Understanding Natural Variability of VSFs and Its Impact on Remote Sensing Reflectance

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It is known that VSF shapes affect Rrs. This effect, and the effect due to the viewing geometry are often lumped together into f/Q in ocean color.

$$R_{rs} = \frac{f}{Q}\frac{b_b}{a + b_b}$$

Gordon & Morel – type f/Q

Shape effect is implicitly contained in f/Q that were simulated using one or a set of VSFs. Examples:

Morel & Gentili (1991; 1993; 1996), Petzold's PF with Bp = 1.83%

Morel et al. (2002), mixing of two simulated PFs, Bp = 1.4% for small and =0.19% for large particles

Lee et al. (2011), mixing of two PFs, Bp = 1% FF for phytoplankton and average Petzold Bp = 1.83% for mineral particles.

Zaneveld – type f/Q

VSF shape is explicitly contained in f/Q that were derived from the RTE. Zaneveld (1982; 1995)

Several ways to define a shape of a VSF

Normalized by b: the phase function

$$\overline{\beta}(\theta) = \frac{\beta(\theta)}{b}$$

$$b = 2\pi \int_0^{\pi} \beta(\theta) \sin\theta d\theta$$

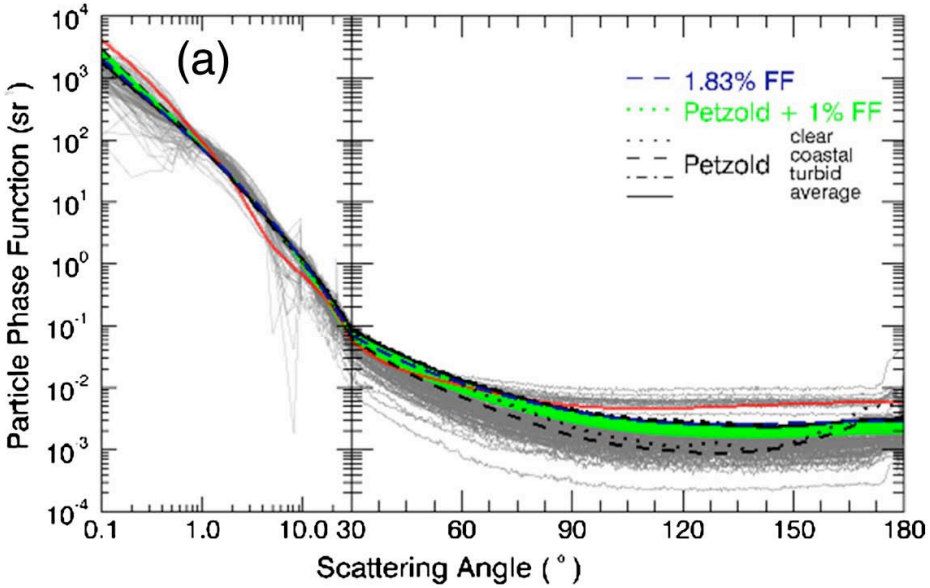
Normalized by b_b: the χ factor

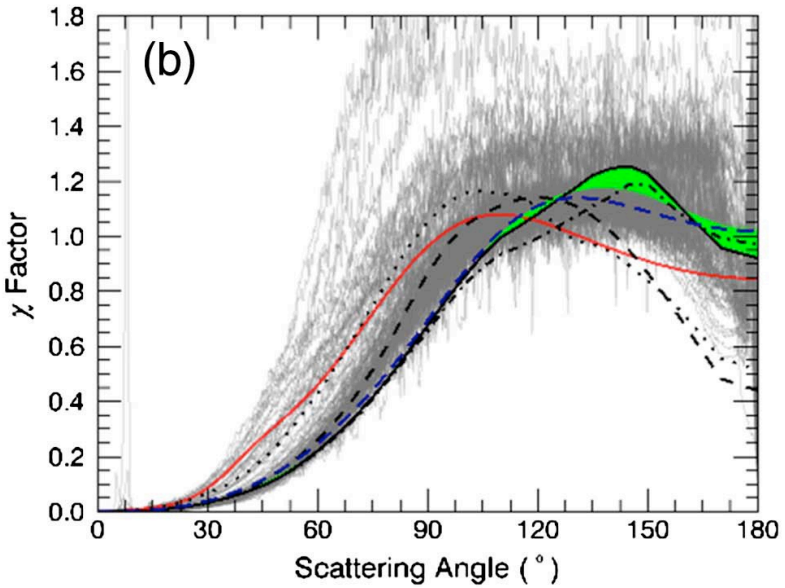
$$\alpha(\theta) = \frac{1}{\chi(\theta)} = \frac{2\pi\beta(\theta)}{b_b}$$

