Retrieval of Layer Averaged Relative Humidity Profiles from MHS Observations over Tropical Region

R. K. Gangwar, B. S. Gohil, and A. K. Mathur

Geophysical-Parameter Retrievals Division, Atmospheric and Oceanic Sciences Group Earth, Ocean, Atmosphere, Planetary Sciences and Applications Area Space Applications Centre (ISRO), Ahmedabad 380015, India

Correspondence should be addressed to R. K. Gangwar; rgphybhu@gmail.com

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1. Introduction

Being the strongest greenhouse gas, water vapor is the most important constituents in the Earth’s atmosphere, as its spatial and temporal variations affect various meteorological phenomena like formation of clouds, development of severe storms, and global warming [1]. The latent heat released during the condensation of water vapour is crucial in the triggering and development of the convective systems [2]. Nearly all-weather capability of microwave sounders provides an added advantage for remote sensing of water vapor from such sensors. In microwave region, water vapour has two absorption line peaks at 22.235 and 183.31 GHz. The line strength at 22.235 GHz is weak, and in clear conditions the atmosphere typically absorbs less than 20% of the radiation propagating through it at this frequency. Therefore, most of the attempts to retrieve water vapor by remote sensing near this frequency are necessarily limited to total integrated precipitable water [3, 4]. To retrieve water vapor in a few layers over oceans or land requires a strong absorption line such that around 183.31 GHz. Profiling of the atmospheric water vapour has been made with radiometric measurements from the airborne microwave moisture sounder (AMMS) and millimeter wave imaging radiometer (MIR) by [5, 6] to study the effects of clouds on these frequencies. A similar sounder operating around 183.31 GHz, namely, SAPHIR, onboard MEGHA-TROPIQUES a joint ISRO-CNES mission is in orbit since October 2011. SAPHIR provides measurements in six water vapour channels around 183.31 GHz for sounding the atmospheric humidity. Brogniez et al. [7], Gohil et al. [8] have shown the potential of SAPHIR sounder in retrieving the atmospheric humidity profile.

Since Microwave Humidity Sounder (MHS) has three channels (described in next section) similar to SAPHIR; an algorithm has been developed for the retrieval of the atmospheric humidity profiles using MHS data that can also be used for retrieval from SAPHIR observations [9, 10]. The algorithm is based on the relationship between the brightness temperatures (BT) of three MHS channels and relative humidity in seven TOLs from 1000 to 100 hPa pressure values. From these TOLs, six TILs from 1000 to 100 hPa are derived. To examine the behavior of these brightness temperatures with humidity, various radiative transfer simulations have been performed and after that an empirical relation has been
established between them. By making use of this relationship, the retrieval of humidity profiles from MHS brightness temperature data has been validated with near simultaneous radiosonde as well as NCEP reanalysis water vapor fields.

2. Data Used

The present technique has been developed on the basis of simulated data for the MHS channels having frequencies around strong water vapour absorption band in microwave region of electromagnetic spectrum at 183.31 GHz (183.31 ± 1.0, 183.31 ± 3.0, and 183.31 ± 7.0). To simulate the brightness temperature, the atmospheric fields have been taken from NCEP reanalysis for year 2009 to cover the spatial and temporal dynamic variability of relative humidity. Table 1 gives the statistics of the simulated brightness temperatures and the tropical atmospheric relative humidity for seven thick overlapping layers used for establishing the empirical relation between them.

The algorithm has been tested on the brightness temperature data of MHS onboard METOP-A (available from EUMETSAT) for the last 10 days of each March, July, and December 2010 for the global tropical region (30°S–30°N). The results have been compared with the concurrent observations from radiosonde (Wyoming University) as well as NCEP analysis fields (1° spatial grid).

3. Methodology

The retrieval algorithm for the atmospheric humidity profiles has been developed based on sensitivity analysis of the brightness temperature data simulated from scattering based microwave radiative transfer model (RTM) [11] and atmospheric profiles from NCEP reanalysis (as described in Table 1). This RTM includes absorption models for various atmospheric gases such as water vapour, oxygen, and emissivity model for ocean surfaces as described in [12, 13], respectively. Over land, emissivity of 0.9 has been used. Details of sensitivity analysis are presented in the next section.

3.1. Sensitivity Analysis. The sensitivity of simulated brightness temperatures on humidity has been studied under varying atmospheric conditions for various types of humidity layers taking into account that the weighting functions of MHS channels are very wide and highly overlapping. These weighting functions do not cover the near surface layers as well as the 250–100 hPa layer significantly. This experiment is useful in selecting the atmospheric TOLs influencing maximum number of channels to be considered for better retrievals.

