Analysis of Water Vapor over Nigeria Using Radiosonde and Satellite Data

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ABSTRACT

The Satellite Application Facility on Climate Monitoring (CM-SAF) focuses on retrieving geophysical parameters from satellite data by using inversion schemes that are based on radiative transfer theory. In this study, the focus is on the daily mean vertically integrated water vapor [i.e., total precipitable water vapor (TPW)] and the monthly mean layered vertically integrated water vapor [i.e., low-level precipitable water vapor (LPW), midlevel precipitable water vapor (MPW), and upper-level precipitable water vapor] obtained from CM-SAF Germany for the 2004–08 period and for 20 radiosonde stations distributed over Nigeria. The mean annual cycle shows a structure with two maxima, in May and September, respectively, for all low- and midlevel water vapor in the coastal and Guinea savannah regions, whereas at the midland and Sahelian regions, an almost constant maximum lasting between May and September occurs. The two-maxima structure manifested by TPW, LPW, and MPW at the coastal and Guinea savannah regions and the single maximum exhibited by them at the midland and the Sahelian regions are in synchronism with the movement of the intertropical discontinuity. In addition, comparisons have been made between the precipitable water from CM-SAF (CM-SAF PWV) and precipitable water from radiosonde (RS-PWV). Comparisons of the products at the seasonal scale show that CM-SAF PWV at all levels is larger than that of RS-PWV. In addition, a seasonal intercomparison between them shows that CM-SAF PWV and RS-PWV agree significantly at all of the stations that were investigated.

1. Introduction

Water vapor is fundamental to the transfer of energy in the atmosphere (Rocken et al. 1997; Li et al. 2003). It is one of the most important and most abundant greenhouse gases in the earth’s atmosphere, keeping the temperature of the surface of the earth above the freezing level. Atmospheric water vapor plays a key role in the hydrological cycle, which in turn has a fundamental impact on the earth’s climate. The distribution of water vapor varies greatly both in space and time, with values ranging from about 50 mm near the equator to less than one-tenth as much at the poles (Mockler 1995). These variations can lead to sudden changes in local weather.

To develop accurate weather prediction and global climate models, it is vital to monitor water vapor as accurately as possible. The water vapor–greenhouse feedback is considered the strongest positive feedback in the climate system. Recent climate-model simulations (Rind et al. 1991; Del Genio et al. 1991; Shine and Sinha 1991) lend theoretical support to a positive feedback among surface temperature, tropospheric water vapor, and the greenhouse effect. Observational studies of the feedback (Raval and Ramanathan 1989; Stephens and Greenwald 1991; Duvel and Breon 1991) have relied on correlations between satellite measurements of column water vapor over open oceans and sea surface temperature.

In geodesy, tropospheric delay in radio signal due to water vapor is known to be a major source of error for geodetic observations from very-long-baseline interferometry, radar altimetry, the global positioning system, and interferometric synthetic aperture radar (INSAR). INSAR techniques have been used to study water vapor (Hanssen et al. 2001) despite the fact that water vapor serves as a major limitation to it. The
knowledge of the amount of atmospheric water vapor is also essential in appreciating the significant roles it plays in the attenuation of microwaves in the atmosphere. Atmospheric water vapor and oxygen absorb radio waves in the frequency range of 100–50 000 MHz (Ajayi and Adeyemi 2009). Information on the climatic variation of water vapor will therefore be of great help in radio engineering and communication.

Precipitable water vapor (PWV) estimates can be obtained in a number of ways ranging from in situ measurements to remote sensing from satellites (Mockler 1995; Chaboureau et al. 1998). The radiosonde network has long been the primary in situ observing system for monitoring atmospheric water vapor. Radiosondes provide vertical profiles of meteorological parameters such as pressure, temperature, relative humidity, and, occasionally, wind information. The use of radiosondes is limited by their high operational costs, decreasing sensor performance during the harmattan period when a dry easterly wind is blowing from the Sahara desert across the West African region during the dry season, and their poor coverage over oceans and in the Southern Hemisphere (Li et al. 2003). Radiosondes are usually expected to measure PWV with an uncertainty of a few kilograms per meter squared, which is considered to be the accuracy standard of PWV for meteorologists (Niell et al. 2001). These reasons, among others, have made spaceborne monitoring the only effective way to assess water vapor distribution on a global basis (Reuter 2005; Adeyemi 2008). Various missions have been deployed to monitor water vapor amount [e.g., Television and Infrared Observation Satellite Operational Vertical Sounder (TOVS), Advanced TOVS (ATOVS), Advanced Microwave Sounding Unit (AMSU-A and AMSU-B), and Special Sensor Microwave Image (SSM/I)] (Chaboureau et al. 1998; Randel et al. 1996).

