Annales Geophysicae

Capturing the signature of heavy rainfall 1 events using the 2-d-/4-d water vapour information derived from GNSS measurement in Hong Kong

The work described in the manuscript is generally worth publishing however the manuscript itself requires major revisions to be accepted - both on the side of content and the way how are the results presented.

General comments

1. Based on your findings you provide very strong statements about a superiority of your GNSS results however evidences for it are often either very poor or completely missing. Except radiosonde profiles (which seem to have somehow limited vertical resolution) you do not use any reference product which would support the results provided by your GNSS tomography. You also do not describe at all the meteorological situation itself – what type of precipitation occurred (convective, stratiform), how was it developed, etc. Generally, you directly link the increase of water vapour or its vertical movement to a formation of hydrometeors and consequent rainfall. Although this can be potentially correct, there can be situations where an increase of water vapour or its vertical movement will not lead to any precipitation – just because the rainfall life cycle is not related only to water vapour as it is a much more complex process. Have you checked this? I strongly recommend you to discuss your results with somebody who has strong knowledge in meteorology since I miss this knowledge. It would allow you to much better justify your results. And please see my major comment 6 and 7 for more information regarding this general comment.
2. The overall quality of some of your figures is rather poor and it is really not easy to follow and interpret them. Therefore, I recommend you to do edit some of your figures in the below given major comment 5.
3. Although the quality of written English is not bad, some issues occur occasionally. I recommend you to let a native speaker proofread your manuscript before a next submission.

Major comments

1. I have some comments on how you compute your values of SWV (equation 2, P5L121):
    - Please use the term *horizontal tropospheric gradients* instead of just *gradients* and introduce their meaning
    - It would be worthy to at least mention that horizontal tropospheric gradients represent a gradient of ZTD, not just of ZWD. Are you aware of this? Although during the periods you describe in your study the prevailing gradient was probably the gradient of water vapour, it would be possibly worthy to subtract the hydrostatic part from the total gradient
    - Probably you are aware, that you should use gradient mapping function for mapping the gradients to the elevation angle of the observation, not the wet mapping function (m_w). Although your formula corresponds to Bar-Sever gradient mapping function, you should explicitly state it, because there are other gradient mapping functions based on different formulas. In the manuscript you don't mention anywhere which mapping function you did use for hydrostatic and wet components.

- Did you use the conversion factor kappa (which was used to convert ZWD to PWV) also to scale the original values of gradients to “PWV gradients”? I ask because according to your eq. 2 you did not do that and
- Have you considered using post-fit residuals for SWV computation? If not you should at least mention their existence since during severe weather events they can contain important information about tropospheric water vapour distribution which cannot be captured by ZTD or gradients (see i.e. Kačmařík et al., 2017)

2. P6L169: Are you sure that solar radiation data provided by a global model with a 0.5x0.5 ° horizontal resolution and 6h time interval of outputs is a reasonable source of solar radiation data for the level of local meteorological events you work with? And maybe even more importantly: it is absolutely clear that solar radiation is dependent on day/night change and an occurrence of clouds and that it influences the temperature and relative humidity. Why do you include it in your study, what exactly you want to show using it?
3. P7L173: I miss important information about your GNSS data processing:
    - Which PPP software did you use? Which mode (I guess post-processing), precise products, mapping function, cut-off elevation angle, etc. did you use?
    - Are you sure that you estimated ZTD every 30 s (what was then the observation time interval)? Usually while a deterministic modelling of tropospheric parameters is used, the ZTD is estimated in a 5-minute or longer interval (and on P9L232 you also mention that you used PWV in 5-minute interval). Does the software used for your processing is based on a deterministic or a stochastic modelling of troposphere? Since you state that horizontal tropospheric gradients were estimated in 2-hour interval, I guess that it used deterministic approach. Why have you chosen this type of setting to estimate ZTD every 30 s, but gradients only every 2 h?
    - What is meant with the presented “accuracy” of estimated ZTD parameters? Is it standard deviation or root-mean-square error or any other statistical parameter? Although you don’t provide the information on what exactly these numbers represent, I don’t consider 7 or 8 mm as high quality ZTD estimates. For example, the official IGS ZTD product is stated to have an overall accuracy of 4 mm (Byram et al., 2011). I didn’t check the referenced paper of Zhao et al. (2018d), however I would suggest you to provide more information on what these values represent and what kind of solutions using Gamit or Bernese were used for these comparisons.
4. P8L208: Could you please explain what presented values of bias/standard deviation mean? Is it a, a comparison between Tm from your regional and standard empirical model or b, a comparison between Tm computed from radiosonde profiles and Tm from your regional and standard empirical model? I guess the b, is right however it is not fully clear. Anyway I would be careful with your statement that shown results indicate that “the established regional Tm model is superior to the empirical formula”. Because if you used radiosonde profiles to correctly establish your regional model, then it MUST be very close to the actual radiosonde profiles. So you only proofed that the established model should provide good results in your area (supposing the radiosonde data are considered to be error-free).
5. Comments regarding selected figures:
    - Figure 2: since the differences in PWV estimated using different Tm are very small, it is practically impossible to see anything in the figure. Therefore, I propose not to include the figure at all and only optionally provide some statistical information about the variation of PWV based on various Tm values.

