Results from the first Argo float deployed by India

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Argo is a revolutionary concept in ocean observation system that envisages real-time sampling of the temperature and salinity profiles of the global oceans at an approximate spatial resolution of 300 km, once in ten days. Argo float is an autonomous drifting profiler that pops up and down in the ocean from the surface up to 2000 m, measuring two most important physical properties of the water column, viz. temperature and salinity as a function of pressure (depth). Moreover, it can provide an estimate of currents both at the surface and at the parking depth in near-real time. India is an active participant in the Argo programme and has already deployed 31 out of 150 proposed floats. In this article, we describe the data received from the first Argo float deployed by India in the southeastern Arabian Sea. The data demonstrate that the temperature and salinity profiles from Argo floats present possibilities for oceanographic studies and spatial and temporal scales that had been hitherto impossible.

OCEAN and climate have a symbiotic connection through complex exchanges of heat and mass. The oceans are the dominant heat reservoirs of the complete air–sea–land system and play a critical role in our climate and its variability. The ocean currents transport heat from the tropics to higher latitudes through their intricate circulation system. Observations made during the World Ocean Circulation Experiment (WOCE) indicate that the poleward heat transport by the oceans has comparable magnitude with that of the atmosphere[1] and shows large variability from year to year[2]. Examples of other important elements of climate variability that influence weather patterns over large regions and on which ocean dynamics plays a critical role are the monsoons, El Nino Southern Oscillation, North Atlantic Oscillation, decadal oscillation of the tropical oceans and the Indian Ocean dipole. Therefore, long-term monitoring of the oceans is essential to detect signals of climate change and to understand the processes that trigger and maintain inter-annual and longer time variability of our climate. Monitoring the oceans is also required for diverse purposes such as forecasting weather at seasonal and longer time scales; determining, understanding and predicting ocean conditions for the use of oceanographic research as well as marine industries, including fisheries.

The ocean observation systems consists of (a) *in situ* measurements (using sensors mounted on ships, buoys, moorings, coastal stations) to monitor changes in time and depth at specific locations or tracks, and (b) remote-sensing systems (satellites, aircraft, radar, sonar, acoustic tomography, etc.) to map the spatial and temporal variations. The Tropical Ocean and Global Atmosphere Programme and the WOCE are significant milestones for observing the global ocean. It is important to note that the WOCE required seven years and the combined resources of many nations to obtain a single sparse realization of temperature, salinity, velocity and geo-chemical parameters. Our inability to observe the ocean at spatial and temporal resolutions with accuracies that are appropriate and useful, has effectively limited progress until now, especially with respect to climate. For example, the TOPEX/Poseidon has been providing maps of sea surface height (SSH) anomaly since 1993 and the SSH measurement mission is being followed up by a satellite known as *Jason*. Subsurface observations to complement the sea surface height data are limited to temperature profiles sampled along the major shipping tracks and few moored buoys in the equatorial oceans. Subsurface salinity observations are lacking over major part of the global oceans. Therefore, Global Ocean Observing System (GOOS) recommended the implementation of a global network of profiling floats to integrate with other elements of ocean-observing systems and models. The Argo programme was endorsed by the Climate Variability and Predictability experiment, and the Intergovernmental Oceanographic Commission assembly has endorsed for international co-operation in successful implementation of the Argo programme. Statistical analysis of expendable bathythermograph observations[3] indicates that a spatially uniform array of 3°lat. × 3°long. is required to (a) meet an error criterion of 0.5°C in temperature; (b) resolve the temporal variability of mid-depth geostrophic

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fields; (c) estimate the heat storage in the surface layer with an accuracy of 10 W/m^2 on seasonal time scales and over an area 1000 km on a side; (d) resolve basin-wide signals in the sub-tropical Atlantic, and (e) study altimetry data.

The Argo project is aimed at measuring the physical state of the ocean at any given time using an array of 3000 floats in the global ocean, each float measuring the profile of temperature and salinity in the upper ocean, once in ten days. Though the float does not measure velocities, it can be estimated from the drift. The name Argo is chosen to be in synergy with the satellite *Jason*. The application of Argo data in ocean and climate studies falls into three broad categories[4]. First, it is expected to provide a global description of the upper ocean thermohaline state at spatial and temporal scales that have been hitherto unavailable. Second, Argo will generate the datasets required by numerical models for ocean analysis and prediction. Finally, Argo shall complement the satellites in monitoring the climate signals in the ocean.

The need for observing oceans has been well realized in India. This demand has been driven by the necessity for understanding and predicting the indispensable monsoons. Various observational programmes, which are either long-term or short-term but intensive, stand testimony to this. Stressing its importance, the National Institute of Ocean Technology, Department of Ocean Development deployed several moored data buoys in the seas around India. Under the auspices of various institutions the observations programme BOBMEX (Bay of Bengal Monsoon Experiment) was successfully conducted during 1999. The first experimental phase of ARMEX (Arabian Sea Monsoon Experiment) was conducted in 2002 and the second phase in 2003. Also, the Indian Space Research Organization launched the OCEANSAT satellite. India is one of the participants in the Argo programme. The first contingent of ten Indian Argo floats were deployed in November 2002 and the second set of 21 floats were deployed both in the Arabian Sea and Bay of Bengal during May/June 2003. Prior to this a Canadian float was deployed by India, on-board FORV *Sagar Sampada*, in the southeastern Arabian Sea on 22 December 2001. In this article, we describe data obtained from this first Argo float deployed by the country. The next section provides a brief overview of the Argo system and its components. We then examine the thermohaline field constructed using the float data and compare it with climatology. Next we describe surface drift computed from the float data. Finally, we outline the new uses that Argo data can be put to.

