6th International SKYNET Workshop 2021，Japan (online)

The spectral dependency of the cirrus cloud backscattering by lidar and radar soundings in SKYNET Hefei Site

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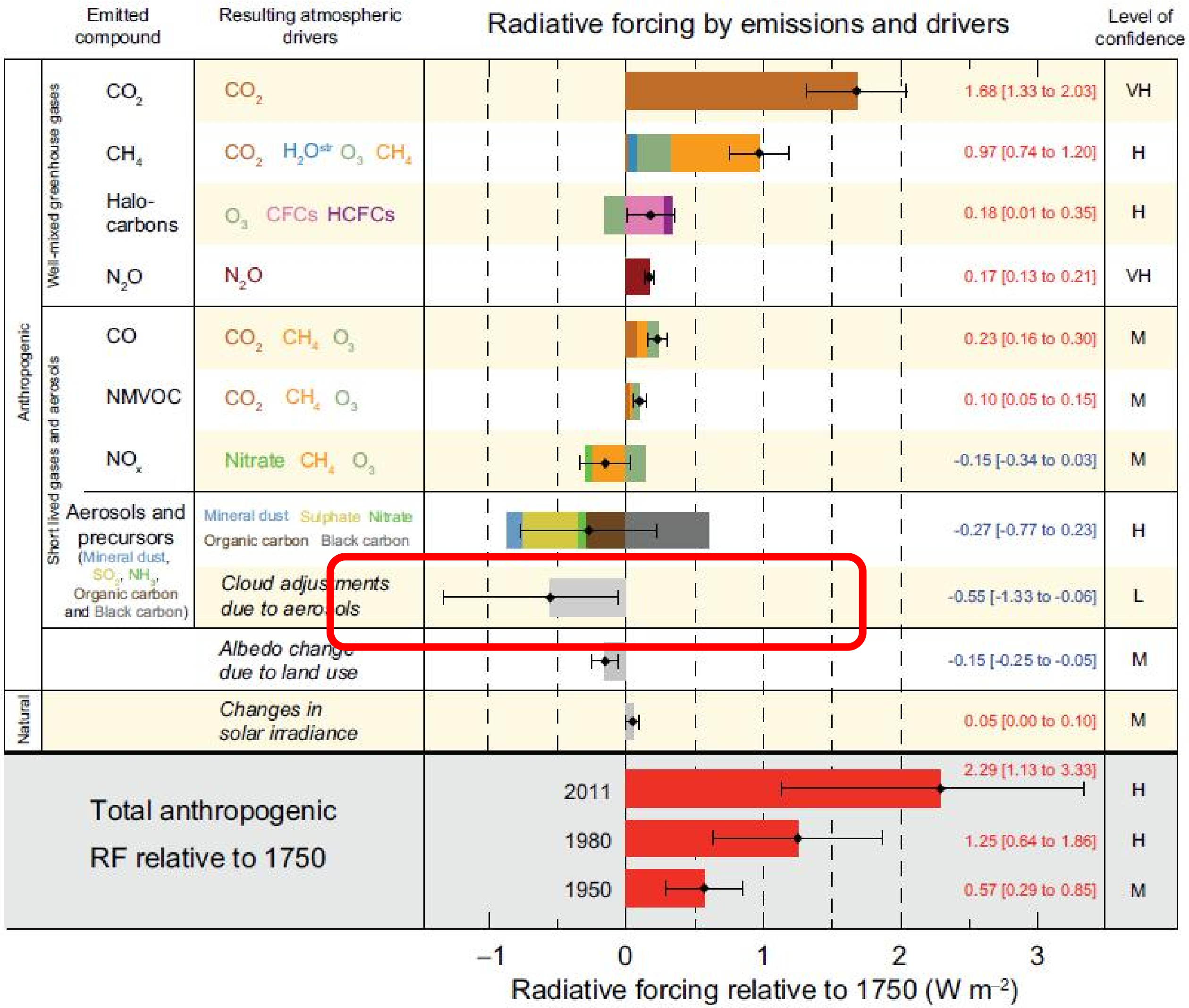
Outline

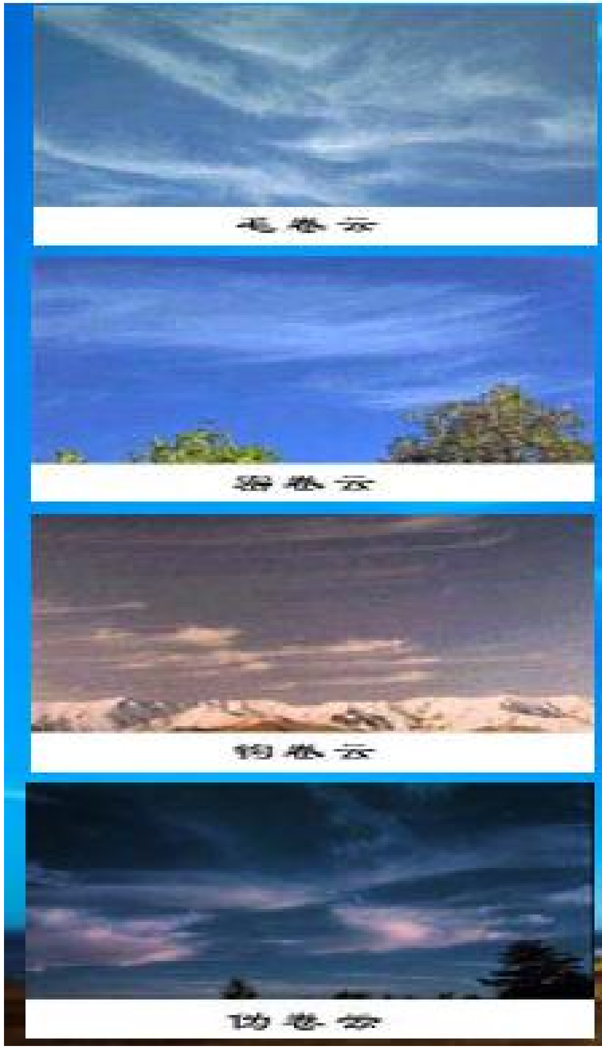
- Background
- Systems and Methods
- Results
- Conclusions

Background



《IPCC AR5 2013》

Background



◆Cirrus cloud is one of the most commonly types globally.

