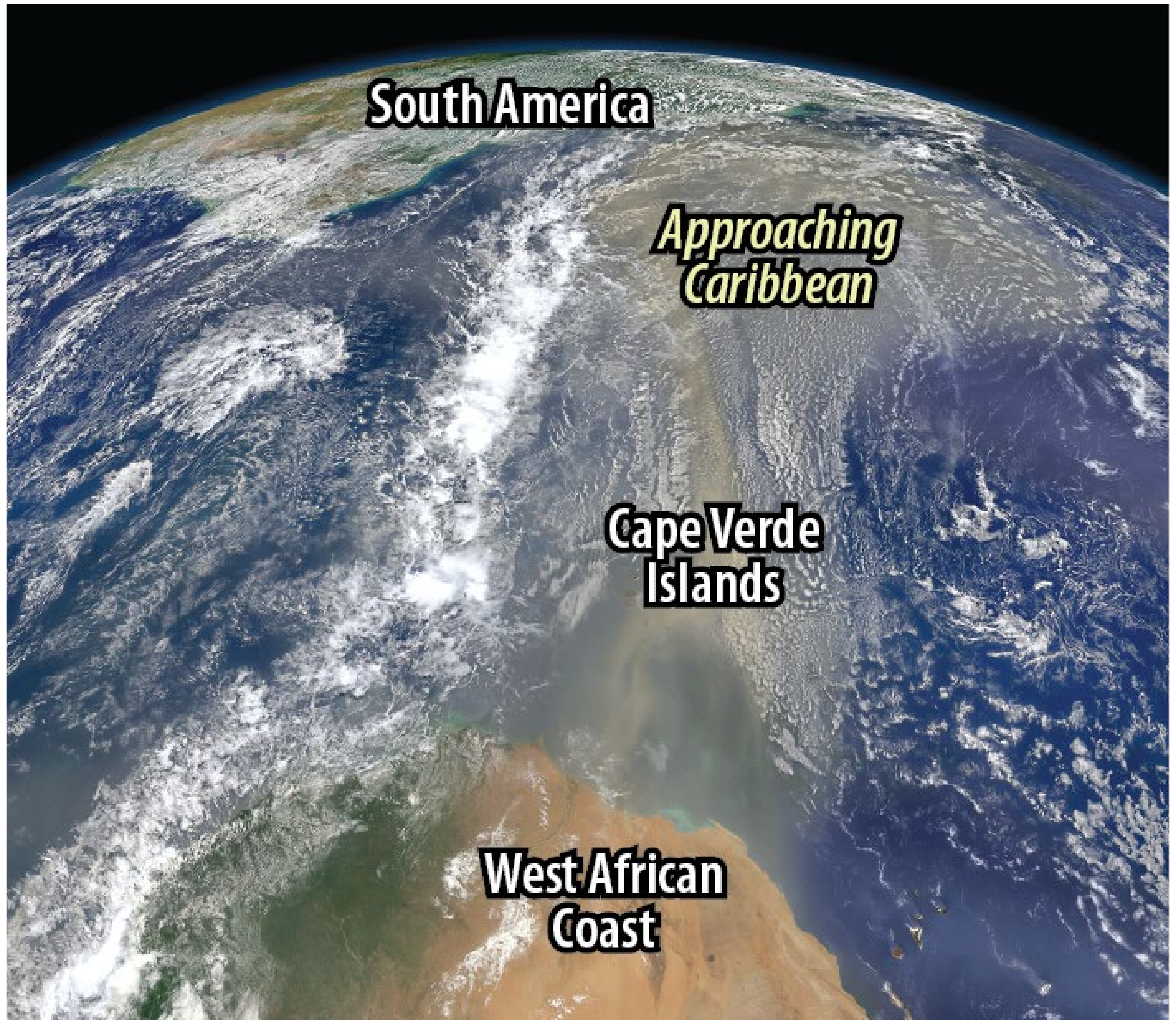
A Review of the Treatment of Dust Optical Properties in Earth System Modeling

