A Radiation Closure Study of Arctic Cloud Microphysical Properties using Collocated Satellite-surface Data and Fu-Liou RTM

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Location of ARM Northern Slope of Alaska (NSA Site)

1) Time period: 7 years from March 2000 to December 2006
2) A total of 207 snow-free cases (R_{SFC}<0.3) and 108 snow cases (R_{SFC}>0.3) have been selected. They all are single-layered overcast clouds (liquid dominant mixed phase).
3) ARM cloud microphysical properties are retrieved from the method of Dong and Mace (2003), and CERES-MODIS results are from Minnis et al. (2011).
4) CERES cloud and radiation results are averaged over a 30 km x 30 km grid box centered on the ARM NSA site. ARM results are averaged over 1-h interval centered at satellite overpass.

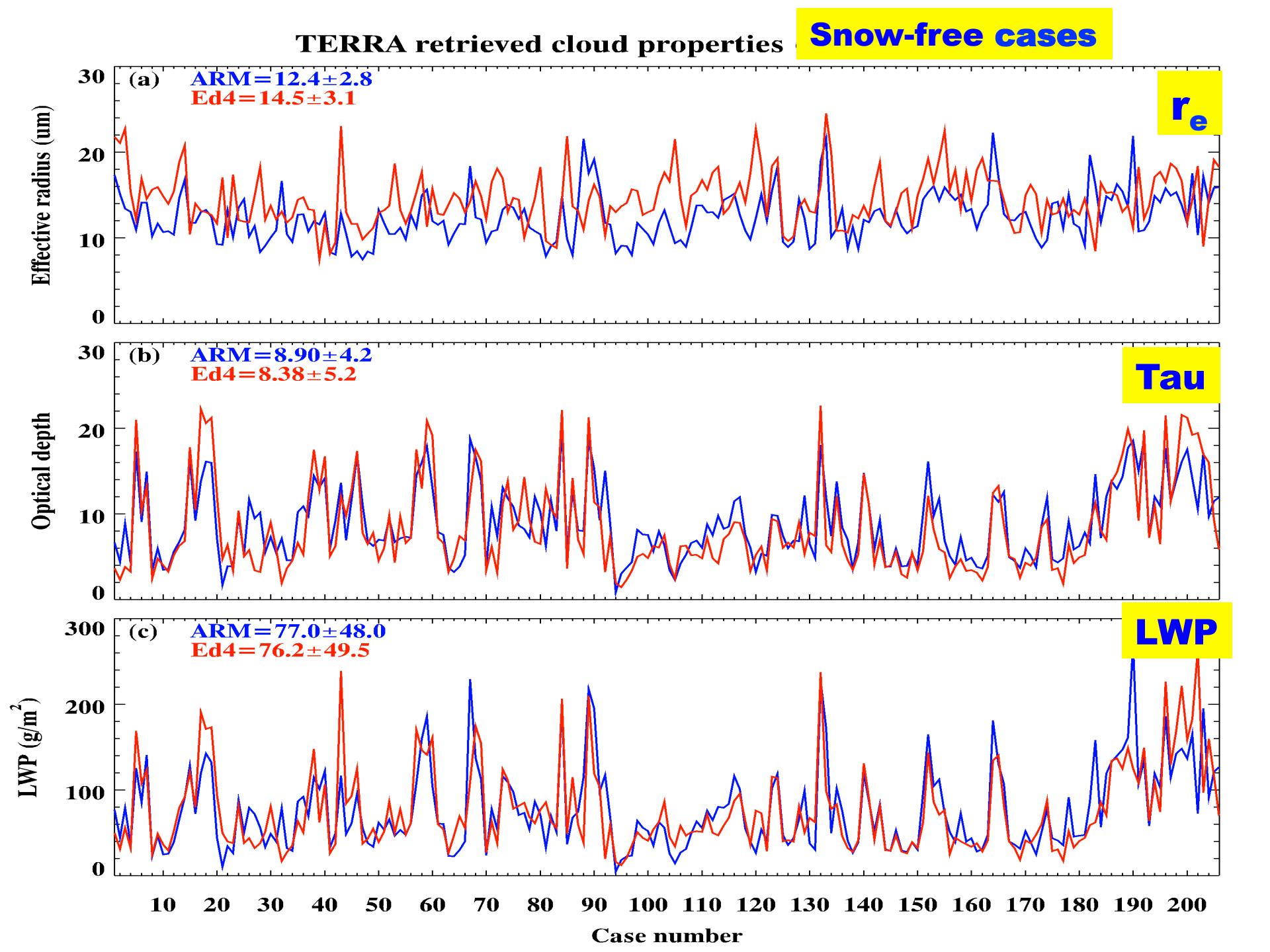
Questions to be answered from this study

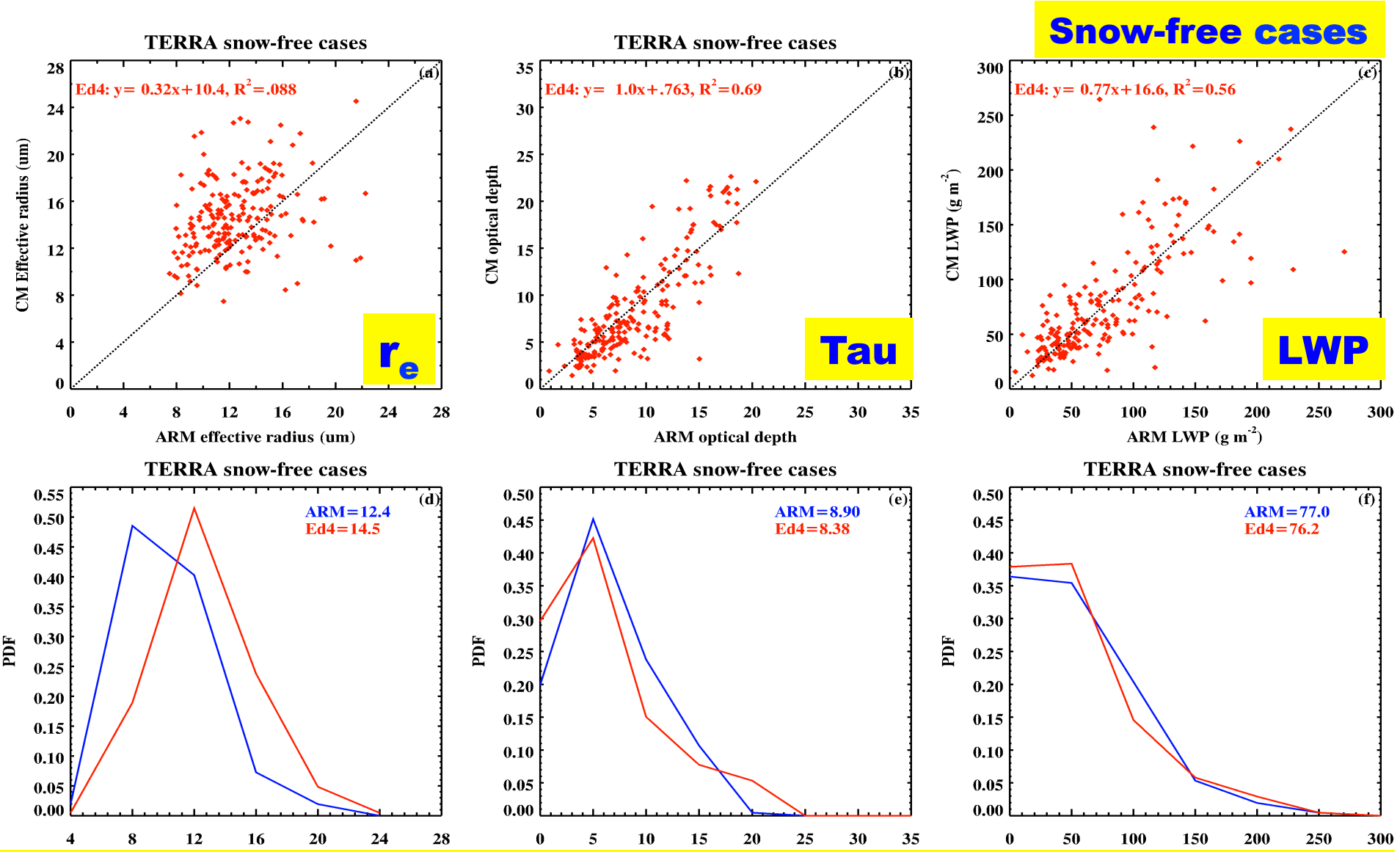
1. To what degree do the CERES Ed4 cloud microphysical properties agree with the ARM's retrievals over snow-free and snow surfaces?

