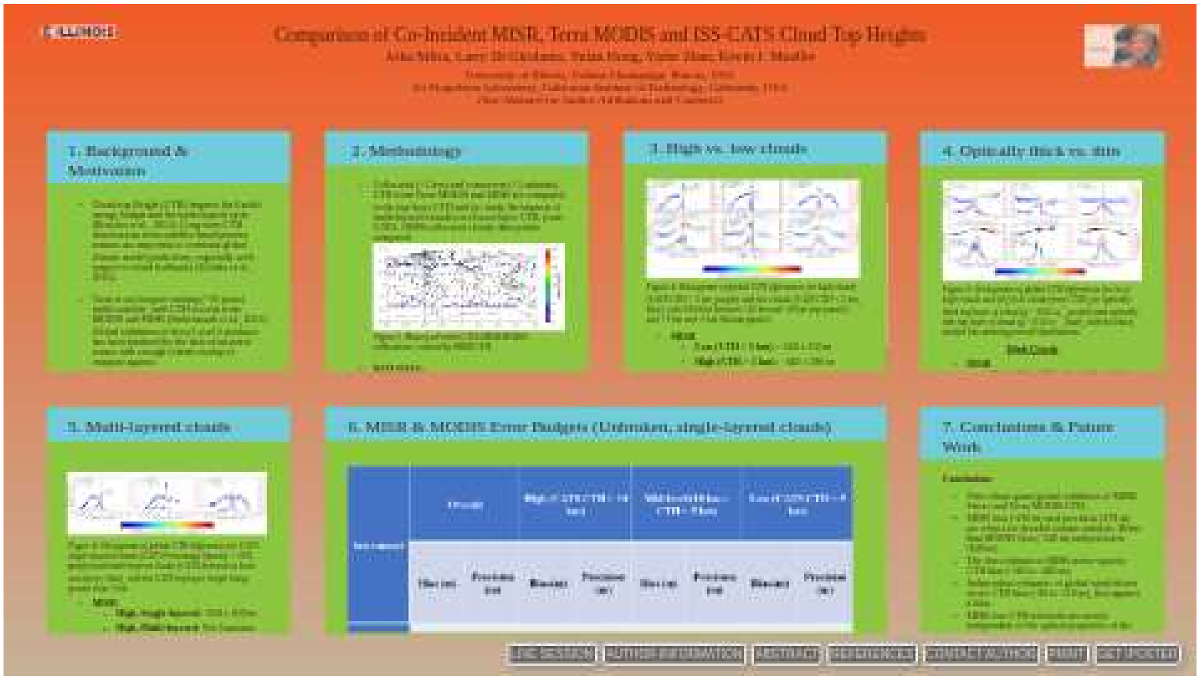
Comparison of Co-Incident MISR, Terra MODIS and ISS-CATS Cloud Top Heights



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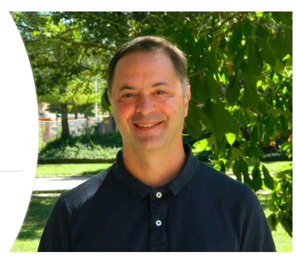

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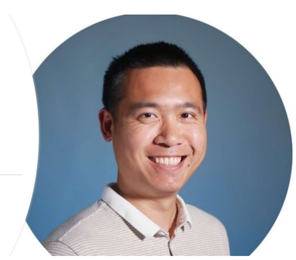

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1. BACKGROUND & MOTIVATION

Cloud-top Height (CTH) impacts the Earth's energy budget and the hydrological cycle (Boucher et al., 2013). Long-term CTH observations from satellite-based passive sensors are important to constrain global climate model predictions, especially with respect to cloud feedbacks (Zelinka et al., 2013).

Terra is our longest-running (~20 years) stable satellite, with CTH records from MODIS and MISR (Stubenrauch et al., 2013). Global validation of these Level 2 products has been hindered by the lack of an active sensor with enough orbital overlap to compare against.

