Marine Biofouling on Moored Buoys and Sensors in the Northern Indian Ocean

AUTHORS
Ramasamy Venkatesan
Jagadeesh Kadiyam
Puniyamoorthy SenthilKumar
Rajagopalan Lavanya
Ocean Observation Systems,
National Institute of Ocean Technology, Chennai, India
Loganathan Vedaprakash
Titanium Tantalum Products Limited, Chennai, India

ABSTRACT
Equipment and structures deployed in seawater and other marine environments are susceptible to marine growth. This marine biofouling is one of the critical factors that affects the measurement of continuous real-time data from the oceanographic sensors deployed for long-term observations. To understand the characteristics of biofouling on marine sensors, an investigation was conducted on sensors deployed in a moored buoy network deployed and maintained by the National Institute of Ocean Technology (NIOT) in the Arabian Sea and Bay of Bengal regions. The present paper attempts to elucidate the characteristics of biofouling on sensor components deployed at seven locations in the Bay of Bengal and five locations in the Arabian Sea, at varying depths ranging from the surface to 500-m depth. Biofouling on bare sensor surfaces and surfaces with various antifouling measures has been studied for 2 consecutive years (2015 and 2016), and the effect of antifouling measures is discussed in this paper. Among the locations studied, buoys deployed in the Arabian Sea exhibited a higher biofouling load compared to the buoys deployed in the Bay of Bengal. The study showed that the pedunculate barnacles *Lepas anatifera* Linnaeus, 1758, was the predominant biofouling species on these sensors. Furthermore, observations show that the use of copper- and zinc-based antifouling methods reduced the incidence of biofouling by 59% on average.

Keywords: marine sensors, biofouling, antifouling, marine coatings

Introduction
Marine biofouling is the rapid and undesirable biological growth (i.e., settlement of microorganisms, plants,algae, and/or animals) on structures exposed to the marine environment (Delauney et al., 2010; Nurioglu et al., 2015). The first event in the sequence of biofouling of a surface is the accumulation of an organic conditioning film comprising chemical compounds (mostly protein and polysaccharides) changing the physiochemical properties of the surface. Adsorption of macromolecules such as protein, polysaccharides, and suspended solids forms the conditioning film, which is the primary fouling event that changes the physicochemical properties of the surface and initiates the fouling process. It is followed by a secondary fouling event of colonization by bacteria involving two distinct phases—a reversible phase (adsorption) where van der Waals forces hold it loosely and a nonreversible phase (adhesion) where exopolymers are secreted forming biofilms, which hold the bacteria to the surface (Venkatesan et al., 2006). The biofilm formation aids in recruitment of macrofouling organisms, which form the tertiary event of biofouling. Macrofouling species are represented by barnacles, goose barnacles, mussels, and serpulids, leading to heavy growth on the unprotected surfaces. The prevention, occurrence, and relapse of the fouling events appear to depend on the physicochemical and surface properties of the substratum concerned (Vedaprakash, 2013).

Biofouling formation is one of the critical factors that affects the quality of the data and increases the weight of the buoy hull and marine sensors, thus resulting in high mooring loads (Det Norsok Veritas [DNV], 2010). Growth of macrofoulers obstructs the water flow to the sensors, thereby obstructing the sensor function, while slime formation by microfoulers on the inner surfaces of conductivity cells drastically weakens their measurement capabilities, which results in sensor measurement drift, hence increasing the maintenance frequency. Thus, biofouling is of utmost concern to offshore moored buoy operators, and consequently, the antifouling measures assume greater significance and are a necessity. The major benefit of antifouling strategies includes preservation of measurement quality by safeguarding the measuring instruments from the microorganisms;
they should have lower power consumption to preserve the endurance of the observation platform and reliability of the system in hostile conditions (Laurent et al., 2009). This necessitates the development of an alternative environmental-friendly antifouling technology.

