Validation of humidity profiles obtained from SAPHIR, on-board Megha-Tropiques

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The Megha-Tropiques, an Indo French mission, with four on-board payloads was launched in October 2011 to improve our understanding on hydrological cycle and radiation budget. The SAPHIR (Sondeur Atmosphérique du Profil d'Humidité Intertropicale par Radiométrie), a sounder for profiling humidity, is a key payload and expected to play a major role in fulfilling the mission objectives. The present article focuses on the evaluation of SAPHIR-derived humidity profiles against a variety of reference datasets, like measurements from GPS radiosondes and ground-based microwave radiometer, reanalysis datasets and satellite retrievals. The data collected during July–November 2012 were employed to validate humidity profiles. A variety of colocations (matching the sampling volumes of radiosonde and SAPHIR) were employed for the validation against radiosondes, launched from Gadanki. The bias (SAPHIR-derived RH – reference RH) and the rms error are found to be small for near-nadir measurements than those far away from the nadir. Further, the bias shows a clear height dependence with positive (negative) bias dominating in the lowest (uppermost) layers. The RH bias and rms errors are small (within 15%) in the middle layers, altitudes at which the sensitivity of SAPHIR channels is high. The comparisons with ECMWF interim reanalysis (ERA) and advanced infrared sounder (AIRS) data, used to extend the evaluation of SAPHIR data to the entire tropics, reveal strikingly similar spatial and vertical structure in RH bias. The vertical structure of RH bias is somewhat similar to that obtained with the radiosonde. Large biases are seen in regions adjacent to South America and Africa in the latitude band of 20°–30°S and large negative bias is seen along the Intertropical Convergence Zone. Possible reasons for such large biases in those regions are discussed.

Keywords: Humidity profiles, radiosonde, RH bias, rms error.

Introduction

ATMOSPHERIC water vapour plays a vital role in the hydrological cycle, radiation budget and Earth's climate system with puzzling feedback loops, although recent studies found observational evidence supporting its positive feedback that climate models have been projecting for quite some time, i.e. the increase in atmospheric humidity amplifies the warming from carbon dioxide[1]. Further, the latent heat release due to condensation of water vapour is the primary driving source for several tropical circulations. The atmospheric water vapour profiles are being used extensively by researchers and operational forecasters to improve weather forecasts. Atmospheric water vapour is the most abundant greenhouse gas, however its variability with space and time complicates its quantification. Although the ground-based instruments do provide reliable measurements of water vapour, they are limited to the observational site. Recent advances in microwave remote sensing for humidity, on the other hand, offer height-resolved global-scale measurements of atmospheric water vapour with reasonable accuracy. The advantage of microwave sounders over traditional infrared sounders is their ability to provide humidity profiles even in the presence of optically thin clouds.

One such microwave sounder, SAPHIR (Sondeur Atmosphérique du Profil d'Humidité Intertropicale par Radiométrie), on-board the Megha Tropiques, an Indo-French mission, was launched in October 2011 with a prime focus on improving the hydrological cycle and Earth's radiation budget[2]. The main advantages of SAPHIR over other microwave humidity sounders are its higher repetitive cycle in the tropics (because of low inclination) and the availability of six channels for water vapour profiling. However, SAPHIR products (particularly atmospheric humidity profiles) need to be validated systematically before researchers and operational forecasters use them for scientific explorations/weather forecasts. Like any other scientific mission, the calibration and validation campaign is an important and integral part of the Megha-Tropiques mission, because it gives credibility to the data. The procedure employed for the validation of satellite products looks simple, but in practice it is complex and challenging because of several issues, like proper matching of the reference and satellite measurements both in space and time, differences in the sampling volumes and their representativeness as measured by the reference and satellite sensors, etc.