2. To what percentages do the RTM calculated downward SW flux and transmission at the surface, and reflected SW flux and albedo at the TOA agree with the collocated ARM surface and CERES TOA observations?

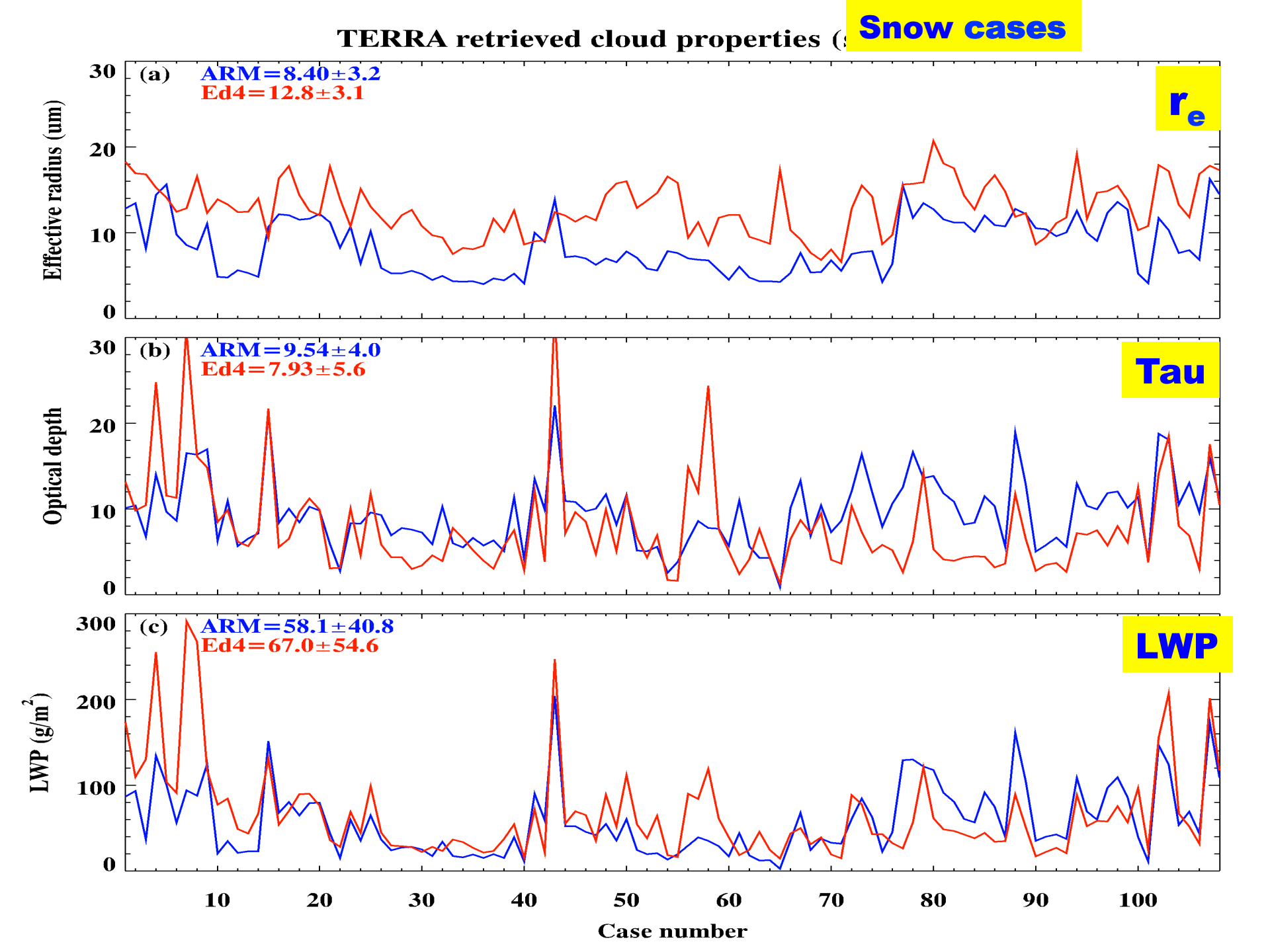
3. Do SW transmission at the surface and TOA albedo vary with cloud optical depth, solar zenith angle (*SZA*), and surface albedo?

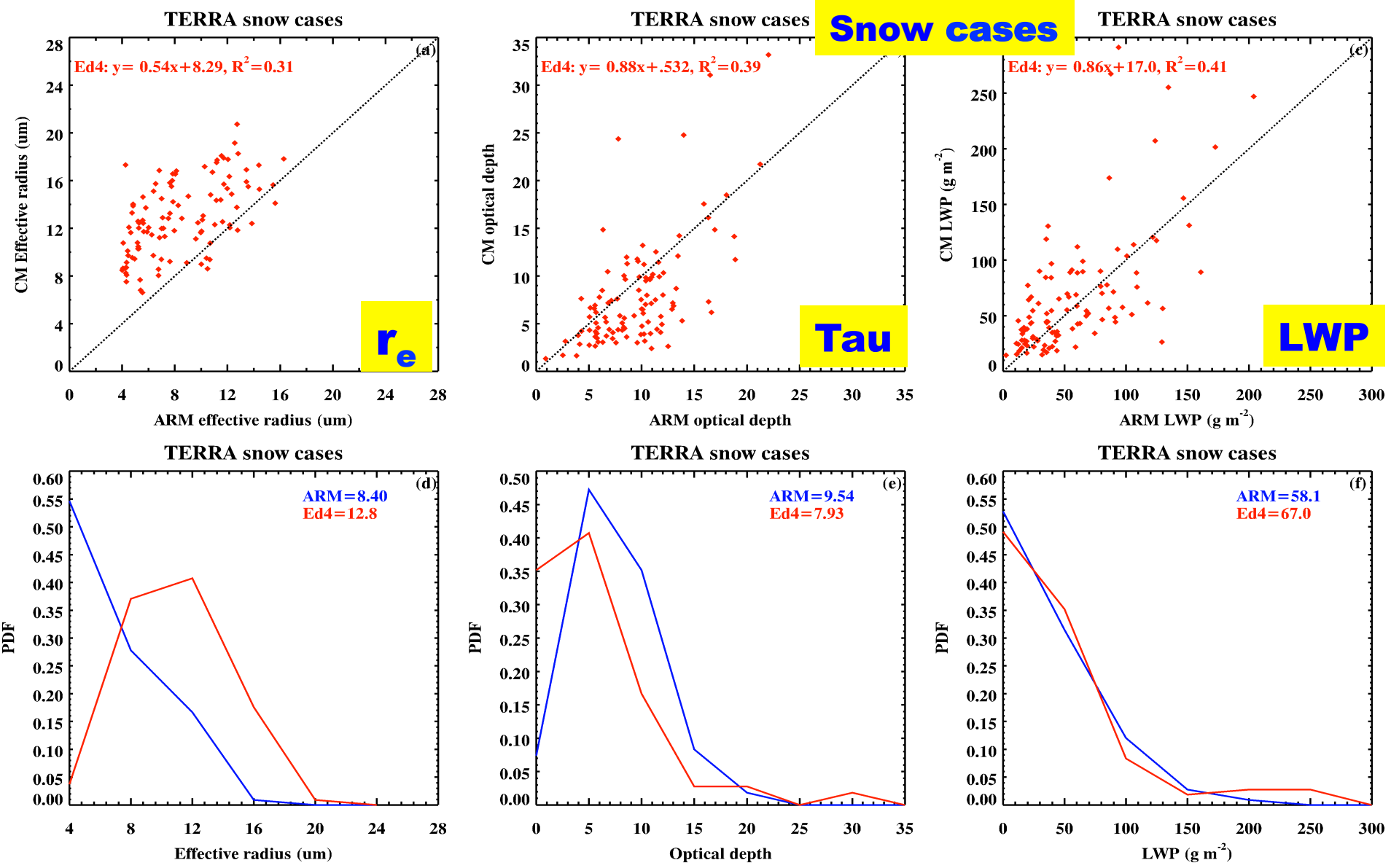
1. To what degree do the CERES Ed4 cloud microphysical properties agree with the ARM's retrievals over snow-free ($R_{SFC} \leq 0.3$) and snow ($R_{SFC} > 0.3$) surfaces?


