CLIVAR (Climate and Ocean - Variability, Predictability, and Change) is the World Climate Research Programme’s core project on the Ocean-Atmosphere System.
Editorial
A Word from the Guest Editor
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THIS EDITION of Exchanges focuses on the recent decadal review of the Indian Ocean Observing System (IndOOS) and its outcomes. IndOOS was established in 2006 under the visionary leadership of Dr. Gary Meyers (1941-2016), the founding chair of the CLIVAR/IOC-GOOS Indian Ocean Regional Panel (IORP), to address the need for a sustained observing system that consists of a variety of observing platforms to support weather and climate research and prediction. Key founding components of the IndOOS were a tropical basin-wide mooring array – the Research moored Array for African Asian Australian Monsoon Analysis and Prediction (RAMA) – and a network of repeat expendable bathythermograph (XBT) lines. Broad international participation and support, facilitated and coordinated by the regional GOOS alliance (IO-GOOS) and the IndOOS Resources Forum (IRF), have played a crucial role in maximizing the limited resources available to implement the IndOOS.

IndOOS has now passed the 10-year milestone. A full decadal review report has recently been released as the outcome of a three-year review effort led by the IORP co-chairs, Lisa Beal, Jérôme Vialard, and Mathew Koll Roxy, with a writing team comprising more than 60 scientific experts. As highlighted in their article in this issue, the decadal review has generated 136 actionable recommendations and led to a roadmap of an enhanced observing system for the next decade (2020 – 2030). This second phase, IndOOS-2 (Figure 1, cover page), is designed to meet the current and future societal needs for seamless prediction of Indian Ocean climate and ecosystems across a wide range of timescales, from days to seasons to years to decades to centuries and beyond. Achieving goals of IndOOS-2 will depend critically on capacity building, resource management, regional partnerships, and information sharing. It is becoming more important than ever that the scientific community actively engages with stakeholders, policy makers, and civil society in the Indian Ocean rim countries to build and sustain IndOOS-2, and to address the grand challenges identified by the World Climate Research Program and the societal outcomes envisioned under the UN Decade of Ocean Science for Sustainable Development.

The main body of this edition is a condensed version of the full IndOOS-2 report, re-organized under five main science themes: natural and anthropogenic warming of the Indian Ocean, monsoon and regional air-sea interaction, ocean processes and modelling, physical and biogeochemical processes and interactions, and climate information and prediction across timescales. These themed articles, written by many lead authors of the full report, are meant to provide collective reviews that address the progress made and the gaps that still exist in understanding the complex dynamical and biogeochemical processes in the Indian Ocean, and in improving prediction skills for weather, climate, and ecosystems.

The OceanObs’19 (16-21 September 2019, Hawaii) called for new cooperative models for Observing System Governance to better align the science, technology, and human capacity of ocean observing over the coming decades. Juliet Hermes and Yukio Masumoto led a community white paper on the IndOOS contribution to OceanObs’19. Here, they and others summarize a perspective of key outcomes from OceanObs’19 and what they mean for implementation of the IndOOS-2 and for improvement of subsequent information and knowledge transformation into products and services for society.

This issue ends with an essay by Michael McPhaden on the origins of IndOOS. His reflections draw on experience in Indian Ocean research over a span of more than four decades. This article recounts in rich detail the development of the Indian Ocean observing system starting with the TOGA era when most emphasis was placed on the Pacific and El Niño.

I served on the panel during the design of the original IndOOS plan (2005 – 2010) and am now back on
the panel (2019 – present). Fifteen years have elapsed, and IndOOS has evolved into a major component of the global ocean observing system (GOOS). One thing I can say is that IndOOS would not have been possible without the support of international collaborative efforts and the contributions from many dedicated individuals from around the world. Finally, I would like to thank Dr. Jose Santos, Executive director of ICPO, for his support and assistance that makes this special issue possible.
THE INDIAN Ocean Observing System (IndOOS) is a network of sustained observations operated and supported by various national agencies and coordinated internationally under the Global Ocean Observing System (GOOS) framework by the Indian Ocean Region Panel (IORP). The IORP is sponsored by CLIVAR (Climate and Ocean: Variability, Predictability and Change), a core project of the World Climate Research Program, and by the Intergovernmental Oceanographic Commission of UNESCO. The IORP is made up of an international group of scientists and science leaders from countries and institutions within and outside the Indian Ocean region who have a commitment to sustained observations of the Indian Ocean. The goal of IndOOS is to provide sustained high-quality oceanographic and marine meteorological measurements that can support knowledge-based decision-making and policy development through improved scientific understanding, and ultimately, improved regional weather, ocean, and climate forecasts.

About one third of the global population live around the Indian Ocean, many in small islands, developing states, and least developed countries. Many of these countries are dependent on fisheries and rain-fed agriculture, making them especially vulnerable to climate variability and extremes (Allison et al. 2009). Vulnerability over this region is further increasing due to coastal population growth in conjunction with climate change (Neumann et al. 2015). Cyclones, floods, droughts, and heatwaves are becoming more extreme around the Indian Ocean (Elsner et al. 2008; Rajeevan et al. 2013). Projections foresee accelerating sea level rise, more frequent extremes in monsoon rainfall, and decreasing oceanic productivity (Srinivasu et al. 2017; Collins et al. 2019; Barange et al. 2014; Bopp et al. 2013; Roxy et al. 2016).

The Indian Ocean is the warmest among tropical oceans and helps sustain deep-atmospheric convection as well as hosting natural climate phenomena with global impacts, such as the Madden-Julian Oscillation (MJO) and the Indian Ocean Dipole (IOD). Over the past two decades the Indian Ocean alone has absorbed 30% of the global oceanic heat uptake (Lee et al. 2015; Nieves et al. 2015; Cheng et al. 2017), causing droughts and threatening terrestrial resources in south Asia and east Africa (Roxy et al. 2015; Funk et al. 2008), as well as modulating the Pacific atmospheric circulation (Luo et al. 2012; Han et al. 2014; Hamlington et al. 2014) and North Atlantic climate (Hu and Fedorov 2019; Hoerling et al. 2004). In the face of these challenges, there is growing societal demand for better monitoring, understanding, and predicting the state of the Indian Ocean and its climatic influences.

The existing IndOOS design was established on the basis of an implementation plan drafted by the IORP in 2006. Since then, societal and scientific priorities and measurement technologies have evolved, many practicalities of implementation have been learned, and the pace of climatic and oceanic change has accelerated. Over the past three years IORP has led a review of the IndOOS, culminating in a roadmap that includes 136 actionable recommendations for consolidation and enhancement of the observing system over the next decade. The full review and roadmap can be accessed at doi: https://doi.org/10.36071/clivar.rp.4.2019. Recognizing from the outset the importance of biogeochemical measurements in the future of IndOOS, IORP partnered with the Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) alliance of the Indian Ocean GOOS regional alliance (IOGOOS) to conduct the review. The review process involved 60 scientific authors from around the world and many more who participated in 3 international workshops, plus the scrutiny of a review board appointed by various partners of GOOS.

Review of the IndOOS

THE FIRST decade or so of IndOOS provided unprecedented measurements of weather, ocean, and
climate phenomena. These observations have, for instance, supported the study and forecast of tropical cyclones and marine heatwaves (Article 2 of this special issue); Improved our understanding of the Madden Julian Oscillation (MJO) and Monsoon Intra-Seasonal Oscillation (MISO) and their influence on sub-seasonal variations of the global hydroclimate (Articles 2 & 5); Mapped the equatorial and monsoon circulations and captured variability of the Indonesian Throughflow (Articles 1 & 3); And elucidated year-to-year climate variations in the tropical Indian Ocean (Indian Ocean Dipole, IOD) and their relationship to El Niño-Southern Oscillation (ENSO) (Article 5).

There remain, however, significant limitations and gaps in the existing IndOOS such that, so far, it falls short of meeting many of society’s demands for climate forecasting and prediction. These limitations are starkly illustrated by the low prediction skill of sub-seasonal to seasonal forecasts, which lack sufficient information of initial upper-oceanic conditions (Article 5), by large discrepancies in climatologies and trends of heat exchange at the air-sea interface (Article 2), and by the lack of sustained ecosystem measures (Article 4). IndOOS must also support ocean state estimations (Article 3) that are used to initialize climate predictions and drive biogeochemistry models, yet lack of observations in high flux boundary regions and in the deep ocean leave these products poorly constrained.

**Roadmap to IndOOS-2**

A SYNTHESIS of the more than 100 actionable recommendations to come out of the IndOOS review process has led to a handful of core findings which we describe here. A full list of prioritised actionable recommendations can be found online in the Executive Summary [https://doi.org/10.36071/clivar.rp.4-1.2019](https://doi.org/10.36071/clivar.rp.4-1.2019).

First, the western equatorial Indian Ocean and Somali basin have suffered from an extreme lack of observations, largely as a result of piracy and vandalism. Here, the uniquely seasonal Somali Current and western boundary upwelling system are associated with strong oceanic productivity and an expansion of regional sub-surface anoxia (Articles 3 & 4), while semiannual variability in mixed layer depth and air-sea fluxes influence monsoon variability and predictability (Articles 2 & 5). **Coverage of the Arabian Sea and western equatorial Indian Ocean, including biogeochemical measurements, must be rapidly intensified.**

Better measurements of the mixed layer, the upper oceanic layer that interacts with the atmosphere, and of the barrier layer, a salinity-stratified layer below the mixed layer, are needed to improve sub-seasonal to seasonal forecasting. Diurnal cycles in near-surface-ocean stratification impact regional sea surface temperature patterns, winds, and the development and propagation of the MJO and MISO, that in turn influence monsoon rainfall and global hydroclimate (Articles 2, 5). Hot spots of this fine-scale vertical variability occur in regions of upwelling at the eastern equatorial boundary near Sumatra, in the southeastern Arabian Sea, and in the Seychelles-Chagos Thermocline Ridge, as well as in the salinity-stratified Bay of Bengal (Article 2). These are also regions of high variability in air-sea fluxes of CO$_2$ and in primary productivity (Article 4). **Enhanced vertical and temporal resolution of upper-ocean measurements are needed in tropical regions together with the addition of near-surface biogeochemical observations.**

Recent studies suggest that the Indian Ocean has stored an astounding 30% of the global oceanic heat uptake from the atmosphere over the last two decades. This heat uptake has strongly contributed to the temporary slowdown in global surface atmosphere temperature warming, often referred to as the climate change “hiatus”. The heat is thought to have largely entered the basin from the Pacific via the Indonesian Throughflow, yet its relationship to warming in the southern subtropics and to regional sea level rise is unclear (Article 1). And its ultimate fate, regarding a possible return to the atmosphere to contribute to a future acceleration in global warming, is unknown. This motivates the need for observations that can monitor the dominant oceanic fluxes of mass and heat and ultimately constrain basin-scale budgets associated with decadal variability and change. **Boundary flux arrays in the Agulhas and Leeuwin Currents need to be established, plus an enhancement of Indonesian Throughflow monitoring, and an increase in observations of the deep ocean below 2000 m.**

Perhaps most importantly, there is an overarching need for sustained biogeochemical measurements as an integral part of the IndOOS. De-oxygenation and acidification trends, the marine carbon cycle, primary productivity variability, and ecosystem changes are largely unconstrained throughout the Indian Ocean. Management of the Indian Ocean's
natural resources, including coral reefs and wild-catch fisheries, under a changing climate will require a step-change in the amount of biogeochemical data collected. An increase in biogeochemical measurements is needed throughout the basin, initially targeted to regions of high variability and change, such as the Arabian Sea, Bay of Bengal, and eastern equatorial Indian Ocean.

Consolidations are also recommended. For instance, RAMA is proposed to reduce from 46 to 33 sites in light of logistical constraints. A smaller number of sites will allow more rapid technological advancement, additional instrumentation on existing sites, and more flexibility for new sites. The XBT program has been largely superseded by Argo, with only sections across boundary fluxes (IX01 and IX21) prioritized. A brief summary of top tier recommendations by observing system element is given in Figure 1 (front cover).

In addition to these in situ observing system priorities, the review identified three essential ingredients for the future advancement and success of the IndOOS. First, continuous, overlapping satellite measurements are central to the IndOOS, providing the only basin-wide view of the ocean and of air-sea fluxes. Second, there is urgent need for advancements in data assemblage and coupled data assimilation techniques. Quality control, archiving, inter-calibration, mapping, and accessibility of oceanographic datasets can be fragmented and un-even and needs to be improved if these data are to connect with end-users and decision-makers. Advancements in assimilation techniques are needed to better leverage the potential of the IndOOS observations in products, state estimations, and predictions. Finally, there is a necessity for increased engagement and partnerships among Indian Ocean rim countries.

Much of the expansion of the IndOOS into coastal and upwelling regions will be reliant on increased involvement and cooperation of regional countries and agencies, along with their commitment to observing best-practices, and to data sharing and dissemination. Collaboration, resource sharing, and capacity building between nations are essential in this. These challenges are not new to ocean observing. The Framework for Ocean Observing, GOOS, its partners, and the GOOS regional alliances (IO-GOOS for the Indian Ocean) provide the tools and models for success (www.goosocean.org). For the Indian Ocean, a pro-active and inclusive IORP, IO-GOOS, and Indian Ocean Resources Forum (IRF) are essential to entrain, guide, facilitate, support, collaborate with, and provide resources for new IndOOS partners and components. These bodies will need more support from the World Climate Research Program and from the Intergovernmental Oceanographic Commission of UNESCO, while the scientists who volunteer to work in them require more support and recognition from their home institutions and funding agencies.
Figure 1 IndOOS-2. Argo: Maintain the core 3° x 3° array; add 200 BGC-Argo floats; develop a Deep-Argo program. RAMA: Consolidate from 46 to 33 sites, occupy 3 remaining western sites; increase resolution of upper-ocean measurements and add biogeochemical measurements at flux reference sites; add new site off Northwestern Australia. XBT: Maintain IX01 and IX21 lines; install auto-launchers and increase near-coastal resolution on IX01. Tide gauges: Add colocated measurements of land motion; add sites in SW Indian Ocean and on islands. Surface drifters: Maintain core 5° x 5° array, evaluate addition of barometric pressure measurements. Boundary current arrays: Add measurements of mass, heat, and salt fluxes of the Agulhas and Leeuwin Currents, including hydrographic end-point moorings to capture basin-scale overturning. GO-SHIP: Find national commitment for section I01; add measurements of phytoplankton community structure. Satellites: Maintain overlapping, inter-calibrated missions; enhance spatial resolution of SSH and/or currents.
References


Recent Temperature Change in the Indian Ocean

TO DATE, the world’s oceans have absorbed 93% of the global heat gain due to anthropogenic increases in greenhouse gases over the last 150 years (Cheng et al. 2017). The oceans are acting as a buffer to global warming. Although the Indian Ocean is the smallest of the world’s oceans, it has accounted for more than one quarter of global ocean heat gain over the last twenty years (Lee et al. 2015; Cheng et al. 2017) and perhaps as much as 45% over the upper 2000 m in the last ten years (Desbruyères et al. 2017). Since 1950 the Indian Ocean has warmed about 1°C at the surface (Figure 1.1), compared to a global average of 0.6°C. This rapid warming may be due to a faster response to climate change, or to natural decadal variability (Lau and Weng 1999; Alory et al. 2007; Roxy et al. 2014). Oceanic heat content influences the climate of Indian Ocean rim countries through its feedback on winds, rain-
fall, storm intensity, and sea level rise (Han et al. 2014b). And can influence fisheries and marine ecosystems due to associated changes in stratification, oxygen, and nutrient levels (Roxy et al. 2016). Warming trends in the equatorial Indian Ocean are predicted to drive decreases in rainfall over eastern Africa, resulting in larger undernourished populations (Funk et al. 2008). Sea level rise has accelerated along the coasts of India and Australia since the late 1990s and greater than global increases have been estimated along the coasts of Indonesia, Sumatra, Oman, and Madagascar (Han et al. 2010; Watson 2011). Understanding more about Indian Ocean heat content change and predicting future changes will require sustained observations of its dominant flux components as part of IndOOS. One particularly difficult issue for the Indian Ocean is that little is known about its natural decadal climate variability, and thus it is difficult to attribute some of the above changes unambiguously to anthropogenic forcing.

Decadal Variability

THE LACK of data and dedicated studies indeed make natural decadal variability in the Indian Ocean a “grey area” (Han et al. 2014a). This is a problem for attributing climate change signals in this basin. For instance, is the rapid ∼1°C Indian Ocean surface warming between 1950 and 2015 (compared to the ∼0.6°C global average) due to a faster response to climate change in this basin or to natural decadal climate variability? (Lau and Weng 1999; Alory et al. 2007; Roxy et al. 2014). The Indian Ocean also has a clear decadal heat content variability in response to the IPO, and has absorbed a quarter of the global oceanic heat uptake over the last decade (Lee et al. 2015; Nieves et al. 2015; Liu et al. 2016; Gastineau et al. 2018). It is finally the region of highest skill for decadal surface temperature predictions, due to a relatively weak internal variability relative to the forced signal (Guemas et al. 2013), offering better prospects for accurate decadal predictions.

The Pacific and Indian Oceans are closely connected at interannual timescales, with El Niño events leading to a basin-scale Indian Ocean warming (e.g. Klein et al. 1999; Xie et al. 2009). El Niño events also tend to trigger positive IOD events (e.g. Annamalai et al. 2003). Thus, a close connection between the two basins is expected at decadal timescales.