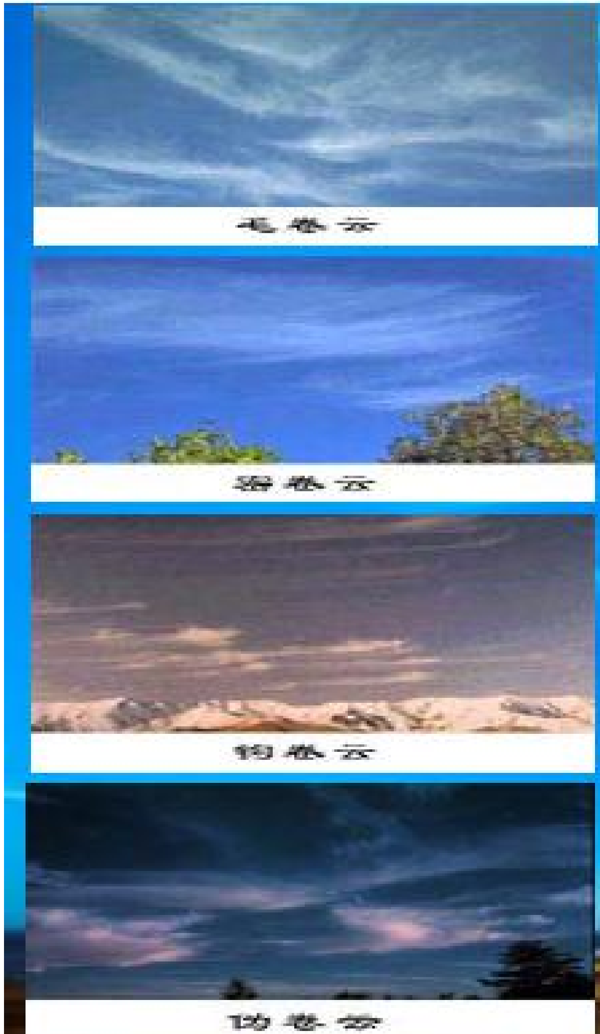
◆It forms in the upper part of troposphere, due to synoptic scale lifting, or as a result of moisture transport by deep convection.

◆Cirrus clouds cover about 30% of the Earth surface .

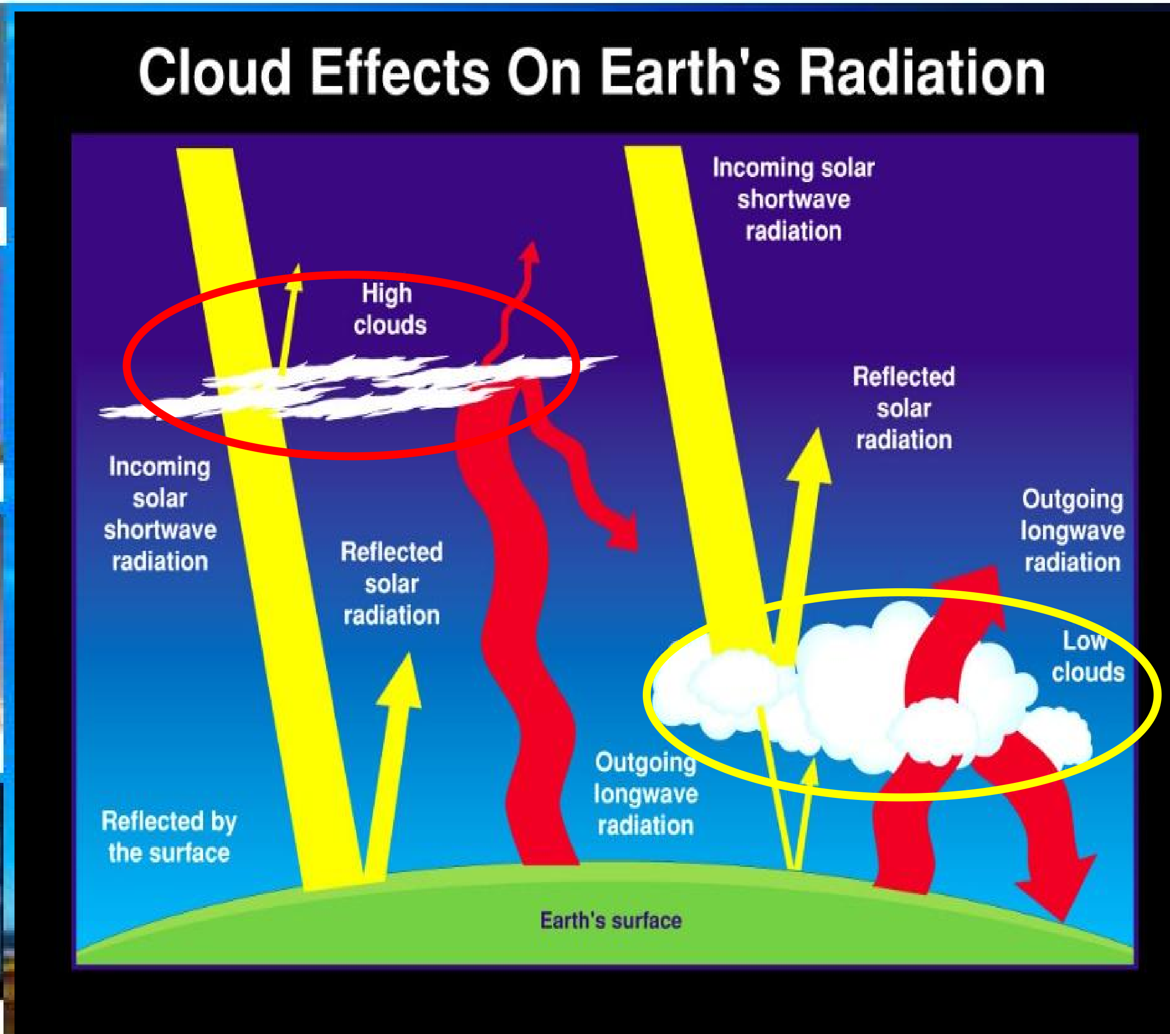
◆It impacts on the radiative budget of the Earth and, on the climate.

