Scattering of ice clouds in Infrared forward RT models

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Outline

- Bulk scattering properties of ice clouds
  - What determines the bulk scattering properties of ice clouds?
  - What is our current understanding of those factors?
- The importance of scattering and a simple IR RT model for cloudy conditions
  - Is scattering important in IR RT models?
  - How is scattering treated in $I_{TOA}=(1-\varepsilon)I_{clr}+\varepsilon B(T_c)$; $\varepsilon=1-exp(-(1-\omega)\tau/\mu)$? Where/Why does it do a good/bad job?
- Rigorous fast IR RT model for cloudy conditions
  - Why the adding-doubling method is suitable for hyperspectral RT model?
  - FIRTM-AD (Fast Infrared RT model based on the adding-doubling principle)

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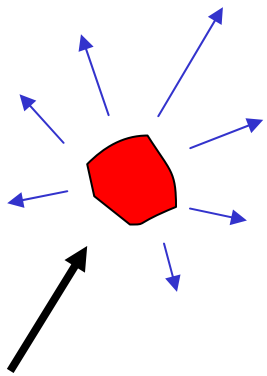
What controls the scattering of ice clouds?

- If a photon hits an ice crystal, how many things must we know about the ice crystal to determine the next state of the photon?

➢ How large is the ice crystal?
  - Particle size distribution

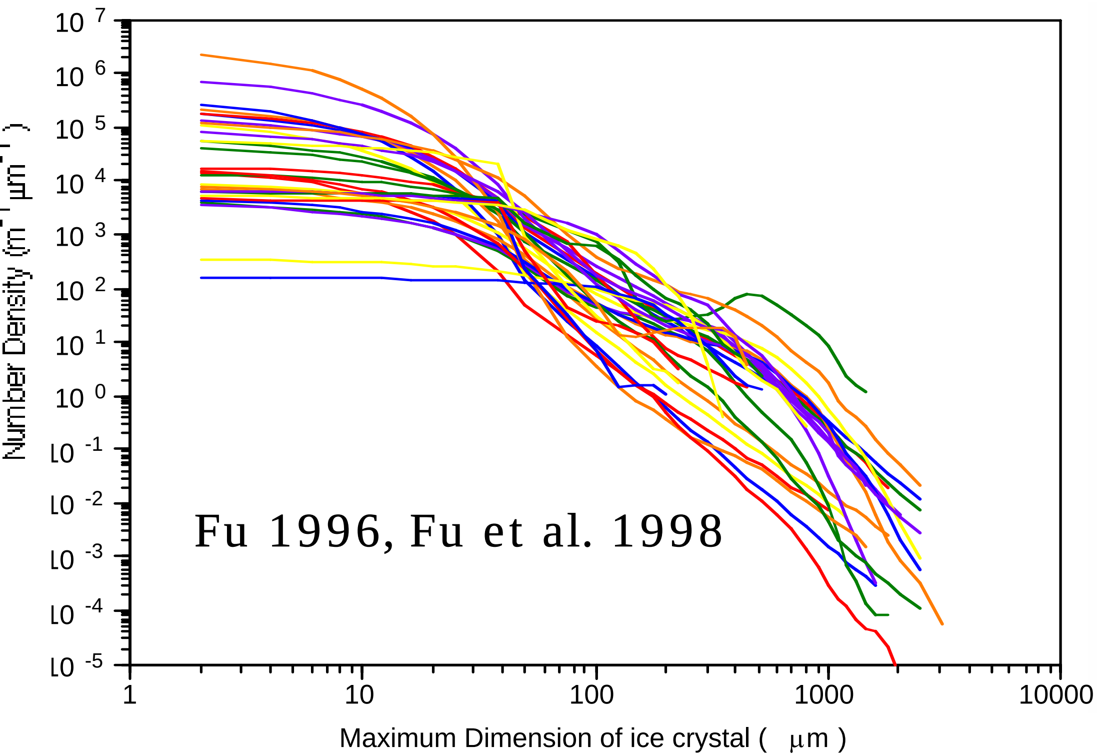
➢ What does the crystal look like?
  - Ice crystal habit/habit distribution