The leading mode of decadal Indian Ocean SST variability is associated with a relatively homogenous basin-scale signal (Figure 1.2 (a)), referred to as the decadal Indian Ocean Basin-mode (decadal IOB). The decadal IOB is in phase with the IPO (Tozuka et al. 2007; Han et al. 2014b; Dong et al. 2016). “Pacemaker” experiments with specified SST in the equatorial Pacific are able to reproduce the observed decadal IOB phase, demonstrating that the decadal modulation of ENSO is its primary driver, essentially through zonal shifts in the Walker circulation, similar to what happens at interannual timescales (Dong et al. 2016). But other studies suggest that the Indian Ocean may feedback on the Pacific at decadal timescales, and may have contributed to enhance Pacific easterlies (e.g. Dong and McPhaden 2017).

The second mode of decadal tropical Indian Ocean SST variability is associated with an east-west SST dipole (Figure 1.2 (b)) which has been interpreted as a decadal modulation of the IOD (Ashok et al. 2004; Tozuka et al. 2007). The large gaps in the Indian Ocean SST dataset prior to the satellite era (e.g. Deser et al. 2010; Izumo et al. 2014) however, complicate the description of the SST pattern associated with IOD decadal modulations, which is different in observations and models (Tozuka et al. 2007). Similarly, it is difficult to constrain decadal sea-level variability observationally. There is indeed a large spread in the decadal sea-level variability reconstructed from observations in this region (Nidheesh et al. 2017).

Modelling studies have identified decadal sea-level (Nidheesh et al. 2019), mixed-layer depth and SST variations (Yamagami and Tozuka 2015) in the southern subtropical Indian Ocean, east of Madagascar, possibly associated with decadal fluctuations in the Mascarene anticyclone intensity, as occurs at the interannual timescale for the subtropical Dipole. The particularly large gaps in the observational record in this region (e.g. Deser et al. 2010) again make it difficult to verify those modelling results.

In addition to the Walker circulation atmospheric bridge described above, the Indian Ocean is also connected to the Pacific via the Indonesian through-flow. Negative IPO phases induce positive sea-level signals off the west coast of Australia (Feng et al. 2004). The negative IPO phase between the late 1990s and 2013 favored more frequent marine heatwave events with large ecosystem consequences along the west coast of Australia (Ningaloo Niño,
Figure 1.2 Spatial patterns of the (a) first (37% of total variance) and (b) second (14% of total variance) Empirical Orthogonal Function of decadal (9-35 years) observed SST (ERSST product). Adapted from Tozuka et al. 2007.

Feng et al. 2013; Feng et al. 2015). An important fraction of the heat uptake in the Pacific during the last decade negative IPO phase was transferred to the Indian Ocean following this pathway (e.g. Lee et al. 2015; Nieves et al. 2015) and its fate is not known.

Anthropogenic Change

CLIMATE MODEL simulations indicate that anthropogenic emissions accounts for about 90% of surface warming in the Indian Ocean (e.g., Dong and Zhou 2014, Dong et al. 2014). The basin-wide warming trend is primarily attributed to atmospheric forcing via radiative and turbulent fluxes associated with increased greenhouse gases in the atmosphere (e.g., Du and Xie 2008; Dong et al. 2014), while anthropogenic aerosols have regional cooling effects (Figure 1.3; Dong et al. 2014). The heat is redistributed in the basin via local ocean and atmospheric dynamics (Liu et al. 2015, Rahul and Gnanaseelan 2016), the oceanic tunnel (Indonesian Through Flow, Susanto et al. 2012; Sprintall and Revelard 2014; Lee et al. 2015; Susanto and Song 2015; Zhang et al. 2018) and the atmospheric bridge (Walker circulation, Roxy et al. 2014; Abish et al. 2018).

In contrast to these results, surface heat fluxes show a negative trend over the Indian Ocean (for the period 1984-2007, Rao et al. 2012), which therefore cannot explain the observed warming in SSTs. Considerable uncertainty exists about the sign of the net heat flux into or out of some parts of the Indian Ocean (Yu et al. 2007). In fact, surface fluxes are the most uncertain geophysical measurement in the Indian Ocean observing array at present.

The frequency of extreme positive IOD events is projected to increase by a factor of three, from a one-in-seventeen-year event in the 20th century to a one-in-six-year event in the 21st century (Cai et al. 2014). Though future projections indicate an IOD-like pattern of mean changes, the bias in the CMIP5 models and internal variability could enlarge the projected increase in the extreme positive IOD events (Li et al. 2016). For example, the historical climate model simulations under CMIP5 using observed greenhouse gases forcing does not reproduce the zonal SST gradient or the observed warming pattern over the Indian Ocean (Cai and Cowan 2013; Roxy et al. 2014). Internal variability and ENSO forcing also plays a major role in the IOD-like response (Yang et al. 2015; Hui and Zheng 2018), necessitating coordinated studies including both improved long-term observations in the equatorial Indian Ocean and model experiments for reliable detection and attribution of the inhomogeneous changes in the Indian Ocean.

Components of Heat Content Change

THE HEAT budget of the Indian Ocean, north of 35°S, is dominated by three components estimated to have similar magnitude (Figure 1.4): an inflow of fresh tropical waters via the Indonesian Throughflow (Sprintall et al. 2009; Zhang et al. 2018; Roberts et al. 2017), a vertical overturning circulation (0-2000 m) linking upwelling in the northern hemisphere and in the equatorial gyre with subduction and inflow of mode waters at the southern reaches of the basin (Schott 2004; Schott et al. 2009; Han et al. 2014a), and a horizontal subtropical gyre circulation dominated by the warm and salty waters of the Agulhas Current at the western boundary (Bryden and Beal...
Figure 1.3 The SST trends during 1870-2005 averaged in Indian Ocean (40°S-15°N, 40°E-100°E) under all forcing runs, GHG-only forcing runs, and AA-only forcing (historical-historicalGHG-historicalNat) from 17 CMIP5 models and the MME of them (number 18). The dashed line represents the trends in observation. Units: K (100 year)-1 (Dong and Zhou 2014).

Figure 1.4 The dominant components of the Indian Ocean heat budget and required observing system elements. The components are: The Indonesian Throughflow, the cross-equatorial and subtropical overturning cells linking regions of upwelling with regions of subduction, and the horizontal subtropical
In the past decade of the IndOOS most targeted assets have been concentrated within the equatorial region, yet subsurface temperature and salinity in the southern Indian Ocean are a good place to look for climate change signals (Banks et al. 2002), not least because natural variability is smaller than in the tropics. The greatest rates of heat content changes have been in the Southern Indian Ocean and Agulhas system (Cai et al. 2007; Wu et al. 2012; Alory et al. 2007; Yang et al. 2016). With Argo it is possible to map the distribution of heat content change across the basin (Desbruyère et al. 2017), yet to understand this distribution and the time scale of storage — how long will the Indian Ocean continue to warm at a rapid pace? Where will the heat go next? — and to try to reconcile tropical drivers with those at higher latitudes, it is necessary to also monitor the major heat flux components in the subtropics.

Here the horizontal gyre component, dominated by the Agulhas Current, and the upper-ocean overturning cell, which appears largely separated from the deep cell at about 2000 m depth, contribute almost equally to the heat budget (Sloyan and Rintoul 2001; Bryden and Beal 2001; Hernández-Guerra and Talley 2016). Almost nothing is known about the seasonal-to-decadal variability of these components nor their response to changes in the Indonesian throughflow, which is typically modelled as a barotropic export although its buoyancy flux must surely cause baroclinic change within the basin. It is also possible that other components, such as the warm, southward Leeuwin Current, play important roles in the time-varying heat budget even though their mean contributions are small (Zhang et al. 2018).
Figure 1.5 Tide gauge observed and OGCM simulated annual mean sea level anomalies (SLA) and their trends during 1961-2008. The 10 tide gauge stations with records longer than 30 years (20 years for Zanzibar) are shown. All trends exceed 95% significance except for stations 6 and 9. Middle color panel shows trend of HYCOM SLA for 1961-2008. Light blue/green regions are below and the rest above 95% significance. Figure from Han et al. (2010).
and Lenaerts 2016). While continued altimetry and GRACE (gravity recovery and climate experiment) missions are crucial, consistent and sustained in situ measurements are vital for inter-calibrating satellite missions in order to generate continuous merged altimetry records.

Heat Content and Sea Level as a Driver of the IndOOS: EOVs

To gain a better understanding of how wind and thermohaline changes impact the basin-wide Indian Ocean heat budget and vice versa we need to measure variability and change in its major flux components. This requires the collection of temperature, salinity, velocity, and where possible oxygen data along the open southern boundary of the basin, latitudes ~32°-34°S (Figure 1.4). 34°S is the latitude of climatological mean maximum wind curl. Daily observations of these EOVs at 10 km (inshore)—50 km (offshore) horizontal resolution, and 100 m (upper)—1000 m (bottom) vertical resolution are needed to capture the intense, narrow Agulhas Current and its heat flux at the western boundary, and similarly for the Leeuwin Current at the eastern boundary. Moorings in 2000 m (or more) of water as part of these arrays will double as endpoint moorings to capture geostrophic, basin-wide, upper-ocean overturning, in a similar manner to the overturning array of the North Atlantic (Rayner et al. 2011). Across the interior, profiles (down to 2000 m) of EOVs T,S,O2 at monthly resolution are needed to capture inflows of intermediate waters, changes in mode waters, and constrain gyre circulation. Decadal GO-SHIP sections (full-depth), which include the collection of silicates, CFCs and other properties, are required to provide important constraints on circulation and heat flux estimates (Robbins and Toole 1997) as well as measures of abyssal warming. These in situ observations must be augmented by sustained, consistent satellite observations of sea level, sea surface temperature, and wind stress to obtain estimates of barotropic fluxes and meridional Ekman transport.

Better describing Indian Ocean decadal climate variability is a must for detecting climate change signals in this under-sampled basin & for global decadal climate projections. The overall picture of natural decadal Indian Ocean climate variability is very incomplete, with many questions yet to be resolved. This requires sustained basin-scale observations over several decades in key regions for decadal climate variability quantification, with at least ~monthly resolution.

Long term changes in Indian Ocean SST and heat content are occurring but internal climate variability at decadal timescales can obscure the attribution of those signals to anthropogenic drivers. It is therefore difficult to distinguish the climate change signal from internal climate variability without long-term observations. The solution requires the maintenance of sustained observations of key variables over a long period.

Sea level represents an integral effect of surface and subsurface oceanic processes. In addition to surface winds, ocean heat content (or thermosteric sea level) is a primary contributor to regional sea level patterns, and salinity (or halosteric sea level) also has significant contributions in many regions (Fukumori and Wang 2013; Nidheesh et al. 2013; Llovel and Lee 2015; Srinivasu et al. 2017). In situ temperature and salinity profiles over the upper 700 m of the ocean from expendable bathythermographs (XBTs) and the Argo program can explain a large portion of the observed sea level variability and change. However, there remain significant differences from total sea level, as observed with satellite observations since the 1990s and reanalysis products since the 1950s (Han et al. 2018). Consequently, more deep ocean observations are needed to capture missing steric sea level variations and close the global sea level change budget.

Actionable Recommendations

Based on the suggested EOVs listed above, the actionable recommendations on the current IndOOS design are:

1. Maintain and complete the RAMA array, which provides sustained, high-frequency observations of, in particular, SST, winds, subsurface temperature, air-sea fluxes in key regions of the tropical Indian Ocean. In particular, expand the array into the Arabian Sea and western Indian Ocean – where the uncertainties regarding air-sea fluxes are large.

2. Maintain the current Argo coverage in the Indian Ocean but also: a) enhance coverage near the ITF exit and b) support the development of Deep Argo (Johnson et al. 2015), in particular in the Southern subtropical Indian Ocean, e.g., along ~32°S. This will improve
the observed flux divergence between the entry (ITF) and exit (Agulhas) and provide better estimates for the variability and changes in the heat gain in the Indian Ocean. This is also necessary to estimate the freshening due to ITF waters at 12°S. Explore the technical feasibility of enhancing Argo observations in the ITF region. Explore the technical feasibility of a long-distance glider line along 32°S.

3. Maintain the GO-SHIP array of repeat hydrographic sections in the Indian Ocean (sections: IO7S, IO5, IO7N, IO1W, IO5, IO8N, IO3, IO8S, IO9N, IO1E, IO10, IO9S) to ensure that long-term, full-depth measurements are available to quantify ongoing change and provide important regional calibration for Argo in the region.

4. Maintain the IX01 XBT line with at least a fortnightly resolution (geostrophic mass and heat transport at the throughflow exit and crosses the region of strong decadal sea-level signal off the west coast of Australia). Experimental doubling of the IX01 line by gliders. Enhance with automated launchers and regional Argo float deployments (for salinity).

5. Maintain and augment (in particular in the southwestern tropical Indian Ocean Islands & Madagascar) the existing tide-gauge network, and ensure open distribution and common processing of the data. Ensure that all contributing stations begin capturing geodetic information relevant to the site (add GNSS), so that sea-level data quality can be ensured.

6. Re-establish and maintain an Agulhas System volume, heat, and freshwater array at the western boundary near 34°S, including an “end-point” mooring to measure interior geostrophic overturning down to ~2000 m.

7. Enhance and maintain a Leeuwin Current array to measure volume, heat, and freshwater flux at the eastern boundary near 34°S, including an “end-point” mooring down to ~2000 m.

8. Maintain satellite observations and intercalibration-work that allow the development of basin-scale wind, sea level and SST records that span several decades.

9. Improved long-term observations in the equatorial Indian Ocean hand-in-hand with model experiments for separating the role of climate change, internal variability and ENSO forcing on the inhomogeneous SST changes in the Indian Ocean.

10. Develop collaborations with the paleo-proxy community.

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**Theme 2. Monsoon and Regional Air-Sea Interaction**

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A LARGE portion of the Indian Ocean exhibits SST exceeding the 28.5°C threshold for deep atmospheric convection, hence facilitating very active air-sea interactions across a variety of time scales. Aside those involved in the seasonal course of the monsoon, they also occur at subseasonal and synoptic variability. The monsoon itself does not occur as a continual downpour but rather as intraseasonal pulses, referred to as active and break periods (e.g. Goswami 2005). Despite the strong atmospheric control on these pulses, the SST signatures they promote may significantly affect these atmospheric intraseasonal perturbations (Klingaman et al. 2011). The Indian Ocean is also home to about 25% of the global tropical cyclone (TC) activity. Although not the strongest, TCs in the Bay of Bengal (BoB) have catastrophic impacts, with 14 of the 20 deadliest TCs having occurred in that region (Needham et al. 2015). While TCs primarily arise from atmospheric processes, they are nonetheless strongly influenced by ocean-atmosphere interactions. The SST cooling under TCs (Vincent et al. 2012; Neetu et al. 2012) indeed reduces the total enthalpy flux to the atmosphere and hence limits the cyclone intensification (Lengaigne et al. 2018; Neetu et al. 2019). Ocean-atmosphere interactions may therefore modulate climate variability over a wide range of time and spatial scales and must hence be carefully monitored.

1. Monsoon and Upper Ocean Processes

THE SEASONAL-MEAN monsoon rainfall largely dictates the socio-economic conditions of small-scale farming communities in south and southeast Asia, which has a direct impact on world rice production. Furthermore, diabatic heating associated with the monsoon influences the global atmospheric circulation. Given the global manifestation of the monsoon, understanding and modelling the processes responsible for its variability remains a grand challenge of the World Climate Research Program (Clouds, Circulation and Climate Sensitivity).

In conjunction with land surface heating, the monsoon annual cycle is driven by the seasonal displacement of the Intertropical Convergence Zone (ITCZ), which is anchored by the north-south migration of the Indo-Pacific warm pool (regions where SST is >28°C). Over the past few decades, research has elucidated some of the complex interactions among the ocean, atmosphere, and land components of the climate system that influence the south-Asian monsoon. At the same time, progress in improving the coupled models used to simulate and predict the monsoon has been slow (Turner and Annamalai 2012), despite an increase in data from multiple observing platforms. Due to the complexity of the monsoon, identifying specific causes for the slow progress is difficult but major challenges are: (i) persistent model errors, not due to limitations in one particular parameterization (e.g., convection) but in multiple processes and their interactions, and (ii) inadequacies of the existing suite of observations for understanding monsoon systems and to constrain model physics (Annamalai et al. 2017). We will focus in the following on upper-ocean physics which needs to be monitored to better understand and simulate the coupled processes involved in the south-Asian monsoon.

