Deriving cloud microphysics from radiometric measurements in the Amazon Basin

Alexandre L. Correia* and Patricia B. Catandi

Institute of Physics, University of São Paulo, Brazil

Abstract

A prototype suite comprised of calibrated radiometric cameras was developed to derive estimates of key cloud properties such as brightness temperature and droplet effective radius, with high spatial and temporal resolution. The system was assembled aboard an airplane to measure shortwave radiation scattered by clouds, and longwave infrared radiation emitted by clouds. This allowed deriving cloud droplet radii in shallow cumuli, with values ranging from about 6 to 14 μm. The measured longwave radiance was inverted using Planck’s equation to derive the brightness temperature, with results ranging between −18°C and +15°C.

Keywords: cloud microphysics; droplet size; brightness temperature; Amazon Basin

1. Introduction

The Amazon Basin plays a crucial role on Earth’s energy balance and water cycle. Moisture, latent and sensible heat fluxes in the Amazon can potentially influence climate patterns around the planet (Gat and Matsui, 1991; Angelini et al., 2011; Drumond et al., 2014). In particular the physical processes surrounding cloud formation in the Amazon still cry for a deeper level of understanding. Clouds are highly dynamic systems, strongly controlled by environmental parameters at the surface and in the atmosphere (Ramos da Silva et al., 2011; Dubreuil et al., 2012; Sena et al., 2013). In the Amazon Basin, in particular, the best available cloud resolving models still fail to reproduce the daily cycle of cloud formation, the transition from shallow to deep convection, and the observed precipitation patterns. Aerosols can also influence cloud development, lifetime and fate (Tao et al., 2012; Rosenfeld et al., 2014; Chang et al., 2015). However, because aerosol microphysical properties and concentration are intrinsically linked to complex variations of meteorological parameters, there is still debate on the interplay between meteorology and aerosols over cloud response (Stevens and Feingold, 2009).

In order to reduce the uncertainties on the study of developing convective systems, and their interaction with aerosols, one needs to perform measurements to properly characterize the spatial and temporal evolution of cloud microphysics (Chang et al., 2015). In-situ measurements using aircraft, radiosondes, or retrieving cloud properties from satellite sensors, rain and cloud radars are some of the techniques used to seek a better understanding of cloud dynamics. However useful, these techniques lack the proper spatial and temporal resolution to really tackle this issue. Because clouds are strongly susceptible to local environmental conditions, the use of large-area averaging, as usually is the case in different remote sensing techniques, results in mean conditions that may not accurately represent actual clouds. Instead we need a solution that provides sufficiently large statistics of single clouds, with detailed information about the cloud vertical structure on a cloud-by-cloud basis. Martins et al. (2011) showed a system with that kind of capability, although the post-processing phase to analyze the data was complex and time consuming. Here, we report proof-of-concept for a suite of instruments that is simpler than the system devised by Martins et al. (2011), and can be used to derive hundreds of independent profiles for a single cloud. The instruments were assembled aboard an aircraft, with sensors measuring reflected solar radiation and emitted thermal radiation from clouds. Interpreting these measurements allowed deriving cloud microphysical properties of single clouds in the Amazon Basin.

2. Materials and methods

2.1. Site description

Flights were conducted in the Brazilian Amazon, in the vicinity of the city of Porto Velho (8.7619°S, 63.9039°W). The city is located at the Southern border of the Amazon forest, as indicated in Figure 1, where one notices forest reserves to the North, East and West of Porto Velho with little or no anthropic impact, while the Southwest to Southeast sector is heavily degraded. The site can be severely impacted by biomass burning smoke during the dry season every year (August–October). The measurements were made between 23 and 28 September 2012, over regions with varying conditions of smoke and cloud presence. Meteorological conditions during the whole range of flight days were typical for the region, with shallow convection in the morning developing into thunderstorms in...
early afternoon. Daily showers helped to wet-deposit some of the smoke aerosol, but at the same time it was possible to observe the formation of pyrocumulus clouds. These very localized spatial patterns are one of the reasons why cloud properties need to be assessed for individual clouds, since strong nonlinearities can arise during cloud formation.

2.2. Acquisition system

For the cloud measurements described here we required an unobstructed view of single clouds. For this reason a suite of scientific instruments was combined on board a rented unpressurized aircraft for which windows on both sides had been removed. Figure 2 shows how the system was assembled on a tripod to allow viewing clouds on both sides of the aircraft by rotating the instruments as necessary and thus accommodate the best illumination or viewing conditions. The system was composed of a calibrated thermal infrared camera (FLIR SC-640), a context visible RGB camera (Nikon D-7000), a near infrared camera (Xenics Xeva 320, not used in this study), and a 3-D Global Positioning System (GPS) and attitude sensor (Xsens Mti-G). These components were aligned and assembled on a stainless steel platform attached to the tripod. For safety reasons the suite was powered by a rechargeable 12 V car battery, keeping the system electrically isolated from the aircraft power line.

