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TECHNICAL REPORT

All sky simulation of MetOp-A MHS Radiance using RTTOV-SCAT during tropical cyclone Fani

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National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences, Government of India
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Abstract

Satellite radiance assimilation in the NWP system is achieved through a fast radiative transfer model as the radiance observation operator, which calculates a model equivalent to the observation. Many of the satellite radiances which are affected by clouds and precipitation may have valuable information even about important weather features. However, the observation operator being used in the assimilation system of the National Centre for Medium Range Weather Forecasting (NCMRWF) Unified Model (NCUM), like many other NWP systems, assimilation system mostly simulates the radiances (brightness temperature) under clear sky conditions. A step forward in the efforts to use all-sky radiance in the NCUM data assimilation system, a standalone radiative transfer model simulation is carried out under all sky condition and compared with the observations. Microwave Humidity Sensor (MHS) onboard MetOp-A satellite radiances are simulated during the period of cyclone "Fani" formed over the Indian Ocean in April - May 2019. A standalone RTTOV radiative transfer model with multiple scattering, RTTOV-SCAT, is used in this study. NCUM model profiles are used as the input to the simulations. All sky simulations showed the signatures of the cyclone in all five channels of MetOp-A MHS even above 400 hPa whereas the clear sky simulations did not show any signs of the cyclone. All-sky simulated brightness temperatures have a better match with the observations, especially for the high-altitude peaking channels. This study brought out the requirement of the use of all-sky radiance observation operators in the NCUM system, specifically for the microwave humidity instruments, to improve the proper representation of severe weather signatures for its accurate forecast.

1. Introduction

Satellite observations in visible, infrared and microwave regions of the electromagnetic spectrum play a pivotal role in understanding different atmospheric phenomena and also in modern era Numerical Weather Prediction (NWP) systems. Visible channel observations are only available during the daytime, infrared radiances are affected by clouds and precipitation. Though microwave radiances are also affected by precipitating clouds, the radiances are transparent to thin clouds and water vapour. Often, during severe weather, infrared soundings fail due to the presence of clouds. Microwave measurements can help to improve the NWP over these areas by providing more information about the state of the atmosphere.

Many studies reported the advantage of cloud-affected microwave radiance assimilation compared to the clear sky in NWP systems (Bauer et al. 2011; Kelly et al. 2008; Geer et al., 2017; Honda et al., 2018; Migliorini and Candy, 2019; Zhu et al., 2016; Yang et al., 2019). As an initial step to the assimilation of cloud-affected radiances in the NCMRWF operational models, the cloud-affected radiances from satellite microwave instruments are simulated using standalone radiative transfer models. Madhulatha et al. (2017) reported all sky simulations of SAPHIR microwave radiances onboard the Megha-tropique satellite during the cyclonic condition. This report describes all-sky simulation of the Microwave Humidity Sensor (MHS) onboard MetOp-A satellite using a standalone multiple scattering radiative transfer model, during the period of severe tropical cyclone "Fani" formed over the Bay of Bengal in April-May 2019.

2. Instrument Details

MetOp-A satellite is in a sun-synchronous orbit keeping a fixed equatorial crossing time. The orbit of the satellite is inclined at 98.7° to the equator at an altitude of 827 km. MHS is one of the twelve payloads of MetOp-A, which is a cross-track scanning microwave radiometer providing humidity-sounding measurements in 5 channels. Channels 1 and 2 are the near-surface channel that gives water vapour information about the lowest atmospheric layers. Channels 3, 4 and 5 are the middle and upper troposphere peaking channels which detect the water vapour in the middle and upper tropospheric layer of the atmosphere. NCMRWF receives these data through EUMETCast. MetOp-A MHS channel specifications such as centre frequency, bandwidth, the peak height of the weighting function, etc., are given in Table1. The equator crossing time of the MetOp-A satellite is 9.30 am local time.

Table 1: MetOp-A MHS specifications

Channel	Central Frequency (GHz)	Bandwidth (GHz)	Polarization	NEΔT (K)	Weighting function peaks (approximate)
1.	89.0	2.8	V (Vertical)	0.22	Near Surface
2.	157.0	2.8	V	0.38	Near Surface
3.	183.31±1.0	2.0	H(Horizontal)	0.42	400 hPa
4.	183.31±3.0	1.0	H	0.57	600 hPa
5.	190.311	2.0	V	0.45	800 hPa

3. Tropical cyclone "Fani"and NCMRWF Unified Model (NCUM) system

Tropical cyclone "Fani" originated near the west of Sumatra in the Indian Ocean on 26 April 2019 as a depression. The system intensified as it moved northward and become a cyclonic storm on 27th April and intensified as an extremely severe cyclonic storm on 2nd May 2019. More details of the tropical cyclone "Fani" is available at http://www.rsmcnewdelhi.imd.gov.in/images/pdf/archive/bulletins/2019/rfani.pdf.

