Review of Characterizing the Tropospheric Water Vapor Variation using COSMIC Radio Occultation and ECMWF Reanalysis Data: Shao et al.

We thank the reviewers for the helpful comments and suggestions. We have previously replied and revised the manuscript according to the first reviewer's comments. Therefore, our further revision of the manuscript and reply to the second reviewer's comment are based on the revised manuscript from the first round. In the following, we summarize our reply to the reviewer.

Title indicates the characterization of water vapour variability using measurements and reanalysis data, but the results and discussion are mostly on the comparison of COSMIC water vapour data with reanalysis at different spatial and temporal scales.

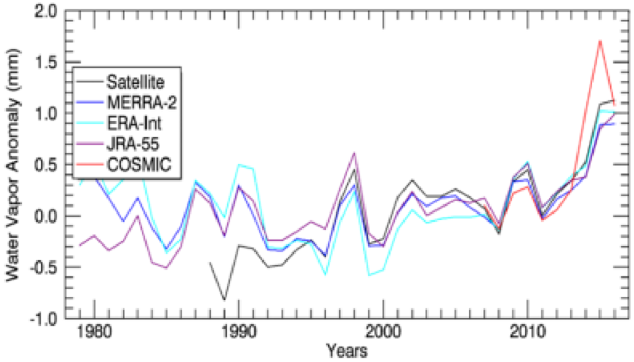
We have revised the title to "Characterizing the tropospheric water vapor spatial variation and trend using 2007-2018 COSMIC radio occultation and ECMWF reanalysis data" following the suggestion from Reviewer #1. This paper focuses on quantifying the consistency and differences of the spatial variability and trend of water vapor from COSMIC RO retrievals and ERA5 reanalysis data. The COSMIC and ERA5 water vapor data at lower (850 hPa), mid- (500 hPa), and upper troposphere (300 hPa) from 2007 to 2018 are compared in terms biases and trends over spatial scales ranging from global, latitudinal to regional. The general consistency between the two datasets demonstrated in this study help cross-validate the water vapor variation and trend at different scales and assure the quality of these datasets for climate studies. We also showed the differences such as the biases at different pressure levels and the differences in water vapor trend estimation between COSMIC and ERA5 over regions in the ITCZ. We provided explanation for the negative water vapor biases in lower troposphere and the need to address and resolve super refraction or ducting in RO 1DVAR retrieval. We agree with the reviewer and point out that further studies with other long-term water vapor data will be needed to resolve the COSMIC vs. ERA5 water vapor trending differences.

Major:

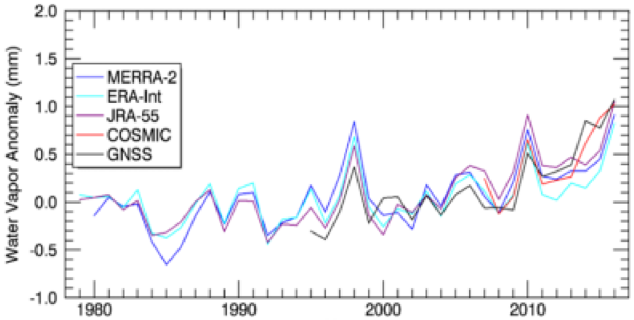
1. Its global comparison, why cannot use ground-based observations like radiosonde, GNSS, GPS, which are commonly used for validation and comparisons. This is very important as reanalysis data can have a relatively large bias in some regions (e.g. tropics, what we have found in our studies).

The ground-based radiosonde, GNSS or GPS observations cover mostly over land. The radiosonde water vapor measurements can differ by different type of radiosondes, e.g., RS41 vs. RS92, and the calibration or correction implemented at the stations (Ho et al., 2010; Sun et al., 2019; Ho et al., 2020a; Shao et al., 2021b). Radiosonde measurement is more suitable to study regional water vapor variability and trends over land. Inter-calibration among different radiosonde stations will be needed to assess global water vapor trend over land. For ground-based GNSS stations, there have been ongoing work of deriving global total column water vapor time series from their observations and check its consistency with other type of observations. Fig. 1 (from Ho et al., 2020a) shows example of global water vapor trend comparison over ocean and land with multiple datasets. The global water vapor trend from GNSS station over land is in general consistent with COSMIC and other reanalysis model results. We agree with the reviewer that the comparison with independent ground-based observations will help address the biases and trend differences between RO and reanalysis model over land.

We cited the paper by Mears et al., 2017 and Patel and Kuttippurath, 2022 and added in Section 6 about the importance of using ground-based GNSS and GPS data for global and regional validation and using radiosonde for regional validation of water vapor data from RO and reanalysis.



(a) Oceans



(b) Land

Figure 1: Global mean total precipitable water vapor annual anomalies for (a) ocean only and (b) land only for observations and reanalysis averaged over 60°S to 60°N. The shorter time series have been adjusted so that there is zero mean difference relative to the mean of the three reanalyses over the 2006–14 period (constructed from same data as in Mears et al. 2017, their Fig. 2.16). (from Ho et al. (2020a))

Mears, C., S. P. Ho, J. Wang, H. Huelsing, and L. Peng, 2017: Total column water vapor [in "States of the Climate in 2016"]. *Bull. Amer. Meteor. Soc.*, **98** (8), S24–S25, https://doi.org/10.1175/2017BAMSStateoftheClimate.1.

