocean around 12ºS and 25ºS. These are the major routes along which anomalies propagate of tropical and subtropical origin (Xie et al., 2002; Schouten et al., 2002a). Eddies formed in the northern Mozambique Channel and south of Madagascar propagate poleward (Biastoch and Krauss, 1999; De Ruijter et al 2004; Quartly and Srokosz, 2004) and, on arrival at the Agulhas Retroflection, control the shedding rate of Agulhas rings (Schouten et al., 2002b). The latter drift into the Atlantic and feed the Atlantic meridional overturning circulation with warm and salty Indian Ocean waters.

Mesoscale variability in the Mozambique Channel: connection to large-scale interannual climate modes
Recently, Palastanga et al. (2006a) showed that there is a dynamic connection between interannual variability of the eddy activity around Madagascar and large-scale interannual variations over the Indian Ocean. An analysis of altimeter observations showed significant interannual variations of the Sea Surface Heights (SSH) fields in the Mozambique Channel and east of Madagascar. This was shown to be a lagged response to the Indian Ocean Dipole (IOD) events which generate large-scale SSH-anomalies that propagate westward as forced Rossby waves in the latitude band around 10ºS (Webster et al., 1999, Feng and Meyers, 2003). They arrive at the coast of Madagascar about one year after each IOD event. The SSH-anomalies are related to shifts in the strength and position of the tropical and subtropical gyres of the south Indian Ocean. In particular, the intensity of the South Equatorial Current (SEC) and its branches along East Madagascar varies: it weakens in response to a positive IOD event and strengthens due to a negative one. Subsequently, the strength of the currents through the narrow section of the Mozambique Channel, around 17ºS, varies associated with the IOD cycle. In particular after the 1997-1998 IOD a two year period of positive SSH-anomalies was followed by a two year period of negative anomalies. Variations in the eddy kinetic energy (EKE) in the central Mozambique Channel were dominated by a similar interannual modulation. Stronger currents after the positive IOD phase reinforce eddies in the narrows while eddy activity is weakened after the negative IOD phase (Fig.1, Page 17)

The Subtropical Indian Ocean Countercurrent and variability around 25ºS.
No such clear relation was found between the IOD generated anomalies in the East Madagascar Current (EMC) and variation of the EKE southwest of Madagascar. In this region the eddy activity appears controlled by variability generated in the subtropical band of enhanced variability around 25ºS east of Madagascar. In a follow-on paper Palastanga et al. (2006b) analyzed the background flow structure in this band of variability. They identified from the climatology and individual hydrographic sections the existence of a surface intensified eastward jet around 25ºS, concentrated mostly in the upper 200m. It flows over and against the westward, deeper reaching SEC. This Subtropical Indian Ocean Countercurrent (SICC) is probably a frontal jet along the northern branch of the subtropical front. Similar subtropical countercurrents have been identified in the Pacific (Qiu, 1999; Qiu and Chen, 2004).

The situation with a countercurrent flowing in opposite direction over the SEC creates favorable conditions for baroclinic instability (Palastanga et al., 2006b). A stability analysis based on hydrographic data along 80ºE gave a range of unstable frequencies around 4-5 times per year, consistent with the observed peak in the SSH spectrum in the western part of the variability band (Schouten et al., 2002). Further to the east the variability is dominated by semiannual Rossby waves, forced near the eastern boundary (Birol and Morrow, 2001).

Variability in the sources of the flow in the Mozambique Channel
North of Madagascar, the South Equatorial Current is concentrated into a narrow and swift stream. Satellite imagery of the chlorophyll content of the waters carried by this current suggests a seasonal switch between predominantly tropical and subtropical sources. In the austral summer, relatively nutrient-poor and oxygen-rich subtropical waters flow towards the Mozambique Channel (Schouten et al., 2005). Interannual variations of the water mass characteristics within the Mozambique Channel are observed by comparing hydrographic sections taken between 2000 and 2005. The upper 200 m of sections sampled in 2000/2001 contained anomalously saline water, compared to those in 2003/2005. Adjustment to seasonal winds, and anomalous open-ocean upwelling in 2000/2001 over the SEC further east, seem to relate both the observed seasonal and interannual oceanic variations to variations in the atmospheric forcing by wind stresses.

The long-term LOCO observations
A pilot-project (Agulhas Current Sources Experiment, ACSEX) with an array of current meter moorings in 2000-2001 showed that the meridional mass transport through the Mozambique Channel fluctuates remarkably regularly between 20 Sv northwards and 60 Sv southwards. The mean value for this one year of observations was some 15 Sv southwards. The spatial structure of the observed current field suggested a regular passage of southward migrating anti-cyclonic eddies (Ridderinkhof & de Ruijter, 2003) consistent with altimetric observations.

At intermediate and deep levels against the African continental slope a northward flowing Mozambique Undercurrent was observed with a mean northward speed of 4.6 cms-1 (1500 m) and 4.5 cms-1 (2500 m). Hydrographic observations showed that the deepest flow consists of North Atlantic Deep Water.

As part of the Dutch Long-term Ocean Climate Observations (LOCO) program a new array of moorings, with many more current meters, ADCP's and T-S sensors, was deployed at the same section in the Mozambique Channel in November 2003 (Fig.2). Observations from these sub-surface moorings will continue until 2008. Every 1.5-2 years a detailed hydrographic survey along the mooring section is performed, combined with a servicing of the moorings. The main objective is to determine the inter-annual variability of the currents and hydrography in this source region for the Agulhas Current. First results of the mooring section are presented in figure 3 that combines

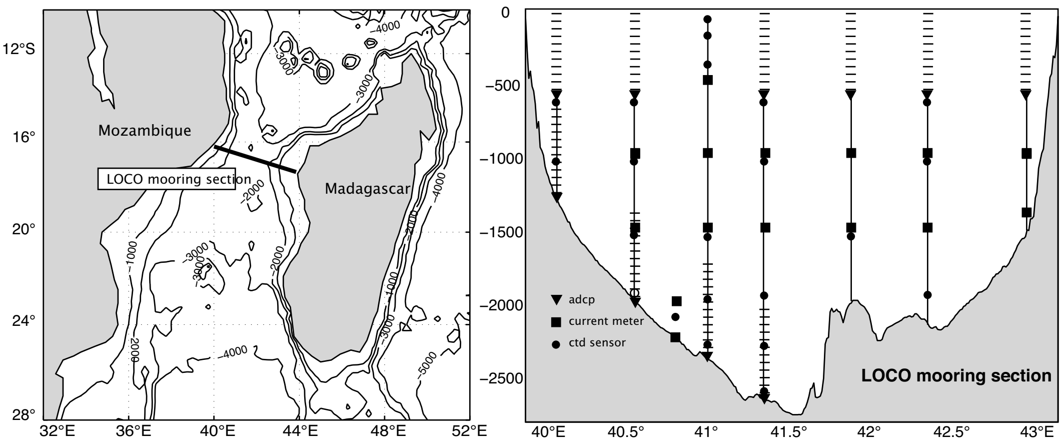

Fig. 2. The LOCO mooring section in the Mozambique Channel consisting of an array of moorings with ADCP's, single point current meters and C-T sensors

observations from the pilot experiment with the present LOCO observations. At first glance observations from both periods look similar in that the currents are dominated by the regular passage of anti-cyclonic eddies. The main difference between the years 2000-2001 and 2004-2005 seems to be that intraseasonal variability in the current strength is present only in the latter period. Explanations for this (and other new observations) await further analysis.