Definitions of the TOL and TIL are given below.

LARH is the relative humidity (RH) averaged with respect to logarithm of pressure over a layer between two pressure limits “p1” and “p2” as defined below:

\[
\text{LARH}_{p1, p2} = \frac{\int_{\ln(p1)}^{\ln(p2)} \text{RH}(p) \delta(\ln(p))}{\ln(p1) - \ln(p2)}.
\]

Additionally, these TOLs are also innovatively utilized to derive humidity for TILs which otherwise will have large retrieval errors when directly derived from the channel brightness temperatures (due to broad overlapping nature of channel’s Weighting Functions (WFs)).

As mentioned above, TILs have been derived from two TOLs as follows.

From known LARH values for two TOLs with pressure levels “p1” to “p3” and “p2” to “p3”, the LARH value for a TIL with pressure levels “p1” to “p2” can be derived as

\[
\text{LARH}_{p1, p3} = \frac{\int_{\ln(p1)}^{\ln(p3)} \text{RH}(p) \delta(\ln(p))}{\ln(p1) - \ln(p3)}.
\]

\[
\text{LARH}_{p1, p3} = \left[ \frac{\int_{\ln(p1)}^{\ln(p2)} \text{RH}(p) \delta(\ln(p)) + \int_{\ln(p2)}^{\ln(p3)} \text{RH}(p) \delta(\ln(p))}{\ln(p1) - \ln(p3)} \right],
\]

\[
\text{LARH}_{p2, p3} = \frac{\int_{\ln(p2)}^{\ln(p3)} \text{RH}(p) \delta(\ln(p))}{\ln(p2) - \ln(p3)}.
\]
The LARH for TIL between “p1” to “p2” is derived using expressions ((2b) and (2c)) as

\[
\text{LARH}_{p1,p2} = \left[ \text{LARH}_{p1,p3} \cdot \left( \ln(p1) - \ln(p3) \right) - \text{LARH}_{p2,p3} \cdot \left( \ln(p2) - \ln(p3) \right) \right] \\
\times \left( \ln(p1) - \ln(p2) \right)^{-1}.
\] (2d)

This approach of deriving TILs from TOLs is explained in Figures 1(a), 1(b), 1(c), and 1(d) and Table 2. Figures 1(a) and 1(b) show the correlation of TOLs (1000–400) hPa and (850–400) hPa with BT corresponding to 190.31 GHz as well as 180.31 GHz, respectively. Similarly, Figures 1(c) and 1(d) show the variation of TIL (1000–850) hPa with BT corresponding to 190.31 GHz as well as 180.31 GHz, respectively. From these figures, it can be clearly seen that TOLs have better correlation (~0.5) with BTs while TIL does not show any such trend with BT.

Table 2 gives the correlation coefficients for all TOLs and TILs with BTs. Again, from Table 2 it can be inferred that TOLs are better correlated with BTs as compared to TILs.

A typical example of variation of LARH with BT is given in Figure 2 for three layers (1000–400, 850–400, and 700–250 hPa). As observed in Figure 2, an exponential trend between LARH and BT is used for developing the retrieval model.
Table 2: Correlation coefficient between TOLs and TILs and brightness temperature of three MHS channels.

| Channel frequency (GHz) | Correlation coefficient (R) |
|-------------------------|-----------------------------|
|                         | TOL (1000–550) hPa | TOL (850–250) hPa | TOL (700–100) hPa | TOL (550–100) hPa | TOL (300–850) hPa | TOL (850–700) hPa | TOL (700–550) hPa | TOL (550–400) hPa | TOL (400–250) hPa | TOL (250–100) hPa |
|                         | TIL (1000–400) hPa | TIL (850–250) hPa | TIL (700–100) hPa | TIL (550–100) hPa | TIL (300–850) hPa | TIL (850–700) hPa | TIL (700–550) hPa | TIL (550–400) hPa | TIL (400–250) hPa | TIL (250–100) hPa |
| 190.31                  | 0.6              | 0.7              | 0.8              | 0.7              | 0.5              | 0.5              | 0.3              | 0.4              | 0.6              | 0.7              | 0.5              | 0.2              |
| 180.31                  | 0.4              | 0.6              | 0.7              | 0.9              | 0.9              | 0.8              | 0.1              | 0.3              | 0.6              | 0.8              | 0.9              | 0.4              |
| 182.31                  | 0.6              | 0.8              | 0.8              | 0.9              | 0.9              | 0.7              | 0.1              | 0.4              | 0.7              | 0.8              | 0.7              | 0.2              |
3.2. Retrieval Technique. Based on the nature of BT dependency on LARH as seen in Figure 2, the following optimum relationship between LARH and BT has been established for deriving LARH:

\[
\ln (\text{LARH}_p) = A_{0,p} + \sum_{i=1}^{N} A_{i,p} \text{TB}_i, \quad (3)
\]

where \( A_{0,p} \) is the retrieval constant for \( p \)th layer spreading between pressure values \( P_{\text{lower}} \) to \( P_{\text{upper}} \), \( A_{i,p} \) is the retrieval coefficient for \( i \)th channel and \( p \)th layer, and \( \text{TB}_i \) is the brightness temperatures of \( i \) th sounding channel. These coefficients have been established using the BT (with random noise of 1 K in all channels) simulated through RTM using NCEP model clear-sky atmospheres with WVC varying over the entire range (0–8 g/cm\(^2\)). The above algorithm used is named here as NORM algorithm. For a typical layer between 1000 to 500 hPa, the correlation between LARH and BT for different sounding channels is shown in Figure 3(a).

Since the RH can vary over a wide range irrespective of the total moisture content of the atmosphere, the trend of LARH with BT under limited WVC range between 2.0 g/cm\(^2\) and 5.0 g/cm\(^2\) is shown in Figure 3(b). It is clearly observed that correlation \( R^2 \) between LARH and BT has improved significantly for 190.31 GHz channel (from 40 to 63\%) and marginally for 180.31 GHz and 182 GHz channels. Restricting the range of WVC inherently limits the natural range of temperature participating in emission while preserving the dynamic range of RH hence yields better correlation between LARH and BT. This aspect has been exploited in the present study.

Thus, (3) for water vapour dependent (WVD) algorithm can be rewritten in the following form:

\[
\ln (\text{LARH}_p) = A_{0,p,\delta w} + \sum_{i=1}^{N} A_{i,p,\delta w} \text{TB}_i, \quad (4)
\]

where \( \delta w \) is a range of WVC (described in next section) and the associated retrieval coefficients are \( A_{0,p,\delta w} \) and \( A_{i,p,\delta w} \). These coefficients are established separately for each \( \delta w \) varying over the entire range. In order to retrieve LARH, the required WVC information can be obtained externally through microwave radiometer or from the climatological database. As known, the WVC from radiometer has characteristic errors while that from the climatology has variability when used on instantaneous basis necessitating the use of broader and overlapping ranges of WVC under WVD algorithm. The improvements in retrievals by using WVD algorithm has been studied in detail based on simulations for MHS channels with limited testing with MHS data presented next.

4. Results and Discussions

In the present study, retrieval has been performed for the seven TOLs lying between the pressure values 1000–550 hPa, 1000–400 hPa, 850–400 hPa, 850–250 hPa, 700–250 hPa, 700–100 hPa, and 550–100 hPa, respectively, on the basis of their sensitivity with MHS channels’ brightness temperatures. From these seven TOLs, the LARH for six TILs has been derived using WVD algorithm, the chosen WVC ranges with minor overlaps are 0 to 3 g/cm\(^2\), 2 to 5 g/cm\(^2\), 4 to 7 g/cm\(^2\), and 6 to 10 g/cm\(^2\). The aggregate (overall or profile) retrieval error is defined here as root mean sum of squares (RMSS) of root mean square (RMS) of differences of the two data sets.

4.1. METOP-A/MHS Simulation Results. Table 3 gives the root mean square differences for the seven overlapping thick layers retrieved by making use of NORM and WVD retrieval algorithms. From the table it can be inferred that there is a significant improvement of ~23\% in the errors in retrievals from WVD algorithm over retrievals from NORM algorithm for the overlapping layers.

The algorithms have been first tested for TOL employing the retrieval coefficients for different incidence angles (Table 4) followed by its evaluation for TIL.

From Tables 3 and 4 it is clear that there is a significant reduction in RMS difference for RH retrieval in TOL (~23\%) as well as TIL (~15\%) using WVD algorithm. Hence, the retrieval of LARH from actual MHS observations has been done using WVD algorithm only.