TERRA retrieved cloud properties
Snow-free cases
(a)
ARM=12.4±2.8
Ed4=14.5±3.1
r_e
Effective radius (um)
(b)
ARM=8.90±4.2
Ed4=8.38±5.2
Tau
Optical depth
(c)
ARM=77.0±48.0
Ed4=76.2±49.5
LWP
LWP (g/m^2)
Case number



The CERES Ed4 τ and LWP retrievals have excellent agreement with ARM retrievals under snow-free conditions although there are a few large differences. For r_e comparisons, the CERES Ed4 r_e values, on average, are ~ 2 μm greater than the ARM ones.

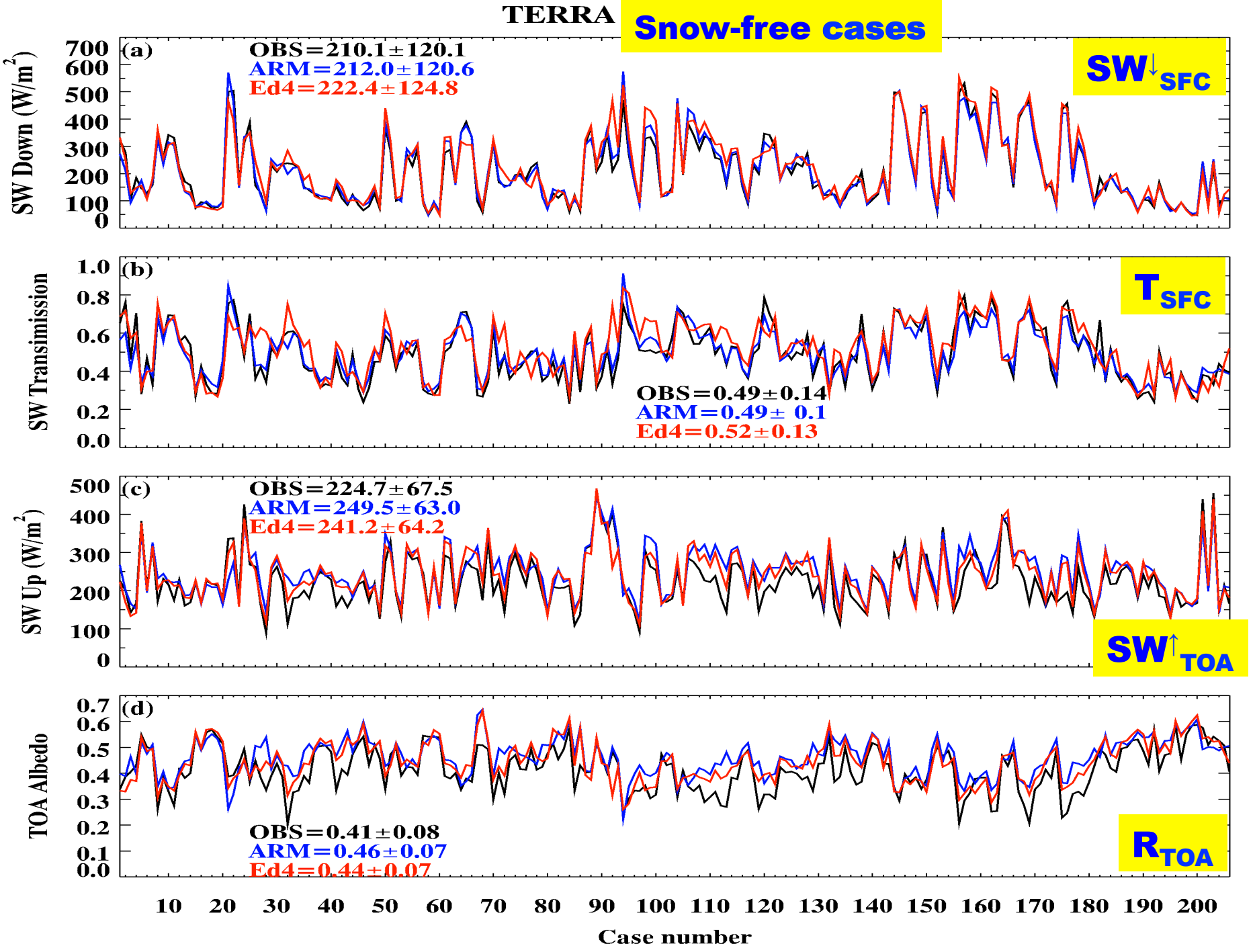

TERRA retrieved cloud properties (
Snow cases
(a)
ARM=8.40±3.2
Ed4=12.8±3.1
r_e
Effective radius (um)
(b)
ARM=9.54±4.0
Ed4=7.93±5.6
Tau
Optical depth
(c)
ARM=58.1±40.8
Ed4=67.0±54.6
LWP
LWP (g/m^2)
Case number



