Sensitivity of radiation polarization to microphysical properties of thin ice clouds

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- Objective
- Subvisually thin cirrus clouds
- Review of polarization fundamentals
- Modeling polarized radiation for clouds
- Sensitivity of polarized radiation to ice cloud particle shapes
- Summary

Objective

To build an accurate and efficient Polarization Distribution Model (PDM) for the CLARREO inter-calibration applications, we must understand the sensitivity of the TOA polarized radiation to all components of the Earth-atmosphere system.

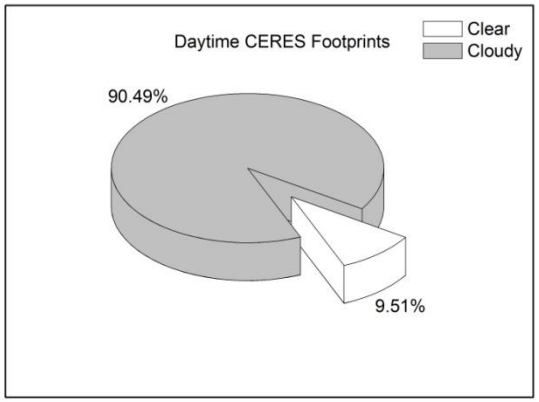
The components of the Earth-atmosphere system which affect the TOA radiation polarization may include:

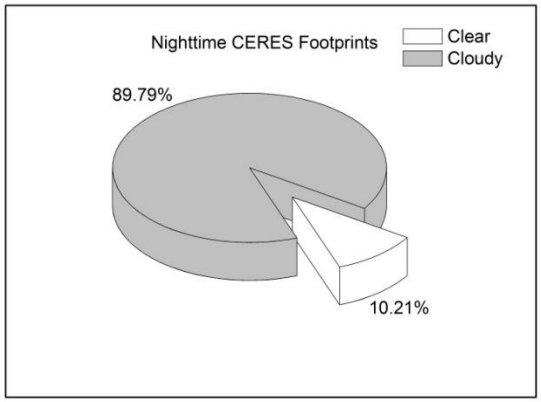
1. Land surface reflection condition
2. Ocean surface reflection condition (wind-caused roughness)
3. Atmospheric gas absorption
4. Atmospheric particle scattering (aerosol, ice crystal, water droplets)
5. Solar and viewing geometry

We must study the effect of all these components on TOA polarized radiation, to exclude any components, to which the polarized radiation is not sensitive, from the indices leading to a specific PDM.

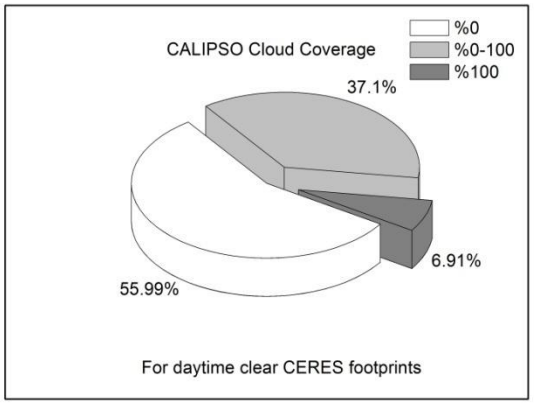
In this study, we will examine the sensitivity of the TOA polarized radiation to thin ice cloud (optical thickness < 0.3) particle shapes, to quantify the uncertainty caused by these undetected cirrus microphysical properties in the CLARREO PDM.

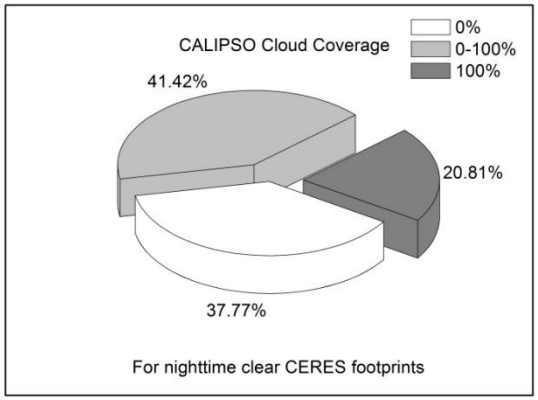
Subvisually thin cirrus clouds





MODIS-derived 12-month clear percentage of CERES FOVs

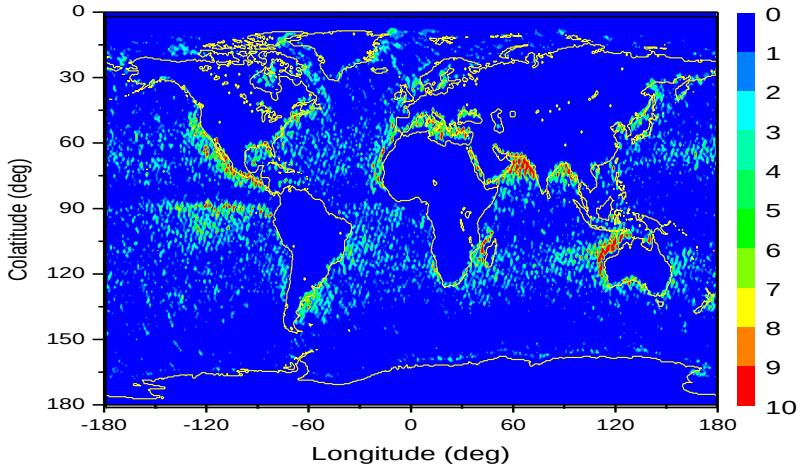




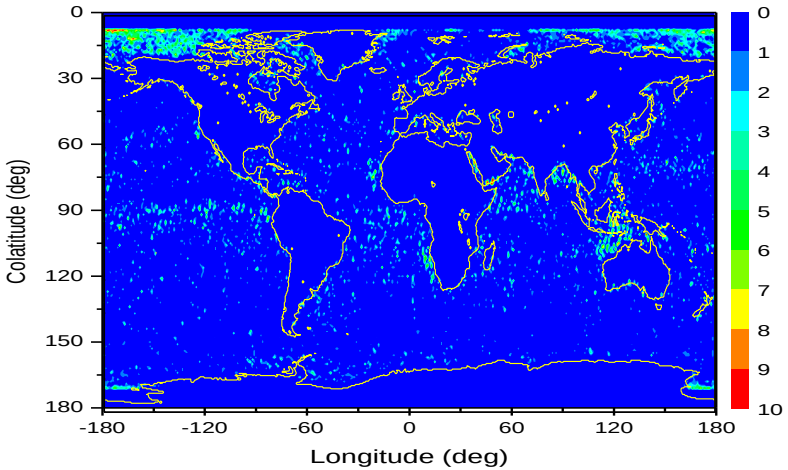
CALIPSO-derived cloudy percentage in MODIS-clear CERES FOVs

~50% of CERES FOVs claimed clear by MODIS have thin cirrus clouds

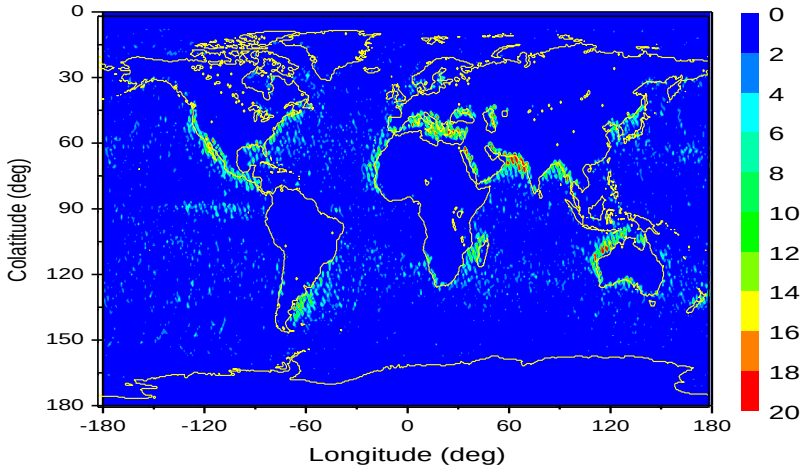
12-month CERES FOVs Sampling Distribution