Meanwhile, a new Netherlands Indian Ocean Programme is being prepared to address the above and related issues, including both an actuo- and a paleoceanographic programme in the region around the LOCO moorings. If granted it will be carried out in the period 2008-2010 (hopefully long enough to catch an IOD/ENSO event). It is still open for coordination with plans from other groups.

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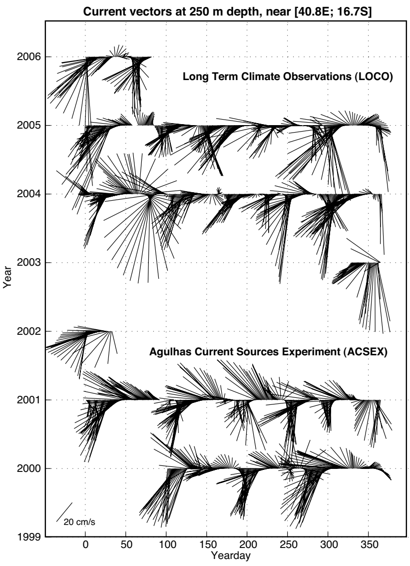

Fig 3. Observed currents at a mooring near the centre of the channel. Observations are from the pilot experiment (2000-2002) and from the present LOCO program (2003-2008)

Modelling The Variability Of The Source Regions Of The Agulhas Current And Inter-Ocean Exchange

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1. Introduction

Exchanges of water south of Africa, between the South Indian and South Atlantic Oceans, are an important component of the global thermohaline circulation. It has also been shown that the meso- through to interannual variability in these exchanges may influence weather and climate patterns in the southern African region (e.g. Walker and Mey, 1988; Crimp et al., 1998; Reason and Mulenga, 1999).

The linkage between the South Indian and South Atlantic Oceans has been shown to be largely a function of mesoscale variability in the Agulhas Current proper, as well as in its source regions. There are thought to be three major sources in the South Indian Ocean for the Agulhas Current; namely, re-circulation in the South West Indian Ocean, flow through the Mozambique Channel, and the East Madagascar Current.

A recent experiment dedicated to the source regions of the Agulhas Current (ACSEX – Agulhas Current Sources Experiment) focused on the East Madagascar Current and flow through the Mozambique Channel (e.g. Ridderinkhof and de Ruijter, 2003; Schouten et al., 2002). Data from current meters deployed during ACSEX indicate that the flow from the Mozambique Channel is mainly contributed to by anticyclonic eddies rather than an obvious southward current. However, these observations occur over a limited time and are unable to fully establish variability in the source regions, thus pointing to the need for model investigations.

Similarly the southern limb of the East Madagascar Current was previously thought to be a direct tributary to the Agulhas Current. However, satellite observations (e.g. Lutjeharms, 1988), have suggested that this current retroflects south of Madagascar and may only contribute to the Agulhas Current in the form of mesoscale eddies. During ACSEX, it was confirmed (de Ruijter et al., 2004) that this region is a source of both cyclonic and anti-cyclonic eddies. As in the case of the Mozambique Channel, there is no steady current here, but instead considerable variability due to eddies.

The most important source of the Agulhas Current is the re-circulation. Gordon et al. (1987) suggested that south of 32°S the Agulhas Current is in fact enhanced by a further 30 Sv from this re-circulation subgyre. However, although previous modelling and observational work has acknowledged the existence of Agulhas Current re-circulation, its influence on the current itself has not been considered.

2. The Model

We have used the eddy-permitting, regional ocean AGAPE model (Biastoch and Krauß, 1999) to investigate the variability of the three source regions on monthly to interannual scales. AGAPE is based on the Modular Ocean Model (MOM version 2; Pacanowski, 1996). The model domain extends over the South Indian and South Atlantic Oceans from 65-6.5°S and 60°W to 115°E. Within the South West Indian and South East Atlantic Oceans (20°W - 70°E), the horizontal resolution is 1/3° × 1/3°. Outside this region, it gradually coarsens in the zonal direction to reach 1.2° at the meridional boundaries. There are 29 vertical levels from the surface to realistic bottom topography that resolves important features like the Walvis and Southwest Indian Ridge, the Agulhas Plateau and Bank, etc. Near the surface, the layers are 15 m thick in order to better resolve the mixed layer and thermocline, and this vertical grid coarsens to 250 m at deep levels. At the surface, the model is forced with monthly mean wind stresses and temperature fluxes from the 1986-1988 monthly climatology (Barnier et al., 1995) of the European Centre for Medium-Range Weather Forecast (ECMWF) model interpolated to three day values. The surface salinity is restored on a 50-day time scale to the Levitus et al. (1994) climatology. The model run was integrated for a further twelve years after the 30-year spin-up.

The model results support suggestions from previous observational (e.g. Quartly and Srokosz, 1993) and model (e.g. Matano et al., 2002; Reason et al., 2003) work that the Agulhas Current region and its sources are highly variable on eddy, seasonal and interannual time scales. Observations are sparse but those that do exist suggest that our model is able to realistically represent the circulation in the Agulhas Current region and its mesoscale variability; hence, there is a level of confidence in the model results.

3. Results

In agreement with observations (e.g. Schouten et al., 2003), flow through the model Mozambique Channel consists of a continuous train of southward moving eddies, focused in the western part of the channel. However, if the transport across the whole of the channel is considered, a strong annual cycle is seen, with maximum southward volume transport occurring in August and minimum in March.

The model East Madagascar Current was found to have an annual and semi-annual signal. This variability was partly related to that of the local wind stress curl and partly to that in the southern branch of the South Equatorial Current. Eddies were found to form south of about 20°S and the southern tip of Madagascar. On rounding the southern tip of Madagascar, the eddies drifted westwards. The model results suggest that this region is also influenced by the re-circulation of the Agulhas Current.

Re-circulation of the Agulhas Current back into the South West Indian Ocean was shown to be the most significant source region for the volume transport of the Agulhas Current north of 35°S. Although the re-circulation is by far the major contributor to the volume transport in the Agulhas Current (Fig. 1), the other source regions make a significant contribution to the temperature transport. There are occasions when the temperature transport into the Agulhas Current is contributed to mostly by flow from the East Madagascar Current due to the higher heat content of the tropical water in that current.