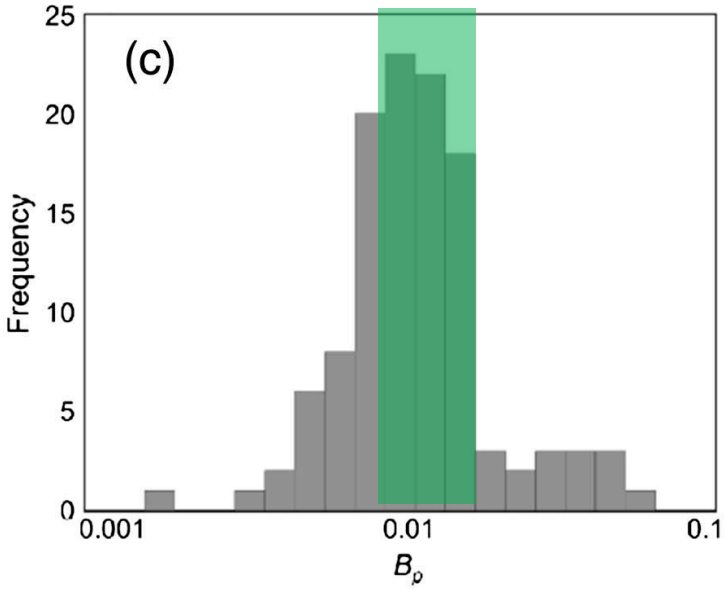
$$b_b = 2\pi \int_{\pi/2}^{\pi} \beta(\theta) \sin\theta d\theta$$

Backscattering ratio

$$B = \frac{b_b}{b}$$







Conclusion 1: regardless what shape definition is used, the VSF shapes used in the previous studies have underestimated the range of variabilities of natural particles

Q1: What is the impact on Rrs given the observed natural variability of the VSF shapes
Q2: Among the three shape factors that can be used to describe a VSF shape, which one is most useful in improving our understanding of f/Q.

Use HydroLight to simulate Rrs using 116 VSFs measured in Chesapeake Bay, Mobile Bay, Monterey Bay and North Atlantic Ocean. Following the IOCCG Report No. 6 (2006, ed. Zhongping Lee).

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- 500 values of [C] (over 20 ranges, and 25 random values within each range)
- For each [C] value, a and b_b are generated at 532 nm
- For each set of a and b_b, each of 116 measured phase functions was used for Hydrolight simulation
- The simulation was run for ϑ_s = 0:15:75, ϑ_v = 0:10:70, and φ = 0:15:180.
- Over 2 million simulated Rrs.

Quasi-single-scattering approximation

$$r_{rs} = \frac{1}{\cos\theta_v + \cos\theta_s} \frac{\beta(\gamma_s)}{a + b_b}$$

$$= \frac{\beta(\gamma_s)}{B} \frac{1}{\cos\theta_v + \cos\theta_s} \frac{b_b}{a + b_b}$$

$$= \frac{1}{2\pi\chi(\gamma_s)} \frac{1}{\cos\theta_v + \cos\theta_s} \frac{b_b}{a + b_b}$$

