Validation of Satellite Remote Sensed Cloud Properties using Combined Lidar and Radar Measurements

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Introduction

The recent availability of operational High Spectral Resolution Lidar (HSRL) measurements (Eloranta 1997) offers a unique opportunity to evaluate the performance of infrared satellite remote sensed cloud microphysical retrievals. This paper will present new satellite validation techniques designed to utilize the advanced capabilities of the AHSRL and Millimeter Wavelength Cloud Radar (MMCR) measurements. The paper will investigate the sensitivity differences between the lidar and radar (active) and satellite (passive) measurements. From this investigation new validation methods using AHSRL and MMCR measurements will be developed that account for the sensitivity differences that result from comparing an active measurement to satellite retrieval. The new validation methods will be used to evaluate aircraft infrared retrievals of cloud height, optical depth, and cloud effective radius.

Instrumentation

Arctic High Spectral Resolution Lidar (AHSRL)

The Arctic High Spectral Resolution Lidar (AHSRL) is a multi-channel lidar capable of independent measurements of the cloud depolarization, extinction, and backscatter cross-section (Eloranta 1997). The AHSRL measures two signals that can be processed to yield separate lidar returns from aerosol and molecular scattering. The separation is possible because the wavelength spectrum of the molecular lidar return is Doppler broadened by molecular thermal motion. The separation of molecular and aerosol returns permits the HSRL to measure the extinction and aerosol backscatter cross-sections independently. The AHSRL also provides circular particulate depolarization measurements allowing for discrimination between ice and water. Photons backscattered on the surface of spherical water droplets have very little depolarization in contrast to high depolarization for ice crystals.

Millimeter Wavelength Cloud Radar (MMCR)

Both the ARM SGP and the NOAA SEARCH facility have operational Millimeter Cloud Radar (MMCR) measurements with similar instrument specifications. Both are 35 GHz radars with signals processed to provide measurements of the received power, Doppler velocity, and spectral width. The Doppler measurements allow for particle fall velocity retrievals. The radar reflectivity is measured to an altitude of 20 km allowing for both low and high cloud detection. The MMCR is capable of running in four different modes. Each mode is optimized for different atmospheric conditions. The MMCR alternates between the four modes every 2 seconds and completes an entire mode sequence in under 18 seconds. The SGP MMCR alternates between the stratus and five other modes. The mode sequence is:

BL CI BL GE BL PR BL GE BL CI BL GE BL PO BL GE

Where BL is the Stratus mode, GE is the general mode, CI is the cirrus mode, PR is the precipitation mode and PO is the dual-polarization mode. The complete mode sequence takes approximately 32 seconds.

Cloud Physics Lidar (CPL)

The Cloud Physics Lidar (CPL) is a cloud lidar developed by NASA Goddard and flies on the ER2 high altitude aircraft (McGill, Hlavka et al. 2002). The CPL is an active remote sensing system, capable of very high vertical resolution cloud height determinations (30 meters), cloud visible optical depth, and backscatter depolarization. The depolarization measurement allows for the discrimination between ice and water clouds. Photons backscattered on the surface of spherical water droplets have very little depolarization in contrast to ice crystals where the backscatter results in large depolarization. For CPL measurements, depolarization of

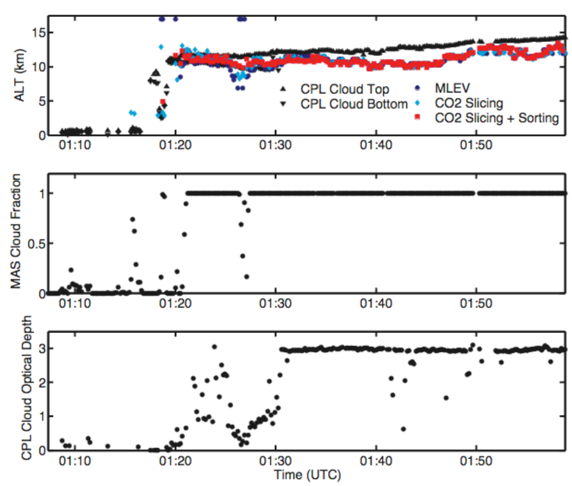

Figure 1: The S-HIS cloud-top retrievals collocated with the CPL measured cloud-top and base measurements from February 22nd 2003 (top panel). The mean CPL measured optical depth is presented in the bottom figure. The cloud-top, base and optical depth are the mean of all the CPL measurements found to be in S-HIS FOV.

greater then 25% are ice while polarizations less then 10% are generally water clouds.