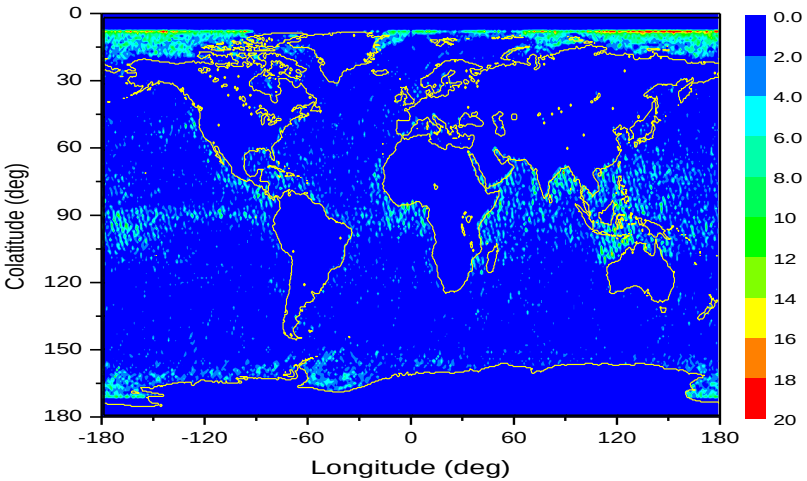
Daytime Purely Clear



Daytime Invisibly Cloudy

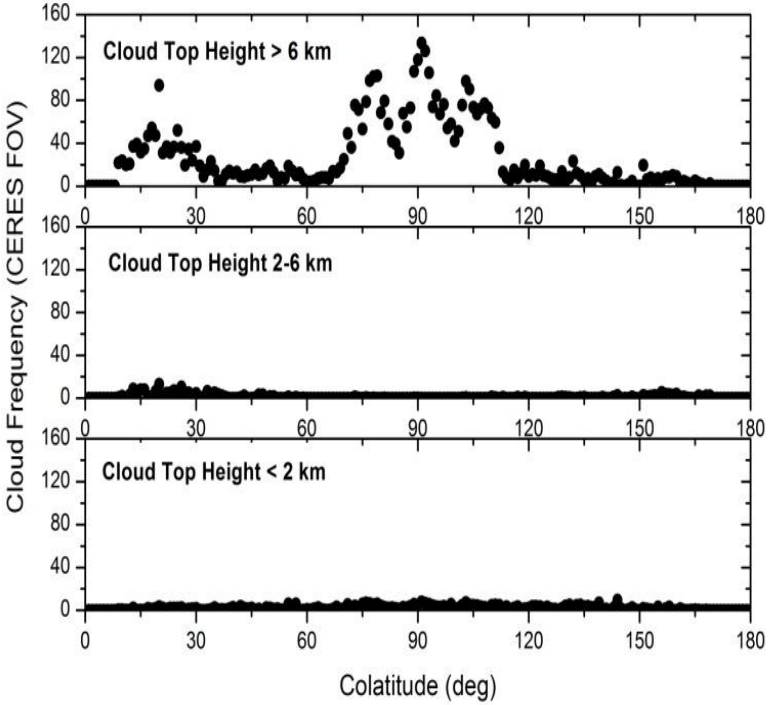


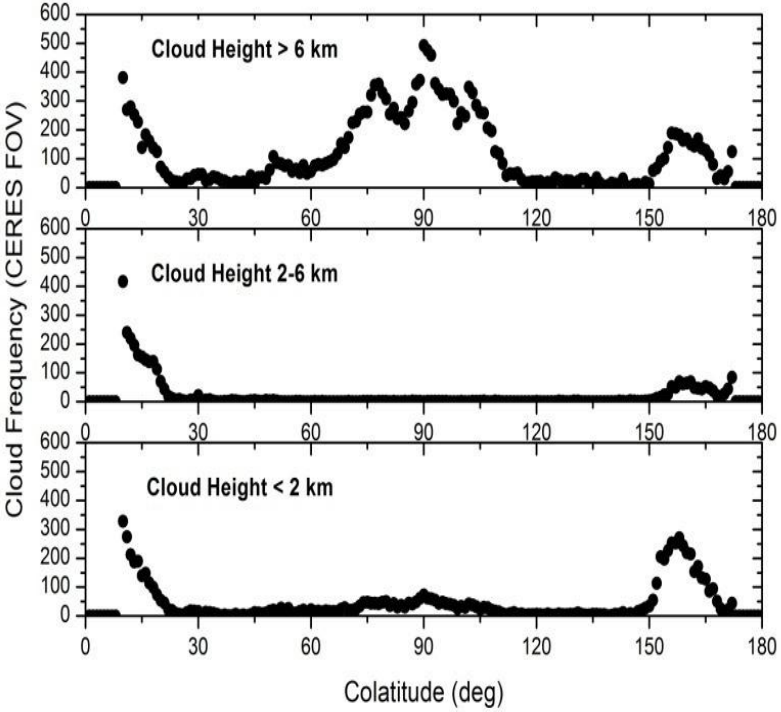
Nighttime Purely Clear



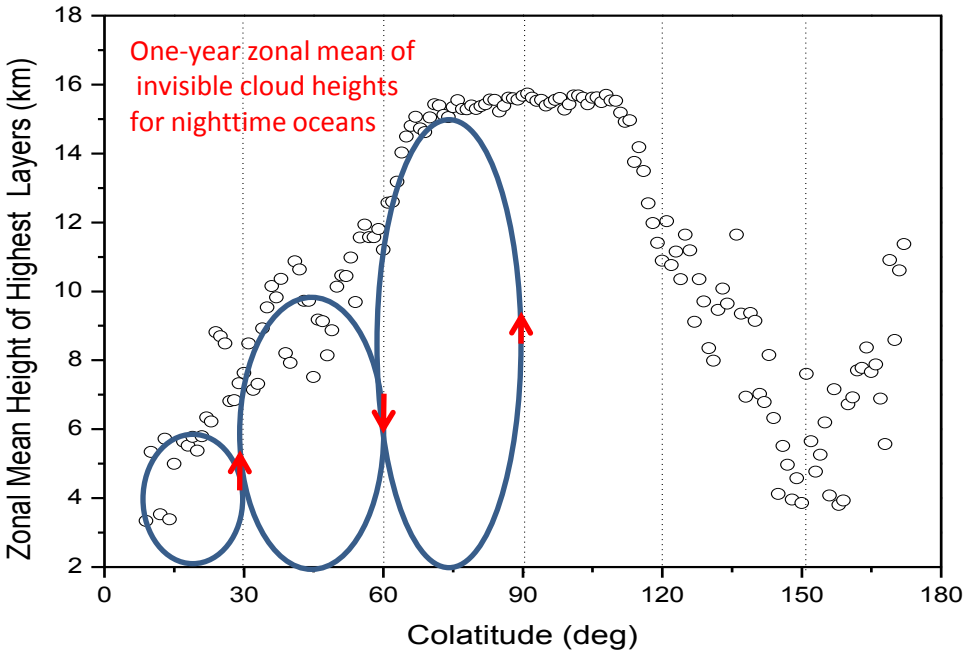
Nighttime Invisibly Cloudy

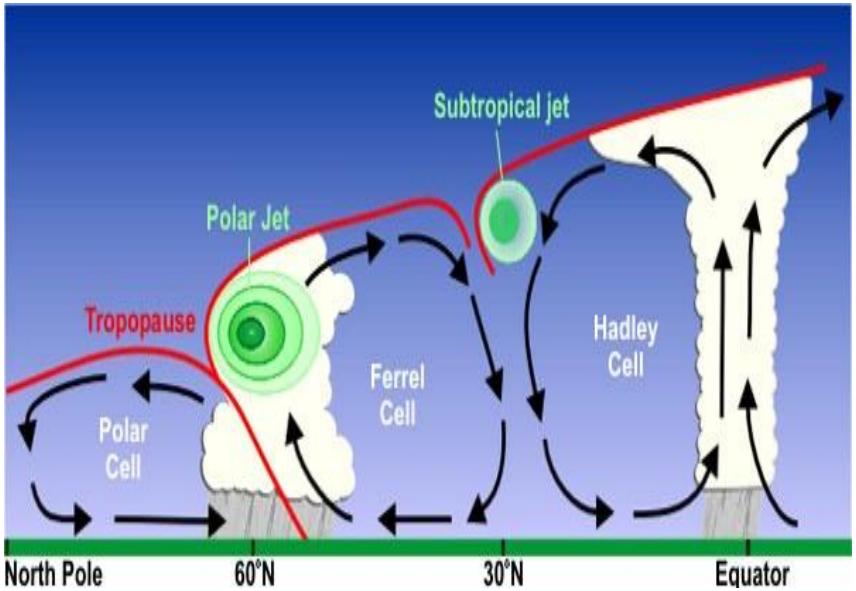
Zonal and altitude distribution of thin cirrus clouds





