

*Experience with  
Downward-looking Aerial Microwave  
Radar Based Sea-level Gauges deployed  
along Indian Coasts and Islands*

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## ○ Abstract

Subsequent to the disastrous December 2004 Indian Ocean tsunami event, near real-time reporting integrated coastal observation network (ICON) providing sea-level, sea-state and surface meteorological information has been developed and established by CSIR-NIO at selected locations on Indian coasts and Islands. Sea-level data are obtained from several remote and coastal locations using downward looking aerial microwave based radar gauges. Apart from monitoring long term sea-level variations at a particular location, the internet-based ICON could be useful in near real-time tracking and monitoring of sea-level, sea-state and surface-meteorological conditions from a network of several island and coastal stations providing the much needed information to disaster managers and local administrators during episodic events such as storms, storm-surges and tsunamis.

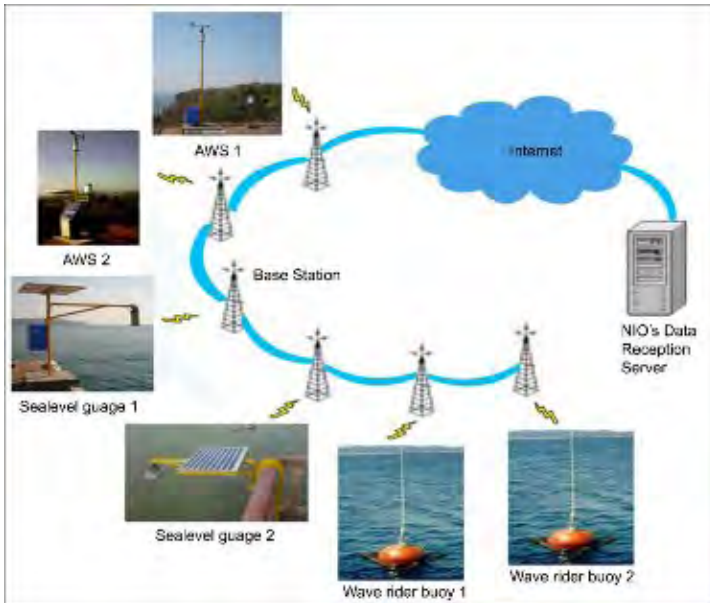
## ○ Introduction

Sea-level, sea-state and surface meteorological data are of considerable value to the research community in a variety of applications for a wide range of scientific studies including those of long-term changes and the statistics of extreme events. Long-term changes in atmospheric warming and global mean sea-level due to climate change continues to be the focus of much research in recent years because of the potential impacts on the environmental, economic, and social infrastructure at the coasts and islands. Considering the vulnerability of the Indian coasts and islands to storm surges and the recently felt threat of tsunamis, including the powerful December 2004 global tsunami (Titov et al., 2005; Joseph et al., 2006) near real-time reporting of sea-level, sea-state, and surface meteorological information has become all the more important for multi-hazard monitoring and early-warning purposes. Thus, establishment of a network of near real-time reporting sea-level, sea-state and surface meteorological stations providing high-quality data sets will lead to improved operational utilities and more efficient forecasting results (Joseph and Prabhudesai, 2005). Further, good quality data availability will facilitate promotion of oceanographic and climatologic research programmes to improve understanding of critical global and regional ocean- and climatologic- processes and their relationship to the sustainable development and stewardship of ocean resources.



**Figure 1.** Radar based sea-level gauges and autonomous weather stations installed along the Indian coasts and islands.