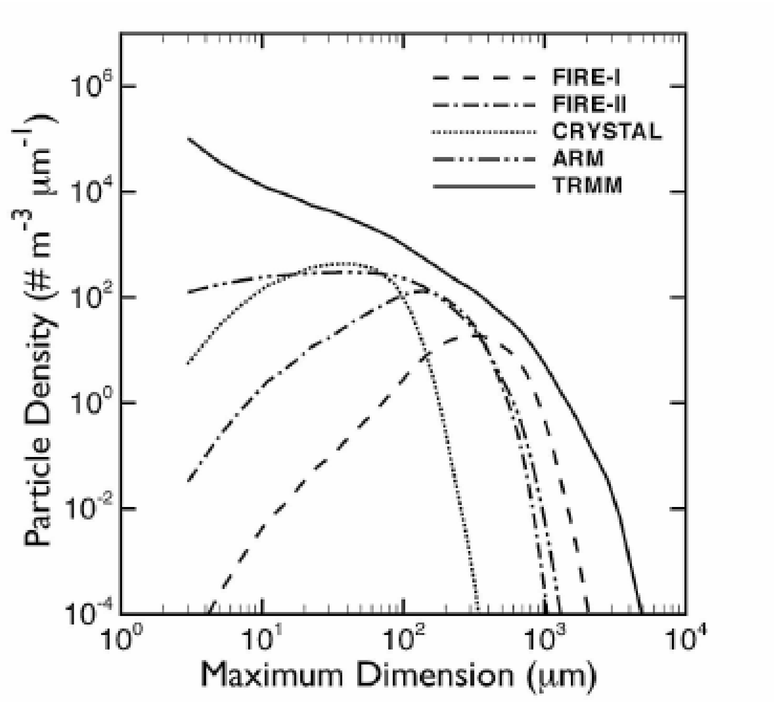


➢ How do ice crystals interact with the photon?
  - Single scattering properties of ice crystals

Particle Size Distribution (PSD)

How much chance for a photon to hit
An ice crystals with certain size?

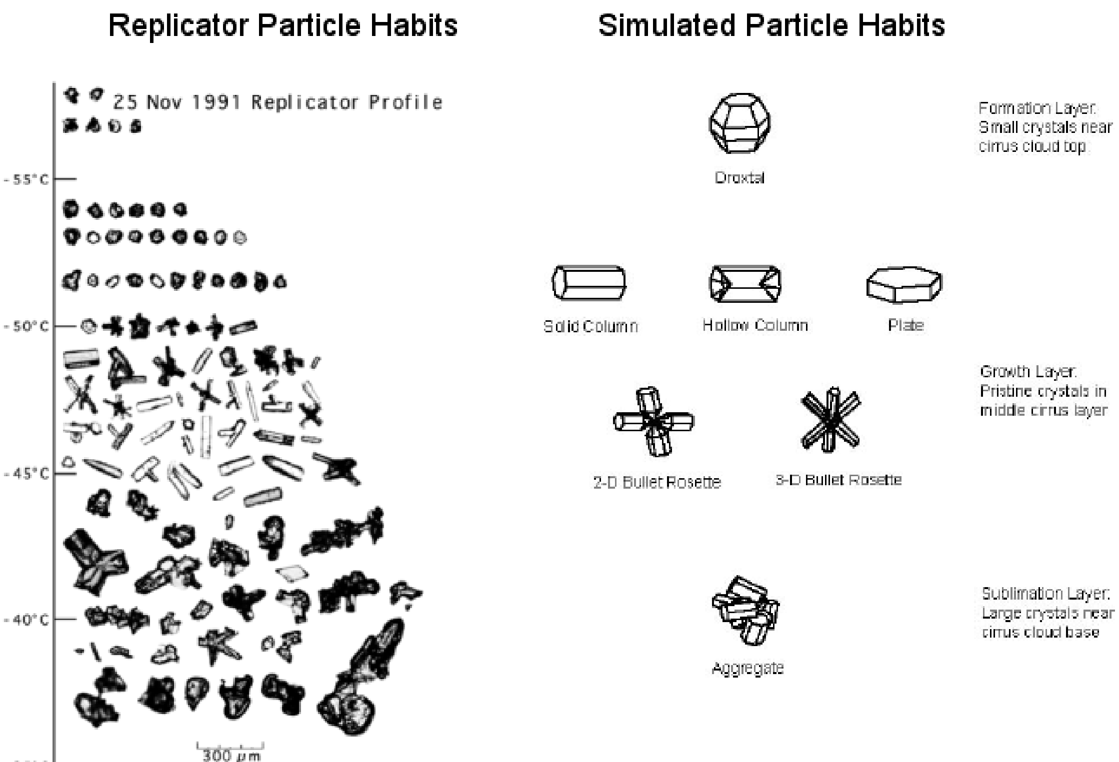




Baum et al. 2005

Ice crystal habits/shapes

- Ice crystal habits
  - In reality "*no two snowflakes are alike*"



http://www.ssec.wisc.edu/~baum/Cirrus/MidlatitudeCirrus.html

In practice, 6 habits are widely used

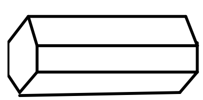
- Droxtal
- Hexagonal column
- Hollow column
- Hexagonal plate
- Bullet rosette
- Aggregate

