Cloud property retrievals from satellite passive spectral observations

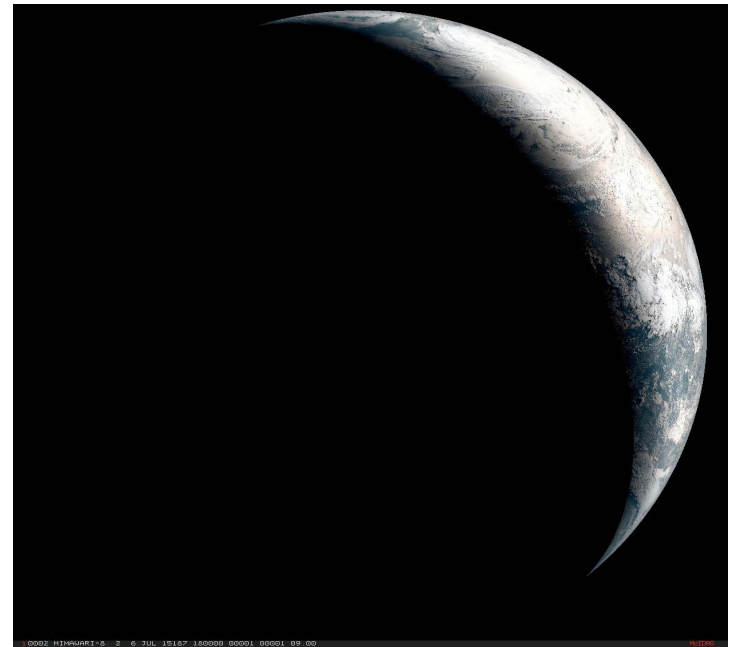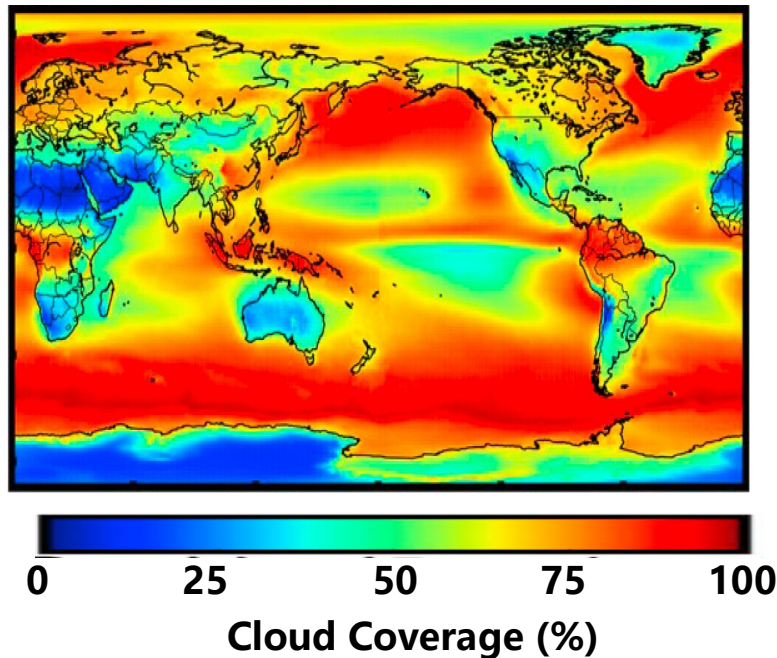## from fundamental models to new algorithms

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Contributed by: Shiwen Teng, Zhonghui Tan, Bin Yao, Yuxin Song, and et al.

Prof. Byung-Ju Sohn

Clouds are one of the most fundamental but complicated components in the atmosphere

Cloud Coverage (%)

Over two-thirds of the globe is covered by clouds

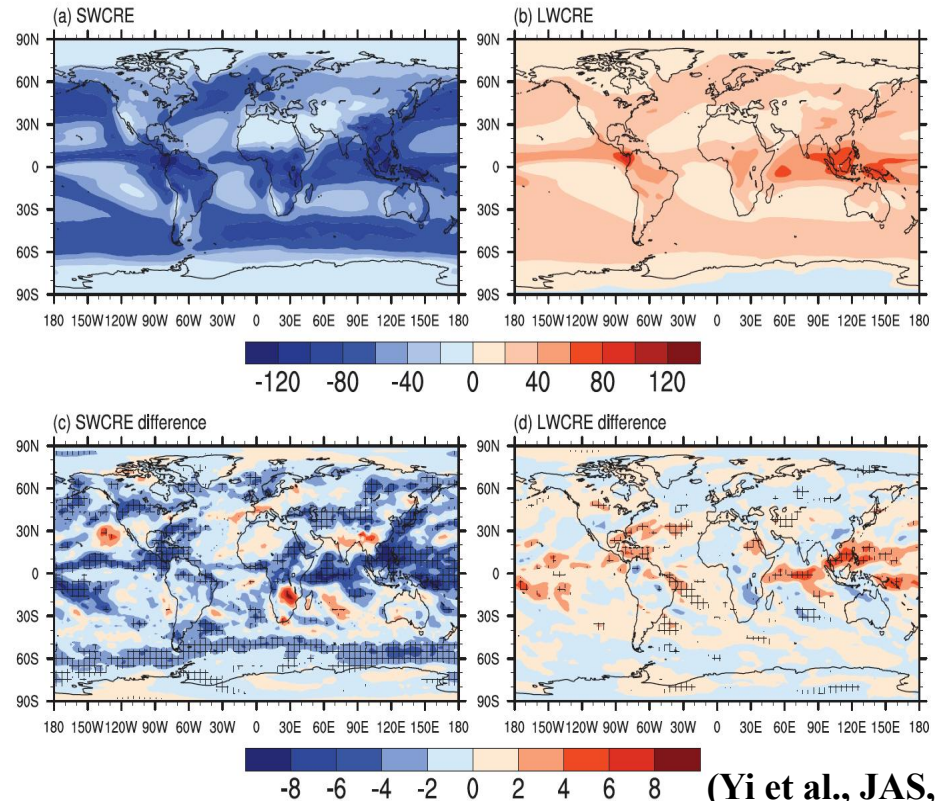(Yao et al., AR, 2020)

From particle to global scales

Clouds are one of the most fundamental but complicated components in the atmosphere

Smooth particles

TOA cloud radiative effects

(Yi et al., JAS, 2013)

Roughened particles

SW: -1.83W/m²
LW: 0.37W/m²

Radiative Forcing of doubling CO₂: 2.16 W/m²

Satellites play an important role for cloud detection

Long-term, wide range, and stable observations for:

➤ **Better understanding of clouds**

➤ **Improve weather and climate models**

Chinese Fengyun satellites are well developed, while

FY 3H/4B

- CER
- COT
- DQF
- IWP
- LWP
- OBIType
- algorithm_product_version_cor
- geospatial_lat_lon_extent

(Before 2025)

MODIS

- cloud_top_pressure_1km (dimension)
- cloud_top_height_1km (dimension)
- cloud_top_temperature_1km (dimension)
- cloud_emissivity_1km (dimension)
- cloud_top_method_1km (dimension)
- surface_temperature_1km (dimension)
- cloud_emiss11_1km (dimension)
- cloud_emiss12_1km (dimension)
- cloud_emiss13_1km (dimension)
- cloud_emiss85_1km (dimension)
- Cloud_Effective_Rad
- Cloud_Effective_Rad
- Cloud_Effective_Rad
- Cloud_Effective_Rad
- Cloud_Optical_Thick
- Cloud_Optical_Thick
- Cloud_Optical_Thick
- Cloud_Optical_Thick
- Cloud_Effective_Rad
- Cloud_Optical_Thick
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- Cloud_Water_Path_:
- Cloud_Water_Path_:
- Cloud_Effective_Rad
- Cloud_Effective_Rad
- Cloud_Effective_Rad
- Cloud_Optical_Thick
- Cloud_Optical_Thick
- Cloud_Top_Height (dimension)
- Cloud_Top_Height_Nadir (dimension)
- Cloud_Top_Height_Nadir_Day (dimension)
- Cloud_Top_Height_Nadir_Night (dimension)
- Cloud_Top_Pressure (dimension)
- Cloud_Top_Pressure_Nadir (dimension)
- Cloud_Top_Pressure_Night (dimension)
- Cloud_Top_Pressure_Nadir_Night (dimension)
- Cloud_Top_Pressure_Day (dimension)
- Cloud_Top_Pressure_Nadir_Day (dimension)
- Cloud_Top_Temperature (dimension)
- Cloud_Top_Temperature_Nadir (dimension)
- Cloud_Top_Temperature_Night (dimension)
- Cloud_Top_Temperature_Nadir_Night (dimension)
- Cloud_Top_Temperature_Day (dimension)
- Cloud_Top_Temperature_Nadir_Day (dimension)
- Tropopause_Height (dimension)
- Cloud_Fraction (dimension)
- Cloud_Fraction_Nadir (dimension)
- Cloud_Fraction_Night (dimension)
- Cloud_Fraction_Nadir_Night (dimension)
- Cloud_Fraction_Day (dimension)
- Cloud_Fraction_Nadir_Day (dimension)
- Cloud_Effective_Emissivity (dimension)
- Cloud_Effective_Emissivity_Nadir (dimension)
- Cloud_Effective_Emissivity_Night (dimension)
- Cloud_Effective_Emissivity_Nadir_Night (dimension)
- Cloud_Effective_Emissivity_Day (dimension)
- Cloud_Effective_Emissivity_Nadir_Day (dimension)
- Cloud_Top_Pressure_Infrared (dimension)
- Spectral_Cloud_Forcing (dimension)
- Cloud_Top_Pressure_From_Ratios (dimension)
- Radiance_Variance (dimension)
- Cloud_Phase_Infrared (dimension)
- Cloud_Phase_Infrared_Night (dimension)
- Cloud_Phase_Infrared_Day (dimension)
- Cloud_Phase_Infrared_1km (dimension)

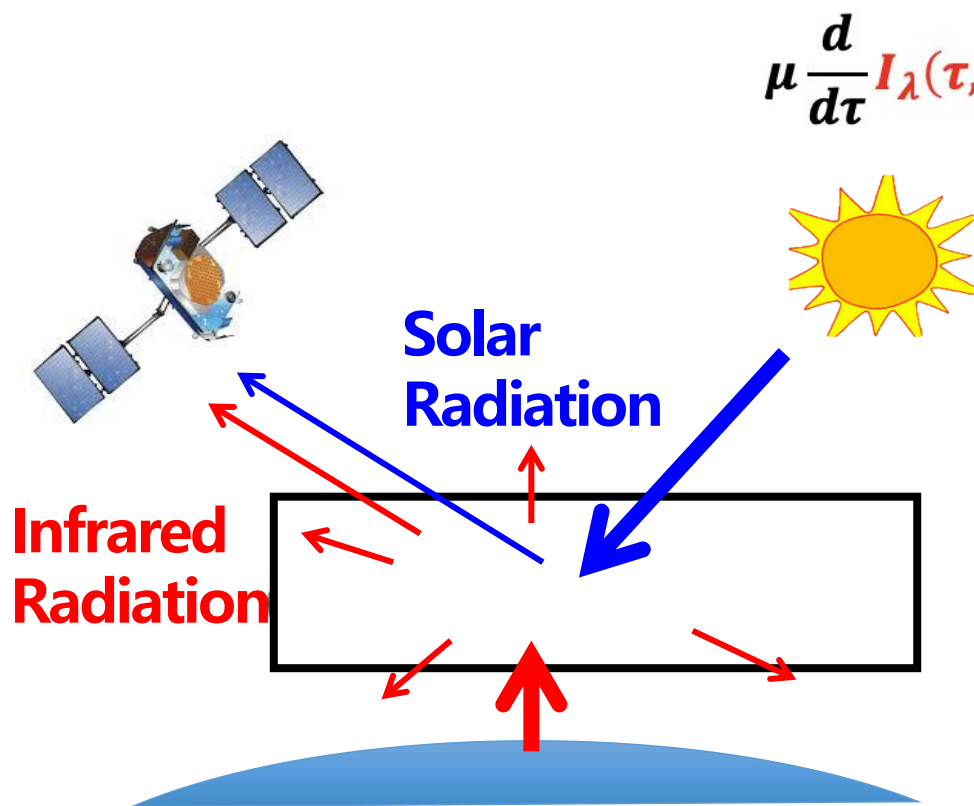# Cloud optical and microphysical property retrievals from spectral observations seem straightforward

$$\mu \frac{d}{d\tau} I_\lambda(\tau, \Omega) = I_\lambda(\tau, \Omega) - [1 - \varpi(\tau)] B_\lambda(\tau)$$

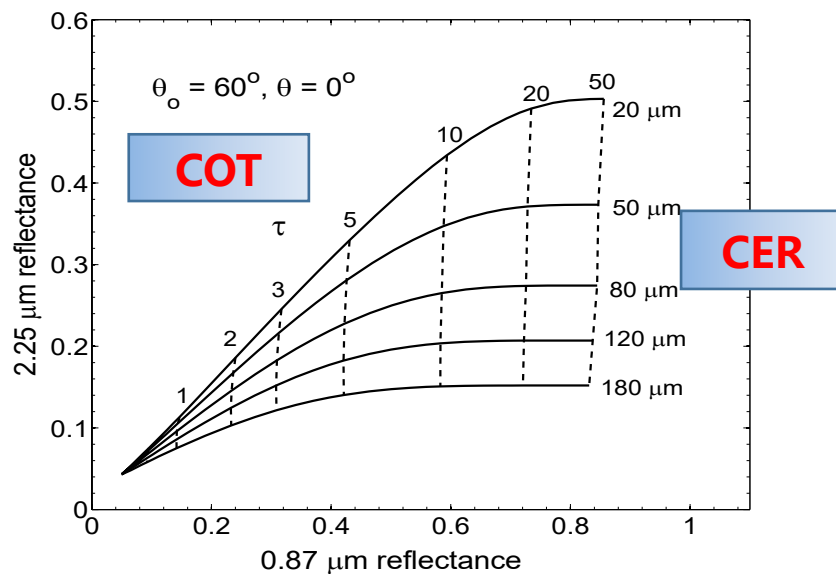$$- \varpi(\tau) \int_0^{4\pi} \frac{P_\lambda(\tau, \Omega, \Omega')}{4\pi} I_\lambda(\tau, \Omega') d\Omega'$$

Solar Radiation

Infrared Radiation

COT

CER

θₒ = 60°, θ = 0°

2.25 μm reflectance

0.87 μm reflectance

(Nakajima and King, 1990)

Cloud optical and microphysical property retrievals from spectral observations seem straightforward

$$\mu \frac{d}{d\tau} I_\lambda(\tau, \Omega) = I_\lambda(\tau, \Omega) - [1 - \varpi(\tau)] B_\lambda(\tau)$$

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Solar Radiation

Infrared Radiation

COT

CER

$\theta_o = 60^o$, $\theta = 0^o$

τ

2.25 µm reflectance

0.87 µm reflectance

20 µm
50 µm
80 µm
120 µm
180 µm

(Nakajima and King, 1990)