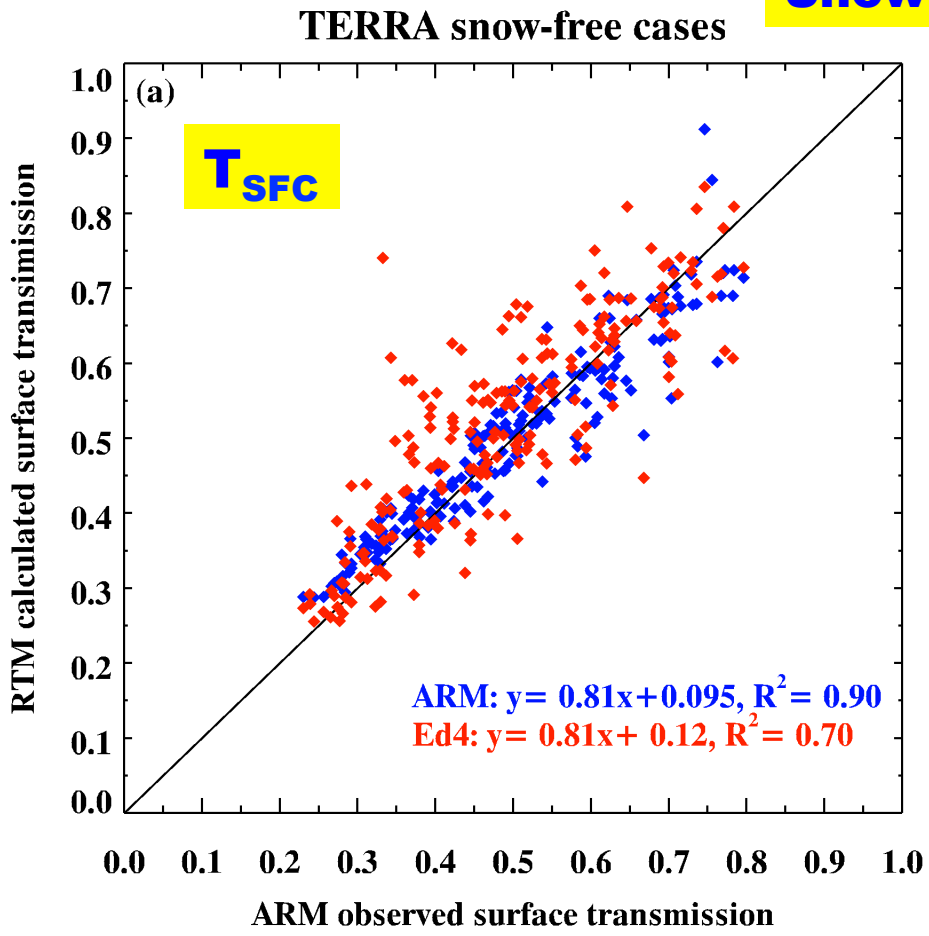
The differences in tau and *LWP* between Ed4 and ARM over snow surfaces are slightly larger than their snow-free comparisons due to highly reflectivity surfaces. The r_e difference is ~ 4.2 μm.

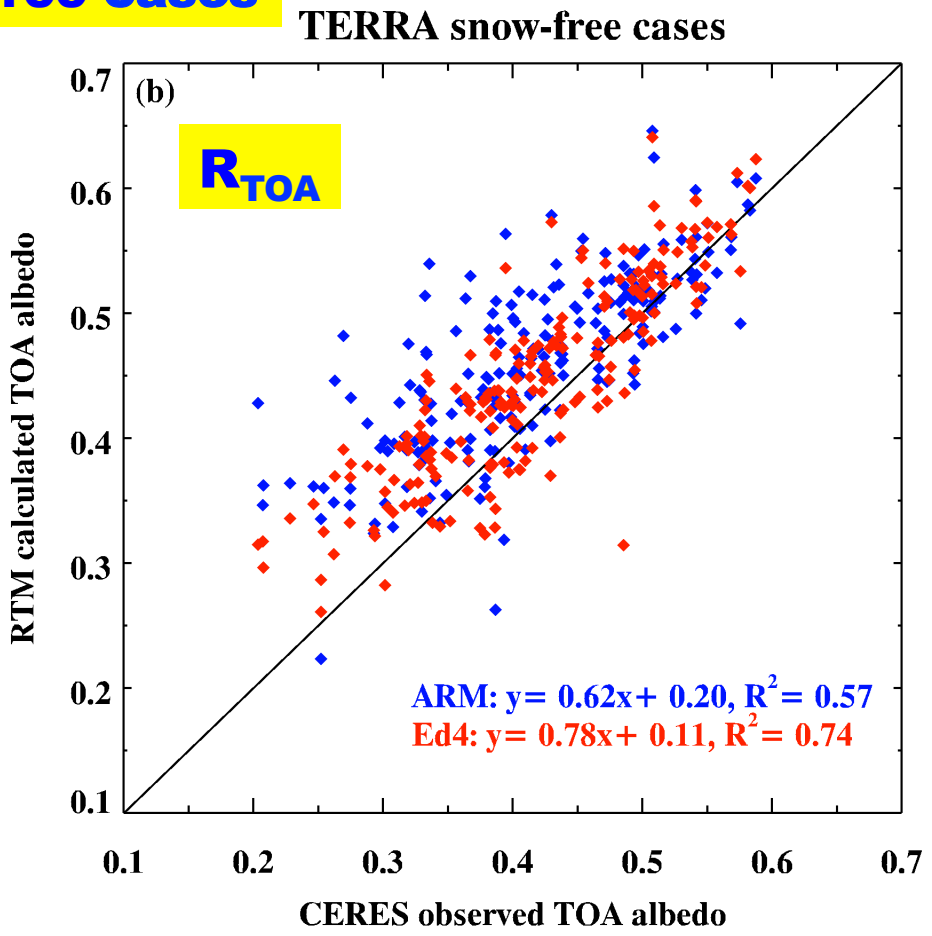
2. To what percentages do the RTM calculated downward SW flux and transmission at the surface, and reflected SW flux and albedo at the TOA agree with the collocated ARM surface and CERES TOA observations?

