CLIVAR Indian Ocean Panel report, in preparation for the July 2014 Pan-CLIVAR meeting

A. Highlight of IOP's achievement over the last 10 years

1. Observing the IO : building IndOOS

The Indian Ocean (hereafter, IO) has a spectrum of variability that spans intraseasonal to multi-decadal time-scales, and has important climate impacts. Despite this, there was no systematic and sustained ocean observing system in the IO in the late nineties. Recognizing this gap, an enthusiastic spirit emerged from the OceanObs99 meeting, resulting in the development of a plan for the IO Observing System (IndOOS) under the coordination of the CLIVAR/GOOS Indian Ocean Panel. IndOOS is a regional contribution to the Global Ocean Observing System (GOOS). Ten years ago, the IO was the least observed tropical ocean; today it benefits from an equivalent observing network to the tropical Pacific and Atlantic. The CLIVAR IOP has been instrumental in underlining of sustained, basin scale observations in the IO and establishing an implementation plan for those (International CLIVAR project Office, 2006; Masumoto et.al., 2010).

a. Overview of the IndOOS design

Overview. IndOOS is a multi-platform long-term observing system, which consists of a surface mooring array, Argo floats, surface drifting buoys, tide gauges, Voluntary Observing Ship (VOS) based XBT/XCTD sections and satellite measurements (Fig.1). The system is designed to provide high-frequency, near real-time climate-related observations, serving the needs of climate research, forecasting, and services.

Satellites. Satellite remote sensing provides maps of surface variables such as temperature, sea surface height, sea surface winds, sea surface salinity and ocean colour, as well as several meteorological input parameters for estimating air-sea momentum, heat, and fresh water fluxes. The recent addition of satellite based surface salinity is particularly important for the IO due to large contrasts across the basin. Satellite data are especially critical in regions where the in situ data are sparse.

RAMA. The main platform for in situ observations in the tropical IO is the Research moored Array for African-Asian-Australian Monsoon Analysis and prediction (RAMA, http://www.pmel.noaa.gov/tao/rama/index.html), which is similar to the TAO/TRITON array in the Pacific and PIRATA array in the Atlantic Ocean (McPhaden et al., 2009a). The RAMA array consists of a total of 46 moorings, of which 38 are ATLAS/TRITON-type surface moorings. Eight of these surface moorings are surface flux reference sites, with enhanced flux and subsurface ocean measurements. The surface mooring system can measure temperature and salinity profiles from the surface down to 500 m depth as well as the surface meteorological variables, and the observed data are transmitted in real-time via ARGOS satellites. In addition to these surface buoys, there are four subsurface ADCP moorings along the equator and one near the coast of Java to observe current profiles in the upper ocean, and three deep current-meter moorings with ADCPs in the central and eastern equatorial regions. The RAMA array design was evaluated and supported by observing system simulation experiments (Oke and Schiller, 2007; Vecchi and Harrison, 2007).

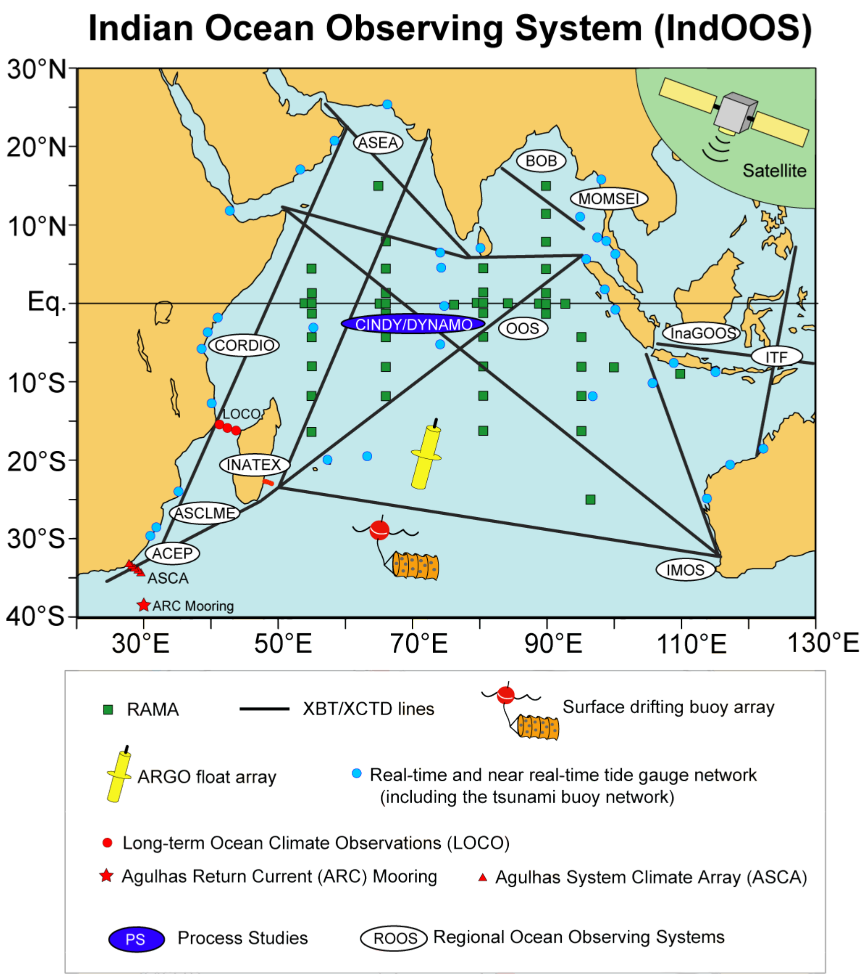

Figure 1: Overview of the various components of the IndOOS observing system.

Argo. Argo floats provide temperature and salinity profiles down to 2000 m depth with a temporal resolution of 10 days. The build-up of the Argo array in the IO began in 2002. The IO (north of 40°S) requires 450 floats to meet the Global Argo design of one float per 3x3 deg. The Argo program's unprecedented spatial and temporal coverage of density and geostrophic current is opening new perspectives on circulation-research and for seasonal forecasting.

Ship of opportunity lines. Several SOOP XBT lines obtain frequently repeated and high-density section data. The frequently repeated lines in the IO are narrow shipping routes allowing nearly exact repeat sections. At least 18 sections per year are recommended in order to avoid aliasing the strong intraseasonal variability in this region. The CLIVAR/GOOS IO Panel reviewed XBT sampling in the IO and prioritized the lines according to the oceanographic features that they monitor (International CLIVAR Project Office, 2006). The highest priority was on lines IX1 and IX8. IX1 monitors the Indonesian throughflow (Wijffels et al., 2008). The IOP recommended weekly sampling on IX1 because of the importance of throughflow in the climate system. IX8 monitors flow into the western boundary region, as well as the Seychelles-Chagos Thermocline Ridge, a region of intense ocean-atmosphere interaction at inter-annual time scales (Xie et al. 2002;Vialard et al. 2009). IX8 has proven to be logistically difficult so an alternate line may be needed. The other active lines in the Indian Ocean include IX12, IX22, IX15/21.

Surface drifting buoys. Surface drifting buoys have also been extensively deployed over the decade after OceanObs99, and the targeted coverage of one buoy per 5-degree box is almost achieved. The key application of surface drifter data is reduction of the bias error in satellite

SST measurements. They are also used for documentation of large-scale surface-current patterns. A problem in the IO is that the strong Asian summer monsoon winds drive drifters out of the North IO. A more frequent seeding program is needed to maintain the 5-degree sampling. To our knowledge, the sampling density required to map surface currents at say monthly time scale has not been determined.

Tide gauges. Sea level measurements from tide gauges along the coast is another important parameter to study our environment and the physical mechanisms which control it such as secular changes in the mean sea level, understanding the physical processes near the coast, calibration of satellite altimeters, improving and validating tidal, storm surge, Tsunami and climate models.

Regional ocean observing systems. The various Regional ocean observing systems (ROOSs) that complement IndOOS measurements are India's Ocean Observing System (OOS) of deep-sea current meter moorings along the equator, Australian Integrated Marine Observing System (IMOS), Indonesian Throughflow (ITF), Indonesian Global Ocean Observing System (InaGOOS), Monsoon Onset Monitoring over Andaman Sea and its Social & Ecosystem Impact (MOMSEI), Arabian Sea (ASEA) and Bay of Bengal (BOB) Regional Ocean Observing System, CORDIO-Coral Reef Degradation in the IO (Multinational program—Headquarters in Kenya), Long-Term Ocean Climate Observations (LOCO), Agulhas & Somali Current Large Marine Ecosystems (ASCLME) (Multinational program—Headquarters in South Africa), Agulhas Return Current (ARC) mooring, African Coelacanth Ecosystem Program (ACEP), and Agulhas System Climate Array (ASCA).

Liaising with SIBER. The IOP has established a unique interdisciplinary relationship with SIBER, a regional program of IMBER. SIBER-motivated deployment of biogeochemical sensors on RAMA (Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction) moorings in the IO is on-going, with an ocean color sensor to measure chlorophyll recently recovered from a RAMA mooring at 0°, 80.5°E and another deployed at 25°S 100°E in 2012; and a CO_2 sensor package recently deployed by NOAA on a RAMA mooring in the central Bay of Bengal in November 2013 in collaboration with the Bay of Bengal Large Marine Ecosystem (BOBLME) program. The IOP/SIBER collaboration has also motivated the deployment of Bio-Argo floats (16 floats with Oxygen sensors and 11 floats with chlorophyll, oxygen and back-scatter sensors) in different parts of the IO. Ongoing IOP-SIBER motivated projects include a biogeochemical sensor study of chlorophyll variability in the equatorial IO and efforts to estimate nutrient flux variability through the ITF. The interdisciplinary relationship between IOP and SIBER has also been very successful in promoting the development of interdisciplinary programs in the IO such as the IIOE-2 and the Eastern IO Upwelling Research Initiative, and it has become a model for development of interdisciplinary research projects and programs in CLIVAR.

