Technological Advancements in Observing the Upper Ocean in the Bay of Bengal:

Education and Capacity Building

By Amit Tandon, Eric A. D'Asaro, Kathleen M. Stafford, Debasis Sengupta, M. Ravichandran, Mark Baumgartner, R. Venkatesan, and Theresa Paluszkiewicz

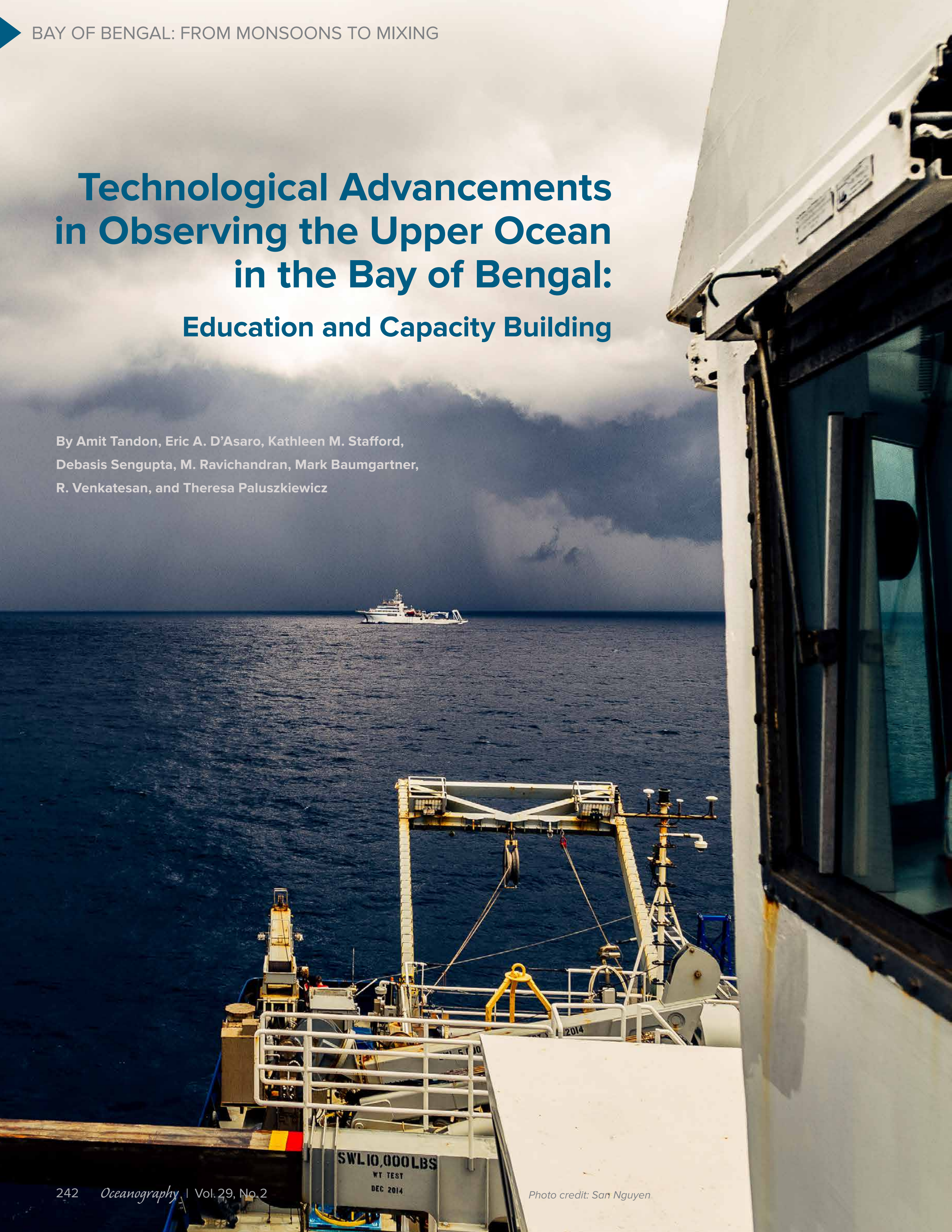


Photo credit: San Nguyen

> We hope that the examples of successful capacity building initiatives described in this article will help other international oceanographic collaborations. Long-lasting collaborations and friendships that transcend national boundaries have been built by ASIRI-OMM largely due to the program's capacity building and training.

ABSTRACT. Because the monsoon strongly affects India, there is a clear need for indigenous expertise in advancing the science that underlies monsoon prediction. The safety of marine transport in the tropics relies on accurate atmospheric and ocean environment predictions on weekly and longer time scales in the Indian Ocean. This need to better forecast the monsoon motivates the United States to advance basic research and support training of early career US scientists in tropical oceanography. Earlier Indian field campaigns and modeling studies indicated that an improved understanding of the interactions between the upper ocean and the atmosphere in the Bay of Bengal at finer spatial and temporal scales could lead to improved intraseasonal monsoon forecasts. The joint US Air-Sea Interactions Regional Initiative (ASIRI) and the Indian Ocean Mixing and Monsoon (OMM) program studied these interactions, resulting in scientific advances described by articles in this special issue of *Oceanography*. In addition to these scientific advances, and while also developing long-lasting collaborations and building indigenous Indian capability, a key component of these programs is training early career scientists from India and the United States. Training has been focusing on fine-scale and mixing studies of the upper ocean, air-sea interactions, and marine mammal research. Advanced methods in instrumentation, autonomous robotic platforms, experimental design, data analysis, and modeling have been emphasized. Students and scientists from India and the United States at all levels have been participating in joint cruises on Indian and US research vessels and in training participants in modern tools and methods at summer schools, at focused research workshops, and during research visits. Such activities are building new indigenous capability in India, training a new cadre of US scientists well versed in monsoon air-sea interaction, and forging strong links between Indian and US oceanographic institutions.

INDIAN OCEANOGRAPHIC CAPABILITY

In India, teaching and research in oceanography began at Andhra University, Waltair, shortly after independence in 1947, followed by establishment of other university departments. In recent decades, India has made impressive strides in all areas of oceanography. The National Institute of Oceanography (NIO), Goa, was established in 1973; the National Institute of Ocean Technology (NIOT), Chennai, and the Indian National Centre for Ocean Information Science (INCOIS), Hyderabad, were set up in 1992 and 1999, respectively, by the Department of Ocean Development (now the Ministry of Earth Sciences, or MoES). These institutes have contributed to the development of basic scientific knowledge of the Indian Ocean (e.g., Jayaraman, 2007), as well as to applied ocean science and technology that have direct social impact. For example, NIOT operates a regional oceanographic buoy network consisting of moored buoys at a dozen locations in the northern Indian Ocean (Venkatesan et al., 2013). INCOIS is a major partner in the international collaboration in maintaining the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA; McPhaden et al., 2009) and the Indian Ocean Argo float network (Riser et al., 2016). INCOIS also partners with the Indian Institute of Tropical Meteorology (IITM), Pune, and the India Meteorology Department (IMD), Delhi, in forecasting severe weather and monsoon variability using coupled models. NIO leads national efforts in coastal oceanography (Chaitanya et al., 2014; Mukherjee et al., 2014), equatorial current measurements (Sengupta et al., 2004; Murty et al., 2006), long-term expendable bathythermograph (XBT) lines, and continuing ship-based sections using traditional conductivity-temperature-depth (CTD) casts at O(50–100) km spacing (Murty et al., 1992; Shetye et al., 1996; Gangopadhyay et al., 2013).