The December 2004 Indian Ocean tsunami caused heavy damage to life and property, which led to serious efforts towards development and establishment of related technologies to monitor sea-level, tsunamis, storm surges and high waves. CSIR-NIO also joined in this endeavor by developing an internet enabled sea-level gauge capable of providing information in near real-time (Prabhudesai et al., 2006). The first such in-house designed and developed sea-level gauge using an absolute pressure sensor (Honeywell Inc.) was deployed at Verem Jetty, Goa in September 2005. Later on another sea-level gauge using OTT Kalesto downward looking microwave based radar sensor was installed in Verem Jetty in September 2007. Steadily, the number of field stations increased and also most of these sites have been complemented with in-house designed and developed autonomous weather stations (NIO-AWS). In this paper, we report the experience gained in developing and operating an in-house designed internet-accessible, cellular based, near real-time reporting sea-level, sea-state and surface meteorological system known as Integrated Coastal Observation Network (ICON) established by the CSIR-National Institute of Oceanography, Goa, India, at several locations on the Indian coasts and Islands as shown in **Figure 1** (Prabhudesai et al., 2010). The data acquired by ICON is also upload at <http://inet.nio.org> for the benefit of various stakeholders.



**Figure 2.** Schematic illustration of the network of distributed near real-time reporting sea-level, sea-state and surface meteorological stations.

(AWS), sea-level gauges and wave rider buoy as shown in **Figure 2** are incorporated in the ICON. **Figure 3** shows some of the typical installations at different locations using microwave radar sensor. The sea-level and surface meteorological data are acquired using dedicated Linux based data loggers and uploaded to an Internet server at 5- and 10-min intervals respectively, with the use of GPRS cellular modems. The sensors and data loggers are powered from sealed lead acid batteries, which are charged through solar panels (**Figures 2 and 3**).

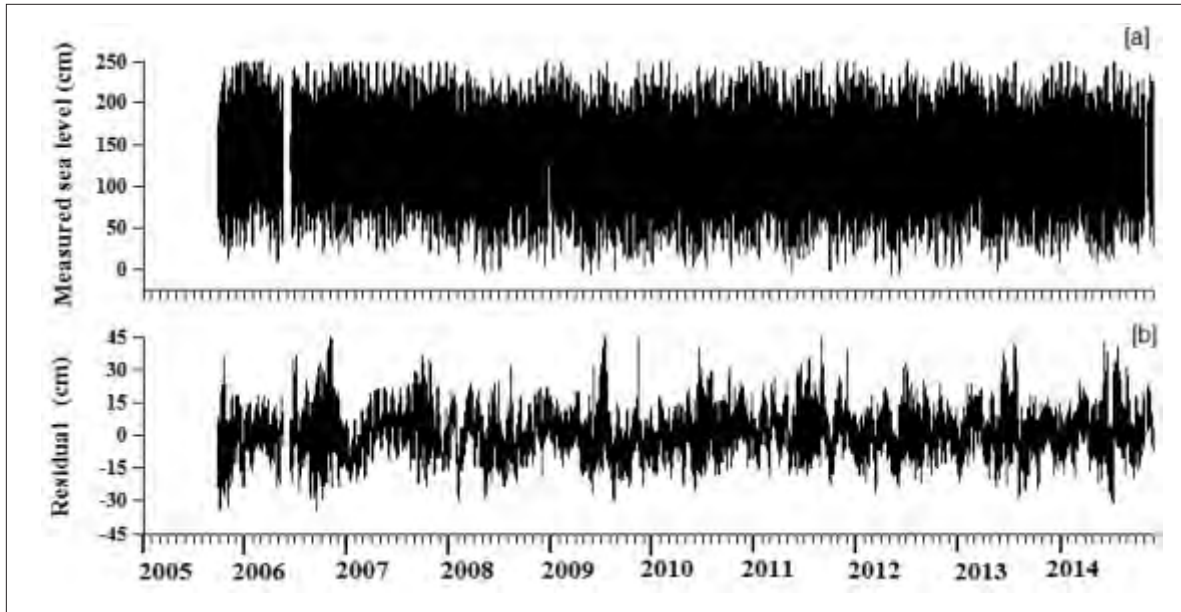
The ICON provides graphical presentation of sea-level information (observed sea-level, predicted tide, sea-level residual) and surface meteorological information (such as vector-averaged wind speed & direction, barometric pressure, atmospheric temperature, relative humidity, solar radiation and rainfall). The network maintains accurate time-stamp of the dataset through Internet-time synchronization using network time protocol (NTP). Recently, the sea-level gauges and AWS are also provided with a GPS receiver to update the time in case internet network is not available.

