Humidity profile retrieval from SAPHIR on-board the Megha-Tropiques

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The Megha-Tropiques (MT) satellite, a joint Indo-French mission, was launched by ISRO's PSLV-C18 on 12 October 2011 from Sriharikota, India. SAPHIR, a microwave humidity sounder on-board Megha Tropiques operates in six channels with frequencies around 183.31 GHz. A radiative transfer simulation-based operational algorithm has been developed to retrieve layer-averaged relative-humidity (LARH) for six atmospheric layers from the surface to nearly 12 km using SAPHIR observations over land and ocean under non-rainy conditions. SAPHIR-derived LARH for the period July to November 2012 has been validated with concurrent quality-controlled radiosonde observations as well as with ECMWF analysis data. Global validation with radiosonde and ECMWF data shows that root mean square deviation in LARH for all the six layers is nearly 20% and 15% respectively, after bias correction.

Keywords: Atmospheric layers, humidity sounder, radiosonde observations, relative humidity.

Introduction

THE Megha Tropiques (MT), a joint Indo-French satellite, was launched by the Indian launch vehicle, PSLV-C18 on 12 October 2011 from Satish Dhawan Space Centre, Sriharikota, India. The satellite is positioned in a highly inclined equatorial plane of 20° at a height of 867 km above the Earth so as to orbit the tropical region (30°S to 30°N) nearly 14–15 times per day. The four payloads on-board MT consisting of a microwave radiometer (MADRAS), a microwave humidity sounder (SAPHIR), a radiation budget instrument (SCARAB) and a radio-occultation sounder (ROSA) are important for the study of tropical convective systems and hydrological cycle.

The microwave sounder SAPHIR (Sondeur Atmosphérique du Profil d'Humidité Intertropical par Radiométrie) is a six-channel instrument to measure radiation around 183.31 GHz for deriving profiles of atmospheric humidity. The SAPHIR sensor measures radiation with cross-track scanning of 43° yielding data swath of 1705 km with variable local incidence angle at the Earth's surface. The specifications of SAPHIR are given in Table 1.

At frequencies around water vapour resonance line at 183.31 GHz having very high atmospheric absorption, the radiation is dominantly emitted by broad atmospheric layers whose thickness and mean altitude vary with operating frequency as well as with humidity and temperature conditions of the atmosphere. This necessitates the use of a combination of sounding channels for deriving humidity profile due to altitudinal overlaps of dominantly radiating layers. Over the oceanic regions, combined use of microwave radiometer and sounder improves humidity retrieval both in clear[1] and partly cloudy areas, while retrieval under deep convective clouds and precipitating regions is still a challenge. Even for clear sky, retrieval of humidity from sounders with limited number of channels needs to be further improved specifically in the lower troposphere over tropical regions. Humidity profiles derived using the humidity sounder alone are relatively erroneous due to lack of information about temperature, which also modifies the measurements. Various retrieval techniques like statistical, physical, 1D/3D variational, iterative and several others[2–5] have been developed for this purpose with their respective merits and limitations. The statistical approaches primarily involve a priori information matrix of either simulated or observed radiation data. The present study deals with the statistical technique-based algorithm developed to derive humidity profiles from SAPHIR[5]. The subsequent sections briefly describe the algorithm for layer-averaged relative humidity (LARH) from SAPHIR followed by validations. Retrieval has been performed for six layers, viz. 1000–850, 850–700, 700–550, 550–400, 400–250 and 250–100 hPa (referred to hereafter as layers 1–6). Validation criterion of LARH as derived from SAPHIR data for five months (July–November 2012) with near-simultaneous quality-controlled radiosonde observations and European Centre for Medium Range Weather Forecasting (ECMWF) analysis fields has been described in the validation section. The results and discussion section deals with the validation statistics and issues specifically related to validation of humidity for layer-6.