Jensen, 1996; Nazaryan, 2008

Background

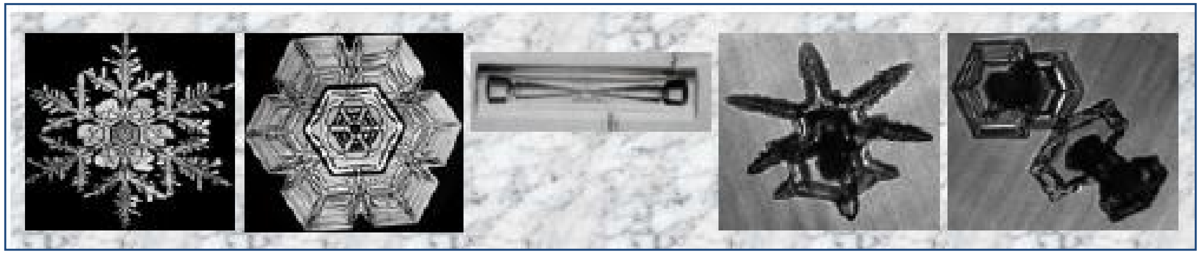


毛卷云
密卷云
钩卷云
伪卷云

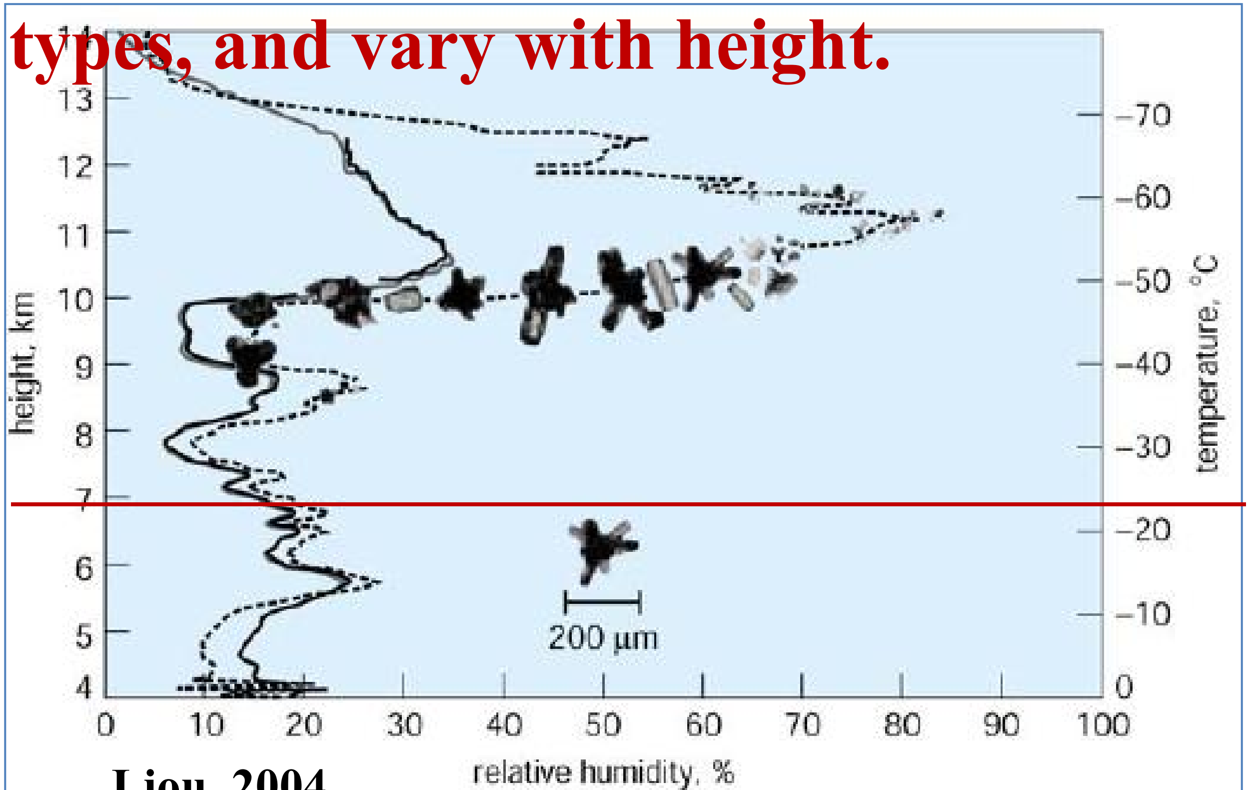


Cloud Effects On Earth's Radiation
Incoming solar shortwave radiation
High clouds
Reflected solar radiation
Incoming solar shortwave radiation
Reflected by the surface
Reflected solar radiation
Outgoing longwave radiation
Low clouds
Outgoing longwave radiation
Earth's surface

Background



Cirrus cloud normally exist below -25 ^{0}C with different types, and vary with height.



Liou, 2004

Cirrus@4.18km，Tomsk

Background

Recent years, many works focus on cirrus clouds in experiment using Lidars all over the world:

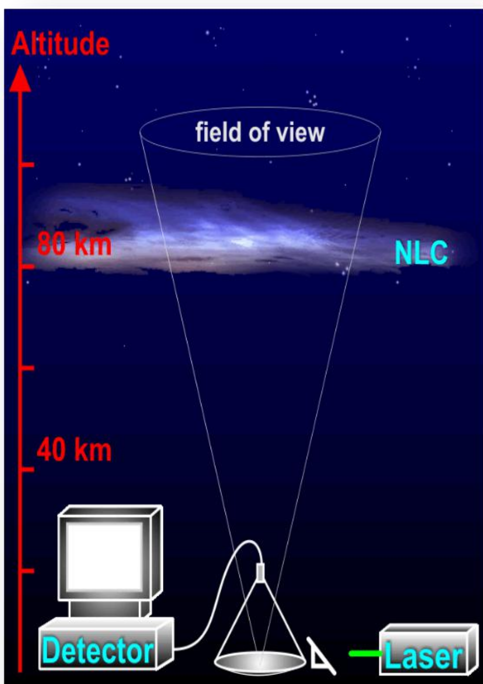
- **Wei-Nai Chen,** "Lidar ratio and depolarization ratio for cirrus clouds" Appl. Opt., 2002
- **Zhenzhu Wang，** "Depolarization properties of cirrus clouds from polarization LIDAR measurements over Hefei in spring," Chin. Opt. Lett 2008
- **Yurii S. Balin,** Observations of specular reflective particles and layers in crystal clouds" Opt. Exp. ,2011
- **Zongming Tao ,** "Measurements of cirrus clouds with a three-wavelength lidar" Chin. Opt. Lett 2012
- **Borovoi, A.,** "Layers of quasi-horizontally oriented ice crystals in cirrus clouds observed by a two-wavelength polarization lidar," Optics Express 2014.
- **Konoshonkin A**,. Backscatter by azimuthally oriented ice crystals of cirrus clouds.[J]. Optics Express, 2016.
- **Zhenzhu Wang，** Extinction matrix for cirrus clouds in the visible and infrared regions[J]. Optics Letters, 2018.

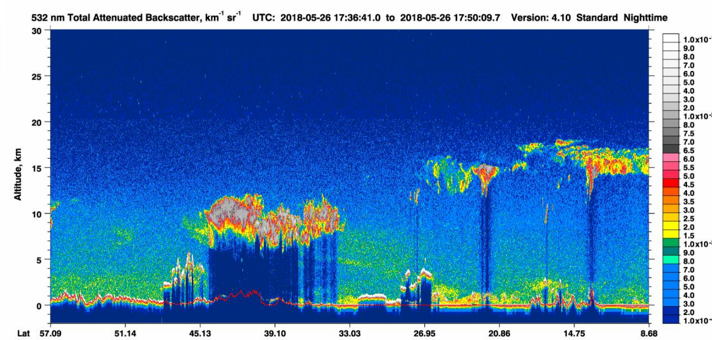
And in theory, the famous are:

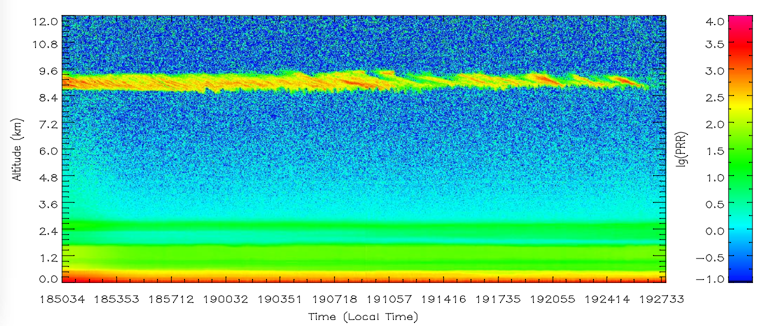
- **Yang, P.,** "**Geometric-optics**-integral-equation method for light scattering by nonspherical ice crystals,"
- **Borovoi, A.,** "The **physical-optics** approximation and its application to light backscattering by hexagonal ice crystals,"

Background

- Measurement of microphysical and optical properties of cirrus is a basic requirement for climate use
- Ground-based lidars could give useful information about these properties and Lidar working on routing basis are operated at SKYNET Hefei （*31.90 °N,117.16 °E*） site, China