With input of ARM and CERES ED4 cloud retrievals

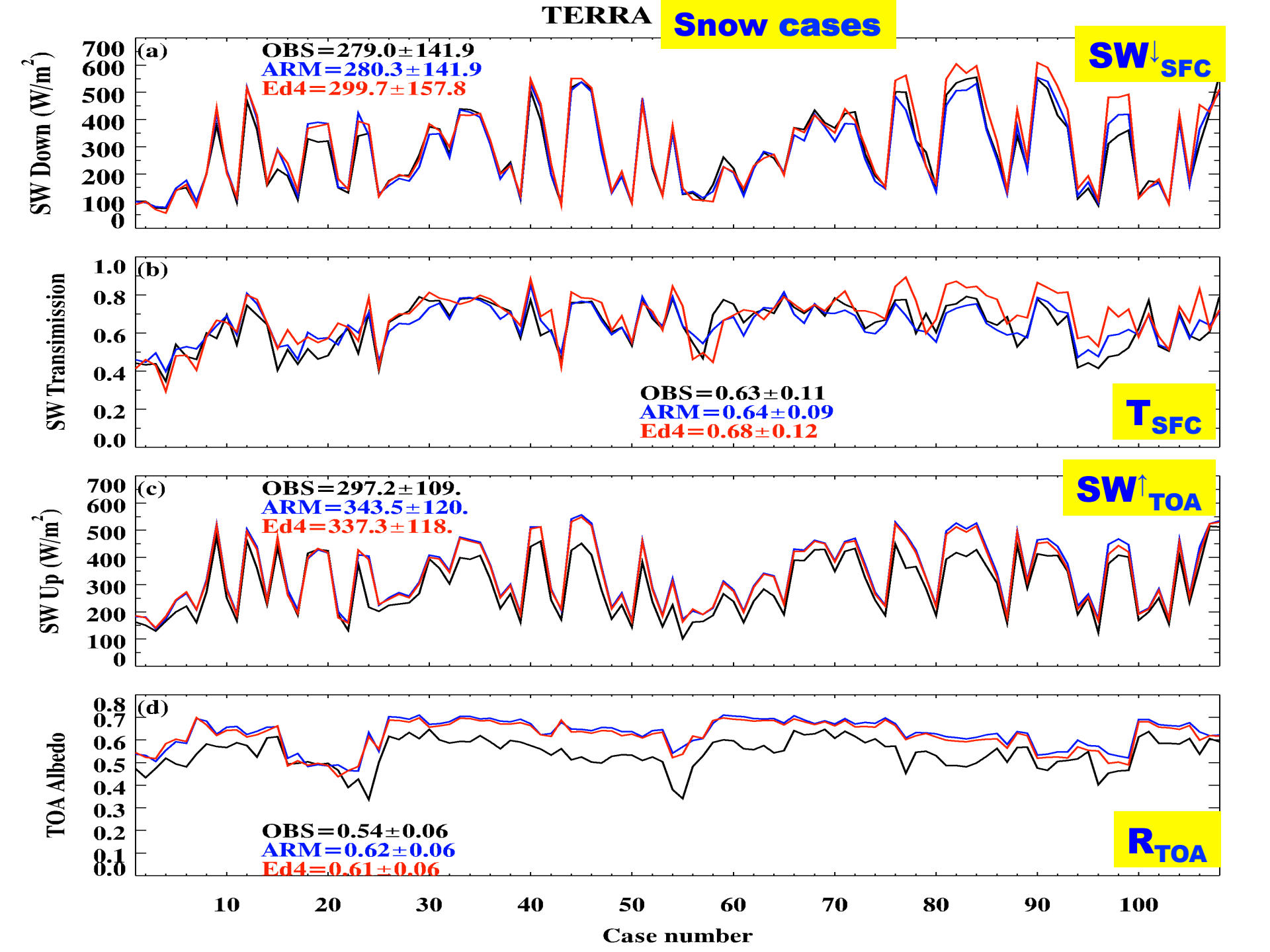

TERRA
Snow-free cases
(a)
OBS=210.1±120.1
ARM=212.0±120.6
Ed4=222.4±124.8
SW Down (W/m2)
SW↓SFC
(b)
SW Transimission
TSFC
OBS=0.49±0.14
ARM=0.49± 0.1
Ed4=0.52±0.13
(c)
OBS=224.7±67.5
ARM=249.5±63.0
Ed4=241.2±64.2
SW Up (W/m2)
SW↑TOA
(d)
TOA Albedo
OBS=0.41±0.08
ARM=0.46±0.07
Ed4=0.44±0.07
RTOA
Case number

Snow-free cases

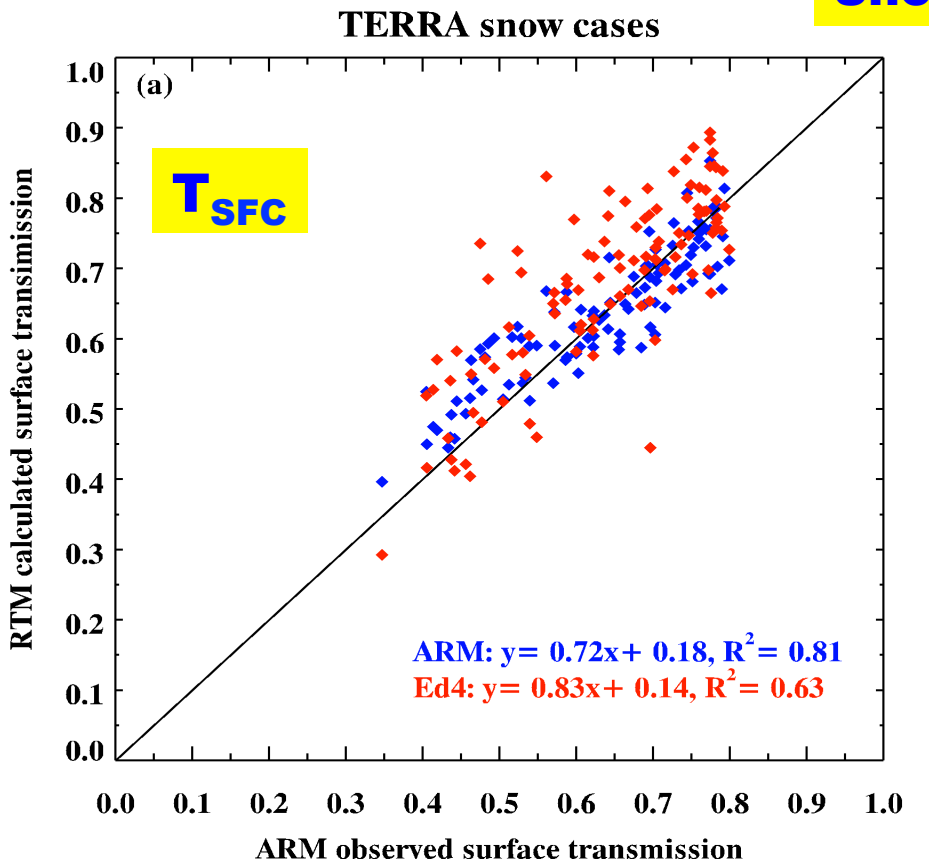


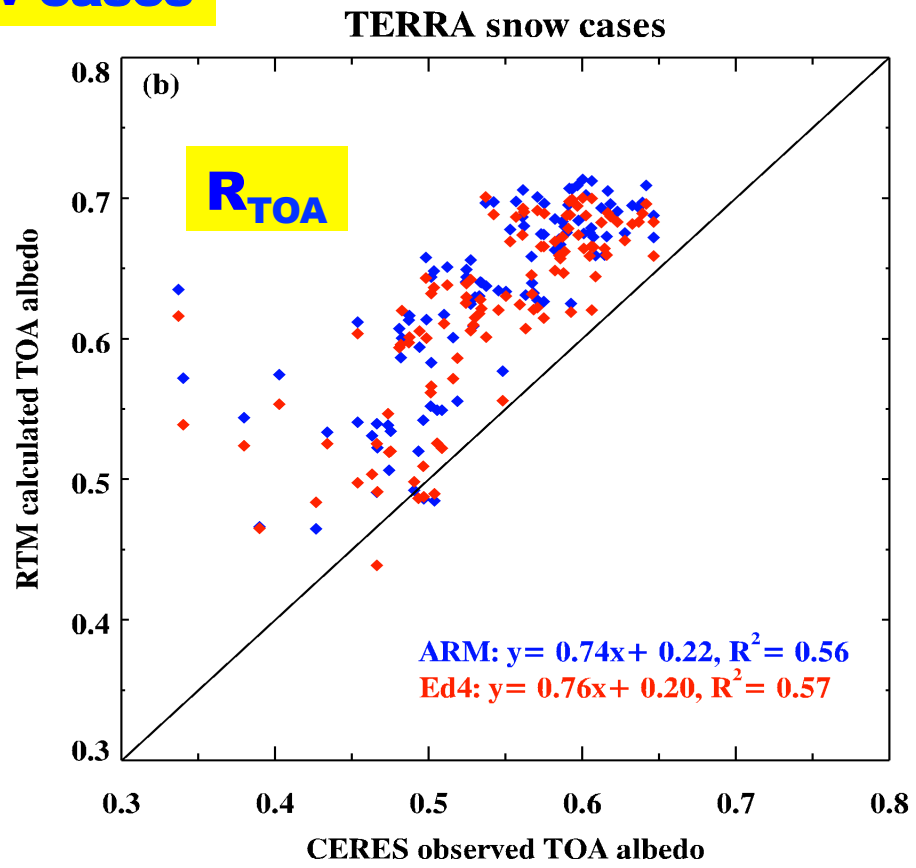


Since the calculated T_{SFC} and R_{TOA} are determined by input of cloud optical depth retrievals, the excellent agreement in tau and clear-sky $SW^{\downarrow}_{sfc}$ comparisons can explain the small differences in cloudy $SW^{\downarrow}_{sfc}$ flux and T_{SFC}, and provide a consistency check for cloud retrievals, but can't explain the large differences in $SW^{\uparrow}_{TOA}$ flux and R_{TOA}.


