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Article

Global Evaluation of Radiosonde Water Vapor Systematic Biases using GPS Radio Occultation from COSMIC and ECMWF Analysis

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Abstract: In this study, we compare specific humidity profiles derived from Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) radio occultation (RO) from August to November 2006 with those from different types of radiosonde and from ECMWF global analysis. Comparisons show that COSMIC specific humidity data agree well with ECMWF analysis over different regions of the world for both day and night times. On the contrary, evaluation against COSMIC specific humidity shows a distinct dry bias of Shang-E radiosonde (China) and an obvious wet bias of VIZ-type (USA). No obvious specific humidity biases are found for MRZ (Russia) and MEISEI (Japan) radiosondes. These results demonstrate the usefulness of COSMIC water vapor for quantifying the dry/wet biases among different sensor types.

Keywords: COSMIC; GPS radio occultation; global evaluation of radiosonde water vapor systematic biases; ECMWF analysis

1. Introduction

Water vapor (WV) is one of the most important greenhouse gases in the atmosphere. Accurate and consistent water vapor measurements in the troposphere are critical for studying the water vapor feedback on clouds and hydrological cycles, which are still one of the largest uncertainties in understanding the global warming mechanism [1]. Radiosondes have provided long-term and all-weather *in situ* operational measurements of atmospheric pressure, temperature, and humidity for decades and have been the backbone observation system for numerical weather prediction and climate monitoring [2]. However, because radiosonde sensor characteristics can be affected by the changing environment [3,4], its measurement accuracy varies considerably in times and locations for different sensor types [5]. Various methods have been developed to correct known humidity observational errors for individual type of radiosonde within a region through either statistical approaches [6,7] or laboratory or physical based correction schemes [8,9]. Due to lack of benchmark humidity references, it is still difficult to quantify the possible geographically and temporally dependent errors even after applying those humidity corrections. The moisture climatology constructed using radiosonde measurements is still subject to significant uncertainty.

All-weather water vapor profiles can also be obtained from Global Positioning System (GPS) radio occultation (RO) data [10-12]. The vertical resolution of RO derived humidity profile is from ~100 to 200 m in the lower troposphere and ~1.4 km in the stratosphere. The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), composing six satellites in separate orbits, was successfully launched in April 2006. With up to 2,500 RO profiles uniformly distributed in time and space every day, COSMIC provides a unique opportunity to investigate global water vapor distribution with a high vertical resolution and with a moderate spatial and temporal resolution. With an advanced tracking technique, known as the 'open-loop tracking' [13], more than 90% of COSMIC soundings penetrate to the lowest 2 km of the troposphere. The precision and quality of COSMIC data are quantified in [14]. COSMIC-derived integrated water vapor (IWV) has been validated using those from Special Sensor Microwave Imager (SSM/I) over oceans [15]. Results show that the mean COSMIC-SSMI/I IWV difference is close to zero. Initial global comparisons of COSMIC-derived IWV and those derived from ground-based GPS measurements [16] over lands show a 0.17 mm mean bias (for COSMIC minus ground-based GPS IWV) with a 2.7 mm standard deviation [17].

In this study, we perform a global comparison of water vapor profiles from the close collocated COSMIC, radiosondes, and European Centre for Medium Range Forecasts (ECMWF) analysis. ECMWF analysis represents optimal humidity estimates from high quality observations among multi-satellite sounders, imagers, and conventional *in situ* observations including radiosondes through a data assimilation system [18]. To test whether COSMIC WV can reasonably identify known radiosonde moisture bias for different sensor types, the COSMIC-radiosonde pairs are grouped into different sensor types. COSMIC data from August to November 2006 are used. The datasets and analysis methods used in this study are described in Sections 2 and 3, respectively. Comparisons of COSMIC and radiosonde water vapor profiles and evaluation of day/night water vapor differences are presented in Sections 4 and 5, respectively. Conclusions are presented in Section 6.