### ○ Integrated Coastal Observation Network (ICON)

The in-house designed and developed Internet-accessible near real-time reporting cellular based sea-level, sea-state, and surface meteorological (Met) stations deployed at several locations on the Indian coasts and Islands has been described in detail by Prabhudesai et al. (2010). The network of autonomous weather stations



**Figure 3.** Typical installations of microwave based radar gauges at [a] Karwar, [b] Port Blair and [c] Dona Paula.



**Figure 4.** Time series measurement at Verem, Goa from September 2005–December 2014. [a] Sea-level. [b] Estimated sea-level residual.

## ○ Results

Sea-level measurements by pressure and radar gauges from September 2005 - December 2014, the longest time series data available under ICON from Verem, Goa is shown in **Figure 4**. The tidal range is up to 250 cm with fortnightly variation in spring and neap tides (**Figure 4[a]**). The tides off Verem have a 'form factor' of 0.64, implying that the tides are mixed, mainly of semi-diurnal nature (Murty and Henry, 1983). When the tidal signal was removed from the sea-level records using the TASK (Bell et al., 2000) tidal analysis and prediction algorithm, sea-level residuals (SLR) are estimated as shown in **Figure 4[b]**. The sea-level residual at Verem varies between  $\pm 40$  cm with a variance of  $\sim 70$  cm<sup>2</sup>. The continuous measurement of sea-level data has been made possible due to the reliability of the radar sensor and the in-house development of electronics, software and mechanical hardware, resulting in the minimum downtime of the system.

### **Comparison between radar and pressure gauges**

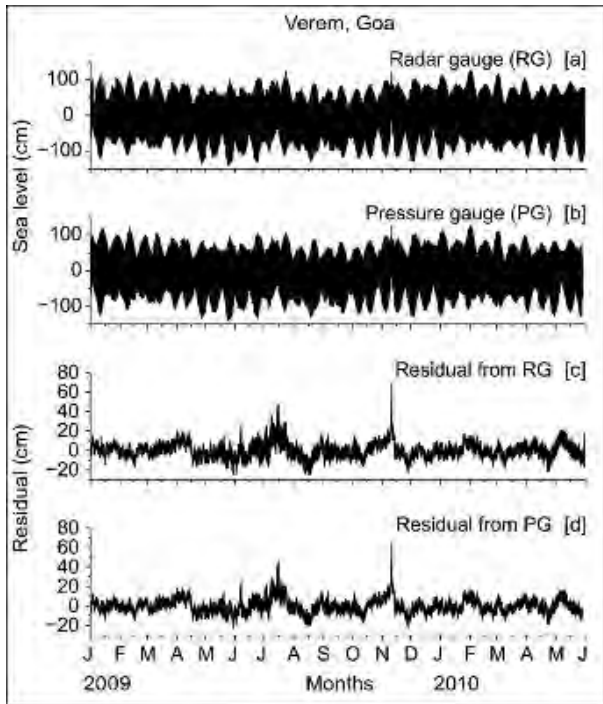
The first comparative study between the radar and pressure gauge at Verem was reported by Mehra et al., 2009 using data from September 2007 to April 2009. It was observed that the variance of difference between the radar and absolute pressure gauge was 15.9 cm<sup>2</sup>, which reduces to 5.7 and 4.0 cm<sup>2</sup> respectively, when atmospheric pressure and water density variations were introduced for obtaining sea level from an absolute pressure gauge. Later, more comparative analyses were

