The following is a point-to-point response to the reviewer's comments.

Response to Referee #2:

The paper investigates the water vapour variations, as derived from GNSS, during heavy rainfall events in Hong Kong. Both the 2-d Precipitable Water Vapour (PWV), and 4-d variations (from tomography) are studied. I find the study of the 4-d variations especially interesting.

I have already reviewed this paper when it was recently submitted to a different Journal. Since I see that the Authors did not modify the paper before submitting it to ANGEO, I will include also some major comments arisen in the second round of that review. I will refer all the comments to the document angel-2018-76-AC1-supplement.pdf.

- ✓ Thanks for the reviewer's comments, actually, we have tried our best to modify the comments and suggestions proposed by two reviewers before submitting it to ANGEO, and the corresponding responses to two reviewer's comments have been uploaded with the manuscript when we first submitted this manuscript to ANGEO.
- ✓ Additionally, we appreciate for the reviewer's second review of this manuscript. we have tried our best to revise the manuscript according to the reviewer's comments and suggestions.

General comments

The research design is not appropriate to make most of assessments; the results are not clearly presented and commented. The conclusions are not fully supported by the shown figures. The paper needs to include more comparison/validation data in order to evaluate the results.

- ✓ Thanks for the reviewer's comments, this manuscript has been improved by reducing some contents about 2-d PWV variations and some figures have been removed. Figures 2 and 3 have been replaced to make it observed clearly. The results and conclusions have been revised according to the reviewer's suggestion. Additionally, the explanation about the comparison/validation of tomographic result has been added in section 4.2.

The topic of the application of GPS tomography to study the water vapour variations during rainfall is definitively worth to be deeply investigated. However, such a study needs to include validation using an alternative technique or at least a detailed discussion on what variations one could expect. If that would be done, the study would also serve as a further validation of the GNSS tomography technique.

In this paper it is hard to say if the detected variations are real or simply some artifacts of the tomographic solution. As a matter of fact, the comparison with radiosondes made in the paper (Fig 6) is not convincing. It is reasonable not expecting a perfect agreement between radiosondes and tomography for a number of reasons. But, the tomographic profiles show too many abrupt variations respect to the radiosonde profiles. It should be pointed out that the resolution of the radiosondes may not be as bad as it looks like. Commonly, a radiosonde samples with a relatively high vertical resolution (10-50 m). However, reported are normally only the values at heights where there are significant

variations in at least one of the meteorological parameters, as well as for a number of predefined standard pressure levels. Hence, a big gap in the radiosonde data does not necessarily mean that data is missing, but rather that the variations of the meteorological parameters in this interval were rather smooth. Under these circumstances the tomographic solution should be further checked in order to demonstrate that the temporal variations seen in the tomographic profiles are real (what is important for the conclusions of the paper).

✓ Yes, we agree with the reviewer's opinion that the study needs validation. Actually, we have performed the validation and the tomographic results have been compared with that from radiosonde and ECMWF ERA-Interim data in our previous studies (Yao and Zhao, 2016, 2017; Zhao et al., 2017; Zhao et al., 2018). Due to this paper is mainly focus on the analysis of 4-d water vapour variations vertically during the heavy rainfall events and a series of quality evaluations of vertical profiles derived from GNSS tomography reconstruction have been carried out by our research group for the research area in the previous studies, therefore, a more detailed comparison information is not presented in this paper. The corresponding description and explanation have been added in P13L300-305.

✓ In our opinion, the detected variations derived from tomographic technique are relatively real for some reasons: (1) it can be observed from Figure 4 that the tomographic profiles are consistent with that from the radiosonde data at most heights; additionally, some studies have been carried out to obtain the atmospheric water vapor field in Hong Kong using the tomography technique by our research group and a good performance of tomographic result has been verified (Yao and Zhao, 2016, 2017; Zhao et al., 2017; Zhao et al., 2018); (2) Yes, it can be found that some abrupt variations are existed derived from tomographic result in Figure 4, but it is related with the weather conditions. According to the reported from Hong Kong Observatory, it is rained during the period of 19 to 27 July, 2015, and the following Figure (Figure 1) gives the hourly precipitation of SSP rain gauge during the period of 20 to 23 July, 2015. This station is selected because it is close to the radiosonde station (45004). It can be observed from Figure 1 that it was rained at UTC 00:00 of 20, 21, 22 and 23, therefore, the profile fluctuations are relatively large at those times as presented in Figure 4. On the contrary, there was no rain happened at UTC 12:00 of 20, 21, 22 and 23, and the profile fluctuations are relatively small. (3) it can be observed from Figure 5 that the profile fluctuations are not always large, and their fluctuations correspond to the occurrence of rainfall. Therefore, we think the tomography-derived water vapor profiles are relatively real in this paper, at least it can reflect the general variation of water vapor in vertical direction, especially during the rainfall period.