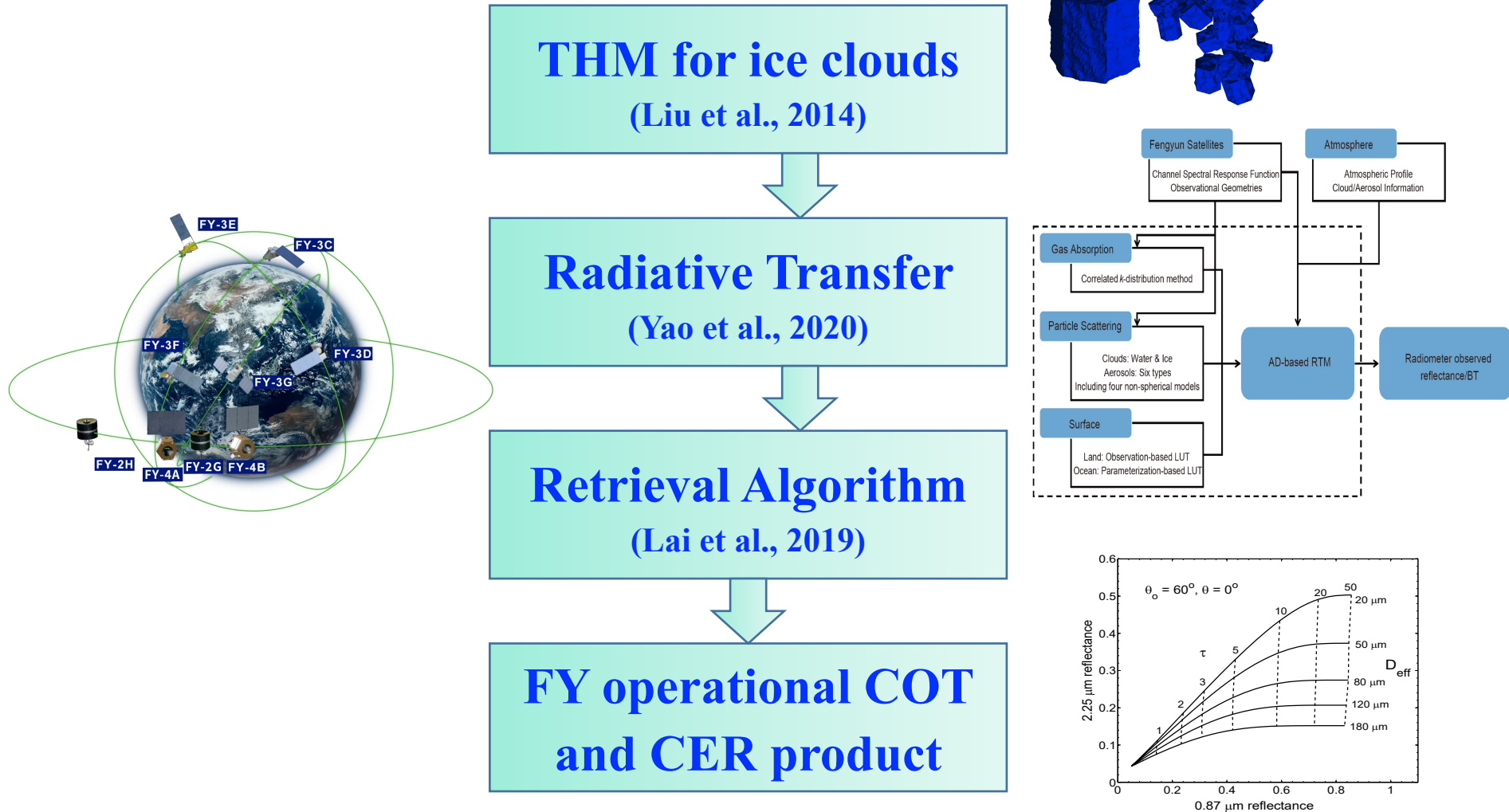# Cloud optical and microphysical property retrievals: from forward RT models to retrieval algorithms

Forward RT

Atmospheric Properties (Clouds)

Satellite Observations

Retrievals

(Nakajima and King, 1990)
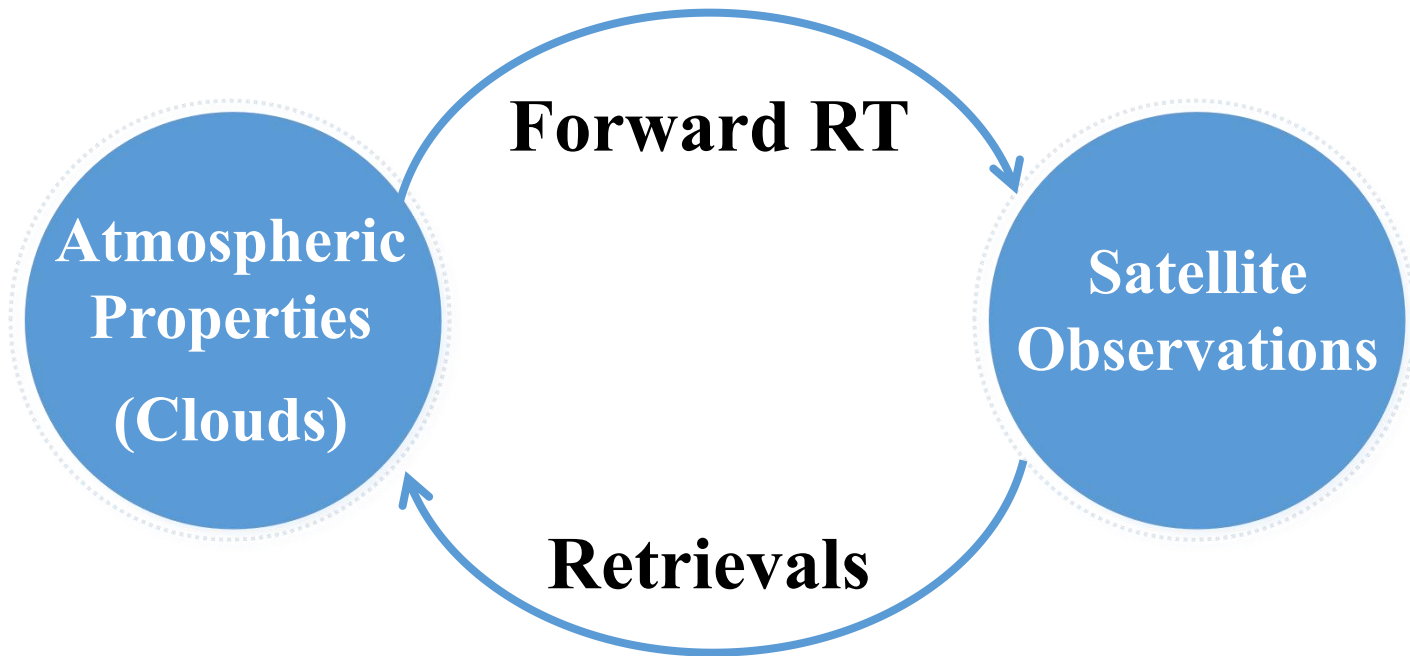
Challenges

Microphysics:
Ice Crystals

Macrophysics:
Vertical structures

System:
Algorithms & Techniques
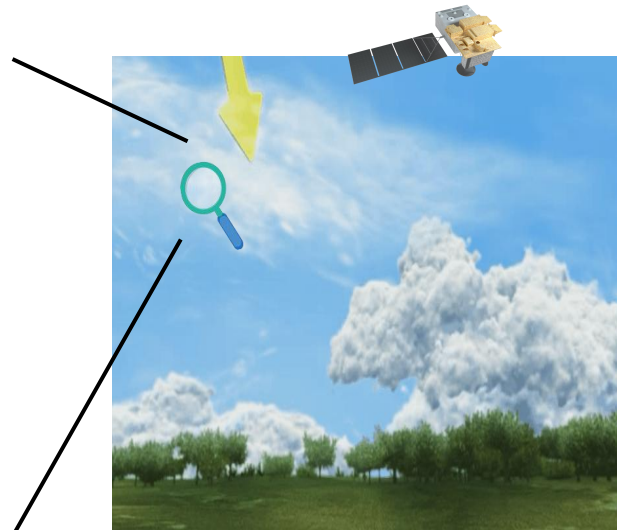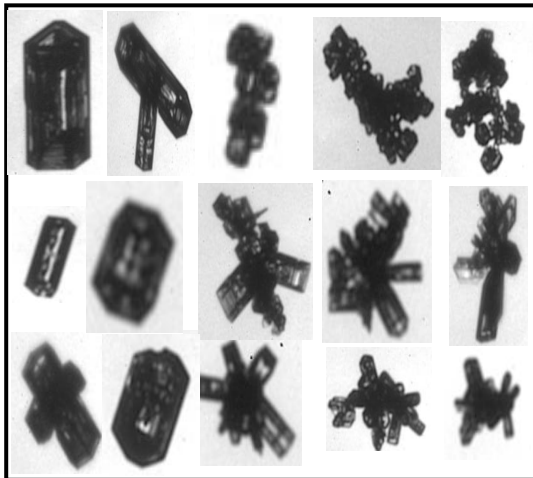
- Particle scattering

- Radiative transfer

- Cloud model

- Retrieval algorithm

- Instrument information

- Atmospheric influences

- ……

Let's start from ice cloud crystals

➤ **Actual ice crystals**
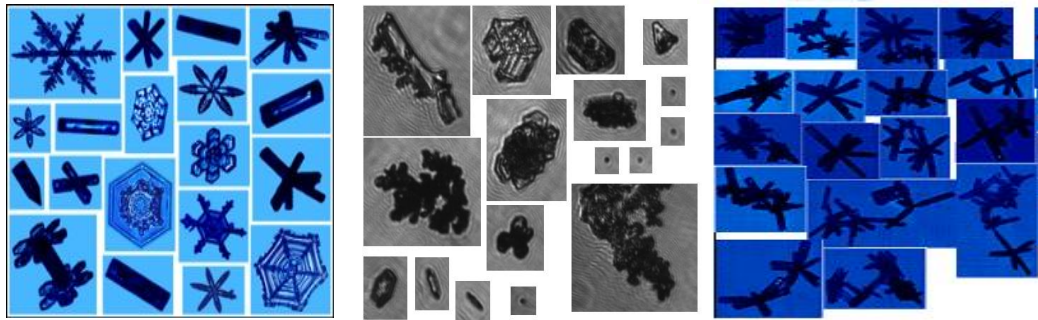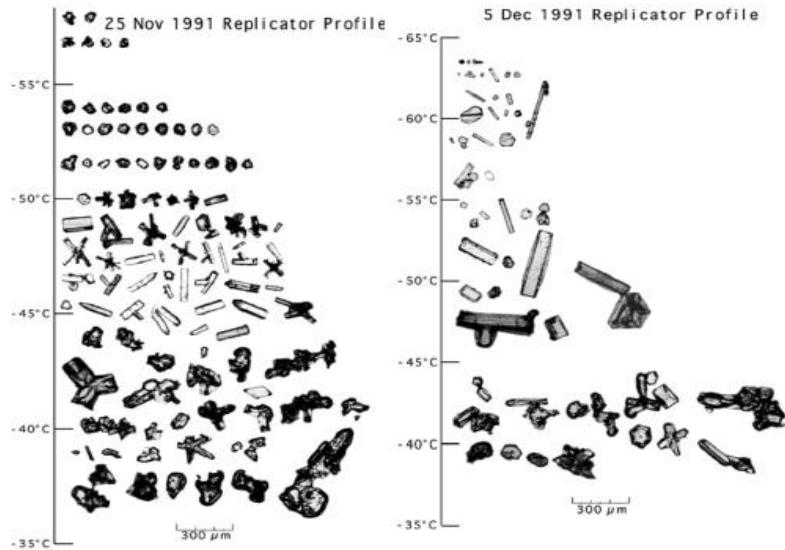
➤ **Numerical models**
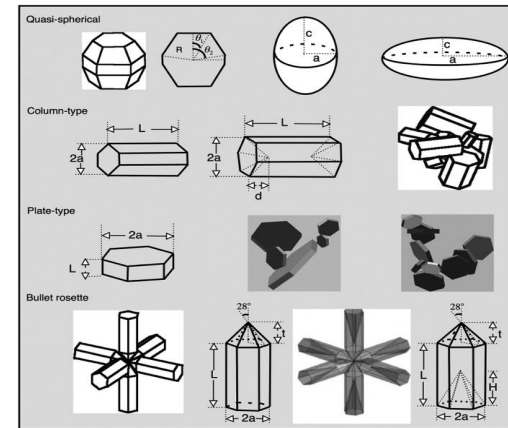
Yang et al., 2013
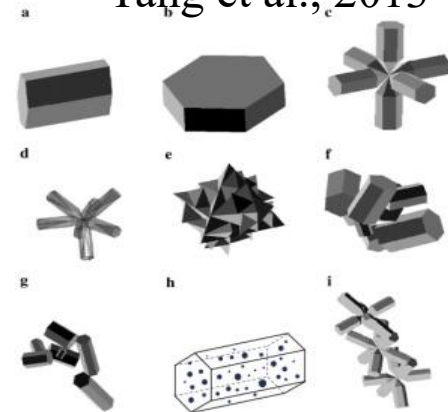
Baran, 2012

➤ **Models are still complex and less representative**

A two-habit model (THM) for ice crystals

- Single column structures
- Column combinations
- Roughened surface

- Simple

- Complex

L

a

L

- Compact

$V=0.65L^3$

- Loose

$V=0.026L^3$

| Crystal model | → | Single-scattering properties | → | Ice cloud optical properties | → | RT for retrievals |

(Liu et al., ACP, 2014; Wang, Liu* et al., 2018)
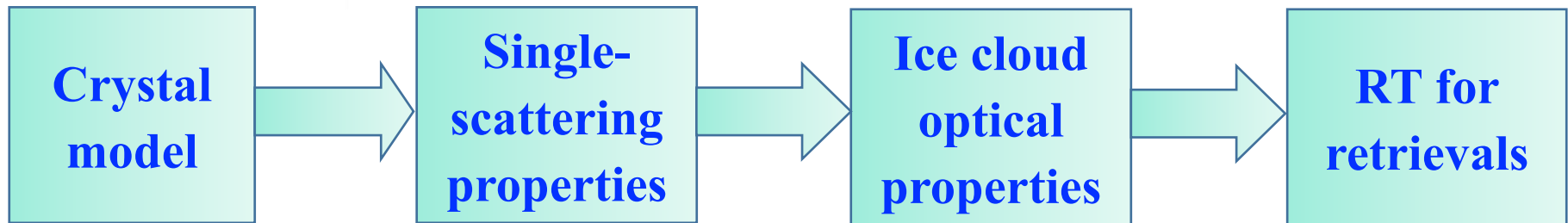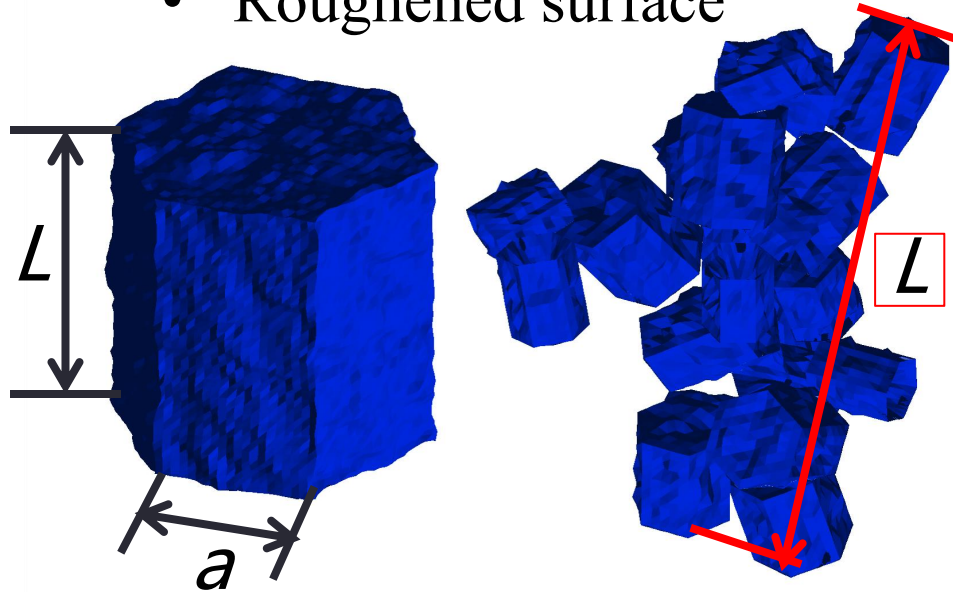
Microphysical properties of the THM