Ice crystal habit distribution

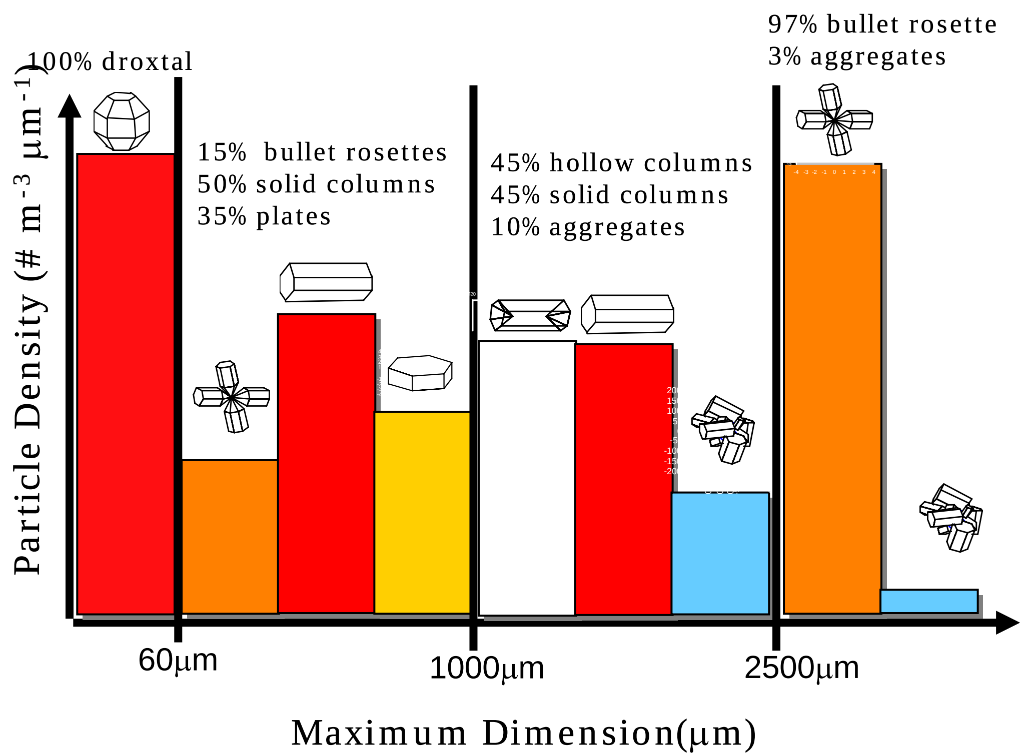
An on-going research topic

In current CAM3.0, all ice crystals are assumed to be solid hexagonal columns

100%

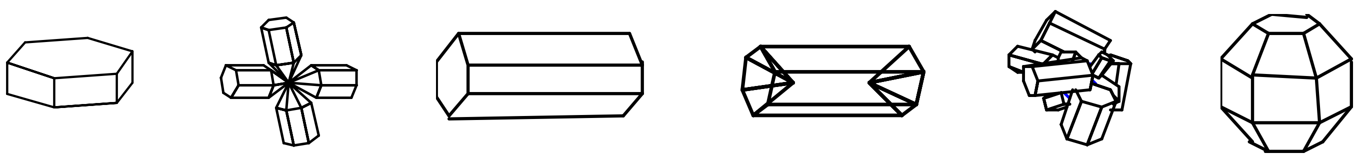


Baum et al. 2005



An extensive database of single-scattering properties of ice crystals in IR region

- Scattering properties
  - $Q_e \quad \varpi \quad P \quad g$
- The shape of ice crystals:



- Wavelength:
  - 49 wavelengths from 3.08- to 100 μm
- Size bin:
  - 45 Size bins from 2 μm to 10000 μm (in maximum dimension of ice crystal)

How do they work together?

Single scattering properties: the ice crystal actually has

Bulk scattering properties:the ice crystal would most likely have.

