Simulation and Validation of INSAT-3D sounder data at NCMRWF

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Abstract

India's advanced weather satellite, INSAT-3D, the first geostationary sounder system over Indian Ocean, was launched (located at 83°E) on 26 July 2013, for the improved understanding of mesoscale systems. INSAT-3D carries a 6 channel imager and 19 channel sounder payload. Along with other polar satellite soundings, INSAT-3D provides fine resolution vertical profiles over India and surrounding region. National Centre for Medium Range Weather Forecasting (NCMRWF) routinely receives near-real time soundings from polar orbiting satellites, and recently started receiving INSAT-3D sounder and imager data. Simulation of INSAT-3D sounder Brightness Temperature (BT) using Radiative Transfer models and Numerical Weather prediction models has been done at NCMRWF during the North Indian Ocean Cyclone (NIOC) period of 2013. BTs during four different cyclones, viz., Phailin, Helen, Lehar and Madi are simulated and validated against the observed BTs. The RT model used to simulate the BT is Radiative Transfer for TOVS (RTTOV) version-9 and the NWP model used is Direct Broadcast CIMSS Regional Assimilation System (dbCRAS). Clear sky condition is assumed during RTTOV simulation, though the cloudy pixels are not removed, since the cloud information is not available in the then dataset. RT model simulated sounder BT of three channels (12.66 µ, 12.02µ and 11.03 µ) and DbCRAS simulated 11 µ BTs are compared with the corresponding INSAT-3D sounder BTs. Bias in RT model simulated BT is less for the window channel 11µ compared to the other two 12 µ channels, and this is mainly because of the window channel is not conducive to moisture and can be used for moisture correction in other channels. Observed BT showed fast bias with respect to the RT simulated BT for the 12 µ channels, whereas slow bias for the window channel in all the cyclone cases. The biases and standard deviations were higher for the cyclone Phailin with respect to the RT simulated BTs. Validation of INSAT-3D window channel BT with respect to dbCRAS simulated 11 µ showed slow bias and the standard deviation was maximum for Phailin.

1. Introduction

INSAT-3D, India's advanced weather satellite, is the first geostationary sounder over India and the surrounding Oceanic regions. It is the second of its kind after the Geostationary Operational Environmental Satellites (GOES). INSAT-3D, which was launched on 26 July 2013, is located at 82°E. Along with soundings from polar satellites INSAT-3D provides fine resolution vertical profiles over India and the surrounding regions. National Centre for Medium Range Weather Forecasting (NCMRWF) routinely receives near-real time soundings from INSAT-3D from India Meteorological Department (IMD) and also through Meteorological and Oceanic Satellite Data Archival Centre (MOSDAC), Indian Space Research organization (ISRO). Simulation and validation of INSAT-3D sounding data is going on at NCMRWF for the possible assimilation of the same in NCMRWF's global models. In this study, simulation and validation of INSAT-3D BTs have been carried out during North Indian Ocean Cyclone (NIOC) period of 2013.

A brief description of various cyclones over the North Indian Ocean during 2013 is given in Section 2. A brief introduction of the INSAT-3D Imager and Sounder Channels is given in Section 3. The RT model used to simulate the data is Radiative Transfer for TOVS (RTTOV) version-9, and Section 4 gives a brief description of RTTOV. The NWP model used to simulate the Brightness Temperature (BT) is Direct Broadcast CIMSS (Co-operative Institute for Meteorological Satellite Studies) Regional Assimilation System (dbCRAS). A brief description of dbCRAS is provided in Section 5. The results are discussed in Section 6, with sub-section 6.1 describes the results from simulation and sub-section 6.2 describes the validation results. The remarks from the present study are summarized in section 7.

2. North Indian Ocean Cyclone (NIOC) Period, 2013

The NIOC period is an event in the annual cycle of tropical cyclone formation, which usually occurs between May and December, with the peak in October and November. An average of 4 to 6 storms forms in the two main seas in the North Indian Ocean, the Arabian Sea (ARB) and the Bay of Bengal (BOB), every season. Features of four cyclonic storms formed in the North Indian Ocean during 2013 are simulated and validated against INSAT-3D BTs. The four cyclonic storms discussed in this study are the Very Severe Cyclonic Storm (VSCS) Phailin, Severe Cyclonic Storm (SCS) Helen, VSCS Lehar and VSCS Madi formed during October to December 2013. A brief description of each of these systems is given below.

2.1 Phailin (8 -14 October 2013)

Phailin was the second-strongest tropical cyclone which made landfall in India, after the 1999 Odisha cyclone. The system was first noted as a tropical depression within the Gulf of Thailand on 4th October, 2013. Further the system moved westward within an area of low to moderate vertical wind shear, and moved out of the Western Basin on 6th October. The system was named Phailin on 9th October, afterwards it had developed into a cyclonic storm and passed over the Andaman and Nicobar Islands into the Bay of Bengal. Phailin intensified rapidly and became a very severe cyclonic storm on 10th October. The system started to weakening on 12th October as it approached the Indian state of Odisha. It made landfall later in 12th October, near Gopalpur in Odisha coast around 2130 IST (1600 UTC) on 12th October. Phailin subsequently weakened over land as a result of frictional forces, before degenerating into a well marked area of low pressure.

2.2 Helen (19 -23 November 2013)

Helen was a relatively weak tropical cyclone formed in the BOB on 18th November 2013 from the remnants of the tropical storm Podul. While moving very slowly in the northwest direction, it became a Cyclonic storm on 20th November and brought light to heavy rainfall in eastern India. The system then became a Severe Cyclonic Storm on the afternoon hours of 21st November.

2.3 Lehar (23 – 28 November 2013)

Lehar was the second most intense tropical cyclone of the NIOC season of 2013, after the cyclone Phailin, as well as a one of the relatively strong cyclones that affected Southern India in November 2013. Lehar was formed from an area of low pressure in the South China Sea on 18th November, 2013. While moving westwards, the system entered BOB and quickly became a depression on 23rd November. The system moved west-northwest into an improving environment for further development before the system was named Lehar on 24th November and thereafter it had developed into a cyclonic storm. Lehar gradually intensified further into a VSCS reaching its peak on 26th November, and rapidly weakened to a depression on 28th November and made its landfall over the coast of Andhra Pradesh in the east coast of India.

2.4 Madi (6 – 13 December)

A low pressure area formed south of India close to the equator on 30th November 2013. This low pressure slowly drifted northeastward and slowly intensified for the next couple of days. The moderate vertical wind shear kept the system from strengthening, though the sea surface temperature was conducive for the intensification. The system further strengthened on 6th December 2013, and remained nearly stationary over the next 24 hours. On 8th December, the system became a deep depression and thereafter the Cyclonic storm Madi. The storm then quickly intensified into a severe cyclonic storm. A poleward outflow with deep convection wrapped into a well-defined centre was developed on 8th December, and further it became a VSCS, the third in NIOC season of 2013. On 9th December Madi had weakened into severe cyclonic storm and further developed an eye on 10th December despite of the shear. The storm continued to track in a northerly direction and unexpectedly made a sharp, sudden southwestward turn and started losing all its convection to the strong wind shear. The subtropical ridge located over India had steered the system southwestward. On 11th December Madi weakened into a cyclonic storm and later into a deep depression. Further the system weakened into a depression and crossed the east coast of India near Tamil Nadu.