Median Mass Diameter

THM

Ice model for MODIS C6
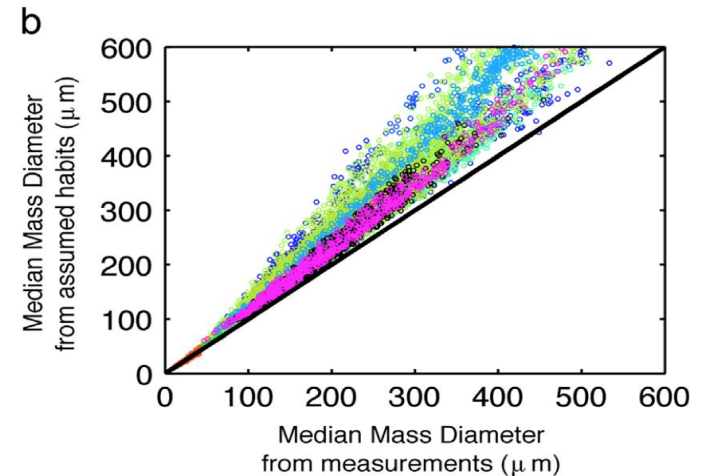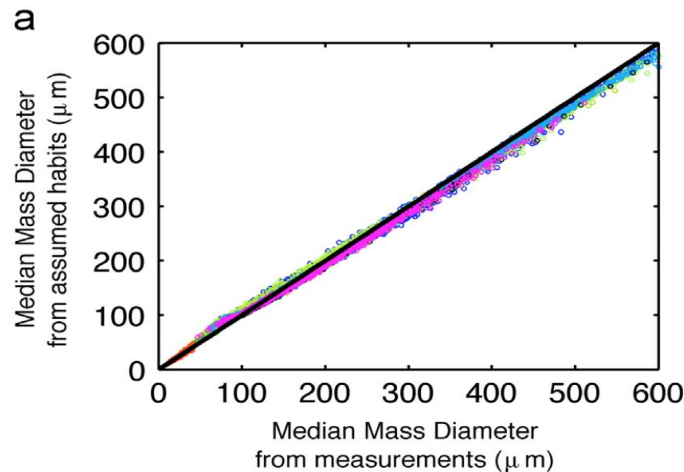
Ice Water Content
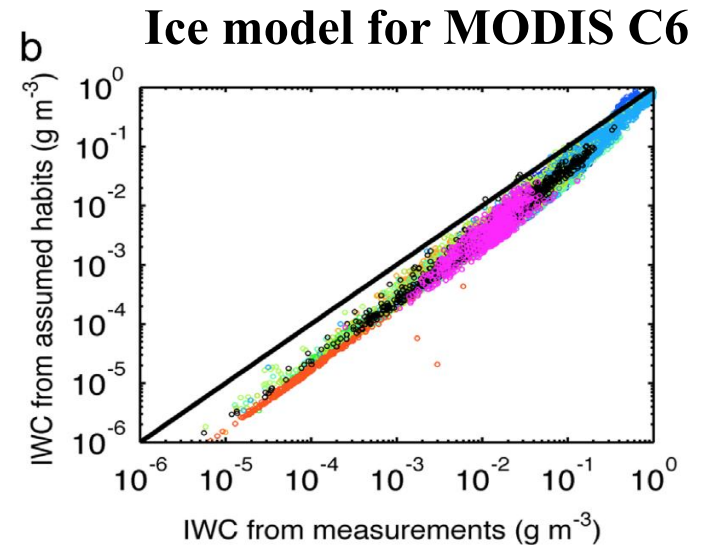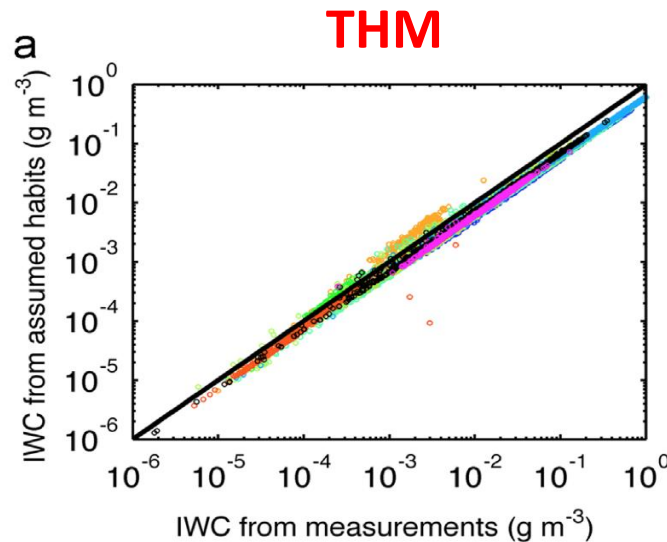
Comparing with aircraft observations from 11 field campaigns

Optical and Radiative Properties of the THM
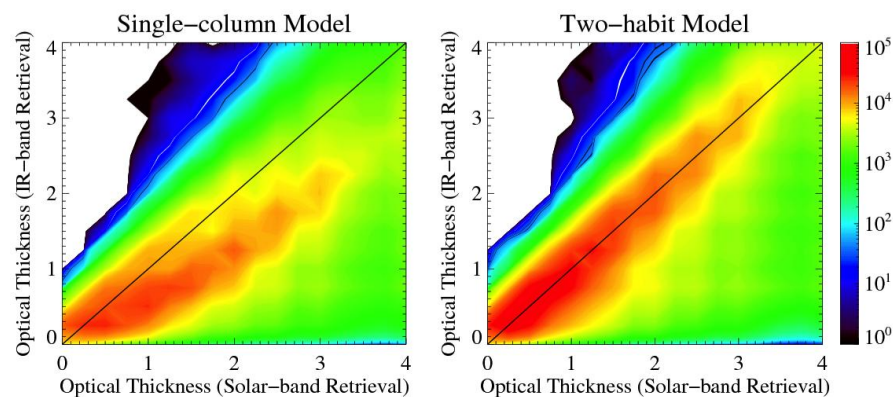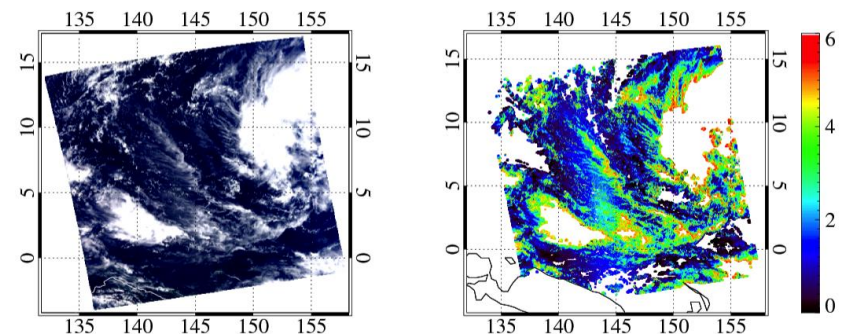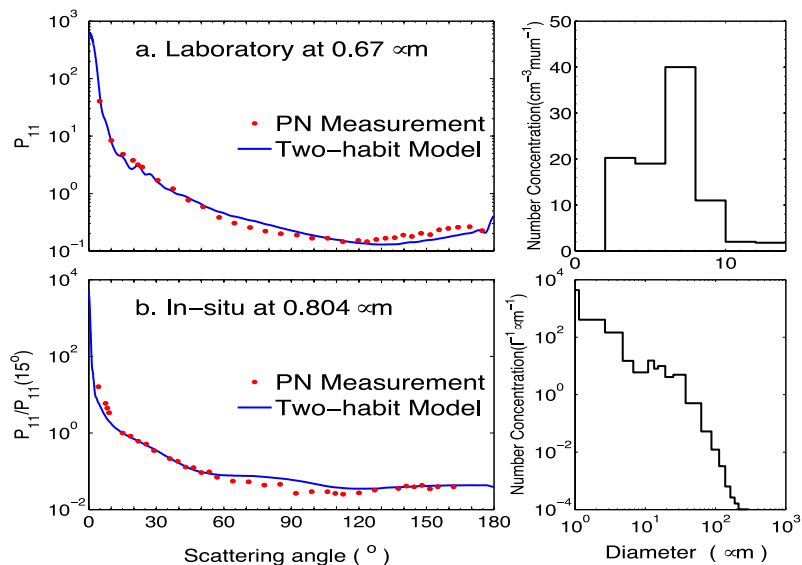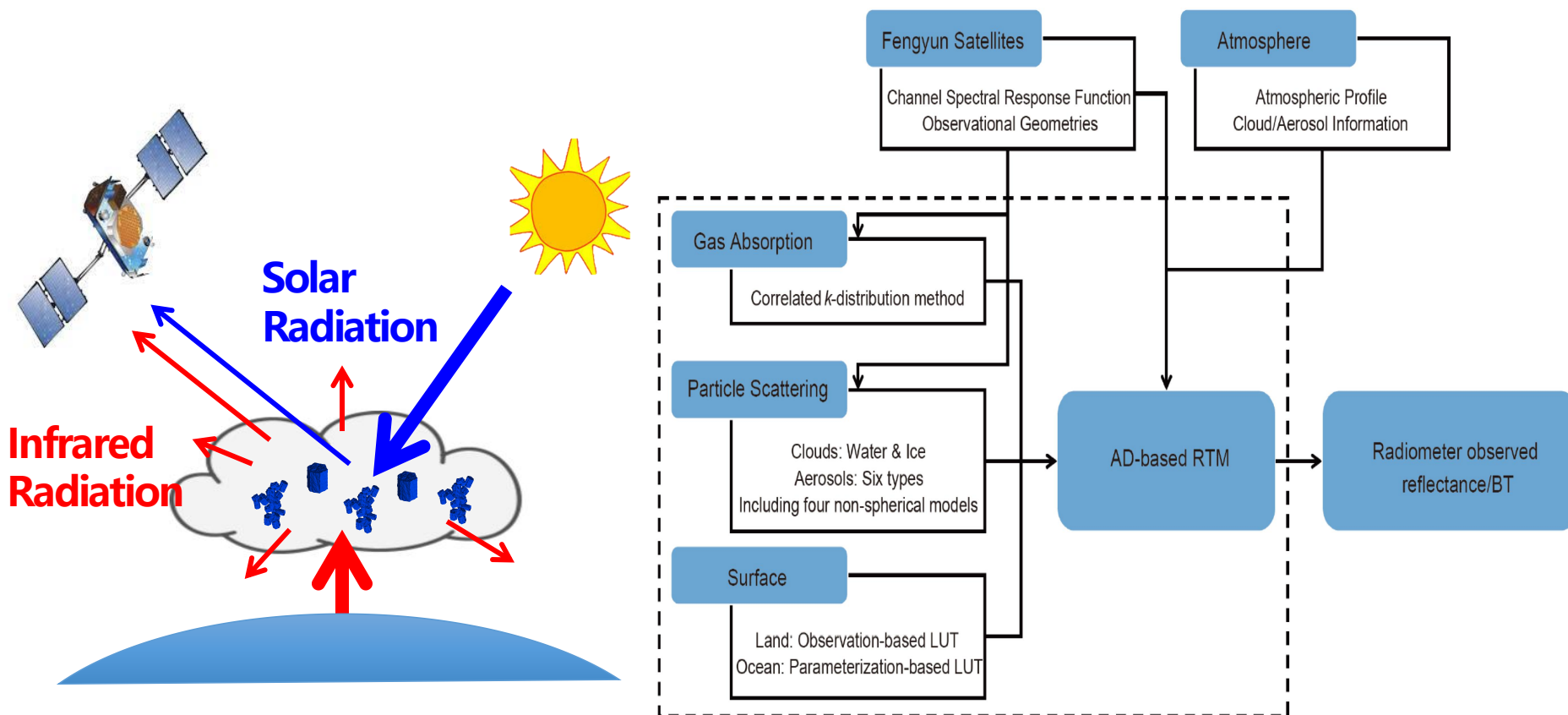
RT models for the forward simulations

(Yao et al., 2020; Ling et al., 2025)

RT models for the forward simulations


Solar Radiation

Infrared Radiation
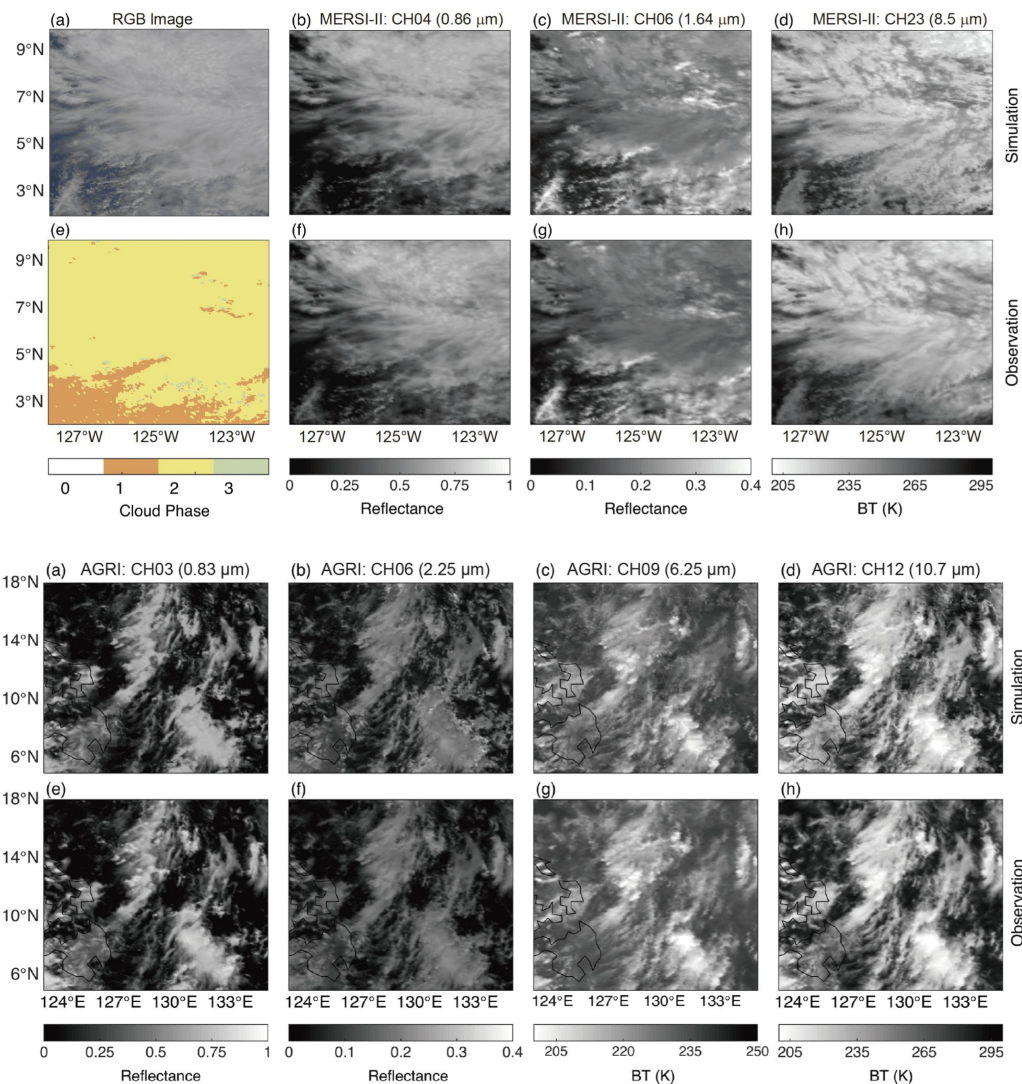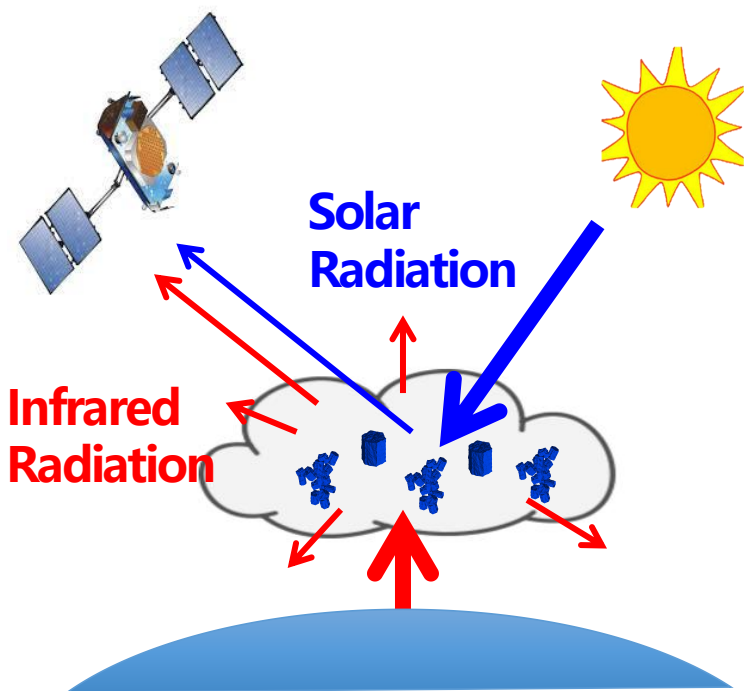
(Yao et al., 2020; Ling et al., 2025)