MODIS is a multi-spectral instrument that calculates CTH in the infrared (IR) from either CO_2-slicing (high, ice clouds) or from 11 μm Brightness Temperature technique (low clouds) (Baum et al., 2012; Menzel et al., 2008). MISR is a multi-angular instrument that detects stereoscopic CTH in the visible to near-IR [see Figure 1] (Moroney et al., 2002; Mueller et al., 2013).

The first evaluation of these Level 2 Terra CTH records against collocated Cloud-Aerosol Transport System (CATS) lidar observations between 50ºN - 50ºS is reported. CATS (Yorks et al., 2016) was an elastic backscatter lidar that operated from the International Space Station (ISS) between 2015-2017.

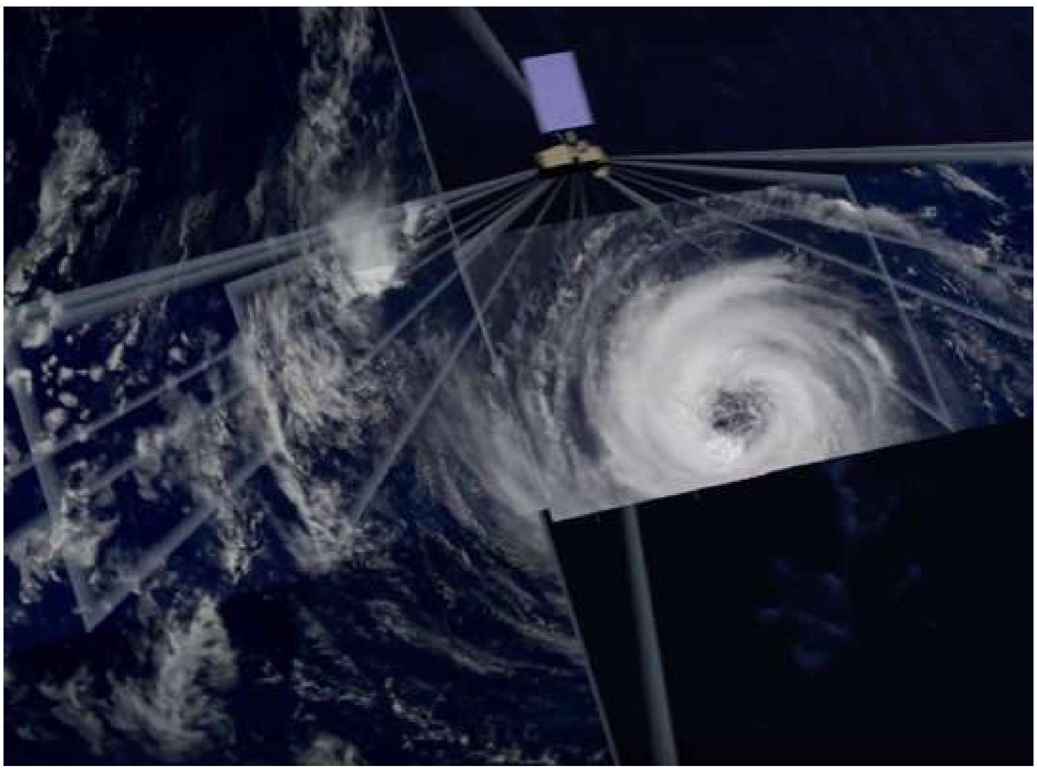

Figure 1. Terra Satellite with MODIS and MISR swaths visualized. [Snapshot from:
[VIDEO] https://www.youtube.com/embed/yOc30VWFzn0?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0
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2. METHODOLOGY

Collocated (<1 km) and concurrent (<5 minutes) CTH from Terra MODIS and MISR are compared to the top-layer CTH and (to study the impacts of multi-layered clouds) on closest-layer CTH, from CATS. 18986 collocated cloudy data points compared.