Peter Colarco, NASA Goddard Space Flight Center



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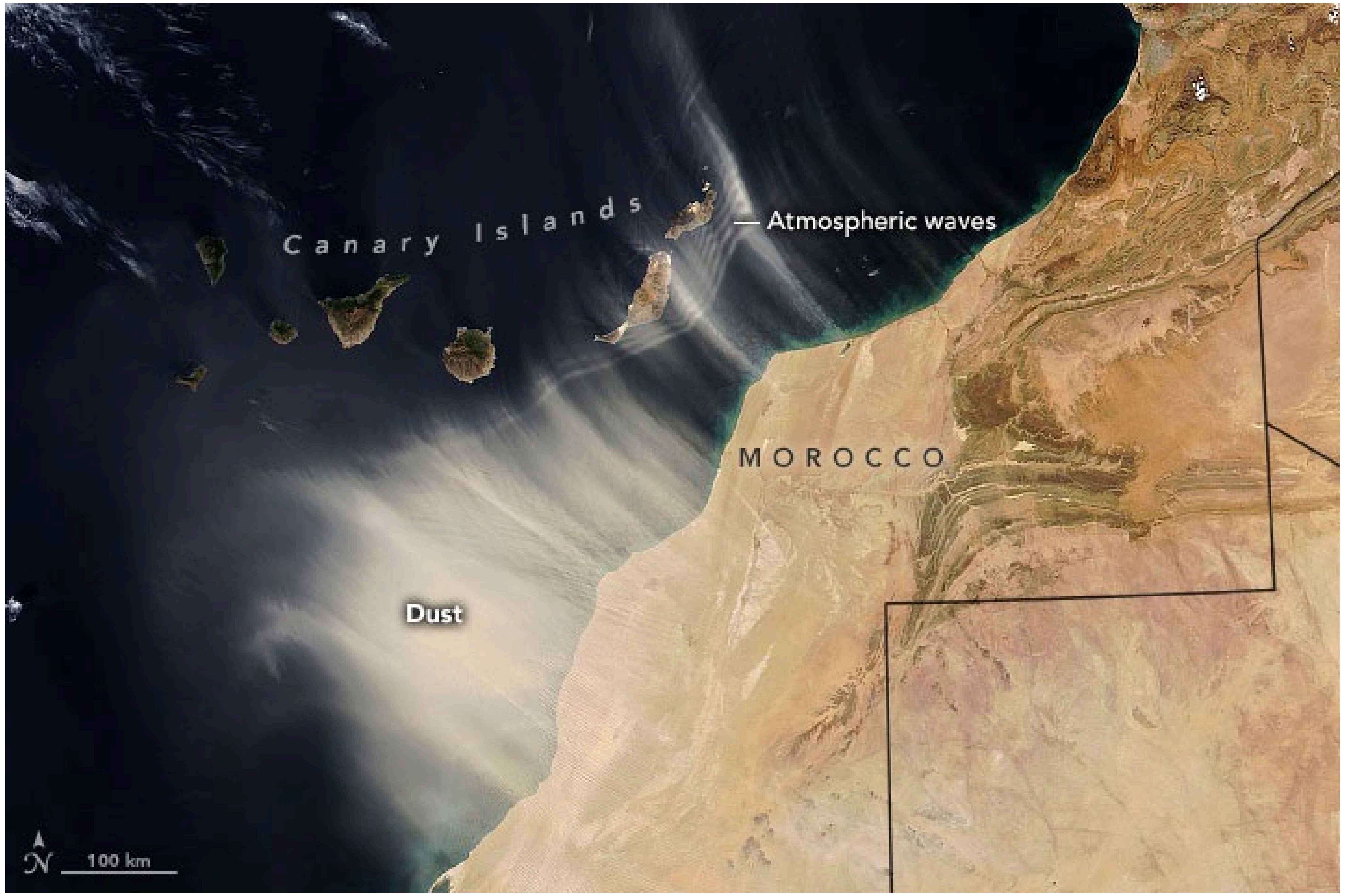
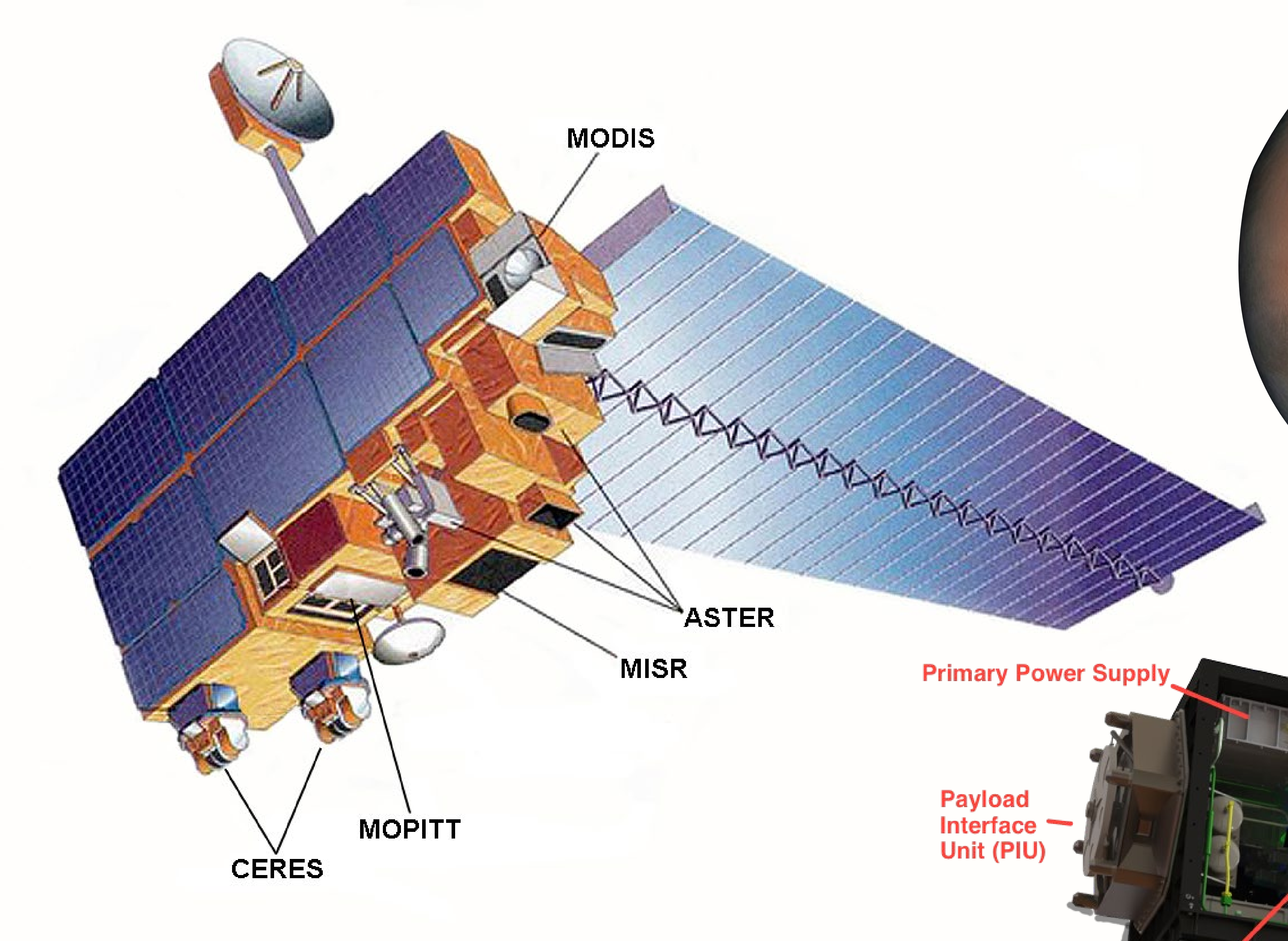
Motivation

