

## COMMENTS FROM DAVE ADAMS (REVIEWER 3).

We wish to thank Dave Adams for his helpful review. We first copy the comments of the reviewer (**in bold**) with our response below. In cases where the text is modified, we show both the original text and the revised text, with the significant changes shown in blue.

### Minor Comments.

**Line 26 You can probably be a bit more emphatic here. Water is the most important greenhouse gas, critical in the energy balance, responsible for storms etc... Line 29 Should be Sherwood et al., (2010) And you should probably include a few more “big picture” type references related to water vapor in the climate system.**

To address this comment, we will make substantial changes to the first paragraph in section 1.

Original text:

Water vapor is an important constituent in Earth’s atmosphere and its distribution in space and time must be known to understand and predict weather and climate. Despite its importance, we do not have precise observations of its distribution in the atmosphere, its trend with time, or a good understanding of the factors controlling these (Sherwood et al., 2013). Water vapor is challenging to measure because of the wide range of concentrations and scales across which it varies. Water vapor observations must be unbiased and capture the full range of variability in clear and cloudy conditions across the globe in order to improve the understanding and analysis of water vapor, which is used to initialize weather prediction systems, to monitor trends and variations and to improve weather and climate models through constraints on and refinement of processes affecting and affected by water vapor (e.g., Bony et al., 2015).

Revised text:

Water vapor is an important constituent in Earth’s atmosphere and its distribution in space and time must be known to understand and predict weather and climate. **Water vapor is fundamental to the radiative balance of the Earth, both as the most important greenhouse gas and indirectly through clouds. Through its latent heat, water vapor is crucial to formation and evolution of severe weather, transport of energy both upward and poleward in the troposphere and transfer of energy between the surface and atmosphere. Furthermore, water vapor dominates tropospheric radiative cooling which drives convection (Sherwood et al., 2010). Uncertainty in modeled cloud feedback results in the factor of 3 spread in predictions in the surface temperature response to a doubling of atmospheric CO<sub>2</sub> concentrations and the cloud feedback depends critically on the strength of the water vapor feedback [Held and Soden, 2000]. Predicted amplification of extreme precipitation with warmer temperatures is tied directly to predicted increases in extreme water vapor concentrations and it may be underestimated (e.g., Allan and Soden, 2008).**

The date on this reference item was incorrectly listed as 2013 and will be changed to 2010.

Sherwood, S. C., R. Roca, T. M. Weckwerth, and N. G. Andronova (2010), Tropospheric water vapor, convection, and climate, *Rev. Geophys.*, 48, RG2001, doi:10.1029/2009RG000301

The following new references will be added to the reference list:

Held, Isaac M. and Soden, Brian J. (2000), Water vapor feedback and global warming, *Annu Rev Energy Environ.*, 25, 441 – 475, doi: 10.1146/annurev.energy.25.1.441.

Allan, R.P., and B.J. Soden (2008), Atmospheric warming and the amplification of precipitation extremes. *Science*, 321, 1481-1484, doi: 10.1126/science.1160787.

**Line 30 Water vapor observations must be unbiased and capture the full range of variability in clear and cloudy conditions across the globe... This sentence is a bit awkward, it could be written in a more concise manner or turn into two sentences.**

This sentence has been removed based on the proposed change to the comment immediately above.

**Page 2.**

**Satellite systems typically do not have sufficient temporal or spatial resolution to capture many of the important processes related to the distribution of water vapor (such as deep convection in the Tropics). And if the satellite systems do have this appropriate temporal and spatial resolution (e.g. GOES water vapor channels), they only provide column water vapor and not its vertical structure. You should include a bit more detail in this paragraph to give greater force to your proposed system.**

To fully address this comment, we propose to make substantial changes and additions to Section 1 of the paper, Introduction/Motivation. We show the original text of the three paragraphs that begin on line 3 of page 2. After that, we show the proposed new text that will replace those paragraphs.

Original Text (starting on line 3 of page 2):

Satellite observations are required to gain a global perspective for weather prediction and climate monitoring and constraining the critical processes at work in different regions across the globe. Unfortunately, present satellite observations provide limited constraints on the water vapor field, particularly when clouds are present, which in turn limits the skill of the weather forecasts and our detailed knowledge of water vapor across the globe. Yue et al. (2013) compared the water vapor estimates from the NASA's AIRS retrievals and ECMWF analyses and found large fractional differences between the two data sets in terms of both biases and centered, root mean-square differences (CRMSD) that were associated with clouds and surface conditions. Biases were +/-10% near the surface and 35% dry at 200 mb. CRMSD ranged from 15% to 40% near the surface to 45% to 80% at 200 mb, where the range at each pressure level reflects the dependence on cloud type and surface conditions. The point is that present state-of-the-art, radiance-based satellite water vapor remote sensing systems have serious limitations in

terms of performance and sampling biases associated with clouds and surface conditions, accuracy, vertical resolution and the ambiguity inherent in the conversion of radiances to the atmospheric state (Rodgers 2000).

GPS radio occultation (RO) has become an important data source for numerical weather prediction (NWP), despite its relatively sparse coverage to date [e.g., Cardinali and Healy, 2014]. Its high impact comes from its unique combination of ~200 m vertical resolution, all weather sampling and very low random and absolute uncertainties via its direct connection to atomic frequency standards. GPS RO profiles atmospheric refractivity. Two limitations of GPS RO are (1) its inability to separate the dry air and water vapor contributions to refractivity and (2) its insensitivity to water vapor in the colder regions of the troposphere and above.

In recognition of the strengths and weaknesses of GPS RO and radiance measurements and the need for better information about water vapor, in 1997 research groups at the University of Arizona and the NASA Jet Propulsion Laboratory (Herman et al., 1997 and Hajj et al., 1997) identified and began developing an RO system that is now called the Active Temperature, Ozone and Moisture Microwave Spectrometer (ATOMMS), which is designed to overcome these limitations by transmitting and receiving signals between satellites in low Earth orbit (LEO) near the 22 and 183 GHz water vapor absorption lines as well as nearby ozone absorption lines. Profiling both the speed of light like GPS RO as well as the absorption of light, which GPS RO does not measure, enables ATOMMS to precisely profile temperature, pressure and water vapor simultaneously from near the surface to the mesopause (Kursinski et al., 2002). It will also profile ozone from the upper troposphere into the mesosphere, scintillations produced by turbulence, slant path cloud liquid water and detect larger cloud ice particles, with approximately 100 m vertical resolution and corresponding 70 km horizontal resolution (Eq. 13, Kursinski et al., 1997). Kursinski et al. (2002) found that such a system could provide water vapor retrievals with a precision of 1 – 3% from near the surface well into the mesosphere. Kursinski et al. (2009) estimated the degradation in clouds would be less than a factor of 2.