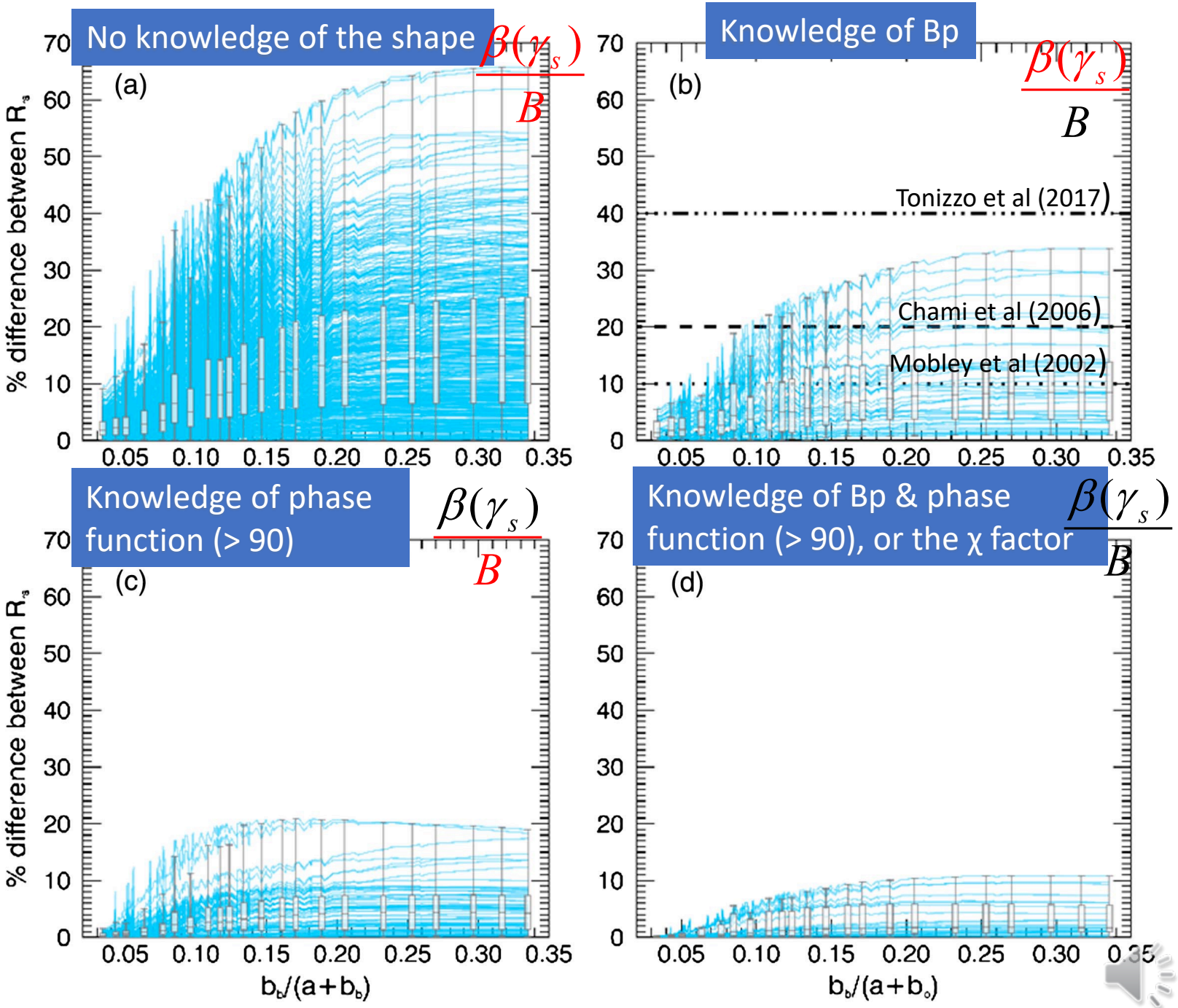
Xiong et al. (2017) Applied Optics.

$$\Delta R_{rs} = \frac{\left|R_{rs}(i) - R_{rs}(j)\right|}{\frac{R_{rs}(i) + R_{rs}(j)}{2}}$$

$\theta_s = 30°$,
$\theta_v = 0°$

$$r_{rs} = \frac{\beta(\gamma_s)}{B} \frac{1}{\cos\theta_v + \cos\theta_s} \frac{b_b}{a + b_b}$$

1. With increasing constraint on the knowledge of VSF shape, the variability in Rrs decreases from 65% (15%) for (a), 35% (8%) for (b), 20% (5%) for (c), and to 10% (2%) for (d).
2. Among the variability in Rrs due to VSF shapes, 71% can be explained by Bp, 90% by PF (> 90), and 97% by the X factor.



