P-55. Validation of Cloud Properties from Multiple Satellites Using CALIOP Data

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Introduction

The NASA Langley Satellite ClOud and Radiative Property retrieval System (SatCORPS) is routinely applied to multispectral imagery from several geostationary and polar-orbiting imagers to retrieve cloud properties for weather and climate applications. Validation of the retrievals with independent datasets is continuously ongoing in order to understand differences caused by calibration, spatial resolution, viewing geometry, and other factors. The CALIOP instrument provides a decade of detailed cloud observations which can be used to evaluate passive imager retrievals of cloud boundaries, thermodynamic phase, cloud optical depth, and water path on a global scale. This paper focuses on comparisons of CALIOP retrievals to retrievals from MODIS, VIIRS, AVHRR, GOES, SEVIRI, and MTSAT.

Data and Validation Strategy

Satellite imager data:

- Aqua-MODIS, CERES Clouds Edition 4; subsampled 1-km pixels
- SNPP-VIIRS, CERES Clouds Edition 1; subsampled 750-m pixels
- NOAA-18 AVHRR 4-km Global Area Coverage (GAC) data
- GOES-11, GOES-12, Meteosat-9, SEVIRI, and MTSAT-1R (collectively referred to as geostationary or GEO), CERES Clouds Edition 4; subsampled 4-km pixels
- MODIS, AVHRR, and GEO data are from January, April, July, and October (JAJO) of 2008. VIIRS data are from JAJO 2012.

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)

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 are 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. While MODIS views the CALIPSO ground track near nadir, VIIRS, AVHRR and GEO imagers frequently have larger view angles. All VIIRS, AVHRR, and GEO pixels were corrected for parallax. In the following sections, all differences are computed as MODIS/VIIRS/AVHRR/GEO minus CALIOP.

INSTRUMENT/PRODUCT	APPROX. SPATIAL RES.	CLOUD PROPERIES PROVIDED
VFM	1/3 – 80 km	cloud mask, phase, and opacity
05kmCLay	5 km	cloud top altitude (CTA), optical depth (COD), and ice water path (IWP)
333mCLay	1/3 km	cloud top altitude

Cloud Detection and Phase

CALIOP VFM data were used to identify clear and cloudy scenes. Segments with cloud fraction CF < 0.5 and CF > 0.5 were considered clear and cloudy, respectively, and segments containing faint cirrus detected by CALIOP using 80-km horizontal averaging were excluded from the analysis. The fraction of correctly identified clear and cloudy scenes (FC) is shown in the chart below for all four imagers and for different surface types.

GLOBAL FRACTION OF CORRECTLY IDENTIFIED CLEAR AND CLOUDY SCENES

	MODIS	VIIRS	AVHRR	GEO
DAY				
Land & Ocean	0.89	0.87	0.86	0.85
Ocean	0.91	0.88	0.86	0.86
Land	0.87	0.85	0.83	0.84
Snow/Ice	0.83	0.84	0.82	0.98*
NIGHT				
Land & Ocean	0.89	0.87	0.87	0.86
Ocean	0.90	0.88	0.87	0.86
Land	0.85	0.84	0.85	0.84
Snow/Ice	0.77	0.72	0.70	0.85*

*fewer than 100 data points

The cloud mask makes the correct clear/cloudy determination in over 85% of cases over ocean and land surfaces. Snow/ice surfaces are more problematic, especially at night.

MODIS and VIIRS show remarkable consistency. AVHRR and GEO FC values are typically within 2-5% of the MODIS and VIIRS values. Reduced agreement relative to MODIS is expected because of time and resolution differences.

Cloud phase retrievals agree with CALIOP over 84% of the time except over snow/ice. Daytime FC values are up to 8% higher than nighttime and reach up to 94%.

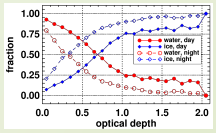
Snow/ice-covered surfaces are observed much less frequently in geostationary imagery compared to polar-orbiting instruments so statistics are less robust.

VFM data were also used to validate imager cloud phase retrievals. Where possible, a single cloud phase was assigned to each 5-km segment. For scenes with more than one phase, the dominant phase was chosen. For particularly complex scenes, the quality flags helped guide the phase selection. The fraction of correctly identified scenes is shown in the chart below for scenes with 100% cloud cover.