3. INSAT-3D Instrument description

INSAT-3D is the second of this kind after GOES and the first over the India and surrounding oceanic regions. INSAT-3D is a multipurpose geosynchronous spacecraft with main meteorological payloads (imager and sounder). The mission goals are to provide an operational, environmental and storm warning system to protect life and property. The satellite has three payloads viz., Meteorological (MET), Data Relay Transponder (DRT), and Satellite Aided Search and Rescue (SAS&R).

INSAT-3D imager provides imaging capability of the earth disc in six different channels. One in visible and five in infrared. The visible imager (VIS) channel operates in 0.52 – 0.72 μ. The other five infrared channels are in short wave infrared (SWIR) (1.55 – 1.70 μ), Mid wave infrared (MIR) (3.80 – 4.00 μ), water vapor (WV) (6.50 – 7.00 μ), and in two thermal infrared (TIR) channels. The split TIR channels are 10.2 – 11.2 μ (TIR-1) and 11.5 – 12.5 μ (TIR-2). The ground resolution at the sub-satellite point is 1km for both visible and SWIR channels. The ground resolution for MIR and TIRs is 4km each for WV channel, the ground resolution is 8 km. Details of INSAT-3D imager channels are tabulated in Table 1.

Distributed over long wave and short wave bands, INSAT-3D sounder has 18 infrared channels, and an additional visible channel which provides synoptic view of the clouds and the earth, and hence the three dimensional map of temperature and humidity structure of the atmosphere. Out of the 19 sounder channels, 6 bands are in the SWIR, five are in the MIR, 7 are in the long wave infrared (LWIR) and one in the visible regions. The ground resolution of all channels is 10 km $\times$ 10 km. Table 2 describes the details of INSAT-3D sounder channels.

Table 1: INSAT-3D Imager channel Description

Spectral Band	Wave length (μm)	Ground Resolution
VIS	0.55 – 0.75	1km
SWIR	1.55 – 1.70	1 km
MIR	3.80 – 4.00	1 km
WV	6.50 – 7.10	8 km
TIR-1	10.3 – 11.3	4 km
TIR-2	11.5 – 12.5	4 km

Table 2: INSAT-3D Sounder IR Channel Description

Spectral Band	Wave length (μm)	Principal Absorbing Gas	Purpose
1. LWIR-1	14.71	CO_2	Stratosphere Temperature
2. LWIR-2	14.37	CO_2	Tropopause Temperature
3. LWIR-3	14.08	CO_2	Upper-level Temperature
4. LWIR-4	13.64	CO_2	Mid-level Temperature
5. LWIR-5	13.37	CO_2	Low-level Temperature
6. LWIR-6	12.66	H_2O	Total Precipitable water
7. LWIR-7	12.02	H_2O	Surface Temperature, moisture
8. MWIR-1	11.03	Window	Surface Temperature
9. MWIR-2	9.71	Ozone	Total ozone
10. MWIR-3	7.43	H_2O	Low-level moisture
11. MWIR-4	7.02	H_2O	Mid-level moisture
12 MWIR-5	6.51	H_2O	Upper-level moisture
13. SWIR-1	4.57	N_2O	Low-level Temperature
14. SWIR-2	4.52	N_2O	Mid-level Temperature
15. SWIR-3	4.45	CO_2	Upper-level Temperature
16. SWIR-4	4.13	CO_2	Boundary layer Temperature
17. SWIR-5	3.98	Window	Surface Temperature
18.SWIR-6	3.74	Window	Surface Temperature, moisture

4. RTTOV

The RTTOV model was originally developed at European Centre for Medium Range Weather Forecasting (ECMWF) (Eyre and Woolf, 1988) to retrieve temperature and humidity profiles from the Television InfraRed Observation Satellite (TIROS-N) Operational Vertical Sounder (TOVS). The code has been gone through several changes subsequently (Matricardi et al., 2004) within the EUMETSAT NWP Satellite Application Facility (SAF) of which RTTOV-10 is the latest released version. In this study RTTOV-9.3 is used to simulate the INSAT-3D sounder BT. RTTOV covers the spectral range 500 cm^{-1} to 3300 cm^{-1} in the IR and the frequency range 10 – 200 Ghz in the microwave and supports large number of platforms and sensors. The RTTOV model, which is essential for NWP environment is that it performs fast computation of the forward radiances as well as the fast computation of the gradient of the radiances. RTTOV model uses channel averaged transmittances in the RT equation (polychromatic form of the radiative transfer equation) based on the assumption that this is equivalent to the convolution of the monochromatic radiances (Matricardi et al., 2004).

RTTOV-9 fast transmittance algorithm supports a range of predictor sets, viz., RTTOV-7 predictors, RTTOV-8 predictors, and RTTOV-9 predictors. The selection of the predictors is made according to the coefficients file supplied to the program. The RTTOV-9 predictors allow varying the amounts of H_2O, O_3, CO_2, N_2O, CH_4, and CO. In addition RTTOV-9 predictors can be used to compute optical depths for the long atmospheric paths involved in the computation of top of the atmosphere (TOA) radinaces if solar radiation is required to be included in the short-wave infrared channels.

5. dbCRAS

dbCRAS, a Numerical Weather Prediction (NWP) software able to predict/simulate weather phenomena using International MODIS/AIRS package (IMAPP) Level 2 total precipitable water (TPW), cloud top pressure and cloud fraction as part of assimilation. This assimilation improves the depiction of clouds and moisture in the initial condition to the model, which is generally taken from the National centre for Environmental Prediction (NCEP) or National Centre for Medium Range Weather Forecasting (NCMRWF) Global Forecast system (GFS). In addition to the assimilation of archived MODIS sounder data products, dbCRAS is capable to assimilate the MODIS sounder data products directly receiving at the broadcast antenna set up and hence “Direct Broadcast”. The dbCRAS is “regional” since it predicts/simulate the weather over a limited area.

The main components of dbCRAS are pre-analysis, forecast model and the post processor. The pre-analysis part collects large amounts of weather observations (wind, temperature, humidity, clouds) checks them for errors, and analyzes them onto the 3-dimensional model grid. It also gathers and prepares gridded fields from a large scale model for use as initial and lateral boundary conditions. The second part, the forecast model is initialized with the data prepared during the pre-analysis. The horizontal resolution of the model ranges from 127 km to 20km. A 12 hour assimilation cycle is used to incorporate the sounder products from both geostationary and polar orbiting satellites. The third component, the post-processor takes output and generates numerous products including synthetic satellite images (Infrared (11 µ) and Water Vapor (6.7 µ) channel). Table 3 describes the dbCRAS configuration used in this study.