In the northern Indian Ocean, there is a remarkable east-west asymmetry in SST and precipitation during the monsoon (Figure 2.1 (a)). During summer, there is intense upwelling of cold water along the Somali and Omani coasts driven by the cross-equatorial low-level jet, and SST drops to about 23–24°C. Subsequently, horizontal advection by ocean currents, in conjunction with evaporative cooling, results in cold SST in the central Arabian Sea, weakening rainfall there. In contrast, SST over the BoB remains high and rainfall is stronger resulting in upper-ocean salinity stratification (Shenoi et al. 2002) in response to local precipitation and river runoff as well as lateral advective processes (Akhil et al. 2014). These surface freshwaters thin the surface mixed layer and generate barrier layers that prevent entrainment of cold subsurface waters (Lukas and Lindstorm 1991) and subsurface temperature inversions (Tadathil et al. 2016), which help sustaining warm SSTs during winter (Figure 14.1b, Shenoi et al. 2002). High-
resolution observations from multiple instruments collected during ASIRI (An Ocean-Atmosphere Initiative for the BoB; 2013-17) identified shallow, salinity-controlled mixed layers of \(\sim 20\) m depth resulting from high river runoff and heavy rainfall (Wijesekera et al. 2016) and modified by lateral mixing due to mesoscale features (Mahadevan et al. 2016). Barrier layers are spread southward and into the interior by the wintertime anticyclonic circulation and the east India Coastal Current (Akhil et al. 2014). These low-saline waters are further advected in the southeastern Arabian Sea in winter (Durand et al. 2004), which may influence the monsoon onset. Interannual variations in the timing of monsoon onset are also linked to SST variations over the Seychelles-Chagos Thermocline Ridge (SCTR) during boreal spring, through their impact on the poleward migration of the ITCZ (Annamalai et al. 2005). The linkage is particularly strong during years after the peak phase of El Niño, when fluctuations in thermocline depth and SST are most strongly coupled (Xie et al. 2002). There is evidence for the formation of salinity stratification at intraseasonal timescales (Vialard et al. 2009), but because of data scarcity the dynamical impact remains unclear. Owing to strong atmospheric convection over the eastern equatorial Indian Ocean (Figures 2.1 (a),(b)), the equatorial Indian Ocean also experiences semi-annual westerly winds during the intermonsoon periods, which force the eastward-flowing Wyrtki Jets (Wyrtki 1973) intensified by the near-surface salinity stratification (Masson et al. 2003). The Wyrtki Jets are an important component of the Bjerknes’ feedback along the equator for simulating monsoon processes (Annamalai et al. 2017).

Based on our current knowledge, there are key regions where observations (salinity, temperature, and mixed-layer depths) are needed to improve understanding of the processes that shape the upper-ocean, and thereby improve models’ physical parameterization schemes:

A. Over the BoB core region for a rectangular mesh (12°N-22°N, 80°- 100°E), we recommend a rectangular mesh of Argo floats equipped with auxiliary surface temperature and salinity (STS) sensors (\(\sim 10\) cm vertical resolution in the top 2–4 m) similar to those implemented in few regions of the BoB (Anderson and Riser 2014). We also strongly recommend deploying RAMA array poleward of 14°N to cover the northern BoB, including the continental shelf where Argo floats cannot enter.

B. To measure upper-ocean salinity and thermal distributions over the Arabian Sea mini warm pool (68°–77°E, 6°–15°N), deployment of Argo floats with auxiliary STS (preferably at a spatial interval of 5°in longitude and latitude) in conjunction with additional RAMA arrays are recommended.

C. Over the equatorial Indian Ocean, ADCP networks need to be deployed over the central basin (65°E- 85°E) to measure the Wyrtki Jets. Over both the eastern (at 100°E and 110°E) and western (at 45°E, 50°E, 55°E, 60°E and 65°E) regions, high vertical resolution (\(\sim 10\) cm) observations of upper-ocean salinity and
thermal stratifications are needed to measure the accumulation and discharge of heat.

D. Over the thermocline ridge, place auxiliary STS sensors on Argo floats and deploy additional RAMA buoys to locations along 65°E and 75°E extending from 12°S-Eq, yielding a rectangular mesh of buoys with the existing ones.

2. Intraseasonal Air-Sea Coupling

THE MADDEN-JULIAN Oscillation (MJO; Madden and Julian 1972) and the monsoon intra-seasonal oscillation (MISO; Yasunari 1980) are major sources of intra-seasonal variability in the tropics. Here we discuss the role of the ocean and of air-sea interaction in the initiation and propagation of the MJO and MISO over the Indian Ocean. The MJO is associated with large-scale atmospheric circulation and deep convection. It propagates eastward around the globe on an approximate timescale of 30-60 days. The MJO impacts a variety of weather and climate variability, including the onsets and breaks of Indian and Australian monsoons, tropical cyclone activity, precipitation in the extra-tropics, and interannual variability such as ENSO and the Indian Ocean dipole (e.g., Lau and Waliser 2011). The MISO is a dominant mode of intra-seasonal variability in the tropical troposphere during boreal summer over the Asian Monsoon region. It is characterized by 30-60 day variations of convection and low-level winds, propagating northward from the equator towards south and southeast Asia. The MISO causes fluctuations in rainfall during the Indian summer monsoon and plays an important role in triggering the monsoon onset (e.g., Goswami 2011).

A comparison of many coupled and uncoupled numerical model experiments suggests that including air-sea feedbacks improves simulations of MJO's amplitude, period, and propagation (e.g., De Mott et al. 2016). The MJO indeed drives significant fluxes of momentum and heat into the tropical western Pacific and Indian Oceans (Shinoda et al. 1998), causing large upper ocean responses, including strong equatorial currents, fluctuations of mixed layer temperature, and changes of thermocline depth (e.g., Kessler et al. 1995). While surface shortwave radiation and latent heat flux are the primary controllers of intra-seasonal variation of SST (Shinoda and Hendon 1998), the contribution of ocean dynamical processes can be significant over the Indian Ocean. One such location is the SCTR where the main thermocline is very shallow. Intraseasonal SST variability is much larger in the SCTR region than most other areas in the tropical Indian and western Pacific Oceans. The relative importance of surface heat fluxes and ocean dynamics in controlling intra-seasonal SST in the SCTR region still remains unclear (e.g., Halkides et al. 2015). Another area of large SST variability associated with the MJO is the Timor Sea off the northwest coast of Australia (e.g., Vialard et al. 2013) (Figure 1). It appears that SST warming (cooling) in this region is driven by surface heat fluxes and coastal downwelling (upwelling) generated by easterly (westerly) wind anomalies during the suppressed (active) phase of the MJO (Marshall and Hendon 2014). However, quantitative clarification requires better spatial and temporal data coverage of in-situ observations. SST warming during the suppressed phase of the MJO is also enhanced by the diurnal cycle of shortwave radiation (e.g., Shinoda 2005). This effect could play an important role in the initiation of the MJO, since warm SSTs can enhance moisture accumulation in the troposphere, stimulating the initiation of atmospheric convection. Significant SST signals are also observed over the Maritime Continent where eastward MJO propagation often weakens. Regional coupled model simulations further demonstrated the importance of the diurnal cycle for the initiation of MJO convection during the CINDY/DYNAMO field campaign (Seo et al. 2015). Further experiments, as well as observations of many different events, are necessary to confirm the role of diurnal warming. Three active episodes of large-scale convection associated with the MJO propagated eastward across the tropical Indian Ocean during the CINDY/DYNAMO field campaign in October-December 2011 (Yoneyama et al. 2013). While the strength of atmospheric convection was similar for the three MJO events, the oceanic response was strong for the second event (e.g., Moum et al. 2013) but much weaker for the first event. This difference suggests that the role of air-sea coupling in the MJO varies substantially from event to event (MJO diversity; e.g., Fu et al. 2015). Hence, it is crucial to maintain and enhance long-term measurements that cover many MJO events to advance our understanding of air-sea coupled processes associated with the MJO.

As for the MJO, air-sea coupling is thought to be important for MISO development and propagation (e.g., Webster et al. 1998). Coupled and uncoupled numerical model experiments demonstrate that the inclusion of air-sea interaction leads to more realistic
Figure 2.2 Composite SST anomalies (°C) for phase 3 (left panel) and phase 6 (right panel) of the MJO (based on Wheeler and Hendon 2004) over the November-April season calculated from the microwave OI SST.

Simulation and better prediction skills of the MISO (e.g., Fu et al. 2003). As the MISO propagates from the equator to southeast Asia, it is thought to be influenced by underlying SSTs in the BoB. While previous observational and modelling studies indicate that shortwave radiation, latent heat flux, and ocean dynamics are all important for controlling intra-seasonal SST variability in the BoB (e.g., Sen Gupta et al. 2001), the relative contribution of these processes varies among the studies. The BoB receives a substantial amount of freshwater through precipitation and river runoff, creating a complex upper ocean stratification including a strong halocline, temperature inversion, and thick barrier layer. Recent studies suggest that SST variability caused by strong salinity stratification significantly influences atmospheric convection over the BoB associated with the MISO (Li et al. 2017). Realistic model simulations of upper ocean structure and variability in the northern BoB are severely hampered by uncertainties in estimates of river discharge, which directly influence salinity variability. Long-term measurements in the northern BoB would be thus useful for understanding the overall impacts of salinity stratification on the MISO intensity and propagation.

Sustained measurements, especially the RAMA array and Argo program, are crucial for the study of intra-seasonal air-sea coupling over the Indian Ocean. Other specific recommendations are listed below:

A. The increase of vertical resolution in the upper 10 m of RAMA buoy for monitoring the diurnal cycle in the near-surface layer.

B. Adding a new RAMA site off northwestern Australia in the Timor Sea at 14°S, 115°E where large SST anomalies associated with the MJO are observed.

C. Continuation of surface buoy measurements at 18°N, 90°E in the northern BoB to monitor upper ocean and SST variability.

D. Enhancement of the RAMA buoy in the SCTR (4°S, 65°E), which includes velocity (ADCP) measurements.

E. Additional buoy measurements in the southern part of the Banda Sea where the largest intra-seasonal SST anomalies are found within the Indonesian Seas.

3. Extreme Events

HIGH POPULATION density distributed along low-lying coastal areas and poor disaster management strategies largely explain the vulnerability of countries surrounding the Indian Ocean to extreme events, including Tropical Cyclones (TCs) and Marine Heat Waves (MHWs). In the northern Indian Ocean, TCs are prevalent in the western and central BoB part (Figure 2.3a), occurring mostly before and after summer monsoon. In the southern Indian Ocean, TCs occur across the basin around 15°S, from November to April (Figure 2.3a). Strong TCs winds can cause an SST cooling (Figure 2.3b) and hence limit TC intensification (Lengainge et al. 2018). The order of magnitude of this cooling is modulated by oceanic subsurface stratification (Vincent et al. 2012), with larger cooling in regions with
Figure 2.3 (a) Observed climatological distribution of normalised cyclogenesis (color) and TC density (contour) in the Indian Ocean and (b) composite evolution of the TC-induced SST cooling (from OI_SST) within 200 km of all TC-tracks in the Indian Ocean (°C) derived from the IBTrACS (Knapp et al. 2010) over the 1989-2009 period. Compostited SST anomalies in spring following (c) El Niño and (d) La Niña over the 1982-2015 period. The white contours and dots indicate anomalies exceeding the 95% significance level based on a two-tailed Student's t test. Adapted from Lengaigne et al. (2018) and Zhang et al. (2017)
a shallow thermocline, and hence a larger negative feedback on TC intensification.

Unique characteristics of upper ocean thermohaline structure in the Indian Ocean may result in different ocean-atmosphere coupling compared to other basins and therefore different TC sensitivity. For instance, there can be strong haline stratification in the BoB that causes a barrier to mixing and cooling (Thadathil et al. 2016). RAMA moored buoy data in the BoB have shown that a warm subsurface layer and strong salinity stratification played an essential role in the rapid intensification of Nargis TC (Yu and McPhaden 2011). At seasonal timescales, these data demonstrated that thick barrier layers are induced by stronger haline stratification and a deeper thermocline after the monsoon (Thadathil et al. 2016). These thick barrier layers contribute to much weaker TC-induced cooling as compared to the pre-monsoon period (Neetu et al. 2012, 2019), fostering post-monsoon TC intensification (Balaguru et al. 2012). Similarly, the SCTR is one of the rare oceanic regions where warm SSTs coexist with a shallow thermocline, which can enhance cooling under a TC. There, TC activity decreases dramatically during strong El Niño events due to large-scale variations of the atmospheric environment (Astier et al. 2015) and oceanic stratification (Xie et al. 2002; Vincent et al. 2014). TCS in the northwest Australia basin are also related to ENSO (Ramsay et al. 2011) but the role of subsurface oceanic conditions is less clear in this region (Vialard et al. 2013). Climate change is thought to increase the intensity of major BoB TCs after the monsoon (Balaguru et al. 2014) and in the Arabian Sea before the monsoon (Murakami et al. 2011).

Marine Heat Waves (MHWs) are another type of extreme events, characterized by episodic warm SST extremes that persist for days to months (Hobday et al. 2016). The subtropical coast of west Australia has witnessed major MHWs during the past decades, such as in 2010-2011 (Feng et al. 2013), resulting in massive coral bleaching and decimation of economically important fish species (Wernberg et al. 2013). These MHWs are generally instigated by an anomalous strengthening of the Leeuwin Current during strong La Niña events (Figure 2.3d) and further facilitated by local air-sea-land coupling and the MJO (Kataoka et al. 2018). Further north, MHWs have also led to massive coral bleaching in the equatorial eastern Indian Ocean, the tropical oceans near the maritime continent, and off the coast of northwest Australia (Zhang et al. 2017), such as in early 2016. These events generally occur around the peak of strong El Niño events (Figure 2.3c), in response to reduced cloud coverage and Australian monsoon weakening. Major coral bleaching events have also been observed elsewhere following major El Niño, especially over the western Indian Ocean (e.g. Perry and Morgan 2017; Gudka et al. 2018). With unabated global warming, MHWs and related coral bleaching events will become more frequent in the future (Lough et al. 2018).

SST and upper ocean stratification influence TC intensification, while air-sea flux and boundary current variability influence MHWs. In-situ measurements as part of IndOOS are essential for providing measurements of the subsurface oceanic conditions important to TC intensification, particularly since cooling under the TC is not well observed by satellite remote sensing, even by microwave radiometers, due to strong precipitation. Therefore, to better monitor, understand, and predict these extreme events requires:

A. New satellite technology and intercalibration work to (i) develop continuous, basin-scale wind and SST records reliable in rainy/cloudy regions, (ii) increase resolution of altimetry for oceanic currents and surge response to TCs.

B. Maintain the Argo network in TC-prone regions. Sustain RAMA-2.0 and enhance air-sea flux measurements at sites in the BoB and southwestern Indian Ocean.

C. Maintain coastal tide-gauge measurements, particularly around the BoB and along the west coast of Australia to measure storm surge. Enhance along east African coast.

D. Enhance glider observations along the west coast of Australia and across the Leeuwin Current.

E. Establish a RAMA flux mooring site in the northwestern Australian basin to provide better observations of both TCs and MHWs, while enhanced monitoring of the Leeuwin Current would improve understanding of MHWs off west Australia.

F. Enhance barometric measurements from surface drifters to improve initial conditions for TC forecasting.

G. Enhance glider observations of oceanic response to TCs in the BoB.
4. Air-Sea Fluxes

WHEN DESIGNING RAMA 10 years ago (McPhaden et al. 2009), there was strong consensus on the need for sites with enhanced measurement capabilities for comprehensive air–sea fluxes (i.e., “flux reference site” moorings) in key dynamical regimes. The rationale was plain and clear: better surface heat and moisture flux climatologies are highly desirable in regions where surface fluxes dominate mixed-layer temperature and salinity variability over diurnal to intraseasonal and longer timescales (e.g. Yaremchuk 2006; Yu et al. 2007). Better surface fluxes are also essential for improving numerical weather prediction and climate forecast skills, and for understanding the mechanisms responsible for frontal-scale air-sea interaction over western boundary currents.

The net heat flux, $Q_{net}$, going into the ocean is the sum of a number of heat exchange processes at the air-sea interface. These processes include incoming and reflected solar radiation, outgoing and re-emitted longwave radiation, turbulent sensible heat (SH) transfer by conduction and convection, and turbulent latent heat (LH) release by evaporation of sea surface water. The turbulent heat flux components cannot be remotely sensed by satellite because they neither absorb nor emit electromagnetic radiation. These components are commonly computed from bulk flux parameterizations using surface meteorological variables that can be obtained from numerical weather prediction (NWP) reanalysis, ship reports from the Comprehensive Ocean-Atmosphere Data Set (COADS), and satellite retrievals (Josey et al. 2013). However, no data source is error free and uncertainties can arise from sample errors and statistical and/or dynamical interpolation errors. Moreover, flux algorithms adopt various physical/statistical approaches and may underestimate subgrid processes. These uncertainties could lead to substantial differences among the surface flux products.

Significant progress has been made in the past 10 years in improving surface flux estimates by both satellite analyses and atmospheric reanalyses. Two factors have played an instrumental role.

A. One is the ever-advancing satellite technology for retrieving flux-related variables, such as SST and near-surface wind, and, most significantly, surface radiation products; the NASA Clouds and the Earth’s Radiant Energy System (CDERES) instrument on-board the polar-orbiting Aqua satellite and follow-on missions since 2000 has provided the first-ever complete coverage of highly accurate energy budget and cloud observations over the Indian Ocean, this allows the surface radiative budget to be computed from an energy balanced and filled (EBAF) approach (Kato et al. 2013), previous surface radiation products, such as the International Satellite Cloud Climatology Project (ISCCP) and the Global Energy and Water Exchanges (GEWEX) Surface Radiation Budget (SRB), were constructed from geostationary satellites and have a broad gap in coverage over the Indian Ocean (Zhang et al. 2004). This gap presents a major challenge to the studies of basin-scale variability and change of $Q_{net}$ and hinders our ability to understand the nature of air-sea interaction during the unprecedented rise in SST and heat content in recent decades (Roxy et al. 2014; Lee et al. 2015).

B. The other factor is the improvement of atmospheric reanalyses as a result of better physical models, more observations to constrain the models, and better assimilation methods. There has been a growing number of new updates of global reanalyses at major centers, including the NCEP Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010), the Japanese 55-year Reanalysis (JRA55) (Kobayashi et al. 2015), the NASA Modern Era-Retrospective Analysis for Research and Applications-2 (Rienecker et al. 2011), and the ECMWF Reanalysis interim (Dee et al. 2011).