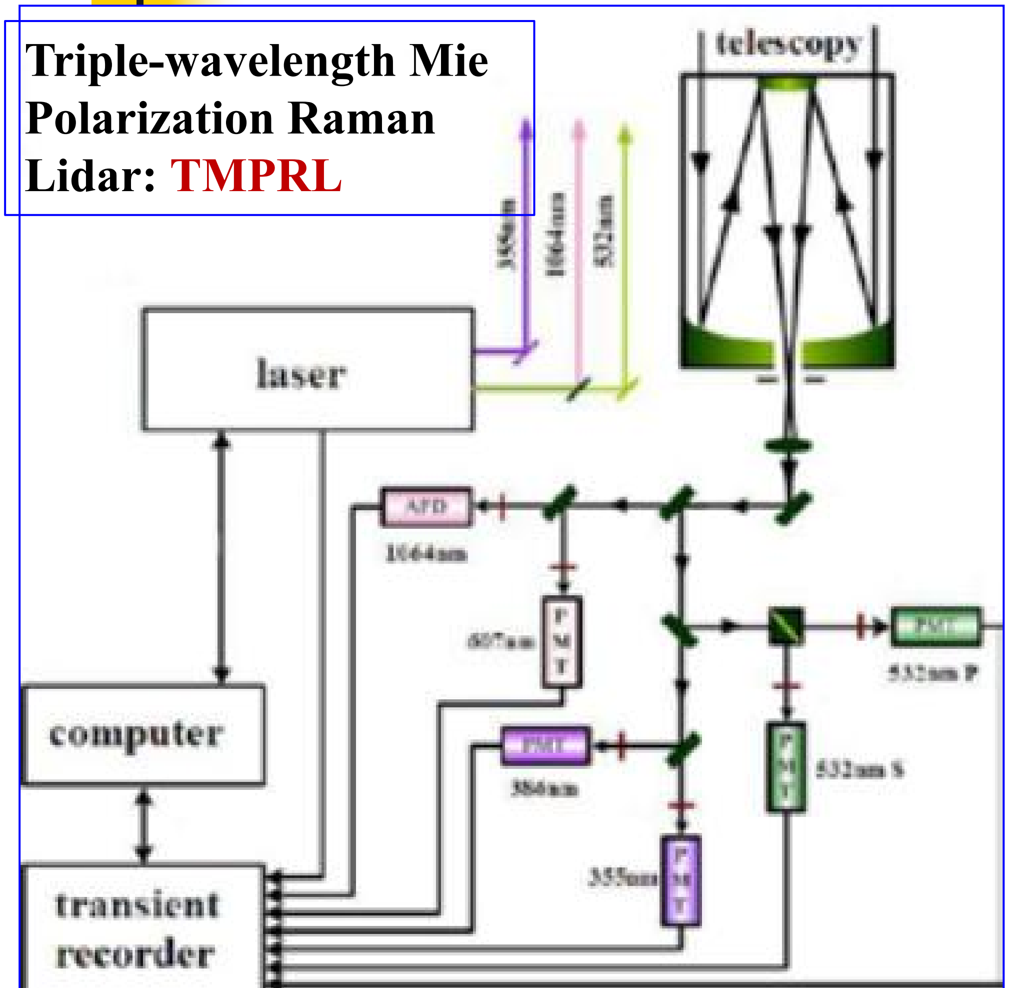


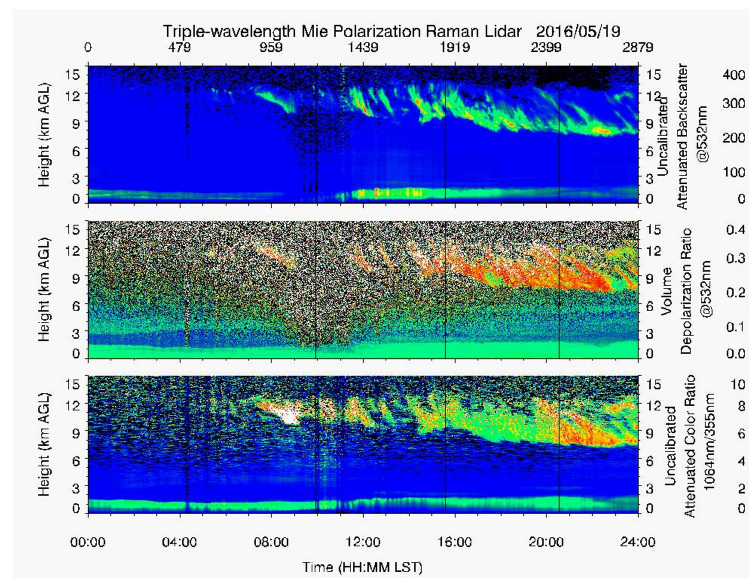




TRMPL Lidar System

Triple-wavelength Mie Polarization Raman Lidar: TMPRL





Cirrus: Methods

Lidar equation

$$X(z) = z^2 P(z) = C\beta(z) e^{-\tau(0,z)}$$

$$\beta(z) = \beta_p(z) + \beta_m(z)$$

$$\tau(0,z) = \tau_p(0,z) + \tau_m(0,z)$$

backscatter coefficients and optical depths for particles and molecules

$$\beta_p(z) = c(z)\sigma_\pi(z) \qquad \tau_p(0,z) = \int_0^z c(z')\sigma_e(z')dz'$$

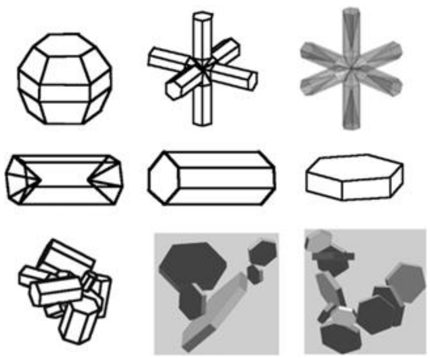
$$\delta(z) = \frac{\sigma_\pi^\perp(z)}{\sigma_\pi^\parallel(z)} = \frac{\beta^\perp(z)}{\beta^\parallel(z)}$$ depolarization ratio

$$\chi(z) = \frac{\sigma_{\pi,\lambda 1}(z)}{\sigma_{\pi,\lambda 2}(z)} = \frac{\beta_{\lambda 1}(z)}{\beta_{\lambda 2}(z)}$$ color ratio

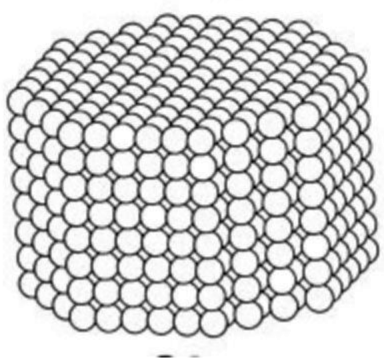
$$L(z) = \frac{\sigma_e(z)}{\sigma_\pi(z)}$$ lidar ratio

Wang, 2014

Cirrus: Methods



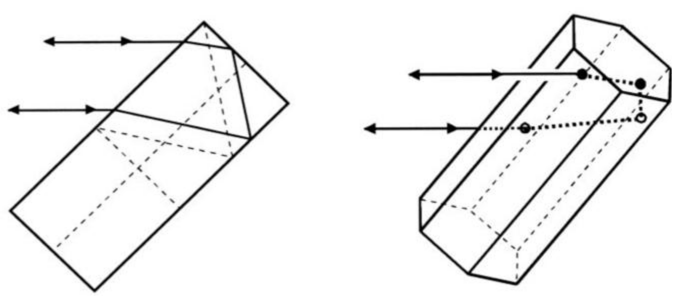
1. Exact methods (FDTD, DDA, T-matrix)



Ping Yang, K.-N. Liou,
M. Yurkin, M. Mishchenko, et al.