Data portal. A data portal for IndOOS data is available at INCOIS from http://www.incois.gov.in/Incois/iogoos/home_indoos.jsp. The main idea is to provide a one-stop shop for IO-related data and data products. The distributed data archives are maintained by the individual groups at their institutes and made available to the community via the web portal. The portal contains data from basin-scale observations from mooring arrays, Argo profiling floats, expendable bathythermographs (XBT), surface-drifters and tide gauges, as well as the data from regional/coastal observation arrays (ROOS). Satellite derived gridded data sets such as sea surface temperature (TMI), sea surface winds (QuikSCAT, ASCAT, OSCAT) and sea surface height anomaly (merged altimeter products) are also available. The agencies contributing to the IndOOS are committed to follow the CLIVAR data policy (http://www.clivar.org/data/data_policy.htm).

b. Facilitating the development of IndOOS

The collaborative concept. IndOOS has been implemented largely through bi-lateral activities. Presently U.S., Japan, India, Indonesia, France, China, Australia, Netherlands and nine east African nations (Kenya, Tanzania, Mozambique, South Africa, Madagascar, Mauritius, Seychelles, Somalia, and Comoros; that make up the Aguhlas and Somali Current Large Marine Ecosystem or ASCLME) are contributing to build and sustain IndOOS. During the past decade, there are about 1490 cruise days to service 203 RAMA buoy locations using 14 different vessels. These cruises do not include many other independent cruises for the deployment of Argo floats, drifters and XBT voyages using VOS or research vessels. The detailed account of cruises for servicing RAMA moorings is available at http://www.pmel.noaa.gov/tao/rama/cruises.html.

The IndOOS Resource Forum (IRF) was created by directors of regional agencies under the auspices of the Regional Alliance of the Indian Ocean *Global Ocean Observing System (IOGOOS)* (http://www.incois.gov.in/Incois/iogoos/home.jsp). The objective of the IRF is to provide a multi-institutional forum to facilitate the allocation of sustained resources for the implementation of IndOOS. It's terms of reference are (i) To review the requirements for the implementation of IndOOS; (ii) To facilitate and coordinate resources that may be applied to the system, especially ship time for the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA); (iii) To encourage scientific and technological initiatives, in the participating countries, to meet the objectives of IndOOS, including the uptake of observations for societal benefit; and (iv) To report on its activities to the Heads of the institutions providing resources for IndOOS. The major challenge to complete and sustain IndOOS is the availability of sufficient ship time. Substantial other challenges are: the need for increased resources and technical support; logistical complexities due to piracy; harmonizing with the emerging complementary bio-geochemical measurements initiative, and ensuring a long term commitment to sustained observations. Up to the present time, resources have been allocated by research-agencies on a project-basis, and ship-time arranged on an annual basis through bi-lateral agreements. The short time-lines and somewhat *ad hoc* nature of these arrangements has led to lost opportunities, and the IRF has thus been asked to help providing a 3 year-lead outlook on ship availability and planning.

Piracy in the western IO has become one of the major impediments to establishing and maintaining IndOOS/RAMA and to carrying out research in the piracy-affected region of the western basin. The IOP has asked the IRF to commit additional resources and effort necessary to implement security measures on cruises that need to enter the piracy exclusive zone to service buoys and collect other measurements. The IRF was also asked to formulate a strong statement on the impact of piracy on IndOOS/RAMA and regional climate research. Some cruises have been successfully undertaken with the security personal onboard while servicing buoys. Vandalism and damage to buoy systems is another problem for sustaining the in-situ observing system.

c. Present status of IndOOS

RAMA. As of March 2014, 32 RAMA mooring sites have been occupied out of 46 planned locations (i.e. 70% complete, Fig.2). Of the remaining RAMA sites, 13 of the 14 are in the piracy exclusion zone. Three RAMA moorings were instrumented with microstructure sensors provided by Oregon State University to study turbulent mixing near the equator associated with MJO atmospheric forcing in the framework of CINDY/DYNAMO. CO_2 measurements are now being collected at the 15°N, 90°E flux reference site in collaboration with the BOBLME program.

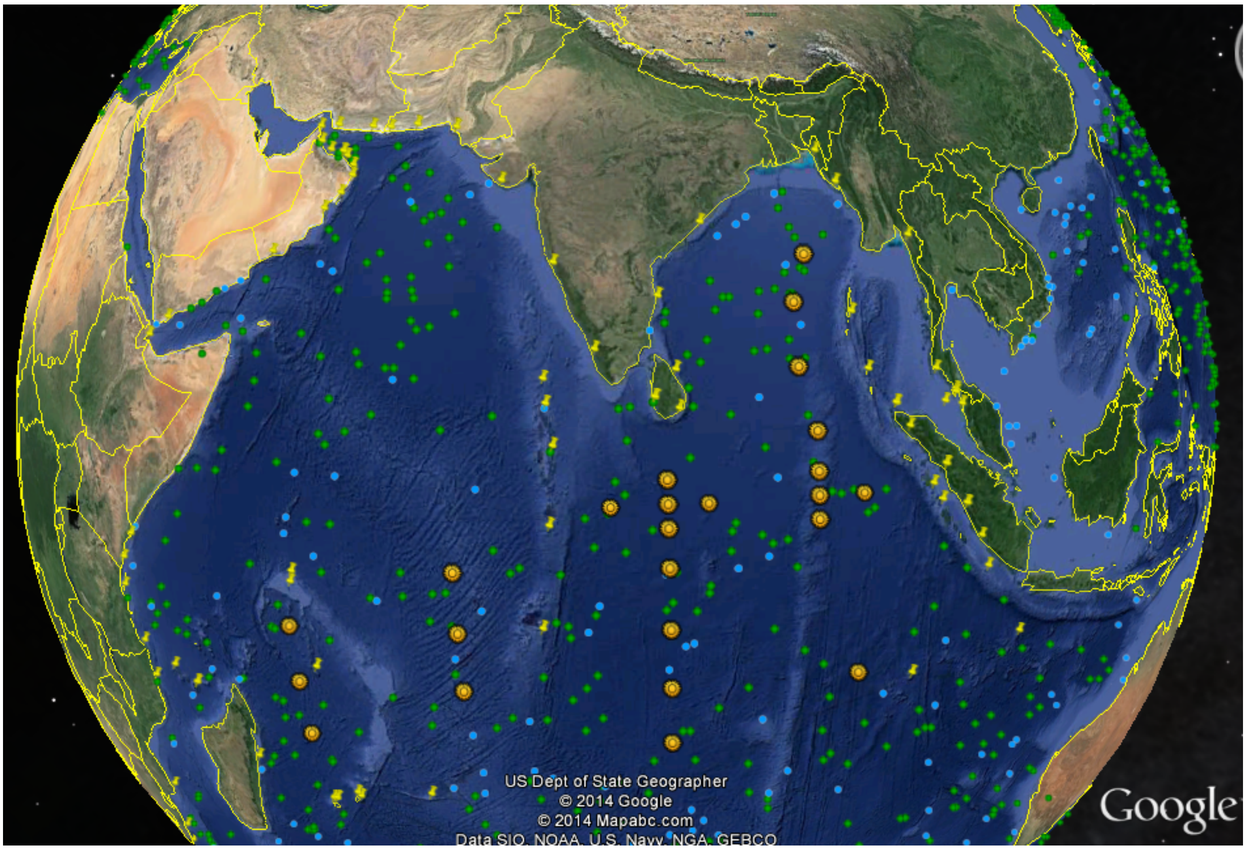

Figure 2: Present status of RAMA moorings (yellow dots) including sub-surface current meter moorings, Argo floats (green dots), drifters (blue dots) and tide gauges (yellow marker).

Argo. There are 769 Argo floats are active in the total IO and about 491 floats to the north of 40°S. Since 2006, the Argo array in the IO has been maintained at the nominal Argo design specification of 1 float per 3°x3° box. There are however some gaps where no floats exist, especially in the Western Equatorial IO, due to piracy issues. About 50 % of active floats are less than one year old, with most of the new deployments using iridium communications to provide higher vertical resolution and longer lifetimes. Many IO floats are deployed with biogeochemical sensors such as oxygen, chl-a, backscatter and nitrate.

Surface drifters and tide gauges. There are about 115 active surface drifters that provide 2500 observations per day. Many drifters have been deployed with Iridium communication to resolve diurnal variability in recent years. The required number of drifters was maintained in the past, but it has deteriorated during last five years. Efforts are underway to maintain the required number of drifters. Furthermore, about 67 coastal tide gauges and 7 open ocean tide gauges (bottom pressure recorder - tsunami buoys) provide data in real-time in the IO.

d. Endorsed and regional process studies

The IOP has endorsed many regional program and process studies in the IO. In late 2006 and early 2007, MISMO (Yoneyama et al. 2008) and VASCO/CIRENE (Vialard et al. 2009a) were the first ever campaigns that directly observed in-situ atmospheric and oceanic features in the presence of a strong positive IO dipole event. These two process-oriented campaigns also activated a broader interest for this unique Ocean. The coordinated international CINDY/DYNAMO field campaign (Yoneyama et al. 2013) was also designed to advance our knowledge of the Madden-Julian Oscillation initiation with the goal to improve its simulation/prediction. This campaign attracted researchers from 70 institutes/universities of 16 countries and collected unprecedented observations during October 2011 – March 2012. As of

January 2014, over 60 papers have been published from these campaigns and quality-controlled data have been released to the public.

ASCA / ACP. The Agulhas System Climate Array (ASCA) is a international program to monitor the Agulhas current, in collaboration between South Africa (ship time, consumables), USA (instruments, technicians) and Netherlands (instruments, technicians). The Agulhas Current Time-series (ACT) is a planned mooring array to continue previous measurements in the Mozambique channel and Agulhas current after 2014 (continuation of LOCO moorings and of 2010-2013 ACT program by USA).

