Answers to Reviewer 2 comments

Precipitable water vapor retrievals using a ground infrared sky camera in subtropical South America

Elion Daniel Hack, Theotonio Pauliquevis, Henrique Melo Jorge Barbosa, Marcia Akemi Yamasoe, Dimitri Klebe, and Alexandre Lima Correia
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We address below the comments by Reviewer 2 about our manuscript *"Precipitable water vapor retrievals using a ground infrared sky camera in subtropical South America"*. We thank the reviewer for these comments and suggestions. As requested, we have included further discussions in the revised manuscript. These modifications contributed to clarifying key aspects of our methodology and framing the text more precisely.

RC2: 'Comment on amt-2022-283', Anonymous Referee #2, 19 Dec 2022

Review on Precipitable water vapor retrievals using a ground infrared sky camera in subtropical South America.

The paper addresses an important scientific question, as water vapor, an important trace gas, is known to be difficult to represent spatially and temporally with current instrumentation and this instrumentation could help in this regard. The idea of the paper is novel, taking from Mims et al. (2011) idea of using an IR thermometer to point to the sky, but improving it with a camera that can give us spatial distribution information. The conclusions could be extended a bit (see my comment below), and I cannot say they are substantial but they are a first approximation to the problem of retrieving water vapor information with a ground infrared sky camera. The methods are clearly outlined and, in my opinion, the assumptions are valid. The results are just a start (one site, some periods of a few days, ...), but I think they are enough for a first approximation to the topic and determining the best approach for extended studies. Regarding the description of the experiments, I think that some things are missing but in general the description is good (see my specific comments below). Title, abstract, and bibliography are correct in my opinion, and the presentation is well structured and clear. The language is generally correct in my opinion (see technical issues for some small corrections). I therefore recommend minor changes in the paper before it is ready for publication.

Specific comments
It is not clear how the synthetic profiles are obtained. It would be interesting also to indicate the equations of these profiles.

We thank the reviewer for this comment. The synthetic profiles are discussed in manuscript Section 2.4. They were obtained from wintertime radiosonde profiles with clear skies or few clouds. Within this subset, we aggregated cases for which the median humidity altitude was either “low altitude” or “high altitude”. The synthetic profiles were built by visual inspection, representing simplified versions of these two classes of vertical humidity distribution. They do not refer to the total amount of integrated humidity (i.e. the PWV), but rather to the relative vertical distribution of humidity, which is crucial for describing the measured downwelling infrared radiance L_λ. The simplified profiles capture this essential information used in the retrieval process. We included in the revised manuscript a table with the data points representing each of the profiles, and adapted the paragraph starting at line 157:

> “The variability of the vertical profile of water vapor was studied on winter days with clear skies or few clouds. Winter was used because it is the season with the majority of available measurements since it is drier and therefore with less frequent clouds than summer. A dataset with 09:00 LT radiosondes for the austral winter months (July-September) was scrutinized to select profiles that represented fewer cloud cover conditions. This was done by taking the frequency of AERONET PWV retrievals within ±30 min from the radiosonde launching time as a proxy for the occurrence of clouds. Radiosonde profiles were retained for analysis whenever at least 5 sunphotometer retrievals were successful within the 1 h time matching window. The median humidity altitude in the radiosonde subset was investigated to identify typical “low altitude” and “high altitude” profiles, regardless of their absolute PWV, and average profiles were computed (Fig. 2). From these, synthetic simplified versions of such profiles were built by visual inspection. A~~n average~~ profile corresponding to “medium altitude” was computed as the average between the low and high altitude profiles. Figure 2 shows the three resulting synthetic profiles, which are meant to be used when no radiosonde information is available for a given day, as described further below. Table 1 shows the data points used in the profiles. The same synthetic profiles were used for summer PWV retrievals, i.e. by keeping the same relative vertical distribution of water vapor, while the method retrieves PWV values within the expected range for summer. Even though there will always be discrepancies between real radiosondes and synthetic profiles, in general such differences show little influence on the final integrated PWV.”

Table 1. Synthetic atmospheric humidity profiles shown in Fig. 2.