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Solar Radiation

Infrared Radiation

COT

CER

$\theta_o = 60°, \theta = 0°$

2.25 μm reflectance

τ

20 μm
50 μm
80 μm
120 μm
180 μm

1 2 3 5 10 20 50

0.87 μm reflectance
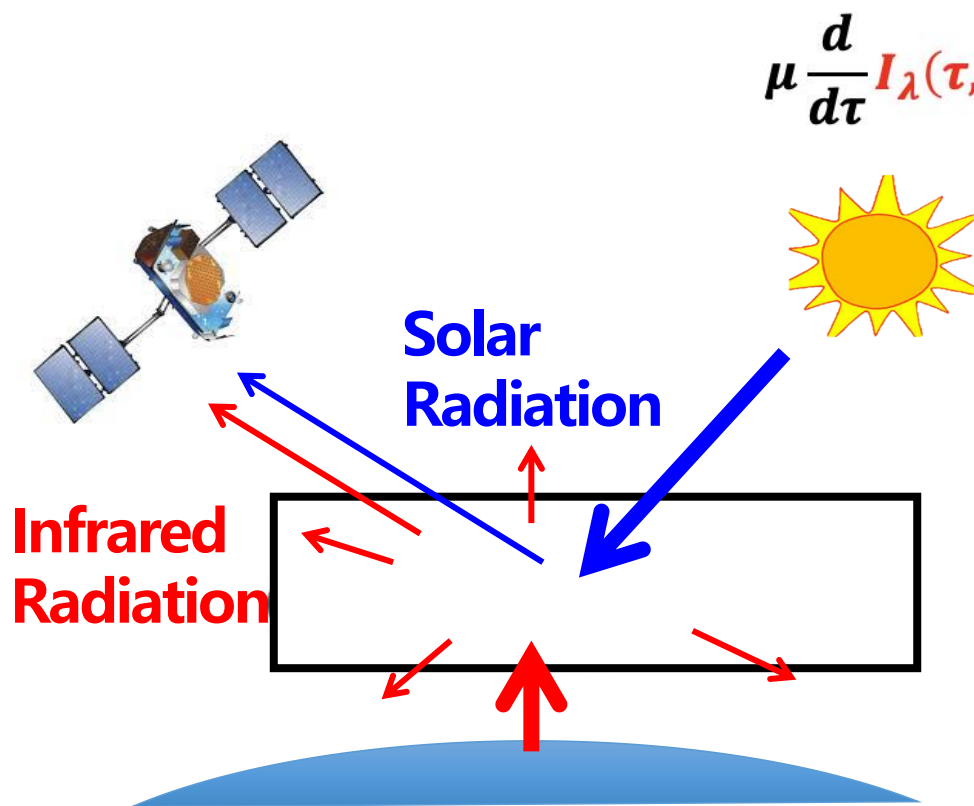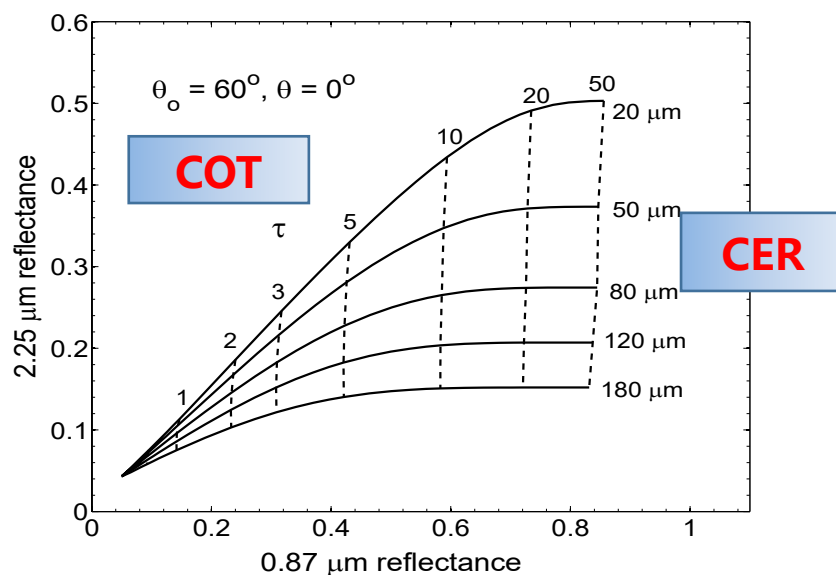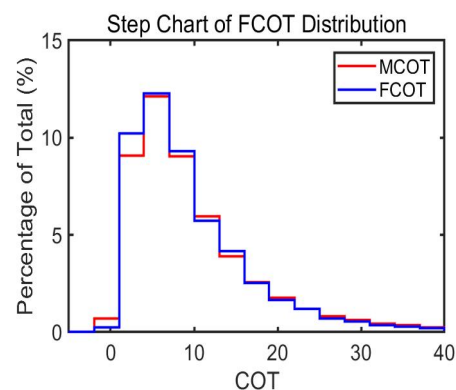
(Nakajima and King, 1990)

Framework for Fengyun-3/4 COT and CER retrievals
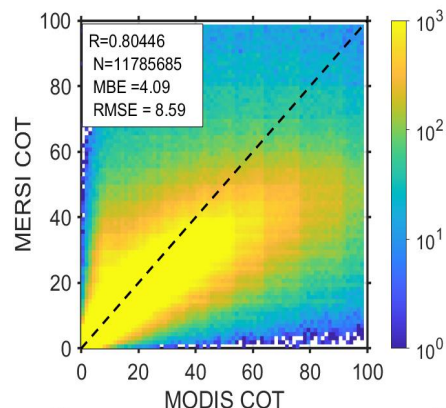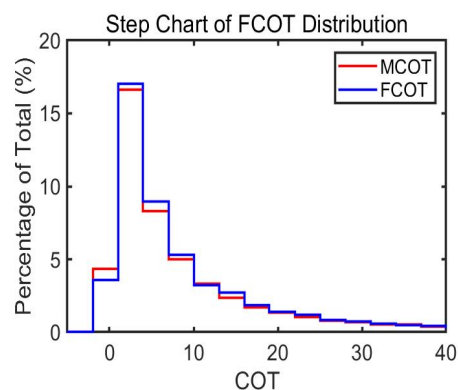
Cloud optical and microphysical properties for FY
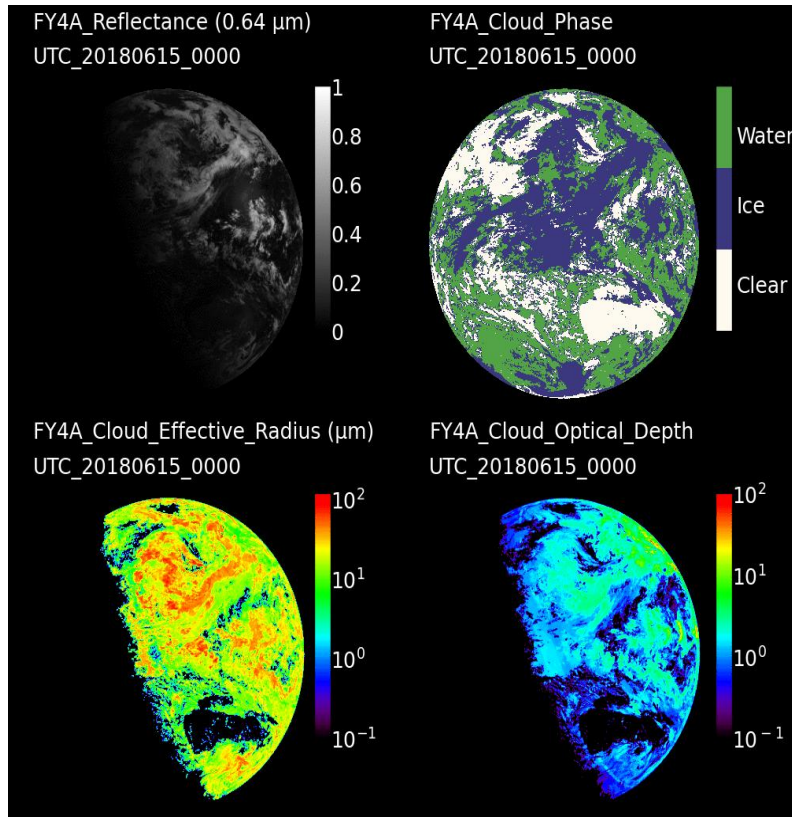
The algorithms provide stable and robust retrievals
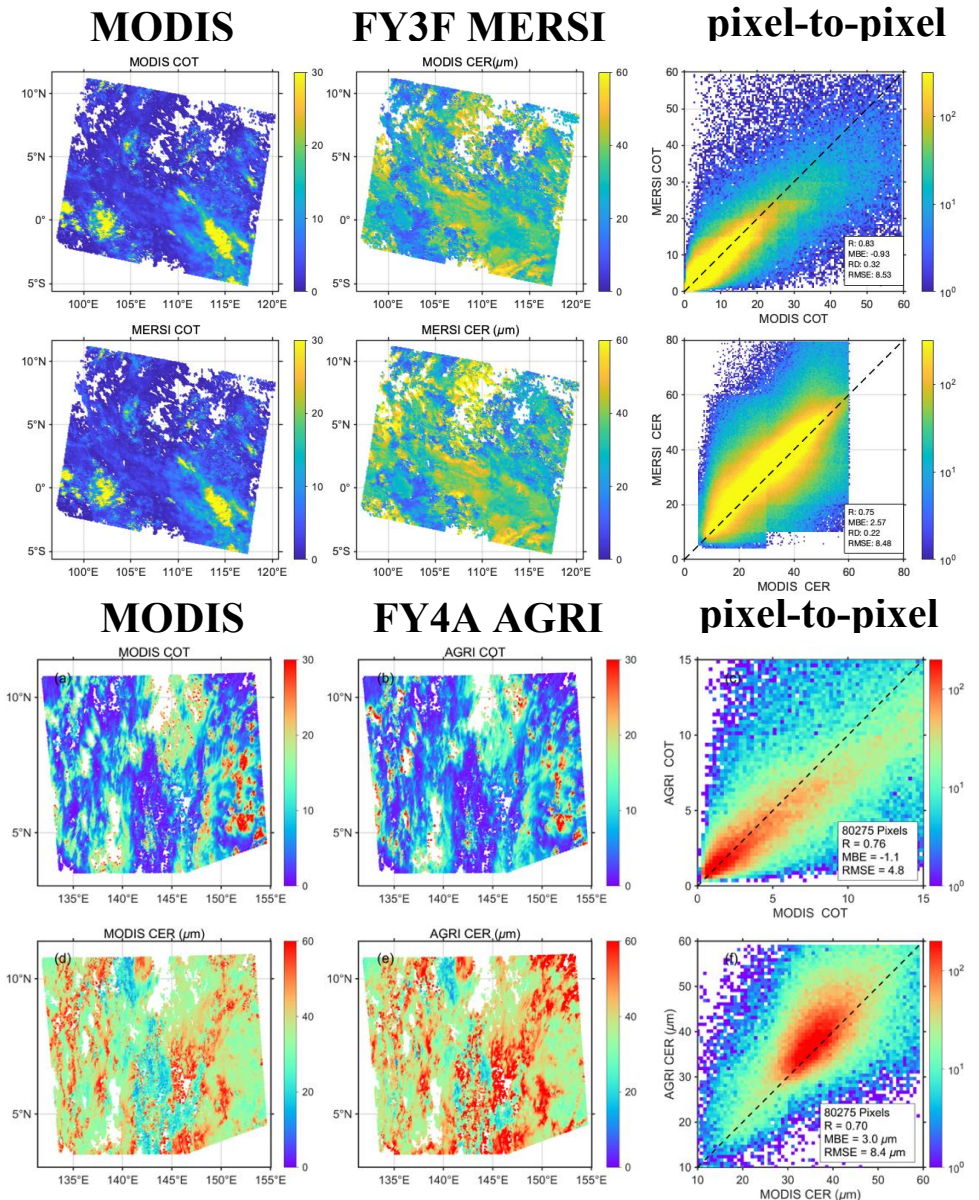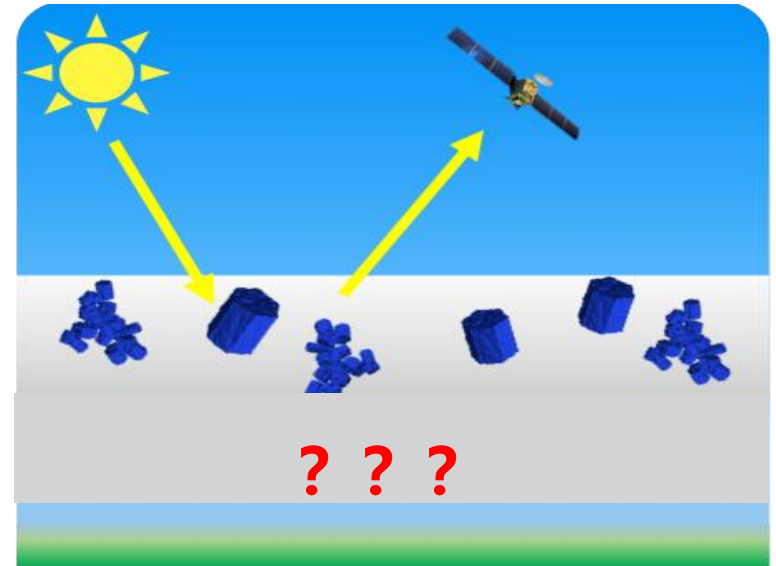
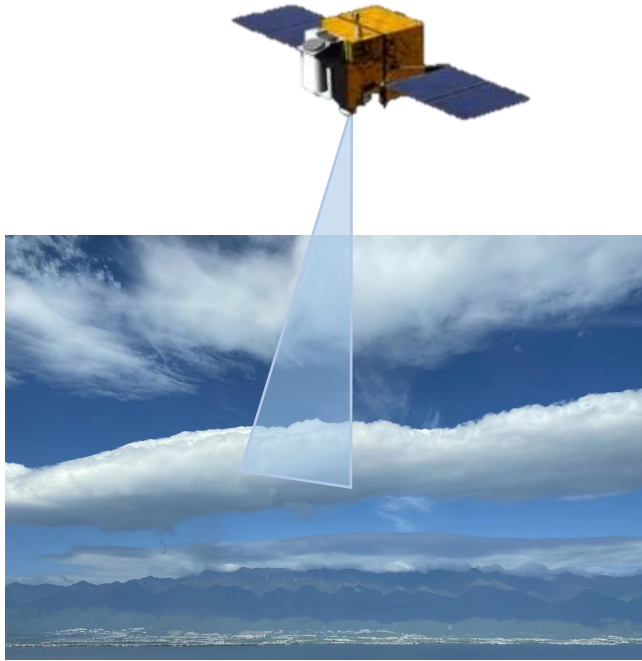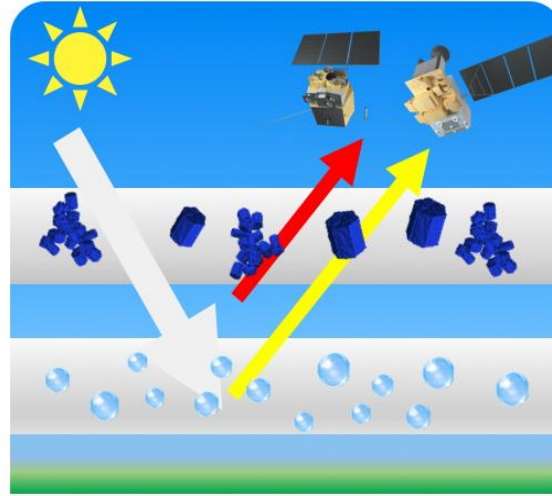# Cloud optical and microphysical properties for FY
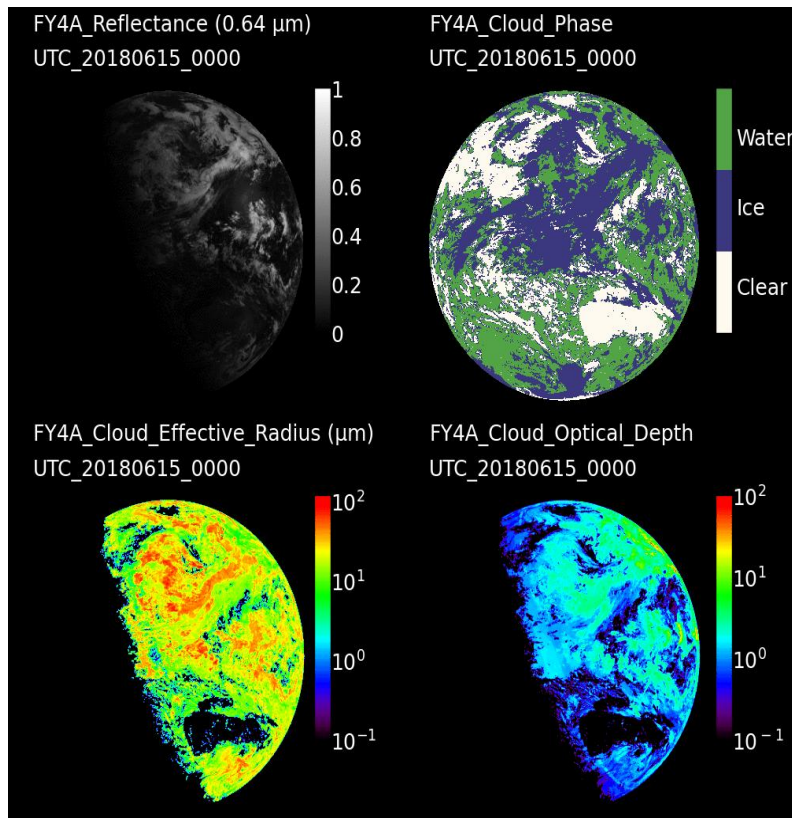
The algorithms provide stable and robust retrievals
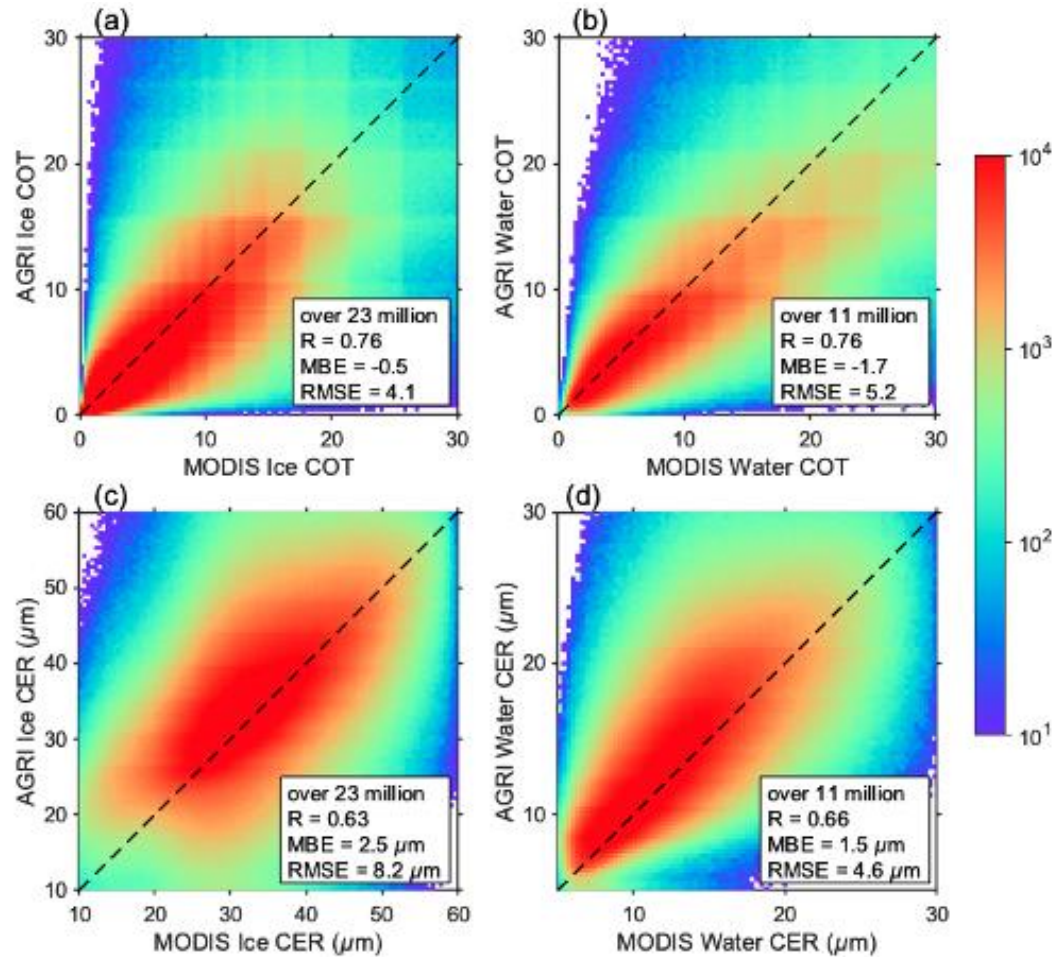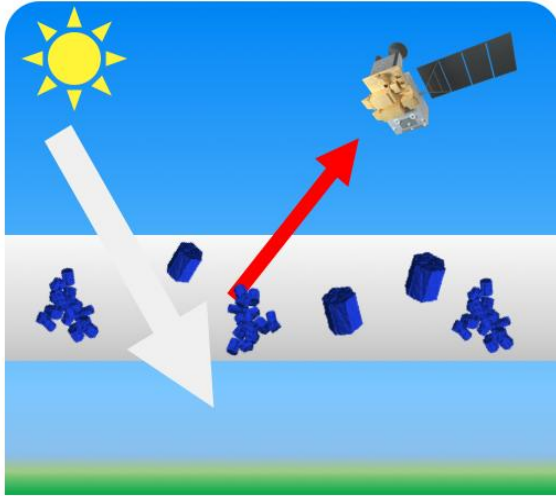
Cloud optical and microphysical properties for FY
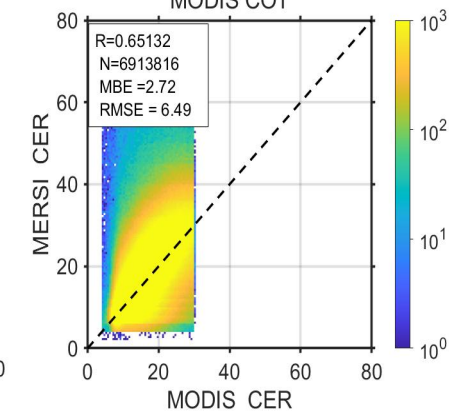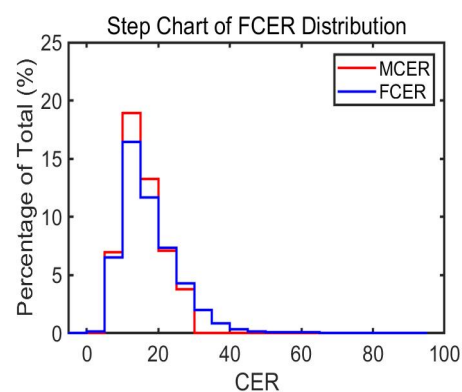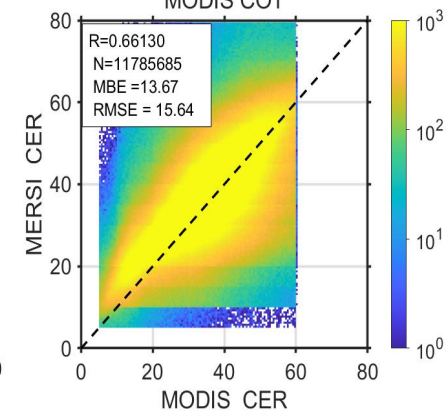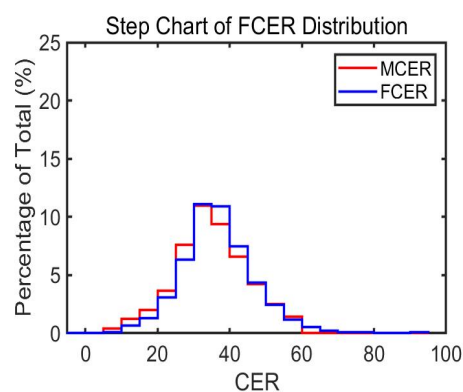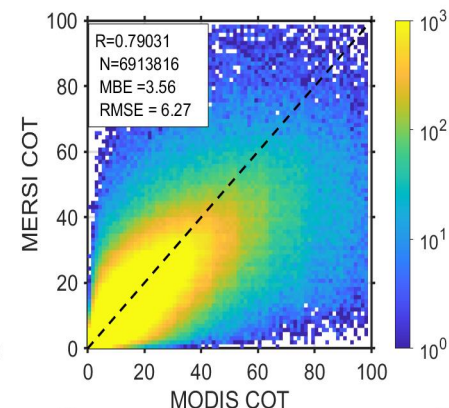
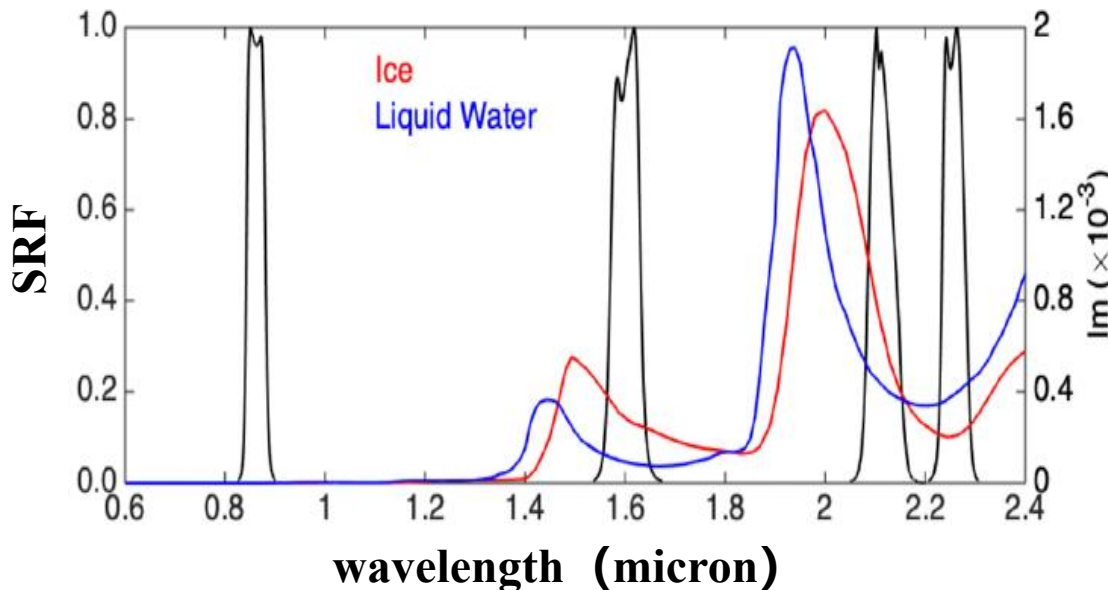# Limitations for current operational cloud retrievals