Zonal and altitude distribution of invisible cloud occurrence frequency (in the unit of CERES FOV number) for daytime (left panel) and nighttime (right panel) ocean





Zonal mean altitude of thin cirrus clouds

Review of polarization fundamentals

Any arbitrarily polarized incoherent radiation can be represented by the linear sum of an unpolarized part and a 100% polarized part as

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} I - \sqrt{Q^2 + U^2 + V^2} \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} \sqrt{Q^2 + U^2 + V^2} \\ Q \\ U \\ V \end{bmatrix}$$

$$I_{pol} = \sqrt{Q^2 + U^2 + V^2} = DOP \cdot I$$

$$I_{unpol} = I - \sqrt{Q^2 + U^2 + V^2} = (1 - DOP) \cdot I$$

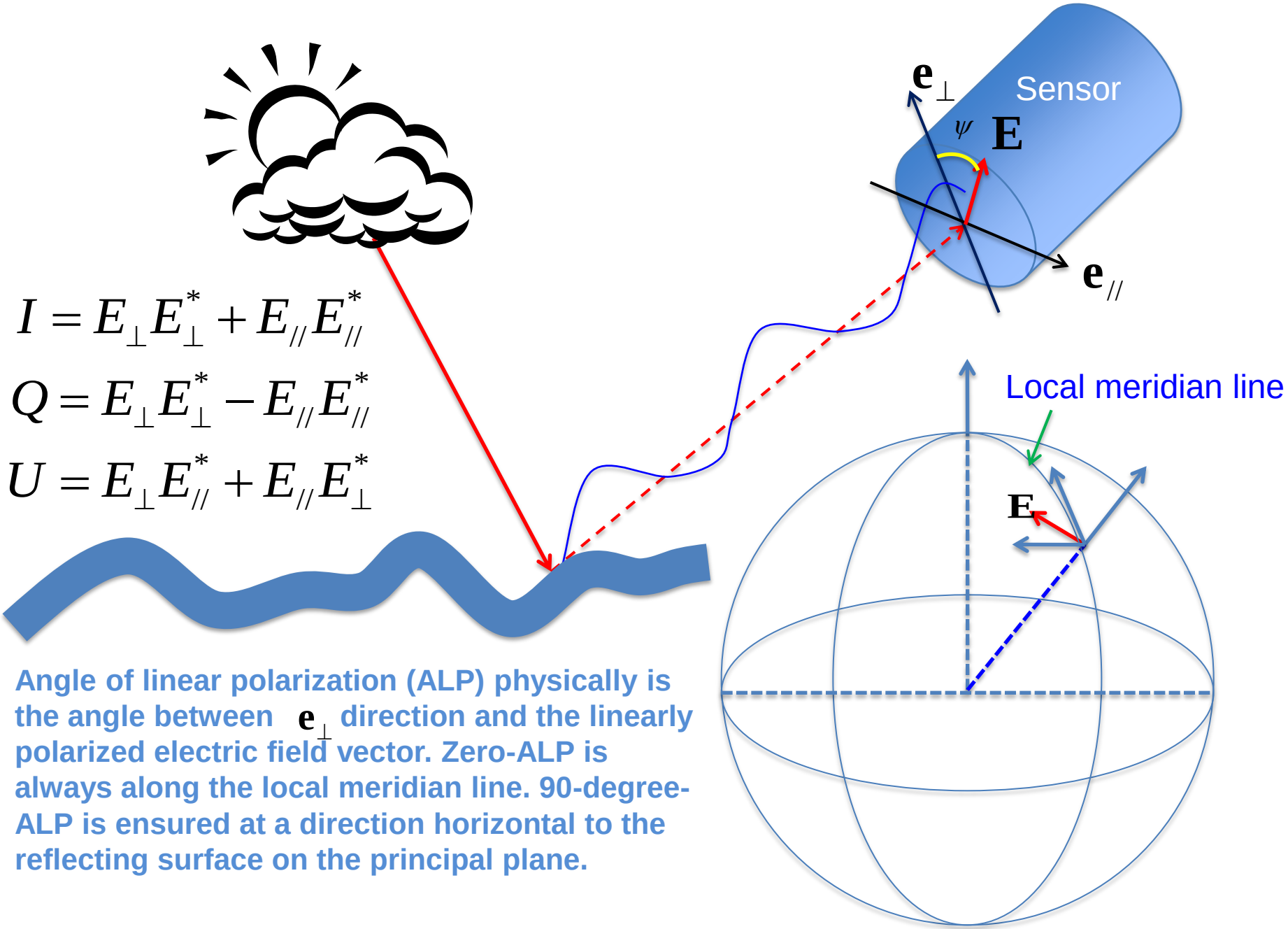
$$DOP = \frac{\sqrt{Q^2 + U^2 + V^2}}{I} = I_{pol} / I$$

$$\tan(2\psi) = \frac{U}{Q}$$

$$I = E_{\perp}E_{\perp}^{*} + E_{//}E_{//}^{*}$$

$$Q = E_{\perp}E_{\perp}^{*} - E_{//}E_{//}^{*}$$

$$U = E_{\perp}E_{//}^{*} + E_{//}E_{\perp}^{*}$$



Angle of linear polarization (ALP) physically is the angle between $\mathbf{e}_{\perp}$ direction and the linearly polarized electric field vector. Zero-ALP is always along the local meridian line. 90-degree-ALP is ensured at a direction horizontal to the reflecting surface on the principal plane.

Modeling polarized radiation for clouds

Modeling radiation from clouds needs optical properties of cloud particles

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \frac{1}{(kr)^2} \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \begin{bmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{bmatrix}$$

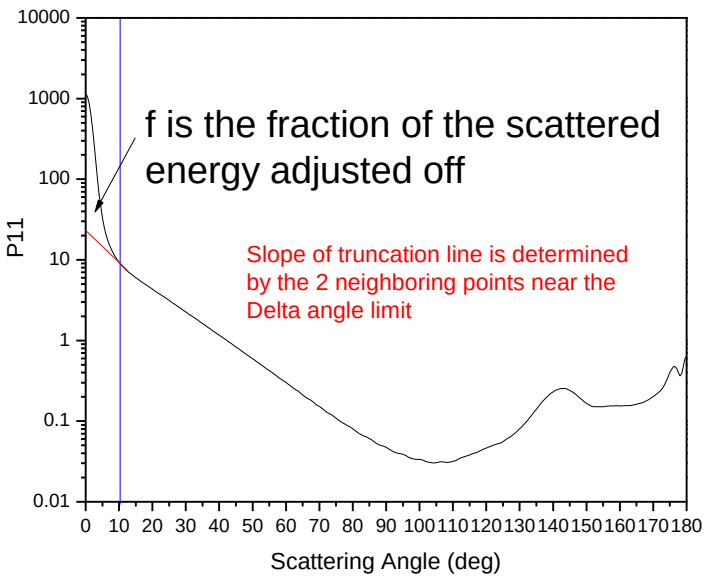
$$\begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} \\ P_{21} & P_{22} & P_{23} & P_{24} \\ P_{31} & P_{32} & P_{33} & P_{34} \\ P_{41} & P_{42} & P_{43} & P_{44} \end{bmatrix} = \frac{4\pi}{k^2 \sigma_s} \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix}$$