carried out using sea-level data collected off Goa using near real-time reporting pressure (Honeywell Inc.) and radar gauges at Verem, located near the mouth of the Mandovi estuary (January 2009 to May 2010), Tuticorin, and Mandapam (Sea-Bird Electronic), Tamil Nadu (June 2010 to March 2011) by Mehra et al., 2013 as shown in **Figure 5**. The root-mean-square difference between the estimated sea level from radar and pressure gauge (incorporating atmospheric pressure correction) was 2.69, 2.73, and 1.46 cm at Verem, Tuticorin, and Mandapam, respectively. Harmonic analysis of the two time-series of sea-level data at Verem produced similar residuals (**Figure 5 [c] and [d]**). The monthly variability as shown in **Figure 6** was with negligible difference. The high residual variability ( $\sim 163$  cm<sup>2</sup>) seen in November 2009 is the response of the sea-level to the tropical cyclonic storm 'Phyan', which developed in winter in the south-eastern Arabian Sea and swept northward along the eastern Arabian Sea during 9–12 November 2009 as reported by Joseph et al., 2010.

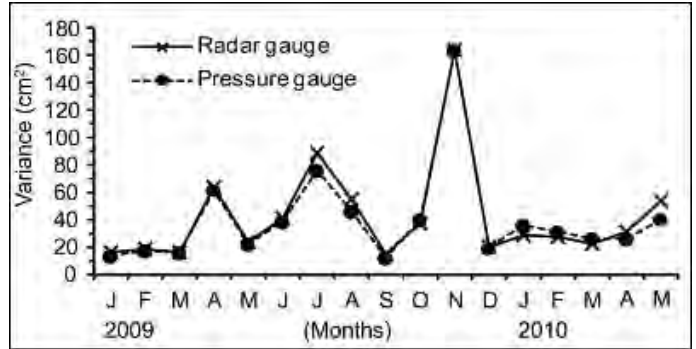
### **Comparison with altimeter and GPS buoy at Kavaratti**

Installation of four radar gauges at Kavaratti, Colachel, Machilipatnam and Port Blair were funded by Space Application Centre (SAC), Ahmedabad, India from June 2011 for three years duration where the footprint of the altimeter (SaraL-Altika in particular) passes. During the measurement period, the calibration/validation (CAI/Val) experiment was conducted at Kavaratti Island during 1-5 October 2012 jointly by SAC, Ahmedabad, CSIR-NIO,





