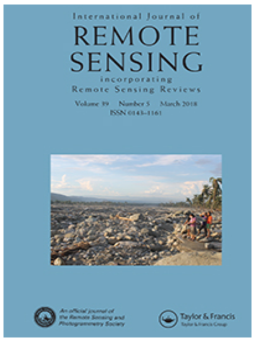

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INSAT-3D and MODIS retrieved sea surface temperature validation and assessment over waters surrounding the Indian subcontinent

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ABSTRACT
The INSAT-3D imager (4 km) and Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on-board Aqua and Terra space-platforms level-2 (1 km) sea surface temperature (SST_{skin}) product accuracy has been analysed over waters surrounding the Indian subcontinent by *indirect comparison method* using collocated bulk *in-situ* measurements (SST_{depth}) for 3 years (October 2013–October 2016). Statistical results show that root mean square error of all the three satellites is in range of around 0.60–0.70°C. Retrieval error is found to be slightly more in case of validation against iQuam data set. INSAT-3D is showing more underestimation with bias ranging from about −0.16°C to −0.20°C than MODIS sensor having bias in range of about 0.06°C to −0.12°C. All the three missions are slightly underestimating over open-ocean with bias ranging in 0–0.17°C. INSAT-3D is significantly underestimating *in-situ* observations over the Arabian Sea (approximate bias = 0.27°C). Seasonal validation analysis reveals relatively high retrieval error during monsoon season than pre-monsoon and post-monsoon seasons. MODIS sensor is showing significant underestimation during monsoon with bias ranging from approximately −0.29°C to −0.58°C. Overall, all the three missions are performing similarly well over the study area.

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1. Introduction

Sea surface temperature (SST) is the most extensively used variable in oceanography. SST is not only an indispensable parameter for study of physical, chemical, and biological characteristics of oceans but it also plays first and foremost role in the atmospheric studies as it commands exchange of heat, momentum, and gases between ocean and atmosphere. To understand the role of ocean biosphere at seasonal-to-decadal time scales, a highly consistent time series of observations is required which is difficult to obtain through conventional *in-situ* measurement techniques for the entire oceanic region. Therefore, to overcome the limitations of *in-situ* measurement techniques, SST retrieval from satellite remote-sensing technique with much improved data coverage is essential.

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More than three decades back, launch of the Advanced Very High Resolution Radiometer (AVHRR) on-board the National Oceanic and Atmospheric Administration series of polar-orbiting satellites has marked the inception of SST retrieval from satellite platform. Since then, many advanced satellite sensors have been introduced for SST retrieval by measuring thermal infrared (TIR) and microwave emission from sea surface successfully serving the purpose to obtain a highly consistent time series of observations. A new generation of imaging radiometer, the Moderate Resolution Imaging Spectroradiometer (MODIS) with improved instrument technology, was launched by National Aeronautics and Space Administration (NASA, USA) in December 1999 on-board Earth Observing System satellite-platform Terra and in May 2002 on platform Aqua. Both Aqua and Terra are polar-orbiting space platforms. In addition to the MODIS sensor, the Aqua satellite also carries the Japan Aerospace Exploration Agency's microwave instrument known as the Advanced Microwave Scanning Radiometer Earth Observing System (AMSR-E). Since the poorly calibrated Scanning Multichannel Microwave Radiometer was launched in 1987, the AMSR-E is the first polar-orbiting microwave radiometer capable of accurately measuring global SSTs (Wentz et al. 2000). Unlike infrared sensors which provide skin SST (approximately 1 μm thick), microwave-derived SSTs are representative of a depth of a few mm below the skin layer of the ocean. Microwave SST retrievals are generally unaffected by non-precipitating clouds, therefore providing better coverage than infrared sensors, but have rather poor accuracy and resolution. As both infrared and microwave SST retrievals have their own pros and cons, researchers are aiming towards compiling SST analyses using both infrared and microwave SST sources as well as *in-situ* data (Guan and Kawamura 2004; Banzon et al. 2014). The MODIS operates in both visible and infrared parts of the electromagnetic spectrum. The MODIS infrared sensors are capable of providing SST data sets at about 4 and 11 μm wavelengths in cloud-free conditions (Minnett et al. 2004) with larger temporal and spatial coverage. Due to high sensitivity and low signal-to-noise ratio of the MODIS instrument, the SST estimates under cloud-free oceanic regions are supposed to be more reliable with retrieval accuracy of about 0.4 K (Kilpatrick et al. 2015). However, to monitor diurnal variability in SST for studying convective systems in tropical regions such as India, geostationary space platforms were required (Mathur et al. 2006). Hence, in July 2013, India launched the INSAT-3D satellite, successor of the Kalpana-1 mission. The INSAT-3D is an exclusive Meteorological Satellite with six-band imager paired with 19-band sounder, deployed in the geostationary orbit. Unlike the Kalpana-1 satellite having single TIR channel, the INSAT-3D imager is using split thermal window channels (10.2–11.3 and 11.5–12.5 μm) for a better SST retrieval during daytime as well as night-time over cloud-free oceanic regions. Recently, to further improve the accuracy of the INSAT-3D SST estimates for near-real-time applications, the synergistic use of MODIS (Aqua) SST estimates was proposed (Prakash et al. 2017). Over the last few years, with the advancement in computational facilities and increased channels in newer sensors, some model-based SST retrieval algorithms have been introduced for providing improved quality of product retrieval along with more data coverage (Koner, Harris, and Maturi 2015; Koner and Harris 2016a; Koner and Harris 2016b). However, currently available operational products are still employing SST algorithms derived through regression techniques in which measurements are directly correlated with geophysical parameters without considering a proper physical model (Koner, Harris, and Maturi 2015).

