MOISTENING PROFILE OF THIN CLOUDS IN THE AMAZON DERIVED WITH UV RAMAN LIDAR

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ABSTRACT

Since mid-2011 a Raman-Lidar is being used to perform night time measurements of the vertical distribution of water vapor mixing ratio in the Amazon forest. The instrument is installed 30 km up-wind from Manaus-AM, in a low impacted site, and remotely senses the troposphere with a 95 mJ Nd-Yag laser at 355 nm from 350m up to 12km. The elastic backscattered and inelastic signals due to the Raman crossection of N_2 (387 nm) and H_2O (408 nm) were recorded yielding the determination of the vertical profile of vapor mixing ratio. Further it was calibrated with collocated soundings. In this paper we report on a set of measurements across thin clouds ($< 300\ m$) in the lower and mid-troposphere ($< 6\ km$) for which the signal to noise ratio of the water vapor channel is still acceptable. From 110 nights of measurements, 7 cases were selected. The profiles before and after each cloud overpass were considered to be a reference of the cloud-free environment. A large systematic enhancement (reduction) of about 5 g/kg (-1 g/kg) in the vapor mixing ratio was observed up to 150 m above (within/below) the cloud layer for these very thin clouds.

1. INTRODUCTION

The concentration of water vapor in the tropics is highly variable in both time and space. Its vertical distribution above the boundary layer depends on slow advection and on deep convection, which serves as the free troposphere's water vapor source. In the Amazon basin shallow warm clouds that form during the morning and early afternoon have an important role on regulating the diurnal cycle of temperature and humidity. The vertical redistribution of sensible and latent heat exchanged at the surface prepares the environment for the development of deep convection latter during the day [1; 2]. At the same time, deep convection itself is sensitive to the distribution of humidity in the free troposphere, developing more vigorously in humid environments. Moreover, recent modeling studies [3; 4] have shown that representing this diurnal cycle in atmospheric models is extremely important because it is the injection of energy in such high frequency that excites slower modes in the atmosphere (e.g. El Nino, Maden-Julian Oscilation or Pacific Decadal Oscilation).

Since mid-2011, a new experimental site was implemented near Manaus-AM, in the Brazilian Amazon Forest. The ACONVEX (*Aerosols, Clouds, cONVection EXperiment*) site will run continuously during the next years applying a synergy of different instruments, as described in section 2.1. This paper focus on the Raman-Lidar system used for measurements of water vapor and aerosol optical properties vertical distributions. Further details about the system is given in section 2.2. For reliable water vapor measurements, Lidar profiles were calibrated with collocated soundings launched during an intensive campaign between in September 2011, as described by [5]. In this paper we report on a set of measurements across thin clouds ($< 300\ m$) in the lower and mid-troposphere ($< 6\ km$) for which the signal to noise ratio of the water vapor channel is still acceptable. Section 4 presents the results and discussions.

2. ACONVEX

ACONVEX intends to fill in the gap of a long time series of measurements with high spatial and temporal resolution necessary for understanding the interactions and feedback mechanisms between humidity, convection, clouds and aerosols. It was initially implemented by a partnership between different research projects: AERO-CLIMA (Direct and indirect effects of aerosols on climate in Amazonia and Pantanal), CHUVA (Cloud processes of tHe main precipitation systems in Brazil: A contribUtion to cloud resolVing modeling and to the GPM) and Amazonian Dense GNSS Meteorological Network [6].

2.1. Site Description

The ACONVEX site is located up-wind from Manaus-AM, Brazil, inside the campus of Embrapa Amazônia Ocidental, on 2.89^{o}S 59.97^{o}W. Figure 1 gives an overview of the area which is partially impacted by land use change. Instruments installed include: a meteorological weather station, a disdrometer, a multi filter shadow band radiometer, a cimel sun photometer (AERONET), a 24 Ghz micro rain radar, a ceilometer, a Trimble GNSS Receiver/Vaisla met. station and an UV Raman Lidar.

2.2. UV Raman Lidar

The UV Raman Lidar is operational on the ACONVEX site since July 2011. It uses a Quantel CFR-400 Nd-YAG laser at 355 nm with 95 mJ per pulse and 10 Hz repetition rate. Beam is expanded by 3 and final laser divergence is 0.25 mrad. The optical system uses a bi-axial setup with a 400 mm separation between the cassegrain telescope and the laser axis. The telescope's primary mirror has 400 mm diameter, while the secondary has a diameter