Retrieval algorithm

The retrieval algorithm for humidity profiles from SAPHIR observations is based on that described by Gohil

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Table 1. Specifications of SAPHIR microwave sounder

Channel no.	Centre frequency (GHz)	Maximum passband (mHz)	Sensitivity (K) at 300 K Goal/requirement	Polarization
S_1	183.31 ± 0.2	200	1/2	*H*
S_2	183.31 ± 1.1	350	0.7/1.5	*H*
S_3	183.31 ± 2.8	500	0.7/1.5	*H*
S_4	183.31 ± 4.2	700	0.6/1.3	*H*
S_5	183.31 ± 6.8	1200	0.6/1.3	*H*
S_6	183.31 ± 11.0	2000	0.5/1.0	*H*

et al.[6] and the operational algorithm is described here. Operational products of LARH for six layers which are thin isolated layers (TILs) have been derived using seven thick overlapping layers (TOLs) as the weighting functions for SAPHIR channels are wide and overlapping vertically. The operational algorithms for retrieving humidity profile have been developed based on sensitivity analysis of brightness temperature (BT) simulated through radiative transfer model[7] using NCEP atmospheric profiles. The operational algorithm for retrieving LARH for TOLs under rain-free conditions having the following form has been developed.

$$\mathrm{LARH}_p = A + \sum_{i=1}^{N} A_{i,p,\delta w} \ln(310 - TB_i) + \sum_{i=1}^{N} B_{i,p,\delta w} [\ln(310 - TB_i)]^2, \quad (1)$$

where *i* and *N* are the channel number and total number of channels used respectively, LARH_p is the layer-averaged relative humidity for the *p*th TOL, δw is a small range of WVC and $A_{i,p,\delta w}$ are the retrieval coefficients for the *p*th layer between pressure values. The retrieval coefficients for the *i*th channel and *p*th layer are established separately for each δw varying over the entire range. TB_i is the BT for the *i*th channel of SAPHIR.

In order to retrieve LARH, the required WVC information has also been derived from SAPHIR channels using the associated retrieval model mentioned as:

$$\mathrm{WVC} = C_0 + C_1 TB, \quad (2)$$

where *TB* is mean BT of all the six SAPHIR channels, WVC is the total water vapour content, and C_0 and C_1 are simulation-based regression coefficients. The retrieval coefficients *A* and *B* are established separately for different incidence angles as well as surface type (land and ocean) and the interpolated values of *A* and *B* at the desired incidence angle are used for calculating WVC and LARH values. The LARH for the six TILs has been derived using the two associated TOLs as follows

$$\mathrm{TIL} = D_0 + D_1 \mathrm{TOL}_1 + D_2 \mathrm{TOL}_2, \quad (3)$$

where coefficients D_0, D_1 and D_2 are established using NCEP data.

Prior to the retrieval of humidity from SAPHIR, the offset between simulated and observed brightness temperatures for all SAPHIR channels has been evaluated based on the highest probability values which have been incorporated for retrieval. Typical examples of daily averaged LARH (14 orbits) derived from SAPHIR for 30 October 2012 are shown in Figure 1 for all the six layers. Cyclonic structure and impact of high rainfall activity around Tamil Nadu (TN) coast (depicted by small white gaps) during *Nilam* cyclone is clearly seen in the LARH image shown for layer-2. The high moisture availability from 850 to 400 hPa around TN coast is also evident from Figure 1.

Validation of SAPHIR LARH with ECMWF model analysis

Data

Two types of humidity profile are used in this study: (a) LARH retrieved from SAPHIR and (b) the high-resolution relative humidity profile from the ECMWF analysis. A brief summary of each dataset is as follows:

SAPHIR LARH: As previously defined, LARH retrieved from SAPHIR[5] available in six broad atmospheric layers: (layers 1–6) used for this study. The final version of SAPHIR LARH available from July 2012 to November 2012 is used for validation.

