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A Road Map to IndOOS-2

Better Observations of the Rapidly Warming Indian Ocean

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ABSTRACT: The Indian Ocean Observing System (IndOOS), established in 2006, is a multinational network of sustained oceanic measurements that underpin understanding and forecasting of weather and climate for the Indian Ocean region and beyond. Almost one-third of humanity lives around the Indian Ocean, many in countries dependent on fisheries and rain-fed agriculture that are vulnerable to climate variability and extremes. The Indian Ocean alone has absorbed a quarter of the global oceanic heat uptake over the last two decades and the fate of this heat and its impact on future change is unknown. Climate models project accelerating sea level rise, more frequent extremes in monsoon rainfall, and decreasing oceanic productivity. In view of these new scientific challenges, a 3-yr international review of the IndOOS by more than 60 scientific experts now highlights the need for an enhanced observing network that can better meet societal challenges, and provide more reliable forecasts. Here we present core findings from this review, including the need for 1) chemical, biological, and ecosystem measurements alongside physical parameters; 2) expansion into the western tropics to improve understanding of the monsoon circulation; 3) better-resolved upper ocean processes to improve understanding of air–sea coupling and yield better subseasonal to seasonal predictions; and 4) expansion into key coastal regions and the deep ocean to better constrain the basinwide energy budget. These goals will require new agreements and partnerships with and among Indian Ocean rim countries, creating opportunities for them to enhance their monitoring and forecasting capacity as part of IndOOS-2.

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While the Indian Ocean is the smallest of the four major oceanic basins, close to one-third of humankind lives in the 22 countries that border its rim. Many of these countries have developing or emerging economies, or are island states, and are vulnerable to extreme weather events, to changes in monsoon cycles, and to climate variations and climate change.

Many Indian Ocean rim countries depend on rain-fed agriculture. In India, for example, 60% of jobs are in agriculture, which accounts for 20% of GDP, and there is a tight link between grain production and monsoon rainfall (Gadgil and Gadgil 2006). Indian Ocean sea surface temperatures (SST) influence monsoon rainfall over India (Ashok et al. 2001; Annamalai et al. 2005a), floods and droughts over Indonesia, Africa, and Australia (Saji et al. 1999; Webster et al. 1999; Reason 2001; Ashok et al. 2003; Yamagata et al. 2004; Ummenhofer et al. 2009; Taschetto et al. 2011; Tozuka et al. 2014), and wildfires in Indonesia and Australia (Abram et al. 2003). The tropical Indian Ocean is the warmest among global oceans and is part of the Indo-Pacific warm pool (SST > 28°C), which plays a key role in sustaining deep-atmospheric convection (Graham and Barnett 1987; Emanuel 2007) and maintaining the tropical atmospheric circulation (Bjerknes 1969). Observations indicate that the Indian Ocean has been warming faster than any other basin in response to anthropogenic climate change (Annamalai et al. 2013; Dong et al. 2014; Roxy et al. 2014). This warming contributes to increasing droughts over South Asia (Roxy et al. 2015), and eastern Africa where it is predicted to increase the number of undernourished people by 50% by 2030 (Funk et al. 2008).

The Indian Ocean hosts many countries dependent on fisheries and whose fisheries have poor adaptive capacity, including India, Indonesia, Sri Lanka, Maldives, Pakistan, Thailand, Madagascar, Mozambique, and Tanzania (Allison et al. 2009). Climate change is predicted to reduce fish catches for most of these nations (Barange et al. 2014). For instance, the intense marine productivity of the northern Indian Ocean is under threat (Bopp et al. 2013; Roxy et al. 2016; Gregg and Rousseaux 2019). In the Arabian Sea, oxygen-depleted waters reach the surface more frequently, causing more fish mortality events (Naqvi et al. 2009). Marine heatwaves also affect fisheries and ecosystems, with the first recorded bleaching of the pristine Ningaloo reef off Western Australia in 2011 (Feng et al. 2013).

The Bay of Bengal region already witnesses more than 80% of global fatalities due to tropical cyclones, because of coastal flooding (Needham et al. 2015). The frequency of extremely severe cyclones in the Arabian Sea is also projected to increase (Murakami et al. 2017), with 2019 already a highly unusual year (Joseph et al. 2019). Sea level rise in the northern Indian Ocean averaged 3.28 mm yr^{-1} from 1992 to 2013 (Unnikrishnan et al. 2015) and is projected to rise at a faster pace in the future (Collins et al. 2019). Coastal population density around the Indian Ocean is projected to become the largest in the world by 2030, with 340 million people exposed to coastal hazards (Neumann et al. 2015). This rapid population growth is conflating with climate change–induced sea level rise and tropical cyclone intensification to increase vulnerability (Elsner et al. 2008; Rajeevan et al. 2013).

Beyond these direct impacts on rim countries, the Indian Ocean influences climate globally. The tropical Indian Ocean warm pool is the breeding ground for the Madden–Julian oscillation (MJO) and for monsoon intraseasonal oscillations (MISO), ocean–atmosphere coupled phenomena that modulate rainfall and tropical cyclone activity on subseasonal time scales (Zhang 2005). Year-to-year variability of Indian Ocean SST can influence the evolution of El Niño–Southern Oscillation (ENSO) in the neighboring Pacific Ocean (Clarke and Van Gorder 2003; Annamalai et al. 2005a; Luo et al. 2010; Izumo et al. 2010), and may force tropical–extratropical atmospheric variability with impacts extending over the northeast Pacific (Annamalai et al. 2007). The Indian Ocean is also an important component of the so-called global ocean conveyer belt that drives climate variability at multidecadal and longer time scales (Broecker 1991). A redistribution of heat from the Pacific to the Indian Ocean over the last decade is thought to have played a key role in regulating global mean surface temperatures (Tokinaga et al. 2012; Liu et al. 2016), with the Indian Ocean representing about one-quarter of the global ocean heat gain since 1990 (Lee et al. 2015; Nieves et al. 2015; Cheng et al. 2017). This Indian Ocean warming has had far-reaching impacts, causing droughts in the West Sahel, Mediterranean and South America (Giannini et al. 2003; Hoerling et al. 2012; Rodrigues et al. 2019), modulating the Pacific atmospheric circulation (Luo et al. 2012; Han et al. 2014a; Hamlington et al. 2014; Dong and McPhaden 2017), the Atlantic oceanic circulation and North Atlantic climate (Hu and Fedorov 2019; Hoerling et al. 2004). Finally, the basin accounts for about one-fifth of the global oceanic uptake of anthropogenic CO_2 (Takahashi et al. 2002), helping to buffer the effects of global warming.

The role of the Indian Ocean in regional and global climate and the vulnerability of its rim populations articulate the need to better understand and predict its variability and change. The Indian Ocean Observing System (IndOOS; Fig. 1), established in 2006, is a multinational network of sustained oceanic measurements that underpin understanding and forecasting of weather and climate for the Indian Ocean region and beyond (International CLIVAR Project Office 2006). With the accelerating pace of climatic and oceanic change there is an urgent need to develop a more resilient and capable observing system that can better meet scientific and societal requirements for climate information and prediction over the next decade and beyond: IndOOS-2.

Here we provide an overview of the road map for IndOOS-2 (Beal et al. 2019), the result of a 3-yr internationally coordinated review of the IndOOS by more than 60 scientists (see “The IndOOS review” sidebar for details on the review process and sponsors, and a link to the full report). First, we briefly present the circulation and biogeochemistry of the Indian Ocean and their interaction with climate variability and change. We then describe the IndOOS and its components, summarizing past successes and limitations of the observing system in terms of the “state of the science,” thereby articulating the needed changes in its design. Finally, we present the

Fig. 1. Artist’s illustration of the Indian Ocean Observing System and its societal applications. IndOOS data support research to advance scientific knowledge about the Indian Ocean circulation, climate variability and change, and biogeochemistry, as well as societal applications due to its contribution to operational analyses and forecasts. Credit: JAMSTEC.

The IndOOS review

The IndOOS review and resulting IndOOS-2 road map were initiated as a system-based evaluation to update and fill gaps in the IndOOS and increase its readiness level, under the leadership of the Climate and Ocean: Variability, Predictability and Change (CLIVAR)/Intergovernmental Oceanographic Commission (IOC) Indian Ocean Region Panel (IORP) and in collaboration with the Integrated Marine Biosphere Research (IMBeR) project/Global Ocean Observing System (GOOS) Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) panel. The review was conducted over the course of 3 years under the scrutiny of an independent review board appointed by sponsoring organizations (see acknowledgments for details). As background material for the review, a group of 60 international scientists drafted 25 white papers on observing system components and scientific drivers. The terms of reference for the review, as well as the chapters and their contents, and the framework for prioritizing the many resulting actionable recommendations, were developed, discussed, and evolved by this community during three workshops in Australia (2017), Indonesia (2018), and South Africa (2019).

Fig. SB1. Numbers of the IndOOS-2 review exercise.

