Eastern Indian Ocean Upwelling Research Initiative (EIOURI)

The EIOURI Science Plan

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February 29, 2016

SUMMARY

The eastern Indian Ocean (EIO) is an area of active ocean-atmosphere interactions, affecting monsoons and other regional and global climate variations. In turn, variability in monsoonal winds and rainfall together with water mass exchanges with surrounding regions, including the unique throughflow from the Pacific, modify physical and biogeochemical conditions in the EIO. Although upwelling in the EIO is an essential process modulating the upper-ocean conditions within a warm water pool region and connecting regional physics with biogeochemistry, ecology and climate variations, our understanding of the characteristics and mechanisms of the upwelling systems and their roles in larger systems in the ocean and climate are very limited due mainly to scarcity of *in situ* observations both in physical and biogeochemical parameters.

Motivated by the critical need to understand coupled ocean-atmosphere dynamics leading upwelling in the eastern Indian Ocean, their impacts on local oceanographic characteristics, ecological systems and economies and their vulnerabilities to climate change, an international research collaboration, the Eastern Indian Ocean Upwelling Research Initiative (EIOURI) is proposed for a period of five years, beginning in December 2015. EIOURI mainly focuses on upwelling processes along the coast of Sumatra and Java, which is a largest upwelling system in the EIO, but also includes research interests in other coastal and open-ocean upwelling systems in the EIO and their impacts on adjacent ocean systems. EIOURI covers *i*) physical processes, *ii*) biogeochemistry and ecology, *iii*) bio-physical relations, and *iv*) societal impacts of the upwelling systems, with research activities involving *in situ* and remote observations, analyses of existing datasets, and numerical and analytical modeling. EIOURI will also contribute as one of core programs of the International Indian Ocean Expedition-2 (IIOE-2), a broad basin-scale research initiative that will be conducted under SCOR, IOC and IOGOOS during the same period.

EIOURI will advance our knowledge of the biophysical dynamics of upwelling systems and their response to climate variability and change and their socio-economic impacts. In addition, EIOURI will increase scientific capacity in the EIO, and enhance international collaboration in the region. EIOURI will establish a solid foundation of regional knowledge on physical, biogeochemical and ecological aspects of ocean variability upon which future research can build. New insights obtained during EIOURI will be utilized by the wider research communities and policy makers in the region to improve management of marine resources. In addition, capacity building components of EIOURI's observational activities will contribute to sustaining the current basin-scale observing system and lead in further development of regional ocean observing capabilities.

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1. Introduction

The Indian Ocean is unique among the three tropical oceans in being blocked by a continental landmass at about 25°N. Monsoonal winds and intense seasonal rains over the Indian subcontinent, Southeast Asia, East Africa, and Australia, resulting from seasonal heating and cooling of the land, generate rich and complex seasonal variations of upper-ocean conditions, with dramatic current reversals particularly in the northern hemisphere. The Indonesian throughflow (ITF) from the western Pacific Ocean has water mass and biogeochemical characteristics that differ substantially for those in the Indian Ocean, causing unique distributions of physical and biogeochemical parameters in the southeastern part of the basin. In addition, both short time-scale variability, such as meso-scale eddies and intraseasonal disturbances forced by the atmosphere, and much longer time-scale phenomena, like interannual variations associated with the Indian Ocean Dipole (IOD) and the Pacific El Niño/Southern Oscillation (ENSO), strongly modify seasonal variations over a large part of the Indian Ocean and in the eastern Indian Ocean (EIO) in particular.

Surface waters of the EIO are mostly warmer than 28°C, providing the necessary condition for active interaction between the ocean and atmosphere. Variability in the surface temperature and salinity affects physical and biogeochemical/ecological phenomena within the region as well as globally. Upwelling in the EIO is one of the processes that modulates the upper-ocean conditions by connecting key factors responsible for maintaining the mean fields and their variability, such as the equatorial and coastal wave guides, coastal and open-ocean exchanges, surface and subsurface variability, physical forcing and biogeochemical/ecological responses, and ocean and climate variations. Despite their importance for climate systems, material circulations, and socio-economic influences, the complex interactions of physical and biogeochemical processes associated with upwelling are not fully understood. This is due mainly to the sparseness of observational/experimental data and to the multi-scale aspects of upwelling that are difficult to measure and simulate in climate/ocean models.

CLIVAR and IOGOOS have developed a basin-scale observing system in the Indian Ocean (IndOOS) that is centered around the deployment of a mooring array (the Research moored Array for African-Asian-Australian Monsoon Analysis and Prediction or RAMA) along with repeated XBT lines, surface drifters, profiling floats, and ship-based hydrography surveys. This observing system has led to a better understanding of large-scale physical phenomena, such as climate modes and planetary wave propagations, but observations of the region's upwelling systems are still very limited due to their intrinsically smaller scales associated with eddies and coastal boundary processes. These processes (and their biological impacts) cannot be understood without more focused, smaller scale process studies and observations.

Motivated by these issues, interested scientists initiated discussions on ways to fill the scientific gaps about upwelling systems of the EIO with a focused research initiative. Three planning workshops were held; the first at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) in Yokohama, Japan on 25-26 April 2013, the second at the First Institute of Oceanography/State Oceanic Administration in Qingdao, China on 18-19 Nov. 2013, and the third at the Marine Biological Center in Phuket, Thailand. on 9-12 Apr. 2014.

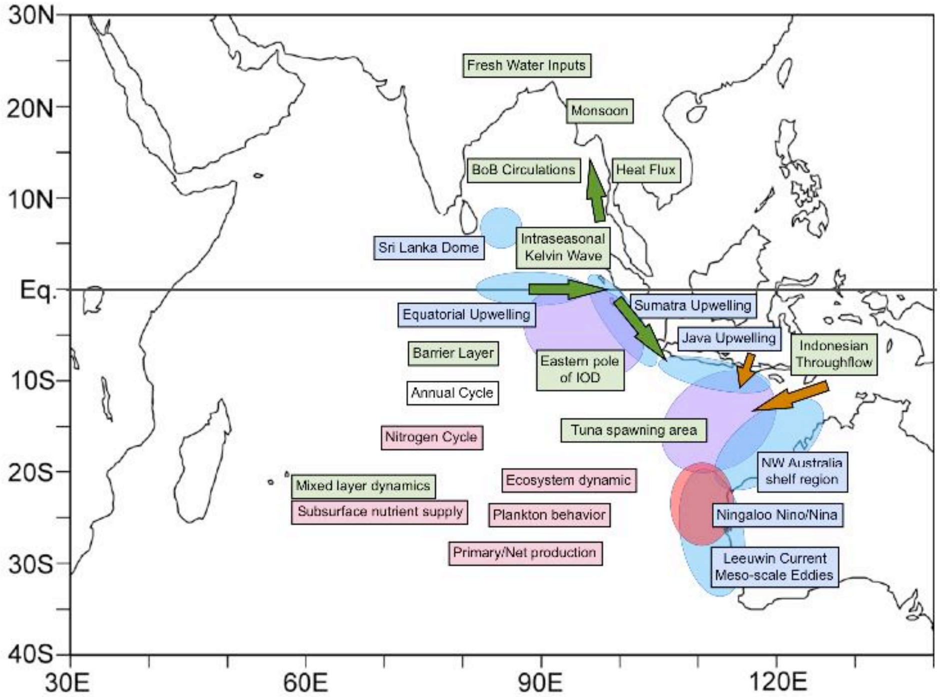

Figure 1-1: Target area and relevant processes of EIOURI

Additional discussions were held on 23 Jun. 2014 at the Open Science Conference of the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) program in Bergen, Norway. A diagram indicating the possible target areas and processes of the Eastern Indian Ocean Upwelling Research Initiative (EIOURI) is shown in Fig. 1-1.

This EIOURI science plan is a summary of the three planning workshops and a prospectus for further investigations of upwelling systems in the EIO, as a core research initiative of the Second International Indian Ocean Expedition (IIOE-2) that is being carried out during 2015 to 2020 (see Hood et al., 2015). EIOURI mainly focuses on upwelling along the equatorial EIO and in an area between the southern coast of Sumatra-Java-Alor and northwestern coast of Australia, but it does not exclude other upwelling systems in the EIO, such as coastal upwelling in the Bay of Bengal, the Sri Lanka Dome region, and eddy-induced upwelling in the open ocean.

2. Physical oceanography

Focusing on the upwelling along the island chain stretching thousands of kilometres from Sumatra, Java, Bali, Lombok, Flores to Alor (hereinafter Sumatra-Java-Alor) and the northwestern coast of Australia, we advance the following two hypotheses as major areas of physical oceanographic interest for EIOURI.

1. Upwelling along the Sumatra-Java-Alor coast is influenced by both local wind stress forcing and wind stress variability further to the west in the equatorial waveguide. Similarly, upwelling along the northwestern coast of Australia is affected by local winds

and signals from the Pacific Ocean, transmitted through coastal waveguides. The timing, duration, intensity, and spatial structure of upwelling depend on the relative importance of these local and remote drivers.

2. The strongest upwelling signal is concentrated within O(100km) of the coasts, while the broader spatial extent of SST cooling during the upwelling season reflects horizontal advection of cold upwelled water masses offshore, modified by air-sea heat exchanges and internal variability in the ocean, such as meso-scale eddies.

2.1 Upwelling processes: local and remote forcing

(1) Ocean circulation and ocean-atmosphere interaction

Basin geometry, combined with monsoonal wind forcing, defines a unique and complex three-dimensional circulation in the tropical Indian Ocean (Schott et al., 2009). The Asian landmass blocks the ocean circulation to the north, so that currents cannot carry heat from the tropics to higher northern latitudes as in the other oceans. On the other hand, the upper Indian Ocean is fed fresh warm water from the Pacific via the Indonesian throughflow (Sprintall et al., 2009) while leaking mass to the Atlantic via the Agulhas Current system (Beal et al., 2011) as part of the upper branch of the global meridional overturning circulation. North of 10°S, the circulation is characterized by dramatic wind-forced seasonal reversals of the Somali Current, flows along and immediately to the north of the equator, and along the coasts of India. Intense semi-annual eastward flows along the equator in boreal spring and fall — the Wyrtki jets (Wyrtki, 1973) — are generated by strong westerly winds in the transitions between the winter and summer monsoons.

Ocean–atmosphere interactions in the basin are highly dynamic, involving vigorous exchanges of heat across the air–sea interface on a range of time scales of relevance to climate. Feedbacks between the ocean and the atmosphere help to generate unique phenomena spawned in the Indian Ocean, such as the Madden-Julian Oscillation (MJO; Zhang, 2005), the IOD (Saji et al., 1999; Webster et al., 1999), and the subtropical dipole (Behera and Yamagata, 2001). Feedbacks between the ocean and the atmosphere also modulate the impacts of forcing from the Pacific associated with ENSO teleconnection.

The existence of the ITF contribute to the meridional steric height gradient in the south-east Indian Ocean, which drives the surface eastward flows toward the Australian coast and the poleward flowing eastern boundary current, the Leeuwin Current (Godfrey and Ridgway, 1985; Smith et al., 1991). The Leeuwin Current brings warm, lower salinity tropical waters southward along the West Australia coast, and has profound impacts of the regional climate and marine ecosystem (Pearce & Phillips 1988; Caputi et al., 1996). ENSO variability in the Pacific tends to drive interannual variations of the ITF transport (Meyers, 1996; Wijffels and Meyers, 2004), and downstream along the coastal waveguide to affect the interannual variations of the Leeuwin Current (Feng et al., 2003). La Niña is also associated with heavy precipitation in the Indonesian seas and has caused substantial freshening of the ITF during an extended event (Phillips et al., 2005), as well as the Leeuwin Current (Pearce and Feng, 2007). The Leeuwin Current is predominantly a downwelling current (Thompson, 1984), due to onshore geostrophic flow and related surface convergence.

Monsoonal rather than steady trade wind forcing at low latitudes of the Indian Ocean means that, unlike in the Pacific and Atlantic Oceans, there is no permanent eastward flowing equatorial undercurrent in the thermocline. Instead, a transient undercurrent appears in March and again, with weaker amplitude, in September (Iskandar et al., 2009). In addition, lack of steady trades means that there is no permanent upwelling centered on the equator. Instead, water subducted at higher latitudes is upwelled in a variety of off-equatorial locations, including the Somali Coast, the Seychelles-Chagos Thermocline Ridge (SCTR), The Sri Lankan Dome, along the coasts of Java and Sumatra, and off the coast of Northwest Australia. Upwelling in these regions is strongly modulated seasonally by monsoon wind forcing. Interannually, large variations in upwelling also occur in the SCTR and off Java and Sumatra associated with the IOD and ENSO. Cold sea surface temperatures (SSTs) in these upwelling zones stabilize the atmospheric boundary layer, affecting exchanges of heat and momentum across the air-sea interface (Vecchi et al., 2004).

The existence of coastal upwelling along the Northwest Shelf of Australia was first suggested by Schott (1933) and Wyrtki (1962). Holloway and Nye (1985) showed that weak upwelling events occurred, both in the summer and winter months, along the Northwest Shelf when the currents were flowing north-eastward and suggested that this north-east flow occurred when the south-west winds were sufficiently strong to overcome the steric height gradient and thus to reverse the dominant south-westward flow. Off the west coast of Australia, localized short-term upwelling occurs sporadically where the continental shelf is narrow such as at the Capes (Gersbach et al., 1999; Hanson et al., 2005) and Ningaloo (Hanson et al., 2005, Woo et al., 2006, Rossi et al., 2013) as well as north of Rottnest Island due to flow curvature of the Capes Current around the western end of the Island (Alaee et al., 2007). These upwellings predominantly occur during the austral summer, due to the prevailing southerly wind. Rossi et al. (2013) pointed out that upwelling can also occur due to the interaction between the onshore geostrophic flow and the shelf bottom bathymetry during other seasons. It has also been found that the interaction between the Leeuwin Current meander/eddies and the shelf bathymetry can drive localized upwelling events (Koslow et al., 2008).

Key questions include: How does the variability in ocean currents and air-sea interactions at intraseasonal to interannual time-scales influence upwelling dynamics and phase propagation of upwelling signals along Sumatra-Java-Alor? What are detailed mechanisms responsible for such influences? How does variability of the ITF and Leeuwin Current affect the upwelling system off northwestern Australia?

(2) Seasonal development and decay of the upwelling off Sumatra-Java-Alor coasts

Forced by the Asian-Australian monsoon, the eastern boundary upwelling in the Indian Ocean develops most significantly along Sumatra-Java-Alor coasts during the southeast monsoon period. A quick check of the seasonal feature of this upwelling evolution reveals a dramatic contrast between its progressive development from eastern end of the island chain to the west and its almost simultaneous retreat (Fig. 2-1). The cool temperature signal of upwelling first occurs east of Lombok Island from late April to early May. Then, it proceeds westward along the south Java coast, reaching the Sunda Strait in late June, from where it further marches northwest to the west coast of southern Sumatra in early August. However, the upwelling retreat in October is very rapid and simultaneous across the whole island chain. The peak upwelling season is August, with its strongest signal south of Java. A key question associated with the seasonality of upwelling is: **What drives the progressive development of upwelling along Sumatra-Java-Alor, in contrast to its quick retreat?**

One hypothesis is that the upwelling manifests as a direct response to the monsoon forcing. The along-shore monsoon wind does develop progressively along the island chain as the monsoon trough and convection center are set in the northern Bay of Bengal. However, the process may be more complex. Another hypothesis invokes the potential air-sea coupling associated with the Lindzen-Nigam mechanism (Lindzen and Nigam, 1987), i.e., the SST gradient along Sumatra-Java-Alor drives the along-shore wind and vice versa. More work is needed to confirm the above hypothesis. One application of this research is to better understand the local climate variations along Sumatra-Java-Alor, from the wet climate in Sumatra and Java to very dry climate in Alor, which is also reflected in landscape changes along this island chain. A key question is: **What are the governing mechanisms of SST seasonal cycle in the Sumatra-Java-Alor upwelling region?**

SST is usually taken as the upwelling indicator. However, the upwelling region along Sumatra-Java-Alor is within the tropical convection center and exposed to the ITF, which makes the SST mechanism very complex. The strong negative SST-cloud-radiation feedback (Li et al., 2003; Liu et al., 2011) and advection contribution from the ITF blur the upwelling footprint on SST. Detailed diagnosis needs to be done to clarify the different contributions from upwelling, surface heat-flux and horizontal advection to the SST evolution. For this, the key questions are: **How well is the Sumatra-Java-Alor upwelling resolved in coupled climate models (like CMIP), and what is its future projection?**

Since the Sumatra-Java-Alor upwelling plays a critical role in the local and basin climate

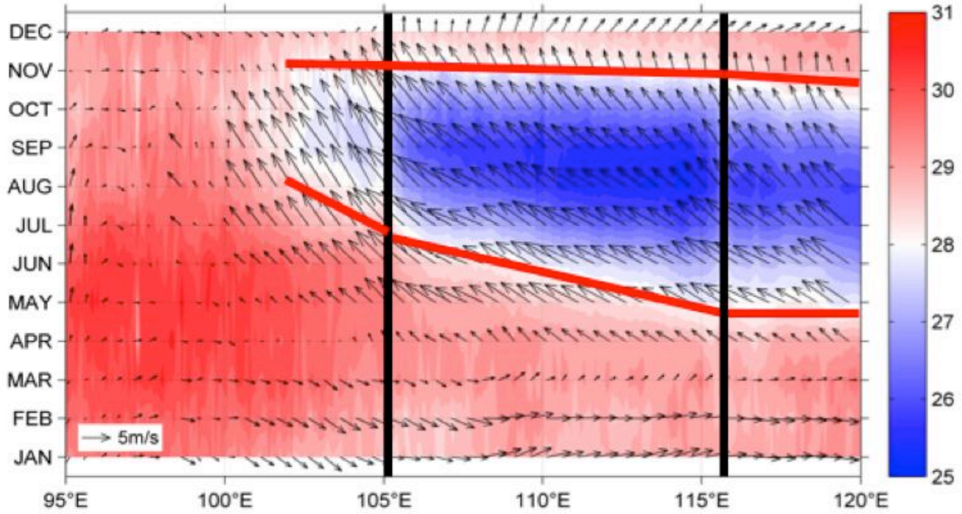

Figure 2-1: The mean seasonal cycle of the AVHRR SST (color) and QSCAT wind (vector) evolution along the eastern Indian Ocean boundary. The two vertical black lines (from left to right) indicate the locations of Sunda Strait and Lombok Strait. The red lines illustrate the envelope curve of upwelling development and decay.

(and even beyond), CMIP-type coupled climate models should be checked to see if they are capable of resolving the upwelling process. If not, then what are the consequent errors introduced into the model climate? It would also be highly desirable to learn the future projection of the Sumatra-Java-Alor upwelling in the model warming scenarios.

(3) Intra-seasonal and inter-annual variability

The defining feature of climate variability in the Indian Ocean region is the seasonal monsoon, i.e. the seasonally reversing monsoon winds and ocean currents, and the shifting patterns of seasonal rainfall that are an integral part of history, culture, and economies of Indian Ocean rim countries. Embedded within this seasonal cycle is a range of interacting time scales with tropical cyclones and synoptic-scale weather events at one end of the spectrum and interannual and decadal fluctuations at the other. In addition, significant multi-decadal trends have been detected in warming SSTs, rising ocean heat content, and wind stress patterns which may be a manifestation of human induced climate change (Han et al., 2014). A complete understanding of the climate system in the Indian Ocean region must take into account this broad range of interacting time scales. Below, we describe some of the highlights of variability on intraseasonal to interannual time scales that are likely to have greatest impacts on short-term studies of upwelling in the eastern Indian Ocean.