The infrared radiometry is capable of providing SST measurements with high spatial resolution, but only in cloud-free conditions. Therefore, quality of SST retrievals in the infrared region significantly depends on the cloud detection scheme (Koner, Harris, and Maturi 2016; Koner and Harris 2016a). The remote-sensing observations of SST in the TIR region are subjected to degrade in its accuracy after passage of radiation through the atmosphere where it encounters several environmental factors. The major sources of error include sun glint and absorption due to water vapour, trace gases as well as dust aerosols (Esaias et al. 1998). Therefore, prior to use any satellite data for study or research purpose, it is mandatory to confirm the accuracy of the satellite product using the most reliable *in-situ* measurements from ships and buoys (Emery and Yu 1997; Peng and Yanchen 2008). One of the major challenges in the direct validation of satellite skin SST product is that it requires *in-situ* skin SST measurements and it is difficult to develop, maintain, and deploy such an instrument. Very few *in-situ* measurements of the surface skin temperature are made on a regular basis. Consequently, most of the researchers are performing indirect SST validation that is based on the comparison of satellite skin SST (depth < 1 mm) with *in-situ* bulk SST (depth around 0.5–5 m) measurements at a specified depth known as *in-situ* SST_{depth}. However, the indirect validation approach using *in-situ* SST_{depth} is appropriate only when wind speed is greater than 6 m s^{-1} (Donlon et al. 2002) resulting in increment of mixed layer depth homogenizing the temperature structure in the upper ocean. Low winds and strong net heat fluxes into the ocean can result in noticeable diurnal variations of SST signals up to several degrees of Celsius which may be confined only at the surface but fails to reach at typical *in-situ* observation depths (Reynolds 1988). The diurnal variation in SST is noticeable if solar radiation is greater than 150 W m^{-2} and sea surface wind is less than 6 m s^{-1} (Hosoda et al. 2007). The air–sea interaction is responsible for modifications in the relationship between bulk and skin SSTs causing an observable difference between them (Schluessel et al. 1990). Generally, it is expected that skin temperature is around 0.3°C colder than the layer directly below the skin of the ocean (Webster, Clayson, and Curry 1996) and satellite analysis is approximately 0.5°C colder than the *in-situ* SST (Reynolds 1988). As a result of absorbing aerosols from volcanic eruptions, even a negative bias of over 2°C in the satellite SST retrievals has been reported (Strong 1983). This reveals that the difference between the skin and the bulk SSTs is not constant and has a short spatial as well as temporal variations. These variations mainly depend upon the prevailing atmospheric conditions including wind-speed and net air–sea heat fluxes (Wick et al. 1996).

In this article, the authors are reporting the results of 'indirect validation' of the INSAT-3D and the MODIS (Aqua and Terra) SST product by comparing the satellite measurements with two independent *in-situ* SST data sets under strong wind conditions (>6 m s^{-1}) for 3 years (October 2013–October 2016) over the waters of Indian subcontinent including the Arabian Sea and the Bay of Bengal. In addition, evaluation of the performance of all three satellites during pre-monsoon (January–April), monsoon (May–August), and post-monsoon (September–December) seasons has also been carried out by comparing satellite data sets with corresponding *in-situ* data sets for these three different seasons.

2. Data and methodology

2.1. *Study area*

The *in-situ* measurements are done at different geo-locations in coastal as well as open ocean regions of the Indian subcontinent which can be further divided into two regions – the Arabian Sea and the Bay of Bengal. Although the Arabian Sea and the Bay of Bengal share several similarities such as their location on the same latitude band, exposure to the changing monsoon winds, getting similar amount of solar radiations at the top of the troposphere, etc., there are striking differences between the two regions in terms of their climatological aspects leading to the evolution of their SST (Shenoi, Shankar, and Shetye 2004). The north Indian Ocean becomes the warmest among the world oceans before the onset of summer–monsoon (April–May) (Joseph 1990). However, soon after the onset of summer–monsoon (during June), the Arabian Sea cools rapidly under the influence of strong winds while SST of the Bay of Bengal remains higher than 28°C and throughout the summer–monsoon the Bay of Bengal remains warmer than the Arabian Sea (Shenoi, Shankar, and Shetye 2004). The contrasting nature of the Arabian Sea and the Bay of Bengal evokes an interest to carry out their comparative study. Hence, in this validation exercise, we have evaluated the performance of all the three satellites with respect to *in-situ* SST measurements over the collective waters surrounding the Indian subcontinent as well as over the individual waters of the Arabian Sea (5°–25° N; 65°–78° E) and the Bay of Bengal (5°–25° N; 78°–92° E) regions.

2.2. In-situ *data collection*

In this study, the *in-situ* SST data sets from two independent sources have been used in order to verify the validation results. One set of *in-situ* SST data is obtained from Indian moored buoy (IMB) network provided by Indian National Centre for Ocean Information and Services and the other one is iQuam (*in-situ* SST Quality monitor) data set developed in National Environmental Satellite Data and Information Services/Centre for Satellite Applications and Research that has been downloaded from website, http://www.star.nesdis.noaa.gov. The corresponding *in-situ* wind speed observations have also been considered along with SST measurements. Only the SST measurements with wind speed more than 6 m s^{-1} are considered for this validation exercise while all other measurements are completely ignored so that a homogeneity between SST_{skin} and SST_{depth} could be obtained.

The sensor of IMBs is at around 3 m depth below the sea surface and is capable of measuring SST in the range of −5–45°C with an accuracy of ±0.1°C and the resolution of 0.01°C. There are total 17 IMBs used in this study. Ten IMBs (nine open ocean buoys and one coastal buoy) are located in the Arabian Sea while seven IMBs (six open ocean buoys and one coastal buoy) are located in the Bay of Bengal region. Unlike IMB network, the iQuam data set has been collected worldwide at different geolocations including open-ocean as well as coastal waters of the Indian subcontinent. The iQuam data set comprises *in-situ* observations from a large number of platforms including conventional drifters, high-resolution drifters, tropical moorings, coastal moorings, coral reef watch (CRW) buoys, conventional ships, and IMOS ships. The data are collected

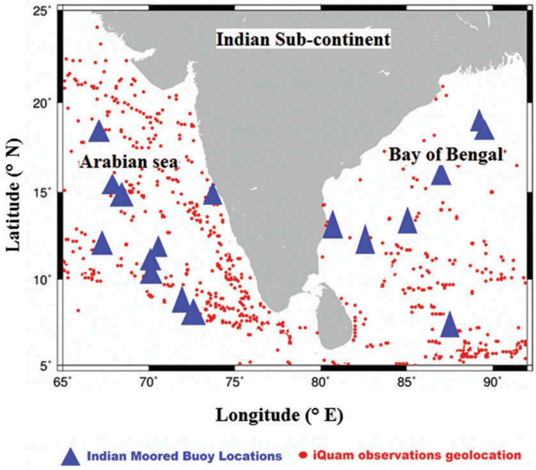

Figure 1. Geolocations of the Indian moored buoy (IMB) network (indicated by solid triangles) and the iQuam observations (indicated by solid circles) within the study region.

at a typical depth of about 3–7 m with an accuracy of approximately ±0.3°C (for more details of iQuam data set, refer to Feng and Ignatov 2014). The iQuam SST data set is assigned with certain quality levels ranging from 0 to 5. The data set quality improves with increase in the quality level. Therefore, the best quality data set with quality level 5 is used for this study. Figure 1 is showing geolocations of the IMB network and the iQuam observations over the study region.

