Reconstructed morphology of rough ice facets by variable pressure scanning electron microscopy

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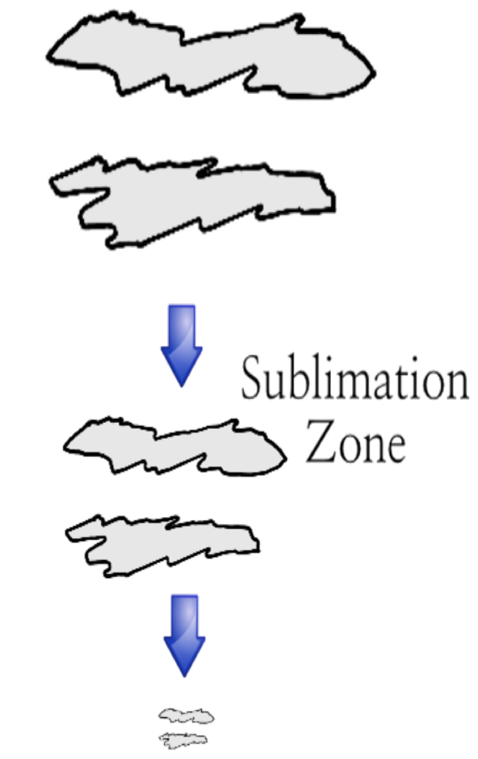
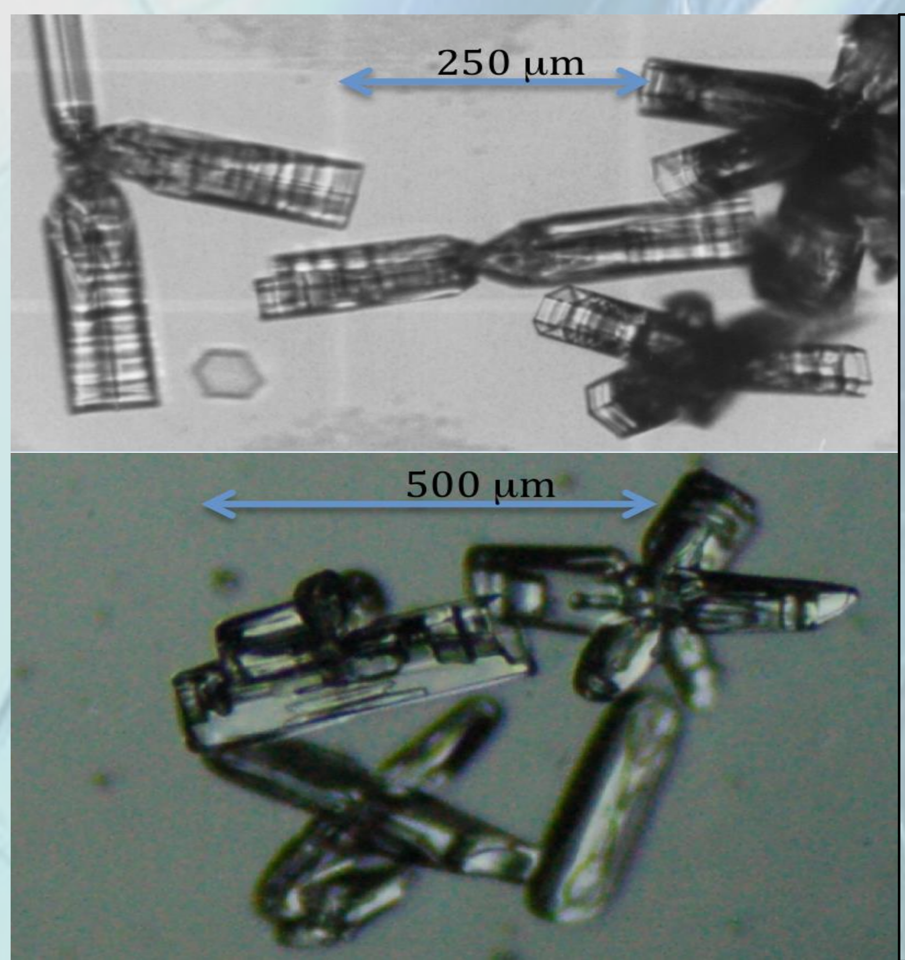
1. Introduction

It has been well established that differences in the size and habit of atmospheric ice crystals have a large effect on their light scattering properties.[1] Because cirrus and contrail cirrus clouds are composed primarily of ice, and these clouds have a large impact on the radiative budget of the planet, an accurate understanding of the single-scattering properties of atmospheric ice would help to improve climatological models and remote sensing capabilities.[2] Although it has been hypothesized that changes in mesoscopic (micrometer scale) surface morphologies can greatly influence these scattering properties, much less is known about the scattering effects of differences on this scale than more general crystal size and shape. Another motivation for studying ice crystal roughness at this scale is the fact that ice surface morphologies are known to catalyze a variety of atmospheric chemical reactions.[3]