THE NEED FOR ADVANCED CAPABILITIES

The response of the upper ocean to surface fluxes, as well as the fluxes themselves, are shaped by the unique thermodynamic structure of the Bay of Bengal, with a shallow fresh layer above a deep subsurface warm layer (Sengupta et al., 2004; Mahadevan et al., 2016, in this issue). Earlier ocean measurements (Harenduprakash and Mitra, 1988; Sanilkumar et al., 1994; Bhat et al., 2001; Rao and Sikka, 2005) and models typically resolved the ocean at horizontal scales of roughly 10 km or larger, and vertical scales of 10 m or larger. Recent assimilation of data from moorings, CTDs, and Argo floats into numerical ocean models (see Chowdary et al., 2016, in this issue) points to an urgent need for measurements and an understanding at higher vertical and horizontal resolutions as well as to a focus on the near-surface ocean. Recent studies using both forced ocean models and coupled models suggest that ocean physics on subgrid scales is critically important for realistic simulations and forecasts. In particular, operational models have serious deficiencies in simulating the shallow, fresh layer in the Bay of Bengal. The model ocean mixed layer is too deep (Ravichandran et al., 2013; Fousiya et al., 2015). Examination of the existing data sets and field measurements indicates that neither upper-ocean physical processes nor the details of momentum, heat, and freshwater exchange across the air-sea interface are adequately resolved. Resulting errors in sea surface temperature (SST) and thus air-sea fluxes appear to limit the ability to realistically forecast intraseasonal variations in the monsoon.

Observations from moorings, floats, and satellites suggest significant variability on 1–10 km spatial scales, which have not been accessible by traditional observing methods. Study of near-surface physical processes at these scales requires new tools. Therefore, training and capacity building in fine-scale ocean observations and flux measurements is necessary. Such training has been an important component of the collaboration between the Ocean Mixing and Monsoon program (OMM), funded by the Monsoon Mission of the Indian Ministry of Earth Sciences, and the Air-Sea Interactions Regional Initiative (ASIRI), funded by the US Office of Naval Research. About 20 Indian and US institutions and national laboratories are involved in this collaborative effort. This alliance has led to training in higher-resolution horizontal and vertical measurements using underway CTDs (uCTDs), Lagrangian and EM-APEX floats, Seagliders, acoustic Doppler current profilers (ADCPs), and near-real-time oceanography based on adaptive cruise planning and new and emergent dynamical ideas, as well as in the techniques and analysis of air-sea flux measurements from ships and buoys.

A variety of additional educational and training initiatives are also being carried out as part of the ASIRI-OMM collaboration. Training activities at US and Indian institutions during assembly and testing of sensors before and after research cruises are an integral part of this collaboration. Educational activities include summer workshops and training schools as well as onboard training on both US and Indian research vessels during cruises in the Bay of Bengal. Some of this training is individual-to-individual by design, and some includes a large number of participants. In addition, virtual online meetings as well as a number of visits of Indian scientists to US institutions and US scientists to Indian institutions has helped achieve the education and capacity-building goals. The outreach component of this collaboration has included more than 100 participants.

> “Working together on research cruises has played an important role—not only has it promoted detailed discussion on observing techniques and science but it has also fostered mutual understanding and friendship between personnel from different Indian and US institutions.”

Upper-Ocean Physics Workshop at the Indian Institute of Science, Bangalore (July 2014)

Authors Sengupta and Tandon organized a two-week workshop in July 2014 at the Center for Atmospheric and Oceanic Studies, Indian Institute of Science (IISc), Bangalore. The theme of the workshop was upper-ocean physics with applications to the Bay of Bengal. Eighteen early career scientists attended (Figure 1), including four women from seven Indian institutions: IISc (host institution); INCOIS, Hyderabad; NIO, Vishakhapatnam; NIOT, Chennai; Indian Institute of Technology (IIT), Madras, Chennai; Space Application Centre, Ahmedabad (ISRO/SAC); and Tata Institute for Fundamental Research (TIFR), Hyderabad. Though all attendees had master’s degrees or more advanced degrees in physics, biology, or mathematics, their backgrounds and exposure to oceanography were quite varied depending on the missions of their home institutions. The content of the lectures thus progressed from very introductory to the latest observational and modeling studies in physical oceanography.

The workshop featured about 20 lectures of 1.5 hours each by four US scientists. The first week featured an introduction to ocean turbulence and ocean observations by Karan Venagayamoorthy (Colorado State University) and Lou St. Laurent (Woods Hole Oceanographic Institution). The second week featured

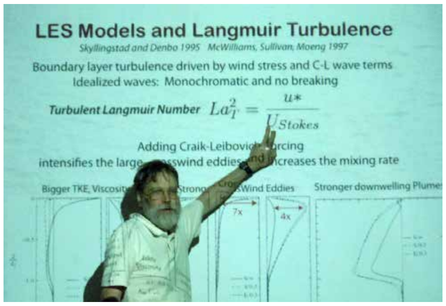


FIGURE 1. The upper-ocean physics workshop at the Indian Institute of Science, Bangalore, featured lectures (upper left), demonstrations (lower left), and short group projects. Participants and instructors are shown in the photo on the right.

lectures on upper-ocean processes and their observations by author D'Asaro (University of Washington) and modeling by author Tandon (UMass Dartmouth). In addition, G.S. Bhat (IISc Bangalore) presented a lecture on surface fluxes, and R. Venkatesan (NIOT Chennai) discussed observations in the Indian Ocean. Mornings were devoted to lectures and discussion specific to lectures while afternoons and evenings featured demonstrations and team meetings to make progress on projects. Five oceanographically relevant demonstrations were conducted in the afternoons using a compact, portable "weather in a tank" setup provided by author Tandon (courtesy of John Marshall of the Massachusetts Institute of Technology; http://paoc.mit.edu/labguide/projects.html), which reinforced the concepts learned in morning lectures.

Workshop attendees were divided into four teams that each included participants from different institutions. Each team, named after a river terminating in the Bay of Bengal, was assigned to work on a project that involved using an upper-ocean data set, a flux data set, or modeling. The projects focused on the following topics: one-dimensional estuarine modeling (guide: K. Venagayamoorthy), North Atlantic Tracer Experiment upper-ocean dissipation data (guides: Lou St. Laurent and Eric D'Asaro), Tropical Rainfall Measuring Mission data analysis (guide: V. Venugopal from IISc), and Exploring Arabian Sea data set using one-dimensional modeling (guide: Amit Tandon). The students worked on their projects into the evenings and over the weekends, with several groups reporting that they worked on their projects overnight as the presentation day grew closer. The groups reported on their projects on the last day of the workshop, with all students participating in the presentations.