ECMWF analysis: The ECMWF global analysis data with spatial grid of 0.125° × 0.125° at four synoptic hours, viz. 0000, 0600, 1200 and 1800 UTC respectively are used. The relative humidity from 25 vertical levels is used here for validation purpose for the period from July to November 2012. The high spatial resolution enables a better representation of topographical fields. ECMWF analysis also produces an accurate description of horizontal and vertical structures. The quality of ECMWF analysis is evaluated[7] with observations collected during the Atmospheric Radiation Measurement (ARM) Mixed-Phase Arctic Cloud Experiment (M-PACE) at its North Slope of

Alaska (NSA) site and it is reported that the ECMWF analysis reasonably represents the dynamic and thermodynamic structures of the large-scale systems. It is seen that the difference between these two datasets is typically less than 1 ms^{-1} in horizontal winds, 0.3°K in temperature and 5% in relative humidity. These numbers are close to the typical uncertainties in the sounding measurements.

Methodology for validation

The relative humidity retrieved from SAPHIR is layer-averaged in six layers, while the same from ECMWF analysis is in 25 vertical layers. To validate the SAPHIR LARH products, the relative humidity from ECMWF is converted to LARH corresponding to six layers. Towards this, the ECMWF analysed relative humidity profile from the surface to 100 hPa is used to generate the corresponding LARH analysis. The LARH between the pressure level p1 and p2 has been calculated using following formula

$$\mathrm{LARH}_{p1,p2} = \int_{\ln p_1}^{\ln p_2} \mathrm{RH}(p)\,\mathrm{d}\ln p \Big/ \int_{\ln p_1}^{\ln p_2} \mathrm{d}\ln p, \tag{4}$$

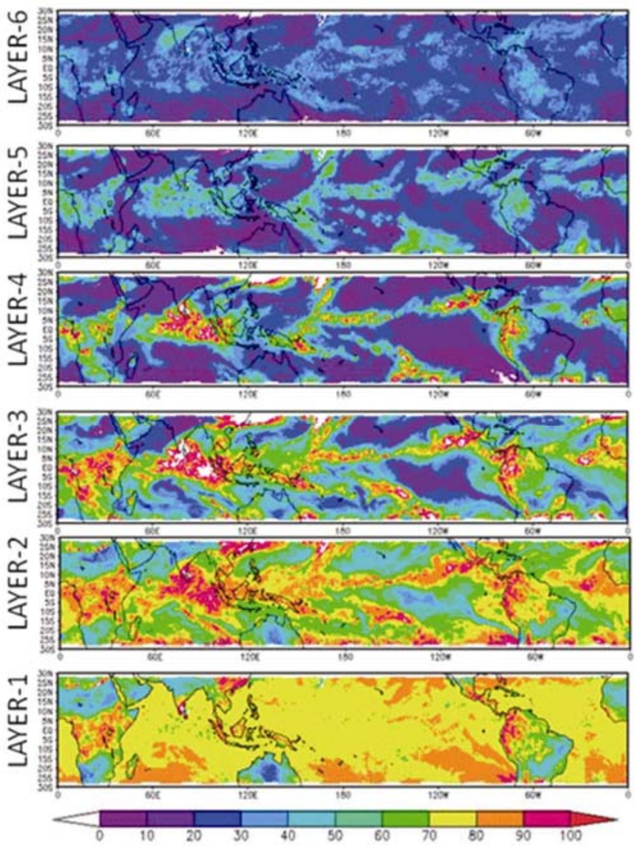

Figure 1. Typical daily averaged LARH fields derived from SAPHIR for layer-1 (1000–850 hPa), layer-2 (850–700 hPa), layer-3 (700–550 hPa), layer-4 (550–400 hPa), layer-5 (400–250 hPa) and layer-6 (250–100 hPa) for 30 October 2012.

where RH(p) is the relative humidity at a given pressure level p. In case of temporal collocation ± 1 h was taken at each synoptic hour, viz. 0000, 0600, 1200 and 1800 UTC of ECMWF analysis. The ECMWF analysed LARH and SAPHIR retrieved LARH are both at different spatial resolution. The SAPHIR retrieved LARH is resampled to 0.125° × 0.125° using bilinear interpolation in order to compare it with the ECMWF analysis. Here, mean difference (MD) and root mean square difference (RMSD) are considered as the standard quantification to validate the SAPHIR LARH with ECMWF analysis. The MD and RMSD are defined as follows

$$\mathrm{MD} = \frac{1}{N}\sum_{i=1}^{N}(\mathrm{LARH}_{\mathrm{SAPHIR}} - \mathrm{LARH}_{\mathrm{ECMWF}}), \tag{5}$$

$$\mathrm{RMSD} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\mathrm{LARH}_{\mathrm{SAPHIR}} - \mathrm{LARH}_{\mathrm{ECMWF}})^2}. \tag{6}$$