? ? ?

➤ **Single-layer cloud assumption**

➤ **Limited vertical structure information**

Can overlapping cloud properties be extracted?

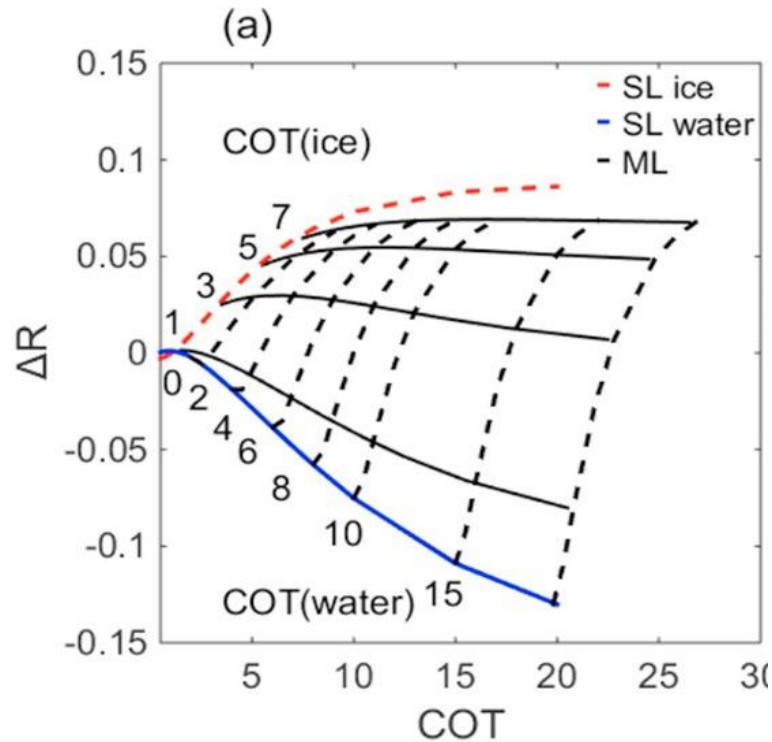
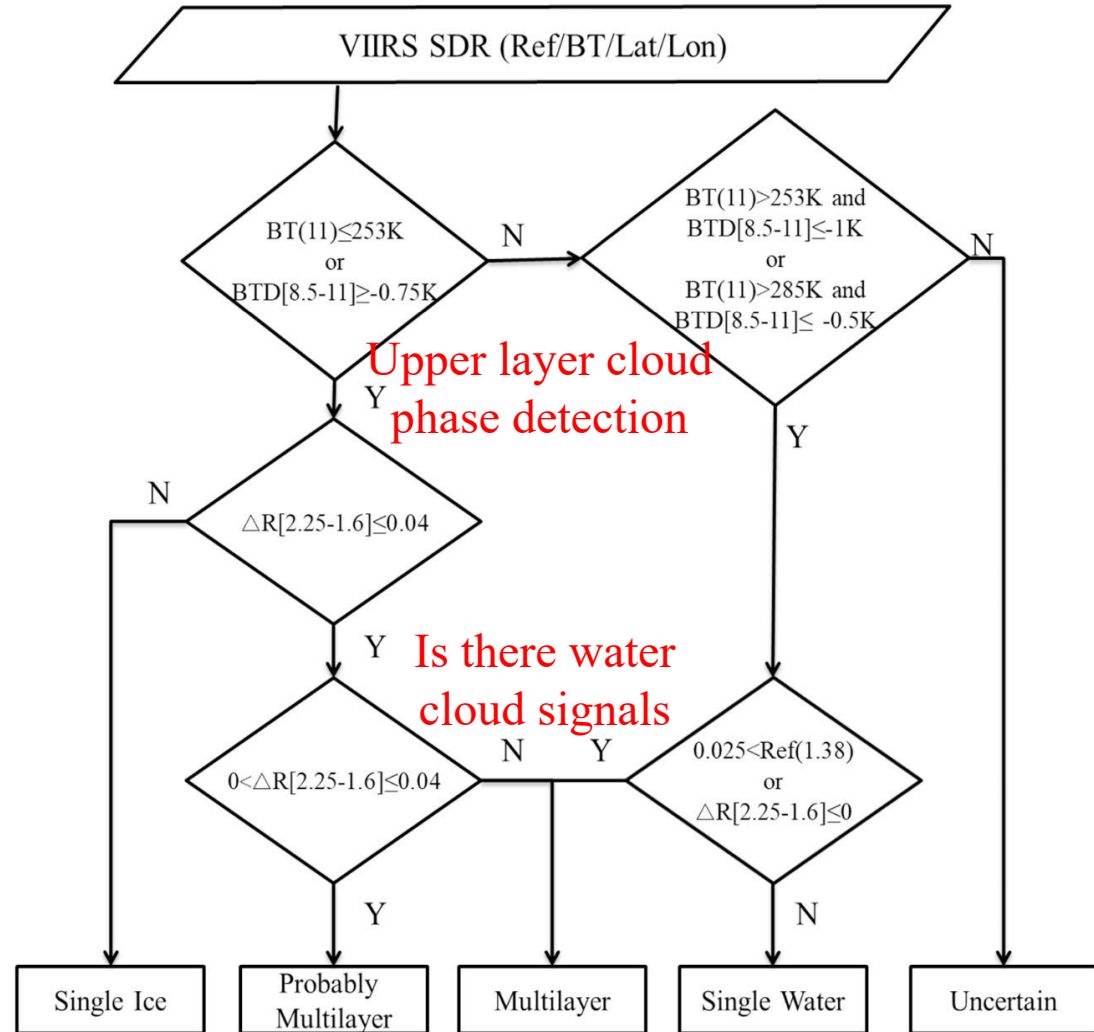- Typical overlapping cloud type: a lower water layer beneath an upper ice layer