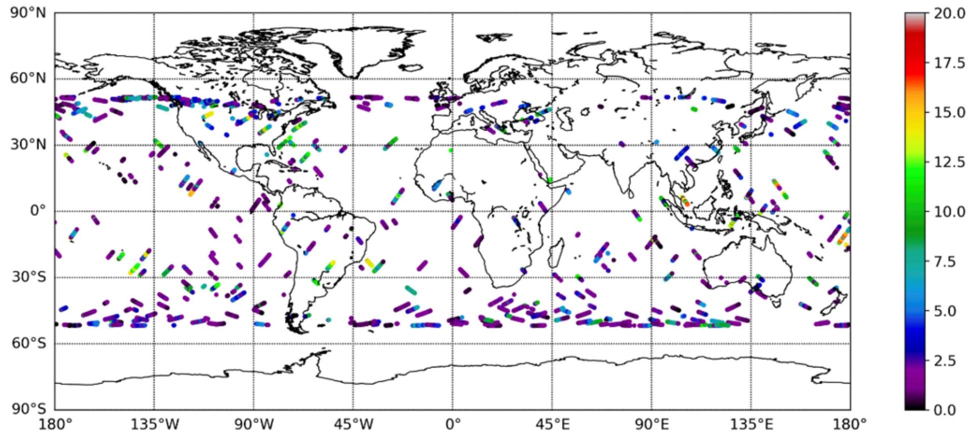

Figure 2. Map of all valid CATS-MISR-MODIS collocations, colored by MISR CTH.

DATA FILES:

MISR: TC_CLOUD version F_001

MODIS: MOD06_L2 collection 6.1

CATS: Level 2 PRODUCT version 2.01

Mean geo-location error ~ 400 m. Mean collocation-related CTH variance ~300 m (MISR) and ~500 m (MODIS).

Error analysis is done based on CTH difference histograms, like the one in Figure 3. Their approximate Gaussian nature is seized upon to define:

(a) Bias: Deviation of mode from 0.

(b) Precision: FWHM/(2 log 2), where FWHM is the full width at half-maximum.

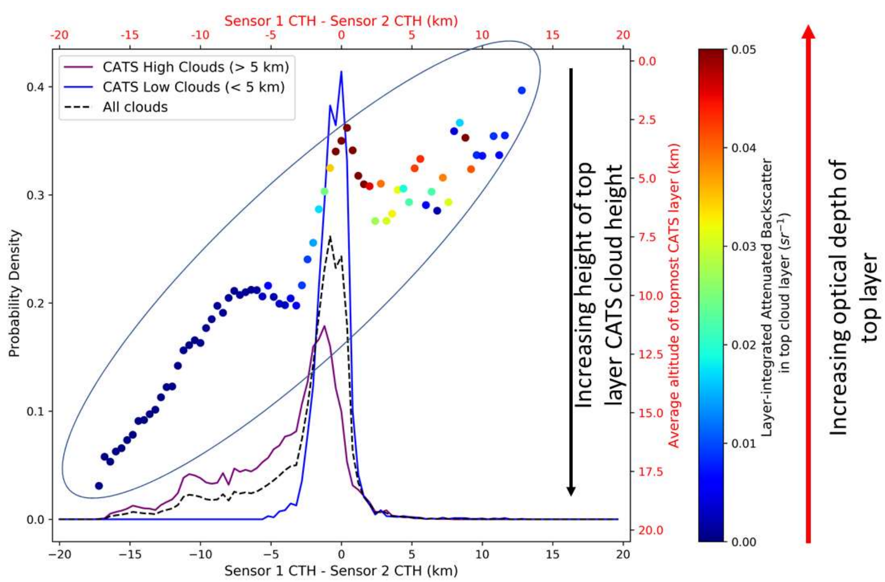

Figure 3. A representative CTH difference histogram [Sensor 1 = MODIS/MISR and Sensor 2 = CATS]. Each histogram bin is associated with a point whose position represents the mean top cloud-layer height and whose color represents the mean opacity of all samples in that bin.

Histograms are sub-divided on the basis of some relevant cloud property (that might influence bias), such as height or opacity of the topmost layer, multi-layering, and so forth. CATS CTH is assumed to be unbiased, and hence, true.