Results and discussion

The error statistics, mainly RMSD and MD (in brackets) during this validation period (July to November 2012) is shown in Table 2. It shows high RMSD in the top layer (33.6% in 250–100 hPa) for this validation period, less RMSD (< 20%) is observed in the remaining layers. These high errors are mainly attributed to the high bias in these layers. It shows that higher RMSD is mainly governed by the systematic biases observed in these LARH layers. A systematic bias is observed in layers 2, 3, 5 and 6 of the SAPHIR-derived LARH during this period of validation. A bias correction methodology is used to remove the spatial systematic bias. Spatial bias is estimated for each spatial grid using ECMWF and SAPHIR LARH for the first ten days of July 2012 and applied to the data of the remaining period. Large error reduction is observed in all the layers after bias correction method (Table 3), especially in layers 1, 2 and 6. After bias correction, all the layers of SAPHIR show less than 20% RMSD, which is well within the mission goal of the SAPHIR sensor. The percentage improvement (Table 3, within brackets) after applying the bias correction during July to November 2012, is significant, except for layer 4. Layers 1, 3–5 are comparatively in good agreement with ECMWF analysis. All the four layers are able to capture the moisture variability over the tropical region.

Figure 2 shows the vertical profile of RMSD and MD during July to November 2012. The LARH derived from SAPHIR shows MD of 0.5%, 14.4%, 10.6%, 0.6%, –8.6% and –31.7% and RMSD of 14.6%, 23.1%, 16.8%, 10.7%, 17.5% and 36.3% in the six atmospheric layers respectively. The spatial bias-corrected RMSD is observed to be 12.2%, 15.8%, 12.6%, 11.4%, 15.2% and

Table 2. Error statistics of SAPHIR-retrieved LARH

Month	Layer-1 1000–850 hPa (%)	Layer-2 850–700 hPa (%)	Layer-3 700–550 hPa (%)	Layer-4 550–400 hPa (%)	Layer-5 400–250 hPa (%)	Layer-6 250–100 hPa (%)
July	14.4 (0.2)	22.6 (14.0)	17.4 (11.0)	10.7 (0.2)	17.7 (–9.0)	35.8 (–30.8)
August	14.5 (0.6)	23.5 (14.7)	17.3 (10.8)	10.5 (0.6)	17.8 (–8.6)	35.3 (–30.6)
September	14.3 (0.4)	23.8 (15.0)	16.7 (10.6)	10.8 (0.6)	17.4 (–8.6)	36.3 (–32.0)
October	15.3 (1.2)	23.4 (15.0)	16.0 (9.9)	10.8 (1.0)	16.8 (–8.0)	37.0 (–32.7)
November	14.4 (0.3)	22.4 (13.4)	16.4 (10.6)	10.7 (0.8)	17.6 (–8.7)	37.0 (–32.6)

Table 3. Error statistics of SAPHIR-retrieved LARH (after bias correction)

Month	Layer-1 1000–850 hPa (%)	Layer-2 850–700 hPa (%)	Layer-3 700–550 hPa (%)	Layer-4 550–400 hPa (%)	Layer-5 400–250 hPa (%)	Layer-6 250–100 hPa (%)
July	11.1 (23)	15.3 (32)	12.5 (28)	11.2 (–05)	13.8 (22)	13.4 (62)
August	11.3 (22)	14.9 (36)	12.4 (29)	11.1 (–05)	14.0 (21)	14.2 (60)
September	11.1 (22)	15.2 (36)	12.3 (26)	11.2 (–04)	14.3 (18)	14.4 (60)
October	12.1 (21)	15.0 (36)	12.2 (24)	11.2 (–04)	14.9 (11)	15.5 (58)
November	11.6 (19)	15.0 (33)	12.3 (25)	11.3 (–05)	14.9 (15)	15.2 (59)

