# Response to Anonymous Referee #2

*Original References are in italic and with serifs.*
Answers are without serifs.

We thank the reviewer for her/his valuable comments. We respond to all comments and modified the paper accordingly.

*Most of my comments were properly addressed by the authors during the previous rewiev. The article presents the interesting results of a multi-instrument campaign with focus on short-term variability. Since the spatio-temporal variability of water vapour is not well known and measured yet, I recommend a publication in ACP.*

***RC1:*** *I only see one point for improvement. The theory and the past research works about small-scale variability of water vapor are not well described in the ACPD article. Thus a reader can loose the orientation inside the article when the basic principles of IWV variability are not explained. As a consequence the reader don't get a comprehensive picture and may not see your research strategy or a need for high-resolution measurement campaigns. It might be good to tackle this problem by starting from theoretical considerations, e.g., which atmospheric processes can induce a fast change of IWV over a small horizontal distance? Possibly you come to the sensitivity of IWV to convection cells. Generally it will be helpful for your research and for the readers if you add an half page about the theory and past works. In this context a recent PhD thesis by L. Fischer might be useful too:*
*http://edoc.ub.uni-muenchen.de/16208/1/Fischer_Lucas.pdf*
*L. Fischer, Statistical Characterisation of Water Vapour Variability in the Troposphere, Thesis , 2013*
*There were multi-instrument campaigns such as COPS and HyMex which are not mentioned yet.*

**AR1:** We modified the beginning of the introduction to: "Water vapour is not only the most effective greenhouse gas (Kiehl et al., 1997) but also an important part of the hydrological cycle, so that the exact knowledge on atmospheric moisture is absolutely essential for both numerical weather prediction (NWP; e. g., Weckwerth et al., 1999) and climate modeling (e. g. Bony et al., 2006). Due to its importance water vapour has been investigated in several field campaigns such as HYMEX (Drobinskie et al., 2014) and COPS (Wulfmeyer et al., 2011). However, there is still need for research about its role in various atmospheric processes. The interaction between atmospheric humidity and convection, for example, is still poorly understood (Sherwood et al., 2010).

The amount of water vapour in the atmosphere is influenced by both mixing and transport as well as sources and sinks, such as condensation and evaporation of clouds and precipitation and evaporation of soil moisture. The subsequent vertical transport of the atmospheric water vapour occurs by turbulent mixing on small-scales (1 min and 10 m). Convective processes on different scales, such as meso-scale up- and downdrafts, and eddies at convective (10-30 min, < 2 km) and smaller scales, dominate the further vertical transport of water vapour. A prominent example of the convective scale is the atmospheric boundary layer where evaporation from the heterogeneous land surface and turbulent mixing create strong water vapour variability (Shao et al., 2013, cf. Fig. 10). Additional to these circulations, on large-scales (> 1000 km, > 1 day) water vapour is transported by advection of air masses. The combination of these various processes results in a high variability of atmospheric water vapour in both space and time.”

***RC2:*** *To some extent the statistical methods of the present article could be improved and the model data could be analyzed on a higher level (e.g. derivation of vertical water vapour flux). However this could be also realized in a follow-on-study.*

**AR2:** We agree that the analysis could go further. However, we think this is beyond the scope of this study.

*Minor remarks:*

***RC3:*** *abstract: line 9 "a good agreement in terms of standard deviation" do you mean the standard deviation of the diffences between coincident measurements of two instruments? I am asking since later standard deviation is used to characterize the temporal variability of water vapour. actually one has to characterise the mean differences and their uncertainties*

**AR3:** We modified the sentence to: “The statistical intercomparison of the unique set of observations during HOPE (microwave radiometer (MWR), Global Positioning System (GPS), sunphotometer, radiosondes, Raman Lidar, infrared and near infrared Moderate Resolution Imaging Spectroradiometer (MODIS) on the satellites Aqua and Terra) measuring close together reveals a good agreement in terms of random differences (standard deviation <=1 kgm^-2) and correlation coefficient (>= 0.98).”

***RC4:*** *p.22839, line 6 "However, the interaction between atmospheric humidity and convection..." How about the temporal and spatial scales of convection? What happens to IWV in convection cells? I think there are studies which can provide the reader with numbers, e.g. convection time scales: 10-30 min , horizontal scales < 2 km. It is your task to give such infos to the reader within the introduction.*

**AR4:** We agree that this is an important information. Therefore we included this in the introduction as you can see in the answer to RC1.