Anonymous written feedback was collected after the workshop. The attendees were asked which components of the workshop appealed to them and which aspects they would like to see retained or changed in the future. They were asked about the balance between the time spent on content of the workshop, including demonstrations and the time needed for the projects. The anonymous survey elicited unanimously positive responses on the demonstrations and the teaching. Both introductory and advanced topical lectures were highly appreciated by the students. They commented on the enthusiasm of the teachers and the active learning with demonstrations, and they appreciated the effort put in by the teachers in making difficult topics accessible. The surveys suggested that two hour-long lectures per day with the rest of the time devoted to demonstrations, discussions, and projects would work best for future workshops. Topics for future workshops suggested by attendees included glider training and training related to air-sea flux moorings, internal waves, and geophysical fluid dynamics, and there was a demand for more lectures on upper-ocean processes. Additionally, a book on real-time observations in the ocean is planned with US and Indian authors from more than 15 institutions.

Training Activities

Training on US Ships

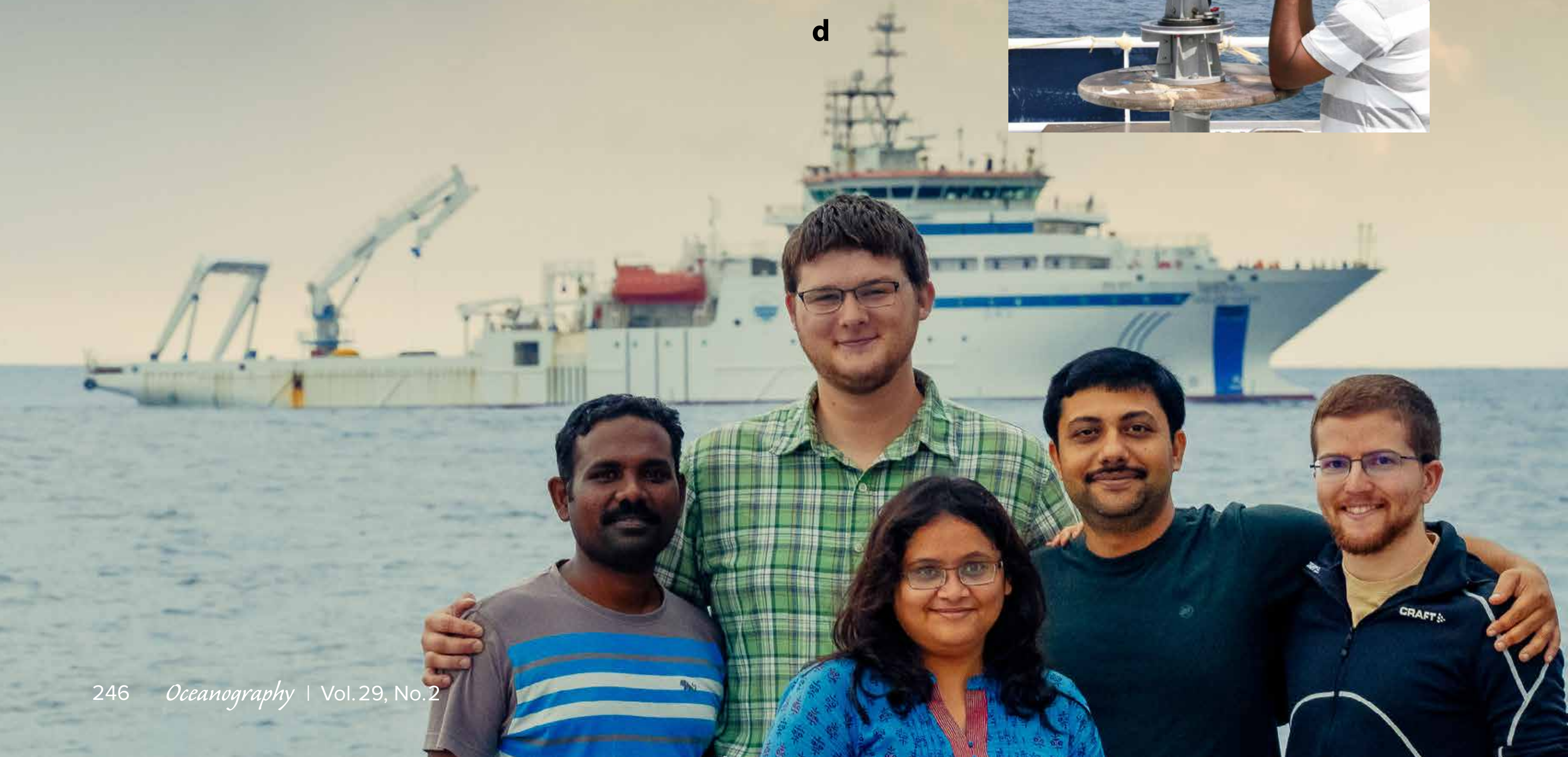
Indian, Sri Lankan (see Box 1), and US students and junior scientists participated in all three R/V *Roger Revelle* cruises (Figure 2) in the Bay of Bengal in 2013, 2014, and in 2015. On these cruises, participants from India included early career scientists from NIOT; INCOIS; NIO; ISRO/SAC; TIFR; National Centre for Biological Sciences, Bangalore; and the National Centre for Antarctic and Ocean Research (NCOAR), Goa. During the cruises, the Indian participants were trained to deploy and analyze a wide variety of both commercially available and specialized (noncommercial) research instruments, including standard shipboard CTD and ADCP systems, and the high-resolution underway CTD and microstructure systems, as well as to deploy and recover specialized autonomous Wirewalker, glider, SOLO float, and boat systems.

An intensive water sampling, filtration, and analysis campaign was incorporated into all cruises over the three years. Researchers from India supported collection of water samples to measure nutrients, high-performance liquid chromatography (HPLC) pigments, particulate organic carbon (POC), dissolved organic carbon (DOC), colored dissolved organic matter (CDOM), dissolved inorganic carbon (DIC), pH, alkalinity, and phytoplankton taxa, and they provided cross calibration for flow-through nitrate, oxygen, and chlorophyll sensors. The cruises led to a joint effort to describe the large-scale biogeochemical distributions within the Bay of Bengal (Sarma et al., 2016, in this issue). There was also onboard training for marine mammal observers (see later section). Each cruise also featured evening lectures, presentations, and scientific discussions led by Indian, Sri Lankan, and US members of the science party. All early career scientists on the cruises were encouraged to begin plotting, analyzing, and discussing the available data streams.

Ongoing Training

A key aspect of modern oceanographic research is the close coupling of fieldwork, data processing, data analysis, and scientific synthesis. Training in this synergy has been mostly through one-on-one

FIGURE 2. (a–c) Scientists from multiple countries aboard US R/V *Roger Revelle*. (d) Early career scientists from Indian and US institutions on the *Revelle* deck with Indian ORV *Sagar Nidhi* in the background. (e) Marine mammal operations.