The 136 actionable recommendations that came out of the IndOOS review were prioritized as follows. All chapters and recommendations were first reviewed by the board of six international experts. They were then presented and discussed at the second IndOOS review workshop. A synthesis of breakout discussions allowed classifying actionable recommendations into three tiers: I—high priority (maintain and consolidate essential capacities, while considering the practicalities of implementation); II—desirable (extend IndOOS capacities to better address scientific and operational drivers); and III—lower priority (pilot projects to investigate the efficacy, sustainability, and potential for integration into the IndOOS). With the final versions of chapters in hand, the impact of the actionable recommendations was assessed objectively according to the number of scientific and societal drivers each address and their niche importance.

Finally, the list of tiered and prioritized recommendations was sent out for final comments from the review board and from the CLIVAR to the broader science community. Results of the survey feedback were presented and discussed during the third and final IndOOS review workshop, and recommendations revised accordingly. This rigorous community-led review and discussion process resulted in a list of prioritized actionable recommendations that form a framework for the implementation of IndOOS-2 (Fig. SB1).

The full report (Beal et al. 2019) is available online (https://doi.org/10.36071/clivar.rp.4.2019).

core findings of the review, highlight some of the most important recommendations of the IndOOS-2 road map, and discuss some of the implementation challenges.

Oceanic and climatic phenomena of the Indian Ocean

Monsoon-induced climatology. The Indian Ocean is the only tropical ocean that is bounded by a landmass to the north, resulting in the strongest and most extensive monsoon on Earth and many unique oceanographic features. Perhaps the most significant is the monsoon-induced complete seasonal reversal of the oceanic circulation north of 10°S (Fig. 2). Strong alongshore winds in the western Arabian Sea during the southwest monsoon (Findlater 1969) induce coastal upwelling of cold subsurface waters (Fig. 3a; Schott and McCreary 2001), which modulate evaporation and moisture transport toward India (Izumo et al. 2008; Xie et al. 2009) and provide a globally significant source of atmospheric CO_2 (Takahashi et al. 2002). The upwelled waters also bring nutrients to the surface, fostering intense oceanic productivity (Fig. 3b; McCreary et al. 2009; Hood et al. 2017), which induces large oxygen consumption within the poorly ventilated lower layers. The result is a thick oxygen minimum zone (OMZ) between about 200- and 1,500-m depth (Fig. 3b; Resplandy et al. 2012). In the Bay of Bengal, excess freshwater input from monsoon rains and river runoff creates a shallow, low-salinity surface layer (Fig. 3c). By inhibiting vertical mixing of heat, nutrients, and oxygen this salinity stratification is thought to favor warmer SSTs, which promote monsoon rainfall (Shenoi et al. 2002) and more intense cyclones (Sengupta et al. 2008; Neetu et al. 2019), to reduce oceanic productivity (Prasanna Kumar et al. 2002), and to lead to an OMZ in the Bay of Bengal (Sarma et al. 2016).

The annual-mean westerly winds along the equator in the Indian Ocean damp the equatorial upwelling that is found to the east of other tropical oceans. Instead, wind-driven open ocean upwelling is found in the southwestern tropical Indian Ocean, forming the Seychelles–Chagos thermocline ridge (SCTR; Fig. 2). The SCTR hosts warm SSTs and shallow thermocline (Fig. 3a), such that small perturbations in the atmosphere can easily induce an SST response, and vice versa. This results in strong air–sea coupling at various time scales

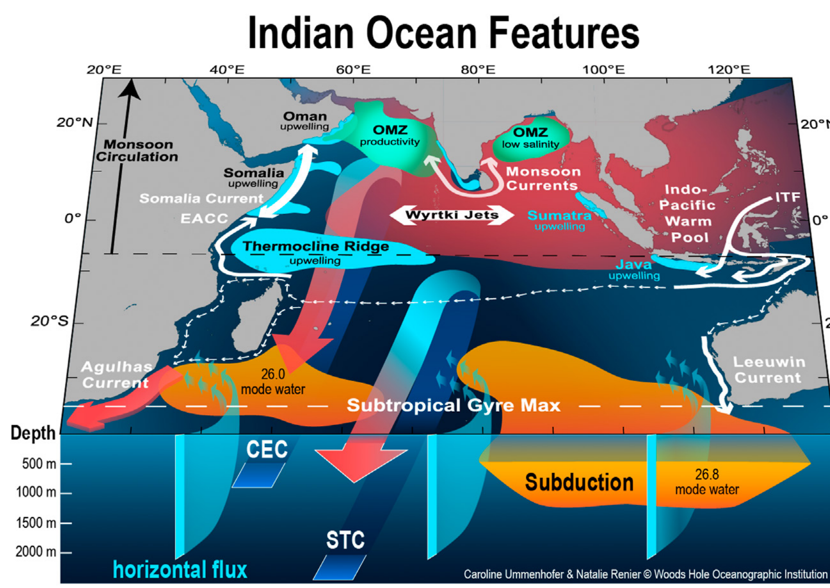

Fig. 2. Indian Ocean main oceanographic features and phenomena. The surface circulation seasonally reverses north of 10°S under the influence of monsoons. The summer monsoon also promotes the intense Somali current as well as upwellings and high productivity in the western Arabian Sea. High surface layer productivity, sinking of biomass, and its remineralization at depth also lead to the formation of subsurface oxygen minimum zones (OMZs) in the Arabian Sea and Bay of Bengal. The Indo-Pacific warm pool is a region of intense air–sea interactions, where the Madden–Julian oscillation, monsoon intraseasonal oscillation, and Indian Ocean dipole develop. The Indian Ocean is a gateway of the global oceanic circulation, with inputs of heat and freshwater through the Indonesian Throughflow, which exit the basin though boundary currents, mainly the Agulhas Current along Africa, but also the Leeuwin Current along Australia. There are two vertical overturning cells connecting subducted waters south of 30°S to the tropical Indian Ocean: the shallow subtropical overturning cell where water upwells in the "thermocline ridge" open-ocean upwelling region, and the cross-equatorial cell where water upwells farther north in the Arabian Sea of the coast of Somalia and Oman. These cells are the main source of subsurface ventilation due to the presence of continents to the north.

(e.g., Xie et al. 2002; Vialard et al. 2009; Yokoi et al. 2012) linked to tropical cyclones, the MJO and the Indian Ocean dipole (IOD), as described below. Observational studies have also documented concentrated tuna fishing activities in the SCTR upwelling (Fonteneau et al. 2008).

The breeding ground of atmospheric intraseasonal variability. The Indian Ocean is the breeding ground of the MJO, which modulates rainfall and cyclogenesis throughout the global tropics at 30–90-day time scales (Zhang 2005). The MJO propagates eastward over the Indian Ocean into the western Pacific Ocean and beyond, also impacting midlatitude weather (Figs. 4a,b). In summer, intraseasonal variability is often associated with northward-propagating rainfall anomalies known as the MISO, which manifest as the active and break phases of the Indian monsoon (Figs. 4c,d; e.g., Goswami 2005). The MJO and MISO induce SST variations (Fig. 4) that are larger in the Indian Ocean than in the Pacific Ocean, particularly in the northwestern Australian Basin, SCTR, and Bay of Bengal (e.g., Vialard et al. 2012, 2013). Accounting for these SST responses and their feedbacks can improve the forecast range of the MJO by about 10 days (Fig. 4e), yielding enhanced rainfall predictability throughout the tropics (De Mott et al. 2015).

Interannual climate variability. Until 20 years ago, the Indian Ocean was seen as passively responding to its giant Pacific neighbor, which hosts ENSO, the dominant mode of year-to-year climate variability globally (e.g., Timmermann et al. 2018). We now know that there is intrinsic climate variability in the Indian Ocean, with important climatic consequences regionally and beyond. El Niño events induce subsidence over the Indian Ocean, which warms almost uniformly as a result (Fig. 5a; Yu and Rienecker 1999; Klein et al. 1999). This Indian Ocean Basin Mode (IOBM) is maintained through

