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Megha-Tropiques/SAPHIR measurements of humidity profiles: validation with AIRS and global radiosonde network

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Abstract

The vertical profiles of humidity measured by SAPHIR (Sondeur Atmospherique du Profil d' Humidité Intropicale par Radiométrie) on-board Megha-Tropiques satellite are validated using Atmosphere Infrared Sounder (AIRS) and ground based radiosonde observations during July–September 2012. SAPHIR provides humidity profiles at six pressure layers viz., 1000–850 (level 1), 850–700 (level 2), 700–550 (level 3), 550–400 (level 4) 400–250 (level 5) and 250–100(level 6) hPa. Segregated AIRS observations over land and oceanic regions are used to assess the performance of SAPHIR quantitatively. The regression analysis over oceanic region (125° W–180° W; 30° S–30° N) reveal that the SAPHIR measurements agrees very well with the AIRS measurements at levels 3, 4, 5 and 6 with correlation coefficients 0.79, 0.88, 0.87 and 0.78 respectively. However, at level 6 SAPHIR seems to be systematically underestimating the AIRS measurements. At level 2, the agreement is reasonably good with correlation coefficient of 0.52 and at level 1 the agreement is very poor with correlation coefficient 0.17. The regression analysis over land region (10° W–30° E; 8° N–30° N) revealed an excellent correlation between AIRS and SAPHIR at all the six levels with 0.80, 0.78, 0.84, 0.84, 0.86 and 0.65 respectively. However, again at levels 5 and 6, SAPHIR seems to be underestimating the AIRS measurements. After carrying out the quantitative comparison between SAPHIR and AIRS separately over land and ocean, the ground based global radiosonde network observations of humidity profiles over three distinct geographical locations (East Asia, tropical belt of South and North America and South Pacific) are then used to further validate the SAPHIR observations as AIRS has its own limitations. The SAPHIR observations within a radius of 50 km around the radiosonde stations are averaged and then the regression analysis is carried out at the first five levels of SAPHIR. The comparison is not carried out at sixth level due to inaccuracies of radiosonde measurements of humidity at this level. From the regression analysis, it is found that the SAPHIR observations agree very well with the radiosonde observations at all the five levels with correlation coefficients 0.65, 0.72, 0.84, 0.88

and 0.78 respectively. Among the three regions considered for the present study, the correlation was poor at the first level over East Asia.

Further, statistical analysis showed that at first level the SAPHIR observations have wet bias at low humidity magnitudes and dry bias at high humidity magnitudes. The humidity magnitude at which wet bias changes to dry bias varied from one level to the other. The mean bias between the radiosonde and the SAPHIR observations are also estimated separately for the three regions. The mean bias profiles showed that SAPHIR has wet bias at all the five levels over South/North America and South Pacific regions. However, the results showed dry bias at all the levels except 2nd and 3rd levels, where it showed wet bias, over East Asia. In a nutshell, the results indicated that SAPHIR has wet bias over dry regions and dry bias over wet regions. The important outcome of the present study is the quantitative validation of the SAPHIR humidity observations using both space and ground based measurements. The present results are very encouraging and envisage the great potential of SAPHIR observations for meteorological applications especially in understanding the hydrological cycle at shorter temporal and spatial scales in the Tropics.

1 Introduction

The atmospheric water vapor plays a vital role in wide range of atmospheric processes, such as earth's radiation budget, atmospheric convection, hydrological cycle, solar tide generations and global warming to name a few. The modification of thermal structure of the lower atmosphere by water vapour through radiative and latent heating processes is of surmount importance to the atmospheric community. An accurate knowledge of vertical/horizontal distribution and short/long-term variability of water vapor is an essential component for climate change assessment and weather prediction and therefore its accurate measurement is vital in routine meteorological observations (Held and Soden, 2000; Hartmann, 2002; Sohn and Schmetz, 2004; Zveryaev and Allan, 2005). Most of our understanding of water vapour distribution in the lower atmosphere so far, came

from in situ radiosonde observations, which are limited in both space and time. Now, it is well established that the water vapour vary largely at various spatio-temporal scales and hence it becomes important to have space based measurements.

Space based water vapour observations have been available for more than four decades, beginning with the launch of Nimbus 3 satellite in 1969 (Wick, 1971). The estimation of the upper tropospheric humidity in ∼ 500–200 hpa layer using clear-sky radiances of water vapour channel (6–7 µm) on-board geostationary satellite provided much needed information on high temporal and spatial resolution free tropospheric humidity. Now, there are adequate number of geostationary satellites providing operational product of upper tropospheric humidity over the globe (e.g., METEOSAT7 and Kalpana). However, the vertical resolution of the humidity provided by these instruments was very coarse. The radio occultation based CHAMP (CHAllenging Minisatellite Payload) was launched in the year 2000, which provided high vertical resolution water vapour measurements using the refractivity measurements. However spatial resolution of these measurements were coarse as the measurements were possible only when CHAMP could see the GPS satellite occulted by the Earth's atmosphere. However, after the launch of CHAMP, subsequently few more satellites carrying GPS receivers were launched for water vapour measurements thus improving the spatial resolution marginally. The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) was launched in 2006 with six microsatellites into a circular, 72° inclination orbit at an altitude of 512 km (Cheng et al., 2006). One of the disadvantages of COSMIC is the less number of observations over Tropics as compared to mid-latitudes. Owing to demand on high spatial resolution humidity observations, Atmospheric Infrared Sounder (AIRS) aboard Aqua mission was launched in 2002, which provide twice daily atmospheric profiles over the most parts of the globe (Aumann et al., 2003). AIRS is a high-spectral resolution infrared sounder instruments for measuring the atmospheric water vapour. The IR spectral channels used in AIRS are in the range of 3.74 to 15.4 µm with an accuracy of 3 %. At nadir, the spatial resolution of the IR channels is 13.5 km from the orbital altitude of 705 km. Thus there are sufficient numbers of

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space based instruments providing humidity measurements over the globe. However, the existing humidity soundings per day from satellites are in-adequate to study the hydrological cycle of the earth's atmosphere at shorter spatial and temporal scales, especially over Tropics. But with the launch of Megha-Tropiques (MT) satellite dedicated to tropical belt, more frequent humidity observations are now possible over tropical region.