Patel, V. and Kuttippurath, J.: Significant increase in water vapour over India and Indian Ocean: Implications for tropospheric warming and regional climate forcing, Science of Total Environment, https://doi.org/10.1016/j.scitotenv.2022.155885, 08 May 2022.

2. You have shown the bias and differences, but no valid reasons are given. Please discuss the reasons for the differences

We added in Section 6 to discuss about the relative water vapor biases between COSMIC and ERA5 at three pressure levels.

"At 300, 500, and 850 hPa, the differences between COSMIC water vapor retrievals and water vapor from ERA5 over the globe are 5.67±34.30%, -1.86±30.09%, and -2.30±21.21%, respectively. Ho et al. (2010) and Shao et al. (2021b) showed systematic negative water vapor biases below 5 km for RO retrievals in comparison with radiosonde data. Such negative water vapor biases can be traced to the negative RO bending angle biases when compared with reanalysis model (Ho et al., 2020a). The negative water vapor biases below 5 km, *e.g.*, at 500 and 850 hpa as studied in this paper are mainly due to the underestimation of water vapor in RO retrieval in the presence of atmospheric super-refraction or ducting in the moisture-rich low-troposphere (Sokolovskiy, 2003; Ao et al., 2003; Xie et al., 2006; Ao, 2007). Super-refraction occurs when the vertical atmospheric refractivity gradient exceeds a critical refraction threshold, *i.e.*, in the presence of a sharp change in refractivity. Such sharp change often exists around the planetary boundary layer where sharp vertical gradient in moisture and temperature inversion are frequently observed. To address the negative moisture biases in RO retrieval and account for super-refraction or ducting, there are efforts of improving the 1DVAR retrieval algorithm by incorporating the reconstruction method introduced in Xie et al. (2010). Our study shows that the negative water vapor biases at 850 hPa are dominantly in the -40^o to 40^o (tropical and sub-tropical) moisture-rich regions. This study does show that the global (Fig. 4 and Table 1) water vapor trends are in general consistent with ERA5 at 500 and 850 hPa although the negative water vapor biases are present at these two pressure levels. At 300 hPa, there is a positive bias in COSMIC global water vapor compared to ERA5. Johnston et al. (2021) showed opposite sign of the ERA5 and MERRA2 model water vapor differences relative to COSMIC-2 in the upper troposphere. The positive bias we observed is consistent with Johnston et al. (2021) and can be due to the large uncertainties in retrieving water vapor in reanalysis model in the upper troposphere with low concentration of water vapor."

On the trending difference between COSMIC and ERA5, we explained in Section 6 as "From our analysis, the regions with notable trend differences between COSMIC and ERA5 water vapor trend estimations are mostly distributed within the northern and southern boundary of the ITCZ area, over the Indo-Pacific warm pool or central Africa. These regions experience frequent convection, such as deep convective clouds. Because of the cloud-penetration property of GNSS signal and higher height-resolution of RO retrieval, it can be better characterized for the height and temporal distribution of water vapor in RO retrievals than ERA5 in the presence of convection, such as deep clouds. The better representation of water vapor in RO data may cause the difference in water vapor trend estimation between COSMIC and ERA5 over these regions, which will need further studies with other long-term water vapor data.".

Ao, C. O., T. K. Meehan, G. A. Hajj, A. J. Mannucci, and G. Beyerle (2003), Lower-troposphere refractivity bias in GPS occultation retrievals, *J. Geophys. Res.*, **108**(D18), 4577, doi:10.1029/2002JD003216.
Ao, C. O. (2007), Effect of ducting on radio occultation measurements: An assessment based on high-resolution radiosonde soundings, *Radio Sci.*, **42**, RS2008, doi:10.1029/2006RS003485.

Johnston, B.R., Randel, W.J., Sjoberg J.P.: Evaluation of Tropospheric Moisture Characteristics Among COSMIC-2, ERA5 and MERRA-2 in the Tropics and Subtropics. *Remote Sensing*. 13(5), 880, DOI: 10.3390/rs13050880, 2021.
Sokolovskiy, S. (2003), Effect of superrefraction on inversions of radio occultation signals in the lower troposphere, *Radio Sci.*, 38, 1058, doi:10.1029/2002RS002728, 3.
Xie, F.; Syndergaard, S.; Kursinski, E.R.; Herman, B.M. An Approach for Retrieving Marine Boundary Layer Refractivity from GPS Occultation Data in the Presence of Superrefraction. *J. Atmos. Ocean. Technol.* **2006**, *23*, 1629–1644, https://doi.org/10.1175/jtech1996.1.
Xie, F.; Wu, D.L.; Ao, C.O.; Kursinski, E.R.; Mannucci, A.J.; Syndergaard, S. Super-refraction effects on GPS radio occultation refractivity in marine boundary layers. *Geophys. Res. Lett.* **2010**, *37*, https://doi.org/10.1029/2010gl043299.
Ho S-p, Kireev S, Shao X, Zhou X, Jing X.: Processing and Validation of the STAR COSMIC-2 Temperature and Water Vapor Profiles in the Neutral Atmosphere. *Remote Sensing*., 14(21):5588, doi.org/10.3390/rs14215588, 2022.