All cameras were set to take measurements at ~1 Hz rate. The GPS/attitude system recorded position and 3-D viewing angles at 10 Hz. The context camera was used to acquire imagery data at 14 bit resolution.

2.3. Analysis of thermal infrared imagery

The thermal infrared images were analyzed using proprietary acquisition software, applying an internal calibration for estimated target temperatures between $-100^\circ\text{C}$ and $+20^\circ\text{C}$. The camera is responsive to a band of thermal infrared emission between 8 and 14 μm. The radiation emitted by clouds detected at the sensor is weighted by the sensor’s filter function and
the signal is inverted considering Planck's blackbody equation considering a unity emissivity factor.

The distance to the cloud is a required parameter for analyzing thermal imagery acquired during the flights, since the absorption and emission of thermal infrared radiation by the water vapor along the optical path between the clouds and the sensors must be accounted for. In order to derive the distance between clouds and the sensor we calculated the parallax in consecutive context images while the aircraft was flying in a straight path. The context camera was calibrated in terms of angular response, in such a way that a change in the (pixel) position of a cloud feature could be translated to a angular variation. Combining this data with the latitude/longitude position given by the GPS it was possible to derive the distance to the clouds using trivial geometrical relationships.

2.4. Analysis of glory images to derive droplet size

The glory effect manifests itself as a series of colorful bows around an observer’s shadow cast over a cloud of water droplets. The angular position of the bows can be accurately described by the Mie theory given basic properties such as droplet size, refractive index, and wavelength, although a full account of the physics behind the phenomenon has been accomplished only recently (Nussenzveig, 2002, 2003). From Mie scattering simulations of glory bows it has been possible to retrieve droplet effective radii \( r_{\text{eff}} \) in naturally occurring warm clouds (Laven, 2004, 2008) and the standard deviation in their distribution (Mayer et al., 2004).

The formation of glory images is very sensitive of the droplet size distribution. Considering an idealized plane-parallel cloud, a 10% variation in droplet size compromises significantly the visualization of the bows, and a 20% variation renders the bows virtually extinct (Catandi, 2015). However, the analysis of cloud imagery often raises the question on how possibly non-uniform droplet sizes would impact retrievals. Martins et al. (2011) argue that \( r_{\text{eff}} \) is fairly constant at a given level above cloud base, while large variations of droplet concentration can occur. Vertical profiles of \( r_{\text{eff}} \) show smaller droplets at cloud base, growing in size with height (Rosenfeld and Lensky, 1998; Martins et al., 2011). Consistently, when the observer is above a
uniform cloud, glory bows are circular and the droplets have retrieved sizes with narrow distributions (Mayer et al., 2004). On the other hand, when the cloud is observed obliquely, one can have \( r_{\text{eff}} \) values varying from cloud base to top, or a superposition of parts of different clouds, resulting in distorted glory bows (Laven, 2008). Non-circular bows can be analyzed to infer \( r_{\text{eff}} \) as discussed by Laven (2008). Thus, while non-uniform droplet size distributions may require extra calculation steps, they do not prevent accurate glory retrievals.

The retrieval of \( r_{\text{eff}} \) from satellites is usually done by deploying some variation of the Nakajima and King (1990) methodology, i.e. combining a strongly absorbing observation wavelength and a weakly absorbed one. Strongly absorbed sunlight photons have a small mean free path once they get their few first scattering interactions within clouds, and are thus able to distinguish the droplets’ \( r_{\text{eff}} \). In this regard, the glory retrievals work in a similar fashion, since glory bows arise from single scattering interactions between sunlight and cloud droplets, which happens only at the outermost parts of clouds (Mayer et al., 2004). However, one important advantage of the glory retrievals performed from aircraft is the smaller footprint on the cloud surface, when compared to what a sensor in orbit can measure. Because cloud microphysics can vary quickly in space, a glory footprint from aircraft, which is smaller than typical cloud physical sizes, can pinpoint these rapid changes in \( r_{\text{eff}} \) (Mayer et al., 2004).

Glory images acquired with the context camera during the flights were analyzed to derive cloud droplet sizes. For each 14-bit image the Bayer planes (R, G and B channels) were processed separately. For a given channel, the intensity in arbitrary units was measured as a function of pixel location. This intensity vs. pixel profile was analyzed typically 10–20 times for each image, to better represent different angles in the glory image, and the results were averaged. An angular calibration was applied to convert pixel into angular distances. In this way for a given scene, it is possible to derive the angular position of a bow in a particular channel (R, G or B).