Considering several aspects, like the availability of a suite of suitable instrumentation for humidity and rainfall

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measurements, relevant scientific potency and higher repetivity of measurements at ~13°–14°N, the National Atmospheric Research Laboratory (NARL), Gadanki (13.45°N, 79.18°E) was identified as a super validation site for evaluating the Megha-Tropiques products. The main objective of this article is to validate SAPHIR-derived atmospheric humidity profiles against a variety of collocated reference datasets available at Gadanki. The reference datasets for atmospheric humidity include measurements from radiosondes, a microwave radiometer, reanalysis datasets and measurements from other satellite humidity sounders. ECMWF interim reanalysis (hereafter ERA)[3] and Advanced Infrared Sounder/ Advanced Microwave Sounding Unit (AIRS/AMSU) suite on-board Aqua[4] data products were employed to extend the validation study to the entire tropics. However, more emphasis is laid on the validation results over Gadanki. Note that the relative humidity (RH) in some of the above reference datasets (like ERA and AIRS) is a derived product (not a direct measurement). However, RH in the above datasets is well validated with a variety of ground truths. Therefore, these datasets can serve as reference datasets for validation studies, particularly to study the spatial variability of RH biases over the entire globe.

Data and instrumentation

SAPHIR is a cross-track scanning passive radiometer with six channels near the absorption band of water vapour at 183.3 GHz (see Table 1 for the frequencies and bandwidths of all channels of SAPHIR). It has a swath width of ~1700 km and a footprint size of 10 km at nadir. The availability of more (six in case of SAPHIR) channels, in comparison with the three usual channels employed by other microwave sounders like AMSU-B, improves the retrieval of RH in the entire troposphere. Simulations studies show that the scatter in the correlation between simulated and reference (radiosonde in this case) RH values reduced considerably with an increase in the correlation coefficient, when six channels were used instead of three[5,6]. The SAPHIR provides layer-averaged RH values in six pressure layers (1000–850, 850–700, 700–550, 550–400, 400–250 and 250–100 hPa). The SAPHIR RH profiles (version 2) were obtained from MOSDAC website (www.mosdav.gov.in). The operational algorithm for the retrieval of RH is described in ref. 6. They developed an optimum relationship between the layer averaged RH and brightness temperatures using simulated atmospheric state variables and brightness temperatures obtained from a radiative transfer model. For the present validation study, RH profiles during 7 July 2012–25 November 2012 were employed. The above period is chosen for two reasons. (1) The SAPHIR RH profiles were available only from 7 July 2012. (2) The Meisei radiosonde data at Gadanki were available only up to 25 November 2012. As we wanted to perform the analysis with the same type of sonde (read Meisei), we restricted our analysis to the above period. For the sake of uniformity, other comparisons (with ERA and AIRS) were also confined to the above period. However, to check the consistency in the bias estimations, data collected during a different time-period (December 2012–January 2013) were employed.

Table 1. Specifications of SAPHIR microwave sounder

Channel no.	Centre frequency (GHz)	Max. Passband (MHz)	Polarization
1	183.31 ± 0.2	200	H
2	183.31 ± 1.1	350	H
3	183.31 ± 2.8	500	H
4	183.31 ± 4.2	700	H
5	183.31 ± 6.8	1200	H
6	183.31 ± 11.0	2000	H

NARL has two dedicated instruments for humidity profiling: Meisei GPS radiosonde (RS-06G) and a hyper spectral microwave radiometer (MP3000A by Radiometrics). NARL launches radiosondes regularly at ~12 UT (17 : 30 LT) to support its scientific activities. In addition, few radiosondes were launched to coincide (in time) with satellite overpass close to Gadanki. A total of 48 coincident (defined later in this section) sonde profiles were selected for comparison. The specified accuracy of radiosonde RH sensor is 2%; however, in reality it may increase due to several error sources such as time-lag error and radiation correction error[7–9]. Note that several improvements have been made to the Meisei RS-06G temperature and humidity sensors and packaging unit[10]. In spite of these improvements in sensors, a recent WMO campaign on inter-comparison of high-quality radiosonde systems revealed that the above sensors are still having significant bias in the upper troposphere and above[11]. This bias is found to be larger during daytime, indicating an insufficient treatment to radiation errors. The spatial resolution of Meisei radiosonde is quite high (1 Hz). These high-resolution measurements were averaged to match the resolution of SAPHIR. The radiosonde data corresponding to SAPHIR pressure layers (i.e. 1000–850, 850–700, etc.) were averaged with equal weightage to the data at all heights within each layer.