MT is an Indo-French satellite, launched in October 2011 to explore the energy budget and water cycle within the tropical belt (Aires et al., 2012). Owing to its low inclination of 20°, MT allows frequent observations of the atmospheric water cycle and thus to study the life cycle of tropical mesoscale convective systems. MT can revisit at least 3 times per day over the areas located in latitudes up to 25° (Karouche et al., 2012). MT satellite carries four instruments viz., (1) MADRAS (Microwave Analysis and Detection of Rain and Atmosphere System) is a conical scanning microwave imager designed to estimate precipitations and cloud properties (2) SCARAB (Scanner for Radiation Budget) is a wide band optical radiometer used to retrieve the Earth's Radiation budget parameters (3) GPS-ROS (Radio Occultation Sounder) sensor for temperature and humidity profiles of the Earth's atmosphere and (4) SAPHIR (Sondeur Atmospherique du Profil d' Humidité Intropicale par Radiométrie) is a microwave radiometer sensor used to retrieve vertical humidity profiles at six pre-determined pressure levels. Details of MT mission can be found in Karouche et al. (2012). The present study focus on the SAPHIR observations of humidity profiles. By providing 3–6 times daily humidity profiles over tropics, the SAPHIR observations are expected to provide significant improvements in numerical weather prediction and studying the role of the space-time distribution of humidity on the development of deep convection. However, a reliable validation of SAPHIR humidity observations is necessary before going to use them in operational numerical weather prediction models. The central objective of the present study is to validate the SAPHIR humidity observations using space based AIRS and ground based radiosonde observations quantitatively. Section 2 describes the data and

methodology, results are discussed in Sects. 3 and 4 provides the summary and concluding remarks.

2 Data and methodology

Humidity profiles from SAPHIR, AIRS and radiosonde are used for the presented study. The humidity measurements from these three completely independent observing systems are based on distinct measurement principles, retrieval methods and sampling procedures. In this section, the most relevant features of these instruments are briefly described.

2.1 Megha-Tropiques/SAPHIR

MT satellite with four scientific pay loads was launched in the month of October 2011. Among these four pay-loads, SAPHIR instrument observes the tropospheric relative humidity using six microwave channels in the strong water vapor absorption band near 183.31 GHz (ranging from ±0.2 to ±11 GHz). These six frequency bands have been selected to obtain a maximal sensitivity to humidity at different heights from the Earth surface up to ~ 12 km in the atmosphere. SAPHIR thus provides the humidity measurements at the six pressure levels corresponding to 1000–850 hPa, 850–700 hPa, 700–550 hPa, 550–400 hPa, 400–250 hPa and 250–100 hPa. The frequency and bandwidth of each channel are given in Table 1 along with the sensitivity of the each channel as measured at ground and in flight. From this table it is evident that the SAPHIR sensitivities are slightly better in flight mode as compared to that measured at ground. The channel 6, which provides humidity observations at the lowest levels, has sensitivity deep into the atmosphere as evident from relatively large bandwidth. The noise temperature of 1 K corresponds to ~ 10 % uncertainty in the humidity measurement (Eymard et al., 2001). A footprint of SAPHIR at nadir is 10 km and its swath is ~ 1705 km. SAPHIR has a cross-track viewing geometry, with 130 pixels per scan line from nadir to ±42.96°. The footprint shape becomes elliptic when it is far from nadir due to the increased incidence angle. This means that the pixel size of 10 km at nadir increases with the scanning angle. The extreme foot print size is 21.96 km × 14.29 km. The calibration is carried out for every scan using sky as cold target and a heat source deployed on-board as hot target. As mentioned in the introduction section, the MT's tropical orbit has an important advantage allowing one to have 3 to 6 observations per day over a given geographical location between 23° S and 23° N (Karouche et al., 2012).

The retrieval of humidity from SAPHIR observed microwave radiance uses a water vapor content dependent statistical relationship utilizing radiation data as predictor known as water-vapor-dependent algorithm. This algorithm uses following relation for layer averaged relative humidity (LARH) retrieval,

$$\ln(\mathrm{LARH}_p) = A_{0,p,\delta\mathrm{w}} + \Sigma A_{i,p,\delta\mathrm{w}} \mathrm{TB}_i$$

where δw is small range of water vapor content, $A_{0,p,\delta\mathrm{w}}$ is the retrieval constant for the pth pressure layer, $A_{i,p,\delta\mathrm{w}}$ is the retrieval coefficient for the ith channel and the pth layer and TB_i is the brightness temperature of the ith sounding channel. This algorithm is expected to improve the humidity retrievals through indirectly restricting the dynamic variability of the measurements. Full details about SAPHIR retrieval algorithm and its theoretical assessment can be found in Gohil et al. (2012). For the present study, we use three months of SAPHIR's Level 2A humidity profile data during June-July-August 2012.

2.2 AIRS

To validate the SPAHIR observations quantitatively, we use AIRS version 5 Level 2 humidity data which are available from the Goddard Earth Sciences Distributed Archive Center (http://disc.sci.gsfc.nasa.gov/data/dataset/AIRS/). A detailed description of the AIRS retrieval method was reported by Susskind et al. (2003, 2006). Although AIRS makes measurements in 2378 spectral channels, significantly fewer channels are used in the AIRS physical retrieval. Susskind et al. (2006) indicates that 58 channels are

used for the temperature profile retrieval, 49 channels for water vapor, and 26 channels for ozone. AIRS has infrared footprints approximately 13.5 km in diameter at nadir and utilizes cross track scanning to collect 90 cross track footprints every 2.667 s with a swath width of 1650 km (Aumann et al., 2003). There were many efforts to validate the AIRS products. Divakarla et al. (2006) evaluated the temperature and moisture profiles retrieved from AIRS instrument with collocated radiosonde measurements and found that for clear-only cases over "sea" and "all" categories, accuracies are 1° K in 1 km layers for the temperature and better than 15 % in 2 km layers for the water vapour in the troposphere. In a recent study, Jiang et al., (2012) reported that the useful altitude range of AIRS measurements, which is 1000 hPa to 300 hPa over ocean and 850 hPa to 300 hPa over land. These authors also reported the estimated uncertainty to be 25 % in the tropics, 30 % at midlatitudes and 50 % at high latitudes. However, AIRS has its own limitations in retrieving the water vapour over the cloudy regions. Keeping these limitations in view, we use radiosonde observations also for quantitatively assessing the SAPHIR observations.

