Macrophysical properties of tropical cirrus clouds from the CALIPSO satellite and from ground-based micropulse and Raman lidars

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Introduction

- Tropical cirrus clouds are optically thin, but widespread and therefore important regulators of the radiation balance which constrains various atmospheric processes.
- Characterizing the vertical structure of all cirrus clouds requires lidar observations.
- We compare cirrus cloud macrophysical properties over the ARM Darwin site from three lidars: the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite, the ARM micropulse lidar (MPL) and the ARM Raman lidar (RL).
- The ARM RL was recently deployed at the Darwin site and has several unique characteristics compared to either the MPL or CALIPSO including the transmission of a more powerful laser beam, the ability to retrieve backscatter and extinction profiles independently, and a shorter wavelength laser.

Comparing the MPL and CALIPSO at the ARM TWP sites Thorsen et al. *JGR* [2011] showed:

- The MPL detects significantly less cirrus than CALIPSO, suggesting that the MPL is less sensitive than CALIPSO. **Does the RL improve (relative to the MPL) the ARM program's ability to observe tropical cirrus clouds? How does the RL compare to CALIPSO?**
- During the daytime, cirrus clouds occur less frequently and are geometrically thinner than at night; which could be non-physical and/or due to increased daytime noise. **The RL elastic channel operates at a wavelength (355 nm) where the sun emits less energy compared to the MPL/CALIPSO (532 nm). Can we use the RL to determine if these diurnal cycles are physical?**

Datasets

MPL:

- Cloud mask applied [Wang and Sassen, *JAM*, 2001] to the backscattered signal averaged to 2 min at a 30 m vertical resolution.
- Background noise from *mplpolavg* VAP.

RL:

- Cloud mask applied to depolarization ratio (δ; *rlprofdep* VAP) averaged to 2 min at a 30 m vertical resolution.
- Cloud is defined as $\delta > 3\%$ with a random error less than 20%.
- Background noise from *rlprofmerge* VAP.

CALIPSO:

- L2 5 km v3 cloud layer product (CLay).
- L2 5 km v3 cloud profile product (CPro).
- L1B v3 profile product.
- Cloud mask applied [Vaughan et al., *JTECH*, 2009] to the backscatter signal averaged to 5, 20 or 80 km. Vertical resolution is 30 m below 8.2 km and 60 m above.

Comparison Method

- CALIPSO data taken from a 5° by 5° domain centered on the ARM Darwin site.
- Two periods of data:
  (1) June 2006 through August 2011: MPL and CALIPSO.
  (2) December 2010 through December 2012: RL and CALIPSO.
- Two sets of ground-based data:
  (1) All available profiles.
  (2) Profiles collocated to within ± 4 hours of CALIPSO overpasses.
- Cirrus clouds defined as a cloud layer with a base above 7 km.
- Sampling uncertainty calculated using the moving block bootstrap resampling method (shaded region in figures).

Solar Background

Table 1: Ratio of the median daytime background root mean squared (RMS) noise to that at night for profiles transparent to the lidar.

Jun. 2006 - Aug. 2011		Dec. 2010 - Dec. 2012	
CALIPSO	9.3	CALIPSO	10.0
MPL	25.3	RL	2.1
MPL, ± 4 h	28.9	RL, ± 4 h	2.5

- The impact of the solar background on the RL is non-negligible, but is about 4 times less than CALIPSO and about 12 times less than the MPL.

Signal to Noise Ratio (SNR)

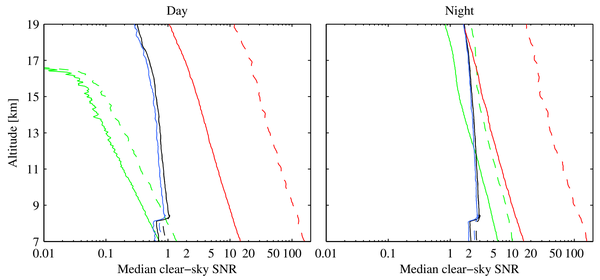

Figure 1: Median SNR in the clear-sky portion of profiles transparent to the lidar.