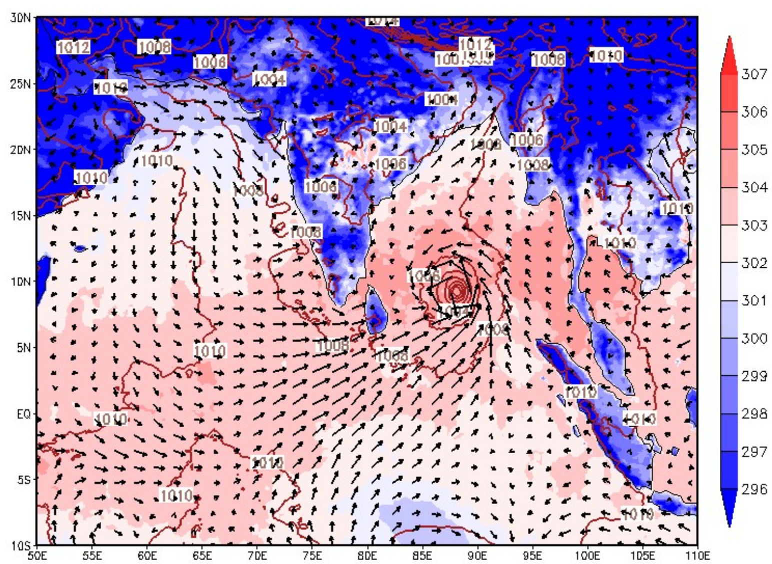

Figure 1: Surface temperature (K, shading), mean sea level pressure (hPa, contours), and wind vector (m/s) from NCUM analysis valid for 00 UTC of 29thApril 2019.

The NCUM (NCMRWF Unified Model) system, adapted from the Unified Model (UM) system of "UM Partnership", uses a hybrid-4DVar data assimilation system and an advanced NWP model (Rajagopal et al., 2012; George et al., 2016; Kumar et al., 2018). Currently, NCUM uses RTTOV (Radiative Transfer for TOVS) -direct (details in section 4) as the observation operator for the radiances under clear sky conditions. Since the equator crossing time is 9:30 local time (ascending), MetOp-A provides observational coverage over the Bay of Bengal around 06 UTC. Short lead forecasts (short forecast) from NCUM are used as input to RTTOV simulations presented here. NCUM analysis of surface temperature, mean sea level pressure, and wind vector valid for 00 UTC of 29thApril 2019 shown in figure 1clearly shows the cyclonic circulation associated with cyclone Fani.

4. Radiative Transfer for TOVS (TIROS Operational Vertical Sounder): RTTOV

RTTOV version 12 is the development of the fast radiative transfer model RTTOV which was originally developed at ECMWF in the early '90s (Eyre, 1991) for TOVS. The model permits the simulation of radiances for satellite visible, infrared or microwave nadir scanning radiometers given an atmospheric profile of temperature, variable gas concentrations, and cloud and surface properties referred to as the state vector. Water vapour is mandatory variable gas for RTTOV v12. The model can allow input profiles on any defined set of pressure levels. The valid range of temperatures and water vapour concentrations depends on the training datasets. The limits for temperature, water vapour and ozone are derived from the strict profile dataset minimum/maximum envelopes by applying a stretching factor (±10% for temperature max/min respectively, and ±20% for each gas max/min). The RTTOV v12 coefficient files contain the *strict* min/max envelopes that are applied within RTTOV and are calculated while reading the coefficient file. The majority of RTTOV v12 coefficient files are based on the 54 levels, however, coefficients for some hyperspectral sounders are also available on 101 levels. The spectral range of the RTTOV v12 model is 0.4-50 microns in the visible and infrared bands. The frequency range in the microwave region varies from 10-800 GHz.

RTTOV model not only carries out the forward (or direct) radiative transfer calculation but also computes the radiance gradient to the state vector variables. Radiance vector 'y' is computed at given state vector 'x'

$$y = H(x) \qquad (1)$$

Where H is the radiative transfer model also referred to as the observation operator.

In addition to the forward model (calculating the radiance or brightness temperature from the input of geo-location, underlying surface parameters and the atmospheric profiles), RTTOV computes the tangent linear and adjoint, and jacobian matrix which makes it a useful tool (i) for developing physical retrievals from satellite radiances (Li et al., 2000),(ii) for direct radiance assimilation in NWP models (Eyre et al., 1993) and producing simulated imagery from NWP models (Blackmore et al., 2014; Lupu and Wilhelmsson, 2016), (iii) for identifying future instruments(Andrey-Andrés et al., 2018).

