

Response to Referee #1

We thank the referee #1 for the insightful comments and constructive suggestions. We have addressed all their comments in the revised manuscript. Below are our response to the referee's critical comments (*Italics*).

General comments

1. I prefer the term 'integrated water vapor' (or IWV) to 'precipitable water vapor' although I know that various authors use the latter. In this context the word precipitable seems to be either meaningless or confusing (a reader new to the subject might think there is some split between precipitable and non-precipitable water vapor)

Authors: Thank you for your consideration. The term 'integrated water vapor' (or IWV) may be widely used in meteorological analysis. While the determination of Precipitable Water Vapor, PWV, is one of the basic objectives of GPS meteorology. Precipitable water vapor (PWV) is the total atmospheric water vapor contained in a vertical column of cross-section unit (King et al, 1992; Ichoku et al, 2002a). One way to monitor water vapour is through measurements of precipitable water vapor (PWV) using a variety of instruments onboard different platforms. Since this paper aims to obtain PWV field with higher accuracy through GPS signals using the precipitable water vapor (PWV) observation, the term precipitable water vapor (PWV) is used in this manuscript. The total precipitable water vapor is atmospheric water vapor contained in a column of unit cross section extending all of the way from the earth's surface to the "top" of the atmosphere. And this explanation has been added in the revised manuscript.

2. What is the purpose of the manuscript: to present an IWV product for Hong Kong? There is no discussion of who the users of such a product would be. End users are much more likely to be interested in clouds or precipitation. There is a complex link between IWV and rainfall, discussed briefly in section 4.2 but I didn't feel that I learnt anything new on the subject.

Authors: Thank you for your question. We are sorry for the unclear purpose of discussion in the article. On the one hand, accurate measurement of water vapor is vital for improving the predictability of regional precipitation, weather and visibility. With advances of GPS technology and spreading the GPS network around the globe, it is a great challenge to explore the application of GPS such as for rainfall, which is a cost-effective and low maintenance cost for a satellite tracking solution. The results from rainfall inferred from GPS can be used to improve nowcasting and weather prediction. The analysis of spatial and temporal variation of PWV in section 4 is to explore the application potential of PWV fusion models in meteorological analysis. ECMWF data are the main source of data for meteorological research. However, the spatial resolution of PWV distribution presented in this part is much higher than that of

ECMWF data or GNSS data.

On the other hand, the precision of PWV derived by fusion model is improved compared with commonly used ECMWF PWV data. This high-precision and high-resolution PWV data is more distinct for analyzing weather changes in a region. As mentioned in the article, the feature of north-south difference and its variation with precipitation can be clearly obtained. The application in climatology of PWV fusion model is the focus of section 4. Since the analysis of link between PWV and rainfall is in section 4.2 is too simple, we removed this part from the paper. Besides, PWV maps can also be used for water vapor correction in InSAR. With more precise PWV, the accuracy of the InSAR measurement will be improved.

Therefore, GNSS and ECMWF can be combined to obtain better-precision regional PWV products, which can not only serve for geodetic techniques, but also provide more accurate data for meteorological research.

3. Another possible purpose is to persuade ECMWF (and others) to assimilate the GNSS data and hence improve analyses and forecasts (this is the gist of the last paragraph of the Conclusions). The authors cite various papers about the use of GNSS in mesoscale numerical weather prediction (NWP) systems but nothing about the use in larger scale or global NWP. They do not address the problem caused by the integrated nature of the measurement - a total increment has to be split up into a vertical profile of humidity increments and how this is done is important and far from trivial. I know that ECMWF has trialled assimilation of ground-based GNSS data (in the form of time delays) but the results were slightly disappointing and the data are not assimilated operationally for now, or in ERA5 (the replacement for ERA-Interim). Of course there is scope for improving humidity analyses and forecasts and GNSS data may well be part of that (along with improvements to the forecast model, and to the ensemble system indicating the likely structure of forecast humidity errors)

Authors: Thank you for the suggested useful references, as shown in the articles, GNSS ZTDs are, since many years, assimilated into the NWP global models at Meteo France and the UK Met Office. And the impact of assimilating ZTD observations in numerical weather prediction (NWP) models has previously been described by authors such as Yan et al. (2009), Boniface et al. (2009), Macpherson et al. (2008), Poli et al. (2007), Faccani et al. (2005), and Vedel and Huang (2004). These paper have been cited in the revised manuscript. Although they found no improvement in temperature, wind, and humidity forecasts, these experiments indicated positive impact on improvement in the prediction of precipitation patterns in cases where ZTDs were assimilated. The fusion model established in our paper is local model and only for PWV, there are no other meteorological elements. According to *Yao Y, Shan L, Zhao Q. Establishing a method of short-term rainfall forecasting based on GNSS-derived PWV and its application [J]. Sci Rep, 2017, 7(1):12465*, it is feasible to predict rainfall based on single factor of PWV. Considering the fact that ECMWF products currently have not assimilated ground GNSS data, our paper provides an idea of integrating GNSS data to improve PWV accuracy issued by ECMWF, other meteorological elements are not involved.