Table 3: Configuration of dbCRAS used in this study

Domain Centre	28° N, 77°E (Delhi, India)
Horizontal Resolution	48 km (210 x150 grids)
Vertical Sigma levels	38
Topography	2 minute USGS Global dataset
Boundary Condition	NCEP GFS forecast at 6- hourly interval
Analysis	12 hour assimilation with MODIS cloud parameters and precipitable water
Cloud assimilation	Bayler et al., 2000
Initialization	Vertical normal mode (Bourke and McGregor, 1983)
Model physics Convective Parameterization Cloud microphysics	Modified Kuo type (Raymond and Aune, 2003) Explicit cloud and precipitation microphysics (Raymond et al., 1995) with diagnosed liquid/ice phase (Dudhia, 1989) Water/ice cloud sedimentation (Lee, 1992)
Shortwave and Long wave Radiation	Ackerman and Stephens, 1987
Land-surface processes	Vertical turbulent exchange (Raymond, 1999) 5-layer soil model (Kondo et al., 1990 and Lee and Pielke, 1992)
Model products	Different meteorological parameters 11 µ Infra-Red and 6.7µ Water Vapor synthetic satellite images

6. Results and Discussions

INSAT-3D sounder BTs during NIOC season of 2013 are simulated using RT and NWP models to ensure the quality of observed BT. RTTOV and dbCRAS models are used to simulate the BTs during four different cyclones, viz Phailin, Helen, Lehar and Madi in North Indian Ocean. The simulated BTs are then validated against the observed BT.

6.1 Simulation

RTTOV version 9 is used to simulate the 18 channel sounder BTs. Single level surface parameters like specific humidity, temperature, surface pressure, surface wind and sea level pressure and profiles like temperature and humidity from NCMRWF global model are used. Ozone profile used in this study is the climatological profile. Radiances are calculated assuming the clear sky condition.

Since the INSAT-3D data being received at NCMRWF has not contains cloud information, clear sky condition is assumed during simulation. The cloudy area in the simulated BTs is compared with Tropical Rainfall Measuring Mission (TRMM). dbCRAS model simulated 11 µ and 6.7 µ BTs are also compared with the corresponding observed INSAT-3D channel BTs.

Before simulating the BTs during cyclone, BTs are simulated during a calm day through RTTOV and dbCRAS to ensure that both can simulate the INSAT-3D sounder BTs accurately with minimum error. Figure 1 shows the INSAT-3D channel-8 (~ 11 µ) observed and simulated BTs valid for 00 UTC of 2nd January 2014.

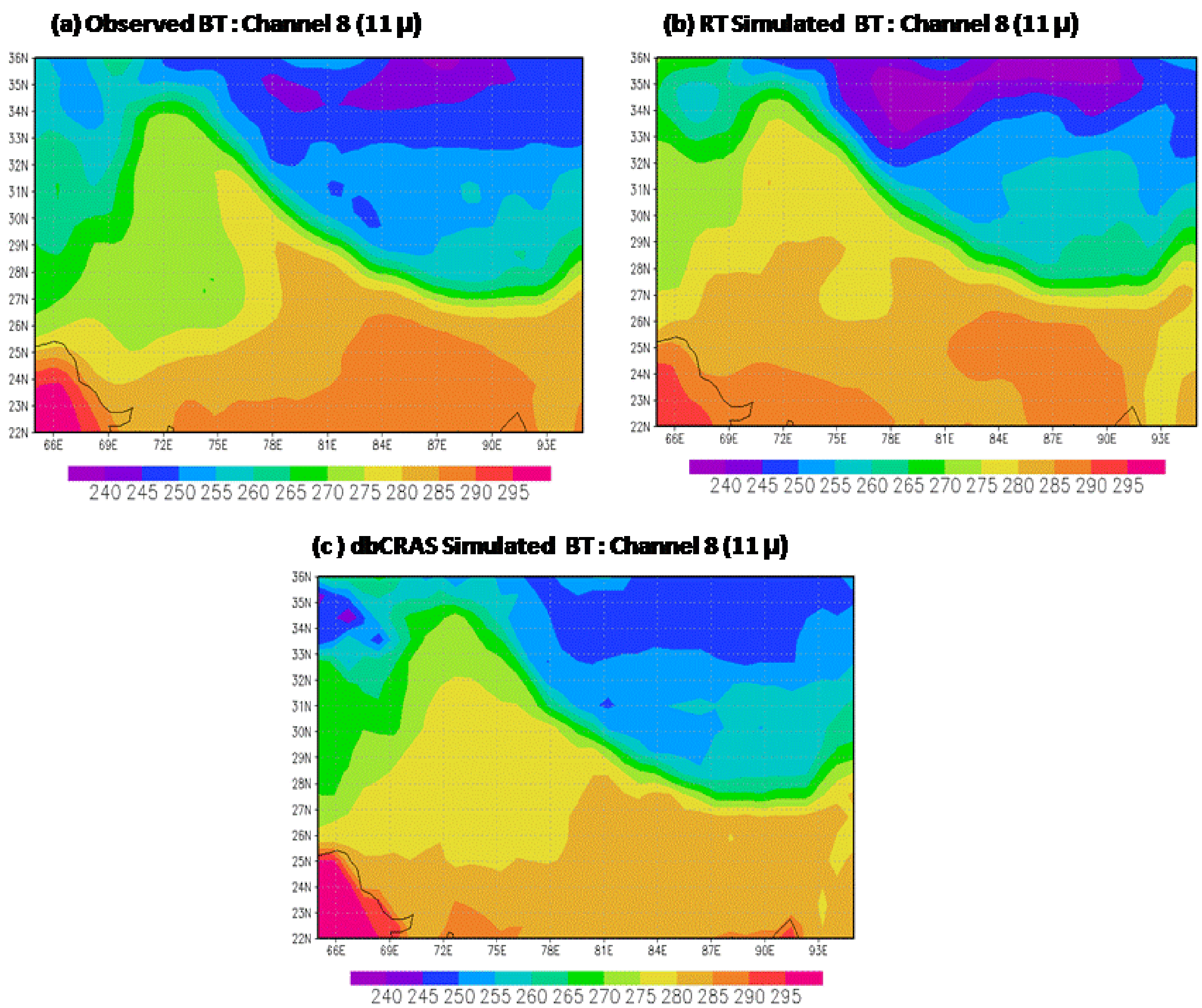

Figure 1: Observed and simulated INSAT-3D channel 8 (11 µ) BTs (a) Observed, (b) RTTOV simulated and (c) dnCRAS simulated valid for 00 UTC of 2nd January 2014.

6.1.1 Simulation using RTTOV

From Figure1, it is clear that the simulated BTs are matching fairly well with the observed BT characteristics. The RT model simulated BT could not capture the maximum observed BT near the Gujarat coast, and this may be due to the use of model surface temperature instead of Sea surface temperature. dbCRAS simulated BT captured the maximum BT observed over the Gujarat Coast, however, it could not capture the minimum BT as seen in the observation as well as in the RT simulated BT. Thus a difference of 5 K in the maximum and minimum end is noticed in the dbCRAS simulated and RT model simulated BTs respectively. This difference is acceptable since the simulated BTs are not bias corrected. Before bias correction, the observed and simulated BT differences are around 9 – 13 K for different satellite channels being used in NCMRWF global models.