The consistency between model and observation-based $Q_{net}$ products is evaluated using 6 latest products (Figure 2.4). Four are atmosphere reanalysis products, including CFSR, ERA-interim, JRA55, and MERRA-2, and the other two are based from observations. The $Q_{net}$ from the National Oceanographic Centre (NOC) was constructed from ship surface meteorological observations, and the combined $Q_{net}$ product from Objectively Analyzed air-sea Fluxes (OAFlux) and CERES EBAF were developed from satellite observations. The ensemble mean and standard deviation (STD) between the 6 products were constructed for the overlapping period of 2001-2010. The $Q_{net}$ fields have a similar spatial pattern but different magnitude. Large STD difference with values exceeding 25 Wm$^{-2}$ appears in three regions, the equatorial zone, the western Arabian Sea, and the Agulhas return current regime.
Figure 2.4 (a) Ensemble mean and (b) STD spread of 6 $Q_{\text{net}}$ products for the period 2001-2010. The six products are OAFluxHR+CERES, NCEP1, CFSR, NOCS2, ERA-interim, and MERRA2.

The STDs here represent a 40% reduction to the STDs generated 12 years ago (Yu et al. 2007).

Flux reference sites at the ocean surface are critically needed for validating improvements and new developments of satellite retrieval algorithms and flux products. Although satellite products are promising for providing high quality, gridded flux estimates into the future, efforts are continuing being made in improving the statistically based satellite retrieval algorithms and transfer functions. Retrieving near-surface air temperature and humidity from satellite scanners and sounders remains difficult (Yu and Jin 2018) and the uncertainty in bulk flux algorithms is not negligible (Brunke et al. 2002). Sustained RAMA observations are an important part of the Global Tropical Moored Buoy Array (McPhaden et al. 2010) and the OceanSites program (Send et al. 2010), and they provide essential benchmark for validating atmospheric analyses and reanalyses. The following recommendations are proposed to enhance the science and operational values of RAMA:

A. Implement unoccupied flux reference sites in Arabian Sea and western Indian Ocean and maintain established flux reference sites in the revised RAMA-2.0 design (Chapter 2).

B. Enhance a subset of the flux reference sites with direct flux measurements to validate bulk algorithm flux computations.

C. Engage with the atmospheric reanalysis community to evaluate and guide the future improvement of tropical convective parameterizations.

D. Engage with the satellite surface radiation producers to diagnose and validate surface radiative products.
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THE LOW-LATITUDE northern boundary of the Indian Ocean, the seasonally-reversing monsoonal forcing, and the connection with the Pacific engender some unique boundary current systems (Figure 3.1). Such as the Indonesian throughflow (ITF) drains some of the western Pacific warm pool into the tropical Indian Ocean, and the ITF and the Agulhas Current form the warm return route of the global overturning circulation, which regulates global climate on multi-decadal and centennial time scales. The Indian Ocean is uniquely characterized by seasonally evolving upwelling systems associated with monsoonal winds. The seasonal development and decay of each upwelling system are not well understood and are further modified by intraseasonal, interannual, and decadal modes of variability. Ocean boundary currents and upwelling systems of the Indian Ocean are major gaps in IndOOS, which is the focus of this review.

An important driver for IndOOS is to advance ocean state estimation or ocean data assimilation (ODA) systems to support (a) research in oceanic variability and the underlying processes and (b) initialization of ocean forecasts and climate predictions. Much of the IndOOS observations from in-situ and satellite platforms have provided the necessary backbone observational constraints for these systems. Significant progress has also been made in the development and enhancement of ODA systems to support (a) and (b) (cf. reviews articles by Dombrowsky et al. 2009; Lee et al. 2009; and Fujii et al. 2015). In particular, the development of Argo and RAMA since the mid-2000s have provided important measurements to constrain subsurface ocean state estimates (e.g., Huang et al. 2008; Rahaman et al. 1996; Alford et al. 1999; Hatayama 2004; Koch-Larrouy et al. 2007; 2010; 2015; Nagai and Hibiya 2015; Ray and Susanto 2016). Intense vertical mixing produces upwelling and cooling of surface waters in the Indonesian Seas that affects regional precipitation and wind patterns (Sprintall et al. 2014). Sustaining direct in situ measurements of the ITF within the passages is logistically challenging and expensive. A 30-year time series exists from the IX1 XBT line between Fremantle, Australia and Sunda Strait, Indonesia, as the ITF outflow first enters the Indian Ocean (Meyers et al. 1995; Wijffels et al. 2008). Measurements in all major ITF passages were taken simultaneously for the first time from 2003 to 2007 (Gordon et al. 2010; Sprintall et al. 2009), revealing a total ITF transport of 15 Sv. The ITF is influenced by ENSO, El Niño causes a shoaling and slowing of the ITF, and by the Inter-decadal Pacific Oscillation (IPO) and the Indian Ocean Dipole mode (Meyers 1996; Sprintall et al. 2014; Liu et al. 2015).

The Leeuwin Current is forced by meridional pressure gradient in the southeast Indian Ocean, which also supports shallow, broad eastward currents that feed into it (Thompson 1984; McCreary et al. 1986; Furue et al. 2013; 2017; Benthuysen et al. 2014). The Leeuwin Current transports about 3 Sv of warm, fresh tropical waters southwards, influencing the upper ocean heat and freshwater balances in the southeast Indian Ocean (Domingues et al. 2007; Feng et al. 2008). The Leeuwin Undercurrent carries waters of Subantarctic origin along the western Australian coast (Woo and Pattiaratchi 2008), leaving the coast near 22°S to contribute to the lower limb of the zonal overturning (Furue et al. 2017). The Leeuwin Current system channels Pacific influences such as ENSO and IPO into the Indian Ocean through the planetary waveguides (Feng et al. 2003; Wijffels and Meyers 2004). Measurements of the Leeuwin Current have been patchy. Since 2009, the Australian IMOS program has been monitoring the part of the Leeuwin Current system.

The Agulhas Current is the strongest western boundary current in the southern Hemisphere,
Indonesian Throughflow
Agulhas Current
East African Coastal Current
Somali Current
Boundary currents
Leeuwin Current

**Figure 3.1** Schematic of the ocean boundary currents of the Indian Ocean. Existing and planned observation system elements are denoted.

Relying an average 85 Sv of warm and salty waters poleward, including 60 Sv of wind-driven subtropical gyre transport and about 25 Sv of ITF and overturning transport. The bulk of the ITF waters eventually feed into the Agulhas Current through the Mozambique Channel or via the east Madagascar Current (Nauw et al. 2008; Ridderinkhof et al. 2013). The southern Agulhas system is a hotspot for air-sea interaction, pumping moisture into the atmosphere and accelerating winds (Rouault et al. 2009). Rising sea surface temperatures of the Agulhas system (Wu et al. 2012) are expected to alter regional wind and rainfall patterns and may act to dry the adjacent southern African continent (Rouault et al. 2010; Neukom et al. 2014). Ocean reanalyses suggest that warming of the Agulhas system is related to an intensification and poleward shift of the currents (Wu et al. 2012), driven by changes in the Westerlies which are projected to continue over the twenty-first century under anthropogenic forcing (Cai 2006). In situ observations combined with satellite altimetry point instead to a potential increase in eddy kinetic energy, such that the Agulhas Current has broadened but its transport has not strengthened over the past 25 years (Beal and Elipot 2016). The most comprehensive measurements of the Agulhas Current were undertaken during the US Agulhas Current Time-series experiment (Beal et al. 2015). The Agulhas System Climate Array was in the water from 2016 to 2018.

At the western boundary of the equatorial gyre the East African Coastal Current overshoots the equator during boreal summer monsoon to supply a northward Somali Current (Schott and McCreary 2001; Beal et al. 2013) which builds in strength from about 5 Sv in June to 37 Sv in September (Beal and Chereskin 2003). During boreal winter monsoon, the Somali Current is weaker and flows southward. Roles of the Somali Current in upwelling, monsoon rainfall, and Arabian Sea heat balance are poorly understood, but expected to be important given its large transport (e.g. Beal and Chereskin 2003).

The Southwest Monsoon Current flows eastward during the boreal summer monsoon (May-September) and the Northeast Monsoon Current flows westward during the winter monsoon (November-February). These currents are mainly geostrophic, forced by both local and remote winds, and propagate along the Indian coastal waveguides (Schott and McCreary 2001; Shankar et al. 2002). They exchange heat and freshwater between the Arabian Sea and the Bay of Bengal and, together with seasonal upwelling, are important for the biogeochemical processes and fisheries off the Indian subcontinent.
The ITF is observed to have strengthened during the climate change hiatus in recent decades (Liu et al. 2015). Over the long term it is projected to weaken under the influence of human-induced climate change, associated with weakening of the deep upwelling in the Pacific and a slowdown of the global overturning circulation (see Sen Gupta et al. 2016; Feng et al. 2017). On the other hand, the Agulhas leakage is expected to increase with climate change (Biastoch and Boning 2013) and could bolster the Atlantic Meridional Overturning Circulation (AMOC; Weijer and Van Sebille 2014) at a time when Greenland ice melt is expected to weaken it.

The main strength of the IndOOS has been to obtain basin-scale data, away from the boundary areas. It is essential to capture decadal variations of the Indian Ocean’s boundary currents and the ITF in order to understand their roles as carriers of heat, freshwater, nutrients, and carbon, and in driving decadal climate variability and rapid warming trends in the Indian Ocean. Sustained observations of boundary currents have been a priority for international CLIVAR/GOOS for almost a decade, as articulated in an OceanObs09 white paper (Masumoto et al. 2010). Yet currently there is no framework in place for systematic coverage of any of the boundary currents of the Indian Ocean. Sustained observing of the following EOVs is needed: velocity, temperature, salinity, and pressure at hourly to monthly temporal resolution, dependent on regional tides and variance, at 5 to 50 km horizontal spacing, dependent on local topography and scales of flow which change across the current, and at vertical resolutions of 10-100 m close to the surface, reducing to 500-1000 m below the thermocline, dependent on local (seasonal) stratification and the depth penetration of the current/undercurrent system. A desirable addition would be to integrate these physical EOVs with nutrient, plankton biomass, and carbon measurements, which are becoming feasible with new automated sensors.

**Open ocean upwelling systems**, such as the Sri Lanka Dome of the southwest monsoon (Vinayachandran and Yamagata 1998) and the persistent Seychelles-Chagos thermocline ridge (SCTR; Yokoi et al. 2008; Hermes and Reason 2009), are associated with cyclonic wind stress curl and modulated by remotely forced Rossby waves (Figure 3.2). Sea surface temperature is very sensitive to variability in the depth of the shallow thermoclines in these upwelling systems, linking them to cyclone activity (Xie et al. 2002), the Asian monsoons (Annamalai et al. 2005; Izumo et al. 2008), and fisheries (Menard et al. 2007) at seasonal and interannual time-scales. The SCTR is located in a region of MJO initiation and exhibits the strongest intraseasonal variability of SST in the Indian Ocean (Vialard et al. 2009). It also has large interannual variability due to westward propagating Rossby waves triggered by IOD events and the remote influence of ENSO (Xie et al 2002). Upwelling and strong variability mean the SCTR is more productive than the nearby oligotrophic subtropical ocean. The establishment of the IndOOS, in particular RAMA and the Argo program, have brought much new knowledge about the subsurface structure of the SCTR, including the anomalous oceanic conditions associated with intraseasonal and interannual variations in SST and the seasonal mixed-layer heat budget (Vialard et al. 2009; Foltz et al. 2010).

**Upwelling, Coastal-Open Interactions**

THERE ARE two major coastal upwelling systems in the Indian Ocean; in the east off the islands of Sumatra and Java, and in the west off the coasts of Oman and Somalia (Figure 3.2). Fundamental forcing is along-shore monsoonal winds in both regions. The Sumatra/Java upwelling is also affected by remote forcing to the west via the equatorial waveguide (Iskandar et al. 2005; Chen et al. 2016), while the Oman/Somalia upwelling is influenced by wind stress curl in open oceans to the east through westward propagating Rossby waves (Vic et al. 2017). These upwelling systems are also affected by interannual climate modes, such as the Indian Ocean Dipole (Saji et al. 1999), which is associated with anomalous primary productivity in the basin (Wiggert et al. 2009; Currie et al. 2013). Some basic characteristics of seasonal cycle and upwelling strength have been estimated for the Oman/Somalia upwelling (Schott and McCreary 2001; Schott et al. 2002), yet there is only a qualitative description of the Sumatra/Java upwelling, of which there are few hydrographic observations (Horii et al. 2018). The strongest upwelling signals are concentrated within about 100km of the coasts, while broader regions of SST cooling and high chlorophyll concentration result from offshore advection and are modified by air-sea heat exchange and by locally and remotely generated mesoscale and submesoscale variability. There are other coastal upwelling systems, monsoonal-driven upwelling along the southwestern coast of India (Gopalakrishna et al. 2008) and along the west coast of Australia (Rossi et al. 2013).
Figure 3.2 Climatological chlorophyll concentration in September from Aqua MODIS. The major upwelling regions are indicated by higher chlorophyll concentration and are highlighted by red ovals. Superposed on the satellite image are locations of Argo floats (black dots) as of March 2018 and of RAMA-2.0 buoys (red (occupied) and white (unoccupied) diamonds).

The SCTR attracts a high concentration of tuna fishing activities associated with large tuna schools and is a region of elevated surface phytoplankton levels (Fonteneau et al. 2008). However, the multiscale dynamics and their implications for biochemical processes, linkages between trophic levels, and fisheries resources have yet to be explored. Fisheries and fish products associated with upwelling regions are an important source of protein in developing Indian Ocean rim countries, and provide direct employment to millions of people (FAO 2004). For example, increases in upwelling in the Java Current are linked to increases in sardine (Sardinella leumuru) catch in Bali Strait (Ghofar 2005). Variations in the strength of the Java Current and the intensity of upwelling are linked to the Indian Ocean Dipole mode and give rise to dramatic interannual variations in sardine catch, which impacts food supply, and therefore market prices and the income of artisanal fishers in Indonesia (Sartimbul et al. 2010). Similar phenomena are observed in other Indian Ocean upwelling systems (Hood et al. 2017).

The future fate of upwelling, in the context of global warming, is a subject of debate. Several studies have argued that there will be intensification of coastal upwelling in response to the amplified land-sea pressure gradient in the warming world (Bakun 1990; deCastro et al. 2016; Praveen et al. 2016). However, the story in the monsoonal Indian Ocean may be far more complex.

For the open-ocean, upwelling system in the SCTR is observed by RAMA and Argo. However, for important coastal upwelling systems in situ observations hardly exist. Although these upwelling systems appear regional, they are connected to basin-scale circulation and overturning and can influence basin-scale variability across a broad range of timescales. The IndOOS, therefore, should provide data on background conditions in these upwelling systems, with a focus on intraseasonal to interannual timescales and phenomena responsible for mixed-layer processes and their interactions. Relationships between physical forcing, biogeochemical, ecological responses, and air-sea interactions need to be captured. The fact that these coastal systems are located within EEZs of Indian Ocean rim countries causes some challenges. Essential Ocean Variables for the upwelling systems are: (1) Temperature and salinity down to 1000m, resolving the di-
urnal cycle in several key locations. (2) Satellite data: SST, ocean color, surface winds, and SSH. (3) Biogeochemical and ecological parameters: nutrients, chlorophyll, oxygen, pH, CO$_2$, and plankton community structures. (4) Microstructure measurements in the upper layer to evaluate vertical mixing processes.

**Ocean State Estimation**

INDOOS DATA are essential for improving the consistency among the ODA products as well. IndOOS is an integral element of the global ocean observing system, of which data have been used in various intercomparison and evaluation of ODA systems under the Ocean ReAnalysis Intercomparison Project (ORA-IP) (Balmaseda et al. 2015). As an extension of the ORA-IP effort, the consistency of six ODA products covering the common multi-decadal period of 1980-2010 have been evaluated. Comparison of these products shows that there is a generally better consistency among these products since the mid-2000s (i.e., since the development of Argo and RAMA) than the previous decades (see example in Figure 3.3).

Despite the encouraging improvements of ODA systems brought by IndOOS and other observations, there remain significant discrepancies between ODA products and observations as well as among different ODA products. These arise from the limitations of the forward ocean models and the data assimilation schemes. Improving ocean models and data assimilation is a longer-term effort than the relatively short development time of IndOOS. For testing the impacts of ODA on initializing seasonal-to-interannual prediction, the observational records need to cover many realizations of interannual events such as IOD. Moreover, observational records for the Indian Ocean, especially from the Argo and RAMA arrays, are too short to evaluate ODA products on multi-decadal time scales. Therefore, sustaining measurements from IndOOS is imperative for future improvements of ODA systems.

Enhancement of IndOOS is also necessary. For example, the roles of the deep ocean below 2000 m may become important at the longer time scales. Deep-ocean (> 2000 m) structure in ODA products is not well constrained (e.g., Palmer et al. 2017; Storto et al. 2017), thus the need for Deep Argo. Other areas where IndOOS need to be enhanced include the coverage of coastal regions that are not sampled or under-sampled by Argo and RAMA. Continuity and enhancement of satellite measurements are also important to improving ODA products. Examples include (1) improving the temporal sampling of satellite wind measurements to capture the diurnal cycle, and (2) the continuity, enhancement of spatial resolution, and improvement of data quality for satellite sea surface salinity (SSS), which is especially important for the Indian Ocean due to the very dynamic variability of SSS across various spatiotemporal scales.