Single-scattering albedo

Probability of an ice crystal being hit

HID

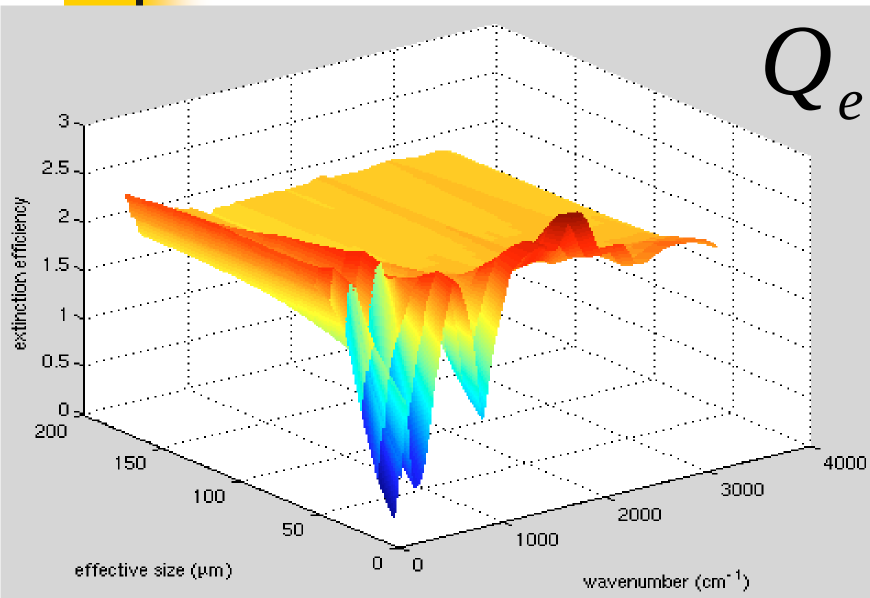
PSD

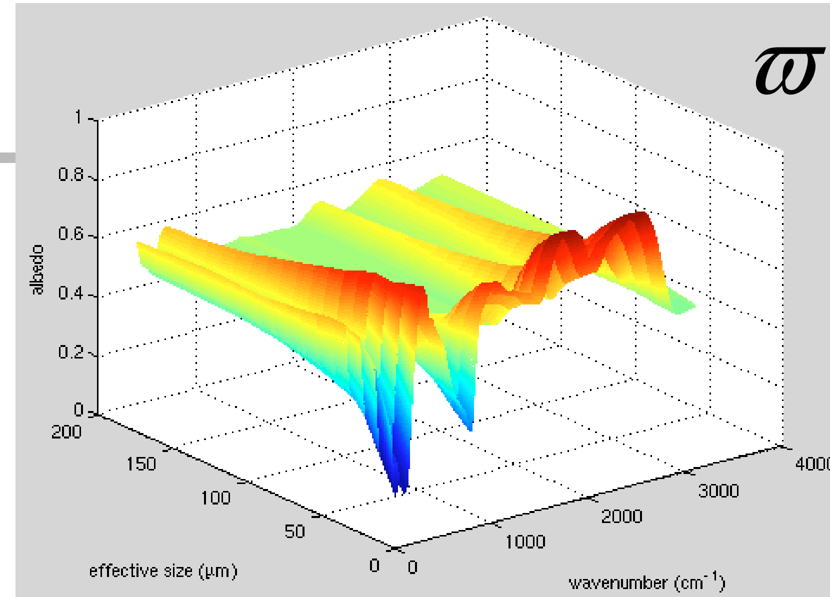
$$\langle \varpi \rangle = \frac{\int_0^\infty \left(\sum_i \varpi_i(D) Q_{e,i}(D) A_i(D) w(D) \right) n(D)\, dD}{\int_0^\infty \left(\sum_i Q_{e,i}(D) A_i(D) w(D) \right) n(D)\, dD}$$

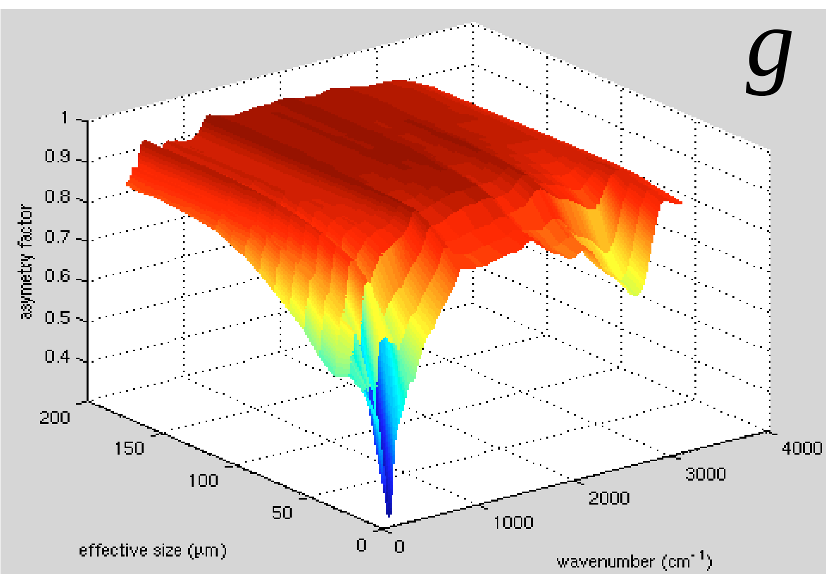
Cloud bulk albedo

Bulk scattering properties of ice clouds in IR region

(Baum et al. *J. Appl. Meteor.* 2005)







For ice cloud with large D_e ,under single-scattering conditions, about 50%of the incident energy is scattered and a large portion of the scattered Energy is concentrated in the "forward direction"

For ice cloud with small D_e, the situation is more complex

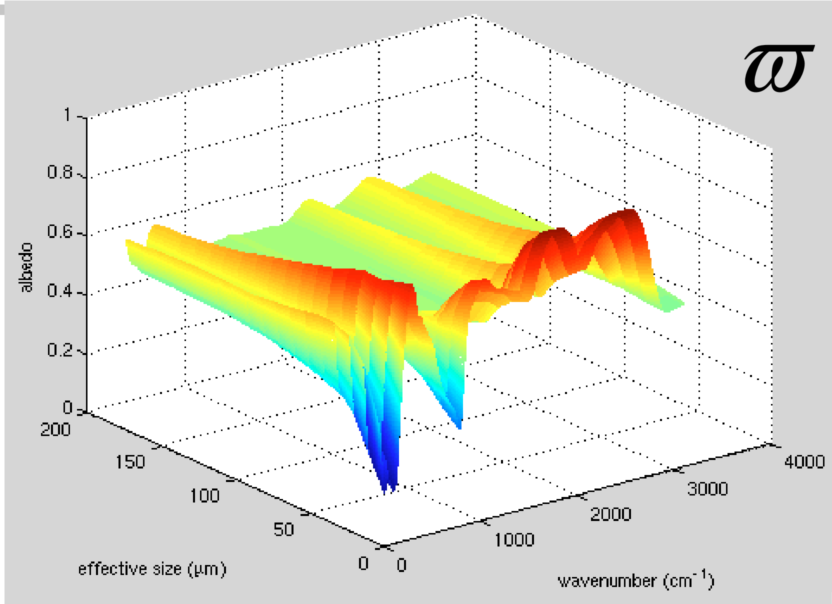
Summary of Part1

- PSD, HD and single-scattering properties together determine the bulk scattering properties of ice clouds.

- *In-situ* observations have substantially improved our understanding of the microphysics and bulk scattering properties of ice clouds

Is scattering important for IR RT computations?