Figures 2, 3, 4, and 5 respectively show different channels observed BTs, simulated BTs and the difference between observed and simulated BTs along with TRMM accumulated rainfall for particular days during the four different cyclones Phailin, Helen, Lehar and Madi during 2013. Mainly simulated BTs from three channels were compared with the observed BT, two 12 µ channels (channels 6 and 7) and one window channel (11µ) (channel 8). From figure 2, the simulated BT during VSCS Phailin valid for 0000 UTC of 9th October 2013, was not matching with the observed BT even in the cloud free region (in comparison with the TRMM rainfall). NCMRWF GFS (NGFS) showed some lag in the predicted VSCS Phailin compared to the observation, and since NGFS surface parameters and profiles are used in RTTOV to simulate the BT, the features have not simulated properly. The window channel simulated BT is matching with the observed BT in the cloud free area, this is mainly because of 11 µ window channel has no affinity to moisture, or it is not contaminated by moisture.

Figure 3 is similar to Figure 2, but valid for 0000 UTC of 20th November 2013 during cyclone Helen. In this case, the RTTOV simulated BTs are matching with the observed BT during the clear sky conditions in the three channels (12.66, 12.02 and 11.03 µ). The difference between observed and simulated BTs in the cloud free region is around -4 to 4 K. Figure 4 is similar to figure 2, but valid for 0000 UTC of 26th November 2013, during the cyclone Lehar. In the case of Lehar also the RTTOV simulated BTs are matching with the observed BTs in the clear sky conditions. Figure 5 is similar to Figure 2, but valid for 0000 UTC of 10th December 2013, during cyclone Madi. As in the cases of Helen and Lehar, the RTTOV simulated BTs during Madi also matching with the observed BT during clear sky condition. Thus except in the case of VSCS Phailin, the RTTOV simulated BTs are matching well with the observed BT in the clear sky condition as compared with TRMM accumulated precipitation.

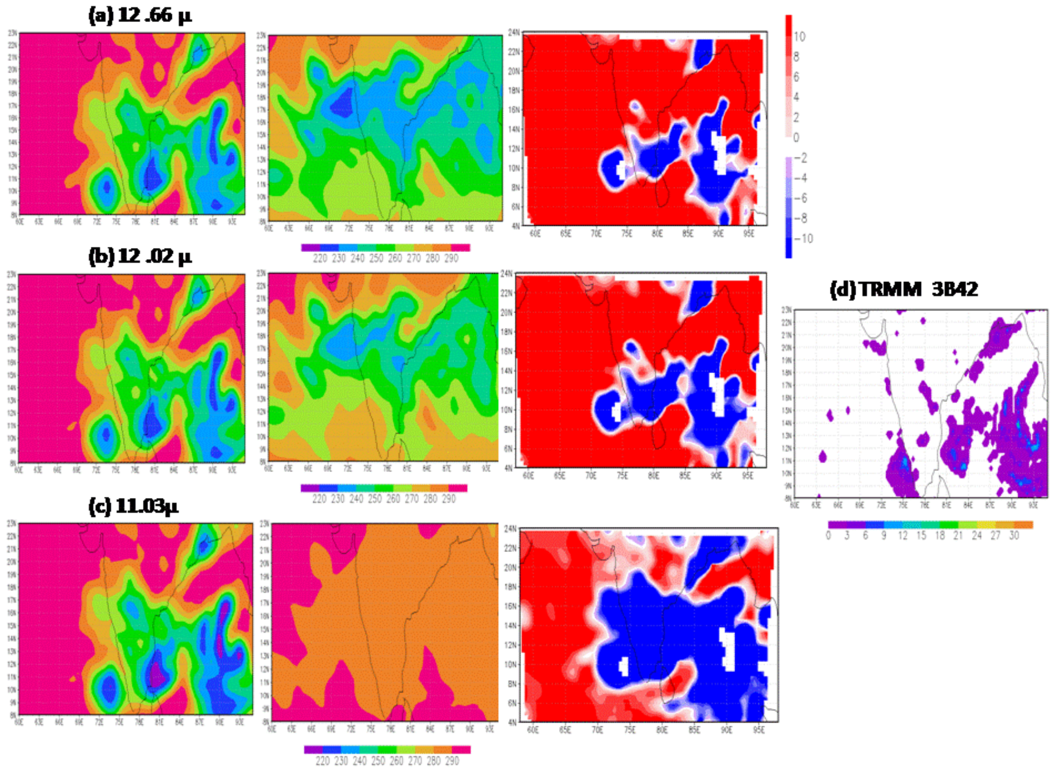

Figure 2: INSAT-3D observed and RTTOV simulated BTs. First column is the observed BT, second column is the simulated BT and third column is the difference between observed and simulated BT for (a) 12.66 µ (b) 12.02 µ and (c) 11.03 µ. (d) is the TRMM 3B42 precipitation valid for 00 UTC of 9th October 2013 during Phailin cyclone.

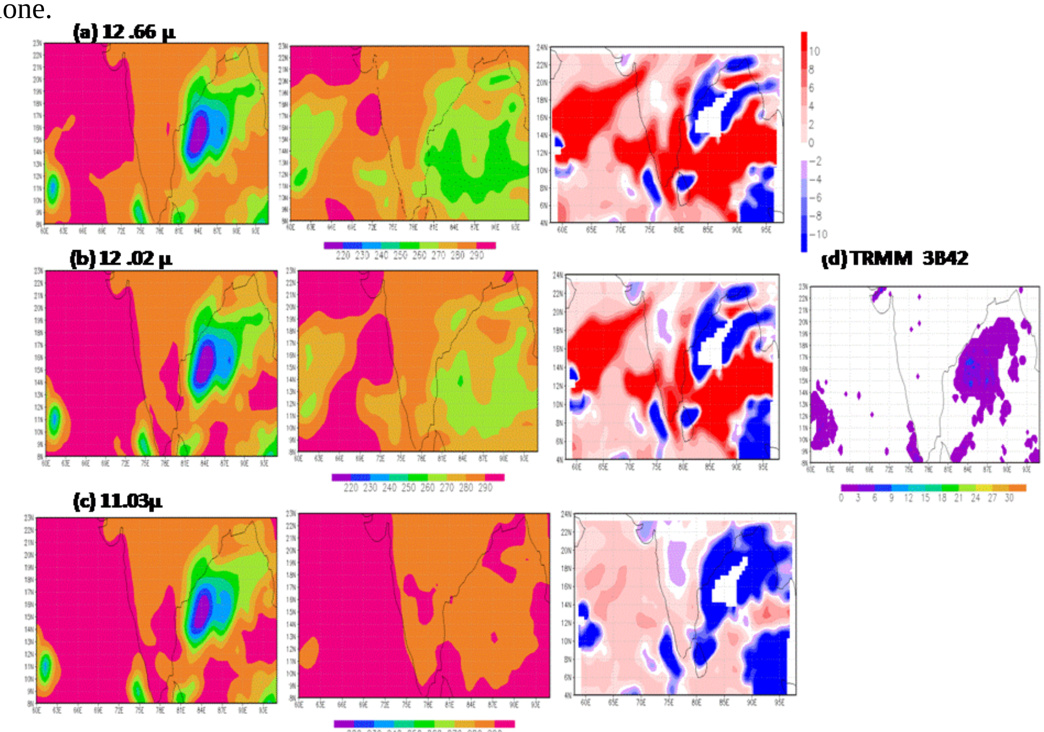

Figure 3: Same as Figure 2, but for Cyclone Helen, valid for 00 UTC of 20th November 2013 00 UTC.