The observations of the Indonesian throughflow (ITF) are of particular importance to the Indian Ocean. The current observing system for the ITF is adequate. However ODA products have significant discrepancies in representing the ITF (Lee et al. 2010). This has ramifications to the representation of the state of the Indian Ocean. Development of a sustained observing system for the ITF is thus an important aspect that needs to be considered between IndOOS and the Tropical Pacific Observing System (TPOS).

While the ITF and the related transports (e.g., of volume, heat, and freshwater) play pivotal role in the linkages between the Indian and Pacific Oceans, the Agulhas Current and the circulation across the southern boundary of the Indian Ocean (near 32°S) are critical to the exchanges between the Indian Ocean and the Atlantic and Southern Ocean, respectively, especially on the longer (e.g., multi-decadal) time scales (e.g., Biastoch et al. 2009; Beal and Elipot 2016). No effort has been made to systematically examine the consistency of ODA products in characterizing these inter-ocean exchanges. However, due to the lack of multi-decadal measurements of the Agulhas Current and the meridional transports across 32°S, it is conceivable that ODA systems are under-constrained in representing the related inter-ocean exchanges. Therefore, long-term monitoring capabilities for the Agulhas Current (Morris et al. 2017) and the meridional transports across 32°S (e.g., McDonagh et al. 2005) are expected to be important to constraining ODA systems.

Surface meteorology measurements from IndOOS are significantly under-exploited by most ODA systems as they do not assimilate these data. Efforts of coupled ocean-atmosphere data assimilation are emerging (e.g., Saha et al. 2010). The measurements of the coupled ocean-atmosphere boundary layers can provide effective constraints on such cou-
Figure 3.3 Ensemble spread of subsurface temperature near the thermocline in the tropical (a) and subtropical Indian Ocean (b) among eight multi-decadal ocean state estimation products. The consistency (as indicated by smaller spread) is significantly better since the mid 2000s after the development of the Argo and RAMA arrays.
pled assimilation systems (Penny and Hamill 2017). These measurements include not only the air-sea fluxes (of momentum, heat, and freshwater), but upper-ocean measurements that are important to air-sea interactions.

ODA or coupled assimilation systems can be used to evaluate the relative effectiveness of various observing system elements in constraining state estimates and on improving climate predictions. These can be done using Observing System Experiments (OSE) for existing observations and through Observing System simulation Experiments (OSSE) for future observations (Fujii et al. 2015; Penny and Hamill 2017). Such efforts have the potential to guide the strategy forward for prioritizing sustained observations for IndOOS and its future enhancement. However, the results from OSE and OSSE can be system-dependent. Therefore, coordinated efforts based on multiple systems and close interactions among modelers, data assimilators, and observationalists are important to maximize the effectiveness of OSE and OSSE efforts in observing system evaluation and design for IndOOS.

**Actionable Recommendations**

FOR THE boundary current systems, the actionable recommendations include:

A. Maintain the frequently repeated IX1 XBT section across the ITF, and enhance with an auto launcher for increased resolution (also of the South Java Current at the northern end) and with Argo float deployments for salinity measurements.

B. Maintain the repeated IX12 XBT section, which crosses the Somali Current and Leeuwin Current systems at its northern and southern ends, respectively, and enhance resolution with an auto launcher.

C. Maintain the existing network of island and coastal sea level stations and ensure open accessibility of these data so that boundary current transports can be estimated using sea level proxies.

D. Maintain satellite altimeter missions to characterize long term variations of mesoscale eddy energetics in ocean boundary currents.

E. Establish an international alliance to measure ITF volume and heat transports, as well as biogeochemical fluxes, in different passages in order to contextualize and constrain the sustained upper-ocean geostrophic estimates from the IX01 XBT section.

F. Re-establish the ASCA mooring array for the Agulhas Current system through regional alliances, combining mooring observations with periodic glider and ship surveys.

G. Enhance the Leeuwin Current array to monitor full-depth volume and heat transports through combined mooring and glider observations.

H. Monitor the Somali Current and the South Java Current using ocean gliders.

I. Sustain observations of the monsoon currents off the Indian subcontinent through regional alliances.

To build the IndOOS towards sustained observing of upwelling systems, we recommend:

A. Maintain RAMA sites along 8°S within the Seychelles-Chagos thermocline ridge and in the equatorial region.

B. Maintain satellite observations of SST, sea level, surface momentum and heat fluxes, and ocean color. Since the satellite based SSH data near the coast is affected by land, tide gauges must also be maintained.

C. Extend the IndOOS into the Sumatra/Java upwelling region, by enhancing deployment of Argo and BGC-Argo floats or adding glider sections.

D. A pilot study of new observing platforms within the Oman/Somalia upwelling region, potentially a RAMA site, BGC-Argo deployment, and/or glider sections. An intensive process study is needed with a capacity development component.

E. A process study to obtain sectional cruise observations across the upwelling regions (Sumatra/Java and/or the Seychelles-Chagos thermocline ridge) during upwelling and non-upwelling seasons to conduct microstructure measurements for evaluation of vertical mixing processes and to obtain water samples for nutrients, chlorophyll, oxygen, pH, CO₂, and plankton community structure analyses.

The recommended actions for IndOOS to improve the consistency and fidelity of ODA products:

A. Augment deep ocean measurements such as deep Argo.
B Develop a systematic monitoring system for the Indonesian throughflow.

C Enhance the capabilities to monitor exchanges between the Indian Ocean and the Atlantic and Southern Oceans.

D Continue the development of coupled ocean-atmosphere data assimilation systems.

E Strengthen the collaborations among data assimilators with modelers and observationalists to improve the capabilities for reanalysis, prediction, and observing system evaluation.

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ALTHOUGH THERE have been significant advances in our understanding of the physical variability and processes in the Indian Ocean in recent years, our understanding of biogeochemical variability and processes is still rudimentary in many aspects. This is largely because Indian Ocean biogeochemical quantities and rates remain under-sampled in both space and time. The situation is compounded by the Indian Ocean being a dynamically complex and highly variable system under monsoonal influence. Here we briefly review the current state of our understanding of biogeochemical variability in the Indian Ocean and make specific recommendations for how this understanding can be improved through enhancement of IndOOS.

Carbon Cycle, Acidification, and Ecological Impacts

Current Understanding

THE OCEANIC uptake of atmospheric CO₂ is estimated to be 2.6 Gigatonnes (Gt) of carbon per year, which is nearly comparable to the uptake by land (LeQuéré et al. 2015). It has been estimated that the Indian Ocean as a whole accounts for ~20% of the oceanic uptake (Takahashi et al. 2002). The Arabian Sea is a source of CO₂ to the atmosphere because of elevated pCO₂ within the southwest Monsoon-driven upwelling (Figure 4.1; see also Takahashi et al. 2009; 2014). Overall, the Indian Ocean north of 14°S loses CO₂ at a rate of 0.12 PgC/yr (Takahashi et al. 2002; 2009; 2014). Whether the Bay of Bengal is a CO₂ source or sink remains ill-defined due to sparse sampling in both space and time (Figure 4.1; Bates et al. 2006). The southern Indian Ocean appears to be a strong net CO₂ sink (-0.44 PgC/yr in the band 14°S-50°S; Figure 4.1). Observations of ocean carbon system are very important to constrain these fluxes. Compared to other oceans there have been relatively few carbon system observations in the Indian Ocean (Figure 4.1; Bakker et al. 2014, see also www.socat.info).

The uptake of anthropogenic CO₂ by the global ocean induces fundamental changes in seawater chemistry that could have dramatic impacts on upper ocean ecosystems. Estimates based on the Intergovernmental Panel on Climate Change (IPCC) business-as-usual emission scenarios suggest that atmospheric CO₂ levels could approach 800 ppm near the end of this century (Feely et al. 2009). The associated global trend of increasing oceanic CO₂ concentrations will lead to lower pH and acidification of the Indian Ocean over the coming decades, with potential negative impacts on coral reefs and other calcifying organisms (Doney 2010). In addition, some commercially fished species (e.g., shelled mollusks) are directly vulnerable to ocean acidification (Hoegh-Guldberg et al. 2007). The average surface pH values for the northern (20°E-120°E, 0°-24.5°N) and southern Indian (20°E-120°E, 0°-40°S) oceans in 1995 were 8.068 +/- 0.03 and 8.092 +/- 0.03, respectively (Feely et al. 2009), the lowest of the major ocean basins. The causes for these differences are not understood (Takahashi et al. 2014). Seasonally occurring very low surface pH (<7.9) off the Arabian Peninsula results from upwelling of (more acidic) subsurface waters during the SW monsoon (Takahashi et al. 2014). There are only a few studies on the temporal evolution of surface ocean acidification in the Indian Ocean because of the lack of time-series measurements. The results of a recently published study from the eastern Bay of Bengal indicate a decrease in pH of 0.2 in the period from 1994 to 2012 (Rashid et al. 2013), which is much faster than the global rate of 0.1 over the last 100 years (IPCC 2007).

Clearly, understanding current carbon uptake by the Indian Ocean is critical for understanding how the global carbon cycle and climate are evolving under the impact of human activities. Understanding and predicting rates of carbon uptake and ocean acidification are also fundamental to understanding the
biogeochemical and ecological evolution of the Indian Ocean.

**Essential Ocean Variables (EOVs)**

THE OBSERVATIONS required to constrain the carbon system at a point in space and time are any two of Dissolved Inorganic Carbon (DIC), Total Alkalinity (TA), partial pressure of carbon dioxide (pCO$_2$) and pH; plus temperature and salinity. The products that can be derived from these carbon system measurements include saturation state (aragonite, calcite), dissolved carbonate ion concentration, air-sea flux of CO$_2$, anthropogenic carbon, and the change in total carbon. These observations can be obtained from ships, moorings, gliders, wave gliders and Argo floats.

The GO-SHIP program has several sections in the Indian Ocean that are part of the global decadal survey (see: https://www.go-ship.org/RefSecs/go-ship_ref_secs.html). All of these sections include carbon system measurements. Some have national commitments for occupation over the next 5 – 10 years. These surveys will be crucial for filling in the current large spatial gaps in carbon system measurements in the Indian Ocean.

Moored Autonomous pCO$_2$ (MAPCO$_2$) systems (Sutton et al. 2014) provide high-resolution data that can measure interannual, seasonal, and sub-seasonal dynamics and constrain the impact of short-term biogeochemical variability on CO$_2$ flux. The deployment of a MAPCO$_2$ system at the Bay of Bengal Ocean Acidification (BOBOA) mooring site, established at 15°N, 90°E on 23 November 2013, is providing the first continuous surface water carbon system measurements along with physical measurements in the northern Indian Ocean (see: https://www.pmel.noaa.gov/co2/story/BOBOA). Deployment of additional MAPCO$_2$ systems on Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) moorings could help to fill in the current large temporal gaps in carbon system measurements in the Indian Ocean that cannot be addressed by the less frequent large-scale surveys.

In addition to GO-SHIP and the deployment of MAPCO$_2$ systems on RAMA moorings, carbon system measurements can be made underway from ships of opportunity and also from gliders, wave gliders and Argo floats. The Ship of Opportunity CO$_2$ program (SOOP-CO$_2$) has outfitted numerous
ships with automated instruments that take surface water pCO\textsubscript{2} measurements. Increasing the number of SOOP-CO\textsubscript{2} measurements in the Indian Ocean could also help fill in the spatial gaps in carbon system measurements. Similarly, deployment of gliders and wave gliders equipped with automated instruments could help to fill in spatial gaps. However, the feasibility of motivating and maintaining routine deployments of gliders and/or wave gliders as part of IndOOS is unclear.

The SOCCOM (Southern Ocean Carbon and Climate Observations and Modeling) project (see https://soccom.princeton.edu/content/overview) is deploying Argo floats in the Southern Ocean that have been augmented with biogeochemical sensors that can be used to constrain the carbon system. The project will ultimately increase the number of carbon system measurements made monthly in the Southern Ocean by 10-30 times. These deployments include the Indian Ocean sector of the Southern Ocean. Argo floats equipped with biogeochemical sensors have also been deployed in the northern and southeastern Indian Ocean (see, for example, https://research.csiro.au/iobioargo/). Increasing the number of biogeochemical Argo float measurements in the Indian Ocean could help to fill in both temporal and spatial gaps in carbon system measurements.

Ocean Primary Productivity Variability, Predictability and Change

Current Understanding

THE INDIAN Ocean is a basin of considerable primary productivity variability in both space and time. The boundary currents, particularly in the west, are extremely productive and support fisheries of local and global importance (Lee et al. 2005). The productivity of the equatorial band and the northern basin is strongly modulated by the monsoons and wind reversals (Hood et al. 2017; Strutton et al. 2015). The surface Indian Ocean is rapidly warming (Roxy et al. 2014) and there is evidence for long-term change in the productivity of the basin, particularly in the west (Roxy et al. 2016).

Compared to the Pacific and Atlantic, the Indian Ocean is poorly sampled with respect to biogeochemistry in general and ocean productivity in particular. This presents both a problem and an opportunity for the future of IndOOS. The opportunity is obvious, but the problem is that in many areas of the basin, there are insufficient observations to inform the spatial distribution of platforms and sensors.

The primary productivity of the Indian Ocean is strongly forced by the monsoons, the equatorial jets and the stratification of the south Indian Ocean Gyre. Figure 4.2 shows the climatology of seasonal variability in Indian Ocean chlorophyll, where the seasons are defined by months that correspond with the monsoons. In June through September, the southwest monsoon drives the Arabian Sea upwelling and productivity there is at its seasonal maximum. Equatorial productivity is low. Winter mixing in the southern hemisphere likely enhances productivity in the subtropical gyre slightly.

In October-November, the northeast monsoon stimulates productivity in the Arabian Sea. There is high productivity in the central equatorial Indian Ocean, while the size of the oligotrophic subtropical gyre expands. In December through March, there is still high productivity in the central Arabian Sea, and the oligotrophic gyre expands and productivity along the equator is decreasing. In April-May, productivity across the basin is low. The Arabian Sea upwelling is absent, equatorial productivity is low and the oligotrophic subtropical gyre is near its (ustral) summer maximum spatial extent.

Like the tropical Pacific and Atlantic observing systems, sustained productivity observations in the Indian Ocean are limited to one very important data stream: Satellite ocean color. Since the launch of SeaWiFS in 1997 and MODIS Aqua in 2002, the data sets are robust and have been used to document a long-term decrease in Indian Ocean productivity (Roxy et al. 2016).

As with the carbon system, biogeochemical Argo floats have the potential to help answer questions regarding large scale spatial patterns and seasonal to long term trends in Indian Ocean productivity, but also more targeted features such as the role of eddies in nutrient fluxes and sub-surface chlorophyll patterns (Dufois et al. 2017; Gaube et al. 2013; Biogeochemical-Argo Planning Group 2016).

Essential Ocean Variables (EOVs)

THE GLOBAL Ocean Observing System defines nutrients, ocean color and phytoplankton biomass and diversity as the relevant EOVs for ocean primary productivity (http://www.goosocean.org). Obtaining nutrient and chlorophyll measurements from moor-
ings at appropriate depths and with sufficient resolution of vertical variability represents a challenge. To do so would require accurate knowledge of the vertical scales or features that need to be resolved. We do not have this information for the Indian Ocean. A similar statement could be made for dissolved oxygen, mapping features such as oxygen minimum zones (OMZs) from moorings would require large numbers of sensors located at depths we can only guess at. For these reasons, making oxygen, nutrient and bio-optical measurements on Argo floats would likely be the best way to observe these EOVs in the Indian Ocean. Autonomous nutrient measurements are currently limited to nitrate. To obtain the full suite of nutrients (nitrate, phosphate, silicic acid, and ammonium) requires ship-based sampling and this could be achieved during GO-SHIP occupations of the aforementioned established Indian Ocean sections. These voyages also represent the best opportunity to collect data on phytoplankton community structure.

Deoxygenation in the Indian Ocean

Current Understanding

UNDER THE influence of anthropogenically driven climate change, the world’s oceans are experiencing a clear trend in deoxygenation that is already having profound impacts on ecological function. Oceanic deoxygenation has been slower to gain recognition in the scientific community relative to other high-profile impacts such as warming, sea level rise, and ocean acidification (Gruber 2011). The onset and acceleration of oceanic deoxygenation is driven by global warming through both reduced oxygen solubility as temperatures increase, and reduced ventilation as stratification increases. Ventilation is the process of low O$_2$ waters within the thermocline outcropping into the mixed layer to allow air-sea exchange. Reduced dissolved oxygen (DO) levels within thermocline waters then result because the oxygen demand associated with heterotrophic remineralization of sinking organic matter is no longer met by the solubility and ventilation-mediated supply of oxygen.

Two of the world’s most severe oxygen minimum zones (OMZs) occur in the northern Indian Ocean. The Arabian Sea OMZ contributes 20% of the global mesopelagic denitrification budget and has been identified as a hotspot of oceanic efflux of N2O, which is a greenhouse gas that factors into atmospheric ozone cycling (Bange et al. 2001; Codispoti et al. 2001; Bange et al. 2005; Naqvi et al. 2010). The intensity of the Bay of Bengal OMZ has not
reached hypoxic and anoxic conditions and hence its biogeochemical impact is less significant (Bange 2009). However, there has been a systematic de-oxygenation of the northern Indian Ocean over the last fifty years (Figure 4.3; Stramma et al. 2010). In the Bay of Bengal this de-oxygenation trend may trigger a transition to permanent, wide-spread hypoxia. In the Arabian Sea, where thermocline hypoxia is well-established, this de-oxygenation trend is consistent with an estimated 63% expansion of the OMZ since the 1990s (Rixen et al. 2014; Morrison et al. 1999).

