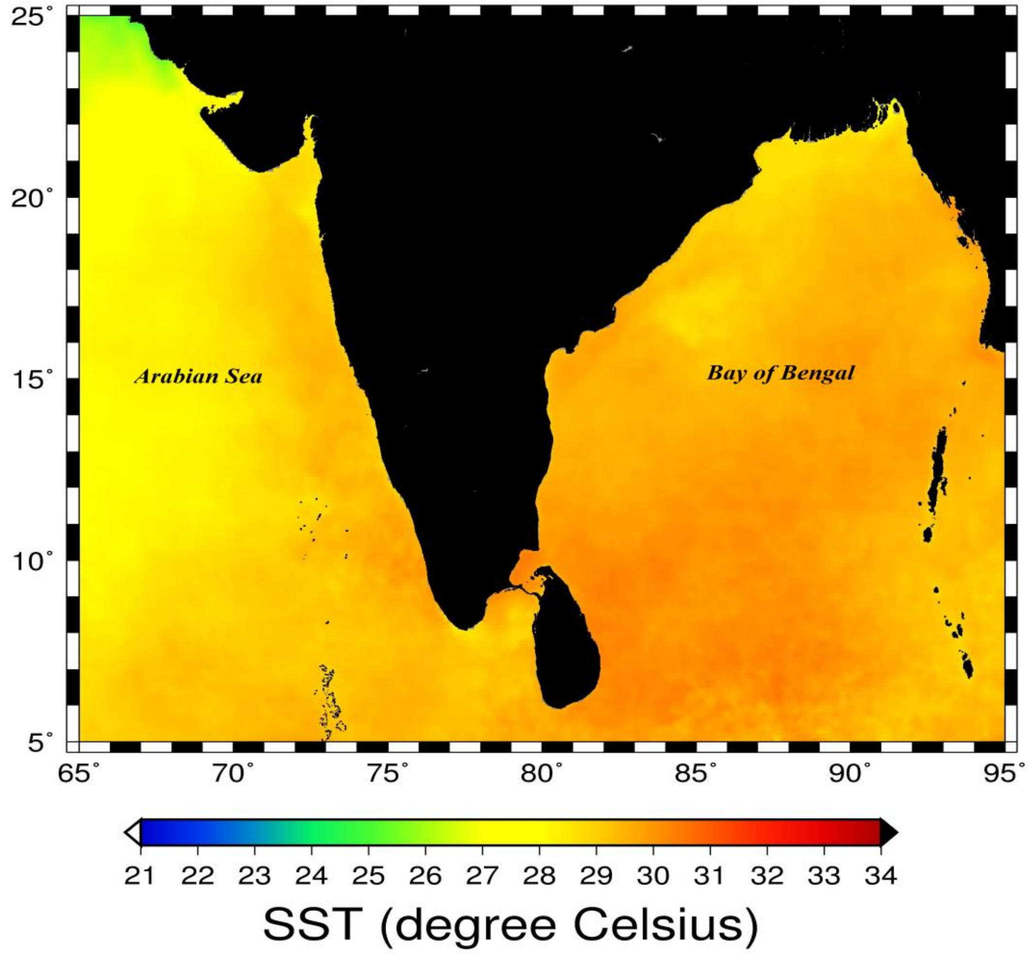
Technical Report SAC/EPSA/CVD/CAL-VAL/2016

# Validation and Assessment of INSAT-3D and MODIS-Derived Sea Surface Temperature Over Indian Sub-Continent




**By**

Geetika Tyagi, K. N. Babu, and A. K. Mathur

Calibration and Validation Division
EPSA
Space Applications Centre (ISRO)
Ahmedabad – 380015

**July 2016**

# Document control and data sheet

| | | |
|---|---|---|
| 1 | Date | July, 2016 |
| 2 | Title | Validation and Assessment of INSAT-3D and MODIS-Derived Sea Surface Temperature Over Indian Sub-Continent |
| 3 | Report No. | SAC/EPSA/CVD/CAL-VAL/2016 |
| 4 | Report Type | Technical |
| 5 | No.of pages | 31 |
| 6 | No. of references | 21 |
| 7 | Authors | Geetika Tyagi, K. N. Babu and A. K. Mathur |
| 8 | Originating unit | CVD/EPSA |
| 9 | Abstract | This technical report presents the validation of INSAT-3D and MODIS-Derived Level-2 Sea Surface Temperature over Indian Sub-Continent with a spatial resolution of 4km and 1km respectively for two years (2013-2014). Two different sets of quality-controlled *in-situ* data obtained from INCOIS Met Buoy and iQUAM have been used for this validation exercise. Results shows that MODIS is having RMSE of ~ 0.5 to 0.8 $^{o}$C while INSAT-3D is having a higher RMSE of ~0.8 $^{o}$C during the year 2013 and much higher in the year 2014 (>1 $^{o}$C). |
| 10 | Keywords | Sea Surface Temperature, Validation, INSAT-3D, MODIS, Skin Temperature, Bulk temperature |
| 11 | Security classification | Unrestricted |
| 12 | Distribution | Among all concerned |

## Contents

**Summary**

INSAT-3D imager level-2 (4km) Sea Surface Temperature (SST) product and daytime level-2 (1km) SST product of Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard AQUA and TERRA space platforms have been analysed for their accuracy in the coastal and open ocean of Indian sub-continent. The accuracy of satellite skin-SST ($SST_{skin}$) is estimated by indirect comparison with collocated bulk *in-situ* measurements of near sea surface temperature ($SST_{depth}$) from Met buoys (available from INCOIS) and iQuam (*in-situ* SST Quality monitor) for the time period of two years (2013-2014). The statistical results show that the Root Mean Square Error (RMSE) of MODIS derived SST with buoy data is ~ 0.5 to 0.8 $^{o}$C on instantaneous basis while INSAT-3D is having a higher RMSE of ~0.8 $^{o}$C during the year 2013 and much higher in the year 2014 (>1 $^{o}$C). In addition, we have also evaluated the performances of all three satellites over Arabian Sea and Bay of Bengal and found that the SST products of MODIS sensor agrees well over both the regions with slightly better performance in Arabian Sea as compared to Bay of Bengal but INSAT-3D is revealing relatively higher error w.r.t. MODIS sensor.

## 1. Introduction

Sea Surface Temperature (SST) is the most extensively used variable in oceanography. SST is not only an indispensable parameter for the study of physical, chemical and biological characteristics of oceans but it also plays a first and foremost role in the atmospheric studies as it commands the exchange of heat, momentum and gases between the ocean and the atmosphere. To understand the role of the ocean biosphere at seasonal-to-decadal time scales, a highly consistent time series of observations are required which is difficult to obtain through conventional *in-situ* measurements technique for the entire oceanic region.

More than three decades back, the launch of Advanced Very High Resolution Radiometer (AVHRR) onboard NOAA series of polar orbiting satellites, have marked the inception of SST retrieval from satellite platform with much improved data coverage as compared to *in-situ* techniques. Since then so many advanced satellite sensors have been introduced for SST retrieval by measuring the infrared and microwave thermal emission from the 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 NASA (US) in December 1999 onboard Earth Observing System satellite platform Terra and in 2002 on platform Aqua.

MODIS operates in both the visible and infrared parts of the electromagnetic spectrum. The MODIS infrared sensors are capable of providing the SST datasets at about 4 and 11µm wavelengths in cloud-free conditions (Minnett, 2004) with larger temporal and spatial coverage. In July, 2013, India launched INSAT-3D which is an exclusive meteorological satellite. The SST from INSAT-3D is derived from split thermal window channels (10.2-11.3µm, 11.5 –12.5µm) during daytime and using additional mid IR window channel (3.7 – 4.1µm) during night time over cloud free oceanic regions.

The major advantage of using Infrared radiometry is that it is capable of providing SST measurements with high spatial resolution ~1 $km^2$, but only in the cloud-free conditions. The remote sensing observations of SST in the thermal infrared is subject to degrade in its accuracy after passing 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 aerosols (Wayne, 1998). Therefore, prior to use any satellite data for study or research purpose, it is mandatory to confirm the accuracy of satellite product through its validation using the most reliable *in-situ* measurements from ships and buoys (Emery and Yu,1997; Peng and Yanchen, 2008).

Satellite skin SST algorithms are derived through regression technique using the *in-situ* skin SST measurements. But one of the major challenges in the direct validation of satellite skin SST product which requires *in-situ* skin SST measurements is the lack of *in-situ* skin SST data as so far it is difficult to develop, maintain and deploy such an instrument in cloud-free conditions. Consequently, most of the researchers are performing indirect SST validation that is based on the comparison of satellite skin SST (depth <1mm) with *in-situ* bulk SST (depth ~0.5 - 5m) measurements at a specified depth known as *in-situ* $SST_{depth}$. But the indirect validation using *in-situ* $SST_{depth}$ is appropriate only when the wind speed is >6m/s (Donlon, 2002) which results in the increment of Mixed Layer Depth homogenizing the temperature structure in the upper ocean. Low winds and strong net heat fluxes into the ocean can results in the 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 air-sea interaction is responsible for the modifications in the relationship between bulk and skin SSTs causing an observable difference between them (Prabhakara et. al; 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 et al., 1996) and satellite analysis is approximately 0.5°C colder than the *in-situ* SST (Richard, 1988). As a result of aerosols from valconic 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 report, we are reporting the results of 'Indirect Validation' of INSAT-3D and MODIS SST product by comparing the satellite measurements with two different *in-situ* SST datasets under strong wind conditions for a period of two years (2013-2014) over the waters of Indian sub-continent including Arabian Sea and Bay of Bengal. We have also attempted to evaluate the relative performance of INSAT-3D imager during pre-monsoon, monsoon and post-monsoon seasons by comparing satellite data sets for three different seasons with *in-situ* datasets.

The *in-situ* measurements are done at different geo-locations in the coastal as well as open ocean regions of the Indian sub-continent which can be further divided into two regions-Arabian Sea and Bay of Bengal. Although Arabian Sea and Bay of Bengal share several similarities like 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 dissimilarities between the two in terms of their climatological aspects leading to the evolution of their SST (Shenoi et al, 2004). The contrasting nature of Arabian Sea and Bay of Bengal evokes an interest to carry out their comparative study. Hence, in this validation exercise, we have evaluated the performance of all three satellites with respect to *in-situ* SST measurements over Arabian Sea (5°-25° N; 65°-78° E) and Bay of Bengal (5°-25° N; 78°-92° E). Figure-1 represents SST over Arabian Sea and Bay of Bengal during post-monsoon season (Oct-Dec) for the year 2013 generated from INSAT-3D sensor.