Revised text:

Satellite observations are required to gain a global perspective for weather prediction and climate monitoring and for constraining the critical processes at work across the in different regions of across the globe. Unfortunately, present satellite observations provide limited constraints on the water vapor field, particularly when clouds are present, which in turn limits the skill of weather forecasts and our detailed knowledge of water vapor across the globe. Yue et al. (2013) compared the water vapor estimates from the NASA's AIRS retrievals and ECMWF analyses and found large fractional differences between the two data sets in terms of both biases and centered, root mean square differences (CRMSD) that were associated with clouds and surface conditions. Biases were +/- 10% near the surface and 35% dry at 200 mb. CRMSD ranged from 15% to 40% near the surface to 45% to 80% at 200 mb, where the range at each pressure level reflects the dependence on cloud type and surface conditions. For example, GOES observations provide high time and horizontal resolution but very limited vertical information.

While hyperspectral IR on polar orbiting satellites provide more information, their temporal sampling is limited and their water vapor estimates are quite noisy with fractional, root mean-square (RMS) differences ranging from 25% in the lower troposphere to 70% around 400 hPa and a tendency toward dry biases up to 30%, depending on cloud type (Wong et al., 2015). While downward looking microwave radiance measurements are particularly useful for determining the column water over the ocean (e.g., Wang et al., 2016), they provide significantly less vertical information than IR and are inherently ambiguous over land, snow and ice due to surface emissivity variations. The point is that present state-of-the-art, radiance-based satellite water vapor remote sensing systems have serious limitations in terms of performance and sampling biases associated with clouds and surface conditions, accuracy, vertical resolution and the ambiguity inherent in the conversion of radiances to the atmospheric state (Rodgers 2000).

Because of these satellite limitations, balloon-borne sondes and dropsondes continue to be the measurement of choice for field campaigns focused on answering key questions about the atmosphere. In fact, the globe would be covered with sondes if the cost to do so were not so completely prohibitive. Operational global weather observing systems therefore rely primarily on more affordable but vertically coarse satellite radiance measurements and the inherent ambiguities in the information they provide. Unfortunately, this limits how much understanding we can gain from these observations about important atmospheric processes like those associated with clouds, convection and surface exchange.

In this context, GPS radio occultation (RO) has provided a welcome advance in satellite remote sensing through its ability to profile the atmosphere with ~200 m vertical resolution, approaching that of sondes, in all-weather conditions, with very small random and absolute uncertainties via its direct connection to atomic frequency standards. As such, GPS RO has become an important data source for numerical weather prediction (NWP), despite its relatively rather sparse coverage to date [e.g., Cardinali and Healy, 2014]. GPS RO profiles atmospheric refractivity. Two important limitations of GPS RO are (1) its inability to separate the dry air and water vapor contributions to refractivity and (2) its insensitivity to water vapor in the colder regions of the troposphere and above.

In recognition of the strengths and weaknesses of GPS RO and radiance measurements and the need for better information about water vapor, in 1997 research groups at the University of Arizona and the NASA Jet Propulsion Laboratory (Herman et al., 1997 and Hajj et al., 1997) identified and began developing an RO system that is now called the Active Temperature, Ozone and Moisture Microwave Spectrometer (ATOMMS), which is designed to overcome these GPS limitations by transmitting and receiving signals between satellites in low Earth orbit (LEO) near the 22 and 183 GHz water vapor absorption lines as well as nearby ozone absorption lines. Profiling both the speed of light, like GPS RO, as well as the absorption of light, which GPS RO does not measure, enables ATOMMS to precisely profile temperature, pressure and water vapor simultaneously from near the surface to the mesopause (Kursinski et al., 2002). It will also profile ozone from the upper troposphere into the mesosphere, scintillations produced by turbulence, slant path cloud liquid water and ~~detect~~ larger cloud ice particles, with approximately 100 m vertical resolution and corresponding 70 km horizontal resolution (Eq. 13, Kursinski et al., 1997). Kursinski et al. (2002) found that such a system could provide water vapor retrievals

with a precision of 1 – 3% from near the surface well into the mesosphere. Kursinski et al. (2009) estimated the degradation in clouds would be less than a factor of 2.

Regarding the sampling densities that can be achieved with ATOMMS, Kursinski et al. (2016b) noted that a constellation of 60 very small satellites, carrying both ATOMMS and GNSS RO sensors, would produce approximately 26,000 ATOMMS and 170,000 GNSS occultations profiles each day, for a fraction of the cost of a single, operational, polar orbiting weather satellite. These numbers of profiles are approximately 10 and 100 times present GPS RO and radiosonde sampling densities. Such an orbiting ATOMMS constellation providing dense, very high vertical resolution, precision and accuracy water and temperature profiling via radio occultation will complement existing observations of clouds, precipitation and energy fluxes and tie the entire weather and climate system together. This combination will also dramatically improve the realism and utility of global analyses for climate as well as forecasting (increasingly extreme) weather (Kursinski et al., 2016b).

With regard to constraining processes, we briefly discuss three important and representative application areas: moist convection, weather fronts and polar weather and climate.

**Moist convection** is ubiquitous across the globe but inadequately understood which leads to inaccurate representation in models. Environmental variables critical for understanding and predicting moist convection and associated severe weather include temperature, water vapor, stability, and conditional instability in particular, the level of free convection, convective available potential energy (CAPE), convective inhibition (CIN), winds and divergence. Unfortunately, coarse vertical resolution and ambiguities inherent in converting radiance spectra to the atmospheric state limit the ability of satellite radiances to provide detailed constraints on convection related processes. GPS RO provides much needed vertical information across the globe and is particularly useful for determining temperatures and stability in the upper troposphere where conditions are very dry. However, the ambiguity of the wet and dry gas contributions to refractivity under the warmer, moister conditions deeper in the troposphere limit the utility of GPS RO refractivity profiles there.

In contrast, ATOMMS will be the first orbiting remote sensing system to simultaneously profile temperature and water vapor with very high ~100 m vertical resolution and very small uncertainties needed to tightly constrain these environmental quantities relevant to convection, in clear and cloudy conditions, through the troposphere, across the entire globe. While ATOMMS profiles will not resolve detailed horizontal structure at scales much below 70 km, they are sensitive to these scales via the phase and amplitude scintillations that small scale turbulence produces on the ATOMMS signals (Kursinski et al., 2016b). Furthermore, 100 km, which is approximately the horizontal resolution of ATOMMS, is the scale most important for forecasting severe convection in the form of thunderstorms (Durrán and Weyn, 2016).

**Weather fronts** are another fundamental class of severe weather poorly constrained by satellite radiance measurements. Unlike radiances, RO measurements can profile fronts from orbit because RO profiles readily penetrate through clouds and the vertical and horizontal resolutions of RO are well matched to the vertical and horizontal scales of weather fronts. While GPS RO can profile fronts in the upper troposphere (e.g. Kuo et al., 1998), the lack of refractivity contrast between the warm-wet and the cold-dry sides of fronts deeper in the troposphere limits GPS RO profiling of fronts there (Hardy et al., 1994). ATOMMS high precision temperature, pressure and water vapor profiles in clear and cloudy conditions will readily distinguish between the warm and cold sides of fronts down through the lower

troposphere and precisely determine the location of any frontal surface that crosses an ATOMMS profile (Kursinski et al., 2002).