ΔRrs due to VSF shapes

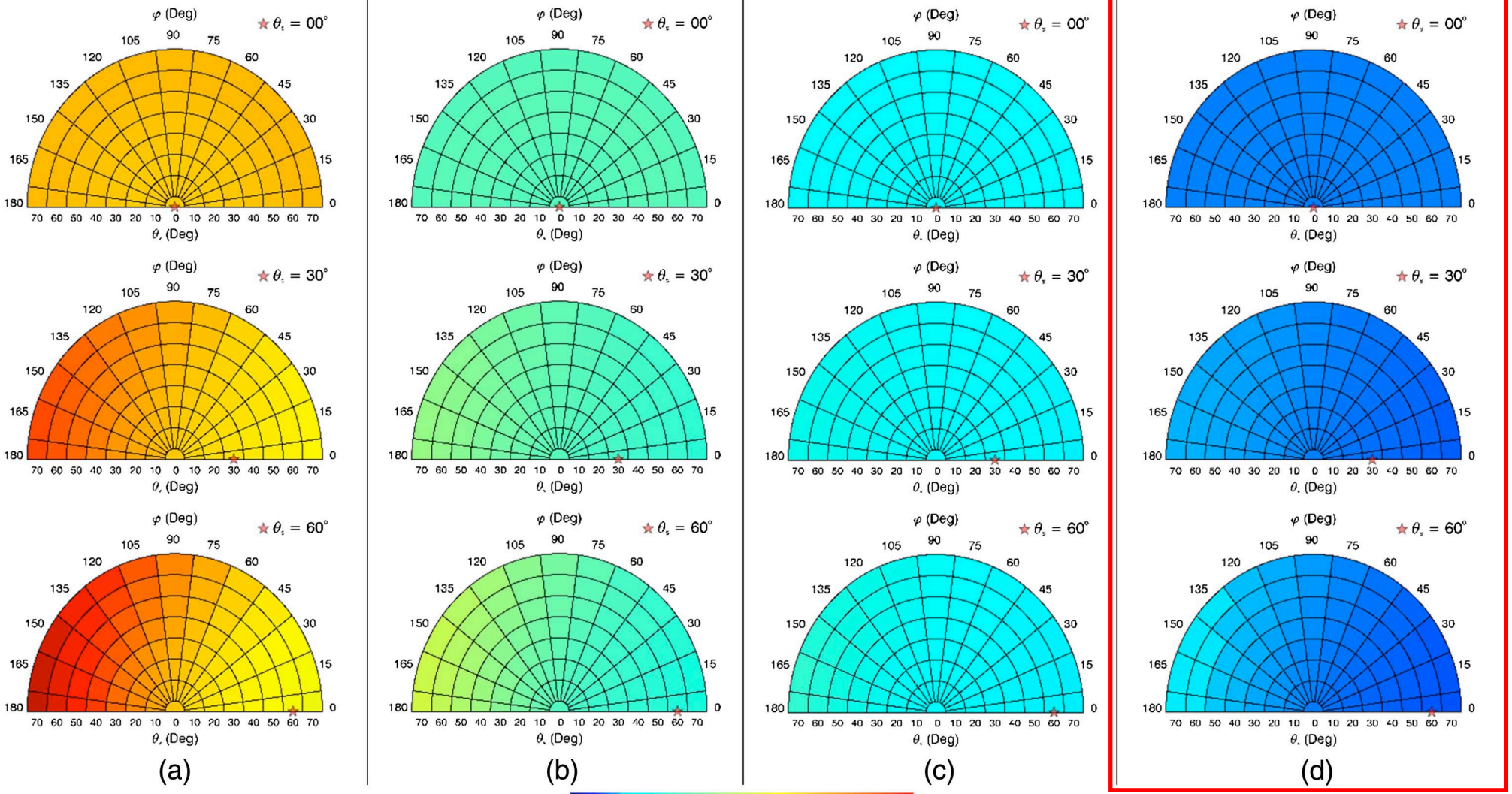
$$r_{rs} = \frac{\beta(\gamma_s)}{B} \frac{1}{\cos\theta_v + \cos\theta_s} \frac{b_b}{a + b_b}$$

No knowledge of the shape

Knowledge of Bp

Knowledge of phase function (> 90)

Knowledge of Bp & phase function (> 90), or the χ factor



VSF shape effect increases with increasing solar angle and/or viewing angle, most prominently in the opposite direction of the sun.

Even though the backscattering ratio and phase function are frequently used describing VSF shapes, it is the χ factor that is most useful to ocean color remote sensing.