3. HIGH VS. LOW CLOUDS

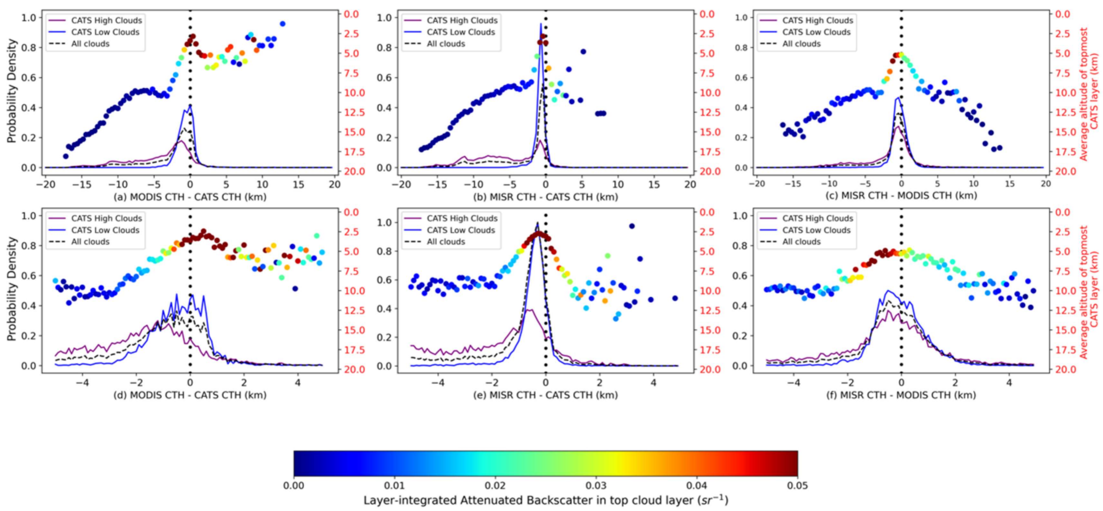

Figure 4: Histograms of global CTH differences for high clouds (CATS CTH > 5 km, purple) and low clouds (CATS CTH < 5 km, blue), with 100 bins between +20 km and -20 km (top panels) and +5 km and -5 km (bottom panels).

MISR

Low (CTH < 5 km) : -320 ± 250 m

High (CTH > 5 km) : -540 ± 590 m

MODIS

Low (CTH < 5 km) : 40 ± 730 m

High (CTH > 5 km) : -1200 ± 1080 m

For MODIS, in both high and low cloud cases, there is a clear behavior of dependence on the optical properties of the top-cloud layer.

For MISR, such a dependence seems to be minimal, at first glance.