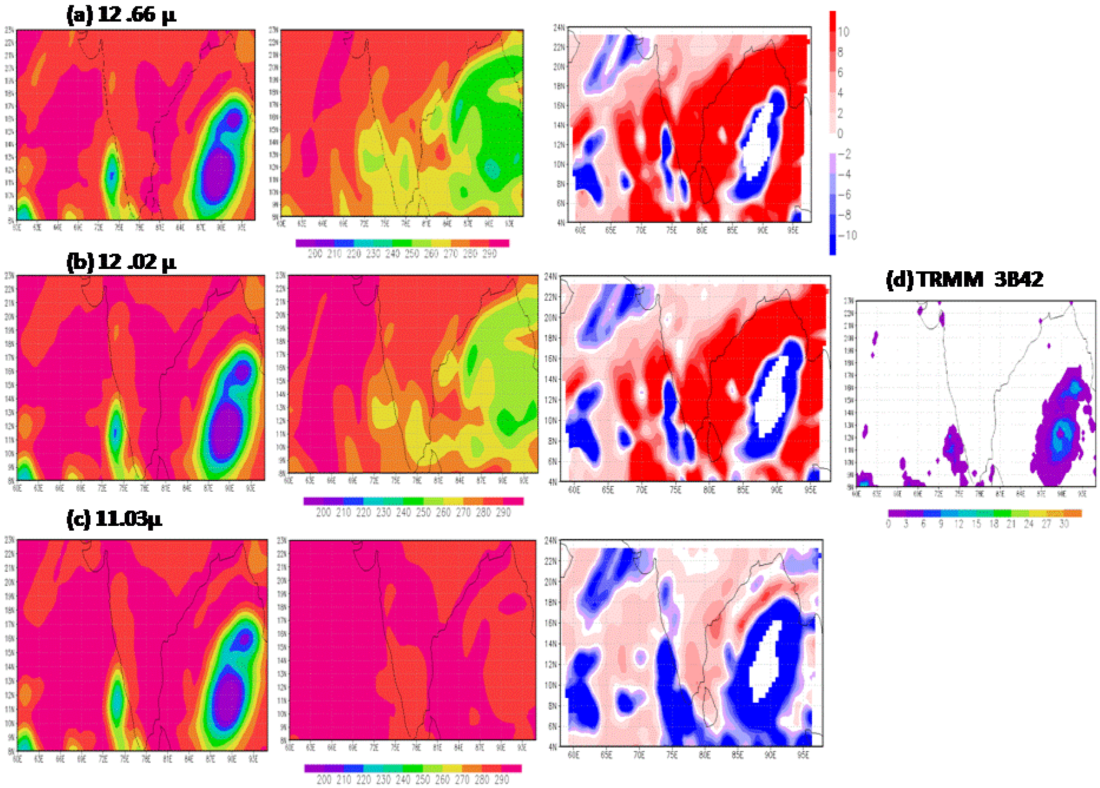

Figure 4: Same as Figure 2, but for Cyclone Lehar, valid for 00 UTC of 26th November 2013 00 UTC.

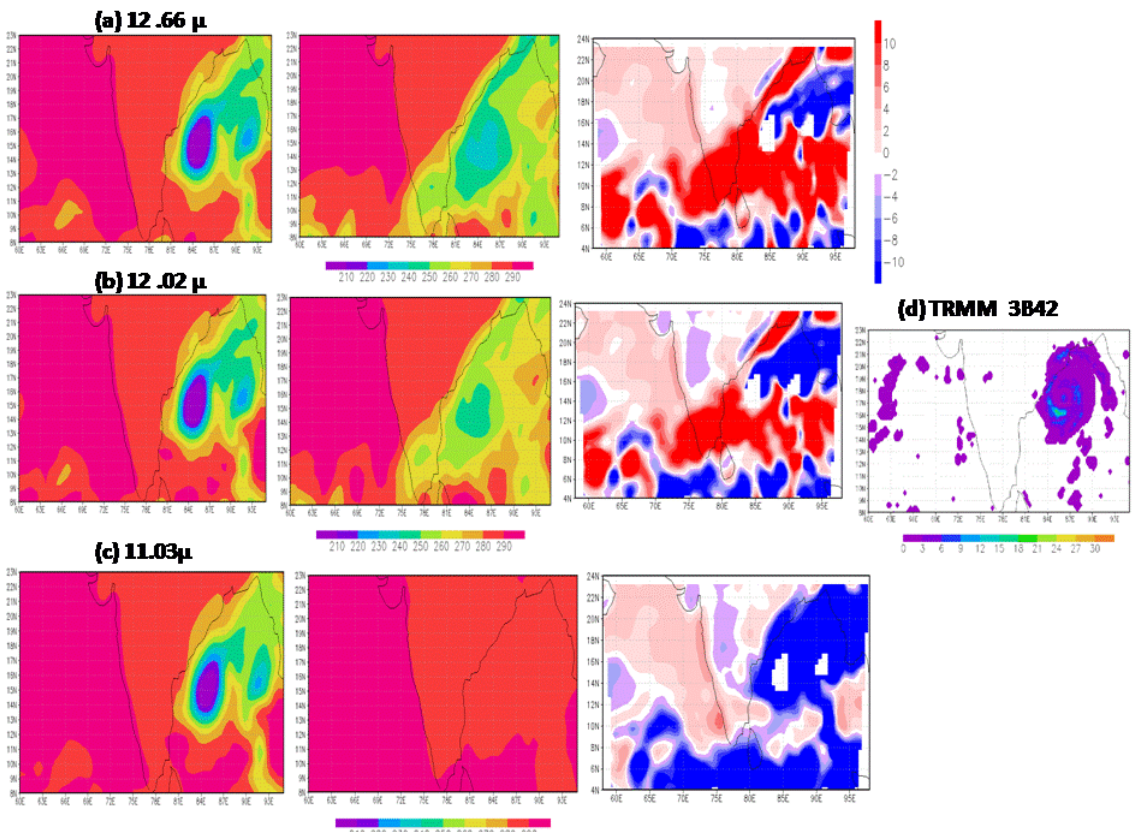

Figure 5: Same as Figure 2, but for Cyclone Madi, valid for 00 UTC of 10th December 2013 00 UTC.

It is noted that the mean error during different cyclone period is minimum in the window channel compared to the other two 12 μ channels. The errors (cloud free region) in the window channel were generally less than 5 K except in the case of Phailin. The 12 μ channels also showed high mean difference in the case of Phailin compared to other three cyclones, where the differences in the cloud free region are in the range of 15- 20 K. The 12 μ channels showed similar high mean differences in the case of other cyclones also.

6.1.2 Simulation using dbCRAS

Two different channels (6.7 μ and 11 μ) BTs also simulated using dbCRAS model and compared to observed BT in the same line as that of RTTOV simulated BT. Here the comparison of dbCRAS simulated 11 μ window channel BTs with observed BTs is discussed in the case of four cyclones. Figures 6, 7, 8, and 9 are the comparison of dbCRAS simulated 11 μ BT with that of observed BT and the differences in the observed and simulated BTs in particular days during the cyclones Phailin, Helen, Lehar and Madi.

