All-sky radiance simulation of Megha-Tropiques SAPHIR microwave sensor using multiple scattering radiative transfer model for data assimilation applications

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Incorporation of cloud- and precipitation-affected radiances from microwave satellite sensors in data assimilation system has a great potential in improving the accuracy of numerical model forecasts over the regions of high impact weather. By employing the multiple scattering radiative transfer model RTTOV-SCATT, all-sky radiance (clear sky and cloudy sky) simulation has been performed for six channel microwave SAPHIR (Sounder for Atmospheric Profiling of Humidity in the Inter-tropics by Radiometry) sensors of Megha-Tropiques (MT) satellite. To investigate the importance of cloud-affected radiance data in severe weather conditions, all-sky radiance simulation is carried out for the severe cyclonic storm ‘Hudhud’ formed over Bay of Bengal. Hydrometeors from NCMRWF unified model (NCUM) forecasts are used as input to the RTTOV model to simulate cloud-affected SAPHIR radiances. Horizontal and vertical distribution of all-sky simulated radiances agrees reasonably well with the SAPHIR observed radiances over cloudy regions during different stages of cyclone development. Simulated brightness temperatures of six SAPHIR channels indicate that the three dimensional humidity structure of tropical cyclone is well represented in all-sky computations. Improved correlation and reduced bias and root mean square error against SAPHIR observations are apparent. Probability distribution functions reveal that all-sky simulations are able to produce the cloud-affected lower brightness temperatures associated with cloudy regions. The density scatter plots infer that all-sky radiances are more consistent with observed radiances. Correlation between different types of hydrometeors and simulated brightness temperatures at respective atmospheric levels highlights the significance of inclusion of scattering effects from different hydrometeors in simulating the cloud-affected radiances in all-sky simulations. The results are promising and suggest that the inclusion of multiple scattering radiative transfer models into data assimilation system can simulate the cloud-affected microwave radiance data which provide detailed information on three dimensional humidity structure of the atmosphere in the presence of cloud hydrometeors.

1. Introduction

Increase in quality and quantity of satellite data plays a major role in improving the forecast performance of NWP (Numerical Weather Prediction) models (Rabier 2005). Microwave remote sensing of clouds has been recognised to be promising

when compared to visible and infrared regions as microwaves can penetrate clouds and interact directly with hydrometeors. Passive microwave measurements from space-borne instruments offer three-dimensional temperature and moisture information of atmosphere even in the presence of clouds and precipitation and have great potential

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in improving the global weather analyses and subsequent model forecasts. Use of cloud clear satellite radiances from infrared and microwave sounding data have already brought improvements to moisture and temperature analyses (Eyre *et al.* 1993; English *et al.* 2000).

Assimilation of satellite radiances over cloudy and precipitating regions is still a major challenge in NWP. Cloud-affected radiances are not fully exploited as it is difficult to separate the information of main observables such as temperature and moisture from cloud and precipitation effects. Previously, most cloud/precipitation affected radiances are largely discarded in NWP data assimilation system as clouds and precipitation are discontinuous in time, space and their formation is associated with complex, non-linear and not well modelled processes and also current data assimilation systems are constrained to using linearised versions of these non-linear processes (Ohning and Bauer 2011). Considering all these limitations, number of NWP centres make use of cloud-free microwave radiance observations by employing the approach of clear sky simulations in which cloud- and precipitation-affected radiances are generally screened out in the quality control system based on bias calculated against the clear sky background. Assimilation of clear sky radiance data from different microwave satellite sensors has already shown positive impact on forecast accuracy (Cameron *et al.* 2005; Le Marshall *et al.* 2006; McNally *et al.* 2006).

Better exploitation of cloud- or precipitation-affected satellite measurements has great potential for further improvements of weather forecasting (Bauer *et al.* 2011). Assimilation of microwave radiance data produces impact on deeper atmospheric moisture structures (Bauer *et al.* 2011) and is particularly important for accurate prediction of severe weather. The advantage of microwave radiometer observations for nowcasting severe convective activity over southeast India is reported in Madhulatha *et al.* (2013). Few efforts have been made for assimilating the cloud-affected radiance measurements in microwave and infrared regions (Bauer *et al.* 2006, 2010, 2011; Geer *et al.* 2008). In European Centre for Medium-Range Weather Forecasts (ECMWF) assimilation of cloud- and precipitation-affected radiances from different satellite observations, viz., Special Sensor Microwave/Imager (SSM/I), Advanced Microwave Scanning Radiometer (AMSR), Tropical Microwave Imager (TMI) radiance observations (Bauer *et al.* 2010; Geer *et al.* 2010) and Microwave Humidity Sensor (MHS) (Geer *et al.* 2014) have been performed.