The Argo system

The Argo is a revolutionary concept that enhances the real-time capability for measurement of temperature and salinity through the upper 2000 m along with reference-level velocities of the ocean. It contributes to the global description of the variability of the upper ocean thermohaline structure and circulation on seasonal and inter-annual time scales. Under a unique internationally coordinated effort, it is envisaged to establish a global array of about 3000 floats by the year 2005, at a spatial resolution of 3° in lat. and long. through the collective participation and contributions from various countries. Under the international cooperative effort, 450 floats will be deployed in the Indian Ocean by the year 2005. India has proposed to deploy about 150 Argo floats in the tropical Indian Ocean in a phased manner under the Indian Argo Project.

Argo floats are deployed in the open ocean and outside the Exclusive Economic Zones. The float pops up at the surface at the end of each cycle and transmits the data collected during its ascending phase to a communication satellite (e.g. ARGOS). Figure 1 shows the typical Argo float mission for acquiring temperature and salinity profile. Once the float is activated at the point A, it is ready to deploy between the points A and B. The float will dive from point B to a predefined depth, after 6 h from point A, irrespective of the time of deployment. The ascending and descending rates are fixed at 0.08 m/s. However, due to the current shear at different depths, this may vary according to the environment. The float reaches its parking depth (1200 m in case of the float described here) at time C and drifts nearly 10 days at that depth up to the point D. The float ascends to the surface from point D, and acquires data at predefined depth intervals during the ascent. As soon as the float reaches the surface, it starts sending data to an ARGOS satellite every 90 s (repetition period) from the point E to F. The float continues to send data in the form of 32 byte messages to the ARGOS satellite. The float sends 10 to 15 such messages or packets for one complete profile acquired during ascend. Each time the message number and repeat number are also transmitted sequentially to the ARGOS satellite. From the repeat number and

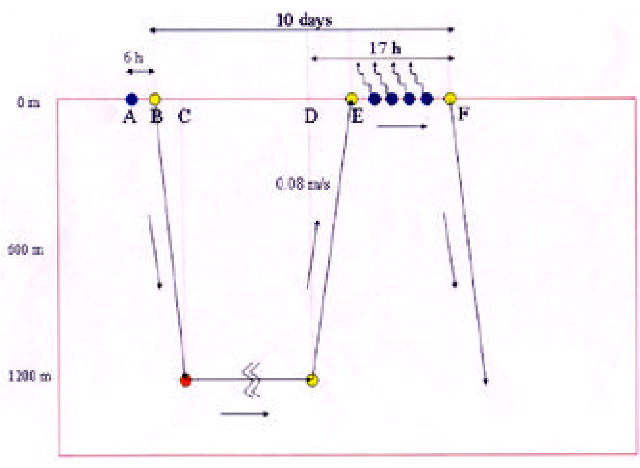

Figure 1. Typical float cycle of an Argo float. The float deployed at A sinks at B to the parking depth, drifts there for 10 days and ascends to D. Then it stays at the surface for nearly 15 h before it sinks for the next cycle at F. Between E and F, the float transmits data at 90 s interval.

the time of the repeat, it is possible to determine the exact time of surfacing of the float. The ARGOS satellite receives the profile data from the Argo floats during its drift on the sea surface. The ground stations receive data from the satellite and calculate the positions of the floats based on the Doppler shift of the receive frequency. Using this information the current velocity at the surface can be estimated (see later in the article). The Argo float data are made available by the National Argo Data Centres to the global community on the Global Telecommunication System (GTS) to enable its use for operational forecasts and on the Internet within 24 h of collection to other research communities (http://www.ifremer.fr/coriolis/cdc or http://www.usgodae.org). Regional Argo Data Centers also make quality-controlled global datasets available to the global community within six months.

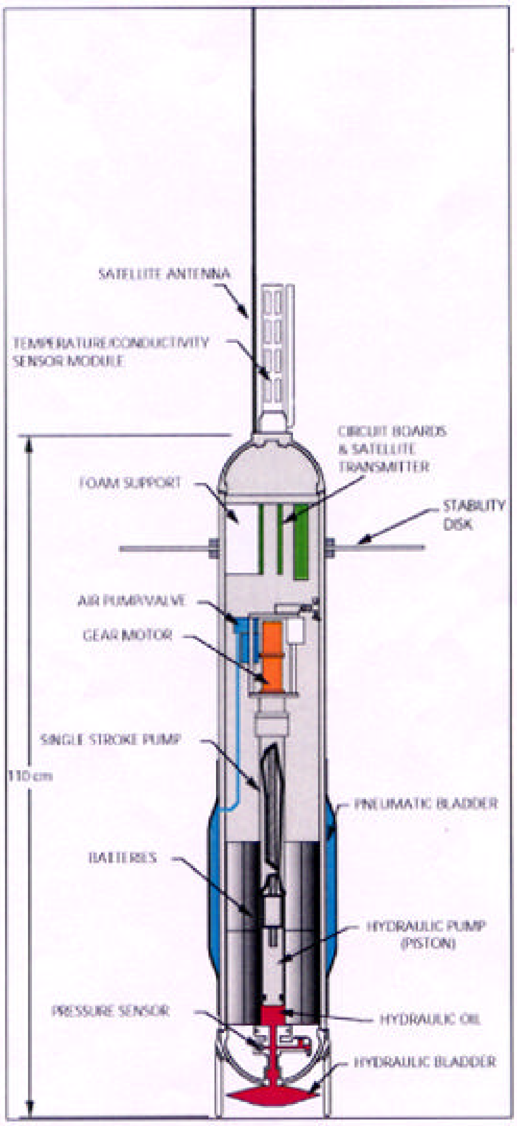

Figure 2. Schematic diagram of an Argo profiling float. (Source: www.argo.ucsd.edu).