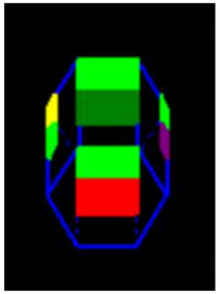
particle size < 20 wavelengths

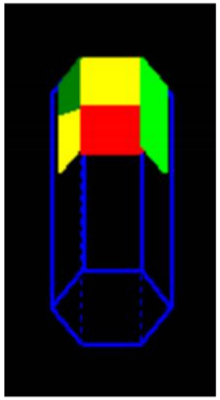
2. Geometrical optics methods



2a. Ray-tracing

K.-N. Liou, A. Macke, et al.

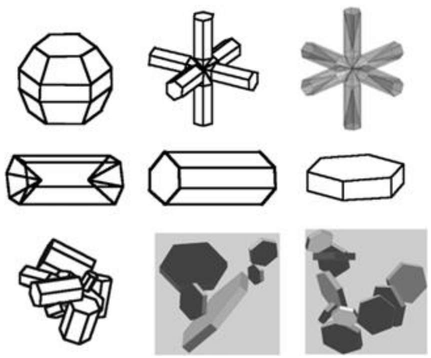




2b. Facet-tracing or beam splitting

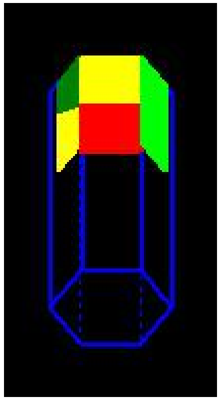
M. Del Guasta, A. Borovoi, Lei Bi, et al.