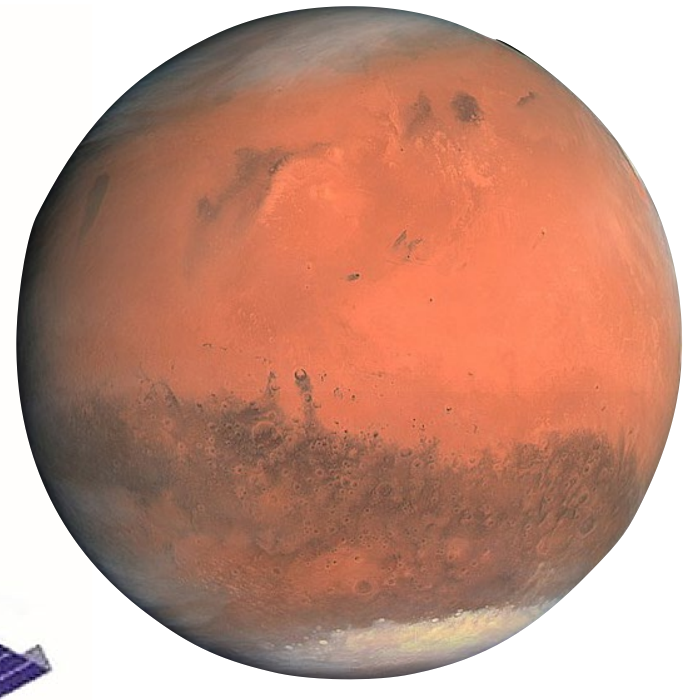
- Most abundant aerosol species in the atmosphere
- Clearly visible from space
- Important to Earth's radiative balance
- Important to aerosol-cloud interactions
- Source of nutrients to land and ocean surfaces
- Impacts air quality and visibility