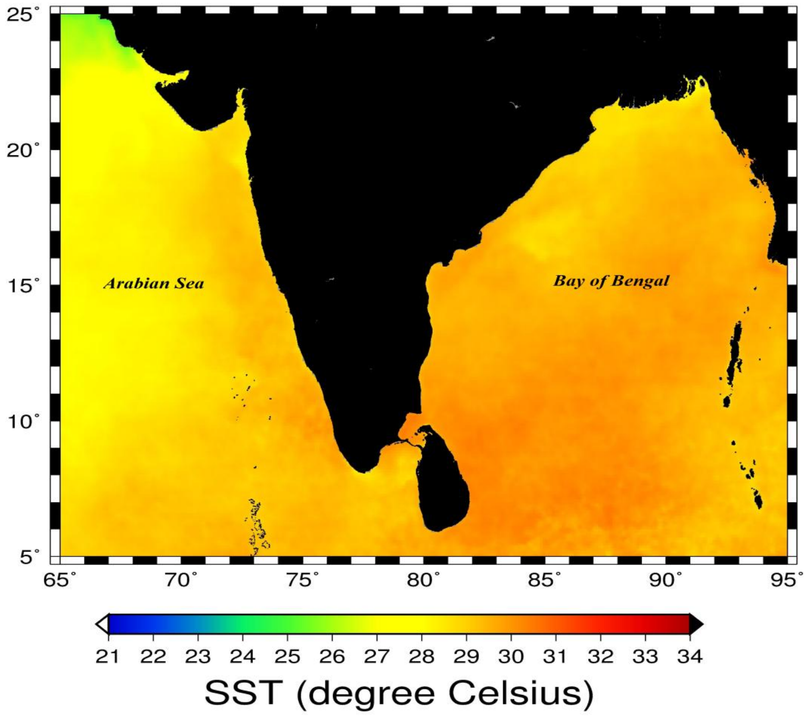



**Figure-1:** INSAT-3D image showing SST (during October, 2014) over study areas.

## 2. Data and Methodology

### 2.1. *In-situ* data collection

In this study, two different *in-situ* data sets for SST have been used in order to get more number of observation points and to verify the validation results. One set of *in-situ* data is obtained from INCOIS (Met buoy data) and the other one is iQuam (*in-situ* SST Quality monitor) dataset developed in NESDIS/STAR that has been downloaded from website, www.star.nesdis.noaa.gov. The corresponding *in-situ* wind speed observations have also been considered along with the SST measurements. Only the SST measurements with wind speed more than 6m/sec are found to be suitable 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 INCOIS Met buoys is at ~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 resolution of 0.01°C. Figure-2 is showing Met buoy locations (indicated by triangles) within the study region.

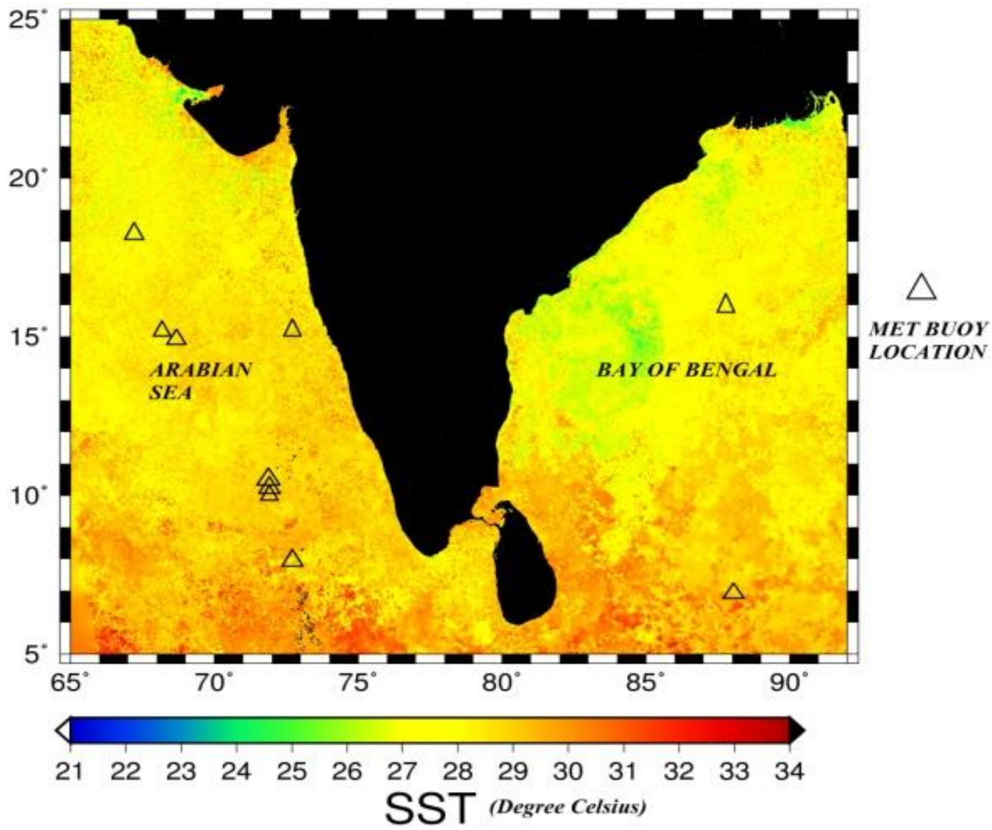



**Figure-2:** INCOIS Met buoy locations (indicated by triangles) within the study area**.**

Unlike INCOIS, the iQuam dataset has been collected world-wide using a large number of platforms including ships, drifters and mooring buoys at different geolocations including the Indian sub-continent for obtaining a continuous quality controlled *in-situ* SST observations of global waters for an effective calibration/validation exercise. The iQuam data sets comprises *in-situ* observations from; conventional drifters, high-resolution drifters, tropical moorings, coastal moorings, coral reef watch buoys, conventional ships and IMOS ships. The geo-location of iQuam observations for the year 2014 is shown in Figure 3. The data is collected at a typical depth of ~3-7 m with an accuracy of approximately 0.3 °C.

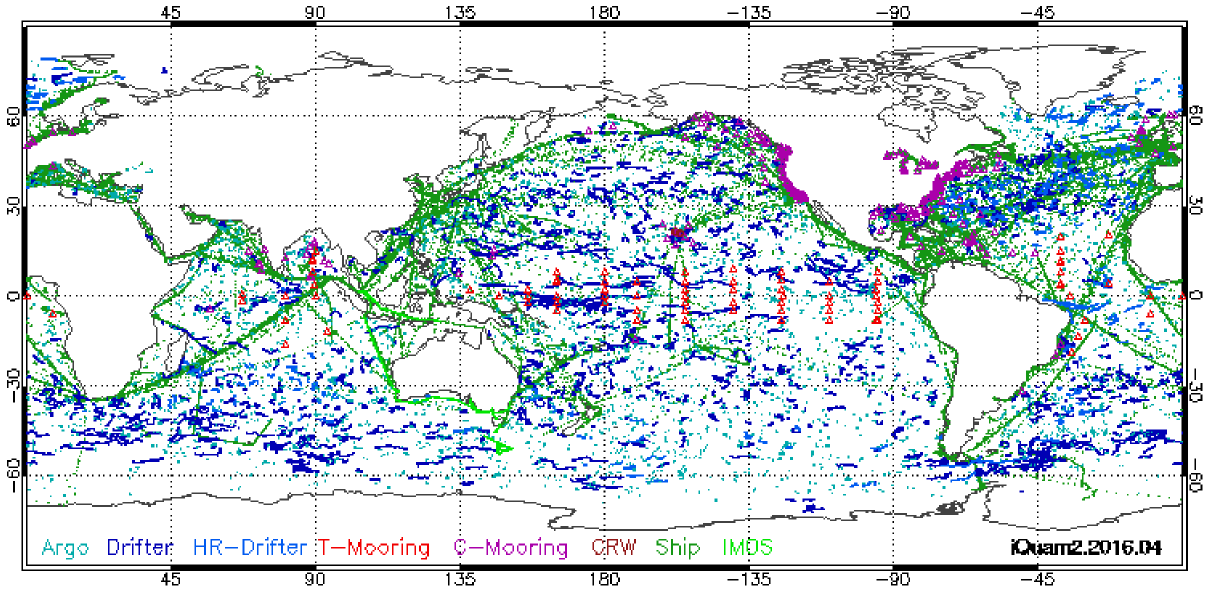



**Figure 3:** The geo-location of iQuam (source: www.star.nesdis.noaa.gov) observations for the year 2014.

### 2.2. Satellite data

Level-2 INSAT-3D SST data product has been obtained from MOSDAC (Meteorological and Oceanographic Satellite Data Archival Centre) website, www.mosdac.gov.in, at a spatial resolution of 4km from October, 2013 to December, 2014 as the mission started in July, 2013 and the Imager payload was commissioned in October, 2013.

While in case of MODIS-Aqua and MODIS-Terra sensors, level-2 data with 1km of spatial resolution have been used for a period of entire two years (2013-2014) from the National Aeronautics and Space Administration (NASA) Ocean Biology Processing Group (OBPG) website, http://oceancolour.gsfc.nasa.gov. The technical specifications of all three satellite sensors used in this study have been mentioned in the Table-1.

**Table-1: Major characteristics of INSAT-3D, MODIS-Aqua and MODIS-Terra sensors**

| Sr. No. | Parameters | INSAT-3D | MODIA-Terra | MODIS-Aqua |
|---|---|---|---|---|
| 1 | Orbit | Geostationary (Altitude- 36000 km) at 82 degrees E | Sun-synchronous, near-polar, circular (705 km) | Sun-synchronous, near-polar, circular (705 km) |
| 2 | Repetivity | 26 minutes | 1-2 Days | 1-2 Days |
| 3 | Spatial resolution | 1km (VIS, SWIR)<br>4km (MIR, TIR)<br>8km (water vapour) | 250m (bands 1-2),<br>500m (bands 3-7),<br>1000m (bands 8-36) | 250m (bands 1-2),<br>500m (bands 3-7),<br>1000m (bands 8-36) |
| 4 | Spectral Bands | VIS, SWIR * | B1 – B19* | B1 – B19* |
| | | MIR: 3.80 – 4.00 ( µ) | B20 : 3.750 (µ) | B20 : 3.750 (µ) |
| | | Water vapour * | B22 : 3.959 (µ) | B22 : 3.959 (µ) |
| | | TIR 1: 10.20 – 11.30 | B23 : 4.050 (µ) | B23 : 4.050 (µ) |
| | | TIR 2: 11.50 – 12.50 | B24 - B30*<br><br>B31 : 11.030 (µ)<br>B32: 12.020 (µ)<br>B33 – B36 | B24 - B30*<br><br>B31 : 11.030 (µ)<br>B32: 12.020 (µ)<br>B33 – B36 (µ) |
| 5 | Quantization bits | 10 | 12 | 12 |

- not meant for SST observations

The computation of SST from INSAT-3D imager has been done using the following algorithms (INSAT-3D products catalog, 2014):

During daytime, for cloud free pixels, SST is computed as

$SST= A0 + A1* T11+ A2*dT + A3*dT^2$ ........................................................................................ 1

Where, A0, A1, A2, and A3 are satellite zenith angle dependent coefficients determined by radiative transfer model.

$dT = T11 – T12$

Where, T11 and T12 are brightness temperatures for the split-window channels.