Specific Comments:

Line 110-117: Please move these sentences to Data section, where COSMIC water vapour description is given.

L110-117 have been moved to Section 2.2 COSMIC WETPrf water vapor retrieval.

Line 147: The ERA5 water vapour…….pressure levels. This sentence is about the availability of ERA5 water vapour at different pressure levels, so please move this to lines 140-145.

This sentence has been moved to the suggested location.

Line 182: Why only three pressure levels? 850, 500 and 300 hPa, and why these particular altitudes?

We have added the motivation for selecting three pressure levels in this study in Section 2.2 (L173) as "For RO data, the fine vertical resolution COSMIC RO water vapor profiles are interpolated onto three pressure levels, e.g., 300, 500, and 850 hPa, selected to characterize water vapor variations at representative heights around 9 km, 5.5 km, and 1.5 km, respectively. In particular, the pressure level at 850 hPa is close to the surface, and the COSMIC water vapor retrieval is strongly affected by super-refraction in the moisture-rich regions (Ho et al., 2010). The retrieved water vapor at 850 hPa from COSMIC data could differ from ERA5, making it worth evaluating the relative biases and consistency in the trends between these two datasets. Starting from the pressure level at 500 hPa, the RO-water vapor retrieval uncertainty increases as height decreases. The 300 hPa pressure level represents the water vapor with less horizontal variations at higher heights."

Line 186: Give references

We added the reference "Fujiwara et al., 2017 and Hersbach et al., 2020".

Figure 1 and Line 185-197: What is the need of comparing COSMIC water vapour with both ERA5 and ERA-Interim, if it is already stated in Line 185-186 that the ERA5 water vapour retrieval is better than that of ERA-Interim? Also, why only January and July are considered here"?

The UCAR's 1DVAR retrieval algorithm for COSMIC WETPrf (water vapor and humidity) uses ERA-Interim background profiles as the *a priori* input (Wee et al., 2022). In addition, the UCAR water vapor/temperature retrieval also enforces a retrieval constraint to the residual refractivity (refractivity computed from the final temperature and moisture minus the observed refractivity). Such constraint can determine the influence of ERA-Interim on the final water vapor retrieval at different pressure levels. On the other hand, the ERA5 provides a more comprehensive and reliable reanalysis by using improved weather forecast and data assimilation models with various ground, in-situ, and satellite measurements compared to ERA-Interim (Fujiwara et al., 2017 and Hersbach et al., 2020). To understand the impacts of ERA-Interim on the UCAR 1DVAR COSMIC water vapor retrieval, we use the comparison of the COSMIC retrieval with ERA5 as the reference. We have added these explanations to the paragraph above Figure 1 (L182 to L188).

The two months (January and July) are selected as two representative months (winter and summer of northern hemisphere) to show the relative seasonal consistency in the comparisons of collocated COSMIC water vapor retrieval versus ERA5 and ERA-Interim water vapor data. We also revised L187 to explain the motivation as "**Error! Reference source not found.** depicts the monthly (using January and July of 2007 as representative winter and summer months of the northern hemisphere) scatter plots of the collocated COSMIC global water vapor versus ERA5 and ERA-Interim water vapor data at three pressure levels." to explain the motivation.

Section 3.1 Global distribution of water vpour:

Why authors have shown the distribution of water vapour at 10-degree latitude and longitude grid not in the original resolution of COSMIC and ERA5? If bias is computed at a coarser spatial resolution, there might be a chance of large uncertainty and the regional variability will not be reflected in the bias estimates.

The 10×10 degree latitude and longitude grids were chosen to match the later discussion of regional trends over the same 10×10 degree resolution grids. While ERA5 can have finer uniform longitude and latitude grids, the COSMIC profile locations are non-uniform. We have to specify grids with finite latitude and longitude bins to organize the COSMIC data. As we showed in Figure 6 (The percentage of missing monthly data over the 2007 to 2018 interval on the global $10^o \times 10^o$ grids), there can be locations with missing monthly data on the global $10^o \times 10^o$ grids due to the varying number of COSMIC data. Our analysis excludes grids with > 2-month missing monthly data from the trend calculation. We agree with the reviewer that it is a tradeoff of choosing finer grids to reduce regional variability and uncertainty while keeping sufficient samples in the grid. The 10×10 degree grids seem to be optimal for both COSMIC bias and trend estimation.

Line 232: Why COSMIC water vapour overestimates ERA5 in the upper troposphere?

The main cause for higher water vapor retrieved by COSMIC than ERA5 at 300 hPa can be due to the low concentration of water vapor in the upper troposphere and the large uncertainty in retrieving water vapor in the reanalysis model. Johnston et al. [2021] analyzed COSMIC-2 and reanalysis models (ERA5 and MERRA2) water vapor difference in different latitude zones and their results are shown in the figure below. The UCAR COSMIC-2 water vapor retrieval is consistently lower than both ERA5 and MERRA2 water vapor data in the lower troposphere (below 2 km). However, COSMIC-2 water vapor retrieval is higher than ERA5 data and lower than MERRA2 data at heights above 4 km. The magnitude of COSMIC-2 vs. ERA5 water vapor difference is smaller than that of COSMIC-2 vs. MERRA2. The opposite sign and large magnitude of the ERA5 and MERRA2 model water vapor differences relative to COSMIC-2 in the upper troposphere suggest the large uncertainties in retrieving water vapor in reanalysis model over this height region.