Box 1. Training and Capacity Building with Sri Lankan Scientists

By Hemantha W. Wijesekera and Harindra J.S. Fernando

The ASIRI-Effects of Bay of Bengal Freshwater Flux on Indian Ocean Monsoon (EBOB) project had a dedicated training and capacity-building component. As part of the training, US scientists taught courses in physical oceanography at the National Aquatic Resources Research and Development Agency (NARA) in Sri Lanka, and NARA scientists visited the United States. The Partnership for Observing the Global Oceans (POGO) supported part of this activity through scholarships. Capacity building included conducting training courses in instrument deployment, maintenance, and retrieval and in data processing for a group of students from NARA, the Colombo Meteorological Department, and the University of Ruhuna (Figure B1a,b). A large number of Sri Lankan university faculty members, government scientists, undergraduates, and high school students visited R/V *Roger Revelle* during its port calls to Colombo (Figure B1c). Tens of Sri Lankan scientists participated in *Revelle* cruises, jointly deployed instruments, and collaborated on data analysis. Periodic cruises were conducted by NARA using R/V *Samuddrika* (Figure B1d) for coastal measurements. During these cruises, Sri Lankan scientists gained experience in deploying shallow moorings and gliders. A set of new instruments was donated through ASIRI to improve NARA's measurement and scientific capabilities, and especially to equip R/V *Samuddrika* with sensors that could record advanced air-sea measurements. A number of young Sri Lankan scientists are involved in research under the supervision of US scientists, and some have used their research for preparing PhD and MS theses. An undergraduate from the United States visited Sri Lanka for the summer and worked under the mentorship of senior NARA scientists, helping to process data and to set up an around-the-clock Ocean Observation and Early Response Center.

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FIGURE B1. Training sessions for (a) radiosonde launching and (b) data processing were conducted at the Colombo Meteorological Department. (c) Elementary school children visiting R/V *Revelle* and (d) small boat operations/training took place in July 2014 off Sri Lanka.

interactions between US principal investigators and Indian graduate students. For example, Craig Lee (University of Washington) and author D'Asaro visited NIOT, INCOIS, IISc Bangalore, and IIT Madras to deliver lectures and work with local scientists; D'Asaro similarly visited ISRO/SAC in December 2014. Jennifer Mackinnon (Scripps Institution of Oceanography), Jonathan Nash (Oregon State University), and Andrew Lucas (Scripps Institution of Oceanography) visited IISc Bangalore to work with students on data processing and analysis. Five joint cruise planning and data analysis meetings of the ASIRI-OMM team, alternating between US and Indian locations, allowed similar training and exchange of ideas.

The skills addressed in this training are diverse and have been accumulated through the wisdom of community best practices. Examples include identifying the spectral noise levels of particular instruments, matching temperature and conductivity signals to minimize salinity spiking, and making subtle corrections for lateral displacements between ship-mounted ADCPs and GPS/heading sensors to account for differential rotation ship rates, especially for the nonstandard ADCP configurations (e.g., deployments in the well or in hull, or on over-boarding poles on the side of ship) on some of the cruises. These skills include both instrument engineering and subsequent data processing, which are more effectively conveyed by working closely with individuals than through reading documentation. The process of modifying existing codes and algorithms to work for a particular situation teaches the type of flexibility and innovation that leads to robust scientific capacity.

Shipboard Training on Indian Ships

Four OMM cruises of the Ministry of Earth Sciences ORV *Sagar Nidhi* and one cruise on ORV *Sagar Kanya* provided additional training. Personnel from the Woods Hole Oceanographic Institution (WHOI), including Jeff Lord and Emerson Hasbrouck, participated in the WHOI mooring deployment and recovery cruises on *Sagar Nidhi* in December 2014 and on *Sagar Kanya* in January 2016. Engineers and technicians from the Ocean Observations group at NIOT Chennai, led by Arul Muthiah, and supported by S. Ramasundaram and P. Murugesh, worked with the WHOI personnel to assemble and test the mooring instruments at the NIOT facilities prior to the cruise.

Eric D'Asaro and Michael Ohmart, both from the University of Washington, participated in *Sagar Nidhi* cruises during November 2013 and August/September 2014 and 2015. The work focused on the operation and use of measurement systems as well as onboard lectures, individual instruction, and educational activities built into the scientific sampling. The overall goal was to build a core group of young Indian scientists and technicians capable of using modern physical oceanographic equipment to address current oceanographic problems. Sensors, measurement methods, and scientific analysis were all emphasized, as it is their confluence that leads to the most productive and innovative experimental science.

Instrumentation training focused on combining two systems capable of measuring temperature, salinity, and velocity, the most important quantities for understanding ocean circulation. One system, the Oceanscience uCTD, profiles temperature, salinity, and pressure from a vessel underway, at 4–5 kts for *Sagar Nidhi*, to achieve high spatial resolution. It is deployed off the stern of the ship with a small, manually operated winch system. Profiles are made every few minutes continuously for many days using a sensor that can be easily damaged if it hits the side of the ship. Furthermore, the winch system can overheat, and it needs maintenance and repair. These difficulties provided excellent opportunities for training. During the first cruise, US technician Michael Ohmart installed the uCTD and provided instruction on its use. When it needed repairs, the Indian scientists and technicians learned to diagnose the problems with coaching by Ohmart. By the second cruise, all installation and operation, and some repair, was done by early career Indian scientists; by the third *Sagar Nidhi* cruise, the entire operation was conducted by Indian shipboard participants. The uCTD requires a team of at least three to operate; continuous operations thus involved up to a dozen personnel, provided excellent opportunities to include students at many skill levels, and clearly promoted team building. Nearly 4,000 uCTD profiles taken on the Indian cruises comprise a major component of the ASIRI-OMM data set. Not a single probe was damaged during the cruises.

The second system, the RD Instruments ADCP, measures velocity from a set of acoustic transducers mounted on the ship. Navigational and orientation information are necessary to convert these data to Earth coordinates. Indian oceanographers had little prior experience with ship-mounted ADCPs before ASIRI-OMM (*Sagar Nidhi*'s 75 kHz ADCP was not operational when this program began). During the first cruise, a side-pole-mounted system was installed, but it was not sufficiently rigid. Furthermore, it was difficult to merge navigational and orientation information into the ADCP data stream. Most of the effort during this cruise was spent diagnosing these problems and attempting solutions, a joint effort between Eric D'Asaro and S. Shivaprasad of INCOIS, the chief Indian contact for the ADCP work. As a result, on the second cruise, S. Shivaprasad installed a quality pole-mounted ADCP system and a GPS-based attitude system. By the third cruise, *Sagar Nidhi*'s ADCP was replaced with an operating 300 kHz system, which was supplemented by a 500 kHz pole-mounted system. Of equal importance, Dipanjan Chaudhuri, an Indian Institute of Science graduate student, wrote software that duplicated the manufacturer's processing software. Thus, indigenous expertise in both the installation and processing of ADCP measurements was developed.