RTTOV-SCAT is a standalone interface for simulating cloud and precipitation-affected microwave radiances. The microwave (MW) radiation is scattered by hydrometeors and these scattering effects are computed using delta-Eddington approximation. RTTOV-SCAT and cloud overlap are better described in previous studies (Bauer et al., 2006; Geer et al., 2009). RTTOV-SCAT uses a two-independent column approximation, summarized by:

$$T_B^{Total} = (1 - C)T_B^{Clear} + CT_B^{Rainy} \quad (2)$$

Here, C is the effective cloud fraction in a vertical profile. RTTOV-SCAT code uses the core RTTOV algorithm within the code for the computation of the brightness temperature of a clear sky column, T_B^{Clear}, and clear sky transmittances profile. Furthermore, RTTOV-SCAT computes the cloud or rain-affected brightness temperature, T_B^{Rainy}, using clear sky transmittance and lookup tables for Mie scattering properties. Finally, from equation (1), a linear combination of both produces total brightness temperature.

Table 2: Input variables required for all sky simulations using RTTOV-SCAT

S. No.	**Surface/Near surface Parameter**	**General atmospheric Profile**	**Hydrometeors profile**	**Geo-location**
1	2m temperature (K)	Temperature (K)	Cloud cover	Latitude
2	Surface pressure (hPa)	Specific Humidity (kg/kg)	Cloud liquid water (kg/kg)	Longitude
3	Specific humidity (kg/kg)		Cloud ice water (kg/kg)	Satellite zenith angle
4	Wind component (u,v) (m/sec)		Rain (kg/kg)	Satellite azimuth angle
5	Surface type			
6	Skin temperature (K)			

RTTOV-SCAT simulates the satellite radiances or brightness temperature at a given location using the hydrometeors profile along with the atmospheric profile of temperature and moisture with surface variables from NWP model analysis/forecast and geo-location information. Table 2 lists the input parameters required to run RTTOV-SCAT for all sky simulations. Simulation of all-sky radiances accounts the scattering effect of hydrometeors in the vertical column. RTTOV-SCAT uses the pre-computed Mie tables along with the coefficientsto represent the hydrometeors' optical properties (Bauer *et al.* 2006). RTTOV software is freely available and can be downloaded from the Numerical Weather Prediction Satellite Application Facility (NWP-SAF) of EUMETSAT. Detailed information on RTTOV-12 used in this study is available at https://www.nwpsaf.eu/site/software/rttov/rttov-v12/. Figure 2 shows the flow diagram of various inputs used by RTTOV-SCAT for all sky radiance simulations carried out in this study.

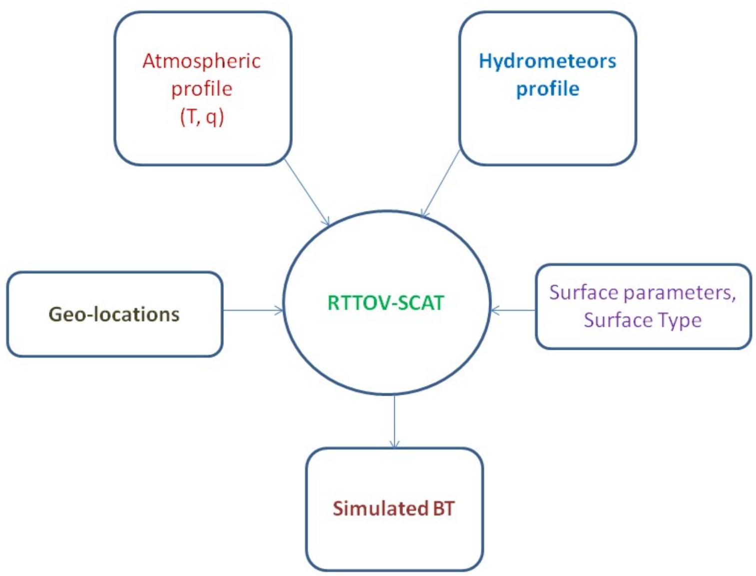

Figure 2: Various input of RTTOV-SCAT for all sky simulations of brightness temperature.