Direct assimilation of radiance data requires relationship between model-state vectors and the observed radiances as satellite radiances are not

components of atmospheric state vectors predicted by weather prediction models. Radiative transfer models are utilised to transform the model fields into radiance space, generally referred as forward models. RTTOV (Radiative Transfer Model for Television Infrared Observation Satellite (TOVS) Operational Vertical sounder) is a rapid radiative transfer model developed by EUMETSAT funded Numerical Weather Prediction Satellite Application Facility (NWP-SAF). To simulate microwave radiances scattered by cloud and precipitation, multiple scattering radiative transfer models are necessary to include the scattering effects of cloud hydrometeors. RTTOV-SCATT (RTTOV for scattering) is the scattering module within RTTOV to calculate the cloudy radiances in microwave regions. For clear sky mode, RTTOV uses temperature, humidity and ozone profiles as input. To compute the cloud-affected radiances, additional inputs of cloud hydrometeor profiles has to be supplied to report the scattering and emission effects by hydrometeors (Weng and Liu 2003).

SAPHIR is one of the four payloads of Megha-Tropiques' satellite. It is a microwave radiometer with six channels operating at frequencies close to the water vapour absorption band at 183.31 GHz (Eymard *et al.* 2001). The radiance observations from SAPHIR sensor provides humidity information from surface to upper troposphere under clear and cloudy weather conditions. Few attempts have been made to investigate the impact of assimilation of cloud clear SAPHIR radiances into global models. Chambon *et al.* (2015) examined that the assimilation of SAPHIR radiances in the Météo-France global model ARPEGE resulted in systematic improvements in the humidity distribution. Assimilation of SAPHIR radiances into WRF assimilation system showed considerable improvements in the moisture analysis and significantly contributed to the prediction improvements (Singh *et al.* 2013). Ingestion of cloud clear SAPHIR radiances into NCMRWF GFS (Global Forecast System) assimilation system has showed positive impact in the prediction of relative humidity (Singh *et al.* 2015). Inclusion of clear-sky SAPHIR radiances in the Met office Unified Model improved the analysis and forecasts (Rani *et al.* 2015). So far, no efforts have been made to assimilate the cloud-affected SAPHIR radiances. Incorporating cloud-affected SAPHIR radiance data into assimilation system is very useful as this data can provide moisture information in presence of severe weather system into the initial analysis of the model. In the present paper, the possibility of ingestion of microwave cloud-affected SAPHIR radiances into global data assimilation system is investigated by using the forward operator multiple scattering radiative transfer models suitable for

simulating the microwave cloud-affected radiances. The paper is structured as follows. Section 2 presents the details about the Megha-Tropiques SAPHIR sensor. Description of radiative transfer model and tropical cyclone case considered for simulation are given in sections 3 and 4. Details of the NCMRWF Unified Model (NCUM) are specified in section 5. All-sky simulation results and comparison with SAPHIR observations and various statistical analyses are presented in section 6 followed by conclusions in section 7.

2. Megha-Tropiques SAPHIR data

Megha-Tropiques (MT) is an Indo-French joint satellite mission by ISRO, India and CNES, France. It is a low earth orbit satellite with circular orbit inclined 20° to the equator at an altitude of 866 km. Main objective of this mission is to understand the diurnal cycle of water vapour distribution, vertical transports associated with the convective structures. SAPHIR instrument is a part of MT payload to study the vertical distribution of water vapour in the tropical troposphere. MT SAPHIR measures radiation with cross-track scanning up to an incidence angle of 50° with a horizontal resolution of 10 km at nadir. It is a microwave scanning radiometer and provides measurements in six water vapour channels near absorption band of water vapour at 183.31GHz for sounding the atmospheric humidity. As moisture in the atmosphere attenuates microwave radiation emitted from the surface of Earth, SAPHIR observations can provide a detailed picture of atmospheric moisture at different channels. Six channels of SAPHIR microwave radiometer provide narrow weighting functions from surface to about 100 hPa and can retrieve water vapour profiles. Three channels out of six channels of SAPHIR are similar to the three channels of AMSU-B and 2 channels of MHS onboard NOAA/METOP satellites and 5 channels of ATMS onboard NPP satellite. Specifications of SAPHIR sensor are given in table 1. More details of the sensor can be obtained from Mathur *et al.* (2013). In the present study, all-sky (clear and cloudy) simulation of microwave SAPHIR sensor

is performed using multiple scattering radiative transfer model RTTOV-SCATT. Level 1 brightness temperature products from SAPHIR are utilised for validation purpose.

3. Observation operator RTTOV SCATT for all-sky radiance simulation

Assimilation of satellite radiance observations into NWP data assimilation system requires radiative transfer models as observation operator. RTTOV is a fast radiative transfer model designed for use in NWP data assimilation system for radiance simulations of passive infrared and microwave sounder/imager channels (Eyre 1991; Saunders *et al.* 2012). It simulates the satellite radiances (in terms of black body equivalent brightness temperature, T_B) for given atmospheric profile of temperature, moisture, variable gas concentrations, and cloud and surface properties at radiometer zenith angle. Parameters related to satellite position such as latitude, longitude and azimuth angle also have to be provided to the radiative transfer model. To simulate the cloud-affected radiances, scattering effects of hydrometeors has to be accounted. RTTOV-SCATT is a multiple scattering radiative transfer model which is a part of RTTOV package for simulating the microwave radiances in all-sky (clear sky and cloudy sky) conditions (Bauer *et al.* 2006). In the present study, RTTOV-SCATT of RTTOV9.3 package is utilised and more information on this model can be obtained from RTTOV-9 User's guide (https://nwpsaf.eu/deliverables/rtm/rttov9_files/users_guide_9_v1.7.pdf).