The objective of this paper is to study the variations of PWV over Nigeria as have been retrieved from ATOVS on board National Oceanic and Atmospheric Administration (NOAA) and European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) satellites. These data will then be compared with data from radiosondes (RS) that were taken over three stations spanning the major climatic regions in Nigeria. This is of importance in Nigeria, because the maintenance of the radiosonde network for national service is costly. Thus, if the radiosondes can be replaced with reliable satellite-derived information, it would be a real benefit to the Nigerian government, because only a few stations delivering a higher quality of data might be retained for quality-monitoring purposes.

2. Data

a. Environmental setting of the study area

For the purpose of this study, Nigeria was divided into four zones reflecting areas that have climates controlled by different mechanisms as explained by Olaniran and Sumner (1989) (see Fig. 1).

These areas are

1) the coastal zone (CO; 4.6°–6.5°N, 3.7°–7.1°E), dominated by tropical maritime (mT) air for most of the year,
2) the Guinea–savannah zone (GS; 6.6°–7.8°N, 3.9°–7.5°E), where mT air dominates for about 7 months and tropical continental (cT) air dominates for the remaining 5 months,
3) the midland zone (ML; 8.0°–10.8°N, 3.9°–9.8°E), which is predominantly highland, where the cT air mass dominates but where the topography effectively extends the length of the humid period because of localized convection and orographic effects, and
4) the Sahelian zone (SA; 11.0°–13.0°N, 3.7°–13.3°E), where the cT air mass predominates and the mT air mass invades for between 3 and 5 months at most (Olaniran and Sumner 1989).

b. CM-SAF water vapor products (CM-SAF PWV)

CM-SAF provides global fields of daily mean vertically integrated water vapor and layered vertically integrated water vapor in five layers (surface–850 hPa, 850–700 hPa, 700–500 hPa, 500–300 hPa, and 300–200 hPa). For this study, data have been extracted from the global products for 20 radiosonde stations in Nigeria (see Fig. 1) for the period 2004–08.

The CM-SAF water vapor products are generated through measurements from NOAA and EUMETSAT polar-orbiting platforms (Schulz et al. 2009). The ATOVS suite of instruments [High Resolution Infrared Radiation Sounder (HIRS), AMSU-A/B, and Microwave Humidity Sounder (MHS)] on NOAA and Meteorological Operational (MetOp) satellites represent infrared spectrometers and microwave radiometers where the combination of all three instruments contains enough information to infer atmospheric profiles of temperature and specific humidity.

Temperature and water vapor profile retrieval mostly employ the one-dimensional variational technique that uses the variational principle to solve the retrieval problem. CM-SAF applies the scheme developed by Li et al. (2000) to TOVS/ATOVS observations. The so-called International ATOVS Processing Package (IAPP) scheme performs an inversion of the radiances to retrieve simultaneously the temperature and humidity...
profiles, as well as the surface temperature and cloud-top pressure and amount. It employs an iterative method that finds the maximum probability solution to a nonlinear retrieval/analysis problem. It can operate on cloud-free or, in some cases, cloudy radiances. The main satellite data source for the retrieval process depends on the cloudiness of a scene and the underlying surface. Retrievals over oceans rely on all sensors whereas retrievals over land surfaces are mainly based on cloud-free HIRS measurements. The retrieval relies on an a priori background that is given by the 6-h forecast from the German numerical weather prediction model (Majewski et al. 2002).

Global daily fields are constructed using a specific kriging algorithm (Schulz et al. 2009). The daily fields are accompanied by an uncertainty estimate that reflects the retrieval uncertainty and the sampling error that is, in particular, important in tropical areas over land.