The most prominent intraseasonal (i.e., weekly to monthly time scale) oscillation is the MJO (Fig. 2-2), which is an eastward-propagating wave-like phenomenon in the atmosphere with a period of roughly 30–60 days (Madden and Julian, 1994; Zhang, 2005). Convection associated with MJO develops over the warm SSTs (≥27°C) of the central Indian Ocean and subsequently propagates eastward as part of a planetary-scale fluctuation. Interaction with the oceanic mixed layer plays an important role in fueling MJO growth and organizing convection (Yoneyama et al., 2013), while surface zonal winds associated with the MJO generate energetic eastward-propagating oceanic Kelvin waves (Han, 2005; Nagura and McPhaden, 2012). These waves, upon encountering Sumatra, continue poleward as coastally trapped waves (Iskandar and McPhaden, 2011; Suresh et al., 2013). Coastally trapped intraseasonal wave energy that propagates southeastward off Sumatra and Java eventually leaks into the Indonesian seas through the Lombok Strait, where it affects ITF transport

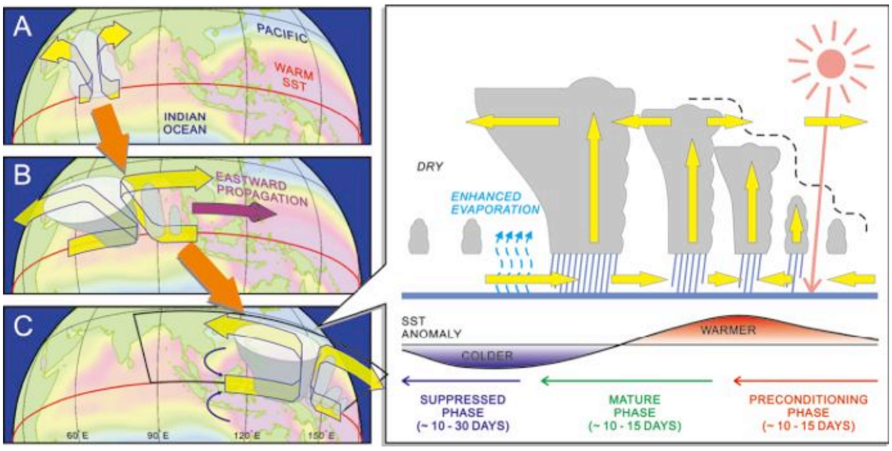

Figure 2-2: Schematic view of the Madden-Julian Oscillation. (After Yoneyama et al., 2008)

(Syamsudin et al., 2004; Pujiana et al., 2013). The MJO is strongest in boreal winter and spring in the southern tropics, with a secondary peak during boreal summer north of the equator (Zhang 2005).

Another prominent mode of intraseasonal variability in the Indian Ocean is the so-called "bi-weekly wave" with energy concentrated at periods of 10-20 days (Sengupta et al., 2004). These waves are primarily forced by fluctuations in the meridional winds at similar periods and have the character of mixed Rossby gravity waves trapped to the equator (e.g. Ogata et al., 2008). They are ubiquitous features of the Indian Ocean circulation and are prominent especially in records of meridional velocity near the equator. Key questions include: **How does oceanic intraseasonal variability affect the upwelling systems off Sumatra and Java? How do the equatorial signals and coastal upwelling interact with each other?**

The Indian Ocean exhibits pronounced interannual variations, the most prominent of which are in response to remote forcing from ENSO in the Pacific (Yamagata et al., 2004; Schott et al., 2009). For example, El Niño leads to an eastward shift in the ascending branch of Walker circulation into the central Pacific, with anomalous subsidence, suppressed convection, high atmospheric surface pressure, and anomalous easterlies over the tropical Indian Ocean. El Niño's influence on precipitation in the Indian Ocean region typically includes reduced rainfall over Indonesia, reduced Indian summer monsoon rainfall, and enhanced rainfall in equatorial East Africa. In boreal spring following the peak of El Niño, basin-scale warming occurs as a result of the combination of increased surface heat fluxes and downwelling Rossby waves south of the equator forced by anomalous ENSO-induced surface wind stresses (Xie et al., 2002; Yu et al., 2005; Schott et al., 2009). This warming leads to increased rainfall during the following boreal summer over much of the basin, extending in time the influence of El Niño on the Indo- and west Pacific monsoon circulation (Yang et al. 2007). La Niña typically has opposite effects on the Indian Ocean.

The IOD is another prominent mode of interannual variability in the Indian Ocean (Fig. 2-3). The IOD arises from coupled ocean–atmosphere interactions that, like those associated with ENSO, develop via feedbacks between zonal wind stress, SST, and thermocline depth anomalies. Positive IOD events are characterized by anomalously cold SSTs and suppressed

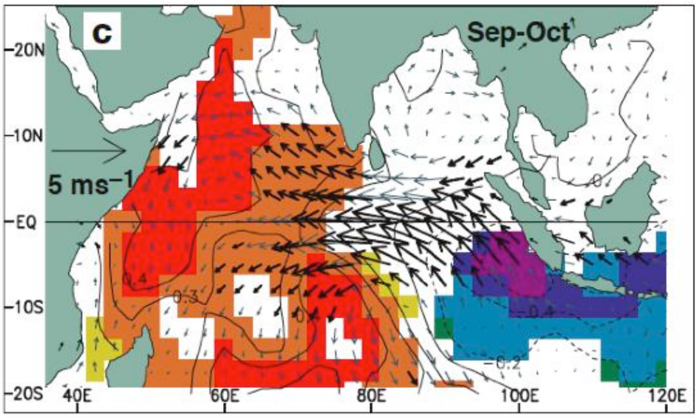

Figure 2-3: Horizontal distribution of SST anomaly (contours and shade) and surface winds (vectors) during Sep.-Oct. season, when the typical IOD takes its mature phase. Color shade and bold arrows indicate statistically significant values. (After Saji et al., 1999)

atmospheric convection off Java and Sumatra, warm SSTs and enhanced convection off East Africa, and easterly wind anomalies along the equator. Negative IOD events develop with anomalies and climatic influences roughly opposite to those of positive events.

ENSO and IOD events often co-occur, with ENSO forcing from the Pacific triggering IOD events through changes in the Walker circulation spanning the two basins. However, not all IOD events are linked to ENSO (Meyers et al., 2007) so that the IOD can be viewed as an independent mode of variability in the Indian Ocean basin. Indeed, it has been argued that ocean-atmosphere interactions in the Indian Ocean associated with the IOD are able to influence the subsequent development of ENSO events up to a year in advance (Izumo et al., 2010).

IOD events are shorter lived than ENSO events, with largest oceanic and atmospheric anomalies confined mostly to the boreal fall season. Annual mean winds along the equator are westerly in the Indian Ocean, tilting the thermocline down to the east. Thus, it is only during the normal September–November upwelling season off the coast of Java and Sumatra when the thermocline is brought close enough to the surface that wind-SST feedbacks can fully develop. In the eastern pole of the IOD, upwelling occurs at a rate of ~3 Sv during normal periods, increasing by 40-50% during positive IOD events and reducing effectively to zero during negative IOD events (Nyadjro and McPhaden, 2014). After that, SST anomalies in the Java-Sumatra upwelling region are overwhelmed by strong seasonality associated with the onset of the northeast monsoon (Tokinaga and Tanimoto, 2004) and by equatorial wave processes that favor a return to normal (McPhaden and Nagura, 2014).

Wyrtki jets in the boreal fall season are typically much weaker during positive IOD events because westerly monsoon transition winds along the equator are weaker (Nagura and McPhaden, 2010). Anomalous westward flow in these currents advects cold water upwelled from the coast of Indonesia westward, contributing to IOD development (Murtugudde et al., 2000). Opposite tendencies occur during negative IOD events. The combined effects of coincident positive IOD events and El Niño, or negative IOD events and La Niña, on the Wyrtki jets are larger than when either IOD or ENSO occur separately (Gnanaseelen et al., 2012).

During the February/March 2011 Ningaloo Niño (marine heatwave), nearshore water temperatures along the Gascoyne and mid-west coast of Western Australia exceeded 5°C above the long-term average for that time of year. This has been attributed to both a very strong Leeuwin Current (anomalously high coastal sea levels) during an intense La Niña period and anomalously high air-sea heat flux entering the ocean (Pearce and Feng, 2013; Feng et al., 2013). Strong anomalies in easterly Trade winds in the equatorial western Pacific and low sea level pressure anomalies off the west coast of Australia have been identified as important in causing the local wind and Leeuwin Current anomalies in early 2011, resulting in the peak of the Ningaloo Niño events (Feng et al., 2013). Historical occurrences of Ningaloo Niño events are found to be associated with La Niña in the Pacific, positive phase of the Southern Annular Mode, Australian monsoon, as well as local air-sea coupling (Katoaka et al., 2013). The Ningaloo Niño (marine heat wave) events appear to have suppressed the coastal upwelling along the west coast of Australia in the austral summer, with devastating effects on the marine biota, with massive mortality in some areas (Wernberg et al., 2012).

MJO related intra-seasonal wind anomalies can also influence the intra-seasonal variability of the Leeuwin Current (Marshall and Hendon, 2014), as well as presumably affecting the intra-seasonal variations of coastal upwelling. Key questions include: **How do the interannual climate modes affect the upwelling system off the coast of Sumatra-Java-Alor and the upwelling associated with the Ningaloo Niño/Niña? What is the ratio of ocean teleconnection impacts from the Pacific ENSO signal to those through the atmospheric teleconnection? Are there any mutual interactions among the climate modes via upwelling variability in the eastern Indian Ocean?**

(4) Local Wind Forcing and Remotely Forced Equatorial Waves

A fundamental concept in the study of eastern boundary current regimes of the world ocean is that upwelling in these regions results from a combination of local and remote wind forcing, with the timing, intensity, duration, and spatial structure of upwelling determined in part by the relative influence of these two distinct driving forces. Coastal geometry, sea floor bathymetry, and density stratification in the water column also affect the character of upwelling, so that its detailed evolution in time and space is very much region and time dependent. For the Sumatra- Java-Alor upwelling region, wind forcing involves along shore winds that lead to local divergence and convergence of surface water in the coastal zone, remote near shore forcing from locations poleward along the coast, and remote forcing from the equator. The spatial structure of local winds is also important, since near-shore wind stress curl, in addition to the along shore wind component, can affect coastal upwelling and downwelling circulations. Key questions include: **How do these various forcing functions combine to affect upwelling off of Java and Sumatra, and by extension SST, sea level, nutrient supply, biological productivity and fisheries?**

Local along-shore winds lead to rapid changes in upwelling since ocean currents in the surface Ekman layer adjust on the time scale of an inertial period, which is O(days) at low latitudes. Local offshore transport of surface water must be balanced by upwelling on these short time scales. Wind stress variations along the coast also generate coastally trapped waves that propagate poleward, affecting locations to the south of where the wind changes occur. Along Java and Sumatra, local winds are mostly upwelling favorable in May-October during the Southwest monsoon, when near-shore winds have a significant southeasterly component in the eastern basin. The ocean response to these seasonally varying winds in terms of SST cooling is greatest along the Java coast, less so along the Sumatra coast (see Fig. 2-1).

Remote wind forcing from near the equator is also an important factor controlling upwelling along the Java and Sumatra coasts. The trapping of wind-forced energy in a waveguide within several degrees of the equator allows for efficient transmission of planetary scale waves over thousands of kilometers in the Indian Ocean. Eastward propagating wind forced equatorial Kelvin waves can transit the entire width of the Indian Ocean in just a few weeks. When they hit the coast of Sumatra, some of the energy is reflected back into the interior in the form of westward propagating equatorial Rossby waves, but some energy is also channeled poleward in the coastal waveguide. The relative mix of reflected vs coastal waveguide transmitted energy depends on the frequency and location along the coast, with coastal trapping being more efficient at higher latitudes and for higher frequency forcing.

Equatorial wave processes operate on a very broad spectrum of time scales in the Indian Ocean from the inertia-gravity wave range with periods of O(days), to intraseasonal times scales (e.g., biweekly waves and equatorial wave responses to MJO forcing), to the seasonal cycle, to interannual time scales associated with the IOD (Luther, 1980; Xie et al., 2002; Sengupta et al., 2004; Han, 2005; Nagura and McPhaden, 2010a,b; 2012; McPhaden and Nagura, 2014). The importance of these waves in controlling variability in large-scale ocean circulation, sea level, and SST in the open Indian Ocean has been the subject of considerable interest for many years. During positive IOD events, for example, significant SST cooling occurs during boreal summer and fall not only along the coast of Java but off the coast of Sumatra. The cooling off Sumatra is mediated by thermocline shoaling associated with easterly equatorial wind stress anomalies that generate upwelling equatorial Kelvin waves. Zonal advection spreads this cold upwelled water offshore during these IOD events to cool much of the eastern equatorial Indian Ocean (Murtugudde et al., 2000).

Seasonal upwelling off the Northwest Shelf and the west coast of Australia are predominantly forced locally by alongshore winds and mesoscale eddies (Fig. 2-4). Due to the existence of the equatorial Pacific waveguide and the Clarke-Meyers waveguide along the New Guinea and Australian shelf (Meyers 1996; Clarke and Liu 1994), interannual variations of the thermocline depth anomalies in the Equatorial Western Pacific, associated with ENSO variability, propagate through the Indonesian archipelago along the waveguide, influencing the thermocline depths along the West Australia coast (Feng et al., 2003). The modulation of the thermocline depths on the interannual time scale related to ENSO appears to influence

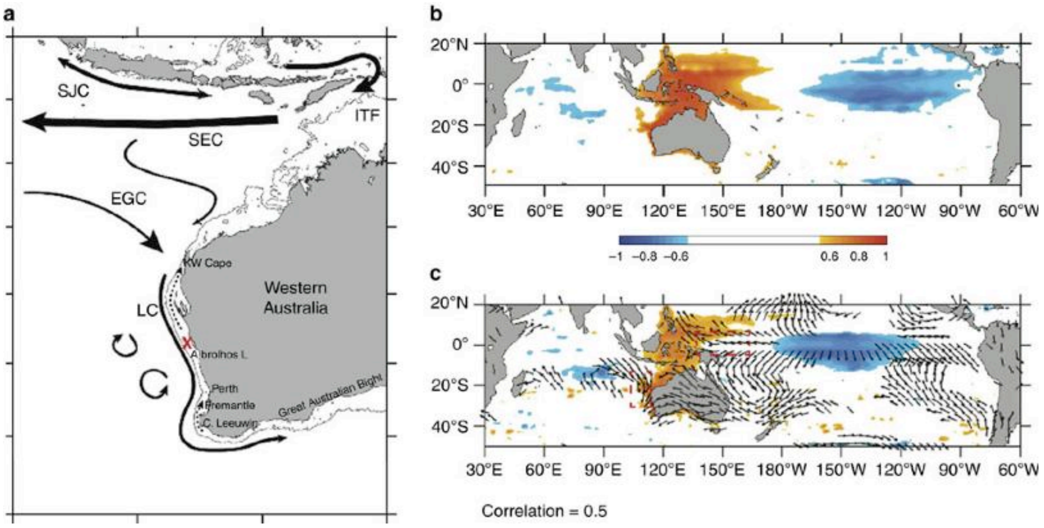

Figure 2-4: (a) Regional surface ocean currents in the eastern Indian Ocean. ITF, Indonesian throughflow; SJC, South Java Current; SEC, South Equatorial Current; EGC, East Gyral Current; LC, Leeuwin Current; dotted arrows, inshore currents. The 200-m isobath of bottom topography is shown as solid line. The X (red) indicates the location of the Houtman Abrolhos Islands. Fremantle is indicated where the sea-level station record was established. (b) Spatial correlation of annual Fremantle sea level (FSL) with global sea surface height (SSH) from Simple Ocean Data Assimilation (SODA) 2.0.4 for the calendar year January–December for 1981–2010. (c) Houtman Abrolhos Islands (HAI) regional SST spatial correlation with global sea surface height (SSH, in color) from SODA 2.0.4, and zonal/meridional wind speed and vectors from twentieth century reanalysis (arrows proportional to correlation with HAI SST). (After Zinke, 2014).

upwelling strength and upper-ocean chlorophyll concentrations in certain portions of the coast (Feng et al., 2009). ENSO-related interannual variability also modulates the strength of the Leeuwin Current and related eddy energetics, such that both are stronger during the La Niña events (Feng et al., 2005), and ocean temperatures tend to be warmer during La Niña and Ningaloo Niño events (Zinke 2014). Nevertheless, the remote-forcing influence on coastal upwelling and primary production has not been fully studied in the region. Key questions include: **How do remote influences from the Pacific affect coastal processes, including upwelling, off the northwestern and western coasts of Australia? What are the relative importance of local *versus* remote influences on the upwelling systems in Sumatra-Java-Alor and northwestern Australia?**

(5) ITF influence on upwelling

The Indonesian Throughflow (ITF) is a major route of fresh and warm water from the Pacific to Indian Oceans and the only low-latitude connection between the world's oceans (Fig. 2-4a). The warm and fresher water flows from the Pacific to Indian Oceans through three major conduits -- the Lombok Strait, the Savu Strait and the Timor passage. Observations suggest that ITF transport reaches up to 15 Sv (Van Aken et al., 2009; Gordon et al., 2010; Sprintall et al., 2010; Atmadipoera et al., 2009). Indian Ocean surface heat flux and stratification between 5° – 25°S region is regulated by ITF transport and its vertical structure (Song and Gordon, 2004).

In normal years, upwelling starts in the eastern part of the southern Java coast and moves northwestward (Susanto et al., 2001; see also Fig.2-1). The large SST depression appears only during Indian Ocean Dipole (IOD) events, and the less significant SST reduction in normal years is alleged to result from warming due to ITF advection (Qu and Meyers, 2005). Wyrtki (1962) estimated that upwelling in the eastern Indian Ocean contributed 2.4 Sv to the South Equatorial Current (SEC) and that it seemed to develop along the boundary of the Java Coastal Current and SEC. While the surface SEC seems to be mainly fed by the ITF in the Timor Sea, some SEC water supplied by the ITF at 100 m also gets upwelled into the surface layer (Qu and Meyers, 2005). The subsurface flow at 100 m shifts southward and is suggested to be a trigger for strong upwelling. The amount of upwelling is also speculated to be determined by the SEC and ITF.

Observations in 1990 and satellite images from 1990-2002 indicated strong upwelling off southern East Java (Purba, 2007). Zonal winds and Ekman transport tended to be stronger off the West Java coast during July and September, while cruise-measured temperature and potential density distributions showed a more intense upwelling signal off East Java and Sumba. Purba (2007) also suggested that total mass transport of the SEC off East Java exceeded that off West Java. This difference in SEC mass transport could be a metric of upwelling magnitude along the South Java coast, due to mass continuity.