2. Data

RO water vapor profiles from the early phase of COSMIC mission from August 2006 to November 2006 are used in this study. These COSMIC profiles are obtained from the COSMIC Data Analysis and Archive Center (CDAAC) (http://cosmicio.cosmic.ucar.edu/cdaac/index.html). In the neutral atmosphere, refractivity (N) is related to pressure (P), temperature (T) and partial pressure of water vapor (PW) by the following equation [19]:

$$N = 77.6\frac{P}{T} + 3.73 \times 10^5 \frac{P_W}{T^2} \tag{1}$$

To resolve the ambiguity of GPS RO *N* associated with both *T* and *WV* in the lower troposphere, a 1D-var algorithm [20] is used to derive optimal temperature and water vapor profiles. The temperature and moisture analyses from National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) model interpolated to the COSMIC sounding times and locations are used as the first guess profiles in the 1D-var algorithm. In this study, the water vapor profiles from ECMWF analyses interpolated to the COSMIC sounding times and locations are used as an independent validation source in the comparison. ECMWF analysis here represents consistent estimates of atmospheric variables among satellite sounders and *in situ* observations through a series of adaptive bias correction and quality control procedures [18]. Because starting in December, 2006 ECMWF assimilated COSMIC data into its analysis system, here we limit our comparison to the period of August 2006 to November 2006. About 2500 close collocated RO-radiosonde pairs are collected for this study.

The operational radiosonde data used in this study are collected by the National Center of Atmospheric Research (NCAR; DS353.4), which was originally acquired from NCEP. Based on comparisons with other data, DS353.4 contains the original data values transmitted by stations [21]. Although some corrections may be made through the ground software from the manufacturers, no radiative or other corrections from NCEP are included in this dataset. Without complete metadata, in this study we do not further distinguish whether the causes of radiosonde humidity measurement uncertainties are due to instrumental errors or problematic corrections previously applied.

3. Comparison Methods

The COSMIC RO sounding's horizontal resolution is around 200 km with a less than 100 km horizontal drift at the height of its tangent point for each profile. The radiosonde data are available at approximately 20 mandatory and significant levels in the troposphere. Radiosondes may also drift horizontally by tens of kilometers after launch depending on the wind speed. To minimize the temporal and spatial mismatches, only radiosonde soundings launched within 2 hours and 300 km of COSMIC soundings are used, where the position of COSMIC sounding is defined at the altitude around 5 km. To make comparisons with a similar vertical resolution, COSMIC, radiosonde, and ECMWF soundings are interpolated into a common 500-meter vertical grid.

Globally, there are roughly 850 radiosonde stations using about fourteen different types of radiosonde systems (Figure 1). To differentiate the performance of different types of radiosonde in the troposphere in different geographical regions, we compare COSMIC data with radiosonde sensors mainly in (1) Russia (MRZ), (2) China (Shang-E and Shang-M), (3) Japan (Meisei), (4) United States (VIZ-type including VIZ, VIZ-B and VIZ-B2). These sondes contain three types of humidity sensors: Goldbeater's Skin, Capacitive Polymer and Carbon Hygristor (see Table 1). Here we compute the mean water vapor bias for Shang-E and Shang-M separately. This is to distinguish a possible systematic water vapor bias from two different humidity sensors (*i.e.*, Shang-M with Goldbeater's

Skin; Shang-E with Carbon Hygristor) in the same geographical region. The specific humidity difference (in g/kg) at level index i for a COSMIC-radiosonde match (index n) is defined as:

$$\Delta q(i,n) = q_{COSMIC}(i,n) - q_{Sound}(i,n) \tag{2}$$

where q_{COSMIC} and q_{Sound} are COSMIC and radiosonde specific humidity data, respectively. The specific humidity difference for COSMIC-ECMWF pairs are also defined as Equation (2) but q_{Sound} is replaced by ECMWF specific humidity profile. The mean specific humidity difference at all available levels from 0.5 km (the RO data below 0.5 km are less frequent) to 8 km for COSMIC and radiosonde matches for different radiosonde types are compared. The mean differences for COSMIC-ECMWF matches over regions of these five radiosonde types are also computed. Note that in this study we focus on above five radiosonde systems that each type of the radiosonde system is mainly distributed in the same geographical region. Because it may need many more COSMIC-radiosonde pairs to distinguish complex water vapor biases among similar radiosonde systems that are distributed in different geographical regions (such as Vaisala including RS80, RS90, RS92, *etc.*), for simplification, we will not further address water vapor biases for those radisonde types in this study.