- Figure 3, 4, 5, 6: It is really hard to a, see something in detail in these figures, b, compare results in figures 3, 4 with results in figures 5 and 6. In different words, it is really complicated to confirm your written description and interpretation of these figures. Therefore, I strongly recommend you to 1, increase the size of these figures, 2, provide detailed looks on interesting periods (i.e. these with the highest rainfall), 3, try to put all the shown parameters into one figure per station (I mean combine information from figures 3 and 5 and from figures 4 and 6, for example show temperature and Rh together with PWV and rainfall in just one figure – the individual curves can be shifted using a constant offset to increase the readability). I also recommend you to use the same scale in axis y in all figures to make their mutual comparison fair (i.e. in figure 3 you use for PWV interval from 20 to 80 mm, but in figure 4 an interval from 30 to 66 mm).
- Figures 8, 9, 10: I recommend you to provide all these figures as ONE figure with ONE caption. I also recommend you to somehow mark time of a beginning of the precipitation in these figures to increase their readability.

6. Section 4.1 – I miss a reasonable discussion of your results together with their short summary. I can see only a description of your figures together with some generally valid information (like that the solar radiation is connected with day/night cycle or cloud coverage or that the IWV time series can exhibit an increase of values before the beginning of rainfall). What is your interpretation of whole shown time series? Is there any clear relation between PWV and any other meteorological parameter? Are your results in agreement with other researches who studied this topic? Can PWV time series help us to predict rainfall? You should deal with questions like these. Please see also my minor comments related to individual sentences in section 4.1.
7. Section 4.2
    - P14L306: I would really correct your statement in sentence "In addition, it also can be observed that more sophisticated water vapour variations detected vertically (with 29 layers) can be provided by the GNSS tomographic technique than by radiosonde data." Firstly, looking on figure 7 I consider your radiosonde profiles not to have a full vertical resolution which is standardly accessible by this instrument (standardly you should get one measurement per approximately 30 m). Could you please explain why your radiosonde profiles are so coarse? Secondly, even if your GNSS tomography could reach a better vertical resolution than a radiosonde (what is not possible with just 29 vertical layers), you could not call your tomography profiles to be "more sophisticated" – because you are not able to proof that variation in your profiles is related to real meteorological conditions and not only to errors of tomographic reconstruction.
    - P18L382: I don't agree with you that "delays to the satellite signals induced by liquid water and icy species … are unavailable in the case of GNSS observations". The GNSS signals ARE influenced by them (see Solheim et al., 1999 and Kačmařík et al., 2017) and therefore the estimated ZTD/SWD/SIWV contain these effects. However, it is not possible to separate them from the estimated parameters. This also means that your GNSS tomography profiles should be influenced by these hydrometeors.
    - I don't see any trustworthy quality evaluation either for your SWV values or for the vertical profiles from GNSS tomography reconstruction. How you can justify that described changes in presented vertical profiles of WV are related to real weather conditions and not only to mismodelling deficiency of your GNSS tomography solution? You should at least discuss this topic.

- Please see also my minor comments related to individual sentences in section 4.2.