2. The main scientific breakthroughs

a. Overview

During the late eighties and early nineties, the focus of the International science community in the tropics was on the Pacific Ocean, because of overwhelming influence of the El Niño phenomenon at the global scale. At the turn of the 21st century, the discovery of the IO Dipole, an intrinsic mode of variability with strong climate impacts in the IO, put the focus back on the IO. The then relatively poorly observed IO progressively became much more monitored during the following years (see section A.1). This wealth of observations allowed quantum leaps in the knowledge of oceanic and climate variability in the IO sector. The review by Schott et al. (2009) provides an excellent description of progress in the knowledge of the IO up to 5 years ago. Below, we summarize the salient features of that review adding in progress since 2009. IO research has been extremely active over the recent years, and the references we provide are selected highlights rather than an exhaustive review.

b. Ocean circulation

The review of the ocean circulation by Schott and McCreary (2001) provides a good summary of the knowledge about the IO circulation 10 years ago. Below, we briefly summarize the main areas of progress since that seminal review.

Meridional overturning cells and the thermocline ridge. Schott et al. (2004) showed that there are two important meridional circulation cells that feed upwellings in the IO. The cross-equatorial cell is fed by waters from recirculation within the subtropical gyre, the subduction regions of the southeastern subtropics, and from the Indonesian Throughflow (ITF). Those waters flows westward as the South Equatorial Current (SEC), then northward as the Somali Current, upwell in the Somalia and Oman upwellings. Its southward return flow is associated with the cross equatorial Sverdrup transport due to the mean wind stress curl associated with the equatorial westerlies in the IO. The Northern Edge of the easterlies drives Ekman pumping and an open ocean upwelling between 5 and 10°S in the western IO. This is the Seychelles-Chagos thermocline ridge or Seychelles Dome (Yokoi et al. 2008, Hermes and Reason 2008). This open ocean upwelling is associated with a secondary meridional overturning cell (the subtropical cell or STC) that links the SEC water to the Seychelles Dome. Those two cells are very important for the meridional heat transport and the heat balance of the IO, and may play a key role in its decadal and multidecadal variations. The Seychelles Dome seems to be a place of strong air-sea interactions at various timescales (e.g. Vialard et al. 2009a for a review).

Inputs from the ITF and Tasman leakage and Leeuwin undercurrent. The Indonesian Throughflow is the main gateway for waters entering the IO. The ITF has a mean outflow of 15 Sv into the IO, for the first time thoroughly monitored during the INSTANT program (Gordon et al. 2010). Significant seasonal (~ 4Sv), interannual and intraseasonal variations of this throughflow were also monitored during INSTANT. New observational results (e.g. Ridgway and Dunn 2007) have also confirmed an input flow to the IO from the Pacific at intermediate levels: the "Tasman leakage" is part of a supergyre that links the Southern Pacific, Indian and Atlantic oceans. The mean Tasman leakage between the Antarctic Circumpolar Current and Southern Australia is estimated from Argo data to be 3.8 ± 1.3 Sv (Rosell-Fieschi et al. 2013). Very little is known about the Leeuwin Undercurrent, which is a subsurface, coastally-trapped current that flows northward along the west coast of Australia at depths below about 300m. Its watermass properties are consistent with Subantarctic Mode Water formed south of Australia (Woo and Pattiaratchi, 2008). Its relationship to the Tasman Leakage is not yet clear.

Exit through Agulhas and Leeuwin currents. Downstream, the main gateways out of the tropical IO are the Agulhas (into the Atlantic) and Leeuwin current (a transport out of the IO in opposite direction to the deeper Tasman leakage south of Australia). The Leeuwin Current has a southward transport of 3 to 4 Sv, and the transport is strongly influenced by the Pacific ENSO (Feng et al., 2005). The main pathway of water originating from the ITF passes north of Madagascar, southward through the Mozambique Channel and downstream into the Agulhas Current. An average 16.7 Sv southward flow was monitored in the Mozambique channel as part of the LOCO program (Ridderinkhof et al. 2010; Ullgren et al., 2012) with an interannual variability of ~50% of the mean transport associated with the IOD. The Agulhas current has both a retroflecting part into the IO, and an Agulhas Leakage part toward the Atlantic (Le Bars et al., 2013), and is thought as important for regulating the Atlantic thermohaline circulation (Beal et al. 2011). Part of the Agulhas Leakage returns into the IO as the southern limb of the 'supergyre" (Speich et al., 2007). The Leeuwin Current is the only poleward-flowing eastern boundary current in the world. It is driven by the north-south gradient in density between warm, fresh waters from the Indonesian Throughflow and the cooler, salty subtropical waters (Furue et al. 2013, Benthuysen et al. 2014).

Main circulation patterns within the IO. In addition to gateways in and out of the IO, this decade has seen major progress in describing important circulation features within the IO. The South IO Countercurrent (SICC, Palastanga et al. 2007) is the eastward flowing southern branch of an anticyclonic gyre east of Madagascar, whose northern branch is the south equatorial current. Vertical shear between the eastward flow near the surface and SEC below is conducive to baroclinic instability and eddy generation. In the eastern side of the basin, the SICC broadens and splits into 3 main pathways, reaching the Australian coastline near 17°S, 25°S and 28°S (Menezes et al., 2013). The northern part of the SICC feeds into the Eastern Gyral Current (Domingues et al. 2007), and then into the Leeuwin Current. The Eastern Gyral Current is unusual in that its eastward geostrophic flow is sustained by the salinity front between fresh ITF and salty subtropical gyre waters (Menezes et al. 2013). Some previously well-known circulation features have been better described over the recent years. Many studies illustrated that the eastward equatorial Wyrtki Jet (and equatorial currents in general) occurs as a single or succession of intraseasonal pulses (e.g. Masumoto et al. 2005) and is largely governed by linear dynamics, with imbalances between the pressure gradient force and surface wind stress leading to zonal mass transport variations along the equator (Nagura and McPhaden 2008). Recent in situ and satellite observations have also allowed an improved description of the Great Whirl (Beal and Donohue, 2013), a large quasi-stationary anticyclone that appears off the coast of Somalia during the southwest monsoon season, and whose exact dynamical nature still remains unclear. The Southern East Madagascar current is the branch of the SEC that flows southward along the east coast of Madagascar: the connection of this boundary current to the Agulhas current is associated to a regular series of eddies, rather than a continuous current (De Ruijter et al. 2004).

c. Cyclones

Modulation of cyclones by climate variability. The recent example of the devastating Nargis tropical cyclone (McPhaden et al. 2009b, Maneesha et al., 2012) is a sad demonstration of the destructive power of tropical cyclones in a densely populated area like the Bay of Bengal. The IO is home to two important cyclogenesis area: the North IO (primarily the Bay of Bengal, and a bit the Arabian Sea) and the South IO (10-25°S with cyclones that can hit either Madagascar and nearby islands or that develop northwest of Australia). Some studies have recently described how the seasonal cycle regulates cyclogenesis in the Northern IO (e.g. Evan and Camargo, 2011; Yanase et al. 2012). Other studies suggest a control of cyclogenesis by ENSO in both the North (Felton et al. 2013; Girishkumar and Ravichandran, 2012) and South (e.g. Kuleshov et al. 2008) IO. Similarly, recent studies have illustrated that IO cyclogenesis is modulated by the MJO, both in the southern (e.g. Bessafi and Wheeler, 2006) and northern (e.g. Yanase et al. 2012) hemisphere.

Oceanic response to cyclones. More interestingly, from the IOP perspective, studies of the oceanic response to cyclones (and potential feedback on the atmosphere) in the IO have flourished over the recent years. This includes direct observations and modelling study of the near-inertial response of the ocean to the cyclone in the Bay of Bengal (e.g. McPhaden et al. 2009b; Wang and Han 2014) or thermocline ridge region (e.g. Cuypers et al. 2013). In the Bay of Bengal, it was suggested that the salinity stratification (Sengupta et al. 2008, Neetu et al. 2012) or mesoscale eddies (Yu and McPhaden, 2011) can influence the cooling below tropical cyclones and potentially their intensity. How this influence of the oceanic stratification on the cooling influences the cyclone itself however still has to be explored specifically for the IO.

d. Intraseasonal variability

Atmospheric intraseasonal variability. The MISMO and CINDY/DYNAMO cruises were built on the concept that the Madden-Julian Oscillation is often initiated in the IO (Zhang et al. 2013), before propagating eastward to the Pacific. The MISMO field experiment captured the onset of the atmospheric intraseasonal convection for the first time from the viewpoint of in-situ observations. It showed stepwise vertical moistening process associated with the Madden-Julian Oscillation, and that the IOD had a critical impact on the life cycle of the MJO (Yoneyama et al. 2008). The CINDY/DYNAMO intensive observation array captured several MJO events and showed that interactions between the Southern Hemisphere Intertropical Convergence Zone with convective activity over the equatorial region might play a key role for the initiation of the MJO (Yoneyama et al. 2013). In addition, dry air intrusions from the subtropics (Kerns and Chen, 2014) and westward-propagating cloud systems from the Maritime Continent also seem to affect convection over the central IO. Those new findings indicate that lateral moisture transport is a key to understand the MJO initiation.

Oceanic response. The oceanic response to atmospheric intraseasonal variability (ISV) in the IO is an area that has witnessed huge progress over the last 10 years. It was realized that the region of strongest SST response to atmospheric ISV is not in the Pacific Ocean but rather in the IO, and in particular in the thermocline ridge (e.g. Saji et al. 2006, Duvel and Vialard 2007) and the North-Western Australian Basin (Vialard et al. 2013, Marshall and Hendon, 2013). During Boreal Summer, recent studies revealed that, in addition to the Bay of Bengal, there are also large-scale fluctuations of the intensity of the Arabian Sea upwellings in response to monsoon active and break phases (e.g. Vialard et al. 2012). Intraseasonal variability in the Bay of Bengal has also been characterized in much more detail from RAMA observations (e.g. Girishkumar et al. 2011, 2013a,b). In addition to this thermodynamic response, many studies have illustrated the very strong dynamical response of the IO equatorial waveguide to atmospheric ISV (e.g. Sengupta et al., 2004, Masumoto et al. 2005, Ogata et al., 2008, Iskandar and McPhaden 2011) in particular at 90-day timescale (e.g. Han 2005; Han et al. 2011; Nagura and McPhaden 2012). This intraseasonal variability escapes the equatorial waveguide into the North IO and Indonesian coastal waveguides, and has a primary influence on the coastal currents variability there (e.g. Vialard et al. 2009b; Iskandar et al. 2006). Data from an ocean reanalysis and observations from the INSTANT program reveal that the deep-reaching subsurface intraseasonal variability in the equatorial eastern Indian Ocean travels for more than 5000km in about 14 days, and t can be detected as far east as the Banda Sea and along the west coast of Australia (Schiller et al., 2010). Off the west coast of Australia, MJO related wind stress anomalies can also influence the intra-seasonal variability of the Leeuwin Current (Marshall and Hendon, 2013).