2.3 Radiosonde observations (RAOB)

The in-situ humidity measurements from radiosonde ascents are often taken as ground truth to validate satellite based humidity measurements. In the past, satellite-based humidity retrievals were validated using spatially and temporally collocated radiosonde measurements over the regions of interest (Birkenheuer and Gutman, 2005; Divakarla et al., 2006; McMillin et al., 2005). The radiosonde routinely measures the height profiles of temperature, humidity, and pressure from surface to heights up to about 30 km. The radiosonde employs two widely used humidity sensors viz., carbon hygristors and planar thin-film capacitance sensors, which provide the humidity measurements with an accuracy of ±5 % as per WMO standards (WMO Guide, 1996). There are routine intercomparison campaigns to evaluate the various radiosonde performances from time to time by WMO (Schmidlin, 1998; Sapucci et al., 2005). Miloshevich et al. (2006) carried out detailed estimates of radiosonde water vapour measurement accuracy for six operational radiosonde, viz., Vaisala RS80-H, RS90, and RS92; Modem GL98; Sippican Mark IIa; and the Snow White chilled mirror hygrometer. Presently, the ground based radiosonde observations are one of the best possible way for assessing the accuracies of space based water vapour measurements. RAOB are typically made once or twice daily from a large number of sites worldwide and are often collocated with other measurements to provide a more complete specification of the atmospheric state. For the present validation study, we used measurements from 140 RAOB stations spread over East Asian region, tropical belt of South and North America, Parts of North Africa (very limited) and South Pacific during July-August-September 2012. These RAOB measurements are extensively used for quantifying the SAPHIR's measurement accuracy.

2.4 Methodology

As mentioned earlier, we use the AIRS measurements of humidity profiles to quantitatively validate the SAPHIR measurements. The Sun synchronous Aqua satellite with its ascending and descending orbits crossing the equator at 13:30 and 01:30 LT respectively coupled with collocation criteria of ±10 min coincides with considerable number of SAPHIR measurements. As the spatial resolutions of AIRS and SAPHIR measurements are different, the latter's resolution is reduced to match the former's spatial resolution such that both measurements can be compared. Figure 1a shows the partly overlapped swaths of AIRS and SAPHIR, which provides an idea of relative density of measurements from both the instruments. Figure 1b shows the zoomed version of Fig. 1a highlighting the measurements within $2^{\circ} \times 2^{\circ}$ grids. For the final regression analysis, we collocated the AIRS and SAPHIR observations in $1^{\circ} \times 1^{\circ}$ grids over selected geographical locations shown in Fig. 2. We chose AIRS observations over the Pacific Ocean (125–180° W; 30° S–30° N) and North African regions (10° W–30° E; 8° N–30° N) for validating the SAPHIR observations over Ocenic and land regions respectively. The red shaded regions in Fig. 2 correspond to the AIRS observations used for the SAPHIR validation. After carrying out the comparison between SAPHIR and AIRS, the

ground based global radiosonde network observations of humidity profiles are then used to further validate the SAPHIR observations as AIRS being an infrared sounder has its own limitations. A criterion is worked out to collocate the humidity observations of SAPHIR and radiosonde. The SAPHIR observations within the 50 km radius around the radiosonde station and within ±1 h of radiosonde observation time are considered for the comparison. The yellow crosses in Fig. 2 correspond to ground based radiosonde observations used for the SAPHIR validation. After collocating the humidity profiles, regression and other statistical analysis are carried out at each pressure levels of SAPHIR to quantify their accuracies.

3 Results and discussion

Figure 3 shows a typical SAPHIR's observation of spatial structure of humidity at level 3 on 12 July 2012 at 08:00 UTC over the Indian Ocean. The white patches within the humidity map correspond to data where retrieval could not be done. The high spatial resolution humidity map shown in this figure has many applications in understanding the role of water vapour in controlling the tropical atmosphere. However, it is essential to validate the SAPHIR observations of humidity before it can be used for any meteorological applications. In this regard, the SAPHIR humidity maps at various pressure levels are compared with those obtained by AIRS to verify whether the former produces the broad features observed by the later. As the AIRS observations were validated extensively by various researchers, we use the same for validating SAPHIR observations. Figure 4a and c show the horizontal distribution of humidity as observed by SAPHIR at 700–550 and 550–400 hPa levels respectively on 9 December 2011 and Fig. 4b and d show the same but observed by AIRS at 700 and 500 hPa respectively. The spatial resolution of SAPHIR is brought down to AIRS resolution such that both can be compared. Also, the pressure levels at which measurements were done differ in the SAPHIR and AIRS observations as mentioned in the Fig. 4. Qualitatively, the spatial patterns of humidity observed by SAPHIR and AIRS show a good agreement. Especially, the

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humidity maps of SAPHIR at 550–400 hPa very well reproduce the AIRS observations of high humidity along the Indonesian coast. Most of the features observed by AIRS are reproduced by the SAPHIR observations. This is confirmed by comparing many coincident measurements of SAPHIR and AIRS (figures not shown). However, quantitatively, AIRS measured humidity slightly differs with the SAPHIR observations. From Fig. 4a and b, it is evident that the SAPHIR observations overestimate the AIRS observations whereas from Fig. 4c and d, it can be noted that both the measurements agrees very well. The differences in humidity measurements by both the pay-loads in part can be attributed to the different retrieval techniques. Moreover, SAPHIR is a microwave radiometer and AIRS is an infrared sounder and both are having their own limitations. Infrared sounding measurements are limited to cloud-free region and SAPHIR being a microwave radiometer can measures in the cloud region also. Keeping these limitations in view, we can ascertain that both the SAPHIR and AIRS humidity maps agree qualitatively. In an attempt to quantitatively assess the SAPHIR measurements, we have carried out regression analysis between the two measurements over land and oceanic regions separately.