	Low altitude	Medium altitude	High altitude
Atmospheric pressure (hPa)	Water vapor mixing ratio (g kg^{-1})		
930	7.000	7.750	8.500
870	6.000	6.875	7.667
810	0.300	6.000	6.833
755	0.273	0.900	6.069
750	0.271	0.891	6.000
700	0.246	0.797	1.500
300	0.050	0.050	0.050

L178-179. It is claimed that averaged profiles are also used but then in lines 185-189 this is not mentioned.

We thank the reviewer for this observation. This refers to section “2.5 Radiative transfer simulations” in the manuscript. This section describes the multiple ways the libRadtran package was used in the work. The software can be used with internal atmospheric profiles (i.e. mid-latitude summer, tropical, etc.), or with user-provided profiles. In the initial step of the work, we studied how the vertical distribution of humidity affects the measured L_λ. We compared libRadtran L_λ simulations using its internal profiles, average humidity profiles, and profiles from single radiosonde launches, all normalized to the same PWV. The results of this comparison were analyzed in Fig. 5. In a later step of the work we developed look-up tables of measured vs. simulated L_λ, that allow retrieving PWV estimates under different methodological strategies. For the libRadtran L_λ simulations in these look-up tables, we have used synthetic and radiosonde humidity profiles. Therefore there is no inconsistency in the passage noted by the reviewer: lines 178-179 describe average profiles used with libRadtran in the first part of the work, while lines 185-189 describe the libRadtran profiles used later. We have changed the text in lines 172-182 in the revised manuscript to seek a better distinction between these cases:

> “In this work, we used the libRadtran software package, a library for atmospheric radiative transfer calculations (Mayer and Kylling, 2005; Emde et al., 2016). The program solves the radiative transfer equation for a given atmospheric setup and then obtains simulated radiances and irradiances for a specified viewing geometry. We used the DISORT (discrete ordinates) method to solve the radiative transfer equation and the plane-parallel atmosphere approximation. Internal and user-provided atmospheric humidity profiles were used in different steps of the work. Three internal standard atmospheric profiles were studied ~~in this work~~: tropical, mid-latitude summer, and mid-latitude winter (Anderson et al., 1986), seeking to understand how they might represent the physical conditions at the observing site. Even though the site location is in the subtropics, midlatitude profiles were included in the analyses for the sake of comparison. We also used ~~alternative~~ average seasonal atmospheric profiles as input, ~~representing seasonal averages~~ obtained from radiosonde data from 2005 to 2015, to study the influence of the vertical distribution of humidity on simulated L_λ.
> Two types of LUTs were computed with libRadtran in this study. Firstly, when radiosonde data is not available, a LUT of simulated $L^{c,s}_{\lambda,i}$ as a function of airmass was produced for the high, medium, and low altitude synthetic humidity profiles (presented in Sect. 2.4)”

L196-197. It is claimed that cloudy pixels are removed, but it is not stated how (by visual inspection, with a threshold value in L, ...).

We thank the reviewer for this very important question, which was also identified by another reviewer. Therefore we repeat the explanation given elsewhere. We have modified Fig. 1b (below) to help explain how cloudy and partially cloudy pixels were identified and removed from the analyses. This was done by excluding pixels with either (a) high spatial L_λ variability, or (b) above a maximum L_λ threshold. The spatial variability filter was applied by computing, for a given pixel, the L_λ sample standard deviation for the 8 nearest neighboring pixels, and removing cases with standard deviation above 0.07 W m⁻² µm⁻¹ sr⁻¹. These correspond to the data points identified as "Filter A" in Fig. 1b. The maximum L_λ threshold filter depends on the pixel airmass, the instrument temperature, and the cloud type possibly present (e.g. it can be more complex to exclude very cold thin cirrus clouds). This limit is defined, for a given temperature condition, as the median L_λ computed at airmass 3.00±0.01. In the particular example shown in Fig. 1b, this threshold was 3.0 W m⁻² µm⁻¹ sr⁻¹, as indicated by the horizontal dashed line. Data points identified as "Filter B" in Fig. 1b were eliminated by the threshold filter. Finally, after applying filters (a) and (b), the minimum L_λ envelope is defined as the median of L_λ, calculated for each ±0.001 airmass interval around discrete airmass values in the LUTs, for airmasses below 2.0. These correspond to "Median envelope" data points in Fig. 1b. Besides clouds, this procedure also excludes pixels corresponding to physical structures in the vicinity of the detector.