Numerical model experiments by Lee et al. (2002) that blocked the ITF showed an anticyclonic circulation loop around Australia and the southern Indonesian seas, which weakened the SEC. The experiments also showed that local Ekman pumping was not a dominant mechanism for controlling seasonal thermocline variability. As mentioned previously, Wyrtki (1962) and Qu and Meyers (2005) showed that upwelling and ITF water supplied the SEC. Hirst and Godfrey (1993) also found that the ITF strengthened the SEC and

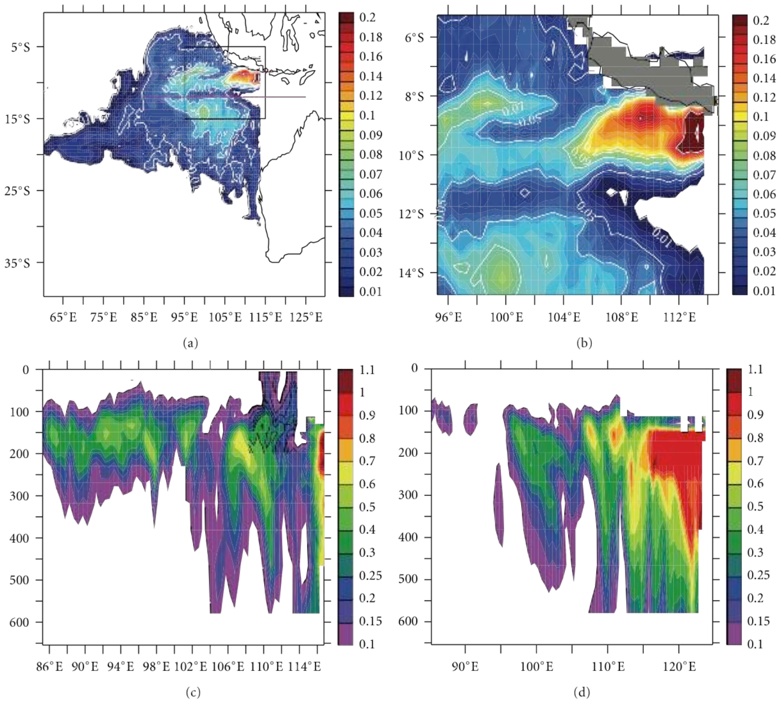

Figure 2-5: Artificial passive tracer concentrations attributed with the seasonal migration of south Java upwelling along the coast (Valsala et al., 2010). The tracer was initially set within the Indonesian Sea region with six different depth ranges.

Agulhas Current. Therefore, the SEC weakened in the Lee et al. (2002) model experiments because the ITF was lacking.

Valsala et al. (2010) suggested that 45% of the ITF water that comes through the Lombok Strait at 100 m depth can be upwelled into the surface along the south Java coast during August. Upwelling supplied from the Lombok throughflow peaks during August to October, and tracer distributions follow the seasonal migration of south Java upwelling along the coast (Fig. 2-5).

In vertical velocity profiles from a numerical model experiment by Kuswardani (in press), upwelling was most pronounced at subsurface depths during the southeast monsoon. The upwelling signal, identified by positive vertical velocity, consistently showed small fluctuations in west Java compared to east Java, where other observations indicated more intense upwelling (Purba, 2007). Since wind was not a dominant factor for the upwelling intensity, it was hypothesized that the ITF may be responsible. Two sensitivity analysis scenarios based on maximum vertical subsurface velocity indicated that the ITF can contribute 55-65% to the East-Java upwelling, with the largest contribution (65.4%) for the Lombok Throughflow and a total contribution of 55.6% for the Ombai Strait, Timor Sea and Lombok Strait during the upwelling season (Kuswardani, in press).

From mooring data in the Lombok Strait, Sprintall et al. (2010) concluded that ITF transport is the strongest in the top 100 m during the southeast monsoon (June to October), and the weakest during the northwest winter monsoon (January to Feb). From February to March, the strongest ITF flow is located between 60-140 m (Fig. 2-6), consistent with numerical experiments (Vasala and Ikeda, 2007; Vasala et al., 2010; Kuswardani, in press).

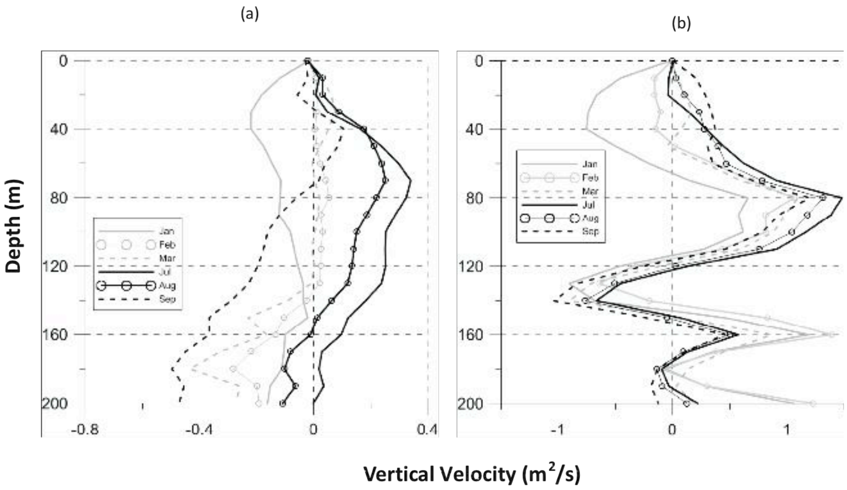

Figure 2-6: Vertical velocity profiles for (a) western and (b) eastern sectors of South Java (Kuswardani, in press).

However, the amount of subsurface ITF transport that influences upwelling is still unknown. Key questions include: **How does the ITF influence upwelling along the South-Java coast and three-dimensional circulations within the region between Indonesia and Australia? How does the partitioning of the ITF into three major passages and their relative transport affect the upper ocean conditions there?**

(6) Small scale mixing and water mass transformations

Wind-driven upwelling is a process by which the thermocline is uplifted to where vertical mixing and entrainment can lead to cooling of the surface mixed layer. In the process, nutrients, trace elements, Chl-*a* and other thermocline properties are mixed up into the surface layer as well. Water mass transformations that result from upwelling affect the gradients of properties across the air-sea interface, and thus turbulent fluxes of heat, moisture, momentum, and gases between the atmosphere and ocean. Enhanced primary productivity that can result from the injection of nutrients into the euphotic layer may alter the vertical profile of light penetration below the surface, affecting both mixed-layer temperature and the vertical structure of the velocity field. Therefore, while large-scale surface wind stress variations may be the motive force for changing the depth of the thermocline through vertical advection, small-scale turbulence is necessary to entrain thermocline water into the mixed layer. A major issue is the vertical scale of the turbulence-generating flow at the base of the mixed layer and in the transition layer below, requiring high vertical-resolution observations and models. Key questions include: **What are the sources and sinks of turbulence energy production near the surface? What are the physical processes that mediate turbulence generation? How do those processes relate to large-scale dynamics so as to inform parameterizations of turbulent mixing in dynamical models?**

(7) Freshwater fluxes and salinity variations

Precipitation and river run-off, along with the ITF, are important sources of freshwater that affect salinity of surface waters in the eastern Indian Ocean. Vertical structure and horizontal distribution of salinity can affect surface mixed-layer processes, hence large-scale ocean and climate variations, through modification of the air-sea interactions. In particular, surface salinity in the Bay of Bengal is known to be significantly influenced by regional precipitation and fresh water flux from Ganges-Brahmaputra Rivers at intraseasonal, seasonal and interannual time-scales. Freshening of the surface layer generates salinity stratification within an isothermal layer, causing a difference in the depth of the isothermal layer and mixed layer depth derived using a density criterion, known as the barrier layer (Lukas and Lindstrom, 1991). Horizontal distributions and generation mechanisms of the barrier layer in the eastern Indian Ocean have been studied using observational and simulation approaches (e.g. Sprintall and Tomczak, 1992; Masson et al., 2002; Qu and Meyers, 2005; Du et al., 2005). The existence of a shallow surface freshwater layer and a barrier layer beneath can modify upper-ocean responses to atmospheric forcing by concentrating surface heat and momentum fluxes in a shallower mixed layer and prohibiting cold-water entrainment at the base of the isothermal layer (e.g. Vialard and Delecluse, 1998; Masson et al., 2004). In addition, the ITF provides low salinity water masses to the eastern Indian Ocean both in the upper layer and subsurface intermediate levels, which may influence strength and water properties in the upwelling off Sumatra-Java-Alor and possibly northwestern Australian coasts. Although the eastern Indian Ocean is characterized by large freshwater fluxes, details of the upper-layer salinity variations and their influences on other ocean processes are still not well understood. Key questions include: **What is the dominant salinity variability in the eastern Indian Ocean, and what are responsible mechanisms of the variations? What are the salinity impacts on the upwelling systems, including relationships to biogeochemical processes?**

2.2. Open ocean-coastal interactions

(1) Eastern Indian Ocean General Circulation

Upwelling brings nutrients from subsurface to surface, but within a quite limited region on the order of 100 km off the coast. However, the SEAWIFS and MODIS satellite images clearly show offshore transport of chlorophyll, which could result from either circulation or eddy processes.

The circulation in the eastern Indian Ocean, particularly the southeastern Indian Ocean, is highly dynamic and variable. The schematic picture (Schott et al., 2009) includes the seasonal reversal of the South Java Coastal Current (SJCC) and its associated undercurrent, the ITF, the SEC, the South Equatorial Counter Current (SECC), the East Gyral Current (EGC) and the Leeuwin Current (LC). The convergence of the SJCC with the ITF during the winter monsoon season and with southeastward flow along the Sumatra coast during the boreal summer monsoon season may generate downwelling, affecting the locations and magnitudes of coastal upwelling.

Two important factors in open-ocean/coastal interactions are equatorial Kelvin waves and the shallow, eastward jets in the tropical zone. As discussed above, the Kelvin waves are an aspect of basin-scale interaction of ocean and atmosphere in positive feedback instabilities. This includes the IOD but may involve other modes. Regardless of feedback, Kelvin waves are generated by equatorial wind variability at all time scales -- synoptic, MJO, seasonal (annual and semiannual), interannual and decadal.

The shallow eastward EGC flow has been known for a long time. The ITF joins the SEC and forms a thermocline ridge along the southern side of the westward flow (about 14°S) (Godfrey and Golding, 1981). The eastward flow south of the ridge was thought to be a gentle, broad current that turned southward to form the Leeuwin Current. Recently better data has shown that the eastward flow is a series of shallow jets, with both temperature and salinity gradients important for their existence. Key questions include: **What is a responsible process for offshore expansion of upwelled tracers and water mass properties? How are the coastal and offshore circulations related? At what timescale does offshore circulation variability affect coastal upwelling? What are the dynamics of the shallow eastward flow and their relation to upwelling in the northwestern coast of Australia?**

(2) Eddies and filaments

Upwelling occurs mainly in the coastal regions, but also appears as eddy-driven phenomena. This mesoscale eddy-induced upwelling plays an important role in the open ocean and should also be investigated in EIOURI. There are two major regions of high mesoscale eddy activity in the eastern tropical Indian Ocean; one is the SEC region between about 10˚S and 20˚S and the other is near the unstable region of Leeuwin Current (LC) along western coast of Australia south of 25°S. High activity of mesoscale eddies appears during boreal summer due to barotropic and baroclinic instabilities associated with the SEC and LC enhancement (e.g. Feng and Wijffels, 2002; Feng et al., 2005). These eddies can influence physical and biogeochemical conditions in the upper ocean through vertical and horizontal advection of heat, salt, nutrients, and marine organisms. The eddy activity is affected by background conditions of the current systems, which are affected by large-scale interannual variations such as IOD and ENSO; for example, the positive IOD condition favors strong baroclinic instability in the SEC region. On the other hand, a numerical model study showed that enhancement of meridional eddy heat transport during the positive IOD events also influence termination of the IOD events, i.e. the duration of strong upwelling off the coast of Sumatra and Java (Ogata and Masumoto, 2010, 2011). Further studies on the roles of mesoscale eddies in climate variability and upwelling systems are needed.

Several physical mechanisms of mesoscale eddy impacts on biogeochemical cycles have been proposed, including eddy pumping (McGillicuddy and Robinson, 1997), eddy-induced Ekman pumping (Martin and Richards, 2001), and eddy advection (Killworth et al., 2004). Since the Java-Sumatra upwelling area is close to a region of high mesoscale eddy activity, linkages between eddy-driven and coastal upwelling should be examined. In addition, since this region is associated with the major outflow straits (Sunda, Lombok, Ombai and Timor) of the ITF, topographically induced mesoscale eddies may play a role in offshore transport of upwelled properties (e.g. Iskandar et al., 2010).

A better understanding of mesoscale eddy structure, activity, and roles in biogeochemical cycles is required to improve climate and biophysical models. To capture the three dimensional physical and biogeochemical structure of mesoscale eddies, eddy-oriented hydrographic observations including water sampling for biogeochemical parameters, satellite altimetry and ocean-color imagery are needed. Key questions include: **What are the structures of the mesoscale eddies in the region between Indonesia and Australia? How do mesoscale eddies affect upwelling systems and biogeochemical processes along the**

Sumatra-Java-Alor and Australia coasts? How much upwelling is generated by the mesoscale eddies themselves in the open ocean? What are the influences of the eddy-driven upwelling in biogeochemical processes of the eastern Indian Ocean?

3. Bio-physical Relationships

(1) Nutrient Sources and Delivery Rates

To first order, a region's potential to support major fisheries and carbon export is determined by the amount of new nutrients, nominally nitrate-N, delivered to surface waters. In many regions of the global ocean, the nutrient fields and physical flows are sufficiently well characterized and modeled to constrain these potentials rigorously. In the eastern IO, however, understanding of the ecological and biogeochemical implication of nutrient fluxes is complicated by diverse mechanisms of nutrient delivery and large uncertainties in the sources and fluxes of major and minor nutrients. For example, seasonally variable flows through the porous island boundaries of the ITF bring water into the eastern IO from the western Pacific, via the Java and Banda inland seas. Nutrient inputs and ratios in the surface mixed layer in these waters are substantially affected by both the local and remote influences of heavy monsoonal rainfall and terrestrial runoff. Advective transport from the northern IO is a further source of altered nutrient relationships from denitrification and microbially mediated low-oxygen processes. In addition, nitrogen fixation is likely a major source of new nitrogen input to offshore oligotrophic waters of the eastern IO for much of the year (Waite et al., 2013; Raes et al., 2015). Further, mesoscale features, such as eddies, may serve both to transport nutrients and productivity from coastal to offshore waters, and as local mechanisms of nutrient entrainment in the offshore habitats. Seasonal, interannual and long-term climate variations in major physical drivers may also affect all of these mechanisms separately and differently. Key questions include: **What are the major sources of nutrient input and variability in the eastern Indian Ocean? What are their linkages to specific physical forcing dynamics on one hand, and ecological and biogeochemical responses on the other?**

One specific challenge of eastern IO biogeochemical research is to characterize the physical and biological sources of nitrogen to the region. Such data are needed to validate coupled physical-biogeochemical models to resolve source and sink pathways, and which can be used, in turn, to frame or test hypotheses regarding the relative contributions of different mechanisms (upwelling, eddies, ITF, freshwater runoff, and diazotrophy) to system productivity, community composition and structure, and trophic interactions leading to fisheries. Major unknowns include the roles of trace elements -- such as iron, zinc, cobalt – which have been shown to be significant in other tropical ocean systems, but might be available in excess in the eastern IO due to island and freshwater influences. Major nutrient ratios, notably silicic acid to nitrate, may be strongly variable in source waters, either limiting or enhancing the growth of large diatoms, a key factor in generating productive, short food chains to fisheries. In addition, phytoplankton responses to nutrient delivery may be masked (from satellites) or significantly delayed (by light limitation) when nutrients are entrained in the subsurface barrier layer, below a low-salinity mixed layer with poor light transmission properties (e.g., with high particulate or colored dissolved organic matter (CDOM) loading).

However, the local Indonesian rainy season (November-March) occurs after the favorable period of wind forcing for seasonal upwelling (June-October). Thus, local freshwater influences on nutrient inputs and utilization (as opposed to remote influences from the Bay of Bengal) might mainly confound interpretations of the seasonal decay of upwelling. Key questions include: **What are the relative contributions of different physical mechanisms to biogeochemical system, such as productivity, community composition and structure, and trophic interactions leading to fisheries? What are the roles of trace elements and nutrient ratios associated with the input waters on biogeochemistry and ecosystem dynamics? What are the local freshwater influences on seasonal upwelling evolution and biogeochemical processes?**

(2) Mesoscale and submesoscale variability in the South Java Upwelling generated by ITF outflow and its implications for plankton and higher trophic levels

As discussed above, a fascinating suite of climatic and oceanographic interactions drives biological productivity in the eastern IO. Southeast monsoon winds cause upwelling along the south side of Indonesia, with this upwelling modulated by planetary Kelvin waves and other factors that cause shoaling of the thermocline seasonally from east to west. In addition, satellite and model data suggest that this coastal upwelling together with mesoscale and sub-mesoscale processes are key to the enhancement and transport of plankton production, which has important implications for higher trophic levels. It is now well established that along the southern coast of Indonesia, the summer monsoon drives Ekman upwelling and enhanced productivity (Susanto et al., 2001). This area, however, unlike typical upwelling systems (e.g., Peru, California, Benguela), has a porous coastal boundary that comprises the exit region of the ITF. This outflow seeds the coastal upwelling system with plankton species

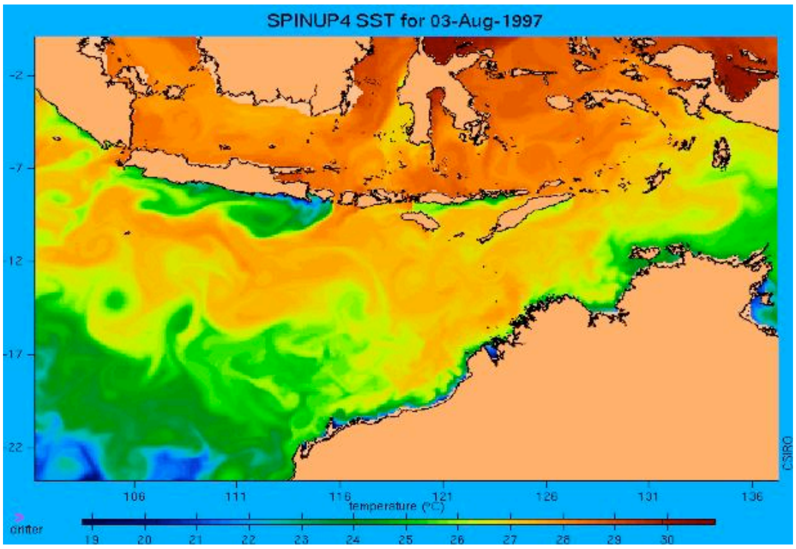

Figure 3-1: Example of mesoscale–submesoscale variability in the eastern Indian Ocean between Indonesia and Australia. This frame from the BRAN model output shows surface temperature during the upwelling season, with the Java upwelling (blue) and filaments and eddies propagating offshore from the ITF outflow.

(Image from: http://www.marine.csiro.au/ofam1/bran1/sp4_LC2_t1/19970803.html) from the ITF, thus providing upstream source populations that mix to an unknown extent with local plankton, the combined species assemblage then blooming to various degrees in the upwelling zone. Water properties and plankton composition varies seasonally and interannually in the ITF outflow (Atmadipoera et al., 2009), thus influencing the biological response to the upwelling. This unique interaction between the porous coastal sources of plankton and those in the coastal upwelling has not yet been studied. Key questions include: **What are the interactions between the porous coastal sources of plankton and upwelling? How do plankton seed populations from the ITF impact bloom dynamics and, ultimately, high trophic level productivity?**

Models of the ITF show pronounced sub-mesoscale and mesoscale features in the offshore waters south of Indonesia, resulting from the strong advective outflow exiting the straits (e.g., Lombok Strait) (Fig. 3-1). These features propagate to the south and west, carrying biologically enriched upwelled water offshore and creating local hotspots of productivity. The flows associated with these offshore propagating features (including filaments, jets, and eddies) can lead to further biological enhancement through isopycnal upwelling (Venrick, 1990, McGillicuddy et al., 2007) and the concentrating effects of local convergent flows interacting with depth-keeping swimming behavior of zooplankton (Olson and Backus, 1985; Franks, 1992; Epstein and Beardsley, 2001).