A significant relationship was found between the volume flux of the model re-circulation and the Agulhas Current on interannual timescales. A semi-annual signal was also present in the re-circulation and was partly in phase with that of the wind stress curl over the subtropical South Indian Ocean. However, certain regions of the re-circulation may be affected by local winds leading to the annual cycle not being completely in phase with the basin scale winds. Previous work has not examined the variability of the re-circulation of the Agulhas system, yet because it is the major contributor to the Agulhas Current (e.g. Stramma and Lutjeharms, 1997) it is probable that it will have more influence on the variability on the Agulhas Current system than the other two sources.

A retroflection index (R) was created in an attempt to monitor the position and strength of the retroflection:

$$R = 1 - \left(\frac{|T_1| - T_2}{|T_1|} \right)$$

where T_1 is the maximum westward volume flux of the Agulhas Current over the area 19-22°E, 35-40°S and T_2 is the maximum eastward volume flux of the Agulhas Return Current over the area 25-35°E, 35-45°S. Using the maximum transport over the defined boxes allows for any shifts in the position of the system, without affecting the index itself. When R=1, a complete retroflection occurs with no leakage, whereas if R=0 then the flow is completely into the South Atlantic Ocean, with no return flow back into the SW Indian Ocean. For intermediate values of R, partial retroflection occurs, and the degree determines the fraction that leaks into the South Atlantic.

The index showed that the retroflection varied on eddy to interannual timescales (Fig. 2). Typically there was rarely a complete retroflection in the model and always some amount of leakage into the South Atlantic. More leakage occurred during austral winter

The sensitivity of the transport in the source regions and the retroflection index to a southward shift in the mean anticyclonic winds was investigated. It was found that the transport increased in the re-circulation subgyre and that there was increased mesoscale activity as well as reduced leakage into the South East Atlantic Ocean (Fig. 3). The increase in eddy scale variability in the run with modified wind forcing was found to be consistent with altimeter observations from years with a similar wind pattern.

4. Conclusions

Considerable variability exists in the model Agulhas region and its source regions on a range of timescales. The model variability on interannual timescales is generated internally by ocean processes since the monthly forcing is repeated each year. Internal ocean variability can be caused by instabilities of wind-driven currents. Jochum and Murtugudde (2005) found the largest internal variability occurred in their model in areas of high EKE (as found here) and related this to the fact that a large part of the Indian Ocean mesoscale variability explains a substantial part of the observed interannual variability. The peak in interannual variability in the recirculation and Agulhas Return Current region in our model is at least of the same order of magnitude as the annual cycle, suggesting its importance in this region.

This study has focussed on variability generated through ocean processes; how it might change under the full spectrum of atmospheric variability (which is not represented in the monthly climatology used to drive the model) is not yet known. Observations, although limited, indicate that the region is highly variable from one year to the next and therefore, were the model forced with the observed winds for particular years rather than a monthly climatology, one would naturally expect the simulated ocean variability to be even greater than analysed here. The second model run reinforces the suggestion that such an increase would be the case, given the changes evident in the variability of the southern Agulhas region in response to the southward shifted wind forcing.

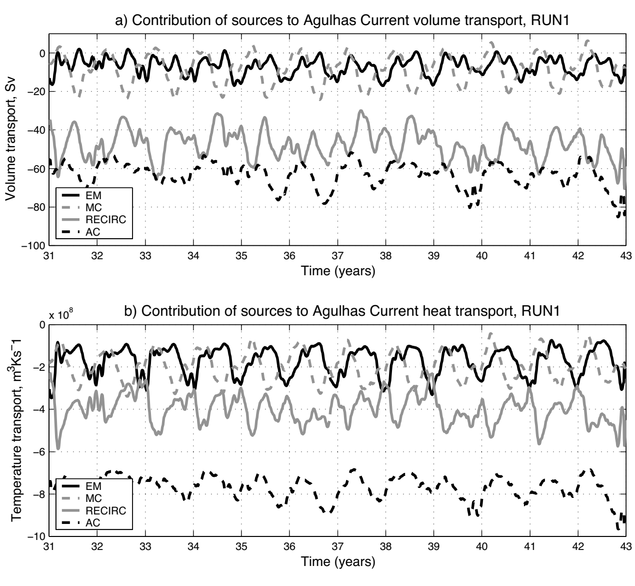

Figure 1 (a) The contribution of the flow through the Mozambique Channel (grey, dashed), the East Madagascar Current (black) and re-circulation (grey) to the Agulhas Current volume transport (Sv) at 35°S (black, dashed); (b) as for (a) but for the temperature transport (m^3Ks^{-1}).

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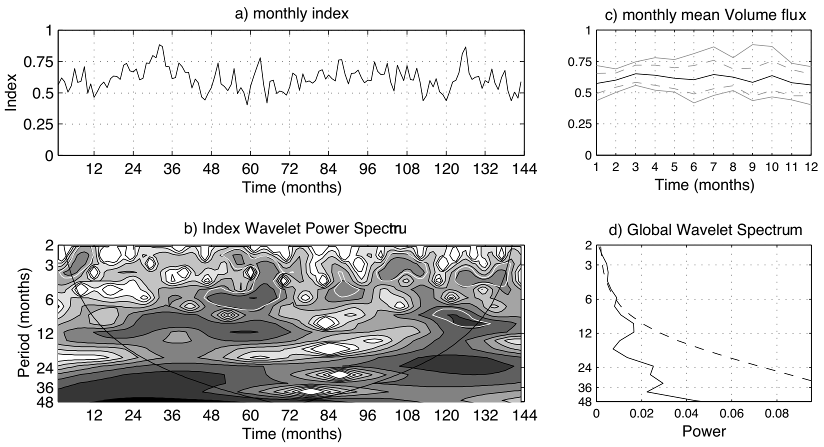

Figure 2 (a) Monthly time series of the index for the first run; (b) wavelet analysis of this time series, 95% significance levels are shown by white contours and cone of influence by black line; (c) the monthly mean value of R (black line) together with the maximum (upper line) and minimum (lower line) values and one standard deviation above and below the mean (grey, dashed lines); (d) power of wavelet analysis significance shown by dashed line

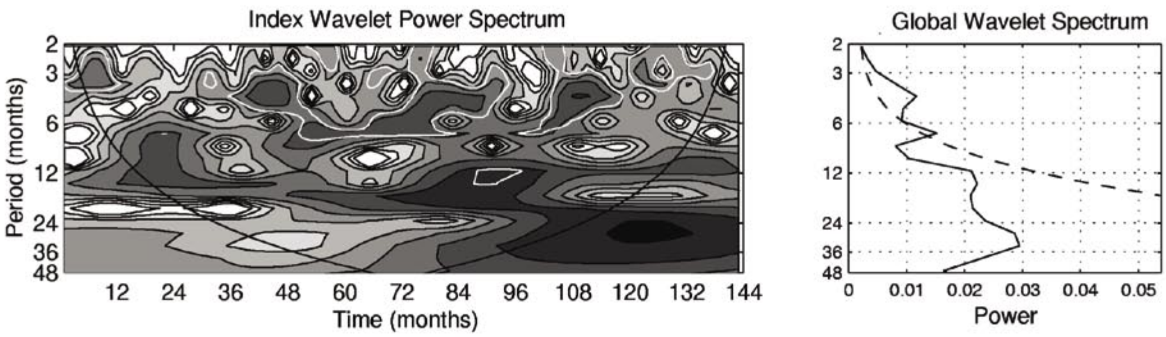

Figure 3 (left) Wavelet analysis of the index for the second run, 95% significance levels are shown by white contours and cone of influence by black line; (right) power of wavelet analysis, significance shown by dashed line.