5. Input Profiles to RTTOV

Figure 3 shows sample input profiles supplied from NCUM analysis/forecast used as an input to RTTOV-SCAT at a particular location (13.5˚N, 82.5˚E) in the vicinity of cyclone "Fani" at 06 UTC of 1st May 2019. Temperature and specific humidity profiles are shown in Figure 3(a), cloud liquid water and cloud ice water are shown in Figure 3(b), and cloud cover and rain are shown in Figure 3(c). The surface temperature at this location is found to be ~ 302 K and the humidity in the lower troposphere varies from 20×10^{-3}kg/kg to 7×10^{-3}kg/kg between the surface and 850 hPa level as seen from Figure 3(a). Both cloud ice water and cloud liquid water were present in the input profiles (Figure 3(b)). Model input profiles showed cloudiness in the middle and upper troposphere with rainwater as depicted in

Figure3(c).Radiative transfer model (RTTOV) weighting functions of MHS channels 3 and 4 peaks respectively at 400 hPa and 600 hPa levels (Table 1) and from the input profiles it can be seen that MHS channels 3 and 4 peaking heights are cloud-covered (Figure 3(c)). Maximum cloud ice water and cloud liquid water concentrations are being seen around 400 hPa and 600 hPa levels at this location.

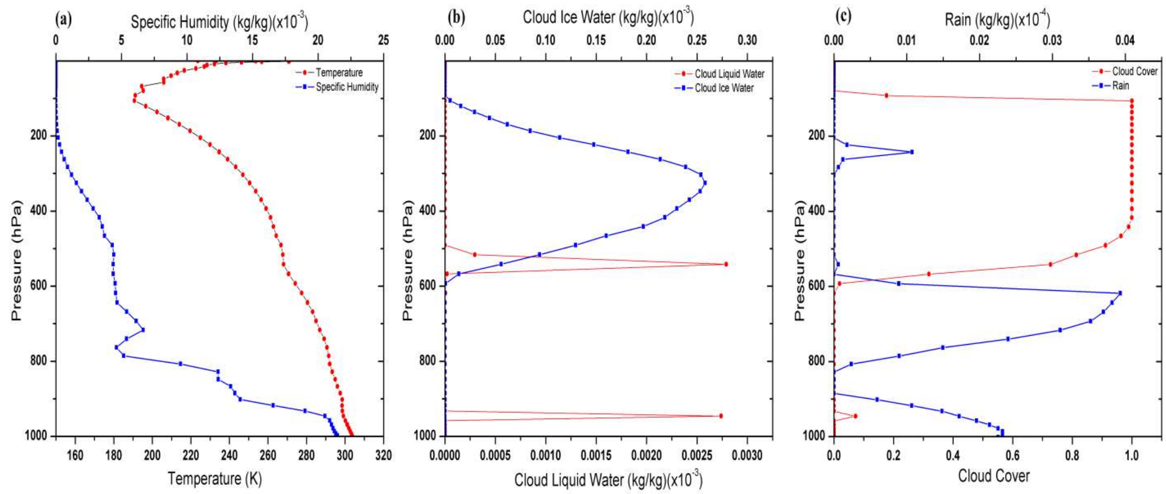

Figure 3: Atmospheric profile of (a) Temperature and specific humidity, (b) cloud liquid water and cloud ice water, and (c) cloud cover and rain from NCUM analysis given as input to RTTOV-SCAT at 13.5˚N latitude and 82.5˚E longitude on 06 UTC of 01st May 2019.

6. Result and Discussions

Figure 4 and 5 show the comparison of clear-sky and all-sky simulated brightness temperature of MetOp-A MHS with observed brightness temperature at 06 UTC on 29th April 2019. In Figure 4, channels 1 to 5 of MetOp-A MHS are represented in different rows from the bottom (a) to top (e) with each column representing the observed brightness temperature (MHS OBS), clear sky simulated brightness temperature (RTCLEAR), all-sky simulated brightness temperature (RTSCAT), and the difference between MHS OBS and RTSCAT. It can be seen that RTSCAT can represent the cyclone features, in all channels of MHS, compared to the RTCLEAR. The maximum and minimum brightness temperatures from the RTSCAT are closer to the observation for all five channels. Though the simulated surface peaking channels in RTSCAT also captured the cyclone features reasonably well, the cyclone features are better resolved in the upper-level peaking channels. The vertical extent of the cyclone is captured well in the RTSCAT simulation. As expected, the difference between the RTCLEAR and observation is higher over the cloudy regions. Even over observed clear sky regions, RTSCAT shows a better match with observation. There is a slight difference in the location of the cyclone in the observation and the RTSCAT, and this is due to the difference in the position of the cyclone in the NCUM data (analysis and short forecast) and the actual observed position. Similar kinds of features also can be seen in figure 5.