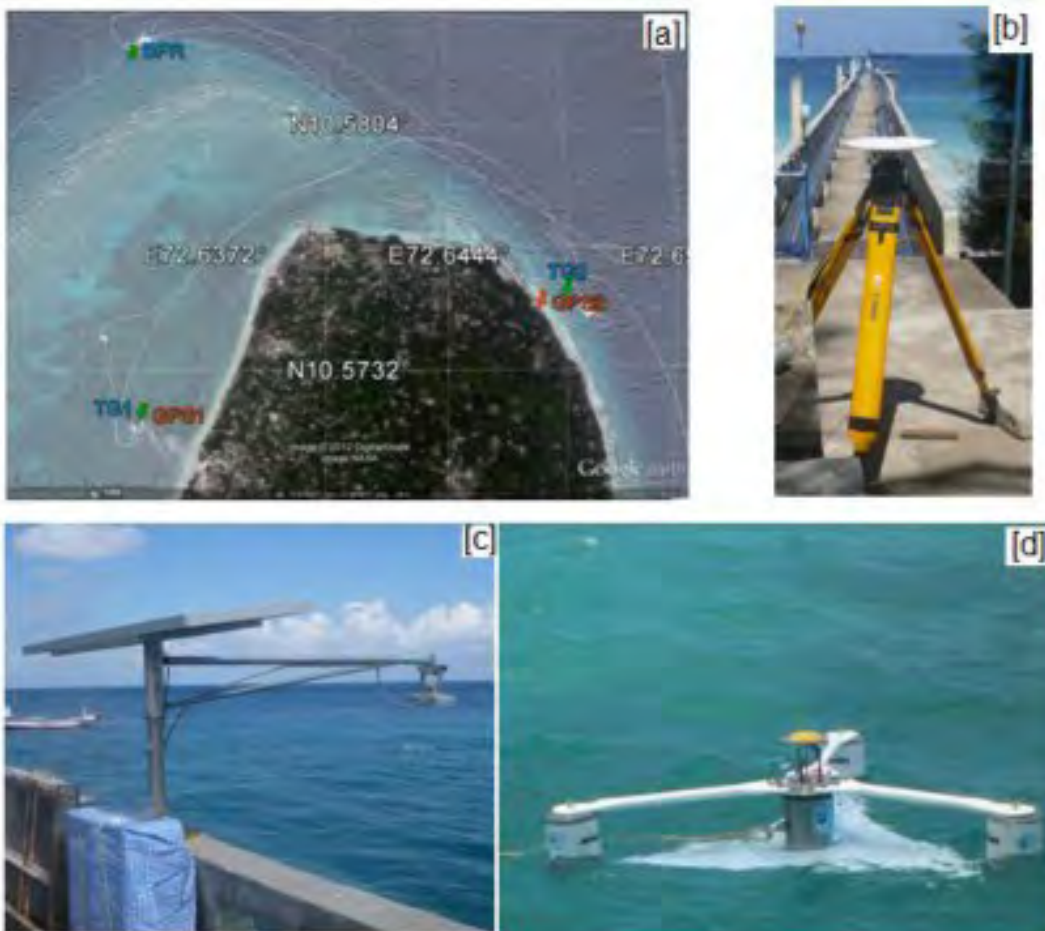
**Figure 5.** Sea level measurements at Goa using [a] radar gauge (RG), [b] pressure gauge (PG) and respective residuals [c] from RG and [d] PG (Mehra, et al., 2013).



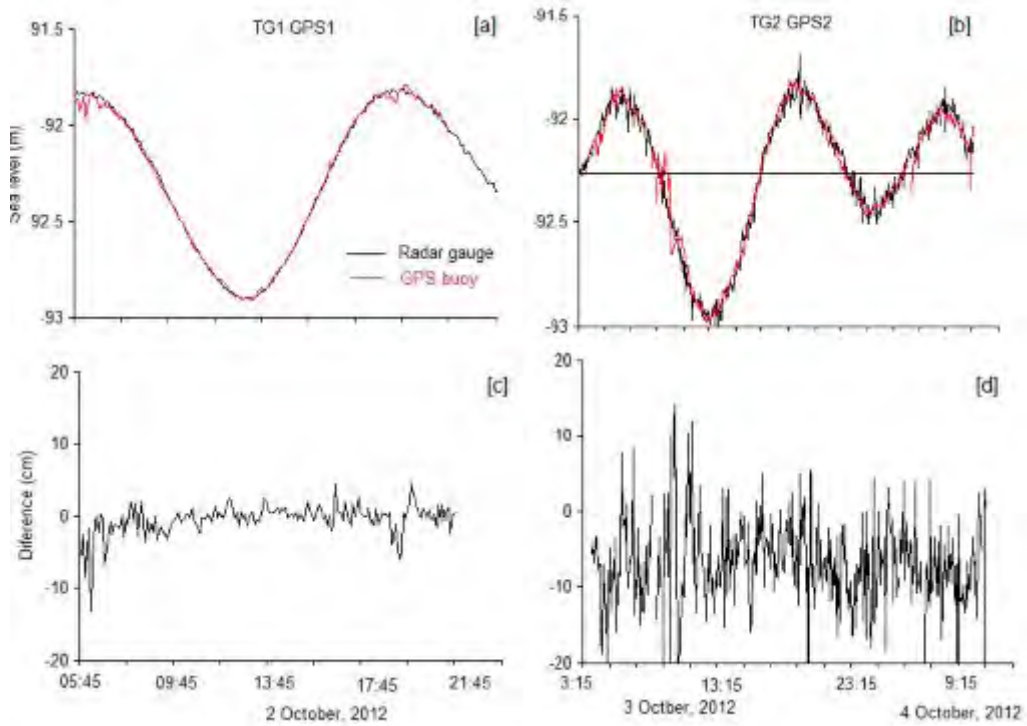
**Figure 6.** Seasonal sea level residual variability at Verem Goa (Mehra et al., 2013).