Figure 1. Global distribution of radiosonde stations colored by radiosonde types. Radiosonde types updated from August 2006 to November 2006 are used. The percentage of each type of radiosonde used among all stations is listed. For those stations that radiosonde types are changed during this period, the latest updated radiosonde type is used in this plot.

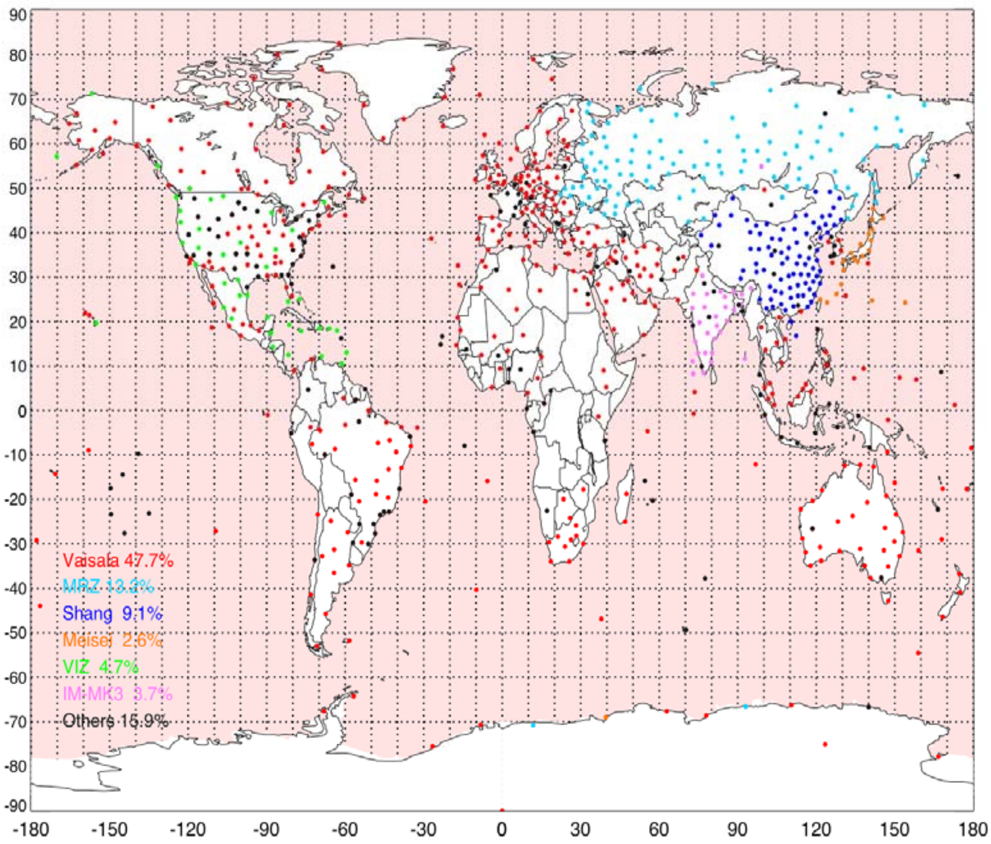


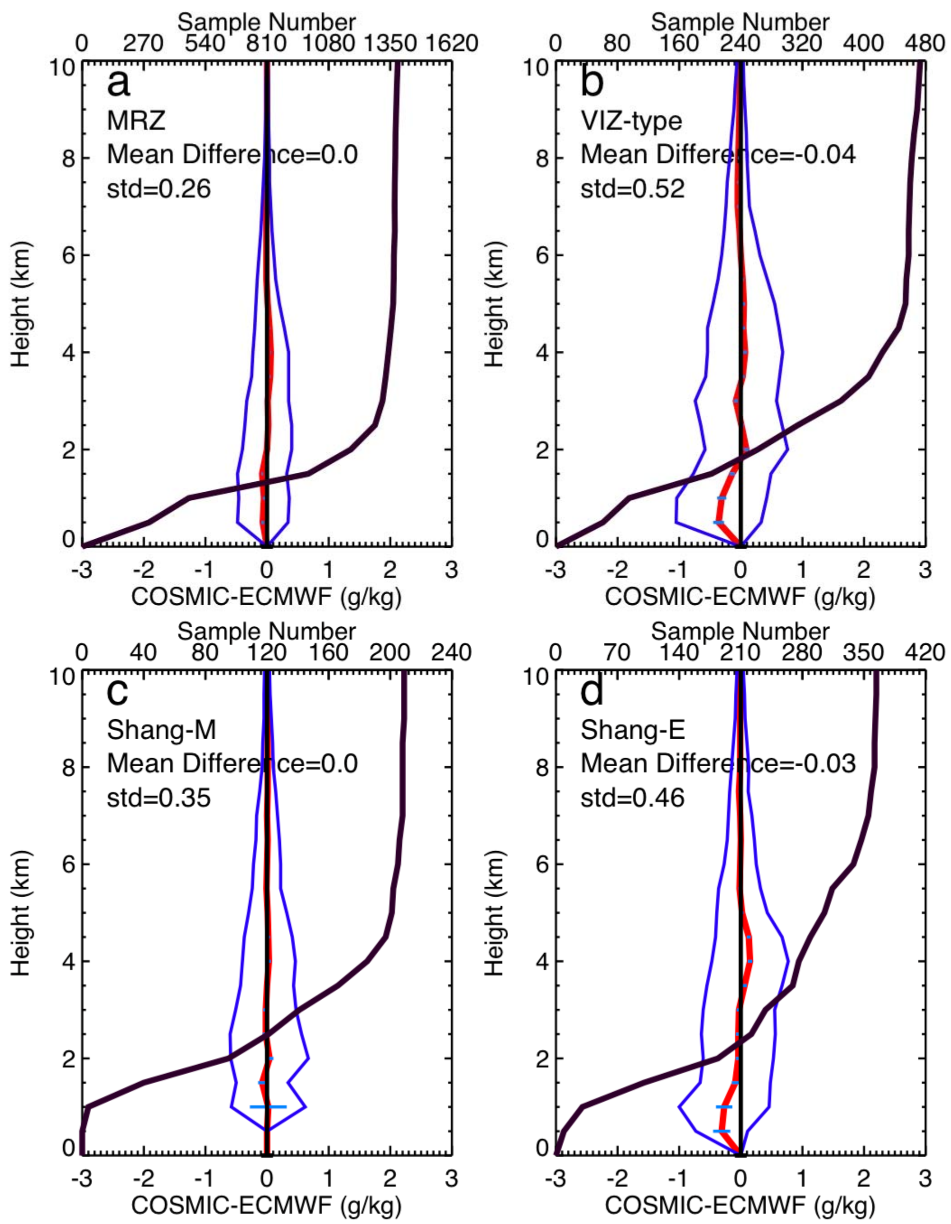
Table 1. Summary of the mean specific humidity (q) difference (Δ q), absolute mean difference (abs Mean Δ q), and standard deviation (std (Δ q)) of specific humidity of the COSMIC-radiosonde pairs and COSMIC-ECMWF pairs for MRZ, Shang/M, Shang/E, MEISEI, and VIZ-type. Numbers of COSMIC-radiosonde pairs at 8 km is used here and are listed as # of matches. The unit of q is g/kg. Δq at all available levels are from 0.5 km to 8 km. The mean Δq for COSMIC-radiosonde pairs and COSMIC-ECMWF pairs are defined as COSMIC minus radiosonde specific humidity and COSMIC minus ECMWF specific humidity, respectively. The Mean Δq, abs Mean (Δq), and std(Δq) of COSMIC-ECMWF pairs are shown in the parenthesis.