Roughness in Cirrus Ice Crystals: Cirrus crystals can fall for kilometers before they completely ablate.[2] During this sublimation (which can comprise up to one third of a cloud's vertical extent) the ice crystals experience roughening on a mesoscopic scale. This roughening has been offered as an explanation for disparities between observed ice cloud asymmetry parameters and values calculated using smooth ice as a model.[3]

More evidence for mesoscopic roughening in atmospheric ice can be found in captured optical images of falling ice crystals. A close examination of the following images reveals roughening rings present along many of the hexagonal columns of crystals that were imaged.



Photographs of atmospheric ice at ground level. The first is was taken on 21 July 1992 at South Pole Station. The second is from 25 February 2011 at Summit, Greenland.[Walden et al. 2003] Note the roughening rings present on crystals in both images.

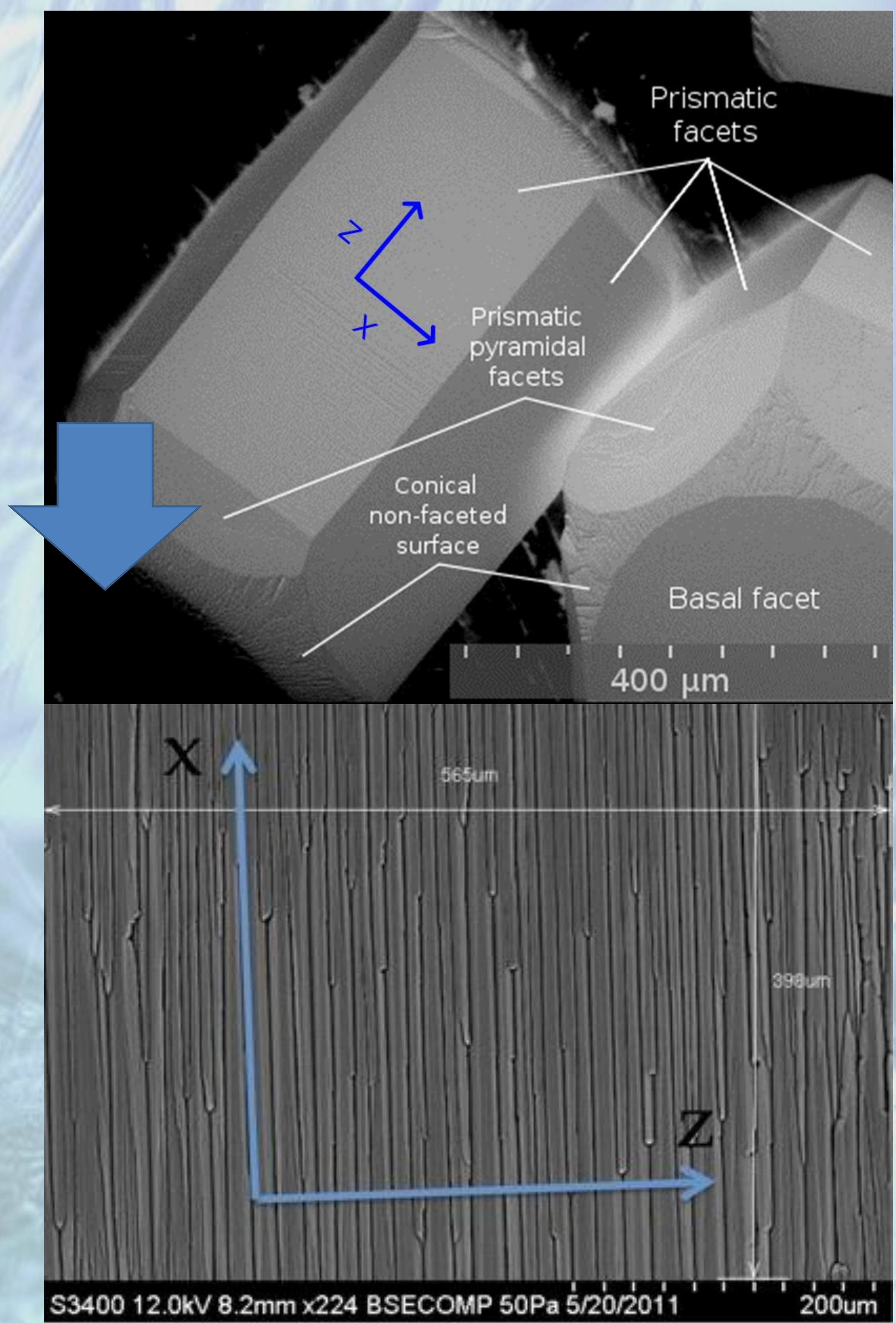
2. VP-SEM Experiments

Variable pressure scanning electron microscopy (VP-SEM) has emerged as an excellent means to study mesoscopic ice crystal roughnesses. It is able to provide high resolution images while controlling vapor pressure and temperature.