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Carbon Cycling and Biogeochemical Variability in the Indian Ocean

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Introduction

The Indian Ocean (IO) basin has unique characteristics that derive from its northern, low latitude land-mass. Terrestrial boundaries to the north, east and west of the IO fundamentally impact this basin's atmospheric circulation, hydrological cycle and thereby the oceanic circulation. This leads to biogeochemical cycling of carbon and associated elements, and the responses of both to natural and anthropogenic change, which is unique to the IO. Specific characteristics that result include: geographic constraints on vertical mixing; a seasonally reversing monsoon system; globally significant oceanic production and net flux of CO_2 to the atmosphere despite the strong autotrophy in northern waters; oceanic biogeochemical cycles disproportionately driven by denitrification, N_2-fixation, Fe- and N-limitation; and physical/biogeochemical forcing by freshwater and aeolian mineral fluxes. The IO is also subject to significant perturbations associated with natural climatic events such as the Indian Ocean Dipole Zonal Mode (IODZM). It is likely that these factors increase the sensitivity of IO carbon cycling to climate and land-use variability relative to other ocean basins. Moreover, the IO is warming faster than any other ocean basin (Levitus et al. 2000) and thus may provide a sentinel for low latitude oceanic response to global warming. Furthermore, human impacts on the region are expected to change significantly over the next half century as populations in southern and eastern Asia increase. These changes are likely to substantially modify the chemical and particulate riverine inputs and the distribution and extent of regional dust sources all of which will impact the carbon cycle. It is therefore important to understand the role of the IO basin in the global carbon cycle and its response to land use and climate change. However, the temporal and spatial variations in air-sea carbon flux in the IO basin and the physical and biogeochemical influences that drive them remain poorly characterized.

The implementation of the planned CLIVAR/GOOS IO observing system (see McPhaden et al., this issue) presents a unique opportunity to carry out combined physical, biogeochemical and ecosystem research in the IO that can help to fill some of the major gaps in our understanding. In this article we highlight several major unresolved questions related to the IO carbon cycle, i.e., 1) Why is the IO a net source of CO_2 to the atmosphere despite exhibiting net autotrophy? 2) To what degree are carbon cycling and export affected by modifications to the available nutrient pool that derive from N_2-fixation and denitrification? 3) What is the role and extent of Fe limitation in controlling N availability and therefore carbon fixation and export? 4) How do hydrological processes and associated nutrient loads influence carbon chemistry and flux? In defining these questions we hope to motivate future research in the IO that will lead to a better characterization of the temporal and spatial variations in air-sea carbon flux in the IO basin and a more complete understanding of the physical and biogeochemical factors that drive it.

Biogeochemical processes and physical variability

During the SW Mosoon (SWM), the Findlater Jet drives coastal upwelling, horizontal advection and offshore mixed layer entrainment in the Arabian Sea that generate widespread phytoplankton blooms (Hood et al. 2003; Wiggert et al. 2005). As well, the Southwest Monsoon Current advects from the southeastern Arabian Sea around the southern limb of the Sri Lanka Dome and into the Bay of Bengal; these two physical features combine to promote the Bay's most prominent annually recurring biological signature east of Sri Lanka (Vinayachandran et al. 2004). Freshwater inputs into the Bay of Bengal modulate surface salinity and stratification in the eastern IO even into the southern tropical region and the associated fluvial nutrient and particulate loads profoundly impact biogeochemical processes in the Bay of Bengal. During the winter the NE Monsoon (NEM) drives convective mixing through evaporative cooling that is most pronounced over the Arabian Sea; this results in the formation of Arabian Sea High Salinity Water (ASHSW) and elevated, entrainment-driven biological productivity (Wiggert et al. 2002). During the Fall and Spring Intermonsoon (FIM, SIM), the semi-annual propagation of the Wyrtki Jet along the equator occurs. These waves are triggered in March and September by equatorial westerlies (Wyrtki 1973), and during both Intermonsoon periods these make leading order contributions to the seasonal variability of phytoplankton biomass and biogeochemical dynamics along the equator and in the southern Bay of Bengal (Vinayachandran et al. 1999; Wiggert et al. 2006).

Over interannual timescales, the Wyrtki Jet and associated physical/biological responses vary as a result of the IODZM (Saji et al. 1999). Anomalous phytoplankton blooms develop in the southern Bay of Bengal and the eastern equatorial IO during the Spring Intermonsoon (SIM) and NEM respectively (Murtugudde et al. 1999) during IODZM events. On the other hand, anomalously low NEM-period chlorophyll concentrations that coincidentally appear in the Arabian Sea have also been documented (Wiggert et al. 2002). Finally, a recent study has suggested that summertime monsoon intensity over the past seven years has been increasing due to reduced Himalayan snow cover and that this has led to a 300% increase in phytoplankton biomass in the western Arabian Sea during the SWM (Goes et al. 2005). The biological response and carbon export associated with these seasonal, interannual and climatic patterns of variability remains poorly understood.

Carbon Cycling and Air-Sea CO_2 fluxes

Takahashi et al. (2002) have identified the IO as a net sink (~330-430 Tg C yr-1) for atmospheric CO_2 that accounts for ~ 20% of the global oceanic uptake of CO_2. However, annual air-to-sea CO_2 flux only occurs south of 20°S in the IO, and questions remain as to the contributions made by the equatorial and northern IO regions and the seasonal and spatial variation in their source/sink status. Recently, Bates et al. (2006a) estimated that the IO north of 35°S is an annual net source of CO_2 to the atmosphere (~240 Tg C yr^{-1}), which is within the range (150-500 Tg C yr^{-1}) of previous estimates (Sabine et al. 2000; Hall et al. 2004). Regions influenced by monsoon forcing were found to be perennial sources of CO_2 to the atmosphere (Table 1).

The seasonal and spatial variability of seawater pCO_2 and air-sea CO_2 fluxes can be influenced by biological, physical and climatic factors including: (1) temperature; (2) salinity and its modification by evaporation, precipitation and freshwater discharge; (3) net metabolic balance of photosynthetic CO_2 fixation and respiration; (4) fluvial input of terrestrially-derived alkalinity and, inorganic and organic carbon and nutrients; (5) $CaCO_3$ and organic matter production and export, and; (6) horizontal and vertical exchange driven by physical factors operating over a variety of time and spatial-scales. Of these, the autotrophic/heterotrophic balance can strongly influence the CO_2 source/sink status of an oceanic system. Thus identifying the contribution of net metabolism, and the other factors noted above, to regional and basinwide biogeochemical cycling is crucial for advancing our insight into how the IO contributes to global air-sea exchanges of CO_2.