Sonde Type	MRZ	Shang-M	Shang-E	MEISEI	VIZ-type
Region	Russia	China	China	Japan	USA
Humidity Sensor	Goldbeater's Skin	Goldbeater's Skin	Carbon Hygristor	Capacitive Polymer	Carbon Hygristor
# of Day/Night Matches # of Day Matches # of Night Matches	1,350 450 900	210 35 175	370 60 310	150 60 90	450 100 350
Mean Δq abs Mean (Δq) std(Δq) in Daytime/Nighttime	0.04 (0.0) 0.04 (0.03) 0.49 (0.26)	0.05 (0.0) 0.07 (0.02) 0.7 (0.35)	0.38 (−0.03) 0.42 (0.08) 0.94 (0.46)	0.07 (0.0) 0.07 (0.04) 0.9 (0.5)	−0.18 (−0.04) 0.19 (0.09) 1.0 (0.52)
Mean Δ q abs (Δq) std (Δq) in Daytime	−0.06 (0.0) 0.06 (0.04) 0.5 (0.27)	0.17 (0.0) 0.17 (0.05) 0.4 (0.24)	0.2 (0.0) 0.26 (0.06) 0.77 (0.4)	0.0 (0.0) 0.1 (0.07) 0.76 (0.43)	0.0 (−0.02) 0.07 (0.05) 0.86 (0.45)
Mean Δ q abs (Δq) std (Δq) in Nighttime	0.03 (0.0) 0.04 (0.03) 0.47 (0.25)	0.02 (0.0) 0.06 (0.03) 0.73 (0.36)	0.44 (−0.04) 0.47 (0.09) 0.96 (0.47)	0.1 (0.01) 0.11 (0.05) 0.9 (0.5)	−0.27 (−0.06) 0.28 (0.11) 1.1 (0.55)

