Quantification of Satellite Cloud Retrieval Uncertainties from Multiple Platforms Using A-Train Observations

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Introduction

Satellite cloud property retrievals are used for both initialization and validation of cloud models and global circulation models. It is therefore important to characterize the uncertainty of satellite retrievals and identify any existing biases. The NASA Langley Cloud and Radiation Group uses a common set of algorithms to retrieve cloud thermodynamic phase, altitude, optical depth, and water path from imagers such as the Advanced Very High Resolution Radiometer (AVHRR), and the Clouds and the Earth's Radiant Energy System (CERES) Clouds Working Group routinely retrieves these same properties from Moderate-Resolution Imaging Spectroradiometer (MODIS) and Visible-Infrared Imaging Radiometer Suite (VIIRS) data. Active remote sensors in the A-Train Constellation such as the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) provide a wealth of information to independently assess the passive satellite retrievals.

Data and Validation Strategy

Satellite imager data:
- NOAA-18 AVHRR 4-km Global Area Coverage (GAC) data (Oct 2008)
- Aqua-MODIS, CERES Clouds Edition 4; subsampled 1-km pixels; 15 days from Oct 2008, Jul 2012, Oct 2012, Jan 2012, Apr 2013
- SNPP-VIIRS, CERES Clouds Edition 1; subsampled 750-m pixels; 5 days from March 2013

Products used to validate imager retrievals:
- CALIPSO Vertical Feature Mask (VFM)
- CALIPSO 5-km Cloud Layers Product (05kmCLay)
- CALIPSO 333-m Cloud Layers Product (333mCLay)
- AMSR-E Level 2 Ocean Product (Wentz Algorithm)

Spatial/temporal matching:
CALIPSO provides cloud heights on various spatial scales ranging from 333 m to 80 km. Many of the CALIPSO products are provided at 5-km resolution which is comparable to the spatial resolution of most imagers. For this reason, all satellite data is matched spatially to 5-km segments of the CALIPSO ground track. Imager pixels within 2.5 km of each segment's midpoint and within 15 minutes of the CALIOP scan time are considered matches. Since AMSR-E has a larger footprint, the mean LWP is computed for all imager pixels within the AMSR-E footprint nearest the CALIOP footprint. While MODIS and VIIRS view the CALIPSO ground track near nadir, AVHRR may have off-nadir views. All AVHRR pixels were corrected for parallax. In the following sections, all differences are computed as AVHRR/MODIS/VIIRS minus CALIOP/AMSR-E.

INSTRUMENT/ PRODUCT	APPROX. SPATIAL RES.	CLOUD PROPERIES PROVIDED
VFM	1/3 – 80 km	cloud mask (see Q. Trepte poster, P6-354) phase
05kmCLay	5 km	optical depth (COD), ice water path (IWP)
333mCLay	1/3 km	cloud top altitude (CTA)
AMSR-E	12 km	liquid water path (LWP)

Cloud Phase

CALIPSO VFM data were used to identify overcast scenes consisting of single-phase clouds, i.e. 100% water or 100% ice. Scenes containing faint cirrus detected by CALIOP using 80-km horizontal averaging were excluded from the analysis. The fraction of correctly identified scenes (FC) is shown in the chart below for all three imagers and for different surface types.

FRACTION OF SCENES WITH CORRECTLY IDENTIFIED PHASE	AVHRR	MODIS	VIIRS
DAYTIME			
Nonpolar, Ocean	0.956	0.978	0.991
Nonpolar, Land	0.913	0.936	0.955
Polar, Ocean	0.922	0.959	0.971
Polar, Land	0.869	0.943	0.978
Global, Snow/Ice	0.809	0.926	0.821
NIGHTTIME			
Nonpolar, Ocean	0.927	0.947	0.976
Nonpolar, Land	0.906	0.914	1.000*
Polar, Ocean	0.823	0.912	0.945*
Polar, Land	0.938	0.915	no data
Global, Snow/Ice	0.873	0.876	0.814

* computed with fewer than 100 data points

The correct phase is identified by all three imagers over 90% of the time in most cases.

AVHRR FC values are typically within 2-3% of the MODIS and VIIRS values.

There is a bias towards ice clouds for "twilight" conditions, i.e., 82° < solar zenith angle < 90° (not shown).

Cloud Altitude

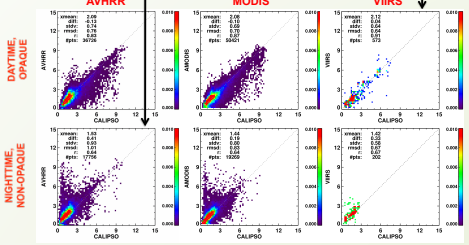
Cloud top altitude (CTA) differences (km, imager minus CALIOP) were computed as a function of thermodynamic phase (water/ice), solar zenith angle (day/night), surface type (snow/ice-free, snow/ice-covered), and cloud opacity (non-opaque, opaque). Root-mean-square differences (RMSD) were also computed and are given in the tables below.