Liquid hydrometeors, viz., cloud water, rain water and frozen hydrometeors, viz., cloud ice and snows required for RTTOV-SCATT are provided using 24-hr forecasts from NCUM. The radiative transfer equation is solved by computing the multiple scattering effects of hydrometeors at microwave frequencies using the Delta-Eddington approximation (Joseph *et al.* 1976; Moreau *et al.* 2003). Hydrometeor optical properties (i.e., extinction coefficient, single scattering albedo, and asymmetry parameter) are provided to the radiative transfer model from pre-computed Mie tables for liquid water, cloud ice,

Table 1. Specifications of SAPHIR sensor.

Channel	Central frequency	Bandwidth (MHz)	Polarization	Pressure levels (hPa)
S1	183.31 $\pm$ 0.20	200	H	~250–100
S2	183.31 $\pm$ 1.10	350	H	~400–250
S3	183.31 $\pm$ 2.80	500	H	~550–400
S4	183.31 $\pm$ 4.20	700	H	~700–550
S5	183.31 $\pm$ 6.20	1200	H	~850–700
S6	183.31 $\pm$ 11.0	200	H	~1000–850

Table 2. *Input parameters necessary for RTTOV-SCATT.*

Parameter	Unit
Pressure	hPa
Temperature	K
Specific humidity	kg/kg to ppmv
Cloud cover	
Cloud liquid water mixing ratio	kg/kg
Cloud ice mixing ratio	kg/kg
Rain flux	kg/m ² /s
Snow flux	kg/m ² /s
Land sea mask	hPa
Surface temperature	K
Surface pressure	hPa
2-m temperature	K
2-m specific humidity	ppmv*
10-m u wind component	ms ⁻¹
10-m v wind component	ms ⁻¹
Latitude	Degrees
Longitude	Degrees
Zenith angle	Degrees
Azimuth angle	Degrees
Surface type	Land/sea

*Parts per million by volume.

rain and precipitating ice (Bauer *et al.* 2006). Transmittance for oxygen and water vapour are computed from regression tables driven by atmospheric predictors as in RTTOV package. Ocean surface emissivity is computed using FASTEM-2 (Deblonde and English 2001) modules which require surface wind speed for its computations. Land surface emissivity comes from TELSEM atlas (Aires *et al.* 2011). More details on microwave radiative transfer modeling in clouds and precipitation can be found in Bauer (2002).

RTTOV-SCATT can simulate radiances both under clear and cloudy sky conditions. Clear sky simulations are performed by calling clear-sky RTTOV within RTTOV-SCATT module which produces brightness temperature of the clear sky column. Cloudy sky simulation is performed by RTTOV-SCATT which computes the cloud and rain-affected brightness temperatures. The all-sky simulated brightness temperature is computed as the weighted average of brightness temperature from clear and cloudy sky simulations. RTTOV model has forward, tangent and adjoint components. In the present study, forward model is only employed as the main aim of the study is to simulate the radiances of SAPHIR sensor in all-sky conditions. Input parameters necessary for RTTOV-SCATT simulation are summarised in table 2.

4. Description of the tropical cyclone ‘Hudhud’

Tropical cyclone is typically associated with various types of cloud structures and ideal to study the

importance of cloud-affected radiances. In the present study, tropical cyclone ‘Hudhud’ which formed over the Bay of Bengal is considered for simulation. The cyclone initially formed as a low pressure system on 6th October 2014 over Bay of Bengal. It subsequently intensified into a depression on 7th October 2014 over north Andaman Sea and adjoining southeast Bay of Bengal and moved west–north–westwards towards Andhra Pradesh coast. The deep depression further intensified into cyclonic storm Hudhud on 8th October 2014 and further moved west–north–westward and concentrated into a severe cyclonic storm. The cyclone crossed north Andhra Pradesh coast around Visakhapatnam by forenoon of 12th October 2014. Subsequently it weakened into a depression and later dissipated. Complete details about the genesis and dissipation of the tropical cyclone ‘Hudhud’ can be available at <http://www.rsmcnewdelhi.imd.gov.in/images/pdf/archive/bulletins/2013/RHUD.pdf>.

5. Description of NCMRWF unified model (NCUM)

Profiles of temperature, specific humidity, cloud cover, liquid water, rain and precipitating snow and surface parameters are extracted from NCUM model forecasts. This global model is based on UK Met Office Unified Model version 7.9 with 4D-Var data assimilation system. It is a non-hydrostatic model with deep atmosphere dynamics using a semi-implicit, semi-Lagrangian numerical scheme. The model includes a comprehensive set of parameterisation, including surface, boundary layer, mixed phase cloud-microphysics and convection. It runs on a latitude–longitude horizontal grid with Arakawa C staggering and a terrain following hybrid height vertical coordinate with Charney–Phillip staggering. Model configuration is provided in table 3. More details of NCUM model and its data assimilation system can be found in Rajagopal *et al.* (2012).

