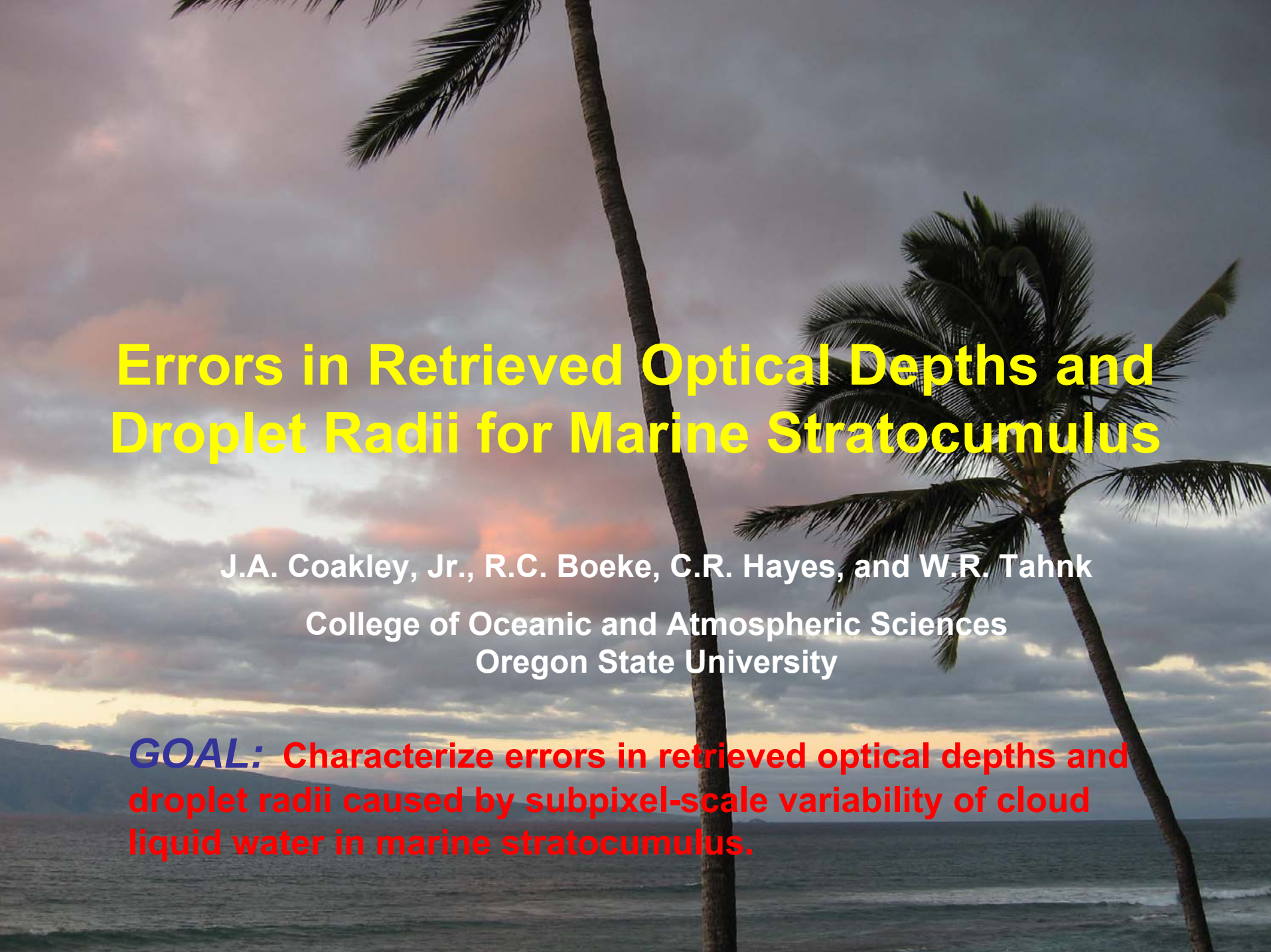


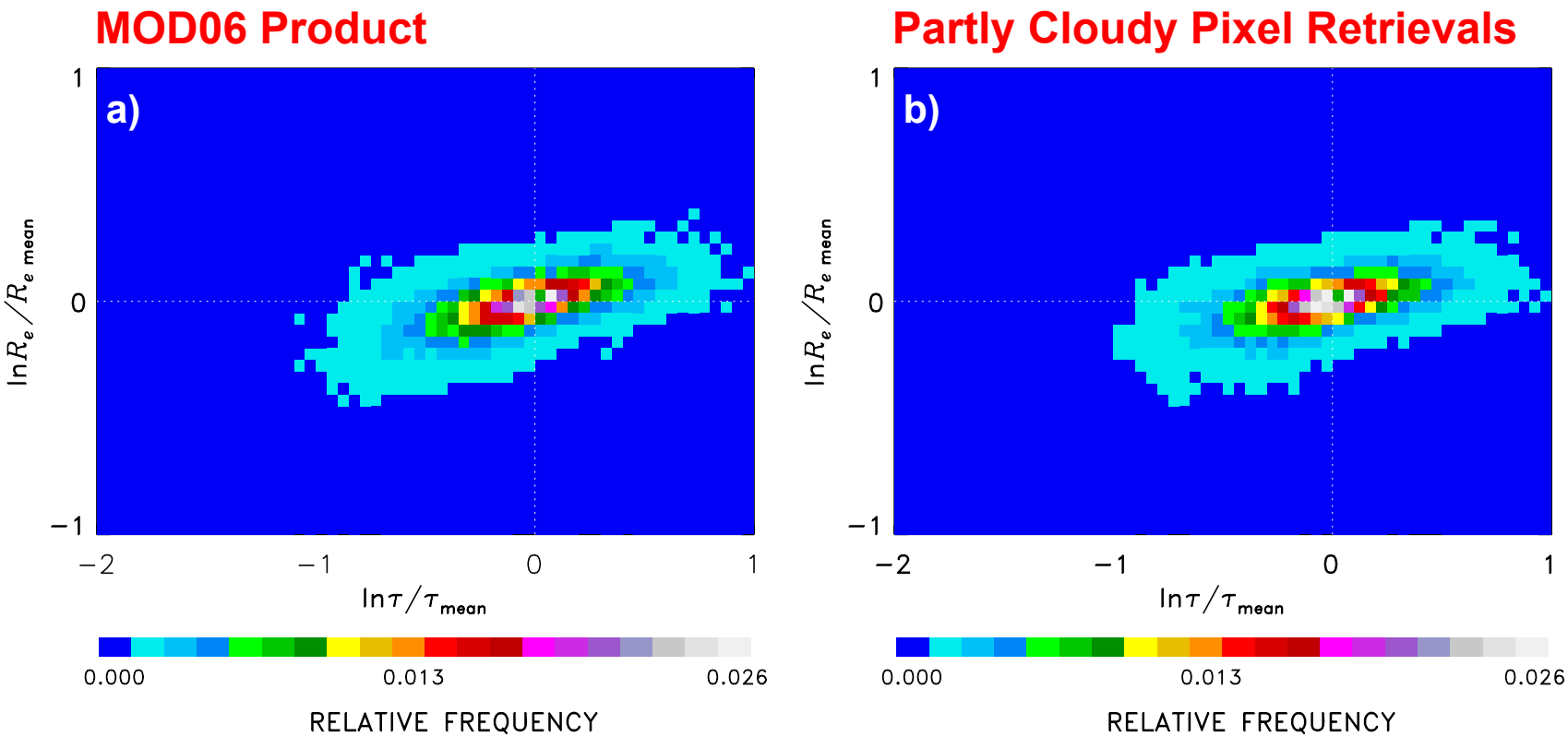
Errors in Retrieved Optical Depths and Droplet Radii for Marine Stratocumulus