4.2. MHS Data Analysis Results: Comparison with Radiosonde and NCEP Profiles. The brightness temperature data of MHS onboard METOP-A for March, July, and December 2010 for the tropical region over the entire globe has been taken to retrieve the seven TOLs from which six TILs have been derived using (4) and (2a)–(2d), respectively. The retrieved TILs have been compared with concurrent radiosonde as well as NCEP reanalysis TIL calculated as per equation (1).
Table 3: Testing of algorithms with overlapping layers.

| Local inc. angle (degree) | Algorithm | WV range (g/cm²) | Retrieval errors of layer-average RH (RH in %) (simulated data = 12286) (overlapping layers) | Profile RMSS (%) | Aggr error (%) |
|---------------------------|-----------|------------------|------------------------------------------------------------------------------------------|-----------------|----------------|
|                           |           | 000–550hPa | 1000–400hPa | 850–250hPa | 700–250hPa | 700–100hPa | 550–100hPa |
|                           | NORM      | 0.0–10.0 | 11.82  | 8.00   | 8.30   | 4.50   | 4.00   | 6.23   | 6.76   | 7.50   | 7.50   |
|                           |           | 0.0–3.0 | 8.87   | 5.64   | 5.34   | 3.24   | 3.14   | 5.56   | 6.15   | 5.71   | 5.19   |
|                           |           | 2.0–5.0 | 7.47   | 4.92   | 5.72   | 3.08   | 3.60   | 5.93   | 6.61   | 5.53   | 5.19   |
|                           |           | 4.0–7.0 | 6.30   | 4.70   | 5.21   | 3.32   | 3.55   | 5.68   | 6.46   | 5.16   | 5.16   |
|                           |           | 6.0–10.0| 4.93   | 3.69   | 3.89   | 2.82   | 3.78   | 4.68   | 5.40   | 4.25   | 4.25   |
|                           | WVD       | 0.0–10.0 | 11.57  | 7.79   | 8.06   | 4.39   | 3.97   | 6.18   | 6.70   | 7.34   | 7.34   |
|                           |           | 0.0–3.0 | 8.75   | 5.57   | 5.35   | 3.23   | 3.14   | 5.53   | 6.09   | 5.66   | 5.66   |
|                           |           | 2.0–5.0 | 7.64   | 5.03   | 5.72   | 3.10   | 3.59   | 5.89   | 6.55   | 5.56   | 5.56   |
|                           |           | 4.0–7.0 | 6.41   | 4.80   | 5.31   | 3.39   | 3.56   | 5.63   | 6.40   | 5.20   | 5.20   |
|                           |           | 6.0–10.0| 5.12   | 3.76   | 3.85   | 2.50   | 3.69   | 4.66   | 5.38   | 4.26   | 4.26   |
|                           | 25        | NORM    | 0.0–10.0 | 11.57  | 7.79   | 8.06   | 4.39   | 3.97   | 6.18   | 6.70   | 7.34   | 7.34   |
|                           |           | 0.0–3.0 | 8.75   | 5.57   | 5.35   | 3.23   | 3.14   | 5.53   | 6.09   | 5.66   | 5.66   |
|                           |           | 2.0–5.0 | 7.64   | 5.03   | 5.72   | 3.10   | 3.59   | 5.89   | 6.55   | 5.56   | 5.56   |
|                           |           | 4.0–7.0 | 6.41   | 4.80   | 5.31   | 3.39   | 3.56   | 5.63   | 6.40   | 5.20   | 5.20   |
|                           |           | 6.0–10.0| 5.12   | 3.76   | 3.85   | 2.79   | 3.69   | 4.66   | 5.38   | 4.26   | 4.26   |
|                           | 50        | NORM    | 0.0–10.0 | 11.25  | 7.54   | 7.61   | 4.21   | 3.88   | 5.97   | 6.48   | 7.09   | 7.09   |
|                           |           | 0.0–3.0 | 8.30   | 5.29   | 5.19   | 3.13   | 3.13   | 5.38   | 5.88   | 5.44   | 5.44   |
|                           |           | 2.0–5.0 | 8.32   | 5.52   | 5.88   | 3.24   | 3.56   | 5.73   | 6.34   | 5.74   | 5.74   |
|                           |           | 4.0–7.0 | 6.78   | 5.21   | 5.77   | 3.65   | 3.77   | 5.44   | 6.15   | 5.36   | 5.36   |
|                           |           | 6.0–10.0| 5.54   | 4.02   | 3.98   | 2.61   | 3.34   | 4.53   | 5.21   | 4.28   | 4.28   |
|                           | WVD       | 0.0–10.0 | 11.25  | 7.54   | 7.61   | 4.21   | 3.88   | 5.97   | 6.48   | 7.09   | 7.09   |
|                           |           | 0.0–3.0 | 8.30   | 5.29   | 5.19   | 3.13   | 3.13   | 5.38   | 5.88   | 5.44   | 5.44   |
|                           |           | 2.0–5.0 | 8.32   | 5.52   | 5.88   | 3.24   | 3.56   | 5.73   | 6.34   | 5.74   | 5.74   |
|                           |           | 4.0–7.0 | 6.78   | 5.21   | 5.77   | 3.65   | 3.77   | 5.44   | 6.15   | 5.36   | 5.36   |
|                           |           | 6.0–10.0| 5.54   | 4.02   | 3.98   | 2.61   | 3.34   | 4.53   | 5.21   | 4.28   | 4.28   |
|                           | Imp. (%)  | 7.31   | 5.60   | 23.38  |
4.2.1. Comparison with Radiosonde. The comparison has been performed for the data of 2010 comprising of 10 days each from March, July, and December months. To collocate the radiosonde TIL with retrieved TIL from MHS, a search radius of 0.2° and ±1 hr temporal window is used. The scatter plot for each TIL retrieved from WVD algorithm and TIL from radiosonde observations is shown in Figures 4, 5, 6, 7, 8, and 9.