Detailed comments

Title: 'Establishment' seems to imply an on-going product but there is no mention of this in the text. 'local' would be more appropriate than 'regional' (and is used at various points in the text).

Authors: We replaced the word 'regional' by 'local' in the title as you suggested and changed the title to "Local precipitable water vapor products based on the combination of GNSS and ECMWF data"

line 10: "Water vapor is the engine of the weather." Overstatement (temperature gradients are more important, although in the tropics humidity plays a more major role than in the extratropics)

Authors: We are sorry for the overstatement. Water vapour is important because of its direct relation to precipitation, its role as a transport agent of energy, and its role as a greenhouse gas. We have changed the sentence into "water vapor is an important factor of the weather" in the revised manuscript.

12-14 "Many techniques ... water vapor ...". Putting GNSS as number two in the list is misleading. Satellite soundings (microwave and IR) are most important, followed by radiosondes and then other sources (see Andersson et al, above). "water vapor radiometer" - it isn't clear if this relates to satellite or surface radiometers (surface radiometers are too few in number to make much difference globally and would require substantial work to assimilate the data in the best way).

Authors: Thank you for your advice, we have adjusted the introduction of water vapor measurements in the revised manuscript. "Many techniques are used for measuring the water vapor in the atmosphere such as satellite soundings (microwave and InfraRed), radiosondes, Global Navigation Satellite System (GNSS) and satellite water vapor radiometer (WVR)."

15 It reads almost as if "ECMWF data" is another humidity measurement rather than a synthesis of many sources of information.

Authors: We have added the explanation about ECMWF data as you suggested. "ECMWF currently provides ERA-Interim reanalysis data, which incorporates many important IFS improvements such as model resolution and physics changes, the use of four-dimensional variational data assimilation (4-D-Var), and various other changes in the analysis methodology (Dee et al., 2011)."

Introduction:

In several places, notably lines 48-49 and 61-62, there are "shopping lists" of references (with few after 2010). Selecting fewer might be better.

Authors: Thank you for your advice, we have deleted some references in the corresponding part.

51-53 "ECMWF ... 4 times a day". There is nothing fundamental about 4 times a day, it

is simply the archiving frequency chosen for ERA-Interim.

Authors: We have revised the detailed time resolution about ERA-Interim.

54 "the consistency and homogenous spatial coverage of ECMWF data" The homogenous coverage is a major advantage for some users, but this does not mean that the quality is homogenous (this depends on observation coverage, the synoptic situation etc). Here and in many other places it would be better to refer to "ERA-Interim data" rather than "ECMWF data"

Authors: We admit that the quality of ECMWF data is necessarily homogenous. Compared with other data sources, ECMWF data is global and consistent, in the sense that its different fields are in some balance. We replaced some "ECMWF data" by "ERA-Interim data" throughout the paper as you suggested

Results:

223 "inconsistent locations" - this is a fact of life dealing with any gridded product

Authors: We agree that interpolation cannot be avoided in the process of using grid data

234 "25 ECMWF grids": "25 ERA-Interim grid points" better (I am not sure if the grid used for archiving is the same as that used by the forecast).

Authors: Thank you for your advice, we replaced some "25 ECMWF grids" by "25 ERA-Interim grid points" throughout the paper as you suggested

Discussion:

Figures 8 and 9. I didn't feel that I learnt anything from all these plots. Just giving DOY (day of year) puts more work on the reader if they want to relate the plots to the usual calendar.

Authors: There two figures show the PWV values for the Hong Kong area during two typical weather condition. It set up a system capable of producing current PWV maps for usage in operational meteorology. Thank you for the helpful advice, we have replotted the plots as the reviewer suggested.

The bias between ERA-Interim and the Hong Kong radiosonde is of some interest. I would be more interested if the vertical distribution of the bias was shown (ideally for different seasons).

Authors: In fact, the PWV derived from the fusion model in this paper is a two-dimensional product without vertical structure, which provide the PWV value at earth surface height.