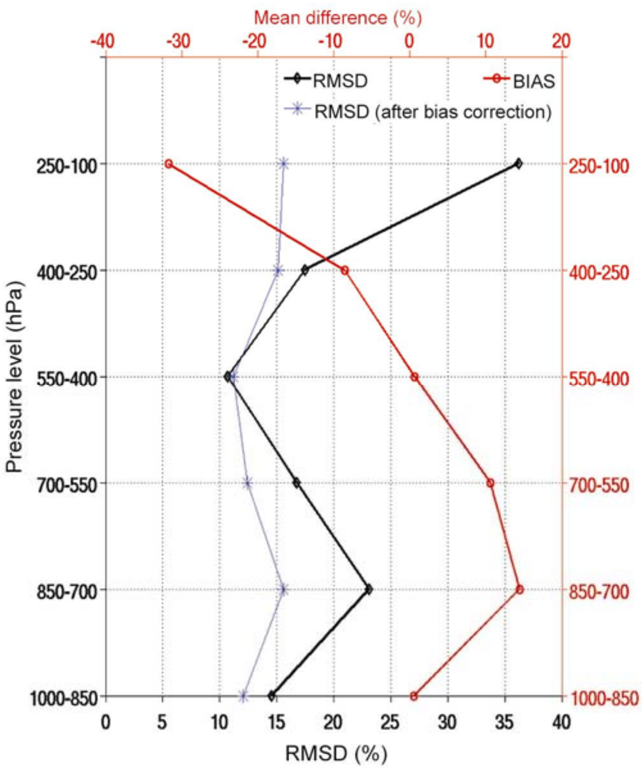

Figure 2. Vertical profile of mean difference, RMSD and RMSD after bias correction for SAPHIR six atmospheric levels.

15.7% respectively. Figure 3 shows the density plot of all the six layers after bias correction during July to November 2012. It shows that in layer-1 most of the observations are confined to high-moisture regions. Layers 2 to 5 are in good agreement with ECMWF analysis and with higher moisture in SAPHIR. Total number of points used for validations is approximately 200 million. Less than 10% points show the large spread during this validation. SAPHIR LARH shows the correlation of 0.79, 0.77, 0.88, 0.89, 0.80 and 0.69 with ECMWF-analysed LARH during this period for the six layers respectively.

Validation of SAPHIR LARH with radiosonde observations

SAPHIR-derived LARH is also validated with global radiosonde observations (RAOB) known as NCEP ADP global upper air and surface weather observations, available from RDA (http://dss.ucar.edu). As these data are primarily used for assimilation into the various NCEP analyses after extensive quality checks, they provide a number of quality flags associated with the data that help in filtering out the spurious RAOB observations and selecting various pressure levels suitable for validation.

The RAOB data are acquired for the period from July to November 2012 at synoptic hours 00, 06, 12 and 18 GMT for each day. The following quality checks are applied on RAOB data.

At a given pressure level all the three variables, i.e. pressure, temperature and humidity must be available.

For pressure, humidity and temperature, quality flag should be less than three (details of quality flag definitions are described in http://rda.ucar.edu/datasets/ds337.0/docs/README_readpb). Although observation with quality flag '9' is not used in NCEP reanalysis processing, in the present validation exercise, humidity quality flag '9' was also taken as valid to accommodate humidity observations above 300 hPa for validation of SAPHIR LARH for layer-6.