This unprecedented capability to measure fronts globally will also enable detailed characterization of the dynamics and moisture fluxes of atmospheric rivers out over remote ocean regions to better predict and prepare for the torrential rainfall and flooding they produce following landfall. These observations will also guide refinements in model representations of atmospheric rivers to increase and extend the accuracy of weather forecasts and the climatologically important mid-latitude water vapor transport in reanalyses and climate models (e.g., Guan and Waliser, 2016).

**Profiling in Polar regions**, particularly the near-surface environment, is critical to understanding the causes of ongoing and future climatic changes there. Reducing uncertainty due to our limited knowledge about the critical processes at work there requires quantitative, process-resolving observations that span the entire range of environmental conditions and behavior across these remote regions. Present understanding comes largely from operational sondes and a small number of field campaigns (e.g., Esau and Sorokina, 2010). While satellites radiance measurements already provide dense sampling of these remote, high latitude regions, they have yielded relatively little insight due to intrinsic ambiguities associated with poor vertical resolution, frequent clouds, near-surface inversions and variations in surface emissivity. As a result, many “global” satellite products do not extend to the poles (e.g. Chen et al., 2008). While GPS RO has much needed very high vertical resolution, cloud penetration and insensitivity to surface conditions, its impact is also limited, because of the unknown contributions of water vapor and the bulk dry gas to the measured refractivity profiles.

In this context, ATOMMS’ precise and very high vertical resolution profiling of temperature, stability, water vapor, pressure gradients, clouds and turbulence, down to the surface, over all types of surfaces, in clear and cloudy conditions, across the diurnal and seasonal cycles, will bring unprecedented information about the high latitudes and, in particular, the lowermost troposphere, to constrain and reduce presently large uncertainties in surface fluxes and the surface energy budget there.

ATOMMS will simultaneously probe through clouds to determine the gas state as well as the cloud properties themselves, including their phase (liquid, ice and mixed) which are critical in the surface energy budget (e. g., Klingebiel et al., 2015) and fundamental to calculating upward and downward short and long wave radiative fluxes through the atmosphere. ATOMMS will profile the frequent polar boundary layer clouds too close to the surface to be characterized by CloudSat (Kay and Gettleman, 2009).

ATOMMS will constrain winds via horizontal pressure gradients to further constrain wind shear and moisture fluxes. This wind and cloud information together with ATOMMS’ simultaneous profiling of stability and turbulent scintillations will provide a new set of observational constraints over the entire high latitude region to expose flaws in and guide improvements to presently inaccurate and poorly constrained model parameterizations of sensible and latent heat fluxes. The ability to estimate turbulence and radiative cooling at cloud top are also critical to determining cloud lifetimes and the radiative budget because turbulent entrainment rates influence droplet size and therefore albedo (Esau and Sorokina, 2010). ATOMMS global perspective would provide critical information for understanding why the two poles are evolving so differently.

The preceding examples reveal inadequacies in our present observing system that limit our understanding, and the substantial increase that ATOMMS promises in our observationally



based knowledge and understanding. The performance of ATOMMS profiles approach that of sondes and, when implemented as a constellation such as in Kursinski et al. (2016b), would provide far denser coverage across the globe. For example, the vast Amazon rainforest which is presently profiled twice a day by only 8 sondes (Itterly et al., 2016), would be sampled by approximately 300 ATOMMS profiles and 1,800 GNSS RO profiles each day via the ATOMMS satellite constellation noted above. Thus, an ATOMMS constellation would create a continuous, dense, global data set, with performance approaching that of sondes, that researchers could divide up as they like into smaller domains (creating essentially their own regional (field) campaigns) to better understand and model key processes and reduce weather and climate prediction uncertainty across the globe.

The last two paragraphs of section 1 remain unchanged.

These changes require the following new items in our reference list.

- Chen, J., A. D. del Genio, B. E. Carlson and M. G. Bosilovich, (2008), The Spatiotemporal Structure of Twentieth-Century Climate Variations in Observations and Reanalyses. Part I: Long-Term Trend. *J. Climate*, 21(11), 2611-2633.
- Durrán, D. R., and J. A. Weyn (2016), Thunderstorms Do Not Get Butterflies, *Bull. Amer. Met. Soc.*, February 2016, P. 237-244, doi.org/10.1175/BAMS-D-15-00070.1.
- Esau, I. and S. Sorokina (2010), Climatology of the Arctic Planetary Boundary Layer, in *Atmospheric Turbulence, Meteorological Modeling and Aerodynamics*, Editors: P. R. Lang and F. S. Lombargo, 2009 Nova Science Publishers, Inc., ISBN 978-1-60741-091-1.
- Guan, B., and D. E. Waliser (2015), Detection of atmospheric rivers: Evaluation and application of an algorithm for global studies. *J. Geophys. Res. Atmos.*, **120**, 12 514–12 535, doi:10.1002/2015JD024257.
- Hardy, K. R., Hajj, G. A. and Kursinski, E. R. (1994), Accuracies of atmospheric profiles obtained from GPS occultations. *Int. J. Satell. Commun.*, 12: 463-473. doi:[10.1002/sat.4600120508](https://doi.org/10.1002/sat.4600120508)
- Itterly, K. F., P. C. Taylor, J. B. Dodson, and A. B. Tawfik (2016), On the sensitivity of the diurnal cycle in the Amazon to convective intensity, *J. Geophys. Res. Atmos.*, 121, 8186–8208, doi:10.1002/2016JD025039.
- Kay, J. E., and A. Gettelman (2009), Cloud influence on and response to seasonal Arctic sea ice loss, *J. Geophys. Res.*, **114**, D18204, doi:10.1029/2009JD011773.
- Klingebiel, M., A. de Lozar, S. Molleker, R. Weigel, A. Roth, L. Schmidt, J. Meyer, A. Ehrlich, R. Neuber, M. Wendisch, and S. Borrmann (2015), Arctic low-level boundary layer clouds: in situ measurements and simulations of mono- and bimodal supercooled droplet size distributions at the top layer of liquid phase clouds, *Atmos. Chem. Phys.*, **15**, 617–631, doi:10.5194/acp-15-617-2015.
- Kuo, Y.-H., et al. (1998), A GPS/MET Sounding through an Intense Upper-Level Front, *Bull. Amer. Meteor. Soc.*, **79**, 617-626.

Kursinski, E. R., D. Ward, A. C. Otarola, A. L. Kursinski and C. McCormick (2016a), Reducing Climate and Weather Prediction Uncertainty via cm- and mm-Wavelength Satellite to Satellite Occultations, *White Paper Submitted to 2017 ESAS Decadal Survey In Applications of ATOMMS\ 072118.docx response to RFI#1, January 2016*, [http://surveygizmoreponseuploads.s3.amazonaws.com/fileuploads/15647/2289356/183-  
ea6d9954df8cfcdb60a500c254348c4\\_KursinskiEmilR.pdf](http://surveygizmoreponseuploads.s3.amazonaws.com/fileuploads/15647/2289356/183-<br/>ea6d9954df8cfcdb60a500c254348c4_KursinskiEmilR.pdf) .

Uttal, T., et al. (2002), Surface heat budget of the Arctic Ocean. *Bull. Amer. Meteor. Soc.*, **83**, 255–275.