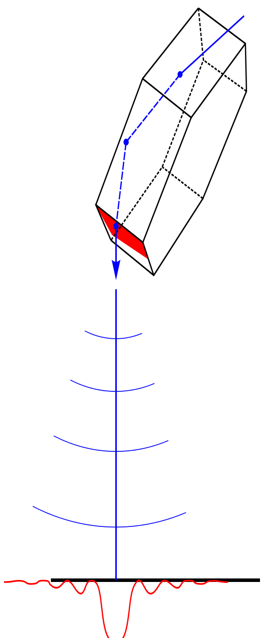
Cirrus: Methods



3a. IGOM- Improved Geometrical Optics Method

P.Yang, K.-N. Liou

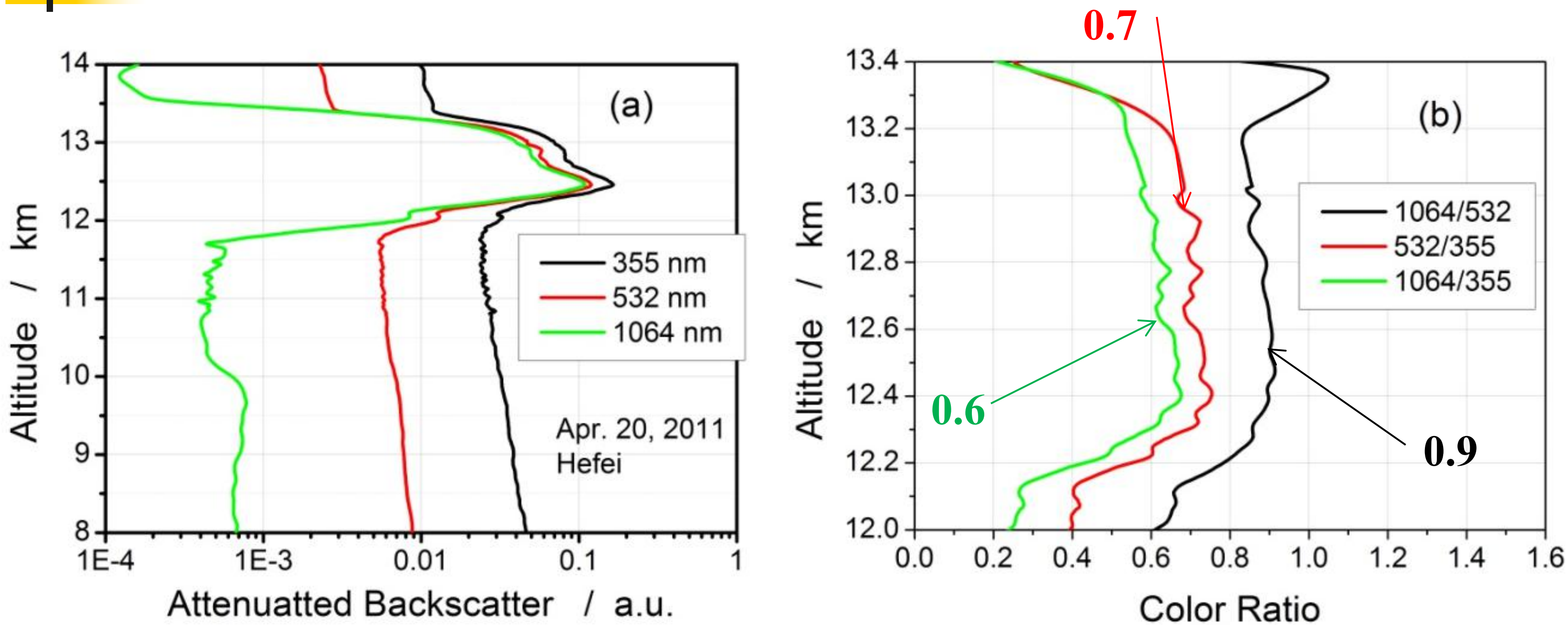




3b. Physical Optics Method

A. Borovoi, A. Konoshonkin, N. Kustova

Results

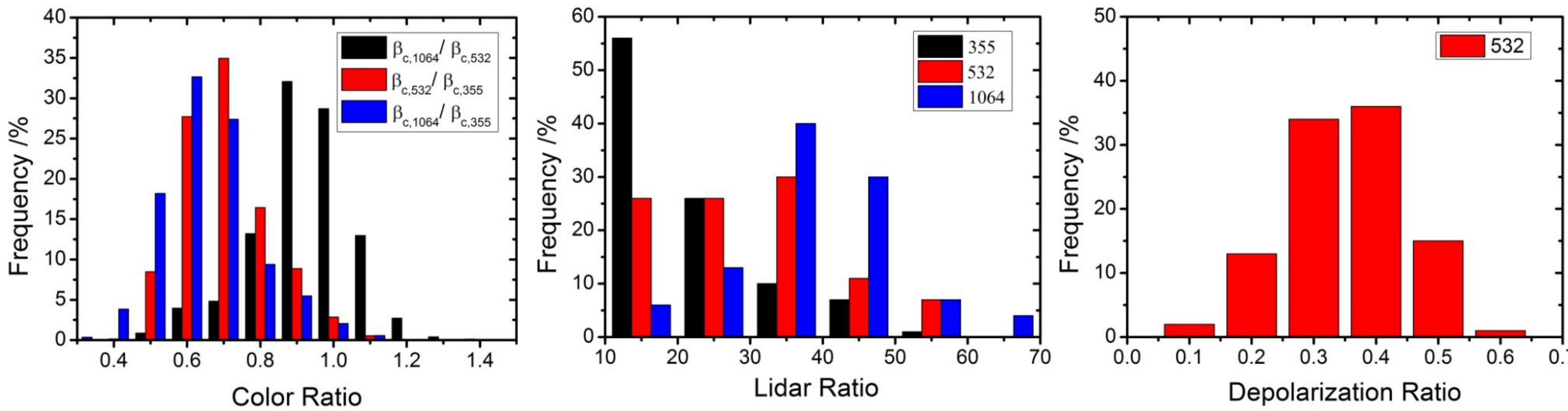


Attenuated backscatter and color ratio profiles by TRMPL

Wavelength	355nm	532nm	1064nm
Optical Depth	0.30±0.01	0.31±0.02	0.28±0.03
Lidar Ratio	25±1Sr	36±3Sr	39±7Sr
Depolarization Ratio		0.4±0.1	

Retrieved Parameters

Results



The statistical characteristics of backscatter ratio for cirrus measured from Dec. of 2010 to Feb. of 2013 over Hefei, China

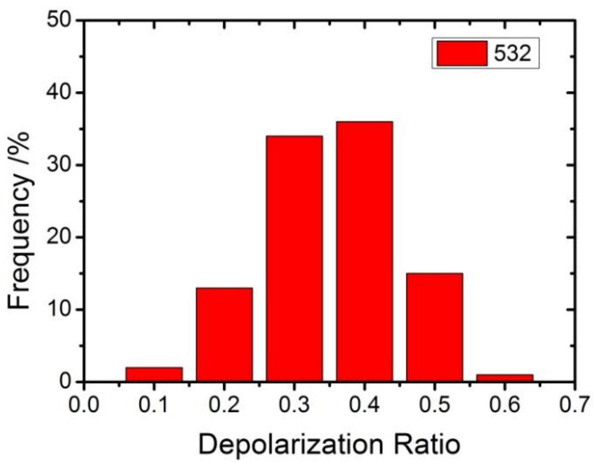
The mean values for color ratios are 0.93, 0.70 and 0.65 with the most frequency existing at 0.9, 0.7 and 0.6;
And the lidar ratios' mean values are 22.1, 29.7 and 38.1 Sr ;
The averaged depolarization ratio is 0.36 varying from 0.2 to 0.5.

Results

Depolarization ratio

$$\mathbf{M} = \sigma \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1-d & 0 & 0 \\ 0 & 0 & -1+d & 0 \\ 0 & 0 & 0 & -1+2d \end{pmatrix}$$

$$\delta = d/(2-d) \qquad d = \frac{2\delta}{1+\delta}$$



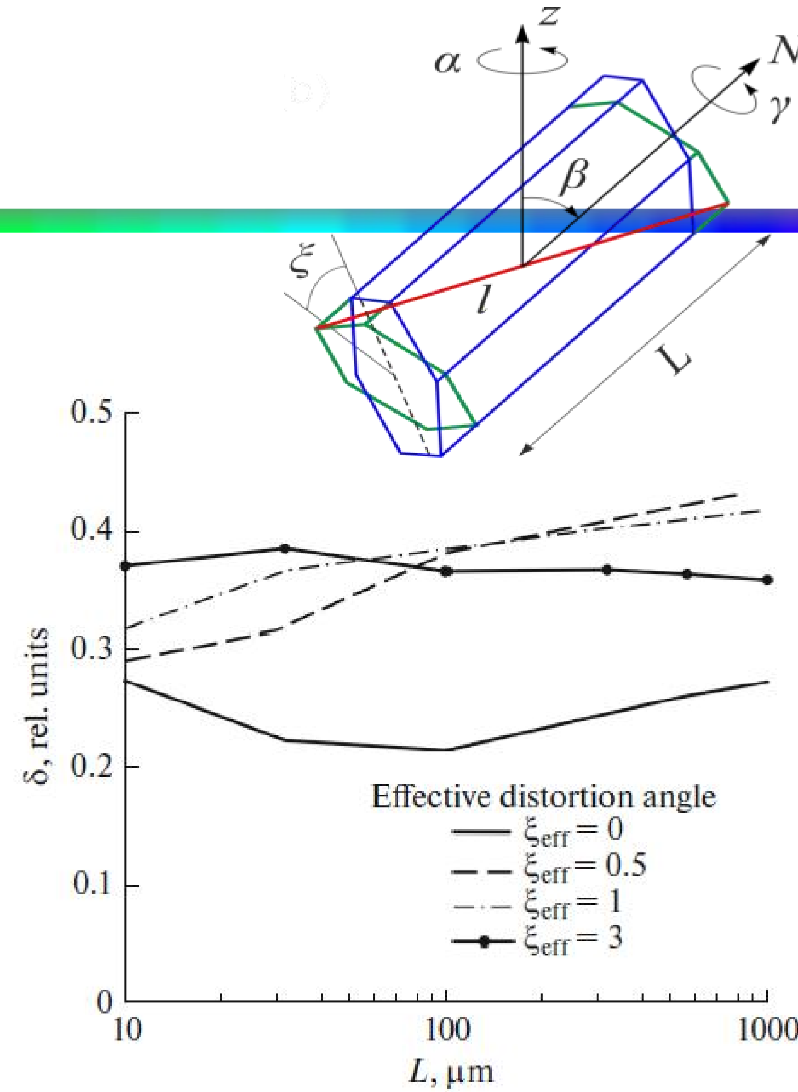


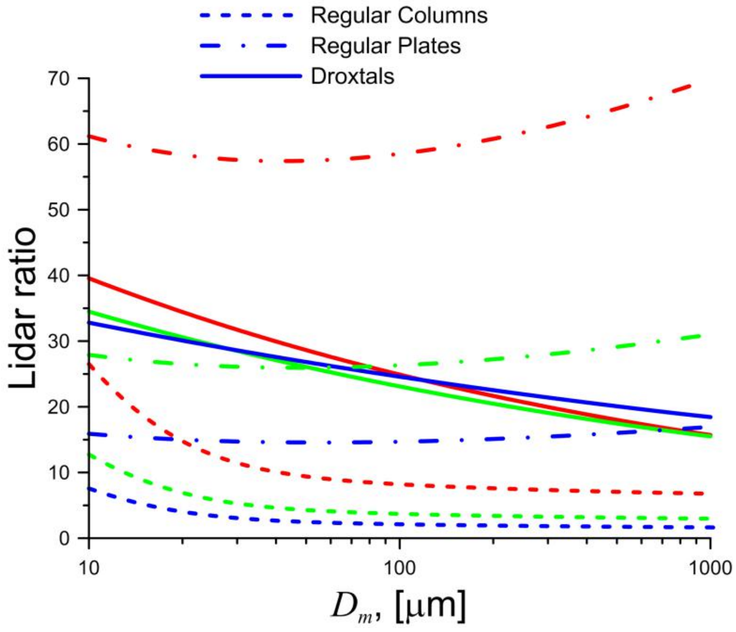
Fig. 2. Linear depolarization ratio calculated for randomly oriented hexagonal columns with effective distortion angles of 0°, 0.5°, 1°, and 3° as a function of the crystal length at an incident light wavelength of 0.532 μm.