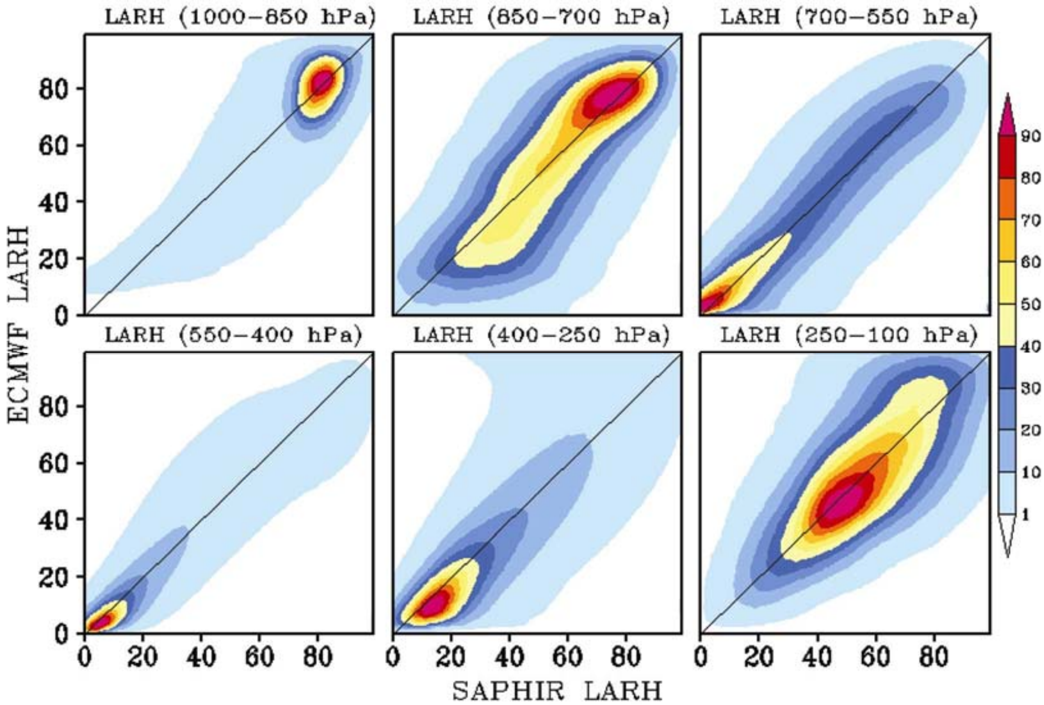

Figure 3. Density plot of SAPHIR LARH with ECMWF-analysed LARH during July–November 2012.

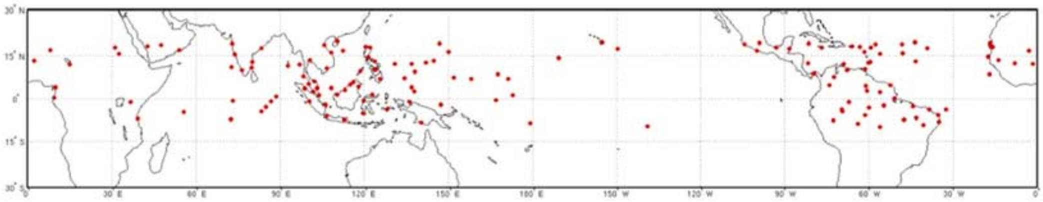

Figure 4. Collocated RAOB stations (July–November 2012).

Using the RAOB observations of pressure, temperature and specific humidity profiles, RH is computed as given below.

$$e = 6.1078\left[10^{\left(\frac{T_d+7.5}{T_d+237.5}\right)}\right], \tag{7}$$

$$e_s = 6.1078\left[10^{\left(\frac{T_d+7.5}{T_d+237.5}\right)}\right], \tag{8}$$

and

$$\mathrm{RH} = 100\frac{e}{e_s}, \tag{9}$$

where T, T_d, e and e_s are temperature, dew point temperature, specific humidity and saturated specific humidity respectively.

These RH values are used to generate LARH values (eq. (4)). Since RAOB does not always provide atmospheric profiles at fixed pressure levels and the total number of pressure levels is variable, therefore additional quality checks are applied when computing LARH from RH profiles provided by RAOB. The LARH values are computed only if at least two levels are present for that layer. In absence of at least two levels for a particular layer, the LARH value is assumed to be undefined. In addition, a quality check is applied on the existence of the uppermost and lowermost level for a given layer. If for a particular layer either the uppermost level or lowermost level is absent, then that particular level is interpolated using its neighbouring levels. In the absence of neighbouring levels, no extrapolation is done and LARH for that particular level is assumed to be undefined.