Goa and CNES, France with the main objectives of the experimental setup as indicated below:

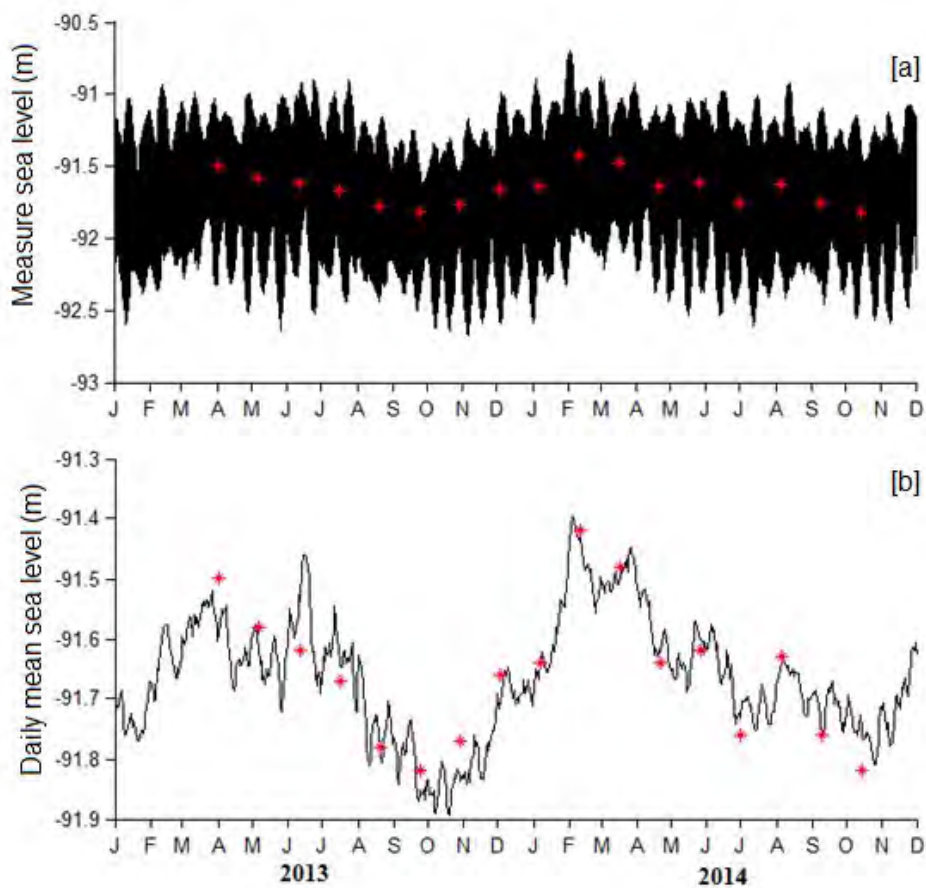
- ✓ To find a place and install a dedicated cal/val radar gauge.
- ✓ To show, train and use the GPS-Buoy for cal/val in India.
- ✓ Conduct the first GPS-Buoy session over a Jason2-Altika cross-over point.
- ✓ Connect each instrument through traditional leveling.



