ICE CLOUD PARTICLE ROUGHNESS INFERRED FROM SATELLITE POLARIMETRIC OBSERVATIONS

Souichiro Hioki and Ping Yang*
Texas A&M University, College Station, Texas

Bryan A. Baum
University of Wisconsin-Madison, Madison, Wisconsin

1. INTRODUCTION

In modern meteorology, which relies on large computational resources, the consistency between models and observations is of great concern. Recent advances in light scattering calculation technique and improvements in computational power have made it possible to calculate ice particle scattering properties across a broad range of size, based on the assumption of particle shape (Yang et al. 2013). The scattering properties can be used to simulate the cloud reflectivities with radiative transfer calculations and can be compared with satellite observations. However, the best shape and the degree of roughness, in other words, the best particle model, is still uncertain. As particle models are engaged in the retrieval of cloud microphysical properties from satellite data, they are for cornerstones for validating cloud schemes in general circulation models. The particle model that is consistent with observations is in need.

The ice particle roughness parameter is one parameter that describes the degree of imperfection in a particle model. It has been known that some degree of roughness improves the agreement between simulations and observations of cloud reflection in terms of both the radiance and the polarization state (Baran and C.-Labonnote 2006, 2007). The retrieval of the parameter benefits from the multi-angle polarimetric observation as it is sensitive to the particle shape and roughness (van Diedenhoven et al., 2012; Cole et al. 2014). In this presentation, we discuss how particle roughness parameter is inferred from satellite polarimetric observations and what the result implies on operational retrieval schemes.

* *Corresponding author address:* Ping Yang, Department of Atmospherics Sciences, Texas A&M University, College Station, Texas, 77840-3150; email: pyang@tamu.edu

2. METHODOLOGY

2.1 ROUGHNESS INFERENCE

In this study, the conventional inference method is refined by utilizing an empirical orthogonal function (EOF) analysis. The conventional method selects the particle roughness parameter from a discrete set, based on the degree of agreement between the simulated cloud polarized reflectivities and observations; a roughness parameter is considered to be the best when the corresponding scattering property results in polarized reflectivities that best match with the multi-angle observations. By applying the EOF analysis, we replaced the discrete parameter space with a continuous parameter space, on which the retrieval error is much easily quantified.

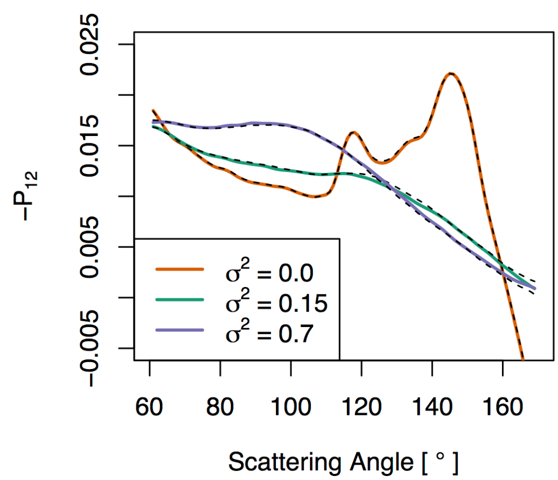

Fig. 1. $-P_{12}$ elements of Mueller matrices in backscattering directions for column-aggregate particle habit with three different roughness parameters (σ^2). Original $-P_{12}$ elements are shown with color solid lines, and reconstructions from two EOFs are plotted with black dot lines. Two EOFs reasonably reconstruct original $-P_{12}$.

Figure 1 displays the three $-P_{12}$ elements of Mueller matrices in backscattering directions. The column-aggregate particle habit is assumed. The particle size distribution is a gamma-like distribution with effective variance of 0.1 and effective radius of 30 μm. The original $-P_{12}$ elements are plotted with color solid lines, and the reconstructions are plotted with black dot lines. The reconstruction is a linear combination of two major EOFs that are obtained from our EOF analysis. The EOF analysis is applied with ten $-P_{12}$ elements for different degree of roughness in the scattering angle range between 60° and 170°. This result implies that the two EOF scores can be retrieved from satellite polarimetry.