4. Comparison of COSMIC, ECMWF, and Radiosonde Water Vapor Profiles

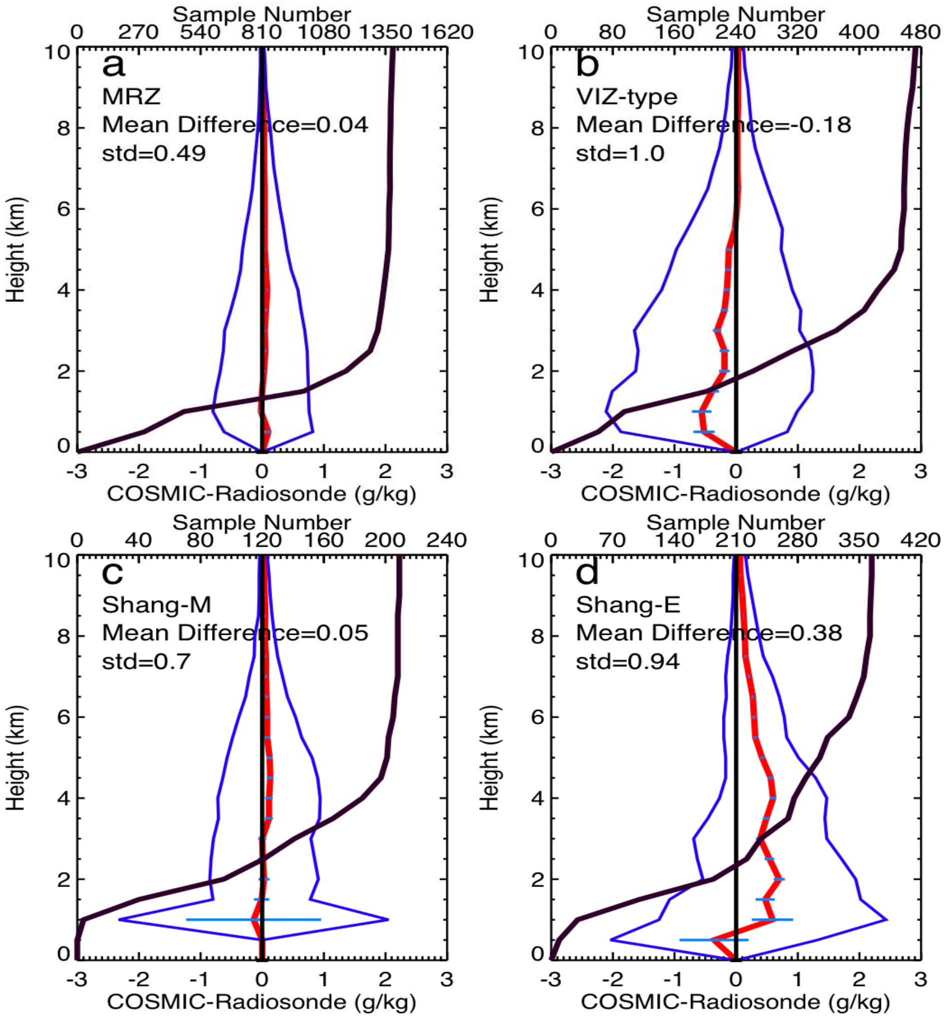
Figure 2 depicts COSMIC-ECMWF specific humidity differences at various locations grouped by different types of radiosondes, such as MRZ, VIZ-type, Shang-M, and Shang-E. In general, the COSMIC specific humidity profiles agree very well with those from ECMWF in different regions. This is evidenced by the relatively smaller variations (in terms of absolute difference and standard deviation (std)) in the COSMIC-ECMWF differences between different geographical areas than those of COSMIC-radiosonde pairs (Table 1). The standard deviations of COSMIC-ECMWF differences for all four regions are about 50% less than those of COSMIC-Radiosonde pairs (see below). This may be due to the fact that COSMIC and ECMWF have similar horizontal resolutions (~100 km for ECMWF) whereas radiosonde data are point measurements. The mean COSMIC-ECMWF biases are very close to zero for different sensors. To estimate the mean specific humidity error due to random error in moisture profiles derived from GPS refractivity profiles and uncertainty of NCEP temperature, here we compute the standard error of the mean (SEM) for each vertical level and plot them in Figure 2. It depicts that the standard error of the computed mean difference (COSMIC RO minus ECMWF specific humidity) at each level in the sampled environment is less than 0.05 g/kg above 2 km, and less than 0.2 g/kg below 2 km, which is consistent with GPS Meteorology (GPS/MET) experiment-ECMWF global comparison from a previous study [12].

Figure 2. Comparison statistics (mean: red; standard error of the mean: horizontal light blue lines superimposed on the mean; mean ± standard deviation: blue; sample number of compared soundings: solid black line) of specific humidity (g/kg) of COSMIC-ECMWF pairs (a) near MRZ radiosondes, (b) near VIZ-type radiosondes, (c) near Shang-M radiosondes, and (d) near Shang-E radiosondes.



Different from the COSMIC-ECMWF specific humidity comparisons, COSMIC-Radiosonde (also for ECMWF-Radiosodne (not shown)) specific humidity differences vary considerably for different sensors (Figure 3). Compared to COSMIC, the VIZ-type contains obvious mean wet biases (0.18 g/kg). This agrees well with the systematic bias of Carbon Hygristors as detailed in [5] (denoted as WZ2008 hereafter). With the same type of humidity sensor, the water vapor differences of COSMIC-MRZ and COSMIC-Shang-M matches are very similar (Figure 3), where both of their mean absolute COSMIC-radiosonde water vapor differences are very close to zero (Table 1). Using IWV derived from ground-based GPS measurements as a reference, WZ2008 found wet biases in IWV for Goldbeater's skin, where the mean absolute COSMIC-radiosonde water vapor difference for MRZ is close to zero (Table 1). This could be due to different dataset used in WZ2008 and this paper, such that, the different spatial and temporal coverage of the radiosonde data used and the different error characteristics of the reference data (ground-based GPS IWV and GPS-RO). For example, most of the COSMIC-MRZ pairs in this study are located in a dry environment with small water vapor variation during the winter season at high latitudes. The mean absolute specific humidity difference for MEISEI is 0.07 g/kg (Table 1), while WZ2008 also found a close to zero IWV bias for Japanese radiosondes.