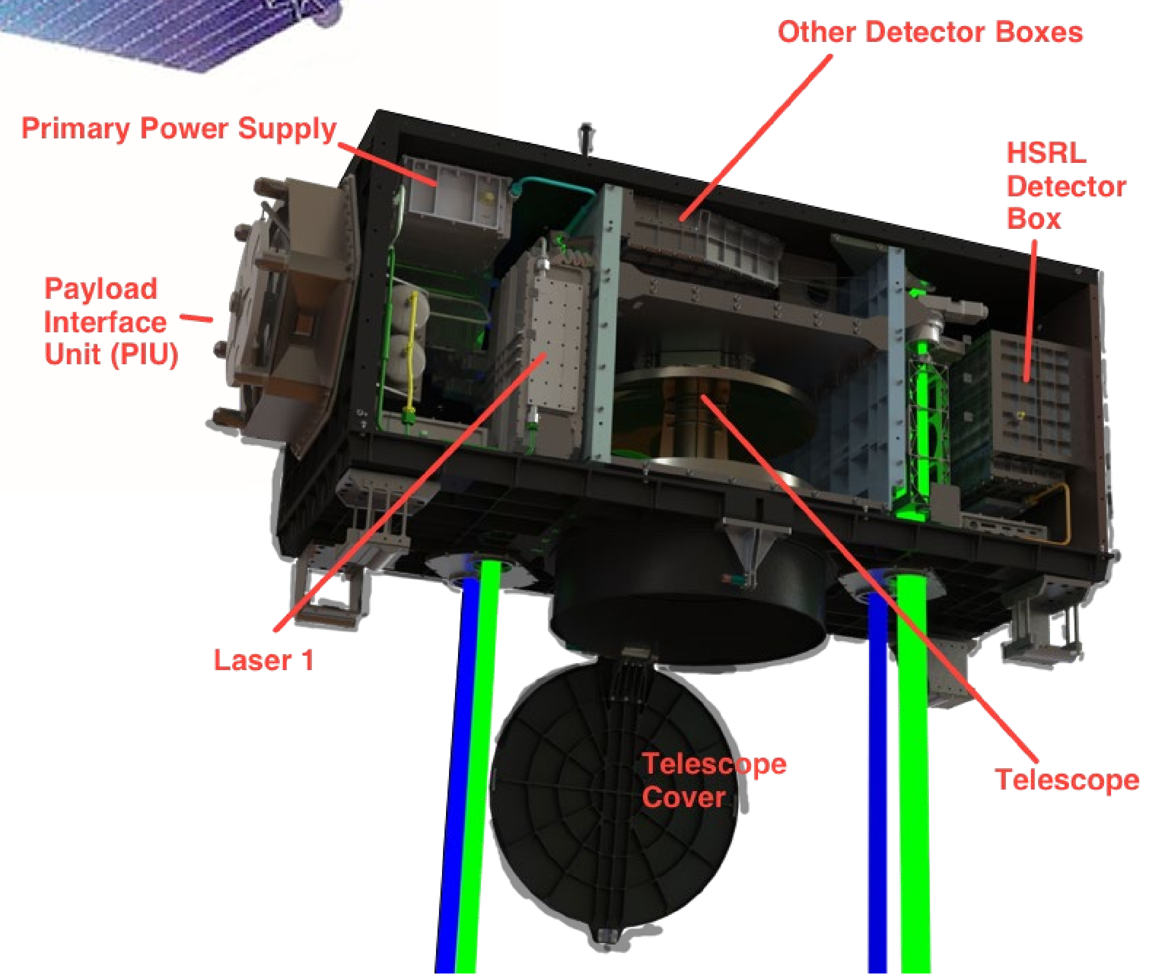


Dust storm engulfs the Canary Islands
VIIRS/NOAA 20, January 14, 2022

Perspective



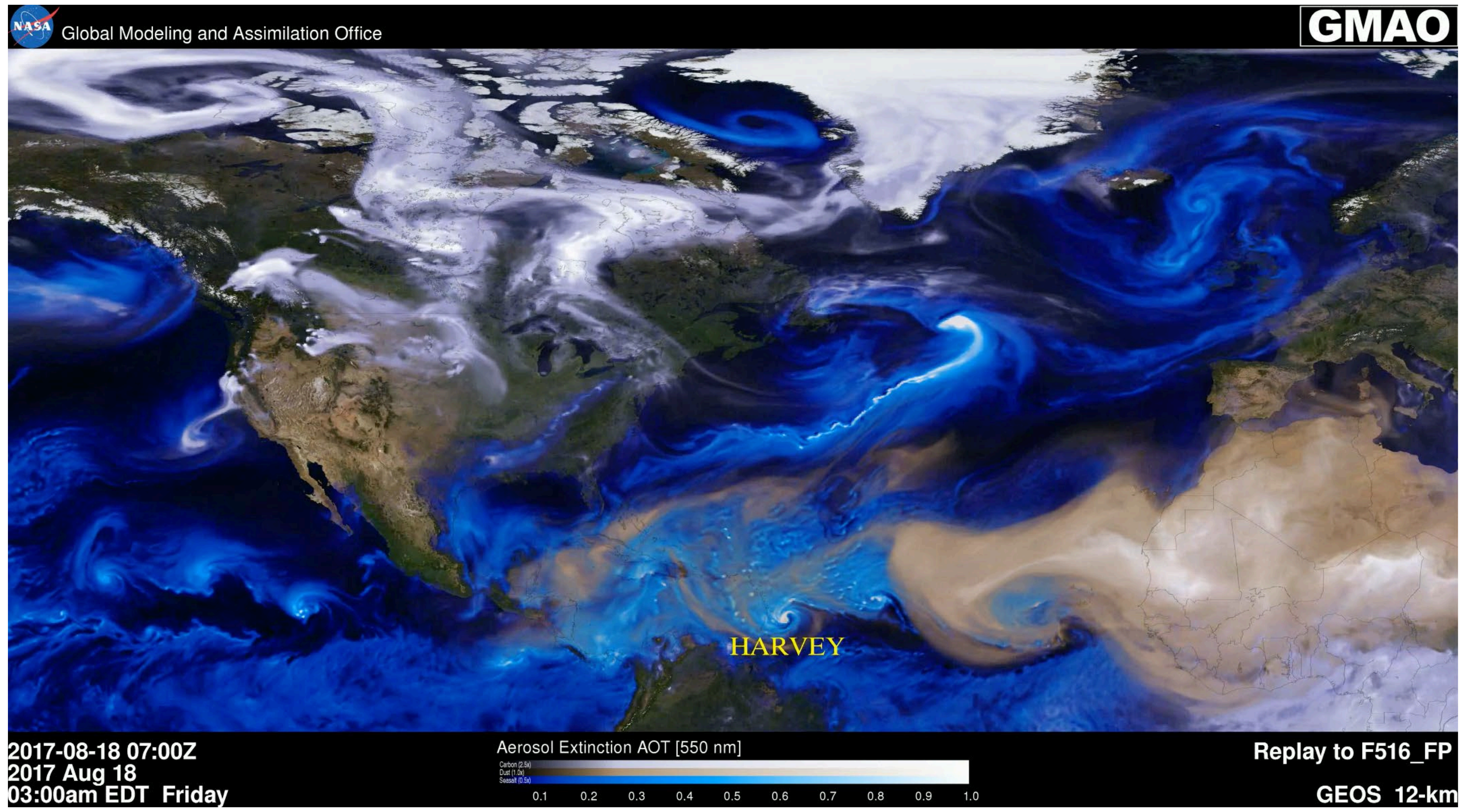




There is a convergence of expertise and interest at Goddard with respect to dust

- Ground-based and airborne remote sensing
- Space-based remote sensing
- Earth system modeling
- Planetary observations and modeling

We are synthesizing across these disciplines to summarize treatment and uncertainties in representation of dust optical properties in models and remote sensing applications



Objective

My objective here today is to present a synthesis and summary of how dust optical properties are treated in various models, and begin to explore the implications

Modeling Context

- Surveyed a number of global aerosol models that treated dust
- Most of the models were drawn from the **ICAP ensemble** of near-real time global aerosol forecasting systems
- Asked all for details on how they approach the treatment of microphysics and optics in their models: sub-bin PSD assumptions, refractive indices, specifics of optical property calculations
- All of the models adopted either a bulk or sectional approach to dealing with dust mass and particle size distribution
- All of the models provided specific optical quantities from their own calculation: MEE and SSA @ 550 nm