- The RL SNR is the largest and similar between day and night.
- Both the MPL and CALIPSO have higher SNR at night.
- MPL performs very poorly during the daytime.

Transparent Cloud Fraction

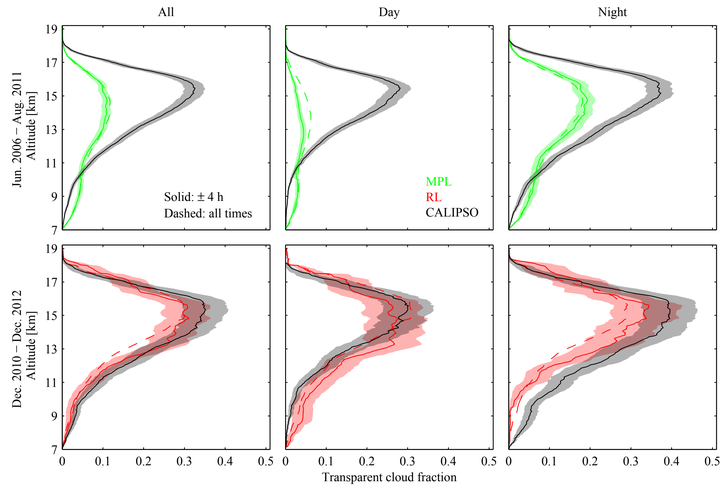

Figure 2: Cirrus cloud fraction in transparent profiles.

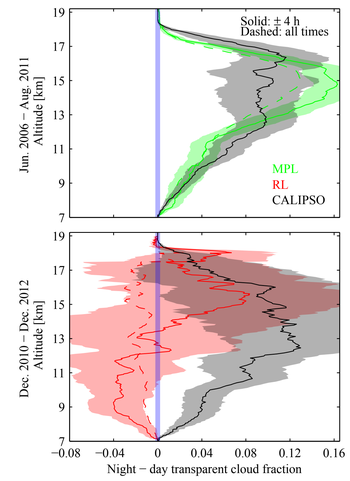

Figure 3: The difference between the day and night mean transparent cirrus cloud fraction profiles.

- MPL detects very few cirrus during the daytime and more cirrus at night, but still significantly less than CALIPSO at most altitudes.
- RL and CALIPSO observations show excellent agreement.
- Both CALIPSO and the MPL show the same diurnal cycle with less cirrus during the daytime at all altitudes.
- The RL also shows less daytime cirrus above about 15 km (though not statistically different than zero), but differs from CALIPSO at lower altitudes.
- The full set of RL observations shows a near zero diurnal cycle.
- Statistically significant conclusions are difficult during the RL sampling period.

Cloud Layer Geometrical Thickness

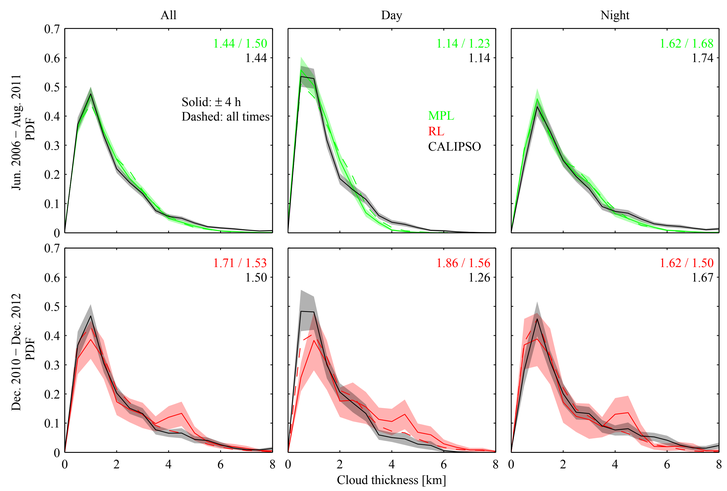

Figure 4: PDFs of cirrus cloud layer thickness in transparent profiles. The median cloud thickness is given in the upper right of each panel with two numbers for the ground-based datasets: the first for the dataset collocated in time and the second for all available profiles.