2.3. *Satellite data*

Level-2 SST product retrieved from the INSAT-3D and the MODIS sensors for 3 years (October 2013–October 2016) have been used for this validation exercise. The INSAT-3D imager SST data product has been obtained from Meteorological and Oceanographic Satellite Data Archival Centre website, http://www.mosdac.gov.in, at a spatial resolution of 4 km. The SST data sets from MODIS sensor with 1 km of spatial resolution have been obtained from the NASA Ocean Biology Processing Group website, http://www.oceancolor.gsfc.nasa.gov. The technical specifications of INSAT-3D and MODIS sensors have been mentioned in Table 1.

The computation of SST during daytime and night-time, for cloud-free pixels from INSAT-3D imager, has been done using the following algorithm,

$$\mathrm{SST} = A_0 + A_1 \times T_{11} + A_2 \times \mathrm{d}T + A_3 \times \mathrm{d}T^2 \quad (1)$$

where A_0, A_1, A_2, and A_3 are satellite zenith angle dependent coefficients determined by radiative transfer model.

$$\mathrm{d}T = T_{11} - T_{12}$$

where T_{11} and T_{12} are brightness temperatures for the split-window channels.

A suitable radiative transfer-based approach was also implemented for the atmospheric corrections for obtaining more reliable SST estimates (Mathur et al. 2006).

Table 1. Major characteristics of the INSAT-3D and the MODIS sensors.

Parameters	INSAT-3D	MODIS
Orbit	Geostationary (Altitude – 36,000 km) at 82° E	Sun-synchronous, near-polar, circular (705 km) *Terra* – 10:30 a.m. (descending node) *Aqua* – 01:30 p.m. (ascending node)
Revisit time	26 min	1–2 days
Spatial resolution	1 km (Vis, SWIR) 4 km (MIR, TIR) 8 km (water vapour)	250 m (bands 1 and 2), 500 m (bands 3–7), 1000 m (bands 8–36)
Spectral bands	Vis, SWIR [a]MIR: 3.80–4.00 (μm) Water vapour [a]TIR 1: 10.20–11.30 (μm) [a]TIR 2: 11.50–12.50 (μm)	B1–B19 [a]B20: 3.750 μm [a]B22: 3.959 μm [a]B23: 4.050 μm B24–B30 [a]B31: 11.030 μm [a]B32: 12.020 μm B33–B36
Quantization bits	10	12

[a]Meant for SST observations.

The MODIS Level 2 global SST (MOD28) is a 1 km clear-sky IR SST product (Brown and Minnett 1999), which is derived using an atmospheric correction algorithm based on the AVHRR non-linear SST algorithm (Walton 1988). The form of the daytime and night-time algorithm is

$$\mathrm{SST} = c_1 + c_2 \times T_{11} + c_3 \times (T_{11} - T_{12}) \times T_{\mathrm{sfc}} + c_4 \times (\sec(z) - 1) \times (T_{11} - T_{12}) \qquad (2)$$

where T is brightness temperatures measured in the channels at n μm wavelength, T_{sfc} is the first guess SST, and z is the satellite zenith angle.

2.4. *Bathymetric data*

The modified ETOPO2 bathymetric data (Sindhu et al. 2007) have been obtained from the National Institute of Oceanography website, http://www.nio.org.

For the validation of satellite SST against *in-situ* measurements, the satellite data sets are collocated over *in-situ* observations within a spatial window of 12 × 12 km (±6 km) with a relaxation of ±0.5 h of particular satellite scan time. The collocated SST data sets are further collocated with the bathymetric data set in order to carry out comparative validation over the coastal waters (<300 m depth) and the open-ocean (>300 m depth) surrounding the Indian subcontinent.

The MODIS SST data sets corresponding to the quality level-0 (the best quality) have been used while in case of INSAT-3D, for minimizing the impact of low level clouds (LLCs) on retrieval accuracy, the satellite observations have been filtered out on both temporal and spatial bases. The satellite observations occurring within ±1.25°C of hourly mean value of *in-situ* SST observations for each month are taken into consideration. Further, the satellite data set is gridded having grid size of 1°× 1. Then, the satellite observations within each grid having mean value in the range of ±1σ (standard deviation) are ultimately considered for the validation activity.

The retrieval error has been estimated by calculating root mean square error (RMSE) and bias as per the following formula,

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\text{SST})_{\text{satellite}} - (\text{SST})_{in-situ}{}^{2}} \qquad (3)$$

$$\text{Bias} = \sum_{i=1}^{N}\frac{(\text{SST})_{\text{satellite}} - (\text{SST})_{in-situ}}{N} \qquad (4)$$

where N is the total number of collocated data points.