TERRA
Snow cases
SW↓SFC
(a)
OBS=279.0±141.9
ARM=280.3±141.9
Ed4=299.7±157.8
SW Down (W/m2)
700
600
500
400
300
200
100
0
(b)
SW Transimission
1.0
0.8
0.6
0.4
0.2
0.0
OBS=0.63±0.11
ARM=0.64±0.09
Ed4=0.68±0.12
TSFC
SW↑TOA
(c)
OBS=297.2±109.
ARM=343.5±120.
Ed4=337.3±118.
SW Up (W/m2)
(d)
TOA Albedo
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
OBS=0.54±0.06
ARM=0.62±0.06
Ed4=0.61±0.06
RTOA
10
20
30
40
50
60
70
80
90
100
Case number

Snow cases





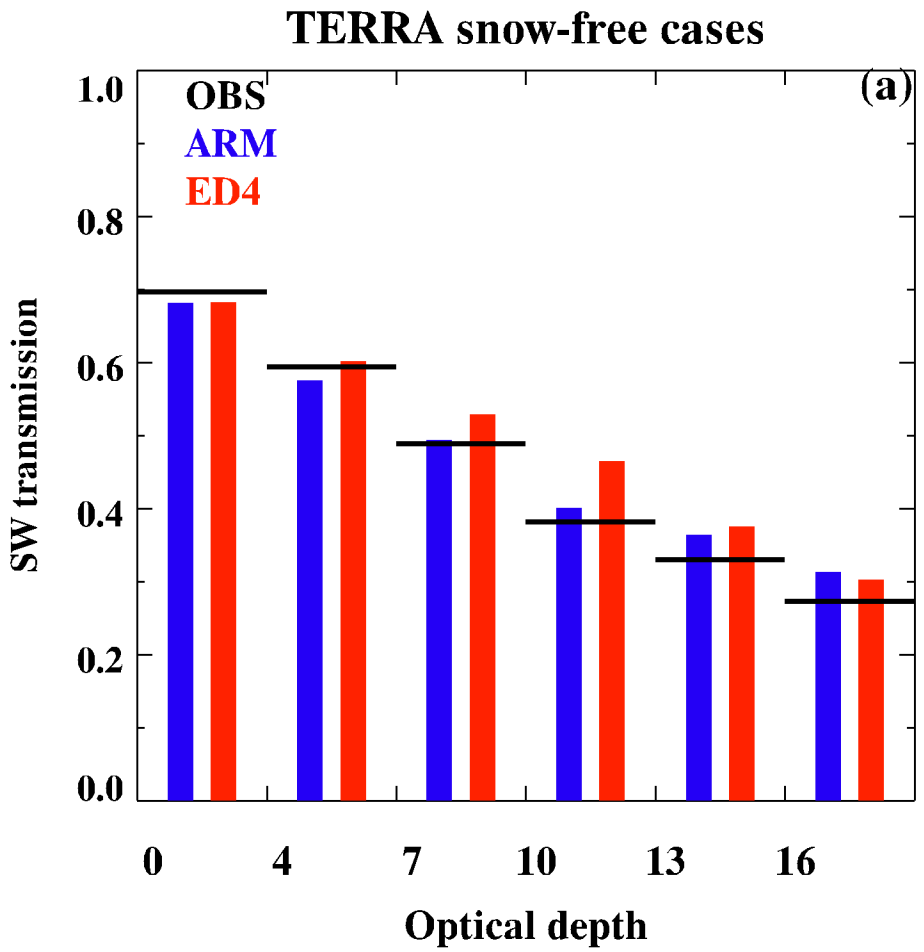
➔The calculated $SW^{\downarrow}_{sfc}$ and T_{SFC} with input of ARM cloud retrievals have the best radiation closure, while the underestimated Ed4 tau retrievals lead to higher $SW^{\downarrow}_{sfc}$ fluxes and T_{SFC} values.

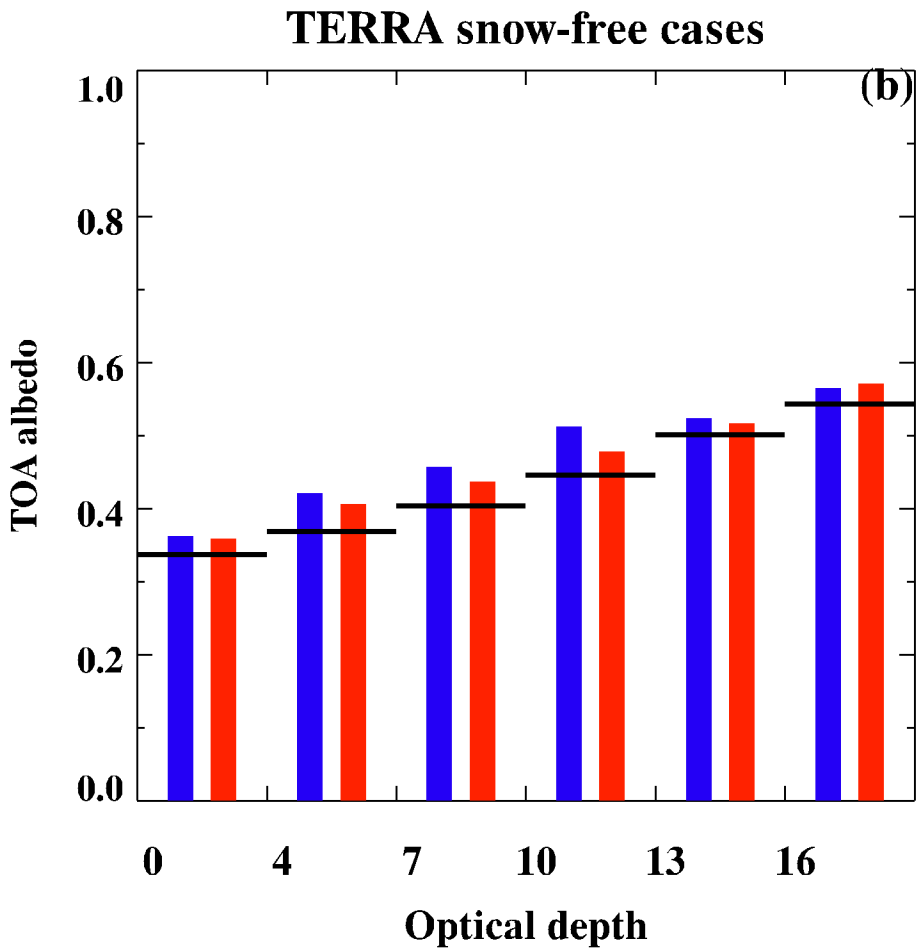
➔The differences in $SW^{\uparrow}_{TOA}$ and R_{TOA} between CERES observations and RTM calculations are much larger than the snow-free differences.

➔In general, the RTM calculations agree with observations better for snow-free cases than snow cases, and also better at the surface than at TOA, consistent with the findings of Shupe et al. (2015).

3. Do SW transmission (T_{SFC}) at the surface and TOA albedo (R_{TOA}) vary with cloud optical depth, solar zenith angle (*SZA*), and surface albedo?