A. Borovoi, Opt. Lett,2014

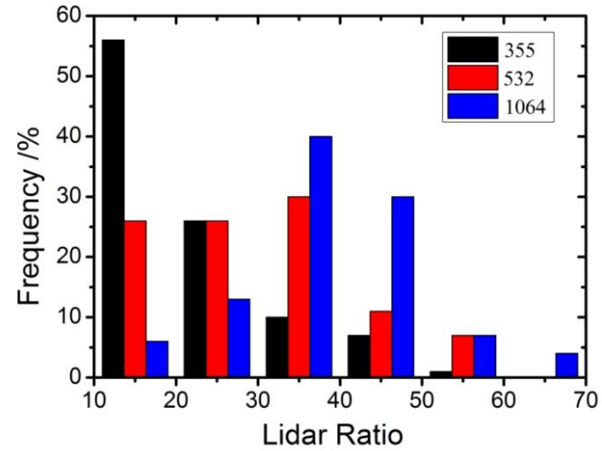
Wang Z., AOO， 2017

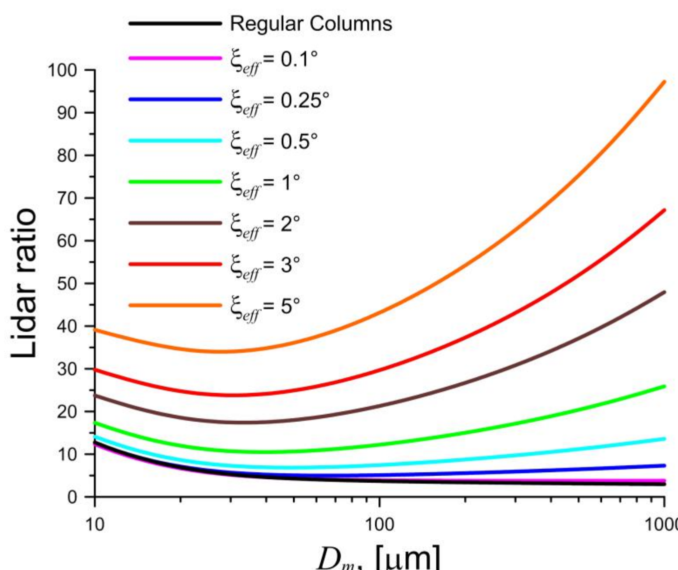
Results

Lidar ratio: (extinction-to-backscatter)



λ= 0.355μm (blue), λ= 0.532μm (green), λ= 1.064μm (red)

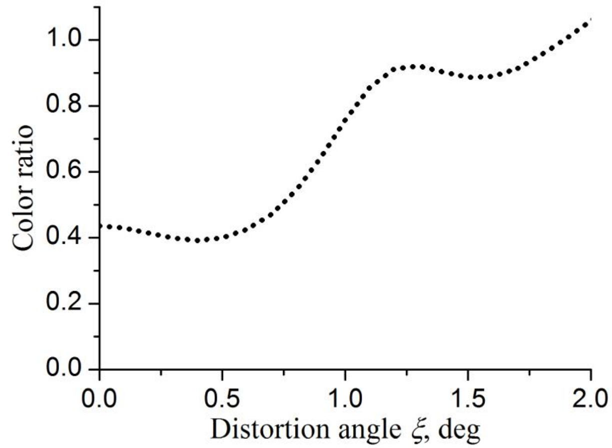


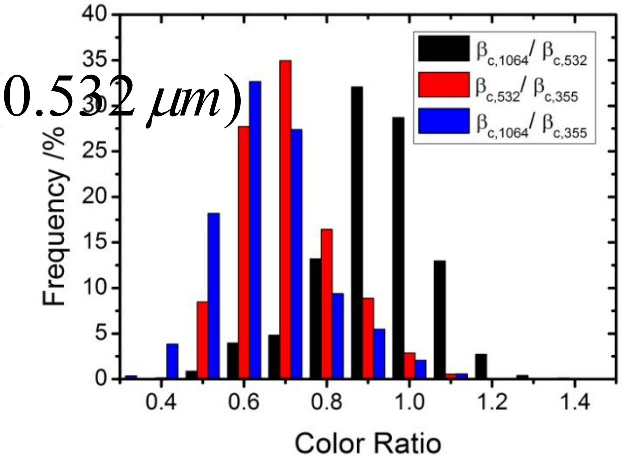


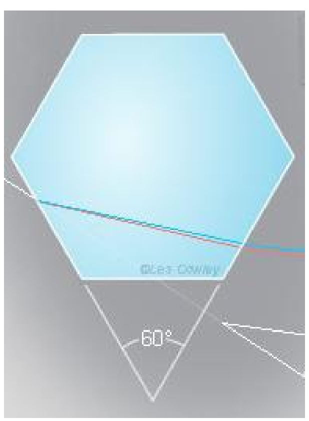
Results

Color ratio

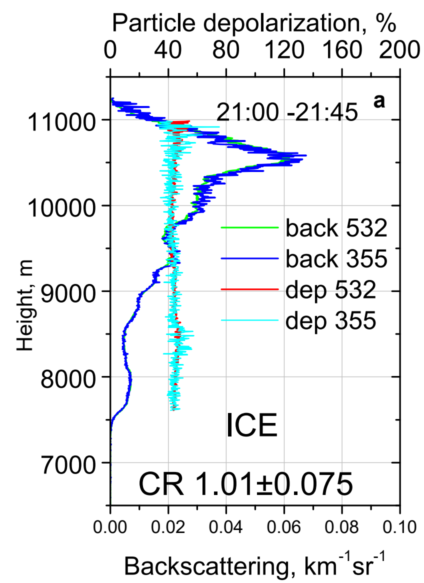
$$\sigma(1.064\,\mu m)/\sigma(0.532\,\mu m)$$