Wang, J., A. Dai and C. Mears (2016), Global Water Vapor Trend from 1988 to 2011 and Its Diurnal Asymmetry Based on GPS, Radiosonde, and Microwave Satellite Measurements, *J. Clim.*, **29**, p. 5205-5222, DOI: 10.1175/JCLI-D-15-0485.1.

**Line 19 Can you be specific as to what you mean here by insensitivity “(2) its insensitivity to water vapor in the colder regions of the troposphere and above.”**

We will add the following sentence to the end of the sentence in question. The new sentence begins on line 20 of page 2.

New Text: *The insensitivity occurs when there is so little water vapor that the majority of the refractivity is dominated by the dry air component (e.g., Kursinski and Gebhardt, 2014).*

**Line 28 I think you should write “It can also profile ozone ...”**

The statement about profiling ozone is provided in the very next sentence. No change here.

### **Page 3**

**Line 2 Probably not necessary to include this “...we developed with funding from NSF,...”**

That part of the sentence will be removed. Instead, this information will be included in an acknowledgement section placed immediately before the references section.

Change to original sentence:

Using ground-based ATOMMS prototype instrumentation ~~that we developed with funding from NSF~~, we demonstrate the ability of ATOMMS to retrieve changes in the path-averaged water vapor between the instruments operating between two mountaintops in Southern Arizona to within 1%, during weather conditions that ranged from clear to cloudy to thunderstorms with heavy rain.

And add the following acknowledgement section:

### **Acknowledgments**

We want to thank Jeff Kingsley for his support in making critical resources available at the University of Arizona’s Steward Observatory needed to complete the ATOMMS instrumentation, and Chris Walker for sharing the Steward Observatory Radio Astronomy



Laboratory (SORAL) facilities with us during development of the prototype ATOMMS instrument. We also want to thank Jim Grantham for providing access and modifications to the Mt Bigelow and Mt Lemmon facilities to support these observations. We thank David Adams and two anonymous reviewers whose constructive criticism improved the presentation of this paper considerably. This work was supported by the National Science Foundation Major Research Instrumentation (MRI) Program grant 0723239 and the National Science Foundation, Division of Atmospheric and Geospace Sciences (GEO/AGS) grants 0946411 and 1313563. In particular, we want to thank Jay Fein, program scientist and manager at NSF, who passed away in 2016. Without Jay's insight and relentless effort and support, this research would never have been funded and taken place.

**Line 6 Clarify what you are referring to here “..and the forward modeled water vapor spectra,..”**

This line is in the introductory section. We do not believe that a detailed explanation belongs here. We will add a note that this is described in section 4.

Original text: The smaller than 1% discrepancies between the measured ATOMMS spectra and the forward modeled water vapor spectra ...

New text: The smaller than 1% discrepancies between the measured ATOMMS spectra and the forward modeled water vapor spectra ([described in Section 4](#)) ...

**Line 10 Don't use contractions in formal writing. “...simply do not work.”**

We will change don't on line 10 to [do not](#).

**Line 16 Write “Sources of uncertainty ...”**

This typo (capitalized letter U) will be changed

Original text: Sources of Uncertainty

Revised text: Sources of [uncertainty](#)

**Line 30 Write Refractivity and “the” extinction coefficient (or write coefficients)**

The word “the” will be added in front of extinction coefficient in the sentence.

Original sentence: From these, occultation profiles of bending angle and absorption are derived and then used to derive radial profiles of refractivity and extinction coefficient using Abel Transforms [*Kursinski et al.*, 2002].

Revised sentence: From these, occultation profiles of bending angle and absorption are derived and then used to derive radial profiles of refractivity and [the](#) extinction coefficient using Abel Transforms (Kursinski et al., 2002).

#### **The hydrostatic assumption would be very dubious during deep convective activity**

As the manuscript notes, based on ATOMMS 100 to 200 m vertical resolution and equation 13 of Kursinski et al. (1997), the horizontal resolution of an orbiting ATOMMS system is approximately 100 km. At the 100 km horizontal scale, hydrostatic equilibrium should be a good approximation.

We also note that NWP systems using non-hydrostatic models can assimilate the ATOMMS LEO observations of bending angle and path-integrated absorption, prior to the Abel transform and hydrostatic equilibrium steps in the retrieval process, to avoid the assumption of hydrostatic equilibrium. Non-hydrostatic NWP systems already do this with GPS RO bending angle profiles.

#### **Page 4**

**Line 11. This is a bit unclear. “The gas phase optical depth is due to water vapor and dry air absorption, which introduces temperature and pressure dependence, and any attenuation due to hydrometers.” You are saying the gas phase optical depth is also dependent up the presence of non-gas constituents like hydrometeors?**

Yes, this does seem confusing. The sentence in question will be changed.

Original: The gas phase optical depth is due to water vapor and dry air absorption, which introduces temperature and pressure dependence, and any attenuation due to hydrometers.

Revised: [The total optical depth is due to the gas phase optical depth plus the attenuation due to hydrometeors. The gas phase optical depth includes water vapor and dry air absorption, which depend on temperature and pressure. The hydrometeor attenuation also depends on temperature \(Kursinski et al., 2009\).](#)

#### **Page 5**

**Again, not sure if this is necessary to state. “With funding from NSF,...”**

That part of the sentence will be removed. Instead, this information will be included in an acknowledgement section placed immediately before the references section. The new acknowledgement is shown above in response to a similar comment.

Change to original sentence:

~~With funding from NSF,~~ We designed and built a ground-based, prototype ATOMMS instrument and then used it to demonstrate some key aspects of ATOMMS capabilities and

performance in several fixed geometries in southern Arizona with path lengths ranging from 800 m to 84 km.

**Page 6.**

**Line 14 “ATOMMS High Band signals” should be**

The original paper is inconsistent with references to the ATOMMS High Band signals.

We will search for all occurrences and change them to ATOMMS [High-Band](#) signals for consistency.

**Page 7.**

**Line 13. Which radar data are you referring to? You need to clarify this point.**

This is similar to a comment from reviewer 2 above. However, this reference to radar data precedes the one pointed out by reviewer 2. Thus, we will specify the radar here and include the reference in both places.

Original Sentence: The RADAR data and field observations indicated that rain was still falling over portions of the path between the two instruments.

Revised sentence: Radar data [from the Tucson WSR-88D radar \(Crum and Albery, 1993\)](#) and field observations indicated that rain was still falling over portions of the path between the two instruments.

As mentioned in our reply to reviewer #2, the following reference will be added.

Crum, T.D. and R.L. Albery, 1993: The WSR-88D and the WSR-88D Operational Support Facility. *Bull. Amer. Meteor. Soc.*, **74**, 1669–1688, [https://doi.org/10.1175/1520-0477\(1993\)074<1669:TWATWO>2.0.CO;2](https://doi.org/10.1175/1520-0477(1993)074<1669:TWATWO>2.0.CO;2)

**Line 13 Write “By 16:30, the rain was considerably lighter”**

We will change the sentence in question by adding the comma after 16:30.

Original: By 16:30 the rain was considerably lighter.