J.A. Coakley, Jr., R.C. Boeke, C.R. Hayes, and W.R. Tahnk

College of Oceanic and Atmospheric Sciences
Oregon State University

GOAL: **Characterize errors in retrieved optical depths and droplet radii caused by subpixel-scale variability of cloud liquid water in marine stratocumulus.**

Overcast, optically thick marine stratocumulus have droplet radii and optical depths that are governed by moist adiabatic parcel ascent…

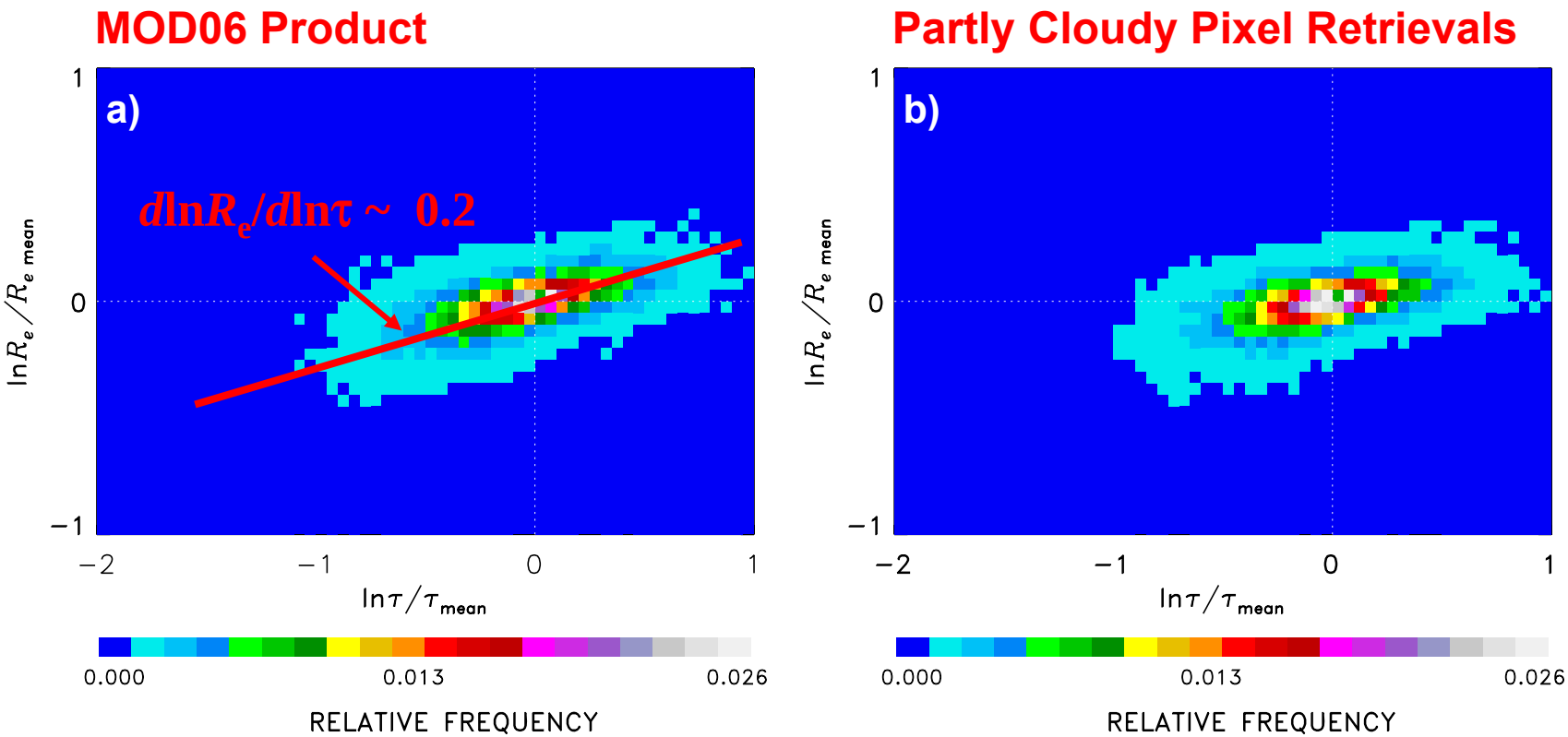


1-km MODIS pixels taken from 50-km segments collocated with the CALIPSO lidar in which no underlying surface was detected in the 532-nm backscatter returns.

All pixels in all segments were overcast by marine stratus.

(Source: Hayes et al. 2010)

Overcast, optically thick marine stratocumulus have droplet radii and optical depths that are governed by moist adiabatic parcel ascent…