The reanalysis datasets ingest a variety of measurements in their model and are often being considered as equivalent to observations. The reanalysis datasets are, therefore, considered as reference datasets for satellite data validation[3,12]. Although the present study primarily uses ERA (available at a resolution of 0.75° × 0.75°) humidity product for validation, NCEP and MERRA reanalysis datasets, interpolated to Gadanki location, were also employed. The spatial resolutions of the above datasets vary from 1.25° × 1.25° (MERRA) to 2.5° × 2.5° (NCEP). The vertical resolution of the above datasets is also different, 27 (25) pressure levels between 1000 and 100 hPa for ERA (MERRA) and eight pressure levels for NCEP between 1000 and 300 hPa. Although these reanalysis datasets are available at six hourly intervals, only the data at two synoptic hours (00 and 12 UT) were employed here.

The microwave radiometer (MP 3000) used here has been in operation at NARL since May 2011. The radiometer at Gadanki has 31 calibrated channels (17 in the frequency range 22–30 GHz and 14 in 51–58 GHz band) for measuring brightness temperatures. The calibrated brightness temperature accuracy is ~ 0.2 K (ref. 13). It uses artificial neural network (ANN) (Stuttgart neural network simulator) to derive temperature and humidity profiles up to 10 km (7–8 km in the case of humidity) with reasonable accuracy. This instrument is capable of taking measurements in all directions (complete azimuth) and at different elevations. However, only three beam positions (zenith, north and south) are fixed for routine operations and the same are used in the present study.

The AIRS-derived RH provides another means of validating SAPHIR products. AIRS-RH was validated extensively against several reference datasets[4]. The AIRS instrument suite provides RH at standard pressure levels (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70 and 50 hPa). It offers RH profiles to an accuracy of 10% (~ 50%) in 2 km layers in the lower troposphere (upper troposphere)[14]. For the present study, humidity data of Level 2 standard products (version 5) were employed[14].

Ideally both reference sensor and SAPHIR should sample the same volume at the same time for better validation. Although such possibility exists, such stringent conditions reduce the data volume available for comparison. In the present study, we have considered satellite and reference profiles as coinciding, if the satellite data are available within 1 h from the reference measurement time (balloon launch time, synoptic hours for reanalysis data and AIRS overpass time). For spatial collocation, the SAPHIR data at pixels within ± 0.1° from the location of the layer averaged reference dataset were collected. Among these pixel data, the data corresponding to the pixel that is closest to the geographic location of the reference is used for the validation.

Results and discussion

Validation against different 'reference datasets' at Gadanki

In this section a variety of humidity measurements were used as reference to validate SAPHIR RH profiles at Gadanki. Figure 1 shows typical comparisons for two events (on 21 and 22 June 2012), where RH profiles derived from SAPHIR, radiosonde, radiometer and ERA, NCEP and MERRA reanalysis datasets were intercompared qualitatively at their original vertical resolution. Below 500 hPa, barring some heights, the agreement in RH as measured/estimated by different datasets is found to be reasonable with a difference < 20% between them. The agreement between the radiosonde-RH and SAPHIR-RH is good (within 20%) even above the 500 hPa level. However, the SAPHIR-derived RH deviates considerably from reanalysis datasets, particularly from ERA, above 500 hPa for the two events in Figure 1. To validate SAPHIR-RH quantitatively and to obtain robust bias estimates, data from several such collocations are congregated.

Validation against radiosonde at Gadanki

In spite of suffering with several, nevertheless, small and quantifiable error sources (see refs 7–9 for more details), the radiosonde still remains as one of the primary sources for obtaining vertical profiles of humidity. The major problem in utilizing the radiosonde for validating satellite products, such as RH by SAPHIR, is the mismatch in their sampling volumes. Further, the radiosonde drifts with horizontal wind by a few tens of kilometres (depending on wind speed) while ascending from the ground to 16 km. Therefore, earlier studies averaged the microwave sounder data over an area with a radius of 50 km centred on balloon launching location[15,16]. This approach is good when the atmosphere is homogeneous within 50 km. However, the standard deviation of brightness temperature within 50 km often exceeds 1 K and can be up to 4 K at times[15]. We, therefore, used pixel data for comparison.