Revised: [By 16:30, the rain was considerably lighter.](#)

**Line 33. Can you back this statement up with any citations or some references. “This is likely the finest spectral resolution sampling of the 183 GHz line ever achieved in the field.”**

Revised text: ~~This is likely the finest spectral resolution sampling of the 183 GHz line ever achieved in the field.~~

**Page 8.**

**Line 22 Should this be capitalized AM**

References to the am7.2 microwave propagation model have been standardized based on comment #18 from reviewer 1 as “*am7.2*”

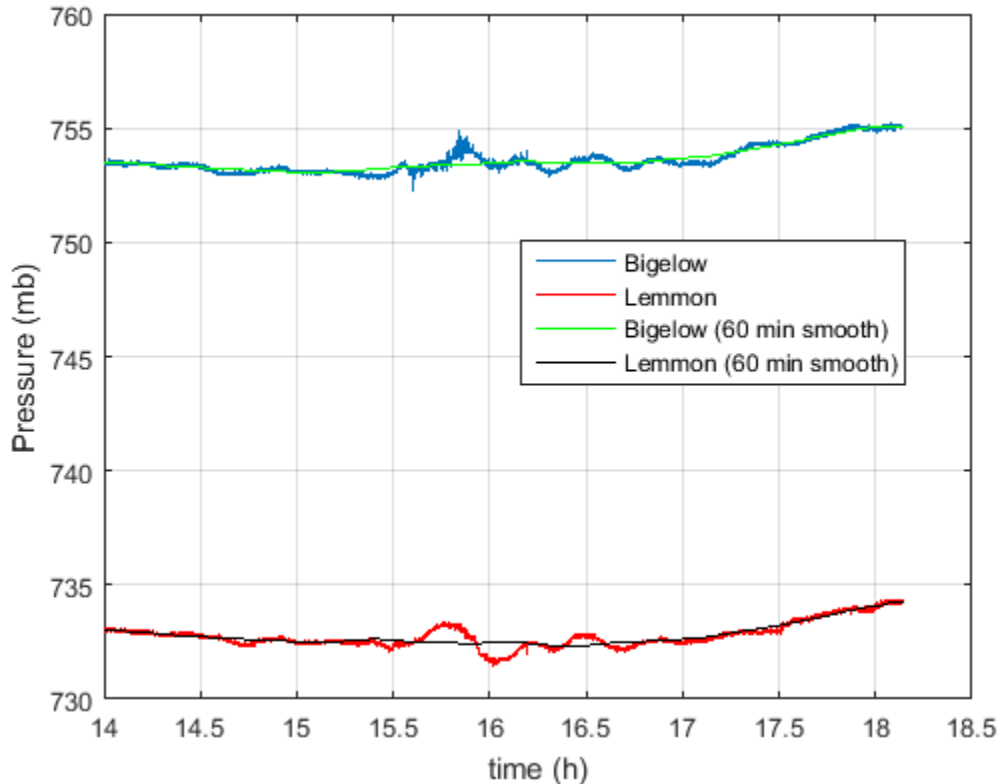
Below is the revised text on page 8, line 22, where we first mention the model and define our terminology. All subsequent references to the model will use “*am7.2*” for consistency.

“... we used an atmospheric propagation tool known as the Atmospheric Model (am), version 7.2 (Paine, 2011), which we will refer to as *am7.2*.”

**Page 9.**

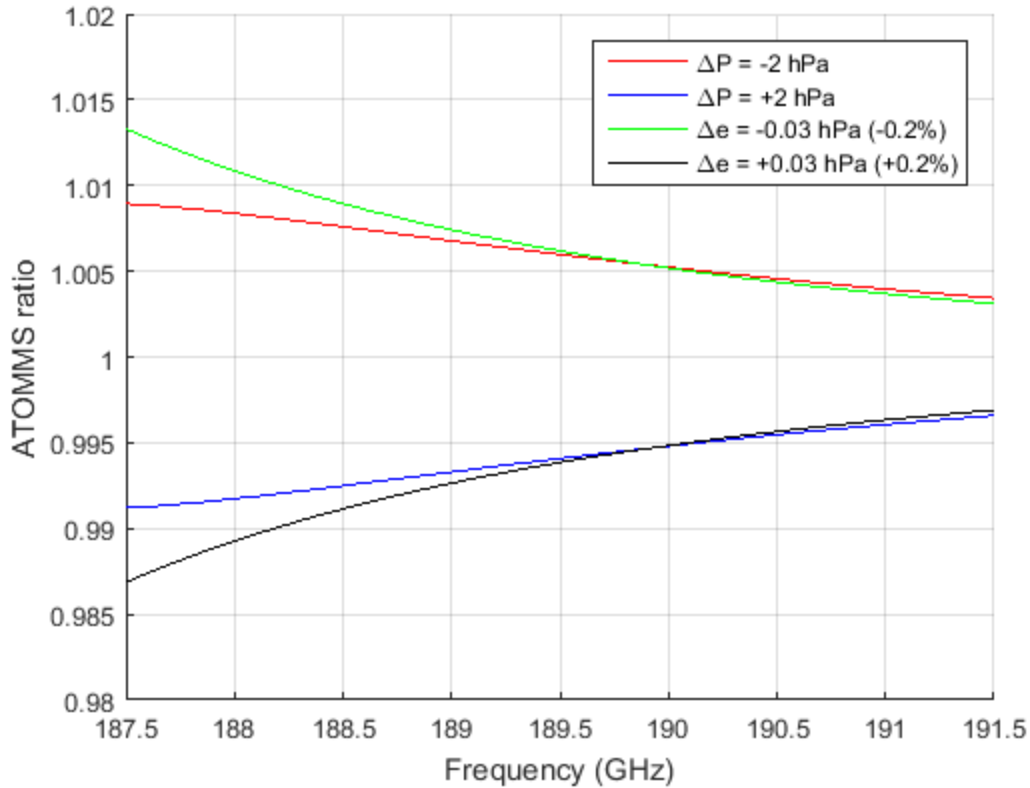
**Line 30. What size of error should we expect given the use of local pressure measurements at each of the sites? That is, across the line of site, there should be some small variability of pressure given updrafts and downdrafts.**

**Background:** The figure below shows the in-situ pressure observations at both instrument locations and the one hour running mean that we used to determine the air temperature using a hydrostatic approximation. This figure is also included above in our response to reviewer #2 concerning **p. 10, line 19**. The figure shows that the unsmoothed pressure variations at each observation site were up to 2 hPa during the time of the convection as shown in the figure below. When we initially thought to use the hydrostatic pressure scale height to infer the average temperature over the path, these short term pressure variations mapped into unphysical temperature variations. As a result, we recognized immediately that these pressure variations must be non-hydrostatic. These 2 hPa variations are consistent with non-hydrostatic pressure variations of up to 2 hPa expected during convection.



That figure also shows that there were slower varying, highly correlated pressure variation of about 2 hPa over the duration of the experiment. As a result of these considerations, we ended up using a 60 minute running mean of pressure to estimate the average air temperature along the signal path.