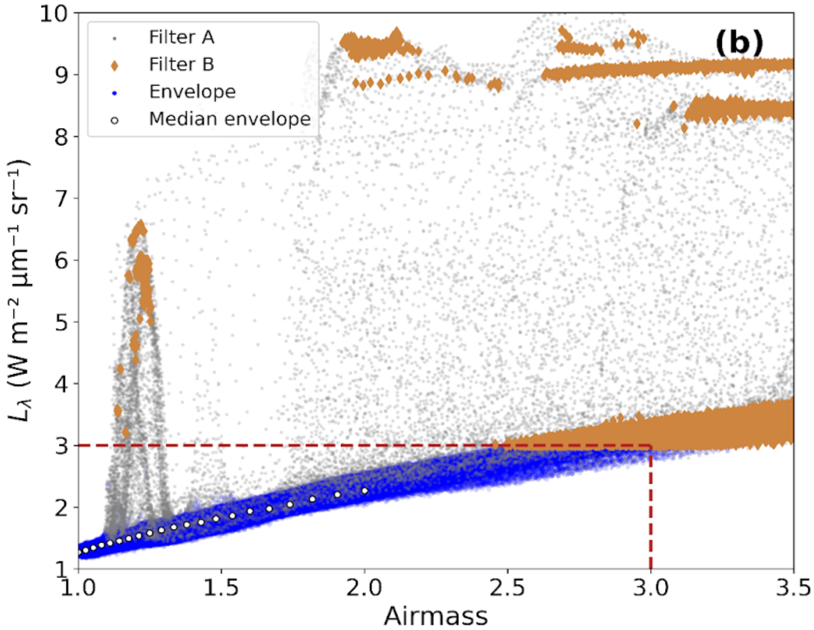

Figure 1b. Spectral radiance (L_λ) measured at ASIVA's channel 4 (10-12 µm) on 2017-07-06 at 15:17 UTC (12:17 LT) in Sao Paulo as a function of the airmass. Cloudy and physical structure pixels were eliminated by applying the procedure described in the text (Filters A and B). Envelope data points correspond to clear sky L_λ, from which medians were computed at specific airmass values.

This explanation was added to the revised manuscript text, originally in lines 97-109:

> "The spectral radiance can then be analyzed as a function of the observation geometry. In this work, we study the spectral radiance as a function of airmass, defined as 1/cos(θ), where θ is the view zenith angle for each pixel. Figure 1 shows, as an example, L_λ measurements using ASIVA's infrared channel 4. Figure 1a presents L_λ for each image pixel ~~of the image~~, and Fig. 1b shows L_λ as a function of airmass. The lower L_λ envelope in Fig. 1b, clearly defined, corresponds to the emission of cooler regions observed in the image, which are those of clear sky, while the points with greater radiance are warmer bodies such as clouds and nearby structures in the camera's view. It is expected that near the zenith the measured radiance for