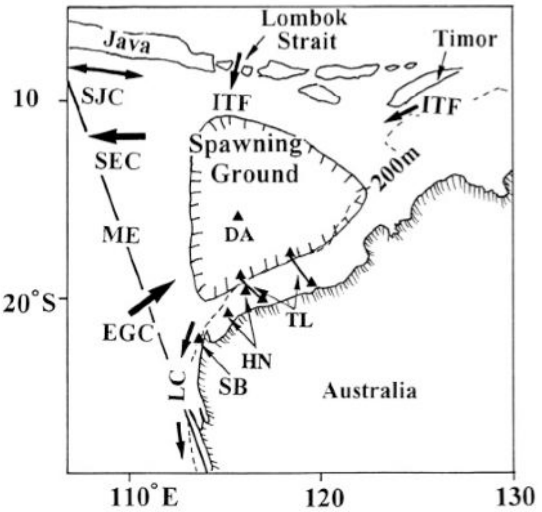

Fig. 3-2: Spawning ground of southern Bluefin tuna (from Matsuura et al,, 1997). Thick arrows indicate major surface currents. Solid triangles and lines indicate positions of observations of past research. ITF (Indonesia Through-Flow), SJC (South Java Current), SEC (South Equatorial Current), EGC (Eastern Gyral Current), SB (Mooring), LE (Leeuwin Current), HN (Current Meter), DA (Surface Drifter), TL (CTD & Water Quality), ME (XBT).

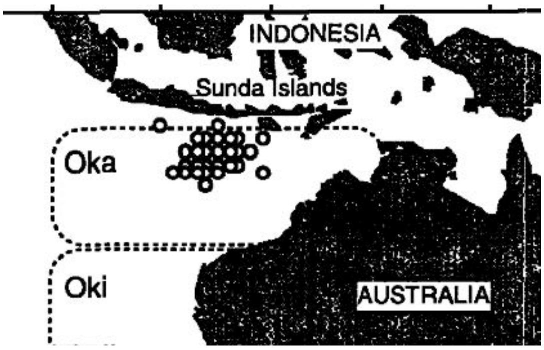

Fig. 3-3: Spawning ground of southern Bluefin tuna (from Farley and Davis, 1998)

Upwelling and offshore transport of the ITF outflow have important implications for coastal and offshore fisheries. Important coastal fisheries, including small pelagic species such as sardines, are influenced by the upwelling off south Java, with highest catches during the SE monsoon (Ghofar 2005). Furthermore, the principal spawning area for the Southern Bluefin Tuna (SBT) is located in the surface waters of the Indo-Australian basin region (Figs. 3-2, 3-3) (Matsuura et al., 1997; Farley and Davis, 1998), with catch data from Farley and Davis (1998) showing the spawning area off Java (Fig. 3-3). Offshore transport of coastal upwelling and subsequent plankton enhancement and aggregation injects plankton-rich waters into this key spawning area. Sexually mature SBT were caught in the spawning grounds, with peaks in October and February (Farley and Davis, 1998). The period of upwelling and enhanced productivity along the south Java coast can persist from August through December, zooplankton produced downstream and carried into the SBT spawning ground could increase larval growth and survival. A recent study of satellite SST and chlorophyll indicated persistent ocean frontal features in the SBT spawning area and emphasized the importance of measuring SBT larval distributions in relation to oceanographic variability in this region (Nieblas et al., 2014). While the satellite data showed low chlorophyll concentrations in the central basin, convergent flow in the observed SST fronts can enhance zooplankton concentrations. SBT larvae carried downstream of this spawning region enter the Leeuwin Current which can form eddies that lead to isopycnal upwelling (cryptic upwelling) and enhanced plankton production. Key questions include: **What are the roles of mesoscale and sub-mesoscale features and advective processes on biogeochemistry, food-web dynamics and habitat quality in the SBT spawning area?**

Existing information points to the critical need for a robust field program of the south Java Upwelling system and downstream transport of productivity into the offshore SBT spawning area, and points south (northwestern Australia and Leeuwin Current). A combination of state-of-the-art technologies can be used to examine the multi-scale temporal and spatial variability and the underlying biological-chemical-physical processes generating these patterns. High-resolution sampling of this area is clearly needed to map the high variability in hydrography, currents, light, nutrients, and plankton. Real-time mapping of plankton taxa and environmental variables will identify key meso-scale and sub-mesoscale features or "hotspots" for conducting targeted rate process studies including nutrient uptake, primary productivity, and micro- and meso-zooplankton grazing. New molecular methods can be used to characterize the genetic composition of the entire plankton community in the ITF outflow. Key questions are: **How does the genetic composition of the plankton community in ITF outflow change in time as it exits the ITF, and how is it influenced by entrainment in the upwelling system and subsequent offshore transport**. The high-resolution surveys should be repeated within and between seasons and years. Long-term measurements from moored and robotic platforms are needed to understand temporal variability in concert with the repeated high-resolution spatial surveys. The resulting high-resolution field data from shipboard, moorings, and robotic platforms, together with concomitant high-resolution satellite data (SST, SSS, SSH, Chla, CDOM), can be assimilated into a multi-scale coupled biological-chemical-hydrodynamic models of the region. Such a combined field and modeling study would provide new insights into the underlying processes controlling this unique and important upwelling system and how it influences the fisheries and downstream ecosystems in the eastern Indian Ocean.

4. Biogeochemistry and Ecology

(1) Unique nutrient uptake stoichiometry of upwelling regions

Talley and Sprintall (2005) estimated the time- and depth-integrated oxygen and silicate transports through the ITF (along with heat and freshwater fluxes) reporting a net oxygen (O_2) flux of -0.2 x 10^{11} µmoles/s and a net silicate (Si) flux of 1.2 x 10^{11} µmole/s, with the latter indicating a significant net source of Si into the Indian Ocean from the Indonesian Seas. They also mapped the impact of these fluxes over the entire Indian Ocean revealing a striking basin-wide silicate anomaly on the 31.96 σ_1 density surface associated with the flux of silicate through the ITF (Fig. 4-1). Subsequently, Ayers et al. (2104) showed that the fluxes of nitrogen and phosphorus through the ITF are significant as well and that they similarly influence the absolute concentrations of these nutrients and their ratios. However, the Ayers et al. (2014) study is the only one to date that has attempted to quantify the time- and depth-integrated nitrogen (N) and phosphorus (P) transports through the ITF and their impact on nutrient concentrations and new production in the eastern Indian Ocean.

The upwelling regions off Sumatra, Java and Timor are almost certainly influenced by nutrient inputs associated with the ITF flows through the Lombok and Ombai Straits. Nutrient measurements collected during the World Ocean Circulation Experiment (WOCE line IR06,

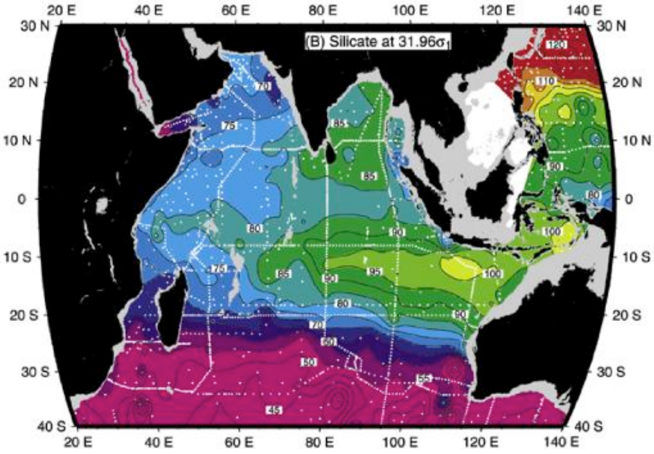

Figure 4-1: Silicate distribution on the 31.96 sigma-1 densitiy surface from Talley and Sprintall (2005).

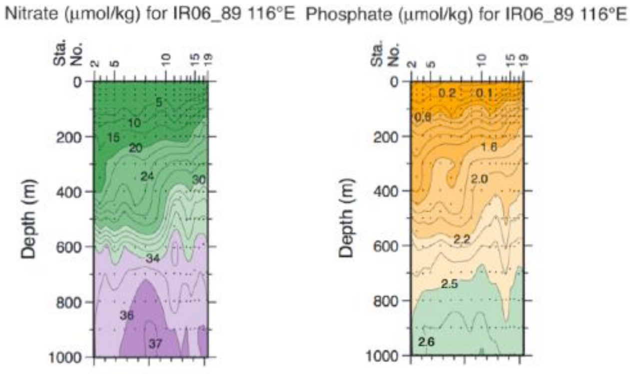
Nitrate (µmol/kg) for IR06_89 116°E Phosphate (µmol/kg) for IR06_89 116°E

Figure 4-2: Nitrate and phosphate sections from WOCE line IR06, extending from northwest Autralia (station 2) to Lombok Strait (station 19).

1989) along a transect from the northwestern coast of Australia to Lombok Strait reveal the upwelling signature off of Java in both nitrate and phosphate distributions (Fig. 4-2). Data from the northern end of the transect suggest an N:P uptake ratio of ~14, which is close to Redfield. In contrast, the absolute N:P ratios estimated from 200 meters depth on the northern end of the transect give values of ~13, revealing what appears to be a denitrification and/or anammox signature. This signature may reflect the influence ITF source waters derived from shallow Indonesian Seas where sediment dentrification and/or anammox results in significant nitrogen removal. Key questions include: **What impacts do these ITF fluxes have on the stoichiometry of upwelled waters in the eastern Indian Ocean? What is the source of the apparent denitrificaion/anammox signature? Is this signature derived from ITF inputs, and does it impact the species composition of phytoplankton blooms that develop in response to upwelling?**

ITF water also contributes to the warm fresh signature of the Leeuwin Current (Domingues et al., 2007). However, upwelling along most of the coast of northern Australia occurs over a wide shallow shelf and so very likely does not draw upon deeper nutrient sources derived from the ITF. Rather, nutrient stoichiometry off of western and northwestern Australia may be significantly influenced by nitrogen fixation that is stimulated by seasonal Fe inputs derived from wind-transported dust from the Australian continent year (Waite et al., 2013; Raes et al., 2015). Key questions include: **What influence does Fe-stimulated nitrogen fixation have on nutrient concentrations and ratios in upwelled waters off of NW Australia? Does nitrogen fixation have a significant impact on N:P ratios and therefore the species composition of the phytoplankton blooms, and how might this, in turn, influence higher trophic levels?**

(2) Phytoplankton production responses to nutrients, mixing and light

Enhanced phytoplankton productivity in upwelling regions is a common feature, largely due to the supply of nutrient-rich deep water to the surface mixed layer (e.g. reviews by Bakun, 1996; Mann and Lazier, 2009). However, timing, magnitude and the phytoplankton species contributing to the production enhancement may vary significantly among different upwelling systems due to the differences in surface forcing, bottom topography, and local mixing and flow regimes. To list a few, phytoplankton production in upwelling regions can be significantly influenced by meso-scale eddies (e.g. Iskandar et al., 2010; Gaube et al., 2014), coastal-trapped waves (e.g. Boyd and Smith, 1983; Jury and Brundrit, 1992), and along-shore flows (e.g. Chase et al., 2007). Generally speaking, the production enhancement can be detected at the surface of upwelling regions, typically featured by elevated chlorophyll concentration throughout the upwelling period (Fig. 4-3 as an example). In some cases, however, so-called cryptic blooms in subsurface layers (e.g. Paterson et al., 2013) may occur instead of a surface expression.

The eastern Indian Ocean features many unique upwelling systems (see Section 2.1 for the physical oceanography description), offering an exciting opportunity to examine responses of phytoplankton productivity to multiple local and remote forcings at different spatio-temporal scales. For instance, in the southern Sumatra-Java-Alor (STJ) region, monsoonal wind is viewed as a key driver for the coastal upwelling (Susanto et al., 2001, Susanto and Marra, 2005), but it is an over-simplification to view the region as a typical wind-driven coastal

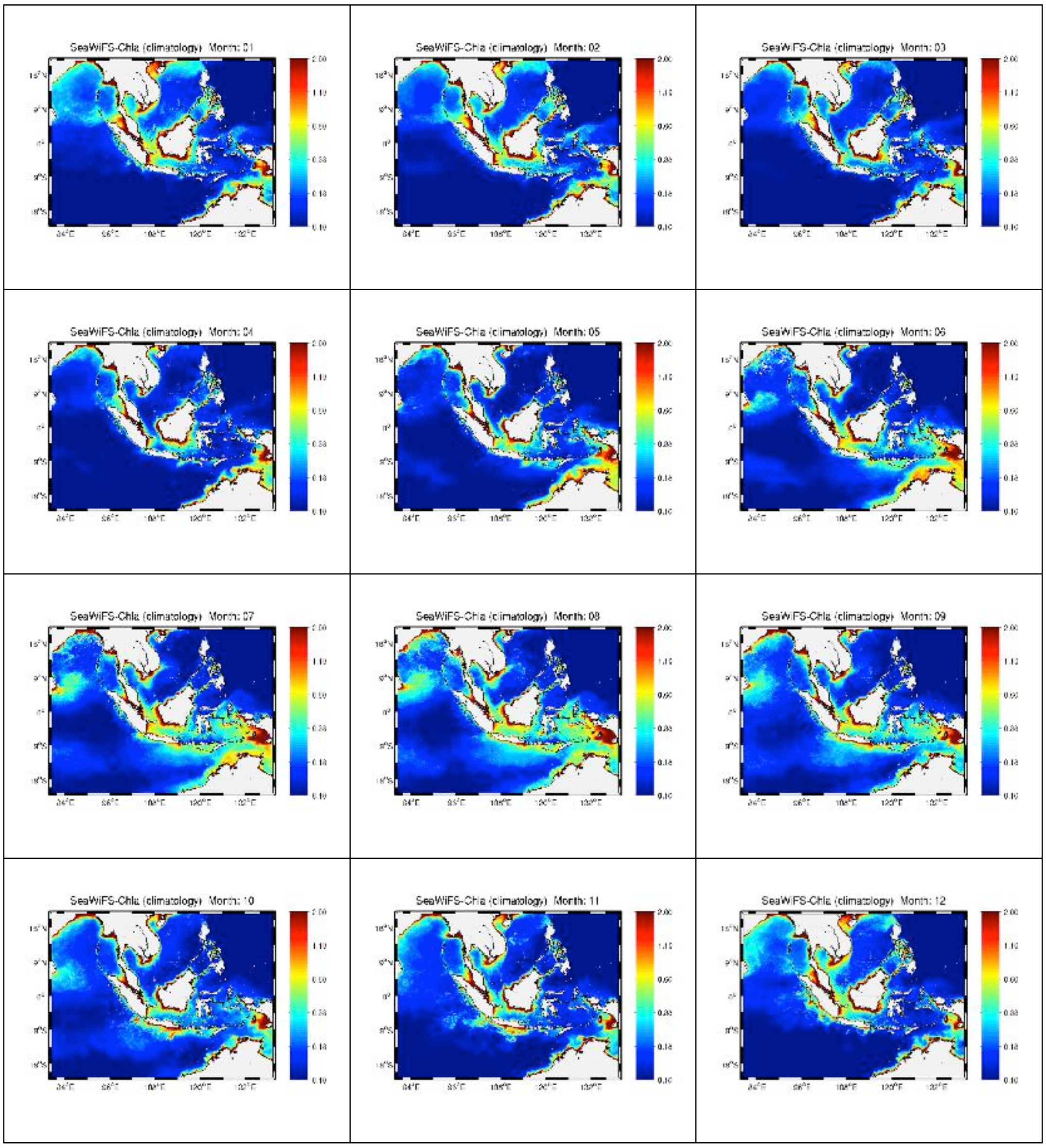

Figure 4-3: Monthly climatology of chlorophyll distribution in the eastern Indian Ocean. Upwelling-induced primary production enhancement along the near shore regions can be inferred from the elevated chlorophyll concentration from from July to October along the Java coast, from November to December along the Sumantra coast, and from May to August along the Northwest Australian coast. Also notice the strong upwelling-induced chlorophyll signal from June to November near the Sri Lanka region.

upwelling. First, the onset of chlorophyll increase shows a northwestward delay along the southern STJ coast (Fig. 4-4, adopted from Susanto and Marra, 2005), which is consistent with the propagation of sea surface temperature cooling, but difficult to explain by an almost synoptic shift of surface wind in the region (see Fig. 2-1). Second, ENSO and IOD appear to play important roles in the interannual variability of chlorophyll enhancement and distribution (Susanto et al., 2001; Susanto and Marra, 2005; Ningsih et al., 2013). Third, additional environmental factors are potentially critical, including (but not limited to): a) ITF modulation of the upwelling dynamics and the horizontal transport of nutrient and phytoplankton from the Indonesian Seas through the porous eastern STJ (e.g. Moore and Marra, 2002; Sprintall et al., 2010); b) equatorial and coastal Kelvin waves that interact with coastal wind-driven

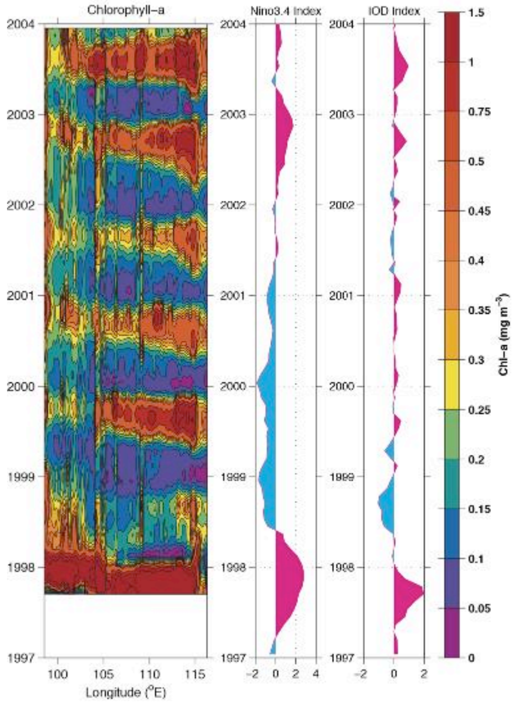

Figure 4-4: Temporal variability of Chl-a along the southern coasts of Java and Sumatra. Higher concentrations are matched well with upwelling during the southeast monsoon cycle. Interannual variability associated with the 1997/1998 El Niño, which coincided with the Indian Ocean Dipole, produced higher Chl-a that extended further northwestward along the Sumatra coast. Note that the increase in ocean color between 2000 and 2003 may signal an increase in monsoonal winds (Goes et al., 2005). The Niño3.4 index (average sea-surface temperature anomaly in the region 120°W–170°W and 5°N–5°S) and the Indian Ocean Dipole index (difference in sea-surface temperature anomaly between the tropical western Indian Ocean, 50°E–70°E, 10°S–10°N, and the tropical southeastern Indian Ocean, 90°E–110°E, 10°S–Equator) are also plotted. (from Susanto and Marra, 2005).

upwelling; and c) meso-scale eddies off the STJ shelf that drive cross-shore exchange of nutrient and production. In other EIO upwelling regions such as the western Australian shelf region, production also shows unique responses due to the cryptic nature of the upwelling, which may be related to wind-driven, onshore geostrophic flow and eddy-shelf interaction associated with Leeuwin Current system. Key questions include: **What are the spatial heterogeneity and dynamic connection of upwelling-induced primary production regimes among different upwelling regions within the entire Indo-Australia Basin (IAB) and within sub-regions such as the Sumatra-Java-Alor and the western Australia coast? What are the key features of upwelling-related production processes in different regions in terms of the relative contribution of new vs. recycled production and local vs. advected production? What is the inter-annual variability of production responses and associated key drivers?** Those drivers could be Monsoon, horizontal advection such as ITF and Leeuwin Current, equatorial and coastal Kelvin waves, IOD and ENSO, and meso-scale eddies.