**Response:** We interpret this question as asking, what is the impact of pressure variations along the path relative to the retrieval of water vapor. While variations in air pressure do impact the water vapor line shape, the resulting changes are quite small. The figure below, which we do not plan to include in the paper, shows the variations in the ATOMMS amplitude ratio over the 187.5 to 191.5 GHz range of signal frequencies that were used in our retrievals. The changes in the ATOMMS amplitude ratio that result from  $\pm 2$  hPa changes in pressure are comparable to changes due to  $\pm 0.2\%$  changes in vapor pressure. The calculations for the figure assumed reference period one conditions, namely vapor pressure = 15 hPa, air temperature =  $20^\circ\text{C}$ , and air pressure = 743 hPa. Thus, the non-hydrostatic pressure variations during the convective period are insignificant relative to 1% variations in water vapor and therefore do not impact our conclusion that ATOMMS observations enabled water vapor retrievals to within 1%.



**Manuscript changes:** In response to this comment from Dave Adams about the impact of pressure variations on the retrievals, we intend to add a line in Figure 6 that represents the change in amplitude ratio that results from a change in pressure of +10 hPa relative to the reference conditions. The point is to show that even for pressure variations much larger than those that were observed, the impact on the water vapor retrieval is insignificant.

Below is the revised Fig. 6 and caption. This is followed by corresponding changes to the text on page 12 beginning with the sentence that starts on line 8, which is where we describe Fig. 6. Those changes are shown below the revised figure and caption.



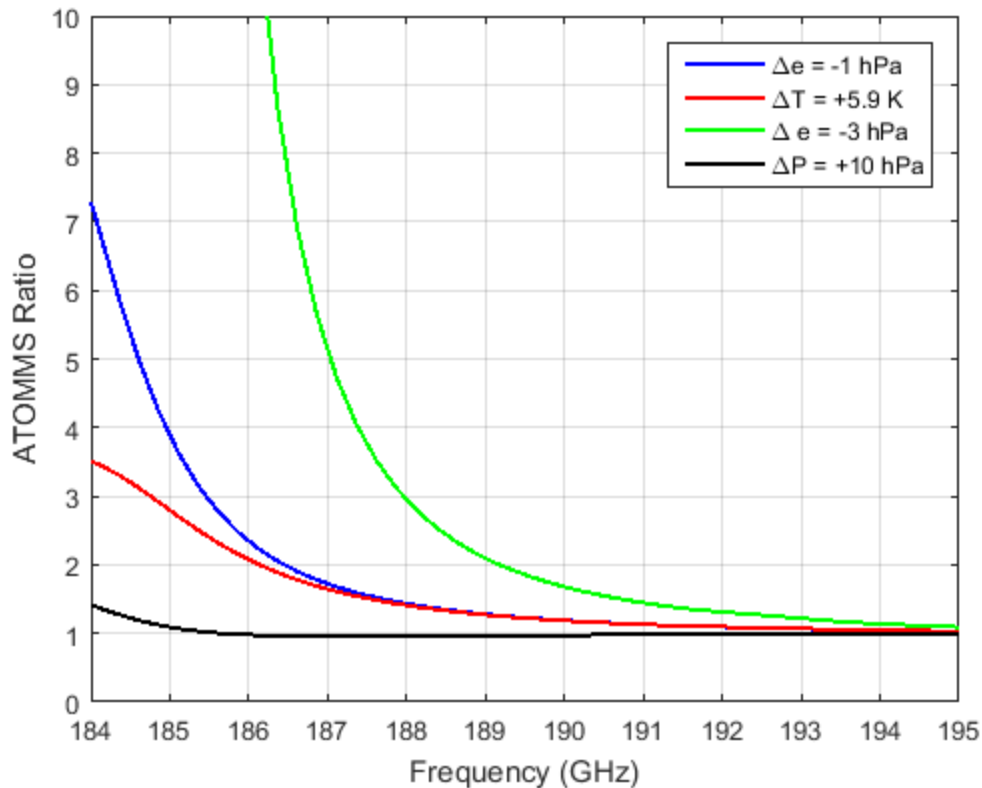


Figure 6: ATOMMS ratio for **four changes in the atmospheric conditions** along the 5.4 km observation path relative to reference conditions: vapor pressure decreased by 1 hPa (blue), temperature increased by 5.9 K (red), vapor pressure decreased by 3 hPa (green), **and air pressure increased by 10 hPa (black)**. The reference conditions were air pressure = 743 hPa, air temperature = 20° C, and vapor pressure = 15 hPa.

Original text beginning on page 12, line 8:

Examples of the sensitivity of the ATOMMS ratio, Eq. (2), to changes in vapor pressure and temperature relative to the reference conditions for this experiment are shown in Fig. 6. The figure plots the forward-computed ATOMMS ratio spectrum for three different changes relative to the reference conditions. For the conditions of the field experiment, we were able to measure amplitudes for signal frequencies of 187.861 GHz and higher. Lower frequencies closer to line center were too attenuated to track. As the figure shows, for frequencies greater than 187.861 GHz, a one hPa decrease in vapor pressure produced approximately the same ATOMMS amplitude ratio spectrum as a 5.9° C increase in air temperature does. Larger changes in vapor pressure, such as the 3 hPa in the figure, are easily distinguished from changes in air temperature. Based on Fig. 4, the uncertainty in the change in temperature relative to the reference period temperature during this experiment was less than 3°C, which places an upper bound of a 0.5 hPa water vapor uncertainty due to the temperature uncertainty.

**Revised text**, with changes highlighted in blue:

Examples of the sensitivity of the ATOMMS ratio, Eq. (2), to changes in vapor pressure, temperature, and air pressure relative to the reference conditions for this experiment are shown in Fig. 6. The figure plots the forward-computed ATOMMS ratio spectrum for ~~three~~ four different changes relative to the reference conditions. For the conditions of the field experiment, we were able to measure amplitudes for signal frequencies of 187.861 GHz and higher. Lower frequencies closer to line center were too attenuated to track. The figure shows the change in the ATOMMS ratio spectrum resulting from a change in air pressure of 10 hPa, which is much larger than the  $\pm 2$  hPa changes in air pressure that were observed over the experiment. Therefore, the sensitivity of the ATOMMS ratio to changes in air pressure is quite small relative to changes in vapor pressure. As the figure shows, for frequencies greater than 187.861 GHz, a one hPa decrease in vapor pressure produced approximately the same ATOMMS amplitude ratio spectrum as a  $5.9^\circ$  C increase in air temperature does. Larger changes in vapor pressure, such as the -3 hPa in ~~line~~ the figure, are easily distinguished from changes in air temperature. Based on Fig. 4, the uncertainty in the change in temperature relative to the reference period temperature during this experiment was less than  $3^\circ$  C, which places an upper bound of a 0.5 hPa water vapor uncertainty due to the temperature uncertainty.

#### Page 11

Line 10 Probably more common “signal-to-noise ratio”

signal to noise ratio will be changed to [signal-to-noise-ratio](#)

#### Page 13

Line 23 Write “comparison with independent, in-situ moisture...”

The comma will be added as suggested.

Original: “comparison with independent in-situ moisture...”

Revised: “[comparison with independent, in-situ moisture...](#)”

#### Page 14

Line 1-3 Maybe you could be a little bit more specific here referring to the map “ between the mountaintops on which instruments sit, while in-situ sensors are located on the ground at each end of the observation path and another in a valley below the observation path.”