WATER CLOUDS NON-OPAQUE

CTA BIASES, RMS DIFFERENCES, [km]	AVHRR		MODIS		VIIRS	
	Bias	RMSD	Bias	RMSD	Bias	RMSD
DAYTIME						
Global, Snow/Ice-Free	-0.16	0.76	-0.04	0.74	0.24	0.87
Global, Snow/Ice-Covered	0.61	1.39	0.24	0.97	1.37*	2.06*
NIGHTTIME						
Global, Snow/Ice-Free	**0.41**	**1.01**	**0.19**	**0.83**	**0.33**	**0.67**
Global, Snow/Ice-Covered	0.22	0.74	0.39	0.88	no data	

WATER CLOUDS OPAQUE

CTA BIASES, RMS DIFFERENCES, [km]	AVHRR		MODIS		VIIRS	
	Bias	RMSD	Bias	RMSD	Bias	RMSD
DAYTIME						
Global, Snow/Ice-Free	**-0.13**	**0.76**	**-0.10**	**0.70**	**0.04**	**0.64**
Global, Snow/Ice-Covered	0.63	1.33	-0.03	0.94	0.17*	0.84*
NIGHTTIME						
Global, Snow/Ice-Free	0.20	0.75	0.05	0.70	0.04	0.46
Global, Snow/Ice-Covered	0.38	0.94	0.37	0.91	no data	



Colorbars indicate relative frequency of data.

Opaque cloud tops are within 200 m of CALIOP retrievals (top row of plots). Differences increase for non-opaque clouds and clouds over snow/ice surfaces.

AVHRR retrievals tend to be more biased than MODIS and VIIRS.

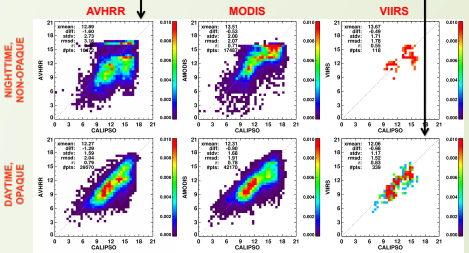
Nighttime retrievals of non-opaque clouds show a consistent bias of 200-400 m (bottom row).

ICE CLOUDS NON-OPAQUE

CTA BIASES, RMS DIFFERENCES, [km]	AVHRR		MODIS		VIIRS	
	Bias	RMSD	Bias	RMSD	Bias	RMSD
DAYTIME						
Global, Snow/Ice-Free	-2.94	3.89	-2.24	3.51	-1.05*	2.08*
Global, Snow/Ice-Covered	-1.58	3.73	-1.76	3.08	-1.03*	1.37*
NIGHTTIME						
Global, Snow/Ice-Free	**-1.60**	**3.16**	**-0.53**	**2.07**	**-0.49**	**1.78**
Global, Snow/Ice-Covered	-0.72	3.66	-0.92	2.62	-0.33*	1.98*

ICE CLOUDS OPAQUE

CTA BIASES, RMS DIFFERENCES, [km]	AVHRR		MODIS		VIIRS	
	Bias	RMSD	Bias	RMSD	Bias	RMSD
DAYTIME						
Global, Snow/Ice-Free	**-1.29**	**2.04**	**-0.90**	**1.91**	**-0.98**	**1.52**
Global, Snow/Ice-Covered	-0.78	2.13	-0.92	2.06	0.34*	0.60*
NIGHTTIME						
Global, Snow/Ice-Free	-1.23	2.09	-0.77	1.80	-1.48	1.89
Global, Snow/Ice-Covered	-1.41	2.29	-1.07	1.80	1.13*	1.38*



AVHRR retrievals show larger biases than MODIS and VIIRS over snow/ice-free surfaces, possibly due to the lack of a CO_2 channel. Biases over snow/ice are similar.

The nighttime algorithm retrieves CTA within 1.6 km of CALIOP for non-opaque ice (top row), as opposed to within 3 km for the daytime algorithm.

Retrievals for opaque ice are within 1.5 km for all three imagers (bottom row). RMS differences for opaque cloud are 1-2 km lower than for non-opaque clouds.

Summary

Cloud property retrievals from imagers such as AVHRR, Aqua-MODIS, and VIIRS are being validated with A-Train sensors such as CALIOP and AMSR-E.