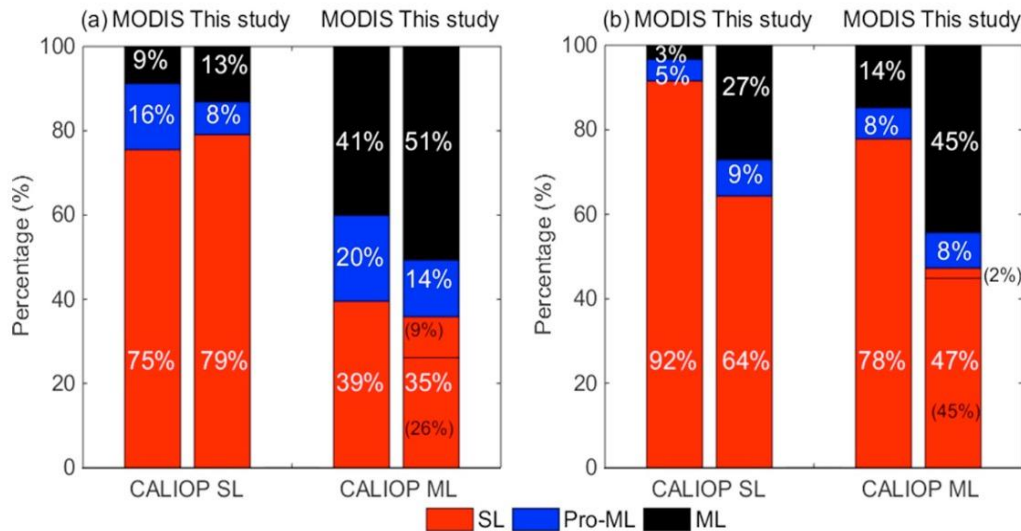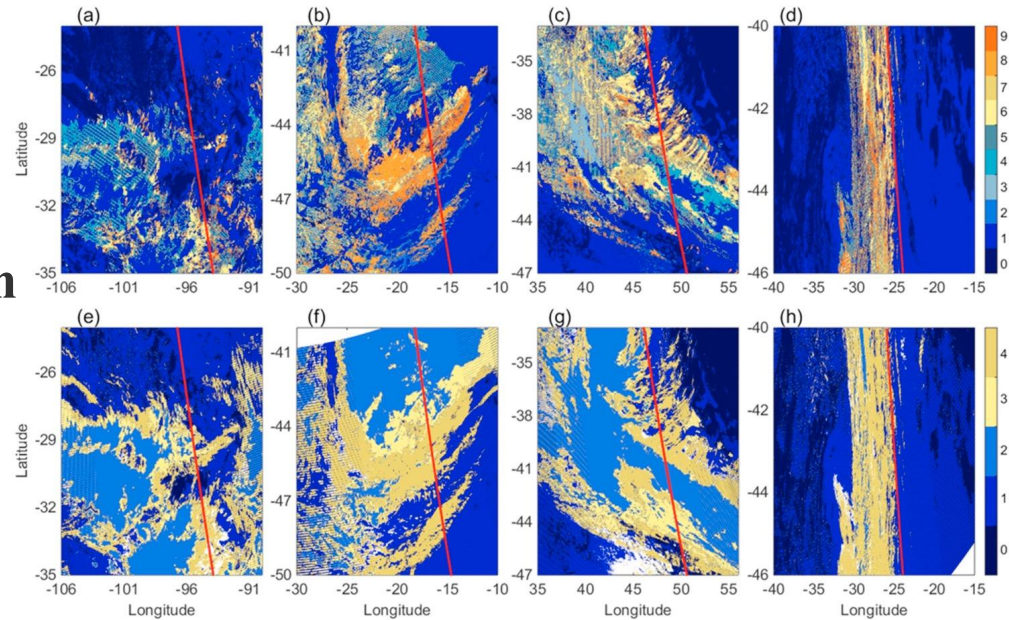- Shortwave infrared channels are sensitive to cloud microphysical and phase properties

Wang, Liu* et al., RSE, 2018

Overlapping cloud detection

(a)

$$\triangle R = R@2.25 - R@1.61$$

VIIRS SDR (Ref/BT/Lat/Lon)

BT(11)≤253K or BTD[8.5-11]≥-0.75K

BT(11)>253K and BTD[8.5-11]≤-1K or BT(11)>285K and BTD[8.5-11]≤ -0.5K

Upper layer cloud phase detection

△R[2.25-1.6]≤0.04

Is there water cloud signals

0<△R[2.25-1.6]≤0.04

0.025<Ref(1.38) or △R[2.25-1.6]≤0

Single Ice

Probably Multilayer

Multilayer

Single Water

Uncertain

Wang, Liu* et al., RSE, 2019

Overlapping cloud detection

Examples and comparison with MODIS results

Correctly detect about two-thirds of overlapping clouds

Wang, Liu* et al., RSE, 2019

Can overlapping cloud properties be extracted?

Signal to noise ratio (SNR) — to quantify the reflectance/BT sensitives of each channel to each overlapping cloud properties
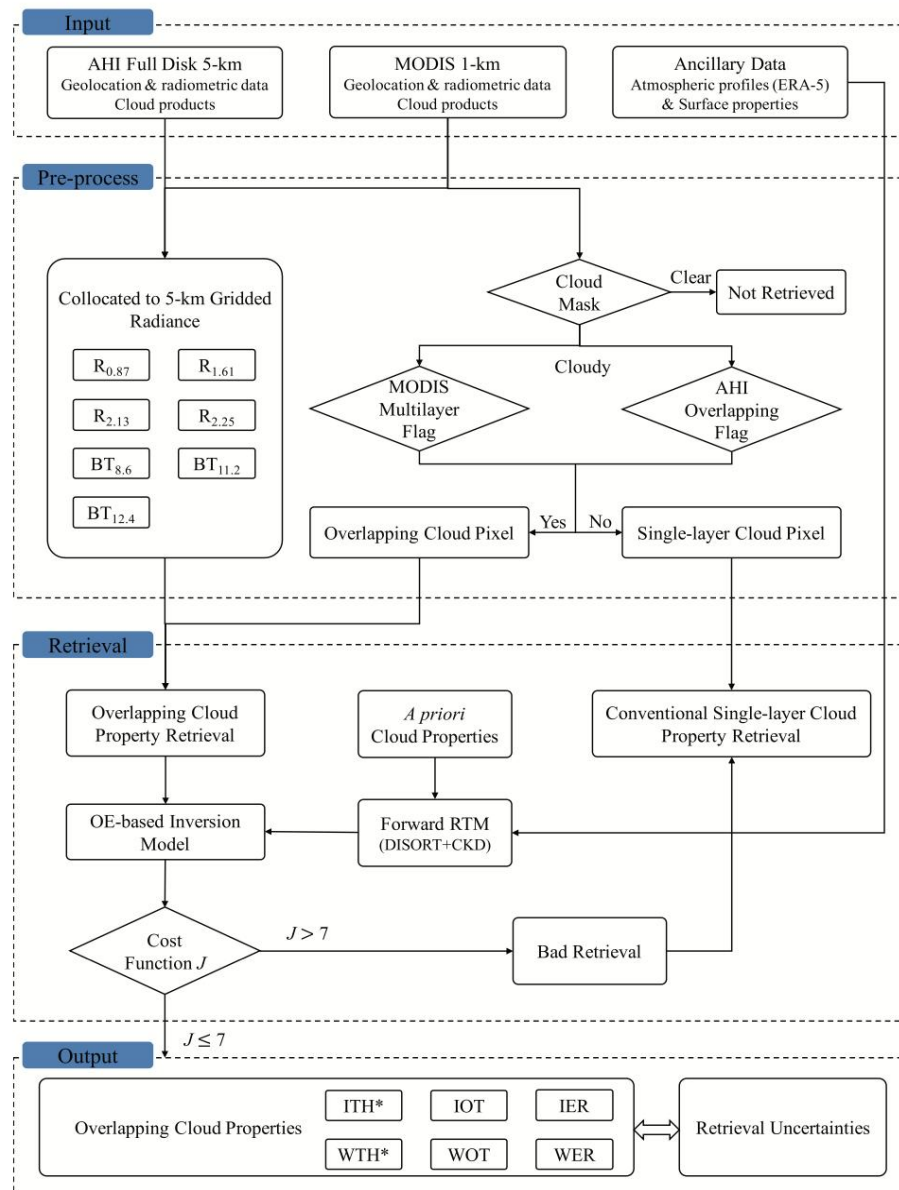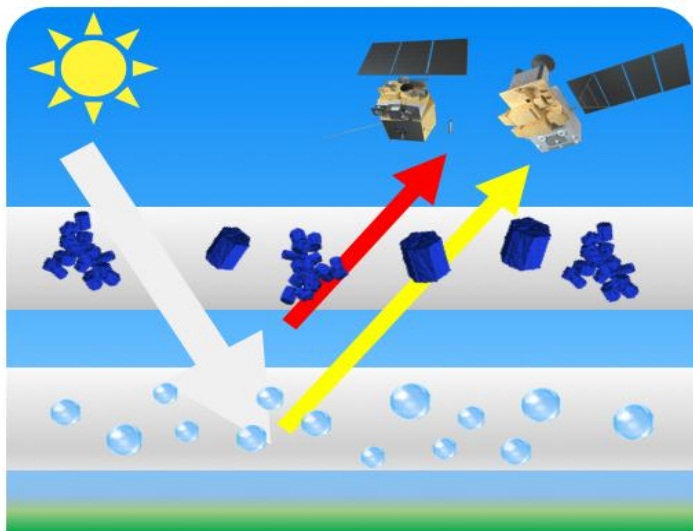
$$SNR = \frac{\Delta I_i}{\Delta x \cdot \varepsilon_i}$$

Changes on radiance

Changes on cloud properties

Noise

Teng, Liu* et al., RSE, 2023
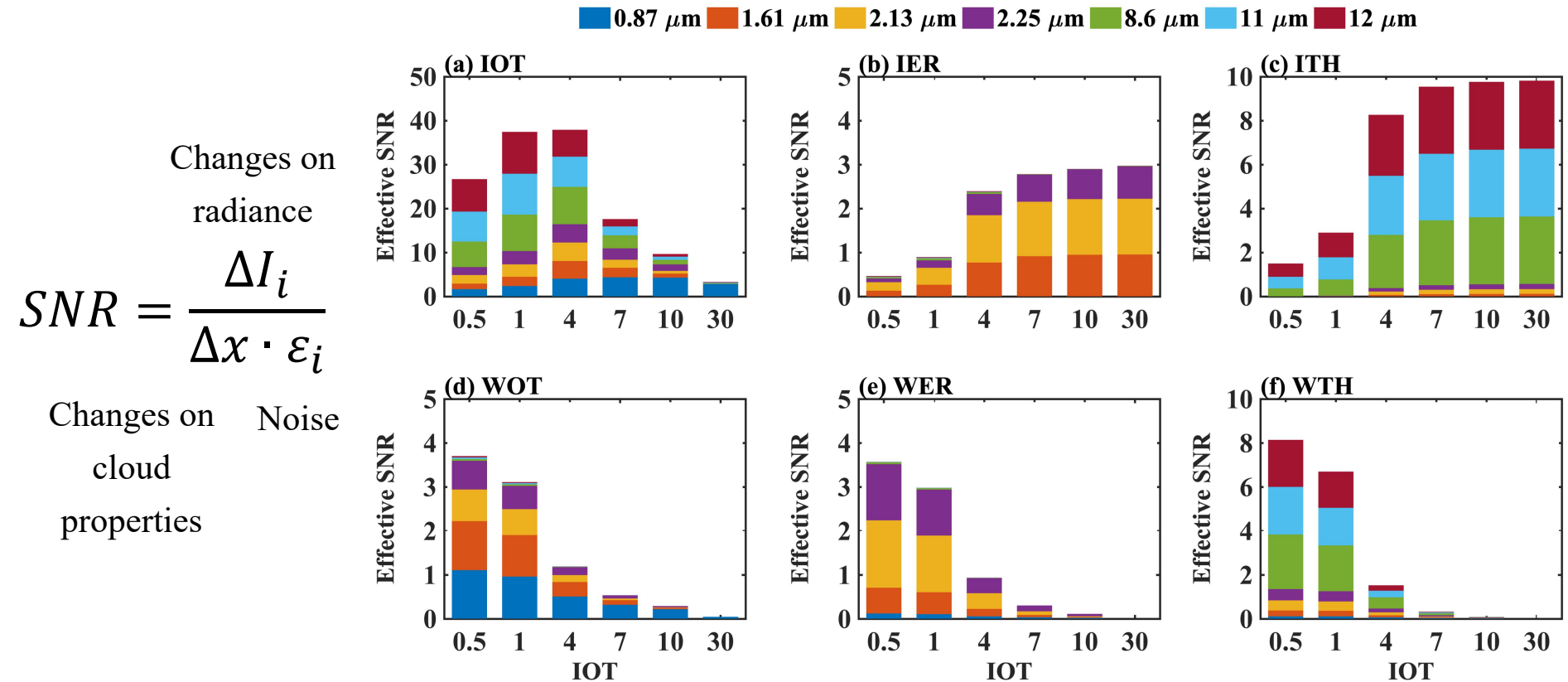
Can overlapping cloud properties be extracted?

➤ Conventional Method：

COT + **CER** = **2 variables**

➤ Our retrieval:

Upper Ice
Lower water
×
CTH
COT = **6 variables**
CER

Input

AHI Full Disk 5-km
Geolocation & radiometric data
Cloud products

MODIS 1-km
Geolocation & radiometric data
Cloud products

Ancillary Data
Atmospheric profiles (ERA-5)
& Surface properties

Pre-process

Collocated to 5-km Gridded Radiance

$R_{0.87}$	$R_{1.61}$
$R_{2.13}$	$R_{2.25}$
$BT_{8.6}$	$BT_{11.2}$
$BT_{12.4}$	

Cloud Mask — Clear — Not Retrieved

Cloudy

MODIS Multilayer Flag

AHI Overlapping Flag

Overlapping Cloud Pixel ← Yes | No → Single-layer Cloud Pixel

Retrieval

Overlapping Cloud Property Retrieval

A priori Cloud Properties

Conventional Single-layer Cloud Property Retrieval

OE-based Inversion Model

Forward RTM (DISORT+CKD)