Figure 5a–f show the regression analysis of humidity observations by AIRS and SAPHIR at six levels over oceanic regions shown in Fig. 2. We used only those AIRS retrievals that are flagged as totally cloud free. From this regression analysis, it can be noted that over oceanic regions the SPAHIR measurements agrees very well at the levels 3, 4, 5 and 6 with correlation coefficients 0.79, 0.88, 0.87 and 0.78 respectively. However, at the level 6 SAPHIR seems to be systematically underestimating the AIRS measurements. At the level 2, the agreement is reasonably good with correlation coefficient of 0.52 and at the level 1 the agreement is very poor with correlation coefficient 0.17. At the level 1, even though the AIRS humidity measurements are varying from 40–100 %, the SAPHIR measurements are confined to 70–100 %. From the Table 1, it can be noted that the channel 6, which corresponds to the level 1, has sufficient sensitivity deep into the atmosphere. There seems to be overestimation of AIRS measurements by SAPHIR at the level1. At the level 2, scatter of measurements seems to

be symmetric about the 1 : 1 line. However, there seems to be slight overestimation by SAPHIR. At the level 3, it is very clear that SAPHIR overestimates the AIRS measurements. At this level one can note the wild points in the 60–80 % and 20–40 % humidity range of SAPHIR and AIRS measurements respectively. Further analysis with respect to scanning angle may be required to comment on this. At the level 4, both the AIRS and SAPHIR measurements seems to be symmetrically distributed about the 1 : 1 line. As mentioned earlier, at level 5 and 6, SAPHIR underestimates the AIRS measurements. However, the useful altitude range of AIRS retrieval is 850–300 hpa over land and 1000–300 hpa over oceanic region (Jiang et al., 2012). So we should have more accurate measurements at level 6 to validate the SAPHIR observations.

Figure 6a–f show the regression analysis of SAPHIR and AIRS over land region (central African region shown in Fig. 2), which readily reveals an excellent correlation between AIRS and SAPHIR at all the six levels. The estimated correlations coefficients are 0.80, 0.79, 0.84, 0.84, 0.86, and 0.65 at the levels 1, 2, 3, 4, 5, and 6 respectively. Even though the correlation coefficient indicates a very good agreement at the level 6, SAPHIR seems to be underestimating the AIRS measurements as discussed earlier. It is surprising to note a very good correlation at level 1 over land region as compared to oceanic region. One should expect the opposite as land emissivity is complex to handle as compared to their oceanic counterpart. This aspect will be discussed further when SAPHIR measurements will be compared with global radiosonde network observations in the next section. At the levels 1, 2 and 3, SAPHIR seems to be over estimating the AIRS observations whereas at other three levels it is underestimating especially at the levels 5 and 6. The estimated mean biases between the AIRS and SAPHIR measurements along with standard deviations over both land and oceanic regions are provided in Table 2. At first three levels, both over land and ocean SAPHIR shows wet bias. At these levels, the SAPHIR shows relatively higher bias over land as compared ocean. At the first level, even though the correlation analysis shows better comparison over land, the mean bias at this level is relatively less over ocean. At the level 4, SAPHIR shows slight overestimation over ocean and underestimations over land. At the levels

5 and 6 SAPHIR underestimates the AIRS observations. Especially, at the sixth level the mean biases are relatively higher over both land and ocean compared to all other levels. Given the AIRS over all accuracy of 25 % over tropics, the SAPHIR observations especially at the levels 2, 3, 4 and 5 show very good agreement with the AIRS measurements over both ocean and land.

After carrying out the quantitative comparison between SAPHIR and AIRS, the ground based global radiosonde network (shown in Fig. 2) observations of humidity profiles are used to further validate the SAPHIR observations. There are enough number of coincident measurements of SAPHIR over these RAOB stations. As mentioned earlier, the SAPHIR observations with in the 50 km radius around the radiosonde station and within ±1 h of the radiosonde observation time are considered for the comparison. All individual collected profiles are grouped for carrying out the regression analysis. Figure 7a–d show the comparison of humidity profiles of SAPHIR (blue) along with standard deviations and radiosonde (red) observations over four randomly selected geographical locations. From this figure, it is clear that at the first three pressure levels, SAPHIR measurements compare very well with the radiosonde observations. The radiosonde observed humidity magnitudes are within the standard deviation of SAPHIR measured humidity magnitudes. However, there are notable differences in humidity magnitude at three higher levels in some cases. The differences are not consistent from one case to other. For example, the comparison shown in Fig. 7b exhibits a very good agreement between the two measurements at almost all the pressure levels except at the sixth level. The possible reasons for these observed discrepancies will be discussed after the regression analysis.

Figure 8a–e show the regression analysis of humidity measurements by SAPHIR and radiosonde at the first five pressure levels of SAPHIR respectively during entire period of July-August-September 2012 over the three geographical locations mentioned in Sect. 2.3. These three geographically distinct locations provided a range of humidity magnitude to test the SAPHIR performance. The measurements from each geographical location are shown in different colours. However, regression analysis is carried out

by considering all the measurements as a whole. As mentioned earlier, the radiosonde observations are averaged in the pressure layers identical to that of the SAPHIR measurements. We restricted the regression analysis to the first five levels of SAPHIR as most of the humidity observations by hygristors used in radiosondes are valid up to a temperature of 210–230 K, which corresponds to ∼ 11–13 km in tropics (WMO, 2006). The sixth level of SAPHIR roughly corresponds to 14–16 km and hence one should have other means of measuring humidity in this altitude region other than radiosonde to quantify the SAPHIR accuracies. The number of data points used for the correlation analysis along with the correlation coefficients are provided in the Fig. 8. All the correlations coefficients given in the figure are significant at 95 % confidence level. From this figure, it is evident that both the measurements agree very well at all the five levels with correlation coefficients 0.65, 0.72, 0.84, 0.88 and 0.78 respectively. However, at the level 1 it can be noticed that SAPHIR has wet bias at low humidity magnitudes and dry bias at relatively higher humidity magnitudes. At the levels 2 and 3 also one can notice the wet bias of the SAPHIR measurements. At these levels the humidity magnitudes are relatively high over East Asian region, which was under the influence of monsoon, as compared to other locations. At the level 4, the scatter is symmetric around the 1 : 1 line depicting very good correlation at all the three geographical locations. At the level 5, the SAPHIR measurements over South Pacific and tropical belt of North/South America compares very well with radiosonde measurements. However, over East Asian region, where humidity magnitudes are relatively high, the SAPHIR measurements have dry bias. Thus at all the levels SAPHIR has dry bias at relatively higher humidity magnitude, which evident from the Fig. 8. So, from the present regression analysis it can be mentioned that the SAPHIR observations agrees well with the ground based observations. Keeping in view, the retrieval techniques and observational volumes and time of observations of SAPHIR and radiosonde, the comparison can be treated as very good. This comparison thus provides much needed validation of the SAPHIR observations of humidity profiles and instil the confidence in SAPHIR data products.