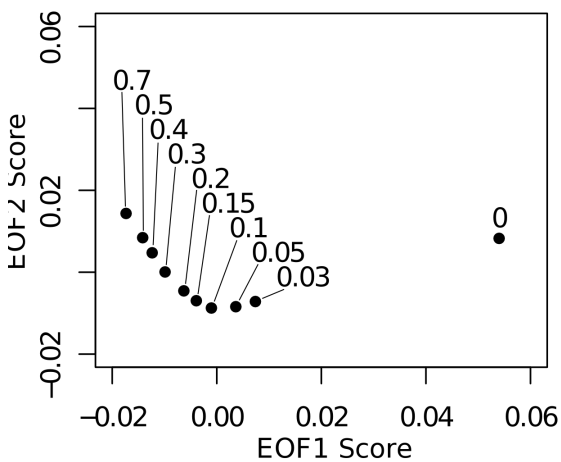

Fig. 2. EOF scores for ten particle roughness parameters (σ^2). EOF1 score is a monotonic function of the roughness parameter.

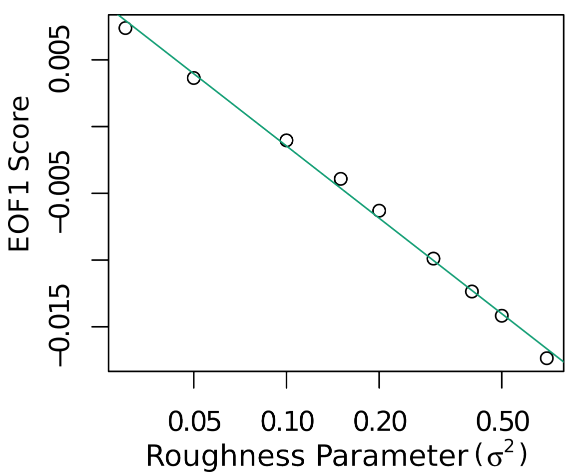

Fig. 3. EOF1 scores are linear function of the logarithm of particle roughness parameters (σ^2).

For each of ten Mueller matrices, the EOF scores are calculated (Fig. 2) and the radiative transfer calculations are conducted. The calculated polarized reflectivities are interpolated in the EOF score space to build a lookup table. The lookup table provides a polarized reflectivity as a function of optical thickness and EOF scores. Once data from multi-angle observation is given, an inversion program utilizes the lookup table to find the best optical thickness and EOF scores that explain the observation.

As the EOF score corresponding to EOF1 (EOF1 score) is a monotonic function of particle roughness parameter (σ^2), retrieved EOF1 score is a proxy to the particle roughness, or it can be interpreted as “effective roughness”. The logarithm of σ^2 is a linear function of EOF1 score (Fig. 3). With this relation, the EOF1 scores that are retrieved from satellite observations can be converted to particle roughness parameters.

2.2 SATELLITE DATA PREPROCESSING

Another aspect on which this study made an improvement is the treatment of cloud top height. Shifting cloud top height from 200 hPa to 500 hPa brings the same magnitude of change in the polarized reflectivity as increasing particle roughness parameter from 0.1 to 0.5 (not shown). However, the variation of cloud top height has not been properly taken into account in previous studies. We developed a simple non-linear regression model that can separate cloud reflection and Rayleigh scattering signal that originate above the cloud.

The cloud polarized reflectivity data from Polarization and Anisotropy in Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL) sensor was collocated and filtered with cloud products from MODerate resolution Imaging Spectroradiometer (MODIS) science team to select ice clouds. Then, the pixels over ocean are processed with the regression model, which utilizes three PARASOL channels at visible and near-infrared wavelengths. The cloud reflectivity obtained with the regression is used to retrieve cloud optical thickness and EOF scores as described in 2.1.

3. RESULTS AND DISCUSSION

The particle roughness is inferred from one month of PARASOL data (September, 2005) over the Western Pacific. The distribution of retrieved roughness parameter is presented in Figure 4. The roughness parameter had a maximum about EOF1 = -0.02, which corresponds to $\sigma^2 = 1$. This result implies that a deeply roughened particle model is more suitable than a pristine particle model, as suggested by previous studies (Baran and C.-Labonnote 2006, 2007; Cole et al. 2014). The distribution is significantly broader than the width predicted by the forward calculation (gray shaded range), and there was a small peak at EOF1 = 0.18. It is not certain what causes the broad distribution and the small peak, but they may imply that there are some pixels for which column-aggregate particle habit is not appropriate. The horizontal cloud heterogeneity and cloud edge pixels may also have an influence on the result.

The density distribution of EOF1 score is plotted in Figure 5. Except for the small peak at EOF=0.18, the density distributions in tropics and extratropics are very similar. These results justify the use of roughened particle model (e.g. MODIS Collection 6) in the cloud property retrieval across the globe.