Cost Function J — $J > 7$ — Bad Retrieval

$J \leq 7$

Output

Overlapping Cloud Properties

| ITH* | IOT | IER |
| WTH* | WOT | WER |

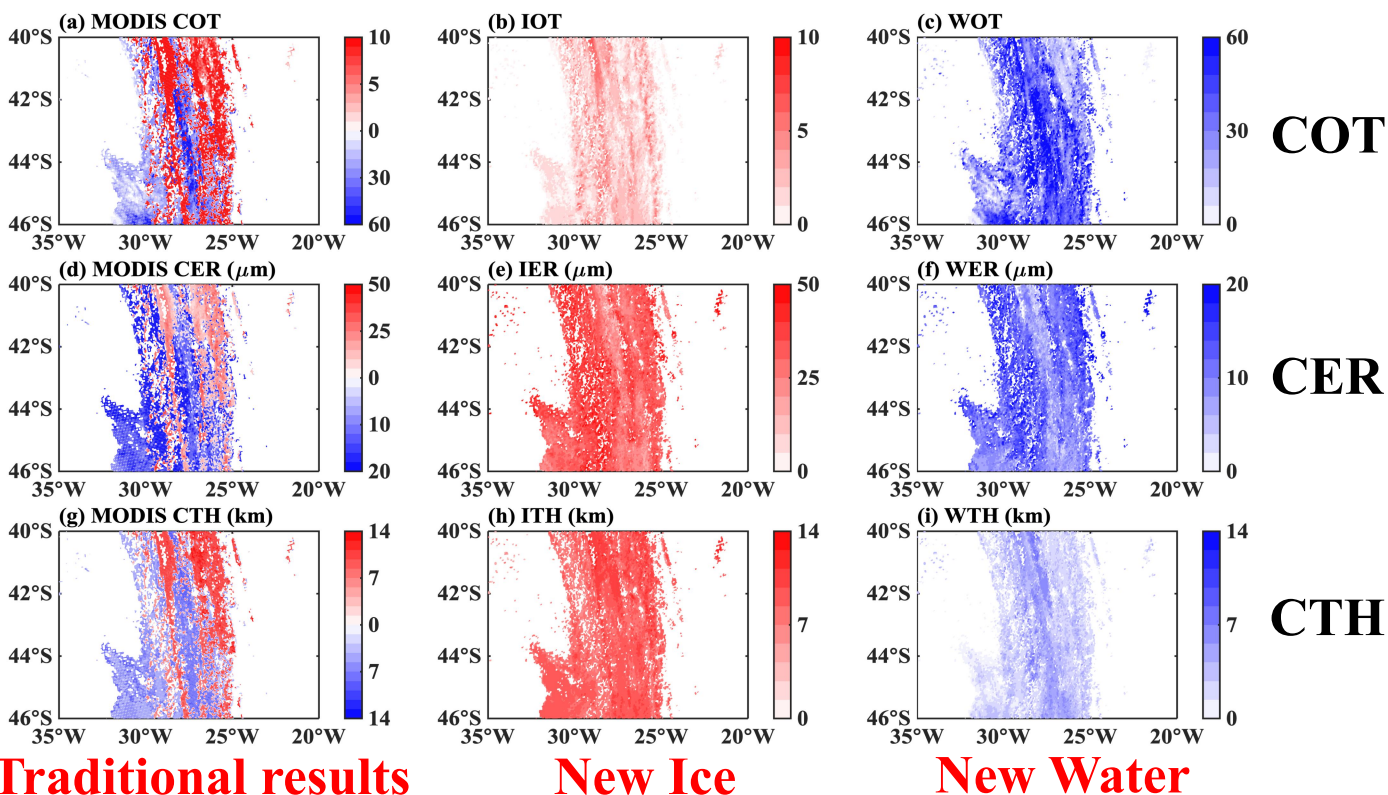Retrieval Uncertainties

Teng, Liu* et al., RSE, 2023

YES! Overlapping cloud properties can be extracted

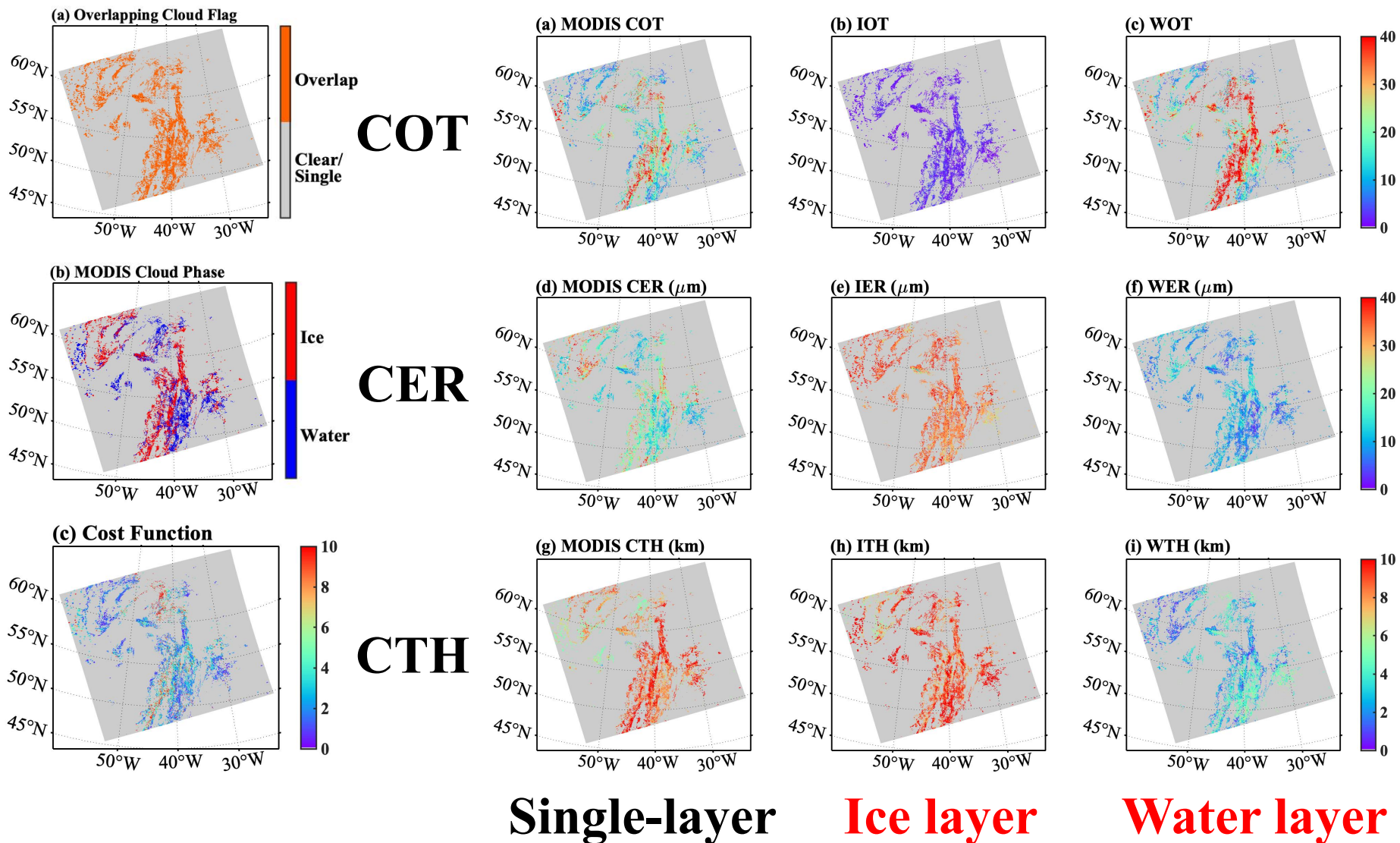Over 75% overlapping cloud pixels are successfully retrieved
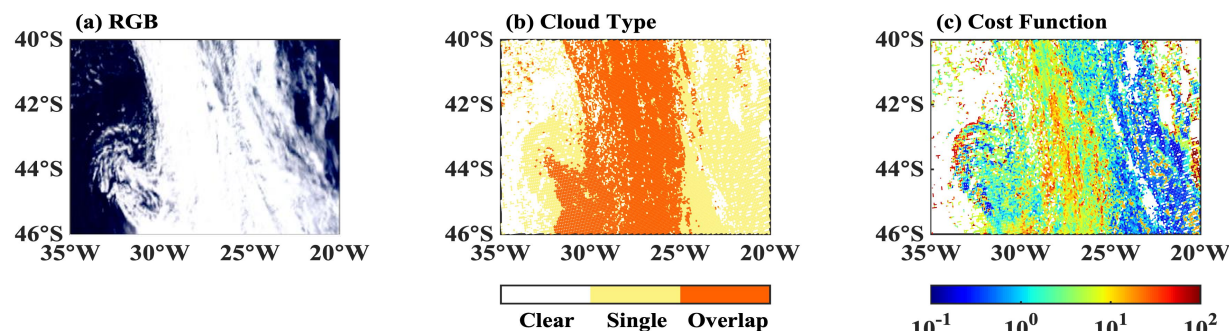
Significant overestimation of ice COT

Unrealistic ice or water CER

Traditional CTHs are mostly between the upper ice and lower water ones

(a) RGB

(b) Cloud Type

Clear   Single   Overlap

(c) Cost Function

10^{-1} 10^{0} 10^{1} 10^{2}

(a) MODIS COT

(b) IOT

(c) WOT   **COT**

(d) MODIS CER (μm)

(e) IER (μm)

(f) WER (μm)   **CER**

(g) MODIS CTH (km)

(h) ITH (km)

(i) WTH (km)   **CTH**

Traditional results   **New Ice**   **New Water**

Teng, Liu* et al., GRL, 2020

YES! Overlapping cloud properties can be extracted
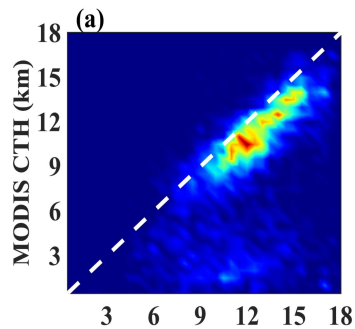
YES! Overlapping cloud properties can be extracted
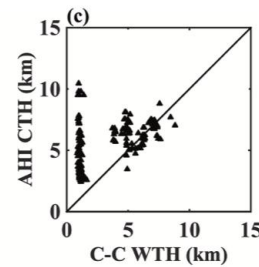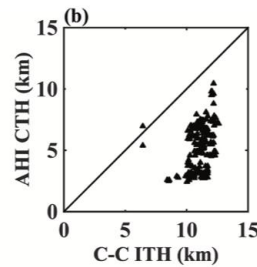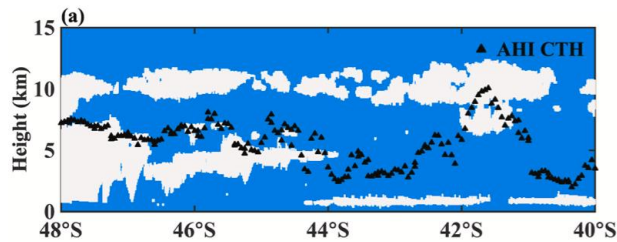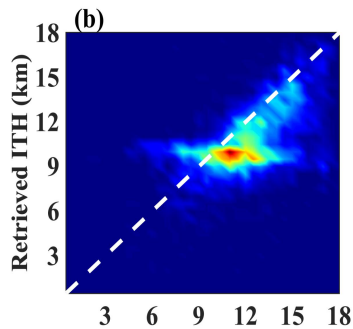

➤ Single layer retrieval results
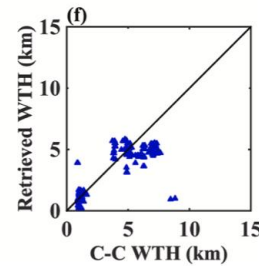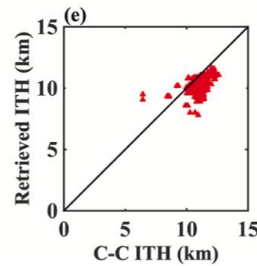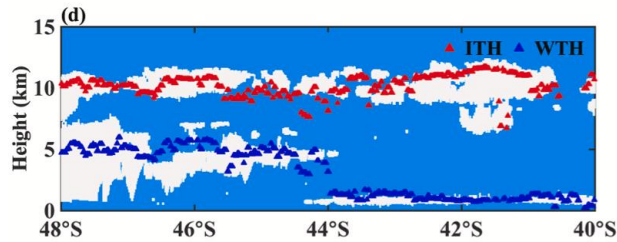
➤ Overlapping retrieval results
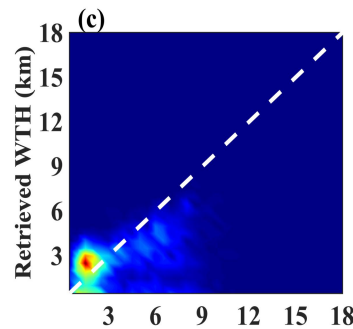
Long-term statistics

-2.89 km

-1.36 km

-1.21 km

Conventional method

New method ice layer

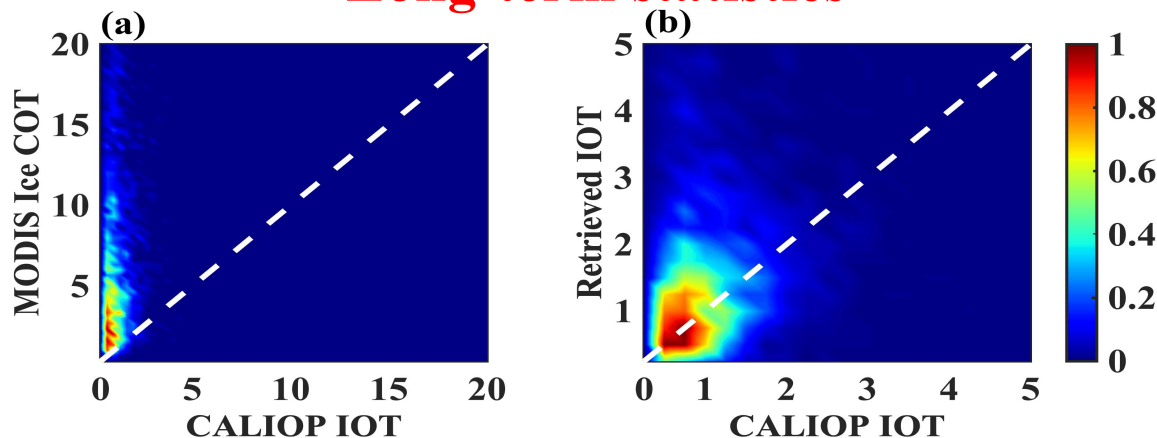**New method water layer**
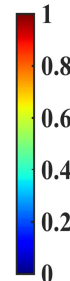
Mean absolute bias is reduced by ~1.5 km

Teng, Liu* et al., RSE, 2023

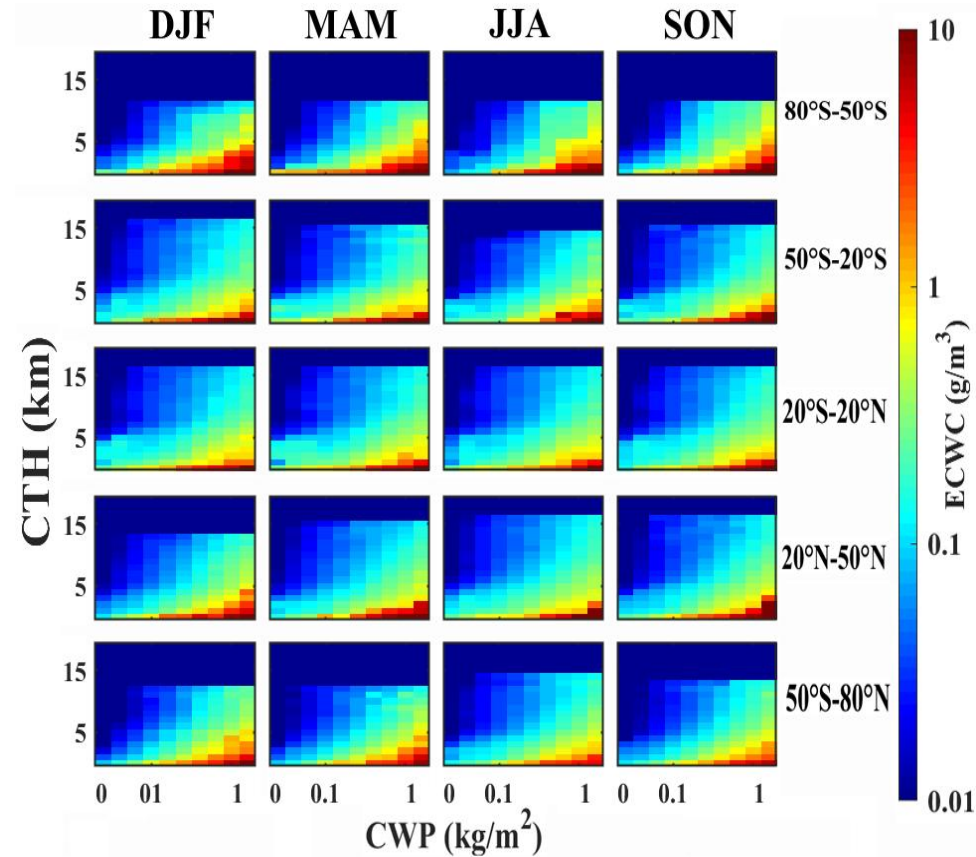# YES! Overlapping cloud properties can be extracted

Comparison of upper ice COT

Long-term statistics

Conventional method
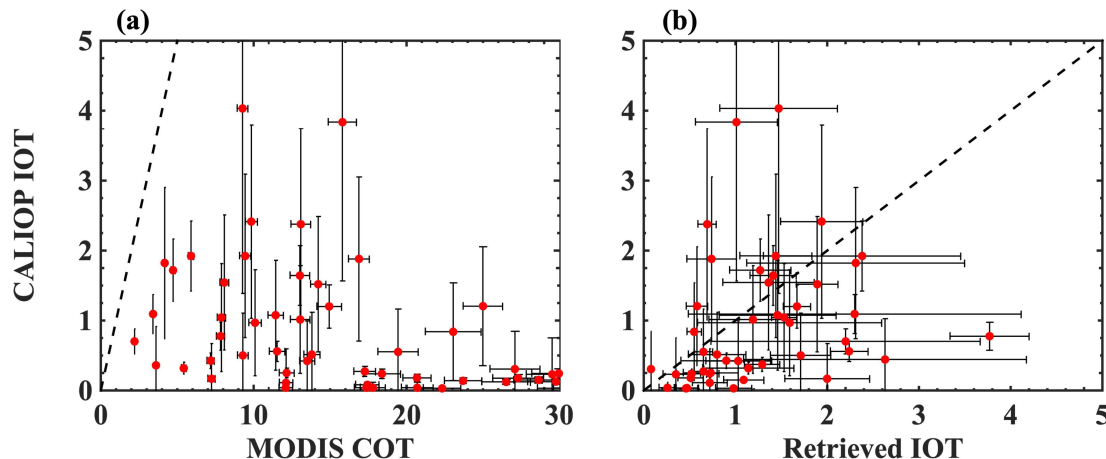
New method

➤ **Our retrievals show closer agreement with active remote sensing results**

Teng, Liu* et al., RSE, 2023

How about cloud base height?