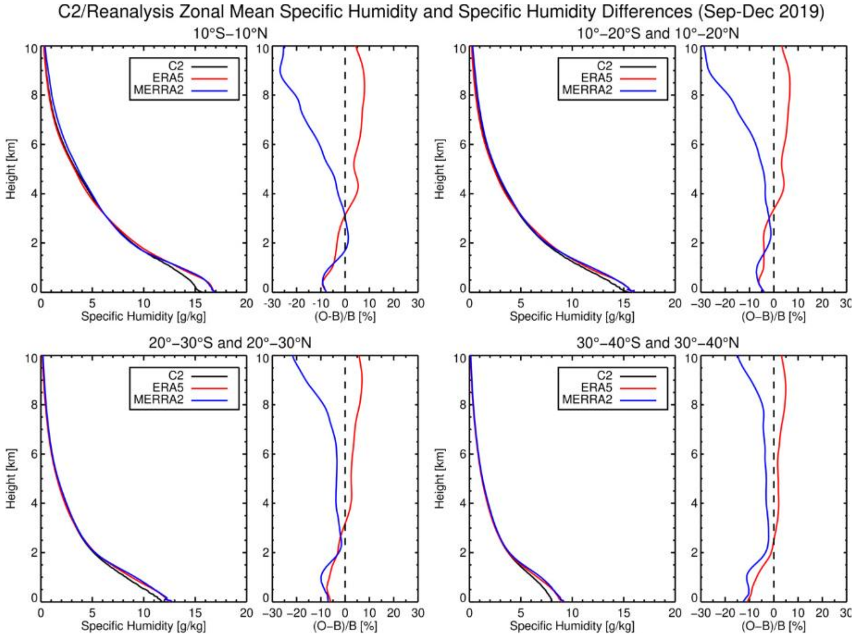


Figure 2: COSMIC-2 and Reanalysis Model (ERA5 and MERRA2) mean water vapor and water vapor difference comparison in different latitude zones (from Johnston et al. (2021)).

Johnston, B.R., Randel, W.J., Sjoberg J.P.: Evaluation of Tropospheric Moisture Characteristics Among COSMIC-2, ERA5 and MERRA-2 in the Tropics and Subtropics. *Remote Sensing*. 13(5), 880, DOI: 10.3390/rs13050880, 2021.

Line 232-233: Since the water vapour concentration at 300 hPa is very small, its contribution to the total precipitable water would also be very small.

We have revised this sentence according to the suggestion.

Section 3.3 Seasonal variability of COSMIC and ERA5 water vapour distribution: If you want to discuss the seasonal variability, discuss the seasonal changes and then present the bias. Also, why authors have divided the latitude in 20-degree interval here? Why not tropics, mid-latitude and Polar Regions then?

This section on seasonal variability analysis has been moved to Appendix 1 following the first reviewer's comments. We followed the reviewer's suggestion and moved the section on seasonal changes to where before discussing the biases between COSMIC and ERA5.

The 20-degree wide latitude bins over northern and southern hemispheres are selected to characterize water vapor latitude-dependence in different reprehensive latitudinal zones such as 0^o-20^o for tropical, 20^o-40^o for sub-tropical, 40^o-60^o for mid-latitude, and 60^o-80^o for high-latitude regions. In this way, we can also study the differences in the northern and southern hemisphere. When discussing the seasonal variability in tropical region, we do combine the -20 to 20 latitude bins.

Line 339-341: It is already mentioned in the previous section "Decline in water vapour in southern hemisphere is faster than the northern hemisphere"

This section have been moved to Appendix 1 and we removed the sentence "In Fig. A.3, the decrease of $Q_{max,COSMIC}$ as |latitude| increases from 20^o are more rapid in the southern hemisphere than in the northern hemisphere,….." in the revised manuscript.

Line 364: This sampling error does not affect the bias discussed in the previous section? If it is, then how authors have addressed this issue?

This sampling error affects the trend estimation and does not affect the relative biases between COSIC and ERA5 discussed in the previous section. The relative biases are estimated from the collocated COSMIC and ERA5 data.

Line 386-387: Sampling error for COSMIC ? Also, for ERA 5?

Thanks for catching this. It is a bit misleading. The sampling error removal is only for COSMIC. As noted on L, for ERA5 data, the application of sampling error Q_{SE} removal to $\overline{Q_{ERA5\_sample}}$ essentially recovers $\overline{Q_{ERA5\_RoI}}$. So, when calculating ERA5 trend, we only need to calculate $\overline{Q_{ERA5\_RoI}}$ and don't need to apply sampling error removal. We made the correction "we need to apply sampling error removal to COSMIC data".

Line 408-409: "which is mainly due to the difference between the orbital-specific distribution of COSMIC RO observations and uniformly-distributed global ERA5 data". Give references for this statement. Also, how orbital-specific distribution of COSMIC RO observations cause oscillations in the sampling error?