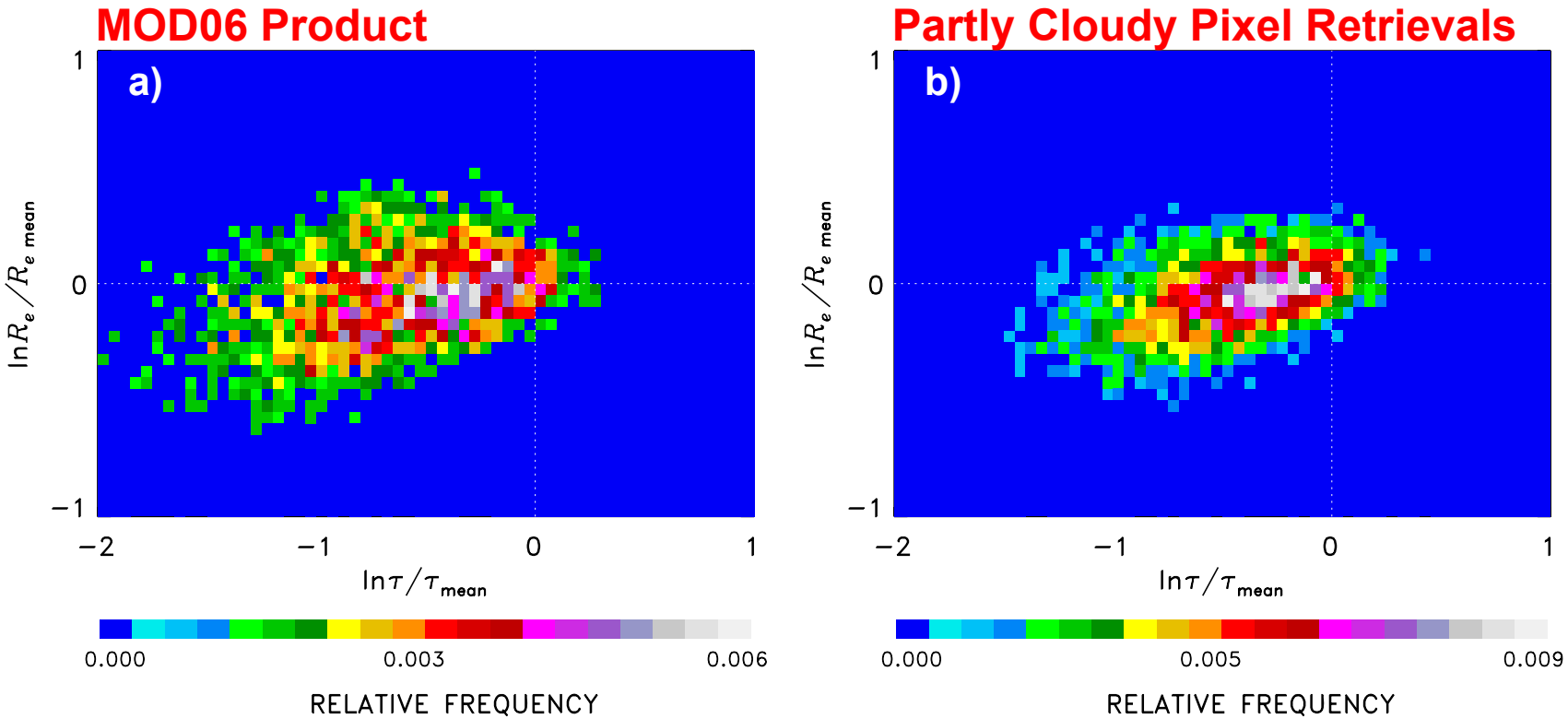


1-km MODIS pixels taken from 50-km segments collocated with the CALIPSO lidar in which no underlying surface was detected in the 532-nm backscatter returns.

All pixels in all segments were overcast by marine stratus.

(Source: Hayes et al. 2010)

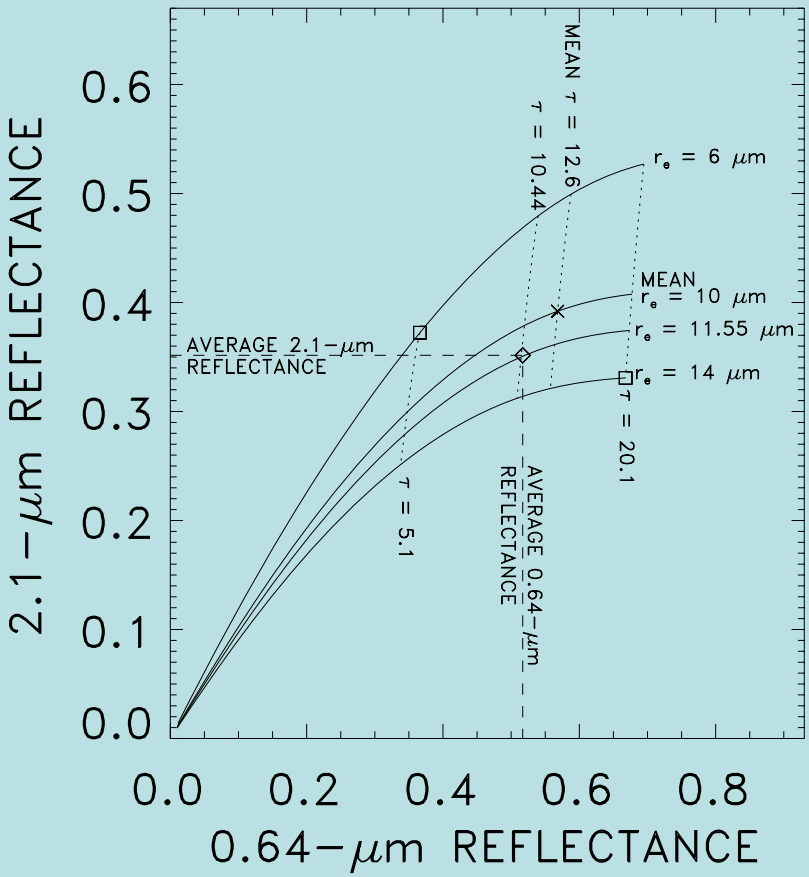
…but marine stratocumulus with cloud-free breaks do not.



Overcast pixels from 50-km segments in which the CALIPSO lidar detected both the marine stratus and the underlying surface. The mean values were taken from overcast pixels within the same 50-km segments that were collocated with lidar profiles in which the underlying surface was not detected.

For MODIS pixels overcast by optically thin clouds (τ_{vis} ~ 5), the optical depth is underestimated and the droplet radius is overestimated in a manner that is similar to the results obtained by applying the overcast assumption to partly cloudy pixels.

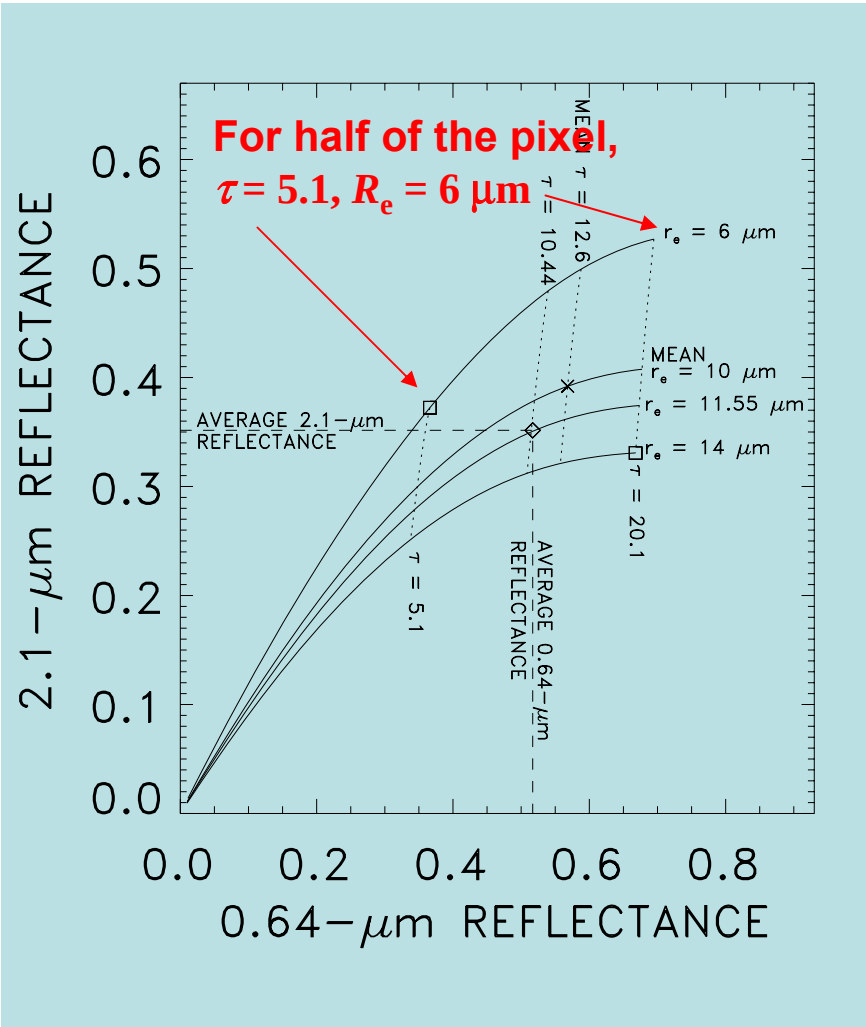
Simulated retrievals illustrate the source of the errors.