Figure 2 shows a variety of colocations employed in the present study. It is known from earlier studies that the

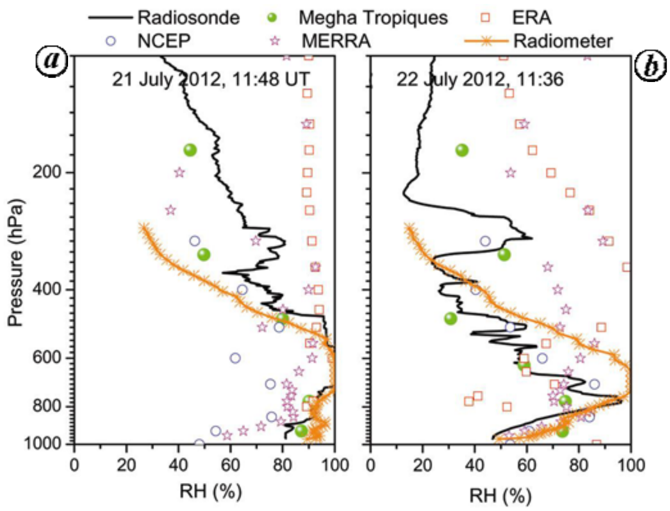

Figure 1. Comparison of SAPHIR (RH) against various ground truths (radiosonde – black solid line, radiometer – orange line with star, ERA – red square, NCEP – blue circle and MERRA – magenta star) at their original resolution over Gadanki on two typical days: (***a***) 21 July 2012 at 11 : 48 UT and (***b***) 22 July 2012 at 11 : 36 UT.

off-nadir retrievals of RH can have larger errors than the near nadir retrievals (so-called limb effect). This is mainly due to the increase in the foot print of the satellite pixel and longer path length travelled by the radiation at higher off-zenith angles. To examine the limb effect, the data are segregated into two categories based on whether the satellite overpass is close to the sampling volume or not. If the sampling volume is within 4° (or ~400 km; 4°–8° (or 400–800 km)) from the overpass, then that measurement is considered as close to (away from) the nadir. Also as mentioned above, the balloon at times drifts far away from Gadanki. In the presence of strong humidity gradients, it is more meaningful to match the satellite pixel in which balloon exists, rather than the pixel corresponding to balloon-launching station.

Figure 2 shows the box plot for RH bias values (SAPHIR retrieved RH – radiosonde measured RH) in different pressure layers for all combinations discussed above, i.e. Figure 2 *a*, the bias is estimated using RH data over Gadanki and Figure 2 *b*, the bias is estimated using RH data of pixel in which the drifted balloon exists. Further in both Figure 2 *a* and *b*, separate bias plots are shown for data close to the nadir (black) and away from the nadir (red). Clearly, irrespective of the collocation employed, it is found that the SAPHIR overestimates RH in the lowest layer with reference to radiosonde, whereas the agreement between them is reasonably good (within 15%) in the middle four layers. The bias in the uppermost layer is somewhat confusing and changes with the method of collocation, probably due to the small sample of measurements employed here and large uncertainty in radiosonde measurements in the upper troposphere (radiation correction, etc.). Although not statistically significant, the mean biases are smaller in most of the pressure layers (in both Figure 1 *a* and *b*) when estimated using close-to-nadir measurements than away-from-nadir measurements. It is much more clearly seen in the corresponding root-mean-square (rms) error plots (solid lines), where the rms errors are larger for close-to-nadir than away-from-nadir measurements. Except for the lowest layer, the rms errors are well within 20%, indicating the retrievals are better than the expected accuracy of the sensor.