Based on these collocated TILs from MHS and radiosonde, the root mean square difference (RMSD) and bias in retrieved TIL have been calculated and shown in Table 4. The least RMSD is found to be 9.93% in TIL 400–250 hPa indicating the maximum sensitivity of MHS channels for this layer. On the other hand, RMSD of 18.45% in 250–100 hPa TIL shows less sensitivity.

However, profile RMSS of RMSD is ~15%.

4.2.2. Comparison with NCEP Reanalysis Data. Dataset of retrieved TIL from MHS used for comparison with radiosonde has also been used to compare with TIL from NCEP reanalysis fields. The collocation of both datasets has been done by taking 1° × 1° spatial resolution and ±3 hr temporal resolution. The comparison is done in terms of RMSD between retrieved and NCEP model profiles as carried out for comparison with radiosonde. Table 5 shows the RMSD and bias in retrieved TIL from MHS and NCEP dataset.

Here, also the RMSD is maximum (~32%) in TIL 250–100 hPa. However, minimum RMSD of 10.33% is found to be in 550–400 hPa TIL.

From Table 5 it can be inferred that the relative humidity profiles can be retrieved from MHS observations with RMSD

![Figure 3](image-url)
Table 5: The RMSD and BIAS in retrieved TIL profiles for the year 2010.

| Dataset          | Isolated layers (hPa) | Bias (%) | Unbiased RMS difference (%) | RMS difference (MHS – RS) (%) | Profile RMSS of RMS difference (%) |
|------------------|-----------------------|----------|-----------------------------|-------------------------------|-----------------------------------|
| Radiosonde       | 1000–850             | -5.02    | 14.82                       | 15.64                         |                                   |
|                  | 850–700              | 0.93     | 18.12                       | 18.13                         |                                   |
|                  | 700–550              | 6.07     | 14.79                       | 15.98                         |                                   |
|                  | 550–400              | 4.75     | 10.14                       | 11.19                         |                                   |
|                  | 400–250              | 3.00     | 9.47                        | 9.93                          |                                   |
|                  | 250–100              | 10.92    | 14.88                       | 18.45                         |                                   |
| NCEP             | 1000–850             | 5.38     | 16.06                       | 17.05                         |                                   |
|                  | 850–700              | 1.37     | 16.86                       | 17.14                         |                                   |
|                  | 700–550              | -2.67    | 14.46                       | 14.71                         |                                   |
|                  | 550–400              | -0.38    | 10.30                       | 10.33                         |                                   |
|                  | 400–250              | 10.71    | 13.03                       | 17.11                         |                                   |
|                  | 250–100              | 21.92    | 21.67                       | 32.24                         |                                   |

Retrieved LARH of (1000-850) hPa from WVD algorithm

Retrieved LARH of (850-700) hPa from WVD algorithm

Retrieved LARH of (550-400) hPa from WVD algorithm

Figure 4

Figure 5

Figure 6

Figure 7
Retrieved LARH of (400-250) hPa from WVD algorithm

Retrieved LARH of (250-100) hPa from WVD algorithm

less than ∼20% for six TILs except at higher altitude (250–100 hPa). Larger errors in retrieving relative humidity profiles at higher altitude (250–100 hPa) can be attributed to the less sensitivity of MHS channels at these levels. These results are significant in view of broad overlapping weighting functions of MHS channels.

5. Conclusion

A new technique for deriving improved layer averaged humidity profiles using microwave sounders has been developed and tested on actual MHS observations. Comparison of LARH profiles with those of radiosonde as well as NCEP indicates improved retrieval using present approach as compared to the standard algorithm. The algorithms developed in the present study are expected to improve further with more number of sounding channels like SAPHIR onboard Megha-Tropiques.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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