NASA GSFC/GEOS-GOCART

NOAA NCEP/GEFS-GOCART

ECMWF/IFS

FMI/SILAM

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NASA GISS/ModelE-OMA

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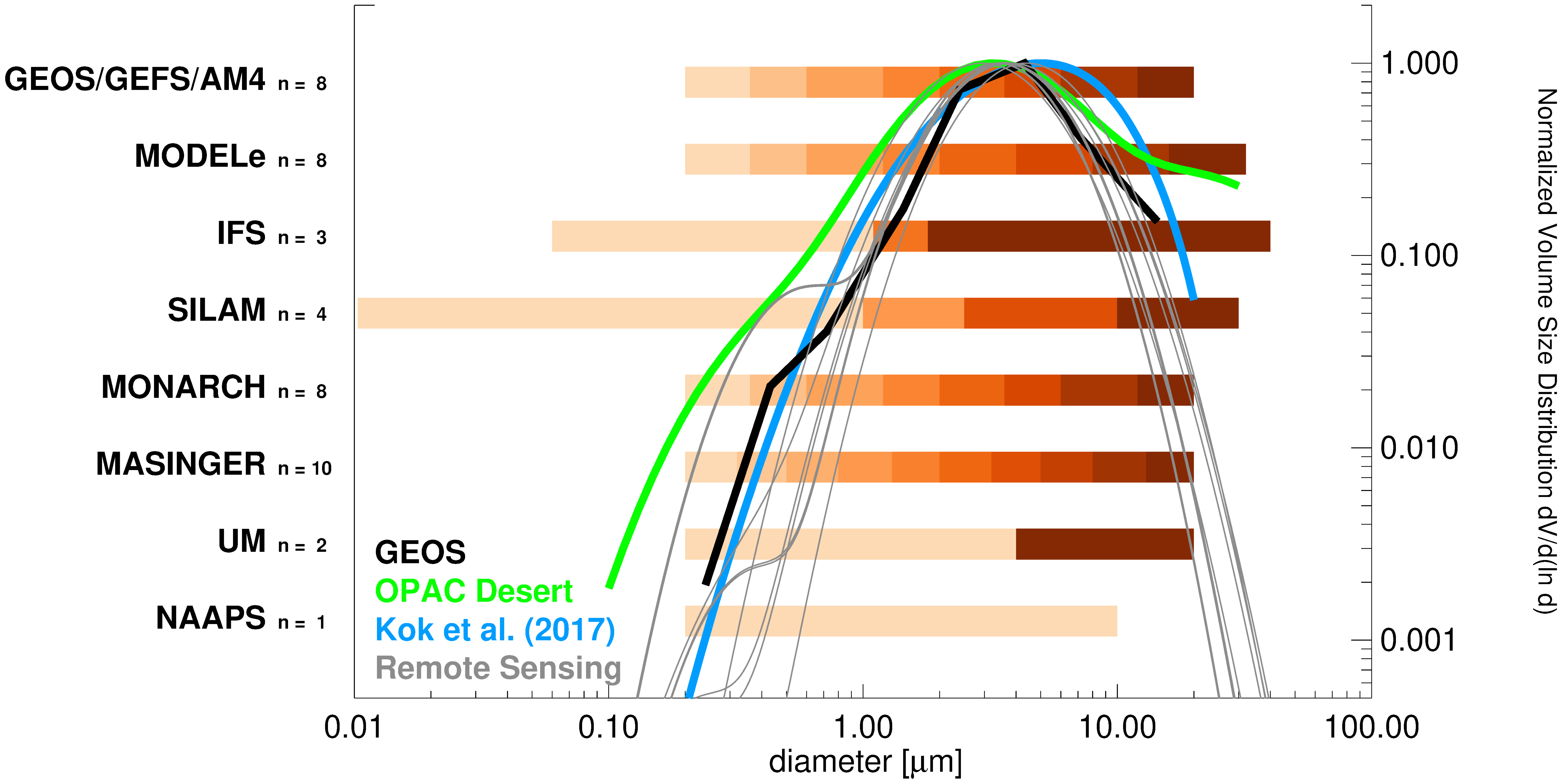
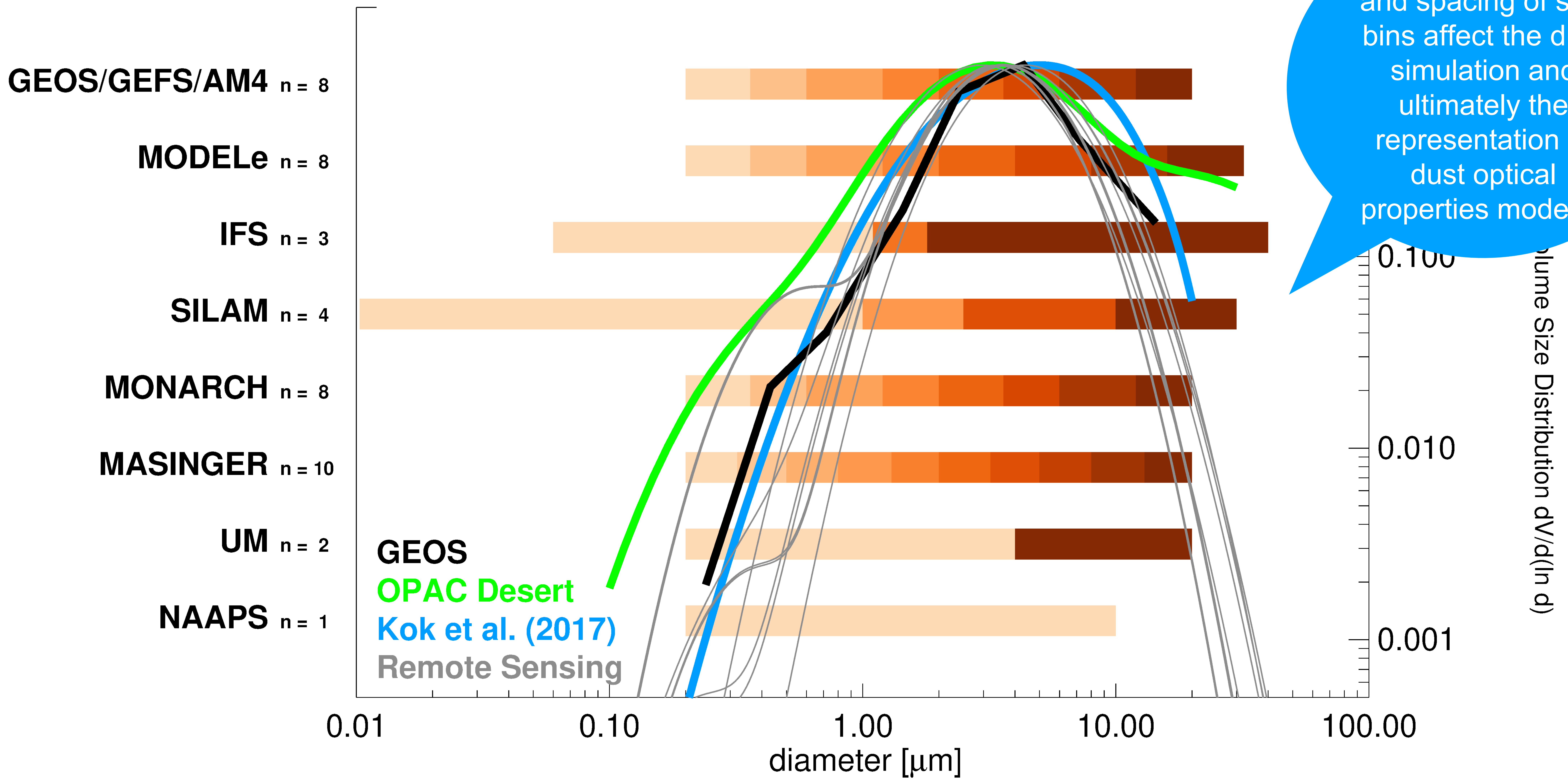
Model Dust Particle Size Binning