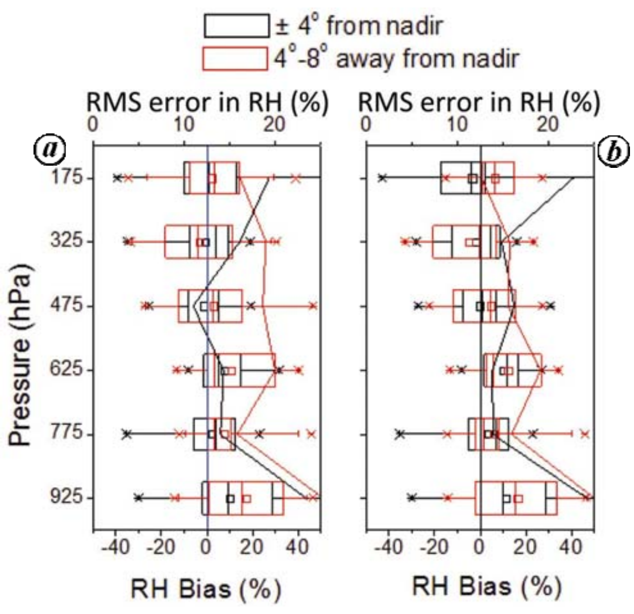

Figure 2. Box plots for the biases and rms errors (solid lines) estimated using different colocation methods by SAPHIR and radiosondes, launched from Gadanki: (***a***) when the bias is estimated using the data over Gadanki location and (***b***) when the bias is estimated using the data at the drifting balloon location. In both plots, the black box corresponds to the data within 4° from the nadir and red box corresponds to the data within 4°–8° from the nadir.

Validation against ERA

The spatial differences of the RH bias in six pressure layers, by taking ERA as reference dataset, are depicted in Figure 3. In general, the vertical variation of the bias is similar to that of the radiosonde in all regions, i.e. large and positive in the lowest two layers, large and negative in the uppermost layer and small in the middle three layers. The spatial variability of the bias is quite large, but the bias remained within 20% in most of the tropics, except for some regions in which it exceeds 40%. Large positive bias is seen over the oceans adjacent to large land mass (South America and Africa) in the southern hemisphere in the latitude band of 20°–30°. They are seen in the western flanks of those land regions. The reasons for the occurrence of such large biases in those regions are not immediately obvious. Several possibilities exist, from problems in the retrieval to geophysical reasons and to limb effect. These are basically dry regions in high-pressure zones and are in the descending branch of Hadley cell. In the absence of large-scale ascent, the humidity is usually confined to the lowest part of the atmosphere. The atmosphere above this narrow, moist layer is generally dry. The occurrence of deep convective clouds is rare and low-level marine stratus clouds persist most of the time in these regions, for the reasons stated above. It is known from earlier studies that the microwave retrievals of RH suffer, particularly in the lowest layers, in regions that are dry and have large vertical gradients of RH. It is, therefore, important to understand the performance of the algorithm in those regions, whether it introduces a wet bias or a dry bias? Even if we assume any or all of the above factors, i.e. dry atmosphere, large gradients in RH, presence of low-level clouds, etc. do play a role in biasing the profile, then SAPHIR-derived RH should be underestimated, because the channels used in SAPHIR are weighted more in the middle and upper troposphere. The comparisons in Figure 3, however, show exactly the opposite feature, i.e. exhibiting large positive biases (SAPHIR overestimates RH) in the lowest two layers.