0.64 and 2.1-μm reflectances calculated for a single pixel in which half is overcast by a cloud having a droplet radius of 6 μm and an optical depth of 5.1 and the other half is overcast by a cloud with a droplet radius of 14 μm and an optical depth of 20.1.

The optical depth retrieved for the average reflectances, 10.44, underestimates the average optical depth, 12.6, and the droplet radius retrieved using the average reflectances, 11.55 μm, overestimates the average radius, 10 μm.

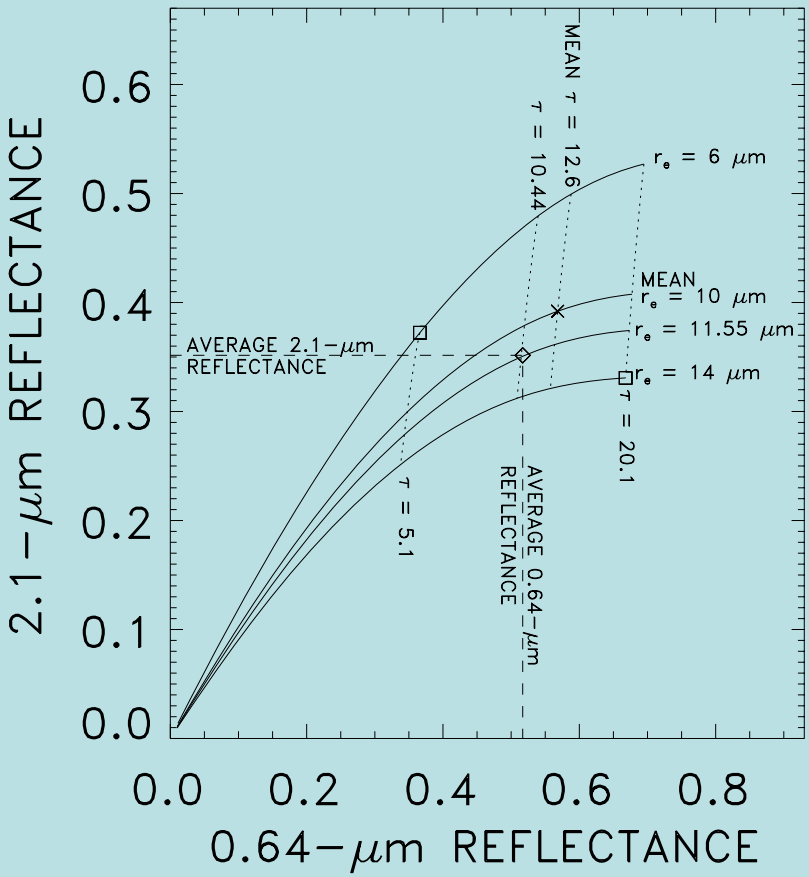
Simulated retrievals illustrate the source of the errors.



0.64 and 2.1-µm reflectances calculated for a single pixel in which half is overcast by a cloud having a droplet radius of 6 µm and an optical depth of 5.1 and the other half is overcast by a cloud with a droplet radius of 14 µm and an optical depth of 20.1.

The optical depth retrieved for the average reflectances, 10.44, underestimates the average optical depth, 12.6, and the droplet radius retrieved using the average reflectances, 11.55 µm, overestimates the average radius, 10 µm.

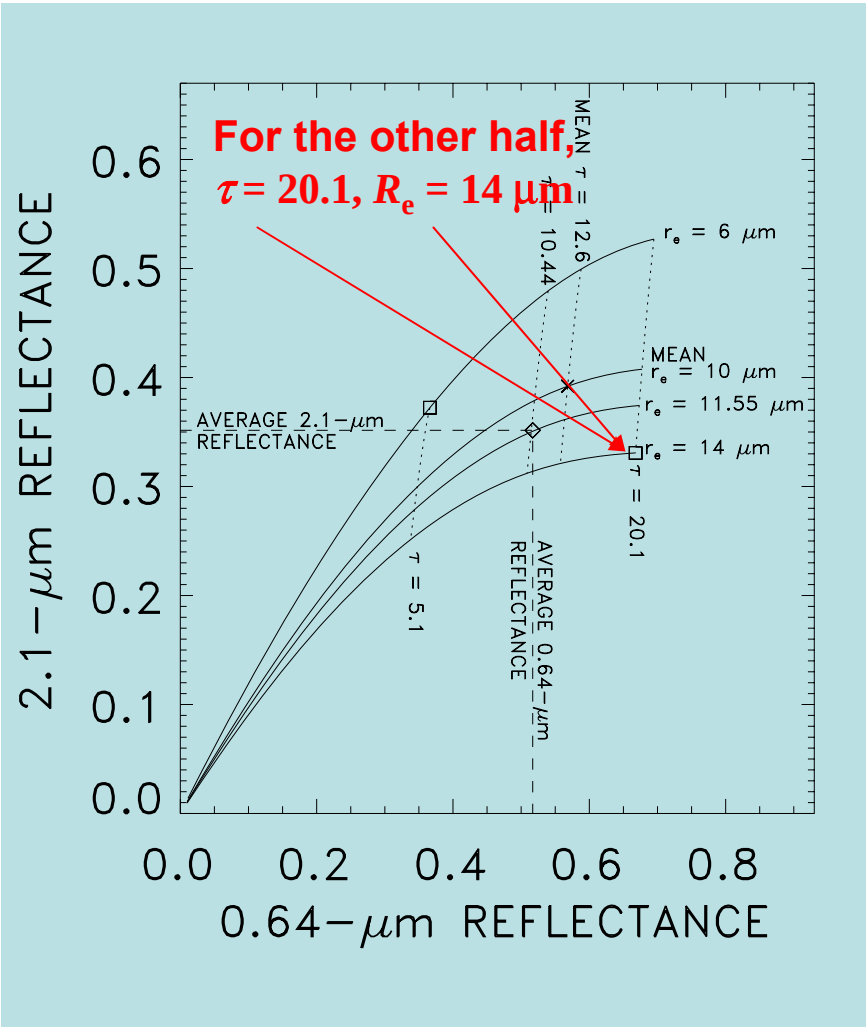
Simulated retrievals illustrate the source of the errors.