During Nighttime, for cloud free pixels, SST is computed as

$SST= B0 + B1* T3+ B2*dT + B3*dT^2$ ------------------------------------------------------------------------------ --- 2

Where, B0, B1, B2, and B3 are satellite zenith angle dependent coefficients determined by radiative transfer model.

dT = T11 – T12

Where, T11 and T12 are brightness temperatures for the split-window channels and T3 is the brightness temperature for channel 3 of IMAGER.

Single channel SST is computed as

SST = a + b*Tb +c*WV ---------------------------------------------------------------------- 3

Where, Tb is brightness temperature of the IR imager channel, WV is total water vapour content, a, b and c are regression coefficients generate through radiative transfer model.

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 nonlinear SST algorithm [Walton, 1988]. The form of the daytime and nighttime algorithm is

SST = c1+c2* T11+c3* (T11-T12)*Tsfc+c4*(sec (z)-1 )* (T11-T12) -------------------- 4

where T is brightness temperatures measured in the channels at n µm wavelength, Tn is a 'climatological' estimate of the SST in the area, and z is the satellite zenith angle.

For the validation of satellite SST against *in-situ* measurements, the satellite datasets are collocated over *in-situ* observations. Initially, to collocate the satellite and *in-situ* datasets, a spatial window of ~25×25 km with relaxation of ± 0.5 hr time span is selected. As fewer number of observations are attained within this window, therefore, to get more number of observation points for establishing a statistically significant validation and keeping the fact in mind that the SST variable generally does not have any significant small-scale spatio-temporal variations, the satellite datasets are re-collocated with *in-situ* measurements within a wider spatial window of ~50×50 km with relaxation of ±1 hr of particular satellite pass.

The error has been estimated by calculating Root Mean Square Error (RMSE), the most common statistical method used in the similar studies that are done previously. The RMSE was calculated as per the following formula:

$$RMSD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(SST_{satellite} - SST_{insitu}\right)^2}$$

Each satellite SST dataset has been validated against three sets of *in-situ* datasets- INCOIS (Met buoy) dataset, iQUAM dataset and total (sum of INCOIS and iQUAM) *in-situ* dataset over Arabian Sea and Bay of Bengal to determine the relative performance of all three satellites over these regions.

## 3. Results and Discussion

### 3.1. Monthly sea surface temperature distribution

Before the onset of summer-monsoon (Apr-May), the north Indian Ocean becomes the warmest among the world oceans (Joseph, 1990). But soon after the onset of summer-monsoon (during June), Arabian Sea cools rapidly under the influence of strong winds while SST of Bay of Bengal remains higher than 28$^{o}$ C and throughout the summer-monsoon Bay of Bengal remains warmer than Arabian Sea (Shenoi et al., 2004).

The monthly mean sea surface temperature distribution images have been obtained from INSAT-3D, MODIS-Aqua and MODIS-Terra (shown in Figure 4) (INSAT-3D SST data for the month of January is not available), The results reveals that the highest temperature is recorded in the month of May (~33 $^{O}$ C ) almost all over the Arabian Sea and Bay of Bengal with a slight lower temperature of ~30$^{O}$ C in the northern region while the lowest temperature is recorded in the months of Jan (~29 $^{O}$ C ) in the southern regions of Arabian Sea and Bay of Bengal which keeps on lowering upto ~20$^{O}$ C on moving northwards.

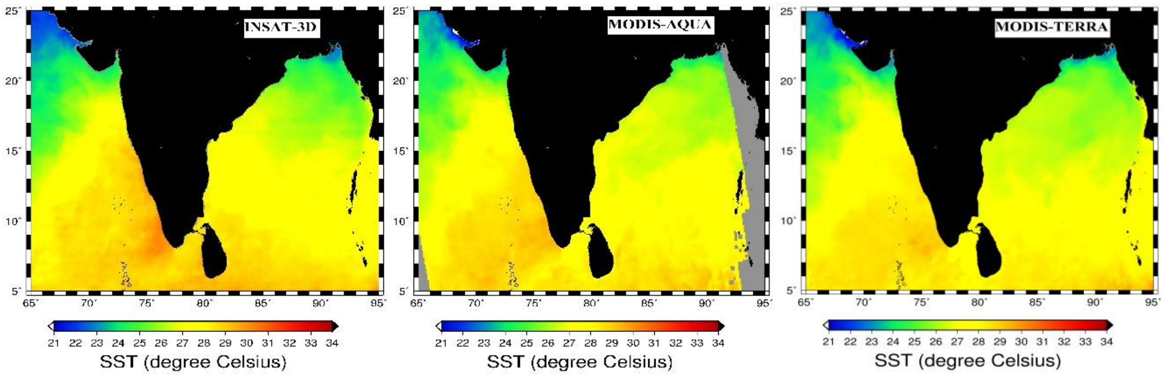
On time scale, the analysis revealed the four phases of SST variations throughout the year over study region namely-

1) First Warming Phase
2) First Cooling Phase
3) Second Warming Phase
4) Second Cooling Phase

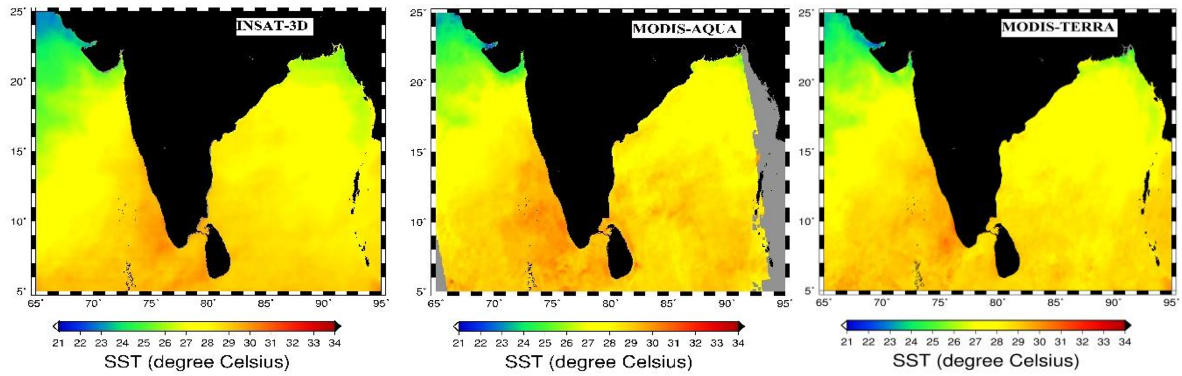
The *First Warming Phase* caused by the increasing intensity of solar radiation starts from the month of March and continues upto the month of May. Although the solar irradiation continues to increase but strong winds and cloud cover cause a decrease in SST as a result of which the *First Cooling Phase* starts from June and continues upto August. Then once again September marks the beginning of *Second Warming Phase* as the low wind speed in September allows the SST to increase again until October while the *Second Cooling Phase* starts from the month of November and continues upto February due to very low solar irradiation. This bimodal seasonal cycle repeats itself every year (Muhammad et al, 2016).

SST derived from both the MODIS sensors are in good agreement with each other with a slight negative bias of around 0.5 -1.0 $^{O}$ C shown by MODIS-Terra w.r.t. MODIS-Aqua throughout the year. While it can be clearly observed from the images that INSAT-3D is showing a noticeable negative bias w.r.t. MODIS throughout the year. Thus, the validation of satellite SST product against quality controlled *in-situ* SST datasets is very much necessary to quantify the error in SST product retrieval through respective satellite sensors over entire Indian sub-continent including Arabian Sea and Bay of Bengal.