The National Institute of Ocean Technology (NIOT), having carried out more than 600 moored buoy system deployments during the period of 1997–2015, has found that biofouling is one of the major challenges in the maintenance of buoys, and collection of quality data from these buoys has been affected immensely as a result of biofouling growth. Hence, attempts are being made to deploy sensors with antifouling measures and to study their effect on biofouling. This paper attempts to elucidate the characteristics of biofouling on bare marine sensors, sensors installed with antifouling protection mounted on moored buoys that are deployed by NIOT.

Materials and Methods

Experimental Systems

Biofouling observation data and sensor data were obtained from buoys deployed by NIOT in the Arabian Sea (AS) and in the Bay of Bengal (BoB), during the years 2015 and 2016. The latitude, longitude, and distance from the coast for these 12 buoy systems are mentioned in Figure 1, where AD and BD refer to the AS data buoy and BoB data buoy, respectively. These buoy systems are of similar design, collect meteorological parameters above the sea surface and oceanographic parameters below the sea surface, and transmit in real time (Venkatesan et al., 2013). The subsurface conductivity and temperature (CT) sensor made of titanium casing is placed on an induction mooring up to 500 m at strategic depths such as 1, 5, 10, 15, 20, 30, 50, 75, 100, 200, and 500 m. Most of the data buoys are moored 200 nm (nautical miles) away from the coast in both AS and BoB.

FIGURE 1
Moored buoy systems network deployed in Indian waters.

FIGURE 2
Antifouling measures taken in moored buoy systems.
As the moored buoy systems are deployed in the deep ocean locations for more than a year, few antifouling methodologies were implemented in NIOT moored buoy systems to protect the sensors from biofouling, as shown in Figure 2. Most of the techniques used for biofouling protection in AS and BoB for our moored buoys were physical methods (Lehaitre et al., 2008) such as copper tape, copper guards, clear packing tape wrap, antifouling coatings, protective antifouling sleeves, and so forth.

Copper Tape
A thin copper foil wrapped over clear packing tape was used on the casing of CT sensors, as copper is toxic at high concentrations to microbial antifouling properties. The outer layer of tape itself was largely responsible for the biofouling resistance, and when freely corroding under quiet conditions, the oxide film would gradually convert to cupric hydroxide (Parvizi et al., 1998). This layer was considered to be less adherent; after a time, it would slough away leaving a protective cuprous oxide film exposed again.

After retrieval, the clear tape acts as a barrier and makes removal of the old copper tape much easier.

Copper Sensor Guard
CT sensors supplied with titanium protection guards by the original equipment manufacturer have the guards replaced with pure copper to control fouling; as copper corrodes in seawater, oxidized molecules release into the water rather than remain on the metal surface, which prevents fouling organisms from attaching effectively.

Clear Packing Tape Wrap
In a few of the moored buoy systems, clear packing tape was wrapped on the casing of the CT sensor and was tested for antifouling properties. This technique also proved good in certain ways as it makes easier the removal of fouling after retrieval.

Antifouling Coatings
Specialized paint with a hybrid TBT-free self-polishing antifouling system incorporating unique copper acrylate technology has been applied on the buoy components like the hull, instrument housing, and so forth and have proved to slow down the growth of subaquatic organisms that may attach to the buoy components. These coatings also have anti-corrosive properties and improve the flow of water past the buoy components due to the hard, smooth, and polished surface.

Zinc-Based Coatings
DESTITIN, a zinc oxide-based coating, is used as a protective barrier to prevent biofouling formation on the transducer face as well as a coupling between the water and transducer face.

Although the above five methods have been applied, the present paper discusses observations on the antifouling effects of copper tape, copper sensor guards, and clear packing tape wrap. Exposed components and their respective area of exposure are given in Table 1.

Biofouling Observations and Analysis
Moored marine sensors were retrieved for observation and maintenance after a period of 1 year. The sensors of all the locations and depths of deployment were observed for biofouling, and data on biofouling area coverage (% area coverage) and biofouling load (kg/sensor) were recorded, according to Vedaprakash et al. (2013) and Venkatesan et al. (2017). For calculating biofouling load, weight accumulated on the sensors as a result of fouling was estimated by subtracting the initial weight of the sensors from the final wet weight of sensors along with fouled organisms. The data were further analyzed to compare the biofouling intensity.