Figure 3. The same as Figure 2 except for COSMIC-Radiosonde pairs.

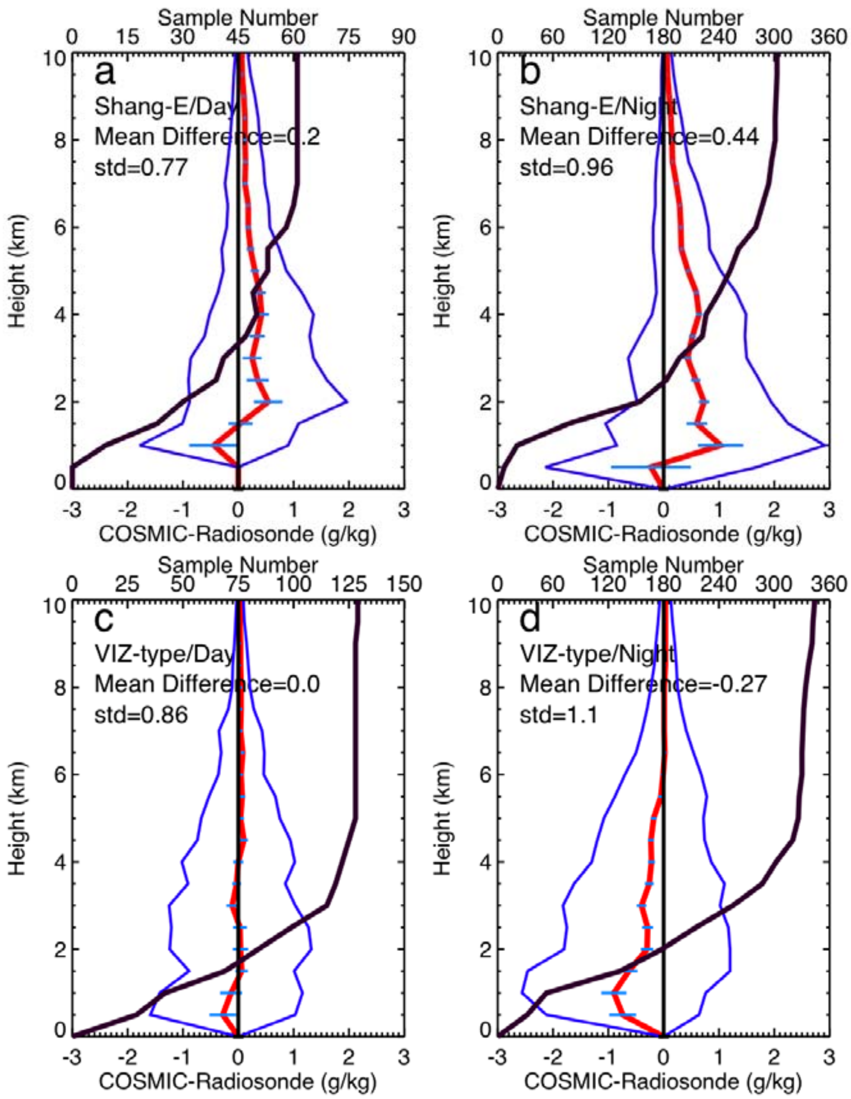


It is depicted in Figure 3 that the water vapor differences for Shang-M and Shang-E are very different. While no obvious specific humidity biases are found for Shang-M, the mean absolute COSMIC-Shang-E specific humidity difference can be as large as 0.38 g/kg. Result here is also consistent with that from WZ2008 although only two stations were used in that study. Note that the collocation criteria for valid RO and radiosonde comparison pairs have a negligible effect on the mean bias calculation. Relaxing the collocation criteria for COSMIC-Shang-E pairs from 2 h and 300 km to 4 h and 500 km merely increases the standard deviation from 0.94 g/kg to 0.96 g/kg.