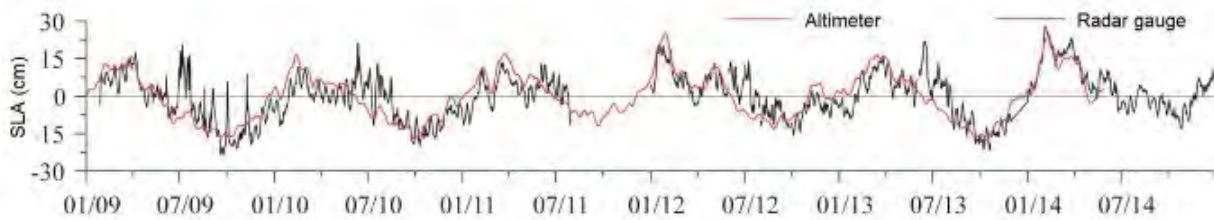
**Figure 7.** [a] Experimental setup and instruments deployed during the Cal/Val experiment at Kavaratti (1-5 October 2012). [b] GPS Base station, [c] Radar gauge (TG2) and [d] GPS buoy (GPS2) deployed at NIOT jettty.



**Figure 8.** GPS buoy comparison with radar gauge at [a] Katchery (main) jetty, [b] NIOT Jetty. Difference (GPS buoy-Radar gauge) at [c] Katchery main and [d] NIOT jetty.



**Figure 9.** [a] Sea-level at 5-minutes interval and [b] Daily-mean sea level data from radar gauge (black line) and sea surface height from Saral-Altika altimeter (red stars) with reference to ellipsoid at Kavaratti [Time is in GMT].



**Figure 10.** Daily mean sea-level anomaly measured by radar gauge (Black line) at kavaratti along with the Merged and gridded products of MSLA (Maps of Sea Level Anomaly, Red line) from 2009-2014. The data derived from satellite altimeter (<https://www.avisioceanobs.com.SLA>) is produced by AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic data), based on TOPEX/Poseidon, Jason 1, ERS-1 and 2 altimeter observations. Daily resolution SLAs for Kavaratti is extracted from the gridded product of MSLA.

This experiment was initiated by Dr. P. Bonnefond (OCA/CNES) and organized by Dr. A.K. Shukla (ISRO/SAC) in the frame of the Indo-French “SARAL/AltiKa” collaboration. CSIR-NIO provided the radar gauges and the French team was led by L. Testut (LEGOS/CSIR-NIO), M. Calzas and A. Guillot (DT/INSU) were responsible for GPS buoy and mooring deployment.

In this report, we present the preliminary results from the Kavaratti Island only. The experimental setup at Kavaratti is shown in **Figure 7**, where radar gauges and GPS buoys were installed/deployed at Katchery main Jetty (TG1 and GPS1) and at NIOT jetty (TG2 and GPS2) as shown in **Figure 7[a]**. **Figure 7[b]** show the temporary GPS base station at NIOT jetty for leveling of the radar gauges with respect to the ellipsoid. The radar gauge (TG2) and the GPS buoy (GPS2) installed/deployed at/near NIOT jetty are shown in **Figure 7[c-d]**. Similar setup was installed/deployed at Katchery main jetty also. Preliminary results obtained between the radar gauges and GPS buoy at Kavaratti are shown in **Figure 8**. The GPS buoy (GPS1) comparison on 2<sup>nd</sup> October 2012 at Katchery (main) jetty with radar gauge (TG1) after removing the offset is shown in **Figure 8[a]**. Similarly, **Figure 8[b]** shows the GPS buoy (GPS2) comparison on 4<sup>th</sup> October 2012 at NIOT jetty radar gauge (TG2) after removing the offset. The standard deviation in difference between GPS and radar gauge at Katchery main (NIOT) jetty is 3.8 (6.2) cm as shown in **Figure 8[c-d]**. The radar gauge station at Katchery (main) jetty is located in a shallow lagoon, because of which wave activity surrounding this station is weak. However, the NIOT Jetty is located in a region of high wave activity. This explains the relatively large noise observed in the measurements from the NIOT Jetty. The experiment can be considered as a satisfactory initiative to make Kavaratti a cal/val site for future use.