4. OPTICALLY THICK VS. THIN

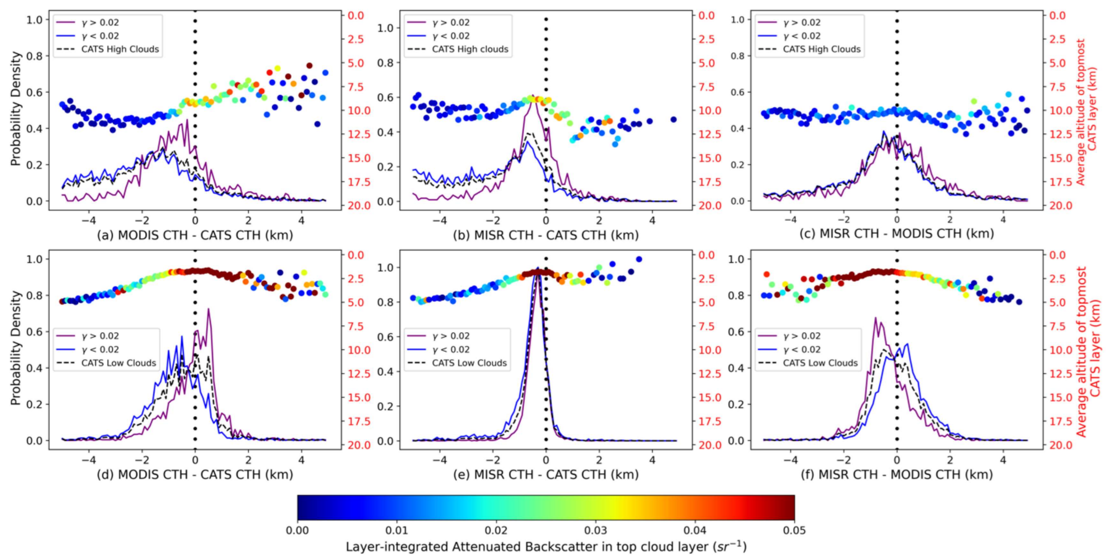

Figure 5: Histograms of global CTH differences for (a-c) high clouds and (d-f) low clouds from CATS, for optically thick top layer of cloud ($g > 0.02\ sr^{-1}$, purple) and optically thin top layer of cloud ($g < 0.02\ sr^{-1}$, blue), with the black, dashed line denoting overall distributions.

High Clouds

MISR

High, Thin (OD < 1) : -680 ± 550 m

High, Thick (OD > 1) : -440 ± 470 m

MODIS

High, Thin (OD < 1) : -1160 ± 1020 m

High, Thick (OD > 1) : -280 ± 730 m

Low Clouds

MISR

Low, Thin (OD < 1) : -320 ± 310 m

Low, Thick (OD > 1) : -280 ± 260 m

MODIS

Low, Thin (OD < 1) : -440 ± 600 m

Low, Thick (OD > 1) : 500 ± 430 m

Low opacity in low clouds causes cloud-top temperatures to diverge from blackbody temperature, leading to underestimation (11 μm brightness temperature technique). Low opacity in geometrically thick high clouds leads to negatively biased CTH in the CO_2-slicing technique (Menzel et al., 2015).

Due to vertical variation of single-scattering properties in a cloud layer, MISR stereo might detect a height at a depth into the cloud, where the spatial contrast is maximum ('stereo-opacity bias')

5. MULTI-LAYERED CLOUDS

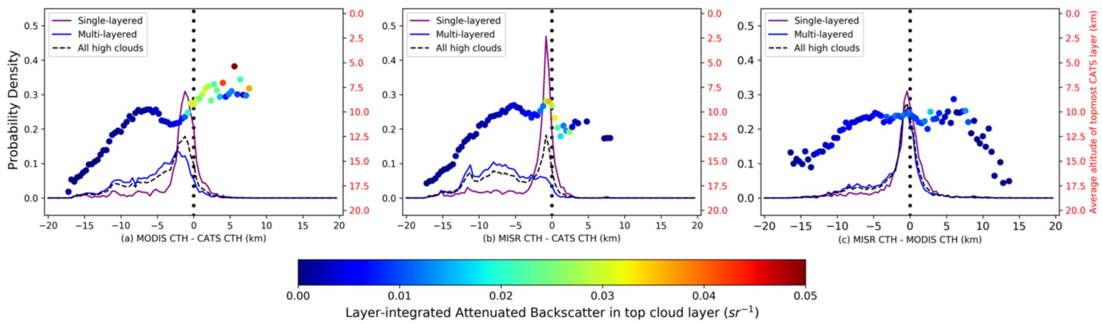

Figure 6: Histograms of global CTH differences for CATS single-layered clouds (CATS Percentage Opacity < 50%, purple) and multi-layered clouds (CATS detected at least two layers, blue), with the CATS top layer height being greater than 5 km.

MISR

High, Single-layered: -820 ± 850 m

High, Multi-layered: Not Gaussian

MODIS

High, Single-layered: -1160 ± 510 m

High, Multi-layered: -2380 ± 1030 m

MODIS and MISR sense the same high cloud CTH to within 1 km of each other 25% of the time for multi-layered and 32% for single-layered ones.