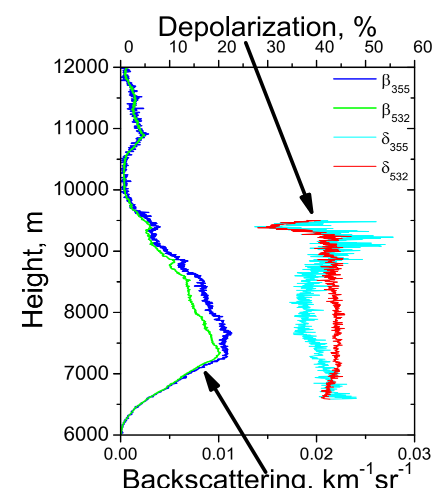






corner-reflection effect





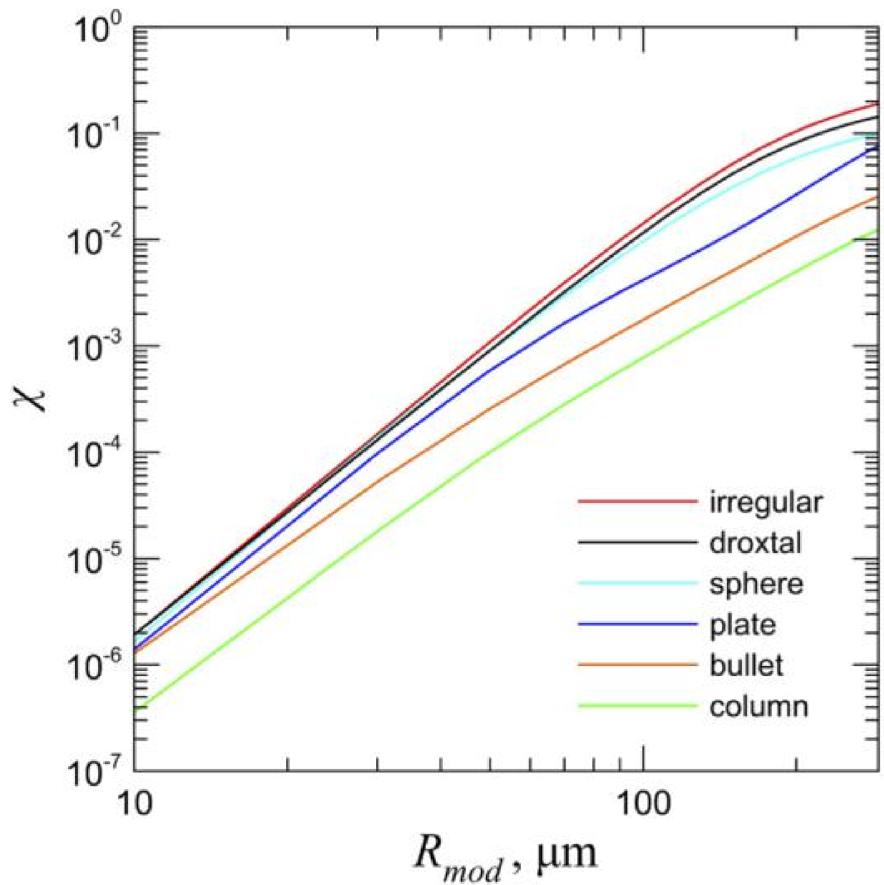
A.Borovoi,, Opt. Express, 2015
Veselovskii et al., JQSRT 2017

Results: Lidar-Radar ratio

$$\lambda_{lidar} = 0.53\ \mu m$$

$$\lambda_{radar} = 8.56\ mm$$

$$\chi_{lidar}^{radar} = \frac{\beta_{radar}}{\beta_{lidar}} = \frac{\sigma_{radar}}{\sigma_{lidar}}$$

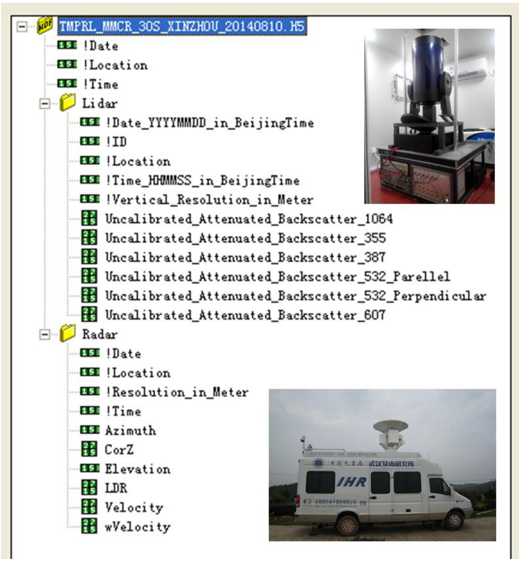


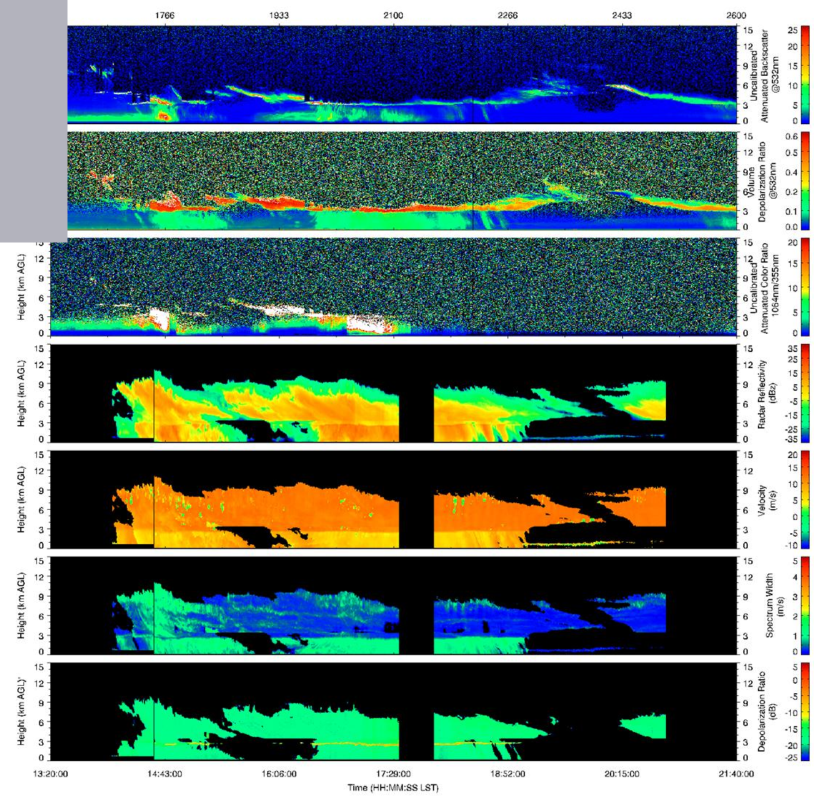
Wang et al.，OPTICS EXPRESS，2021

Combined System

$$\delta = \frac{\beta_{\perp}}{\beta_{\parallel}} = \frac{\sigma_{\pi\perp}}{\sigma_{\pi\parallel}} \qquad \chi_{\lambda_2}^{\lambda_1} = \frac{\beta(\lambda_1)}{\beta(\lambda_{21})} = \frac{\sigma_{\pi}(\lambda_1)}{\sigma_{\pi}(\lambda_{21})}$$

$$l = \frac{\alpha}{\beta} = \frac{\sigma_e}{\sigma_{\pi}} \qquad \varsigma = \frac{\beta}{IWC} = \frac{\sigma_{\pi}}{V} \qquad q = \frac{p(\theta,\varphi)}{p_{\theta=\pi}}$$





激光雷达

衰减后向散射系数
$Km^{-1}Sr^{-1}$

退偏振比

颜色比

微波雷达

雷达反射率
dBZ

多普勒速度
m/s

频谱宽度
m/s

退偏振比
dB

Conclusions

(1) A moveable TRMPL lidar system is developed for cirrus detecting at Hefei, China. The lidar ratio, color ratio, and depolarization ratio for cirrus cloud have been investigated from case study and statistical characteristics.

(2) The parameters, such as DR, LR, CR are matched with the developed model, more complicated crystal shapes with the shape distortion maybe need by using combined lidar and radar.

(3) The radar-lidar ratio simply depends on crystal size and this dependence is close to the power law for the backscattering cross section, which will be a base for creation of algorithms inferring sizes of the ice crystals in this cloud.

Thanks for your attention!