(3) Phytoplankton community structure

Wind-driven upwelling has a strong influence on phytoplankton community structure because it introduces high concentrations of nutrients into well-lit surface waters of the ocean under turbulent conditions, which tend to stimulate diatom blooms (Margalef, 1978). The species composition of the resulting blooms depend upon more subtle factors related to initial conditions in the upwelled water, such as the phytoplankton “seed” populations and nutrient ratios. As blooms progress and upwelled waters age, a succession of species is typically observed transitioning from large, productive coastal diatoms to smaller and less productive diatoms and dinoflagellates and ultimately to the dominance of photosynthetic bacteria flagellates species in stratified, nutrient depleted offshore waters (Margalef, 1978).

Although the Leeuwin Current is downwelling-favorable, diatoms blooms develop in coastal waters off western and northwestern Australia in response to sporadic wind-driven upwelling and to upwelling driven by eddy motion against the continental slope and shelf (Koslow et al., 2008). Meanders in the Leeuwin Current also generate eddies that transport productive coastal phytoplankton communities seaward into oligotrophic offshore waters (Lourey et al., 2013; Waite et al., 2007; Fig. 4-5). These eddies can extend to more than 250 m depth and are enigmatic because they have anticyclonic, downwelling circulations that, in theory, should inhibit the introduction of new nutrients from depth. Yet, these eddies and the relatively high

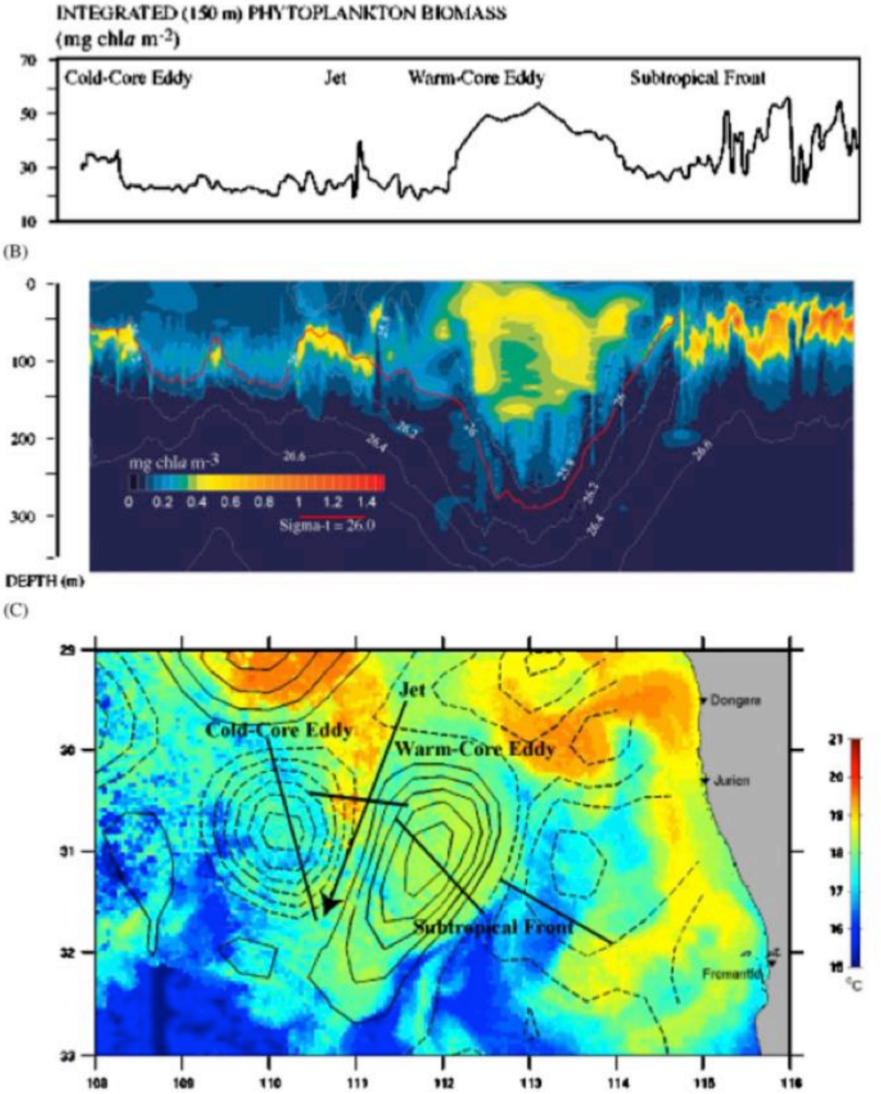

Figure 4-5: 13 (A) Chlorophyll a biomass integrated to 150 m as estimated from calibrated fluorescence as seen in (B), a composite of four SeaSoar transects showing regional scale variation of subsurface fluorescence within the cold-core (CC) and warm-core (WC) eddies separated by the warm surface jet (WSJ) generated between the eddies (solid arrow). East of the WC eddy is Subtropical Front Water(SFW), a mild CC feature typified by an intense fluorescence maximum at depth. White lines are isopycnals. Note that the more diffuse layer of chlorophyll a in the WC eddy in general contains more vertically integrated chlorophyll a biomass than any other regional feature. (C) SeaWIFS sea-surface temperature image showing the location of the CC, WC, WSJ and SFW and the actual ship track for the SeaSoar transects (solid black lines). Figure and caption modified from Waite et al., 2007.

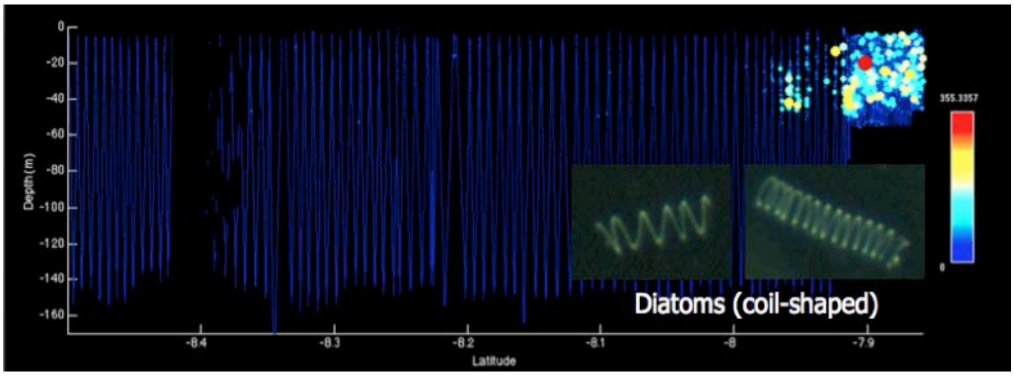

Figure 4-6: Onshore-offshore video plankton recorder (VPR) transect from the Java upwelling region showing the abundance of coil-shaped diatoms. Captured images of the coil-shaped diatoms are superimposed.

chlorophyll-a concentrations and production rates associated with them have been shown to persist for months. Key questions include: **How does sporadic upwelling in Western Australian coastal waters influence the coastal productivity and phytoplankton species composition? How do this upwelling contribute to the high chlorophyll concentrations (and species compositions) that are observed in seaward-propagating downwelling eddies? How are the phytoplankton communities in Leeuwin Current eddies maintained and what is their fate? What kinds of phytoplankton species successions are observed and do they differ from those in more typical coastal upwelling systems?**

Relatively little published information is available on the phytoplankton community compositions that emerge in response to upwelling in other eastern Indian Ocean upwelling regions. Recent video plankton recorder (VPR) surveys in the Java upwelling have documented an increase in chain-forming diatoms in response to wind-driven coastal upwelling (Davis et al., unpublished; Fig. 4-6). The community structure of these blooms appears to be similar to other coastal upwelling systems. However, as discussed above, the N:P ratios in the upwelling water are relatively low. Key questions that need to be addressed include: **How does the phytoplankton community composition of these upwelling blooms vary with initial conditions, specifically the seed populations and nutrient stoichiometry of the upwelled water? Is the subsequent species succession similar to other coastal upwelling areas, or does it promote blooms of diazotrophic species due to low N:P ratios? How do the fates of fixed carbon and nitrogen, trophic transfer efficiency and higher trophic level production vary with evolving plankton community composition?**

(4) Alternate Fates of Phytoplankton Productivity

The seasonal dynamics and spatial heterogeneity of plankton communities in the eastern IO and their influences/impacts on regional fisheries and biogeochemistry are the net results of complex physical-biological mechanisms that produce, utilize and redistribute phytoplankton biomass. While the end results may be evident in observed distributions sampled by ship surveys or other approaches (satellites, gliders), understanding the mechanisms underlying specific phenomena, such as the timing of onset/decline of upwelling blooms or the potential roles of eddies in enhancing offshore fisheries, can only come from focused process studies. In particular, experimental studies with an emphasis on the alternate primary fates of phytoplankton production can help to unravel the effects of local versus advective processes as well as provide a framework of lower-level food web fluxes that link to fisheries and biogeochemistry. For example, for phytoplankton biomass production measured at a given place and time, the contemporaneous loss of production to grazing by microzooplankton (principally by single-celled protistan consumers) is a measure of the material that is mainly cycled in the euphotic zone as remineralized nutrients. In contrast, direct consumption of phytoplankton and microzooplankton biomass by larger zooplankton sets constraints on the portion of primary productivity that can be efficiently transferred to higher trophic levels or to carbon export in large fecal pellets. Similarly, the direct contribution of phytoplankton sinking to export flux, such as from aggregate formation, can be estimated by accumulation rates of intact phytoplankton or Chl-a into sediment traps.

The difference between phytoplankton biomass production and the primary losses to grazing and cell sinking is the net phytoplankton accumulation (or decline) in a water parcel. In Eulerian-based studies, such process experiments can be used to compare lower-level food web fluxes in different water types, for example, to validate regional ecosystem models of the eastern IO or to complement dynamical interpretations based on spatial surveys. They could be used, for instance, to elucidate the relative contributions of production and loss terms during periods of general biomass increase and decline in order to resolve whether blooms decline due to depleted nutrients/reduced growth, enhanced grazing, or aggregation/mass sinking. Similar studies can also be conducted in a Lagrangian context to confirm that measured process rates explain the observed net rates of change of phytoplankton in advected water parcels or to distinguish local enhancement effects of eddy physics (sheer zones, nutricline uplift) from the simple eddy transport of coastal production offshore.

Within the eastern IO study region, eddy dynamics may be essential for understanding recruitment success of major fisheries, as suggested, for example, in on-going research on rock lobster larvae off of western Australia (Wang et al., 2014). More notably for pelagic fisheries, the region of high eddy activity south of Java, a major eastern IO fishing area for tuna, may derive significant resource subsidy from seasonal coastal upwelling production. Key questions include: **What are the fates of phytoplankton productivity generated by seasonal upwelling and eddy dynamics? How do they vary temporally and spatially within the upwelling region with respect to food-web pathways to remineralization, export and efficient transfer to higher trophic levels? What is the balance of new versus export production, and net advective transport to adjacent ecosystems?**

(5) Energy Transfer and Implications for Higher Trophic Levels

Temporal and spatial differences in the efficiency of energy transfer from primary production to fished stocks (e.g., sardines, tuna) or in the habitat quality for their larvae (fish or rock lobster) can be inferred from certain characteristics of the planktonic community, such as size structure, taxonomic composition, and phytoplankton growth-grazing relationships. For example, oligotrophic open-ocean communities, as might be represented by the vast region to the south and west of 10°S, 110°E, are typically dominated by tiny picophytoplankton, photosynthetic bacteria and high grazing losses to micro-grazers. Consequently, most of the productivity of such systems is rapidly recycled to inorganic nutrients, with little available for transfer to higher levels. In contrast, highly productive regions dominated by large phytoplankton like diatoms, which can be consumed directly by large crustacean grazers, lead to short trophic chains and efficient transfer to higher consumers (Ryther, 1969; Pauly et al., 1998). Such favorable characteristics might be expected for the Java-Sumatra coastal ecosystem during the upwelling season and potentially the open-ocean region of high eddy activity south of the Lombok Strait. The latter is a reasonable inference based on the importance of that region for Indonesian tuna and the spawning of southern bluefin tuna. However, the specific reason(s) for that area's fishery importance – habitat structure (fronts and eddies), local productivity or advective transport of food resources from the coastal ecosystem – is a central research question for EIOURI.

On a broader scale, biogeochemical indices of trophic structure might be useful for assessing variability in food web length and nitrogen contributions to the food web base within the study region. For example, Compound-Specific Isotope Analysis of Amino Acids (CSIA-AA) uses the differential ^{15}N enrichment of "trophic" versus "source" amino acids in a consumer's body tissue to assess the consumer's mean trophic position relative to phytoplankton, as well as the mean $\delta^{15}N$ values of source nitrogen to the food web base (the nitrogen sources supporting phytoplankton production). Analyses of this kind have demonstrated latitudinal variability in source nitrogen (ascribed to a denitrification gradient) for tuna of the eastern tropical Pacific (Popp et al., 2007) and temporal variability (ascribed to nitrogen fixation) in subtropical Pacific zooplankton (Hannides et al., 2009). If applied to representative zooplankton, fish or fish larvae specimens from the eastern IO, CSIA-AA might be used to evaluate whether seasonal upwelling shifts the tropic structure to a shorter (more efficient) food chain, how much trophic positions vary temporally or spatially, or whether the food webs in the offshore eddy region are based on nitrate-N, largely derived from upwelling near the coast and transported offshore, as opposed to local nitrogen, presumably with a strong N_2 signal from nitrogen fixation. Key questions include: **How does temporal and spatial variability in the N sources for primary productivity in the eastern IO relate to variability in food web structure and trophic transfer efficiency to higher level consumers?**

(6) Biogeochemical feedbacks to oxygen, pH, export

Elevated nutrient concentrations that are brought into surface waters and onto the shelf by upwelling are usually also associated with lower oxygen concentrations and lower pH. This happens because the remineralization of organic matter that generates higher nutrient concentrations at depth also consumes oxygen and produces CO_2. As a result, upwelling can contribute to the development of hypoxic/anoxic and/or acidic conditions on the continental slope and shelf, which can have significant negative ecological impacts (e.g., Feely et al., 2008). For example, a zone of severe hypoxia develops in the fall on the western Indian continental shelf (Naqvi et al., 2000) due to a combination of anthropogenic eutrophication and upwelling of low oxygen waters associated with the Southwest Monsoon. These low oxygen conditions, which extend over large areas of the shelf, result in widespread mortality of benthic communities and negatively impact the coastal fisheries. Similar upwelling of acidic seawater has been observed along the northwestern coastal zone of the United States (Feely et al., 2008) raising concerns about impacts on benthic communities and the shellfish aquaculture industry. Although the seasonal upwelling of undersaturated waters onto the shelf is a natural phenomenon in these regions, anthropogenic impacts (e.g., eutrophication and acidification) have increased the areal extent of the affected areas.

Given the widespread presence of low oxygen/high CO_2 subsurface waters in the Indian Ocean, this raises the question as to whether or not these kinds of impacts are likely to occur in the eastern Indian Ocean in association with upwelling events, now or in the future, in response to anthropogenic effects. Recent observations have revealed low pH and oxygen signatures associated with upwelling off of Java (Yu et al., unpublished data; Fig. 4-7). Key questions include: **How much does upwelling impact shelf oxygen concentrations and pH during peak upwelling? What are the potential ecological impacts?**

High nitrate and low dissolved oxygen layers have also been observed just below the Leeuwin Current during the onset of the annual phytoplankton bloom along the west coast of Australia (Thompson et al., 2011). These layers, which also have distinct nitrate:silicate nutrient ratios, are entrained into the current as it flows southward and into the warm-core eddies that are transported offshore. These high nitrate and low oxygen waters appear to have significant impacts upon on shelf/slope biogeochemistry and bloom formation in western Australia coastal waters. Key question include: **What is the origin of these high nitrate and low oxygen waters and is the contribution from these layers changing due to anthropogenic effects?**

(7) Influences of regionally unique chemistry, biology and ecology

The eastern Indian Ocean is strongly influenced by freshwater, nutrient and biological inputs from the Indonesian Seas via the ITF. In addition to the influence these inputs have on nutrient stoichiometry, they also influence the physical properties of the region, and

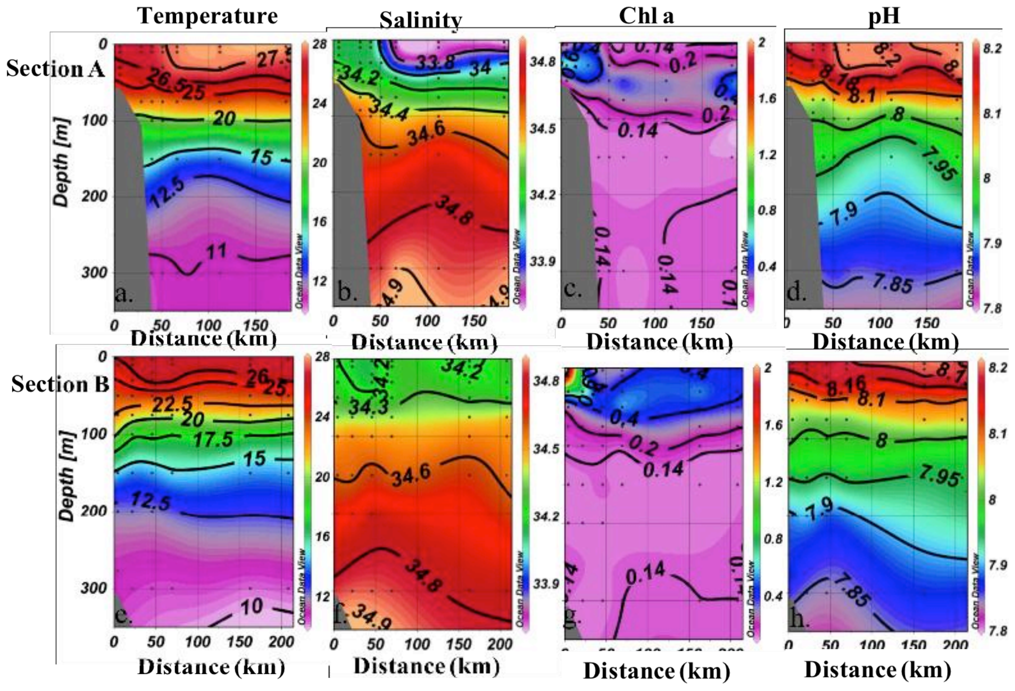

Figure 4-7: Sections of temperature, salinity, chlorophyll-a and pH along two hydrographic transects sampled perpendicular to the Java coastline.

particularly salinity and stratification due to the input of freshwater from the western Pacific Ocean (Talley and Sprintall, 2005). The ITF also provides a direct connection and inflow from the Coral Triangle, which is recognized as a global center of marine biodiversity. This inflow must contribute to the biodiversity of the plankton and higher trophic levels in the eastern Indian Ocean through advective transport and immigration and therefore impact the biological responses to upwelling in the region.