NCUM predictions which have produced reasonably accurate forecast of location and intensity of the tropical cyclone Hudhud are utilised for the

Table 3. *Configuration of NCUM.*

Horizontal resolution	25 km
Model time step	10 min
Dynamics	Terrain following hybrid height coordinates
Time integration	Semi-implicit
Radiation	Edwards and Slingo (1996)
Boundary layer	Lock <i>et al.</i> (2000)
Convection	Gregory and Rowntree (1990)
Cloud micro-physics	Wilson and Ballard (1999)

radiative transfer model simulations. In respect to different phases of cyclone, NCUM model run is carried out for 24 hrs based on 00 UTC initial conditions of 9–12 October, 2014. To assess the performance of NCUM in capturing the rainfall associated with different phases of the tropical cyclone, the predicted rainfall is compared with observed rainfall. For comparison IMD NCMRWF merged satellite gauge data (Mitra *et al.* 2009, 2013) is utilised. This rainfall data is a merged product of satellite estimates (TRMM) and rain gauge observations (IMD) at 0.5° resolution, accumulated for 24 hrs. The observed rainfall (top panel of figure 1) clearly shows the rainfall distribution associated with the movement of cyclone Hudhud. NCUM model (bottom panel of figure 1) is able to capture the rainfall associated with different phases of cyclone with slight variations in spatial distribution and intensity of rainfall; however, model has underestimated the rainfall amounts when compared with observations.

6. Results and discussions

6.1 Simulation of all-sky and clear-sky radiances from RTTOV-SCATT

Radiative transfer simulations are carried out for the tropical cyclone Hudhud using NCUM model outputs. 24-hr forecasts of NCUM available at 3-hr interval closer to the SAPHIR observations are considered for RTTOV simulations. By supplying all

the necessary inputs, RTTOV simulation is performed and brightness temperatures are simulated for all the six channels of SAPHIR. Figure 2 shows the comparison of simulated brightness temperature both in clear-sky (RTTOV clear sky simulations without including hydrometeor profiles) and all-sky (RTTOV-SCATT simulations, including hydrometeor profiles) conditions along with SAPHIR observed brightness temperature at 18 UTC of 11th October 2014 for all the six channels. Associated with Hudhud cyclone, SAPHIR observations (left panel of figure 2) clearly shows the cloud-affected radiances with lower values of brightness temperatures (T_B) indicating the presence of deep convective clouds of cyclone. From different channels of SAPHIR sensor (S6–S1), the signature of cyclone is clearly visible from surface to upper levels (left panel of figure 2) of atmosphere and is more prominent in lower troposphere peaking channel S6 (1000–850 hPa). Lower brightness temperatures associated with the cloud structures of cyclone are not reproduced in clear-sky simulations (medium panel of figure 2). All-sky simulations (right panel of figure 2) are able to produce the cloud-affected brightness temperatures associated with the cyclone.

6.2 Temporal evolution of horizontal distribution of radiance during different phases of cyclone

To understand the temporal evolution of horizontal distribution of cloud-affected radiances during the cyclone movement, radiance simulations are

Figure 1. Observed and predicted 24 hr accumulated rainfall (mm) at 00 UTC during the life cycle of Hudhud. (a) 10th October, (b) 11th October, (c) 12th October, and (d) 13th October 2014.

Figure 2. Comparison of brightness temperatures (K) from SAPHIR observations and radiative transfer model (RTTOV) simulations under clear and all-sky conditions for Hudhud cyclone at 18 UTC of 11th October 2014 for all six channels (channels S1–S6 are given from bottom to top panels).

carried out during different phases of cyclone genesis, movement and landfall. As the high frequency channel S6 (1000–850 hPa) is more sensitive to cloud and precipitation information, the horizontal

distribution for the channel S6 is illustrated in figure 3.

Associated with the cloud structures during different phases of cyclone, SAPHIR observations

Figure 3. Temporal evolution of horizontal distribution of brightness temperatures (K) during different phases of cyclone in channel S6 (183.31 ± 11.0 GHz) from SAPHIR observations and RTTOV simulations.

(left panel of figure 3) clearly shows the signature of cloud-affected radiances with low T_B values in the channel S6. Clear-sky simulations (medium panel of figure 3) are not able to produce the cloud-affected radiances. The horizontal distribution of cloud-affected radiance provides moisture information in the cloudy regions which is well simulated in all-sky simulations (right panel of figure 3).

6.3 Vertical cross-section of tropical cyclone from brightness temperature

Intensity of tropical cyclone can be analysed by investigating the vertical cross-section of tropical cyclone. Latitude/longitude height cross-sections of simulated and observed radiances valid for 18 UTC of 11th October are shown in figure 4. SAPHIR observations (top panel of figure 4) clearly represent the cloud-affected radiances related to the vertical distribution of cloud which are well simulated in all-sky simulations (middle panel of figure 4) and are not simulated in clear-sky simulations (bottom panel of figure 4). The vertical cross-section of cloud-affected brightness temperature

in the vicinity of cyclone provides information on vertical distribution of moisture in the cloudy regions which is well captured in all-sky simulations as in observations.