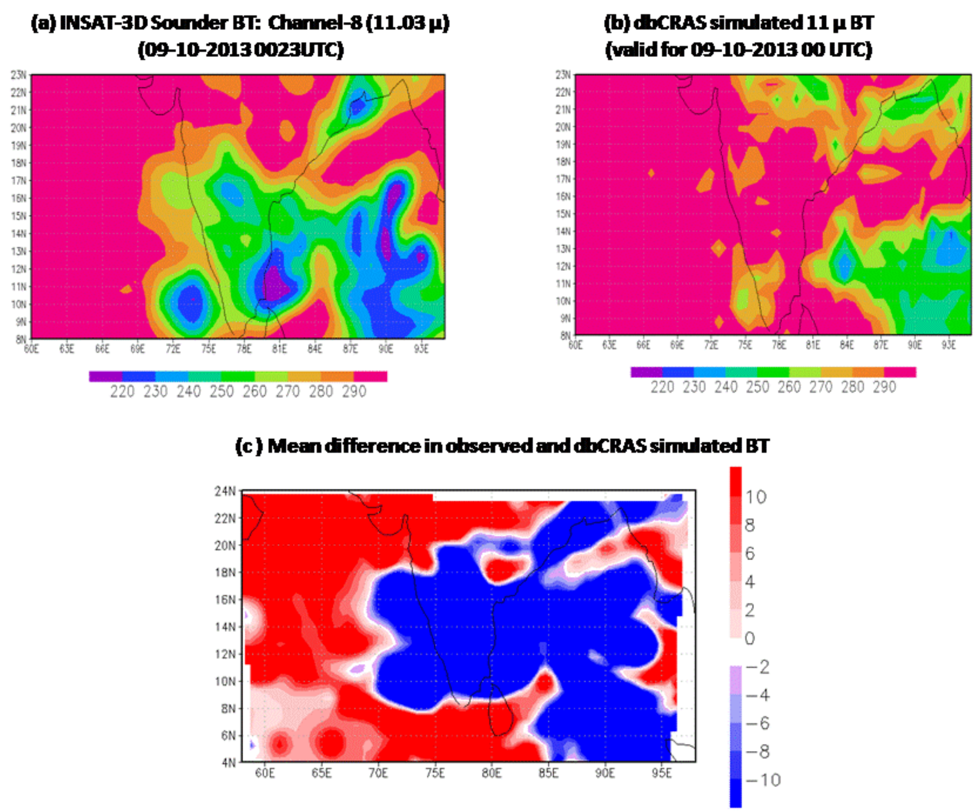

Figure 6: (a) Observed 11 μ (b) dbCRAS simulated 11 μ BT during Phailin valid for 0000 UTC of 9th October 2013, and (c) the mean difference in observed and dbCRAS simulated BT.

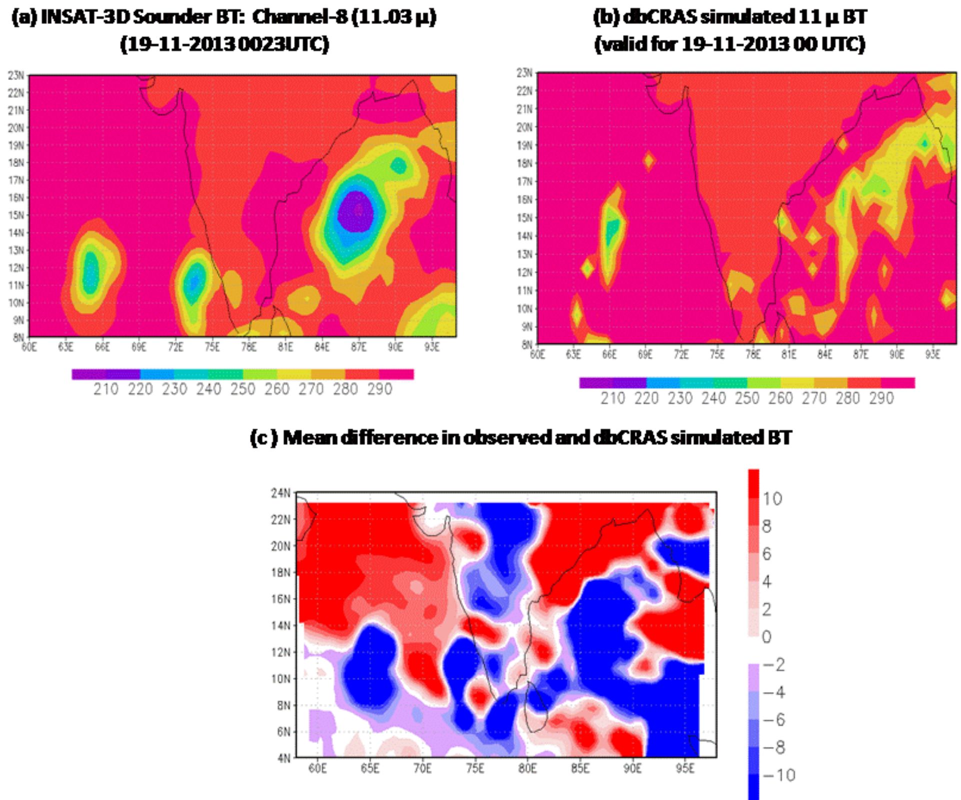

Figure 7: (a) Observed 11 µ (b) dbCRAS simulated 11 µ BT during Helen valid for 0000 UTC of 19th November 2013, and (c) the mean difference in observed and dbCRAS simulated BT.