GLOBAL FRACTION OF SCENES WITH CORRECTLY IDENTIFIED PHASE

	MODIS	VIIRS	AVHRR	GEO
DAY				
Land & Ocean	0.92	0.91	0.89	0.87
Ocean	0.94	0.92	0.90	0.89
Land	0.87	0.86	0.85	0.83
Snow/Ice	0.88	0.86	0.77	0.82*
NIGHT				
Land & Ocean	0.87	0.88	0.87	0.87
Ocean	0.88	0.89	0.87	0.88
Land	0.84	0.84	0.85	0.82
Snow/Ice	0.80	0.81	0.81	0.74*

THIN CIRRUS OVER LOW-LEVEL WATER CLOUDS



Water clouds dominate imager phase retrievals when the upper-layer cirrus has COD < 0.5. IR-only retrievals are able to detect cirrus with COD as low as 0.3. Results shown here are from MODIS data.

Cloud Optical Depth

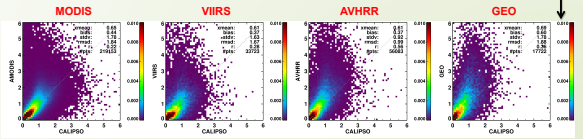
Cloud optical depth (COD) comparisons are limited to non-opaque ice-phase clouds corresponding to COD < ~6, because they do not completely attenuate the lidar beam.

The smallest differences occur for nighttime snow/ice-free conditions when IR-only algorithms are used to retrieve COD. Comparisons with CALIOP constrained retrievals have smaller biases and RMSDs but constrained retrievals occur less frequently during daytime. See Garnier et al. (2012) and Young and Vaughan (*JAOT*, 2009) for details on constrained retrievals.

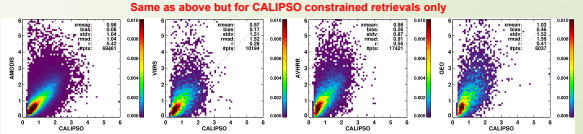
Differences are largest for daytime snow/ice surfaces because of increased reflection from bright surfaces. Techniques are under development to mitigate these difficulties.

GLOBAL COD BIASES, RMS DIFFERENCES [unitless]

	MODIS		VIIRS		AVHRR		GEO	
	Bias	RMSD	Bias	RMSD	Bias	RMSD	Bias	RMSD
DAY								
Snow/Ice-Free	0.86	4.27	0.91	4.83	1.34	4.14	2.25	10.61
Snow/Ice-Covered	13.23	24.95	4.60	7.09	6.17	20.02	-0.70*	1.35*
NIGHT								
Snow/Ice-Free	0.44	1.84	0.37	1.67	0.37	0.99	0.60	1.88
Snow/Ice-Covered	4.20	6.31	2.99	5.20	2.66	4.84	1.99*	2.03*



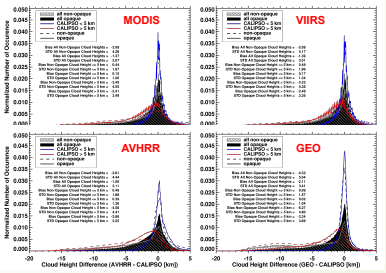
Same as above but for CALIPSO constrained retrievals only



Cloud Top 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). Results for both single and multi-layer clouds are summarized graphically in the histograms below and more detail, including root-mean-square differences (RMSD), are given in the tables for single-layer clouds.

SINGLE AND MULTI-LAYER CLOUDS



Histograms at left show CTA differences for single and multi-layer cloud scenes. Altitudes of the highest layers were compared to the imager retrievals regardless of phase. Phase differences result in larger biases. Biases for scenes where the imagers and CALIOP agreed on phase are shown in the tables at right.

AVHRR and GEO retrievals are generally more biased than MODIS and VIIRS.

Both non-opaque and opaque water cloud tops are within 200 m of CALIOP retrievals. Tops are generally underestimated during the day and overestimated at night.

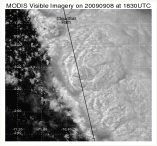
CALIOP is much more sensitive to non-opaque ice clouds than the imagers. The nighttime algorithm retrieves CTA within 2 km of CALIOP for non-opaque ice, as opposed to within 3 km for the daytime algorithm.

Retrievals for opaque ice are within 1.5 km for all four imagers. RMS differences for opaque clouds are 1-2 km lower than for non-opaque clouds.

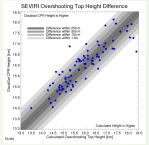
AVHRR and GEO retrievals show larger biases than MODIS and VIIRS over snow/ice-free surfaces, possibly due to the lack of a CO_2 channel. Biases over snow/ice are similar.

OVERSHOOTING CLOUD TOP HEIGHTS

Cloud top height retrievals were improved for overshooting clouds using co-located MODIS, GEO, and CloudSat data. See Griffin et al. (*JAMC*, 2016) for details. Height assignment of overshooting tops is especially challenging using IR observations alone because these clouds are typically colder than any vertical level in a co-located sounding or NWP profile.