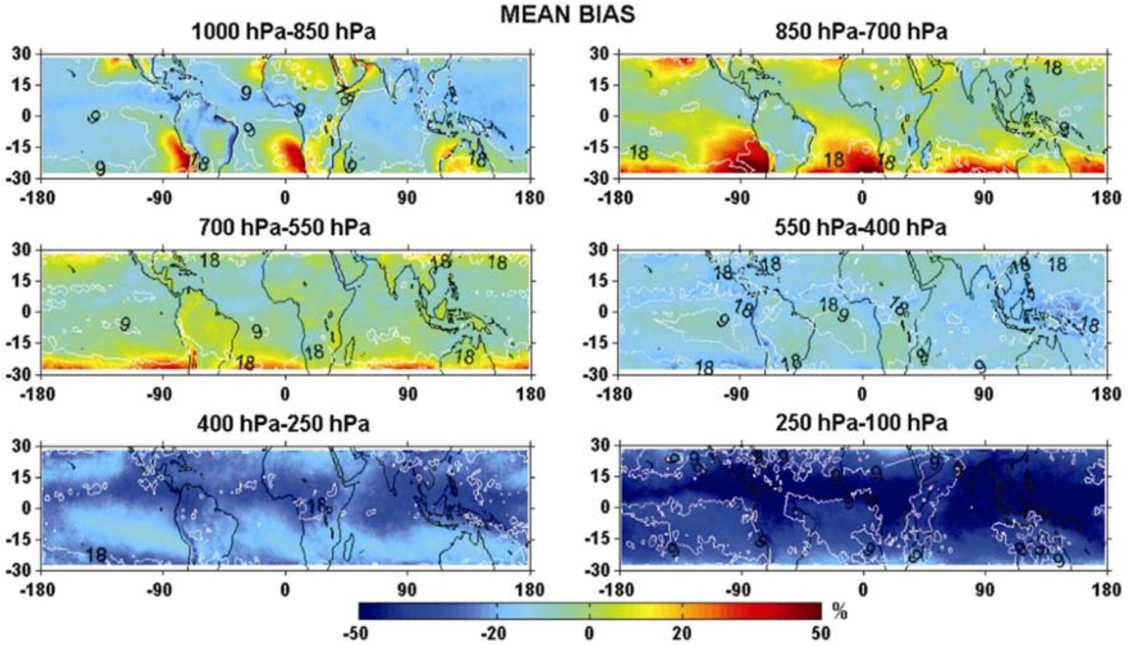

Figure 3. Spatial and vertical distribution of mean RH bias (SAPHIR RH – ERA RH) estimated by considering the ERA data as ground truth.

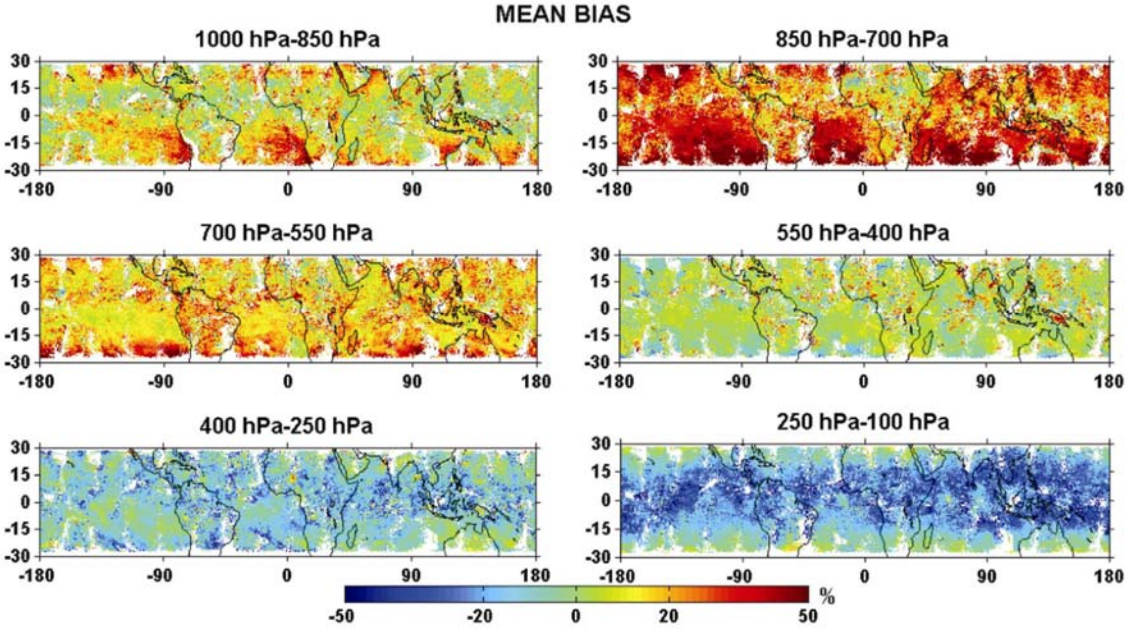

Figure 4. Same as Figure 3, but for AIRS data as ground truth.

Further, the positive bias is much larger in magnitude and spread in the second layer than in the first layer. This needs to be further investigated, as we do not find any conclusive support to any of the above hypotheses. The other possibility is the limb effect as these large biases are seen in latitude bands between 20° and 30°. But the large bias is not seen in that entire band rather observed over oceans adjacent to the large land masses and also the biases are not that large in the same latitude belt in the northern hemisphere. It is therefore clear from the above discussion that the limb effect might be playing a role, but is certainly not the sole reason for the observed large bias.