The relatively poor correlation observed at the first level over East Asian region (refer to Fig. 8a) is further investigated. The relative difference between SAPHIR and radiosonde at the first level for each observation is calculated and the same is used to verify whether there is any systematic over/underestimation of radiosonde observations by SAPHIR. Figure 9 shows the relative difference of SAPHIR and radiosonde observations at the first level as a function of the radiosonde humidity measurements. It is very interesting to note that SAPHIR systematically over estimates the radiosonde measured humidity magnitudes in the 40–60 % range and underestimates the humidity magnitudes in the 80–100 % range. The differences between SAPHIR and radiosonde vary linearly with reference humidity magnitudes. At the first level, as it evident from Fig. 8a, the radiosonde observed humidity magnitudes over East Asian region are mostly populated in 85–100 % range and SAPHIR underestimates these measurements and hence a poor correlation is observed at this level. Same is the case at the first level over oceanic region shown in Fig. 5a, which shows high humidity magnitudes. However, further investigations at retrieval level are needed to arrive at any general conclusion on SAPHIR measurements over humid regions. From Fig. 9, it is clear that SAPHIR has wet bias at low humidity magnitudes and dry bias at high humidity magnitudes in the 1000–850 hPa pressure level. We have examined the same at other levels also, which have confirmed this assertion. However, the humidity magnitude at which wet bias changes into dry bias varied from one level to the other (at the level 1 the wet bias changes to dry bias around humidity magnitude of 60 % as shown in Fig. 9). From the present analysis, it is evident that the bias varies linearly with the reference humidity magnitudes, which instil some optimism to minimize the observed biases by incorporating the corrections in the retrieval algorithms. However, these corrections should be generalized before being incorporated in the retrieval algorithm.

To further quantify the relative difference between the two measurements, we have constructed the contour-frequency by altitude diagram (CFAD) using the relative bias between each coincident observation of SAPHIR and radiosonde and the same is shown in Fig. 10a–c over the three study regions respectively. The relative differences

are grouped in the range of −80 to 80 % with an increment of 10. At each pressure level, the histogram of relative difference is made and presented in the form of CFAD. From Fig. 10a, it can be noted that at the first level over East Asian region, the majority of relative differences appear in −10 to −20 % interval indicating a dry bias of SAPHIR at this level. At the levels 2 and3 the wet bias of SAPHIR is evident. However, the relative difference at the 4 and 5th levels are distributed in a wide range with more spread towards dry bias over this region. The CFAD depicted in Fig. 10b and c corresponding to South Pacific and South/North American region respectively shows similar features with wet bias at all the levels. One contrasting observation from Fig. 10a–c is the relative widening of the CFAD at the higher pressure levels and narrowing at the lower levels over East Asian region and the exact opposite feature over the other two regions i.e., narrowing of CFAD at higher levels and widening at lower levels. Thus it seems that the SAPHIR measurements accuracies vary depending on the range of humidity magnitudes observed at a given level.

In order to find the mean bias between the two measurements, the individual relative difference at each level are averaged and is shown in Fig. 10d along with standard errors over the three study regions. This height profile clearly demonstrates that except at the levels 2 and 3 the SAPHIR measurements have dry bias over the East Asian region. As mentioned earlier, during the study period this region was under the influence of monsoon and the lowest level had the high humidity. From Fig. 9, it is evident that SAPHIR underestimates the high humidity magnitudes at the level 1 and hence the dry bias. Over the other two study regions, the mean bias indicates the wet bias at all the levels. The bias is relatively high at the levels 2 and 3 as compared to other three levels over both the regions. The observed differences in SAPHIR mean bias from radiosonde observations from one region to other can be attributed to the range of humidity magnitude present over the given region. The SAPHIR observations over humid regions show dry bias whereas over dry regions it shows wet bias. Thus the present study evaluated the SAPHIR humidity observations at the six pressure levels using AIRS and radiosonde observations and quantified its performance in terms of correlation coefficients and mean biases. The present results show a very good agreement between SAPHIR and radiosonde measurements at the first five levels thus validating SAPHIR measurements.

4 Summary and concluding remarks

The humidity observations of SAPHIR payload on board Megha-Tropiques are evaluated using space based AIRS hyperspectral sounder and ground based radiosonde observations. The AIRS observed horizontal distribution maps of humidity are used to validate the SAPHIR observed humidity maps at various pressure levels. The spatial resolution of SAPHIR humidity observations is reduced to match the AIRS spatial resolution. The comparison of these humidity maps showed reasonably good agreement qualitatively. SAPHIR could reproduce many of the AIRS observed features in humidity structures. Further, regression analysis has been carried out between the SAPHIR and AIRS measurements separately over ocean and land region. Over oceanic regions, very good correlation was found at all the pressure level except at the first level. However, at the sixth level SAPHIR heavily underestimated the AIRS measurements. Over land region also the correlation was very good at all the six levels. Again at the sixth level SAPHIR underestimated the AIRS measurements. In contrast to oceanic region, the regression analysis at the level 1 showed relatively better correlation over land region. The mean biases between the SAPHIR and AIRS measurements over oceanic and land regions are quantified. Over oceanic region, SAPHIR showed wet bias at the first four levels and dry bias at next two levels. Over land region it showed wet bias at the first three levels and dry bias at next three levels.