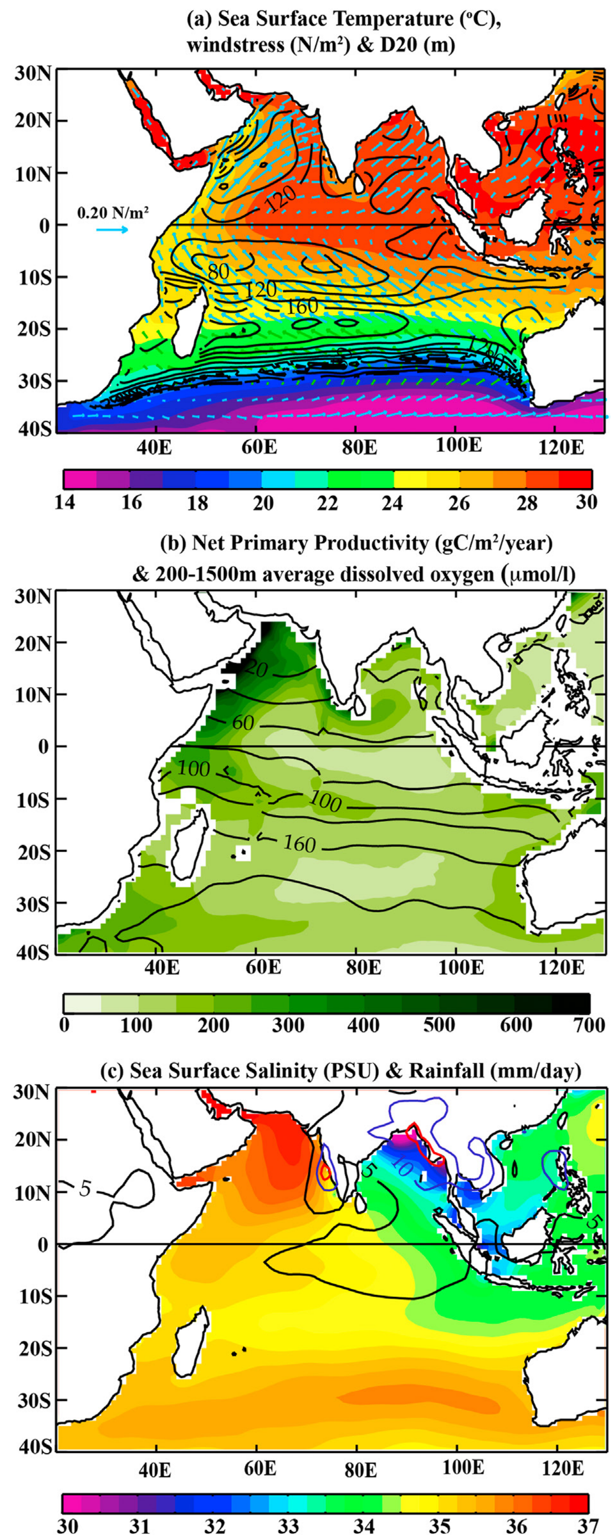

Fig. 3. Boreal summer (JJAS) observed climatologies of (a) sea surface temperature (colors) and wind stress (vectors), (b) primary productivity estimate (colors) and 200–1,500-m average oxygen (contours), and (c) sea surface salinity (color) and rainfall (contours). See the online supplemental material (https://doi.org/10.1175/BAMS-D-19-0209.2) for the equivalent winter figure and for the details of datasets and methods for each figure. The heating of the Asian landmass by the sun's movements yields strong winds and rainfall in the boreal summer. The alongshore winds induce upwelling of cold and nutrient-rich water in the western Arabian Sea, conductive to high oceanic productivity. The combined high oxygen demand from this oceanic productivity and weak ventilation due to the presence of land to the north results in a very extensive OMZ in the Arabian Sea and Bay of Bengal. More detailed methods for Fig. 3 and following are provided in the online supplemental information of this article.

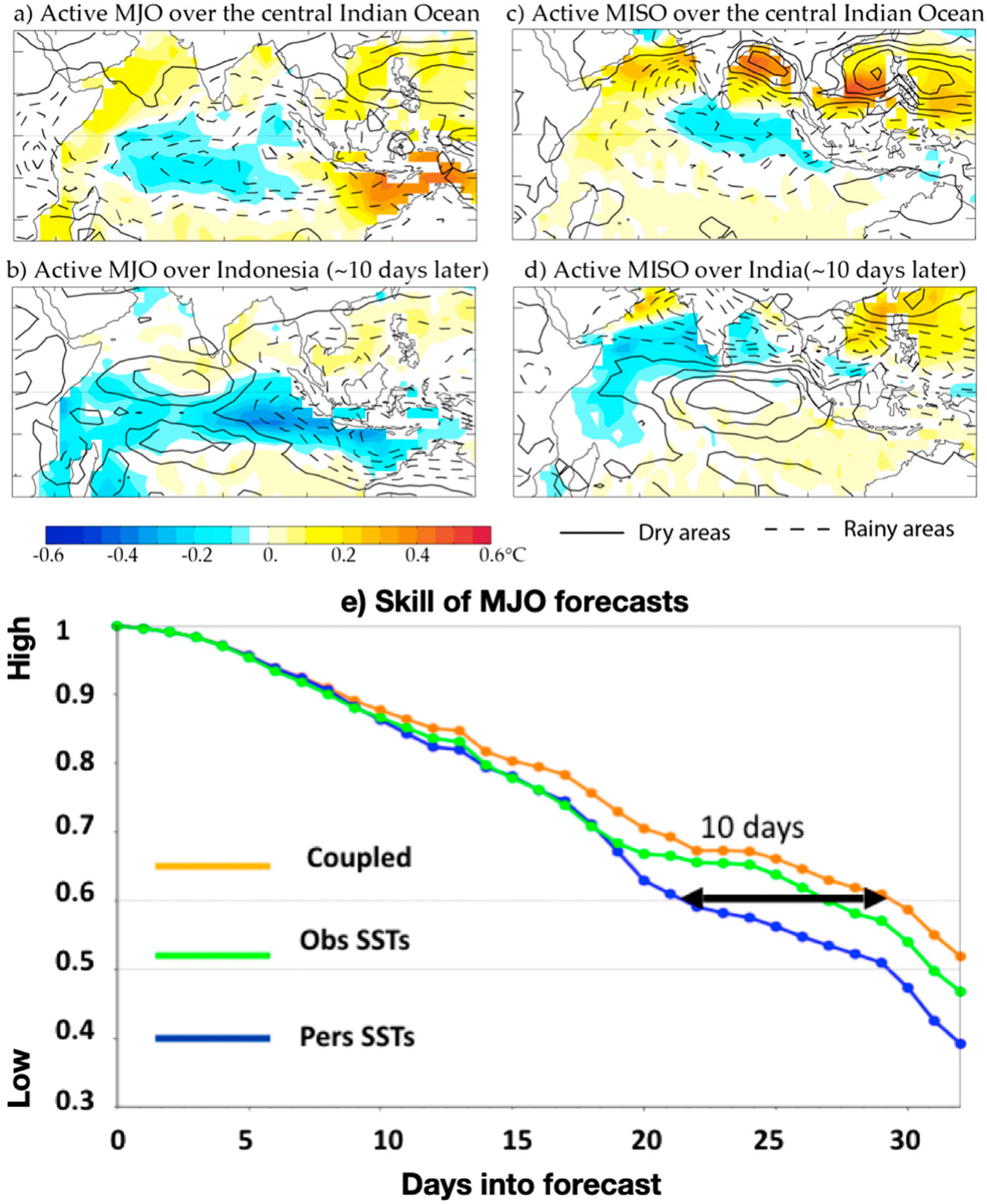

Fig. 4. Atmospheric convection perturbation (outgoing longwave radiation, contours every 10 W m^{-2}) and sea surface temperature (SST; colors) composites of two successive phases of (a),(b) the Madden–Julian oscillation (MJO) during December–March and (c),(d) the monsoon intraseasonal oscillation (MISO) during June–September. (e) MJO forecast skill as a function of lead time (days) for forecasts with fixed SST, observed SST, and active ocean–atmosphere coupling. The MJO and MISO modulate tropical rainfall during boreal winter and summer, respectively. They are associated with SST and oceanic mixed layer processes, which need to be better observed to improve their forecasts.

local air–sea interactions, extending the regional climate impacts (Fig. 5d) beyond those of ENSO (Xie et al. 2009; Taschetto et al. 2011; Roxy et al. 2014). The Indian Ocean also hosts modes of intrinsic climate variability arising from regional air–sea interactions, such as the IOD (Saji et al. 1999; Webster et al. 1999; Murtugudde et al. 2000; Fig. 5b), Ningaloo Niños (Fig. 5c;