IR RTE $\mu \frac{dI}{d\tau} = I - J$



source term $J = \varpi$(scattering

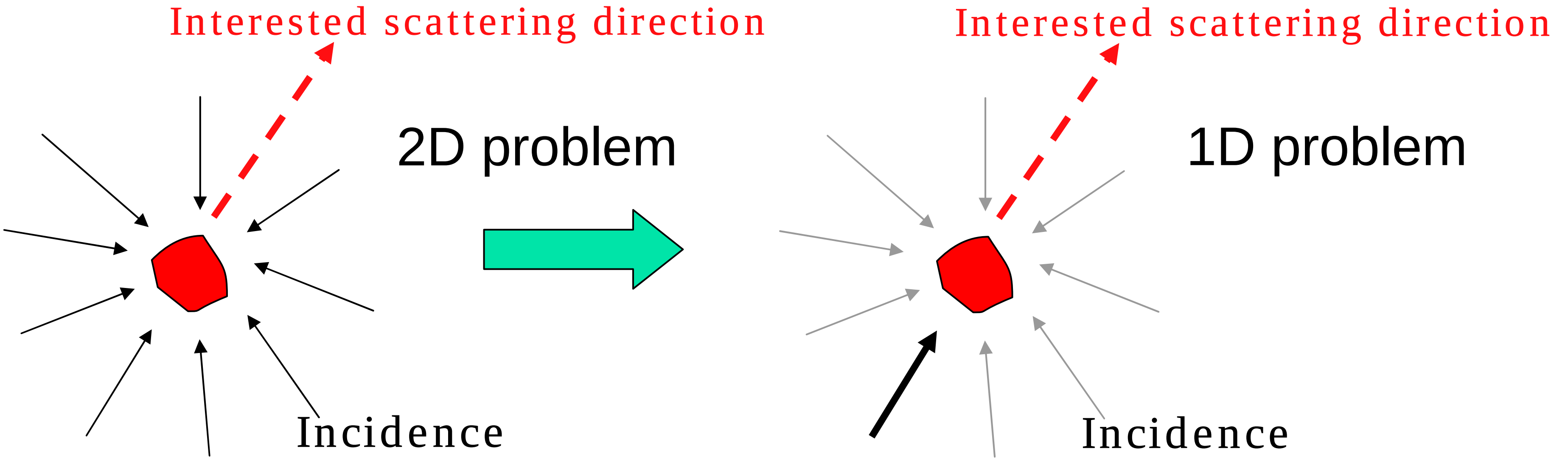
$\varpi \approx 0.5$ for most υ and D_e

T_s and T_{ats} are comparable to T_c

Scattering term has the same order of magnitude as emission.
It can NOT be ignored in IR RT!

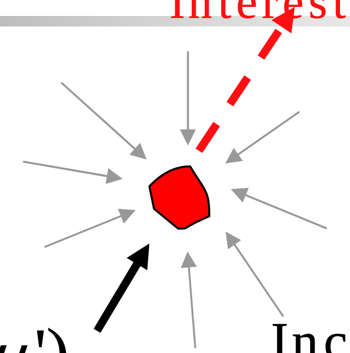
A simplification of the scattering in IR region

$$\varpi(scattering) = \varpi \frac{1}{2}\int_{-1}^{1} P(\mu,\mu')I(\mu')d\mu'$$



The scattering is concentrated mainly in the “forward direction”

A simplification of the scattering in IR region



From the RTE point of view,
The simplification means

$$P(\mu,\mu') = 2\delta(\mu-\mu')$$

$$\mu\frac{dI(\tau,\mu,\upsilon)}{d\tau} = I(\tau,\mu,\upsilon) - \varpi I(\tau,\mu,\upsilon) - (1-\varpi)B[T(\tau)]$$

For a homogenous and isothermal cloud layer with τ^*

$$I_{top}^{\uparrow} = (1-\varepsilon)I_{base}^{\uparrow} + \varepsilon B(T_c)$$

$$\varepsilon = 1 - \exp\left[-(1-\varpi)\tau^* / \mu\right]$$

Isn’t it familiar!

A simple IR RT model for cloudy conditions

– If the atmosphere above an ice clouds can be ignored

– If an ice cloud layer is homogenous and isothermal

$$I_{TOA} = (1-\varepsilon)I_{clr} + \varepsilon B(T_c)$$

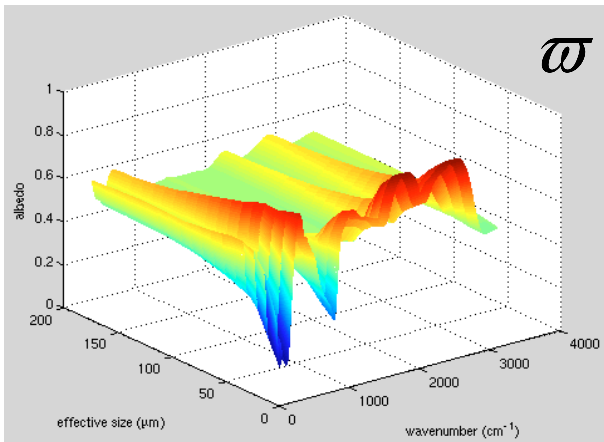
$$\varepsilon = 1 - \exp\left[-(1-\varpi)\tau / \mu\right]$$