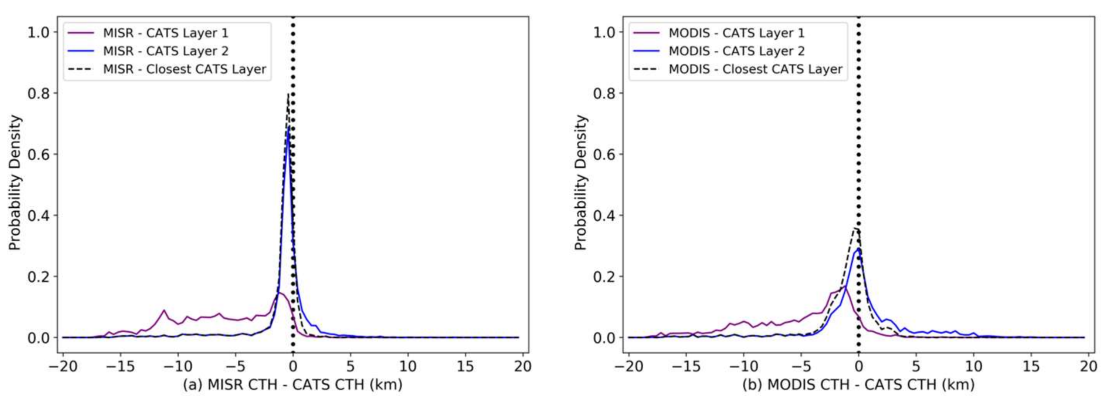

Figure 7: Histograms of global CTH differences for double-layered clouds from CATS, for each passive sensor – (a) MISR and (b) MODIS - and the first layer (blue) and second layer (red) of CATS clouds, respectively, with 100 bins between +20 km and -20 km. The distribution of the difference in cloud top height from each passive sensor and the closest CATS layer is given by a black dashed line and contains 7454 collocated data points.

For two-layered cases, MISR is sensitive to the lower cloud layer, with MISR underestimating this CTH by -400 ± 350 m. This is almost identical to MISR single-layered low cloud bias and precision, suggesting that MISR low CTH accuracy is independent of the presence of high, thin cirrus.

MISR is sensitive to the lower layer in a 2-layered system if the upper-layer OD < ~0.4, hinting at the possibility of an "opacity threshold" required for detection.

6. MISR & MODIS ERROR BUDGETS (UNBROKEN, SINGLE-LAYERED CLOUDS)

Instrument	Overall		High (CATS CTH > 10 km)		Mid-level (10 km > CTH > 5 km)		Low (CATS CTH < 5 km)	
	Bias (m)	Precision (m)	Bias (m)	Precision (m)	Bias (m)	Precision (m)	Bias (m)	Precision (m)
MISR	-280	370	-300	400	-370	400	-240	300
MODIS	-540	690	-950	740	-350	690	60	660

Table 1. MISR and MODIS bias and precision for all, high, mid-level, and low single-layered, unbroken, and optically thick clouds.

MISR overall CTH bias: -280 m.

Radiance Co-registration error : -30 m

Wind-driven bias (based on wind-height biases reported in Horvath 2013, compared to METEOSAT AMVs) :

High clouds: -90 m

Low clouds: -110 m

Stereo-Opacity Bias (limits estimated by assuming biases to be free from wind-driven bias, and then including wind-driven bias)*:

Low clouds: -110 to -200 m

High clouds: -150 to -240 m

MODIS overall CTH bias: -540 m.

Optically thick (as mostly high, also geometrically thick) cloud CTH is underestimated.

MISR overall CTH Precision: 370 m

For unbroken, single-layered clouds, collocation-related errors ~ 0, hence precision for these samples is completely driven by wind-height precision.

Based on these random errors, MISR wind-speed precision is estimated at 3.7 m s-1 (2.8 m s-1 and 4.0 m s-1 for low and high clouds, respectively). These values are quite similar to the findings of Horváth (2013) and Mueller et al. (2017).

MISR error budget is closed.

MODIS overall CTH Precision: 690 m

MODIS CTH random errors are driven by forward modeling and ancillary dataset uncertainty.

Both MISR and MODIS bias and precision shows a strong dependence on cloud height and heterogeneity.