Net community production (NCP) based on seasonal dissolved inorganic carbon (DIC) drawdown suggests that the surface layer of the IO is strongly autotrophic at a rate of 750-1320 Tg C yr^{-1} (Bates et al. 2006b). However, despite its net autotrophy, the IO basin remains a perennial source of CO_2 to the atmosphere. Based on annual budgets (Table 1), Bates et al. (2006b) concluded that annual CO_2 uptake via NCP cannot compensate for CO_2 contributed to the surface layer by processes such as upwelling, lateral transport through the Indonesian Throughflow (ITF), and remineralization of organic matter.

By spatially partitioning the IO, the CO_2 source/sink status of its primary regions has been identified (Table 1). Seasonally, all regions of the IO are net autotrophic during the NEM and SIM, while during the SWM and FIM, a shift to net heterotrophy occurs north of 10°S. The Arabian Sea is a prime example of the complex combination of factors involved in carbon cycling. Upwelling driven by the Findlater Jet supports elevated primary production during the SWM. Due to water column denitrification in the Arabian Sea (e.g., Bange et al. 2005), this upwelling may bring excess DIC to the surface,

Region	CO_2 Flux	NCP	River Input	Vertical Diffusion	Upwelling/ advection
Indian Ocean	-237	-1572 (-802)	+30	+437	+1342 (+572)
Arabian Sea	-64	-0150 (-080)	+02	+058	+0154 (+084)
Bay of Bengal	-13	-0150 (-094)	+25	+025	+0113 (+057)
10°N-10°S	-180	-0486 (-304)	+01	+178	+0487 (+304)
10°S-20°S	-110	-0349 (-072)	+01	+097	+0361 (+084)
20°S-35°S	+130	-0437 (-095)	+01	+095	+0211 (+026)

Table 1. Annual balance of carbon (Tg C yr-1) for the Indian Ocean and sub-regions. Negative (positive) terms are loss from (gain to) the surface layer (0-100 m). Annual sea-to-air CO_2 flux is negative. Losses from the surface layer can be ascribed to NCP. Gains of carbon include; river input of organic matter and TCO_2, vertical diffusion of CO_2, and upwelling/lateral transport that can include upwelling of subsurface respired CO_2 or remineralization of DOC within the surface. For the NCP term, both monthly NCP and seasonal (bracketed) rates are given.

i.e., relative to inorganic nutrients as a result of stoichiometric imbalances. Subsequent photosynthetic fixation of CO_2 to organic matter with Redfield C:N:P stoichiometries may leave residual CO_2 in the surface layer that contributes to seawater pCO_2 supersaturation in the Arabian Sea. During the SWM coastal waters upwelled off the coasts of Somalia and the Arabian Peninsula, characterized by elevated levels of pCO_2, are laterally advected into the central Arabian Sea (Lee et al. 2000; Sarma 2003). Another contribution to the Arabian Sea's CO_2 source status is likely to be the seasonal remineralization of DOC to CO_2 (Hansell and Peltzer 1998). Identifying how these processes contribute to the seasonal shift from net autotrophy to net heterotrophy for the Arabian Sea, as well as in the Bay of Bengal requires further study. With regard to the latter, a more accurate assessment of monsoonal riverine input of DOC will be crucial for clarifying the CO_2 sink/source status.

The Nitrogen cycle

Nitrogen dynamics also play an important role in determining the spatio-temporal variability of the CO_2 sink and sources in the IO. Since fixed N limits primary production in many open ocean areas (Falkowski 1997), it can constrain the oceanic biological pump's ability to sequester atmospheric CO_2. During periods when denitrification removes fixed N from the ocean, the pump can be reversed and oceanic biological activity can become a source of CO_2 to the atmosphere (Codispoti 1989), whereas when nitrogen fixation exceeds denitrification the pump will be enhanced (Hood et al. 2001).

Two aspects of the Arabian Sea provide further biogeochemical complexity through their opposing impacts on regional nitrogen cycling. One is the extensive mid-depth oxygen minimum zone (OMZ) that is one of three prominent open ocean suboxic ($O_2 < \sim 3\ \mu M$) regions that are known to exist and within which denitrification occurs. While the known suboxic zones in today's ocean comprise only ~0.1% of the total oceanic volume, the attendant denitrification has globally significant climate impacts and the Arabian Sea OMZ contributes ~ 20% to the overall mesopelagic denitrification budget (Codispoti et al. 2001).

The other aspect is the demonstrated presence of Trichodesmium spp., a cyanobacterium that performs nitrogen fixation that to some degree counters the OMZ-related losses of fixed N. Based on the isotopic makeup of nitrate in near-surface waters of the Arabian Sea, it has been estimated that 30-40% of euphotic zone nitrate is derived from nitrogen fixation (Brandes et al. 1998) and the annual input of new N via this process has been estimated to be 3.3 Tg N yr^{-1} (Bange et al. 2005). Observational evidence of Trichodesmium and its apparent ubiquity in the Arabian Sea is steadily accumulating (e.g., Capone et al. 1998), but the relative net contribution of this process to the IO nitrogen and carbon budgets is still poorly constrained.

Aeolian mineral flux

A number of arid terrestrial regions act as prominent sources of windblown mineral dust, which is mobilized, transported and subsequently deposited into the surface waters of the IO. The dominance of these source regions distributed around the northern IO lead to pronounced meridional gradients in annual dust deposition rates (Jickells et al. 2005). Moreover, the annually reversing monsoon wind fields lead to significant seasonal variability in aeolian mineral flux (Pease et al. 1998). Given that dissolved iron is an essential micronutrient for phytoplankton photosynthesis, accurate knowledge of both the spatio-temporal distribution of dust and the bioavailability of deposited iron in mineral aerosols is crucial to achieving a complete understanding of biological activity and the biological pump of carbon in the IO.

In the Arabian Sea, it has generally been assumed that phytoplankton growth is not iron limited due to high dust loads. Recent model results however (Fig. 1), show spatial gradients in dissolved iron availability that lead to iron limitation in the western Arabian Sea during the SWM, when lateral advection of coastally upwelled waters dominates (Wiggert et al. 2006). Measurements off the Omani coast in 2004 also suggest that iron limited conditions develop in upwelled waters in the Arabian Sea (Naqvi and Moffett, pers. comm.). We also know that the Southern Ocean sector of the IO is Fe limited (Blain et al. 2002), but it is not known how far north this limitation extends. Piketh et al. (2000) have suggested that dust and Fe transport from South Africa stimulate carbon fixation and create a carbon sink in a broad swath across the southern IO, which is borne out by the strong autotrophy and net CO_2 sink found in the 20-35°S zone (Bates et al. 2006a; Bates et al. 2006b). Iron may then play a similar role in forming carbon sink regions further north. Thus, spatio-temporal balances of iron-replete conditions, iron-limitation, and mineral dust enhancement of primary production and new nitrogen sources (through N_2-fixation) likely play an important role in controlling the biological pump and the CO_2 source/sink balance in the IO basin.