In the southern tropical Indian Ocean there is an increase of thermocline DO in the west and a decrease in the east (Figure 4.3; Stramma et al. 2010), suggesting a potential multi-decadal influence exerted by the Indian Ocean Dipole (Saji et al. 1999) on biogeochemical processes. The IOD’s influence on cross-basin thermocline dynamics is well-established (Webster et al. 1999), and biophysical responses have been identified across all marine trophic levels (Figure 4.3, Menard et al. 2007; Wiggert et al. 2009). The spatial coherence between long-term DO trends and the IOD signature suggests that these readily observed surface biological responses link to underlying biogeochemical variability that is poorly characterized. This inference is supported by a biophysical model of the Indian Ocean that demonstrates a strong positive correlation between elevated chlorophyll and IOD occurrence in the east during boreal summer and fall, and a strong negative correlation in the west during boreal fall and winter (Currie et al. 2013).

It is critical that we understand the physical and biogeochemical controls that regulate OMZ severity within the Arabian Sea and Bay of Bengal. Expansions of these OMZs would profoundly affect oceanic nitrogen cycling, with globally significant contributions to rates of oceanic denitrification and efflux of nitrous oxide (N\textsubscript{2}O), a potent greenhouse gas. Deoxygenation impacts all levels of the marine ecosystem, particularly in combination with global warming. As temperatures in the marine environment increase, the metabolic rates of organisms tend to rise exponentially (e.g., Eppley 1972), leading to higher production and growth rates that necessitate higher metabolic rates that, in turn, rely on oxygen availability to satisfy increased respiratory demands (Doney et al. 2012). Faced with suboptimal dissolved oxygen availability, marine organisms will initiate conservation responses, such as reduced activity and cellular function, or avoidance behaviors that may adversely impact growth, reproduction and survival (Ekau et al. 2010). Moreover, as the projected expansion of suboxic waters and associated shoaling of tropical OMZs unfolds, the habitats of planktonic and pelagic species will compress. The foraging efficiency for large fishes, like billfishes and tuna, may improve as a result, while also making them more vulnerable to exploitation by the fisheries industry (Stramma et al. 2010).

Coastal ocean regions are even more prone to de-oxygenation, due to their proximity to human influences, including agricultural activity, sewage outfalls, regulation of riverine inflows, and atmospheric nitrogen deposition. In the eastern Arabian Sea, eutrophication has led to a multi-decadal trend of expanding coastal hypoxia along the west coast of India that has adversely affected coastal fisheries (Naqvi et al. 1998; Ram et al. 2014). The coastal waters of the Bay of Bengal are similarly at risk (Hood et al. 2017). Projections accounting for evolving agricultural practice and human population growth indicate that the northern Indian Ocean, and particularly the Bay of Bengal, is subject to the highest eutrophication potential globally (Seitzinger et al. 2010). The economies of Indian Ocean rim nations, home to approximately 2 billion people, are the most vulnerable to projected climate change impacts on fisheries production (Allison et al. 2009). In conclusion, the potential societal impact of oceanic de-oxygenation in the Indian Ocean is acute and far-reaching.

**Essential Ocean Variables (EOVs)**

THE GLOBAL database of DO measurements has clear shortcomings in spatial coverage. In fact, there are more observations from the 1960s-1970s baseline period than during the 1990s-2000s (Stramma et al. 2010). A more comprehensive, basinwide dataset of dissolved oxygen is needed to establish changes since the baseline period. In particular, sampling efforts that better resolve the spatial and temporal variability of the basin’s OMZs are crucial. These are regions where hypoxia onset represents a significant elemental cycling transition, and where Earth System Models show the greatest uncertainty. In addition to marginally resolved decadal variability, OMZs likely experience notable variability at seasonal to interannual time scales that impact biogeochemical processes and climate. This variability could be resolved with more observations. Most important EOVs are: DO and NO\textsubscript{3}. Significant deficits of NO\textsubscript{3} within the thermo-
delta serve as an indicator of hypoxia-induced denitrification. To more fully ascertain the degree to which an OMZ is hypoxic, and therefore how substantially it is contributing to global N-cycling, a more comprehensive suite of EOVs with greater precision is required: NO\textsubscript{2}, NH\textsubscript{4}, PO\textsubscript{4}, and \(\delta^{15}N\). These can provide information about the extent and function of biogeochemical processing within a hypoxic/anoxic OMZ. The new insight garnered from sustained observations of the spatial and temporal variability of OMZs would allow for the development of more robust biogeochemical models. In turn, these modeling systems can provide insight into the important biophysical processes that control OMZs, and provide more accurate future climate projections.

**Recommendations**

**Carbon Cycle, Acidification, and Ecological Impacts**

INDOOS SHOULD seek resources to enable deployment of additional MAPCO\textsubscript{2} systems on RAMA moorings to help fill in temporal gaps in carbon system measurements. The RAMA Flux Reference Sites (Equator, 55º E; 16ºS, 55ºE; 15ºN, 65ºE; 8ºS, 67ºE; Equator, 80ºE; 15ºN, 90ºE; 5ºS, 95ºE) should be targeted for deployment of the MAPCO\textsubscript{2} systems (one per mooring) because they provide all of the additional atmospheric and physical oceanographic measurements that are needed to calculate the derived products mentioned above and, in particular, air-sea flux of CO\textsubscript{2}. Proposals should be motivated to obtain national funding for the purchase and deployment of additional systems.

In addition, efforts should be undertaken to increase the number of SOOP-CO\textsubscript{2} measurements in the Indian Ocean to help fill in the spatial gaps in carbon system measurements. Priority should be given to making measurements in the southern central Indian Ocean and also in the northern Arabian Sea and Bay of Bengal where survey lines are particularly sparse (Figure 4.1), though, motivating SOOP-CO\textsubscript{2} measurements to fill specific spatial gaps will be a challenge with ships of opportunity. Additional biogeochemical Argo float deployments should also be motivated. Priority should be given to deployments in the Arabian Sea and the Bay of Bengal where CO\textsubscript{2} measurements are sparse and the temporal variability in air-sea CO\textsubscript{2} flux is high. These are also areas where there is acidic, low oxygen water so pH estimates would be of great scientific value. Deploying additional biogeochemical Argo sensors in the Indian Ocean will require national funding. Efforts should be undertaken to motivate proposal development to secure these funds, especially in India, Australia and the United States. At the time of submission of this article a proposal to deploy a global array of 500 biogeochemical Argo floats was under review at the US National Science Foundation (K. Johnson and L. Talley, personal communication). This proposal, if successful, will provide funds for the deployment of additional 50-55 biogeochemical Argo floats in the Indian Ocean.

**Ocean Primary Productivity Variability, Predictability and Change**

BASED ON the seasonal cycle of satellite ocean color (Figure 4.2), the main regional productivity features that an observing system must quantify are: the intensity and spatial extent of the Arabian Sea upwelling bloom, mostly during the southwest monsoon; the central Arabian Sea, where high productivity begins with the southwest monsoon but extends into northern hemisphere winter (northeast monsoon); the Somali coast; the signal along the equator, linked to the seasonal variability of the
Wyrtki jets; the Bay of Bengal, coastal India and Sri Lanka; and the spatial extent of the southern hemisphere oligotrophic gyre and low levels of productivity there.

Some existing and proposed RAMA mooring locations could host biogeochemical sensors to capture these processes and features. Candidate locations include the northern-most mooring in the Arabian Sea (65°E, 15°N), the three moorings in the Bay of Bengal (90°E line), the mooring closest to Sri Lanka (80.5°E line), the southernmost mooring on the 80.5°E line and the 100°E, 27°S for the gyre, and the equatorial moorings.

The recommended next steps for implementation of productivity-related measurements are to maintain support and advocacy for satellite ocean color missions, for making nutrient measurements on GO-SHIP sections and for including observations of phytoplankton biomass (chlorophyll) and community structure (e.g., HPLC pigments) on GO-SHIP cruises where possible. A plan should be developed, in consultation with the global biogeochemical Argo community, for making additional observations of nutrients, bio-optics and oxygen on Argo floats in the Indian Ocean. This should include identifying areas of significant nitrogen cycle activity, and prioritize these areas for nutrient sensor deployments. Existing data and/or model outputs should be analyzed to determine the locations of strongest productivity variability that needs to be captured by observations. Deployment of biogeochemical Argo floats should target these locations in addition to areas known to be important for the carbon and nitrogen cycles, such as the aforementioned oxygen minimum zones. Finally, a data mining exercise should be undertaken to create matchups of satellite chlorophyll and productivity estimates with in situ chlorophyll and productivity measurements. With these matchups, quantify the accuracy of satellite algorithms from SeaWiFS forward. Consider development of regionally tuned Indian Ocean satellite chlorophyll, phytoplankton functional group and productivity algorithms.

Deoxygenation in the Indian Ocean

THE EXPANSION of the IndOOS to include dissolved oxygen and NO₃ measurements is also essential to assess deoxygenation trends across the basin. As discussed, biogeochemical Argo floats with sensors for automated observations of these and other EOVs now exist and several have already been deployed in the Indian Ocean. Ideally, a suite of 200 biogeochemical Argo floats should be deployed to cover the Indian Ocean as part of a global implementation plan of 1000 BGC-Argo floats (Biogeochemical-Argo Planning Group 2016). As discussed above, a proposal along these lines is now pending at the US National Science Foundation (K. Johnson and L. Talley, personal communication) that will deploy 50-55 biogeochemical Argo floats in the Indian Ocean if it is funded. In situ air calibrations to refine DO measurement precision should be adopted (Bushinsky et al. 2016). Floats should be targeted to regions that exhibit the strongest deoxygenation signals, i.e., the northern Indian Ocean (Figure 4.3). However, as discussed above, for the full suite of EOVs, ship-based observations are necessary. Therefore, efforts should continue to leverage ship-based sampling opportunities (e.g., GO-SHIP, GEOTRACES) to obtain the full suite of biogeochemical EOVs (NO₃, NH₄, PO₄, and δ¹⁵N) and also perform onboard rate experiments within OMZs.

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The Indian Ocean is home to many different modes of variability ranging from weather to subseasonal to interannual timescales and beyond. Here, we briefly review these modes of variability, their predictability, and influences on regional hydroclimate, and list specific recommendations for IndOOS.

Indian Ocean Observations for Operational Subseasonal and Seasonal Forecasts

Intraseasonal Variability (ISV) is a dominant mode of variability in the tropical Indian Ocean-atmosphere system and forms a bridge between weather systems and long-term interannual and decadal climate modes of variability. The tropical ISV influences many temporal and spatial phenomena that include: the diurnal cycle of tropical convection, tropical cyclone activity, synoptic disturbances over the monsoon trough, Asian and Australian monsoons, the El Niño Southern Oscillation (ENSO), and many other weather-climate phenomena. The eastward propagating Madden–Julian Oscillation (MJO) is the most common and energetic mode of ISV in the tropics (Madden and Julian 1994). The MJO represents the planetary scale convectively coupled eastward propagating disturbance of 30–60 day periodicity. In the Indian Ocean region, the monsoon intraseasonal oscillation (MISO) is another manifestation of ISV and refers to a quasi-oscillatory mode that modulates the Asian summer monsoon in the region (Goswami 2005; Waliser 2006).

The processes controlling MISO characteristics like moisture sensitivity and surface-feedbacks are still not well understood (Goswami 2005 and references therein). Major deficiencies are observed in global models in simulating its spatial structure, northward propagation and scale-selection (Sperber et al. 2013).

The fidelity of general circulation models (GCMs) in representing the MISOs accurately depends on the representation of the air-sea interaction over the tropical Indian Ocean region (Lin et al. 2006). A community effort towards improving MJO simulation in many different global models over the last two decades has helped improve the current generation model physics and hence its representation of the MJO (Kim et al. 2009; 2011). The current generation climate and weather forecasting models are still very limited in terms of prediction skill compared to the potential predictability of the MISO events (Neena and Goswami 2010). Hence, a concerted effort in diagnosing deficiencies in the representation of air-sea interaction processes in the tropical Indian Ocean region is much needed for a similar improvement in MISO representation and prediction in current generation models.

Continuing analyses of these unique in-situ and remote observations will further shed light on the role of air-sea interactions in the regions in modulating the boundary layer dynamics in both the ocean and atmosphere and how this links to MJO and MISO convection.

Observing and understanding the diurnal cycle in the upper ocean and how it couples to the atmospheric boundary layer will require a sustained observing system and would be beneficial for both improving model representations and parameterizations of these processes as well as for providing the data assimilated model states for improvement of initial conditions for subseasonal forecasts.

There is an increasing interest in developing coupled data assimilation methods for initialization of extended range forecast and for reanalysis applications that will require collocated observations across the ocean and atmosphere, and the IndOOS will be instrumental for developing such coupled systems.

Interannual Variability and Predictability of Climate Modes in the Indian Ocean

The INDOOS has contributed to improved understanding of interannual climate phenomena in the Indian Ocean. Mechanisms and predictability of four climate phenomena are briefly reviewed in this subsection.
The Indian Ocean Dipole (IOD) is an intrinsic interannual climate mode with positive sea surface temperatures (SST) anomalies over the western tropical Indian Ocean and negative SST anomalies over the southeastern tropical Indian Ocean during its positive phase (Saji et al. 1999; Webster et al. 1999; Fig. 5.1a). The Bjerknes feedback is shown to play a central role in its development (Saji et al. 1999) and ocean dynamics, including equatorial Rossby and Kelvin waves and coastal upwelling along the Indonesian coast is crucial to the evolution (Rao et al. 2002; Nagura and McPhaden 2010). Also, salinity anomalies are suggested to modify the amplitude of SST anomalies in the eastern pole of the IOD. The RAMA moorings have provided valuable observational data for the studies on the IOD. After Wajsowicz (2005) made the first attempt of the IOD prediction and Luo et al. (2008) made the first successful real-time prediction, many studies were devoted to its predictability. It is shown that the ENSO (Luo et al. 2007; Yang et al. 2015) and subsurface processes (Tanizaki et al. 2017) provide sources of prediction. At the moment, the anomaly correlation coefficient (ACC) of the Dipole Mode Index becomes lower than 0.5 only after 3 months (Liu et al. 2017).

The Indian Ocean Subtropical Dipole (IOSD) is a climate mode in the southern Indian Ocean with positive SST anomalies over its southwestern part and negative SST anomalies in its northeastern part (Behera and Yamagata 2001; Fig. 5.1c). Morioka et al. (2010) clarified its mechanism taking account of changes in the upper ocean heat capacity associated with mixed layer depth (MLD) anomalies; negative (positive) MLD anomalies over the southwestern (northeastern) pole induced by anomalous winds associated with changes in the Mascarene High enhance (suppress) warming of the mixed layer by the shortwave radiation and result in positive (negative) SST anomalies. Yuan et al. (2014) is the only study that focused on predictability of the IOSD, but the dynamical prediction skill is almost the same with the persistence.

The Ningaloo Niño is the most recently identified climate mode in the Indian Ocean with positive SST anomalies along the west coast of Australia (Feng et al. 2013; Fig. 5.1d). Both local air-sea inter-
action and remote ENSO influences are shown to contribute to the development of this phenomenon (Feng et al. 2013; Kataoka et al. 2014). Salinity anomalies potentially modulate the amplitude of the Ningaloo Niño through their influence on the southward-flowing Leeuwin Current. Using their coupled model, Doi et al. (2013) showed that the ACC for 3-month lead forecast varies from 0.5 to 0.8 and the ENSO is a potential source of predictability.

The Indian Ocean’s Influence on Regional Hydroclimate

UPPER-OCEAN CONDITIONS in the Indian Ocean influence regional hydroclimate across a range of timescales, from weather to subseasonal to decadal and beyond. For example, northward propagating MISOs over the Indian Ocean are associated with active and break periods in the monsoon, impacting summer rainfall from India to the Philippines (Annamalai and Sperber 2005). The Bay of Bengal is an area of particularly active northward propagating MISOs, as reflected in strong coupling between SST and intraseasonal summer monsoon rainfall variability (e.g., Wijesekera et al. 2016), with SST warming in the northern Bay of Bengal leading the onset of intraseasonal rainfall by 5 days. The rainfall-SST relationship has strengthened in recent years with an anomalously warm Bay of Bengal, resulting in stronger low-level moisture convergence, as occurs during negative IOD events (Ajayamohan et al. 2008; Jongaramrungruang et al. 2017). Several major flooding events in Indonesia and Malaysia have also been associated with strong easterly winds over the eastern Indian Ocean associated with a Rossby wave-type response to the MJO that allowed for anomalous southward penetration of northeasterly winds from the South China Sea and strong low-level convergence (Tangang et al. 2008). Observing the convectively coupled waves during active MJO phases at sufficient spatiotemporal resolution with measurements, such as upper-air soundings, is therefore important.

On interannual timescales, the IOD widely impacts climate in surrounding countries, such as rainfall and flooding in East Africa (Behera et al. 1999; Saji et al. 1999; Webster et al. 1999; Manatsa and Behera 2013), droughts, wildfires, and streamflow in Indonesia (Abram et al. 2003; D’Arrigo and Wilson 2008) and Australia (Ashok et al. 2003; Cai et al. 2009; Ummenhofer et al. 2009; 2011b); and the IOD modulates the well-known teleconnection between ENSO and the Asian monsoon systems (Ashok et al. 2001; Gadgil et al. 2004; Ummenhofer et al. 2011a).