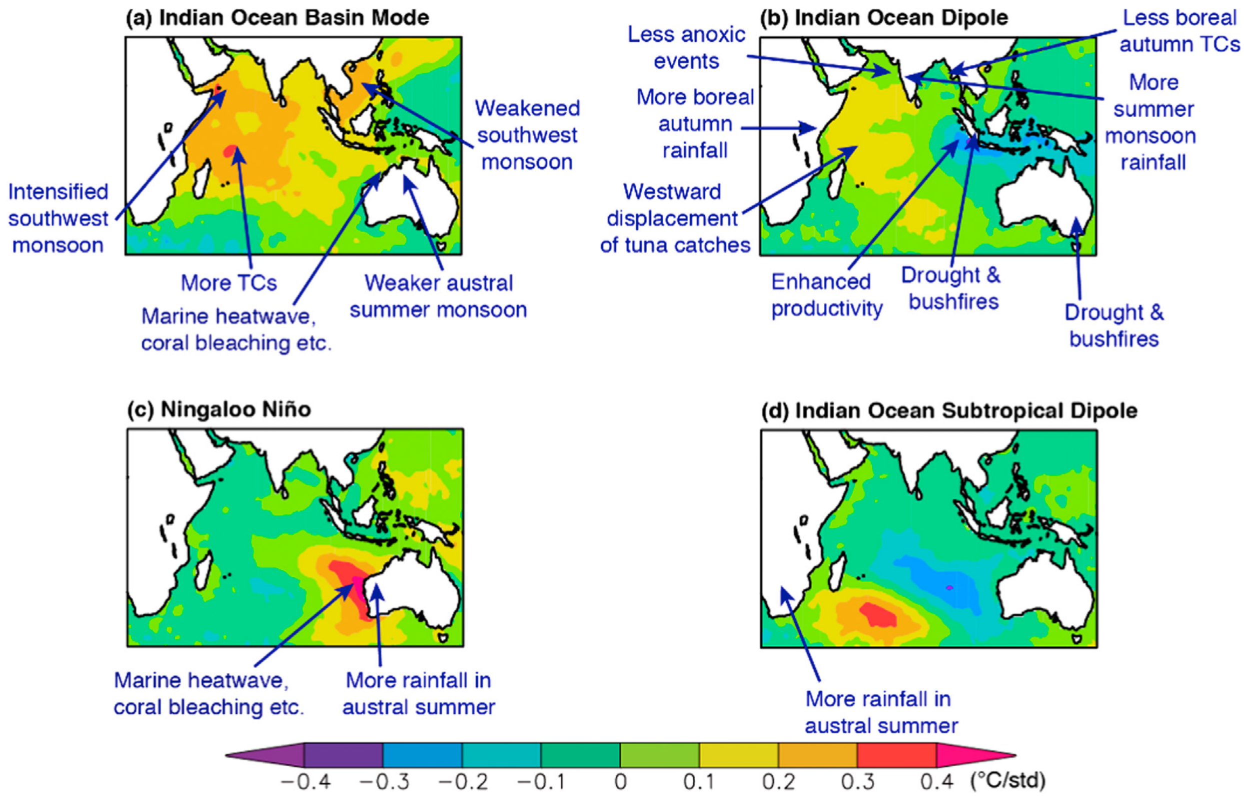

Fig. 5. SST signals associated with the four main Indian Ocean climate modes: (a) Indian Ocean Basin Mode (IOBM), (b) Indian Ocean dipole (IOD), (c) Ningaloo Niño (NN), and (d) Indian Ocean subtropical dipole (IOSD). The four climate modes induce year-to-year SST and rainfall fluctuations over the Indian Ocean region, partly in response to El Niño but also independently. They peak in FMA, SON, DJF, and JFM, respectively. Each of these climate modes has important consequences around the Indian Ocean and beyond, with the most important climate impacts summarized on the figure.

Feng et al. 2013), and Indian Ocean subtropical dipole (IOSD; Behera and Yamagata 2001; Fig. 5d). In addition to their impacts on regional rainfall, these climate modes have biogeochemical and ecosystem signatures (Fig. 5; e.g., Currie et al. 2013; Parvathi et al. 2017; Wiggert et al. 2009; Zinke et al. 2014). The IOD and IOBM are thought to feedback on the ENSO cycle in the Pacific (Annamalai et al. 2005b; Izumo et al. 2010; Cai et al. 2019). The IOD, IOSD, and Ningaloo Niños are sometimes forced by ENSO (Yamagata et al. 2004; Morioka et al. 2013; Feng et al. 2013; Kataoka et al. 2014), which is thus a source of predictability. The subsurface structure of the Indian Ocean also yields predictability for the IOD (Annamalai et al. 2005c; Doi et al. 2017; Ummenhofer et al. 2017; McPhaden and Nagura 2014).

A globally relevant heat buffer at decadal time scales. Due to its large heat capacity, the ocean absorbs more than 90% of the anthropogenically induced excess heat into the Earth system (IPCC 2013). The Indian Ocean has contributed to one-quarter of this global oceanic heat uptake over the last two decades, despite representing only 13% of the global ocean surface (Fig. 6a; Cheng et al. 2017). This heat uptake has contributed strongly to regional sea level rise (Thompson et al. 2016). The heat budget of the entire Indian Ocean, north of its open southern boundary around 35°S, is dominated by three oceanic flux components estimated to have similar magnitude (see Fig. 2 schematic). First, an inflow of fresh tropical waters via narrow and deep passages through the Indonesian Seas [Indonesian Throughflow (ITF); Sprintall et al. 2009; Zhang et al. 2018; Roberts et al. 2017]. Second, a meridional overturning circulation linking subduction of waters into the thermocline from seasonal deep mixed layers at the southern reaches of the basin and an inflow of Antarctic Intermediate

Water with upwelling in the SCTR and in the Arabian Sea (cross-equatorial and subtropical cells; Schott et al. 2002, 2009; Han et al. 2014b; McDonagh et al. 2008). Third, a horizontal subtropical gyre circulation dominated by the poleward-flowing warm and salty waters of the Agulhas Current at the western boundary (Bryden and Beal 2001). Over the last decade or so, the largest changes in Indian Ocean heat content have occurred over the subtropics (Fig. 6b). While variations in the ITF (Wainwright et al. 2008; Lee et al. 2015) and Leeuwin Current (Feng et al. 2004; Zhang et al. 2018) have been linked to Indian Ocean heat content and sea level changes, lack of measurements in the Agulhas Current and the large uncertainties in surface heat fluxes (Fig. 7; Yu et al. 2007) currently make it difficult to constrain the basin-scale heat budget at interannual and longer time scales.

Changing Indian Ocean. The Indian Ocean is responding to anthropogenic climate change, with evidence of increasing surface temperatures and heat content (Figs. 6a,b), rising sea level, increased carbon uptake, and an intensified water cycle (IPCC 2013; Han et al. 2014b). The consequences of these changes on biogeochemical cycles and extreme weather events are serious with, for example, more intense cyclones in the Arabian Sea and Bay of Bengal (Murakami et al. 2017), and long marine heat waves like that north of Australia in 2016 (Wernberg et al. 2016;

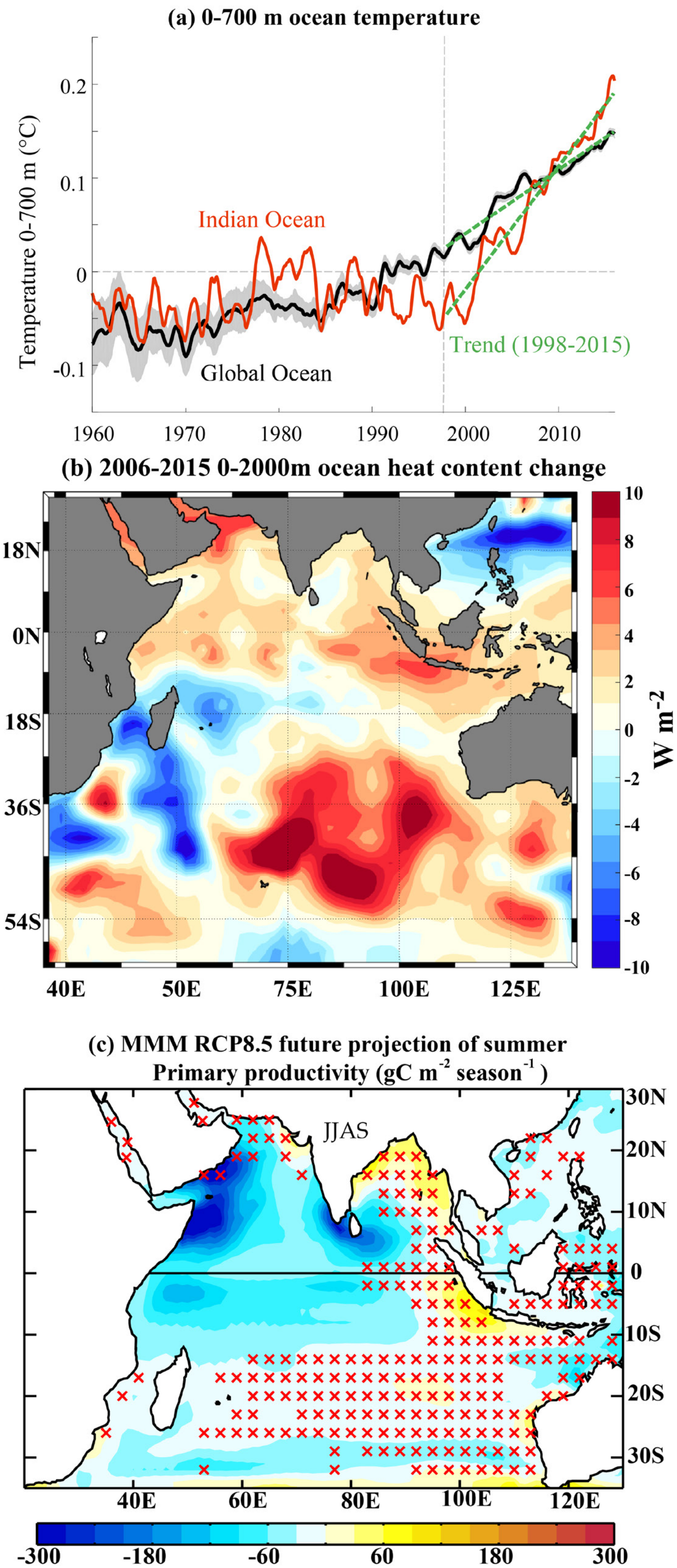

Fig. 6. (a) The 12-month running-mean time series of the 0–700-m-averaged temperature for the global ocean (black, with gray shading for 95% confidence interval) and Indian Ocean (red, with a thin line showing monthly time series). The 1998–2015 linear trends for both series are displayed as green dashed lines. (b) The 0–2,000-m heat content trend (W m^{-2}) during 2006–15, computed from the optimal interpolation of Argo profiles. Deep, 700–2,000-m heat content changes represent about 20% of the trend over the entire Indian Ocean. (c) CMIP5 historical and RCP8.5 multimodel-mean (23 models) projected changes (2080–2100 minus 1980–2000) in boreal summer (JJAS) primary productivity. Red ´ symbols indicate regions where less than 80% of the models agree on the sign of the projected change. The Indian Ocean has been warming faster than the global ocean over the last 20 years, accounting for about 25% of the global ocean heat content increase, with the strongest 0–2,000-m warming in the southeastern subtropics. Climate model projections agree on a large (~20%) decrease of oceanic productivity in the Arabian Sea in the case of unabated carbon emissions and strong deoxygenation in the southern subtropics.