Argo profiling float

The neutrally buoyant float technology to measure subsurface ocean currents was developed simultaneously and independently in the mid-1950s by Stommel[5] in USA and Swallow[6] in the UK. The Argo floats have an aluminum hull, approximately 6″ in diameter by 60″ long, with an antenna for data transmission to the satellite system (Figure 2). The antenna, conductivity sensor and a temperature probe are mounted on the top end of the float and a pressure sensor is fitted near the bottom. A damper plate is attached near the top to stabilize the float in the surface wave field. The present generation of Argo floats is capable of acquiring temperature and salinity profiles up to 2000 m depth for 150 times. The accuracy of approximately 0.002°C in temperature and 0.05 psu in salinity is attainable, the latter requiring a stable water mass at a depth of reference. Each Argo float descends to as deep as 2000 m, where it drifts with the water flow. However, it is possible to change the profiling depth, parking depth and cycling period at the time of the deployment. To control the buoyancy of the float, a small amount of oil is contained within the float. When the float is submerged, all of the oil is kept entirely within the hull. When it is time to rise to the surface, the oil is pumped into an external rubber bladder that expands. Since the weight of the float does not change, but its volume increases when the bladder expands, the buoyancy of the float increases and it rises to the surface. Similarly, when the float is on the surface and it is time to submerge, the oil is withdrawn from the bladder into the hull of the float and the buoyancy decreases. A small high-pressure electric pump pumps oil into the bladder. The depth to which the float submerges is controlled by careful ballasting at the time of manufacturing. Typically, the weight of the float is about 25 kg and must be accurate to within a few grams. A 1 g error results in a depth error of about 19 m. The pressure hulls can withstand over 2500 dB pressure and are designed for mission lifetimes of more than four years.

Data communication

The Argo floats pop up to the surface of the ocean at the end of each cycle and transmit data to the ground station through a communication satellite. The time spent at the sea surface has to be as minimum as possible to (a) reduce the risk to the float and the sensors from bio fouling, (b) increase the life of the battery and hence the float, and (c) reduce the displacement of the float by surface currents. The position of the Argo float has to be determined, while on the surface. Since the Argo floats currently available in the market are not fitted with a GPS receiver, determination of the position has to be through the Doppler effect.

The ARGOS is a satellite-based communication system managed by Collecte, Localisation, Satellites a subsidiary of CNES, France to collect data from autonomous platforms and deliver them to users worldwide. The ARGOS system comprises three interactive subsystems, viz. (a) Platform Transmitter Terminals (PTTs) with an uplink frequency of 401.65 MHz, (b) the space segment with data collection and (c) location system mounted on-board the satellites. The satellites operate in near-polar sun synchronous orbits, with an orbital period of 103 min. At least two satellites are operational at any time. Data from additional satellites are processed on 'as available basis'. At any given time, each satellite simultaneously sees all PTTs within a footprint of approximately 5000 km diameter. At the poles each satellite passes approximately 14 times a day, i.e. a total of 28 passes from two satellites. At the equator there will be 6–7 passes everyday. Duration of transmitter visibility by the satellite is the window during which the satellite can receive data from the PTTs, and it lasts for 8–15 min (10 min on an average).

It takes about 10–12 h to transmit data from one Argo profile in the North Indian Ocean region. The satellites receive the data from a PTT and relay them to the ground stations in real time. They also store the data on tape-recorders and dump them into the three Global Receiving and Processing Centers located at Wallops Island, Virginia (USA), Fairbanks, Alaska (USA) and Lannion (France). The ARGOS has established a powerful processing system to enable transmission of data directly into the GTS, a worldwide operational system for sharing of meteorological data in real-time.

Data management

The Argo Data Management System, as finalized by the International Argo Science Team and its Data Management Group, is configured around three levels of data centres, viz. (a) National Data Centres in each country, which deploy Argo floats, receive the data, and deliver the real-time quality-controlled data to the users and global data centres after processing; (b) Regional Data Centres at selected locations for addressing each basin (Atlantic, Indian, Pacific, Southern Oceans) and (c) Global Data Centres located in France and USA. The Argo data go through two levels of quality control. The first level of quality check is done in real-time to remove spurious signals, spikes, etc. for which 14 checks have been identified by the Argo Data Managment Team.