CloudSat overpass of thunderstorm anvil and OT region



Comparison of OT heights from SEVIRI and CloudSat data

GLOBAL CTA BIASES, RMS DIFFERENCES [km]

SINGLE LAYER WATER CLOUDS		MODIS		VIIRS		AVHRR		GEO	
		Bias	RMSD	Bias	RMSD	Bias	RMSD	Bias	RMSD
NON-OPAQUE	DAY								
	Snow/Ice-Free	-0.17	1.10	-0.09	1.04	-0.46	1.21	-0.52	1.36
	Snow/Ice-Covered	0.21	1.30	0.35	1.24	0.60	1.69	*	*
	NIGHT								
	Snow/Ice-Free	0.00	0.87	0.11	0.94	0.49	1.12	0.22	1.34
	Snow/Ice-Covered	0.11	1.15	0.17	0.92	0.07	1.07	0.01*	0.45*
OPAQUE	DAY								
	Snow/Ice-Free	-0.13	0.84	-0.10	0.93	-0.17	0.95	-0.31	0.98
	Snow/Ice-Covered	0.09	1.00	0.02	1.09	0.81	1.80	0.02*	0.37*
	NIGHT								
	Snow/Ice-Free	0.05	0.81	0.11	0.86	0.43	1.02	0.13	0.98
	Snow/Ice-Covered	0.11	1.03	0.12	0.98	0.41	1.23	0.25*	1.16*

GLOBAL CTA BIASES, RMS DIFFERENCES [km]

SINGLE LAYER ICE CLOUDS		MODIS		VIIRS		AVHRR		GEO	
		Bias	RMSD	Bias	RMSD	Bias	RMSD	Bias	RMSD
NON-OPAQUE	DAY								
	Snow/Ice-Free	-2.09	3.69	-1.43	2.80	-2.92	3.74	-2.85	3.79
	Snow/Ice-Covered	-0.99	3.24	-1.55	2.60	-1.23	2.68	-1.69*	3.51*
	NIGHT								
	Snow/Ice-Free	-0.24	2.27	-0.50	2.43	-1.72	3.26	-1.49	3.16
	Snow/Ice-Covered	-0.92	3.53	-0.89	2.85	-1.58	4.01	-1.09*	1.18*
OPAQUE	DAY								
	Snow/Ice-Free	-0.60	1.80	-1.03	1.88	-1.15	2.00	-1.37	2.17
	Snow/Ice-Covered	-0.57	1.88	-1.02	1.86	-0.39	1.46	0.89*	2.39*
	NIGHT								
	Snow/Ice-Free	-0.44	1.71	-0.60	1.78	-1.18	2.05	-1.26	2.23
	Snow/Ice-Covered	-1.06	2.32	-0.70	1.77	-1.52	2.63	0.06*	1.10*

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Ice Water Path

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

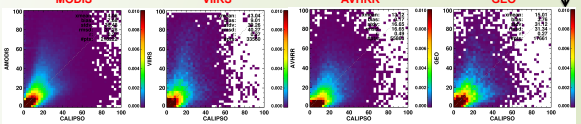
Smallest IWP differences occur for nighttime IR-only retrievals. Imagers overestimate IWP in all cases.

As with COD, biases are smaller when compared to CALIOP constrained retrievals.

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

GLOBAL IWP BIASES, RMS DIFFERENCES [g m^{-2}]

	MODIS		VIIRS		AVHRR		GEO	
	Bias	RMSD	Bias	RMSD	Bias	RMSD	Bias	RMSD
DAY								
Snow/Ice-Free	8.19	83.83	12.36	95.08	19.12	91.38	37.00	220.57
Snow/Ice-Covered	295.65	599.66	90.46	143.86	164.46	470.12	-16.46*	34.65*
NIGHT								
Snow/Ice-Free	7.68	37.28	9.01	40.27	0.17	16.65	3.76	31.34
Snow/Ice-Covered	62.42	106.41	54.51	103.80	41.50	86.62	11.64*	14.61*



Summary

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

Cloud mask and phase retrievals agree with CALIOP VFM data at least 85% of the time for snow/ice-free surfaces. Thin cirrus with optical depth greater than about 0.5 can be distinguished from underlying water clouds.

Top altitudes for opaque water and ice clouds are retrieved to within 200 m and 1.5 km of CALIOP values, respectively. Larger biases exist for non-opaque clouds and clouds over snow/ice surfaces.

Nighttime optical depths and IWP compare reasonably well with CALIOP and biases are smaller when compared to CALIOP constrained retrievals. Increased surface reflection causes large overestimates over snow/ice surfaces during the day. IR-only techniques can help reduce daytime biases.

MODIS and VIIRS retrievals typically exhibit the smallest biases and RMSDs, but AVHRR and GEO retrievals are nearly as accurate as MODIS and VIIRS in many cases.