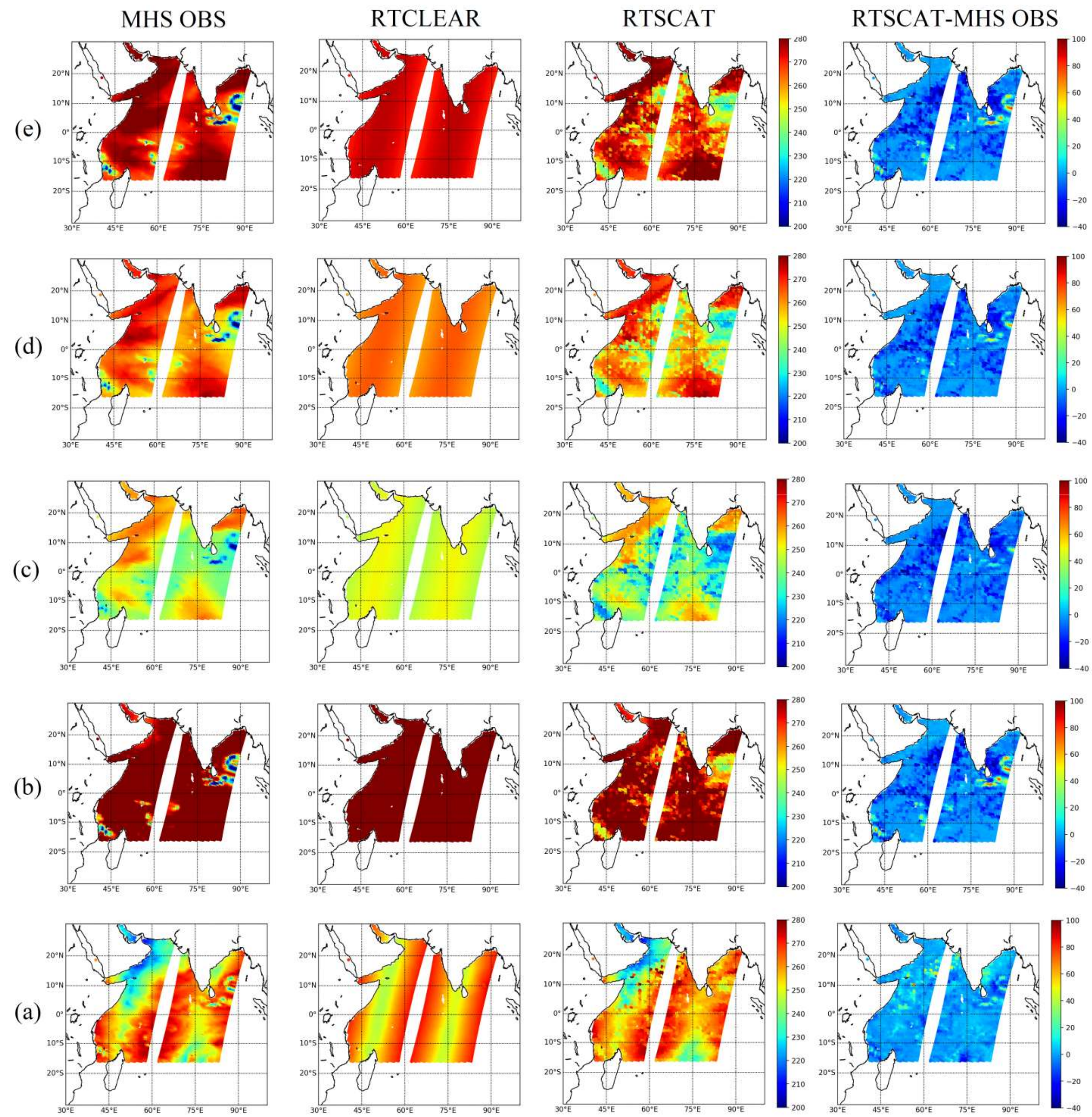

Figure 4: Comparison of MetOp-A MHS clear sky (RTCLEAR) and all-sky (RTSCAT) simulated brightness temperature with observed brightness temperature (MHS OBS) and the difference between RTSCAT and MHS OBS valid for 06 UTC of 29 April 2019 for channels (a) CH-1, (b) CH-2, (c) CH-3, (d) CH-4, and (e) CH-5.