Riverine input

The IO (primarily the Bay of Bengal and eastern IO rim) is subject to significant riverine injections, with globally significant annual freshwater discharges mostly during the SWM (Milliman and Meade 1983). The freshwater is accompanied by terrigenous inputs such as dissolved inorganic nutrients (Fig. 2), dissolved (DOM, including DO(C,P,N,Fe)) and particulate organic carbon and other elements (PC, P(P,N,Fe)) (Seitzinger et al. 2005). Both the freshwater fluxes and biogeochemical loads are affected by interannual variability in monsoon rainfall.

Over the past 50 years, world population, food production, and energy consumption have increased 2.5, 3, and 5-fold, respectively, resulting in a massive mobilization of bioactive nutrients on land, some of which are washed downstream into coastal ecosystems (Galloway et al. 2004). Some of the highest rates of nutrient export are from watersheds in southern Asia (Seitzinger et al. 2002a), a region where the human population is predicted to increase markedly over the next 50 years (United_Nations 1996; Millenium_Ecosystem_Assessment 2005). The result will be an increased export of N and P to coastal ecosystems, with resulting water quality degradation. For example, inorganic N export to coastal systems is predicted to increase 3-fold by the year 2050 (relative to 1990) from Africa and South America (Seitzinger et al. 2002b), with almost half of the total global increased DIN export predicted for those regions alone. The input of an additional 8 Tg N yr^{-1}, presuming it is all fixed and exported to the deep ocean, would decrease the CO_2 source in the IO by ~40-50 Tg C yr^{-1}. This represents about 20-35% of current estimates of CO_2 net efflux from the IO basin (Sabine et al. 2000; Bates et al. 2006a). Thus, anticipated future increases in N loading will very likely have a profound impact on the IO carbon cycle and the role of the IO in the global carbon cycle.

Summary and Conclusions

The IO basin is unique in that physical processes such as wind-driven mixing and upwelling, the influence of freshwater fluxes via rivers and E-P (evaporation-precipitation), as well as biogeochemical factors, including influences on primary production by nutrient sources and sinks derived from biological, aeolian and terrigenous sources, are all expected to influence the carbon cycle. Yet there are large uncertainties in the characterization of IO carbon flux variability and major gaps in our understanding of the physical and biogeochemical factors that drive it. In an effort to guide and motivate the research that is needed to fill these gaps, a major international workshop (SIBER; Sustained Indian Ocean Biogeochemical and Ecosystem Research, see http://ian.umces.edu/siber) will be convened in Goa, India (Oct. 3-6, 2006). The goal of this workshop will be to assess the state of our knowledge of basin-wide biogeochemical and ecological variability in the IO and develop a plan for an observational and modeling program in conjunction with the planned CLIVAR/GOOS observing system that will be deployed in the coming months/years. By providing input crucial to formulating the configuration of biogeochemical and ecological process studies, and long-term observational networks, this effort will contribute to international efforts to understand and predict the consequences of climate variability and change on marine ecosystems.

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Indian Ocean variability linked to interannual rainfall extremes over southwest Western Australia

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There has been great concern about the decline in rainfall over southwest Western Australia in the past few decades (IOCI, 2002). To exacerbate the problem, annual rainfall variations in the region are very large, with changes of up to 70% from one year to the next. Furthermore, periods of unusually high and unusually low rainfall show no clear link to well-documented climate modes such as the El Niño / Southern Oscillation (ENSO; Smith et al., 2000). The aim of this project was to examine what determines rainfall extremes over southwest Western Australia (SWWA) combining observations, reanalysis data, and a long-term natural integration of the global coupled climate system. This information is vital for the management of Western Australia's freshwater supply and for the region's agricultural sector.

Results

A distinctive pattern of Indian Ocean sea surface temperature (SST) anomalies characterises the southwest Australian rainfall variations, involving a dipole structure with unusually warm and cool waters adjacent to Western Australia (see Fig. 1, page 18). Extreme events in rainfall were found to be part of a large-scale phenomenon spanning the Indian Ocean basin, extending south to 50ºS. The characteristic pattern of Indian Ocean SST anomalies during extreme rainfall years turned out to be remarkably consistent between the reanalysis fields and the coupled climate model (see detail analysis in England et al., 2006), but different from previous definitions of SST dipoles in the region. In particular, the dipole exhibits peak amplitudes in the eastern Indian Ocean adjacent to the west coast of Australia (Fig. 1). During dry years, anomalously cool water appears in the tropical/subtropical eastern Indian Ocean, adjacent to a region of unusually warm water in the subtropics off SWWA. This dipole of anomalous SST seesaws in sign between dry and wet years, and appears to occur in phase with a large-scale reorganization of winds over the tropical/subtropical Indian Ocean. The wind field alters SST via anomalous 'Ekman' transport in the tropical Indian Ocean and via anomalous air-sea heat fluxes in the subtropics (England et al., 2006). The winds also change the large-scale advection of moisture onto the SWWA coast. At the basin scale, the anomalous wind field can be interpreted as a large-scale acceleration (deceleration) of the Indian Ocean climatological mean anticyclone during dry (wet) years. In addition, dry (wet) years see a strengthening (weakening) and coinciding southward (northward) shift of the subpolar westerlies, which results in a similar southward (northward) shift of the rain-bearing fronts associated with the subpolar front.

An analysis of the seasonal evolution of the climate extremes revealed a progressive amplification of anomalies in SST and atmospheric circulation toward a wintertime maximum, coinciding with the season of highest SWWA rainfall. The anomalies in SST can appear as early as the summertime months, however, which has important implications for predictability of SWWA rainfall extremes. The techniques and methods employed in the SWWA study have now also been applied to studies of New Zealand rainfall extremes and trends (Ummenhofer and England, 2006), as well as Tasmania's year-to-year rainfall variability (Hill et al., 2006).

Future work

A key outcome of this study is a new opportunity to develop predictive indices – akin to the Southern Oscillation Index – for southwest Western Australian rainfall. A possible oceanic precursor to periods of unusually high and unusually low SWWA rainfall might ultimately lead to improved predictability of the region's freshwater supply. Ensemble atmospheric and coupled climate model experiments are presently underway to test the above SST index in terms of its skill at forecasting SWWA rainfall variations with lead-times of months to seasons.