We added a reference: Ho et al. (2020). Example of monthly local time and latitudinal distribution of RO profiles retrieved from COSMIC-1 data are shown in Fig. 3 (see below). We can see the nonuniform distribution of the COSMIC-1 profiles in both local time and latitudes, which is due to the limited local time and latitude coverage of the orbits of the small satellites in the COSMIC-1 constellation. The non-uniform local time and latitude distribution of COSMIC-1 profiles coupled with the annual variation of the Sun's declination contribute to the seasonal oscillation in the sampling error time series.

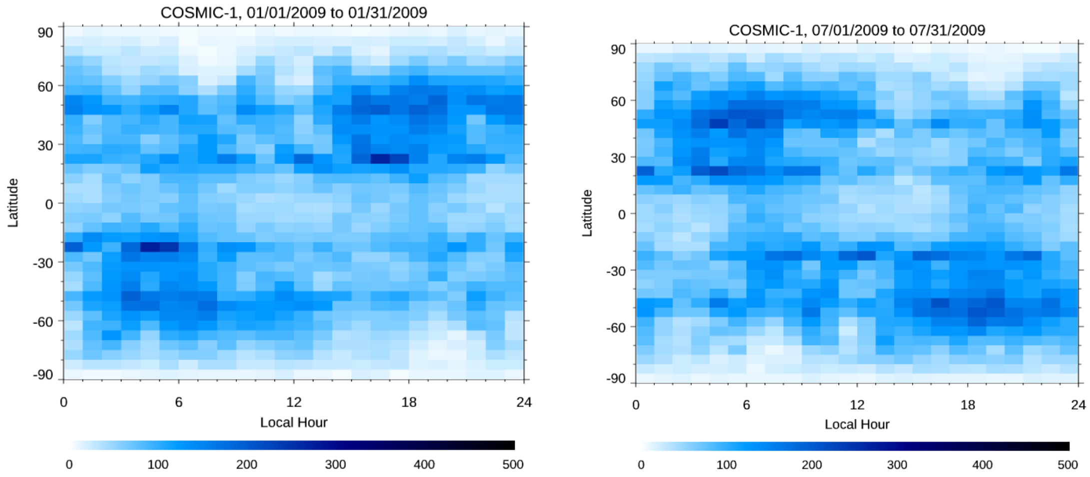


Figure 3: Example of monthly local time and latitudinal distribution of RO profiles retrieved from COSMIC-1 data.

Line 411: Why COSMIC sampling decreases significantly after 2017?

This is due to that three of the six small satellites in the COSMIC-1 constellation stopped working during the time interval from 2015 to 2017. After 2017, there were only two small satellites in COSMIC-1 that were still in operation. See Figure X and answer to the next question for more details.

Figure 8: Sampling is very small in 2011 as compared to that in 2007-2009. Its almost constant in 2011-2014, and then decreases until 2019. Why these disparities in the sample numbers?

There are six small satellites (C1E1 to C1E6) in COSMIC-1 constellation. The service interval and performance of these six satellites vary over time. Figure below shows the variation of the monthly profile numbers of these six small satellites in COSMIC-1. C1E3 is the first satellite that stopped producing data in the middle of 2010. C1E2, C1E3 and C1E4 ended their operations over the time interval from 2015 to 2017. C1E1 and C1E6 continued in operation until the middle of 2019 and early 2020, respectively. Due to the varying performances and availabilities of C1E1 to C1E6, the time series of the combined valid profile numbers from these six satellites thus show the pattern shown in Figure A.4 (Figure 8 in previous draft).

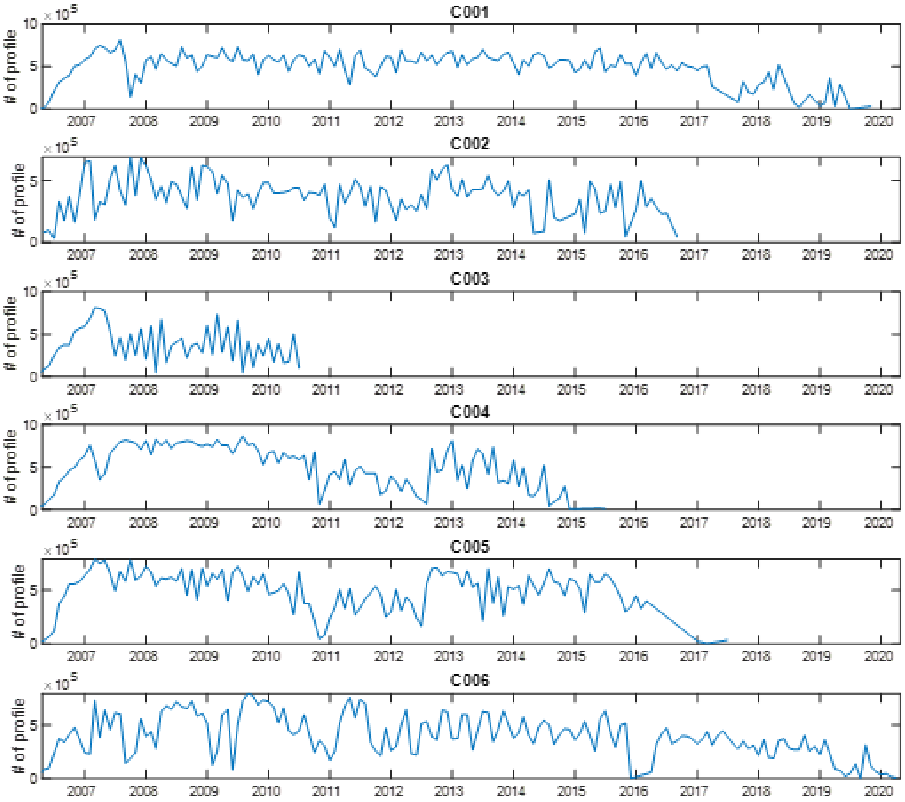


Figure 4: Time series of monthly profile number of the six small satellites (C1E1 to C1E6) of COSMIC-1.