Validation activities are routinely performed by the CM-SAF, but validation results are only presented in globally averaged numbers. On the global scale, radiosondes and satellite-derived water vapor agree reasonably well, with systematic differences of 0.5 kg m$^{-2}$ and root-mean-square difference of approximately 4 kg m$^{-2}$. In this study, the CM-SAF product is tested over an area where the retrieval of water vapor is particularly difficult because of the use of only HIRS observations with limited spectral coverage.

c. Radiosonde water vapor products (RS-PWV)

The radiosonde data from three stations [Lagos (6°28′N, 3°28′E), Minna (9°37′N, 6°30′E), and Kano (12°2′N, 8°30′E)] were used for the in situ computation of PWV in this paper. These data were obtained from the archives of the Department of Meteorological Services, Federal Ministry of Aviation, Oshodi, Lagos, Nigeria. Since the data collected in West Africa have many large spatial gaps, we have combined all available data into monthly climatologies. This was done by finding the monthly average of all available data for each of the stations. Note that these selected stations adequately represent the regions they belong to in Nigeria. The PWV calculations at the three stations have been computed for the surface–850 hPa ($W_a$), 850–700 hPa ($W_b$), 700–500 hPa ($W_c$), 500–400 hPa ($W_d$), and 400–300 hPa ($W_e$). Mean values of these quantities at the different levels were then calculated from (Adeyemi 2008)

$$W_{a,b,c,d,e} = -\frac{10}{g} \int_{p_{lower \ boundary}}^{p_{upper \ boundary}} \bar{q}_v dp = -\frac{10}{g} \sum_{i=1}^{N} \bar{q}_v \Delta p_i,$$  

where $q_v$ is the specific humidity (g kg$^{-1}$) for the layer considered, $W$ is in kilograms per meter squared, and $\Delta p$ is the pressure gradient.

Observations from higher than 300 hPa were not used because in many instances the radiosonde did not reach...
that height. For this analysis, the five layers are combined into three atmospheric layers: low-level water vapor (LPW) = $W_a$, midlevel water vapor (MPW) = $W_b + W_c$, and upper-level water vapor (UPW) = $W_d + W_e$. The CM-SAF data are combined in the same way to make the products comparable. The uppermost layer of the CM-SAF data was not used.

3. Results and discussion

a. Distribution of total and layered PWV over Nigeria

Figures 2a–d and 3a–d show the distribution of total and layered precipitable water and the annual cycles over the four climatic zones making up Nigeria, respectively. From Figs. 2a–d, TPW displays an increase in water vapor from January to April–May in all four climatic zones. This increase is small in the CO and GS zones while in the ML and SA zones the increase is abrupt. The increase continues until June, after which the values slightly decrease in the CO and GS zones. April and May in these zones are associated with the first peak of the rainy season. The ML and SA zones, between May and June, are characterized by high values of TPW. These values are mostly higher than those in the CO and GS zones. Between July and September, the CO and the GS zones experience lower precipitable water, with a minimum in August. In both the ML and SA zones, the opposite is the case. Here, high values observed between May and June persist until the end of September. The August minimum observed at the CO and GS zones does not occur.

Between October and December, the CO and GS zones are characterized by an increasing water vapor content that peaks in October and November for the respective zones. This is associated with the second peak of the rainy season in these zones. The ML and SA zones, on the other hand, maintain a single peak lasting between May and September.

Figures 3a–d, which show the mean annual cycle of layered precipitable water over Nigeria, present some noteworthy characteristics at the different zones. In the CO and GS zones, LPW and MPW display structures similar to their TPW. UPW, on the other hand, displays almost constant and low values throughout the year. These values increase only slightly during the rainy season of May–October. At the ML station of Minna the annual cycles of the layers also display similar structures to their TPW, with the exception of the MPW structure for which the August minimum that was completely absent in the TPW showed up, although it is not as conspicuous as it is in the CO and GS zones. LPW and MPW show similar annual cycles to their TPW at the SA station of Kano. UPW for all the zones has low and almost uniform values throughout the year.