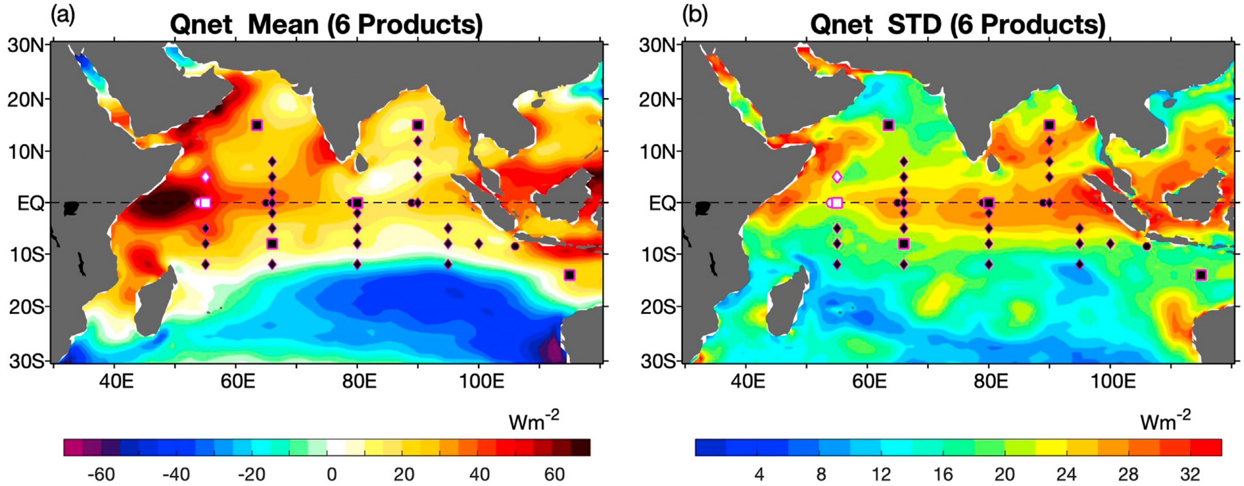

Fig. 7. (a) Time mean of the net surface flux (Qnet, positive for oceanic heat gain) at the ocean surface from the ensemble mean of six different flux products for the 2001–15 period. (b) Standard deviations (STDs) around the mean of the six flux products over that period, giving an idea of the area where flux estimates are most uncertain. The STDs in climatological Qnet are up to 25 W m^{-2} in a large part of the Indian Ocean north of 10°S, on the same order of magnitude as the mean Qnet itself. The large uncertainty in Qnet products hampers the quantification of basin-scale heat budgets at the interannual to decadal time scales. Buoy locations of RAMA-2.0 are superimposed (adapted from McPhaden et al. 2009), with diamonds denoting RAMA surface mooring sites and squares corresponding to "flux reference sites" that provide the essential benchmark time series for validating and improving air–sea parameterizations in models and for improving uncertainty quantification in air–sea flux products.

Oliver et al. 2018). Rapid warming and expansion of the Indo-Pacific warm pool has altered the life cycle of the MJO, resulting in changing rainfall patterns across the tropics and the United States (Roxy et al. 2019). Basin-scale warming, acidification (Bopp et al. 2013), and an expansion of OMZs (Schmidtko et al. 2017) are putting stress on marine ecosystems. A dramatic shift in the ecosystem of the Arabian Sea is already evident as a result of hypoxia (do Rosário Gomes et al. 2014). Observations indicate a decrease in Indian Ocean primary productivity over 1998–2015 (Gregg and Rousseaux 2019), consistent with climate models that project a ~20% decrease by the end of the twenty-first century (Fig. 6c). In contrast, present and future evolution of subsurface oxygen concentration are both inconsistent across models and with observational estimates (Bopp et al. 2013). Understanding regional patterns of change, attributing them to natural variability or anthropogenic forcing, and being able to project them into future decades is an ongoing challenge (Han et al. 2010; Gopika et al. 2020). Only a well-planned and sustained IndOOS can provide the necessary information.

Components of the IndOOS

The IndOOS is currently composed of five in situ observing networks (Fig. 8): profiling floats (Argo), a moored tropical array [Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA)], repeat lines of temperature profiles [expendable bathythermograph (XBT) network], surface drifters, and tide gauges. Augmenting these networks are critical observations of the ocean surface from satellites, as well as a wide range of full-depth ocean sections via Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP).

Argo. The Argo array is global, with a target of one autonomous profiler per 3° × 3° region, each profiling the ocean every ten days to measure temperature, salinity, and pressure down to 2,000 m (Gould et al. 2004). Full coverage of the Indian Ocean north of 40°S was first achieved in 2008. There are currently 538 active floats providing over 20,000 profiles per year (Fig. 8). A growing number of profilers (currently 61), mostly in the Arabian Sea and Bay of Bengal, are equipped with biogeochemical sensors to measure key processes related to plankton blooms, OMZs, and fisheries, to name a few.

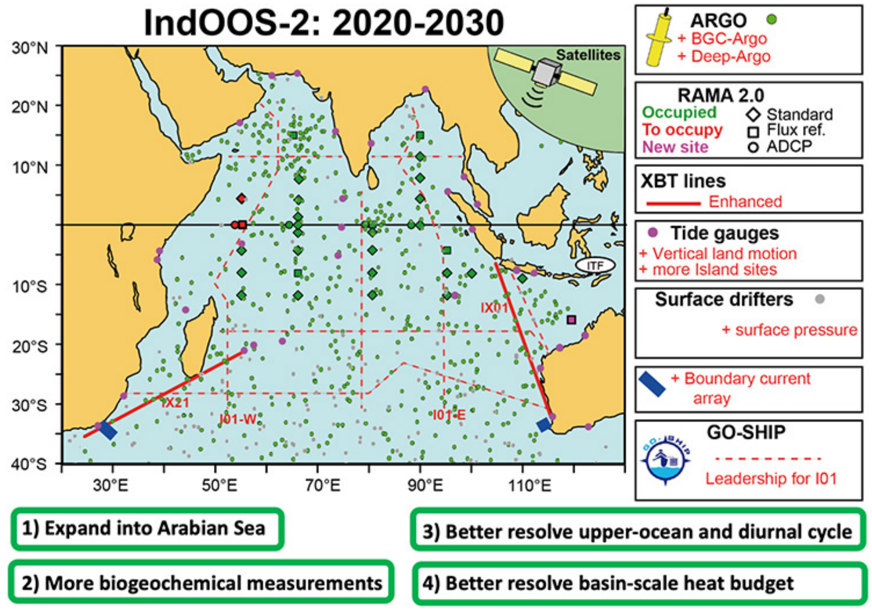

Fig. 8. Main IndOOS-2 recommendations. Argo: Maintain the core 3° × 3° array; add 200 BGC-Argo floats; develop a Deep-Argo program. RAMA: New RAMA-2.0 design that better addresses operational constraints; occupy three remaining sites in Arabian Sea; increase resolution of upper-ocean measurements and add biogeochemical measurements at flux reference sites; add a new flux site off northwestern Australia. XBT: Maintain IX01 and IX21 lines, install autolaunchers, and increase near-coastal resolution on IX01. Tide gauges: Add collocated measurements of land motion; add sites in the southwestern Indian Ocean and on islands. Surface drifters: Maintain core 5° × 5° array; evaluate addition of barometric pressure measurements. Boundary current arrays: Add measurements of mass, heat, and freshwater fluxes of the Agulhas and Leeuwin Currents, including hydrographic end-point moorings to capture basin-scale overturning. GO-SHIP: Find national commitment for IO1-E and IO1-W sections; add measurements of phytoplankton community structure. Satellites: Maintain overlapping, intercalibrated missions; enhance spatial resolution of SSH or currents directly. These recommendations can be summarized in four core findings of the review, listed in green in the frames beside the map.