The influence of the ITF on salinity and nutrient (silicate, nitrate and phosphate) fluxes is significant (Talley and Sprintall, 2005; Ayers et al., 2014). Indeed, elevated silicate concentrations can be seen extending to at least 60° E on the 31.96 σ_1 density surface from approximately 5° to 20° S in the eastern Indian Ocean (Talley and Sprintall, 2005) (Fig. 4-1). Thus, the influence (at least on silicate) extends from the Sumatra-Java-Alor archipelago to the northwest coast of Australia and across the basin all the way to the Seychelles. The upwelling regions off Sumatra, Java and Alor are strongly influenced, in particular, by flows through the Lombok and Ombai Straits (2.6 and 7.5 Sverdrups, respectively, Sprintall et al., 2009; Fig. 4-8). Eddy resolving model simulations of SST and salinity reveal the direct influence of warm, low-salinity surface water inputs from these straits during the upwelling season that appear to prevent surface outcropping of colder water upwelled from depth (see Fig. 3-1). Key questions include: **What influence do these warm, fresh inputs have on the biological response to the upwelling off Java and Timor? How much do they impact nutrient supply and light availability? How much do they influence water column stratification and mixed layer depth? How much do these sources mix with and impact the stoichiometry and seed populations of the phytoplankton blooms that develop in response to the upwelling?**

ITF water also contributes to the warm fresh signature of the Leeuwin Current (Domingues et al., 2007). However, as discussed above, unlike Sumatra, Java and Alor,

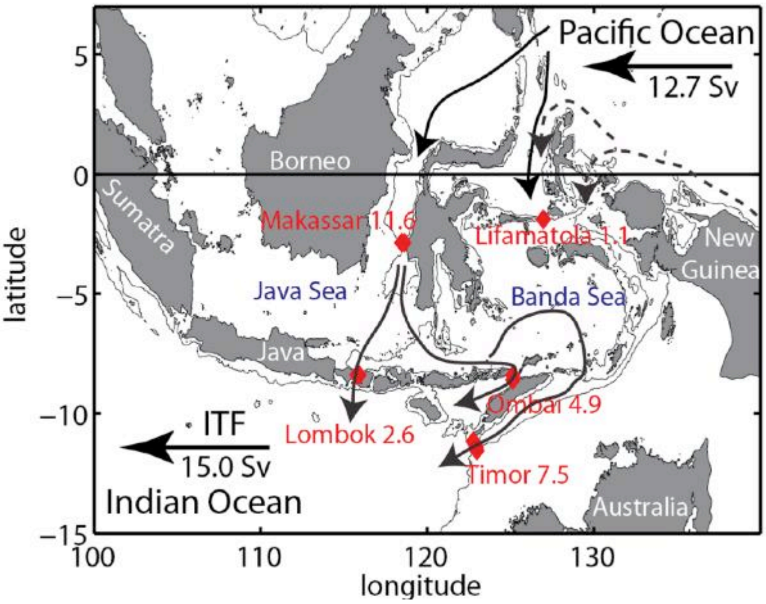

Figure 4-8: Transport estimates from the INSTANT program for Lombok and Ombai Straits and the Timor Passage. Figure reproduced from Sprintall et al., 2009.

upwelling along most of the northern coast of Western Australia occurs over a wide shallow shelf and so likely does not draw as much upon deeper sources from the ITF. Alternative mechanisms, related to local winds, topographic features and internal waves more likely control nutrient supplies on the shallow shelf, especially in the narrow band of upwelling that occurs along the coast of northwest Australia (see Fig. 3-1).

Coral reef ecosystems along the western and northwestern coastline of Australia provide important habitats for diverse communities of higher trophic level species. The coral communities in the northern regions are dominated by corals from the families *Acroporidae* and *Poritidae*, which are less thermally tolerant than those further south (Speed et al., 2013). Changes in the frequency and persistence of upwelling could therefore have significant impacts on these coral reef ecosystems. Key questions include: **How much influence does ITF water have on shallow upwelling systems that predominate along the coastlines of western and northwestern Australia? How does upwelling frequency and persistence change in response to climate forcing and impact these sensitive coral reef ecosystems?**

5. The human dimension, conservation, societal impacts

(1) Upwelling Variations for Sustainable Fisheries

The Sumatra-Java-Alor upwelling area, the main focus of the EIOURI project, has a strong relation to Fisheries Management Areas (FMA) 572 (Indian Ocean – west Sumatera) and 573 (South of Java – East Nusa Tenggara), two of eleven FMAs that are located within the Indian Ocean Tuna Commission (IOTC) area of competence (Satria et al., 2011) (Fig. 5-1). Long line vessels contribute a larger proportion (44 %) of tuna catch compare to other gears, and the number of active long liners registered and operated on the two FMAs has grown from 1118 vessels in 2011 to 1227 vessels in 2013 (Satria et al., 2011; Satria et al., 2013).

The Indonesian catch of the four main tuna species was 101,292 and 168,626 metric tons (mt) in 2009 and 2012, respectively; while total catch for all species by all gear types was ~600,000 and 398,540 mt in 2010 and 2012 (Satria et al., 2011; Satria et al., 2013). Understanding climate variability and its relation to regional biogeochemical variability and ecosystem response will be an important basis for enhancing fisheries regulation and

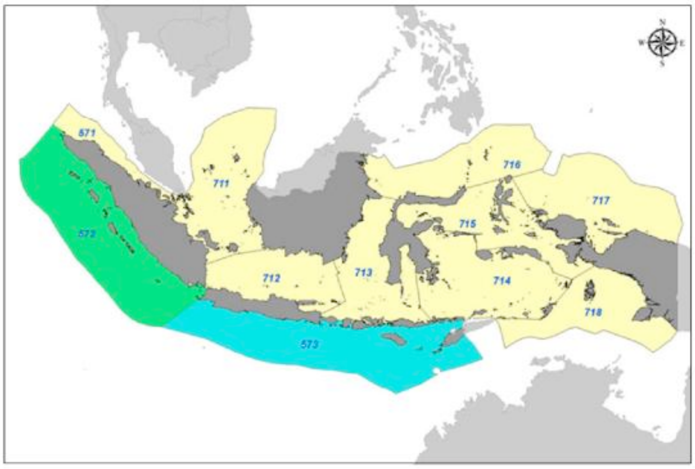

Figure 5-1: Fisheries Management Area (PERMEN KP. 01/2009). Indian Ocean – west Sumatera (FMA-572) and South of Java – East Nusa Tenggara (FMA-573) are within the EIOURI region.

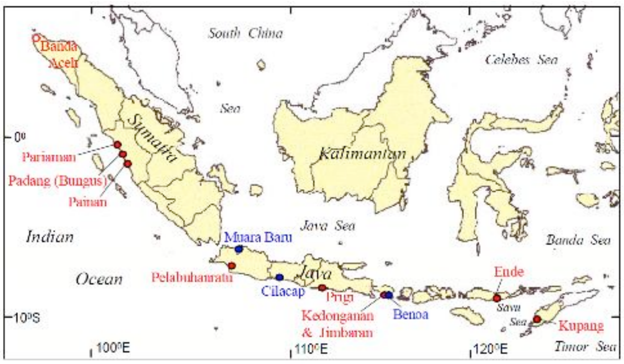

Figure 5-2: Primary fishing port/landing sites; the industrial as blue dots and artisanal as red dots (Proctor et al., 2003).

management policy in this region. Furthermore, improvement of the fish stock assessment database will help to reduce the mean error in catch data linkage with the vessel monitoring system.

The three primary fishing ports/landing sites for Indian Ocean tuna for industrial purposes (i.e. Nizam Zachman Fishing Port at Muara Baru, Jakarta; Cilacap Fishing Port, Central Java; and Benoa Fishing Port, Bali) are impacted by regional ocean-atmosphere interactions. Also, at least 9 artisanal fisheries (i.e. Pariaman, Bungus and Painan on the west coast of Sumatra, Pelabuhanratu and Prigi on the south coast of Java, Kedonganan and Jimbaran on Bali, Ende on Flores, and Kupang on Timor) (Fig. 5-2) are affected by intra-seasonal and inter-annual variability of the Indian Ocean. In fact, gillnet fishing at Cilacap Artisanal Fishing Port is located closer to the coast in July and October than in April, which can be considered a manifestation of upwelling (Widodo et al., 2011) (Fig. 5-3). July is the upwelling peak, and October is the peak month of fish landings at Cilacap (Kuswardani, 2013).

A very limited region south of Java, Indonesia and off northwest Australia is the only known spawning area and nursery ground of the Southern Bluefin Tuna (SBT) (Shinguu, 1981; Nishikawa et al., 1985; Matsuura et al., 1997; Farley and Davis, 1998) (see Figs. 3-2 and 3-3). There are two peak spawning seasons of SBT; one during October-November and another in January-February seasons (Tsuji, 1998). According to Tsuji (1998), juveniles migrate seasonally southwards along the west coast of Australia and stay in coastal waters southwest, south and southeast of Australia, as well as in the central Indian Ocean.

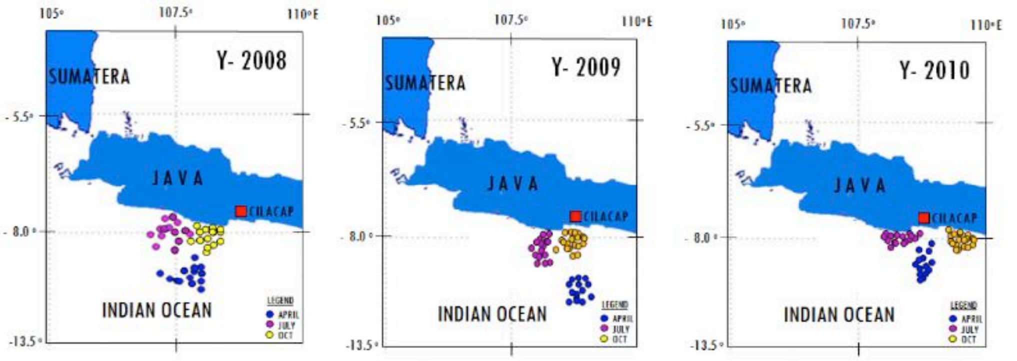

Figure 5-3: The fishing locations of gillnet, based at Cilacap Artisanal Fishing Port, collected by the onboard observation in April (blue dots), July (red dots) and October (yellow dots) 2008, 2009 and 2010 (Widodo et al., 2011).

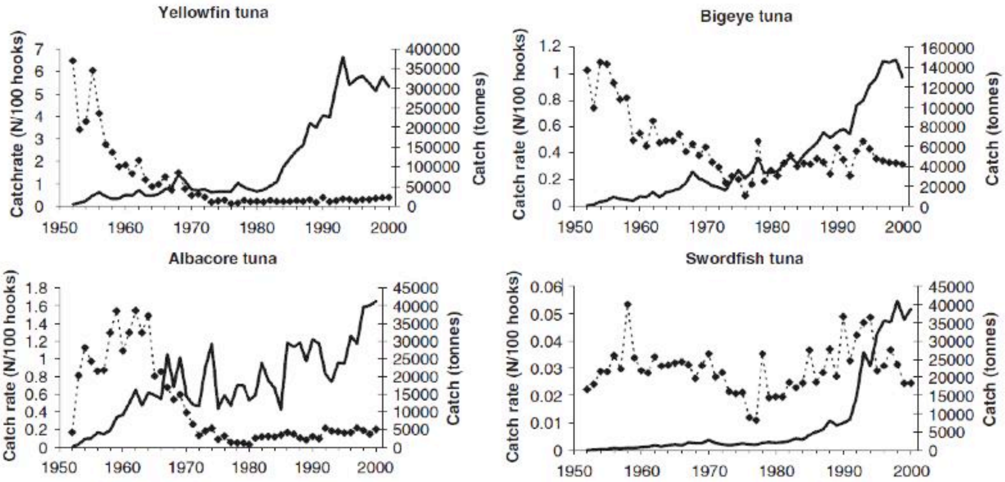

Figure 5-4: Comparison of the annual nominal catch rates by Japanese longliners (dotted line) and estimates of total catch from all fisheries (solid line) for tuna (Yellowfin, Bigeye, Albacore, Swordfish) caught by longliners in the Indian Ocean (Polacheck, 2006).

Furthermore, as the fish grow, they extend their distribution to cover the circumpolar area throughout the Indian, Pacific and Atlantic Oceans (Tsuji, 1998). Key questions include: **What is the variability in primary productivity and trophic transfer efficiency that determine the food resources for larvae and juvenile SBT? What are their relations with physical and biogeochemical conditions in order to achieve better management of SBT**?

Polacheck (2006) suggests that environmental aspects are not the only factors influencing tuna catch. By harvesting fish, for example, humans play the functional role of a top predator in the system. The degree of the ecosystem impacts depends both on the functional role of the fish being harvested and on magnitude of removals from the system. Polacheck (2006) also emphasized the lack of data and understanding of the effects on the functioning of the ecosystem as the result of changed tuna abundances. The major significant impacts of tuna catches on ecosystem function would have been expected to begin in the mid 1980s with increasing tuna harvest. This initial increase in total catch from tuna fisheries in the Indian Ocean was followed by a modest decreasing catch rate in the 1990s (see Fig.5-4). Current total removals for the Indian Ocean are estimated more than 600,000 mt (Polacheck, 2006; Satria, et al., 2013). More research to enhance understanding of the Indian Ocean carrying capacity including its fisheries stock assessment for higher trophic level species like the SBT is needed for further development on catchment quota regulation (OPRT, 2008). Key questions include: **What are the impacts of tuna catch on ecosystems in the eastern Indian Ocean? How do climate and ocean variability, such as intraseasonal and interannual variations, affect tuna larvae, recruitment, behavior and, ultimately, the tuna catch?**

(2) Physical-Biogeochemical Dynamics and Marine Protected Area Management

To complement the Fisheries Management Areas, the Government of Indonesia published the Indonesia Marine Ecoregion Map (MEM) (Fig. 5-5), as a resource for the development of management plans for marine protected areas. The MEM is organized by geographical

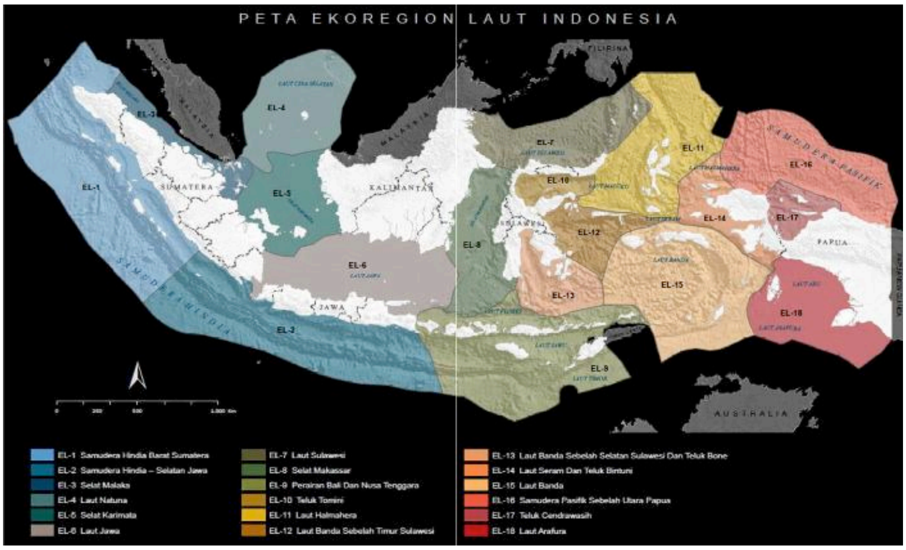

Figure 5-5: Indonesia Marine Ecoregion map (Rosalina et al., 2013). The target location for EIOURI study is laying in the Indian Ocean West Sumatra (EL-1), Indian Ocean South Java (EL-2), and Indian Ocean South Bali - Nusa Tenggara- Savu & Timor Sea (EL-9).

conditions, seawater properties and ecosystem biodiversity (Rosalina et al., 2013). Data and information taken during the Indian Ocean West Sumatra cruises in 2011-2012 under the Indonesia-China research project on “Monsoon Onset Monitoring and Its Social and Ecosystem Impacts” (MOMSEI) contributed to the development of the Indonesia MEM to support the national action plan for climate change adaptation (Pranowo et al., 2013).

Understanding the linkages between the high biodiversity of Sumatra-Java-Alor upwelling region and regional physical-biogeochemical dynamics will be important to enhance the second level of the MEM, which will help to delineate submarine ecoregions of the eastern Indian Ocean West Sumatra (EL-1), South Java (EL-2), and South Bali-Nusatenggara-Savu sea-Timor Sea (EL-9). Physical, biogeochemical, and ecological data and information from the EIOURI will contribute to the development of the MEM and, ultimately, management of FMAs in Indonesia. Key questions include: **What are the impacts of climate variations and anthropogenically-induced changes on the marine ecosystems in these ecoregions and how do these impacts effect management of marine protected areas?**

6. Implementation Strategy

1) Existing observing networks

Implementation of EIOURI requires sustained coastal and open ocean observing systems to provide the long-term context for targeted studies. Measurements in the equatorial waveguide are especially important because of the importance of wind-forced equatorial waves in the Java-Sumatra upwelling. IndOOS, which is network of in situ ocean observing systems designed to complement a constellation of earth observing satellites, provides this context for surface winds, ocean currents, temperatures, salinity, sea-surface height, ocean color, and other variables such are precipitation and outgoing long-wave radiation. Long-term measurements in the Western Australia coastal zone are particularly important for understanding the interaction of remote and local forcing variability and their influence on the strength of the Leeuwin Current and upwelling variability. The Australian Integrated Marine Observing System (IMOS) program, which is deploying long-term combined biological/physical moorings and gliders in shallow (< 200 m) waters off the south, west and northwest coasts of Western Australia, provides this context for ocean currents, temperatures, salinity and ocean color.

2) In-situ observations in upwelling regions

Implementation will also require specialized measurements in the targeted upwelling regions off Sumatra-Java-Alor and Western Australia to define the processes that locally affect the timing, intensity, duration and spatial structure of upwelling and its impacts on SST, nutrients, primary productivity and related quantities. Upwelling observation is very challenging, however, since its vertical velocity is too small to be measured, at reasonable signal-to-noise ratio by available current meters. Because some indirect measurements, including offshore currents, temperature, salinity, oxygen, pH, isotopic signatures, nutrients, chlorophyll-a, plankton species abundance, do help in understanding the upwelling process, multi-disciplinary observation is required to gain the full picture of upwelling dynamics and its biogeochemical and ecosystem impacts.

The design of the field program should encompass at least three years of specialized sampling to understand the seasonal cycle and year-to-year variations, particularly with regard to the IOD, should an event occur during the 3-yr period.

To better capture the multi-scale variations of the upwelling in the EIOURI region, particularly from the intra-seasonal to inter-annual time-scales, it is essential to conduct the following observations:

A) Time series observation

ADCP moorings along lines perpendicular to the Sumatra-Java-Alor coast are suggested, for example, along the two red lines in Fig. 6-1, to resolve the upwelling structure and its progressive phase. The left red line takes advantage of the present RAMA ADCP mooring.

Surface buoys south of Java and west of Sumatra are suggested to capture the seasonal and interannual signals of the upwelling variations. This surface-enhanced measurement is particularly useful to shed light on the mechanisms that drive SST variability there. Biogeochemical sensors can/should be added onto the surface buoys and subsurface moorings to characterize the related biogeochemical variability.

Similar kinds of targeted mooring and/or glider deployments could be motivated to study upwelling processes off of Western Australia, including surface buoys with physical and biogeochemical sensors that compliment IMOS mooring and glider deployments.

B) Transects of cruise observation

Cruise observations along sampling transects are crucial for acquiring the multidisciplinary data that are needed to provide the full picture of upwelling from the dynamic, biogeochemical and ecosystem points of view. The transect design in Fig. 6-1, similar to the one for IIOE by SIO R/V Argo in Jan. 1-Feb. 12, 1963, is recommended, for example, for the Sumatra-Java-Alor upwelling region. VPR and towed CTD are powerful observational tools

Figure 6-1: Proposed cruise tracks for Sumatra-Java-Alor upwelling observation. The solid lines represent the transections with CTD/VPR/Sampling/Net, while the dashed lines represent the transections with VPR only. The red lines represent the glider repeated transections during the monsoon peak months June-July-August, among which the left red line passes by the RAMA ADCP mooring location at (106.75E, 8.5S).

that can/should be deployed in both the Sumatra-Java-Alor and Western Australia coast zones along with standard CTD/net/water sampling. These kinds of transects should be done during upwelling development, peak phase and, decay, if possible.