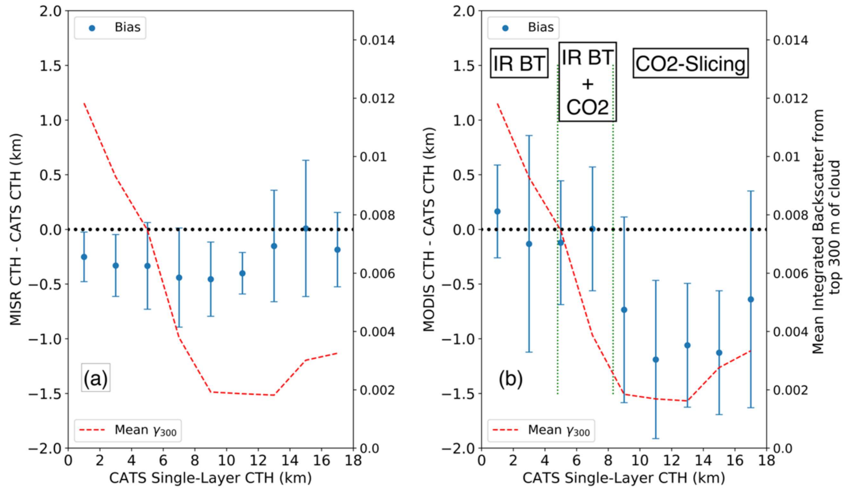

Figure 8. Distribution with altitude of (a) MISR and (b) MODIS CTH bias and precision (1σ error-bars) for CATS single-layered, unbroken, and optically thick clouds. The results are binned every 2 km, with mean CATS integrated backscatter for the top 300 m into the cloud (γ_{300} in sr-1) shown in red. Green dotted lines in (b) denote the 75th-percentile CATS CTH for scenes employing IR BT (left line) and CO2-slicing, respectively. Each bin has a minimum of 150 samples.

7. CONCLUSIONS & FUTURE WORK

Conclusions

First robust quasi-global validation of MISR Stereo and Terra MODIS CTH.

MISR bias (-280 m) and precision (370 m) are robust for decadal climate analysis. Better than MODIS bias (-540 m) and precision (640 m).

The first estimate of MISR stereo-opacity CTH bias (-110 to -240 m).

Independent estimates of global wind-driven stereo CTH bias (-90 to -110 m), first against a lidar.

MISR low CTH retrievals are mostly independent of the optical properties of the top layer.

MODIS and MISR sense the same layer to within 1 km of each other 25% of the time for multi-layered and 32% for single-layered ones. Both instruments detect high CTH very rarely.

Future Work

Independent validation of stereo CTH error characteristics from field experiment data, free from collocation-related uncertainties.

Radiative transfer simulation investigation into the physical nature of “opacity threshold” for stereo detection of a cloud layer.

AUTHOR INFORMATION

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ABSTRACT

Comparison of Co-Incident MISR, Terra MODIS, and ISS-CATS Cloud Top Heights

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Cloud-top heights (CTH) from the Multiangle Imaging Spectroradiometer (MISR) and the Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra constitute our longest-running single-platform CTH record from a stable orbit. Here, we provide the first evaluation of the Terra Level 2 CTH record against collocated International Space Station Cloud-Aerosol Transport System (CATS) lidar observations between 50ºN - 50ºS. Bias and precision of Terra CTH relative to CATS, calculated from the normality of CTH error histograms, are shown to be strongly tied to cloud horizontal and vertical heterogeneity and altitude. For single-layered, unbroken, optically thick clouds observed for all altitudes, the uncertainty in MODIS and MISR CTH are -540±690 m and -280±370 m, respectively. The uncertainties are generally smaller for lower altitude clouds and larger for optically thinner clouds. For multi-layered clouds, errors are summarized herein using both absolute CTH and CATS-layer-altitude proximity to Terra CTH. We show that MISR detects the lower cloud in a two-layered system, provided top-layer optical depth < ~0.3, but MISR low-cloud errors are unaltered by the presence of thin cirrus. Systematic and random errors are propagated to explain inter-sensor disagreements, as well as to provide the first estimate of MISR stereo-opacity bias. For MISR, altitude-dependent wind-retrieval bias (-90 to -110 m) and stereo-opacity bias (-110 to -240 m) and for MODIS, bias due to low opacity near cloud-top lead to overall negative CTH bias. MISR's precision is largely driven by wind-speed uncertainty (3.7 m s-1), whereas MODIS precision is driven by forward-modeling uncertainty.

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