Meso-scale oceanic variability. In addition to variability forced by the atmosphere, there is also intraseasonal oceanic variability arising from internal instabilities, and giving rise to eddies and filaments. This variability arises from baroclinic instabilities associated with the shear between the SEC and SICC at ~ 25°S (Palastanga et al. 2007). There is also intense eddy variability in the Mozambique channel and around south Madagascar (de Ruijter et al. 2002, 2004; Ridderinkhof et al., 2013). There is another major eddy generation region between 5 and 12°S in the central-eastern IO, which is favoured by the destabilizing effect of ITF water on the stratification (Zhou et al. 2008). Cheng et al. (2013) found two distinct bands of high eddy activity in the western and central BoB, with southwestward eddy propagation and the eddy occurrence modulated by intraseasonal coastal Kelvin waves. The Leeuwin Current has the strongest eddy energy among the mid-latitude eastern boundary current systems (Feng et al. 2005), and there have been intensive field studies of eddy dynamics and biogeochemical responses off the west coast of Australia in recent years, to understand the enhanced phytoplankton concentrations in the anticyclonic eddies (Feng et al., 2007; Waite et al., 2007).

e. Interannual variability

IO Dipole. After a heated debate about whether the IOD was El Niño-driven or partially independent, the consensus has more or less settled on an independent mode of variability arising from air-sea interactions in the IO (Yamagata et al. 2004), but that can be triggered by ENSO remote forcing (e.g. Annamalai et al. 2003, Shinoda et al. 2004). The major achievements in terms of IOD knowledge since then have been a better characterization of its climate impacts (e.g. Yamagata et al. 2004), its subsurface oceanic preconditioning (Horii et al. 2008), interpretation in terms of delayed oscillator (Nagura and McPhaden 2013) and the role of nonlinear advection in producing large negative than positive SST anomalies near the Indonesian coast (e.g. Hong et al. 2008). The IOD can be skilfully predicted by a dynamical seasonal prediction system based on a CGCM with 3-4 months lead and some events can be predicted 3-4 seasons ahead, but a winter prediction barrier exists (Luo et al. 2007). IOD also interacts with atmospheric and oceanic intraseasonal variability. During positive IOD events, atmospheric intraseasonal variations tend to be supressed as a result of reduced convection in the eastern Indian Ocean, and the total level of intraseasonal zonal wind variability averaged over the equatorial region is reduced (Shinoda and Han 2005). On the other hand, these intraseasonal equatorial winds often generate strong surface currents near the equator and influence the onset and termination of some positive IOD events (Han et al. 2006a).

IO Basin wide warming. ENSO also generates uniform SST variability over the IO through Walker circulation-mediated changes of cloudiness over the IO. This SST anomaly is maintained beyond the end of ENSO by local air-sea interactions in the IO. It can be hence compared to a "capacitor" that releases heat to the atmosphere after the end of ENSO and hence maintains its regional impacts, such as rainfall anomalies (Xie et al. 2009).

Remote influence of the IO. Recent studies have highlighted that SST anomalies in the IO (and in particular in the thermocline ridge region) have important remote influences through atmospheric teleconnections. These influences are felt both over the mid-latitudes (e.g. Annamalai et al. 2007), but are also thought to influence the evolution of ENSO although it is not clear if this influence is associated with the IOD (Izumo et al. 2010) or the IO basin-wide warming (e.g. Kug and Kang, 2006).

Ningaloo Niño. In February-March 2011, an unusually strong southward Leeuwin current resulted in an unprecedented 5°C anomaly on the west coast of Australia, which resulted from remote forcing from the strong La Niña in the Pacific, further enhanced by decadal trends and intraseasonal variations in the IO (Feng et al. 2013). This event had major impacts on the marine life and resulted in widespread coral bleaching (Pearce and Feng 2013, Depczynski et al. 2013). A recent study suggests that this type of event is in fact a recurrent mode of SST variability with strong impacts over Australia, that can either be remotely forced from the Pacific Ocean or associated to a local positive interaction between the SST anomaly and alongshore wind (Kataoka et al. 2014). This climate mode seems to be predictable about two seasons ahead by a coupled model (Doi et al. 2013).

Subtropical Dipole. The existence of a subtropical dipole in SST linked to fluctuations of the Mascarene high and influencing South-African rainfall was first discussed by Behera et al. (2000). Recent studies (e.g. Morioka et al. 2012, 2013) have explored the mechanisms of those SST variations, and shown that the subtropical dipole is forced by both tropical (ENSO) and high latitude (Antarctic circumpolar wave) influences.

f. Decadal and multidecadal variations

Review paper. In comparison with the Pacific and Atlantic, IO decadal and multidecadal variations have been much less studied. This led several members of the IOP to write a review paper on decadal climate variability in the IO (Han et al. 2014). Most of the research in that field is relatively recent, and this paper is a very good summary of progress accomplished in the last 10 years. A brief summary follows.

Multidecadal signals. In situ and satellite observations, ocean-atmosphere reanalysis products and reconstructed datasets show multi-decadal trends in upper IO heat content, temperature, salinity and sea level since the 1950s (e.g. Levitus et al. 2009). Model experiments suggest that those observed multidecadal trends are associated with anthropogenic forcing (e.g. Pierce et al. 2006). While basin-wide warming is attributed to forcing by anthropogenic green house gases (e.g. Du and Xie 2008), the slower warming rate over the North IO results from reduced solar radiation caused by loading of the atmosphere with anthropogenic aerosols of South Asian origin (Chung and Ramanathan 2006) with possible contributions from the slowdown of the CEC (e.g. Schoenefeldt and Schott 2006). Basin-scale near-surface warming accompanies thermocline cooling and falling sea level over the tropical-subtropical South IO (e.g. Han et al. 2006b). The distinct spatial structures of temperature and sea level can largely explained by the changing wind patterns over the IO, which are partly driven by the Indo-Pacific warming (e.g. Han et al. 2010). The change in the ITF transport clearly contributes to multidecadal changes in sea level near the west coast of Australia (e.g. Feng et al. 2011). On the other hand, there is no consensus on the relative contributions of local winds and remote forcing from the Pacific via the ITF to long-term sea level changes in the southern central Indian Ocean (e.g. Schwarzkopf and Böning 2011). The SSS trend has a spatial pattern resembling that of the mean SSS, which is consistent with an enhanced hydrological cycle associated with global warming (e.g Terray et al. 2012). There is an apparent upward trend of positive IOD occurrence since the 1950s, which is attributed to the mean state change associated with global warming (e.g. Cai et al. 2013). It is important to understand multidecadal changes of the Indo-Pacific winds and Walker Circulation, because they largely drive the spatial structures of IO sea level and thermocline changes. There is, however, no consensus on multidecadal trends in equatorial IO westerly winds and the Indo-Pacific Walker Circulation over the past 50-100 years.

Decadal signals. Superimposed on the multi-decadal trends, there are decadal time scale fluctuations. The observed decadal variability in IO basin-wide sea level, salinity and thermal structure results primarily from forcing by IO winds (e.g. Nidheesh et al. 2013), with a significant contribution from the ITF in the interior of the South IO after 1990 (Trenary and Han, 2013). Satellite measurements of wind stress and SSH indicate a 70% reduction in the strength of this STC during 1992-2000 (Lee 2004) followed by a partial recovery during 2000-2006 (Lee and McPhaden 2008). These changes are opposite from those of the Pacific STC, suggesting the opposite roles of the Pacific and South Indian Ocean STCs in regulating upper ocean heat content in the tropical Indo-Pacific region during this period. Lee and McPhaden (2008) suggested an atmospheric bridge (through the Walker Circulation branches) and oceanic linkage (via the Indonesian Archipelago) between the tropical Pacific and Indian Ocean during this period. While the oceanic linkage also operates on multi-decadal time scales (Feng et al. 2011), atmospheric reanalysis winds do not suggest that the atmospheric bridge is active during prior decades (Nidheesh et al. 2013). Whether this is indeed true or due to the lack of observational constraints in the atmospheric reanalysis products remains to be investigated.

Decadal modulation of the IO basin mode, the IOD, and subtropical dipole are observed. Some studies suggest that decadal variability of the IOD is not correlated with the Interdecadal Pacific Oscillation (IPO) or the decadal variability of ENSO (e.g. Ashok et al. 2004), while some climate model studies suggest that the IOD undergoes decadal variation owing to changes in the Walker Circulation (Meehl and Arblaster 2012) and changes in the Indonesian Throughflow and/or the Mascarene High (Tozuka et al. 2007). The relative roles of IO internal variability versus Pacific forcing on decadal modulation of the IOD thus need to be clarified. This knowledge gap indicates the importance of sustained oceanic and atmospheric observations in the Indian Ocean region.

g. Influence of physical processes on biogeochemistry

Overview. The cross fertilization between the SIBER and IOP members has resulted in several joint interdisciplinary research publications. A good review of the progresses over the last 10 years in Indian Ocean bio-physical interactions is provided by the review paper by McCreary, et al., 2009. In particular, noteworthy progress in the description of Indian Ocean bio-physical interactions over the last 10 years include: a general description and modelling of the chlorophyll blooms in the Indian Ocean (e.g. Levy et al. 2007, Koné et al. 2009, Marra et al. 2009); advances in our understanding the influence of the IOD and ENSO on biogeochemical and ecological processes (e.g. Wiggert et al. 2009, Currie et al. 2013); and quantification of the influences of advection, mixing and biological oxygen demand in determining the distribution of low oxygen water in the Arabian Sea (e.g. Resplandy et al. 2012, McCreary et al. 2013).