We used a freely available Mie code (IRIS software http://www.atoptics.co.uk) to simulate different cloud and observation conditions, such as \( r_{\text{eff}} \), size distribution widths, illumination and acquisition wavelengths. No correction was applied for other atmospheric phenomena such as the presence of aerosols, but in general the distances between clouds and sensors for glory measurements were less than ~2 km, so any corrections would not impact the results in first order. Also the presence of aerosols would most likely scatter more light in the shorter wavelengths, so as a precaution we used only red channel images to minimize their possible influence on the results. The wavelength for the red channel or Bayer plane in the context camera was measured using a diffraction grating, with center wavelength and width of 630 ± 50 nm. A Gaussian filter function approximation using this result was used for the glory simulations. Finally, by comparing measured and calculated glory angular dependences for a particular condition, we were able to derive estimates of cloud droplets sizes.

3. Results and discussions

Figure 3 shows an example of result from the inversion of cloud emitted thermal infrared radiation, to derive the brightness temperature. The context picture in Figure 3 allows for a quick comparison and understanding the general conditions surrounding the acquisition of thermal imagery. The vertical lines depicted in the thermal infrared indicate simply that one can assess the cloud temperature profile with high spatial resolution, and for a given cloud it is possible to combine several independent vertical profiles to derive a mean cloud temperature profile. The clouds shown in Figure 3 have bottom temperatures of about +10°C, and the coldest portions of the cloud show about −10°C. The image in this example was from a shallow cloud, likely to contain only water phase droplets, although one cannot rule out the possibility of ice being present. Other clouds analyzed during the flights had temperatures ranging from about −18°C to +15°C.

The most important aspect of the example result shown in Figure 3 is the fine temporal and spatial scales of the temperature measurements. Usually it is possible to derive cloud temperature in a much coarser spatial resolution, either by using \textit{in-situ} probes, radio or drop sondes, tethered balloons, or satellite sensors. The result shown in Figure 3, on the other hand, has a spatial resolution that is limited only by how far the cloud is from the airplane. For this particular case shown in Figure 3, we estimated a vertical resolution of 0.5 m or better, i.e. that is the vertical distance that corresponds to each pixel in the thermal image. Considering the temporal scale the result corresponds to a snapshot of that particular cloud in a given moment in time, since the acquisition time is of the order of milliseconds. Currently there is no other way to retrieve this kind of information for cloud temperature using other types of instruments. \textit{In-situ} probes cannot sample a whole cloud in such a nearly instantaneous way, and cannot have many independent temperature profiles at the same time. Satellites can retrieve cloud top temperature in a similar way, but they necessarily measure thermal infrared photons that are emitted at the cloud top, so results represent only the top of clouds, with a much coarser spatial resolution.

Figure 4 shows an example of glory measurement performed to derive \( r_{\text{eff}} \). Figure 4(a) shows a glory picture taken for context, where one can see the aircraft shadow indicating the direction of the Sun’s backscatter, and the several bows of different colors that compound to make up the glory effect. A black horizontal line is superimposed to the image for reference. Figure 4(b) shows a graph of relative intensity in arbitrary units for each one of the Bayer planes R, G and B, represented by the red, green and blue lines respectively. The graph in Figure 4(b) shows the intensity along the
Figure 3. Example result from thermal infrared imagery: (a) context picture; (b) brightness temperature inverted from the measurement of emitted thermal radiation.

Figure 4. Example result from glory analyses: (a) context picture showing the aircraft shadow and glory bows; (b) intensity along the black line shown in (a), for each RGB Bayer plane as the red, green and blue curves, respectively. The aircraft shadow corresponds to the minimum intensity for all curves. Peak intensities occur at different pixel distances from the minimum due to the glory effect; (c) comparing the context picture (left) to the glory simulation (right) using Mie theory, with a droplet $r_{\text{eff}}$ of 12.5 μm and standard deviation of 0.5 μm. Simulation software ‘IRIS’ provided by www.atoptics.co.uk.
black line indicated in Figure 4(a), where the minimum intensity (normalized to 1.0) corresponds to the aircraft’s shadow: it is a minimum in the intensity graph for all the three planes. As one moves away from the aircraft’s shadow, the intensities rise, and peak at different pixel distances from the shadow, corresponding to the color dispersion shown by the bows in Figure 4(a). Note that one can only have access to the smooth nuances in the graph shown in Figure 4(b) if the images are acquired at 14-bit resolution (at least), otherwise with 8-bit imagery the intensity fluctuations would be flattened out, making it impossible to perform this kind of analysis. The pixel distance between the minimum intensity and the peak for, say, the red channel can be converted to angular distance using the angular calibration for the camera. The angular distance was then compared to simulated results. Figure 4(c) shows the comparison between the glory context RGB picture (on the left) and a Mie simulation of the effect (on the right) considering a droplet $r_{\text{eff}}$ of 12.5 $\mu$m and a distribution standard deviation of 0.5 $\mu$m, with both images at the same angular reference.