RAOB and SAPHIR-derived LARH values are collocated with ± 1 h time difference and within the spatial radius of 0.125°. Locations of collocated RAOB stations are shown in Figure 4. Total number of such collocated points for all the six layers is ~ 16,000 to ~ 8000 (July to November 2012) pertaining to nearly 150 RAOB stations (Figure 4).

Table 4. Month-wise RMSD, bias and unbiased RMSD between SAPHIR and RAOB LARH for July–November 2012

LARH	Months				
	July	August	September	October	November
Layer-1 (%)	14.9, 1.4, 14.8	13.1, 1.5, 13.0	14.1, 0.03, 14.1	14.2, –0.5, 14.2	15.1, –0.2, 15.8
Layer-2 (%)	19.5, 10.2, 16.6	17.7, 8.6, 15.4	18.4, 9.9, 15.5	19.1, 10.3, 16.0	17.2, 10.0, 16.1
Layer-3 (%)	20.6, 12.7, 16.2	19.6, 11.1, 16.2	19.8, 11.7, 16.0	18.9, 9.2, 16.5	20.1, 12.2, 16.5
Layer-4 (%)	17.8, –3.5, 17.5	19.8, –3.7, 19.5	18.5, –2.6, 18.3	18.3, –2.0, 18.2	17.2, –1.2, 18.0
Layer-5 (%)	18.2, –5.4, 17.4	17.9, –4.1, 17.4	17.7, –4.3, 17.2	16.8, –3.6, 16.4	17.0, –4.5, 17.9
Layer-6 (%)	31.9, –16.8, 27.2	33.1, –14.1, 30.1	33.4, –15.4, 29.8	27.8, –14.9, 23.6	31.0, –10.1, 29.3

Mean RMSD for July–November 2012. 14.4, 15.9, 16.3, 18.3, 17.6 and 28.0 for layers 1–6 respectively.

Results

SAPHIR-derived LARH values in six layers have been validated with near-simultaneous (within ± 1 h and 0.125°) observations of LARH from quality-controlled RAOB. Analysis of five months' (July–November 2012) comparison shows less than 20% RMSD for all the layers, except layer-6 where RMSD is ~33% (Table 4). As evident from Table 4, RMSD and biases in each layer are nearly stable for all the five months. It suggests that biases of all six SAPHIR channels with respect to simulations are stabilized during these months and so a mean bias (calculated as the average of five months for each layer) can be applied in SAPHIR LARH for all the five months for each layer to get a better estimate. The RMSD after mean bias correction is also given in Table 4, showing improvements in all the layers. Larger RMSD in layer-6 could be due to the dry bias error in radiosonde (RS92-Vaisala) humidity data at these altitudes[9].

Conclusion

Radiative transfer-based algorithm developed for the retrieval of LARH from SAPHIR observations is able to capture vertical humidity distribution over land and ocean as in the case of Nilam cyclone around TN coast on 30 October 2012.

Validation of SAPHIR LARH values with those of ECMWF shows RMSD for six layers as 18.9%, 23.9%, 16.2%, 11.1%, 16.1% and 34.8% respectively, which further improved to 14.3%, 18.2%, 14.0%, 11.7%, 14.8% and 15.5% respectively, after bias correction for the validation period. The RMSD values are well within the mission goal.

Validation of SAPHIR LARH with quality-controlled collocated radiosonde data indicates RMSD less than 20% for all the layers, except layer-6. RMSD for layer-6 is nearly 30%. Dry bias error in radiosonde measurements at these heights may be one of the reasons for such a large RMSD. In the near future, methods to correct this dry bias will be adopted to validate the SAPHIR LARH more precisely. Furthermore, bias with respect to land and ocean, if incorporated separately, may further improve the LARH retrievals.

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