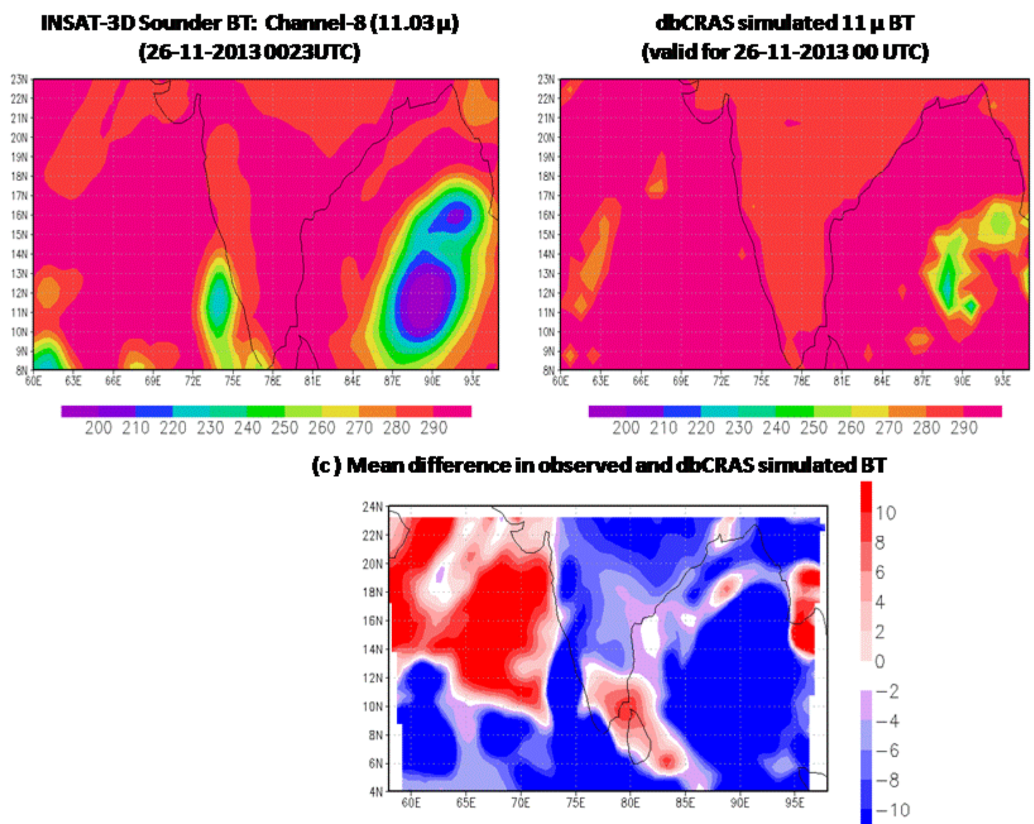

Figure 8: (a) Observed 11 µ (b) dbCRAS simulated 11 µ BT during Helen valid for 0000 UTC of 26th November 2013, and (c) the mean difference in observed and dbCRAS simulated BT.

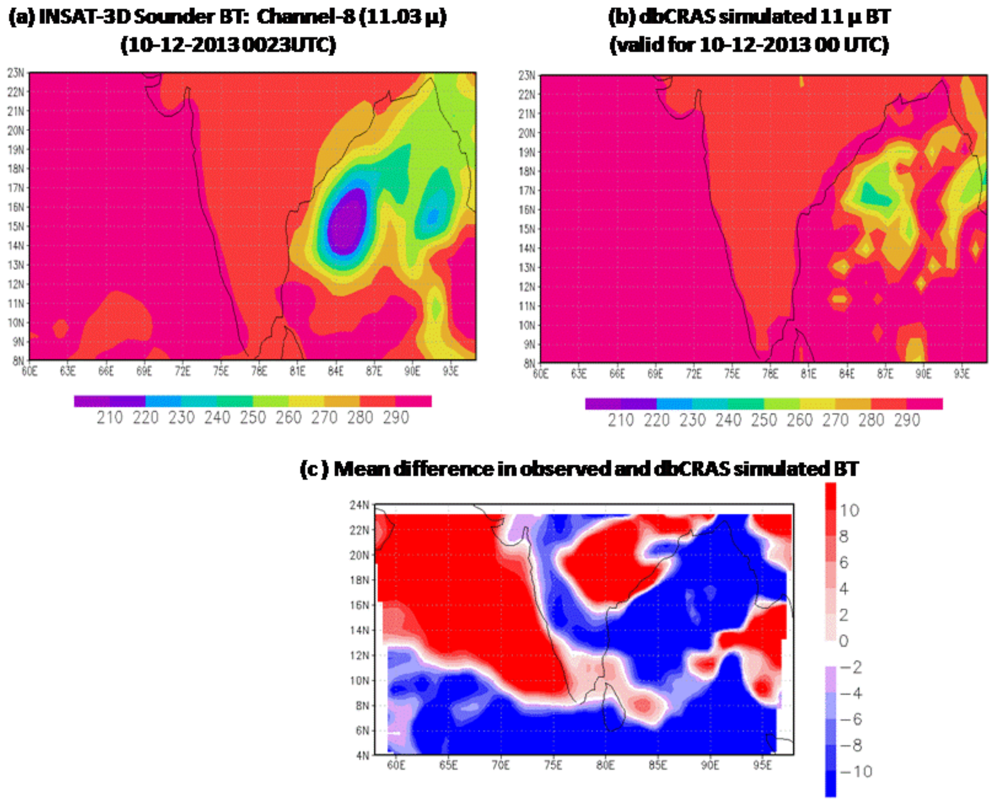

Figure 9: (a) Observed 11 µ (b) dbCRAS simulated 11 µ BT during Helen valid for 0000 UTC of 10^{th} November 2013, and (c) the mean difference in observed and dbCRAS simulated BT.

It is noticed from figures 6, 7, 8, and 9 that dbCRAS simulated the 11 µ BT fairly well compared to the observation, with slight difference in the cyclone intensity and location. The lowest observed BT could not be simulated using dbCRAS. 5 – 10 K difference in the lowest BT is noticed in the simulated BT compared to the observation. This may due to the usage of GFS initial and lateral boundary conditions for forcing the dbCRAS which may be hot compared to the environment. The mean difference in BT was also less than 10 K over the cyclone locations even in the case of Phailin.

6.2 Validation

After the successful simulation of INSAT-3D BTs using both RTTOV and dbCRAS, the simulated BTs are validated against the observed BTs for each cyclone through density plots and calculated the bias and standard deviation. Figure 10 is the density plots of observed and RTTOV simulated BTs of three different channels during the period of Phailin and Helen. Figure 11 is similar to Figure 10, but for the cyclones Lehar and Madi. From Figures 10 and 11, it is clear that RTTOV didn't capture the BTs at the lower side in the case of four cyclones.

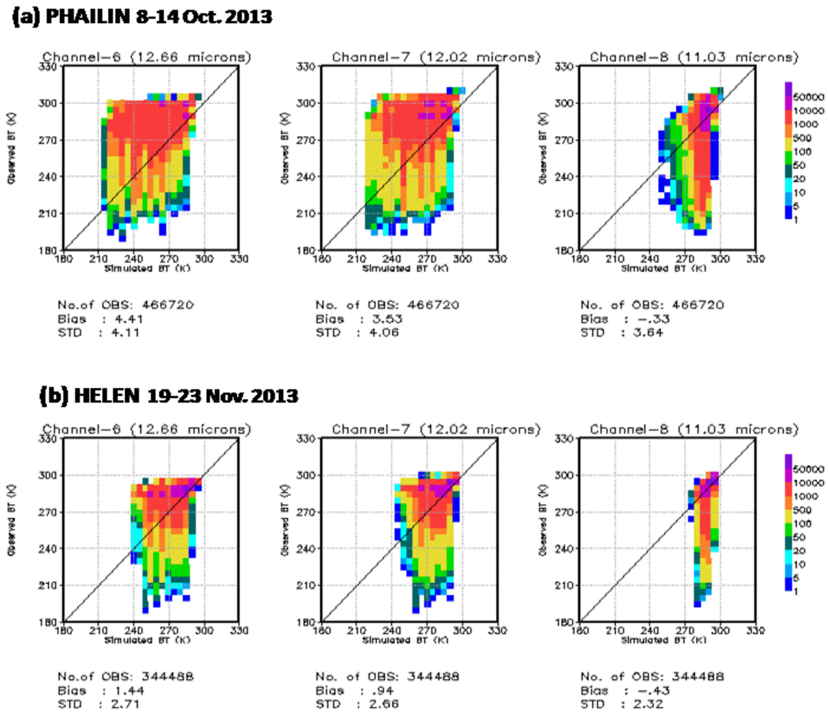

Figure 10: Density plots of observed BTs versus RTTOV simulated for three different channels during (a) Phailin and (b) Helen.