In contrast to the large positive biases discussed above, there are regions with large negative bias (i.e. SAPHIR underestimates the RH relative to ERA) and the magnitude of bias increases with altitude. These regions are observed in the wettest parts in the Intertropical Convergence Zone (ITCZ). Note that the mean biases estimated here include all types of data, i.e. data during clear sky and cloudy conditions, but excludes the deep convective

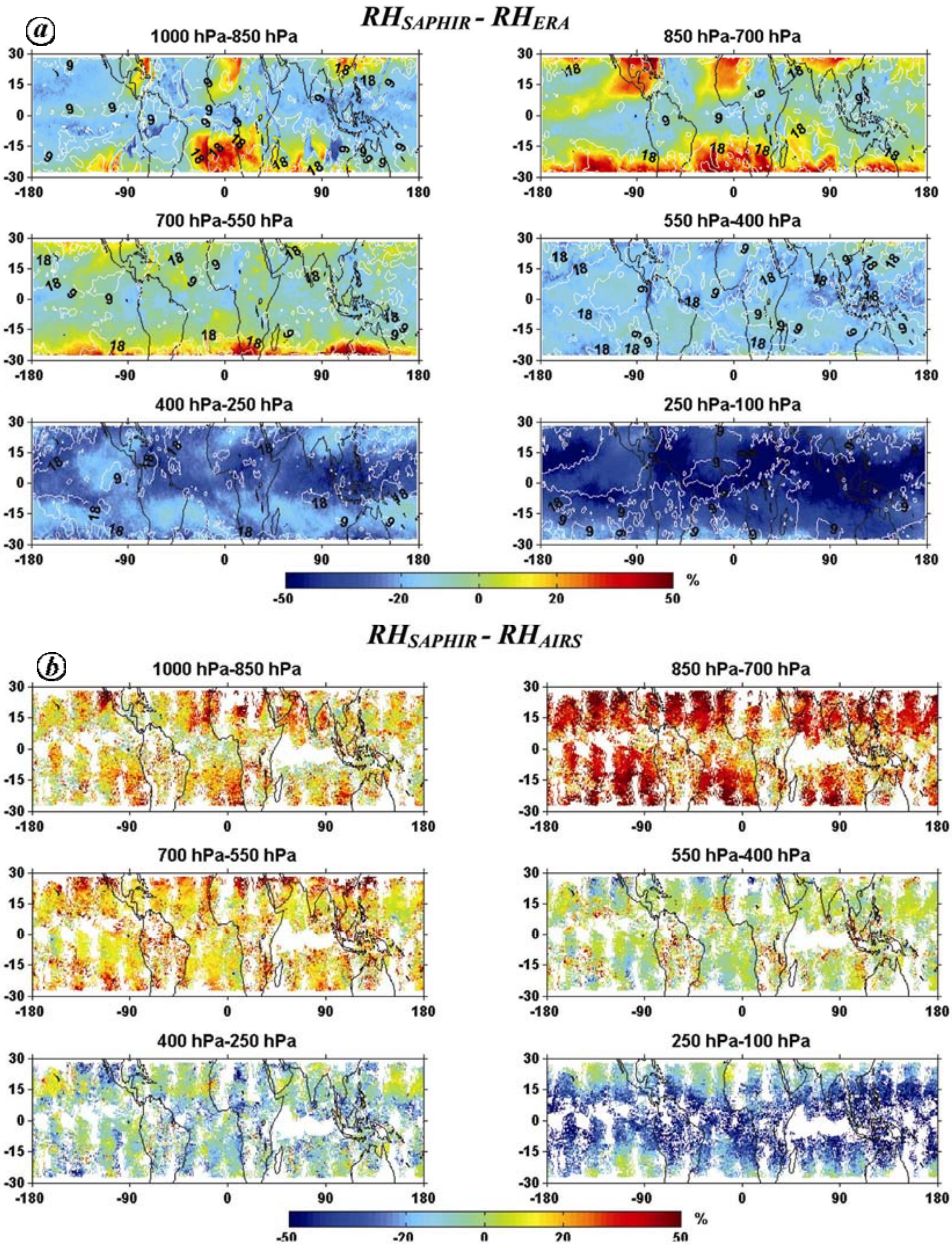

Figure 5. Same as Figure 3 for (***a***) and Figure 4 for (***b***), but for a different time-period (i.e. during December 2012–January 2013).

systems. Therefore, it is possible that these estimates might have been biased by the measurements during cloudy conditions.

Validation against AIRS

The AIRS water vapour profiles are validated and the error characteristics are well characterized. Therefore, these measurements provide another reference to validate SAPHIR-RH over the entire tropics. In case of AIRS, retrieval of RH is possible only in cloud-free conditions. Therefore, the estimated bias represents the bias for cloud-free conditions.