Minor comments

1. P2L42: you write about using GNSS PWV for severe weather and climate studies, however you provide only two references. Since there are many studies related to GNSS meteorology and (a) severe weather monitoring (i.e. Japanese team around Y. Shoji); (b) climate (i.e. Gradinarsky et al., 2002, Vey et al., 2010, Ning a Elgered 2012, Bock et al., 2014), I recommend you to cite at least the most important ones and cite them separately for (a) and (b).
2. P2L44: what do you mean with "traditional sounding stations" – radiosondes? It should be explicitly given. Are you aware of WV observations from remote sensing satellites or of other instruments as WVR or Raman Lidar?
3. P2L50: I would rather write that GNSS PWV can be used to provide information about water vapour distribution, which is related to form of precipitation and not only to severe weather events. In this regard – how do you define a severe weather event in your perspective?
4. P2L52: I would rather write that GNSS PWV is operationally used for their assimilation into numerical weather prediction models (NWM) than just for operational meteorology. Italy doesn't use GNSS PWV operationally, work presented in Barindelli et al. (2018) was just a case study to promote an operational deployment.
5. P2L56: I would rather say that ZTD or PWV *can be used* for early warnings than that *it is used*. I recommend you here to cite the work of Brenot et al. (2013) at least.
6. P3L65: there are much more (recent) studies that used radiosonde profiles for GNSS tomography validations, i.e. Shangguan et al. (2013)
7. P3L68: COSMIC is not an instrument for water vapour sensing, it is whole program designed for various purposes – in this regard I would rather write GNSS Radio occultation technique to be consistent.
8. P3L75: I would not say that *iterative reconstruction techniques* deal with resolution of tomography models or division of tomography areas.
9. P4L91: please correct your statement that ionosphere causes signal delay – since ionosphere causes a delay for code measurements, but an advance for phase measurements (see i.e. Hofmann-Wellenhof et al. 2008). Also you cannot fully eliminate ionosphere with just the IF linear combination – this eliminates only the first order effect, but not effects of higher order.
10. P4L95: I would firstly introduce the hydrostatic and non-hydrostatic part of the delay and then call the non-hydrostatic the *wet* delay. Also please use *zenith direction* all the time (instead of a *vertical direction*)
11. P4L101: replace the word *measurements* with a more appropriate *signals*
12. P4L102: provide references for given processing software
13. P4L103: you should rather mention that in the GNSS data processing the ZHD is usually taken from an a priori model and later precisely computed from i.e. real meteorological observations to subtract ZWD from ZTD. Because strictly speaking in the GNSS data processing you do not estimate a ZWD, but a correction to a priori modelled ZHD.
14. P4L107: use rather base SI units for all the given coefficients. It would be also worthy to mention that different sets of refractivity constants exist (see Rueger, 2002)
15. P5L117: I recommend replacing the term SWV with SIWV (Slant integrated water vapour)

16. P5L142: Rohm (2013) developed a GNSS tomography solution using no constraints, so please correct your sentence according to that
17. P6L169: could you provide a reference for given CRU-NCEP solar radiation data sets you used in your study?
18. P7L191: with the “layered parameters” you mean that information about vertical profile of some meteorological parameters as water vapour pressure or air temperature is not available? I recommend you rewriting this sentence to make better understandable what you mean.
19. P8L209: I recommend you to see the paper of Ning et al. (2016) providing a rigorous evaluation of uncertainty in GNSS IWV estimation including impact of Tm uncertainty. I would also like to put you into perspective with the number of overall achievable accuracy of IWV estimates from GNSS which is meant to be around 0.4 – 0.6 mm (see Guerova et al., 2016) – it would be possible good to mention it in the paper.
20. P9L227: 300 mm is a value for one day and one station? Or for whole studied period from July 19 till July 25? It is not clear from your sentence.
21. P9L240: with the sentence “Additionally, the PWV time series data present a downward trend at four stations during this period” you mean the whole processed period from June 19 till July 25 or anything else? If yes, why do you state it? It is from whatever reason important for your study?
22. P10L244: please add information at which stations these values of cumulative rainfall occurred.
23. P10L249: what do you want to say with your sentence that “the PWV values during rainfall are much larger than that of no rainfall time” You just want to state the fact, that this situation occurred in your selected time periods or you want to state it as a general fact which is valid every time? Because I would not agree with the second option.
24. P14L314: The sentence starting “For the SPP rain gauge” is not understandable for me.
25. P14L325: I would consider rewriting the sentence starting “The above phenomenon indicates”. The heavy rainfall could be induced by vertical motion of water vapour, but the opposite (variation of water vapour induced by heavy rainfall) is not so logical.
26. Table 1 and Table 2: could you provide a more detailed look on the precipitation? I mean provide the rainfall information not only in 1-hour interval, but for example in 5-minutes or 10-minutes time interval. You don’t need to provide it in a table, in can be in a figure (optionally in the figures 8, 9, 10 themselves or in figure 11). It would provide the reader a much better idea how was the rain spread out in time.

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