Northern Indian Ocean: Efforts have also been undertaken to explore the role of eddies in primary production of the Bay of Bengal and Arabian Sea (Prasanna Kumar et al. 2004, Resplandy et al. 2011); investigate the response of Bay of Bengal productivity to cyclones (e.g. McPhaden, et al., 2009); examine the chlorophyll signature of the MJO in the thermocline ridge region (Resplandy et al. 2009); and analyse results from Bio-Argo floats (Ravichandran et al.; 2012 Prakash et al., 2012; Prakash et al., 2013).

Southeastern Indian Ocean: IOP and SIBER have been very successful in engaging and motivating bio-physical research in the southeastern Indian Ocean associated with the impacts and dynamics of the Leeuwin Current. Important advances have emerged from a detailed study of the biological oceanography of the Leeuwin Current from 22-34°S that has generated a series of papers covering the physical oceanography (Feng et al. 2010, Weller et al. 2011), nutrients (Thompson et al. 2011), primary production (Lourey et al. 2013) and larval fish assemblages (Holliday et al. 2012). Important new findings have also emerged concerning the transport and ecology of the planktonic larval phase of the western rock lobster (Saunders et al. 2012, O'Rorke et al. 2012).

Southwestern Indian Ocean. SIBER and IOP-relevant research in the southwestern Indian Ocean includes a recently completed (2009-2011) multidisciplinary program to investigate the influence of mesoscale dynamics (eddies) on biological productivity at multiple trophic levels in the Mozambique Channel (MESOBIO). Findings from this program are now available in a special issue of Deep Sea Research II (Ternon et al. 2013). Important bio-physical results include a demonstration of how eddies moving southward off the east coast of Mozambique draw off coastal production, visible as filaments of chlorophyll, into the oligotrophic open ocean (Roberts et al. 2013) and characterization of the variability of plankton biomass and adaptation of plankton communities associated with these mesoscale eddies (Lamont et al. 2013; Barlow et al. 2013; Huggett 2013; Lebourges-Dhaussy et al. 2013). Other studies explored the influence of the eddies on higher trophic levels, including micronekton (Béhagle et al. 2013, Menard et al. 2013, Potier et al. 2013), large pelagic fish (Potier et al. 2013) and seabirds (Jaquemet et al. 2013). An important overarching conclusion that has emerged from this research is that, in order to understand the complex biological patterns within mesoscale eddies, knowledge of the life-history of the eddies is critical.

3. Capacity building activities

The Indian Ocean Panel has fostered a significant number of capacity building activities over the last 10 years, which are summarized here:

- AGU Chapman conference on the "Agulhas system and its role in changing Ocean Circulation, Climate and Marine Ecosystems" (Stellenbosch, South Africa, 8-12 October 2012). An impressive amount of $60,000 dedicated sponsoring was granted to facilitate participation of a large number of African students and young scientists. Township schools were visited and local school children visited the RV Knorr when in Cape Town for Lisa Beal's ACT cruise. Sponsors involved IUGG, IAPSO, SCOR, Nature, IRD, IOC Perth, NOAA, NSF, ONR, Thermoscientific, NIOZ, IMAU-Utrecht and AGU.
- Transfer of TRITON mooring technology to BPPT, Indonesia.
- Capacity building program in South Africa supported by JICA-JST of Japan, on downscaling prediction of climate variations.
- Series of IOC/WMO In- Region DBCP CB Workshops for Countries of the Western IO (Cape Town 2010; Mauritius 2011; Mombasa 2012; Tanzania 2013). Those workshops attempted to demonstrate the crucial role of IO observations, and build regional and national human mentoring networks, as well as institutional and infrastructure capacity needed to acquire, process and deliver socio-economic benefits from ocean observations;
- NOAA's Office of Climate Observation is also working closely with India's Ministry of Earth Sciences (MoES) and Agencies in Indonesia to build capacity associated with RAMA/IndOOS (e.g. 9th Capacity Building Workshop in Indonesia during Summer 2014).
- During field campaigns such as MISMO, CINDY/DYNAMO or CIRENE, scientists made several lectures to local staff and some students from IO rim nations were trained to collect data during the cruises.
- Capability building workshop focusing on the Indonesian Seas (January 2014, Bandung, Indonesia), an effort of the CLIVAR Indonesian Throughflow Task Force fostered by the Indian Ocean and Pacific Panels.

B. Plans for the next 5 years

- Complete and sustain IndOOS.
- Undertake IIOE-2: a coordinated international, interdisciplinary experiment in the IO
- Convene a summer school on Indian Ocean physical & biogeochemical oceanography in India, in 2016
- Promote coordinated studies of decadal and multidecadal variations in the IO
- Develop studies of the influence of IO SST on the atmosphere from the diurnal to the decadal timescale.
- Improve understanding of meso- and sub-meso scale variability in the IO, and its impacts including biogeochemical and ecological impacts
- Support two emerging regional programs (both of which are part of IIOE-2):
    - Eastern IO upwelling system: its dynamics and ecosystem impacts.
    - Agulhas System Climate Array
- Improve understanding of the influence of air-sea interactions and climate variability on tropical cyclones
- Better define inter-basin exchanges (via the ITF, Aghulhas system, ACC), including quantifying nutrient and organic matter fluxes.
- Develop coordinated modelling experiments for the IO, and in particular the evaluation of seasonal to decadal forecast.
- Exploit new information on satellite derived Sea Surface Salinity variability from Aquarius and SMOS in the IO.
- Liaise with the YMC (Year of the Maritime Continent) initiative: a field campaign which connects IO and Pacific, and ocean-atmosphere-land (CLIVAR-GEWEX-SPARC).

C. IOP activities that will contribute to CLIVAR research foci and WCRP Grand Science Challenges

CLIVAR research foci with obvious contributions from the IOP:

- **Decadal variability and predictability of ocean and climate variability:** characterizing decadal variability in the IO sector and its relation with known modes of decadal variability, in particular the Interdecadal Pacific Oscillation (IPO). The review by Han et al. (2014) provides a good overview of this active research area over the last 10 years.
- **Dynamics of regional sea level variability:** already several studies of the dynamics or regional sea level changes in response to global warming in the IO, in particular regional sea level fall in south-western IO
- **Marine biophysical interactions and dynamics of upwelling system:** strong existing IOP-SIBER collaboration that led to several multidisciplinary advances (e.g. documentation of biogeochemical signature of the major climate modes in the IO) that will be pursued within projected observational projects: IIOE-2, Eastern IO upwelling system initiative.
- **Intraseasonal, seasonal and interannual variability and predictability:** Areas of research covered by the IOP have extensively contributed to this theme: documentation of the ocean's response to intraseasonal variability in the IO (MJO, monsoon onset and its active/break phases), better understanding of the respective processes of the IOD and IO basin wide warming related to ENSO, bieogeochemical and ecological impacts of intraseasonal to interannual variability. Measure of the variability of the Agulhas Current and seasonal cycle.

- **Trends, nonlinearities and extreme events:** understanding the rate and regional variability in SST warming trends (like, e.g. the fact that the northern IO warms less than the southern IO), Ningaloo Niños, oceanic response to cyclones in the IO, biogeochemical and ecological impacts including, for example, coral bleaching
- **ENSO in a changing climate:** Past IOP-endorsed research has explored both how changes in ENSO may affect monsoon variability, the IOD, the ITF, and IO circulation but also how changes in the IO may affect the future character of ENSO (with, i.e., studies that show that SST signals in the Indian Ocean can influence the evolution of ENSO)

Other CLIVAR research foci with no obvious contribution from IOP:

- **Consistency between planetary heat balance and ocean heat storage**

References

Annamalai, H., H. Okajima and M. Watanabe, 2007: Possible impact of the IO SST on the northern hemisphere circulation during El Niño, *J. Climate,***20,** 3164-3189.

Annamalai, H., R. Murtugudde, J. Potemra, S.P. Xie, P. Liu, and B. Wang, 2003: Coupled dynamics over the IO: Spring initiation of the zonal mode. *Deep Sea Research II,***50,** 2305-2330.

Ashok, K., W.-L. Chan, T. Motoi, and T. Yamagata, 2004: Decadal variability of the Indian Ocean dipole. *Geophys. Res. Lett.*, **31**, L24207, doi:10.1029/2004GL021345.

Barlow, R., Lamont, T., Morris, T., Sessions, H. & Van Den Berg, M. 2013. Adaptation of phytoplankton communities to mesoscale eddies in the Mozambique Channel. Deep-Sea Research II, http://dx.doi.org/10.1016/j.dsr2.2013.10.020

Beal, L. M., and coauthors (2011), On the role of the Agulhas system in ocean circulation and climate, *Nature,***472,** 429-436.

Benthuysen, J., Furue, R., McCreary, J., Bindoff, N. and Phillips, H., 2014: Dynamics of the Leeuwin Current: Part 2. Impacts of mixing, friction, and advection on a buoyancy-driven eastern boundary current over a shelf. *Dynamics of Atmospheres and Oceans.* Vol. 65, pp 39-63.

Behagle, N., Du Buisson, L., Josse, E., Lebourges-Dhaussy, A., Roudaut, G. & Menard, F. 2013. Mesoscale features and micronekton in the Mozambique Channel: an acoustical approach. Deep-Sea Research II, http://dx.doi.org/10.1016/j.dsr2.2013.10.024

Cai, W., X.-T. Zheng, E. Weller, M. Collins, T. Cowan, M. Lengaigne, W. Yu, and T. Yamagata, 2013: Projected response of the Indian Ocean Dipole to greenhouse wraming. *Nature Geoscience*, DOI:10.1038/NGEO2009.