3. Results and discussion

3.1. *Validation of satellite SST against* in-situ *observations surrounding the Indian subcontinent*

In general, the retrieval error (RMSE) of all the three satellites w.r.t. *in-situ* observations is in the range of around 0.60–0.70°C. Figures 2(a,b) show combined density plots for all the 3 years (October 2013–October 2016) indicating overall statistics of satellite validation against *in-situ* measurements. The retrieval error is observed to be slightly higher in case of satellite SST validation against iQuam data set (RMSE ranging in 0.67–0.70°C) as compared to IMB *in-situ* SST data set (RMSE ranging in 0.60–0.66°C). The value of coefficient of determination (R^2) is also lower in case of validation against iQuam data set (0.55–0.71) than that against IMB data set (0.64–0.76). Like satellite observations, *in-*

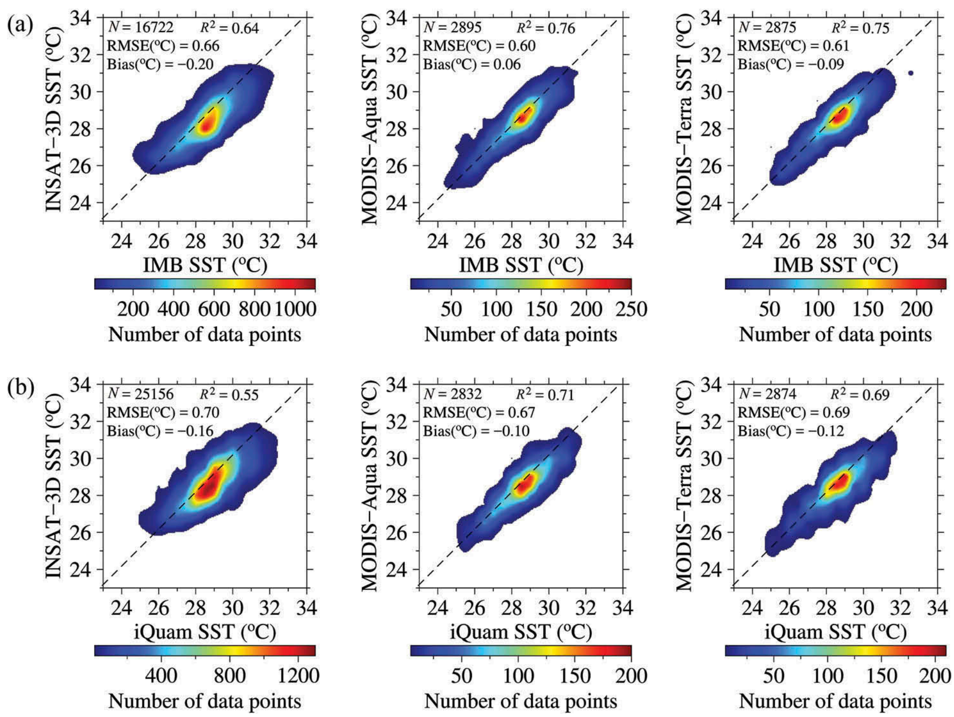

Figure 2. Density plots of the satellite SST validation against (a) the IMB *in-situ* SST measurements and (b) the iQuam *in-situ* SST measurements.

situ SST observations are also never fully accurate (Feng and Ignatov 2010) and are subjected to variations in their accuracy. However, the accuracy of buoy SST observations is usually better than 0.5°C (Reynolds 2001) which in turn is much better than the SST measurements taken through ships having typical RMSE larger than 1°C (Kent, Challenor, and Taylor 1999). The use of ship-borne measurements may introduce errors of depth variations and may impact the accuracy of the SST retrievals (Donlon et al. 2002). In order to confirm the accuracy of iQuam SST w.r.t. IMB SST, the former *in-situ* data set was collocated within a spatial window of ±1 km and temporal window of ±0.5 h of particular IMB SST observation. Although both *in-situ* SST data sets (IMB SST and iQuam SST) are found to be in good agreement (R^2 = 0.92) showing RMSE of about 0.34°C with a negligible bias of less than 0.01°C, use of conventional ships and IMOS ships in case of iQuam could probably lead to slight inaccuracy in the iQuam *in-situ* SST data set. The additional errors may be induced during transmission and processing stages of *in-situ* measurements.

It has already been mentioned previously that the iQuam data set comprises *in-situ* observations from a large number of platforms including drifters, moorings, and ships. It is also well known that sensor accuracy differs greatly across these platform types. Therefore, it is imperative to determine the statistics of satellite SST validation against iQuam SST data set associated with each individual platform. Moreover, this exercise would be beneficial to confirm the exact reason behind inaccuracy in the iQuam *in-situ* SST data set. Table 2 shows combined statistical analysis of satellite SST validation against iQuam SST data set associated with each individual platform for all 3 years. In general, quality-controlled iQuam data set is globally obtained from eight different types of platforms, namely (1) ships (conventional), (2) drifting buoys (conventional drifters), (3) tropical mooring buoys (TMB), (4) coastal mooring buoys (CMB), (5) argo floats, (6) high resolution drifters, (7) IMOS ships, and (8) CRW buoys. Out of these eight platforms, the entire iQuam data set over this study region is found to be associated with only three platforms, namely conventional ships, TMB, and CMB. The statistical results clearly reveal that all three satellite sensors are showing higher RMSE (0.78–0.94°C) and least R^2 (0.32–0.66°C) when validated against iQuam SST data set obtained from conventional ships. On the other hand, satellite SST validation against TMB and CMB data sets is showing comparable results with RMSE ranging from 0.52°C to 0.65°C and R^2 ranging from 0.62°C to 0.79°C. The satellites are found to be underestimating SST obtained from all three platforms. Unlike the INSAT-3D which is having near similar RMSE (0.63–0.78°C) and bias (−0.16°C to −0.20°C) in case of all three *in-situ* platforms, the MODIS is showing considerably high retrieval error (RMSE = 0.84–0.94°C, bias = −0.20°C to −0.25°C) in case of validation against ship data set as compared to that against the other two platforms

Table 2. Satellite SST validation against iQuam *in-situ* SST dataset associated with each individual platform.