The observations described above are in agreement with the findings of Adedokun (1986), Balogun and Adedokun (1985), Balogun (1981), Olaniran and Sumner (1989), Adeyemi and Aro (2004), and Adeyemi (2008) using radiosonde data taken over the regions. The increasing precipitable water vapor observed between January and May is linked to the movement of the rain-producing zone known as the intertropical discontinuity (ITD) from the coast inland, and the decrease in water vapor occurring during September–December is due to its retreat. The movement of the ITD is in close association with the northward movement of the intertropical convergence zone (ITCZ) during boreal summer. The intervening minimum that is prominent in August in the CO and GS zones and less prominent at the ML zone is well related to the period of dryness of 2–3 weeks occurring at the middle of the rainy season in the coastal part of West Africa. This phenomenon, known as the intramonsoonal period, is believed to be a consequence of several factors such as coastal upwelling and the northern advance of the subtropical high pressure systems of the southern Atlantic Ocean. It is also caused by the circulation aloft, which becomes divergent and subsident as a result of the frequent occurrence of inversions and isothermals in the upper atmosphere along the coast when the weather zone E

1 West African weather, as demarcated by the movement of the ITD (ITCZ), has been classified into zones depending on the location of a place with respect to the ITD (Olaniran and Sumner 1989). Its northward and southward movements bring about the onset and retreat of rain, respectively. These weather zones are known as A, B, C, D, and E, with E located over the oceans.
(i.e., lifting of the boundary layer). The persistent heating of the lowest layers of the atmosphere through surface heating causes surface air to become hot. It expands and becomes less dense and then rises. Water vapor is then transported upward, resulting in its depletion at the lowest layer of the atmosphere and making MPW larger than LPW. The dry-season reversal at the CO zone is most likely because there is enough evaporation over the ocean to replace the uplifted water vapor.

b. Comparisons between CM-SAF PWV and radiosondes (RS-PWV)

Comparisons have been made between the two sources of water vapor estimates at the seasonal scale. It is important to note that the CM-SAF PWV values were averaged over monthly intervals to correspond to available radiosonde data.

Figure 4 and Table 1 show PWV from CM-SAF water vapor products averaged over the period of 2004–08 in comparison with retrieved data from radiosondes, as mentioned in section 2. High correlations (see Table 1) ranging from 0.55 [coefficient of determination (CD) = 32%] to 0.93 (CD = 88.4%) have been observed at all of the levels of PWV and at all of the available stations except at the midlevel in Lagos and the upper level in Kano where the regressions have been found not to be significant. The CM-SAF PWV at all of the levels observed has been found to be significantly larger than RS-PWV with very high standard deviation (STD) at the lower and middle levels of the atmosphere, whereas at the upper level the STD was low. This was observed at all of the stations. The scattergram (Fig. 5) also indicates that CM-SAF PWV was larger than RS-PWV with scale factors of 0.1572 ± 0.07 in Lagos, 0.8766 ± 0.105 at Minna, and 2.416 ± 0.696 in Kano at the low level; 0.938 ± 0.149 at Minna and 1.231 ± 0.1411 at Kano at the midlevel; and 1.257 ± 0.467 at Lagos and 1.255 ± 0.500 at Minna at the upper level (note that the regressions that are not significant are not considered).
Figure 5 shows clearly the scatterplots of the differences in PWV (i.e., CM-SAF PWV − RS-PWV) at the different levels and for the stations for which radiosonde data were available. Figure 5 (top panel) shows that the difference in PWV at higher values of CM-SAF PWV at the lower level in Lagos was low whereas at the midlevel it was high and at the upper level an increasing tendency with a high coefficient of determination ($R^2 = 0.74$) was noticeable. That is, at this level, the difference in PWV increases as CM-SAF PWV increases. Figure 5 (middle panel) shows that differences in PWV at Minna are found within the same range for all values of CM-SAF PWV at the lower level whereas at the midlevel an increasing tendency has been established with $R^2 = 0.76$. In the case of Kano (Fig. 5, bottom panel), an increasing tendency has been established between the differences in PWV and CM-SAF PWV with high correlation ranging from 0.73 to 0.96. This shows that at this station the differences increase with the amount of CM-SAF PWV.