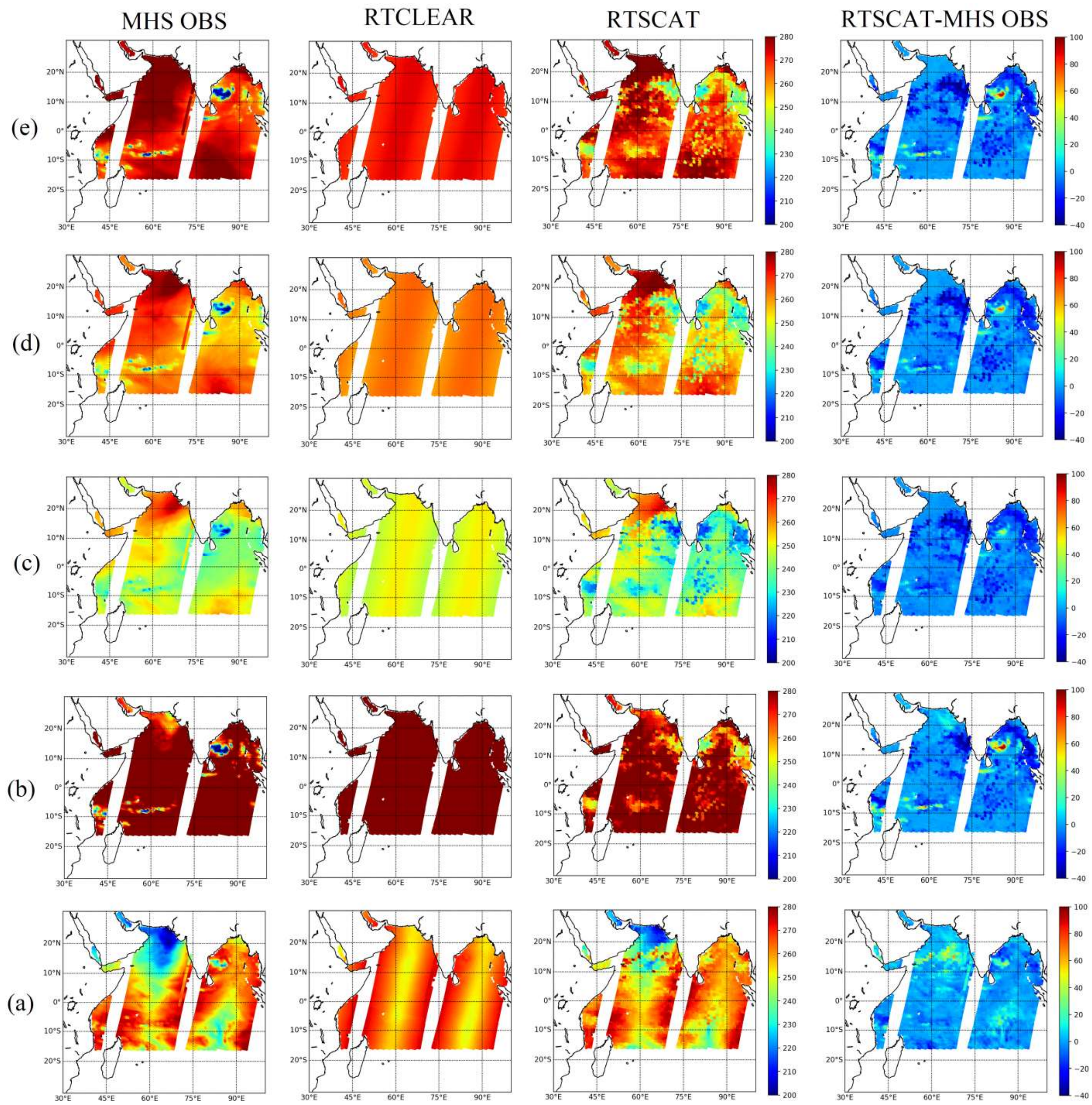

Figure 5: Similar to figure 4 but for 06 UTC of 01st May 2019

Figure 6 shows the comparison of zonal (left) and meridional (right) cross-sections of simulated brightness temperatures and MetOp-A observations from all five channels at 06 UTC of 1st May 2019. The zonal cross-section is along 13.5˚N and the meridional cross-section is along 82.5˚E. Cyclone core has fewer brightness temperatures in the observation both in the zonal (Figure 6a) and meridional (Figure 6d) cross-section between 80-85°E and 10-15°N. RTSCAT simulated low brightness temperature values in the same region match well with the observation, as seen in Figures 6b and 6e. Altitudes around the channel peaking heights of channels 3 and 4 show extended cloud bands (less brightness temperature) in the RTSCAT simulations (Figures 6b and 6e). The RTCLEAR failed to simulate the cyclone characteristics as seen in Figures 6c and 6f, mostly due to the shift of the cyclone position in the NCUM simulations (short forecast).