5. Diurnal Water Vapor Differences between COSMIC, ECMWF, and Radiosonde

The bias of radiosonde measurements may also vary during the day and night for different radiosonde sensor types [4,5,22]. Here we compare COSMIC-Radiosonde WV differences for daytime and nighttime for Shang-E and VIZ-type sondes in Figure 4. It depicts that Shang-E radiosondes contain larger dry biases relative to COSMIC during the night than that during the day. The mean wet bias for VIZ-type radiosonde is equal to 0.27 g/kg with a standard deviation of 1.1 g/kg during the night. WZ2008 also identified a larger wet bias for VIZ-type radiosonde during the night than that during the day. The mean dry bias for Shang-E is equal to 0.44 g/kg with a standard deviation of around 0.96 g/kg during the night whereas it is 0.2 g/kg with a standard deviation of 0.77 g/kg during the day. These water vapor biases may be caused by the combined effect of radiosonde temperature biases due to radiative effect [23] or time lag, or contamination of humidity sensor or hysteresis. For simplification, here we do not further discuss how each effect including the temperature bias from each radiosonde type impacts its water vapor bias. Instead, we use COSMIC-ECMWF specific humidity differences for daytime and nighttime to confirm the accuracy of COSMIC specific humidity profiles and the COSMIC-Radiosonde specific humidity results. Results show that COSMIC specific humidity profiles are very close to those of ECMWF near locations of these five types of radiosonde for both daytime and nighttime (see Table 1). For example, the mean COSMIC-ECMWF specific humidity difference near VIZ-type radiosondes in daytime is equal to −0.02 g/kg with a standard deviation of 0.45 g/kg and it is equal to −0.06 g/kg with a standard deviation of 0.55 g/kg in nighttime (Table 1). The mean COSMIC-ECMWF specific humidity difference near locations of Shang-E radiosondes in daytime is equal to 0.0 g/kg whereas it is −0.04 g/kg in nighttime (Table 1). This demonstrates the usefulness of COSMIC WV for assessing diurnal/geographical water vapor biases for different radiosonde systems.

Figure 4. The same as Figure 3 except for (a) COSMIC-Shang-E pairs during the day, (b) COSMIC-Shang-E pairs during the night, (c) COSMIC-VIZ-type pairs during the day, and (d) COSMIC-VIZ-type pairs during the night.



6. Conclusions and Future Work

In this study, we compare water vapor soundings from different types of radiosonde from August to November 2006 with close collocated COSMIC RO and global ECMWF analyses. We reach the following conclusions.

1. Specific humidity profiles derived from COSMIC data are in a close agreement with those of global ECMWF analysis over different regions for both day and night with a close to zero mean bias and a less than 0.5 g/kg standard deviation. This demonstrates the quality of COSMIC water vapor profiles in the middle and lower troposphere and shows the usefulness of COSMIC WV as an independent reference for quantifying humidity uncertainties among different sensor types.

2. We found that Shang-E radiosondes contain a systematic 0.38 g/kg mean dry bias in the troposphere and VIZ-type contains an obvious 0.18 g/kg wet bias relative to COSMIC specific

humidity retrievals. No obvious water vapor biases are found for MRZ and MEISEI radiosondes. A much larger dry bias (~0.44 g/kg) for Shang-E radiosondes is found during the night than that during the day (~0.2 g/kg). With uniform distribution in time and space, multi-year COSMIC RO data will be very useful to quantify and assess the diurnal/geographical systematic humidity errors among different radiosonde types, which shall help to improve the quality of global radiosonde climate records. This will be the subject for a future study.

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