clear skies will be lower than in regions closer to the horizon. This is clearly observable in Fig. 1a, and in the shape of the lower envelope in Fig. 1b. This is due to the thinner atmosphere between the camera and outer space at the zenith, with this thickness increasing with the airmass. Cloudy and partially cloudy pixels were identified and removed from the analyses by excluding pixels with either (a) high spatial L_λ variability, or (b) above a maximum L_λ threshold. The spatial variability filter was applied by computing, for a given pixel, the L_λ sample standard deviation for the 8 nearest neighboring pixels, and removing cases with standard deviation above 0.07 W m^{-2} μm^{-1} sr^{-1}. ("Filter A" data points in Fig. 1b). The maximum L_λ threshold filter depends on the pixel airmass, the instrument temperature, and the cloud type possibly present (e.g. it can be more complex to exclude very cold thin cirrus clouds). This limit is defined, for a given temperature condition, as the median L_λ computed at airmass 3.00±0.01. In the particular example shown in Fig. 1b, this threshold was 3.0 W m^{-2} μm^{-1} sr^{-1}, as indicated by the horizontal dashed line. Data points identified as "Filter B" in Fig. 1b were eliminated by the threshold filter. Finally, after applying filters (a) and (b), the minimum L_λ envelope is defined as the median of L_λ, calculated for each ±0.001 airmass interval, around discrete airmass values in the LUTs described further ahead, for airmasses below 2.0. These correspond to "Median envelope" data points in Fig. 1b. At the channel 4 range, the sky radiance L_λ strongly depends on the amount of columnar PWV, its vertical distribution and temperature, the optical path from the emission to the sensor, and the transmittance of the medium. Using radiative transfer simulation software, such as libRadtran, the expected L_λ as a function of airmass can be calculated for a series of atmospheric humidity profiles. A PWV retrieval can be obtained by determining, for a given humidity profile, which of the simulations most closely matches the measured lower envelope such as the one shown in Fig 1b."

In general, I am missing some table showing the statistics in the different methodologies/situations to compare them to each other easily. The conclusions could also benefit from this kind of information.

We thank the reviewer for this important suggestion. We have added a table to the revised manuscript, comparing our PWV results to the established techniques using radiosondes and AERONET, and the corresponding discussion, at line 347:

"The largest PWV discrepancy between the two series at ∼16:00 UTC is about the same size as the differences discussed in Fig. 8b. The ASIVA PWV around 12:00 UTC is compatible with the radiosonde data point within the 3% uncertainty range. The retrieved ASIVA PWV time series in Fig. 8b is very similar to the solution using the medium altitude synthetic profile (green curve in Fig. 7c). The conclusion here is that there are inherent discrepancies between the source radiosonde data and the AERONET PWV retrieval for this particular complex case. Hence the radiosonde-derived ASIVA series will also show differences from the AERONET results. Such differences, however, are still under the variations that can be expected statistically. The ASIVA retrieval results discussed in Fig. 8, based on radiosonde profile data, correspond to the solution circled "4" in Fig. 3b.

Table 2. ASIVA, sunphotometer, and radiosonde PWV retrieval statistics for the cases shown in Figs. 7 and 8.

Figs. 7/8		a	b	c	d
Date		2018-02-07	2018-02-09	2018-08-19	2017-07-06
Number of daytime measurements					
ASIVA		36	18	20	152
Sunphotometer (SP)		38	32	38	36
Radiosonde (RS)		1	1	1	1
Average daytime PWV (sample standard deviation), in mm					
ASIVA	SH F7	23.4 (1.7)	26.2 (1.1)	19.7 (1.2)	14.0 (0.7)
	SM F7	20.6 (1.5)	23.0 (1.0)	17.4 (1.0)	12.4 (0.6)
	SL F7	15.8 (1.1)	17.6 (0.7)	13.4 (0.8)	9.6 (0.4)
	RS F8	19.9 (1.2)	27.2 (1.1)	17.2 (0.9)	12.4 (0.6)
SP		19.4 (1.4)	23.5 (1.0)	14.4 (0.6)	12.5 (0.5)
RS		21.9	27.2	16.3	12.7
Average bias: Instrument PWV - Reference PWV, in mm					
ASIVA - SP	SH F7	4.0	2.6	5.3	1.4
	SM F7	1.3	-0.5	3.0	-0.1
	SL F7	-3.6	-5.9	-1.0	-2.9
	RS F8	0.5	3.7	2.8	-0.1
ASIVA - RS	SH F7	1.4	-1.1	3.4	1.2
	SM F7	-1.3	-4.2	1.1	-0.3
	SL F7	-6.2	-9.7	-2.9	-3.1
	RS F8	-2.1	0.0	0.9	-0.4
SP - RS		-2.6	-3.7	-1.9	-0.2

SH F7, SM F7, SL F7 refer to the ASIVA retrievals in Fig. 7 using the synthetic high, medium, and low altitude profiles, respectively. RS F8 is the ASIVA retrieval using the radiosonde profile in Fig. 8.