c. Dry- and wet-season comparisons

Previous studies over West Africa (Adeyemi and Aro 2004; Balogun and Adedokun 1985; Olaniran and Sumner 1989) have confirmed that there are seasonal
Fig. 4. Comparison between layered CM-SAF-PWV and RS-PWV over Nigeria. Only the stations for which radiosonde data are available have been considered.
differences in the quality of relative humidity measurements by radiosondes. To study the effect of the seasonal differences, comparisons between CM-SAF PWV and radiosonde PWV were also made by separating dry- and wet-season cases (see Table 2). During the dry season, linear relationships between CM-SAF PWV and RS-PWV were only found at Minna at both the lower and upper levels (see Table 2) whereas for other stations at all of the levels and for Minna at the midlevel the relationships are not significant. During the wet season, no relationship was found between CM-SAF PWV and RS-PWV at all levels and for all stations except at Kano at the midlevel and Lagos at the lower level, where linear relationships of very high correlation have been observed. By comparison, the scale factors for the RS-PWV relative to CM-SAF PWV measurements changed abruptly from a low value ranging from 0.08 to 1.5 kg m\(^{-2}\) at Lagos during the dry season to a high value ranging from 1.5 to 9.2 kg m\(^{-2}\) at the same station during the wet season.

d. Discussion

There are many potential causes for these differences that are almost impossible to discern from the available data. It is evident that the availability and quality of radiosonde data in Nigeria have significant shortcomings. In carrying out good quality assurance of the data, series of averaging and reaveraging processes were carried out to filter the radiosonde data. The few available radiosondes are characterized by large temporal gaps. An example of this can be seen in Fig. 4 at the Lagos station where the low- and midlevel water vapor contents dramatically dropped off in August. Also the low-level water vapor at the Kano station shows a very small annual cycle with absolute water vapor values of less than 10 kg m\(^{-2}\). This seems to be unrealistically small when compared with European Centre for Medium-Range Weather Forecasts reanalysis results. A possible cause for the larger scale-factor variation at Lagos may be that, during the dry season, radiosonde sensors are heated up, resulting in lower relative humidity measurements than expected (Smout et al. 2001).

The satellite-derived product is also prone to problems—in particular, in areas such as Nigeria. The ATOVS observing system and the associated retrieval system (Li et al. 2000) use different sensor combinations over land and ocean and are restricted to cloud-free HIRS observations (Schulz et al. 2009). The use of only infrared (IR) measurements, employing the differential absorption in the atmospheric window channels (11.11 and 12.47 μm) and using directly the absorption features in the water vapor channels (6.52 and 7.33 μm), limits the information content regarding the profile of the lower and upper layers. The midlevel is almost left without information. The retrieval is then driven toward the background used in the iterative retrieval scheme of Li et al. (2000). The depth of this information gap becomes larger the more humid the atmosphere is, because the peaks of the water vapor channels are high up in the atmosphere and provide little information to the midlevel estimate. This effect might be observed in Fig. 4 for the Kano station where the difference in midlevel water vapor clearly increases during the wet season.

It is also known that changes in the IR surface emissivity can strongly influence the retrieval of the layer-averaged water vapor contents. Bennartz et al. (2008) have shown that retrievals of total column water vapor using IR window channels have a sensitivity of 0.6 and 2 kg m\(^{-2}\) % emissivity change in the two HIRS window channels, respectively. Using available IR emissivity

### Table 1. Values of best-fit parameters \(A\) and \(B\) in the regression equation of CM-SAF PWV at different levels on RS-PWV, i.e., CM-SAF PWV = \(A(\text{RS-PWV}) + B\). Here, \(A\) and \(B\) are parameter estimates, SE is standard error, and \(p\) value is the probability value. In the remark column, S stands for significance and NS stands for not significant.