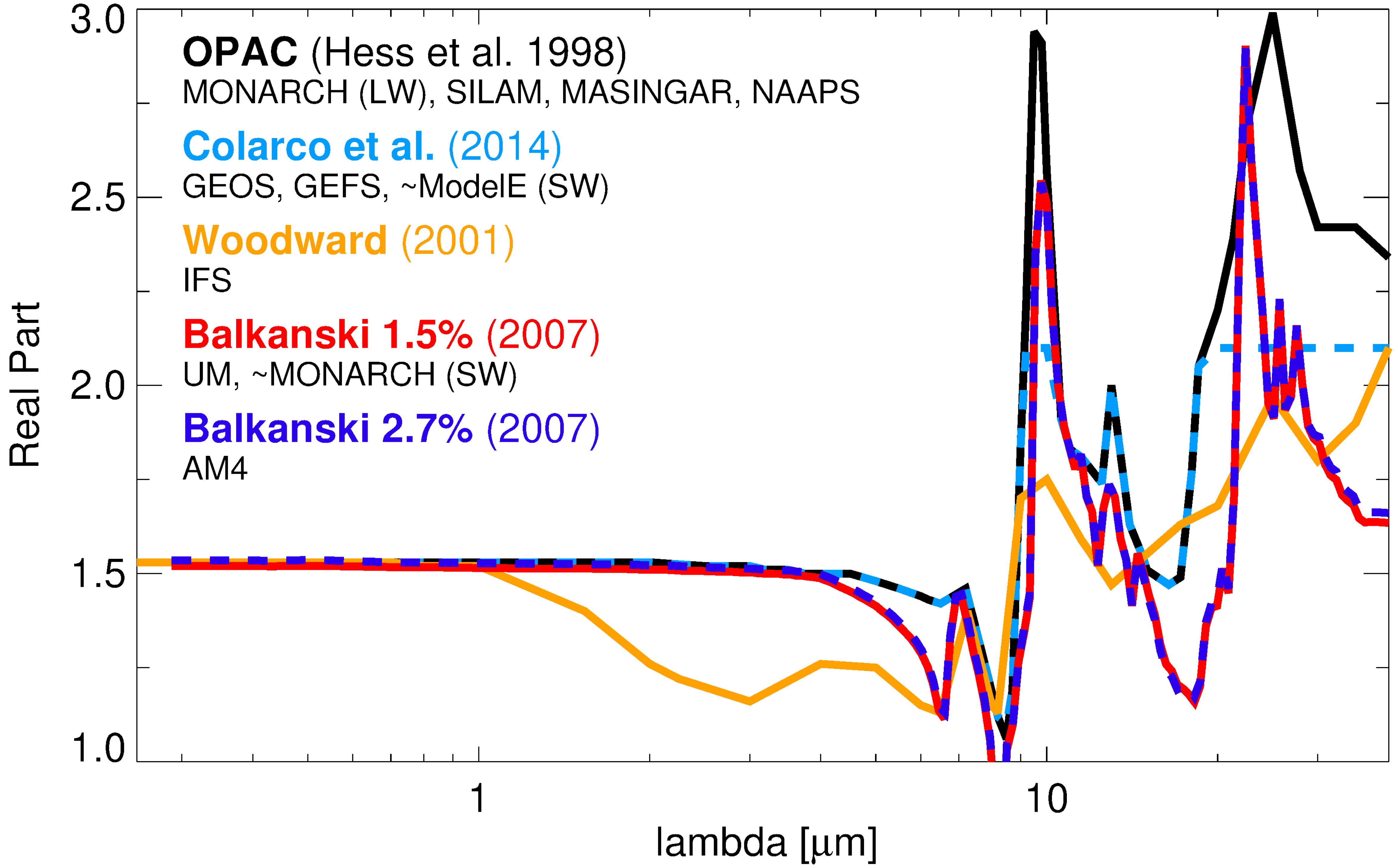


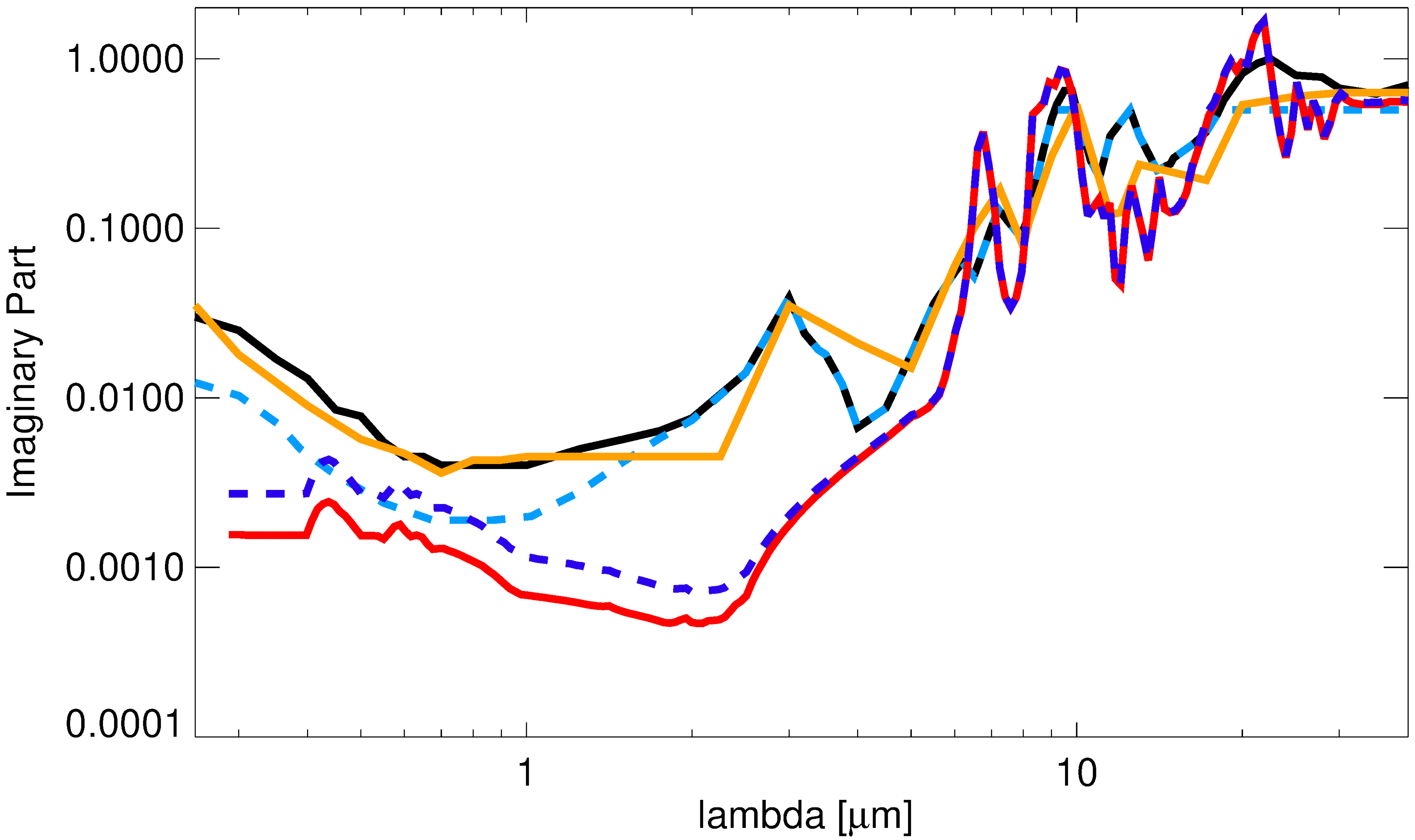
Model Dust Particle Size Binning



How do the number and spacing of size bins affect the dust simulation and ultimately