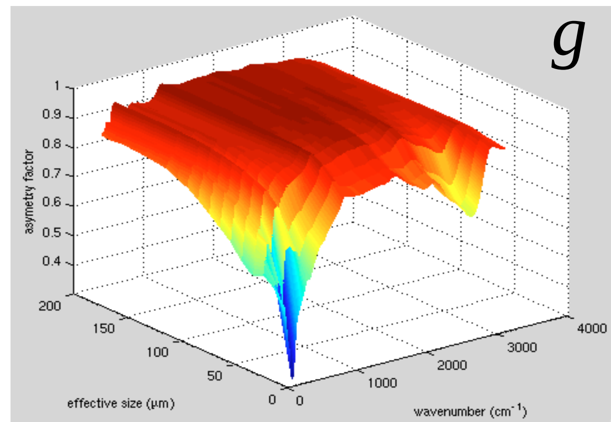
It is NOT because scattering is ignored(or non-scattering) but a result of the "forward-scattering"simplification

Problems

$$I_{TOA} = (1-\varepsilon)I_{clr} + \varepsilon B(T_c)$$

$$\varepsilon = 1 - \exp\left[-(1-\varpi)\tau / \mu\right]$$





forward-scattering $\rightarrow$ no cloud reflection

I_{TOA} tends to be overestimated

particularly for ice clouds with small D_e.

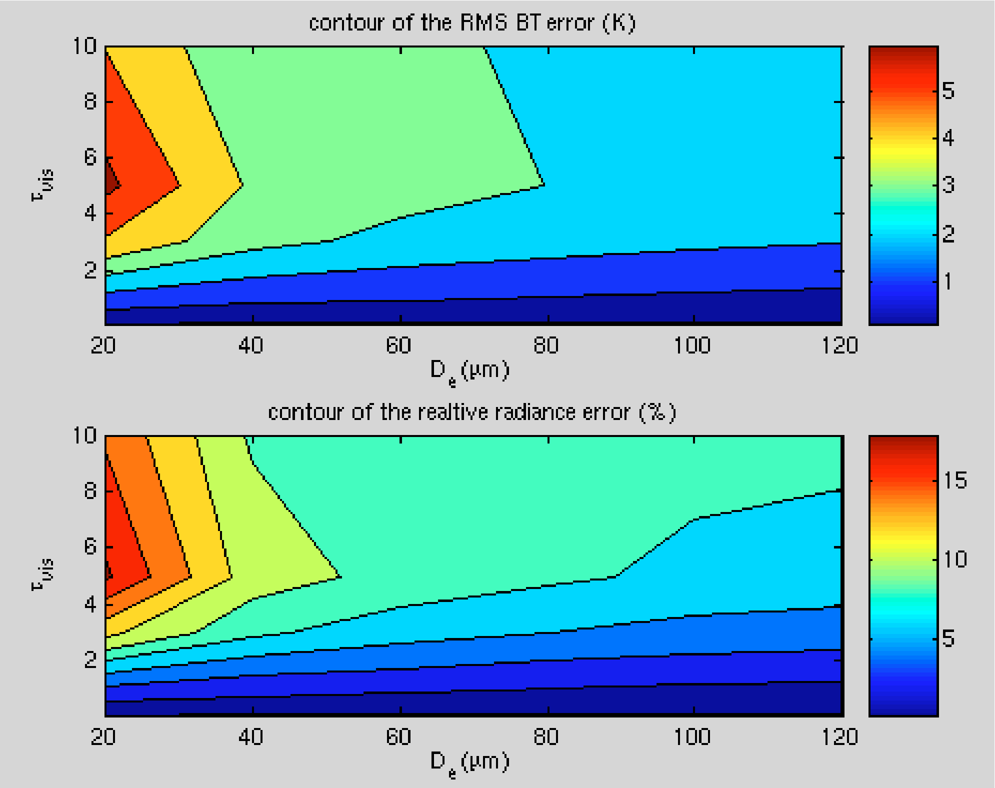
because g is relatively small and ϖ is realtively large when D_e is small.

Errors: How good is it?

No atmosphere above

ice cloud layer @ 12km
homogenous and isothermal

Lower atmosphere



RMS BT error generally >2K;~5K for small D_e
Relative radiance difference generally >8%;~15% for small D_e

Summary of Part2

- Scattering term in IR RTE has the same magnitude as the thermal emission term

- $I_{TOA} = (1-\varepsilon)I_{clr} + \varepsilon B(T_c)$ is a result of the "forward scattering" simplification. It does a reasonably good job, except for small D_e.

- To achieve higher accuracy, a rigorous RT model with is needed.