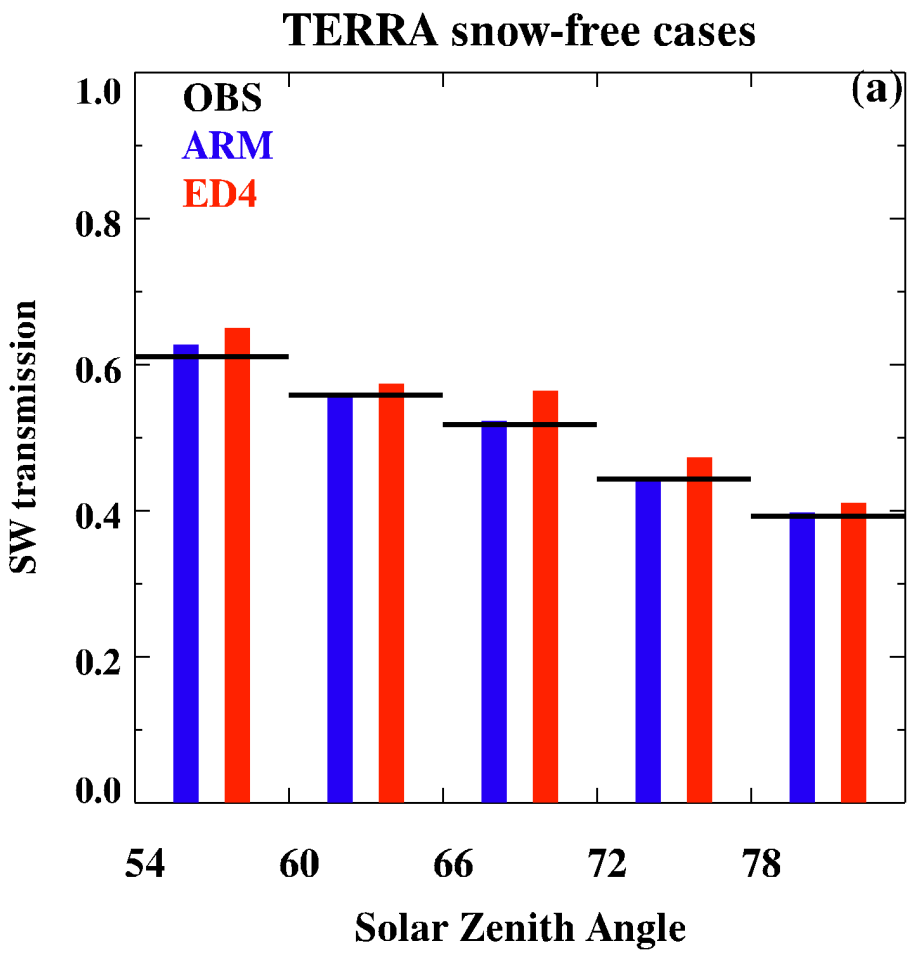
A sensitivity study of T_{SFC} and R_{TOA} on cloud optical depth

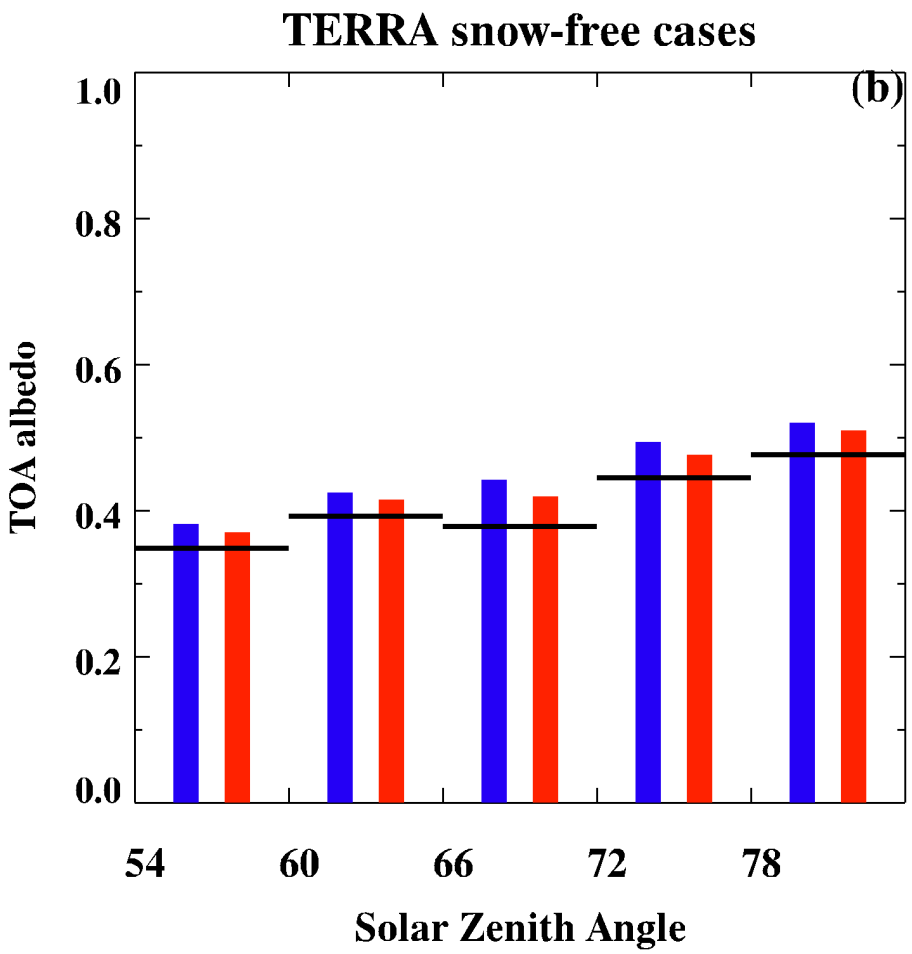




Both observed and calculated T_{SFC} (with input of ARM and ED4 cloud retrievals) values monotonically decrease, but R_{TOA} values increase with increasing cloud optical depth.
Differences between observations and calculations are < 0.06.

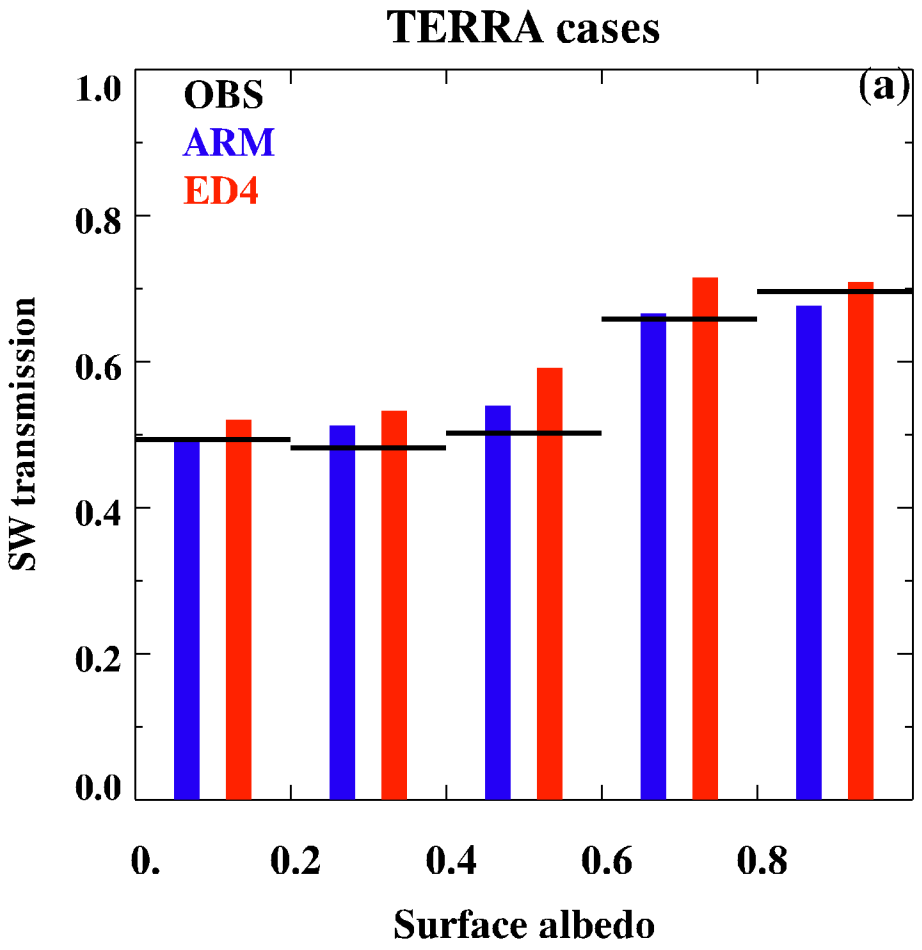
A sensitivity study of T_{SFC} and R_{TOA} on Solar Zenith Angle