<table>
<thead>
<tr>
<th>Station</th>
<th>(A)</th>
<th>SE</th>
<th>(B)</th>
<th>SE</th>
<th>STD</th>
<th>CD (%)</th>
<th>(p) value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lagos</td>
<td>0.1572</td>
<td>0.0721</td>
<td>20.37</td>
<td>1.271</td>
<td>4.888</td>
<td>32.2</td>
<td>0.05</td>
<td>S</td>
</tr>
<tr>
<td>Minna</td>
<td>0.8766</td>
<td>0.1048</td>
<td>10.03</td>
<td>1.337</td>
<td>6.242</td>
<td>87.5</td>
<td>0.00</td>
<td>S</td>
</tr>
<tr>
<td>Kano</td>
<td>2.416</td>
<td>0.6960</td>
<td>-5.037</td>
<td>5.284</td>
<td>5.530</td>
<td>54.6</td>
<td>0.01</td>
<td>S</td>
</tr>
<tr>
<td>Lagos</td>
<td>0.2227</td>
<td>0.1660</td>
<td>20.87</td>
<td>2.006</td>
<td>7.132</td>
<td>15.3</td>
<td>0.21</td>
<td>NS</td>
</tr>
<tr>
<td>Minna</td>
<td>0.9379</td>
<td>0.1487</td>
<td>10.32</td>
<td>2.138</td>
<td>6.498</td>
<td>79.9</td>
<td>0.00</td>
<td>S</td>
</tr>
<tr>
<td>Kano</td>
<td>1.231</td>
<td>0.1411</td>
<td>6.282</td>
<td>1.711</td>
<td>7.153</td>
<td>88.4</td>
<td>0.00</td>
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<tr>
<td>Lagos</td>
<td>1.257</td>
<td>0.4665</td>
<td>2.267</td>
<td>0.1844</td>
<td>1.236</td>
<td>42.1</td>
<td>0.02</td>
<td>S</td>
</tr>
<tr>
<td>Minna</td>
<td>1.255</td>
<td>0.5004</td>
<td>2.021</td>
<td>0.2765</td>
<td>1.151</td>
<td>38.6</td>
<td>0.03</td>
<td>S</td>
</tr>
<tr>
<td>Kano</td>
<td>0.013</td>
<td>0.6410</td>
<td>2.739</td>
<td>0.3348</td>
<td>1.173</td>
<td>0.004</td>
<td>0.98</td>
<td>NS</td>
</tr>
</tbody>
</table>
FIG. 5. Scatterplots of differences in PWV (diff in PWV) = CM-SAF PWV minus RS-PWV at the different levels for (top) Lagos, (middle) Minna, and (bottom) Kano. The least squares regression line was also shown.
A last possible cause for the discrepancies observed mostly during the wet season between CM-SAF PWV and RS-PWV is associated with the comparison method used here. The radiosonde PWV is the vertical integration of specific humidity along its flight trajectory, for which the horizontal drift of the radiosonde is significant. The collocation to an average of vertically integrated satellite-derived instantaneous water vapor profile based on the starting location of the radiosonde can lead to very large differences—in particular, for the upper-layer water vapor estimates (Li et al. 2003).

### 4. Conclusions

Satellite retrievals of total precipitable water over Nigeria, as obtained from the archives of the CM-SAF, Deutscher Wetterdienst, Germany, have been found to increase from January to April–May at all of the four climatic zones in Nigeria. This increase is a small one in the case of the CO and GS zones whereas at the ML and SA zones the increase is abrupt. Two maxima are discernible in the mean annual cycles at all vertical levels at both the CO and GS zones, whereas at the ML and SA zones a single maximum was observed. Comparisons between the PWV values derived from CM-SAF and radiosonde data were also performed. High correlations (see Table 2) ranging from 0.55 (CD = 32%) to 0.93 (CD = 88.4%) have been observed at all of the levels of PWV and at all of the available stations except at the