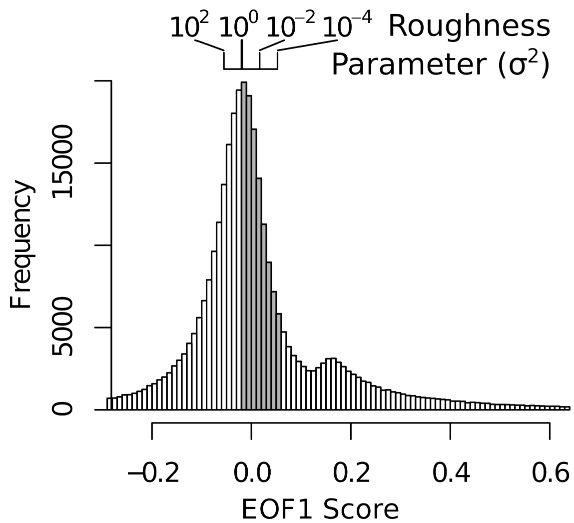

Fig.4. The histogram of EOF1 score retrieved from one month of PARASOL data over Western Pacific. The maximum is at EOF1 = -0.02, which corresponds to the roughness parameter $\sigma^2 = 1$.

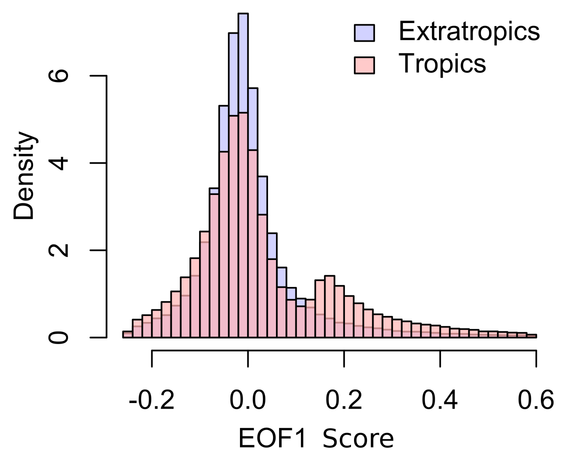

Fig. 5. The density distributions of EOF1 score in tropics and extratropics. Distributions are similar to each other except the small peak at EOF=0.18 for the tropics case.

4. SUMMARY

In this study, the inference of ice cloud particle roughness is refined and applied with data from the PARASOL sensor. The construction of continuous parameter space is aided with an empirical orthogonal function (EOF) analysis, and the data from PARASOL sensor is preprocessed with a regression model to remove Rayleigh scattering signals that originate above the cloud tops. The retrieved EOF1 score favored the roughened particle model both in tropics and extratropics. The result justifies the application of roughened particle model for the ice cloud retrieval scheme across the globe. However, the broad EOF1 distribution and theß unexpected small peak may suggest that the assumed particle habit is inappropriate in some cases. Further investigation is needed to evaluate the extent to which observational error and retrieval assumptions contribute to the result.

5. Acknowledgement

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5. REFERENCES

Baran, A. J. and L. C-Labonnote, 2006: On the reflection and polarisation properties of ice cloud. *J. Quant. Spectrosc. Radiat. Transf.*, **100**, 41-54.

——, and ——, 2007: A self-consistent scattering model for cirrus. I: The solar region. *Q. J. R. Meteorol. Soc.*, **133**, 1899-1912.

Cole, B. H., P. Yang, B. A. Baum, J. Riedi, and L. C.-Labonnote (2014), Ice particle habit and surface roughness derived from PARASOL polarization measurements, *Atmos. Chem. Phys.*, **14**, 3739-3750.

van Diedenhoven, B., B. Cairns, I. V. Geogdzhayev, A. M. Fridlind, A. S. Ackerman, P. Yang, P. and B. A. Baum, 2012: Remote sensing of ice crystal asymmetry parameter using multi-directional polarization measurements – Part 1: Methodology and evaluation with simulated measurements, *Atmos. Meas. Tech.*, **5**, 2361–2374.

Yang, P., L. Bi, B. A. Baum, K-N. Liou, G. W. Kattawar, M. I. Mishchenko, and B. H. Cole., 2013: Spectrally Consistent Scattering, Absorption, and Polarization Properties of Atmospheric Ice Crystals at Wavelengths from 0.2 to 100 μm, *J. Atmos. Sci.*, **70**, 330–347.