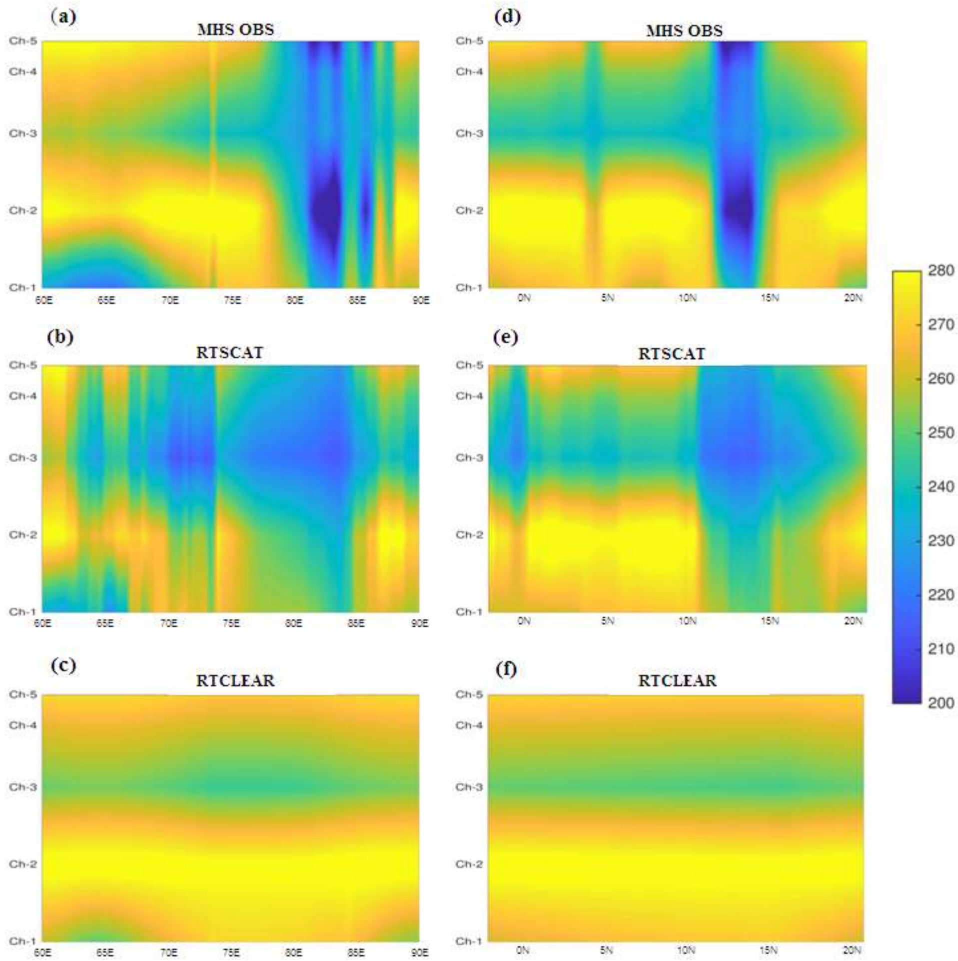

Figure 6: MHS observed brightness temperature (K) and all-sky and clear-sky simulated brightness temperatures (K). Left panel: Zonal cross-section along 13.5˚N, and right panel: Meridional cross-section along 82.25˚E valid for 06 UTC of 01st May 2019 during the "Fani" cyclone period.

Correlation and covariance of the simulated brightness temperature from RTSCAT and RTCLEAR are computed against the observed brightness temperature for all five channels of MetOp-A MHS to compare the simulated and observed brightness temperatures. Figure 7 shows the density-scatter plot of simulated and observed brightness temperature of the five channels of MHS during the period of the "Fani" cyclone from 26 April to 5 May 2019 over the Indian Ocean region (-16°S to 32° N) and (40°E - 100°E). The left and right panels of Figure 7 respectively show the scatter plots of RTCLEAR and RTSCAT simulations against MHS observations.