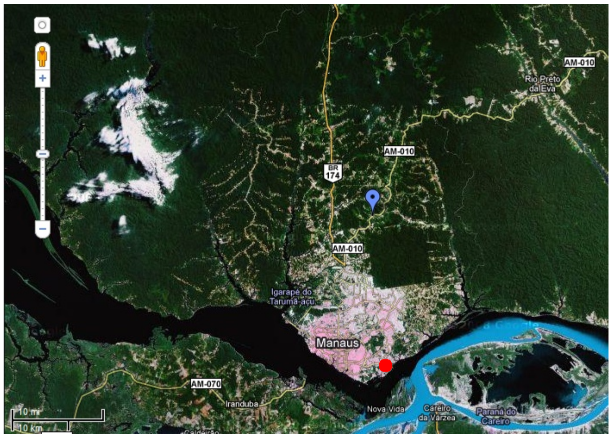

Figure 1: The location of ACONVEX site up-wind from Manaus-AM, Brazil, is indicated by the blue balloon. The red dot marks the position of the operational soundings.

of 90 mm. Focal length is 4000 mm resulting in a f/10 system. An iris is used at the focal plane which gives a field of view of 1.75 mrad and an initial overlap at 85 m and full overlap at 450 m.

No fiber optics are used and light passing through the iris goes directly in the optical detection box. Interferometric filters separate the elastic backscattered signal and the inelastic signals due to the Raman cross-section of N_2 (387 nm) and H_2O (408 nm) which are read collected in different photo-multiplier-tubes. Signals from 355 and 387 nm were recorded in analog and photon-count modes, while 408 nm only in photon count. The optical system was designed to give an uniform signal on the cathode surface almost independent of height of the detected signal. A neutral density filter is used to attenuate the elastic signal avoiding saturation, and a good signal to noise ratio (S/N) is found above 15 km depending on the atmospheric conditions. The N_2 channel, 1-min average signals have good S/N up to 15 km but only during night time. For the H_2O channel, 1-min average signals have good S/N only up to 6 km during night time.

3. METHODS

3.1. Water vapor measurement

The Raman Lidar equation for a pulse of wavelength λ returning at a Raman wavelength λ' can be written as

$$\begin{aligned} P(z,\lambda,\lambda') &= P_0 \frac{c\Delta T}{2} A_{tel} \eta_{eff}(\lambda') \frac{O(z)}{z^2} \beta(z,\lambda,\lambda') \\ & \quad exp\left[\int_0^z (\alpha(z',\lambda)+\alpha(z',\lambda'))dz'\right] \end{aligned}$$

where P_0 is the pulse energy, $c\Delta T/2$ is its length, α is the volumetric attenuation coefficient, $\beta(z,\lambda,\lambda')$ is the Raman backscatter coefficient, A_{tel} is the telescope effective area, $\eta_{eff}(\lambda')$ is the detection quantum efficiency, and $O(z)/z^{-2}$ is a geometric factor.

As the atmospheric mixing ratio of N_2 is constant, it is possible to measure the mixing ratio of H_2O by taking the ratio of both background corrected signals. As shown by [5] this results in the following expression

$$w_{H_2O} = C\Gamma_A\Gamma_M \frac{\overline{S_{H_2O}} - \overline{BG_{H_2O}}}{\overline{S_{N_2}} - \overline{BG_{N_2}}}$$

where the constant Γ_A and Γ_M are the differential aerosol and molecular transmission between 387 nm and 408 nm and the over bars denote temporal and spatial averages. This smoothing is necessary for obtaining a good signal to noise ratio, but care was taken not to smooth too much and remove real variations in the water profile.

To obtain the term $C\Gamma_A\Gamma_M$, [5] did least square fits between the uncalibrated Lidar profiles and eight independent collocated soundings, performed during an intensive campaign between August 30^{th} and 5^{th} September 2011. The largest correlations were found at +8 min (i.e. $\sim$2 km height) when using 5 min and 30 m averages.

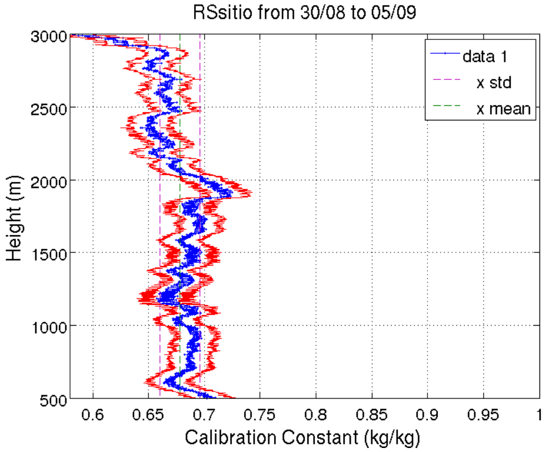

Figure 2: Ratio between uncalibrated Lidar profiles and reference water vapor measurements for collocated soundings. Data shown is the average of 8 sounding between August 30^{th} and September 5^{th} 2011.

Figure 2 shows the vertical variability of the calibration constants. The valued used in the current study corresponds to the vertical average, which was found to be 0.681±0.045 g/g [5].