	INSAT-3D *versus* iQuam SST			MODIS-Aqua *versus* iQuam SST			MODIS-Terra *versus* iQuam SST		
	Ship	TMB	CMB	Ship	TMB	CMB	Ship	TMB	CMB
N	6431	7785	10,940	483	1428	921	1115	647	1112
R^2	0.32	0.62	0.63	0.59	0.75	0.74	0.66	0.71	0.79
RMSE (°C)	0.78	0.63	0.65	0.94	0.60	0.61	0.84	0.52	0.54
Bias (°C)	−0.18	−0.20	−0.16	−0.20	−0.10	−0.07	−0.25	−0.06	−0.03

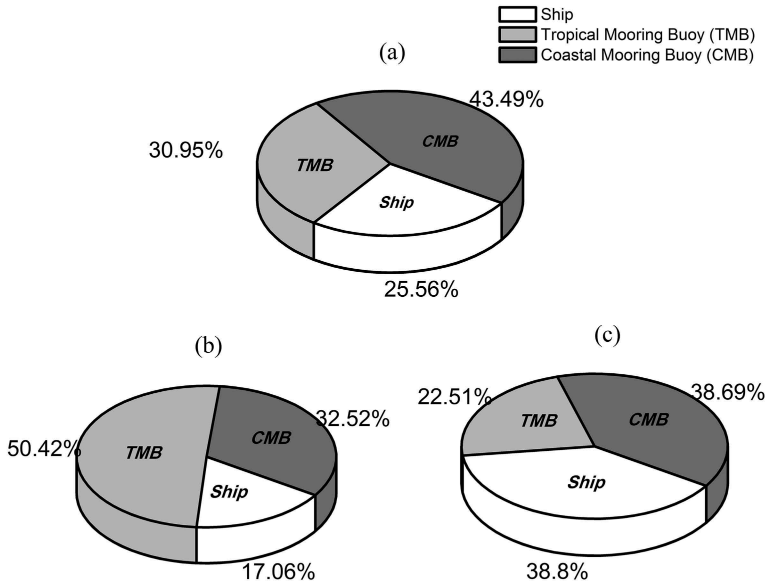

Figure 3. Percentage of match-up observations obtained on validation of (a) INSAT-3D, (b) MODIS-Aqua, and (c) MODIS Terra-retrieved SST against iQuam SST associated with individual platform.

(RMSE = 0.52–0.61°C, bias = −0.03°C to −0.10°C). Figure 3 is showing percentage of match-up observations obtained on validation of satellite SST against iQuam SST associated with individual platform. Since the iQuam *in-situ* SST data sets obtained from all three platforms are significantly contributing to the validation statistics, therefore collective iQuam data set from all three platforms has been used for further study and analysis.

Figures 4(a,b) show combined frequency histogram for all 3 years for the temperature difference between satellite observations and *in-situ* measurements. The temperature difference is in the range of −2.5°C to +2.5°C. In case of almost all three satellites, maximum number of satellite observations is found to be underestimating the *in-situ* SST observations. Overall, approximately 46–61% of the total collocated satellite SST data set is showing underestimation w.r.t. *in-situ* SST observation. In particular, around 58–61% observations of INSAT-3D are showing underestimation while in case of MODIS sensor, around 46–58% observations are indicating underestimation. A significant number of INSAT-3D observations are showing temperature difference w.r.t. *in-situ* observations in the range of −1–0.5°C. On the other hand, maximum number of MODIS observations are showing temperature difference in the range of −0.5–0.5°C.

Year-wise statistical analysis shows a consistency in the retrieval accuracy of all the three satellites (Table 3). In case of satellite SST validation against iQuam *in-situ* data sets, the range of RMSE for the INSAT-3D is approximately 0.67–0.71°C while for the MODIS, the RMSE range is around 0.64–0.69°C. The underestimation of SST is found to be relatively more in case of the INSAT-3D sensor with bias ranging around −0.18°C to −0.23°C as compared to the MODIS sensor having bias in the range of about −0.11°C to −0.17°C. Similarly, the results of satellite SST validation against IMB *in-situ* data sets show that the approximate range of RMSE for the INSAT-3D and the MODIS sensor are 0.64–

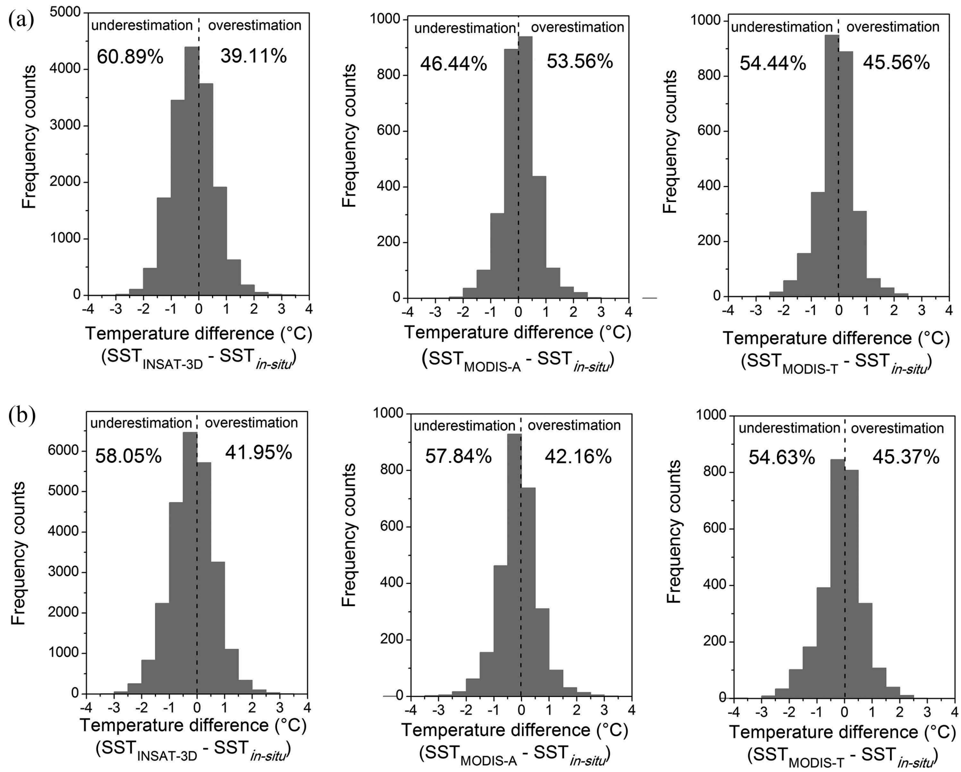

Figure 4. Frequency histogram for temperature difference between the satellite observations and (a) the IMB *in-situ* SST measurements and (b) the iQuam *in-situ* SST measurements.