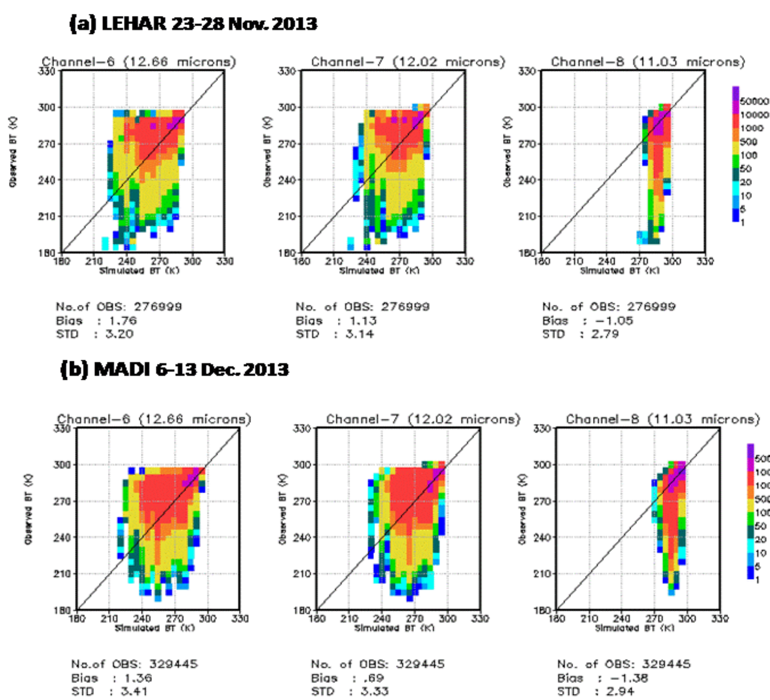

Figure 11: Density plots of observed BTs versus RTTOV simulated BTs for three different channels during (a) Lehar and (b) Madi.

The bias in observed BTs with respect to the RTTOV simulated BTs are positive for the 12 µ channels whereas it is negative for the window channel (11 µ). The bias and standard deviations in different channels during different cyclones are tabulated in Table 4. The bias was positive for 12 µ channels, whereas it was negative for the window channel in the case of all the four cyclones. The bias in the 12 µ channels was maximum for Phailin of the magnitude of ~ 4 K, whereas for other cyclones, it was less than 2K for other three cyclones. However the bias in the window channel was minimum for Phailin compared to other cyclones. The standard deviations in the three channels also were maximum during Phailin, of the magnitude of 4K. The maximum bias and standard deviation were observed for 12.66 µ channel.

Table 4: Bias and standard deviation in observed BT with respect to the RTTOV simulated BT during the four different cyclones.

Cyclone and Period	Bias (K)			Standard Deviation (K)		
	12.66 µ	12.02 µ	11.03 µ	12.66 µ	12.02 µ	11.03 µ
Phailin (8 – 14 October 2013)	4.41	3.53	-0.33	4.11	4.08	3.64
Helen (19-23 November 2013)	1.44	0.94	-0.43	2.71	2.66	2.32
Lehar (23-28 November 2013)	1.78	1.13	-1.05	3.20	3.14	2.79
Madi (6 – 13 December 2013)	1.39	0.69	-1.38	3.41	3.33	2.94

Density plots are also created for observed window channel BTs versus the dbCRAS simulated window channel BTs. Figure 12 is the density plots of observed and dbCRAS simulated window channel BTs for the four different cyclones. Similar to the bias observed with respect to the RTTOV simulated window channel BTs, the bias in the observed BTs with respect tothe dbCRAS simulated window channel BTs are also negative for all the cyclones. Thus the dbCRAS simulated BTs are also less than the actual observed BTs. Table 5 shows the bias and standard deviations in the observed window channel BT versus dbCRAS simulated BTs during the four different cyclones. In this case also, the standard deviation was maximum for Phailin. Compared to the RTTOV simulated window channel BTs, the bias and standard deviation with respect to the dbCRAS simulated window channel were high.

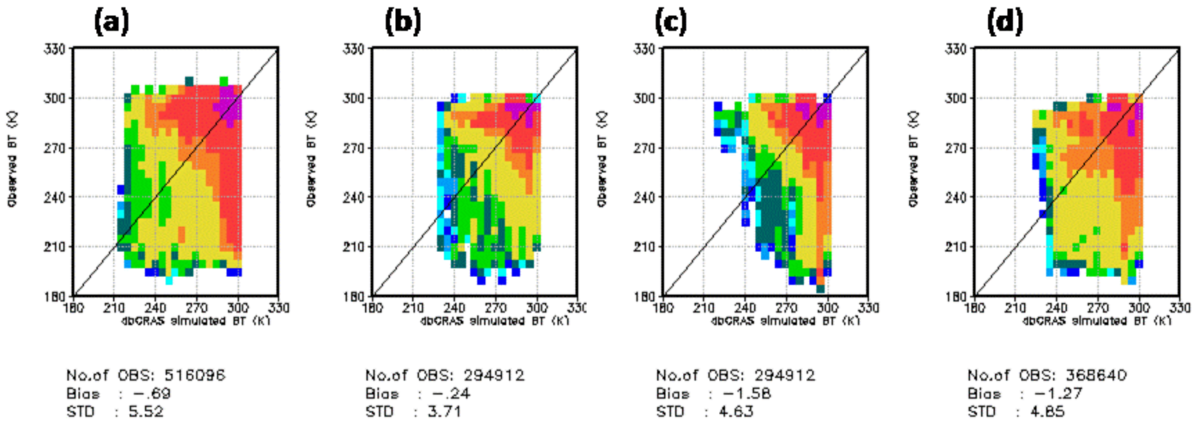

Figure 12: Density plots of observed BTs and dbCRAS simulated 11 µ BTs for (a) Phailin, (b) Helen, (c) Lehar and Madi.

Table 5: Bias and standard deviation in observed BT with respect to the dbCRAS simulated window channel BT during the four different cyclones.

Cyclone and Period	Bias (K) 11 µ	Standard Deviation (K) 11 µ
Phailin (8 – 14 October 2013)	-0.69	5.52
Helen (19-23 November 2013)	-0.24	3.71
Lehar (23-28 November 2013)	-1.58	4.63
Madi (6 – 13 December 2013)	-1.27	4.85

7. Summary

Simulated the INSAT-3D sounder BTs using RTTOV-9 and dbCRAS model and the observed sounder data has been validated against the simulated data during four different cyclones in the NIOC season 2013. Mainly validated the 12 µ and 11 µ channel BTs. The bias in the observed 12 µ channels' BTs with respect to the RTTOV simulated BTs are positive whereas the bias in the window channel is negative for both BTs simulated through RTTOV and dbCRAS. The standard deviation in window channel BT was also less than that of 12 µ channels during different cyclones. Indian Space Research organization (ISRO) has updated the RTTOV coefficients after the launch, and use of updated RTTOV coefficients may improve the BT simulation. Similarly, in this study, 10m temperature from NCMRWF global model is used for the simulation. Use of real SST may improve the BT simulation over Ocean. Moreover, this study has carried out during disturbed weather conditions and without the removal of cloudy pixels, same time assuming the clear sky conditions. Proper cloud clearance and simulation of BT during fair weather conditions may give good picture of the quality of observed BTs.

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