The small-scale salinity fronts and

eddies of primary interest to ASIRI-OMM are spatially localized and change with time. A flexible sampling strategy that uses information merged from multiple ships, satellites, and models is far more effective here than employing a predetermined, fixed sampling strategy. In particular, maps of surface salinity from the Aquarius satellite combined with maps of ocean eddies from satellite altimetry provided by the Space Applications Centre of the Indian Space Research Organization were effective in directing shipboard sampling toward regions of low-salinity riverine water. Reliable Internet communication was essential for such a strategy. During the first cruise, a slow Internet connection was available only on the ship's bridge with the captain's permission. Improved transfer speeds and access were made available on the second and third cruises.

The practical sampling instructions were supplemented by evening lectures on *Sagar Nidhi* by both US and Indian scientists and students. The talks covered both background scientific topics, recent findings on the cruise, and plans for the next day's work.

The success of both of these indigenous technological improvements and the increasing scientific experience of the Indian team became clear during the third ASIRI-OMM cruise. ORV *Sagar Nidhi* and R/V *Roger Revelle* worked together (Figure 3) to sample an evolving salinity front, first on a regular grid involving both ships and then in an adaptive pattern following a drifting surface buoy tagging the front. On *Sagar Nidhi*, the adaptive sampling was conducted entirely by the Indian team, with continuous uCTD measurements used to create evolving maps of the density structure that were then used to direct the ship track to resample the front. A Lagrangian float was deployed from *Sagar Nidhi* within a cluster of surface drifters deployed from *Revelle*. The combined efforts of the two ships and autonomous instrumentation deployed from them enabled production of detailed maps of the temperature, salinity, and density structure of the frontal region along with air-sea fluxes and oceanic mixing rates.

Glider Training

Modern physical oceanography increasingly relies on autonomous (i.e., robotic) vehicles to sample the ocean continuously, remotely, and without requiring the presence of a research vessel. Development of an indigenous capability for using this technology (Figure 4) is an important goal of ASIRI-OMM, with a special emphasis on using the Seaglider, developed and operated by the Applied Physics Laboratory of the University of Washington (APL/UW) and commercially available from Kongsberg Marine. The Seaglider typically dives to 1,000 m while traveling horizontally about 5 km

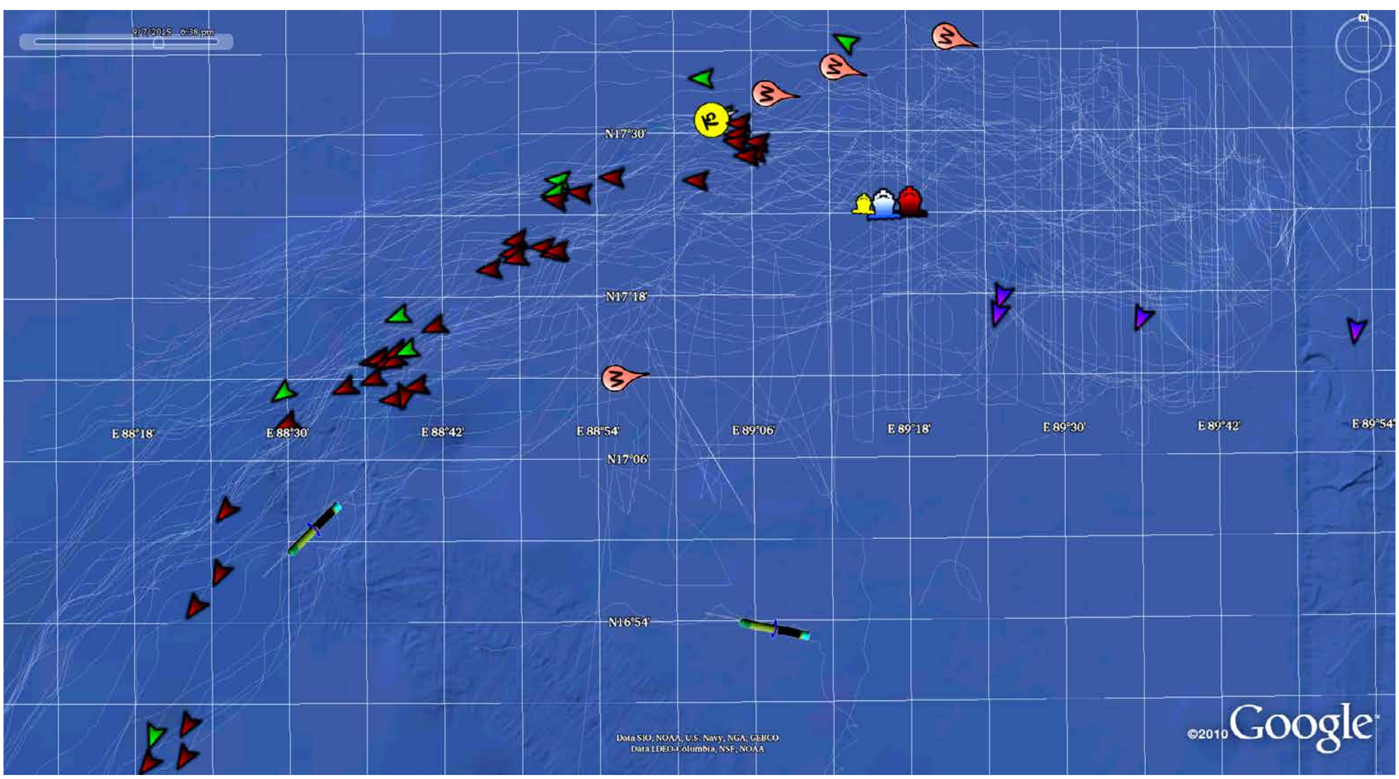

FIGURE 3. A snapshot of ship positions and the assets deployed from them during the ASIRI-OMM collaborative cruise, August–September 2015. The ship icons show ORV *Sagar Nidhi* (red), R/V *Roger Revelle* (blue), and the Robotic Oceanographic Surface Sampler (ROSS; small yellow symbol) during a frontal mapping experiment. The Wirewalker instruments are denoted by Ws, and SOLO floats appear as elongated float icons. Lagrangian float 75 is the yellow circle marked 75. Red arrows mark the drifters that measure near surface salinity and temperature, green arrows denote temperature drifters, and purple arrows indicate wave drifters. The faint white threads mark the tracked positions of all assets. *Figure courtesy of Jared Buckley*

per dive. It can thus be steered along a section, or maintained at a fixed location for up to about six months. A team of three scientists from INCOIS, M.S. Girishkumar, S. Shivaprasad, and V.P. Thangaprakash traveled to Seattle, Washington, in June 2015 for training, first at Kongsberg and then at APL/UW. Benjamin Jokinen of APL/UW visited Chennai for a week before the cruise and trained several IISc and INCOIS personnel on preparing and testing the Seaglider. The team deployed a Seaglider from *Sagar Nidhi* on September 2, 2015, and operated near the Bay of Bengal WHOI mooring in a butterfly pattern (Figure 5) until it was recovered by an Indian research vessel in January 2016. These operations were conducted almost entirely by the Indian team and demonstrate the development of an indigenous Indian glider operational capability.