### Table 2. As in Table 1, but for the dry and wet seasons.

<table>
<thead>
<tr>
<th>Station</th>
<th>Season</th>
<th>A</th>
<th>SE</th>
<th>B</th>
<th>SE</th>
<th>CD (%)</th>
<th>p value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
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<td>Lagos</td>
<td>Dry</td>
<td>1.463</td>
<td>1.097</td>
<td>−17.44</td>
<td>24.81</td>
<td>37.2</td>
<td>0.2744</td>
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<tr>
<td></td>
<td>Wet</td>
<td>2.762</td>
<td>1.871</td>
<td>−46.67</td>
<td>43.77</td>
<td>30.4</td>
<td>0.1999</td>
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<tr>
<td>Minna</td>
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<td>0.974</td>
<td>0.219</td>
<td>−8.287</td>
<td>3.501</td>
<td>86.8</td>
<td>0.0213</td>
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</tr>
<tr>
<td></td>
<td>Wet</td>
<td>−0.469</td>
<td>0.975</td>
<td>26.57</td>
<td>23.24</td>
<td>4.4</td>
<td>0.6596</td>
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<tr>
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<td>0.692</td>
<td>4.413</td>
<td>4.348</td>
<td>3.5</td>
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<td></td>
<td>Wet</td>
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<td>0.077</td>
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<td>Wet</td>
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<td>4.571</td>
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<td>44.6</td>
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<tr>
<td>Kano</td>
<td>Dry</td>
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<td>2.868</td>
<td>12.14</td>
<td>3.5</td>
<td>0.7622</td>
<td>NS</td>
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<tr>
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<td>Wet</td>
<td>0.758</td>
<td>0.176</td>
<td>−4.225</td>
<td>4.356</td>
<td>78.8</td>
<td>0.0076</td>
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</tr>
<tr>
<td>Lagos</td>
<td>Dry</td>
<td>0.118</td>
<td>0.170</td>
<td>−0.030</td>
<td>0.409</td>
<td>13.9</td>
<td>0.5372</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>1.403</td>
<td>0.322</td>
<td>−3.701</td>
<td>0.948</td>
<td>79.2</td>
<td>0.0073</td>
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<tr>
<td>Minna</td>
<td>Dry</td>
<td>−0.402</td>
<td>0.2366</td>
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<td>0.531</td>
<td>49.0</td>
<td>0.1882</td>
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<td></td>
<td>Wet</td>
<td>0.341</td>
<td>0.296</td>
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<td>0.3019</td>
<td>NS</td>
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<tr>
<td>Kano</td>
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<td>−0.356</td>
<td>0.632</td>
<td>1.318</td>
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<td>0.6124</td>
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<td>0.518</td>
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Databases such as Seemann et al. (2008), Bennartz et al. (2008) have shown that the variability of surface emissivity in the window channels is approximately 1%, leading to uncertainties on the order of the sensitivity in the window channels. The Li et al. (2000) retrieval as employed in CM-SAF uses a constant surface emissivity (0.99) for the window channels. Thus, already small deviations from this value can lead to large changes in the low-level water vapor estimates. The Seemann et al. (2008) emissivity database shows that the emissivity in the IR channels varies with changing vegetation cover, which is not considered in the satellite retrieval scheme.

Bennartz et al. (2008) also showed that iterative retrievals over land may introduce large artificial daily variations in retrieved column water vapor that were negatively correlated with surface temperature. This is caused by the background and its error covariance in the retrieval that do not match the local conditions. In the presented comparison the satellite observations are taken under very different surface temperature conditions. During the day, the morning NOAA satellite overpass is looking at relatively cold surfaces, whereas the afternoon overpass is looking at a very hot surface, particularly in the dry season. This of course can lead to biases, especially in the low-level water vapor estimate over arid surfaces where the surface temperature variation during the day can be larger than 40 K. Since the comparison with the radiosondes is only possible at seasonal scales, no more insight into this problem could be gained.
midlevel in Lagos and at the upper level in Kano, where the regressions are not significant. This shows that the CM-SAF data are a better alternative in the regions where there is good agreement between these data and the radiosonde data in Nigeria. The CM-SAF data will therefore provide the much-needed data in this part of the world where there is general lack of upper-air data. The CM-SAF PWV at all of the levels observed has been found to be greater than RS-PWV, with very high STD at the lower and middle levels of the atmosphere and low STD at the upper level. This observation was found at all of the stations and may be likened to the presence of a dry bias in the radiosonde humidity measurements at both the upper and the lower levels of the atmosphere (Häberli 2006). CM-SAF PWV was larger than RS-PWV with scale factors of 0.1572 ± 0.07 in Lagos, 0.8766 ± 0.105 at Minna, and 2.416 ± 0.696 at Kano at the low level; 0.938 ± 0.149 in Minna and 1.231 ± 0.1411 in Kano at the mid level; and 1.257 ± 0.467 at Lagos and 1.255 ± 0.500 at Minna at the upper level. It was generally observed also that at Lagos the differences between measurements of CM-SAF PWV and RS-PWV have an increasing tendency at the upper level only, at Minna an increasing tendency is noticed at both the middle and the upper levels, and at Kano all of the levels show increasing tendency. This implies that the differences in PWV measurements at these stations and at the levels considered increase as PWV increases. Seasonal effects on data acquisition revealed that, in some cases, discrepancies exist between the PWV estimates retrieved from both sources during the dry- and the wet-season periods.

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REFERENCES