RAMA. The RAMA (McPhaden et al. 2009), the Indian Ocean component of the Global Tropical Moored Buoy Array (McPhaden et al. 2010), provides subdaily time series of key oceanographic and surface meteorological variables in real time in a region where the oceanic response to atmospheric forcing is rapid and coupled feedbacks are critical. All RAMA surface moorings measure meteorological surface parameters, oceanic temperature and salinity from 1 m down to 500 m and from 1 m down to 120 m, respectively, and ocean mixed layer currents. Some "flux reference sites" have additional measurements for computation of air–sea momentum, heat, and freshwater fluxes (Fig. 8). A few sites have biogeochemical sensors.

XBT. The voluntary observing ship XBT network collects temperature observations over the upper ~1 km of the ocean along regular commercial shipping routes. Prior to the advent of Argo, XBTs provided more than 50% of all subsurface temperature observations. The IX1 XBT section between Australia and Indonesia has been used to monitor variations of the Indonesian Throughflow for more than three decades (Meyers 1996; Liu et al. 2015).

Global drifter program. This program consists of surface drifters drogued to follow ocean currents at 15 m, at a design density of one drifter per 5° × 5° region (Centurioni et al. 2017). All drifters also measure temperature and about half now measure sea level pressure, which has been shown to significantly improve numerical weather prediction (Centurioni et al. 2017). Coverage in the Indian Ocean has been about 70% since 1996 and about 90% since 2014.

Tide gauges. The tide-gauge network (Merrifield et al. 2009) around the Indian Ocean rim provides measurements of sea level near coasts or on islands. The network has been enhanced since the 2004 tsunami and provides important tsunami warnings. A subset of tide gauges also monitor land motion (King 2014), a necessary condition for a precise quantification of long-term trends in mean sea level.

Satellites. Satellite data are the only source of basin-scale measurements at subseasonal frequencies. Satellite measurements of sea surface temperature and salinity, sea surface height, ocean color (a proxy for primary productivity), significant wave height, and ocean mass provide key measurements of the state of the Indian Ocean. Atmospheric variables such as surface wind and wind stress, surface shortwave radiation, precipitation, and outgoing longwave radiation at the top of the atmosphere characterize forcing on the ocean, coupled climate processes, and air–sea fluxes. Satellite sea surface height and wind stress also allow the estimation of the geostrophic and wind-driven components of surface currents.

GO-SHIP. GO-SHIP is an internationally coordinated program of decadally repeated multidisciplinary scientific cruises, which perform transbasin hydrographic surveys (Talley et al. 2016). GO-SHIP collects a wide variety of high-quality measurements including physical and geochemical properties of seawater to full ocean depth that can be used to constrain the mean ocean circulation and long-term water mass changes. Given the magnitude of decadal and multidecadal climate variability and change in the Indian Ocean, and the dearth of geochemical measurements, GO-SHIP is an increasingly important component of the IndOOS.

Innovative technologies. Innovative instrumentation and platform technologies are likely to transform the IndOOS in the future. Some of these technologies, such as gliders, are well-established research tools with immediate potential for IndOOS pilot programs in difficult-to-measure regions (Beal et al. 2019), such as upwelling zones and boundary currents. Other autonomous vehicles and drifters—such as sail drones and wave gliders—have potential to improve surface flux estimates in the near future.

Evaluating the IndOOS

The full IndOOS review ("The IndOOS review" sidebar; Beal et al. 2019) consists of 25 chapters that together detail how the IndOOS, as well as numerous shorter-term process-oriented experimental studies over the past decade, have profoundly changed our scientific understanding of the Indian Ocean and its links to weather and climate. At the same time, the review underscores how there are significant limitations to our knowledge and predictive capabilities that can be overcome with future enhancements to the IndOOS. Here we synthesize these findings in the context of the important climatic phenomena of the Indian Ocean and their time scales.

Extreme events. The RAMA and Argo programs have allowed case studies of the Indian Ocean's response to, and feedback on, tropical cyclogenesis, showing that thick isothermal and salinity-stratified layers in the Bay of Bengal can cause rapid intensification of cyclones (Lin et al. 2009; Yu and McPhaden 2011; Yun et al. 2019; Neetu et al. 2019) and that an anomalously deep thermocline in the SCTR region increases cyclone activity (Xie et al. 2002; Vincent et al. 2014; Burns et al. 2016). These observations are particularly important since air–sea coupling and cooling under cyclones is not well measured from satellites due to rain (Gentemann et al. 2010). New satellite technologies are needed to observe SST in all weathers. Coastal tide gauges measure the storm surges associated with tropical cyclones, as well as the amplitude of tsunamis, but there are few in the tropical southwest Indian Ocean. An essential input for cyclone forecasts, and for weather forecasting more generally, is sea level pressure data and upper ocean (<200 m) temperature and salinity. While RAMA sites provide some observations in cyclogenesis regions, improved vertical and spatial coverage is needed. Marine heat waves and their persistent subsurface signatures invisible to satellites have been characterized by Argo data. Yet, for better understanding of how Ningaloo Niño develops, the Leeuwin Current needs to be better observed (Feng et al. 2013).

Subseasonal variability. Much has been learned about the MJO and MISO from the IndOOS. The Argo dataset has revealed the spatial scale of oceanic coupling to these intraseasonal oscillations (e.g., Drushka et al. 2012). High-frequency RAMA data have captured the dynamical response within the equatorial waveguide (e.g., Nagura and McPhaden 2012), as well as the thermodynamical response in regions of strong air–sea coupling, such as the SCTR (e.g., Vialard et al. 2008) and Bay of Bengal (Girishkumar et al. 2017). Basin-scale fluctuations in SST, SSH, surface wind, and convective perturbations associated with the MJO and MISO and their active and break phases have been characterized and analyzed using satellite data (Vialard et al. 2012, 2013). Subseasonal-to-seasonal prediction models rely on these datasets to initialize their forecasts (Subramanian et al. 2019). Yet, predictions of the MJO and MISO remain disappointing, with little skill beyond 20–30 days (Kim et al. 2018)—one-third to one-half of the typical length of an MJO or MISO event (Fig. 9).

Many studies (e.g., Woolnough et al. 2007; Roxy and Tanimoto 2007; Achuthavarier and Krishnamurthy 2011; Seo et al. 2014) and recent field experiments (e.g., Yoneyama et al. 2013; Wijesekera et al. 2016) have pointed the way toward potential improvements in prediction skill through better representation of air–sea coupling, and in particular the SST response to the MJO (Fig. 4e). Large diurnal warming, mostly in the top 2–3 m, is associated with the suppressed phase of the MJO (e.g., Shinoda 2005), pointing to the need to measure the near-surface ocean at high vertical and temporal resolution in regions of strong MJO and MISO signals: the 10°N–10°S band, the eastern Arabian Sea, and the Bay of Bengal (Fig. 4). The largest SST signals associated with the MJO globally occur between Australia and Indonesia (Vialard et al. 2013), making this a prime site to establish new in situ measurements. A pilot mooring was already successfully deployed there 2018–19 (Feng et al. 2020), paving the way for improved subseasonal-to-seasonal forecasting, including predictions of hydroclimate over Australia.

Monsoons. Our understanding of the monsoon circulation in the Indian Ocean has been greatly refined through the IndOOS. Strong seasonal current variations, in particular the Somali Current during the

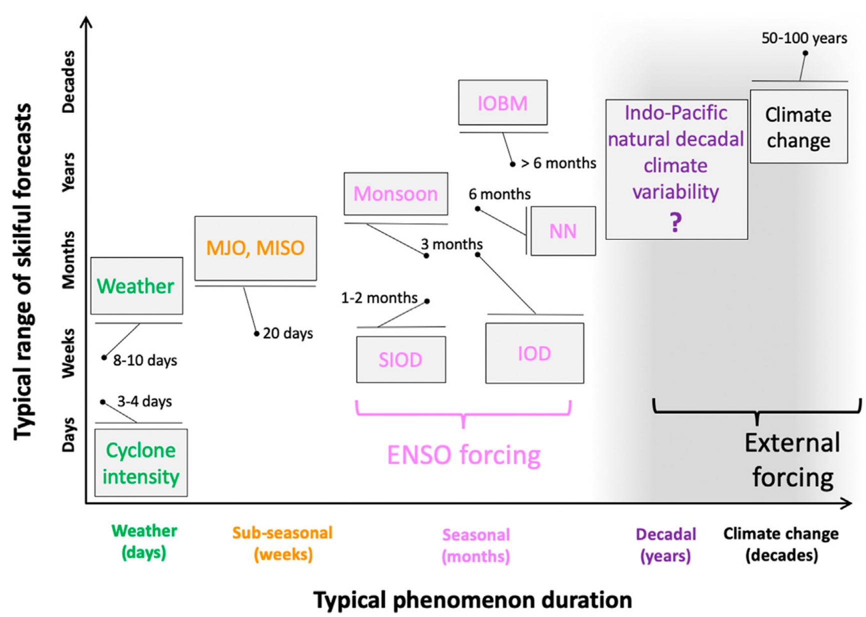

Fig. 9. Range of skillful state-of-the-science forecasts for Indian Ocean weather and climate phenomena, as a function of their time scale. The MJO and MISO have quite a short skillful prediction range (1/4 to 1/3 of their time scale), but a better monitoring of upper-ocean variability may allow better forecasts (Fig. 4). IndOOS subsurface data enhance IOD forecast scores. While ENSO is a source of predictability for Indian Ocean climate, ocean–atmosphere interactions in the Indian Ocean itself are also important and can potentially feedback on ENSO. Indian Ocean natural decadal climate variability is currently a "gray area," limiting our capacity to clearly delineate climate changes signals from those associated to forcing external to the climate system, such as anthropogenic climate change.