0.64 and 2.1-μm reflectances calculated for a single pixel in which half is overcast by a cloud having a droplet radius of 6 μm and an optical depth of 5.1 and the other half is overcast by a cloud with a droplet radius of 14 μm and an optical depth of 20.1.

The optical depth retrieved for the average reflectances, 10.44, underestimates the average optical depth, 12.6, and the droplet radius retrieved using the average reflectances, 11.55 μm, overestimates the average radius, 10 μm.

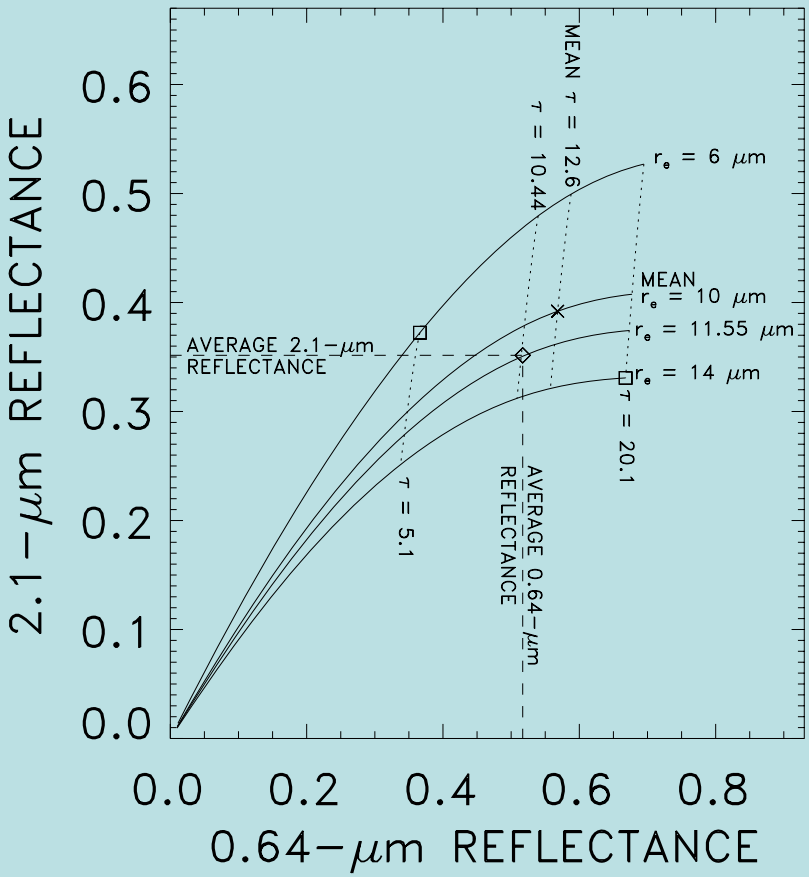
Simulated retrievals illustrate the source of the errors.



0.64 and 2.1-µm reflectances calculated for a single pixel in which half is overcast by a cloud having a droplet radius of 6 µm and an optical depth of 5.1 and the other half is overcast by a cloud with a droplet radius of 14 µm and an optical depth of 20.1.

The optical depth retrieved for the average reflectances, 10.44, underestimates the average optical depth, 12.6, and the droplet radius retrieved using the average reflectances, 11.55 µm, overestimates the average radius, 10 µm.

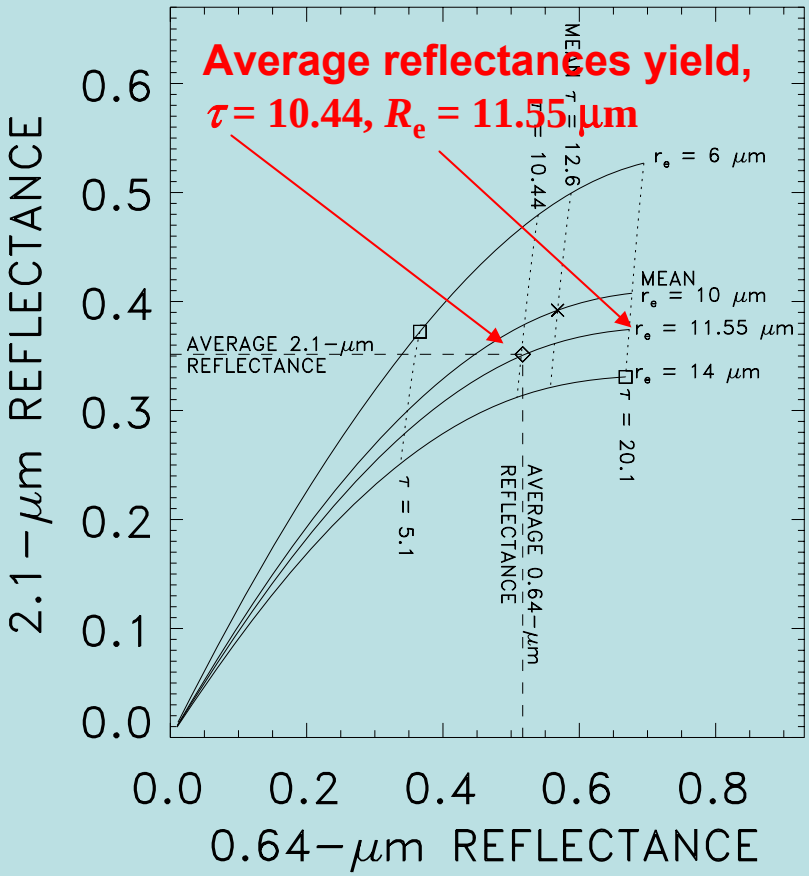
Simulated retrievals illustrate the source of the errors.



0.64 and 2.1-μm reflectances calculated for a single pixel in which half is overcast by a cloud having a droplet radius of 6 μm and an optical depth of 5.1 and the other half is overcast by a cloud with a droplet radius of 14 μm and an optical depth of 20.1.

The optical depth retrieved for the average reflectances, 10.44, underestimates the average optical depth, 12.6, and the droplet radius retrieved using the average reflectances, 11.55 μm, overestimates the average radius, 10 μm.