Training of Early Career US Scientists

Many formal and informal discussions and workshops, starting with the November 2011 workshop at WHOI and followed by other meetings, have helped define/formulate open science questions in diverse areas such as basin-scale circulation of the Bay of Bengal, upper-ocean dynamics and mesoscale eddies, dispersion of river water, near-surface and subsurface stratification and mixing, surface air-sea fluxes, and the interaction of the Bay of Bengal with tropical cyclones and the monsoon. Graduate students and early career scientists from various US institutions have been exposed to many different topics that encompass the ASIRI-OMM collaboration, and are now collaborating actively with early career and senior Indian scientists. Working together on research cruises has played an important role—not only has it promoted detailed discussion on observing techniques and science but it has also fostered mutual understanding and friendship between personnel from different Indian and US institutions.

We mention several early career scientists from US institutions and the research areas/specific science questions that they are currently working on. Graduate student Jared Buckley (UMass Dartmouth) is analyzing air-sea fluxes from ships, moorings, and reanalyses, and is studying the effects of cold pool events (abrupt cooling of air accompanying monsoon rainfall) on turbulent heat fluxes in the Bay of Bengal. Mara Freilich (MIT/WHOI Joint Program in Oceanography) is working on inferring mixing from a combination of ship-based measurements in the Bay of Bengal and remote sensing. Gualtiero Spiro Jaeger (MIT/WHOI) is studying water mass evolution, including mixing of seawater and freshwater in the river-dominated Bay of Bengal, from ASIRI-OMM data sets and satellite observations. Sebastian Essink (MIT/WHOI) is studying dispersion of freshwater from ASIRI drifter data sets. Among early career scientists, Hieu Pham (University of California, San Diego [UCSD]) is studying the fine-scale processes of mixing and frontal instabilities in the highly stratified environment of the Bay of Bengal through large eddy simulations. Sanjiv Ramachandran (UMass Dartmouth) is analyzing instability mechanisms from the ASIRI-OMM observational process

FIGURE 4. US and Indian scientists on board ORV *Sagar Nidhi* with two modern autonomous instruments, the Indian Seaglider (left) and a Lagrangian float.

experiments with the help of submesoscale simulations. Sally Warner and Johannes Becherer (both at Oregon State University) are analyzing near-surface and subsurface turbulent mixing in the Bay of Bengal with the help of fine-scale temperature variance observations from χpods mounted on moorings and profiling instruments. Amy Waterhouse (Scripps Institution of Oceanography, UCSD) is examining enhanced mixing and near-inertial wave response from shipboard and mooring data during and after Cyclone Madi. Mathew Spydell (Scripps Institution of Oceanography, UCSD) is analyzing ADCP data from ships and wave-powered profiling instruments obtained during multiple cruises. Sean Haney (Scripps Institution of Oceanography, UCSD) plans to conduct stability analyses inspired by the Bay of Bengal data sets. Caitlin Cullen (University of Washington) is examining various ASIRI data sets. A heartening development is that early career scientists from the United States and India are working together on some of these projects, and a number of other specific collaborations are being planned.

Hosting of Junior Scientists at US Institutions

Training of Indian scientists in data analysis using ASIRI-OMM data has included extended visits at US universities. B. Praveen Kumar (INCOIS, Hydrabad) spent a month at APL/UW in Seattle during November/December 2015 to continue joint work with author D'Asaro on the analysis of Lagrangian float data from the 2015 cruise. Indian PhD student Sreelekha Jarugula (IISc Bangalore) visited UMass Dartmouth in May 2015, and Jarugula and another PhD student, Dipanjan Chaudhuri (IISc Bangalore), went to WHOI and UMass Dartmouth in March 2016 for a weeklong visit. Indian PhD student Ritabrata Thakur (TIFR Hydrabad) visited Oregon State University, and Chaudhuri and Jarugula visited Scripps Institution of Oceanography in May 2016. Further, a joint USA-India data analysis workshop was conducted at Oregon State University in May 2016.

Training for Marine Mammal Surveying

During late November and early December 2013, a cetacean sighting survey was conducted aboard the *Revelle* as part of the ASIRI-OMM pilot cruise. Employing standard marine mammal