6.4 Three dimensional distribution of simulated brightness temperature in the vicinity of cyclone

To visualise the spatial (latitude, longitude and height) distribution of cloud-affected radiances, the three-dimensional distribution of simulated and observed radiances is plotted. In all the six channels of SAPHIR, cloud-affected brightness temperatures associated with the cloud structures embedded in tropical cyclone is clearly observed (left panel of figure 5) which are not visible in clear sky simulations (middle panel of figure 5). All-sky simulations are able to produce the cloud-affected lower values of T_B associated with the various cloud bands of cyclone (right panel of figure 5). Three-dimensional structures of cloud-affected radiances which provide moisture distribution in the vicinity of cyclone is well represented in all-sky simulations. This analysis suggests that the inclusion of scattering processes from different hydrometeors in all-sky

Figure 4. Longitude-height and latitude-height cross sections of simulated brightness temperature (K) along with SAPHIR observations at latitude 15° (left panel), at longitude 83° E (right panel) for cyclonic storm Hudhud at 18 UTC of 20141011.

Figure 5. Three-dimensional distribution of brightness temperature (K) from SAPHIR observations and simulations at 18 UTC of 11th October 2014.

simulations improved the simulation of cloud-affected radiances in all the channels.

To evaluate the performance of the RTTOV-SCATT in simulating the cloud-affected microwave radiances of SAPHIR sensor, various statistical analyses are carried out by comparing the simulated radiances against observed radiances. The region (10° – 20° N; 60° – 120° E) which covers the life cycle of Hudhud cyclone is considered for the statistical analyses.

6.5 Probability distribution functions (PDF)

To understand the distribution of simulated and observed brightness temperatures, probability distribution functions (PDFs) analysis has been performed. PDFs of simulated brightness temperature (T_B) from clear-sky and all-sky simulations for various channels along with SAPHIR observations are shown in figure 6. Cloud-affected lower T_B values in a particular channel indicate the presence of cloud and high T_B values generally correspond to cloud free regions. For upper troposphere peaking channels (S1–S3) (figure 6a, b, c), PDFs of simulated radiances from both clear-sky (RTTOV-Clear) and all-sky (RTTOV-All sky) simulations

(blue and black lines, respectively) are nearly equal with some shift to lower T_B values compared to observations (red solid line). Generally, at upper levels, the cloud content from different hydrometeors at cloudy regions is less and hence, the impact of cloud scattering may be low at upper levels and therefore, no significant differences are noticed between clear and all-sky simulated radiances for the upper troposphere peaking channels (S1–S3).

For the lower troposphere peaking channels (S4–S6), PDFs of all-sky simulated radiances (black dotted line) shows a shift towards lower T_B values as in observations which are missing in clear sky (blue line) simulations (figure 6d, e, f). In all-sky simulations (black dotted line), the number of occurrences of cloud-affected lower T_B values ranging from 240 to 260 K in the channels S4–S6 is more and comparable to observations (red line). However, in clear-sky simulations (blue line), the frequency of occurrence of cloud-affected lower T_B values are less (figure 6d, e, f). From the PDF analysis it is clear that the lower tropospheric peaking channels S4, S5 and S6 (figure 6d, e, f) which represents middle to lower levels of the atmosphere are more sensitive to the cloud–radiation interaction processes as cloud amount is more concentrated at these levels.

At higher levels, the scattering associated with clouds may be low, thus the differences between both the simulations are small (figure 6a, b, c) for channels (S1–S3). In general, these upper level peaking channels are strongly affected by scattering from frozen particles in the upper parts of convective systems (Hong *et al.* 2005). In simulation of the higher T_B values in upper level channels, no considerable differences are noticed between both the simulations. The reason may be due to underestimation of NCUM simulations in estimating the mass of frozen hydrometeors in the upper levels of convective clouds.

Comparatively, all-sky simulations (black line) are able to capture the cloud-affected lower values of T_B in all channels which are not produced in clear-sky simulations (blue line). Generally, the PDF distributions of all-sky and clear-sky simulations in simulating cloud-affected lower T_B values are different due to the inclusion of scattering processes associated with cloud hydrometeors in all-sky simulations. In clear-sky simulations, T_B values are more biased towards higher temperatures since radiative properties of clouds are not accounted in the simulations. Inclusion of hydrometers in the cloudy simulations accounts for scattering by clouds at different layers, therefore all PDFs from all-sky simulation (black dotted lines) shows a shift towards the lower T_B values which are closer to observations indicating cloudier atmosphere associated with the cyclone structure. However, the differences between all-sky simulations against observations can also be attributed to underestimation of different cloud hydrometeors from NCUM.

Improper estimation of temperature and moisture profiles from NCUM could also result in differences between simulations and observations.

6.6 Density scatter distribution

To understand the density distribution and correlation between simulated and observed T_B values of different SAPHIR channels, density scatter plots are prepared. Density scatter plots of all-sky and clear-sky simulated radiances against the observations for the upper troposphere channels (S1–S3) show no significant differences (left and middle panels of figure 7). This indicates that distribution of T_B is more or less similar in both the simulations. All-sky and clear-sky simulations tend to produce higher T_B values compared to observations. For channel S3 (right panel of figure 7), all-sky simulation is able to produce lower T_B values associated with cloud as in observations which are not simulated in clear-sky simulations.