Table 2 shows a summary of PWV statistics for ASIVA, sunphotometer, and radiosonde retrievals, for the cases analyzed in Figs. 7 and 8. Although the PWV can vary along the day, Table 2 shows the daytime number of samples, average, and sample standard deviation for the three instruments, for the sake of comparison. The ASIVA can operate at a higher frequency than AERONET, as exemplified in Figs. 7d and 8d, with 152 daytime retrievals. The PWV sample standard deviations behave similarly when comparing ASIVA and AERONET. A day with larger PWV variations (Figs. 7a and 8a) shows the AERONET standard deviation of 1.4 mm, while the ASIVA retrieval strategies varied between 1.1 and 1.7 mm. When smaller PWV variations were observed (Figs. 7d and 8d), the AERONET standard deviation was 0.5 mm while ASIVA showed 0.4 to 0.7 mm. Differences between the daytime average PWV retrieved by ASIVA and either AERONET or radiosondes are generally within a few millimeters. In particular, for the cases under analysis the ASIVA retrieval method using the radiosonde humidity profile discussed in Fig. 8 (RS F8 in Table 2) showed smaller absolute biases w.r.t. the radiosonde PWV, ranging from -2.1 to +0.9 mm, than the AERONET biases, which varied from -3.7 to -0.2 mm. However, since only the single available daytime radiosonde profile was used in Fig. 8 ASIVA retrievals, this result is contingent on the atmospheric profile remaining relatively stable throughout the day, and more statistics are necessary to study these results in greater detail."

The flowchart in Figure 3 looks very clear to me, so I congratulate the authors for it.

We thank the reviewer for this observation. Indeed we have dedicated an appreciable amount of time to developing the flowchart in Fig. 3 to convey all key aspects of the methodology discussed in the manuscript. We appreciate the mention.

Technical issues
1. L.155 measured --> compared

As requested, the sentence was changed to reflect the fact data from AERONET and ASIVA were compared, such as:

> "AERONET PWV retrievals have been performed in Sao Paulo from November 2000 to the present day, with some gaps from February 2012 to November 2014. We used the AERONET retrievals in two different ways in this work. First, all available PWV retrievals were used in comparison with radiosonde data. This was done by averaging sunphotometer retrievals within ± 30 min of each 12:00 UTC (09:00 LT) sounding launch. Secondly, AERONET and ASIVA PWV retrievals were compared ~~to ASIVA estimates for~~ on selected days ~~of~~ with clear sky~~,~~ or ~~with~~ few clouds~~, on which both time series were measured~~."

2. L.158. I am not sure this is completely correct, there can be places in which winter is dry and with clouds. It also depends on what "dry" really means (less relative humidity? less specific humidity?).

We agree with the points raised by the reviewer. Specifically, the sentence relates to the weather conditions observed in our sampling site. Other sites can have different typical wintertime conditions. In our case, the word "drier" refers to lower yearly PWV values observed at this time of the year. The text in lines 157-160 has been adapted in the revised manuscript to clarify these points, such as:

> "The variability of the vertical profile of water vapor was studied on winter days with clear skies or few clouds. Winter was used because it is the season with the majority of available measurements since in Sao Paulo it is drier (i.e. lowest yearly PWV observed) and therefore with less frequent clouds than summer. A dataset with 09:00 LT radiosondes for the austral winter months (July-September) was scrutinized to select profiles that represented fewer cloud cover conditions."

3. L296-298. Maybe rewrite the sentence as: "Thus, provided that both the temporal trend and variability from the two series can be equivalent,...".

We thank the reviewer for this suggestion. The revised manuscript was updated to reflect this change:

> "If the ASIVA retrievals were to match AERONET, we would need to use a synthetic profile with a slightly more elevated median for the humidity distribution than the one in the medium altitude profile (cf. Fig. 2). Thus, provided that both the temporal trend and variability from the two series can be considered equivalent ~~in both series~~, the PWV distance between them can be seen as a proxy for the effective median humidity distribution along the vertical."