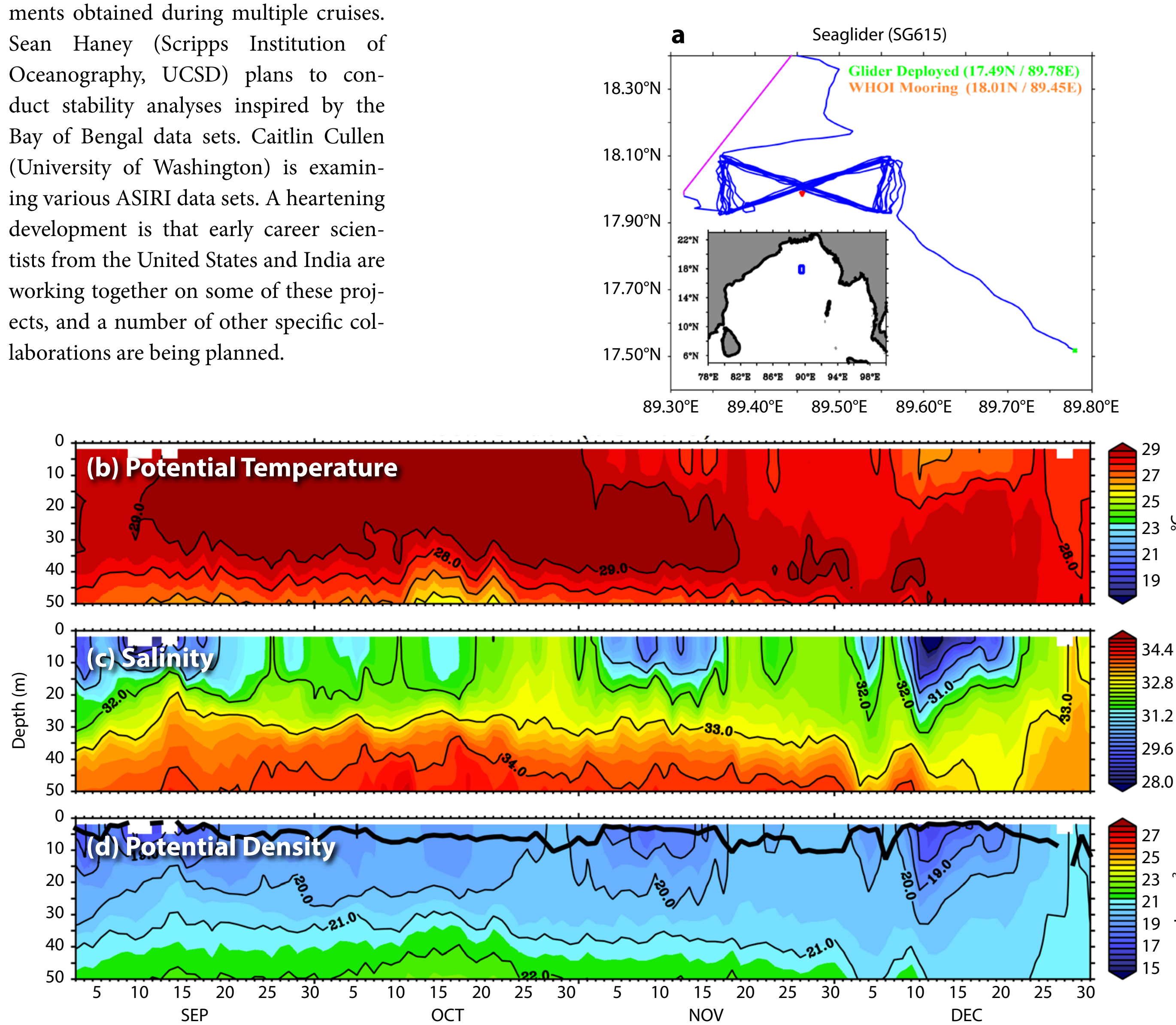

FIGURE 5. Results from the first Indian Seaglider (SG615) deployment during ASIRI-OMM. (a) Glider track and (b–d) temporal evolution of potential temperature, salinity, and potential density. *Figure courtesy of V.P. Thangaprakash, INCOIS*

survey methodology, an international team of eight observers collected visual observations using 25 × 150 mounted "big-eye" binoculars, 7 × 50 handheld binoculars, and the naked eye. The sighting team consisted of two expert observers (independent contractors Suzanne Yin, USA, and Ernesto Vázquez, Mexico), two very experienced observers (authors Stafford and Baumgartner), and four novices (Ajith Kumar and Divya Panicker, both from the National Centre for Biological Sciences, Bangalore, India, and Upul Liyange and Ishara Rathnasuriya, both from the National Aquatic Resources Research and Development Agency in Sri Lanka). The expert and experienced observers provided extensive training to novice observers in survey methodology, the use of both the big-eye binoculars and survey software, and species identification while actively surveying and also during regular evening meetings throughout the cruise. Evening training sessions included review of survey methodology, simulations of sighting events, and subsequent data entry using role-playing and group discussions, discussion of diagnostic features for identifying tropical cetaceans, review of each day's sightings and observer issues, and a species identification quiz. For daily homework during the cruise, participants completed detailed reports of survey methodology and numerous species sketches (Figure 6). During December 2014, Stafford and Baumgartner traveled to India to teach a short course on bioacoustics at the Indian National Centre for Biological Sciences (NCBS) in Bangalore. The three-day short course was attended by over 20 students and postdocs of the NCBS Program in Wildlife Biology and Conservation (Figure 6). One of the student participants in the *Revelle* cruise, Divya Panicker, traveled to WHOI in both 2014 and 2015 for eight-week internships to learn additional methods for marine mammal research. She worked both in the lab and on a marine mammal cruise to obtain additional training in passive acoustic analysis, oceanographic sampling, zooplankton sampling, sighting surveys, and the operation of autonomous ocean gliders.

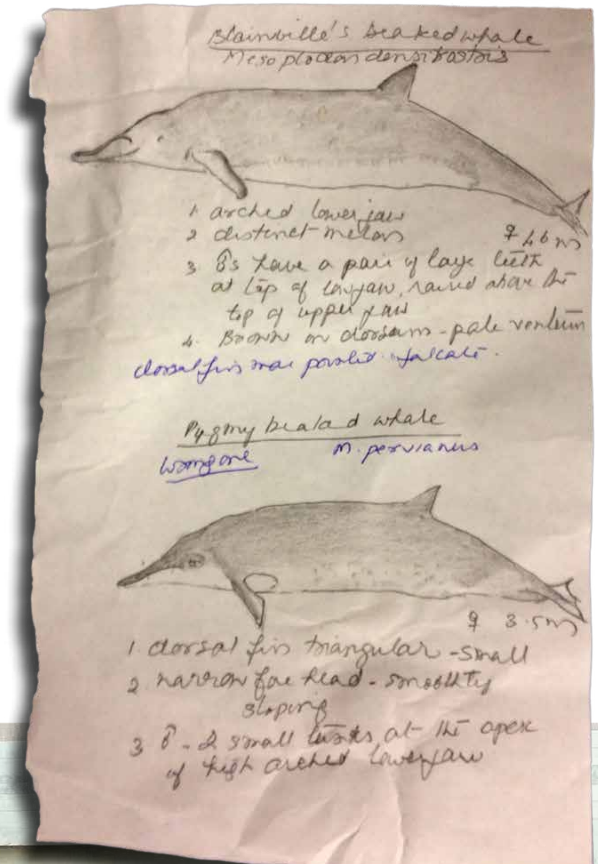

FIGURE 6. (left) Example of species identification homework (sketch by Ajith Kumar). (below) Participants in a bioacoustics short course taught by Kathleen Stafford (far right) and Mark Baumgartner (sixth from left) at the Indian National Centre for Biological Sciences, December 10–12, 2014.

SUMMARY AND LESSONS LEARNED

The success of these training and capacity building programs resulted from a commitment by US and Indian scientists to the effort and the understanding on both sides that progress on the scientific problems was strongly connected to the success of the educational efforts. The initial demonstration of this commitment was an important component in overcoming bureaucratic problems on both sides. The high level of education and strong existing oceanographic expertise in India was also critical in allowing the incremental training from US investigators to have a significant impact. Most important to our success was the enthusiasm and eagerness to learn shown by the early career Indian and US scientists.

The main success of these efforts has been to improve indigenous measurement capability at a technical level. Indian scientists now make measurements that were not possible before the ASIRI-OMM collaboration. Continuing efforts will focus on data analysis, publication, and most critically, the development of indigenous scientific programs using these new measurement skills to address current problems in oceanography, particularly those relevant to India.

For many young scientists from India and the United States, this collaboration provided their first exposure to tropical oceanography and monsoon research. We hope that the examples of successful capacity building initiatives described in this article will help other international oceanographic collaborations. Long-lasting collaborations and friendships that transcend national boundaries have been built by ASIRI-OMM largely due to the program's capacity building and training.

This special issue of *Oceanography* demonstrates that scientific progress has resulted from collaborations by these international teams, and almost every article in this issue has authors from multiple countries. We hope that future efforts will incorporate the knowledge presented in all the fine- to large-scale observations and models into predictive monsoon models.