Figure 9: Water vapour is increasing from 2008 to 2010, almost constant from 2011 to 2014, then again increased during the period 2014-2017, and finally it shows constant (i.e., no trends) at all three pressure levels. Why these particular distributions? Discuss

The two intervals of water vapor increase over 2009-2010 and 2015-2016 are associated with the two large El Nino events during these two periods. These warm events can enhance surface evaporation, increase tropospheric water vapor, and warm the entire tropical troposphere (e.g., Zveryaev and Allan 2005; Trenberth et al. 2005). However, even without the ENSO impact, global mean tropospheric water vapor especially in the tropics still shows evident upward trend following global surface warming (e.g., Allan et al. 2022).

Trenberth K.E., J. Fasullo, and L. Smith, 2005: Trends and variability in column-integrated atmospheric water vapor. Clim. Dyn., doi:10.1007/s00382-005-0017-4.

Zveryaev, I.I. and R.P. Allan, 2005: Water vapor variability in the tropics and its links to dynamics and precipitation. J. Geophys. Res.-Atmos., 110, D21112, doi:10.1029/2005JD006033.

Allan et al. (2022): Global changes in water vapor 1979-2020. JGR-Atmos, 127, e2022JD036728. https://doi.org/10.1029/2022JD036728.

Line 480: How these results can be consistent or even comparable with Chen and Liu (2016)? They have computed the PWV trends (entire column of water vapour). Here only three pressure levels are taken. Please cite some other references, in which tropospheric water vapour trends are computed.

We added a reference to Allan et al. (2022). The revised texts read "Allan et al. (2022) studied the global-scale changes in water vapor and responses to surface temperature variability since 1979 using coupled and atmosphere-only CMIP6 climate model simulations. In the water vapor trend estimation over the 1988 to 2014 period, Allan et al. (2022) showed positive increase of global water vapor at near surface, at 400 hPa and Column Integrated Water Vapor from ensemble of climate model simulations with the CMIP6 historical and amip experiments. The period of COSMIC RO data studied in this paper partially (2007 to 2014) overlaps with the simulations from Allan et al. (2022). The increasing trend in the global atmospheric water vapor concentration at three pressure levels from our trend analysis is generally consistent with the results from Allan et al. (2022)".

Line 488-491: Again, Chen and Liu (2016) is used here for the comparison.

We removed the citation to Chen and Liu (2016) and added citation to Allan et al., (2022). The sentence has been revised as "It was also shown in Allan et al. (2022) that in the ensembled historical experimental model simulations, the water vapor increases by 1.53 and 3.52 %/Decade at surface and at 400 hPa, respectively. Our study shows that the increasing global water vapor trends estimated with 2007-2018 COSMIC data are 2.03±0.65, 3.25±1.25, 3.47±1.47 %/Decade at 850, 500 and 300 hPa, respectively, which are in general agreement with the results from in Allan et al. (2022), considering that the two work cover two distinct periods with 8 overlapped years. In Allan et al. (2022), there is an increase of water vapor trend from surface to at 400 hPa by ~2 %/Decade. Our work shows an increase of positive water vapor trend by 1.44 %/ Decade when height varies from near surface (at 850 hPa) to 300 hPa, which is also in general consistent.".

Line 523-527: It can't be directly attributed to the dry atmosphere.

We revised the sentence as "The only latitude bin with a small negative water vapor trend with large uncertainty is in the -80^o to -60^o southern high latitude bin at 500 hPa. From the global surface temperature trend analysis by Gu and Adler, 2022, there is a mixture of weak decreasing trend in the surface temperature at the Southern Ocean around Antarctic and an increasing trend of over Antarctic in the 60 to 80 degree southern latitude zone. However, the uncertainties of estimating both the temperature and water vapor trends in this latitude zone are large."

See Figure 5 below for the global surface temperature trend map from Gu and Adler, 2022.