Cheng, X., S.-P. Xie, J. P. McCreary, Y. Qi, and Y. Du, 2013, Intraseasonal variability of sea surface heightin the Bay of Bengal, *J. Geophys. Res. Oceans,***118,** 816–830, doi:10.1002/jgrc.20075.

Chung, C. E., and V. Ramanathan, 2006: Weakening of North Indian SST gradients and the monsoon rainfall in India and the Sahel. *J. Clim*. **19**, 2036–2045.

Cuypers, Y., X. Le Vaillant, P. Bouruet-Aubertot, J. Vialard, M. McPhaden, 2013: Tropical storm-induced near inertial internal waves during the Cirene experiment: energy fluxes and impact on vertical mixing, *J. Geophys. Res.,***118,** 358-380.

De Ruijter, W. P. M., and coauthors, 2004, Eddiesand dipoles around South Madagascar: Formation, pathwaysand large-scale impact, *Deep Sea Res., Part I,***51,** 383–400.

Depczynski, M., and Coauthors, 2013, Bleaching, coral mortality and subsequent survivorship on a West Australian fringing reef, *Coral Reefs, 32*, 233-238.

Doi, T., S. K. Behera, and T. Yamagata, 2013: Predictability of the Ningaloo Niño. Sci. Rep., 3, 2892, doi:10.1038/srep02892.

Domingues, C. M., M. E. Maltrud, S. E. Wijffels, J. A. Church, and M. Tomczak, 2007. Simulated Lagrangian pathways between the Leeuwin Current System and the upper-ocean circulation of the southeast Indian Ocean. Deep-Sea Res. II, 54, 797–817.

Du, Y., and S.-P. Xie, 2008: Role of atmospheric adjustments in the tropical Indian Ocean warming during the 20th century in climate models. *Geophys. Res. Lett.*, **35**, L08712, doi:10.1029/2008GL033631.

Duvel, J-P. and J. Vialard, 2007, Indo-Pacific Sea Surface Temperature Perturbations Associated with Intraseasonal Oscillations of the Tropical Convection, *Journal of Climate*, **20,** 3056-3082.

Evan, A. T., and S. J. Camargo, 2011: A climatology of ArabianSea cyclonic storms. *J. Climate,***24,** 140–158.

Felton, C., B. Subrahmanyam, and V.S.N. Murty, 2013: ENSO modulated cyclogenesis over the Bay of Bengal. *J. Climate*, **26**, 9806-9818.

Feng, M., C. Böning, A. Biastoch, E. Behrens, E. Weller, and Y. Masumoto, 2011: The reversal of the multi-decadal trends of the equatorial Pacific easterly winds, and the Indonesian Throughflow and Leeuwin Current transports. *Geophys. Res. Lett.*, **38**, L11604, doi:10.1029/2011GL047291.

Feng, M., M. J. McPhaden, S. P. Xie, and J. J. Hafner, 2013, La Niña forces unprecedented Leeuwin Current warming in 2011, *Sci. Rep.,***3,** 1277, doi:10.1038/srep01277.

Feng, M., Majewski, L., Fandry, C., Waite, A., 2007. Characteristics of two counter-rotating eddies in the Leeuwin Current system off the Western Australian coast.*Deep-Sea Research II*, **54**, 961-980.

Feng, M., S. Wijffels, S. Godfrey, G. Meyers, 2005: Do eddies play a role in the momentum balance of the Leeuwin Current? *Journal of Physical Oceanography*, **35**(6), 964-975.

Feng, M., Slawinski, D., Beckley, L.E. & Keesing, J.R. 2010. Retention and dispersal of shelf waters influenced by interactions of ocean boundary current and coastal geography. Marine and Freshwater Research 61:1259-126.

Furue, R., McCreary, J.P., Benthuysen, J., Phillips, H. and Bindoff, N., 2013:Dynamics of the Leeuwin Current: Part 1. Coastal flows in an inviscid, variable-density, layer model. *Dynamics of Atmospheres and Oceans.* Vol. 63, pp 24-59.

Girishkumar, M. S., and M. Ravichandran., 2012, The influences of ENSO on tropical cyclone activity in the Bay of Bengal during October–December, *J. Geophys. Res.,* **117,** C02033, doi:10.1029/2011JC007417.

Girishkumar, M. S., M. Ravichandran and M. J. McPhaden, 2013b: Temperature inversions and their influence on the mixed layer heat budget during the winters of 2006-07 and 2007-08 in the Bay of Bengal. *J. Geophys. Res., 118,* doi:10.1002/jgrc.20192.

Girishkumar, M. S., M. Ravichandran, and W. Han, 2013a: Observed intraseasonal thermocline variability in the Bay of Bengal. *J. Geophys. Res. Oceans, 118,* doi:10.1002/jgrc.20245.

Girishkumar, M. S., M. Ravichandran, M. J. McPhaden, and R. R. Rao, 2011: Intraseasonal variability in barrier layer thickness in the south central Bay of Bengal, *J. Geophys. Res., 116,* C03009, doi:10.1029/2010JC006657.

Gordon, A.L., and Coauthors, The Indonesian throughflow during 2004–2006 as observed by the INSTANT program, *Dynamics of Atmospheres and Oceans,***50,** 115-128.

Han, W. and co-authors, 2014: Indian Ocean decadal variability : a review. *Bull. Am. Met. Soc.,* **in revision.**

Han, W., 2005: Origins and dynamics of the 90-day and 30–60-dayvariations in the equatorial IO. *J. Phys. Oceanogr.,* **35,** 708–728.

Han, W., G.A. Meehl, and A. Hu, 2006: Interpretation of tropical thermocline cooling in the Indian and Pacific Oceans during recent decades. *Geophys. Res. Lett*., **33**, L23615, doi:10.1029/2006GL027982.

Han, W., G.A. Meehl, and coauthors, 2010: Indian Ocean sea level change in a warming climate. *Nature Geosci*., **3**, 118-121, doi:10.1038/NGEO729.

Han, W., J. P. McCreary, Y. Masumoto, J. Vialard and B. Duncan, 2011 : Basin modes in the equatorial Indian Ocean, *J. Phys. Oceanogr.,* **41,** 1252-1270.

Han, W., T. Shinoda, L-L. Fu, and J. McCreary, 2006: Impact of atmospheric intraseasonal oscillations on the Indian Ocean dipole. *J. Phys. Oceanogr.*, 36, 670-690.

Hermes, J., and C. J. C. Reason., 2008, Annual cycle of the South IO (Seychelles-Chagos) thermocline ridge in a regional ocean model, *J. Geophys. Res., 107*, C04035, doi:10.1029/2007JC004363.

Holliday, D., Beckley, L.E., Millar, N., Olivar, M. P., Slawinski, D., Feng,M. & Thompson, P.A. 2012. Larval fish assemblages and particle back-tracking define latitudinal and cross-shelf variability in an eastern Indian Ocean boundary current. *Marine Ecology Progress Series* 460: 127-144.

Huggett, J. 2013. Mesoscale distribution and community composition of zooplankton in the Mozambique Channel. Deep-Sea Research II, http://dx.doi.org/10.1016/j.dsr2.2013.10.02

International CLIVAR Project Office., 2006: *Understanding the Role of the Indian Ocean in the Climate System—Implementation Plan for Sustained Observations.* ICPO Publication Series 100; GOOS Report No. 152; WCRP Informal Report No. 5/2006, International CLIVAR Project Office, Southhampton UK, 60 pp, 30 fig's.

Iskandar, I., and M. J. McPhaden, 2011: Dynamics of wind-forced intraseasonal zonal current variations in the equatorial Indian Ocean, *J. Geophys. Res., 116,* C06019, doi:10.1029/2010JC006864.

Iskandar, I., T. Tozuka, H. Sasaki, Y. Masumoto, and T. Yamagata, 2006: Intraseasonal variations of surface and subsurface currents off Java as simulated in a high-resolution OGCM. *J. Geophys. Res.,* **111,** C12015, doi:10.1029/2006JC003486.

Jaquemet, S., Ternon, J.F., Kaehler, S., Thiebot, J.B., Dyer, B., Bemanaja, E., Marteau, C. & Le Corre, M. 2013. Contrasted structuring effects of mesoscale features on the seabird community in the Mozambique Channel. Deep-Sea Research II, http://dx.doi.org/10.1016/j.dsr2.2013.10.027

Kataoka, T., T. Tozuka, S. K. Behera, and T. Yamagata.,2014, On the Ningaloo Niño/Niña, *Clim. Dyn.,* doi:10.1007/s00382-013-1961-z.

Kerns, B. W., and S. S. Chen, 2014: Equatorial dry air intrusion and related synoptic variability in MJO initiation during DYNAMO. *Mon. Wea. Rev.*, **142,** 1326-1343..

Koné, V., O. Aumont, M. Lévy, and L. Resplandy., 2009, Physical and biogeochemical controls of the phytoplankton seasonal cycle in the Indian Ocean: A modeling study, *Geophys. Monogr. Ser*., doi:10.1029/2008GM000700.

Kuleshov, Y., L. Qi, R.Fawcett, and D. Jones., 2008, On tropical cyclone activity inthe Southern Hemisphere: Trends and the ENSO connection,*Geophys. Res. Lett.,***35,** L14S08, doi:10.1029/2007GL032983.

Lamont, T., Barlow, R.G., Morris, T. & Van Den Berg, M.A. 2013. Characterization of mesoscale features and phytoplankton variability in the Mozambique Channel. Deep-Sea Research II, http://dx.doi.org/10.1016/j.dsr2.2013.10.019

Le Bars, D., HA Dijkstra, WPM De Ruijter, 2013, Impact of the Indonesian Throughflow on Agulhas Leakage. Ocean Science Discussions 10, 353-391

Lebourges-Dhaussy, A., Huggett, J., Ockhuis, S., Roudaut, G., Josse, E. & Verheye, H. 2013. Zooplankton size and distribution within mesoscale structures in the Mozambique Channel: a comparative approach using the TAPS acoustic profiler, a multiple net sampler and ZooScan image analysis. Deep-Sea Research II, http://dx.doi.org/10.1016/j.dsr2.2013.10.022

Lee, T., 2004: Decadal weakening of the shallow overturning circulation in the South Indian Ocean. *Geophys. Res. Lett.*, 31, L18305, doi:10.1029/2004GL020884.