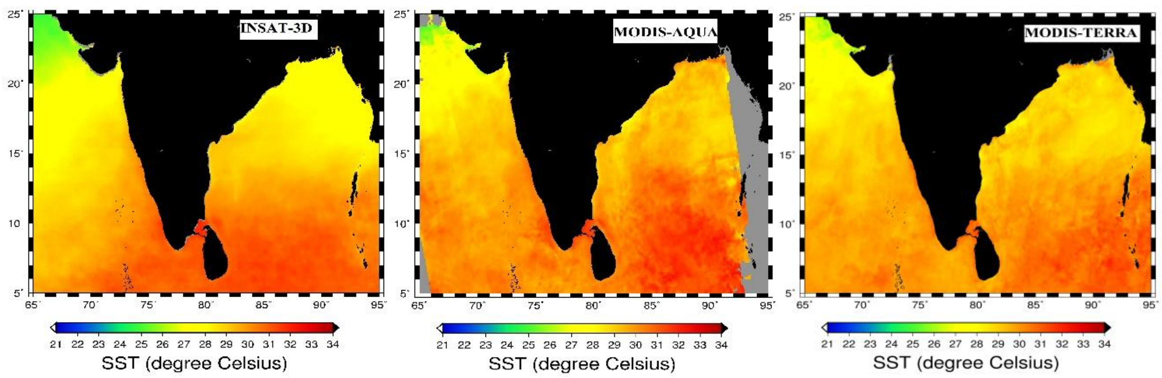
**FEBRUARY-2014**



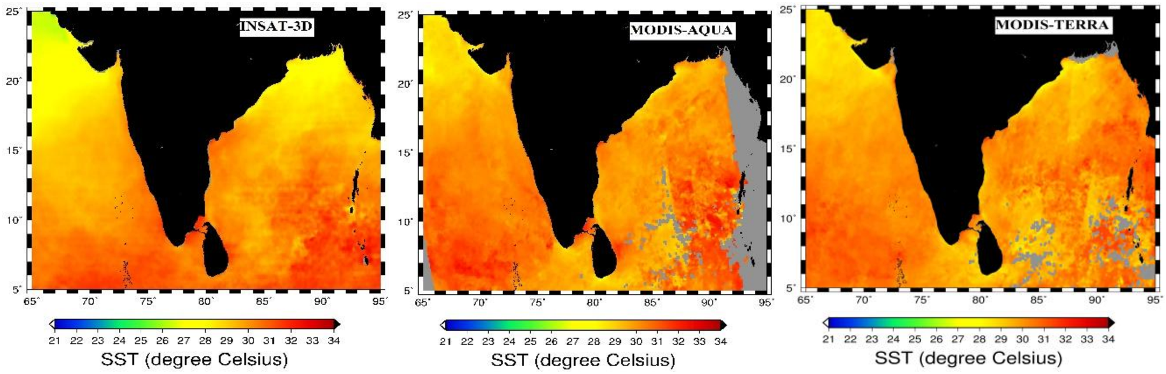

**MARCH-2014**



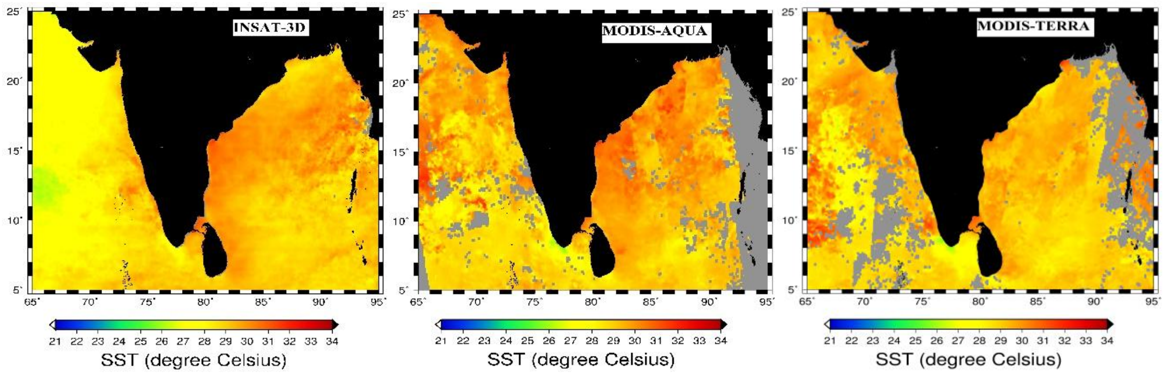

**APRIL-2014**



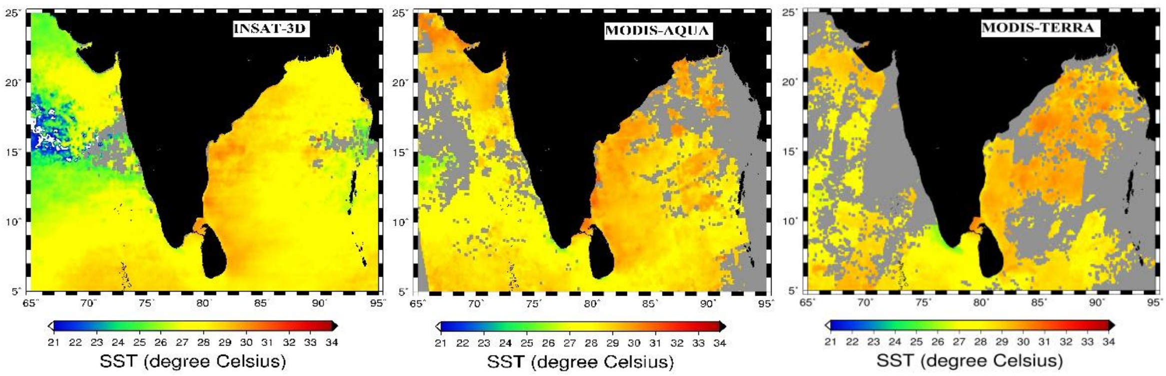
**MAY-2014**



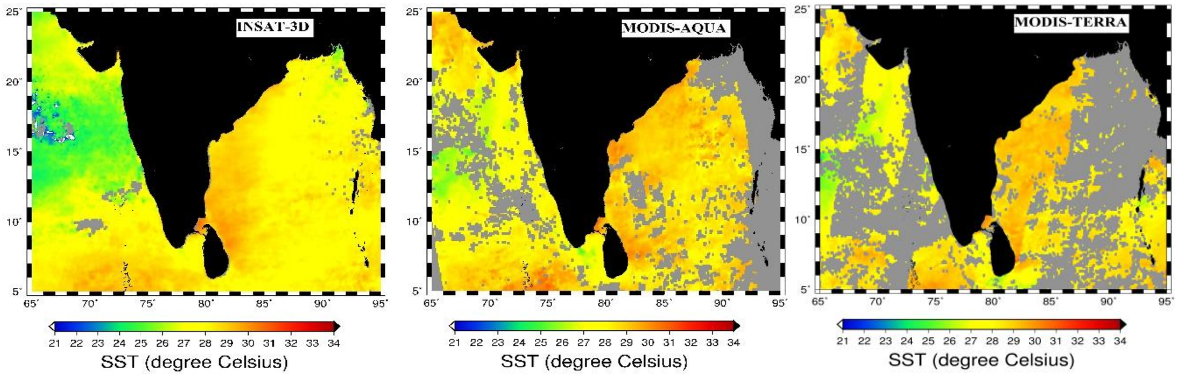

**JUNE-2014**



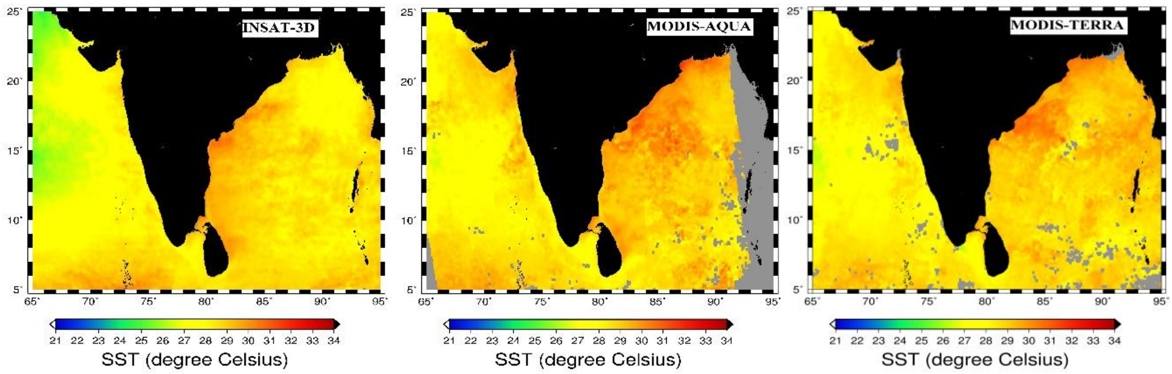

**JULY-2014**



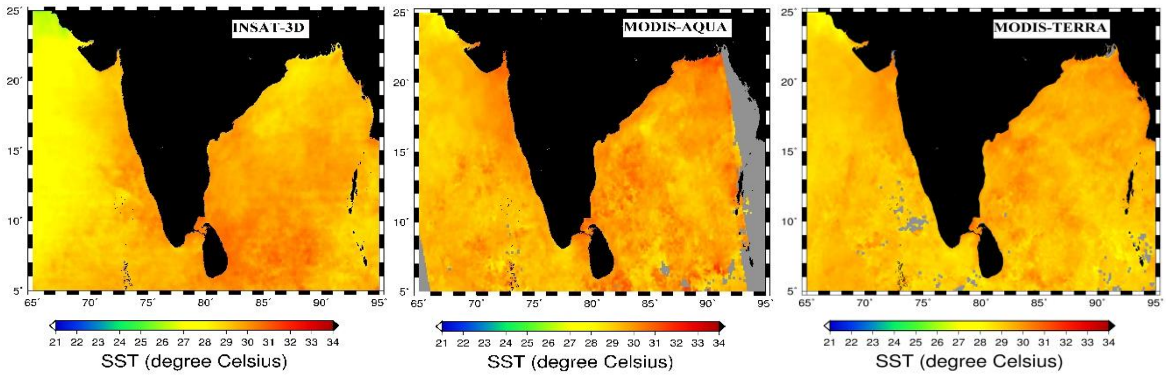
**AUGUST-2014**



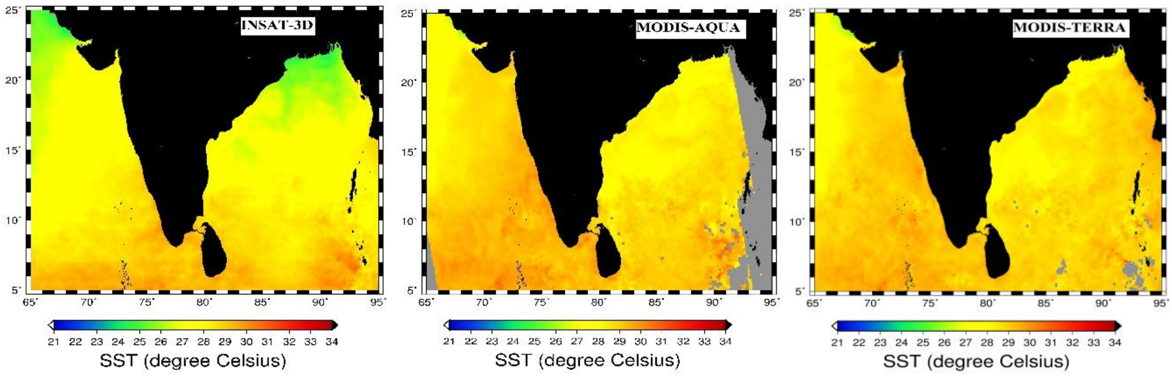

**SEPTEMBER-2014**




**OCTOBER-2014**



**NOVEMBER-2014**




**DECEMBER-2014**

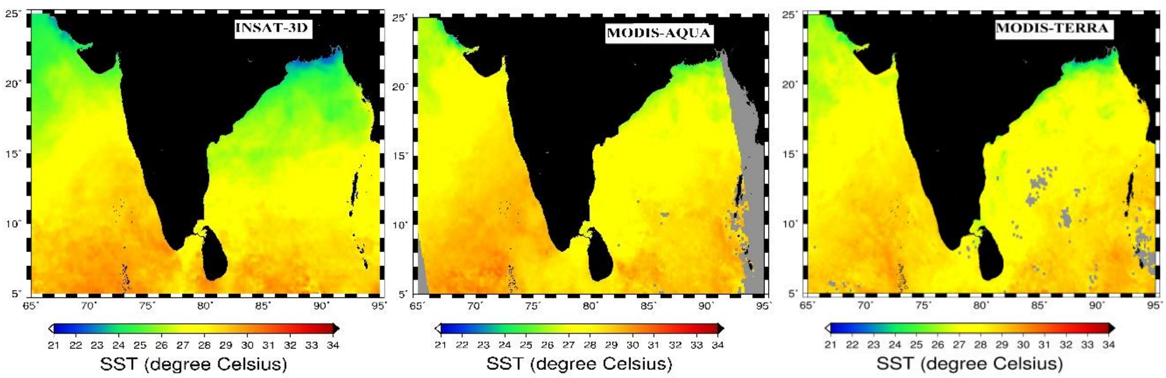



**Figure 4:** Monthly Sea surface temperature spatial distribution over Indian region.

### 3.2. Validation of satellite SST against Met buoy *In-situ* observations over entire Indian sub-continent.

The annual time series of *in-situ* SST observations for the year 2014 at 10.57°N and 72.21°E is shown in Figure 5. We have attempted to observe the SST pattern at the same geolocation by using Met Buoy as well as iQuam *in-situ* data sets for the same year but due to lack of data for a large number of days we got a discontinuous pattern in case of iQuam SST observations. We also attempted to construct the SST time series for other locations of INCOIS met buoy.