Density scatter plots for the lower troposphere peaking channels S4–S6 are shown in figure 8. High correlation is noticed between all-sky simulated and observed radiances for lower troposphere peaking channels. In clear-sky simulation (bottom panels of figure 8), cloud-affected lower T_B values are not simulated; however, all-sky simulation (top panels of figure 8) is able to produce the cloud-affected lower T_B values in the range of 230–260 K and T_B values less than 230 K are not captured. To quantify the strength of linear relationship between observations and simulations, covariance is also given in figures 7 and 8. Large values of covariance

Figure 6. Probability distribution functions of observed and computed SAPHIR T_B in all channels during cyclone Hudhud period.

Figure 7. Density scatter plots of observed and simulated T_B (K) under clear and all-sky conditions for the considered days during cyclone Hudhud for channels S1–S3.

Figure 8. Density scatter plots of observed and simulated T_B (K) under clear and all-sky conditions for the considered days during cyclone Hudhud for channels S4–S6.

are seen for all-sky compared to clear air in all channels which suggests high correlation between all-sky simulations and observations, particularly in simulating cloud-affected lower T_B values. This clearly explains the greater sensitivity of scattering process from cloud hydrometeors in realistic representation of brightness temperatures.

6.7 Box plots

Box plot is a standardised way to display the distribution of observed and simulated radiances in

terms of maximum, minimum, median and quartile values where the box represents 50% of data, 75% of data falls below the upper quartile and 25% falls below the lower quartile. The upper and lower whiskers give information about the values outside the middle 50%. Figure 9 shows the box plot of brightness temperatures from clear and all-sky simulations along with observations. For channel S1 (figure 9a), 50% of data falls in the range of 235–250 K for MT-SAPHIR, 230–245 K in all-sky and clear-sky simulations. Slight differences in median values and upper whisker values are reported

Figure 9. Bar plots of simulated and observed brightness temperatures.

between observations and simulations. However, large variations are seen in lower whisker values. Lower brightness temperature values (figure 9a) around 210 K are noticed in observations which are not produced by both the simulations. For channel S2, the distribution is confined to 245–260 K range as in observations and for simulations the distribution is between 240 and 260 K (figure 9b). Brightness temperatures on lower whisker side are not produced in both the simulations. For channel S3, the distribution is in between 255 and 270 K for both observations and simulations (figure 9c). The lower whisker extends up to around 239 K in all-sky simulations, but not in clear-sky simulations. In channel 4, the distribution of box is similar in observations and simulations whereas the distribution corresponding to lower whisker is well represented in all-sky simulations (figure 9d). For channels S5 and S6 (figure 9e, f), the distribution is more or less similar in observations and simulations for upper whisker side; however, the distribution on lower whisker side is captured better in all-sky simulations which are not replicated in clear-sky simulations.

From the present analysis it is clear that for the upper level channels (S1, S2), the distribution of simulated brightness temperature is different from observations with large variations in lower whisker side of T_B and fewer differences in the upper whisker side. Minimum and maximum values of T_B are not captured properly in both the simulations for upper level peaking channels. For the channels S3–S6, the distribution of all sky-simulated brightness temperature is quite similar to observations; however, the distribution from clear-sky simulation is different from observations. Higher whisker side of simulated brightness temperature corresponds to higher values of T_B associated with clear-sky

Table 4. Maximum and minimum T_B values from simulations and observations.

	All-sky	Clear	MT-SAPHIR	MT-All-sky	MT-Clear
T_{MIN}	212.69	268.33	146.09	−66.70	−122.25
T_{MAX}	294.41	294.31	291.89	−2.52	−2.43

conditions from both the simulations are quite similar to observations. Lower whisker side of brightness temperature corresponds to cloud-affected lower T_B values associated with cloudy scenes are better replicated in all-sky simulations but not in clear-sky. This analysis highlights the importance of cloud hydrometeors in producing the cloud-affected brightness temperatures.

The skill of all-sky and clear-sky simulations in capturing higher and lower T_B associated with clear and cloudy conditions is quantified in table 4. The minimum temperatures are reproduced better in all-sky simulations. Negative bias is noticed between observations and simulations which imply that simulated values are higher than observations. Even though all-sky simulations captured minimum T_B values associated with the cloud, a difference of 66.70 is seen which may be partly due to the underestimation of cloud hydrometeors by NCUM. A bias of 122.24 is noticed in clear-sky simulation, since cloud-radiation interaction is not included in clear-air computation which might have resulted in simulating higher T_B values. In case of maximum temperature, both simulations have very less bias. The lowest T_B values associated with cloud are not fully estimated as in observations even in all-sky simulations. The performance of all-sky simulations in simulating the magnitude of lower T_B values depends on the magnitude of hydrometeors supplied from NCUM forecasts. Even though NCUM predicted the life cycle of Hudhud cyclone

reasonably well, the rainfall associated with the cyclone is underestimated when compared to rainfall observations. Lower rainfall values implies less amounts of hydrometeors and hence leads to lower scattering effects from hydrometeors and affect the respective radiative transfer computations and contributes to the differences in simulating the magnitude of cloud-affected radiances when compared with observations particularly in lower level peaking channels.