### TABLE 1

<table>
<thead>
<tr>
<th>Exposed Components/Sensors</th>
<th>Area of the Component ($m^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hull</td>
<td>1.66</td>
</tr>
<tr>
<td>Cylinder</td>
<td>0.79</td>
</tr>
<tr>
<td>CT sensor</td>
<td>0.09</td>
</tr>
<tr>
<td>Copper guard coverage area in CT sensor</td>
<td>0.02</td>
</tr>
<tr>
<td>Copper tape coverage area in CT sensor</td>
<td>0.06</td>
</tr>
<tr>
<td>Clear tape coverage area in CT sensor</td>
<td>0.06</td>
</tr>
<tr>
<td>DVS sensor</td>
<td>0.20</td>
</tr>
<tr>
<td>Transducer face area in DVS sensor</td>
<td>0.01</td>
</tr>
<tr>
<td>ADCP sensor</td>
<td>0.69</td>
</tr>
<tr>
<td>Transducer face area in ADCP sensor</td>
<td>0.10</td>
</tr>
</tbody>
</table>
between the locations of deployment (AD and BD), between years of study, and between bare sensors and sensors installed with antifouling devices. The data were analyzed with Microsoft Excel and KYPLOT version 2.0 beta 15 (32-bit) software. Microsoft Excel 2007 was used to plot graphs.

Results

Biofouling Observations on Sensors

Biofouling observed on sensors at different depths in a moored buoy system is shown in Figure 3. The subcomponents and sensor surfaces of the moored buoy system were observed to be affected by biofouling settlements that led to a drift in the measurements. Conductivity measurement of a sensor (AD08) at 15-m water depth from the MSB 12N/69E was found to be affected due to biofouling (Figure 4a). Also, the output of the sensor (AD07) in MSB 15N/69E (operational for 128 days from June 26, 2016, to November 1, 2016) installed at 10-m water depth was affected after 3 months of deployment (Figure 4b). In deep sea buoy systems, biofouling was observed on the mounted sensors till 50-m depth and seldom till 75-m depth in both the AS and BoB. All the sensors retrieved were fouled by Lepas anatifera Linnaeus, 1758, commonly known as the pelagic goose-neck barnacle or smooth gooseneck barnacle.

Comparison of Biofouling Between AS and BoB Data Buoys

A comparative study on the biofouling load of sensors at different depths in both the AS and BoB on a spatial scale at different depths was made, and the data are presented in Figures 5 and 6, respectively. Among the sensors studied, the biofouling load on buoys moored in the AS were higher (5.63 ± 2.13 kg/sensor [in 2015], 3.60 ± 1.93 kg/sensor [in 2016]) compared to the sensors deployed in the BoB (0.98 ± 0.66 kg/sensor [in 2015], 0.31 ± 0.20 kg/sensor [in 2016]). The highest biofouling load of 9 kg/sensor was observed in
the AS compared to the highest of 4 kg/sensor in BoB, suggesting that the fouling in the AS is higher compared with the fouling in the BoB. Biofouling was very low or nil beyond a 75-m depth in both BoB and AS locations.

**Comparison of Biofouling Between Bare Sensors and Sensors With Antifouling Devices**

The antifouling methods discussed were exposed to an open ocean environment for long periods and were able to assist in reducing fouling during retrieval. A performance comparison of antifouling techniques used on oceanographic sensors is shown in Table 2. Observations made for the 2 consecutive years 2015 and 2016, with and without antifouling measures, revealed that the percentage of fouling coverage over the sensor area was reduced by 50–70% when an antifouling measure was implemented.

A comparison between bare sensors and those installed with antifouling devices shows that the biofouling load was lower in sensors installed with antifouling devices (1.00 ± 0.34 kg/sensor) compared to the sensors without any antifouling device (2.45 ± 1.69 kg/sensor) (Figure 7). Sensors installed with antifouling devices

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**TABLE 2**

Performance comparisons of antifouling techniques for oceanographic sensors.