A Hitachi S-3400 N VP-SEM was used with a Deben Ultra-Cool stage MK3 version Peltier cooling element to grow crystals on a rough copper stage with ~4 mL DI water.

3. Images

VP-SEM images were collected at pressures from 50 to 100 Pa and temperatures from -20°C to -50°C. By using the SEM in back-scatter detection mode with water vapor as the charge-carrying gas, 3D images of prismatic facets were captured. The goal was to create equilibrium conditions inside the SEM chamber and then capture the mesoscopic roughnesses on the prismatic facets of hexagonal crystals, which resemble those found in cirrus clouds.



4. Algorithm

The largest improvement that the means of analysis presented here has over previous work is the software used to extract 3D surfaces from the SEM images. Using a proprietary software provided by Hitachi, 3D image Viewer v 1.01 by Denshi Kougaku Kenkyusyo Company, 3D surfaces were able to be extracted directly from SEM images with a much greater level of precision than previous work.[1]

References

[1] Macke et al. (1998) *J. Atmos. Sci. 55(17)*, 2874-2883

[2] Crane and Barry (1984) *J. Climatol. 4(1)*, 71-93

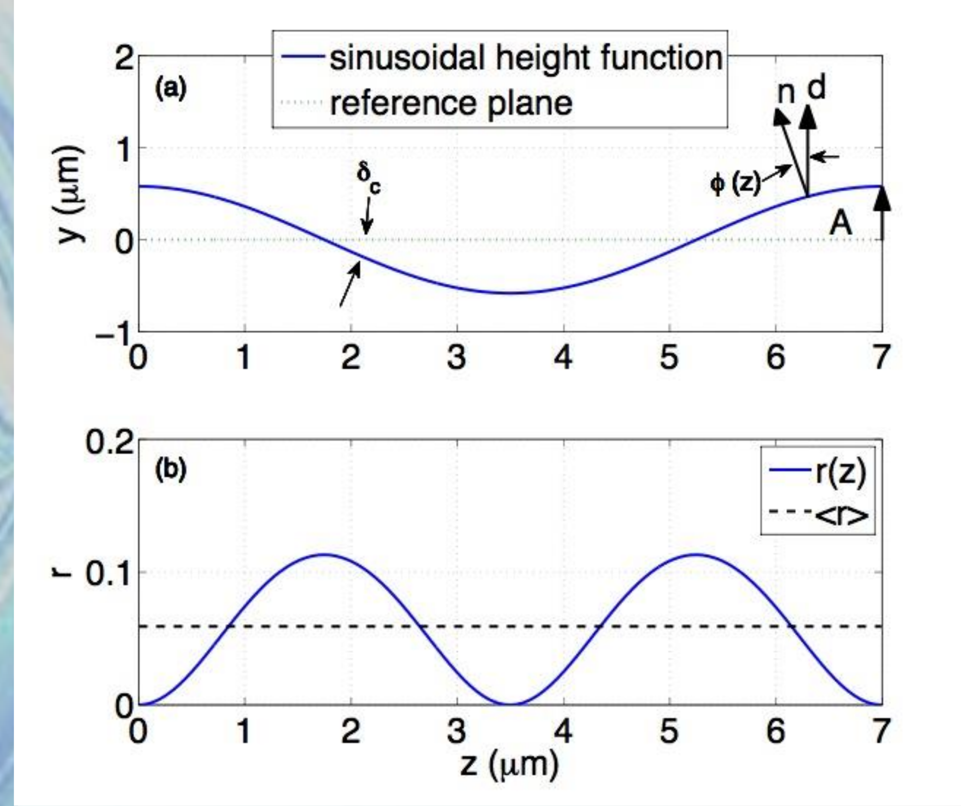
[3] Neshyba et al. (2013) *J. Geophys. Res.-Atmos. 118*, 1-10