C) Transects of repeated glider observations

New technology applications, especially instrumented gliders, should be utilized in the EIOURI. It is suggested to have at least two transects, like the red lines in Fig. 6-1, to be repeatedly occupied by gliders during the upwelling season, particularly July-August-September, complementary to cruise observations. Similar efforts/transects could be motivated as part of targeted studies off Western Australia.

In situ observations of biogeochemical parameters, especially vertical profiles to test for cryptic upwelling and subsurface dynamics, are required in both study regions. These measurements include biomass, productivity, and community structure characterizations (pico-nano-micro phytoplankton, temporal succession and spatial gradients).

Clearances to operate in the Indonesian EEZ will be essential. Agencies in Indonesia with a vested interest in the success of EIOURI must establish administrative mechanisms and work with the international research community to ensure the timely issuance of research clearances for planned fieldwork.

D) Argo Floats and drifting buoy observation

Deployment of Argo floats from cruises servicing in the larger EIOURI study region (Fig. 1-1) and clustered deployments of drifting buoys are useful to monitor water properties and surface divergence, respectively. Deployment of biogeochemical sensors on these floats and buoys can add significant information on biogeochemical processes and bio-physical interactions.

3) Satellite data analyses

Satellite observations will provide the backbone of EIOURI upwelling studies. With the new salinity sensing satellites, such as NASA's Aquarius/SAC-D satellite and ESA's SMOS, sea surface salinity variability can now be measured remotely, along with sea surface temperature, rainfall, chlorophyll-a (ocean color), sea surface height and surface wind. Aquarius satellite has died, but data obtained are invaluable for EIOURI studies. These data can be utilized for describing surface conditions and their variability at high spatial and temporal resolutions. At the same time, the in situ data collected in EIOURI will help to validate and calibrate the satellite data, particularly the new salinity remote sensing products. Continued improvement in surface heat, fresh water and momentum flux products will be required for both diagnostic studies and to force dynamical ocean models. Information on phytoplankton biomass and species composition can also be used to help validate new ocean color-based phytoplankton functional type (PFT) and size spectrum algorithms whose methods are less mature, but worth trying to compare with in-situ observations taken during the EIOURI cruise sampling.

4) Numerical modeling

In situ observation and remotely derived data need to be synthesized with numerical modeling outputs. Model products will provide the best estimates of upwelling variability in EIOURI since it will not be possible to directly measure vertical velocities that are an essential part of the upwelling signal for the full range of time- and space-scales over the domain of interest. Recently, several high-resolution data-assimilated products, such as ECCO and BLUElink, and eddy-resolving prognostic ocean general circulation models, such as OFES, are available for analysis of upwelling systems. These models can resolve both open ocean and coastal dynamics, as well as large-scale circulations. Biological-physical coupled models, which include simple NPZD and also more complex food web models, should also be implemented, and used to study biogeochemical and ecosystem responses to upwelling variability, but improvements of these coupled models are still an important challenge for EIOURI.

Measurements that constrain estimates of vertical velocity can be used for model validation, and they can also be assimilated in model based ocean analyses. Indeed, this will be essential. Improvements in model parameterizations of ocean mixing in upwelling zones will also lead to improved model based estimates of upwelling.

Detailed analyses of these model outputs along with simulations using regional nested models with much higher resolutions will be needed to help interpret for the results from in situ process studies of upwelling systems.

5) Leveraging with other related international and national programs

(a) IIOE-2

International Indian Ocean Expedition (IIOE)-2 is an international effort starting in 2015 to conduct integrated Indian Ocean observations and associated research for 5-year period, under the sponsorship of IOC, SCOR and IOGOOS for strategic and scientific and operational implementations, respectively. The IIOE-2 is conceptually a follow-up of the original IIOE during 1959-1965, but based on new observational and modeling technologies, rapid progress in computational ability, and significant advances in scientific understanding during this half a century (see Hood et al., 2015). EIOURI contributes to IIOE-2 as one of the core regional research activities, together with the Western Indian Ocean Upwelling Research Initiative mentioned below.

(b) WIOURI

The Western Indian Ocean Upwelling Research Initiative (WIOURI) is a sister research initiative of EIOURI under IIOE-2. WIOURI is planning intensive observational cruises and

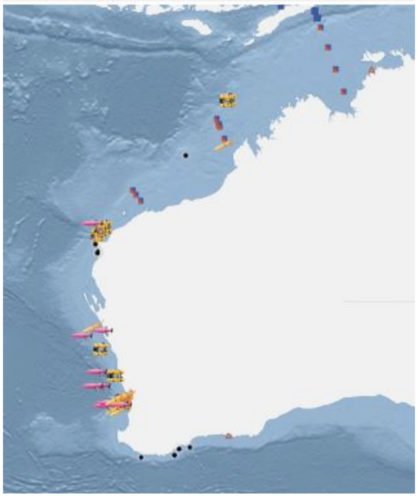

Figure 6-2: IMOS observation network along the Clarke-Meyers waveguide off the coast of Western Australia.

modeling to better understand upwelling systems in the western Indian Ocean. Capacity development programs are another main activity in WIOURI, to help develop basic skills for conducting research and utilizing scientific data for various societal purposes.

(c) IMOS/WA

The IMOS observation network off the coast of Western Australia includes shelf mooring arrays, glider tracks, coastal radar at several shelf locations along the Clarke-Meyers waveguide (Fig. 6-2). IMOS has also established the ITF monitoring capacity at the Timor Passage and Ombai Strait. The network is supplemented by the XBT repeated sections and Argo floats in the East Indian Ocean, especially the IX1 section between Fremantle and Sunda Strait. Biogeochemical sampling along the coast is also being conducted as part of the IMOS program. The IMOS program has drafted its 2015-2025 plan (IMOS, National Science and Implementation Plan 2015-25). Among other things, the IMOS observation network will be used to test the hypothesis that the interannual and intraseasonal thermocline anomalies propagated along the Clarke-Meyers waveguide will impact the strength of coastal upwelling and upper ocean primary production off the coast of Australia.

(d) INA-GOOS

INA-GOOS is an Indonesian national activity to observe ocean conditions within the Indonesian territorial waters and surrounding open oceans, including the eastern Indian and western Pacific Oceans.

6) Data management

Scientific data and knowledge are the common property of everyone. Therefore, basic information and data, i.e. metadata, obtained under EIOURI research activities should be made available to researchers and the public as soon as possible. PIs and responsible scientists participating in EIOURI must follow their national funding agency requirements related to data management and release which generally allow a priority period of two years for data processing and publication, before the data must be uploaded/released to national and/or international data centers for broad distribution. Since EIOURI is one of the core projects of IIOE-2, all the data collected as part of EIOURI will follow the IIOE-2 and IOC data policies (see IPC, 2015). .

7) Program management

A scientific steering group needs to be established to help guide the program development, promote the EIOURI concept with a broader community of possible participants, and seek funding from national sources to carry out elements of the program. The chair of this steering committee will also act as the EIOURI representative on the IIOE-2 Steering Committee (see IPC, 2015).

8) Capacity building

Although EIOURI is a research initiative, several capacity building activities will be motivated. For example, some of the EIOURI cruises will be able to accommodate a few young scientists and/or students with some scientific background to learn observing techniques and data processing and analysis. EIOURI will have several workshops and/or symposia during the 5-year period and young scientists and students will be encouraged/invited to participate in these meetings to present the results from their EIOURI studies, and they will have a chance to learn about all the other EIOURI research that is being conducted. POGO, SCOR and IOC capacity development programs will also be leveraged, which, for example, can provide scientists in developing countries with opportunities to work at research institutes/universities in other countries or attend symposiums/conferences.

9) Outputs and Legacy

EIOURI will advance our knowledge of the biophysical dynamics of upwelling systems and their response to climate variability and change and their socio-economic impacts. In addition, EIOURI will increase scientific capacity in the EIO, and enhance international collaboration in the region. EIOURI will establish a solid foundation of regional knowledge on physical, biogeochemical and ecological aspects of ocean variability upon which future research can build. New insights obtained during EIOURI will be utilized by the wider research communities and policy makers in the region to improve management of marine resources. In addition, capacity building components of EIOURI's observational activities will contribute to sustaining the current basin-scale observing system and lead in further development of regional ocean observing capabilities.

References

Alaee, M.J., C. Pattiaratchi, and G. Ivey (2007), Numerical simulation of the summer wake of Rottnest Island, Western Australia. *Dyn. Atmos. Oceans*, **43**, 171–198, doi:10.1016/j.dynatmoce.2007.01.001.

Atmadipoera, A, R. Molcard, G. Madec, S. Wijffels, J. Sprintall, A. Koch-Larrouy, I. Jaya, and A. Supangat (2009), Characteristics and variability of the Indonesian throughflow water at the outflow straits. Deep Sea Res., Part. Oceanogr. Res. Pap., 56:1942–1954.

Ayers, J.M., P.G. Strutton, V.J. Coles, R.R. Hood, and R.J. Matear (2014), Indonesian throughflow nutrient fluxes and their potential impact on Indian Ocean productivity. *Geophysical Research Letters*, doi:10.1002/2014GL060593.

Bakun, A. (1996), *Patterns in the ocean*. California Sea Grant College System/Centro de Investigaciones Biológicas del Noroeste, México. 323 pp.

Beal, L.M., W.P.M. De Ruijter, A. Biastoch, R. Zahn, and SCOR/WCRP/IAPSO Working Group 136 (2011), On the role of the Agulhas system in ocean circulation and climate. *Nature*, **472**, 429-436, doi:10.1038/nature09983.

Behera, S. K., and T. Yamagata (2001), Subtropical SST dipole events in the southern Indian Ocean. *Geophy. Res. Letter*, **28**, 327-330.

Boyd, C. M., and S. L. Smith (1983), Plankton, upwelling, and coastally trapped waves off Peru. *Deep Sea Research Part A. Oceanographic Research Papers*, **30**, 723-742.

Caputi, N., W.J. Fletcher, A. Pearce, and C.F. Chubb (1996), Effect of the Leeuwin Current on the recruitment of fish and invertebrates along the Western Australian coast. *Marine and Freshwater Research,* **47**, 147-155.

Chase, Z., P. G. Strutton, and B. Hales (2007), Iron links river runoff and shelf width to phytoplankton biomass along the U.S. West Coast, *Geophys. Res. Lett.*, **34**, L04607, doi:10.1029/2006GL028069.

Clarke, A. J., and X. Liu (1994), Interannual sea level in the Northern and Eastern Indian Ocean. *J. Phys. Oceanogr.*, **24**, 1224–1235.

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

Du, Y., T. Qu, G. Meyers, Y. Masumoto, and H. Sasaki (2005), Seasonal heat budget in the mixed layer of the southeastern tropical Indian Ocean in a global GCM, *J. Geophys. Res.*, 110, C04012, doi:10.1029/2004JC002845.

Epstein, A. W., and R. C. Beardsley (2001), Flow-induced aggregation of plankton at a front: a 2-D Eulerian model study, *Deep Sea Res. Part II*, **48**, 395–418.

Farley, J. H., and T. L. Davis (1998), Reproductive dynamics of southern bluefin tuna, *Thunnus maccoyii*, *Fish. Bull.*, **96**, 223–236.

Feely, R.A., C. L. Sabine, J. M. Hernandez-Ayon, D. Ianson, and B. Hales (2008), Evidence for upwelling of corrosive "acidified" water onto the continental shelf. *Science,* **320**, 1490-1492.

Feng, M., and S. Wijffels (2002), Intraseasonal Variability in the South Equatorial Current of the East Indian Ocean, *J. Phys. Oceanogr.*, **32**, 265-277.

Feng, M., G. Meyers, A. Pearce, and S. Wijffels (2003), Annual and interannual variations of the Leeuwin Current at 32°S. *Journal of Geophysical Research,* **108**, 3355, doi:10.1029/2002JC001763.

Feng, M., S. Wijffels, J. S. Godfrey, and G. Meyers (2005), Do eddies play a role in the momentum balance of the Leeuwin Current? *J. Phys. Oceanogr.,* **35**, 964–975.

Feng, M., A. Waite, and P. Thompson (2009), Climate variability and ocean production in the Leeuwin Current system off the west coast of Western Australia. *Journal of the Royal Society of Western Australia*, **92**, 67-81.

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

Franks, P. J. (1992), Sink or swim: Accumulation of biomass at fronts. *Mar. Ecol. Prog. Ser. Oldendorf*, **82**, 1–12.

Gaube, P., D. J. McGillicuddy Jr., D. B. Chelton, M. J. Behrenfeld, and P. G. Strutton (2014), Regional variations in the influence of mesoscale eddies on near-surface chlorophyll, *J. Geophys. Res. Oceans,* **119**, 8195–8220, doi:10.1002/ 2014JC010111.

Gersbach, G.H., C.B. Pattiaratchi, G.N. Ivey, and G.R. Cresswell (1999), Upwelling on the south-west coast of Australia – source of the Capes current? *Continental Shelf Research*, **19**, 363–400.

Gnanaseelan, C., A. Deshpande, and M. J. McPhaden (2012), Impact of Indian Ocean Dipole and El Niño/Southern Oscillation wind-forcing on the Wyrtki jets, *J. Geophys. Res.*, **117**, C08005, doi:10.1029/2012JC007918.

Ghofar, A. (2005), Co-existence in small-pelagic fish resources of the south coast of east Java, Straits of Bali, Alas and Sape-Indonesia, *ILMU Kelaut. Indones. J. Mar. Sci.*, **10**, 149–157.

Godfrey, J. S., and T. J. Golding (1981), The Sverdrup relation in the Indian Ocean, and the effect of Pacific–Indian Ocean throughflow on Indian Ocean circulation and on the East Australian Current. *J. Phys. Oceanogr.,* **11,** 771–779.

Godfrey, J.S., and K.R. Ridgway (1985), The large-scale environment of the poleward-flowing Leeuwin Current, Western Australia: Longshore steric height gradients, wind stresses and geostrophic flow. *J. Phys. Oceanogr.*, **15**, 481-495.

Gordon, A. L., J. Sprintall, H. M. Van Aken, D. Susanto, S. Wijffels, R. Molcard, A. Ffield, W. Pranowo, S. Wirasantosa (2010), The Indonesian Throughflow during 2004–2006 as observed by the INSTANT program. *Dynam. Atmos. Oceans*, **50**, 115–128.

Han, W. (2005), Origins and dynamics of the 90-day and 30–60-day variations in the equatorial Indian Ocean, *J. Phys. Oceanogr.*, **35**, 708–728, doi:10.1175/JPO2725.1.

Han, W., J. Vialard, M. J. McPhaden, T. Lee, Y. Masumoto, M. Feng, and W. P. M. de Ruijter (2014), Indian Ocean Decadal Variability: A Review, *Bull. Amer. Meteor. Soc.*, **95**, 1679-1703, doi: http://dx.doi.org/10.1175/BAMS-D-13-00028.1.

Hannides, C. C. S., M. R. Landry, C. R. Benitez-Nelson, R. M. Styles, J. P. Montoya, D. M. Karl (2009), Export stoichiometry and migrant-mediated flux of phosphorus in the North Pacific Subtropical Gyre, *Deep-Sea Research I,* **56**, 73–88.

Hanson, C.E., C.B. Pattiaratchi, and A.M. Waite (2005), Sporadic upwelling on a downwelling coast: phytoplankton responses to spatially variable nutrient dynamics off the Gascoyne region of Western Australia. *Continental Shelf Research*, **25**, 1561-1582.

Hirst, A. C., and J. S. Godfrey (1993), The role of Indonesian throughflow in a global ocean GCM, J. Phys. Oceanogr., 23, 1057-1086.

Holloway, P.E., and H.C. Nye (1985), Leeuwin Current and wind distributions on the southern part of the Australian North- west Shelf between January 1982 and July 1983. *Australian Journal of Marine and Freshwater Research*, **36**, 123-137

Hood, R.R., H.W. Bange, L. Beal, L.E. Beckley, P. Burkill, G.L. Cowie, N. D'Adamo, G. Ganssen, H. Hendon, J. Hermes, M. Honda, M. McPhaden, M. Roberts, S. Singh, E. Urban, and W. Yu. (2015), Science Plan of the Second International Indian Ocean Expedition (IIOE-2): A Basin-Wide Research Program. *Scientific Committee on Oceanic Research*, Newark, Delaware, USA.

IPC (2015), Implementation Strategy for the Second International Indian Ocean Expedition 2015-20. (Ed. N D'Adamo). Written by: UNESCO IOC IIOE-2 Interim Planning Committee (Group of Experts). *UNESCO Intergovernmental Oceanographic Commission (IOC)*, Paris, France.

Iskandar, I., Y. Masumoto, and K. Mizuno (2009), Subsurface equatorial zonal current in the eastern Indian Ocean. *J. Geophys. Res.*, **114**, C06005, doi:10.1029/2008JC005188.

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., H. Sasaki, Y. Sasai, Y. Masumoto, and K. Mizuno (2010), A numerical investigation of eddy-induced chlorophyll bloom in the southeastern tropical Indian Ocean during Indian Ocean Dipole—2006, *Ocean Dynamics*, **60**, 731–742, doi:10.1007/s10236-010-0290-6.

Izumo, T., J. Vialard, M. Lengaigne, C. de Boyer Montégut, S. K. Behera, J-J. Luo, S. Cravatte, S. Masson, and T. Yamagata (2010), Influence of the Indian Ocean Dipole on following year's El Niño, *Nature Geoscience*, **3**, 168-172.

Jury, M. R., and G. B. Brundrit (1992), Temporal organization of upwelling in the southern Benguela ecosystem by resonant coastal trapped waves in the ocean and atmosphere. *South African Journal of Marine Science*, **12**, 219-224, doi: 10.2989/02577619209504704.

Kataoka, T., T. Tozuka, S. K. Behera, and T. Yamagata (2013), On the Ningaloo Niño/Niña, *Clim. Dyn.*, doi:10.1007/s00382-013-1961-z.

Killworth, P. D., P. Cipollini, B. M. Uz, and J. R. Blundell (2004), Physical and biological mechanisms for planetary waves observed in satellite-derived chlorophyll, *J. Geophys. Res.*, **109**, C07002, doi:10.1029/2003JC001768.

Koslow, J.A., S. Pesant, M. Feng, A. Pearce, P. Fearns, T. Moore, R. Matear, and A. Waite (2008), The effect of the Leeuwin Current on phytoplankton biomass and production off Southwestern Australia, *J. Geophys. Res.*, **113**, C07050, doi:10.1029/2007JC004102.

Kuswardani, R. T. D. (2013), Determination of upwelling index based on three dimensional numerical modeling and its relation with fish catch. *Prosiding Seminar Hasil Penelitian Terbaik Tahun 2013*, ISBN:978-979-3692-54-8, vii+392 pages, p. 155-163.

Lee, T., I. Fukumori, D. Menemenlis, Z. Xing, and L.-L. Fu (2002), Effects of the Indonesian Throughflow on the Pacific and Indian Ocean. *J. Phys. Oceanogr.*, **32**, 1404-1429.

Li, T., B. Wang, C.-P. Chang, and Y. Zhang (2003), A theory for the Indian Ocean dipole-zonal mode. *J. Atmos. Sci.*, 60, 2119–2135.

Lindzen, R. S., and S. Nigam (1987), On the role of sea surface temperature gradients in forcing low-level winds and convergence in the tropics. *J. Atmos. Sci.*, **44**, 2418-2436.