✓ As for the problem of radiosonde data, we have analyzed and removed the data of some layers because of the errors in pressure, water vapor pressure or temperature following some principles (Wang et al., 2008; Wang et al., 2016). Therefore, the radiosonde profiles are relatively coarse. Additionally, we have checked the radiosonde files carefully, which downloaded from ftp://ftp.ncdc.noaa.gov/pub/data/igra/ and found that the vertical resolution is non-uniformed with the value ranges from several hundred meters to more than one kilometer even the outliers are not removed.

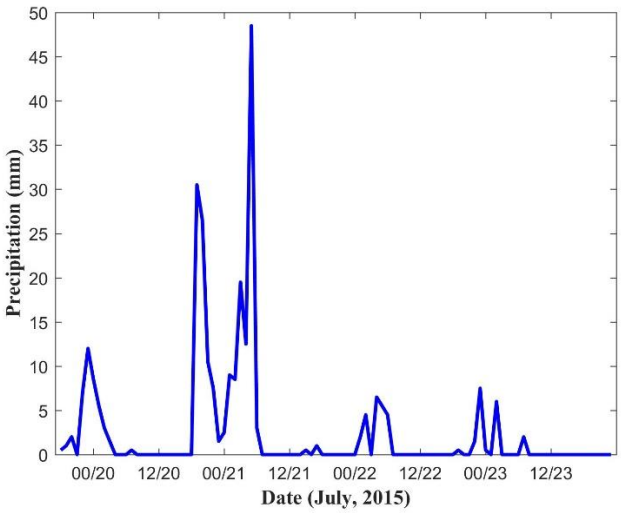

Figure 1. Hourly precipitation of SPP rain gauge during the period of 20 to 23 July, 2015

References:

Yao Y.; Zhao Q. Maximally Using GPS Observation for Water Vapor Tomography. IEEE Transactions on Geoscience and Remote Sensing, 2016, 54(12), 7185-7196.

Yao Y.; Zhao Q. A novel, optimized approach of voxel division for water vapor tomography[J]. Meteorology and Atmospheric Physics, 2017, 129(1), 57-70.

Zhao Q.; Yao Y.; Yao W. A troposphere tomography method considering the weighting of input information[C]//Annales Geophysicae. Copernicus GmbH, 2017, 35(6), 1327-1340.

Zhao Q., Yao Y., Cao X., Zhou F. and Xia P. An Optimal Tropospheric Tomography Method Based on the Multi-GNSS Observations. Remote Sensing, 2018, 10(2), 234.

Wang, J., & Zhang, L. (2008). Systematic errors in global radiosonde precipitable water data from comparisons with ground-based gps measurements. J Clim, 21(10), 2218-2238.

Wang, X., Zhang, K., Wu, S., Fan, S., & Cheng, Y. (2016). Water vapor‐weighted mean temperature and its impact on the determination of precipitable water vapor and its linear trend. Journal of Geophysical Research Atmospheres, 121(2).

Furthermore, I think the authors should also look more on the horizontal motions. For example, can it be shown that the vertical motions seen from the time variations of the vertical profiles are really vertical motions and not actually horizontal motions of sliding clouds?)

- ✓ We appreciate for the reviewer's suggestion. Only the vertical water vapor variations are analyzed in this manuscript for some reasons: (1) according to the recordings derived from the Hong Kong Observatory, the convectional rain happened during the tested period, which is characterized by the vertical motions of atmospheric water vapor, therefore, this paper focus on the atmospheric water

vapor motion in vertical direction during the rainfall period; (2) the primary advantage of GNSS tomography technique is that the three-dimensional atmospheric water vapor distribution can be obtained from the regional GNSS networks. The vertical motion of water vapor variations can be reflected, which is unavailable from the 2-d PWV information. (3) the horizontal motion of atmospheric water vapor has been widely investigated by previous studies while the vertical motion is rarely discussed before; (4) analysis of the horizontal motion of atmospheric water vapor is not the main point of this paper, therefore, we didn't investigate the horizontal motions.

- ✓ The vertical variations of water vapor profiles with time at different heights correspond to the occurrence of rainfall according to the analysis in Section 4.2, therefore, we think the time variations of the vertical profiles are really vertical motions.

Reference:
Yu, C., Penna, N. T., & Li, Z. (2017). Generation of real-time mode high-resolution water vapor fields from GPS observations. Journal of Geophysical Research: Atmospheres, 122(3), 2008-2025.

The paper contains too many figures; I think same of them are not necessary.

✓ Thanks for the reviewer's suggestion, some figures have been removed or combined and only 9 figures are left in the revised manuscript.

Line 56-59 Use NWP only.

✓ Thanks for the reviewer's reminding, this expression has been revised,

Line 180 The "post-processing mode" means that you are using corrections for GPS data not available in real time. What is the data latency of final products downloaded from the ftp site? This could limit very much the use of this technique for nowcasting and/or assimilation in NWP. If you agree this limitation should be included and discussed in Conclusion section.

- ✓ Yes, we haven't used the real-time products in this experiment. This is because: (1) the final products can be available from the ftp site, which is very convenient; (2) the date of experimental data is at the year of 2015; therefore, it is not necessary to use the real-time products. The data latency of final products is about two weeks.
- ✓ Currently, the real-time products of satellite orbit and clock corrections can also be obtained without time latency by our research group, and this experiment can also be performed using the real-time products. Therefore, we think this will not limit the using of tomographic technique for nowcasting and/or assimilation in NWP.