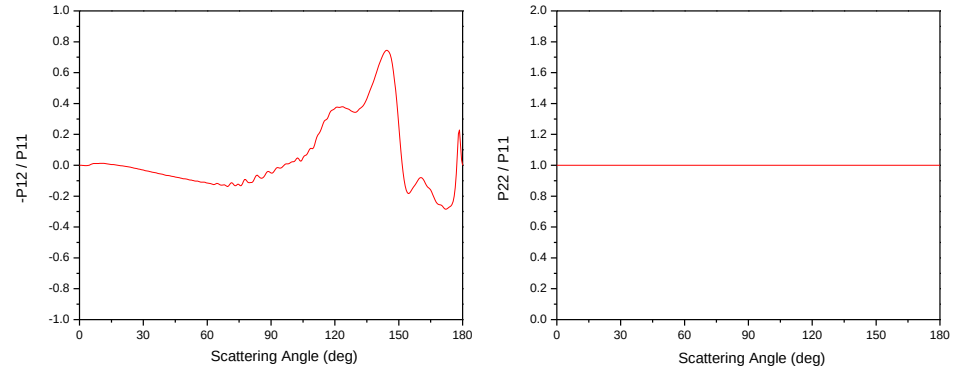
$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \frac{P_{11}\sigma_s}{4\pi r^2} \begin{bmatrix} 1 & P_{12}/P_{11} & P_{13}/P_{11} & P_{14}/P_{11} \\ P_{21}/P_{11} & P_{22}/P_{11} & P_{23}/P_{11} & P_{24}/P_{11} \\ P_{31}/P_{11} & P_{32}/P_{11} & P_{33}/P_{11} & P_{34}/P_{11} \\ P_{41}/P_{11} & P_{42}/P_{11} & P_{43}/P_{11} & P_{44}/P_{11} \end{bmatrix} \begin{bmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{bmatrix}$$

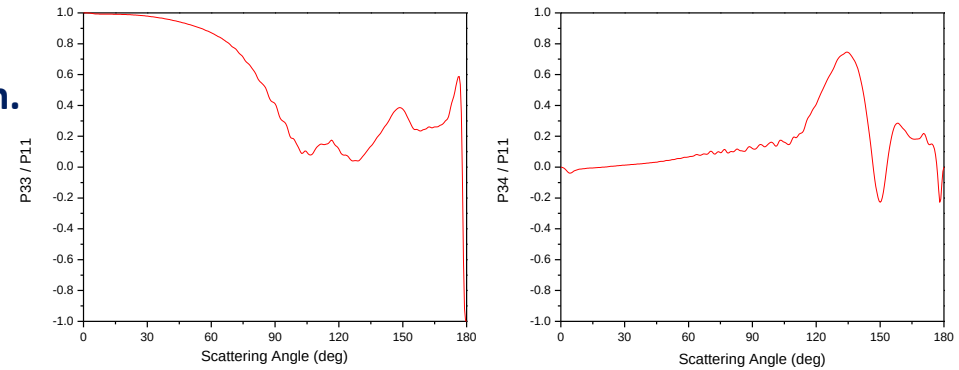
Delta-adjustment to cloud optical properties

Delta-adjustment to cloud phase functions is done to avoid too many Legendre terms and streams in the RT calculation.

Other elements of phase matrix are adjusted with conserving their ratio values to the phase function.