Table 3. Validation of the satellite SST against *in-situ* SST measurements surrounding the Indian subcontinent.

	INSAT-3D *versus in-situ*			Aqua *versus in-situ*			Terra *versus in-situ*		
	2013–14	2014–15	2015–16	2013–14	2014–15	2015–16	2013–14	2014–15	2015–16
a. Satellite validation against the iQuam data set									
N	4500	11,718	8941	1086	1204	544	880	1186	808
RMSE (°C)	0.71	0.67	0.70	0.65	0.68	0.69	0.66	0.67	0.64
Bias (°C)	−0.21	−0.23	−0.18	−0.12	−0.11	−0.17	−0.16	−0.13	−0.16
b. Satellite validation against the IMB data set									
N	3868	7592	5263	1026	1257	610	924	1164	784
RMSE (°C)	0.68	0.64	0.65	0.57	0.59	0.58	0.55	0.63	0.56
Bias (°C)	−0.27	−0.29	−0.24	0.04	0.07	0.01	−0.10	−0.10	−0.05

0.68°C and 0.55–0.63°C, respectively. Again, the INSAT-3D is showing relatively more underestimation with bias ranging from −0.24°C to −0.29°C as compared to MODIS sensor having bias in the range of −0.10–0.07°C, approximately. The probable reasons behind relatively higher retrieval error in case of the INSAT-3D sensor could be the detector-to-detector non-uniform response in the TIR channels of imager giving rise to a horizontal striping impact in TIR-1 as well TIR-2 images. Moreover, the poorer pixel resolution of INSAT-3D leads to more uncertainty in cloud detection, especially the LLCs. The LLCs and the sea surface are having similar cloud-top temperature leading to inaccuracy in satellite SST retrieval. In general, the LLCs are dominated in the first 3 km over the Arabian Sea and the Bay of Bengal throughout the year and continue to form even during development of high clouds probably due to the presence of larger aerosols concentration (Dey et al. 2015). Further, the uncertainty in on-board calibration and fine tuning of the SST algorithm contribute to inconsistency in the INSAT-3D imager channels (Mathur et al. 2015).

3.2. *Validation of satellite SST against* in-situ *observations over coastal and open-ocean regions of the Indian subcontinent*

It is a well-known fact that coastal regions are characterized by hydrodynamic turbulence at smaller scales as compared to that in open-ocean regions. The satellite SST data sets from the INSAT-3D and the MODIS sensors are validated against the iQuam and the IMB *in-situ* observations over the coastal (<300 m depth) as well as the open-ocean (>300 m depth) regions of the Indian subcontinent. Figure 5 (generated using *Modified ETOPO2* bathymetry data) shows bathymetry of the Arabian Sea and the Bay of Bengal demarcating the coastal and the open-ocean regions. The major objective of this exercise is to evaluate and compare the performance of each satellite over the coastal and the open-ocean waters of the Indian subcontinent.

Table 4 shows combined statistics of the satellite SST validation against *in-situ* measurements for all the 3 years over coastal and open-ocean regions of the Indian subcontinent. The results of validation against the iQuam data set show that RMSE for the INSAT-3D is around 0.70°C over coastal and open-ocean regions while the range of RMSE for the MODIS sensor is found to be 0.78–0.87°C over coastal waters and 0.64–0.69°C over open ocean. On the other hand, validation against the IMB data set shows that RMSE for the INSAT-3D is 0.66°C over coastal as well as open-ocean regions while

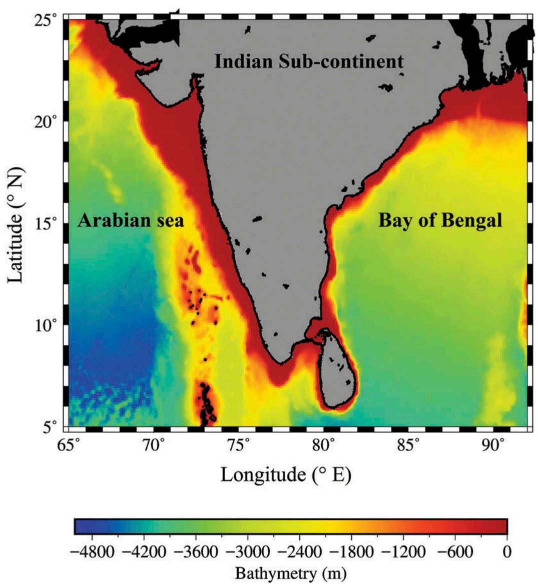

Figure 5. Bathymetry map of the Arabian Sea and the Bay of Bengal.

Table 4. Validation of the satellite SST against *in-situ* SST measurements over the coastal and the open-ocean regions.

	INSAT-3D *versus in-situ*		Aqua *versus in-situ*		Terra *versus in-situ*	
	Coastal region	Open ocean	Coastal region	Open ocean	Coastal region	Open ocean
a. Satellite validation against the iQuam dataset						
N	2209	12,823	190	1106	251	1252
RMSE (°C)	0.70	0.69	0.78	0.64	0.87	0.69
Bias (°C)	−0.02	−0.17	0.18	−0.16	0.05	−0.15
b. Satellite validation against the IMB data set						
N	2189	8553	219	969	200	939
RMSE (°C)	0.66	0.66	0.54	0.59	0.47	0.60
Bias (°C)	0.02	−0.13	0.17	0.01	0.13	−0.12