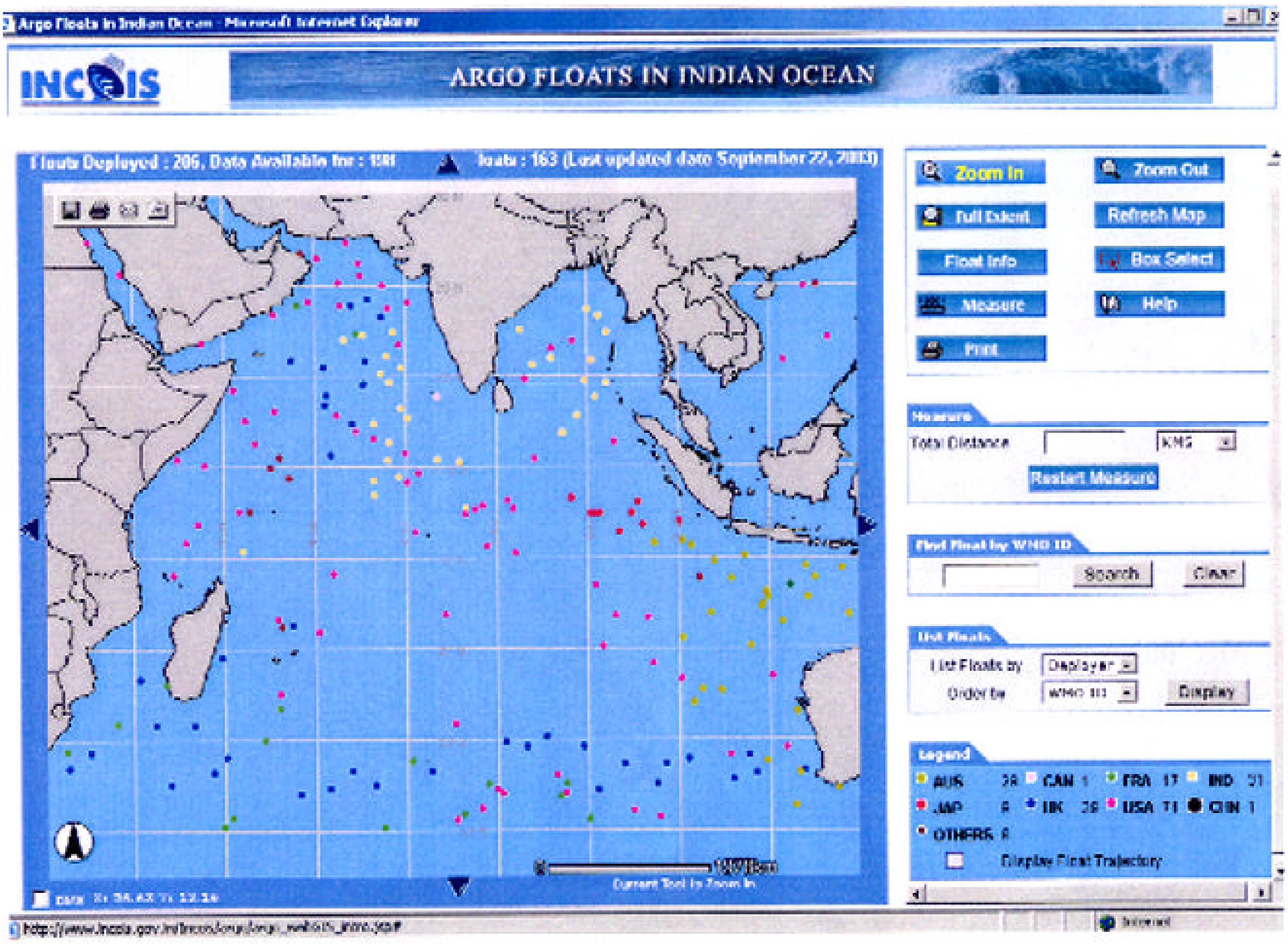

Figure 3. Present status of Argo float locations deployed by different countries in the Indian Ocean.

The scientific community for each basin does the second level of quality check in delayed mode to check sensor drift, if any. The data from the Argo float will initially reach the National Argo Data Centre. After the real-time quality check, the data will be sent to the Global Argo Data Centre (GADC) and in GTS in near real-time (within 24 h). The GADC receives all the data and sends it to the Regional Argo Data Centre for delayed-mode quality control. Users can access real-time quality-controlled Argo data for the entire global ocean from GADC. Argo data for the Indian Ocean region are also available from the Indian National Centre for Ocean Information Services (INCOIS) website (http://www.incois.gov.in/website/argonew/viewer.htm). Users can download ASCII data from the individual float or group of floats deployed by many countries in this region. Figure 3 shows the INCOIS Argo WEB_GIS page showing the present location of Argo floats deployed by different countries, where users can download Argo data. So far (September 2003), there are 206 Argo floats deployed in the Indian Ocean and these data are available to all users. Currently, only 163 floats are active and the remaining have stopped operation due to various reasons. Those who are interested in using Argo data may contact the authors or INCOIS website for further details.