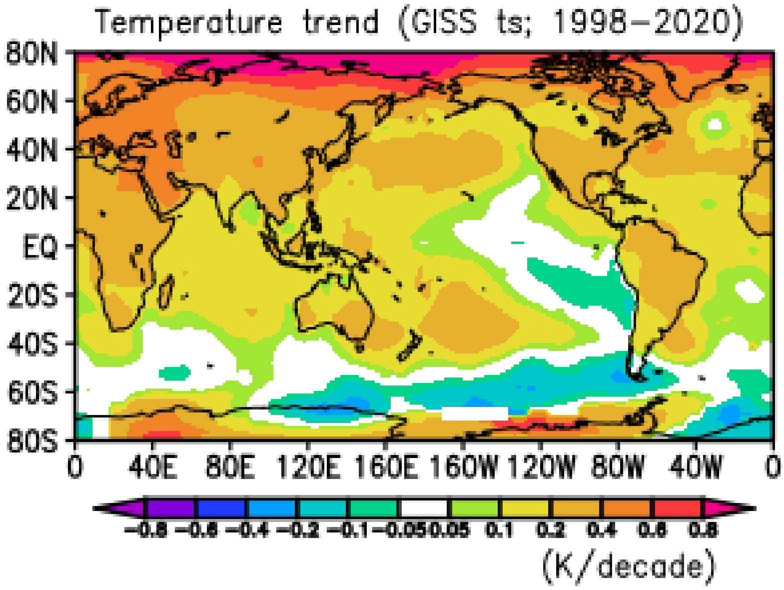


Figure 5: Linear trend in global surface temperature (K/decade) during 1998-2020.

Gu, G., and Adler, R. F.: Observed Variability and Trends in Global Precipitation During 1979-2020. *Clim. Dyn.*, https://doi.org/10.1007/s00382-022-06567-9, 2022.

Line 531: What do you mean by the most stable water vapour trend?

"most stable" is not correct. It should be "the lowest water vapor trend".

Line 622-623: This sentence about sea surface temperature has no meaning here. Better to write the trends in sea surface temperature, which can influence the water vapour trends.

This sentence has been changed to: "Sea surface temperature has been increasing in the western Pacific during the recent decades (e.g., Gu and Adler 2022)".

Gu, G., and R. F. Adler, 2022: Observed Variability and Trends in Global Precipitation During 1979-2020. *Clim. Dyn.*, https://doi.org/10.1007/s00382-022-06567-9.

Line 625: "Indo-Pacific warm pool region and increase in the equatorial region of the Pacific Ocean is what we here observe." I do not see any analysis here for making this statement.

We have revised the sentence to "Sea surface temperature has been increasing in the western Pacific during the recent decades (e.g., Gu and Adler 2022). There is a high correspondence with regards to the trends in sea surface temperature and tropospheric water vapor in the western Pacific during the recent decades (e.g., Gu and Adler 2013). It was shown by Chen and Liu (2016) that the moderate increase in surface temperature over the Pacific Ocean could cause the PWV to increase in the equatorial region of the Pacific Ocean and decrease in this Indo-Pacific warm pool region, which is what we observe here. Further quantitative analysis of trends at selected locations in the Pacific Ocean (Sites # 4, 16 in Fig. 8) and in Indo-Pacific warm pool region (Site #14 in Fig. 8) will be performed in the following sections.”.

Gu, G., and R. F. Adler, 2013: Interdecadal Variability/Long-Term Changes in Global Precipitation Patterns during the Past Three Decades: Global Warming and/or Pacific Decadal Variability? *Clim. Dyn.*, 40, 3009-3022. doi: 10.1007/s00382-012-1443-8.

Line 626-630: How monsoon climate and precipitation affect the trends in water vapour in these regions? Precipitation is known for the sink of water vapour. Discuss this.

We added the discussion as “This region is affected by the monsoon climate over the south of the Himalayas, resulting in a sizeable regional change in precipitation at different seasons. Indian Ocean is the essential part of the coupled Indian monsoon system because it feeds the moist convection over both land and ocean. Convection, precipitation, and water vapor are also a fully coupled process. It is shown that the Indian Ocean has been warming up during the recent decades (see Figure 5 from Gu and Adler, 2022), which is the driver for positive water vapor trend in this region.”

Figure 14: How these sites are selected?

We have added the motivation at L509 in the revised manuscript “In the following sections, we selected a few representative sites, such as stratocumulus cloud-rich sites (section 5.2), sites with notable increasing (wetter) and decreasing (drier) water vapor trends (Section 5.3), and sites with a notable difference between ERA5 and COSMIC trends (Section 5.4) to understand the spatial variability of water vapor trends. Their center locations are shown in Fig. 8. These established sites are in 10^o by 10^o latitude/longitude grids.”

In Section 5.2, 5.3 and 5.4, we explained the selection of the specific group of the representative sites.

Section 5.2: Without analysing cloud data how authors identified the regions of Stratocumulus clouds?

The three regions rich of Stratocumulus clouds are selected according to the regions identified in Wood et al., 2011; Wood, 2012 and Ho et al., 2015. We have added these references.

Ho, S.-P., L. Peng, R. A. Anthes, Y.-H. Kuo, and H.-C. Lin 2015: Marine boundary layer heights and their longitudinal, diurnal, and interseasonal variability in the southeastern Pacific using COSMIC, CALIOP, and radiosonde data. *J. Climate*, **28**, 2856–2872, https://doi.org/10.1175/JCLI-D-14-00238.1.

Wood, R., Mechoso, C. R., Bretherton, C. S., Weller, R. A., Huebert, B., Straneo, F., Albrecht, B. A., Coe, H., Allen, G., Vaughan, G., Daum, P., Fairall, C., Chand, D., Gallardo Klenner, L., Garreaud, R., Grados, C., Covert, D. S., Bates, T. S., Krejci, R., Russell, L. M., de Szoeke, S., Brewer, A., Yuter, S. E., Springston, S. R., Chaigneau, A., Toniazzo, T., Minnis, P., Palikonda, R., Abel, S. J., Brown, W. O. J., Williams, S., Fochesatto, J., Brioude, J., and Bower, K. N.: The VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-REx): goals, platforms, and field operations, Atmos. Chem. Phys., 11, 627–654, https://doi.org/10.5194/acp-11-627-2011, 2011.