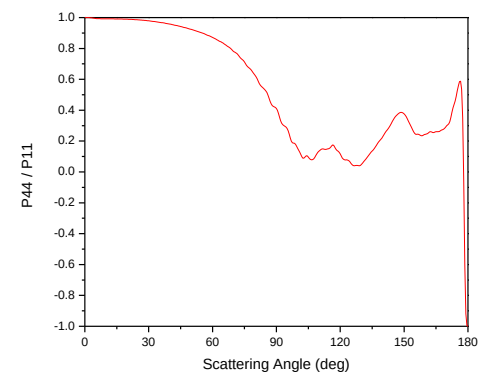


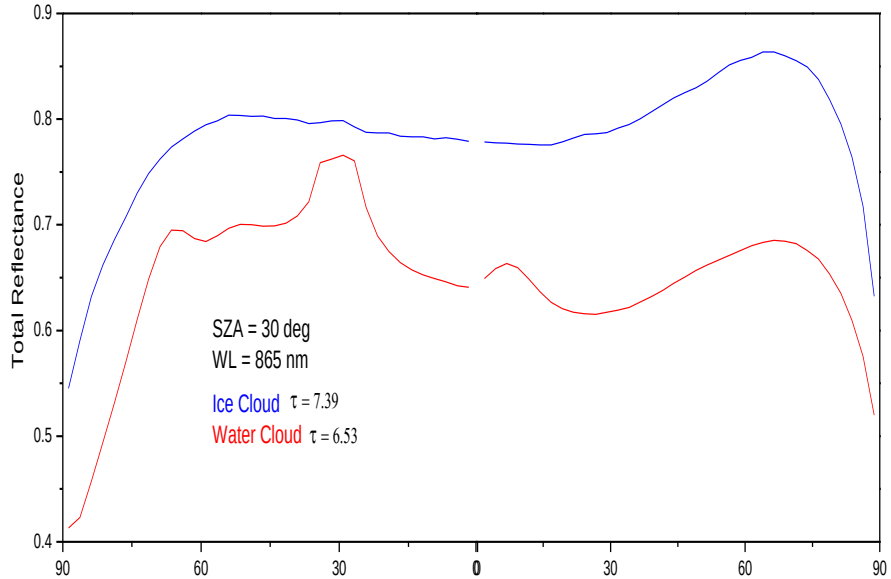


$$\tau_s^{'} = (1 - f)\tau_s$$

$$\tau^{'} = \tau_a + \tau_s^{'}$$

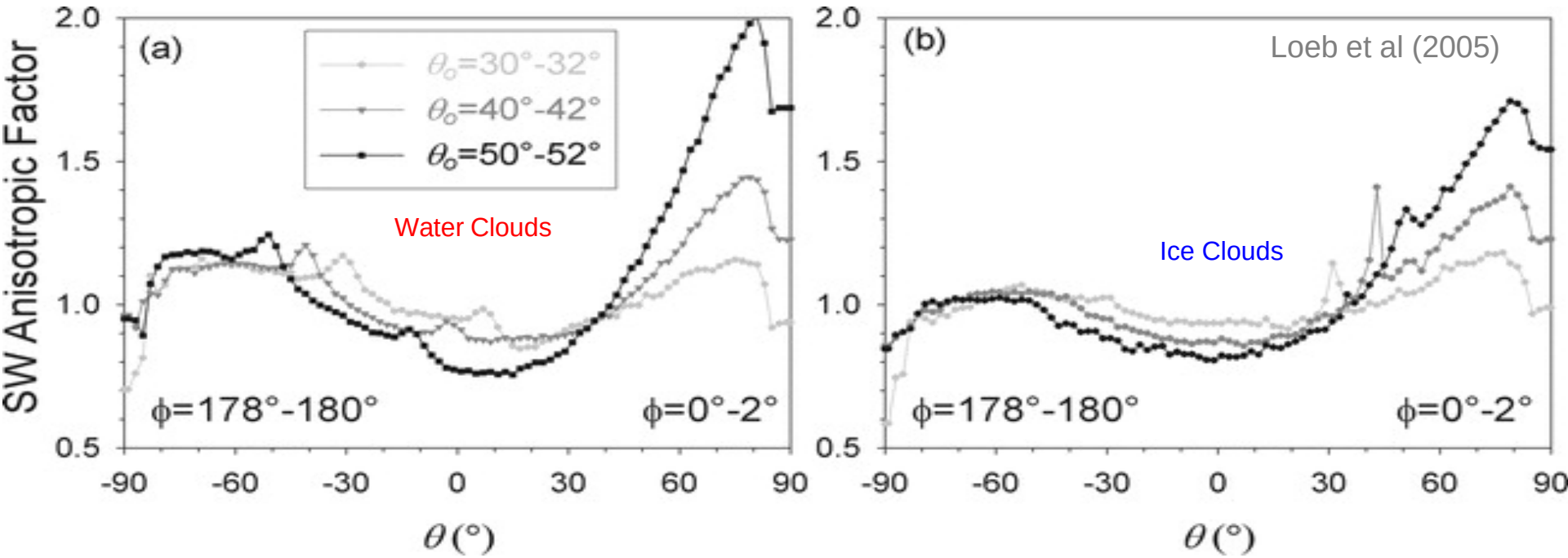
$$\alpha^{'} = \tau_s^{'} / \tau^{'}$$



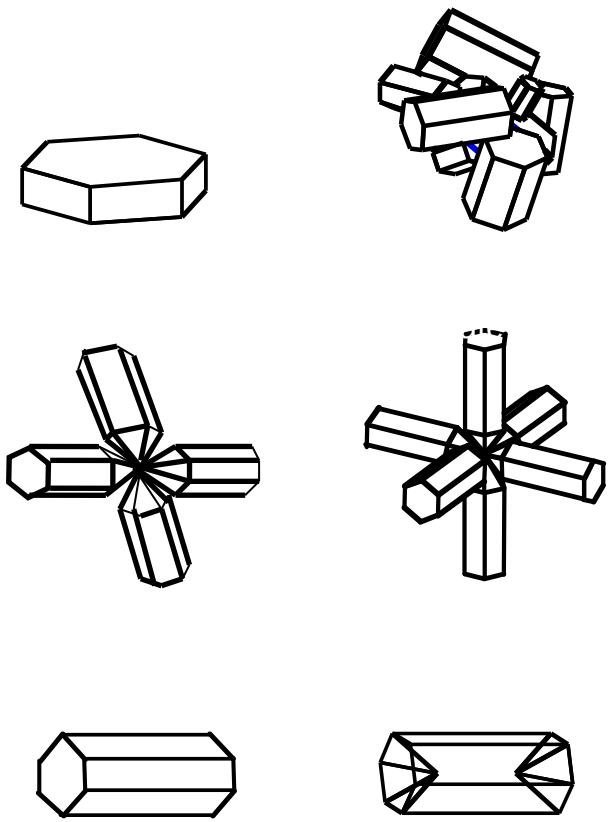


Model results have excellent agreement with CERES data in total radiance angular anisotropy, except the ice cloud specular reflection, since we assume pure randomly oriented ice crystals in the model.

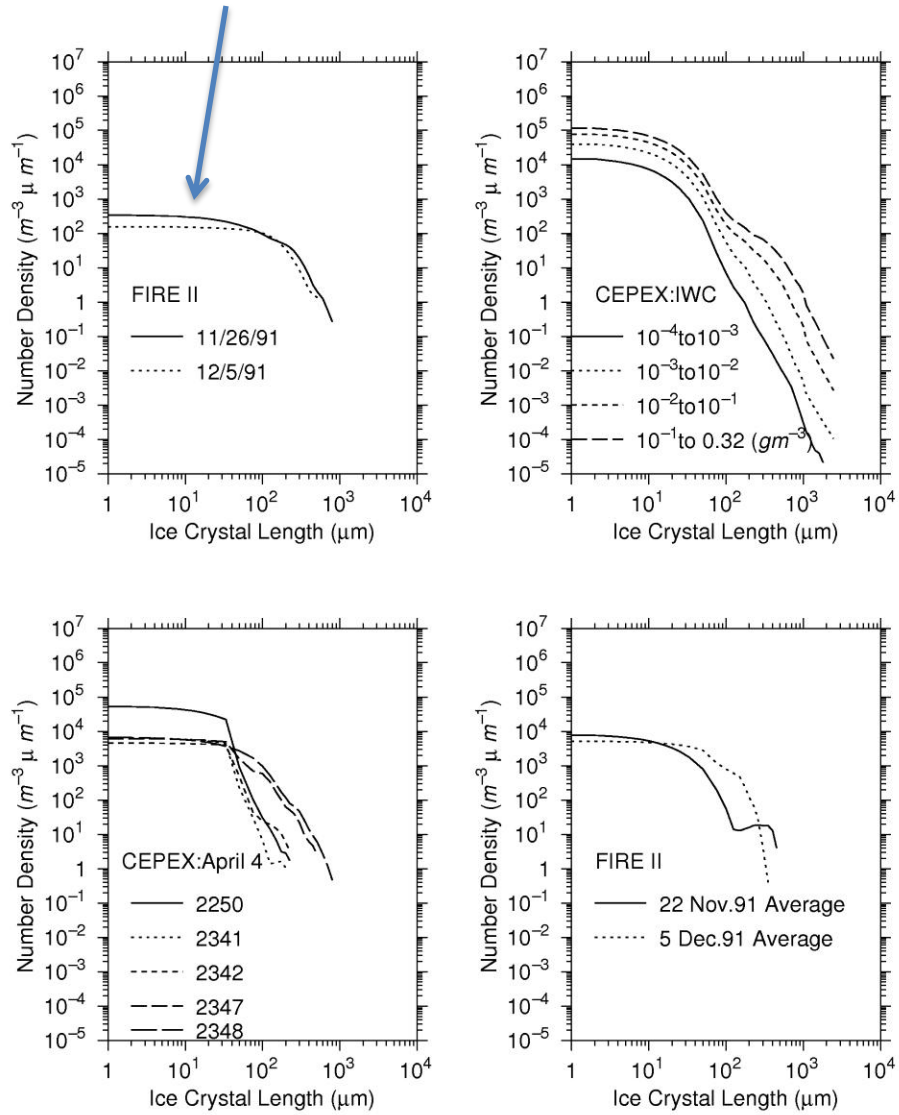
CERES SW anisotropic factors in the principal plane



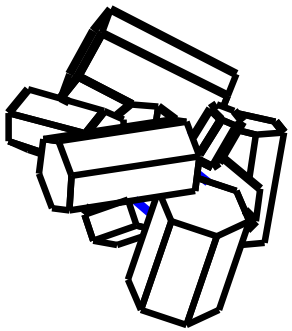
Sensitivity of polarized radiation to ice cloud particle shapes