the representation of dust optical properties models?

Dust Refractive Index Assumptions





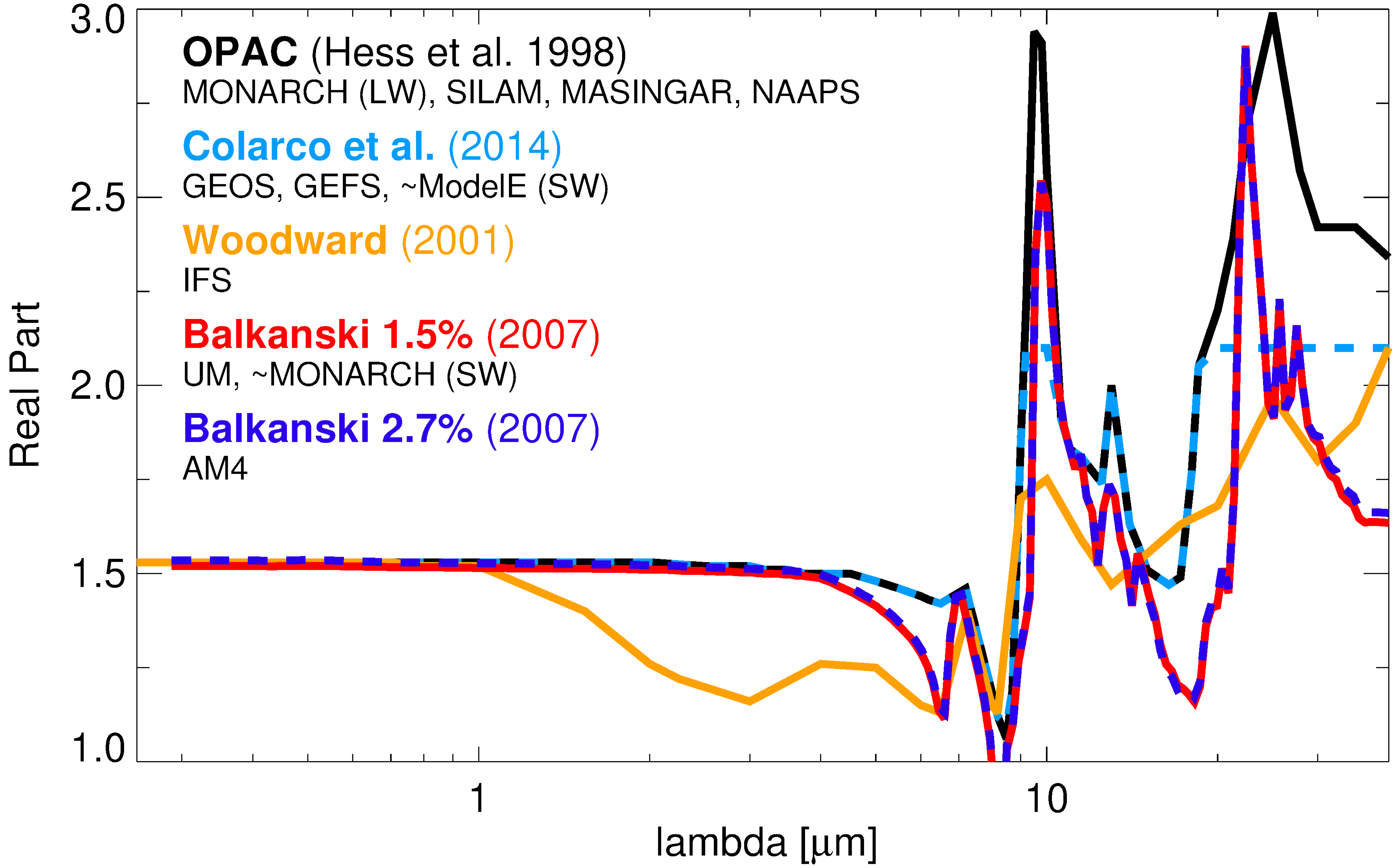
- Calculation of dust optical properties for these models is generally