From RTE, Zaneveld (1982; 1995) derived:

$$r_{rs}(\theta_s,\theta,\phi)=\frac{1}{2\pi\mu_d g(a,\beta,\theta,\varphi)}\frac{1}{\chi(\gamma_m)}\frac{b_b}{a+b_b}$$

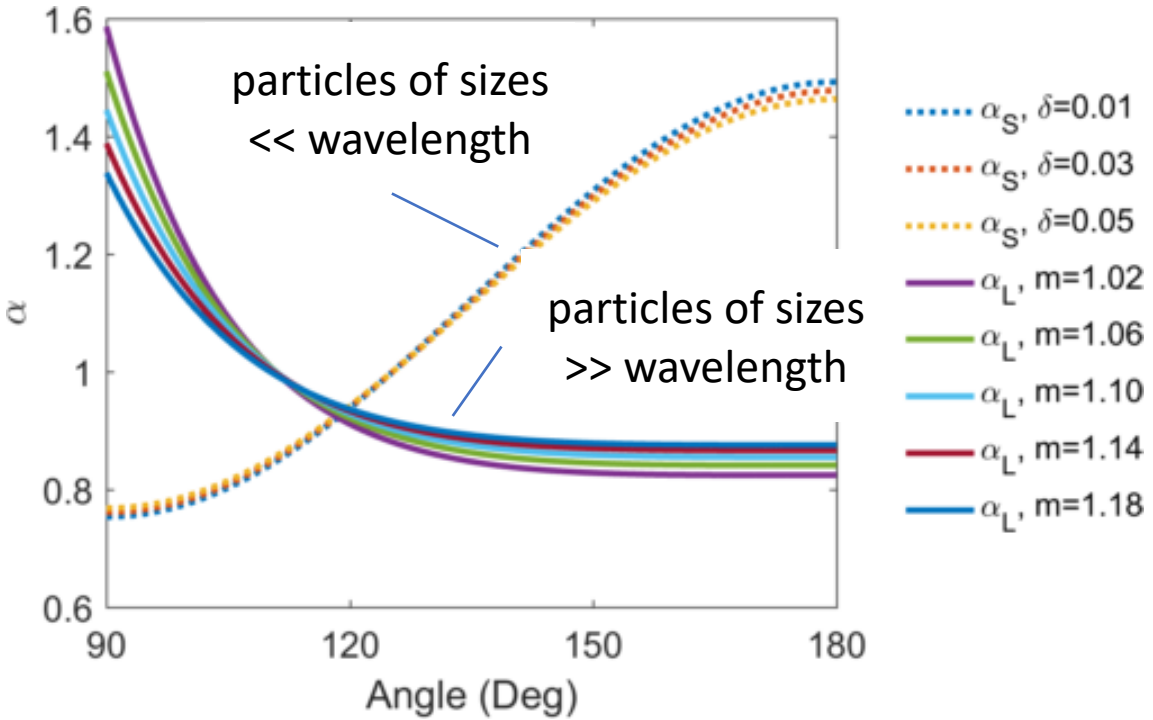
$$g(a,\beta,\theta,\phi)=1-\cos\theta\frac{K_{Lu}(\theta,\phi)}{a+b_b}-(f_L(\theta,\phi)-1)\frac{b_f}{a+b_b}$$