3.2. Vapor profiles across clouds

From 110 nights of measurements, a visual inspection of night-plots of range correct signals led to the selection of 7 cases were single shallow clouds crossed the field of view of the instrument. The number of events selected is rather low because: (1) only thin clouds (¡300m), (2) with bases below ¡6 km (3) and good signal to noise ratio were considered.

The water vapor profiles before or after each cloud overpass were considered to be a reference of the cloud-free environment. The time-slice of the environment and cloud portions always had the same length of about 20 min, and were separated by 10-15 min to avoid contamination steaming from the time-averages. A direct comparison of the environmental and cloudy water vapor vertical profiles was performed, and their difference calculated.

4. RESULTS AND DISCUSSION

Figure 3 show the results for four of the seven selected events. The first column shows the range and background corrected signal (RCS) with no normalization. The second column shows the water vapor field (g/kg). The dashed vertical lines indicate the region for averaging the environmental portion, while the continuous vertical lines indicated that of the cloudy portion. The last column shows the difference between the cloudy and free atmospheres, hereafter called moistening profile, where the horizontal dot-dashed line indicates the cloud base. Each row corresponds to a different date with cloud base increasing downwards: 13 Jul 2h46 / 2.75 km, 19 Jul 2h30 / 2.91 km, 11 Sep 0h30 / 4 km, 13 Jul 3h15 / 5.15 km. In all panels, time is the local Amazon time.

For all cases, the moistening profile, shown in the third column, reaches a maximum about 200 m above the cloud base, and a minimum between 200-500 m below it. The third case shows a vertical profile very similar to those obtained by shallow cumulus parametrizations [7] with a large drying up to 1 km below the cloud base. From all seven cases analyzed, however, this was the only one found. For instance, the first case in Fig.3 shows a stable layer below cloud base, while the last case shows alternating drying and moistening regions. In all cases, the maximum drying below the cloud reaches only -0.5 to -1.5 g/kg.

For the first three cases shown, there is a large amount of water vapor above the cloud. Maximum in second column is reached around 200 m above cloud base, and values of 8-10 g/kg were found even at heights above 3 km. The moistening profile reach values of about 2-5 g/kg. These results, however, must the considered with extra care, since no correction has been made for the differential scattering of the N_2 and H_2O Raman wavelengths, i.e., Γ_A and Γ_M. Moreover, multiple scattering inside the cloud was not considered.

This can be investigated by comparing the last case with the previous three. The range corrected signal in the last case is not so different inside and outside the cloud (note the orange background instead of blue), which means a very low optical depth. At the same time, the second column shows no high value of water vapor mixing ratio on the cloud top edge. This is clearly a strong indication that multiple scattering is indeed important.

5. CONCLUSIONS AND FUTURE WORK

A large systematic enhancement of about 5 g/kg in the vapor mixing ratio was observed up to 150 m above the cloud layer for these very thin clouds. At the same time, a reduction of about -1 g/kg below the cloud base was also found. Only 4 cases were analyzed, out of 7 found, but the current implementation of an automatic algorithm to detect cloud layers [8] should allow for and increased statistics.

Results above the cloud base must the considered with extra care, since no correction has been made for the differential scattering of the N_2 and H_2O Raman wavelengths and multiple scattering inside the cloud was not considered. A simple comparison of optically thin and thick clouds have shown that multiple scattering correction is indeed important.

Currently work is being done to calibrate the water vapor profiles with explicit corrections for the differential molecular and aerosol scattering of the N_2 and H_2O Raman wavelengths. The following step will be to try to correct for multiple scattering inside the cloud what should allow for the evaluation of the moistening profile in the entire column.

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REFERENCES

1. Houze 1993: Cloud Dynamics. International Geophysics Series, **53**, Academic Press
2. Dai, Trenberth and Karl 1999: Effects of Clouds, Soil Moisture, Precipitation, and Water Vapor on Diurnal Temperature Range. *J. Climate*, **12**, pp. 2451.
3. Raupp and Silva Dias 2009: Resonant Wave Interactions in the Presence of a Diurnally Varying Heat Source. *J. Atmos. Sci.*, **66**, pp. 3165.
4. Raupp and Silva Dias 2010: Interaction of equatorial waves through resonance with the diurnal cycle of tropical heating. *Tellus A*.
5. Barbosa, et al. 2012: Intercomparison of water vapor calibration constants derived from in-situ and distant soundings for a Raman-Lidar operating in the Amazon Forest *26th International Laser Radar Conference*, Athens, Greece.
6. Adams K. et al. 2011: A dense GNSS meteorological network for observing deep convection in the Amazon *Atmos. Sci. Let.*.
7. Siebesma et al. 2003: A large eddy simulation intercomparison study of shallow cumulus convection. *J. Atmos. Sci.*, **60**(10), pp. 1201.
8. Wang and Sassen 2001: Cloud Type and Macrophysical Property Retrieval Using Multiple Remote Sensors em Journal of Applied Meteorology, **40**(10), pp. 1665.