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Past Millennia Climate Variability – Synthesis and Outlook: PAGES/CLIVAR workshop

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This workshop followed the spirit of the reorganized PAGES/CLIVAR working group (see PAGES News, 2005/1). It was organized by the PAGES/CLIVAR Intersection Working Group (P. Jones, M. Mann, H. Wanner, K. Briffa) in concert with the PAGES office in Bern. Twenty-four participants (Fig. 1), representing various different climate data and modeling sub-disciplines were invited to discuss the state of the art and future needs in the study of late Holocene climate variability. Two days were devoted to short presentations and extended discussions on hot topics and issues, covering the areas of proxy data, climate reconstructions and paleoclimate modeling. The issue of how to deal with uncertainties in assessing climate variability over the past one-to-two millennia was discussed in detail. Questions posed and addressed included: What do current uncertainty estimates take into account? How relevant are current uncertainties for the general findings regarding past climate variability in the past? The following primary conclusions were reached:

- Late 20th century warming is likely anomalous in the context of the past 1000 years at hemispheric scales. There is evidence for periods of cooling and warming that occur on all timescales and on all spatial scales. For pre-instrumental periods, it is vital to consider both the spatial extent and duration of regional climate anomalies.
- Comparisons of model-predicted and reconstructed climate variations over the past several centuries are generally favorable, taking into account the currently available data and their uncertainties.
- Natural radiative forcing appears to play an important role on the relevant timescales. Solar forcing may account for variability on decadal through millennial timescales. Individual volcanic eruptions impact climate generally for only a few years but longer-term episodes of closely spaced large eruptions (e.g. as in the early 19th century) can lead to multidecadal-scale effects.
- Usefully constraining estimates of global climate sensitivity from paleoclimate data will require a better knowledge of past radiative forcing and the amplitude of internal, as well as forced, natural variability.

The discussions emphasized the importance of distinguishing past hemispheric or global-scale variability from regional variations. For example, it was shown that the widely used term “Medieval Warm Period” is simply not an appropriate description of Medieval climate in many regions of the world. Coral data from Kim Cobb, for example, suggest instead a “Medieval Cool Period” for the tropical Pacific. Such considerations reinforce the principle that a better regional documentation of past climate is necessary to better understand the past. The group that was assembled took note of the importance of focusing not simply on the often emphasized hemispheric mean temperature variations of past centuries, but also on spatial patterns of surface temperature, atmospheric circulation, precipitation and drought. The group also noted the importance of considering dynamical mechanisms such as the El Niño/Southern Oscillation (ENSO) in interpreting past climate changes. The recent PAGES and CLIVAR initiatives on past regional variability in South America and the Mediterranean region follows this principle (see PAGES News 2005/1, 2005/2 and 2005/3).

Fig. 1 The group of participants in front of the Wengen mountains.

The group recognized that additional effort is needed in the archiving of paleoclimate data and associated metadata. They also agreed on the importance of encouraging scientists to provide not just the proxy data and climate reconstructions, but as much information as possible about random and systematic error and uncertainty. The latter information is crucial, for example, in comparisons of paleoclimate evidence with model simulation results.

The participants agreed that progress in climate modeling approaches is also crucial to a better understanding of past climate variability, and to the assessment of current and future anthropogenic impacts on climate. To this end, the workshop participants agreed to plan a community-wide “paleoclimate reconstruction challenge” in the near future (see Program News, page xx, this issue). This challenge will build on the theme of model intercomparison, using synthetically derived “pseudoproxy” test datasets derived from climate models as a test of methods used in paleoclimate reconstruction, similar in many respects to last year’s “EPICA Challenge” initiative (see e.g. EOS, No. 38, 2005). A second project in the area of proxy data uncertainties and data archiving is also being planned, in concert with the world data centers.

The four-day workshop in the unique setting of the snow-covered Bernese Alps provided a perfect setting for informal discussions, setting the stage for productive activities in the months and years ahead. A synthesis publication on the state of the art of late Holocene climate variability will be published by the workshop participants. Follow-up activities are currently being planned.

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Workshop on Climate of the 20th Century and Seasonal to Internannual Climate Prediction

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Introduction

A workshop on the Climate of the 20th Century and Seasonal to Internannual Climate Prediction was held in Prague, Czech Republic, on 4-6 July 2005, jointly organized by the CLIVAR International Climate of the Twentieth Century (C20C) Project and the CLIVAR Working Group on Seasonal to Interannual Prediction (WGSIP). The workshop was hosted by T. Halenka (Czech Republic) and the MAthematical Geophysics, Meteorology, and their Applications (MAGMA) project of the Charles University of Prague (est. 1348), which is funded under the European Union's Fifth Framework Programme for support to Newly Assisted States. A web page including the agenda and copies of the presentations made at the workshop is available at http://meop0.troja.mff.cuni.cz/workshop05/.

The main focus of the C20C project (Folland et al., 2002) is to simulate and understand the climate variability during the 20th century. This includes understanding the impact of changes in sea surface temperature (SST), sea ice, land surface conditions and atmospheric composition and the attribution of the major climate anomalies of the past 130 years. The WMO/WCRP Working Group on Seasonal-to-Interannual Prediction (WGSIP), among other aims, seeks to assess the predictability of the climate system on seasonal to decadal time scales. This necessarily includes understanding and documenting the predictability of climate models over the historical record. These complementary goals and foci are ideal for establishing cross fertilization and collaboration between C20C and WGSIP. The goal of the Prague workshop was to define, implement and analyze collaborative numerical experiments.

The C20C project and WGSIP activities have, in the past, examined how much climate variability can be reproduced by prescribing observed forcing (i.e., global sea surface temperature and atmospheric composition). Recent coupled model results have suggested that important elements of atmosphere-ocean-land co-variability (e.g., monsoons) cannot be reproduced when prescribing global SST, though the extent of this problem may be model dependent. Energetically and dynamically consistent local air-sea feedbacks, created primarily through latent heat fluxes, are essential elements in simulating, and predicting the observed co-variability. The challenge is to design numerical experiments that reproduce the important aspects of this air-sea coupling while maintaining the flexibility to attempt to simulate the observed climate of the 20th century. In order to address this problem, a number of research groups have begun numerical experimentation into regionally coupled or "pacemaker" experiments where tropical Pacific SST is prescribed from observations, but coupled air-sea feedbacks are maintained in the other ocean basins (e.g. Lau and Nath, 2003). Anecdotal evidence indicates that pacemaker experiments reproduce the timing of the forced response to El Niño and the Southern Oscillation (ENSO), but also much of the co-variability that is missing when global SST is prescribed.

Pacemaker experiments can take a variety of forms in terms of what region is used for prescribing the SST, how air-sea feedbacks are incorporated in the interactive coupling region and how the coupled model is formulated (i.e., slab mixed layer, Q-flux-adjusted mixed layer, variable depth mixed layer, relaxation to observed SST, dynamical ocean etc.). A particular goal of the workshop was to design a coordinated experimental protocol to test the pacemaker hypothesis but still including the observed forcing/changes in the atmospheric composition.

Another issue that is yet to be taken up in the C20C framework is the response of the climate system to the changes in land cover and land use. Over the past 250 years, human settlement has made extensive changes to the landscape, primarily in the form of transforming forests into pastures and croplands. Given current trends, it is expected by 2100 that most of the natural vegetation will disappear in Africa and parts of Asia and that there will continue to be a reintroduction of forests in Europe and North America. Such massive changes in land cover produce large regional changes in the surface albedo. These in turn lead to changes in the global radiative forcing comparable to the change due to increasing greenhouse gas concentrations.