To further assess the SAPHIR performance, the ground based radiosonde observations over the three distinct geographical locations (East Asia, tropical belt of North/South America and South Pacific regions), where considerable number of coincident measurements exist, are extensively used. The comparison of some typical humidity profiles showed very good agreement between the two measurements

especially in the lower troposphere. The regression analysis is carried out at the first five levels of SAPHIR to quantify the agreement in terms of correlation coefficients. The analysis showed very good agreement between the SAPHIR and radiosonde observations with correlation coefficients 0.65, 0.72, 0.84, 0.88 and 0.78 at the first five levels respectively. However, the analysis showed a poor correlation between the two measurements at the first level over East Asian region. The preliminary investigations revealed that at the first level, SAPHIR has wet bias at low humidity magnitudes and dry bias at high humidity magnitudes. Further, the relative differences between the individual coincident measurements are used to construct the CFAD, which showed the number of occurrences of particular relative difference between the two measurements at all the levels. The CFAD are constructed separately for each geographical location considered under the present study. The mean bias between the radiosonde and SAPHIR measurements are also estimated, which showed wet bias of SAPHIR at all the five levels over both South/North America and South Pacific regions. Over East Asia, SAPHIR showed dry bias at all the levels except at the 2nd and 3rd levels where it showed wet bias. The present study clearly demonstrated that the SAPHIR has wet bias at low humidity magnitudes and dry bias at high humidity magnitudes. It is also observed that the humidity magnitude at which wet bias switches over o dry bias changes from one level to the other. Thus the present study evaluated the SAPHIR humidity measurements using AIRS and radiosonde observations and showed that the SAPHIR observations are very promising and will have very good implications in understanding the hydrological cycle over the tropics. The future studies will be focusing on evaluating the SAPHIR measurements at the sixth level using MLS observations and diurnal variation of humidity over tropical region.

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Table 1. SAPHIR's channel specifications.

Channel	Central frequency (GHz)	Bandwidth (MHz)	Sensitivity of SAPHIR as measured at ground (in flight)
C1	183.31 ± 0.2	200	1.52 (1.44)
C2	183.31 ± 1.1	350	1.09 (1.05)
C3	183.31 ± 2.8	500	0.95 (0.91)
C4	183.31 ± 4.2	700	0.82 (0.77)
C5	183.31 ± 6.8	1200	0.66 (0.63)
C6	183.31 ± 11.0	2000	0.55 (0.54)

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Table 2. Mean Bias and standard deviation of SAPHIR measurements with respect to AIRS.

Level (mb)	Mean bias (SAPHIR-AIRS) and standard deviations	
	Over Land (%)	Over Ocean (%)
1000–850	13.42 (±12.12)	0.06 (±9.80)
850–700	14.80 (±11.56)	3.22 (±13.38)
700–550	12.27 (±10.69)	8.00 (±12.98)
550–400	−5.16 (±12.75)	0.25 (±8.98)
400–250	−13.09 (±12.09)	−2.24 (±9.45)
200–100	−22.54 (±12.72)	−16.44 (±9.80)

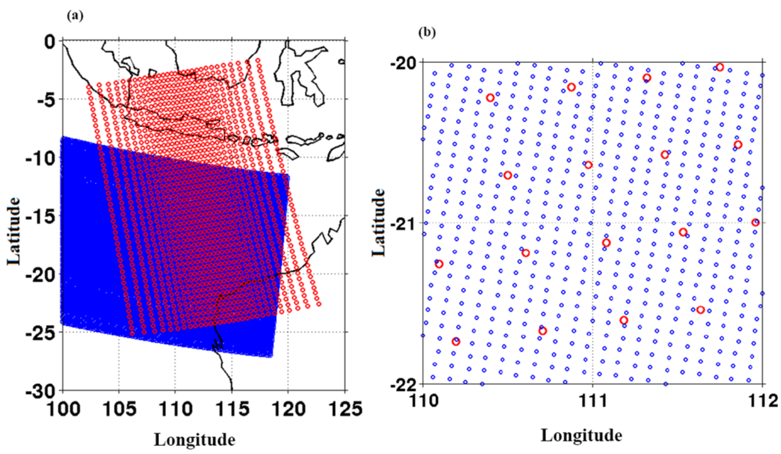

Fig. 1. (a) A typical swath of SAPHIR and AIRS overlapped partially as observed on 9 December 2011 **(b)** zoomed version of Fig. 1a highlighting the measurements within 2° × 2° (latitude × longitude) grids.

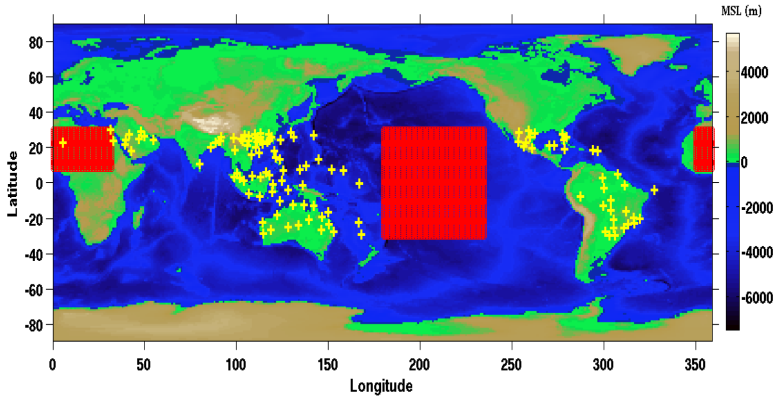

Fig. 2. Geographical map showing the SAPHIR, AIRS and radiosonde collocated measurements used for the present study (red shaded regions are collocated AIRS and SAPHIR observations and yellow crosses represents radiosonde stations).