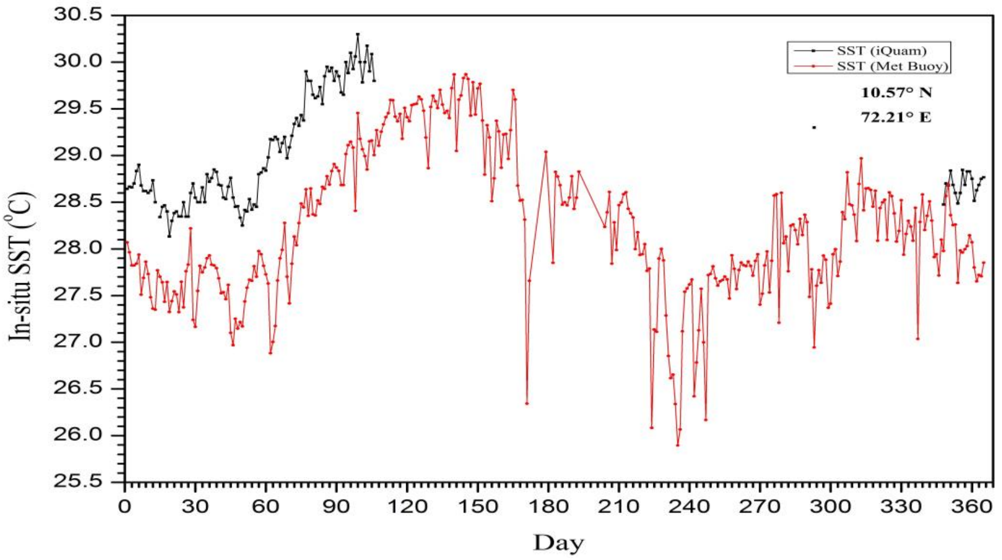



**Figure 5:** Annual distribution of *in-situ* SST observations from Met buoy and iQuam datasets for the year 2014.

Although the *in-situ* observations are never fully accurate (Xu et al., 2010) and there are variations in the accuracy of the buoy SST observations but it is usually better than 0.5°C (Reynolds, 2001), which is much better than the SST measurements taken through ships having typical RMSE larger than 1°C (Kent et al., 1999). The scatter-plot (shown in Figure 6) determines the correlation between *in-situ* datasets used for this validation exercise. The *in-situ* datasets are showing a good correlation (0.97) with an RMSE of 0.19 °C which can be considered to be within the acceptable limits of error. The major reasons behind slight spreading in scatter plot of *in-situ* SST datasets may be the use of a large variety of sensors on different platforms (ships, drifting and mooring buoys). The additional errors may be induced during transmission and processing stages.

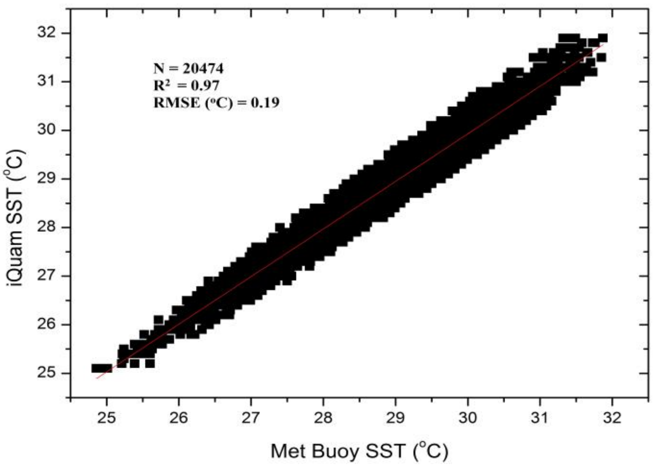



**Figure 6:** Scatter plot between Met buoy and iQuam *in-situ* SST observations

The validation of satellite SST against *in-situ* measurements over entire Indian sub-continent has been carried out by obtaining scatter-plots between all three satellites (INSAT-3D, MODIS-Terra and MODIS-Aqua) SST datasets and *in-situ* measurements following two different criteria of collocation for each satellite dataset. In first criteria, we have taken a spatial window of ~25 × 25 km with 1hr of temporal window. While in second criteria, we have taken a wider spatial window of ~50 ×50 km and temporal window of 2hr in which we are able to get sufficient number of observation points to establish a meaningful statistical relationship between *in-situ* and satellite sensor measurements. The two scatter-plots are superimposed over each other and near-overlapping of the various points in the superimposed scatter plots (Figure 7) reveals that the SST doesn't have any significant spatial and temporal variations within the selected region of study.

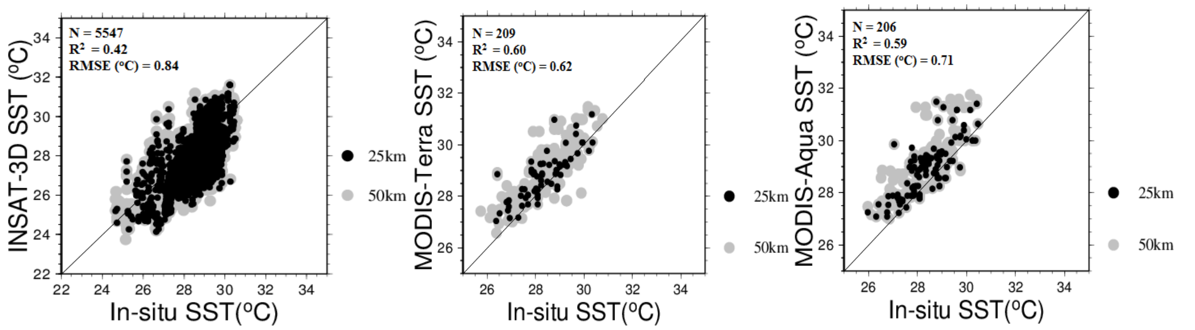



**Figure-7(a):** Scatter plots of INSAT-3D, MODIS-Terra and MODIS-Aqua for the year 2013 against INCOIS Met Buoy *in-situ* datasets.

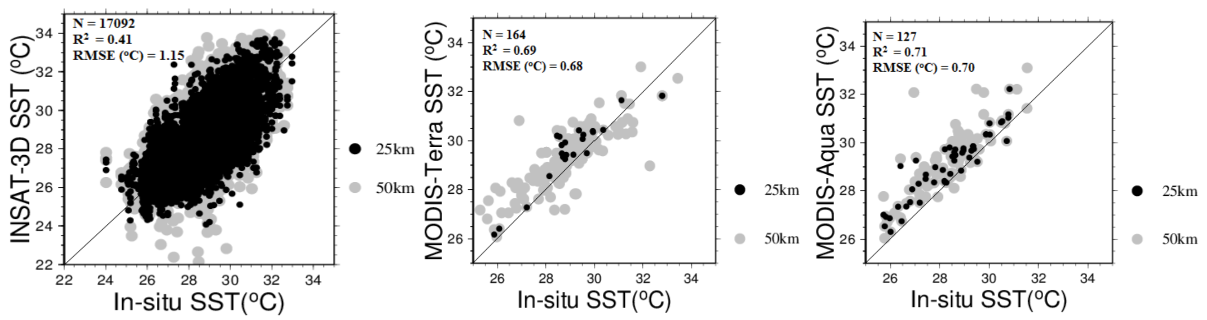



**Figure-7(b):** Scatter plots of INSAT-3D, MODIS-Terra and MODIS-Aqua for the year 2014 against INCOIS Met Buoy *in-situ* datasets.

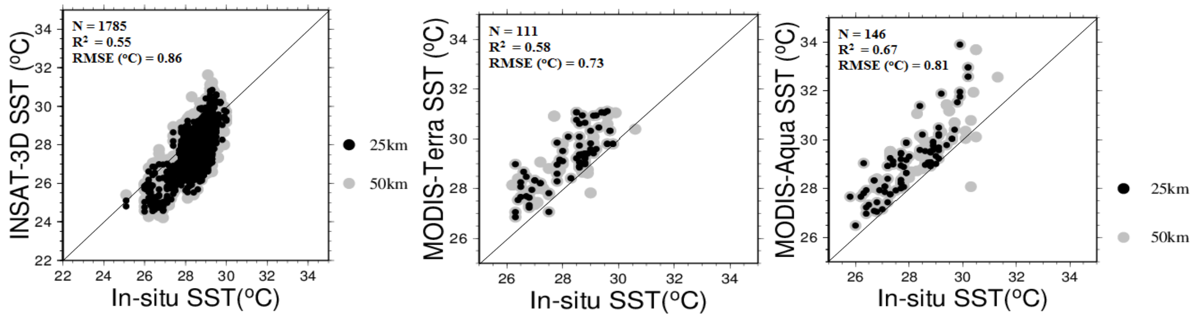



**Figure-7(c):** Scatter plots of INSAT-3D, MODIS-Terra and MODIS-Aqua for the year 2013 against iQuam *in-situ* datasets.

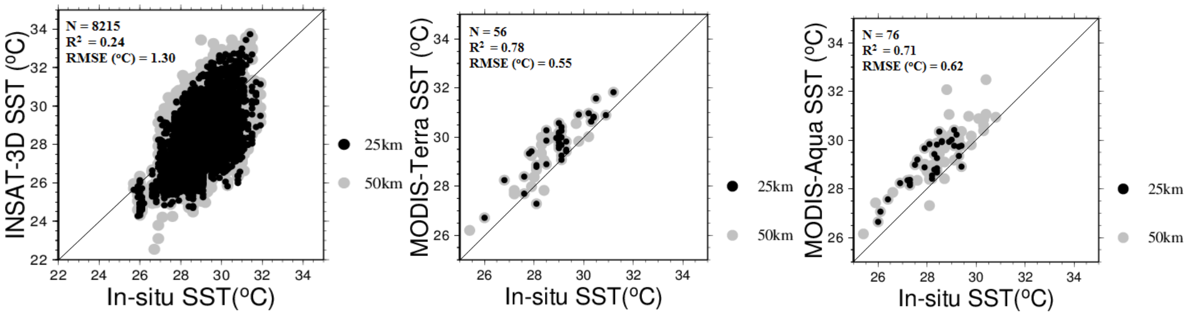



**Figure-7(d):** Scatter plots of INSAT-3D, MODIS-Terra and MODIS-Aqua for the year 2014 against iQuam *in-situ* datasets.

The scatterplot shows that MODIS-Terra is having least RMSE in the range of (0.55 - 0.73) °C as compared to MODIS-Aqua and INSAT-3D for both the years. MODIS-Aqua is having slightly higher RMSE in the range of (0.62 – 0.81) °C while INSAT-3D is showing RMSE of ~0.85 °C in the year 2013 and highest in the year 2014 which is ~1.22 °C. The probable reasons behind exceptionally higher RMSE in case of INSAT-3D during 2014 could be the detector-to-detector non-uniform response in the thermal channels of imager giving rise to a horizontal striping impact in TIR-1 as well TIR-2 images (Mathur A.K. et al., 2015). The poorer pixel resolution of INSAT-3D leads to more uncertainity in cloud detection, especially low level clouds having similar temperature as SST leading to contamination in SST retrieval. Further, the lacking of proper onboard-calibration and in-turn fine tuning of the algorithm contributes to the inconsistency in INSAT-3D imager channels (Mathur A.K. et al., 2015).

### 3.3. Comparative validation of satellite SST against *in-situ* SST measurements over Arabian Sea region

The satellite SST datasets from INSAT-3D, MODIS-Aqua and MODIS-Terra are validated against *in-situ* SST observations from INCOIS (Met buoy) and iQUAM *in-situ* observations over Arabian Sea.