southwest monsoon and the intermonsoon Wyrtki jets along the equator (Fig. 2), dominate the redistribution of heat around the northern basin and across the equator. RAMA velocity data have improved our understanding of the Wyrtki jets (Fig. 2; e.g., Nagura and McPhaden 2010; McPhaden et al. 2015) and the basin-scale climatological surface seasonal circulation is relatively well captured by surface drifters and satellite data (e.g., Beal et al. 2013). However, these seasonal circulations are poorly represented in coupled models, giving rise to strong biases in monsoon rainfall (Annamalai et al. 2017). While in the past the Indian monsoon was thought to have inherently low predictability (Rajeevan et al. 2012), recent work has shown that improved coupled model physics can resolve links between monsoon rainfall and various climate modes, including the IOD and ENSO (Saha et al. 2019). This offers renewed motivation to collect the measurements that can initialize and validate these models. Most important is to enhance observations in the western equatorial Indian Ocean, including measurements of surface meteorological fluxes. Most essential are observations of the Somali Current system and its associated upwelling cells and cross-equatorial fluxes, which are persistently undersampled by drifters and floats (L'Hégaret et al. 2018), a problem for all intense and divergent circulation regimes. Integrated observing system approaches are needed, along with new instrument technologies, to overcome the current cost and logistical constraints of sustained observations near boundaries and to include biogeochemical observations that can track ecosystem variability.

Interannual variability. The IOD is well described by the IndOOS, which captures the equatorial dynamics, many of the subsurface signals and predictors, and the basin-scale surface response (SST, SSH, wind, and SSS) of the IOD (Chen et al. 2015). IndOOS measurements of surface fluxes and subsurface oceanic conditions are assimilated into models and contribute to IOD forecast skill (Luo et al. 2008; Horii et al. 2008; Doi et al. 2017). Yet despite these advances, and the external influence of the more predictable ENSO, the skill of IOD forecasts quickly drops for forecast periods beyond 3 months (Fig. 9; Liu et al. 2017). The lack of forecast skill may result from poorly constrained oceanic subsurface processes in the IOD eastern pole (Tanizaki et al. 2017), which harbors small spatial scales largely unresolved by the IndOOS, including the coastal upwelling systems of Java–Sumatra. New technologies, such as gliders, may provide a feasible way to make sustained measurements closer to the coast in this region. Ocean dynamics and sea level in the SCTR are also important for the IOD (McPhaden and Nagura 2014) and IOBM (Xie et al. 2009; Vialard et al. 2009): a moored velocity time series and more sea level measurements from island tide gauges would capture these signals better. More observations of oxygen, nutrients, and biology are also needed across the basin to characterize the subsurface biogeochemical responses to the IOD and IOBM (e.g., Wiggert et al. 2009; Currie et al. 2013; Parvathi et al. 2017).

The interannual variability of mass and heat fluxes into the Indian Ocean from the Pacific are relatively well constrained by the IX01 XBT line across the mouth of the Indonesian Throughflow (Wijffels et al. 2008), but more salinity measurements are needed to measure freshwater variability in the ITF, which can dominate over thermal changes (Llovel and Lee 2015; Hu and Sprintall 2017). Interannual variability of the subtropical gyre, home to the subtropical dipole and Ningaloo Niño modes (Fig. 5), needs to be constrained with sustained observations of the Agulhas and Leeuwin Currents. While the mean transport of the Agulhas is almost two orders of magnitude larger than the Leeuwin Current, both have been shown to be important components of interannual variability in the basinwide heat budget (Bryden and Beal 2001; Zhang et al. 2018).

Decadal variability and change. The relative paucity and irregularity of past oceanic observations compared to the Pacific and Atlantic make it difficult to discern natural decadal climate variability (Nidheesh et al. 2017) from anthropogenic change in the Indian Ocean (Fig. 9; Thompson et al. 2016; Han et al. 2019). Some studies suggest that decadal climate forecasts could be most skillful for the Indian Ocean, because the externally forced climate change signal overwhelms the inherently less predictable decadal variability in this basin (Guemas et al. 2013).

There are only a handful of continuous multidecadal records, among them tide gauges in the northern and eastern portions of the basin and the exceptional 35-yr IX01 XBT section. The combination of the Fremantle tide gauge and IX01 XBT line, for instance, have allowed estimates of decadal fluctuations in the exchanges of mass and heat between the Pacific and Indian Oceans through the ITF (e.g., Feng et al. 2004; Liu et al. 2015). Evidence for multidecadal trends in deep ocean temperature and salinity, dissolved oxygen, carbon uptake, and ocean acidification come from repeat GO-SHIP hydrographic lines (Talley et al. 2016), but almost nothing is known about the variability of these parameters.

Since the mid-2000s Argo data have tracked the warming of the upper 2,000 m of the Indian Ocean and show it to be concentrated in the southeastern subtropics (Fig. 6b; Desbruyères et al. 2017; Li et al. 2017). However, thermohaline changes deeper than 2,000 m contribute about 10% to Indian Ocean decadal heat content variability (Desbruyères et al. 2017) and remain unobserved between GO-SHIP decadal surveys. Argo data can quantify much of the thermosteric and halosteric contributions to regional sea level change (Han et al. 2010; Desbruyères et al. 2017), but more measurements of vertical land motion need to be collocated with tide gauge records to provide absolute measures of regional sea level.

Since decadal variations of heat storage seemed to play an important role in the recent hiatus of global surface warming (e.g., Lee et al. 2015), there is a strong need to improve our understanding of the Indian Ocean heat storage via better measurements of the surface (air–sea fluxes), entrance (ITF), and exit (Agulhas and Leeuwin Current) fluxes. Net surface heat fluxes are uncertain over most of the Indian Ocean (Fig. 7) and their trend inconsistent with the large heat content increase in the Indian Ocean (Rao et al. 2012), calling for more direct surface flux measurements, including in the subduction zone of the subtropical gyre. New drifting surface platforms may provide the answer to accessing this remote region, where a RAMA site has proven unsustainable. Long-term measurements of temperature, salinity, and velocity in the Agulhas Current, which acts as an integrator of variability across the entire subtropical gyre, are highly desirable (Beal et al. 2011). These observations would improve ocean state estimates and reanalyses, products that are used to initialize ocean models and form the basis of global energy budget estimates.

Biogeochemical cycles and change. There are no repeated measurements of air–sea flux of CO_2 for the Indian Ocean, and only limited observations of nutrients, bio-optics, and oxygen as part of the IndOOS via GO-SHIP. Not one of the 1,698 stations used to develop the most widely used satellite primary productivity algorithm were located in the Indian Ocean (Behrenfeld and Falkowski 1997). The need to integrate these measurements is important enough to be emphasized independently of the physical drivers and time scales above. Uptake of anthropogenic CO_2 and ocean acidification, combined with growth of OMZs and reductions in primary productivity (Fig. 6c; Roxy et al. 2016; Schmidtko et al. 2017; Gregg and Rousseaux 2019), are already inducing fundamental changes in upper-ocean ecosystems (do Rosário Gomes et al. 2014).

Pilot programs for biogeochemical measurements have been conducted on some IndOOS platforms, for example subsurface fluorescence measurements (Strutton et al. 2015), air–sea CO_2 flux estimates at RAMA moorings, and the highly successful Indian–Australian biogeochemical (BGC)-Argo program in the Arabian Sea (Wojtasiewicz et al. 2020). These pave the way for a full integration of biogeochemical measurements over the next decade. Key regions that call for biogeochemical measurements are the OMZ and highly productive upwelling systems of the Arabian Sea, the Bay of Bengal OMZ, the SCTR and Sumatra–Java upwelling regions, and the subtropical subduction zone of the south Indian Ocean.

IndOOS 2020–30: The way forward

The IndOOS review resulted in 136 actionable recommendations for consolidation and enhancement of the observing system. A full list of the recommendations can be found in the IndOOS-2 road map (Beal et al. 2019). Here we present the most significant tier I and tier II recommendations, with tier II exclusively representing new or enhanced observations (see "The IndOOS review" sidebar for a description of how recommendations were prioritized; Fig. 8).