The CPL laser transmits at 355, 532, and 1064 nm and fires 5000 shots/sec. For this paper the 532 nm one second averaged data is used. The high sample rate of the CPL results in a surface footprint that can be approximated as a continuous line with a diameter of 2 meters. A robust collocation algorithm is used to collocate the CPL measurements with the S-HIS. On average, ten CPL are measurements are found in each 2-km S-HIS field of view. The collocated CPL measurements of cloud height, depolarization, and optical thickness are used in this paper to analyze the sensitivity of S-HIS cloud top retrievals. The cloud optical thickness is retrieved by normalizing the elastic backscatter single above the cloud top to the clear sky molecular return. Using a calculated molecular profile the extinction is then computed using the normalized lidar single and the molecular profile. This retrieval technique assumes that the backscatter phase function of the cloud does not vary with altitude.

Scanning High-resolution Interferometer Sounder (S-HIS)

The Scanning High-resolution Interferometer Sounder (SHIS) is an aircraft based scanning Fourier transform interferometer designed to measure atmospheric infrared radiances at high spectral and spatial resolutions (Revercomb, Walden et al. 1998). The S-HIS measures the infrared emission between 3.0 – 16 μm with a spectral resolution of approximately 0.5 wavenumbers. The radiometric calibration allows for RMS noise errors to less than 0.2 K in terms of brightness temperature across the spectral bands except for near the band edges where the calibration is degraded (Revercomb, Walden et al. 1998). The S-HIS has a 100 mrad field of view and is capable of cross scanning. For the preceding analysis only nadir fields of view are used. With a flight altitude of 20 km the nadir S-HIS fields of view have a 2 km diameter surface footprint. The footprint is slightly oval along the flight track due to the 1-second dwell time and 200 m/s along track velocity.

Cloud Top Height Validation

The CPL is capable of retrievals of cloud boundaries, vertically resolved cloud extinction profiles, and cloud phase determination. This capability can be used to explore the relationships between the lidar and infrared cloud top height retrievals. The S-HIS retrieved cloud top altitude using the CO_2 Sorting/Slicing retrieval (Holz, Ackerman et al. 2005) is presented Figure 1. Each S-HIS FOV is collocated with the CPL resulting in matching CPL and S-HIS measurements of the cloud properties. Between 1:20 – 1:25 UTC the cloud is optically thin with a CPL retrieved optical thickness less then 1.0 as presented in Figure 1. Despite the optically thin cloud the geometrical differences between the lidar and S-HIS cloud top heights remain less then 1.0 km. After 1:30 UTC geometric differences become larger with the S-HIS and CPL cloud height differences greater then 2 km. The large differences occurred despite the total CPL cloud optical depths greater then 3.0. This is a surprising result, as one would expect closer agreement between the lidar and IR cloud top heights for optically thick clouds.

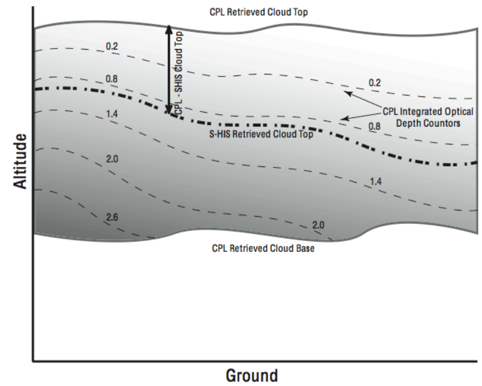

Figure 2: A cartoon to demonstrate the method used to determine the CPL integrated cloud optical depth at the level of the SHIS retrieval. The optical depth contours are determined by integrating the CPL extinction profile through the cloud.

Further investigation reveal the CPL cloud extinction profiles after 01:30 UTC in Figure 1 are optically thin at the cloud top with the extinction increasing towards the bottom of the cloud This case represents a condition where the different sensitivities between and active sensed (CPL) and the passive infrared cloud height (S-HIS) result in significant differences in the retrieved cloud heights. The CPL cloud boundary retrieval being an active measurement is sensitive to the cloud backscatter cross-section while the IR retrieval is sensitive to cloud emission. The result is the IR retrieval, sensitive to the cloud levels of the maximum sensed cloud emission detects the cloud significantly lower then the CPL. As will be discussed, the CPL integrated cloud optical depth is a more representative measure of the IR cloud optical depth for tenuous cirrus.