**Table-2:** Validation of satellite SST against *in-situ* SST measurements over Arabian Sea region.

| Satellite vs. INCOIS (Met Buoy) | | | | | | |
|---|---|---|---|---|---|---|
| **PARAMETER** | **INSAT-3D VS. *IN-SITU*** | | **AQUA VS. *IN-SITU*** | | **TERRA VS. *IN-SITU*** | |
| | **2013** | **2014** | **2013** | **2014** | **2013** | **2014** |
| **N** | 5115 | 8689 | 204 | 121 | 199 | 120 |
| **$R^2$** | 0.40 | 0.30 | 0.59 | 0.67 | 0.58 | 0.63 |
| **RMSE (°C)** | 0.83 | 1.14 | 0.71 | 0.70 | 0.63 | 0.67 |
| **Satellite vs. IQUAM** | | | | | | |
| **PARAMETER** | **INSAT-3D VS. *IN-SITU*** | | **AQUA VS. *IN-SITU*** | | **TERRA VS. *IN-SITU*** | |
| | **2013** | **2014** | **2013** | **2014** | **2013** | **2014** |
| **N** | 1774 | 4259 | 107 | 71 | 88 | 54 |
| **$R^2$** | 0.55 | 0.23 | 0.68 | 0.69 | 0.54 | 0.75 |
| **RMSE (°C)** | 0.86 | 1.27 | 0.63 | 0.61 | 0.74 | 0.53 |

The results of satellite SST validation (shown in Table-2) over Arabian Sea against INCOIS (Met buoy) as well as iQuam datasets are almost same as that over entire Indian sub-continent. The overall results of validation against all three *in-situ* datasets shows that MODIS-Aqua and MODIS-Terra are having almost similar RMSE in the range of 0.53 – 0.74 °C while INSAT-3D is showing highest RMSE in the range of 0.83 – 1.27 °C. The RMSE in case of INSAT-3D is found to be more (>1 °C) during 2014 as compared to 2013 (~0.85 °C) may be due to lack of proper fine tuning of algorithm after post-launch calibration activity of INSAT-3D. MODIS is having almost stable accuracy during both the years over Arabian Sea.

### 3.4. Comparative validation of satellite SST against *in-situ* SST measurements over Bay of Bengal region

Using the same approach, all three satellites datasets have also been validated against *In-situ* datasets over Bay of Bengal region. The validation results (shown in Table-3) over Bay of Bengal region are slightly different as compared to that of Arabian Sea. Due to lack of MODIS-Aqua datasets collocated with INCOIS (Met Buoy) datasets during year 2013 and MODIS-Terra datasets collocated with iQuam datasets during 2014, the statistics could not be calculated.

**Table-3:** Validation of satellite SST against *in-situ* SST measurements over Bay of Bengal region.

<table>
<tr><th colspan="7">Satellite vs. INCOIS (Met Buoy)</th></tr>
<tr><th>PARAMETER</th><th colspan="2">INSAT-3D VS. IN-SITU</th><th colspan="2">AQUA VS. IN-SITU</th><th colspan="2">TERRA VS. IN-SITU</th></tr>
<tr><th></th><th>2013</th><th>2014</th><th>2013</th><th>2014</th><th>2013</th><th>2014</th></tr>
<tr><td>N</td><td>433</td><td>8364</td><td rowspan="3">Insufficient Data</td><td>6</td><td>10</td><td>45</td></tr>
<tr><td>R<sup>2</sup></td><td>0.56</td><td>0.51</td><td>0.93</td><td>0.90</td><td>0.74</td></tr>
<tr><td>RMSE (°C)</td><td>0.95</td><td>1.12</td><td>0.70</td><td>0.27</td><td>0.70</td></tr>
<tr><th colspan="7">Satellite vs. IQUAM</th></tr>
<tr><th>PARAMETER</th><th colspan="2">INSAT-3D VS. IN-SITU</th><th colspan="2">AQUA VS. IN-SITU</th><th colspan="2">TERRA VS. IN-SITU</th></tr>
<tr><th></th><th>2013</th><th>2014</th><th>2013</th><th>2014</th><th>2013</th><th>2014</th></tr>
<tr><td>N</td><td>11</td><td>3956</td><td>39</td><td>5</td><td>23</td><td rowspan="3">Insufficient Data</td></tr>
<tr><td>R<sup>2</sup></td><td>0.59</td><td>0.26</td><td>0.74</td><td>0.72</td><td>0.61</td></tr>
<tr><td>RMSE (°C)</td><td>0.84</td><td>1.31</td><td>0.83</td><td>0.73</td><td>0.81</td></tr>
</table>

The overall validation results over Bay of Bengal shows that MODIS-Aqua and MODIS-Terra are having RMSE in the range of 0.70 – 0.84 $^{o}$C for both the years with an exception of MODIS-Terra showing significantly reduced RMSE of 0.27 $^{o}$C in case of validation against INCOIS (Met Buoy) in the year 2013. The probable reason for this significantly reduced RMSE could be the availability of less number of observation points for that particular dataset. As in the case of Arabian Sea, INSAT-3D is showing highest RMSE in the range of

0.84 – 1.31 °C over Bay of Bengal as well. The RMSE in case of INSAT-3D is again more during 2014 (>1 °C) as compared to 2013 (~0.90 °C ).

**3.5. Seasonal validation analysis of the INSAT-3D SST over Arabian Sea and Bay of Bengal**

Before the onset of summer-monsoon (Apr-May), the north Indian Ocean becomes the warmest among the world oceans (Joseph, 1990). But soon after the onset of summer-monsoon (during June), Arabian Sea cools rapidly under the influence of strong winds while SST of Bay of Bengal remains higher than 28°C and throughout the summer-monsoon Bay of Bengal remains warmer than Arabian Sea (Shenoi et al., 2004).

During monsoon season, there is an unfavorable atmospheric environment for detecting SST using MODIS satellites in the Arabian Sea and Bay of Bengal because of heavy rainfall and cloud cover over the region. Therefore, due to unavailability of sufficient data sets of MODIS during monsoon season, the seasonal analysis of MODIS SST could not be performed. But we have attempted the seasonal validation of INSAT-3D SST over Arabian Sea and Bay of Bengal for the year 2014.

The results of the analysis (mentioned in Table-4) in case of Arabian Sea shows that RMSE is highest during monsoon season as compared to pre-monsoon and post-monsoon season with a value of ~1.30 °C w.r.t. INCOIS (met buoy) and ~1.56 °C w.r.t. iQUAM *in-situ* observations may be due to the fact that low-level clouds within the pixels are usually more during monsoon season.

Similarly, in case of Bay of Bengal, INSAT-3D SST during monsoon season is showing highest RMSE of 1.21 w.r.t. INCOIS (Met buoy) datasets with an exception in case of iQUAM dataset in which pre-monsoon season is showing relatively higher RMSE of 1.30 as compared to monsoon and post-monsoon seasons.

**Table-4:** Seasonal analysis of SST product from INSAT-3D over Arabian Sea and Bay of Bengal for the year 2014.

| INSAT-3D vs. Met Buoy | | | | | | |
|---|---|---|---|---|---|---|
| **Parameter** | **Arabian Sea** | | | **Bay of Bengal** | | |
| | **Pre-monsoon** | **Monsoon** | **Post-monsoon** | **Pre-monsoon** | **Monsoon** | **Post-monsoon** |
| **N** | 2923 | 1619 | 4189 | 5214 | 1304 | 1848 |
| **$R^2$** | 0.36 | 0.18 | 0.20 | 0.59 | 0.09 | 0.46 |
| **RMSE (ºC)** | 1.10 | 1.30 | 1.15 | 1.07 | 1.21 | 1.16 |
| **INSAT-3D vs. IQUAM** | | | | | | |
| | **Arabian Sea** | | | **Bay of Bengal** | | |
| | **Pre-monsoon** | **Monsoon** | **Post-monsoon** | **Pre-monsoon** | **Monsoon** | **Post-monsoon** |
| **N** | 2356 | 2081 | 2925 | 4636 | 2231 | 2525 |
| **$R^2$** | 0.36 | 0.09 | 0.04 | 0.50 | 0.12 | 0.26 |
| **RMSE (ºC)** | 1.34 | 1.56 | 1.12 | 1.30 | 1.21 | 0.97 |

### 3.6. Test Exercise

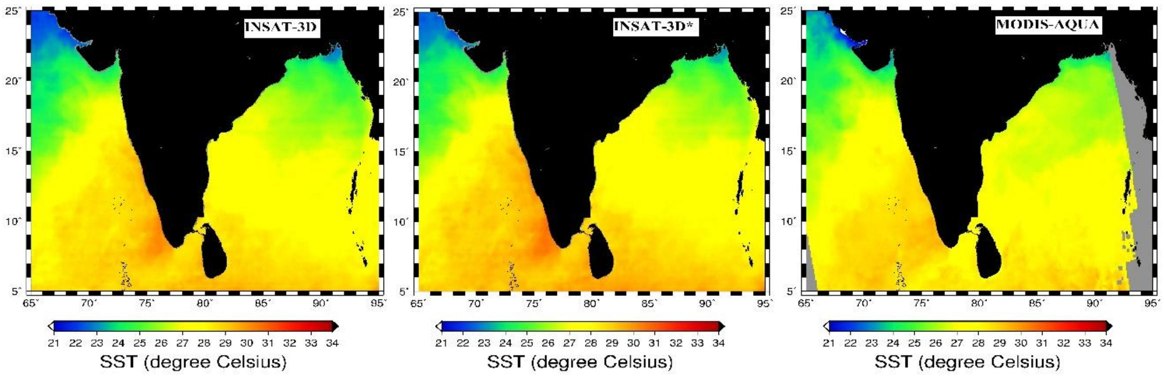
In addition to the above mentioned exercise of validation of INSAT-3D SST w.r.t. in-situ observations, we have attempted to calculate the bias between INSAT-3D and in-situ (iQuam) datasets for the year 2014 and further applied that bias (**-0.60 ºC**) to the INSAT-3D SST dataset in order to check whether there is any improvement in the RMSE in INSAT-3D SST w.r.t. MODIS-SST. Consequently, we have observed a negligible change in RMSE from 1.02 ºC to 1.01 ºC.

Further, we made one more attempt to calculate the bias between INSAT-3D and MODIS dataset for six months (i.e., February, April, June, August, October and December) which is referred as "Training-Dataset" and then further applied this bias (**-0.35 ºC**) to rest of the months, referred as "Test-Dataset" and then checked the RMSE in INSAT-3D SST w.r.t. MODIS SST for any improvement. As a result, we have found that the RMSE is improving from **0.97 ºC to 0.91 ºC**. While on applying this bias on complete INSAT-3D SST dataset for all months, the RMSE is improving from **1.02 ºC to 0.97 ºC**.