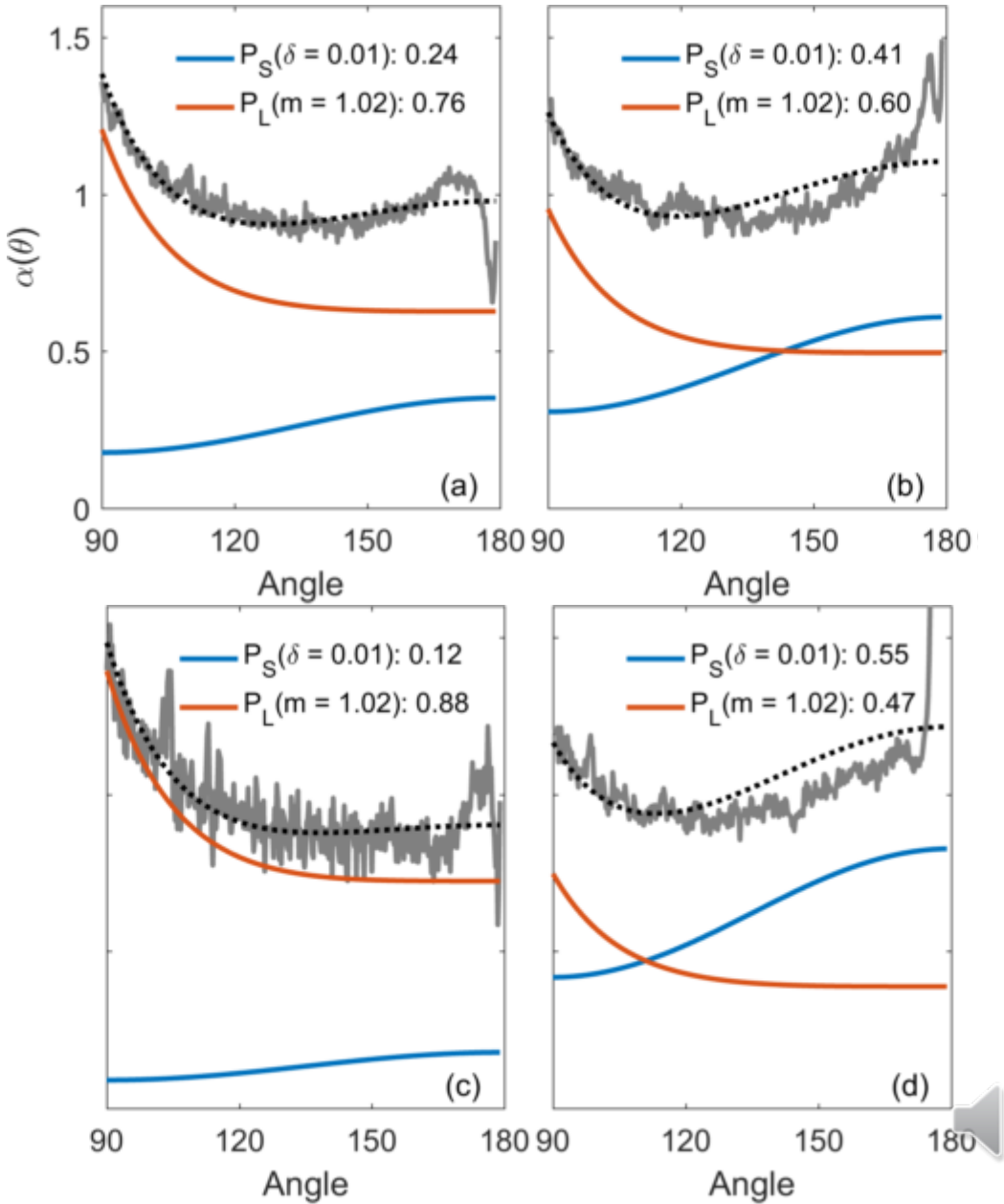
He et al. (2017) expanded the Zaneveld model:

$$r_{rs}(\theta_s,\theta,\phi)=\frac{1}{2\pi\mu_d g}\left(\frac{1}{\chi_w(\gamma_m)}\frac{b_{bw}}{a+b_b}+\frac{1}{\chi_p(\gamma_m)}\frac{b_{bp}}{a+b_b}\right)$$

About the χ_p factor (Zhang et al. 2017)