<table>
<thead>
<tr>
<th>SI No.</th>
<th>Antifouling Method</th>
<th>Fouling Coverage Over the Sensor Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Antifouling Measures</td>
<td>With Antifouling Measures</td>
</tr>
<tr>
<td>1</td>
<td>Copper tape</td>
<td>70–100%</td>
</tr>
<tr>
<td>2</td>
<td>Copper sensor guard</td>
<td>70–100%</td>
</tr>
<tr>
<td>3</td>
<td>Clear packing tape wrap</td>
<td>70–100%</td>
</tr>
<tr>
<td>4</td>
<td>Antifouling coatings</td>
<td>30–80%</td>
</tr>
<tr>
<td>5</td>
<td>Zinc-based coatings on transducer head</td>
<td>60–90%</td>
</tr>
</tbody>
</table>
such as copper guard (Figure 8), copper tape (Figure 9), and zinc-based grease (Figure 10) demonstrated lower biofouling compared to bare sensors and surfaces. Also, the copper taping reduced the fouling on the housing of the sensor, which facilitates easy cleaning of the sensors. Furthermore, observations show that the use of copper- and zinc-based antifouling methods reduced the incidence of biofouling by 59%, on average.

Zinc-based grease applied to the heads of an acoustic Doppler current profiler (ADCP) was also found to inhibit biological growth on bottom-mounted frames. Upon recovery of the ADCP, it was observed that barnacle growth was found to be reduced considerably on the acoustic heads.

The sensors on moored buoy systems wrapped with clear packing tape also exhibited reduced biofouling growth. This simple physical method would facilitate easy removal of biofouling growth after retrieval.

**Discussion**

Development of fouling assemblages on various substrates has been studied for several decades, both toward understanding the variation in community succession (Butler & Connolly, 1996; Vedaprakash, 2013) and developing antifouling measures (Abarzua & Jakubowski, 1995; Dineshram et al., 2009), in an attempt to extend the performances of marine structures. Biofouling varies enormously without interruption seasonally and geographically throughout the year in tropical waters. Several studies have been conducted worldwide on substrates such as metals, glass, polymers, wood, concrete, different types of paint coatings, and engineered surfaces with altered surface properties to understand the surface dependency of the recruitment process or to identify the fouling-induced damage to surfaces or toward developing antifouling surfaces (Vedaprakash, 2013). The paucity of data on biofouling and the effect of antifouling measures on...
moored data buoys instigated this study.

Biofouling Observations on Sensors

Biofouling is a natural process that can disrupt sensor measurements in less than a week (Delauney et al., 2010). Biofouling protection of marine *in-situ* sensors is a challenging issue that necessitates the application of multifaceted preventive measures. Several studies have been made during the last few centuries to characterize biofouling recruitment on various metals (Vedapракash et al., 2013; Venugopalan & Wagh, 1990), polymers (Muthukumar et al., 2011), antifouling coating (Yebra et al., 2004), engineered antifouling surfaces (Dineshram et al., 2009; Howell & Behrends, 2006), and many other materials and surfaces (Vedapракash, 2013). Most of the studies were made on the experimental panels in the coastal region, which had shown a fouling assemblage represented by barnacles, green mussel, serpulids, macroalgae, and so forth. In the present study, the most distinguishing observation is that the sensors retrieved were found to be predominantly fouled by *Lepas anatifera* Linnaeus, 1758, which is abundant in tropical waters and is found attached to floating objects and other offshore equipment (Castro et al., 1999) and is thus a nuisance to maritime operations (Kathe, 2010).

This observation on the predominance of *Lepas anatifera* corroborates the earlier observation made on the instrumented moored buoy sensors operated in the Northern India Ocean (Venkatesan et al., 2017). This variation in the fouling species between the earlier studies on coastal environment (Sathpathy et al., 2010; Vedapракash et al., 2013) could be attributed to the availability of larvae of the settling species in the local ecosystem, presence of required food, variation in the sunlight penetration over the depth, and so forth, which play a limiting factor for recruitment of many biofouling organisms. The most dominant fouling species on the buoy hull deployed in the open ocean is gooseneck barnacle of *Lepas* sp. (Kathe, 2010). Generally, barnacles are concentrated around the buoy hull, on the rubber fender and edges of sharp corners.