CALIPSO CloudSat MODIS

Cloud water content & thickness ? ? ?
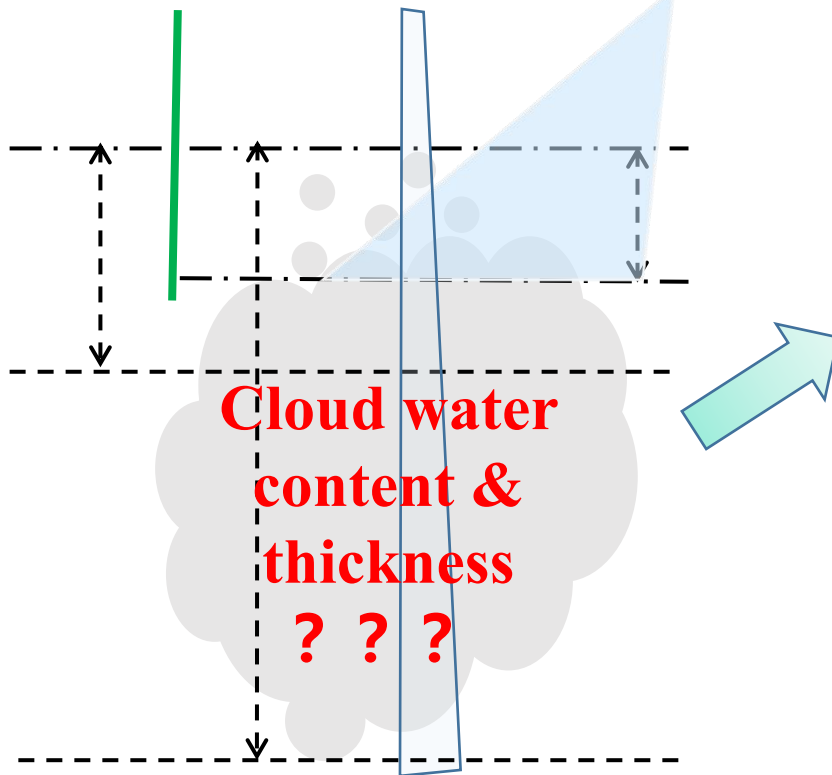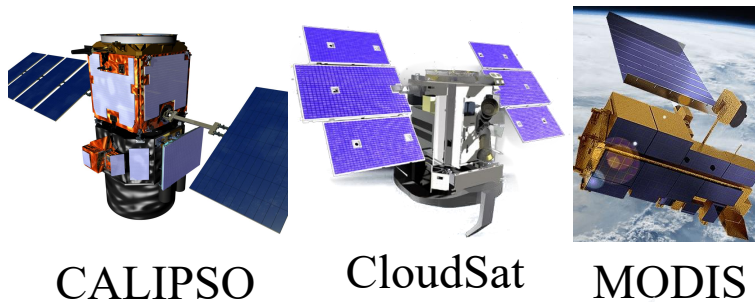
Cloud water content table for different regions and different seasons

Tan, Liu* et al., RSE, 2023

Cloud base height retrievals

Tan, Liu* et al., RSE, 2023
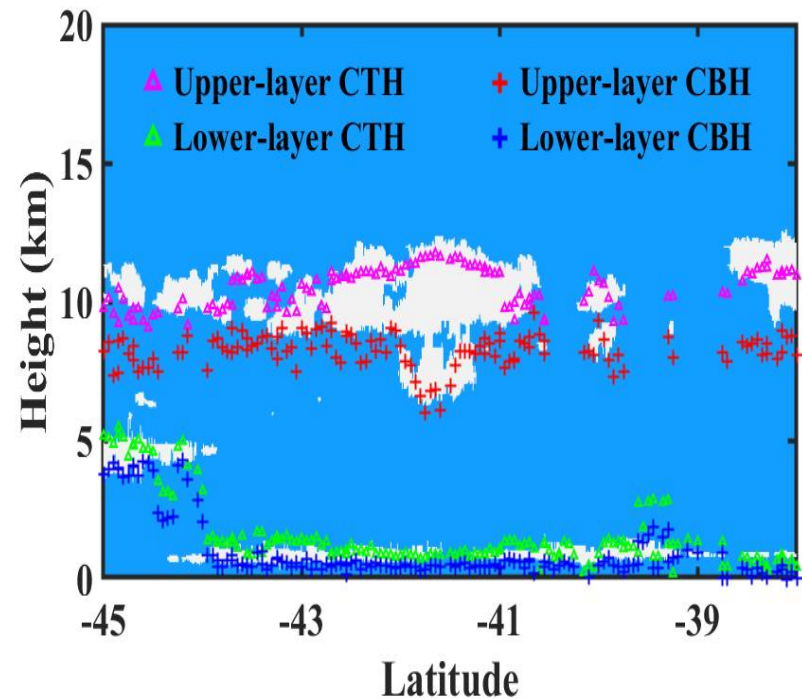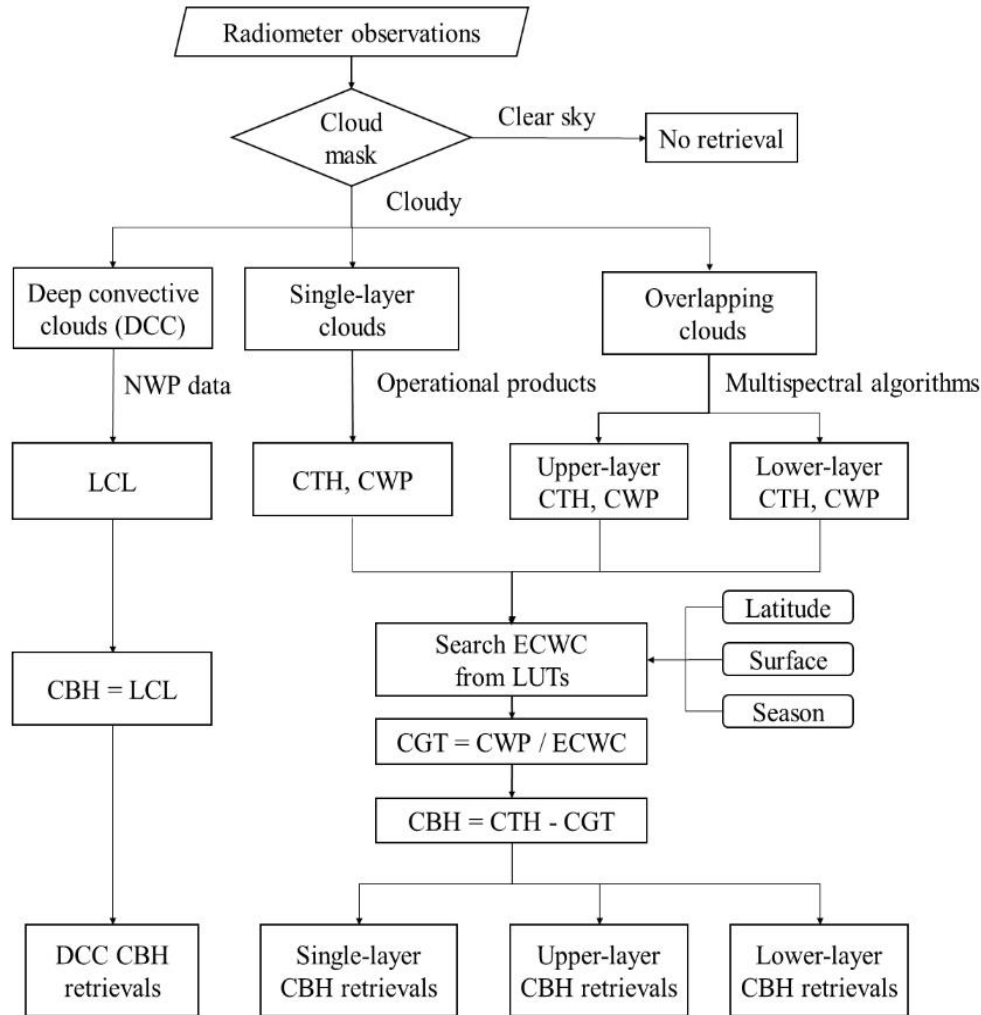
Cloud base height retrievals

	CTH			CGT			CBH		
	Mean bias (km)	STD. bias (km)	R^2	Mean bias (km)	STD. bias (km)	R^2	Mean bias (km)	STD. bias (km)	R^2
MODIS	−0.30	1.95	0.87	−0.36	2.41	0.83	0.11	1.93	0.87
AHI	−0.65	2.33	0.85	−0.45	2.35	0.81	−0.12	2.34	0.84
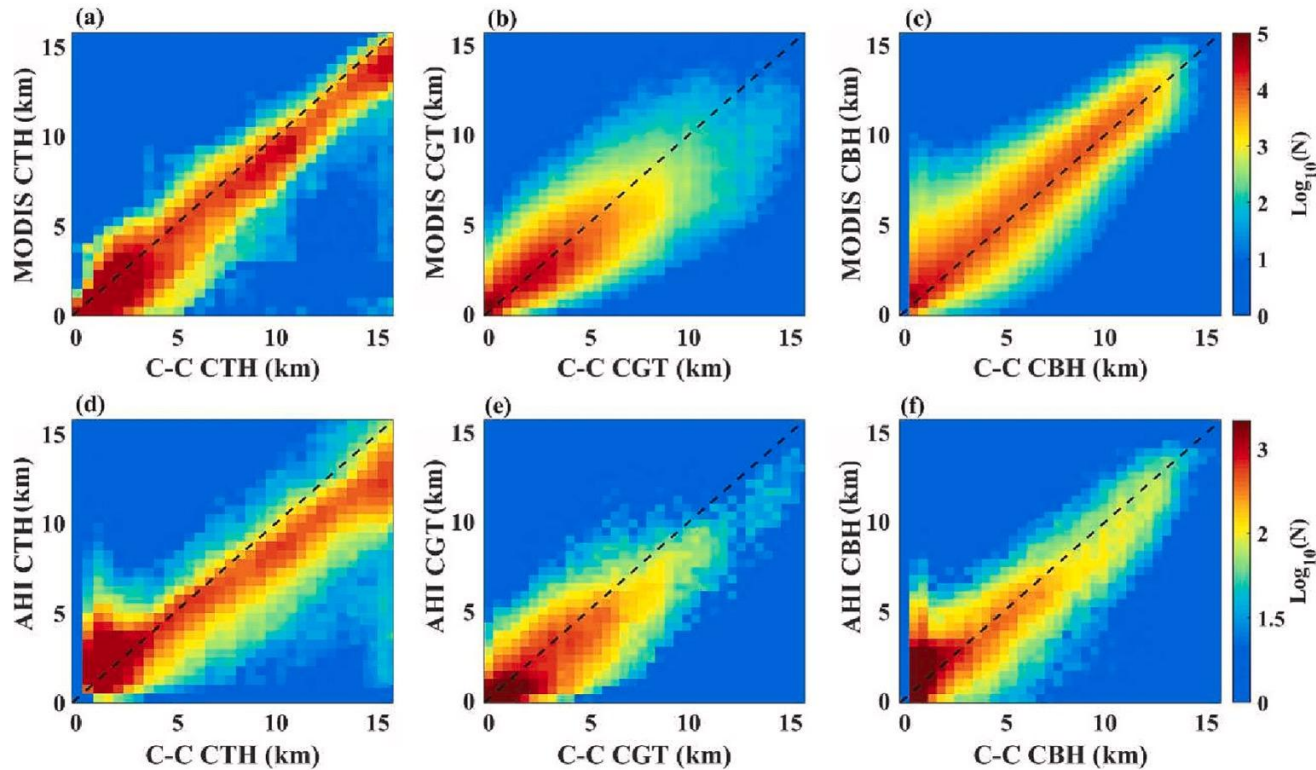
The CBH results may outperform the corresponding CTH results

Tan, Liu* et al., RSE, 2023

Passive spectral observations can provide cloud vertical structures
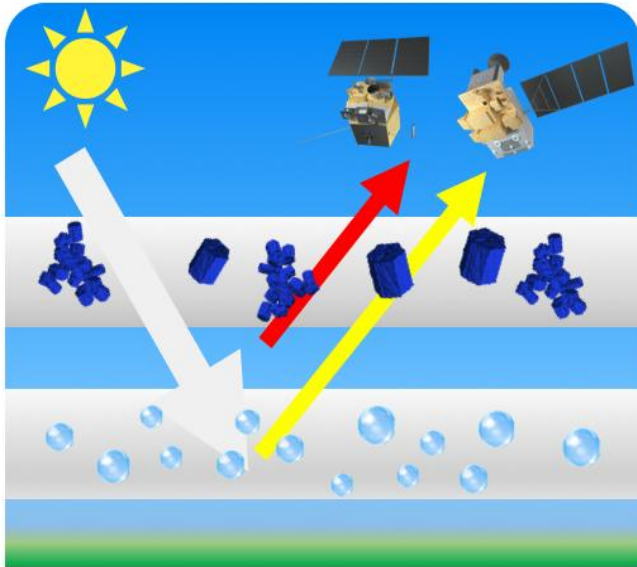
The multi-spectral observations can be used to extract properties of the upper ice and lower water clouds.

By combining passive and active statistics, cloud base heights are inferred.
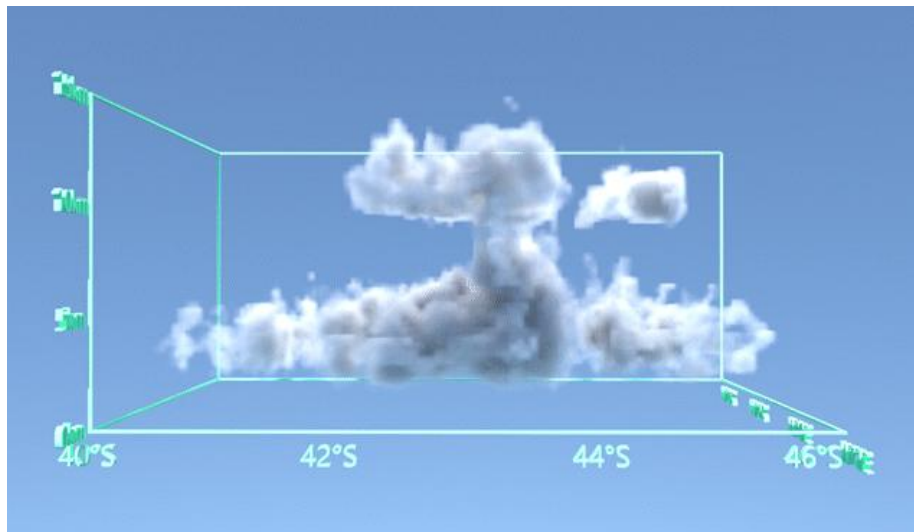
Teng, Liu* et al., GRL, 2020

Teng, Liu* et al., RSE, 2023

Conclusions

➢ Following fundamental ice cloud optical and radiative transfer models, we developed the conventional cloud optical and microphysical property retrieval algorithm for Fengyun spectral imager operational products;

➢ By using multi-sensor and multi-spectral observations, we developed overlapping cloud property retrieval algorithms to better infer cloud vertical structures;

➢ Newly designed satellite instruments and channels provide new opportunities for cloud property retrievals.

Thanks, and questions?