Liu, L., W. Yu, and T. Li (2011), Dynamic and thermodynamic air-sea coupling associated with the Indian Ocean Dipole diagnosed from 23 WCRP CMIP3 models. *J Clim.*, **24**, 4941–4958. doi: 10.1175/2011JCLI4041.1

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

Lukas, R., and E. Lindstrom (1991), The mixed layer of the western equatorial Pacific Ocean, *J. Geophys. Res.*, 96, 3343–3357.

Luther, D. S. (1980), Observations of long period waves in the tropical oceansand atmosphere, Ph.D. thesis, MIT-WHOI Joint Program in Oceanography, Woods Hole, Mass.

Madden, R., and P. Julian (1994), Observations of the 40-50 day tropical oscillation: A review. *Mon. Wea. Rev*., **112**, 814-837.

Mann, K., and J. Lazier (2009), *Dynamics of marine ecosystems: biological-physical interactions in the oceans*, John Wiley & Sons.

Margalef, R. (1978), Life-forms of phytoplankton as survival alternatives in an unstable environment. *Oceanologica Acta*, **1**(4): 493-509.

Marshall, A. G., and H. H. Hendon (2014), Impacts of the MJO in the Indian Ocean and on the Western Australian coast. *Clim. Dyn*., **42**, 579–595.

Martin, A. P., and K. J. Richards (2001), Mechanisms for vertical nutrient transport within a North Atlantic mesoscale eddy, *Deep Sea. Res.*, **48**, 757-773.

Masson, S., P. Delecluse, J. P. Boulanger, and C. Menkes (2002), A model study of the seasonal variability and formation mechanisms of barrier layer in the eastern equatorial Indian Ocean, *J. Geophys. Res.*, 107(C12), 8017, doi:10.1029/2001JC000832.

Masson, S., J. P. Boulanger, C. Menkes, P. Delecluse, and T. Yamagata (2004), Impacts of salinity on the 1997 Indian Ocean dipole event in a numerical experiment, *J. Geophys. Res.*, 109, C02002, doi:10.1029/2003JC001807.

Matsuura, H., T. Sugimoto, M. Nakai, and S. Tsuji (1997), Oceanographic conditions near the spawning ground of southern bluefin tuna; northeastern Indian Ocean. *J. Oceanogr.*, **53**, 421–433.

McGillicuddy, D. J., and A. R. Robinson (1997), Eddy-induced nutrient supply and new production in the Sargasso Sea, *Deep Sea. Res.*, **44**, 1427–1450.

McGillicuddy, D. J., L. A. Anderson, N. R. Bates, et al. (2007), Eddy/wind interactions stimulate extraordinary mid-ocean plankton blooms, *Science*, **316**, 1021–1026.

McPhaden, M. J., and M. Nagura (2014), Indian Ocean dipole interpreted in terms of recharge oscillator theory, *Clim. Dyn.*, **42**, 1569–1586, doi:10.1007/s00382-013-1765-1.

Meyers, G. (1996), Variation of Indonesian Throughflow and the El Niño–Southern Oscillation. *J. Geophys. Res.*, **101**, 12,255–12,263.

Meyers, G., P. McIntosh, L. Pigot, and M. Pook (2007), The years of El Niño, La Niña, and interactions with the tropical Indian Ocean. *J. Climate*, **20**, 2872-2880.

Moore, T. S., and J. Marra (2002), Satellite observations of bloom events in the Strait of Ombai: Relationships to monsoons and ENSO, *Geochem.-Geophys.-Geosyst.*, **3**(2), 1 of 15–15 of 15, doi:10.1029/2001GC000174.

Murtugudde, R., J. P. McCreary, and A. J. Busalacchi (2000), Oceanic processes associated with anomalous events in the Indian Ocean with relevance to 1997–1998. *J. Geophys. Res.*, **105**, 3295–3306.

Nagura, M., and M. J. McPhaden (2010), Dynamics of zonal current variations associated with the Indian Ocean dipole. J. Geophys. Res., 115, C11026, doi:10.1029/2010JC006423.

Nagura, M., and M. J. McPhaden (2012), The dynamics of wind-driven intraseasonal variability in the equatorial Indian Ocean, *J. Geophys. Res.*, **117**, C02001, doi:10.1029/2011JC007405.

Naqvi, S.W.A., D. A. Jayakumar, P. V. Narvekar, H. Naik, V. V. S. S. Sarma, W. D'Souza, S. Joseph, and M. D. George (2000), Increased marine production of N_2O due to intensifying anoxia on the Indian continental shelf. *Nature*, **408**(6810), 346-349.

Ningsih, N. S., N. Rakhmaputeri, and A. B. Harto (2013), Upwelling variability along the southern coast of Bali and in Nusa Tenggara waters, *Ocean Science Journal*, **48**, 49–57, doi:10.1007/s12601-013-0004-3.

Nieblas, A.-E., H. Demarcq, K. Drushka, B. Sloyan, and S. Bonhommeau (2014), Front variability and surface ocean features of the presumed southern bluefin tuna spawning grounds in the tropical southeast Indian Ocean. *Deep-Sea Research II*, **107**, 64-76, doi:10.1016/j.dsr2.2013.11.007.

Nishikawa, Y., M. Honma, S. Ueyanagi, and S. Kikawa (1985), Average distribution of larvae of oceanic species of scombrid fishes, 1956–1981. *Far Seas Fish. Res. Lab S. Ser.,* **12**.

Nyadjro, E. S., and M. J. McPhaden (2014), Variability of zonal currents in the eastern equatorial Indian Ocean on seasonal to interannual time scales, *J. Geophys. Res. Oceans*, **119**, 7969–7986, doi:10.1002/2014JC010380.

Ogata, T., H. Sasaki, V. S. N. Murty, M. S. S. Sarma, and Y. Masumoto (2008), Intraseasonal meridional current variability in the eastern equatorial Indian Ocean, *J. Geophys. Res.*, **113**, C07037, doi:10.1029/2007JC004331.

Ogata, T. and Y. Masumoto (2010), Interactions between mesoscale eddy variability and Indian Ocean dipole events in the Southeastern tropical Indian Ocean—case studies for 1994 and 1997/1998, *Ocean Dynamics,* **60**, 717-730, doi: 10.1007/s10236-010-0304-4.

Ogata, T., and Y. Masumoto (2011), Interannual modulation and its dynamics of the mesoscale eddy variability in the southeastern tropical Indian Ocean, *J. Geophys. Res.*, **116**, C05005, doi:10.1029/2010JC006490.

Olson, D.B., and R. H. Backus (1985), The concentration of organisms at fronts: A cold-water fish and a warm-core Gulf Stream ring, *J. Mar. Res.*, **43**, 113–137.

OPRT (2008), World major tuna longliners suspend fishing. *The Org. Promot. Respon. Tuna Fish. Newslett. Intl.* No. 20, pp.2-5.

Paterson, J. S., S. Nayar, J. G. Mitchell, and L. Seuront (2013), Population-specific shifts in viral and microbial abundance within a cryptic upwelling, *Journal of Marine Systems*, **113–114**, 52–61, doi:10.1016/j.jmarsys.2012.12.009.

Pearce, A., and M. Feng (2007), Observations of warming on the Western Australian continental shelf. *Marine and Freshwater Research,* **58**, 914-920.

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. Syst.*, **111-112**, 139–156.

Pearce, A.F., and B.F. Phillips (1988), ENSO events, the Leeuwin Current and larval recruitment of the western rock lobster. *J. Cons. Int. Explor. Mer.*, **45**, 13-21.

Phillips, H.E., S.E. Wijffels, and M. Feng (2005), Interannual variability in the freshwater content of the Indonesian–Australian basin. *Geophysical Research Letters,* **32**, L03603. doi:10.1029/2004GL021755. -

Polacheck T. (2006), Tuna longline catch rates in the Indian Ocean: did industrial fishing result in a 90% rapid decline in the abundance of large predatory species? *Marine Policy,* **30**, 470-482.

Popp, B. N., B. S. Graham, R. J. Olson, C. C. S. Hannides, M. J. Lott, G. A. López-Ibarra, F. Galván-Magaña, B. Fry (2007), Insight into the trophic ecology of yellowfin tuna, *Thunnus albacares*, from compound-specific nitrogen isotope analysis of proteinaceous amino acids, *Terrestrial Ecology*, **1**, 173–190, doi:10.1016/S1936-7961(07)01012-3.

Pranowo, W., T. R. Adi, A. R. T. D. Kuswardani, S. L. Sagala, and B. Sulistiyo (2013), Research activities on ocean-climate variability impact to marine and fisheries sector. *Proceed. United Nations/Indonesia International Conference on Integrated Space Technology Application to Climate Change*.

Pujiana, K., A. L. Gordon, and J. Sprintall (2013), Intraseasonal Kelvin wave in Makassar Strait, *J. Geophys. Res. Oceans*, **118**, 2023–2034, doi:10.1002/jgrc.20069.

Purba, M. (2007), Dinamika Perairan Selatan Jawa – Sumbawa Saat Muson Tenggara, *Torani: J. Ilmu Kelautan dan Perikanan*, **17**, 140-150 (in Indonesian).

Qu, T., and G. Meyers (2005), Seasonal Characteristics of Circulation in the Southeastern Tropical Indian Ocean, *J. Phys. Oceanogr.*, **35**, 255–267. doi: http://dx.doi.org/10.1175/JPO-2682.1

Qu, T., and G. Meyers (2005), Seasonal variation of barrier layer in the southeastern tropical Indian Ocean. *J. Geophys. Res.* **110**, C11003 (2005).

Raes, E. J., P. A. Thompson, A. S. McInnes, H. M. Nguyen, N. Hardman-Mountford, and A. M. Waite (2015), Sources of new nitrogen in the Indian Ocean, *Global Biogeochemical Cycles*, 29, 1283–1297.

Rosalina, L., Hendaryanto, E. T. Kurniawaty, F. Mohammad, N. E. Putri, G. H. Pramono, D. Trie W. S., Y. H. Ramadhani, W. Pranowo, I. R. Suhelmi, D. Purbani, H. Y. Siry, Mahdan, O. N. Marwayana, Y. Darlan, Y. Permanawati, A. Sudaryanto, M. Hutomo, H. A. Susanto, E. Riani, and M. Khazali (2013), Deskripsi Peta Ekoregion Laut Indonesia. Kementerian Lingkungan Hidup Republik Indonesia. ISBN: 978-602-8773-10-2. 228 halaman. (in Indonesian)

Rossi, V., M. Feng, C. Pattiaratchi, M. Roughan, and A. M. Waite (2013), Linking synoptic forcing and local mesoscale processes with biological dynamics off Ningaloo Reef, *J. Geophys. Res. Oceans.,* **118**, 1211–1225, doi:10.1002/ jgrc.20110.

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

Satria, F., Mahiswara, A. Widodo, L. Sadiyah, and S. Tampubolon (2011), INDONESIA National Report to the Scientific Committee of the Indian Ocean Tuna Commission, 2011. *Report No.: IOTC-SC14-NR10*, 17 pages.

Satria, F., H. E. Irianto, B. Nugraha, and L. Sadiyah (2013), INDONESIA National Report to the Scientific Committee of the Indian Ocean Tuna Commission, 2013. *Report No.: IOTC-SC16-NR10*, 21 pages.

Schott, G. (1933), Auftriebwasser an den australischen Westküsten? Ja und Nein. *Ann. Hydrogr. Bed. 61*: 225-33.

Schott, F.A., S.-P. Xie, and J.P. McCreary Jr. (2009), Indian Ocean circulation and climate variability. *Rev. Geophys.*, **47**, RG1002, doi:10.1029/2007RG000245.

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

Shinguu, C. (1981), Ecology and stock of southern bluefin tuna. *CSIRO Mar. Lab. Rep., No. 131*.

Smith R., A. Huyer, S. Godfrey, and J. Church (1991), The Leeuwin Current off Western Australia, 1986- 1987. *Journal of Physical Oceanography*, **21**:323- 345.

Song, Q., and A. L. Gordon (2004), Significance of the vertical profile of the Indonesian Throughflow transport to the Indian Ocean, *Geophys. Res. Lett.*, **31**, L16307, doi:10.1029/2004GL020360.

Speed C. W., R. C. Babcock, K. P. Bancroft, L. E. Beckley, L. M. Bellchambers, M. Depczynski, et al. (2013), Dynamic Stability of Coral Reefs on the West Australian Coast. *PLoS ONE,* **8** (7): e69863. doi:10.1371/journal.pone.0069863.

Sprintall, J., S.E. Wijffels, R. Molcard, and I. Jaya (2009), Direct estimates of the Indonesian Throughflow entering the Indian Ocean: 2004-2006. *J. Geophys. Res.*, **114**, C07001, doi:10.1029/2008JC005257.

Sprintall J., S. Wijffels, R. Molcard, and I. Jaya (2010), Direct evidence of the south Java current system in Ombai Strait. *Dynam. Atmos. Oceans*, **50**, 140-156.

Sprintall, J., and M. Tomczak (1992), Evidence of the barrier layer in the surface layer of the tropics, *J. Geophys. Res.*, 97, 7305–7316.

Suresh, I., J. Vialard, M. Lengaigne, W. Han, J. McCreary, F. Durand, and P.M. Muraleedharan (2013), Origins of wind-driven intraseasonal sea level variations in the North Indian Ocean coastal waveguide, *Geophys. Res. Lett.*, **40**, doi:10.1002/2013GL058312.

Susanto, R., and J. Marra (2005), Chlorophyll a Variability Along the Southern Coasts of Java and Sumatra, *Oceanography*, *18*(4), 124-127.

Susanto, R., A. Gordon, and Q. Zheng (2001), Upwelling along the coasts of Java and Sumatra and its relation to ENSO, *Geophysical Research Letters*, *28*(5), 1599–1602.

Syamsudin, F., A. Kaneko, and D. B. Haidvogel (2004), Numerical and observational estimates of Indian Ocean Kelvin wave intrusion into Lombok Strait, *Geophys. Res. Lett.*, **31**, L24307, doi:10.1029/2004GL021227.

Talley, L. D., and J. Sprintall (2005), Deep expression fo the Indonesian Throughflow: Indonesian Intermediate Water in the South Equatorial Current. *Journal of Geophysical Research, Oceans*, **110**, C1009.

Thompson, R.O.R.Y. (1984), Observations of the Leeuwin Current off Western Australia. *J. Phys. Oceanogr.*, **14**, 623–628.

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

Tokinaga, H., and Y. Tanimoto (2004), Seasonal transition of SST anomalies in the tropical Indian Ocean during El Ninño and Indian Ocean dipole years. *J. Meteorol. Soc. Jpn*, **82**, 1007–1018.

Tsuji, S. (1998), Stock status of Southern Bluefin Tuna. *Proceed. 7th Expert Consult. On Indoan Ocean Tunas*, pp. 219-226.

Valsala, V., and S. Maksyutov (2010), A short surface pathway of the subsurface Indonesian throughflow water from the Java coast associated with upwelling, Ekman transport, and subduction, *Int. J. Oceanogr.*, **2010**, 540783, doi: 10.1155/2010/540783

Van Aken, H. M., I. S. Brodjonegoro, and I. Jaya (2009), The deepwater motion through the Lifamatola Passage and its contribution to the Indonesian Throughflow. *Deep-Sea Res.,* **53**, 1203–1216.

Vecchi, G.A., S.-P. Xie, and A.S. Fischer (2004), Ocean-atmosphere co-variability in the western Arabian Sea. *J. Clim.*, **17**, 1213–1224.

Venrick, E. L. (1990), Mesoscale patterns of chlorophyll a in the central North Pacific. *Deep-Sea Res.*, **37**, 1017–1031.

Vialard, J., and P. Delecluse (1998), An OGCM study for the TOGA decade: 2. Barrier-layer formation and variability, *J. Phys. Oceanogr.,* **28**, 1089– 1106.

Waite, A. M., S. Pesant, D. A. Griffin, P. A. Thompson, and C. M. Holl (2007), Oceanography, primary production and dissolved inorganic nitrogen uptake in two Leeuwin Current eddies, *Deep Sea Research Part II*, **54**, 981-1002.

Waite, A. M., V. Rossi, M. Roughan, B. Tilbrook, P. A. Thompson, M. Feng, A. S. J. Wyatt, and E. J. Raes (2013), Formation and maintenance of high-nitrate, low pH layers in the eastern Indian Ocean and the role of nitrogen fixation, *Biogeosciences*, 10, 5691–5702.

Wang, M., R. O'Rorke, A. M. Waite, L. E. Beckley, P. Thompson, and A. G. Jeffs (2014), Fatty acid profiles of phyllosoma larvae of western rock lobster (Panulirus cygnus) in cyclonic and anticyclonic eddies of the Leeuwin Current off Western Australia, *Progress in Oceanography*, doi: http://dx.doi.org/10.1016/ j.pocean.2014.01.003.

Webster, P.J., A.M. Moore, J.P. Loschnigg, and R.R. Leben (1999), Coupled oceanic-atmospheric dynamics in the Indian Ocean during 1997–98. *Nature*, **401**, 356–360.

Wernberg, T., D. A. Smale, F. Tuya, M. S. Thomsen, T. J. Langlois, T. de Bettignies, S. Bennett, and C. S. Rousseaux (2012), An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nat. Clim. Change* **3**, 78–82.

Widodo, A. A, F. Satria, L. Sadiyah, and J. Riyanto (2011), Neritic tuna species caught by drifting gillnet in Indian Ocean based at Cilacap-Indonesia. *IOTC Report No. IOTC-2011-WPNT01-21*.

Wijffels, S., and G. Meyers (2004), An intersection of oceanic waveguides: Variability in the Indonesian Throughflow region. *J. Phys. Oceanogr.*, **34**, 1232–1253.

Woo, M., C. Pattiaratchi, and W. Schroeder (2006), Dynamics of the Ningaloo current off Point Cloates, Western Australia. *Marine and Freshwater Research*, 57, 291-301.

Wyrtki, K. (1962), The upwelling in the region between Java and Australia during the southeast monsoon. *Aust. J. Mar. Freshw. Res.*, **13**, 217-225.

Wyrtki, K. (1973), An equatorial jet in the Indian Ocean. *Science*, **181**, 262–264.

Xie, S.-P., H. Annamalai, F.A. Schott, and J.P. McCreary (2002), Structure and mechanisms of South Indian Ocean climate variability. *J. Climate,* **15**, 864-–878.

Yamagata, T., S. Behera, J.-J. Luo, S. Masson, M. Jury, and S. A. Rao (2004), Coupled ocean-atmosphere variability in the tropical Indian Ocean, Earth's Climate: The Ocean-Atmosphere Interaction, *Geophys. Monogr.*, **147**, Amer. Geophys. Union, 189–212.

Yang, J., Q. Liu, S.-P. Xie, Z. Liu, and L. Wu (2007), Impact of the Indian Ocean SST basin mode on the Asian summer monsoon, *Geophys. Res. Lett.*, **34**, L02708, doi:10.1029/2006GL028571.

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

Yu, W., B. Xiang, L. Liu, and N. Liu (2005), Understanding the origins of interannual thermocline variations in the tropical Indian Ocean, *Geophys. Res. Lett.*, **32**, L24706, doi:10.1029/2005GL024327.

Zhang, C. (2005), Madden-Julian Oscillation. *Rev. Geophys.*, **43**, RG2003, doi:10.1029/2004RG000158.

Zinke, J., A. Rountrey, Feng, M., S.-P. Xie, D. Dissard, K. Rankenburg, J. Lough, and M. T. McCulloch (2014), Corals record long-term Leeuwin Current variability including Ningaloo Niño/Niña since 1795. *Nature Communications,* **5**, 3607, doi: 10.1038/ncomms4607.