[4] Shcherbakov et al. (2006) *J. Atmos. Sci. 63(5)* , 1513-1525

5. Results

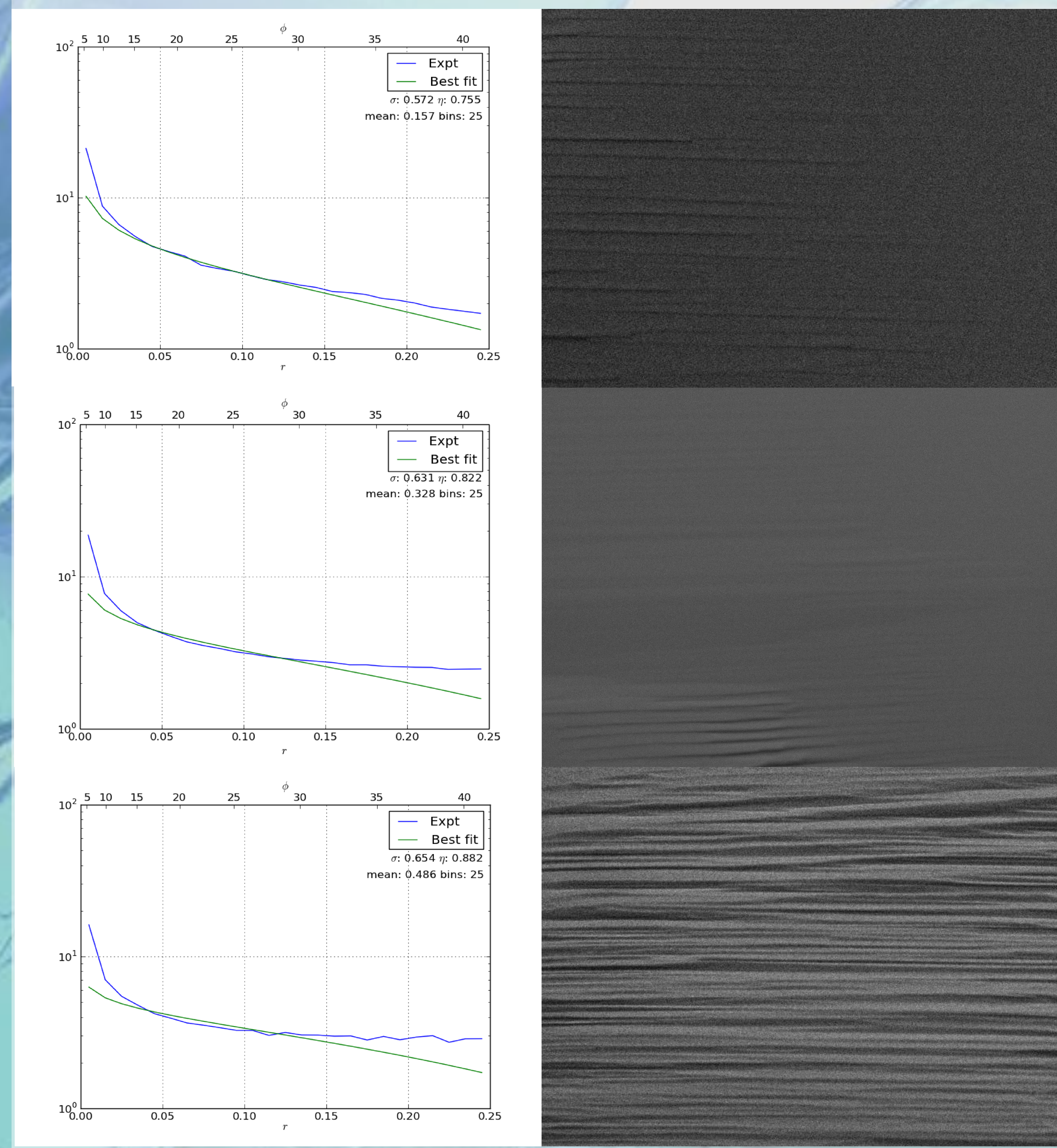
Quantifying Roughness: To quantify mesoscopic roughnesses in the prismatic facets of the crystals, a roughness parameter *r* based on the surface normal projection of the VPSEM on the crystal was used:

$$r = \cos\varphi$$



A plot of y-z roughness shown above a plot of the roughness parameter r against z. The plot below shows how the r parameter varies with the actual roughnesses of the surface. This allows for roughness in the z direction to be quantified.

This roughness parameter *r* can then be used to generate a plot of roughness versus the probabilities obtained from a histogram generated from the data.



It has been proposed that these probability distributions can behave to fit a Weibull distribution[4]:

$$f(r) = \frac{\beta}{\eta}\left(\frac{r}{\eta}\right)^{\beta-1} e^{-\left(\frac{r}{\eta}\right)^{\beta}}$$

6. Future Work

The next step is to attempt applying a 3-paramater Weibull distribution to the data. There is also much work to be done defining the effects of temperature and pressure on prismatic facet roughness, and quantifying roughness on basal facets which appear to have a much less straightforward morphology.