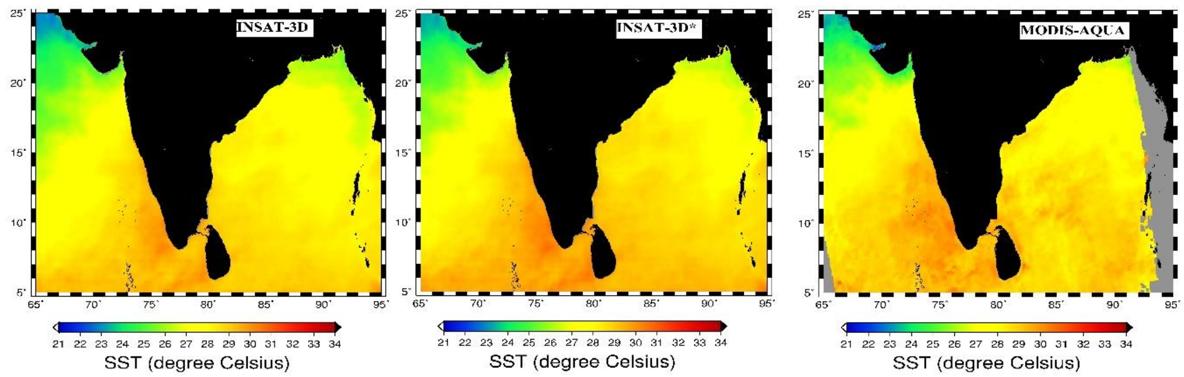
Since, there are so many intervening factors contributing to the bias estimation between two different datasets. Therefore, this test-exercise suggests that for obtaining a near-accurate and consistent bias, it should be monitored for datasets of longer duration which may result to a significant improvement in the RMSE of INSAT-3D SST.

Figure-8 is showing the comparison between original INSAT-3D images, bias corrected INSAT-3D images (INSAT-3D*) and MODIS-Aqua images. **(Data of INSAT-3D SST for the month of January, 2014 is not available).**