Water cloud top altitudes are retrieved to within 400 m of CALIOP values. Opaque ice cloud tops are retrieved to within 1 km. CTA biases are generally smaller for opaque than non-opaque clouds.

Nighttime optical depths and IWP compare well with CALIOP. Increased surface reflection causes overestimates over snow/ice surfaces during the day. IR-only techniques can help reduce daytime biases.

Daytime LWP retrievals for non-precipitating clouds are biased by less than 6 g m^{-2} compared to AMSR-E microwave retrievals and show moderate to high correlation.

AVHRR retrievals are nearly as accurate as MODIS and VIIRS retrievals in many cases.

Validation for VIIRS will be ongoing as the record becomes more extensive.

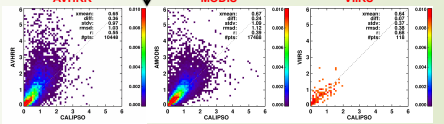
Cloud Optical Depth

Cloud optical depth (COD) comparisons are limited to non-opaque ice-phase clouds, corresponding to COD < ~6, because they do not completely attenuate the lidar beam.

The smallest differences occur for nighttime snow/ice-free conditions when IR-only algorithms are used to retrieve COD.

Differences are largest for daytime snow/ice surfaces because of increased reflection from bright surfaces. See S. Bedka poster (P6-344) for techniques being used to mitigate these difficulties.

COD BIASES, RMS DIFFERENCES, [unitless]	AVHRR		MODIS		VIIRS	
	Bias	RMSD	Bias	RMSD	Bias	RMSD
DAYTIME						
Global, Snow/Ice-Free	1.00	3.82	0.69	3.18	0.67*	1.57*
Global, Snow/Ice-Covered	3.29	14.63	11.39	21.76	1.08*	1.30*
NIGHTTIME						
Global, Snow/Ice-Free	**0.36**	**1.03**	**0.24**	**1.12**	**0.07**	**0.38**
Global, Snow/Ice-Covered	2.41	5.21	4.38	6.66	2.41*	3.83*

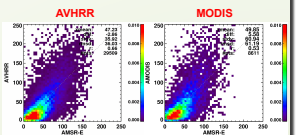


Cloud Water Path

The AMSR-E liquid water path (LWP) retrieval algorithm is performed over water surfaces only, so no comparisons with AMSR-E over land are currently available. Ground-based microwave radiometer (MWR) observations can be used for validation in limited locations. Precipitating clouds were excluded from the analysis, effectively limiting comparisons to clouds with LWP < 200 g m^{-2}, and no distinction was made for opaque and non-opaque clouds.

The AMSR-E and VIIRS data records have no temporal overlap, so LWP comparisons are shown for AVHRR and MODIS only.

LWP BIASES, RMS DIFFERENCES, [g m^{-2}]	AVHRR		MODIS	
	Bias	RMSD	Bias	RMSD
DAYTIME				
Global, Snow/Ice-Free	**-2.86**	**36.03**	**5.58**	**61.19**
Global, Snow/Ice-Covered	31.90	101.16	36.22*	58.88*
NIGHTTIME				
Global, Snow/Ice-Free	-27.57	57.75	-6.71	53.75
Global, Snow/Ice-Covered	-5.66	68.05	-0.37*	44.73*



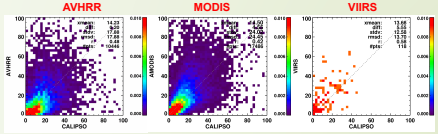
LWP is overestimated over snow/ice-covered surfaces during the day because of surface reflection. Nighttime LWP is underestimated because optical depths greater than 4-6 cannot be retrieved with any certainty using IR-only techniques.

IWP BIASES, RMS DIFFERENCES, [g m^{-2}]	AVHRR		MODIS		VIIRS	
	Bias	RMSD	Bias	RMSD	Bias	RMSD
DAYTIME						
Global, Snow/Ice-Free	10.56	66.03	2.84	32.65	9.30*	35.50*
Global, Snow/Ice-Covered	68.57	242.30	234.19	497.75	5.31*	18.95*
NIGHTTIME						
Global, Snow/Ice-Free	**0.20**	**17.88**	**4.55**	**24.45**	**5.55**	**13.70**
Global, Snow/Ice-Covered	33.29	97.15	61.88	109.79	47.13*	74.67*

CALIOP can retrieve IWP only for thin clouds so results are shown for non-opaque clouds only.

The use of IR-only techniques during daytime may help reduce IWP biases over snow/ice-covered surfaces.

Smallest IWP differences occur for nighttime IR-only retrievals. Values are moderately to highly correlated with CALIOP.



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