To understand the effectiveness of simulated brightness temperature over observations in all channels; correlation, bias and root mean square error (RMSE) between model simulated and observed brightness temperature are calculated. From figure 10(a) it is clear that the bias (RTTOV-SAPHIR observations) is less in all-sky (red colour) compared to clear-sky (blue colour) simulations for all channels. Significant differences are noticed in bias values for the channels S4–S6 (figure 10a) which corresponds to middle to lower levels of atmosphere and are much sensitive to cloud information. The bias in all-sky simulations (red colour) compared to clear-sky (blue colour) is less due to inclusion of cloud hydrometeors. Positive bias indicates simulated T_B values are higher compared to observations which can be due to underestimation of NCUM model in producing the hydrometeor profiles. For the channels S1 and S2 which represents the higher levels of the atmosphere, negative bias is observed for both simulations which implies RTTOV simulated T_B values are lower than observations. These biases in simulated T_B values can be attributed to errors in NCUM predicted atmospheric profiles. RMSE is also significantly

reduced in all sky simulations (figure 10b), particularly for lower level peaking channels. High correlation is noticed in all-sky simulations for all channels (figure 10c). All these statistical scores reveal that all-sky simulated brightness temperature in lower troposphere channels are closer to observations and for the upper troposphere levels the behaviour of both the simulations is more or less similar.

The possible sources of biases in the simulations can be linked to errors in SAPHIR instrument observations, deficiencies related to model forecast fields and the radiative transfer models. As described in Buehler *et al.* (2004), SAPHIR observations are affected by the limb effect: the T_B values scanned at nadir are warmer in average as compared to T_B values scanned at the edge of swath. This could be the reason for negative bias at upper level channels. However, understanding the uncertainties in SAPHIR data is outside the focus of present study. The underestimation of cloud hydrometeors by NCUM can contribute to higher values of T_B which could be the cause for positive bias at lower levels. Errors in RMSE may arise due to two reasons: errors introduced by the radiative transfer simulations due to assumptions in RTTOV and errors associated with the predicted hydrometeor profiles. However, it is difficult to separate these two errors due to non-availability of measured hydrometeors profiles and simultaneous measurements of brightness temperatures from the space borne radiometer. To incorporate the cloud-affected radiances in data assimilation system for real time purpose, one has to rely on model forecasts only.

Figure 10. Bias, RMSE and correlation between RTTOV simulated and observed radiances for all channels in clear and all-sky conditions.

6.8 Role of hydrometeors on brightness temperature simulation

From different statistical analyses it is clear that the inclusion of scattering processes from different hydrometeors is the reason for better simulation of cloud-affected radiances in all-sky simulations. Basically, radiance computations in RTTOV model under clear-sky conditions are based on atmospheric absorption/emission and radiance simulations under cloudy conditions are based on Mie scattering effects through different cloud hydrometeors. In order to investigate the sensitivity of hydrometeors on simulating cloud-affected lower T_B values, correlation analysis is performed between simulated T_B at different channels and various hydrometeors.

The effect of each of hydrometeors, namely cloud water, cloud ice, rain and snow on simulated brightness temperature for all the six SAPHIR channels, S1 (183.31 ± 0.20 GHz), S2 (183.31 ± 1.10 GHz), S3 (183.31 ± 2.80 GHz), S4 (183.31 ± 4.20 GHz), S5 (183.31 ± 6.20 GHz) and S6 (183.31 ± 11.0 GHz) is demonstrated in figure 11. To correlate the hydrometeors with brightness temperatures at different channels, the hydrometeors present at the pressure levels which correspond to the respective channels weighing functions are only considered. For example, to compare the hydrometeor with S1 channel (250–100 hPa) brightness temperature, hydrometeors between the same levels (250–100 hPa) are only

considered. Negative correlation is noticed between simulated T_B and different hydrometeors.

From figure 11(a), it is clear that the channels S3 and S4 are more sensitive to cloud liquid water compared to the rest of channels as the presence of cloud liquid water is more expected between 700 and 400 hPa levels which corresponds to S3 and S4 channels. For cloud ice (figure 11b), the channels S1–S4 are showing low correlation as cloud ice concentration is dominant above 700 hPa to upper levels (100 hPa) of the atmosphere. No correlation can be expected for the channels S5 and S6 as cloud ice cannot be present at these levels (1000–700 hPa). For the case of rain hydrometeor (figure 11c), good correlation exists for the channels S2–S6. Generally, rain is concentrated more at the lower levels, so high correlation is noticed for the channel S6 (1000–850 hPa) followed by the other channels. As the rain water concentration decreases from lower to higher levels, correlation also follows the same pattern. No correlation is noticed for channel S1 (250–100 hPa) as rain cannot be present at these levels. In terms of snow (figure 11d), the channels S1–S4 are sensitive. Good correlation is observed for S1 (250–100 hPa) followed by the other channels. As ice can be more abundant at higher levels and increase with height, more correlation is observed at the higher levels. No correlation is observed for channels S5–S6 as ice cannot form at lower levels (1000–700 hPa).