Challenge for RT model from hyperspectral remote sensing

- Speed
  - Thousands of wavelengths
  - global observations
- Accuracy
  - At least more accurate than $I_{TOA} = (1-\varepsilon)I_{clr} + \varepsilon B(T_c)$
  - Clear sky accuracy < 0.1K
- General applicability
  - Both TOA(space-borne) and user-defined-levels (air-borne & ground)
  - Multiple-layered and vertically inhomogenous clouds

Current fast IR RT models for cloudy conditions

- RTTOV
  - Eyre and Woolf(1988), Saunders et al.(1999)
- CHARTS
  - Moncet and Clough (1997)
- OSS
  - Moncet et al. (2001,2003)
- SHDOMPPDA
  - Evans (2006)
- FIRTM-1,2, and -AD
  - Wei et al. (2004), Niu et al. (2006), Zhang et al. (2006)
- Many others

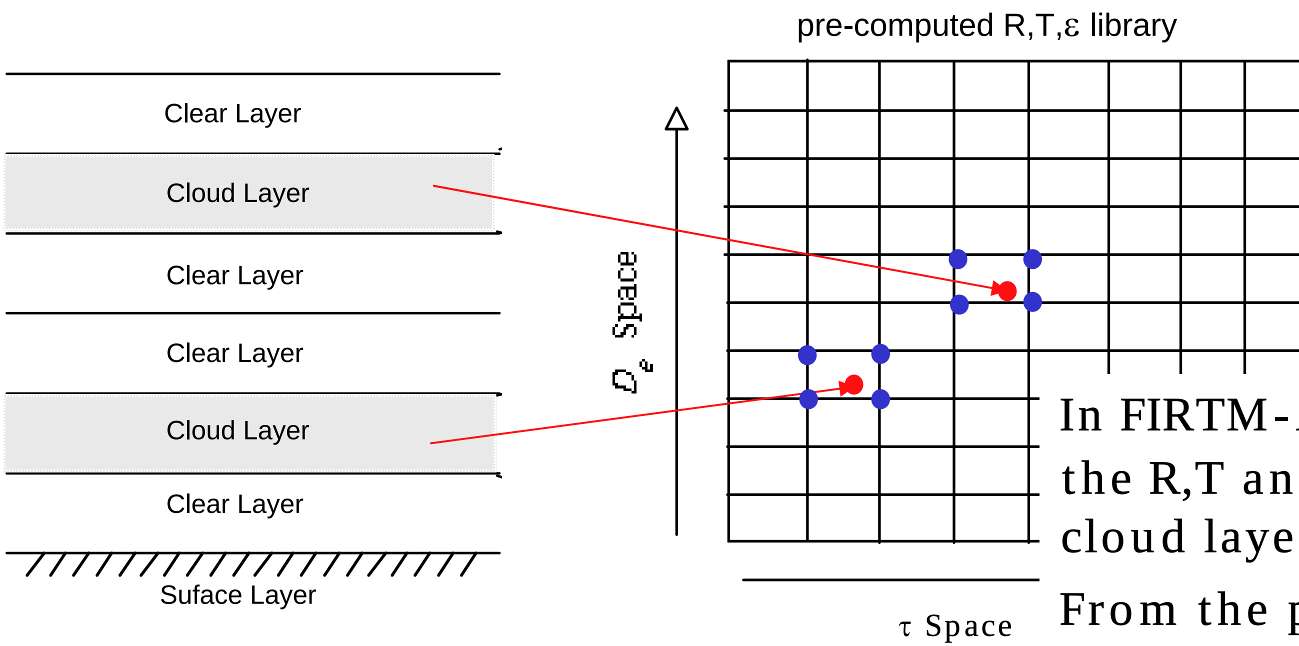
FIRTM-AD (Fast IR RT model based on adding-doubling principle)

why adding-doubling?

- Stable and accurate
- easy to understand
- Applicable to multiple-layered or vertically inhomogenous clouds
- Applicable to computations at different user-level

FIRTM-AD (Fast IR RT model based on adding-doubling principle)

- Why is it fast?
  - Extensive pre-computed look-up library
  - Efficient interpolation scheme



In FIRTM-AD,
the R,T and ε of the whole cloud layer is directly extracted
From the pre-computed library