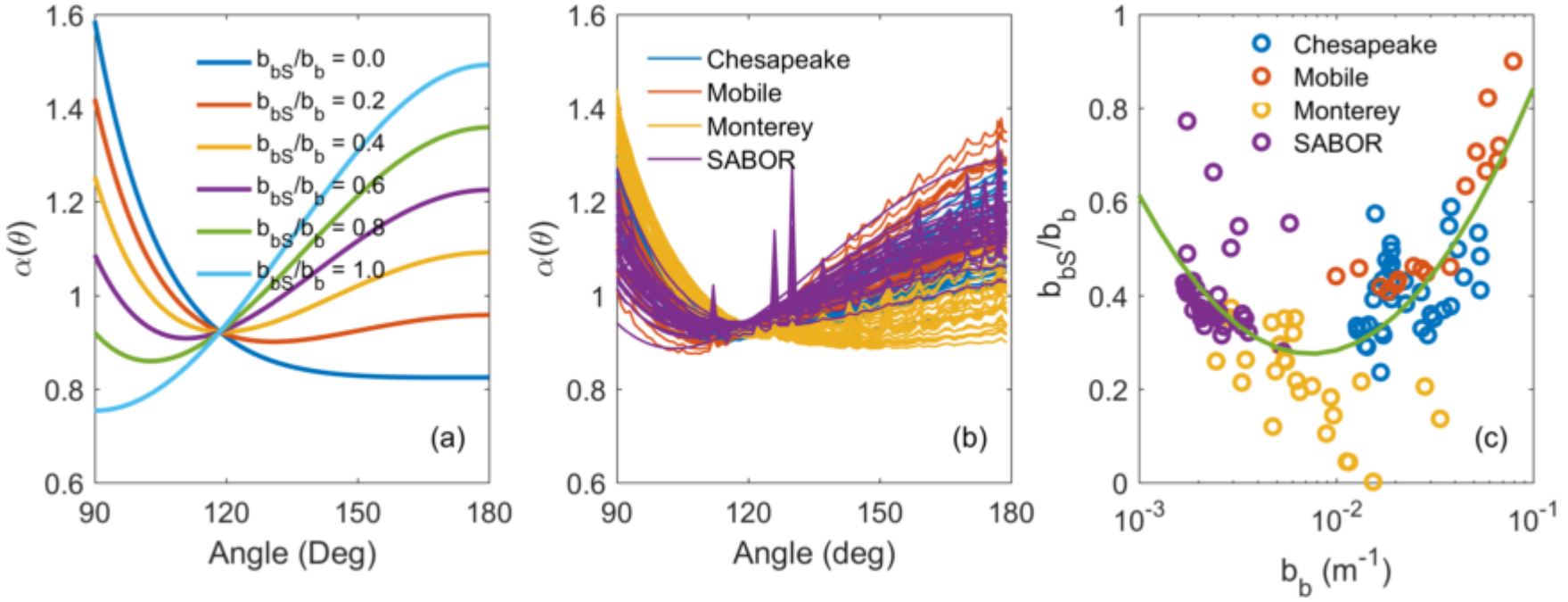
$\alpha = 1/\chi$





Conclusion: the χ factor can be represented by a linear mixing of two end members: one for extremely small particles and the other for large particles as compared to the wavelength.

A preliminary model to estimate the χ_p factor



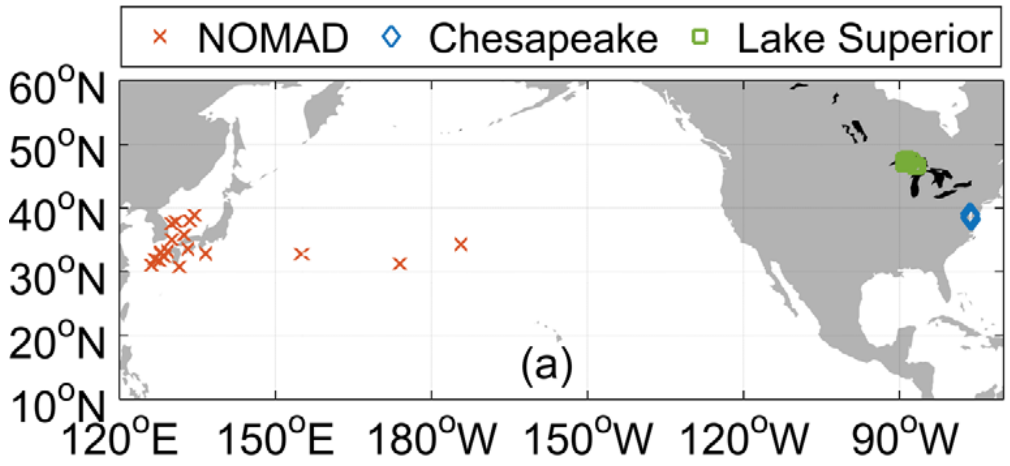
$$\alpha(\theta) = \frac{b_{bS}}{b_b}\alpha_S(\theta) + (1 - \frac{b_{bS}}{b_b})\alpha_L(\theta).$$ where $$\alpha(\theta) = \frac{1}{\chi_p(\theta)}$$