In recent decades, the eastern Indian Ocean has sustained considerable sea surface salinity (SSS) changes, with implications for halosteric impacts (Llovel and Lee 2015; Hu and Sprintall 2016). Over the past decade, rainfall over the Maritime Continent has increased, potentially as a regional manifestation of decadal trends in the Walker Circulation (Du et al. 2015). This freshwater input, in conjunction with Indo-Pacific equatorial wind trends, likely contributed to the strengthened ITF transport (Feng et al. 2015; Hu and Sprintall 2017) playing a key role in the global ocean freshwater and heat distribution. Sustained surface and upper-ocean in situ observations, as provided by the long-standing IX01 line (Liu et al. 2015) and more recently the Argo program, need to be maintained to assess variability and change in upper-ocean properties of importance for the Indian Ocean hydrological cycle.

Observations of precipitation, riverine input (runoff), and evaporation at daily resolution are also warranted. The high riverine input and rainfall make the Bay of Bengal surface waters the freshest of any tropical ocean (Mahadevan et al. 2016). Yet, uncertainty in the freshwater distribution and mixing pathways for riverine input is high, and shallow, salinity-controlled MLD significantly affects upper-ocean heat content and SST (Wijesekera et al. 2016). Since 2010, the Soil Moisture and Ocean Salinity (SMOS) satellite provides SSS measurements consistent with in situ observations of the equatorial and southern Indian Ocean from the RAMA array; however, large biases in the Bay of Bengal and Arabian Sea are likely caused by errors in the SSS retrieval due to land contamination and strong winds (Sharma et al. 2016). With new satellite missions,
remotely sensed SSS measurements will hopefully improve in their utility for marginal seas and coastal regions (Sharma et al. 2016). Satellite remote sensing of surface ocean and atmospheric variables of interest to the hydrological cycle crucially depends on in situ observations for calibration.

Specific Recommendations

Specific recommendations for IndOOS include:

A Maintain the current IndOOS.

B Complete and maintain RAMA-2.0 buoy network. Establish a RAMA surface mooring and flux reference site on the northwest shelf off Australia.

C Sustain observation system and process-oriented field observations in the Indian Ocean region targeting timescales from diurnal cycles to longer time periods to help inform and improve coupled prediction systems in improving their upper ocean representation as well as air-sea interaction processes. These observations will also be highly useful for coupled data assimilation to help improve initial conditions for subseasonal and seasonal forecasting over the entire globe.

D Enhance near-coastal observations so that anomalous coastal current and upwelling associated with the IOD and Ningaloo Niño can be monitored.

E Maintain the current IX01 XBT line to monitor the oceanic teleconnection from the Pacific.

F Maintain existing satellite observations for relevant variables at the air-sea interface with basin-scale coverage over the Indo-Pacific region.

G Maintain and replace SSS-sensing satellites with improved capabilities over marginal seas and coastal regions (cf. SMAP, Aquarius, SMOS).

H Maintain and improve river gauge network to observe runoff and riverine input from Indian Ocean rim countries.

I Maintain current coverage with surface drifter network, especially for drifters equipped with surface barometric pressure sensors; expand drifter coverage in eastern equatorial Indian Ocean and between Australia and Indonesia.

J Maintain surface meteorological measurements and ocean observations from commercial shipping (VOS programme).

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IndOOS, the Indian Ocean Region Panel and OceanObs’19
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OCEANOBS19 TOOK place in September in Hawai‘i (http://www.oceanobs19.net/), with over 1500 participants, there were some key plenary sessions as well as a number of breakout parallel groups; at around the same time, the IndOOS executive summary (https://doi.org/10.36071/clivar.rp.4-1.2019) was published. Themes of OceanObs 19 included observing system governance, data and information systems, observing technologies and networks, pollution and human health, hazards and maritime safety, blue economy, discovery, ecosystem health and biodiversity, climate variability and change, water, food, energy and security. A theme running through all of this was the integration of ‘indigenous’ knowledge. IndOOS was integrated into OceanObs19 through a community white paper (Hermes et al. 20191), as well as a poster (A sustained ocean observing system in the Indian Ocean for climate related scientific knowledge and societal needs). The IndOOS executive summary was also distributed.

The impact of OceanObs09 was the prioritization of ocean information, leading to the Framework for Ocean Observations (http://www.oceanobs09.net/fo0/FOO_Report.pdf). A key thing the FOO did was to identify the classes and priorities of information, the societal impact vs. the technologies’ ability to make the needed observations. The FOO requires partnerships between communities to assess observation elements for every essential ocean variable (EOV), and to expand the quality, scope and relevance of products. But are the EOVs and particularly the BioEOVs robust enough yet?

EOVs are there as a basis for priorities for observing, but metrics for measuring the system performance need to be developed, as well as a consistent set of best practices. The need for, and documentation of, best practices is well established, for instance, through GOOS and GO-SHIP. IndOOS aligns to this through its mission statement: “…sustained, high quality…” and through details within the IndOOS review and white paper. Metrics are reasonably simple for a single platform such as Argo, but that metric is not really echoed in the EOV specs and needs to be evaluated in its effectiveness when considering the whole system. Thinking of new platforms that are piloted, and the options for the optimal design are larger and we lack objective metrics for say measuring the performance of an array of 300 gliders. We need to ensure that the reported global metrics are the best that science can provide (or aspire to) rather than a lowest common denominator that everyone can reach without effort.

Need for Common Methods for Observations and Processing

A KEY focus of OceanObs’19 was governance and communication. The sharing of data, knowledge, capacity, technology, methodologies and infrastructure which is the only way to truly achieve a Global Ocean Observing System. Ideally, there should have been a discussion of the reviews covering the tropical Atlantic, Pacific, Indian and Southern Oceans to look at commonality of process and recommendations and towards building a common and interoperable system. Instead, individual systems such as TPOS and AtlantOS were discussed separately. Through the support of CLIVAR SSG, and the leadership of the CLIVAR/IOC-GOOS Indian Ocean Region Panel (IORP), a multi-panel workshop is being planned in 2021, which will be attended by all

regional panels of CLIVAR. It is not just interoperability between basins which needs focus; additionally, communication between basin-scale observing and coastal/regional observing systems needs to be enhanced. This is a quite difficult and delicate issue, including issues around EEZ’s. However, in order to have a real integrated observing system or observed data/information sharing system, it needs to be addressed. Discussions at an intergovernmental body, such as IOC, should continue and discussions at the regional panel level should be encouraged.

Best practices were a main focus and recommended outcomes included the use of best practices, standards, formats, vocabularies, and the highest ethics in the collection and use of ocean data. There is a strong need to look towards coordinated efforts, such as the GOOS/IODE Ocean Best Practices System, that ensure easy access to trustworthy best practices around collecting EOVs and BioEOVs if we want to ensure that our observations are interoperable, reproducible and reliable. Within IndOOS there is a focus on best practices, particularly with regards to training and capacity development.

**Transdisciplinary**

TRANSDISCIPLINARY WAS highlighted as a priority that needs to be addressed in all aspects of the ocean ecosystem (physical, chemical and biological). This means we need to seriously engage biologists in an ocean observing system that is fit-for-purpose and that delivers value to society, such as is being done, for example, in the collegial relationship that operates between IORP and SIBER in the Indian Ocean and under the auspices of IIOE-2. To ensure a transdisciplinary approach, SIBER was integrated from the start in the process of reviewing the IndOOS and creating a roadmap for IndOOS-2 and the top recommendation arising from this process is the collection of BGC EOVS alongside physical parameters. Such approaches require recognition that many of the observations we make are intended to understand impacts of a changing environment on biology. It requires listening to those that need the information in order to design the observing system required. It requires all the other ocean science disciplines, technologists and engineers, to work together with biologists. And it requires all of us in ocean observing to deliver the right information into hands that understand how to use it. The vision for the next 10 years, as highlighted in the Global Ocean Observing System 2030 Strategy, is really about building a comprehensive system, based not just on GOOS but many players, engaging multiple networks in comprehensive observations including biology. The conference statement highlighted the need to Focus the ocean observing system on addressing critical human needs, scientific understanding of the ocean and the linkages to the climate system, real time ocean information services, and promotion of policies that sustain a healthy, biologically diverse, and resilient ocean ecosystem.

It also emphasized the importance of the need to engage observers, data integrators, information providers, and users from the scientific, public, private, and policy sectors in the continuous process of planning, implementation and review of an integrated and effective ocean observing system. Ocean state analysis should consist of tightly coordinated observing-modeling partnerships, with assessment against agreed targets and objectives. The modeling community is focused on creating quantitative forecasts, which have economic value. In doing this, the impact of gaps in observations on these forecasts need to be quantified to strongly motivate where to make new observations – evaluate the observations impact on models and thus on their application products and their utility to users. In parallel there is a need for continuous validation and model bias correction. Systematic evaluations supported by a common standard from the end-user community will ensure the development of future technologies and observing systems that are sustainably implemented and useful to the user community.

**Communication and Knowledge Sharing**

EFFECTIVE COMMUNICATION and collaboration between scientists from different parts of the world, enhancing collaborations, as well as sharing knowledge, data, technology and equipment should not be something for the distant future. Communication to the ocean and coastal communities is also essential to avoid vandalism to the existing observing system like moored buoys. Increasing the literacy of these communities on the benefits of the system to their daily life is essential. The conference statement highlighted the need to “Involve the public through citizen-engaged observations, information products, outreach, and formal education programs”. The importance of the ocean to society
is becoming better understood, but how to address the many real challenges we are faced is not. Science needs to provide the foundation for that understanding. Open knowledge sharing, including transparency and acknowledging uncertainties and gaps is ever more important.

We need to go one step further than enhancing communication with decision makers, stakeholders and society, we need to improve how our data and knowledge is used. Hand in hand with this, there should be global coordination and effective governance of open and sustained data mechanisms/systems which focus on expansions for supporting best practices discovery and access and training. Global networking and coordination should be implemented to minimize regional gaps in all aspect of observing and governance. Perhaps the Global Ocean Observing System 2030 Strategy (or GOOS 2030 Strategy) could effectively stitch together a visible patchwork of local, national and regional systems, which are beyond the government structure and ensure they are communicating when required. Large Marine Ecosystems (LMEs) are a good example of the need for this with key transboundary programs set up but limited sustainability or interaction with global programs. This was summarised in the conference output with the statement “Evolve ocean observing governance to learn and share, coordinate, identify priorities, increase diversity, promote partnerships, and resolve conflicts, through a process of continuing assessment to improve observing”

Given the need for more resources to sustain and expand the IndOOS requires renewed commitments by the World Meteorological Organization (WMO), the International Science Council (ISC), and the Intergovernmental Oceanographic Commission of UNESCO (IOC) to WCRP in order to support the international expert groups (i.e. the IORP) who develop the plans and standards for the observing system.

Information Provided by Observing Systems

MAINTAINING CONTINUITY of data records is critical to establish long base lines for assessing natural variability and human-forced climate change. It is important to evolve the observing system in light of new scientific understanding by taking advantage of new technologies that are ready for deployment and nurturing those that are not yet ready. But care must be taken when changes are made to the observing system by introducing new technologies to replace older measurement systems. The transition should be managed with awareness and with overlapping measurements to ensure the integrity of the record is not compromised by changing techniques. We have many examples where unmanaged changes (as for winds, SST, upper ocean temperatures) have hampered our ability to accurately define climate signals of the past century.

Data

BUILDING AND maintaining ocean observing systems are expensive propositions and data accessibility and discoverability are essential. The social impact requires that the investments made in ocean observations are validated by the widest possible use of the data for research, forecasting, analyses, assessments, and applications. That is only possible if the data follow the FAIR principles (https://www.go-fair.org/fair-principles/). Data collected is being increasingly used not just by people in oceanography or associated fields (marine biology, ecosystem) but outside the research field by non-experts to deliver services and information for decision making, highlighting the societally relevant system that is being built. The knowledge of these people in proper use (what is and is not possible), appropriate gridding methods etc. is not as complete as the scientists who designed or have in-depth knowledge of the instruments. Therefore, it is important that data systems are easy to harvest by people building products and that information in the metadata enables accurate post processing for products and services. These services need to be built into metrics and this vital need for partnerships down the value chain is fundamental to the GOOS strategy. For example, the data system requirements are ripe for developing strong partnerships with data scientists that will enable us to provide data usable to a wider user community. SOCAT (https://www.socat.info/) is an excellent example of where this has been done successfully.

Artificial intelligence can most certainly improve quality control procedures, identify interesting data points/trends, etc. and Cloud technologies have the potential to completely re-imagine how we store, share and access data. It is essential to ensure that the Data management community helps to provide the tools and guidance to ensure that the data producers are not left behind. These new technologies
are providing faster and more versatile ways of interrogating the information contained in the ocean observation systems. But it is not enough to be able to use the observational data base to be able to estimate the chance of future extreme events, the data base must be capable of being used to recognize any underlying shifts in the controlling physics, and this will mean an enhanced, responsive observing system which redeployed based on what is needed.

People

THERE WAS a strong emphasis at Ocean Obs on the need to develop and nurture a new, diverse generation of transformed and informed ocean scientists where ocean boundaries are not considered and at the same time to foster a culture of sharing and open, inclusive discussions. Much emphasis was placed on integrating early career scientists (ECS) in future processes. For this to be successful it really has to be ECS in permanent positions so that momentum can be maintained. Although the focus in IORP has been more on mid to senior scientists, there is a strong link with the IIOE2 ECS network and it is something that will be further explored at the Indian Ocean meeting in 2020, along with attracting more diverse membership, including people from East Africa and small island developing states. As such a recommendation from Ocean Obs’19 was: “Evolve ocean observing governance to learn and share, coordinate, identify priorities, increase diversity, promote partnerships, and resolve conflicts, through a process of continuing assessment to improve observing.”

Consideration of people, includes consideration of those who are not engaged with ocean observations currently. Implementation of these needs should be framed around the existing infrastructure of the Framework for Ocean Observing (FOO) and the Global Ocean Observing System (GOOS), which have been extremely successful thus far in bringing nations together. For IndOOS, the only Indian Ocean Rim nations contributing to the development and maintenance of the system are Australia, India, Indonesia and South Africa. Most of the investment in the system comes from outside the region, e.g. from the USA, China, Europe, Japan, Korea. The countries of the Indian Ocean Rim Association have identified Blue Economy development as a key priority, yet often lack the capacity to access and influence the development of the observing system and to utilize the data generated to underpin sustainable ocean governance in the region. Thus, building scientific, technological and ocean governance capacity in the small island developing states and least developed countries of the region is critical for both maximizing the value of IndOOS and achieving desired outcomes relating to enhanced ocean management and governance. The situation is similar across the Pacific and Atlantic Oceans, creating a global opportunity to improve regional relevance of IndOOS, TPOS and AtlantOS. Multi-lateral initiatives such as the Commonwealth Blue Charter, with its specific focus on ocean observations, can help build this capacity through bringing different regions together to share knowledge, experiences and good practices. Individual research projects can also aim to work more closely with local partners to build capacity in scientists from each region, with the Nekton First Descent expedition to Seychelles providing a practical example of how to tackle factors such as data ownership and sharing, training of regional scientists and facilitating national Government uptake of results.

Capacity development should be a meaningful engagement that contributes to the global ocean observing system whilst aiding developing countries to manage their resources. There, however, remains a disconnect between the international legal and policy framework and the reality of global ocean science collaboration, capacity development, data sharing and technology transfer. Building capacity through monitoring will build scientific literacy which will in turn enable all countries to engage purposefully in the global dialogue. Sustained observing requires long-term resourcing, that meets identified local, national and regional needs. Given the influence this will have on socio-economic stability for the impacted countries, it is essential that the long-term resourcing be, at the least, a combination of international and local. The UN Decade of ocean science for sustainable development provides the opportunity to ensure that the regional ocean observing systems are inclusive in their goals and can articulate their benefit to all countries and stakeholder groups.

As IndOOS moves into its second phase (highlighted in this CLIVAR Exchanges magazine special issue) there will be much work done to incorporate the key outcomes from Ocean Obs’19 and integrate them into the future, sustained observing system. It is important to maintain the dialogue with the ocean observing community and ensure that the many diverse voices are heard. But the two-way communication needs to go beyond this to the in-
tergovernmental bodies, the policy makers and the indigenous communities. This is a long and complicated journey, but it has begun.

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Reflections on the Origins of the Indian Ocean Observing System (IndOOS)

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NOAA/PMEL. Seattle, Washington

THE INDIAN Ocean Observing System (IndOOS) is the result of a collective effort involving many individuals from around the world working towards a common vision of sustained observations in the Indian Ocean. This article offers some perspectives on the origins of IndOOS viewed through the lens of my own experience in Indian Ocean research over the past 40 years. It is by definition selective and, though others reflecting on this same history would emphasize the significance of certain events differently, I am sure that some milestones would be on everyone's list of highlights.