The impact of land cover change (LCC) has been explored extensively to provide a detailed assessment of regional scale impacts of tropical deforestation, temperature deforestation, and desertification. Several groups have explored the more general question of LCC and its impact on climate. Initial attempts involved using estimates of the change in leaf area index (LAI) using Normalized Difference Vegetation Index (NDVI) and more general estimates of the change in land cover. There is now a vast array of independent estimates of the impact of LCC on the Earth's climate using a suite of models, performed in different ways and subjected to various levels of analysis (e.g., Zhao et al., 2001, among many others). There is some evidence of large-scale atmospheric adjustment caused by regional-scale perturbations, leading to geographically remote changes in temperature and precipitation, and others suggest that LCC may affect extremes in temperature and precipitation. There is a general consensus from paleoclimate models that the LCC since the Holocene has resulted in a general cooling of the global mean surface temperature by 0.5°C, which can be compared with the perhaps 0.9°C increase estimated to have occurred in response to the change in greenhouse gas concentrations over the same period.

One difficulty with interpreting the range of available model results is that the model protocols are sufficiently varied to limit the robustness of their results. There are shortcomings with the experimental design of previous attempts to explore the effect of LCC on the climate using global climate models such as shortness (< 20 years) of the simulations, single realizations, and spatial resolution tends to be quite coarse. A further goal of the workshop was to consider a more robust experimental protocol in which to determine the impact of LCC on climate over the past century or more.

The workshop consisted of two components. The first component was a series of stimulating presentations to (1) review the current status of C20C model simulations in the "classic" SST and sea ice-forced integrations of atmospheric general circulation models (AGCMs) and with other forcings (changing concentrations of greenhouse gases, solar variability, volcanic aerosols and sulphate aerosols); (2) summarize possible strategies for conducting C20C experiments in a coupled air-sea modelling context; and (3) to summarize the issues and possible mechanisms for LCC effects on climate variability and predictability. The presentations are available on the workshop web site. The second component was a focused

"Pacemaker" Experiments	Land Surface Influence Experiments
Tropical Pacific 15°S – 15°N 162.5°E – S.A. coast	Land Cover Change (data set from LCC community)
North Atlantic 30°S – 60°N coast to coast	Fixed Soil Moisture (from "classic" run)
	Interactive Vegetation
GHG concentrations, solar variability, volcanic aerosols, sulphate aerosols	
C20C "classic": observed global SST and sea ice	

Table 1. Listing of consensus C20C experiments to be undertaken. Bottom row is baseline experiment and other rows are built on top of that experiment.

discussion intended to design common experimental protocols for pacemaker and LCC model integrations that would be undertaken by the C20C modelling groups.

Plans for SST Pacemaker and Land Surface Influence Experiments

A consensus was reached on several experiments to be undertaken by many of the C20C modelling groups. The first category of experiments discussed was the pacemaker protocol. It was agreed that the qualitative differences between climate simulations made with coupled and uncoupled models warrant a series of experiments to determine the role of various SST forcing regions on the global climate of the 20th century. Two regions were singled out for attention: (1) the deep tropical eastern Pacific where coupled ocean-atmosphere dynamics produces the ENSO interannual variability, and (2) the north Atlantic. Here there is evidence that interhemispheric modes of variability in SST (or SST gradient), associated with what is often called the Atlantic Multidecadal Oscillation and, quite possibly, variations in thermohaline circulation (e.g. Knight et al, 2005), are important for variations of climate in Europe, North Africa and North and South America (e.g. Knight et al, 2006). The region where SST is to be specified in the tropical Pacific pacemaker experiment is a quasi-rectangular area bounded by 15°S – 15°N and 162.5°E and the South American coast. This region was selected to include the region of maximum coupled variability and to exclude regions likely to respond to ENSO forcing, especially the subtropical Pacific, western tropical Pacific and tropical Indian Oceans. The region where SST is to be specified in the north Atlantic pacemaker experiment is 30°S – 60°N across the entire ocean basin. The details of which type of ocean model to use outside the pacemaker region (slab ocean, mixed layer model, or dynamical ocean model), how to handle model drift (Q-flux or SST relaxation) and how to merge the pacemaker and non-pacemaker regions, were left up to the individual participating groups.

The second category of experiments involves the land surface influence. Based on the presentations and the discussion, a series of three experiments were defined. The first is to include the observed change in croplands and pasture for which a global data set is available for 1871-2002. The crop and pasture data is available on a 0.5° grid with the fraction of C3 and C4 vegetation in each grid at annual resolution. A scheme for inclusion of these data in models with various land surface treatments was developed. The second experiment agreed on was the fixed soil moisture integration. In this experiment, the soil moisture simulated in the control run is to be specified (without feedback) over the course of the integration. The effect of the soil moisture feedback will then be inferred from the difference of this experiment with the control integrations. The third experiment is intended to ascertain the effect of interactive vegetation. A simple method of computing the change in leaf area index is to be included in the participating C20C models to determine the difference in their response to varying greenhouse gas concentrations, solar variability, volcanic aerosols and sulphate aerosols. The parameters for both categories of experiments are summarized in Table 1.

In all experiments, the C20C standards – minimum ensemble size of six integrations for the 1871-2002 period and 10 integrations for the 1949-2002 period – are to be applied. The 1871-1948 period is optional.

The consensus protocols have several advantages. First, it will be possible to create multimodel ensembles of simulations of the key phenomena, so as to obtain an estimate of the reliability of the results. Second, the pacemaker and land surface experiments are intended to make it possible for all participating groups to complete the experiment without major model development efforts, thereby providing the leverage of the large multimodel capability of C20C. This will increase the relevance of the project to improving the science, to IPCC activities (e.g. the IPCC Fifth Assessment Report), to seasonal to interannual prediction work within CLIVAR and to new insights needed for the emerging topic of decadal climate prediction. The benefits to WGSIP also include an experimental strategy for demonstrating how the so-called "two-tiered" approach for seasonal prediction can be generalized to include air-sea coupling outside the tropical Pacific. Third, the C20C community will begin numerical experimentation with coupled, partially coupled and parallel atmospheric models of specific historical phenomena for which there is often good observed data. This has the potential to improve the fidelity of the simulations and the ability of this project to study both mechanisms and predictability including the influence of external forcings.

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Announcement:
The IPCC Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA) is organizing an expert meeting on climate-society-environment interactions that are important to understanding climate change and its potential implications: Integrating Analysis of Regional Climate Change and Response Options. Our purpose is to explore and stimulate innovative research on connections and feedbacks across space, time and systems at scales appropriate to mitigation and adaptation decision-making. The 3-day expert meeting will be held June 20-22 2007 in Nadi, Fiji. Abstracts are requested no later than 30 November 2006. Approximately 40 persons will be selected from the submitted abstracts and invited to participate in the conference. Financial support will be available for invited participants from developing and transition economy countries. Further information, conference announcement, a call for paper abstracts, and a form for submission of abstracts are available from ipcc-wg1@al.noaa.gov .

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