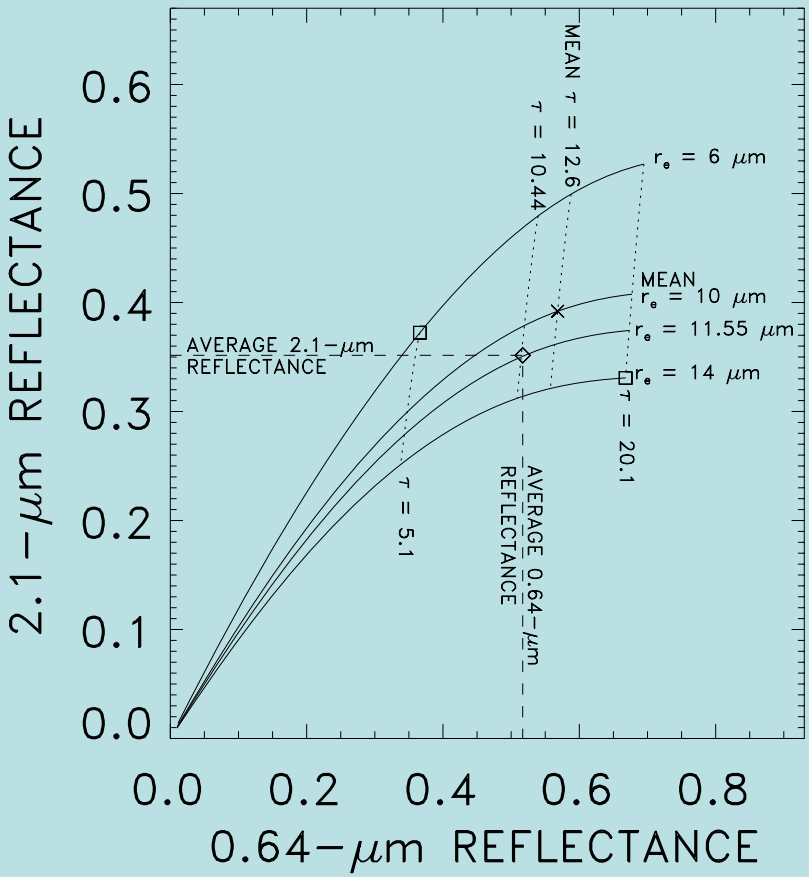
Simulated retrievals illustrate the source of the errors.



0.64 and 2.1-μm reflectances calculated for a single pixel in which half is overcast by a cloud having a droplet radius of 6 μm and an optical depth of 5.1 and the other half is overcast by a cloud with a droplet radius of 14 μm and an optical depth of 20.1.

The optical depth retrieved for the average reflectances, 10.44, underestimates the average optical depth, 12.6, and the droplet radius retrieved using the average reflectances, 11.55 μm, overestimates the average radius, 10 μm.

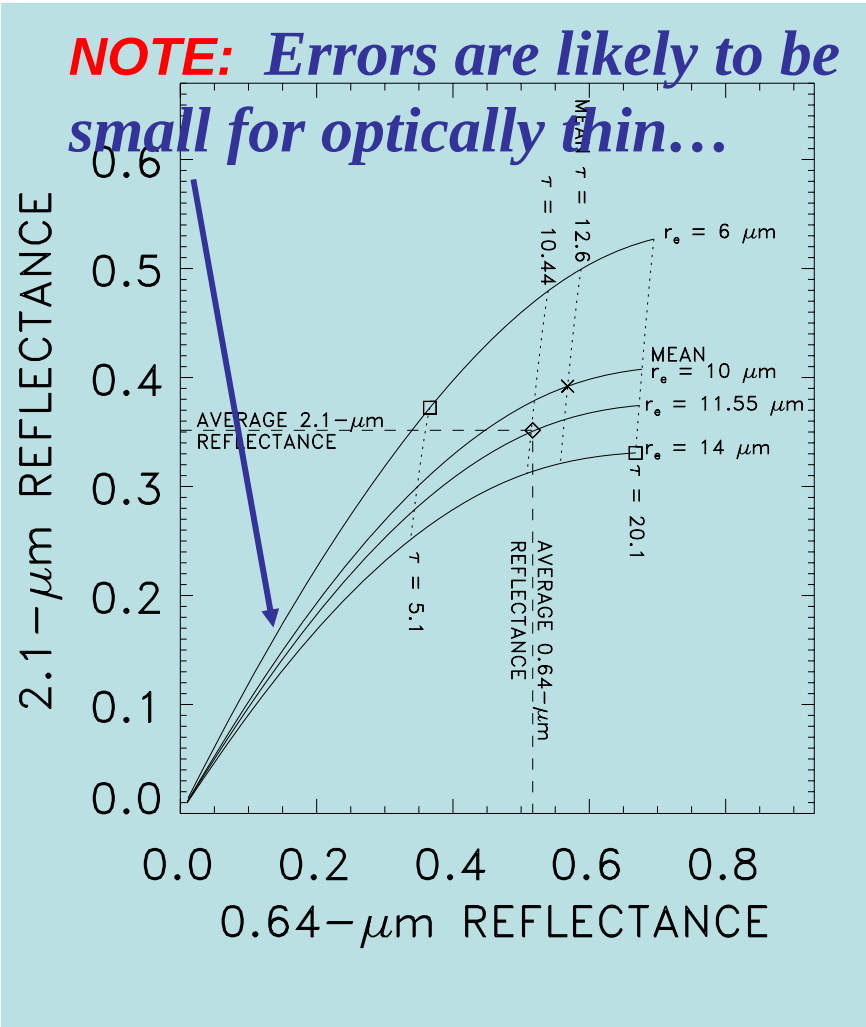
Simulated retrievals illustrate the source of the errors.



0.64 and 2.1-μm reflectances calculated for a single pixel in which half is overcast by a cloud having a droplet radius of 6 μm and an optical depth of 5.1 and the other half is overcast by a cloud with a droplet radius of 14 μm and an optical depth of 20.1.

The optical depth retrieved for the average reflectances, 10.44, underestimates the average optical depth, 12.6, and the droplet radius retrieved using the average reflectances, 11.55 μm, overestimates the average radius, 10 μm.

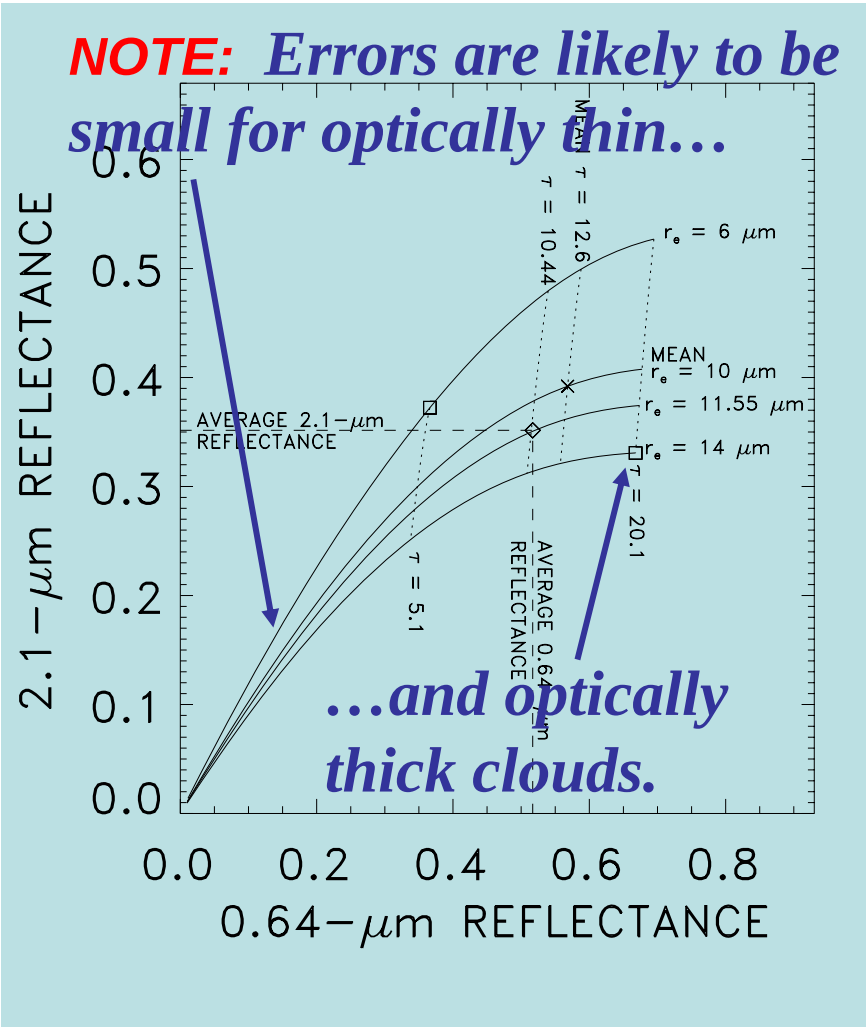
Simulated retrievals illustrate the source of the errors.