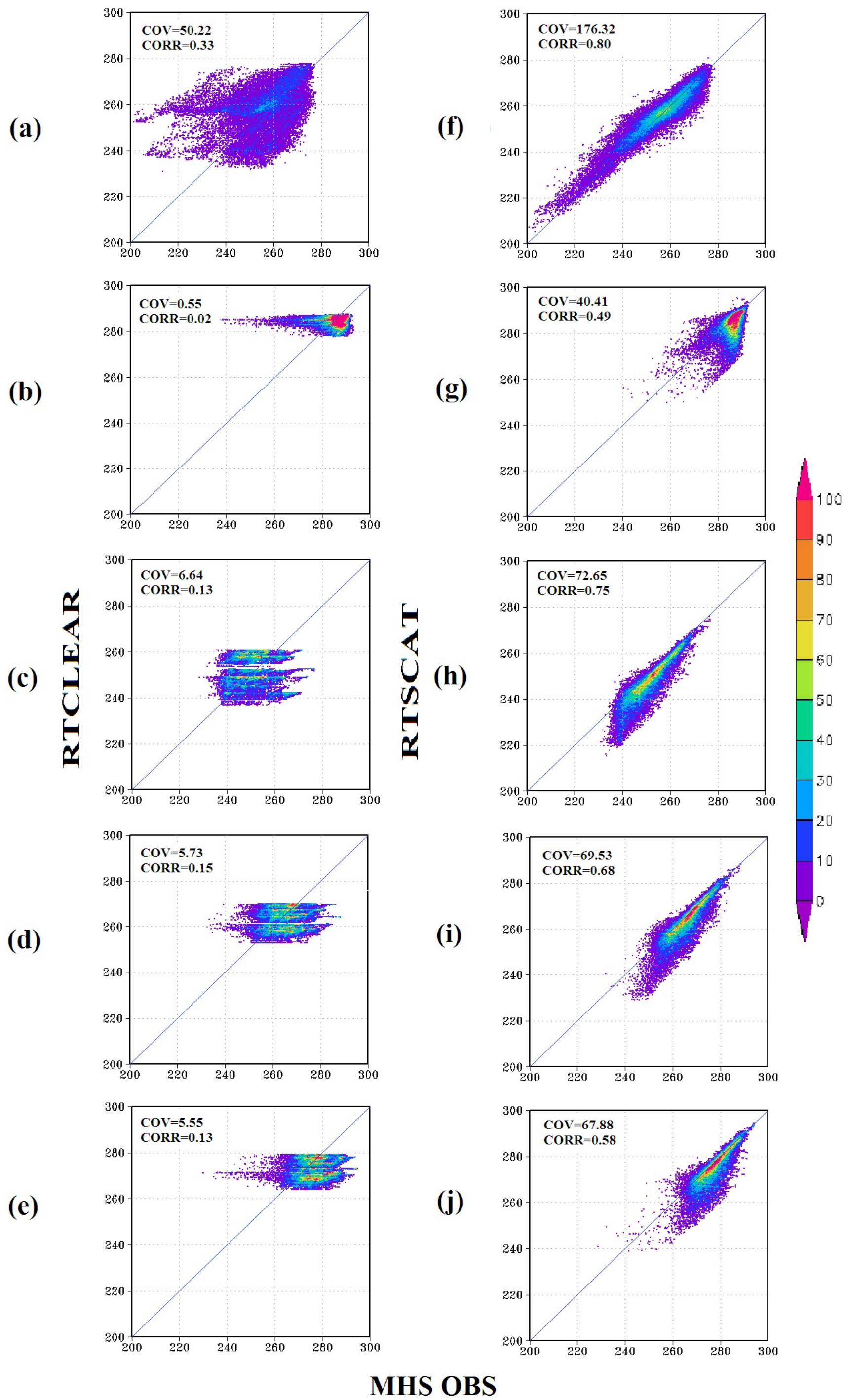

Figure 7: Scatter plots of MetOp-A MHS simulated and observed brightness temperatures over the cyclone "Fani" region from 26 April to 5 May 2019. RTCLEAR simulation (left panel) and RTSCAT simulation (right panel). Both covariance (COV) and correlation (CORR) are also included in each layer of the panels.

Variation of RTCLEAR simulated brightness temperature is not in tandem with the observation in all the five channels, as seen in the covariance indicated in differentatmospheric layers as seen in the left panel of Figure 7. Similar to the covariance, the RTCLEAR simulated and observed brightness temperatures are less correlated. In contrast, the RTSCAT simulated brightness temperatures of the different channels have a good correlation (> 0.5) with the observation, except channel 2 as seen from different layers in the right panel of Figure 7. The increase or decrease in the magnitude of the RTSCAT simulated brightness temperature is in accordance with the observed brightness temperature, as seen in the covariance (indicated in the different layers in the right panel of Figure 7) between the simulations and observations. Maximum agreement in terms of covariance and correlation is observed for channels 1 and 3, while for the other channels, the relationship is slightly weak but significant.

7. Conclusions

NCMRWF receives the microwave radiances from different instruments onboard various satellites, while assimilating only the clear-sky brightness temperatures from most of the instruments. Efforts are ongoing to include the all-sky observation operator (all-sky radiative transfer model) in the NCUM global assimilation system to assimilate the cloud-affected microwave radiances. As part of this effort, a standalone radiative transfer model for the cloudy sky (RTTOV-SCAT) is used for simulating the MetOp-A MHS radiances during the period of cyclone “Fani”. In the comparison of simulated brightness temperature from RTTOV SCAT (RTSCAT), the signature of the cyclone is well captured and all-sky simulated radiances are better matched with the MHS observations. The vertical extent of the cyclone is also captured by the all-sky radiative transfer model. This study reiterates the requirement of all-sky radiance assimilation in the NCUM data assimilation system for improved representation of disturbed weather conditions in the analysis and hence in the forecast, particularly during the high impact weather systems like cyclones when other observations are scarcely available.

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