the MODIS sensor is indicating RMSE in the range of 0.47–0.54°C and 0.59–0.60°C over coastal waters and open ocean, respectively. Over open ocean, almost all the three satellites are slightly underestimating the *in-situ* SST observations with bias ranging in 0.13–0.17°C for the INSAT-3D and 0–0.16°C for the MODIS sensor probably due to contamination by LLCs and absorbing (dust) aerosols. In contrast, over coastal waters, the INSAT-3D is having a negligible bias (±0.02°C) while the MODIS sensor is slightly overestimating the *in-situ* SST observations showing bias in the range of 0.05–0.18°C. Overall, there is no significant difference in the retrieval error between coastal and open-ocean waters for all the three missions. Unlike satellite microwave data, efficient for mainly non-coastal SST retrieval, the higher spatial resolution of infrared radiometry can avoid contamination by shorelines and tend to resolve the smaller hydrodynamic turbulence scales, thereby providing reliable SST estimates in coastal regions as well. The minor differences observed in retrieval error could plausibly be due to the difference in the number of observations found over the coastal and the open-ocean regions. The number of observations over coastal waters is significantly less (around four to six times) than that over open ocean. However, RMSE is again found to be higher in case of satellite SST validation against the iQuam data set as compared to the IMB *in-situ* SST data set and the probable reason behind this is already discussed in Section 3.1. Furthermore, sometimes coastal regions are too shallow and dynamic to obtain stable *in-situ* SST observations for the use in satellite calibration or validation (Feng and Ignatov 2010). Hence, instability in the iQuam *in-situ* observations over coastal waters may probably contribute to higher RMSE for the MODIS sensor (0.78–0.87°C).

3.3. *Validation of satellite SST against* in-situ *SST measurements over the Arabian Sea and the Bay of Bengal*

The satellite SST data sets from the INSAT-3D and the MODIS sensors are validated against the iQuam and the IMB *in-situ* SST observations over the Arabian Sea and the Bay of Bengal. The basic aim of this exercise is to determine and compare the retrieval accuracy of each satellite over these two regions. Table 5 shows the combined statistics of satellite SST validation against *in-situ* measurements for all the 3 years over the Arabian Sea and the Bay of Bengal regions. The results reveal that the RMSE range for the INSAT-3D over the Arabian Sea and the Bay of Bengal is 0.66–0.70°C and 0.64–0.67°C, respectively, while the MODIS sensor is showing RMSE in the range of 0.55–0.68°C over

Table 5. Validation of the satellite SST against *in-situ* SST measurements over the Arabian sea and the Bay of Bengal.

	INSAT-3D *versus in-situ*		Aqua *versus in-situ*		Terra *versus in-situ*	
	Arabian Sea	Bay of Bengal	Arabian Sea	Bay of Bengal	Arabian Sea	Bay of Bengal
a. Satellite validation against the iQuam dataset						
N	12,348	12,811	1771	1063	2273	601
RMSE (°C)	0.70	0.67	0.68	0.65	0.68	0.74
Bias (°C)	−0.26	−0.06	−0.06	−0.18	−0.11	−0.16
b. Satellite validation against the IMB data set						
N	10,480	6243	2375	518	2007	865
RMSE (°C)	0.66	0.64	0.56	0.63	0.55	0.57
Bias (°C)	−0.27	−0.05	0.06	0.15	−0.02	−0.18

the Arabian Sea and 0.57–0.74°C over the Bay of Bengal region. Unlike the MODIS sensor showing overall bias in the range of −0.18–0.15°C, the INSAT-3D is observed to give relatively high underestimation (approximate bias = 0.27°C) over the Arabian Sea as compared to the Bay of Bengal region (bias = ±0.05°C). Many studies reveal that the Arabian Sea is under the influence of continental aerosols almost throughout the year (Rajeev et al. 2004; Patra et al. 2007; Singh et al. 2008; Banerjee and Prasanna Kumar 2014), serving as the most important sink region for mineral dust arriving from South Asia, Southwest Asia, and the eastern horn of African continent (Prospero et al. 2002). Generally, significant aerosol radiative forcing (ARF) was reported over the northern Arabian Sea during monsoon and post-monsoon seasons whereas over the northern Bay of Bengal, ARF is higher during winter and pre-monsoon periods. In particular, the highest ARF was reported over the northern Arabian Sea during southwest monsoon season as a result of large amount of desert dust (absorbing aerosols) transported from the West Asian dust sources (Satheesh, Vinoj, and Krishnamoorthy 2010). The brightness temperature differences are sensitive to dust aerosols and may result into significant negative bias in satellite SST retrieval. Besides dust aerosols, the LLCs also significantly affect the satellite SST retrieval accuracy. Unlike multi-layered convective clouds at high level which are characterized by large variations in infrared radiances, low level-cloud systems are characterized by weaker variability of infrared brightness temperatures. For LLCs, the average cloud water temperature is nearly same as the cloud-top temperature over oceanic regions (Lin et al. 1998). As a result of low contrasting cloud-top temperature of LLCs and sea surface, it is difficult to identify the LLC contamination within the pixel during SST estimation. The increase in atmospheric moisture content at lower levels by evaporation and absence of vertical mixing leads to the formation of LLCs (with cloud-top pressure below 680 hPa) by saturation and these LLCs are unable to grow vertically due to the presence of lower tropospheric thermal inversion. In contrast to the Bay of Bengal region which is characterized by mainly deep-convective (high-level) clouds, the LLCs (mainly Stratus and Stratocumulus) are more prominent over the central and western part of the Arabian Sea region with their peak observed during summer–monsoon season (Sathiyamoorthy et al. 2013). Annually, the contribution of LLCs to the fractional cloud cover (F_c), computed by counting the number of cloudy pixels within the grid, over the Arabian Sea and the Bay of Bengal is 57% and 34%, respectively, while the corresponding relative contributions of high-level cloud cover are 31% and 46%, respectively (Dey et al. 2015). Hence, continental dust aerosols as well as

LLCs could be the plausible reason for the significant underestimation in the INSAT-3D SST over the Arabian Sea. Again, retrieval error for all the three missions is found to be slightly more in case of validation against the iQuam *in-situ* SST data set over the Arabian Sea and the Bay of Bengal region.