***RC5:*** *section 2.1.4 how is the vertical resolution of the Raman lidar?*

**AR5**: The resolution of BASIL is mentioned at page 22845 in line 18: “...water vapour profiles with a vertical resolution of 30 m are provided every 5 min...“

***RC6:*** *p. 22851,line 28 what is a residual layer? I don't see the layer in Fig. 2p.22860*

**AR6:** The turbulence in the planetary boundary layer decreases shortly before sunset. This formerly well-mixed layer is called residual layer. It often exists until the morning when the mixing layer starts to form again (e. g. Stull, 1988). We added this reference to the paper.

***RC7:*** *"... the importance of the IWV variabilty associated with atmospheric turbulence." did you really show this? I have more the picture that IWV can suddenly increase if an updraft region moves through the MWR line of sight. That's not turbulence but convection. In your conclusions it is the second forcing (cloud, cell) which is larger than the third forcing (turbulence) of IWV variability.*

**AR7:** We modified the sentence to: "The previous sections show the importance of the IWV variabilty associated with atmospheric turbulence and convection".

***RC8:*** *For interpretation of the daily cycle of atmospheric water:*
*Linda Schlemmer, Cathy Hohenegger, Jürg Schmidli, Christopher S. Bretherton, and Christoph Schär, 2011: An Idealized Cloud-Resolving Framework for the Study of Midlatitude Diurnal Convection over Land. J. Atmos. Sci., 68, 1041–1057. doi: http://dx.doi.org/10.1175/2010JAS3640.1*

**AR8:** We thank the reviewer for this helpful reference. We modified a paragraph of Sect. 4.3 to: "Interestingly, the spread between the different ensemble members is highest around the time of maximum IWV (~ 17:00 UTC). Since there is interaction between humidity, time and strength of convection and resulting precipitation (Schlemmer et al. 2011) this might be associated with difficulties of the forecast model with convective precipitation."

*Comments from previous review:*

***RC9:*** *I am not a native English speaker, however, some sentences could be optimized and the paper would become clearer. Intercomparison studies can be very complex as in your case. Thus I would recommend to make item lists (or bullets) for agreements, disagreements, important characteristcs. That's easier for understanding, for the memory and for possible future consultations of your article.*

**AR9:** We modified a part of the summary to:
"The multi-instrument intercomparison reveals a number of aspects for the individual instruments:
- Sunphotometer measurements show a good agreement with the other measurements but can only be conducted during clear-sky at daytime and seem to suffer from problems when the sun is low.
- IWV from MWR and GPS differs only slightly (bias: 0.2kgm^-2 (1%), standard deviation: 0.9kgm^-2 (6%), cf. Fig. 6) taking the specified instrument uncertainties into account.
- Near-real time processed GPS data exhibit inconsistencies at the

beginning of each day and each hour due to the processing procedure that might also lead to a shift in the diurnal cycle of IWV. Further work on the processing might increase the performance of the GPS measurements.
Despite the characteristics of the measurements themselves other aspects have to be taken into account to judge the instruments. For example, a comprehensive GPS networks exist, thus making GPS better suited to evaluate models over their whole domain.
The analysis of the temporal variability of IWV reveals three distinct sources.
- Synoptic influence is mainly responsible for the fact that the e-folding time of the auto-correlation is approximately half a day.
- Clouds and broken cloud fields can cause standard deviations of IWV of over 1.5kgm^-2 within time intervals of a few hours.
- Atmospheric turbulence determines IWV variability also in cloud-free conditions on scales below 1 h.
The high standard deviations during cloudy time periods do not occur when only daytime clear-sky IWV estimates are considered (cf. Fig. 8). Therefore, instrument intercomparisons under cloud free conditions are advantageous to assure more homogeneous conditions. The high resolution (a few seconds) of the MWR enables to observe standard deviations higher than 0.5kgm^-2 for time intervals less than 30 min. This information is interesting for the development of sub-grid parameterizations for atmospheric models but also implies that instrument intercomparisons should make use of suitable measures to identify atmospheric conditions with low variability in order to isolate instrument errors.”

***RC10:*** *line 394 what are height-based levels? Same as terrain-following coordinates of COSMO?*
*Please provide a clear description*

**AR10:** Yes, the ICON height levels are terrain-following levels as in COSMO-DE. We changed the description of ICON to make this clearer: “50 generalized terrain-following levels are used in the vertical...”

***RC11:*** *line 202*
*The GPS signal consists of electromagnetic waves with frequencies of …*
*The main effect of the neutral atmosphere is to decrease the propagation speed of the GPS signal ?*

**AR11:** That is true. To make this clearer we modified the text to: **“**The remaining part of the delay is due to the neutral, moist atmosphere, which refracts incoming electromagnetic waves, increasing the travel time of GPS signals (Solheim, 1999).”

References

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