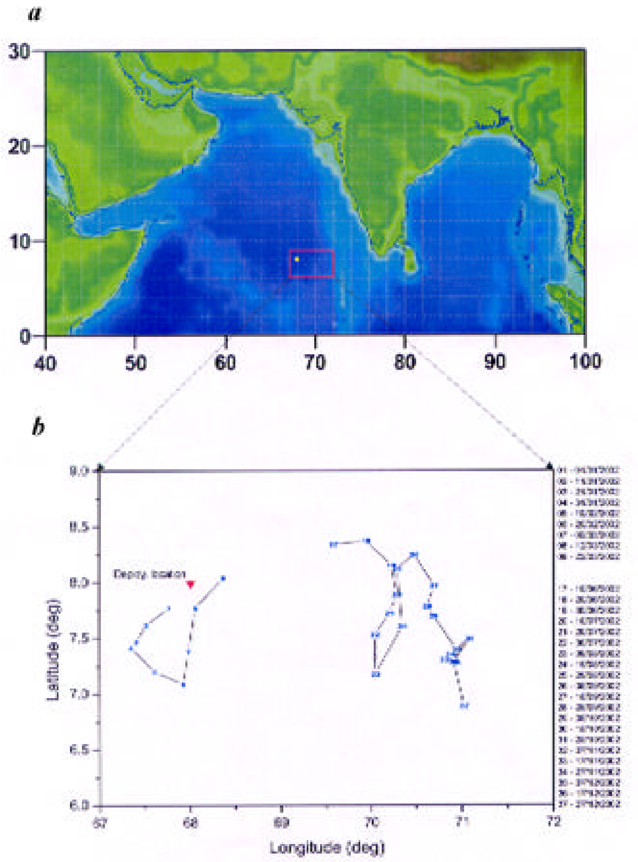

Figure 4. ***a***, Deployment location of the float-193 in the southeastern Arabian Sea. ***b***, Trajectory of float-193 during the year 2002 with its cycling number (the dates (dd/mm/yyyy) for the corresponding cycle number are mentioned on the right).

Comparison with CTD observations

India deployed the first Argo float (provided by Canada) in the southeastern Arabian Sea at 8°N, 68°E on 22 December 2001 from FORV *Sagar Sampada*. The deployment location is shown in Figure 4 *a*. The location of the float whenever it popped up to the surface during the year 2002, is shown in Figure 4 *b*. The float is designed for a parking depth of 1200 m and temporal cycle of 10 days. The ascending rate is 0.08 m/s and the transmission repeat cycle to ARGOS is 90 s. The volume of oil used for varying buoyancy is 180 ml. The float provided good data from 1 January 2002 to 27 December 2002, except for the months of April and May. Data for seven cycles were not transmitted.

After the deployment of the float, CTD was operated at the same location for comparison with the data obtained from the float. Figure 5 shows the temperature and salinity profiles measured with CTD on 22 December 2001 and with Argo float on 1 January 2002. It is seen that the temperature and salinity measured from Argo float and CTD are comparable, except in the top layer. The difference between the two in the top layer may be due the observational time difference between the CTD and Argo float by ten days. Also, the shift between the locations of the Argo float and CTD station could cause some variation. At 1200 m, the difference between temperature and salinity data measured from the Argo float and the CTD is within sensor accuracy.

Figure 6 shows waterfall plot of the temperature and salinity profiles measured by the Argo float from January

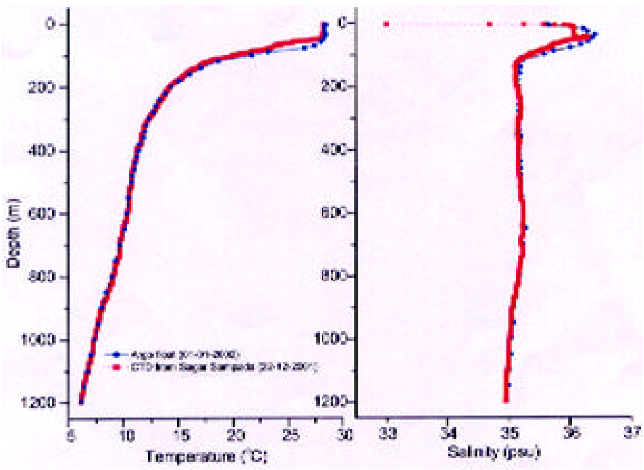

Figure 5. Comparison of temperature (°C) and salinity (psu) profiles measured using Argo float (red) and CTD (blue) on-board FORV *Sagar Sampada*.

to December 2002 (except April and May). Waterfall plots provide a measure of the internal consistency of temperature and salinity profiles measured by the float. Temperatures (salinities) are shifted by 1°C (0.1 psu) from profile to profile. During the design of this float, minimum surface density was estimated as 1023.23 kg/m^3, from the available historical datasets. However, actual surface density observed from the first profile was lower than this, and then it decreased further. Once the environmental density reduces to the critical density, i.e. density of float is greater than the environment density, the float fails to pop-up to the surface. After the onset of monsoon during the first week of June, the environmental surface density becomes greater than the critical density and thereby the float reappears for transmission of data to ARGOS. However, the float cycling might have been continued below the surface during the months of April and May. A similar failure was also observed by Izawa *et al.*[7] and Kobayashi *et al.*[8], and they called this as the 'summer vacation'. When the float surfaced after the summer vacation it did not provide data from 60 m depth to surface, which is most probably due to memory problem. However, the later profiles have the data from 0 to 1200 m depth. Experience gained from this deployment helped in deciding a number of issues related to the Indian Argo Project such as float type, buoyancy required to surface and to reach the required depth of 2000 m in the North Indian Ocean, etc.