Above all, it is clear that the essential observing networks of the IndOOS—Argo, RAMA, satellite missions, tide gauges, surface drifters, XBT, and GO-SHIP lines—must be sustained (tier I) to support understanding and prediction of the many important Indian Ocean phenomena described above. The continuation of these networks is also essential for the future detection and attribution of anthropogenic changes in the Indian Ocean. We recommend RAMA be consolidated to a new design, referred to as RAMA-2.0, reducing sites in the original plan for 46 sites to 33 in consideration of fishing vandalism, available ship time, and termination of some national contributions (Fig. 8). Three western equatorial sites along 55°E need to be occupied at highest priority to complete the array.

The tide gauge network will continue to grow in importance as more regional sea level rise estimates are demanded. The network should include more collocated measurements of land movements, particularly at sites where records are longest (Fig. 8), and with more island stations, which are most effective in comparisons with satellite data. Better network and data availability will improve the quality of the sea level reconstruction products, which are used for determining long-term regional sea level changes.

Much of the XBT network has been superseded by Argo; however, an outstanding priority is to maintain IX01 (Fig. 8), from which the variability of geostrophic ITF transport over the upper 700 m can be estimated. To improve these estimates, we recommend installation of automated launchers to increase resolution and data return, denser profiling over the shelf/slope regions, plus more measures of salinity, potentially via a regional enhancement of Argo. In addition, IX21 (Fig. 8) should be enhanced with collection of pCO_2 data and its potential for capturing changes in the Agulhas Current investigated. The surface drifter program should include more barometric pressure observations in cyclogenesis regions for the benefit of weather forecasting. It is a priority to identify national or multinational support for the GO-SHIP occupation of I01E and I01W sections across the Bay of Bengal and Arabian Sea (Fig. 8).

Enhancements of the IndOOS (tier II) are highly desirable to meet growing societal needs for data, as well as for improved forecasting and prediction. Foremost, we recommend development of sustained measurements toward understanding the carbon cycle and ecosystem variability and change in the Indian Ocean. These observations must be made alongside physical measurements:

- A suite of 200 biogeochemical-Argo floats (measuring nutrients, bio-optics, and oxygen in addition to temperature and salinity) in the Indian Ocean, as part of the global biogeochemical-Argo implementation plan. Floats should be targeted to regions with strongest deoxygenation trends, upwelling zones, high primary productivity variability, and regions important for air–sea carbon flux and the marine nitrogen cycle. These include the Arabian Sea, Bay of Bengal, SCTR, and eastern equatorial coastal region.

- Moored autonomous CO_2 partial pressure and biogeochemical measurements at RAMA flux reference sites, targeting regions with high variability in CO_2 fluxes and/or primary productivity, and/or rapidly decreasing pH, with the Arabian Sea and SCTR highest priority.
- Chlorophyll concentration and phytoplankton community structure observations on key GO-SHIP lines and RAMA maintenance voyages to validate ocean color satellite data and track changes in productivity and the biological carbon pump.
- Continuous plankton recorder surveys in key regions using ships of opportunity to measure phytoplankton community composition variability and change.

Key processes of the near-surface ocean, including diurnal mixed layer and barrier layer variability, need to be better measured to meet the need for improved subseasonal forecasting and surface flux products. We recommend

- continuation of the previous pilot experiment (Feng et al. 2020), a new RAMA flux reference site between Australia and Indonesia in the outflow of the ITF (14°S, 115°E), where tropical SST and rainfall intraseasonal variability are highest (Fig. 4), and
- direct turbulent flux measurements and increased vertical resolution of temperature and salinity sensors (ideally at 0.5, 1, 2, 3, 5, 7, and 10 m, and then every 5 m down to 50 m) at RAMA flux reference sites on the equator, in the Arabian Sea, Bay of Bengal, and SCTR.

The IndOOS must be expanded into shelf/slope regions, with an emphasis on the subtropics, where swift boundary currents and their fluxes dominate basinwide heat, freshwater, and nutrient budgets and where coastal upwelling systems influence primary productivity, air–sea fluxes, and climate variability.

- Reestablish an Agulhas Current array at the western boundary near 34°S, collocated with an altimeter ground track and including an "end point" mooring to measure basinwide geostrophic overturning down to ~2,000 m.
- Enhance the Leeuwin Current array to measure full-depth volume, heat, and freshwater fluxes at the eastern boundary, including an "end point" mooring down to ~2,000 m to measure basinwide geostrophic overturning.
- Monitor heat and salinity fluxes, dissolved oxygen, and core nutrients with gliders or autonomous underwater vehicles in the Sumatra–Java upwelling region and South Java Current, the eastern pole of the IOD.
- Monitor heat and salinity fluxes, dissolved oxygen, and core nutrients along the west coast of India where monsoon currents, upwelling, and the Arabian Sea OMZ intersect and societal implications are greatest.

Finally, seasonal to decadal climate forecasts are initialized from ocean data assimilation products that remain almost entirely unconstrained in the deep ocean. We hence recommend that the IndOOS be expanded below 2,000 m, using a suite of Deep-Argo floats, with priority in the southern subtropical Indian Ocean where deep heat content change is largest (Fig. 6b).

In addition to these in situ observing system needs, there are three overarching ingredients necessary for the future success of the IndOOS. First, continuous and overlapping satellite missions provide the only spatially coherent view of the ocean and remain essential, in particular for SST, sea surface height, surface wind, ocean color, sea surface salinity and rainfall. Second, there is an urgent need for improved data assemblage and data assimilation techniques that can provide long, homogeneous, climate-quality data records, in particular to better constrain models and predictions. Finally, and perhaps most importantly, there is a necessity for increased engagement and partnerships among Indian Ocean rim countries.

Expansion of the IndOOS into coastal regions will require new commitments from, and provide opportunities for, Indian Ocean rim countries and agencies to expand their ocean observing capabilities in collaboration with the IndOOS community. Open access to exclusive economic zones, resource sharing, and capacity building between nations are essential in this, as are commitments to observing best practices, and to data sharing and dissemination, as formalized under the Framework for Ocean Observing and the Global Ocean Observing System (www.goosocean.org).

For IndOOS, improved collaboration and coordination among its regional advisory, implementation, and funding bodies are also essential, as well as stronger institutional and programmatic financial support. In particular, we look to the IndOOS Resource Forum (IRF), an international group of leaders from governments and institutions, to raise and coordinate support and resources that can address the IndOOS-2 recommendations. The United Nations has proclaimed 2021–30 as the Decade of Ocean Science for Sustainable Development (www.oceandecade.org). IndOOS-2 recommendations are in line with the UN Decade program, and we strongly feel that implementing them is crucial for accomplishing its key societal outcomes.

Flat or declining levels of national funding pose a serious threat to sustained ocean observations in the Indian Ocean and elsewhere. Ongoing commitment to the organization and governance of GOOS and IndOOS by the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the World Meteorological Organization (WMO), and the International Science Council (ISC) through their support of the World Climate Research Program (WCRP) is essential. Most important, improvements and enhancements to the system will require increased participation by countries and institutions willing to provide resources.

Dedication to Gary Meyers

This article is dedicated to Gary Meyers (1941–2016), a visionary and leader of ocean observing systems (Fig. SB2). He was the founding chair of the CLIVAR/IOC-GOOS Indian Ocean Region Panel, leading the initial design and development of a sustainable observing system for the Indian Ocean and effectuating the birth of IndOOS. Gary was an eminent oceanographer who received many awards, including the 2006 Australian Meteorological and Oceanographic Society Medal for Leadership in Meteorology and Oceanography. The Indian Ocean scientific community will miss his warm personality, deep scientific knowledge, and inspiring leadership.

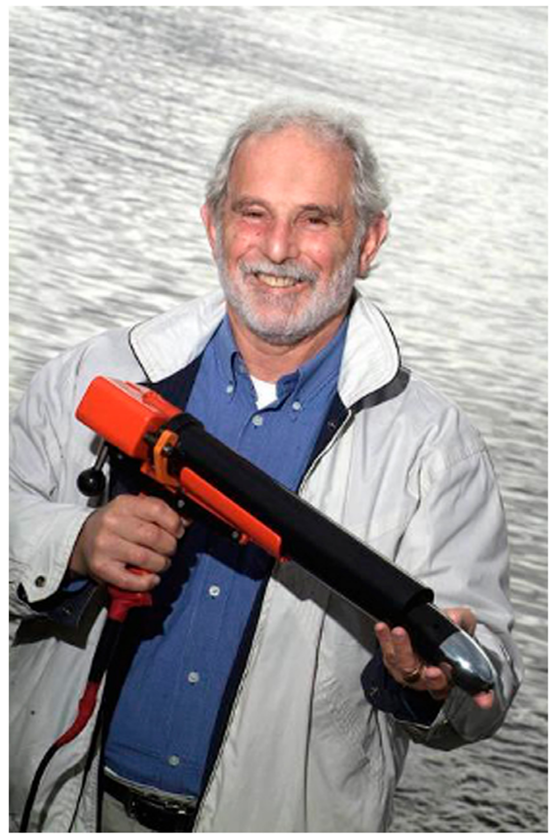

Fig. SB2. The late Gary Meyers, former cochair of the Indian Ocean Region Panel, and one of the promoters of the IndOOS observing system.

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