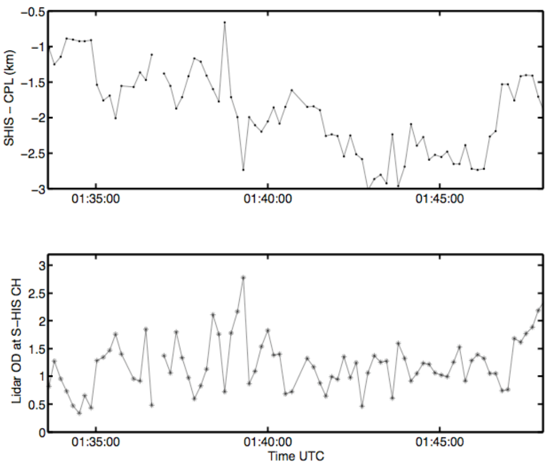

Figure 3:The geometric difference between the SHIS hybrid slicing/sorting retrieval and the collocated CPL cloud height for the February 22 flight is presented in this figure. The integrated optical depth determined by the CPL at the level of the S-HIS hybrid retrieved cloud height (CH) is presented in the lower plot. Notice that integrated optical depth remains relatively constant while the SHIS – CPL cloud height differences vary between 0.5 – 3.0 km.

To investigate relationship between the lidar and S-HIS cloud top height sensitivity collocated CPL extinction profiles were integrated starting from the lidar cloud top to produce integrated optical depth contours at each CPL level. Using the integrated CPL extinction, the integrated optical depth at the level the S-HIS retrieval detected the cloud is determined as illustrated in Figure 2.

The geometric S-HIS – CPL cloud height differences and integrated optical depths using the method described in Figure 2 for the February 22 flight between 1:30 – 1:50 UTC are presented in Figure 3. In Figure 3 the S-HIS and CPL cloud heights progresses from relatively close agreement at 1:30 UTC to differences larger than 2.5 km at 1:45 UTC. Despite the large geometric differences, the CPL integrated optical depth at the level the S-HIS detected the cloud height remains relatively constant with a mean optical depth of approximately 1.0.

This result illustrates the importance of the cloud radiative properties when comparing the lidar and infrared cloud top heights. The close correlation between the lidar integrated optical depth profile and the IR retrieved cloud top heights is easily explained when you consider the sensitivity of the IR measurement. For a cloud with a uniform extinction profile the cloud level with the maximum contribution to the cloud signal measured by the IR sensor occurs at the level of integrated optical of one. For cirrus clouds that are often geometrically thick but tenuous the lidar cloud boundaries may not be representative of the infrared cloud top. The results suggest comparing the satellite cloud height retrieval to a downward lidar integrated optical depth profile will result in a more physically consistent validation of the cloud height. For low and midlevel optically thick liquid water clouds the integrated optical depths typically becomes large near the cloud top resulting in small differences between the infrared and lidar cloud top heights. For these conditions the comparing the geometric cloud boundaries will result in a physically consistent validation.

Optical Depth and Effective Radius Validation

The S-HIS flew on the Proteus high altitude aircraft during the Mixed-Phase Arctic Cloud Experiment (M-PACE) in October of 2004 at Barrow, Alaska. During the experiment the AHSRL and MMCR were operated at the ARM North Slope of Alaska (NSA) measurement facility. In this section methods to validate the S-HIS microphysical retrievals using the active measurements will be investigated.

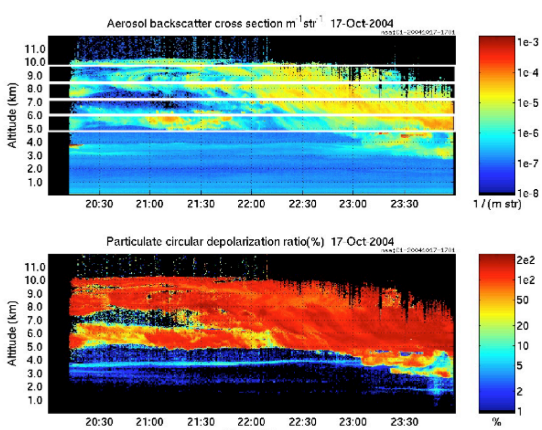

Figure 4: The AHSRL aerosol backscatter cross-section and depolarization at Barrow Alaska on October 17th 2004. The white boxes represent the averaging layers used for the infrared calculations.