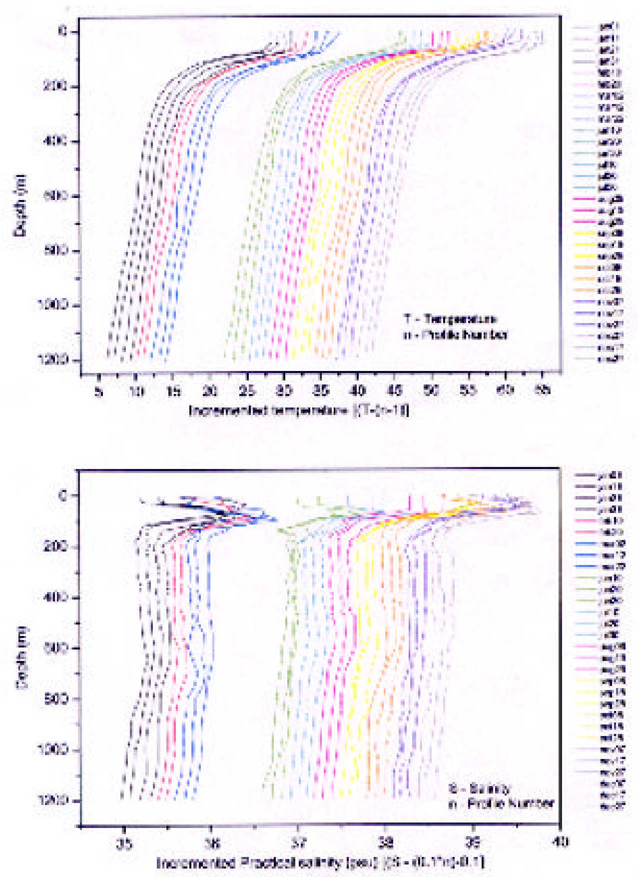

Figure 6. Waterfall plot of temperature and salinity measured by the Argo float during the year 2002.

Seasonal cycle of temperature

The shallowest depth at which data are available from the float is at 4 m. Since the mixed layer in the region of the float is well below 4 m (see below), we use the temperature at this depth as the sea surface temperature (SST). The comparison between the annual cycle of SST measured by the float and the climatological (*World Ocean 2001 Atlas*) SST is shown in Figure 7 *a*. The SST from the Argo float compares well with the climatology. The spring warming of the Arabian Sea is similar in both datasets. However, differences of about 1°C are noted during September–December. These differences are most probably due to the year-to-year variability occurring in this region.

The salinity measured by the float at 4 m is compared with the climatology in Figure 7 *b*. Differences exceeding 1 psu are noted between the two datasets during February. The float salinity is higher than the climatology during January–March and low during October–December. The salinity in the southeastern Arabian Sea undergoes dramatic changes during the northeast monsoon due to the arrival of low-salinity water from the Bay of Bengal. Therefore, the differences between the time and location of measurements in these regions are likely to reflect in the difference between the datasets.

The uppermost layer of the ocean within which temperature, salinity and density are nearly homogeneous, is generally referred to as the mixed layer. The thickness of the mixed layer is considered to be an important parameter for ocean–atmosphere interaction. We have calculated the mixed layer depth (MLD) by finding the depth at which

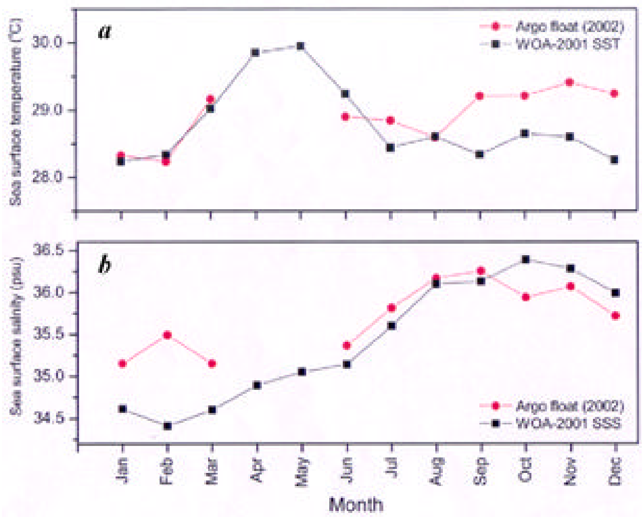

Figure 7. ***a***, Annual cycle of sea surface salinity from *World Ocean 2001 Atlas* and from the float. ***b***, Annual cycle of sea surface temperature from *World Ocean 2001 Atlas* and from the float.

the density increases by 0.2 kgm^{-3} from the nearest surface value available. Rao *et al.*[9] calculated the MLD as the depth at which the temperature is 1°C less than that at a depth of 10 m. This criterion resulted in a deeper mixed layer than in the present study, particularly during the pre-monsoon months. We have also compared the MLD with the isothermal layer depth obtained using a difference criterion of 0.5°C, in order to assess the dependence of MLD on salinity. Figure 8 shows the MLD at the float location obtained using the above criteria. The difference between the two layers shows the barrier layer thickness. The observed mean MLD during January–March, July–September and October–December was 38, 59 and 30 m respectively. A maximum MLD of 59 m was observed during August. During winter, the barrier layer was thickest, which agrees with the results of Rao and Sivakumar[10]. The mixed layer shallows from February to March but due to missing data during April–May, it is not clear whether it remained shallow for the rest of the pre-monsoon period.

The time–depth section of the temperature in the upper 500 m from the float and from climatology is shown in Figure 9. The main thermocline is bounded by the 28°C isotherm at the top and by the 13°C at the bottom in both datasets. During spring warming, the temperature of the near surface layer warms up to 30°C in both datasets. But the second warming that occurs after the summer monsoon is much higher in the float data during 2002, which may be due to the weak monsoon of 2002. The data from the float show rich temporal variability in the thermocline, which is not captured by the climatology. The thermocline dips and shallows during several occasions within the year. Further studies are required to understand these oscillations and their causative factors.

The time-depth section of the salinity in the upper 50om from the float and from climatology is shown in Figure 10. From January to June, there is a high salinity region sandwiched between two low salinity regions; one near the surface and the other below. During June–December, the low-salinity water is replaced by higher salinity water. This general picture is well represented by both datasets. The Argo-float data, in addition, indicate that the low (high) salinity regime near the surface is sometimes interrupted by incursions of high (low) salinity water. As in the case of temperature, the salinity fields also show temporal variability within the halocline.