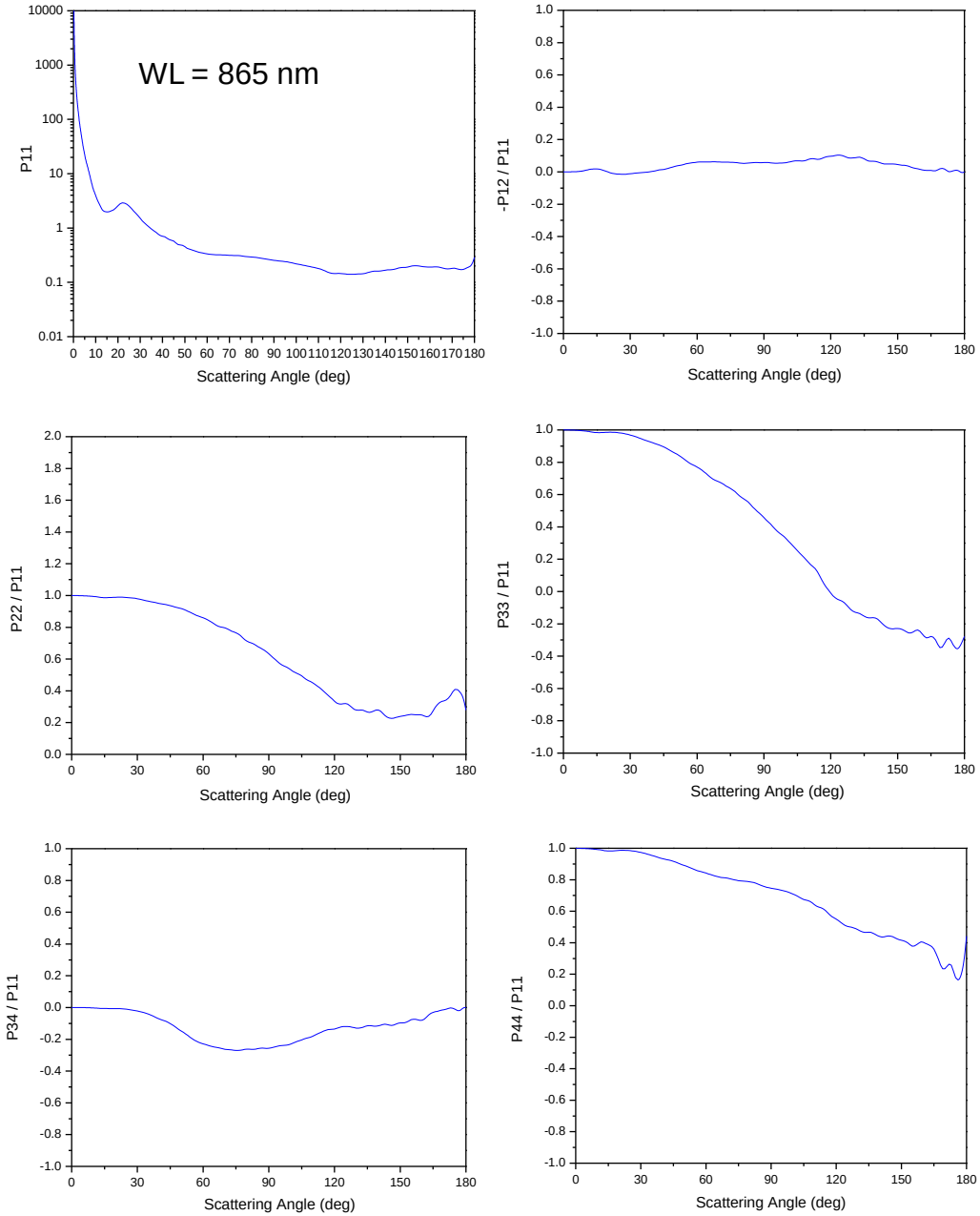


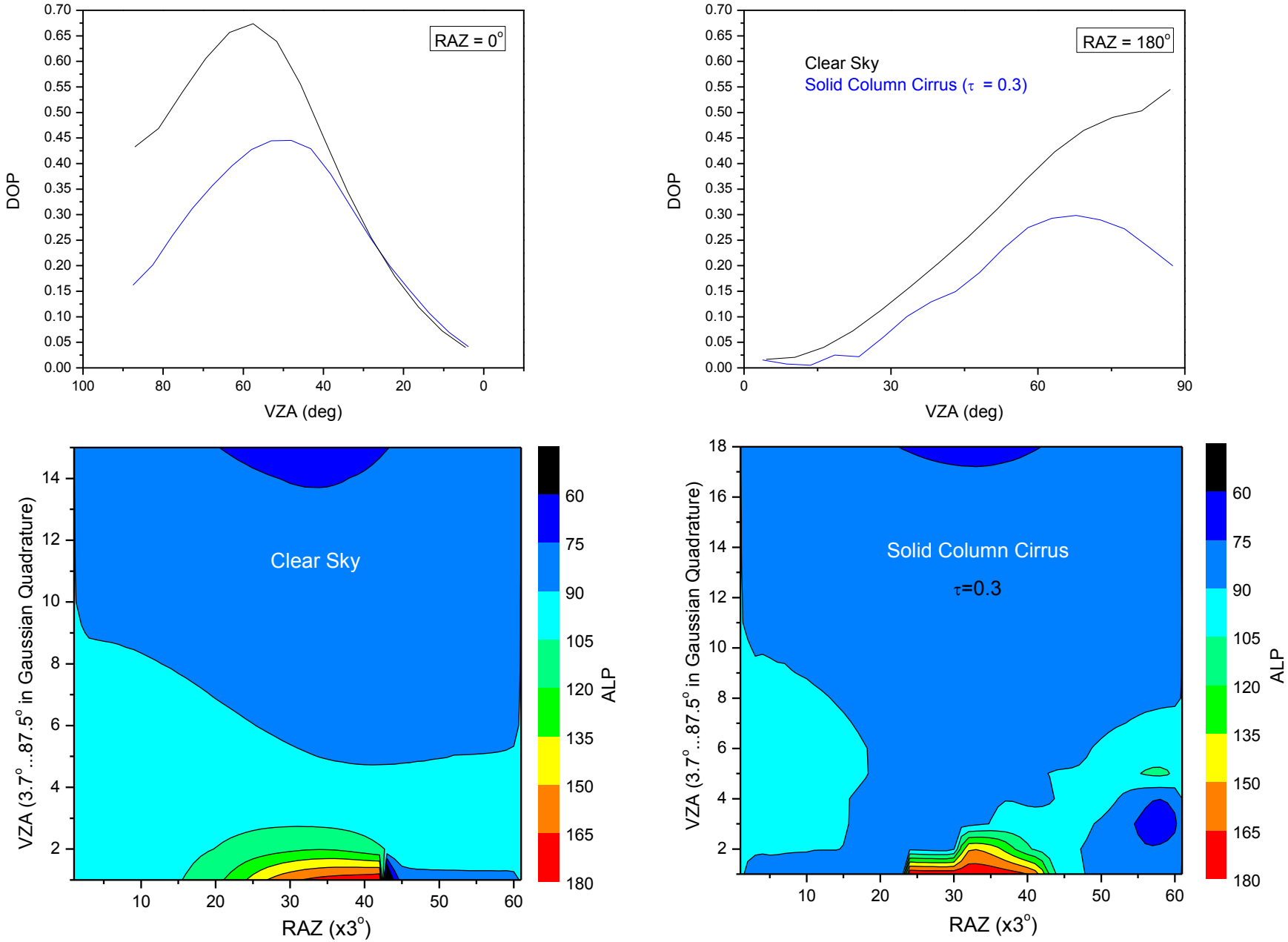
Cloud particle size distribution used in this study



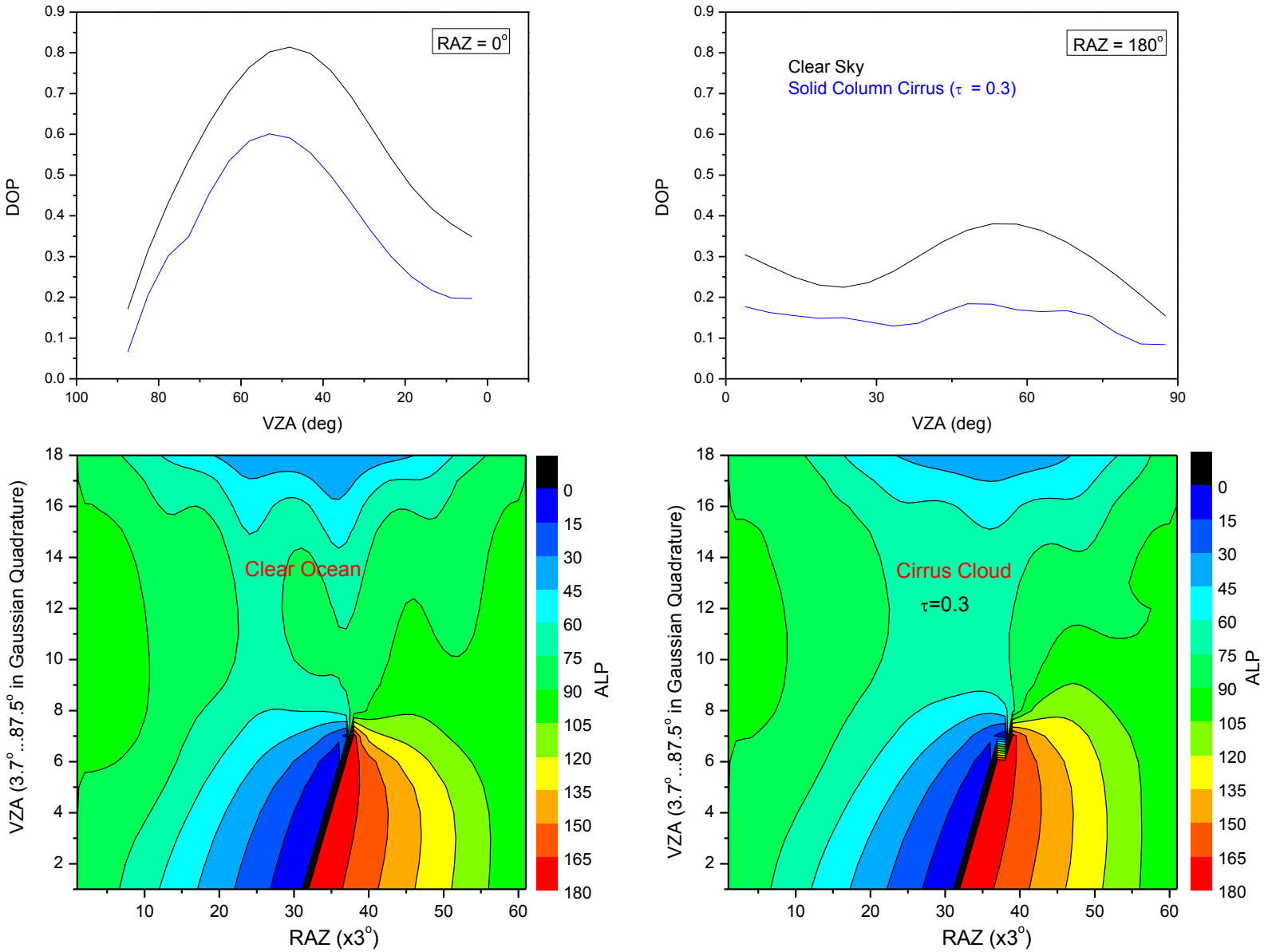
Phase matrix elements of rough ice aggregates