The International Tropical Ocean Global Atmosphere (TOGA) program, the first major initiative of the World Climate Research Program (WCRP, launched in 1980), provided a major impetus for developing a sustained ocean observing system in the tropics. Planning for TOGA began in the early 1980s during which the 1982-83 El Niño unexpectedly occurred. This event was the strongest of the 20th century at the time and, remarkably, it was not detected until nearly at its peak. There are several reasons for this failure, including the coincidental eruption of the Mexican volcano El Chichon in March-April 1982 at the start of the event. The eruption injected sulfuric aerosols into that stratosphere which biased satellite SST retrievals cold so that the huge warm anomalies in the equatorial Pacific were obscured from space. This problem was compounded by the lack of real-time in situ data from the Pacific that could be used to independently track the event (McPhaden et al. 1998). The community planning TOGA was shocked by the inability to adequately observe such a major El Niño. As a result, one of TOGA's headline goals was to design and construct a real-time ocean observing system to monitor evolving ocean conditions, to support ocean and climate research, and to provide data for initializing soon-to-be-developed seasonal forecast models.

Efforts began in earnest to address this goal even before the start of TOGA, which ran from 1985-94 (e.g., McPhaden and Taft 1984). In the wake of the 1982-83 El Niño, it was clear that the need for a comprehensive ocean observing system was most urgent in the Pacific and so that's where TOGA focused most of its efforts. ENSO is the largest source of year-to-year climate variability on the planet, and with limited resources for the scientific community to draw on, the Pacific inevitably held at center stage during TOGA. The cornerstone of the in situ Pacific Ocean observing system was the Tropical Atmosphere Ocean (TAO) array, conceived by Stan Hayes of PMEL (Hayes et al. 1991), enabled by development of the Autonomous Temperature Line Acquisition System (ATLAS) mooring (Milburn and McLain 1986), and completed only in December 1994—the very last month of TOGA (McPhaden 1995). By the end of TOGA, the tropical Pacific also boasted a robust ship-of-opportunity (SOOP) expendable bathythermograph (XBT) network, a basin scale array of island and coastal tide gauge stations, and a network of over 200 drifting buoys developed in collaboration with the World Ocean Circulation Experiment (WOCE; Siedler et al. 2001) for studies of global ocean circulation (Figure 1).

TOGA was meant in principle to address issues related to seasonal to interannual time scale climate variability in all three ocean basins. For the Indian Ocean, the main scientific driver was the seasonally reversing monsoon wind and ocean circulation and the associated shifting patterns of rainfall so crucial to agriculture in the region (Webster et al. 1998). Compared to the Pacific though, both the tropical Indian and Atlantic Ocean basins were TOGA step-children, with fewer XBT track lines and tide gauge stations established, fewer drifting buoys deployed, and no long-term moorings installed (Figure 1).

One important scientific reason why development of an Indian Ocean observing system proceeded at a slower pace than in the Pacific during TOGA was that it was unclear precisely what role the ocean played in the predictability of the monsoons. A central premise of TOGA was that slow variations in the lower boundary conditions of the atmosphere were a significant control on monthly to seasonal time scale climate variability originating in the tropics, with SST being key by virtue of its influence on the regions...
**Figure 1** The *in situ* TOGA Observing System in the Pacific (top) and the Indian and Atlantic Oceans (bottom) in December 1994 at the end of the program. The elements of this observing system are (1) a ship-of-opportunity XBT program (shown by schematic ship tracks); (2) an island and coastal tide gauge network (circles); (3) a drifting buoy program (shown schematically by curved arrows); and (4) a moored buoy program consisting of wind and thermistor chain moorings (diamonds) and current meter moorings (squares). Thick ship tracks indicate XBT sampling with 11 or more transects per year; thin ship tracks indicate sampling with 6-10 transects per year. One drifting buoy schematic represents 10 actual drifters. Only those tide gauge stations that reported their data to the TOGA Sea Level Center in Honolulu within 2 years of collection are shown. By December 1994 most measurements made as part of this observing system were being reported in real time, with data relay via either geostationary or polar orbiting satellites (after McPhaden et al. 1998).
of deep convection and heat sources for the atmosphere (Charmey and Shukla 1981). ENSO SST variations in the Pacific had a well-known remote influence on Indian summer monsoon rainfall (Shukla 1987; Webster et al. 1998), but it was not obvious whether year-to-year variations in Indian Ocean SST had a discernable impact on monsoon rainfall (Shukla and Misra 1977; Mooley and Shukla 1987), whether these SST variations were predictable, or what oceanic processes were involved in generating them. An extreme view held that the Indian Ocean was just a slave to the atmosphere, simply responding to intense forcing related to the monsoon winds but not feeding back to the atmosphere in any significant way.

Despite these challenges, the Indian Ocean was a fascinating laboratory for studies of ocean circulation because of the dramatic monsoon wind-driven ocean current variations unlike anywhere else in the world oceans. My interest in the Indian Ocean had been whetted in the mid-1970s by a unique 2.5-year time series of equatorial ocean velocity and temperature data collected during the Indian Ocean Experiment (INDEX) program (Moore 2006) by my PhD advisor Bob Knox of the Scripps Institution of Oceanography (Knox 1976; Knox and McPhaden 1976; McPhaden 1982). Subsequently, I had the good fortune to join a small number of US colleagues (some of whom are shown in Figure 2) on a National Science Foundation-sponsored trip to India in April 1984 to explore possible collaborations with Indian scientists on problems related to the monsoons and ocean dynamics. This first visit to India was valuable for establishing some important contacts, but not much of substance resulted in terms of joint field work, which was my specific objective, because of the strong emphasis in the US at the time on the Pacific and ENSO.

I kept my interest in the Indian Ocean alive during TOGA while engaged in building the TAO array. In 1992, we established the TOGA-TAO Implementation Panel (TTIP) under sponsorship of the International TOGA Project Office, to coordinate national contributions to the array. We held the second meeting of the Panel (TTIP-2) in Bali, Indonesia in October 1993, in part to consider the possibility of expanding the array into the Indian Ocean (McPhaden 1994). In mid-1993 as a pilot project, we deployed two ATLAS moorings embedded in Fritz Schott’s WOCE-sponsored moored ADCP array along 80.5°E to the south of Sri Lanka (Reppin et al. 1999). Also, as reported in the TTIP-2 meeting proceedings, the Japan Marine-Earth Science and Technology Agency (JAMSTEC) was formulating the concept for what would later become known as the Triangle Trans Ocean Buoy Network (TRITON), with moorings spanning the warm pool of the eastern Indian Ocean and western Pacific Ocean.

At the end of TOGA, TTIP continued on as TIP (with “TOGA” dropped from the name) under sponsorship of the Climate and Ocean: Variability, Predictability and Change (CLIVAR) program, the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS). TIP held its fifth session (TIP-5) in November 1996, jointly with the first meeting of the newly constituted CLIVAR Asian-Australian Monsoon Panel (AAMP) in Goa, India (Mangum et al. 1996). The 50 attendees of these two panels collectively struggled with what to do about the relative lack of data in the Indian Ocean and the lack of understanding of how the Indian Ocean affected monsoon dynamics and rainfall. The AAMP thus established a set of priority goals to focus its deliberations, including determining the limits of monsoon predictability and assessing the relative contributions of the slowly varying boundary conditions vs. the internal dynamics of the atmosphere to that predictability. The AAMP also established an ad hoc task group, coordinated with TIP and the CLIVAR Upper Ocean Panel, to define specific implementation strategies for pilot studies in the Indian Ocean to help address these goals.

Shortly after the Goa meetings, the “climate event of the century” (Changnon 2000) burst onto the scene. The 1997-98 El Niño, which grew to record strength by mid-1997, was extraordinary in its intensity and climate impacts (McPhaden 1999). This event led to discovery of the Indian Ocean Dipole (IOD), which is an ENSO-like phenomenon in the Indian Ocean that develops through coupled ocean-atmosphere interactions similar to those governing the ENSO cycle (Webster et al. 1999; Saji et al. 1999). The IOD, like El Niño that triggered it (Meyers et al. 2007), was exceptionally strong and accompanied by significant rainfall anomalies in east Africa, Indonesia, Australia, and other parts of the globe (Yamagata et al. 2004). Interestingly, the expected reduction in Indian summer monsoon rainfall that accompanies El Niño failed to materialize in 1997 because of the countervailing impact of the IOD (Gadgil et al. 2004). Ocean dynamics clearly played a role in the IOD (Murtugudde et al. 2000) and, as with ENSO in the Pacific, provided a source of predictability for the subsequent development of IOD SST anom-
lies that affect rainfall and far field teleconnections (Wajsowicz 2005). The events of 1997, in highlighting the coupled feedbacks between the ocean and atmosphere that generate the IOD, banished forever the notion that the Indian Ocean was simply a slave to the atmosphere in the generation of seasonal time scale climate variability.

The 1997-98 El Niño also dramatized the impact that the MJO, which is spawned over the Indian Ocean, had on ENSO (McPhaden 1999). While the MJO’s impact on ENSO was not a new discovery, there was a growing appreciation for how ocean-atmosphere feedbacks in the Indian Ocean helped to generate and organize MJO convective events (Flatau et al. 1997; Waliser et al. 1999a). Also, the MJO has far reaching effects on weather variability around the world, including active-break periods of the Asian monsoon, the generation of tropical cyclones in all three ocean basins, and extreme rainfall along the west coast of the US and elsewhere (Zhang 2005). Thus, the potential predictability of the MJO as a source of skill for dynamical extended range weather forecasts was an emerging subject of great interest (e.g., Waliser et al. 1999b).

The Oceanobs99 conference, held in October 1999 in San Rafael, France, was convened to build community consensus on how to evolve the global ocean observing system over the first decade of the 21st century to meet the needs of research, operational oceanography and societal applications (Koblinsky and Smith 2001). The goal of the conference, sponsored by WCRP, GOOS and GCOS among several other international organizations, was to set priorities for both the sustained global observational framework and for regional enhancements designed to address specific phenomena. The conference vision was founded on recent successes in spaceborne satellite missions, the development of ocean data assimilation and state estimation methodologies, and TOGA and WOCE observational advances that included the TAO array, the global network of surface circulation drifters (Niiler 2001), and robotic Argo floats to profile temperature and salinity structure in the upper 2000 m of the open ocean (Argo Science Team 2001).

By the time of Oceanobs99, the TAO array had expanded into the Atlantic Ocean as the Pilot Research Moored Array in the Tropical Atlantic (PI-RATA) program (Servain et al. 1998), leaving the Indian Ocean as the only tropical basin without a
systematic and coordinated in situ observing system. This glaring omission was highlighted in two solicited position papers in the conference proceedings that explicitly called for development of an Indian Ocean observing system based on scientific need, the readiness of existing technologies and the societal value of the measurements (Meyers et al. 2001; McPhaden et al. 2001). Thus, the formal Oceanobs99 conference statement, containing a broad range of recommendations based on participant consensus, “...endorsed a strategy to develop a coherent plan for the Indian Ocean...for the development of a sustained network over a 5-10 year time frame” (Koblinsky and Smith 2001).

Encouraged by the Oceanobs99 recommendation, Gary Meyers organized the Sustained Observations in the Indian Ocean (SOCIO) workshop in Perth, Australia in November 2000 under auspices of a recently established Perth Regional Office of the Intergovernmental Oceanographic Commission (IOC). The goal was to assess current observational efforts already underway and to begin defining a strategy for in situ Indian Ocean observations to complement spaceborne measurements (International CLIVAR Project Office 2000). In addition to regular XBT measurements along some commercial shipping lines, many Argo floats and circulation drifters deployed in the Indian Ocean for WOCE were still operating. Earlier in the year, both JAMSTEC and the Indian National Institute of Oceanography (NIO) had deployed pilot moored buoy arrays in the eastern and central equatorial Indian Ocean (Sengupta et al. 2004; Masumoto et al. 2005). Also, the Indian National Institute of Ocean Technology had established several weather buoys with surface meteorological instrumentation in the Arabian Sea and the Bay of Bengal (Venkatesan et al. 2016). However, these efforts were largely uncoordinated.

With support from CLIVAR, the World Meteorological Organization, the International Council for Science (ICSU) and funding agencies in the US, UK, India and Australia, IOC/GOOS convened a conference in Mauritius in November 2002 at which a GOOS regional alliance was created for the Indian Ocean (IOGOOS) to promote the establishment of both a coastal and deep ocean observing system in the basin. For the coastal zone, the issues of concern were very broad, including biodiversity, coastal erosion, pollution, and sustainable fisheries. For the deep ocean, the focus was primarily on climate-related issues. Given the different scientific drivers, different space and time scales involved, and specific national interests in exclusive economic zones, coastal and deep ocean initiatives discussed at the conference were considered on loosely coordinated parallel tracks. It was also clear by the end of the conference that, to make further progress on the development of a sustained Indian Ocean observing system for climate, an internationally supported committee structure would be required.

With IOGOOS endorsement, Gary Meyers took up the challenge of forming such a committee. Given the predominantly climate focus for the deep ocean, he approached the International CLIVAR Project Office to co-sponsor an IOGOOS/CLIVAR Indian Ocean Panel, analogous to the regional CLIVAR ocean panels that already existed for the Pacific and Atlantic. CLIVAR however initially balked, arguing that panels like the CLIVAR AAMP already had the mandate to consider what observations were needed for monsoon research and forecasting. Gary persisted and ultimately prevailed in convincing CLIVAR that a dedicated panel was needed to ensure that the venture was successful.

Coincidentally, in June 2002 the NOAA Administrator mandated the transfer of TAO array operations and management from PMEL to NOAA's National Data Buoy Center. This decision came as a surprise to the ocean and climate research community, since PMEL had been roundly praised for its cost-effective and responsive management of TAO in an international review of the program in September 2001 (Chapman 2002). The decision to transfer the array out of PMEL was a source of great concern to many, but it had the salubrious effect of freeing up technical capacity to address new research challenges. Buoyed by the momentum that had been building over the past several years, in early 2004 PMEL proposed, and NOAA authorized, funding to expand the TAO array into the Indian Ocean.

The CLIVAR/IOC-GOOS Indian Ocean Panel (later renamed the Indian Ocean Region Panel) was established in 2003 with Gary Meyers as chair. The first IOP meeting (IOP-1) was held in Pune, India in February 2004 jointly with the CLIVAR AAMP. Participants in this meeting, including members of the IOP, AAMP, and invited guests, were an all-star cast of meteorologists, oceanographers, and climate scientists. The product of IOP-1 was a science and implementation plan for a sustained Indian Ocean observing system (International CLIVAR Project Office 2006).
The IndOOS design was based on a complementary set of essential satellite and in situ measurements (Figure 3), with satellites providing broad spatial coverage and in situ elements providing calibration data for the satellites and data from below the surface where satellites cannot directly sample. The in situ components consisted of mature, proven technologies selected for their cost-effectiveness and high impact data sets, including a basin scale moored buoy array, an Argo network of profiling floats, surface circulation drifters, island and coastal tide gauge stations, and SOOP XBT lines. The moored buoy network, later named the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA), incorporated the pioneering JAMSTEC and NIO moorings into its design. RAMA provided high frequency time series measurements needed for observing intraseasonal and shorter time scale variability and surface meteorological data for accurate estimates of surface heat fluxes that were poorly constrained in existing flux products; it also provided continuous velocity measurements both in the mixed layer and in the equatorial waveguide where geostrophy breaks down and direct current measurements are required (McPhaden et al. 2009). Embedded in the basin scale observing system were regional networks like the Indian national moored buoy arrays in the Arabian Sea and Bay of Bengal, and the Australian Integrated Marine Observing System (IMOS) whose founding director was Gary Meyers (http://imos.org.au/news/newsitem/vale-gary-meyers/). Dynamical model studies helped to guide the overall observing system design, ensuring that the final configuration was optimized and integrated across the various platforms (Ballabrera-Poy et al. 2007; Oke and Schiller 2007; Vecchi and Harrison 2007).

The international community has just finalized a review of IndOOS (http://www.clivar.org/sites/default/files/documents/IndOOS_report_small.pdf), which has enabled many scientific advances and discoveries since its debut in the mid-2000s. The focus of the review, which took nearly three years to complete, was primarily on the in situ components of the observing system given the global nature of satellite missions. Thorough vetting of the scientific issues has led to a balanced set of priorities and actionable recommendations that reflect the evolution of our scientific understanding, the availability of new observing technologies, and practical lessons learned over the past decade. The updated design is responsive to new imperatives, like subseasonal to seasonal (S2S) forecasting (for which the MJO is as key target phenomenon), better understanding of decadal variability, and the growing urgency for authoritative information about climate change and its impacts in the Indian Ocean region. Recommendations call for a reconfigured and enhanced RAMA array, a new emphasis boundary flux arrays in the Agulhas and Leeuwin Currents taking advantage of glider technology, enhanced SOOP XBT measurements along two key transects, more biogeochemical measurements including biogeochemical Argo floats, an array of deep Argo floats, and more. These refinements will enhance the scientific impact of IndOOS data in the coming decade for both research and societal applications as part of the second International Indian Ocean Expedition (IIOE-2; Hood et al. 2015) and the UN Decade of the Ocean Science for Sustainable Development (https://en.unesco.org/ocean-decade).

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Figure 3 Schematic of the original IndOOS design. Green squares indicate the locations of RAMA moorings. Tide gauges are indicated by blue dots. Argo floats and surface drifters are indicated by a single symbol, although many of each are spread throughout the basin with 3° latitude x 3° longitude target spacing for Argo and a 5° latitude x 5° longitude target spacing for drifters. Ship-of-opportunity XBT transects are shown as black lines. The satellite in the upper-right symbolizes the constellation of Earth-observing satellites for SST, surface winds, sea level, salinity and other essential ocean and climate variables. Regional observing systems such as the Australian Integrated Marine Observing System (IMOS), and Indian national buoy programs in the Arabian Sea (ASEA) and Bay of Bengal (BOB) shown in white ovals (after McPhaden et al. 2009).
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