The spatial structure of the bias (Figure 4) is similar to that obtained by the ERA as reference dataset, albeit with different magnitude, large positive bias in the lowest three layers, negative bias in the uppermost layer and small bias in 550–400 hPa and 400–250 hPa layers. In general, the negative slope in the vertical variation in the bias (systematic variation in bias from positive to negative with height) is seen here also. Further, the regions with large positive bias (regions on the western flanks of South America and Africa) and negative bias (in the ITCZ) are also strikingly similar in both cases (ERA and AIRS as reference datasets). The only exception is that the large positive bias is confined to the lowest two layers when the bias is estimated with the ERA data, while it is extended to the third layer (700–550 hPa) with AIRS data.

Consistency check

To check whether or not the mean bias remains the same or changes with time, a different time period (December 2012–January 2013) was chosen and the mean RH bias estimated using two reference datasets, ERA and AIRS (Figure 5 *a* and *b* respectively). The vertical (positive bias at lower altitudes and negative bias at higher altitudes) and horizontal (large positive bias on the western flanks of South America and Africa and more negative bias along ITCZ) features in Figure 5 are strikingly similar to those seen in Figures 3 and 4. Here also, the bias is small in the middle layers. It is clear from the above discussion (and from Figures 3 to 5) that the estimated bias is not random, but real.

Conclusions and way forward

A variety of *in situ* and remote-sensing techniques that measure atmospheric humidity are employed as reference datasets to validate SAPHIR-derived RH profiles. Comparison with radiosonde RH reveals that, overall, the MT-derived RH is in good agreement with the radiosonde data (within ± 20%), particularly in the middle layers, where the sensitivity of the radiometer channels peaks. The RH at lowest and highest heights shows relatively large deviations from the sonde data. The rms differences are better than 15% throughout the troposphere, except for the lowest and highest layers. Certainly the above numbers for bias and rms differences are better than the expected retrieval accuracy of 20%. Both the mean bias and rms errors are relatively small when they are estimated with the data within 4° from the nadir compared to estimates using the data within 4°–8° from the nadir, indicating that the accuracy of measurements close to the nadir is better than for those far away from the nadir.

The evaluation of SAPHIR is extended to the entire tropics by considering ERA and AIRS humidity profiles as reference datasets. The bias estimates with both references show strikingly similar vertical and spatial structure. The vertical structure, in both cases, is similar to that obtained by the radiosonde in all regions, i.e. large positive bias in the lowermost layer, large negative bias in the uppermost layer and small bias (within 20%) in the middle layers. Further, large biases are seen over the oceans adjacent (on the western flanks) to the large land masses (South America and Africa) in the latitude band of 20°–30°S with both reference datasets (Figures 3 and 4). Possible reasons for the large negative bias, including retrieval problem to geophysical, were discussed but without any firm conclusion. It seems to be an important issue and warrants further investigation.

In summary, the height variable bias seems to be similar when SAPHIR-derived RH was compared with a variety of reference datasets and also consistent with time (Figure 5), indicating that this bias seems to be real and needs to be accounted somehow to improve RH estimates. The estimated biases presented here are preliminary in nature and a detailed validation campaign is being planned to obtain better bias estimates.

The comparisons were made here to evaluate the final product, i.e. atmospheric humidity, which includes cumulative uncertainty in the measurement of brightness temperature and geophysical parameter retrieval algorithm. Since transforming atmospheric state parameters (temperature and humidity) to brightness temperature or radiance using radiative transfer models is somewhat easy and straightforward[15], future comparisons can be made in radiance space. It facilitates evaluation of satellite radiance measurements and retrieval algorithms independently.

A dedicated validation campaign is planned to further evaluate RH profiles, wherein the latest Meisei RS-11G GPS sondes will be launched coinciding the overpasses of MT (within 4° from Gadanki). A total of 180 sondes will be launched with a considerable fraction of these sondes are planned to be launched during night-time, to overcome some of the sonde radiation correction problems. Moradi *et al.*[16] estimated that the bias (dry bias) due to solar heating over the tropics can be > 16%. Therefore, the above planned campaign with better ground truths (advanced sensors and known correction schemes for errors) is expected to quantify the RH bias in a better way.

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