The noted changes to the text will be made to be more specific.

Original: The observation geometry in Fig. 1, shows that the ATOMMS-derived vapor pressure is an average over the 5.4 km path that runs above a valley between the mountaintops on which

instruments sit, while in-situ sensors are located on the ground at each end of the observation path and another in a valley below the observation path.

Revised: The observation geometry in Fig. 1, shows that the ATOMMS-derived vapor pressure is an average over the 5.4 km path that runs above a valley between the mountaintops on which instruments sit. The High Band transmitter was located at the position marked and labeled as “Physics/Atmos bldg Radio Ridge” at an altitude of 2752 m and the High Band receiver was located at the position marked and labeled as “Catalina Station Steward Observatory” at an altitude of 2515 m. In-situ sensors were located on the ground at the two instrument sites with another at the location marked and labeled as “Sumerhaven,” which is about 830 m from the observation path in a valley at an elevation of 2439 m.

## Page 15

**Line 17. Such behavior where moisture at the surface varies little while air aloft becomes significantly drier following summertime thunderstorms is common in this region (e.g., Fig. 4 in Kursinski et al. [2008]). You can probably find a few more references that describe thermodynamic conditions after T-storms during the NAM**

We will add the following sentence after the sentence that ends on line 17. The sentence ending on line 17 is repeated first, followed by the new sentence, which contains a few new citations.

Revised wording. Such behavior where moisture at the surface varies little while air aloft becomes significantly drier following summertime thunderstorms is common in this region (e.g., Fig. 4 in Kursinski et al., 2008). It is also common in the Amazon (e.g., Fig. 7 in Schiro et al., 2016) and may be associated with mid-level inflow of drier air into the precipitating region that results in evaporative cooling and descent of this air (e.g., Leary, 1980 and Houze, 2004).

This requires the following additions to the reference list

Schiro, K. A., J. D. Neelin, D. K. Adams and B. R. Lintner (2016), Deep Convection and Column Water Vapor over Tropical Land versus Tropical Ocean: A Comparison between the Amazon and the Tropical Western Pacific, *J. Atmos. Sci.*, 73, p. 4043-4063, DOI: 10.1175/JAS-D-16-0119.1.

Leary, C. A. (1980), Temperature and humidity profiles in mesoscale unsaturated downdrafts, *J. Atmo. Sci.*, 37, p. 1005-1012.

Houze, R. A., Jr. (2004), Mesoscale convective systems, *Rev. Geophys.*, 42, RG4003, doi:10.1029/2004RG000150.

## Page 16

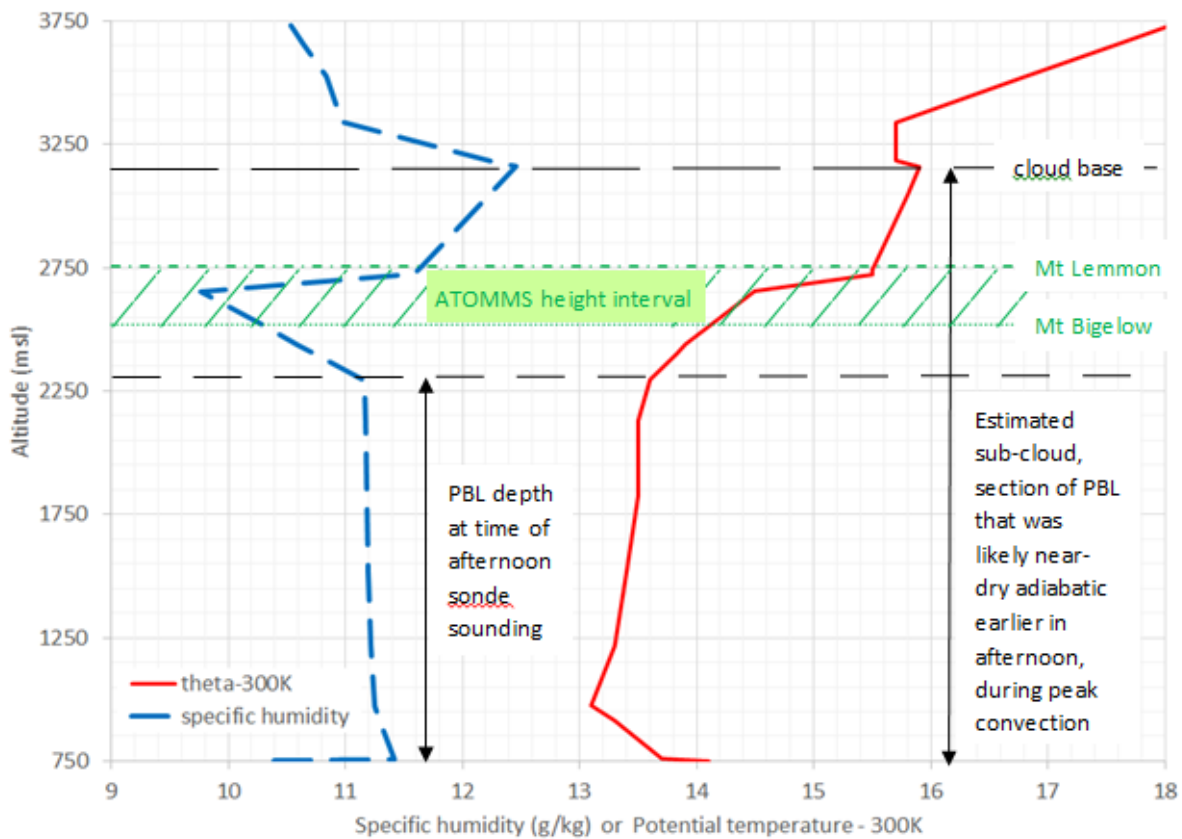
**Line 21 “The nearby Tucson radiosonde indeed indicated that...” With all of the reference in the paper to this sounding, you should include it in the figures.**

Based on this recommendation, we performed a closer examination of the afternoon sonde profile of August 18, 2011, and we have found that we can infer a bit more than we had previously understood about what happened that afternoon.

Therefore the figure, below will be added to the paper. It shows specific humidity,  $q$ , and potential temperature,  $\theta$ , derived from the afternoon sonde. In the absence of sources and sinks,  $q$  and  $\theta$  are conserved variables that can provide additional insight into what happened that afternoon. The figure shows the 3,000 meters above the Tucson valley floor in order to see the boundary layer structures and the ATOMMS' height interval.

**Revisions:** The new figure, which will be Figure 9 in the paper, is shown immediately below with its proposed caption. We also propose to make changes to the text to describe the figure and its significance. The text changes are shown below the new figure.

**Figure 9.**



**Figure 9: Vertical profiles of specific humidity and potential temperature minus 300 K calculated from the 00 UTC Tucson sonde. The local time of the sonde launch was approximately 16:30 on August 18. Theta label for the red line stands for potential temperature and PBL stands for planetary boundary layer.**

To provide the reviewers with some context for the modified text, we first repeat the two paragraphs at the end of Section 6, starting on line 9 of page 15, with minor changes indicated with strikethrough marks for deletion and blue for text changes. Below that, the paragraph shown in entirely in blue is a new paragraph.