REFERENCES

Bhat, G.S., S. Gadgil, P.V. Hareesh Kumar, S.R. Kalsi, P. Madhusoodanan, V.S.N. Murty, C.V.K. Prasada Rao, V. Ramesh Babu, L.V.G. Rao, R.R. Rao, and others. 2001. BOBMEX: The Bay of Bengal monsoon experiment. *Bulletin of the American Meteorological Society* 82:2,217–2,244, http://dx.doi.org/10.1175/1520-0477(2001)082<2217:BTBOBM>2.3.CO;2.

Chaitanya, A.V.S., M. Lengaigne, J. Vialard, V.V. Gopalakrishna, F. Durand, C. Kranthikumar, S. Amritash, V. Suneel, F. Papa, and M. Ravichandran. 2014. Salinity measurements collected by fishermen reveal a "river in the sea" flowing along the eastern coast of India. *Bulletin of the American Meteorological Society* 95:1,897–1,908, http://dx.doi.org/10.1175/BAMS-D-12-00243.1.

Chowdary, J.S., G. Srinivas, T.S. Fousiya, A. Parekh, C. Gnanaseelan, H. Seo, and J.A. MacKinnon. 2016. Representation of Bay of Bengal upper-ocean salinity in general circulation models. *Oceanography* 29(2):38–49, http://dx.doi.org/10.5670/oceanog.2016.37.

Fousiya, T.S., A. Parekh, and C. Gnanaseelan. 2015. Interannual variability of upper ocean stratification in Bay of Bengal: Observational and modeling aspects. *Theoretical and Applied Climatology* 1–17, http://dx.doi.org/10.1007/s00704-015-1574-z.

Gangopadhyay, A., G.N. Bharat Raj, A.H. Chaudhuri, M.T. Babu, and D. Sengupta. 2013. On the nature of meandering of the springtime western boundary current in the Bay of Bengal. *Geophysical Research Letters* 40:2,188–2,193, http://dx.doi.org/10.1002/grl.50412.

Harenduprakash, L., and A.K. Mitra, 1988. Vertical turbulent mass flux below the sea surface and air-sea interaction: Monsoon region of the Indian Ocean. *Deep Sea Research Part A* 35:333–346, http://dx.doi.org/10.1016/0198-0149(88)90014-3.

Jayaraman, K.S. 2007. Oceanography: Steaming ahead. *Nature* 448:642–643, http://dx.doi.org/10.1038/448642a.

Mahadevan, A., G. Spiro Jaeger, M. Freilich, M. Omand, E.L. Shroyer, and D. Sengupta. 2016. Freshwater in the Bay of Bengal: Its fate and role in air-sea heat exchange. *Oceanography* 29(2):72–81, http://dx.doi.org/10.5670/oceanog.2016.40.

McPhaden, M.J., G. Meyers, K. Ando, Y. Masumoto, V.S.N. Murty, M. Ravichandran, F. Syamsudin, J. Vialard, L. Yu, and W. Yu. 2009. RAMA: The Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction. *Bulletin of the American Meteorological Society* 90:459–480, http://dx.doi.org/10.1175/2008BAMS2608.1.

Mukherjee, A., D. Shankar, V. Fernando, P. Amol, S.G. Aparna, R. Fernandes, G.S. Michael, S.T. Khalap, N.P. Satelkar, Y. Agarvadekar, and others. 2014. Observed seasonal and intraseasonal variability of the East India Coastal Current on the continental slope. *Journal of Earth System Science* 123:1,197–1,232, http://dx.doi.org/10.1007/s12040-014-0471-7.

Murty, V.S.N., Y. Sarma, D. Rao, and C. Murty. 1992. Water characteristics, mixing and circulation in the Bay of Bengal during southwest monsoon. *Journal of Marine Research* 50:207–228, http://dx.doi.org/10.1357/002224092784797700.

Murty, V.S.N., M.S.S. Sarma, A. Suryanarayana, D. Sengupta, A.S. Unnikrishnan, V. Fernando, A. Almeida, S. Khalap, A. Sardar, K. Somasundar, and M. Ravichandran. 2006. Indian moorings: Deep-sea current meter moorings in the Eastern Equatorial Indian Ocean. *CLIVAR Exchanges* 11(4):5-8.

Rao, P.S., and D.R. Sikka. 2005. Intraseasonal variability of the summer monsoon over the North Indian Ocean as revealed by the BOBMEX and ARMEX field programs. *Pure and Applied Geophysics* 162:1,481–1,510, http://dx.doi.org/10.1007/s00024-005-2680-0.

Ravichandran, M., D. Behringer, S. Sivareddy, M.S. Girishkumar, Neethu Chacko, and R. Harikumar. 2013. Evaluation of the global ocean data assimilation system at INCOIS: The tropical Indian Ocean. *Ocean Modelling* 69:123–135, http://dx.doi.org/10.1016/j.ocemod.2013.05.003.

Riser, S.C., H.J. Freeland, D. Roemmich, S. Wijffels, A. Troisi, M. Belbéoch, D. Gilbert, J. Xu, S. Pouliquen, A. Thresher, and others. 2016. Fifteen years of ocean observations with the global Argo array. *Nature Climate Change* 6:145–153, http://dx.doi.org/10.1038/nclimate2872.

Sanilkumar, K.V., N. Mohankumar, M.X. Joseph, and R.R. Rao. 1994. Genesis of meteorological disturbances and thermohaline variability of the upper layers in the head of the Bay of Bengal during MONsoon Trough Boundary Layer EXperiment (MONTBLEX-90). *Deep Sea Research Part I* 41(10):1,569–1,581, http://dx.doi.org/10.1016/0967-0637(94)90061-2.

Sarma, V.V.S.S., G.D. Rao, R. Viswanadham, C.K. Sherin, J. Salisbury, M.M. Omand, A. Mahadevan, V.S.N. Murty, E.L. Shroyer, M. Baumgartner, and K.M. Stafford. 2016. Effects of freshwater stratification on nutrients, dissolved oxygen, and phytoplankton in the Bay of Bengal. *Oceanography* 29(2):222–231, http://dx.doi.org/10.5670/oceanog.2016.54.

Sengupta, D., R. Senan, V.S.N. Murty, and V. Fernando. 2004. A biweekly mode in the equatorial Indian Ocean. *Journal of Geophysical Research* 109, C10003, http://dx.doi.org/10.1029/2004JC002329.

Shetye, S.R., A.D. Gouveia, D. Shankar, S.S.C. Shenot, P.N. Vinayachandran, D. Sundar, G.S. Michael, and G. Nampoothiri. 1996. Hydrography and circulation in the western Bay of Bengal during the northeast monsoon. *Journal of Geophysical Research* 101:14,011–14,025, http://dx.doi.org/10.1029/95JC03307.

Venkatesan, R., V.R. Shamji, G. Latha, Simi Mathew, R.R. Rao, Arul Muthiah, and M.A. Atmanand. 2013. In situ ocean subsurface time-series measurements from OMNI buoy network in the Bay of Bengal. *Current Science* 104:1,166–1,177.

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