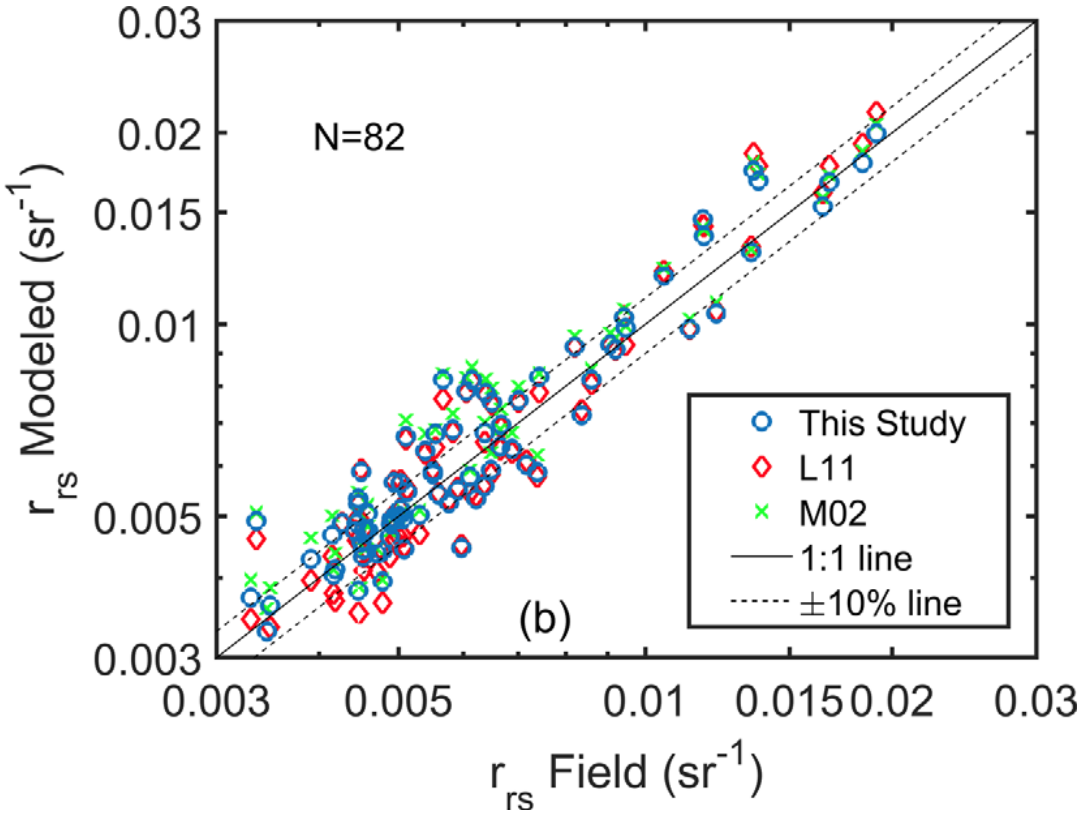
$$\frac{b_{bS}}{b_b} = 0.45(\pm 0.05)(\log b_b)^2 + 1.90(\pm 0.21)\log b_b + 2.29(\pm 0.21).$$

A parameterized Zaneveld Rrs model explicitly accounting for the VSF shapes (He et al. 2017)

$$r_{rs}(\theta_s,\theta,\phi)=\frac{1}{2\pi\mu_d g}\left(\frac{1}{\chi_w(\gamma_m)}\frac{b_{bw}}{a+b_b}+\frac{1}{\chi_p(\gamma_m)}\frac{b_{bp}}{a+b_b}\right)$$

Inputs are a, b_b and χ_p and viewing geometry





Conclusions

- Our VSF measurements showed that the natural variability of the shape of particle VSFs has been underestimated, which in turn leads to an underestimation of the impact of the VSF shapes on Rrs.
- The variability of Rrs due to VSF shapes generally increases with backscattering and with both viewing and sun angles
  - For nadir view, the maximum and median uncertainties are 65% and 15%
- Among the variability in Rrs due to VSF shapes, 71% can be explained by backscattering ratio, 90% by backward portion of phase function (> 90), and 97% by the X factor.
- The X factor for oceanic particles can be modeled using a two-component model.
- We have parameterized the Zaneveld-type Rrs model that explicitly includes the X factor to predict Rrs. (https://goo.gl/UozPNn)
- Zhang et al. (2017) Optics Express 25, A191-A199; Xiong et al. (2017) Applied Optics 56, 6881-6888; and He et al. (2017) J. Geophys. Res: Oceans 122, 8614-8626.