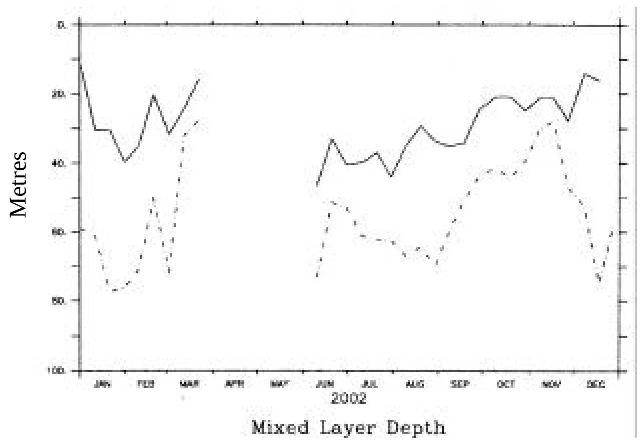

Figure 8. Annual cycle of mixed layer depth (continuous line) and isothermal layer (dashed line). Mixed layer depth is obtained by finding the depth at which the density increases by 0.2 kg m^3 from the nearest surface value available. Isothermal layer depth is the depth at which the temperature is lower by 0.5°C from the surface value. When the two are different, the salinity is important for mixed layer definition.

Surface currents

To understand the oceanic circulation and water-mass formation, observation of current velocity is important in addition to temperature and salinity. Argo floats drift with the deep ocean currents when they are at the parking depth (1200 m), and with the surface currents when they remain at the surface for data transmission. The floats begin data transmission as soon as they surface. But the location of the float can be known only after the ARGOS satellites

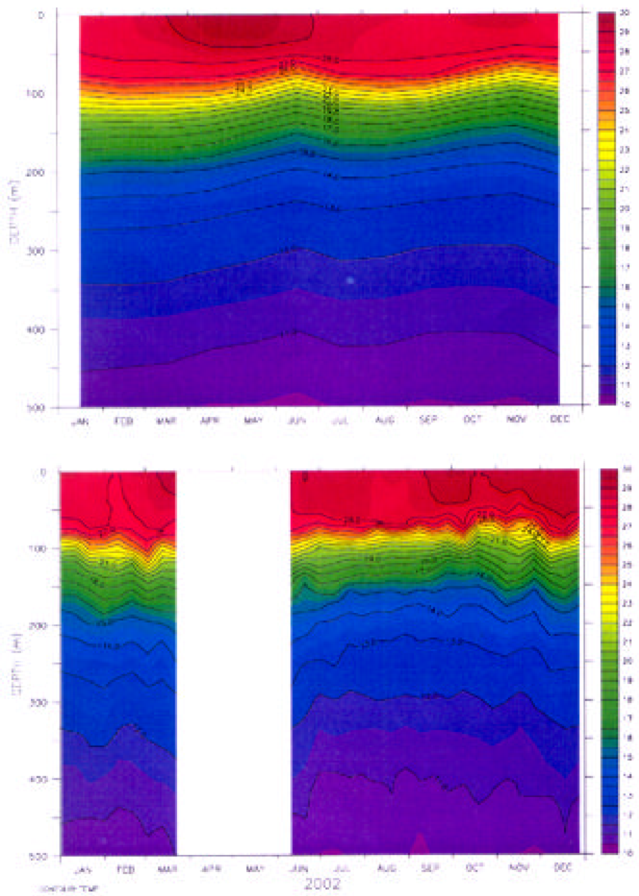

Figure 9. Comparison of time–depth section of temperature from *World Ocean 2001 Atlas* (averaged over the box shown in Figure 2) and Argo float (along the trajectory of the float) in southeastern Arabian Sea.

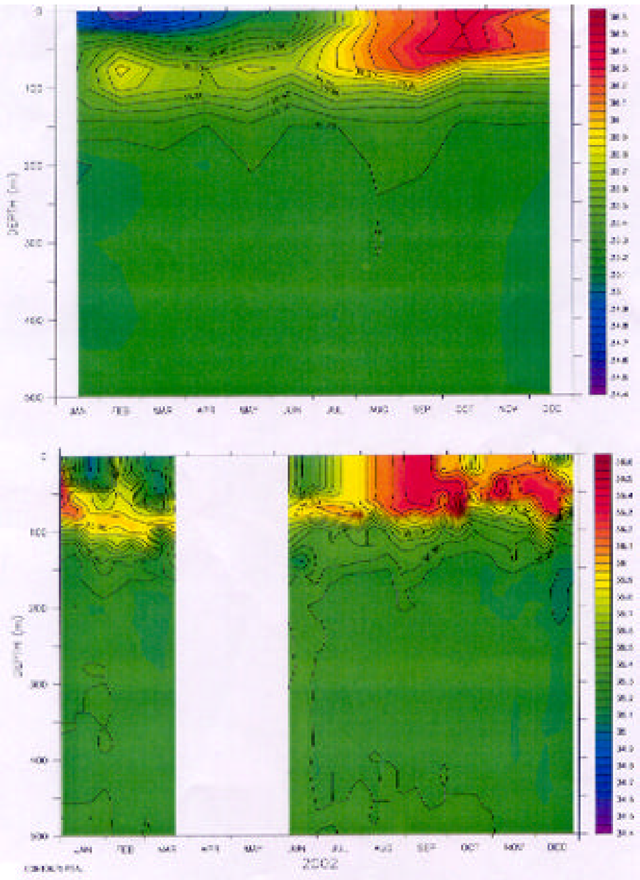

Figure 10. Comparison of time–depth section of salinity from *World Ocean 2001 Atlas* (averaged over the box shown in Figure 2) and Argo float (along the trajectory of the float) in southeastern Arabian Sea.