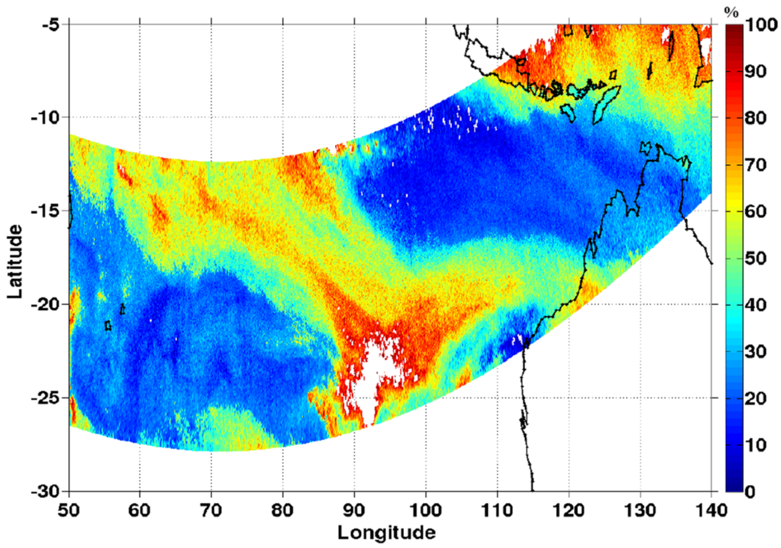

Fig. 3. SAPHIR observed horizontal distribution of humidity at level 3 on 12 July 2012 at 08:00 UTC over the Indian Ocean and surrounding regions.

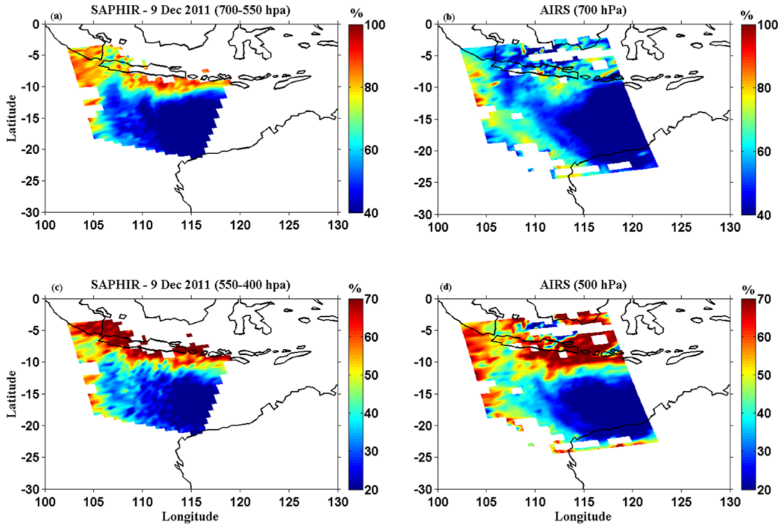

Fig. 4. The horizontal distribution of humidity as observed on 9 December 2011 by **(a)** SAPHIR at 700–550 hPa **(b)** AIRS at 700 hPa, **(c)** SAPHIR at 550–400 hPa and **(d)** AIRS at 500 hPa pressure level.

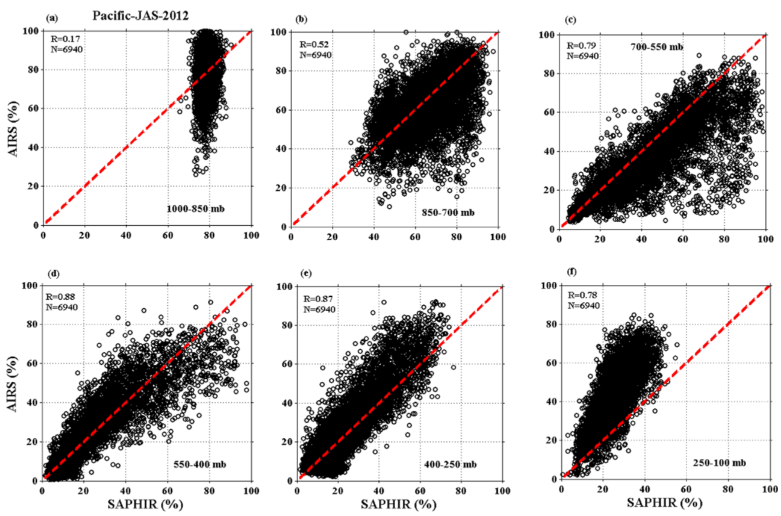

Fig. 5. Regression analysis between AIRS and SAPHIR at six pressure levels over oceanic region shown by red shaded areas in Fig. 2 during the period July-August-September 2012. The number of measurements used for the analysis and correlation coefficient is provided in the each subplot.

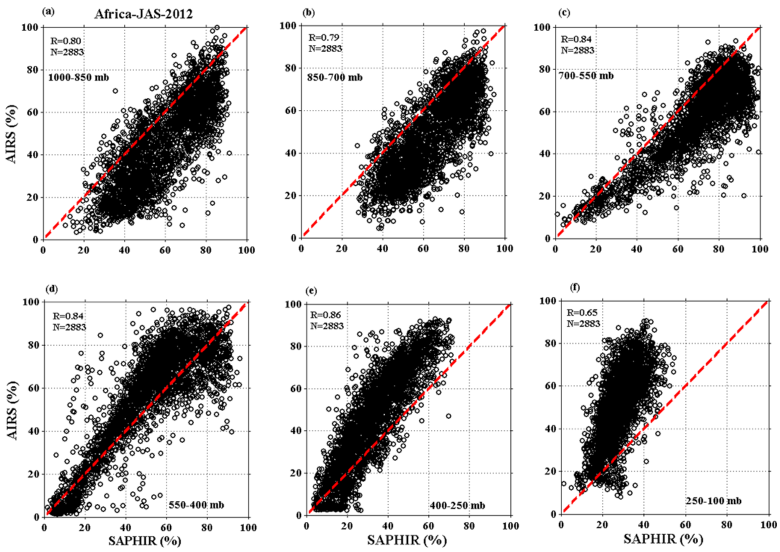

Fig. 6. Same as Fig. 5 but over land region.