FIRTM-AD errors

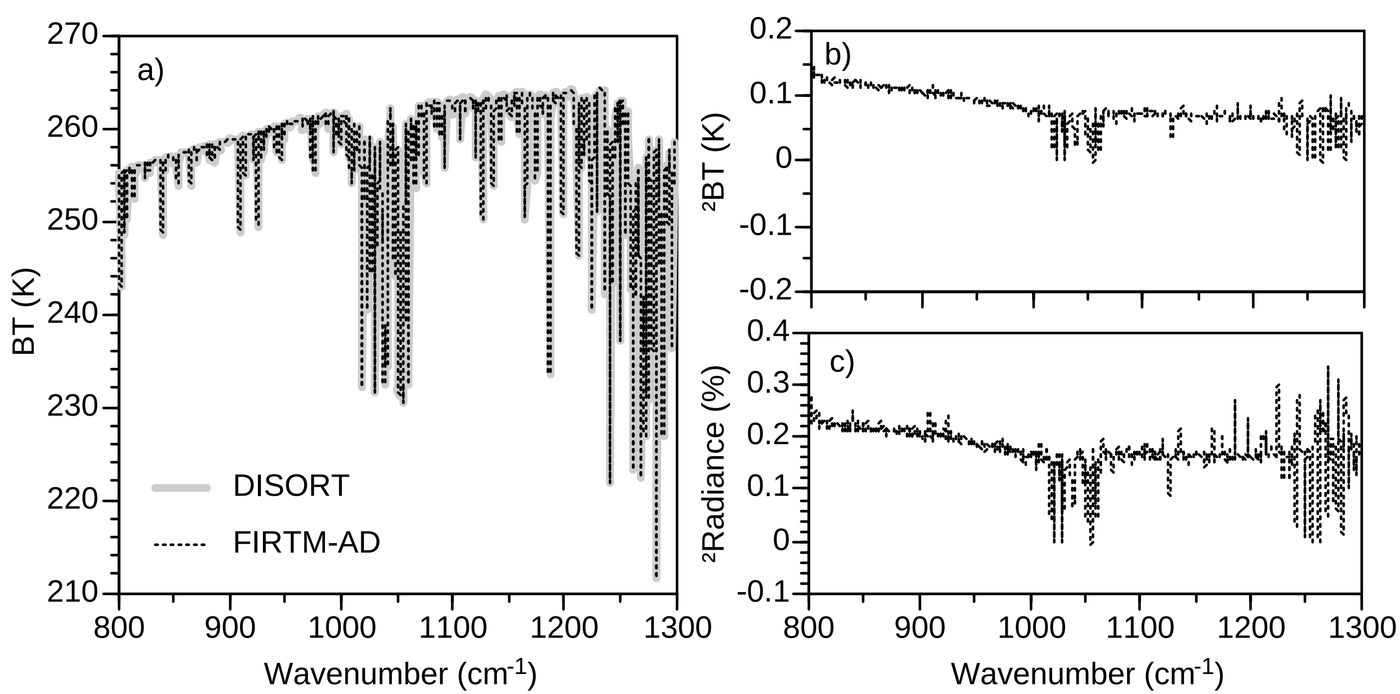
BT spectrum @ TOA
single-layered & isothermal

“on-grid” accuracy <0.1K

(both D_e and τ on gird of the library No interpolation is needed)

250 times faster than DISORT

$\text{single}-\text{layer},\ \tau_{vis}=2,\ D_e=60\mu m,\ \mu=0.9947\ \ @12km$

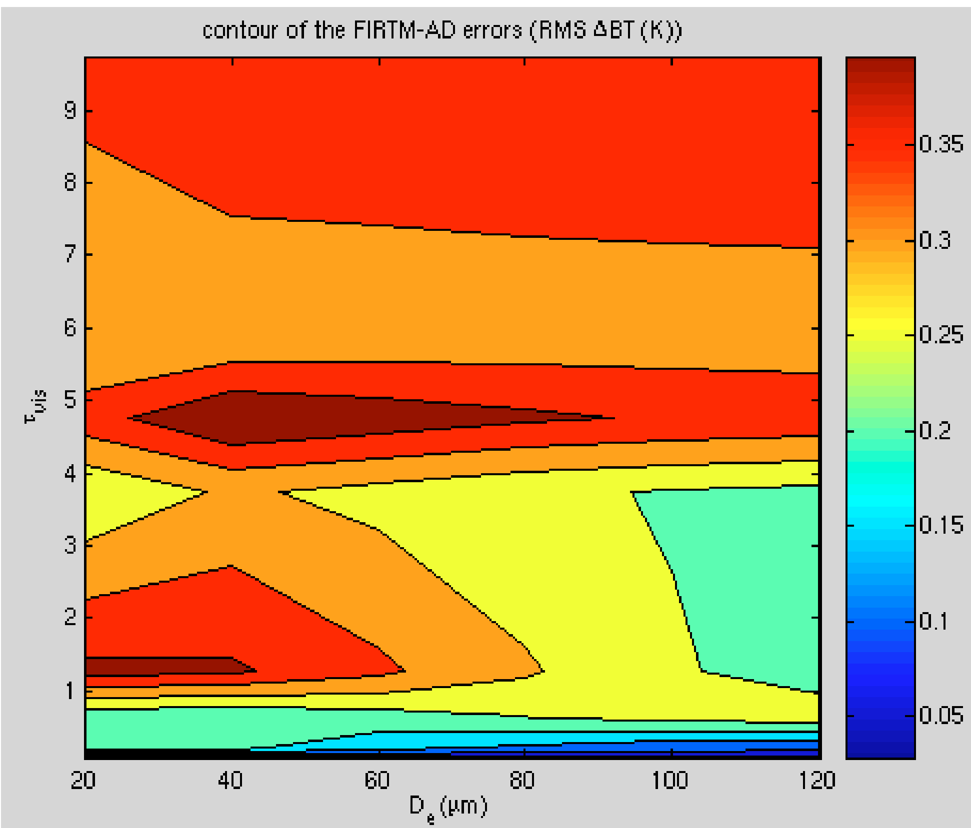


FIRTM-AD errors

BT spectrum @ TOA
single-layered & isothermal

"off-grid" accuracy <0.4K

(both D_e and τ off gird of the library, interpolation is needed)



The resolution of the library is still being tested to achieve better accuracy and smaller size of the library.

Summary

- The adding-doubling method seems a proper approach for a fast hyperspectral RT model
- The time-consuming initialization step in the adding-doubling computation can be replaced by pre-computed look-up libraries
- Current FIRTM-AD has 0.1K “on-grid” accuracy and 0.4K “off-grid” accuracy, and is 250 times faster than DISORT

Thank you