The sea-level measured by the radar gauge (black line) every 5 min are shown along with the sea surface height (SSH) measured by Saral-Altika altimeter (red stars) in **Figure 9** at Kavaratti. The Saral-Altika data is available every ~35 days at a particular location. The altimeter data appears to vary along the mean value and are within the sea level range (**Figure 9[a]**). **Figure 9[b]** shows the daily-mean sea level (black line) and the Saral-Altika altimeter data (red stars) at Kavaratti with similar variations as the daily-mean sea level. **Figure 10** shows the daily mean sea-level data measured by radar gauge at Kavaratti along with the gridded daily sea level anomaly derived from altimeters from 2009-2014 with illustrating similar variations with a correlation coefficient of ~0.73.

## ○ Summary and conclusions

The development of ICON of sea-level gauges and AWS was initiated in the year 2005, immediately after the occurrence of December 2004 Sumatra tsunami and the first near real-time reporting sea-level gauge based on pressure sensor was installed at Verem (Mandovi estuary), Goa in September 2005. However, presently all our sea-level stations use radar sensor. The radar based sea-level gauges deployed under ICON measures the sea-level in a completely different way than the traditional float or bubbler gauges. The ICON is developed with simple supporting structure to mount the sensors, powered by solar energy, and communicating data (using cellular modems) automatically to a web server located at CSIR-NIO, Goa. The system does not need expensive infrastructure, such as stilling-well, intake pipes or cabins, normally seen in ports. However, these features could present some drawback, if the sites are exposed to harsh environment and lacks security. With prior survey of the sites, the drawback of harsh environments and security



aspects are minimized and we, therefore, have been able to operate the network of such stations (see <http://inet.nio.org/>) successfully since September 2005.

The ICON enable us to study the response of sea-level to various meteorological and tsunamigenic events along the Indian coasts and Islands. The sea-level gauges at Verem and Kavaratti Island enabled real-time monitoring of the tsunami at Goa and Kavaratti Island due to the Mw 8.4 earthquake in Sumatra on 12 September 2007 (Prabhudesai et al., 2008). In particular, sea-level gauges, surface meteorological instruments and wave-rider buoys in the network enabled real-time monitoring of the response of west India coastal waters and Kavaratti lagoon to the November 2009 tropical cyclone Phyan (Joseph et al., 2010). The ICON also enabled Mehra, et al. (2012) to examine the observed storm-generated sea-level oscillations (June 2007 and November 2009) along with the Sumatra geophysical tsunami (September 2007), indicating similarities in the sea-level response in the Mandovi estuary of Goa in the eastern Arabian Sea. Likewise, Mehra et al. (2015) investigated the meteorologically induced surges and water level oscillations along select locations in response to the passage of the November-2011 meteorological disturbance in the Arabian Sea and “Thane” storm in Bay of Bengal. The high frequency water level oscillations were observed at Gangavaram (east coast of India) during the events and were found to have been due to the result of harbour resonance.

Several research institutions and universities are gaining mileage from this network in terms of data usage. For example, apart from usage at national level, Titov et al. (2011) used time-series sea-level data from Yanam station (on the east coast of India) in the ICON network to test their newly developed tsunami inundation software package (Community Modeling Interface for Tsunamis-ComMIT) during a weak tsunami triggered by an earthquake in Andaman Islands. In their published research paper, they have specifically mentioned the value of the ICON network and cited the paper published on the ICON (Prabhudesai et al., 2010).

Presently, there are only a few mesoscale weather and sea-level networks in some coastal segments of the Indian and eastern Atlantic oceans to observe such events. It is also expected that this kind of relatively inexpensive and simple networks, similar to the one developed in-house

and established by CSIR-NIO will be affordable to limited-budget institutions in their natural hazard mitigation efforts.

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