Lee, T., and M.J. McPhaden, 2008: Decadal phase change in large-scale sea level and winds in the Indo-Pacific region at the end of the 20th century. *Geophys. Res. Lett*., **35**, L01605, doi:10.1029/2007GL032419.

Levitus, S., J. I. Antonov, T. P. Boyer, R. A. Locarnini, H. E. Garcia, and A. V. Mishonov, 2009: Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems. *Geophys. Res., Lett*., **36**, L07608, doi:10.1029/2008GL037155.

Levy, M., D. Shankar, J.-M. Andre, S. S. C. Shenoi, F. Durand, and C. de Boyer Montegut (2007), Basin-wide seasonal evolution of the Indian Ocean's phytoplankton blooms, *J. Geophys. Res.*, *112*, C12014, doi:10.1029/2007JC004090.

Luo, J.-J., S. Masson, S. Behera, and T. Yamagata, 2007: Experimental forecasts of the Indian Ocean Dipole using a coupled OAGCM. *J. Climate,* **20,** 2178-2190.

M. J. Lourey, M.J., Thompson, P.A., Mclaughlin, M.J., Bonham, P.& Feng, M. 2013 Primary production and phytoplankton community structure during a winter shelf-scale phytoplankton bloom off Western Australia. *Marine Biology* 160:355-369.

Maneesha, K., V.S.N. Murty, M. Ravichandran, T. Lee, Weidong Yu, M.J. McPhaden., 2012, Upper ocean variability in the Bay of Bengal during the tropical cyclones Nargis and Laila. ***Prog. Oceanogr***., **106**, 49-61.

Marra, J., and T. S. Moore II., 2009, Monsoons, islands, and eddies: Their effects on phytoplankton in the Indian Ocean, *Geophys. Monogr. Ser*., doi:10.1029/2008GM000701

Marshall, A. G.and H.H. Hendon, 2013: Impacts of the MJO in the Indian Ocean and on the Western Australian coast. . *Clim.Dyn.,* DOI 10.1007/s00382-012-1643-2

Masumoto, Y. and co-authors., 2010, Observing Systems in the Indian Ocean, In Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306. doi:10.5270/OceanObs09.cwp.60.

Masumoto, Y., H. Hase, Y. Kuroda, H. Matsuura, andK. Takeuchi.,2005, Intraseasonal variability in the upper layercurrents observed in the eastern equatorial IO, *Geophys. Res. Lett.,***32,** L02607, doi:10.1029/2004GL021896.

McCreary J., and coauthors, 2013 : Dynamics of the Indian-Ocean oxygen minimum zones, *Progress in Oceanography,* Volumes 112–113, Pages 15-37

McCreary, J. P., and coauthors, 2009: Biophysical processes in the Indian Ocean, *In: Indian Ocean Biogeochemical Processes and Ecological Variability, J.D.Wiggert, R.R. Hood, S.W.A. Naqvi, S.L. Smith, and K.H. Brink (ed.), American Geophysical Union, Washington, D. C,* pp 9-32.

McPhaden, M. J., and coauthors, 2009a: RAMA: Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction. *Bull. Am. Met. Soc.,***90,** 459-480.

McPhaden, M., and coauthors, 2009b: Ocean-Atmosphere Interactions During Cyclone Nargis, *Eos Trans. AGU,***90,** 53-54.

Meehl, G.A., and J.M. Arblaster, 2012: Relating the strength of the tropospheric biennial oscillation (TBO) to the phase of the Interdecadal Pacific Oscillation (IPO). *Geophys. Res. Lett.*, doi:10.1029/2012GL053386.

Menard, F., Benivary, H.D., Bodin, N., Coffineau, N., Le Loc'h, F., Mison,T., Richard, P. & Potier, M., 2013. Stable isotope patterns in micronekton from the Mozambique Channel. Deep-Sea Research II, http://dx.doi.org/10.1016/j.dsr2.2013.10.023

Menezes, V. V., H. E. Phillips, A. Schiller, C. M. Domingues, and N. L. Bindoff.,2013, Salinity dominance on the IO Eastern Gyral current, *Geophys. Res. Lett.,***40,** 5716–5721, doi:10.1002/2013GL057887

Morioka, Y., T. Tozuka and T. Yamagata, 2013: How is the Indian Ocean subtropical dipole excited? *Clim. Dyn.* **41:**1955-1968.

Morioka, Y., Tomoki Tozuka, S. Masson, P. Terray, J-J. Luo, Toshio Yamagata, 2012: Subtropical Dipole Modes Simulated in a Coupled General Circulation Model. *J. Climate*, **25**, 4029–4047.

Nagura, M., and M. J. McPhaden., 2008, The dynamics of zonal current variations in the central equatorial IO, *Geophys. Res. Lett.,***35,** L23603, doi:10.1029/2008GL035961.

Nagura, M., and M. J. McPhaden.,2013. Indian Ocean dipole interpreted in terms of recharge oscillator theory. *Climate Dynamics,* **42,** pp 1569-1586.

Nagura, M., and M. J. McPhaden, 2012: The dynamics of wind-driven intraseasonal variability in the equatorial Indian Ocean. *J. Geophys. Res., 115,* C07009, doi:10.1029/2011JC007405.

Neetu, S., M. and coauthors, 2012: Influence of oceanic stratification on tropical cyclones-induced surface cooling in the Bay of Bengal, *J. Geophys. Res.,***117,** C12020, doi:10.1029/2012JC008433.

Nidheesh, A.G., Matthieu Lengaigne, Jerome Vialard, A. S. Unnikrishnan, and H. Dayan, 2013: Decadal and long-term sea level variability in the tropical Indo-Pacific Ocean. *Clim. Dyn*., **41**, 381-402, DOI 10.1007/s00382-012-1463-4.

O'Rorke, R., Lavery, S., Chow, N., Takeyama, H., Tsai, P., Beckley, L.E., Thompson, P.A., Waite, A. M. & Jeffs, A. 2012. Determining the diet of larvae of Western Rock Lobster (*Panulirus cygnus*) using high-throughput DNA sequencing techniques. *PLoS ONE* 7(8): e42757. doi:10.1371/journal.pone.0042757

Ogata, T., Sasaki, H., Murty, V.S.N., Sarma, M.S.S., Masumoto, Y. 2008, Intraseasonal meridional current

Oke, P. R. and **A.** Schiller, 2007: A model-based assessment and design of a tropical Indian Ocean Mooring Array, *J. Climate*, 20, 3269-3283.

Palastanga, V., P. J. van Leeuwen, M. W. Schouten, and W. P. M. de Ruijter., 2007, Flow structure and variability in the subtropical IO: Instability of the South IO Countercurrent, *J. Geophys. Res.,***112,** C01001, doi:10.1029/2005JC003395.

Pearce, A. F., and M. Feng., 2013, The rise and fall of the "marine heat wave" off Western Australia during the summer of 2010/2011, *J. Mar. Sys., 111-112*, 139-156.

Potier, M., Bach, P., Ménard, F. & Marsac, F., 2013. Influence of mesoscale features on micronekton and large pelagic fish communities in the Mozambique Channel. Deep-Sea Research II, http://dx.doi.org/10.1016/j.dsr2.2013.10.026

Prakash,S., Balakrishnan Nair, T.M., Uday Bhaskar, T.V.S., Prakash, P. and Gilbert, D., (2012) Oxycline Variability in the central Arabian Sea: An Argo-Oxygen Study, *Journal of Sea Research*, 71, 1-8.

Prakash,S., Prakash, P. and Ravichandran, M. ,2013 Can oxycline depth be estimated using Sea Level Anomaly (SLA) in the northern Indian Ocean?, *Remote Sensing Letters*, Vol. 4, No. 11, 1097–1106

Prasanna Kumar, S., and coauthors, (2004), Are eddies nature's trigger to enhance biological productivity in the Bay of Bengal?, *Geophys. Res. Lett.*, *31*, L07309, doi:10.1029/2003GL019274.

Ravichandran, M., Girishkumar, M.S. and Riser, S., 2012. Observed variability of Chlorophyll-a using profiling floats in the Southeastern Arabian Sea, *Deep Sea Research* I, 65, 15-25.

Resplandy, and coauthors., 2012. Controlling factors of the oxygen balance in the Arabian Sea's OMZ. *Biogeosciences* **9,** 5095–5109.

Resplandy, L., J. Vialard, M. Lévy, O. Aumont, and Y. Dandonneau (2009), Seasonal and intraseasonal biogeochemical variability in the thermocline ridge of the southern tropical Indian Ocean, *J. Geophys. Res*., *114*, C07024, doi:10.1029/2008JC005246.

Resplandy, L., Lévy,M.,Madec, G., Pous, S., Aumont, O., Kumar, D., 2011. Contribution of mesoscale processes to nutrient budgets in the Arabian Sea. *Journal of Geophysical Research* **116,** C11007. http://dx.doi.org/10.1029/2011JC007006.

Ridderinkhof, H., P. M. van der Werf, J. E. Ullgren, H. M. van Aken, P. J. van Leeuwen, and W. P. M. de Ruijter (2010), Seasonal and interannual variability in the Mozambique Channel from moored current observations, *J. Geophys. Res.,***115,** C06010, doi:10.1029/2009JC005619.

Ridderinkhof, W., D. Le Bars, A. S. von der Heydt and W. P. M. de Ruijter, 2013. Dipoles of the south-east Madagascar Current. Geophys. Res. Letters, doi: 10.1002/grl.50157

Ridgway, K. R., and J. R. Dunn (2007), Observational evidence for a Southern Hemisphere oceanic supergyre, *Geophys. Res. Lett.,* **34,** L13612, doi:10.1029/2007GL030392

Roberts, M.J., Ternon, J.F. & T. Morris. 2013. Interaction of dipole eddies with the western continental slope of the Mozambique Channel. *Deep-Sea Research II*, http://dx.doi.org/10.1016/j.dsr2.2013.10.016

Rosell-Fieschi, M., S. R. Rintoul, J. Gourrion, and J. L. Pelegrí (2013), Tasman Leakage of intermediate waters as inferred from Argo floats, *Geophys. Res. Lett.,***40,** 5456–5460, doi:10.1002/2013GL057797.