Line 239-240 "The weather conditions are cloudy and sunny without rainfall happened for the period of 1 to 8, August 2015" —> It would be to describe better the atmospheric conditions and the type of occurred events.

✓ We appreciate for the reviewer's reminding, and we are sorry that we cannot describe more about the atmospheric conditions for the period of 1 to 8, August 2015 currently. Because no more atmospheric conditions information can be acquired currently according to the recording of Hong Kong Observatory (HKO), and we have tried to contact somebody in HKO to obtain more information about the weather information during this period.

Line 240-241 " Those two periods are selected in this paper to investigate the variation characteristics of atmospheric water vapor" —> It can be useful to introduce in the article a graph related to the total reference period.

✓ Thanks for the reviewer's reminding, this sentence has been moved to the beginning of Section 3.1 (P6L167-168).

Line 261-261 "PWV does not show any continuous increasing trend when there is no rainfall" —> Is it a common behaviour within the whole database or does it happen only in the period you are reporting about (1 to 8, August 2015)?

✓ We appreciate for the reviewer's question, in our opinion, this is a common behavior when there is no rain happened.

✓ Actually, we have done some experiments and found that there is a continuous increasing trend when there is the rainfall happened, but this phenomenon is not happened when there is no rainfall occurred, for example in the follow Figure, it can be clearly seen that a continuous increasing trend before the occurrence of rainfall is appeared but not obvious when there is no rain happened.

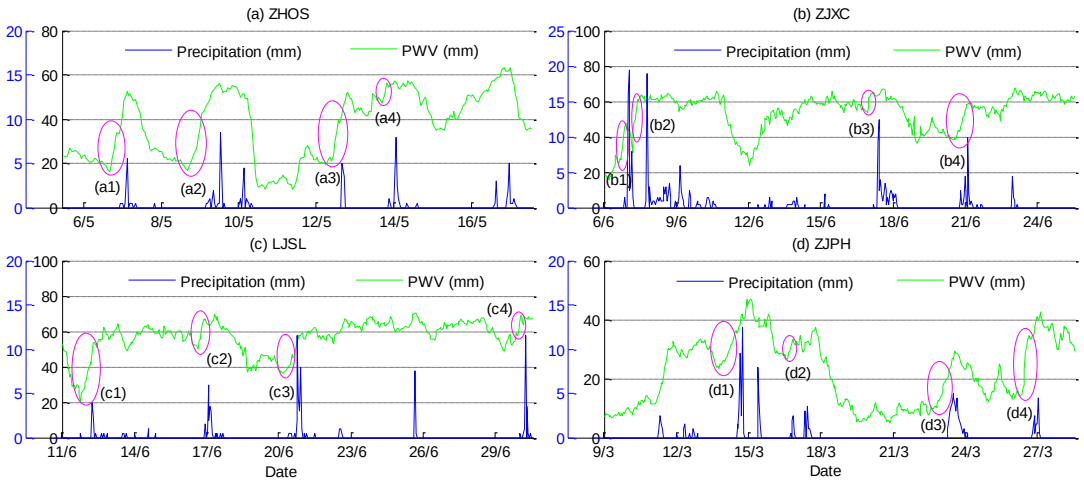

Figure. Hourly precipitation and PWV time series for four stations (ZHOS, ZJXC, LJSL and ZJPH) over different periods

Fig. 2 and 4. The chosen time resolution does not allow making some conclusive assessments. The reader cannot evaluate from the figures if the precipitation effectively reduces the available PWV or how much is related with precipitation. What is the situation the days before the selected events that was generating high PWV values?

Some meteorological description of the selected periods would help very much to understand.

✓ Thanks for the reviewer's suggestion, the Figure 2 has been revised and only the time period of 19 to 21 July, 2015 are presented to better describe the relationship between PWV and rainfall, and the corresponding content has been added in P10L246-249. Additionally, weather condition has been added in the first paragraph of Section 4.

Line 317 Since the main focus is the tomographic 4-d, the amount of introductory figures on 2-d could be too many.

✓ Thanks for the reviewer's suggestion, some figures and description about the 2-d PWV variations have been removed in the section 4.1. In the revised manuscript, only two figures left in the section of 2-d PWV analysis.

Figure 7 to 10 —> Why so many panels? It would be better to reduce and compact the figures, i.e. by including in one single panel the temporal sequence of profiles. Also the description should be improved.

✓ Thanks for the reviewer's question, two successive water vapor profiles are presented in a single panel in order to compare the continuous variations of water vapor profiles with time conveniently. Therefore, there are some panels in a figure. By this way, the continuous water vapor variation with time can be clearly observed during the experimental period. In addition, the corresponding description about Section 4.2 has been improved according to the reviewer's suggestion.

We appreciate for Reviewer's warm work earnestly, which has a significant improvement for our manuscript. And we hope that our corrections meet with the reviewer's requirement. Once again, thank you very much for your comments and suggestions.