0.64 and 2.1-μm reflectances calculated for a single pixel in which half is overcast by a cloud having a droplet radius of 6 μm and an optical depth of 5.1 and the other half is overcast by a cloud with a droplet radius of 14 μm and an optical depth of 20.1.

The optical depth retrieved for the average reflectances, 10.44, underestimates the average optical depth, 12.6, and the droplet radius retrieved using the average reflectances, 11.55 μm, overestimates the average radius, 10 μm.

Simulated retrievals illustrate the source of the errors.

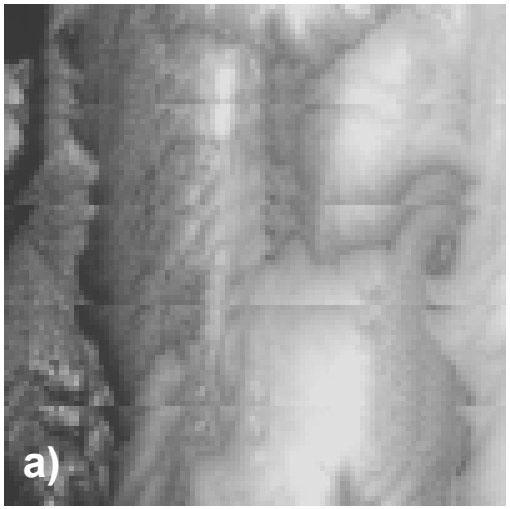


0.64 and 2.1-μm reflectances calculated for a single pixel in which half is overcast by a cloud having a droplet radius of 6 μm and an optical depth of 5.1 and the other half is overcast by a cloud with a droplet radius of 14 μm and an optical depth of 20.1.

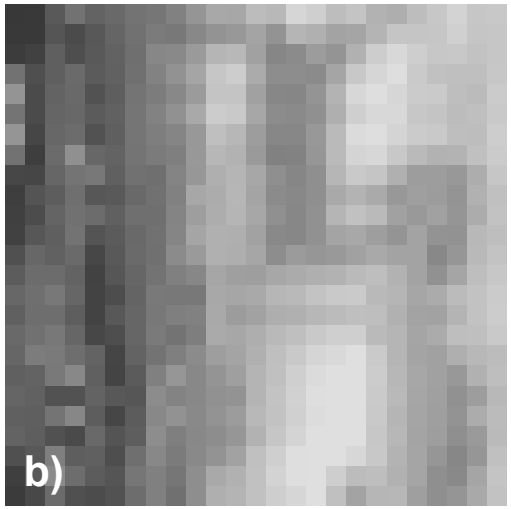
The optical depth retrieved for the average reflectances, 10.44, underestimates the average optical depth, 12.6, and the droplet radius retrieved using the average reflectances, 11.55 μm, overestimates the average radius, 10 μm.

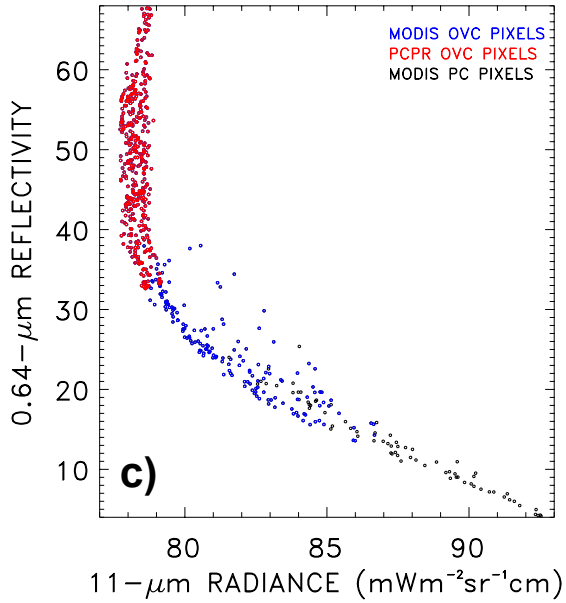
Observations provide realistic estimates of errors.

500-m 0.64-μm



2-km 0.64-μm



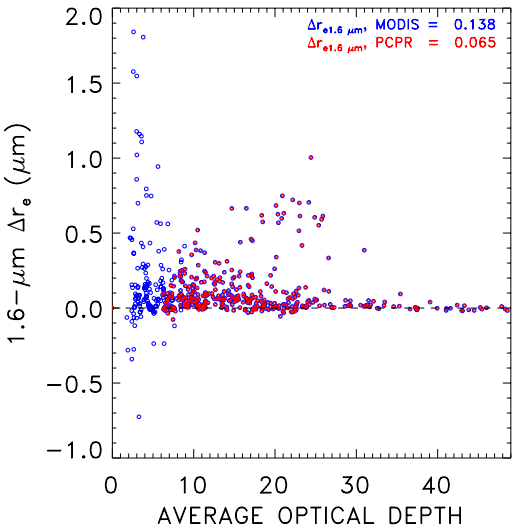


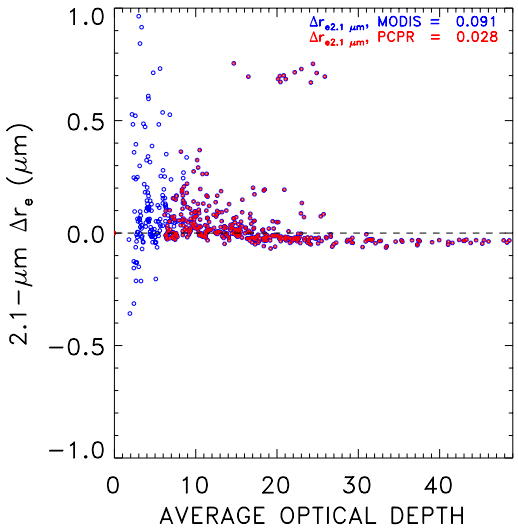
500-m (a) and 2-km (b) 0.64-μm reflectances and 0.64-μm reflectances and 11-μm radiances for overcast and partly cloudy 2-km pixels as identified using partly cloudy pixel retrievals and the 250-m MOD35 cloud mask aggregated to 2 km (c).