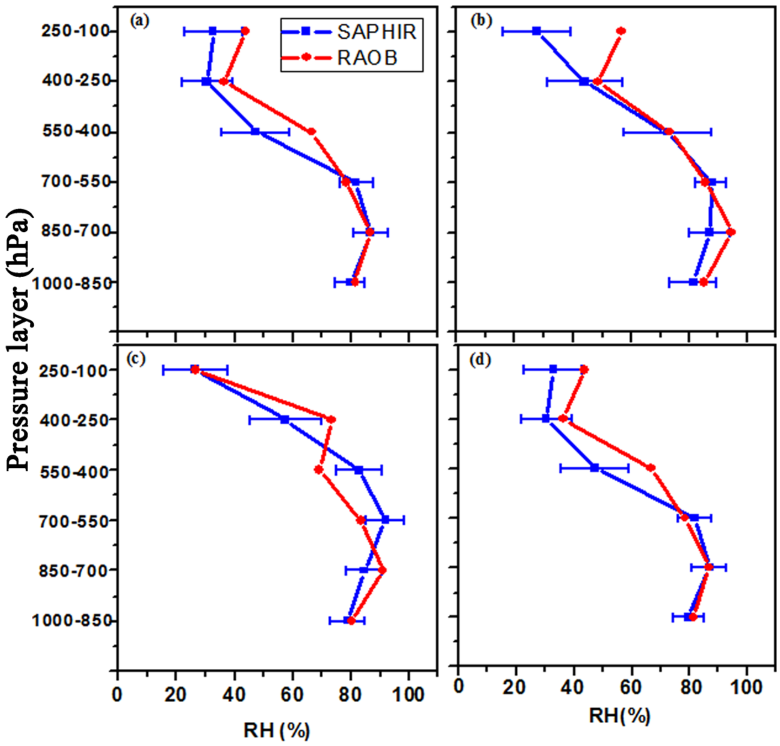

Fig. 7. (a–d): Randomly chosen height profiles of humidity measured by SAPHIR (blue) along with standard deviations and radiosonde (red).

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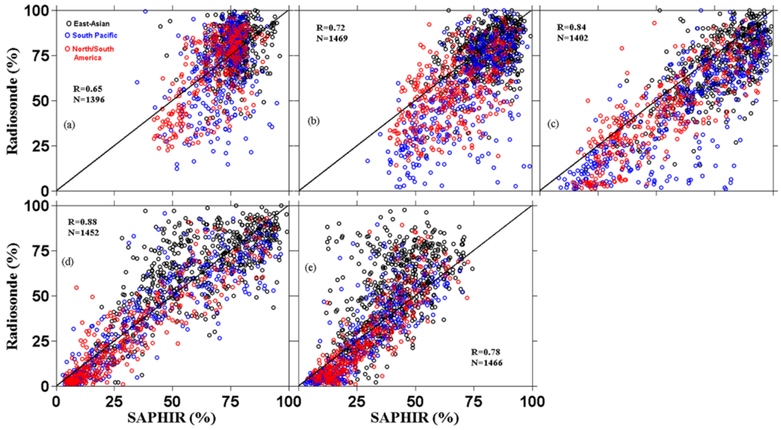

Fig. 8. Regression analysis of SAPHIR and global radiosonde humidity measurements over three geographical locations at five pressure levels during the period July-August-September 2012. The number of measurements used for the analysis and correlation coefficient is provided in the each subplot.

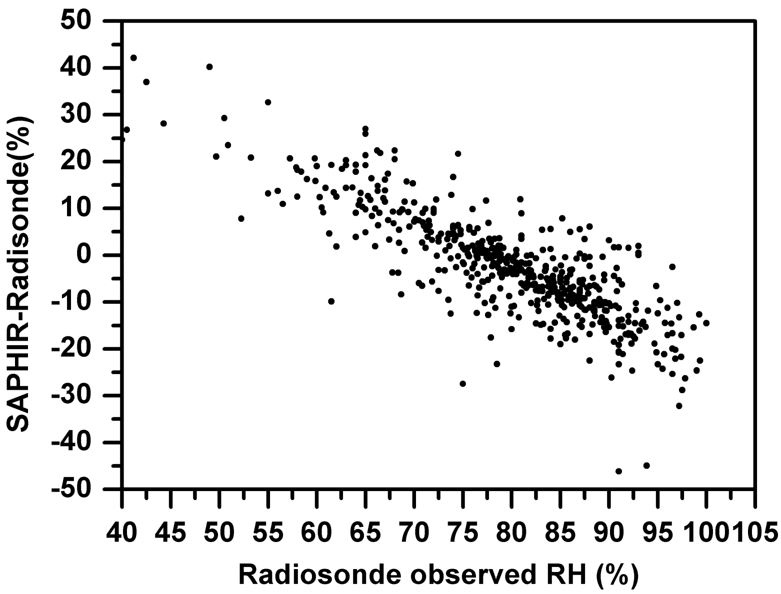

Fig. 9. Scatter plot of relative difference between SAPHIR and radiosonde observations as a function of radiosonde humidity observations.

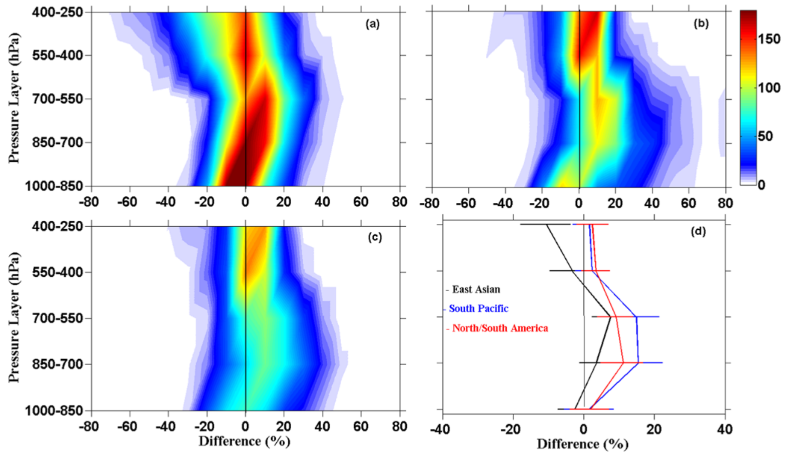

Fig. 10. Contoured-frequency altitude diagram of relative differences between SAPHIR and radiosonde observations over **(a)** East Asian region, **(b)** Tropical belt of South and North America and **(c)** South Pacific. **(d)** Height profiles of mean bias between SAPHIR and radiosonde observations along with standard errors over the three geographical locations as mentioned earlier.