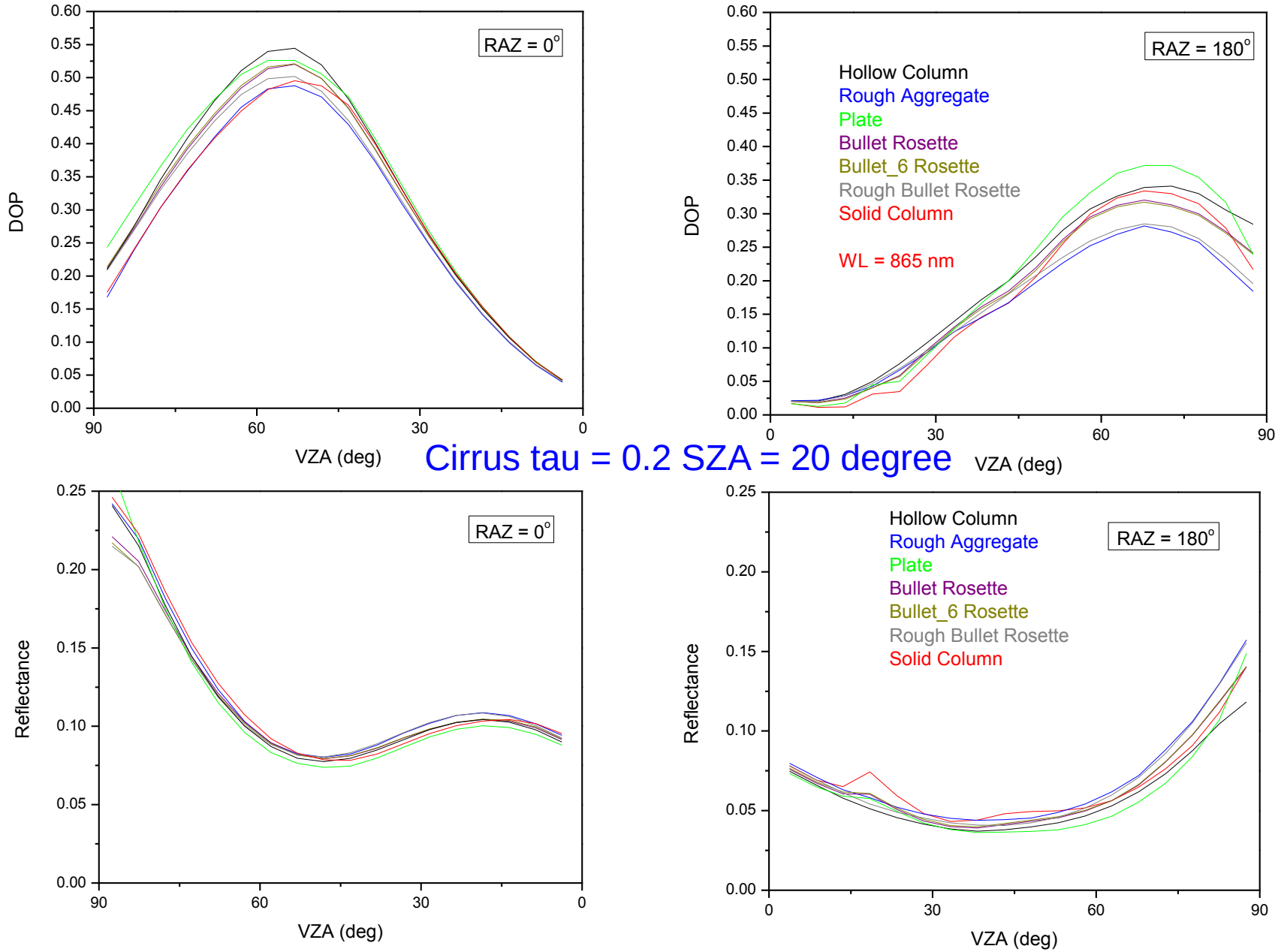




Thin ice cloud effect on TOA polarized radiation at SZA = 20 degree

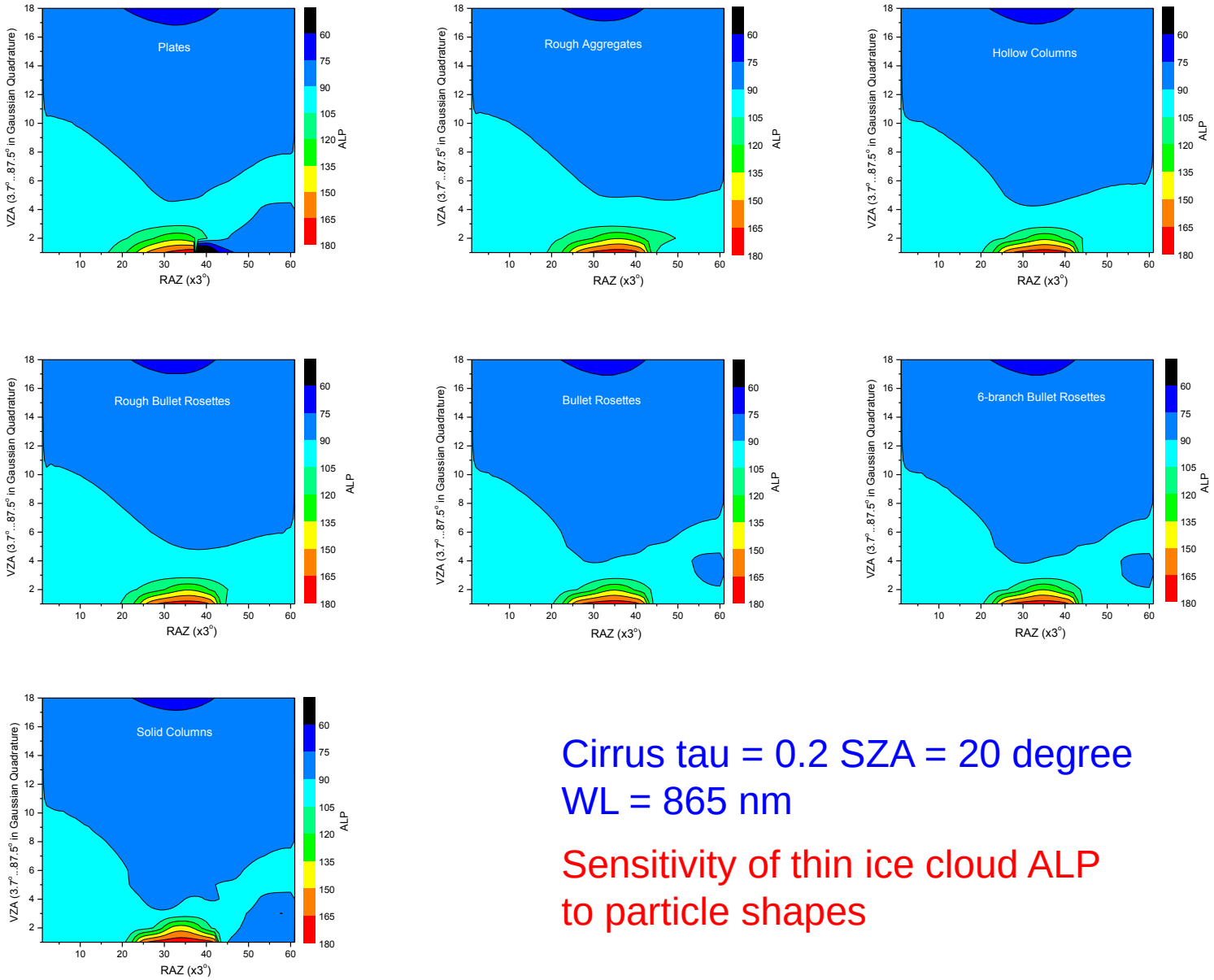


Thin ice cloud effect on TOA polarized radiation at SZA = 60 degree



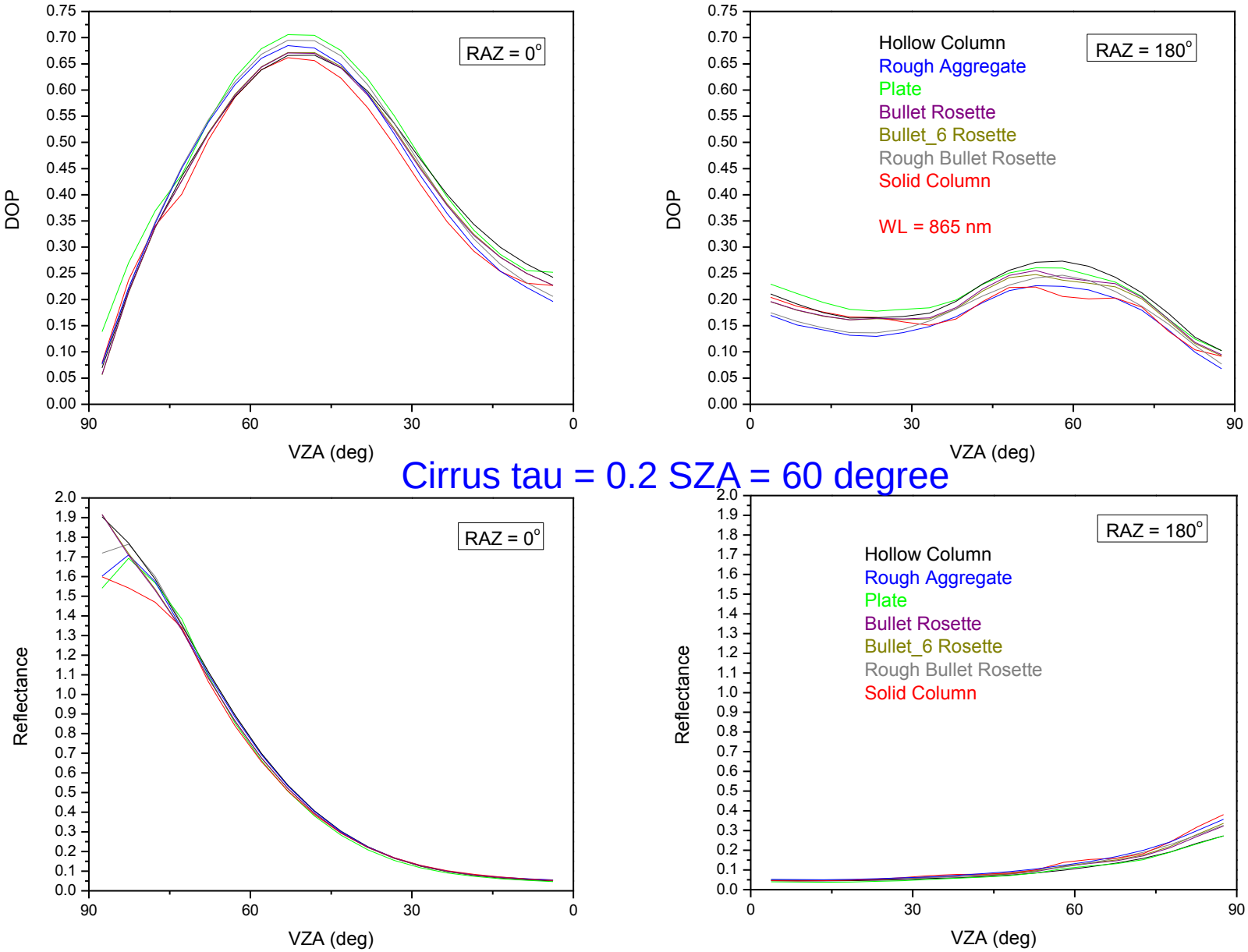
Cirrus tau = 0.2 SZA = 20 degree

Sensitivity of thin ice cloud DOP and reflectance to particle shapes



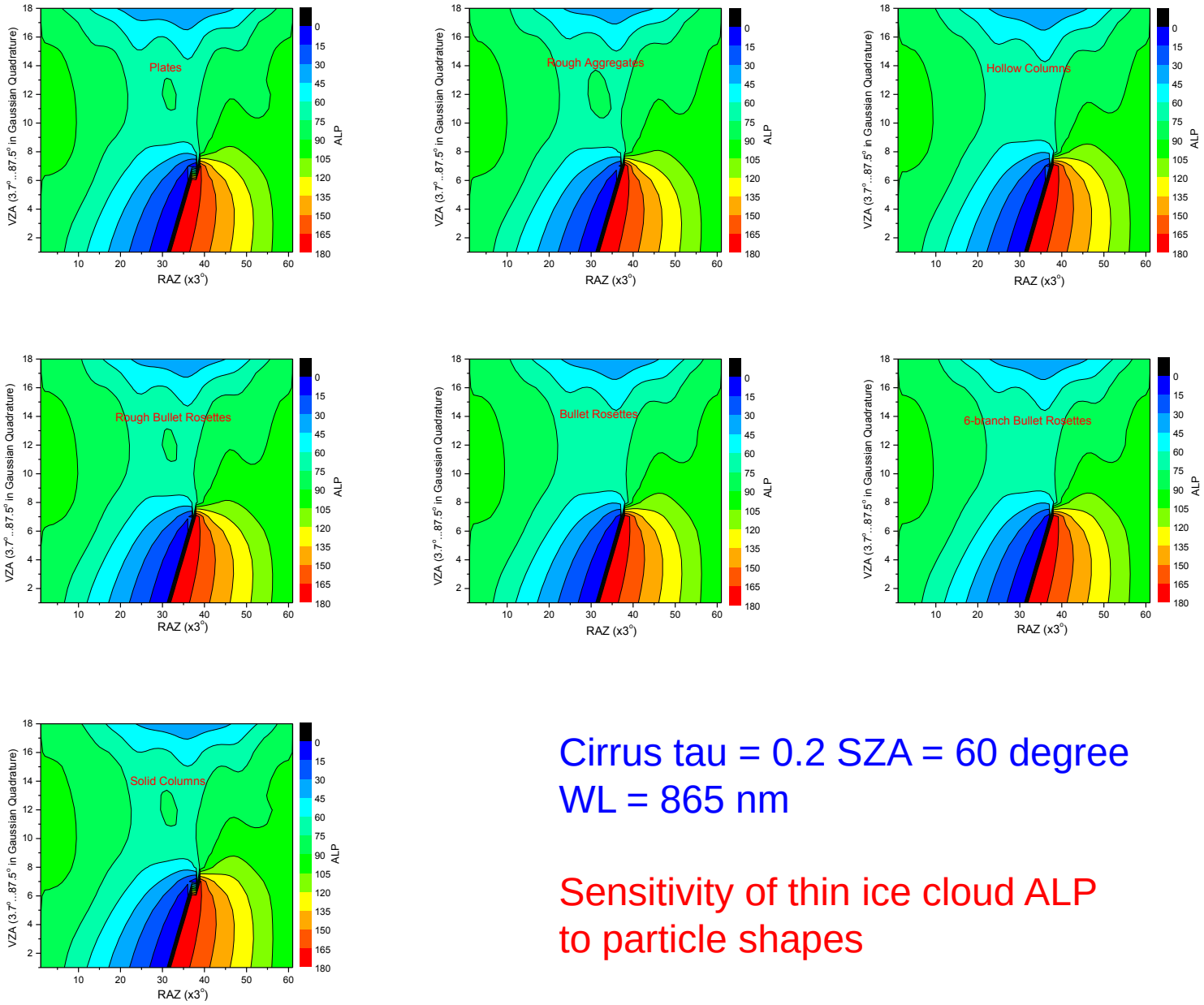
Cirrus tau = 0.2 SZA = 20 degree
WL = 865 nm

Sensitivity of thin ice cloud ALP to particle shapes



Cirrus tau = 0.2 SZA = 60 degree

Sensitivity of thin ice cloud DOP and reflectance to particle shapes



Cirrus tau = 0.2 SZA = 60 degree
WL = 865 nm

Sensitivity of thin ice cloud ALP
to particle shapes

Summary

1. Sensitivity of polarized radiation at TOA to cirrus clouds and their particle shapes is studied.

2. Subvisual cirrus could significantly affect DOP but their effect on ALP is not big.

3. Uncertainty in DOP caused by model particle shapes is ~0.05, with stronger effect at backscattering viewing angles.

4. This study shows that, except spherical particles, different nonspherical ice cloud particle shapes do not significantly change the polarization of the radiation.

5. The major issue related to radiation polarization for thin cirrus clouds is their optical thickness.