Figure 11. Effect of different cloudy hydrometeors on brightness temperature in different channels.

The above analysis clearly demonstrate that the high frequency channel S6 (183.31 ± 11.0 GHz) corresponds to lower levels (1000–850 hPa) of atmosphere is most sensitive to rain (figure 11c) compared to all the other channels followed by S5 and S4. The frequency channel 183.31 ± 0.2 GHz (S1) is most sensitive to cloud ice followed by S2, S3 and S4 channels (figure 11b). The channel S4 (183.31 ± 4.2 GHz) shows highest sensitivity to cloud water (figure 11a) followed by channel S3 (183.31 ± 2.8 GHz). The present results are consistent with the study by Hong *et al.* (2005) in which the sensitivity of brightness temperature at microwave frequencies to hydrometeors in deep convective clouds is clearly discussed. Negative correlation is observed between different hydrometers and T_B in respective channels. In all the channels, brightness temperatures are on lower side with increase in hydrometeor content. All considered cloud hydrometeors (cloud ice, cloud water, snow, rain) contribute to the decrease of T_B in channels as scattering effects from different hydrometeors results in redistribution of radiation. This clearly reveals the importance of hydrometeors in simulating the cloud-affected brightness temperatures and highlights the importance of all-sky radiance simulations. The significance of optical properties of hydrometeors in all-sky radiance simulation is discussed in detail in Mahfouf *et al.* (2016).

7. Conclusions

In the present paper, the possibility of simulation of cloud- and precipitation-affected radiances is investigated by performing all-sky radiance simulations of MT-SAPHIR sensor using multiple scattering radiative transfer models (RTTOV-SCATT). NCUM predicted profiles of temperature, moisture and hydrometeor profiles during different phases of tropical cyclone Hudhud are used as input to RTTOV-SCATT to generate observation equivalent radiances for SAPHIR sensor. Simulated radiances under clear-sky and all-sky conditions are compared with SAPHIR observations. The three dimensional distribution of cloud-affected radiance in the vicinity of cyclone is better captured in all-sky simulations.

Various statistical analyses are carried out to study the capability of all-sky simulations over clear-sky simulations by comparing with SAPHIR observations. PDF analysis revealed that the distribution of all-sky simulations are shifted more towards lower T_B values as in observations which correspond to cloudy sky conditions; however, the distribution of clear-sky simulations are shifted more towards higher T_B values which represents clear-sky conditions. Scatter density plots revealed

that all-sky simulated radiances are more consistent with observations and bar plot analysis showed the ability of all-sky simulations in capturing the cloud-affected lower T_B values. Area averaged statistics carried out by considering different days of cyclone revealed that the bias and RMSE of radiances are reduced in all-sky simulations. Improved correlation against observations is evident in all-sky simulations for all channels. The overall distribution of cloud-affected radiances is well captured in all-sky simulations compared to clear-sky simulations. The role of cloud hydrometeors in simulating cloud-affected brightness temperatures in all-sky simulations is also investigated. Negative correlation is noticed between hydrometeors and brightness temperatures. This implies that the presence of cloud hydrometeors lowers the T_B values due to redistribution of radiation due to multiple scattering processes in presence of clouds. The analysis suggested that inclusion of scattering effects of cloud hydrometeors improved the simulation of cloud-affected lower T_B values in all-sky simulations.

Even though all-sky simulations are able to produce the cloud-affected brightness temperatures, magnitude of simulated cloud-affected brightness temperature are significantly different from observations. The biases and errors in simulations correspond to various assumptions in RTTOV model, improper estimation of hydrometeors and various atmospheric profiles by atmospheric prediction models and also errors related to sensor. A review of sources of systematic errors and uncertainties in observations and simulations at microwave frequencies are discussed in Brogniez *et al.* (2016). In the present study RTTOV-SCATT v9.3 is utilised, however use of later versions can significantly upgrade the quality of all-sky simulations as discussed in Geer and Baordo (2014).

To reduce these biases in RTTOV simulations, improvements in observation operators in terms of treatment of sub-grid scale cloud variability and better parameterisations of particle single scattering properties is very much essential. There is a need for improved prediction of hydrometeors by numerical models by proper representation of physical processes associated with convection and cloud microphysics and also instrument biases related to sensor has to be minimised. Even with all these limitations, the three-dimensional structure of cloud-affected radiances which provide the humidity information in the vicinity of tropical cyclone Hudhud is well represented in all-sky simulations of RTTOV-SCATT. Assimilation of these cloud-affected radiances into the model's initial conditions can provide the moisture information in cloudy regions. To understand the impact of cloud-affected radiance in the initial analysis

of model, assimilation has to be performed which is aimed in our future study. The present study thus highlights the importance of implementation of RTTOV-SCATT observation operator in NCUM data assimilation system to assimilate the cloud-affected SAPHIR microwave radiances.

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