- CALIPSO and MPL observations agree well and both show thinner clouds during the daytime.
- CALIPSO agrees better with the RL at night.
- Cirrus layers observed by the RL show similar day and night statistics.
- Differences between day and night median thicknesses are statistically significant for the MPL/CALIPSO but not for the RL.

Table 2: CALIPSO cirrus cloud layer median geometrical thicknesses (km) derived from the L2 CPro product in transparent profiles. Layer thickness is also derived after applying two different extinction (α) thresholds to the data. Bold values indicate that the difference between day and night is statistically significant.

Jun. 2006 - Aug. 2011			Dec. 2010 - Dec. 2012		
	Day	Night		Day	Night
CALIPSO	**1.26**	**1.80**	CALIPSO	1.38	1.68
CALIPSO, $\alpha > 0.0061$ km^{-1}	1.20	1.20	CALIPSO, $\alpha > 0.0061$ km^{-1}	1.32	1.14
CALIPSO, $\alpha > 0.0035$ km^{-1}	**1.26**	**1.44**	CALIPSO, $\alpha > 0.0035$ km^{-1}	1.38	1.38

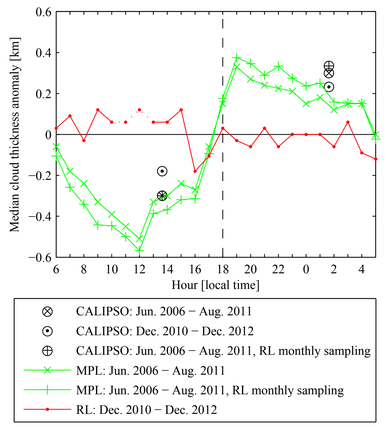

Figure 5: Hourly median cirrus cloud thickness anomaly. Times when the RL sample size is poor are connected using a dotted line. Sunrise occurs at approximately 6 and sunset at 18.

- RL observations show little variation throughout the day.
- MPL cirrus layer thickness is correlated with the sun—becoming thinner as the sun rises and thicker as the sun sets.
- Application of the approximate daytime detection limits [Chepfer et al., *JTECH*, 2012] to all CALIPSO data eliminates or reduces the differences between day and night cloud layer thicknesses.

Total Cloud Fraction

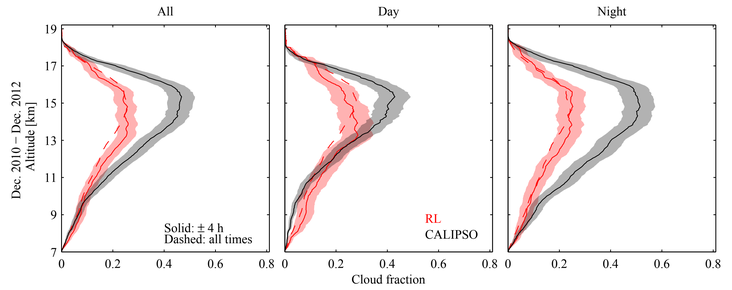

Figure 6: Total ice cloud fraction profiles.

- The amount of attenuated RL profiles (42%) and attenuated CALIPSO profiles (34%) are statistically the same.
- A non-trivial amount of cirrus is missed in attenuated profiles by the RL as the result of it's ground-based platform.

Conclusions

- This study highlights the vast improvement the RL provides (compared to the MPL) in the ARM program's ability to observe tropical cirrus clouds.
- The RL observations show that both the MPL and CALIPSO underestimate cirrus cloud geometrical thickness during the daytime due to increased noise.
- With continued operation the accumulation of a long-term ARM RL dataset of tropical cirrus, with independently retrieved extinction/backscatter and relatively higher-quality daytime measurements, will be a useful tool for CALIPSO validation.
- Future work includes evaluation of CALIPSO/MPL/RL optical depth retrievals.

We thank Rob Newsom and Bill Hunt for their help with this work. This research was supported by the Office of Science (BER), U.S. Department of Energy, grant DE-FG02-09ER64769

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