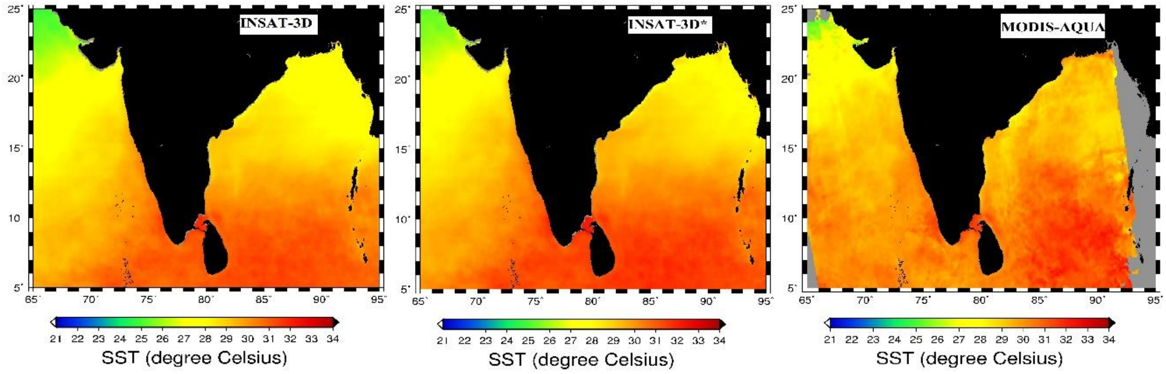
**FEBRUARY-2014**



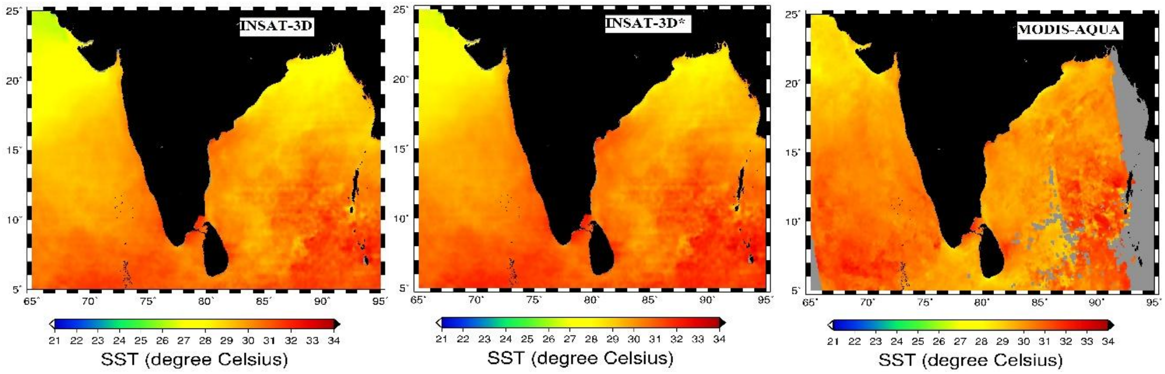

**MARCH-2014**



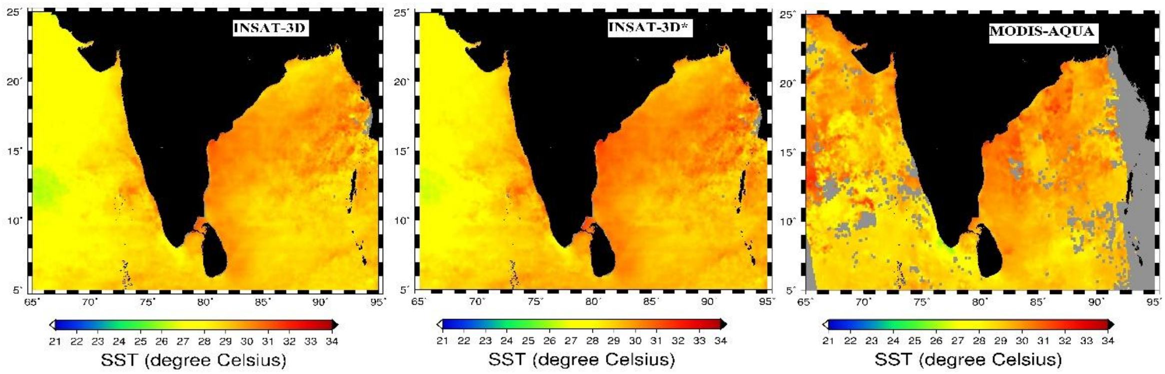
**APRIL-2014**



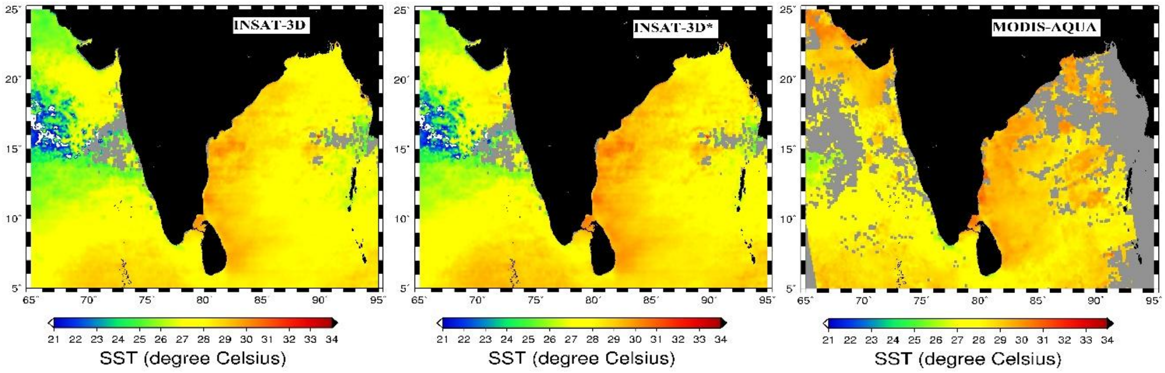

**MAY-2014**



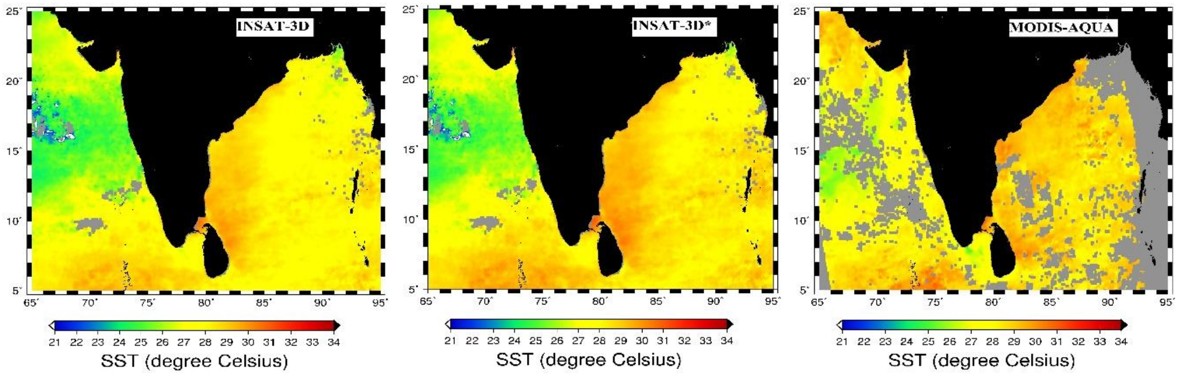

**JUNE-2014**



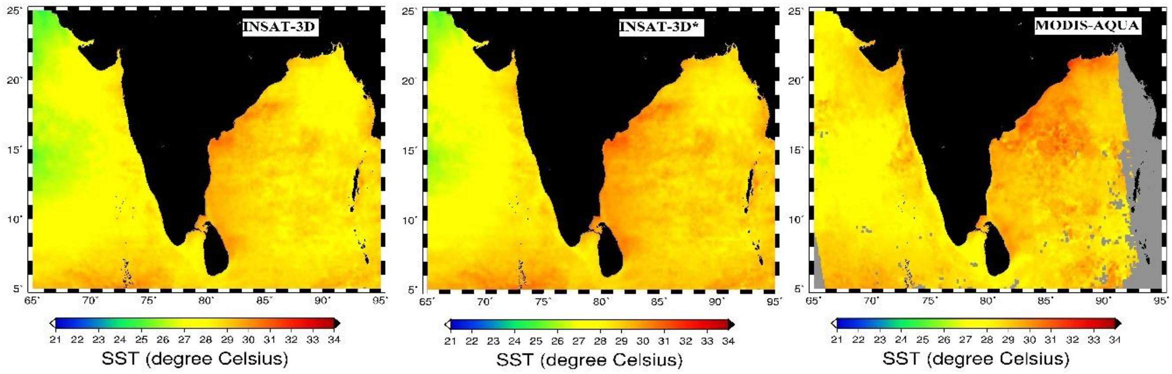
**JULY-2014**



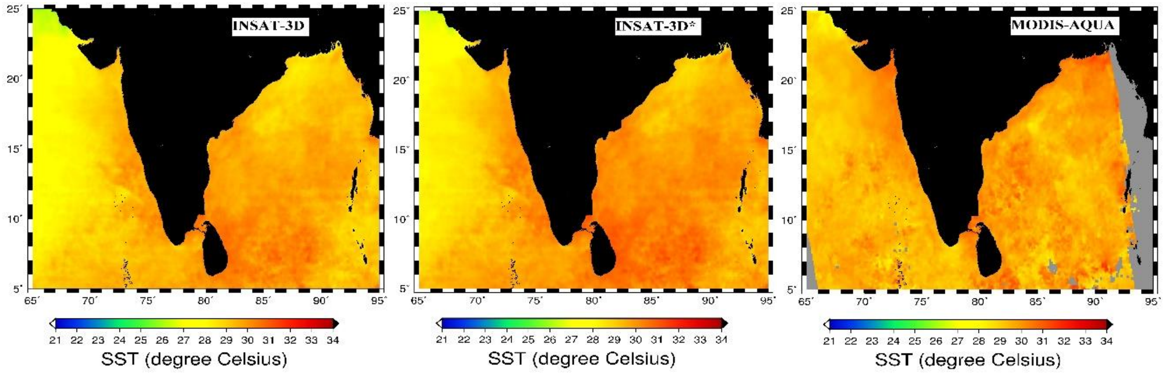

**AUGUST-2014**



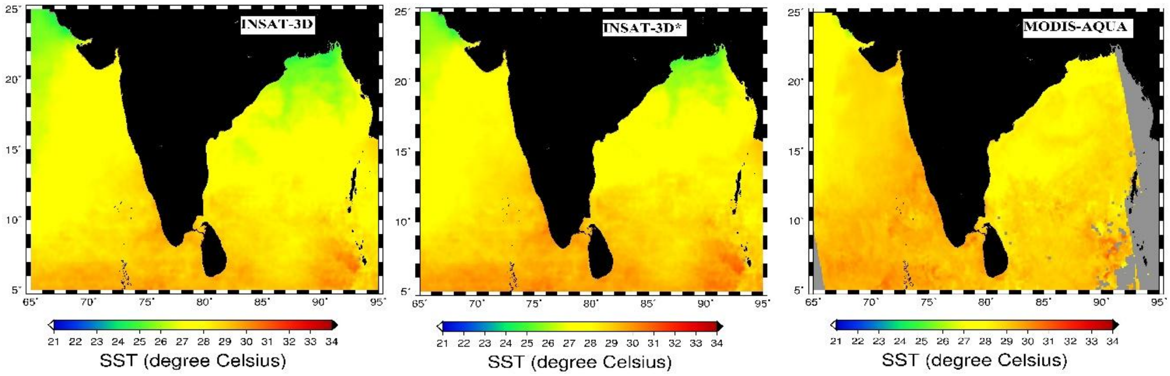

**SEPTEMBER-2014**



**OCTOBER-2014**




**NOVEMBER-2014**




**DECEMBER-2014**

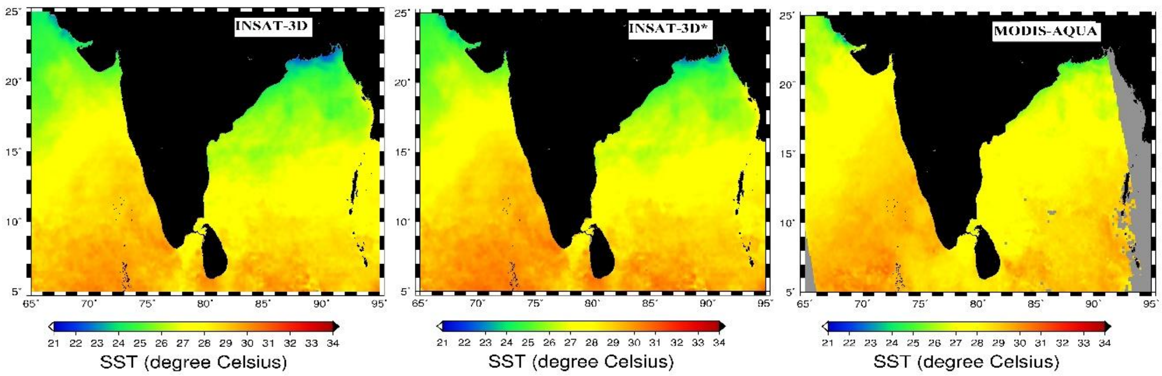



**Figure 8:** Comparison of monthly sea surface temperature spatial distribution over Indian region between INSAT-3D and MODIS-Aqua.

## 5. Conclusion

In the present study, the validation of SST derived from three satellites namely: INSAT-3D, MODIS-Terra and MODIS-Aqua against two different well correlated *in-situ* datasets (Met Buoy and iQuam datasets) has been carried out over Arabian Sea and Bay of Bengal for the years 2013-2014. The overall validation results reveals that the SST retrieved from MODIS satellites are having almost similar RMSE in the range of (0.53 – 0.84) $^{o}$C w.r.t. *in-situ* measurements over Arabian Sea as well as Bay of Bengal which is in accordance with the global retrieval accuracy. While INSAT-3D derived SST is having much higher RMSE as compared to MODIS which is in the range of 0.83 – 1.31 $^{o}$C. We have also tested the validation of INSAT-3D SST data for 2015 (July-Dec) (not mentioned in the present work) and found a marginal improvement with RMSE reduced to ~1.14 $^{o}$C. Further research and development is going on in this direction and we hope to get improved retrieval of SST product from INSAT-3D in near future. From detailed statistical analysis, it can be concluded that the performances of all three satellites are slightly better over Arabian Sea as compared to Bay of Bengal. The seasonal analysis of the INSAT-3D SST over Arabian Sea and Bay of Bengal shows that the RMSE is usually highest during monsoon as compared to pre-monsoon and post-monsoon seasons.

Although using Indirect satellite SST Validation approach based on accurate *in-situ* $SST_{depth}$ observations at a specified depth when wind speeds are greater than 6 m/s is proved to be beneficial for this study, it is also important to recognize that there is a need for a dedicated research and development in the *in-situ* data collection methodologies that can be better targeted to areas characterised by low wind speeds where Indirect Validation approach is not expected to perform well. Moreover, a large geographic area of Arabian Sea as well as Bay of

Bengal is still deprived of sampling by present non-uniform buoy network resulting in lack of *in-situ* measurements required for a more accurate validation exercise. The validation of satellite dataset is of great importance and must be continued so that errors can be better quantified which would be beneficial for an effective post-launch calibration exercise.

**Acknowledgements**

The authors gratefully express their sincere gratitude to Shri Tapan Misra, Director, Space Applications Centre (SAC) for encouragement to carry out this study. The valuable suggestions and guidance received from Dr. B.S. Gohil, Deputy Director, EPSA are gratefully acknowledged. Authors are also very much thankful to INCOIS and NESDIS/STAR for providing the valuable *in-situ* high quality SST database.

## References

C. C. Walton (1988). Nonlinear multichannel algorithm for estimating sea surface temperature with AVHRR satellite data. *J. Appl. Meteorol.*, vol. 27, no. 2, pp. 115–124.

C. J. Donlon, P. J. Minnett, C. Gentemann, T. J. Nightingale, I. J. Barton, B. Ward andM. J. Murray (2002). Toward Improved Validation of Satellite Sea Surface Skin Temperature Measurementsfor Climate Research. Journal of Climate, Vol.15, 353-369.

C. Prabhakara, G. Dalu, and V. G. Kunde (1974). Estimation of sea surface temperature from remote sensing in the 11 μm to13 μm window region. J. Geophys. Res., vol. 79, no. 12, pp. 1744–1749.

Emery W.J., Yu Y (1997) Satellite Sea surface temperature patterns. Int J Remote Sens 18(2):323-334.

Feng Xu and Alexander Ignatov (2010). Evaluation of in situ sea surface temperatures for use in the calibration and validation of satellite retrievals. J. Geophys. Res., 115, C09022.

INSAT-3D: Observing Weather from Space (2014). Products catalog. National Satellite Meteorological Centre (NSMC), India Meteorological Department.

Joseph, P.V. (1990). Warm pool over the Indian Ocean and monsoon onset. Tropical ocean and atmosphere, Newsletter, 53, 1-5, Coop. Inst. For Mar. Atmos. Studies, Miami.

Kent, E.C., P.G. Challenor and P.K. Taylor (1999). A statistical determination of the random observational errors present in Voluntary Observing Ships meteorological reports, J. Atmos. & Oceanic Tech., 16, 905-914.

Mathur A.K., Virendar Singh, Rishi K Gangwar and Sunil Mukherjee (2015). Validation Report on Sea Surface Temperature from INSAT-3D Imager observations. In Scientific Reports of Space Applications Centre, Version1.0, SAC/EPSA/AOSG/SR/32/2015: SAC, Ahmedabad.

Muhammad, S. et al. (2016). Seasonal and spatial patterns of SST in the northern Arabian Sea during 2001–2012, Egypt. J. Remote Sensing Space Sci.

O. B. Brown and P. J. Minnett (1999). *MODIS Infrared Sea Surface Temperature Algorithm—Algorithm Theoretical Basis Document*. Miami, FL: Univ. Miami, A. Under contract NAS5-31361.

P. J. Minnett, O. B. Brown, R. H. Evans, E. L. Key, E. J. Kearns, K. Kilpatrick, A. Kumar, K. A. Maillet, and G. Szczodrak (2004). Sea-surface temperature measurements from the Moderate-Resolution Imaging Spectroradiometer(MODIS) on Aqua and Terra. IEEE, 4576-4579.

Peng G, Yanchen B (2008). Validation of AVHRR/MODIS/ AMSRE Satellite SST Products in the West Tropical Pacific. In: Geoscience and Remote Sensing Symposium, 2008, IGARSS 2008, IEEE International, pp 942-945.

P. Schluessel, W. J. Emery, H. Grassl, and T. Mammen (1990). "On the bulkskin temperature difference and its impact on satellite remote sensing of sea surface temperatures,"J. Geophys. Res., vol. 95, pp. 13 341–13 356.

Richard W. Reynolds (1988). A real-time global sea surface temperature analysis. Journal of Climate, Vol.1, 75-86.

Richard W. Reynolds (2001). Specific contributions to the Observing System: Sea Surface Temperatures. Section 6 — User requirements for climate information. Advances in the applications of marine climatology, 234-241.

Shenoi, S.S.C., Shankar, D., Shetye, S.R. (2004). Why is Bay of Bengal warmer than Arabian Sea during the summer monsoon? Proceedings of the National Symposium METOC - 2004 on Emerging Trends in the Fields of Oceanography and Meteorology, 05-06 February 2004, 87-93p.

Strong, A.E. (1983). Satellite-derived sea-surface temperature errors due to El Chichon aerosol cloud. Trop. Ocean-Atmos. Newslett.,18, 14-15.

Wayne E. Esaias, Mark R. Abbott, Ian Barton, Otis B. Brown, Janet W. Campbell, Kendall L. Carder, Dennis K. Clark, Robert H. Evans, Frank E. Hoge, Howard R. Gordon, William M. Balch, Richard Letelier, and Peter J. Minnett (1998). An Overview of MODIS Capabilities for Ocean Science Observations. IEEE transactions on Geoscience and Remote Sensing, Vol. 36, no. 4, 1250-1265.

Webster, P.J., C.A. Clayson and J.A. Curry (1996). Clouds, radiation and the diurnal cycle of sea surface temperature in the tropical western Pacific Ocean. J.Climate,9, 1712-1730.

Wick, G. A., W. J. Emery, L. H. Kantha, and P. Schlüssel (1996). The behavior of the bulk-skin temperature difference under varying wind speed and heat flux. J. Phys. Oceanogr., 26, 1969-1988.