3.4. *Seasonal validation analysis of satellite SST over the Indian subcontinent*

The seasonal validation analysis for pre-monsoon (January–April), monsoon (May–August), and post-monsoon (September–December) seasons has been carried out for the years 2014 and 2015 (mentioned in Table 6). In case of all the three satellites, the retrieval error (RMSE) is relatively higher during the monsoon season as compared to the pre-monsoon and the post-monsoon seasons. This may probably be due to the fact that the Stratus and the Stratocumulus, the major low-level cloud types, are more prominent over the central and western part of the Arabian Sea region with their peak observed during the summer–monsoon season (Sathiyamoorthy et al. 2013). Consequently, these LLCs within the pixels adversely affect the satellite SST retrieval accuracy. In addition, the southwest monsoon season is characterized by heavy rainfall with relatively higher humidity. Therefore, scattering of radiation by atmospheric water vapour can also contribute to higher retrieval error. Furthermore, aerosol optical depth (AOD) is also at its peak during the summer–monsoon period. However, AOD over the Bay of Bengal is significantly less than that over the Arabian Sea (Rajeev et al. 2004). Highest ARF was reported over the northern Arabian Sea during southwest monsoon season as a result of large amount of desert dust transported from the West Asian dust sources (Satheesh, Vinoj, and Krishnamoorthy 2010). The RMSEs of all the three satellites during the pre-monsoon, monsoon, and post-monsoon seasons are found to be in the range of 0.48–0.68°C, 0.62–0.78°C, and 0.56–0.74°C, respectively. Overall, all the three satellites are giving similar performance during each season in terms of RMSE. However, in terms of bias, unlike the INSAT-3D having overall bias ranging about −0.32–0.05°C, the MODIS

Table 6. Seasonal validation of the satellite SST against *in-situ* SST measurements surrounding the Indian subcontinent for the years 2014 and 2015.

	INSAT-3D *versus in-situ*			Aqua *versus in-situ*			Terra *versus in-situ*		
	Pre-monsoon	Monsoon	Post-monsoon	Pre-monsoon	Monsoon	Post-monsoon	Pre-monsoon	Monsoon	Post-monsoon
a. Satellite SST validation against the iQuam data set (Year – 2014)									
N	1808	926	1841	579	192	471	358	144	317
RMSE (°C)	0.68	0.74	0.58	0.63	0.76	0.66	0.63	0.74	0.68
Bias (°C)	−0.07	−0.15	−0.20	0.01	−0.46	−0.11	0.01	−0.38	−0.06
b. Satellite SST validation against the IMB data set (Year – 2014)									
N	1894	887	1459	508	175	390	529	152	350
RMSE (°C)	0.65	0.72	0.56	0.54	0.68	0.67	0.48	0.62	0.63
Bias (°C)	−0.20	−0.21	−0.19	0.17	−0.43	0.09	−0.02	−0.58	−0.01
c. Satellite SST validation against the iQuam data set (Year – 2015)									
N	7918	2644	3246	629	164	204	667	238	324
RMSE (°C)	0.60	0.62	0.62	0.63	0.75	0.74	0.60	0.78	0.69
Bias (°C)	−0.29	−0.10	0.05	−0.02	−0.44	−0.13	−0.03	−0.52	−0.13
d. Satellite SST validation against the IMB data set (Year – 2015)									
N	6299	663	1189	889	80	155	895	116	233
RMSE (°C)	0.61	0.65	0.58	0.53	0.64	0.59	0.59	0.74	0.59
Bias (°C)	−0.32	−0.17	0.01	0.09	−0.29	0.14	−0.11	−0.52	−0.03

sensor is showing significant underestimation only during monsoon season with bias ranging from around −0.29°C to −0.58°C as compared to the other two seasons when the approximate range of bias is −0.13–0.17°C. Although the MODIS sensor has the most robust atmospheric correction algorithm, it is to be noted that the infrared channels of MODIS are known to cause errors in SST estimation during dense dust conditions (Singh et al. 2008) which are predominantly observed during the southwest monsoon season.

4. Conclusion

In the present study, validation of SST retrieved from the three satellite missions, namely INSAT-3D, MODIS-Aqua, and MODIS-Terra, has been carried out over waters surrounding the Indian subcontinent for the 3 years (October 2013–October 2016). The satellite SST data set is validated against two independent well-correlated *in-situ* data sets obtained from the IMB network and the iQuam. The RMSE of all the three satellites is in approximate range of 0.60–0.70°C and the retrieval error is found to be slightly more in case of validation against the iQuam data set than the IMB data set over coastal as well as open-ocean waters of the Arabian Sea and the Bay of Bengal. The INSAT-3D is showing relatively high underestimation with bias ranging from −0.20°C to −0.16°C as compared to the MODIS sensor having bias in the range of −0.12–0.06°C, approximately. Almost all the three missions show underestimation over open-ocean with bias ranging from 0°C to 0.17°C. The INSAT-3D is significantly underestimating the *in-situ* observations over the Arabian Sea (bias around 0.27°C). The seasonal validation analysis shows that the retrieval error in case of all three satellites is relatively higher during monsoon season as compared to pre-monsoon and post-monsoon seasons. The MODIS sensor is showing significant underestimation during the monsoon season with bias ranging from about −0.29°C to −0.58°C. Overall, all the three missions are performing similarly well over the study region and, therefore, can be used for further applications over waters surrounding the Indian subcontinent.

Over the last decade, with the advancement in model-based SST retrieval algorithms, the regression-based approach employed for currently available SST product is considered outdated for its numerous limitations. It is inappropriate to characterize global geophysical conditions of ocean as well as atmosphere using only a few regression coefficients (Koner, Harris, and Maturi 2015). In addition, the regression-based approach makes it difficult to assign error associated to individual retrievals (Koner and Harris 2016b). Therefore, with the availability of improved computational facilities and increased channels in advanced sensors, efforts should be made to operationalize model-based satellite product with improved quality and more data coverage. A more robust cloud-screening algorithm is strongly required mainly for the INSAT-3D mission so that the error due to low-level cloud contamination could be minimized.

The ‘indirect SST validation’ approach proved to be beneficial for the present study. However, it is important to recognize the need for a dedicated research and development in *in-situ* data collection methodologies targeted to the areas characterized by low wind speeds where the ‘indirect validation approach’ is not expected to perform well. In addition, it would be beneficial to develop SST retrieval algorithms for high wind speed condition. Moreover, a large geographic area of the Arabian Sea as well as the Bay of Bengal is still deprived of sampling by present non-uniform buoy network. For a more accurate validation exercise, the buoy network needs to be extended so that sufficient *in-situ* measurements over coastal and open ocean can be acquired. The validation of satellite data set is of great importance and must be continued so that retrieval errors can be better quantified and minimized.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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