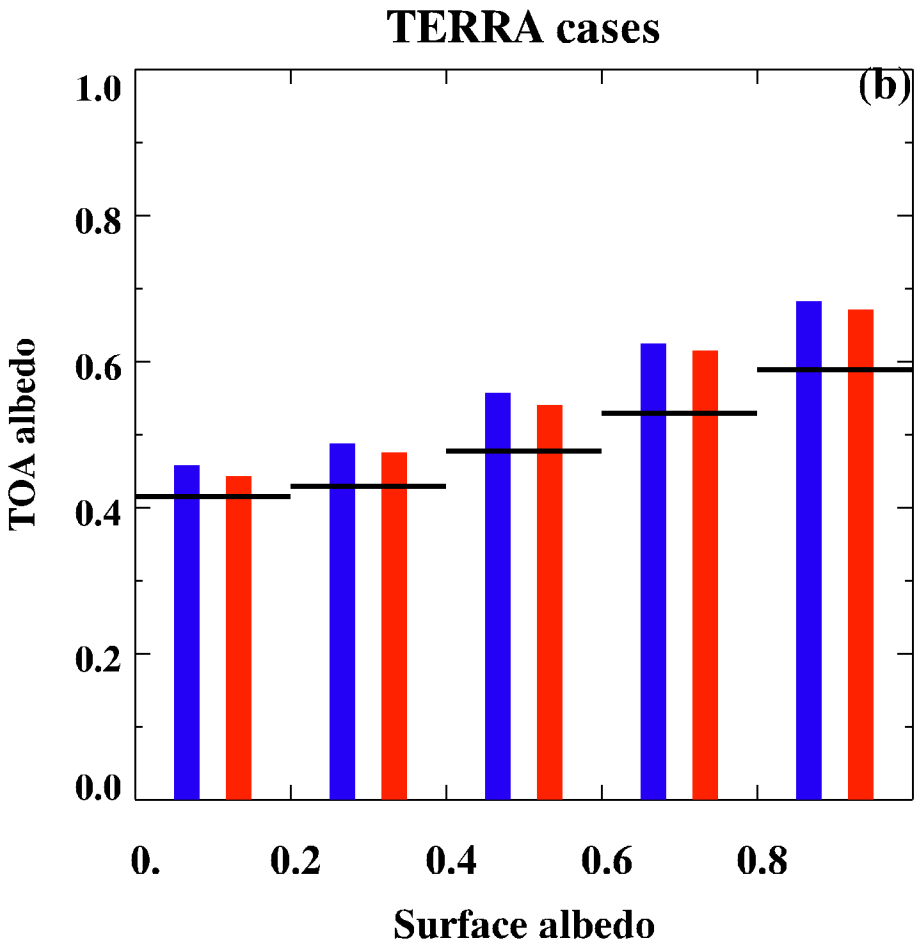




T_{SFC} values decrease, but R_{TOA} values increase slightly with increasing SZA because at larger SZAs, more solar photons will be reflected back to space and few solar photons can penetrate through the cloud layer to reach the ground.

A sensitivity study of T_{SFC} and R_{TOA} on Surface Albedo





Both T_{SFC} and R_{TOA} values increase with increasing R_{SFC} due to the multiple reflections of solar radiation between the cloud layer and highly reflective surfaces.

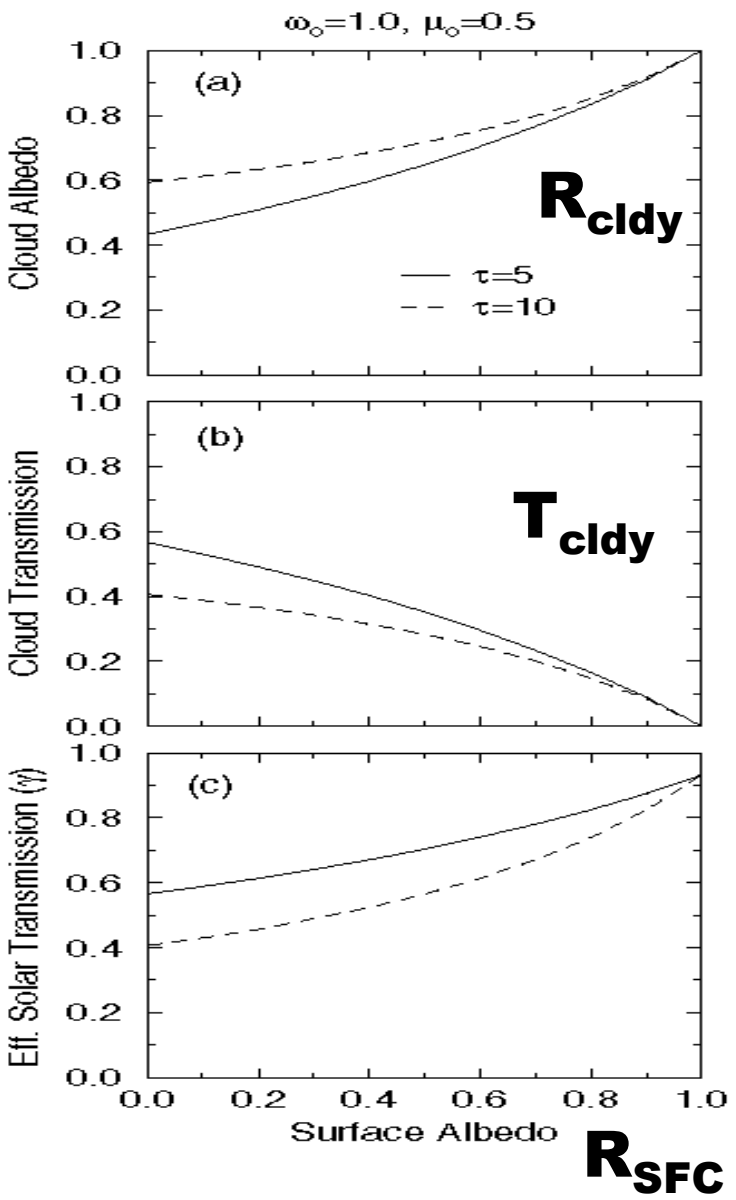
Summary (Answering three questions)

- **For snow-free conditions, the CERES Ed4 tau and LWP retrievals have excellent agreement with ARM retrievals, but CERES r_e values are ~ 2 μm greater than the ARM ones.**

  For snow surfaces, the comparisons are similar to, but have larger biases than their snow-free counterparts.

- **The RTM calculations agree with observations better at the surface than at TOA, better for snow-free cases than snow cases.**
- **A sensitivity study has shown that both observed and calculated T_{SFC} values monotonically decrease, but R_{TOA} values increase with increasing tau and SZA, however, both T_{SFC} and R_{TOA} increase with increasing R_{SFC} due to multiple reflections.**

The effect of surface albedo R_{sfc} on the retrieval of Arctic cloud microphysical properties (Dong and Mace 2003)



For non-absorbing clouds, due to multiple reflections between cloud layer and reflecting surface,

(a) Cloud albedo increases and (b) cloud transmission decreases with increased R_{sfc}.

R_{sfc} becomes dominant for R_{sfc}>0.6.

(c) For the ARM PSP measured solar transmission (γ), which is used in our ground-based retrieval algorithm, increases as R_{sfc} increases due to multiple reflections between surface and cloud layer.

- $re = -1.496 + 2.49\,LWP + 10.25\gamma(1-Rsfc3) - 0.25\,\mu 0 + 20.28\,LWP\gamma(1-Rsfc) - 3.14\,LWP\mu 0$