## Revised text:

Another issue in validating the ATOMMS water vapor retrievals against the in-situ sensor results is a moist bias in the ground measurements relative to the overlying air after the period of heavy rain. The bias is due to evaporation from the wet surface moistening the near-surface air, which is the air whose properties were measured by the in-situ sensors. As a result, with the exception of the cloud around 16:30, the retrieved ATOMMS water vapor amounts over the 80 minutes following the heavy rain were systematically lower than the surface measurements. This continued until approximately 17:20 when the steady increase in water vapor and rain began and continued through the end of the experiment. The largest differences occurred shortly after the most intense rain, when ATOMMS measured a vapor pressure of 10.2 hPa, the smallest of the entire experiment. This value is approximately 25% lower than water vapor measured at the surface stations. Such behavior where moisture at the surface varies little while air aloft becomes significantly drier following summertime thunderstorms is common in this region (e.g., Fig. 4 in *Kursinski et al.*, 2008). It is also common in the Amazon (e.g., Fig. 7 in *Schiro et al.*, 2016) and may be associated with mid-level inflow of drier air into the precipitating region that results in evaporative cooling and descent of this air (e.g., *Leary*, 1980 and *Houze*, 2004).

For the period of relatively dry air following the cloud, the 00Z Tucson radiosonde profile provides perhaps the best validation of the ATOMMS results. The sonde launched between 16:30 and 16:45 from a location about ~~20 km south~~ 28 km southwest of the experiment and ascended through the Mt. Bigelow to Mt. Lemmon altitude interval between 16:35 and 16:50 at a location approximately 20 km south of the ATOMMS' observation path. According to the sonde, the average vapor pressure in the layer between Mt. Bigelow and Mt. Lemmon was about 12.3 hPa which is within a few percent of the ATOMMS water vapor retrievals following the cloud's passage. We also note that moisture concentrations measured on Mt. Lemmon decreased steadily through this period reaching a minimum of 12.7 hPa at 17:25, a value essentially identical to the ATOMMS moisture retrieval at this time (Fig. 7). This decrease, despite the evaporative moistening from the wet surface, suggests that dry air was indeed advecting over Mt. Lemmon. Thus, the combination of the sonde profile, the ATOMMS measurements and Mt. Lemmon surface measurements all indicate passage of a relatively dry, horizontally extended, air layer following the heavy rain.

Further examination of the operational sonde profiles launched in Tucson that morning around 4:30 AM and particularly that afternoon, around 4:30 PM, provide additional clues as to what happened that afternoon. Figure 9 shows the specific humidity and potential temperature calculated from the Tucson August 19, 00 UTC sonde for the lowest 3,000 m above Tucson. The green hatched region shows the altitude interval across the ATOMMS observation path. In the afternoon sonde profile, the potential temperature,  $\theta$ , and specific humidity,  $q$ , are nearly constant between the surface and 2,300 m above sea level (msl), indicating that the boundary layer (BL) near 16:30 local time extended to about 2,300 msl. In contrast, cloud base at 3,150 msl where the dew point equals the temperature in the sonde profile, and the 500 m near-adiabatic layer immediately below it, further indicate that earlier in the afternoon, the well mixed, dry adiabatic, sub-cloud BL very probably extended up to 3,150 msl. Between 2,300 and

2,750 msl is a thermal inversion layer that is noticeably drier than the air immediately above and below it. The ATOMMS measurements were made within this altitude interval. The relatively low moisture concentrations in this layer measured by both ATOMMS and the afternoon sonde combined with the fact that the  $\theta$  of this inversion layer is lower than the  $\theta$  of the peak afternoon BL indicates this air was likely cooled diabatically by evaporation of precipitation falling through it during the turbulent period of heavy rain. The net effect of this process was to increase its  $q$  and reduce its  $\theta$ , causing it to descend from a higher altitude to where it was measured by ATOMMS. Similarly, the fact that the  $\theta$  of the late afternoon boundary layer below the ATOMMS layer, is 2.5 K lower than that of the peak afternoon BL also indicates that air has also been evaporative cooled and descended. Such evaporative cooling and descent and moistening of dry air layers is a well-known feature of squall lines (e.g., Houze, 2004) and cause microbursts which are well known in Arizona (e.g. Willingham et al., 2010). Further understanding of the details of what happened that afternoon will require detailed modeling with a convection resolving model, which is beyond the scope of the present research.

This change requires adding the following new references to our reference list.

Houze, R. A., Jr. (2004), Mesoscale convective systems, *Rev. Geophys.*, **42**, RG4003, doi:10.1029/2004RG000150.

Willingham, K. M. , E. J. Thompson, K. W. Howard and C. L. Demspey (2010), Characteristics of Sonoran Desert Microbursts, *Weather and Forecasting*, 26, p. 94-108, DOI: 10.1175/2010WAF2222388.1.

## Page 18

**Frequency of observations will always be an issue to some extent with the RO technique, particularly when the scales are of the time and space scales need for weather prediction.**

Below we respond to the reviewer's comment. We have proposed text changes to address these points in Section 1, which are in response to your second overall comment with respect to page 2 of the original document. We are not planning to make any additional changes to the text of the paper on page 18 as these have been addressed in Section 1.

The reviewer raises an important point that we have thought about since the conception of ATOMMS. ATOMMS measurements from low Earth orbit (LEO) will profile the atmosphere with very high, 100-200 m vertical resolution with a corresponding horizontal resolution of approximately 100 km as noted in the manuscript. As the results of this paper imply, ATOMMS profiling from LEO will work quite well in both clear and cloudy conditions which is critical for sampling convection. The vertical information that ATOMMS sensors in LEO will provide promises to provide information across the globe on atmospheric stability and particularly conditional instability that are critical for predicting the onset and evolution of atmospheric convection. We also note that ATOMMS' ~100 km horizontal resolution matches the 100 km scale that Durran and Weyn (2016) argue is the most important scale for forecasting thunderstorms.



Thus, ATOMMS LEO data promises to be very useful with regard to convection IF we can create sufficiently dense ATOMMS sampling densities. This issue was discussed in Kursinski et al. (2016) who noted that a constellation of 60 very small satellites, carrying both ATOMMS and GNSS RO sensors, would produce approximately 25,000 ATOMMS occultations and 170,000 GNSS occultations each day, for a fraction of the cost of a NOAA polar orbiting weather satellite. The orbits they noted would sample the entire globe every 6 hours to support the 6 hour update cycle of global weather prediction centers. The average spacing between ATOMMS and GNSS occultations every 6 hours would be approximately 320 and 120 km respectively which is quite dense compared to present GNSS RO and radiosonde sampling. To further put that into perspective from the standpoint of convection, such a system would provide approximately 300 ATOMMS profiles and 1,800 GNSS RO profiles respectively over the Amazon basin, each day.

Thus, an eventual large ATOMMS+GNSS RO constellation, which can be implemented relatively cost effectively, promises to be quite enlightening for improving our understanding and ability to predict atmospheric convection.

These points are made in the updated text in response to Dave Adams comment on page 2.