Comparison of Biofouling Between AS and BoB Data Buoys

Biofouling load on the sensors moored in the AS was found to be 80–90% higher compared to that observed in the BoB sensors during the studies made in 2015 and 2016. The increased biofouling load relates to the increased recruitment of the organisms, which could be attributed to the higher sweeter salinity observed in the AS (Gordon, 2015; Jensen, 2001).

The biofouling weight data show that lower depths are prone to high fouling compared to deeper waters. In the present study, the observations show a clear demarcation in the biofouling pattern along the depth of the study, both in the AS and BoB data buoys. Based on the observations, the distribution pattern of biofouling with respect to depth could be broadly categorized into three regions, namely,

- High fouling region (from surface to 30-m depth);
- Medium fouling region (from 30- to 75-m depth);
- No fouling region (above 75-m depth).

This observation concurs with earlier studies that have reported that biofouling organisms are dense on the upper 30 m of underwater structures (Miller et al., 1984; Oldfield, 1980) and that biofouling load is significantly less at 42-m level and below (Venugopalan & Wagh, 1990).

Comparison of Biofouling Between Bare Sensors and Sensors With Antifouling Devices

In this study, copper has shown a 59% reduction in marine biofouling load for long-term sensor deployments in open ocean environments.
and could be used as an effective replacement for the highly toxic TBT-based methods and other less benign antifoulants that are currently in use. Copper has been widely studied for its antifouling property, which is mainly attributed to the toxicity of copper, although another mechanism of “gross exfoliation”—shredding off of thin parallel layers on the copper metal surface, which causes the organisms to lose their hold and get detached—is possible (WHOI, 1952). This view is also supported by earlier studies that copper leaching from surfaces did not prevent barnacle settlement but killed the attached larvae (Crisp & Austin, 1960; Vedaprakash, 2013).

Similarly, the application of zinc-based gel coat reduced the incidence of biofouling, suggesting that the toxic nature of the zinc element prevents biofouling. Despite the fact that copper- and zinc-based antifouling devices release toxic chemicals, the quantum of such release from these tiny structures used for protecting sensors is relatively much less compared to those protecting larger surface areas on floating vessels and off structures; hence, the effect of the leachates on the surrounding environment would be relatively quite negligible. Also, other antifouling measures studied, such as packing tape and plastic sleeves, either were observed to reduce the incidence of fouling or aided in the easy removal of biofouling on retrieval from the data buoys. Few other moored buoy operators around the world have implemented copper- and zinc-based antifouling strategies successfully in the form of modular shutters and copper guards for moored buoy sensors (Dickey et al., 2009; Manov et al., 2004).

Conclusion

This biofouling study carried out on sensor devices deployed in the AS and BoB demonstrated that biofouling settlement is influenced by the environment, depth, and chemical nature of the settlement substrate. The most distinguishing observation is that biofouling on the moored sensors deployed both in the AS and BoB was predominated by Lepas anatifera. This study corroborates the earlier observation that biofouling is a highly varying phenomenon and that surface chemistry, physical properties, and environmental properties play a major role in the density and composition of biofouling settlement. The observations also show that bare sensors are prone to biofouling, while application of antifouling methods, such as copper guard, copper tape, and zinc gel, reduced the settlement and growth of biofouling organisms, depicted by a reduction in biofouling load of 59%. Hence, the study demonstrates that use of copper- and zinc-based antifouling methods could be used as alternative methods to replace the TBT-based toxic antifoulants. Furthermore, elaborate studies could be taken up to optimize the use of various antifouling methods for sustainable long-term biofouling prevention on sensors, a problem that still poses a big challenge.

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Corresponding Author:
Ramasamy Venkatesan
Ocean Observation Systems, National Institute of Ocean Technology, Chennai, India
Email: rvenkatin5@gmail.com

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