The matching exemplified in Figure 4(c) is remarkable since the Mie model is quite simplistic, considering only single scattering phenomena, and a broadband solar illumination source. One of the reasons to explain the good match is the fact that the glory effect is made by polarized light being scattered only by a thin layer at the cloud top, so the structure below the cloud top, either in the cloud itself or on the surface below, does not interfere with the angular position of the bows.

Figure 4(c) shows a comparison between a context picture and a broadband light source simulation, which simplifies the visual understanding of the analysis process. In our analyses, however, we have used mainly the red channel for comparing measurements and simulation, as explained in Section 2. Considering only the red channel, it is possible to simulate different cloud conditions with the Mie code, and translate the angular dependence of clouds with different droplet sizes back into pixel coordinates for the red channel. Figure 5 shows the final result of such process. The graph in Figure 5 relates the radius of the first red bow, as measured in camera pixels, to $r_{\text{eff}}$. This is significant because it allows one to simply take a picture (with that specifically calibrated camera) and, by measuring the radius in pixels between the aircraft shadow and the first red bow, have immediately an estimate of $r_{\text{eff}}$ in the cloud, without having to resort to other calculations. One caveat is that as droplets get bigger than about 20 $\mu$m in radius the bows get too tight for accurate measurements. Nonetheless here we are describing a process by which one can estimate $r_{\text{eff}}$ directly by measuring the bow size in glory pictures. There is clearly room for improving the system, like for instance having an automated code to detect and measure bow radius to get the droplet sizes.

We applied this methodology to several glory images acquired during the field campaign. The retrieved $r_{\text{eff}}$ are shown in Table 1, with values typically ranging from 6 to 14 $\mu$m. These results are compatible with droplet sizes expected for shallow, warm (i.e. water-only phase) cumuli observed in the Amazon. They are also similar to the glory retrieval obtained by Mayer et al. (2004) for a marine stratus cloud with $r_{\text{eff}}$ of 11.8 $\mu$m.

**4. Conclusions**

We show here proof-of-concept for a system used to measure cloud properties in convective clouds. We measured brightness temperature vertical profiles with a high spatial and temporal scale, with results varying between $-18°C$ and $+15°C$ for the specific cases we studied. We also measured droplet size from the interpretation of acquired images using a Mie code, with typical $r_{\text{eff}}$ ranging from 6 to 14 $\mu$m. The key feature

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**Table 1. Examples of glory retrievals of cloud droplet $r_{\text{eff}}$ in shallow cumuli in the Amazon Basin. Each line represents one glory image.**

| Number of retrievals | Average $r_{\text{eff}}$ ($\mu$m) | $r_{\text{eff}}$ standard deviation ($\mu$m) |
|----------------------|-----------------------------------|---------------------------------------------|
| 16                   | 6.28 ± 0.28                       | 1.13                                        |
| 14                   | 8.93 ± 0.06                       | 0.22                                        |
| 17                   | 8.97 ± 0.10                       | 0.41                                        |
| 15                   | 8.98 ± 0.32                       | 1.23                                        |
| 20                   | 9.68 ± 0.08                       | 0.34                                        |
| 16                   | 9.80 ± 0.11                       | 0.43                                        |
| 26                   | 9.92 ± 0.20                       | 1.02                                        |
| 15                   | 9.96 ± 0.10                       | 0.40                                        |
| 12                   | 10.10 ± 0.49                      | 1.69                                        |
| 20                   | 10.49 ± 0.08                      | 0.38                                        |
| 16                   | 10.55 ± 0.08                      | 0.34                                        |
| 14                   | 11.19 ± 0.09                      | 0.32                                        |
| 16                   | 11.32 ± 0.09                      | 0.36                                        |
| 21                   | 11.39 ± 0.11                      | 0.53                                        |
| 12                   | 11.48 ± 0.16                      | 0.55                                        |
| 25                   | 12.51 ± 0.10                      | 0.52                                        |
| 18                   | 14.16 ± 0.16                      | 0.66                                        |
| 13                   | 14.22 ± 0.12                      | 0.44                                        |

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**Figure 5. Calibration relating the radius of the first red glory bow to the droplet $r_{\text{eff}}$. For this particular camera one can estimate the size of droplets by measuring the pixel distance between the aircraft shadow and the first red bow. Fitted function: $[r_{\text{eff}}, \mu\text{m}] = 6180.75 \times [\text{red bow radius, pixels}]^{-1.14} \pm 0.46$.**
of these results is the ability to measure cloud microphysical properties in single clouds without resorting to in-situ measurements that would be prohibitive in the case of convective clouds. The aim is to continue developing a consistent way to measure single cloud properties and to understand the interplay between the effects smoke aerosols and meteorological conditions have upon clouds in the Amazon Basin.

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