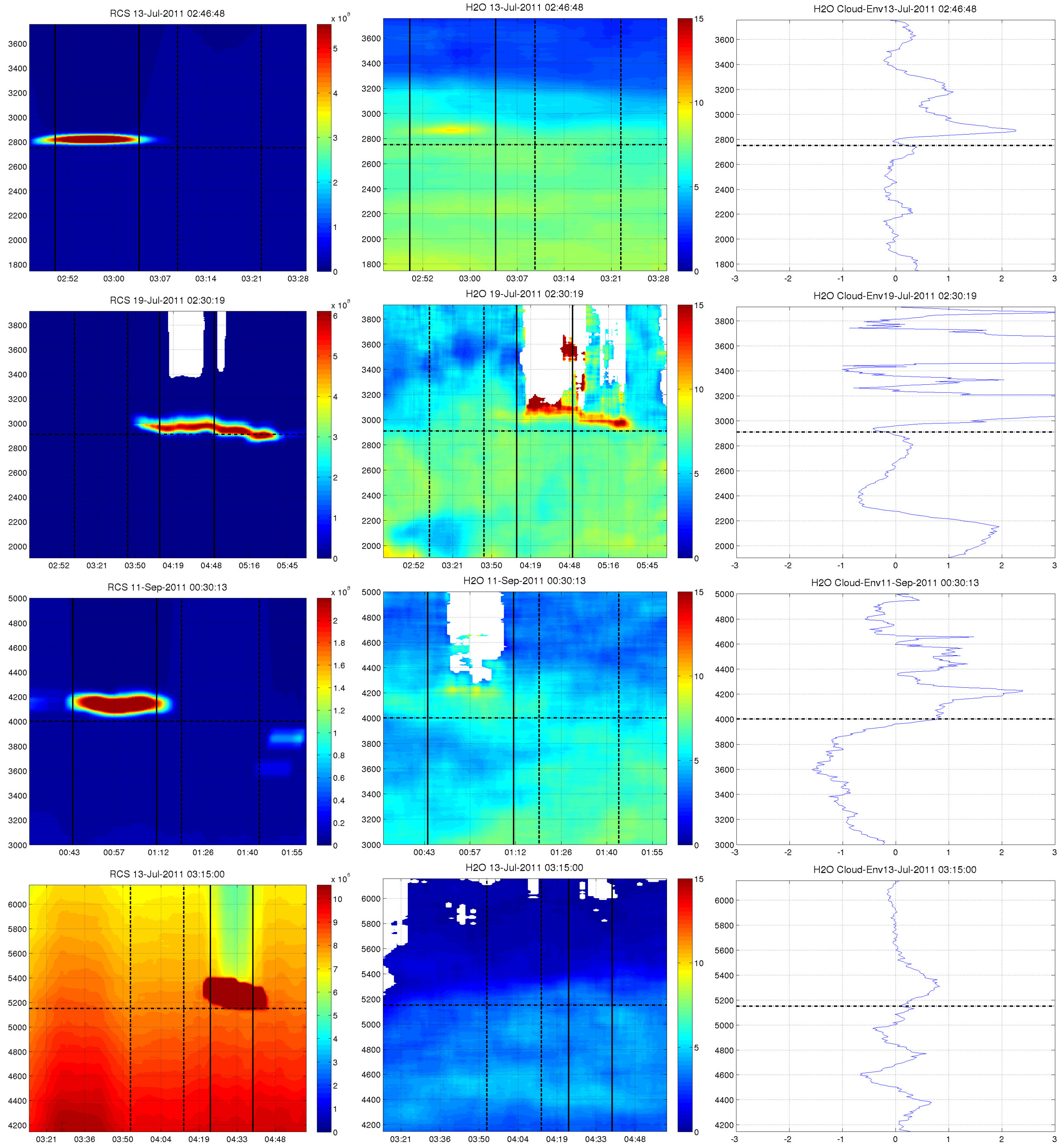

Figure 3: Range corrected elastic signal @355 nm (left), water vapor mixing ratio (g/kg, center) and difference between cloudy and environmental averages are shown. Vertical dashed lines indicated the environmental portion, while continuous lines the cloudy portion. Horizontal line indicates the cloud base altitude. From top to bottom, different cases are shown, with increasing cloud base downwards: 13 Jul 2h46 / 2.75 km, 19 Jul 2h30 / 2.91 km, 11 Sep 0h30 / 4 km, 13 Jul 3h15 / 5.15 km. Time is given as local Amazon time.