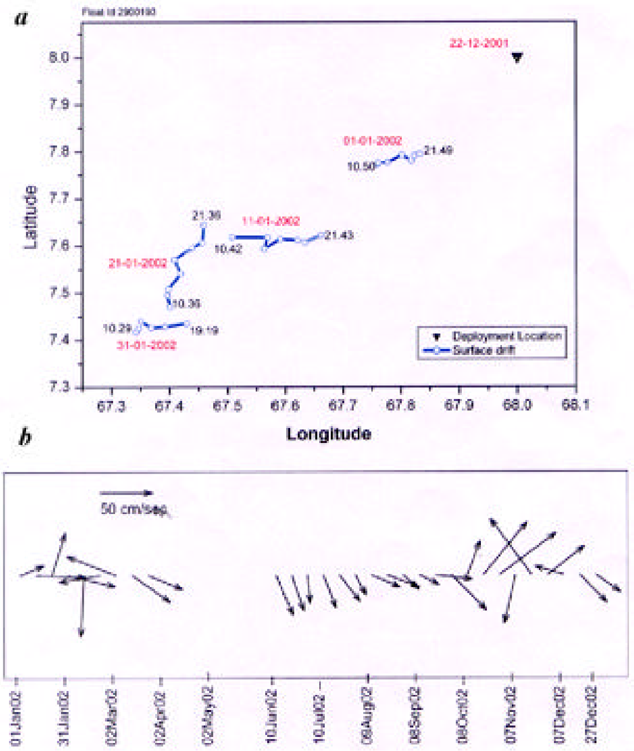

Figure 11. ***a***, Float location fixes during the month of January 2002. The float popping up date and time are also shown. [First location fix (10.50 GMT) and last location fix (21.49 GMT) for the first profile on 1 January 2002 during data transmission.] ***b***, Surface currents derived from the position fixed by the ARGOS satellites during the year 2002.

intercept the transmission. Data transmission continues for 15 h at 90 s interval, before it descends for the next cycle. During this time, usually 10–15 position fixes at an accuracy of 150 m to 1000 m (depending upon the number of satellite in the vicinity) can be obtained. We have calculated surface drift using these satellite fixes whenever the position accuracy is 150 m. Figure 11 *a* shows the float location fixes during the month of January 2002. Figure 11 *b* shows the surface current derived from the location fixes for the year 2002, once in ten days. Surface currents estimated from the float show the well-known reversal of the monsoon current during March and October. The values are comparable to those obtained from drifting buoys[11] and by combining geostrophic and Ekman currents[12].

Estimation of drifting velocity at the parking depth is rather tricky because of (a) error in fixing position by the ARGOS system, (b) error in estimation of float surfacing and diving time and its location, and (c) vertical current shear during its ascend[13,14]. Using the climatological value of vertical current shear, one can estimate the current velocity at the parking depth with an accuracy of 10–25% error. We have not attempted this exercise here.

Concluding comments

In this article, we have described the Argo programme, outlined the operations of the first Argo float deployed by India, evaluated its performance and presented selected applications of the data. With the availability of mature Argo float technology and satellite communications, today it is possible to acquire and monitor the three-dimensional evolution of thermohaline structure of any ocean basin in near-real time. The temperature and salinity profiles measured by Argo floats together with the sea surface topography measured by satellite altimeters provide a dynamically complete description of ocean currents[4]. The Argo profiles are also useful for initialization of ocean and coupled forecast models, data assimilation and dynamical model testing. These data serve as important sea truth to validate the features derived from satellites. The inventory of heat and salt (freshwater) storage and transport of the global ocean derived from as many as 3000 floats would provide valuable inputs for the improved prediction of the weather and climate. It appears that our information of the oceans in the next half a decade, would far exceed that acquired in the past half a century.

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The Biological Diversity Act of India and agro-biodiversity management

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After the Convention on Biological Diversity (CBD) was adopted by the United Nations, in June 1992, the contracting countries were required to integrate consideration of conservation and sustainable use of biological diversity into relevant legal procedures, programmes and policies. The Biological Diversity Act was passed by the Parliament in 2002 after a process of consultation among stakeholders. The Act provides for conservation of biological diversity, sustainable use of its components and equitable sharing of benefits arising out of the use of biological resources. Agro-biodiversity which is a subset of total biological diversity is a major concern for the world food security and the issues of conservation and management of agro-biodiversity are one of the high priorities for a diversity-rich country like India. In this article we analyse the provisions of this Act related to agro-biodiversity management and how the access to these resources may be managed to channel the benefits to the users as well as custodians of agro-biodiversity.

BIOLOGICAL diversity is the variability among all living organisms existing on earth in various ecosystems and ecological complexes. This diversity is the basis of continuous evolution of life forms and in turn maintaining the life-sustaining systems of the biosphere. The conservation of all biological diversity is a common concern of human kind and it is vital to anticipate, prevent and tackle the causes of loss or reduction of biological resources.

The dependence of human beings on biological diversity is undoubted, as evident in everyday life. The food, fibre, fuel, fodder, shelter, health and other needs of the growing world population are dependent on various components of biodiversity. It is also recognized that plant genetic resources for food and agriculture are a common concern of all countries and most countries depend largely on plant genetic resources that have originated elsewhere.

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