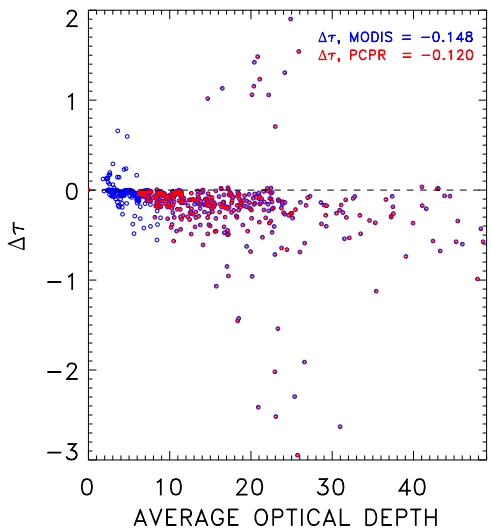
Pixels identified as overcast by the partly cloudy pixel retrievals were also identified as overcast by the MOD35 cloud mask.

Pixels identified as partly cloudy by the MOD35 cloud mask were also identified as partly cloudy by the partly cloudy pixel retrievals.

For 2-km pixels identified as *OVERCAST*, the retrieved droplet radii are larger and the optical depths are smaller than the averages of the retrieved properties obtained using 500-m reflectances.







All retrievals were performed using the partly cloudy pixel retrieval scheme with pixel scale cloud fraction set to unity for pixels identified as overcast.

Errors in droplet radii retrieved using the 1.6-μm reflectances are somewhat larger than those obtained using 2.1-μm reflectances.

Even 2-km pixels identified as overcast by the partly cloudy pixel retrieval scheme show errors in the retrieved optical depths and droplet radii…but the errors tend to zero for optically thick and optically thin clouds.

What happens at larger scales?

50-km scale regions (50 × 50 1-km MODIS pixel arrays) that contained a single layer of marine stratocumulus were selected for analysis.

Regions were divided into those that were nearly *overcast*, $A_C > 0.95$, as deduced using partly cloudy pixel retrievals, and those in which the clouds were *broken*, $0.6 < A_C < 0.8$.

Overcast pixels were identified using the 250-m *MOD35 cloud mask* aggregated to 2 km and *partly cloudy pixel retrievals* applied to 1-km MODIS pixels that constituted the 2-km pixels.

All retrievals were performed using the partly cloudy pixel retrieval scheme with pixel scale cloud fraction $A_C = 1.0$ applied to the 2-km pixels identified as *overcast* by either the *MOD35 cloud mask* or the *partly cloudy pixel retrievals*.

Average Errors in Optical Depths

(Retrieved optical depth using 2-km average reflectances)–
(Average optical depths retrieved using 500-m reflectances)

Means ± Std. Errors and [90% confidence intervals]

	Overcast Regions		Broken Cloud Regions	
	Partly Cloudy Pixel Retrieval Identification			
Optical Depths	$\tau > 15.8$	$\tau < 9.6$	$\tau > 10.9$	$\tau < 6.0$
Number of Regions	806	811	67	37
$\Delta\tau$	–0.086 ± 0.015	0.035 ± 0.005	–0.262 ± 0.015	0.051 ± 0.027
	[–0.110, –0.061]	[0.027, 0.044]	[–0.333, –0.191]	[0.007, 0.096]
	MOD35 Identification			
Optical Depths	$\tau > 14.4$	$\tau < 8.5$	$\tau > 9.4$	$\tau < 5.3$
Number of Regions	814	821	100	103
$\Delta\tau$	–0.125 ± 0.016	0.103 ± 0.009	–0.269 ± 0.047	0.025 ± 0.020
	[–0.151, –0.099]	[0.088, 0.112]	[–0.347, –0.191]	[–0.008, 0.058]

Average Errors in 1.6-μm Derived Droplet Effective Radius

(Retrieved effective radius using 2-km average reflectances)–
(Average of effective radii retrieved using 500-m reflectances)

Means ± Std. Errors and [90% confidence intervals]

	Overcast Regions		Broken Cloud Regions	
	Partly Cloudy Pixel Retrieval Identification			
Optical Depths	$\tau > 15.8$	$\tau < 9.6$	$\tau > 10.9$	$\tau < 6.0$
Number of Regions	806	811	67	37
ΔR_e	0.156 ± 0.008	0.197 ± 0.097	0.420 ± 0.051	0.528 ± 0.12
	[0.143, 0.169]	[0.181, 0.213]	[0.335, 0.510]	[0.330, 0.726]
	MOD35 Identification			
Optical Depths	$\tau > 14.4$	$\tau < 8.5$	$\tau > 9.4$	$\tau < 5.3$
Number of Regions	814	821	100	103
ΔR_e	0.181 ± 0.008	0.351 ± 0.023	0.531 ± 0.066	1.13 ± 0.15
	[0.167, 0.195]	[0.313, 0.389]	[0.422, 0.640]	[0.88, 1.38]

Average Errors in 2.1-μm Derived Droplet Effective Radius

(Retrieved effective radius using 2-km average reflectances)–
(Average of effective radii retrieved using 500-m reflectances)

Means ± Std. Errors and [90% confidence intervals]

	Overcast Regions		Broken Cloud Regions	
	Partly Cloudy Pixel Retrieval Identification			
Optical Depths	$\tau > 15.8$	$\tau < 9.6$	$\tau > 10.9$	$\tau < 6.0$
Number of Regions	806	811	67	37
ΔR_e	0.051 ± 0.006	0.179 ± 0.009	0.181 ± 0.032	0.571 ± 0.120
	[0.041, 0.061]	[0.164, 0.195]	[0.128, 0.234]	[0.373, 0.769]
	MOD35 Identification			
Optical Depths	$\tau > 14.4$	$\tau < 8.5$	$\tau > 9.4$	$\tau < 5.3$
Number of Regions	814	821	100	103
ΔR_e	0.067 ± 0.006	0.326 ± 0.019	0.277 ± 0.043	1.06 ± 0.12
	[0.058, 0.076]	[0.295, 0.357]	[0.206, 0.348]	[0.86, 1.26]

Lessons Learned

Warning!

Reported errors are smaller than actual size.

Cloud liquid water varies significantly at the 100-m scale not the 500-m scale used in this study.

Variability in cloud liquid water at the 100-m scale is larger than that at the 500-m scale.

Lessons Learned

Because pixels that are partly cloudy are separated from those that are overcast in the partly cloudy pixel retrievals, the spatial variability within the pixels identified as overcast is reduced and the retrievals generally produce smaller errors than those obtained using the MOD35 cloud mask.

Errors due to subpixel scale variability in liquid water become small for pixels overcast by optically thin and optically thick clouds.

Droplet radii retrieved using 3.7-μm, where absorption by liquid water is strongest, are less vulnerable to errors than those retrieved using the shorter wavelengths.

Enhancements in visible reflectance caused by radiative smoothing are detected for optically thin clouds.