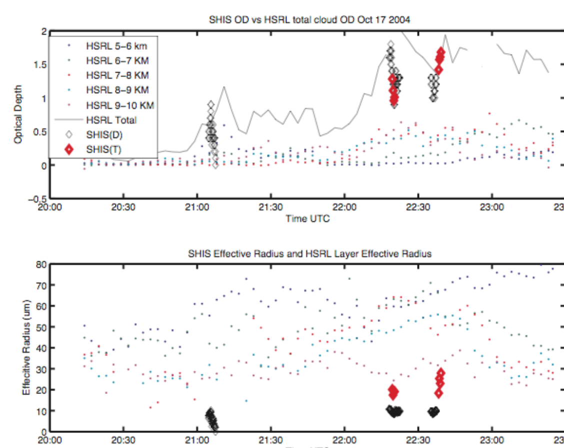

Figure 5: The AHSRL layer optical depth is presented in the top figure. The AHSRL-MMCR layer effective radius is presented in the bottom figure. Two different S-HIS infrared retrievals of the cloud optical depth and effective radius are presented at the overpass times.

The AHSRL aerosol backscatter cross-section and depolarization on October 17th are presented in Figure 4. The AHSRL detects an optically thin but geometrically thick cirrus over NSA between 20:00 – 23:30 UTC. The total cloud optical depth as measured by the AHSRL ranged between 0.1 – 2.0. The AHSRL cloud optical depth and the AHSRL-MMCR effective radius is presented in Figure 5. In this figure the AHSRL capability to resolve the optical depth at high vertical resolution is used to determine the layer cloud optical depth. In this figure the 5 km thick cloud is divided into five 1.0 km thick levels. The mean cloud optical depth and effective radius is then computed for each level.

A representative comparison between the up looking active AHSRL-MMCR effective radius retrieval and the down looking infrared S-HIS retrieval requires that the vertical resolved effective radius measured by the AHSRL-MMCR be weighted relative to the AHSRL extinction profile. The S-HIS infrared optical depth and effective radius retrievals are presented as diamonds in the Figure 5. At the overpass time the cloud extinction profile is weighted to the top of the cloud. The cloud effective radius is vertically stratified with the smallest effective radius weighted to the top of the cloud as presented in Figure 5. The infrared S-HIS retrieved effective radius compares closest to the AHSRL –MMCR effective radius retrieved at the top of the cloud (9 -10 km).

The AHSRL extinction profile can be used to weight the vertical retrieved effective radius. Examples of the AHSRL measured cloud weighting functions are presented in Figure 6. In Figure 6 the AHSRL extinction profile was integrated from the top of the cloud (10 km) to the bottom (5km) to represent the down looking perspective of the aircraft or satellite measurement. Using the integrated optical depth the transmittance profile is calculated. The cloud weighting function is then calculated using equation 1. The peak of the weighing function represents the cloud level that has the largest contribution to the infrared retrieval. In Figure 6 the peak of the weighting function varies significantly with a peak near the top of the cloud at 22:30 UTC (9 km) compared to the weighting function at 23:23 UTC peaking at 6.5 km. Convolving the cloud weighting function with the AHSRL-MMCR effective retrieval will result in a mean effective radius representative of the infrared retrieval.

Conclusions

This paper presents new methods to compare active remote sensed lidar and radar cloud measurements to down looking satellite and aircraft infrared retrievals. For geometrically thick but optically tenuous cirrus clouds the infrared cloud top retrievals significantly underestimated the cloud height by greater than 2.5 km when compared to the lidar. For these cases the S-HIS cloud top retrievals were compared to the lidar integrated optical depth normalized to the lidar cloud top altitude. It is found that

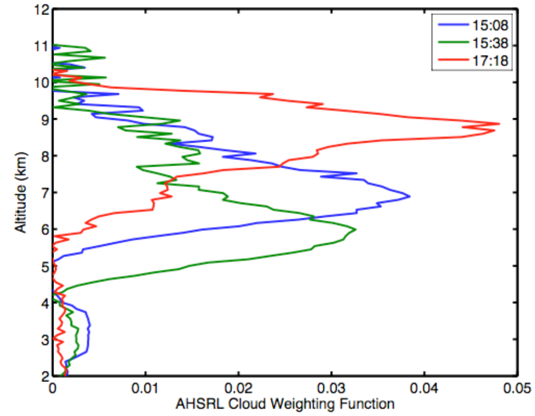

Figure 6: The AHSRL cloud weighting functions for October 17th 2004.

for these cases the infrared cloud top retrieval correlates closely to the level in the cloud where the lidar integrated optical depth is approximately 1.0. Ground based AHSRL-MMCR cloud effective radius retrievals where compared to aircraft S-HIS infrared cloud retrievals. To accurately compare the column averaged infrared retrieval it is necessary to weight the AHSRL-MMCR vertically resolved effective radius using the AHSRL extinction profile. The result is a mean effective radius that is representative of the infrared measurement.

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