Saji, N. H., S.-P. Xie, and C.-Y. Tam (2006b), Satellite observationsof intense intraseasonal cooling events in the tropical SouthIO, *Geophys. Res. Lett.,***33,** L14704, doi:10.1029/2006GL026525

Saunders, M.I, Thompson, P.A., Jeffs, A.G., Sawstrom, C., Sachlikidis, N., Beckley, L.E. & Waite, A.M. 2012. Fussy feeders: Phyllosoma larvae of the Western rock lobster (*Panulirus cygnus*) demonstrate prey preference. *PLoS ONE* 7(5): e36580. doi:10.1371/ journal.pone.0036580.

Schiller, A., S. E. Wijffels, J. Sprintall, R. Molcard and P. R. Oke, 2010: Pathways of Intraseasonal Variability in the Indonesian Throughflow Region, "Modeling and Observing the Indonesian Throughflow" A special issue of *Dynamics of Atmosphere and Ocean*, Guest Editors: A. L. Gordon and V. M. Kamenkovich, 50 (2010) 174–200.

Schoenefeldt, R., and F. Schott, 2006: Decadal variability of the Indian Ocean cross-equatorial exchange in SODA. *Gephys. Res. Lett*., **33**, L08602,, doi:10.1029/2006GL025891.

Schott, F. A., S.-P. Xie, and J. P. McCreary Jr., 2009, IO circulation and climate variability, *Rev. Geophys.*, **47**, doi:10.1029/2007RG000245.

Schott, F., and J.P. McCreary, 2001: The monsoon circulation of the IO. *Prog. Oceanogr.*, **51** , 1-123.

Sengupta, D., R. G. Bharath, and D. S. Anitha.,2008, Cyclone-induced mixing does not cool SST in the post-monsoon north Bay of Bengal,*Atmos. Sci. Lett.,***9,** 1–6, doi:10.1002/asl.162.

Sengupta, D., Senan R Murty, V.S.N., Fernando V. ,2004, A biweekly mode in the equatorial Indian Ocean. *J. Geophys. Res*., 109, C10003, doi: 10.1029, 2004JC002329.

Shinoda, T., and W. Han, 2005: Influence of Indian Ocean dipole on atmospheric subseasonal variability. *J. Climate*, 18, 3891-3909.

Shinoda, T., M. A. Alexander, H. H. Hendon, 2004: Remote Response of the Indian Ocean to Interannual SST Variations in the Tropical Pacific. *J. Climate*, **17**, 362–372.

Speich, S., B. Blanke, and W. Cai.,2007, Atlantic meridional overturning circulation and the Southern Hemisphere supergyre, *Geophys. Res. Lett.,* **34,** L23614, doi:10.1029/2007GL031583.

Ternon J.F., Barlow, R.G., Huggett, J.A., Kaehler, S., Marsac, F., Menard, F., Potier, M. & Roberts, M. 2013. An overview of recent field experiments on the ecosystem's mesoscale signature in the Mozambique Channel: from physics to upper trophic levels. *Deep-Sea Research II,* http://dx.doi.org/10.1016/j.dsr2.2013.10.012

Terray, L., L. Corre, S. Cravatte, T. Delcroix, G. Reverdin, and A. Ribes, 2012: Near-surface salinity as nature's rain gauge to detect human influence on the tropical water cycle. *J. Clim.*, **25**, 958–977, doi:10.1175/JCLI-D-10-05025.1.

Thompson, P.A., Wild-Allen, K., Lourey, M., Rousseaux, C., Waite, A.M., Feng, M., Beckley, L.E. (2011), Nutrients in an oligotrophic boundary current: Evidence of a new role for the Leeuwin Current, *Progress in Oceanography*, **91**(4): 345-359. doi: 10.1016/j.pocean.2011.02.011

Tozuka, T., J.–J. Luo, S. Masson, and T. Yamagata, 2007: Decadal modulations of the Indian Ocean Dipole in the SINTEX-F1 coupled GCM. *J. Climate*, **20,** 2881-2894.

Trenary L., and W. Han, 2013: Remote and local forcing of decadal sea level and thermocline depth variability in the south Indian Ocean. *J. Geophys. Res*., **118**, 381-398, doi:10.1029/2012JC008317.

Ullgren, J., H.M. van Aken, H. Ridderinkhof and W.P.M. de Ruijter, 2012, The hydrography of the Mozambique Channel from six years of continuous temperature, salinity and velocity observations across the Channel. Deep Sea Res., 69, 36-50.

Vecchi, G. A., and M. J. Harrison, 2007: An observing system simulation experiment for the Indian Ocean. *J. Climate,* **20,** 3300–3319.

Vialard, J., and coauthors, 2009a: Cirene : Air-sea interactions in the Seychelles-Chagos Thermocline Ridge region. *Bull. Amer. Meteor. Soc.*, **90**, 45-61.

Vialard, J., and coauthors, 2009b: Intraseasonal response of Northern IO coastal waveguide to the Madden-Julian Oscillation, *Geophys. Res. Lett*., **36,** L14605, doi:10.1029/2008GL037010.

Vialard, J., and coauthors, 2012: Processes of 30-90 day sea surface temperature variability in the Northern IO during boreal summer, *Clim. Dyn*., **38,** 1901-1916.

Vialard, J., and coauthors, 2013: Understanding Madden-Julian-Induced sea surface temperature variations in the North Western Australian Basin, *Clim. Dyn*.,**41,** 3203-3218.

Waite, A. M., Thompson, P. A., Pesant, S., Feng, M., Beckley, L. E., Domingues, C. M., Gaughan, D., Hanson, C. E., Holl, C. M., Koslow, T., Meuleners, M., Montoya, J. P., Moore, T., Muhling, B. A., Paterson, H., Rennie, S., Strzelecki, J., Twomey, L. 2007. The Leeuwin Current and its eddies: an overview. *Deep-Sea Research II,* **54**, 789-796.

Wang, J.-W., and W. Han (2014), The Bay of Bengal upper-ocean response to tropical cyclone forcing during 1999, J. Geophys. Res. Oceans, 119, 98–120, doi:10.1002/2013JC008965.

Weller, E., Holliday, D., Feng, M., Beckley. L.E. & Thompson, P.A. 2011. A continental shelf scale examination of the Leeuwin Current off Western Australia during the austral autumn-winter. *Continental Shelf Research* doi:10.1016/j.cr.2011.08.008

Wiggert, J.D., J. Vialard, and M.J. Behrenfeld, 2009: Basin-wide modification of dynamical and biogeochemical processes by the Indian Ocean Dipole. *In: Indian Ocean Biogeochemical Processes and Ecological Variability, American Geophysical Union, Washington, D. C,* pp 385-408.

Wijffels SE, Meyers G, Godfrey JS.,2008: A Twenty Year Average of the Indonesian Throughflow: Regional Currents and the Inter-basin Exchange. *J. Phys. Oceanogr* **38** (8)**,** 1-14.

Woo, M. and Pattiaratchi, C., 2008: Hydrography and water masses off the Western Australian coast. *Deep-Sea Research I*, **55** (9), 1090-1104.

Xie, S.-P., H. Annamalai, F.A. Schott and J.P. McCreary, 2002: Structure and mechanisms of south Indian climate variability, *J. Climate,* **9,** 840-858.

Xie, S.-P., K. Hu, J. Hafne, H. Tokinaga, Y. Du, G. Duang and T. Sampe, 2009 : Indian Ocean capacitor effect on Indo-western Pacific climate during the sumer following El Niño. *J. Clim.,* **22,** 730-747.

Yamagata, T., S. K. Behera, J.-J. Luo, S. Masson, M. Jury, and S. A. Rao, 2004: Coupled ocean-atmosphere variability in the tropical IO, in Earth Climate: The Ocean-Atmosphere Interaction, *Geophys. Monogr. Ser*.,**147,** pp. 189–212, AGU, Washington, D. C.

Yanase, W., et al., 2012 : Seasonal and Intraseasonal Modulation of Tropical Cyclogenesis Environment over the Bay of Bengal during the Extended Summer Monsoon, *Journal of Climate*,**25**, 2914-2930.

Yokoi, T., T. Tozuka, and T. Yamagata. 2008, Seasonal variation of the Seychelles Dome, *J. Climate, 21*, 3740-3754.

Yoneyama, K., and Coauthors, 2008: MISMO field experiment in the equatorial IO. *Bull. Amer. Meteor. Soc.*, **89**, 1889-1903.

Yoneyama, K., C. Zhang, and C. N. Long, 2013: Tracking pulses of the Madden-Julian Oscillation. *Bull. Amer. Meteor. Soc.*, **94**, 1871-1891.

Yu, L., and M. J. McPhaden (2011), Ocean preconditioning of CycloneNargis in the Bay of Bengal: Interaction between Rossby waves, surfacefresh waters, and sea surface temperatures, *J. Phys. Oceanogr.*,**41,** 1741–1755, doi:10.1175/2011JPO4437.1.

Zhang, C., 2013: The Madden-Julian Oscillation: Bridging weather and climate. *Bull. Amer. Meteor. Soc.*, **94**, 1849-1870.

Zhang, C., J. Gottschalck, E. D. Maloney, M. W. Moncrieff, F. Vitart, D. E. Waliser, B. Wang, and M. C. Wheeler (2013), Cracking the MJO nut, Geophys. Res. Lett., 40, 1223–1230, doi:10.1002/grl.50244.

Zhou, L, Muttugudde, R & Jochum, M., 2008, Dynamics of the Intraseasonal Oscillations in the IO South Equatorial Current*Journal of Physical Oceanography***38,** 121-132.