Wood, R., 2012: Stratocumulus clouds. Mon. Wea. Rev., 140, 2373– 2423, doi:10.1175/MWR-D-11-00121.1.

Line 661: “RO data can penetrate the cloud, and the water vapour retrieval from RO data is not affected by the stratocumulus cloud.” Reference for this statement.

RO signal can penetrate the cloud because the wavelengths for L1 and L2 frequency of radio occultation signals are around 19 cm and 24.2 cm, respectively, which are much larger than the size of cloud water droplets and ice crystals (Kursinski et al., 1997).

Kursinski, E. R., , G. A. Hajj, J. T. Schofield, R. P. Linfield, and K. R. Hardy, 1997: Observing Earth’s atmosphere with radio occultation measurements using the Global Positioning System. J. Geophys. Res., 102, 23 429–23 465, https://doi.org/10.1029/97JD01569.

Line 675: “The possible cause of smaller trends from ERA5 water vapour data over stratocumulus cloud-rich regions could be difficulty in accurately estimating water vapour at low height in ERA5 reanalysis data compared with COSMIC RO measurements”. Can you provide the reference for the statement?

We added the reference to Lonitz and Geer 2017.

Lonitz, K., and Geer, A.: Effect of assimilating microwave imager observations in the presence of a model bias in marine stratocumulus, EUMETSAT/ECMWF Fellowship Programme Research Reports, https://www.ecmwf.int/node/17164, 2017.

Section 5.3: What is the basis for the selection of these sites?

To select sites with notable increasing and decreasing water vapor trends shown in Section 5.3, we searched the 10×10 degree global grids and identified the regions with the largest increasing and decreasing water vapor trends. Within these regions, we selected the representative sites and these sites are listed in Table 4 and Table 5.

Line 695: Where is the analysis of trends in ocean surface temperature?

We have added the citation to the ocean surface temperature studies and revised the sentence as “Many previous studies have explored the trends in surface temperature (e.g., Gu and Adler, 2022 and references therein). Global surface keeps warming up, though with rich spatial structures of temperature change. From the study by Gu and Adler, 2022, ocean surface warming can readily be seen in the Indian Ocean and tropical Pacific Ocean, roughly corresponding to the strong increasing tropospheric water vapor trends for Site#4, #5, and #8 we observed.” See Figure 5 in this reply (from Gu and Adler, 2022) on the global trend in NASA GISS surface temperature during 1998-2020, roughly corresponding to the period focused in our study.

Line 726-729: For site#17 ……….Pacific Ocean is on the west. The reasons stated for the decline in water vapour at site#17 are not convincing.

We did more research on this and attribute the decline in water vapour at site#17 to the regional sea surface temperature decrease in this region. From the above figure "Linear trend in global surface temperature (K/decade) during 1998-2020" from Gu and Adler 2022 in our reply to Line 695, we can see an overall temperature decrease in this region at Site #17. We have revised the corresponding text "From the study of linear trend in global surface temperature during 1998-2020 by Gu and Adler, 2022, there is a trend of decreasing ocean surface temperature (~-0.1 K/Decade) near Site #17, which matches the decrease of water vapor observed by COSMIC.".

Line 729-730: Water vapour at 850 hPa is not a precipitable water vapour. Also, there is no "near-surface precipitable water vapour".

We have removed the word "precipitable".

Line 731: Again, precipitable water vapour, it just water vapour at 850 hPa.

We have removed the word "precipitable".

Line 732: Earlier it is mentioned that COSMIC measurements are not affected by stratocumulus cloud, then how it becomes more challenging here?

The original sentence says "which makes it more challenging to accurately estimate $D_{Q,ERA5}$ than $D_{Q,COSMIC}$" and it intends to state that it is more challenging to accurately estimate water trends from ERA5 data than from COSMIC data. This is consistent with the earlier statement that COSMIC measurements are not affected by stratocumulus cloud.

We have revised the sentence to "which makes it more challenging to accurately estimate water trends from ERA5 data than from COSMIC data".

Section 6: Most of the results and discussion are repeated here with the same references. Please rewrite this section and draw a solid conclusion.

We made the following changes to Section 6.

- We only listed the key findings from this study in this section.
- We added new citation to Fujiwara et al., 2017.
- We added new discussion about the COSMIC vs. ERA5 biases at three pressure levels and cited new references (Sokolovskiy, 2003; Ao et al., 2003; Xie et al., 2006; Ao, 2007; Xie et al., 2010).
- We removed summary about seasonal variability.
- We also added "In particular, the comparison with long-term ground-based GNSS and GPS data (Mears et al., 2017) and radiosonde data (Patel and Kuttippurath, 2022) can help address the biases and trend differences between RO and reanalysis model over land."

Also, please crosscheck the citation Liu et al. (2016) in Line 838.

We have changed the reference to Allan et al., 2022.