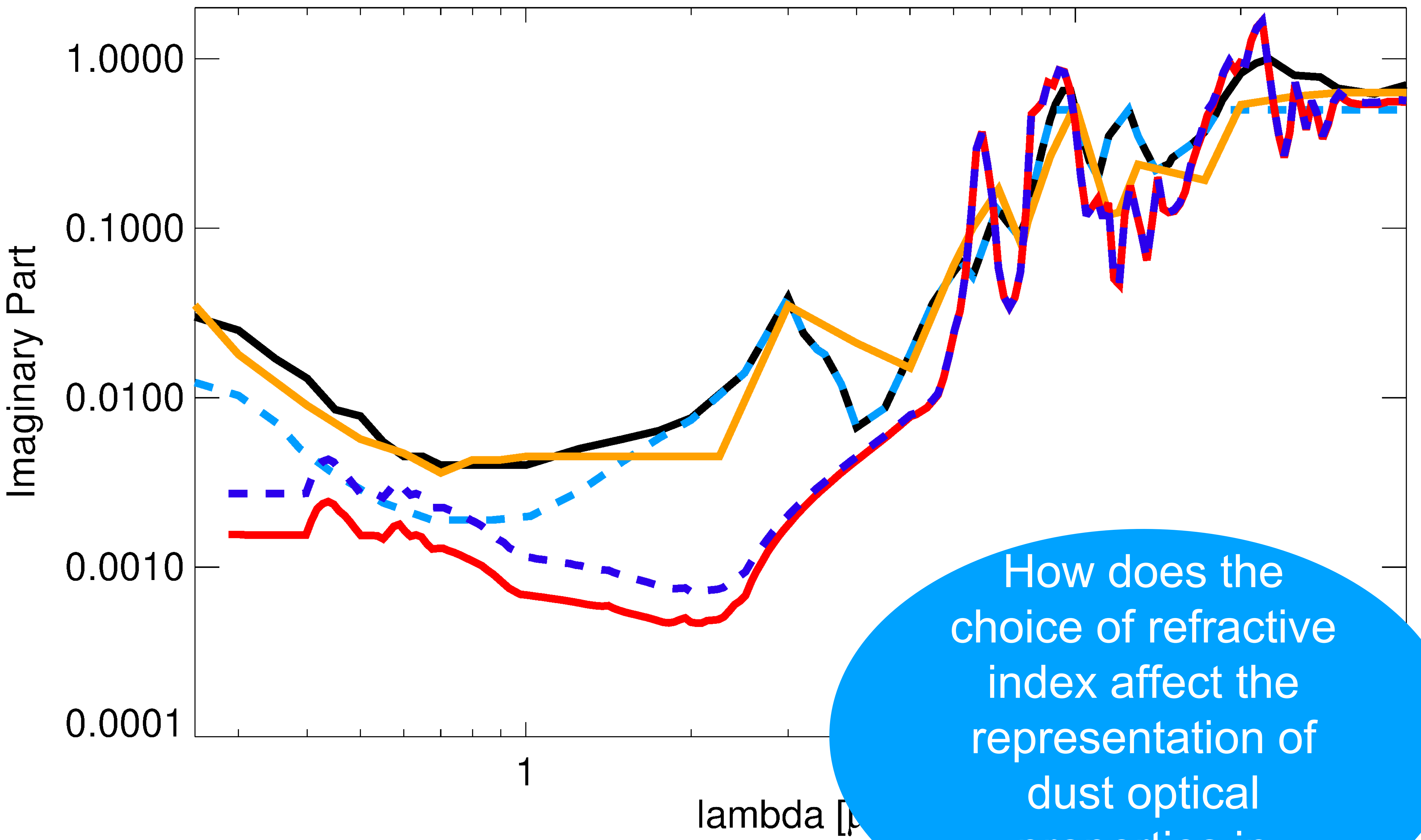
$$\sum_{\text{nbins}} \int \text{sub-bin distribution x f(refractive index, shape)}$$

Could be composition dependent, but in practice for these models is not

Mie theory (most), some non-spherical

Dust Refractive Index Assumptions





How does the choice of refractive index affect the representation of dust optical properties in models?

- Calculation of dust optical properties for these models is generally

$$\sum_{\mathbf{nbins}} \int \text{sub-bin distribution x f(refractive index, shape)}$$

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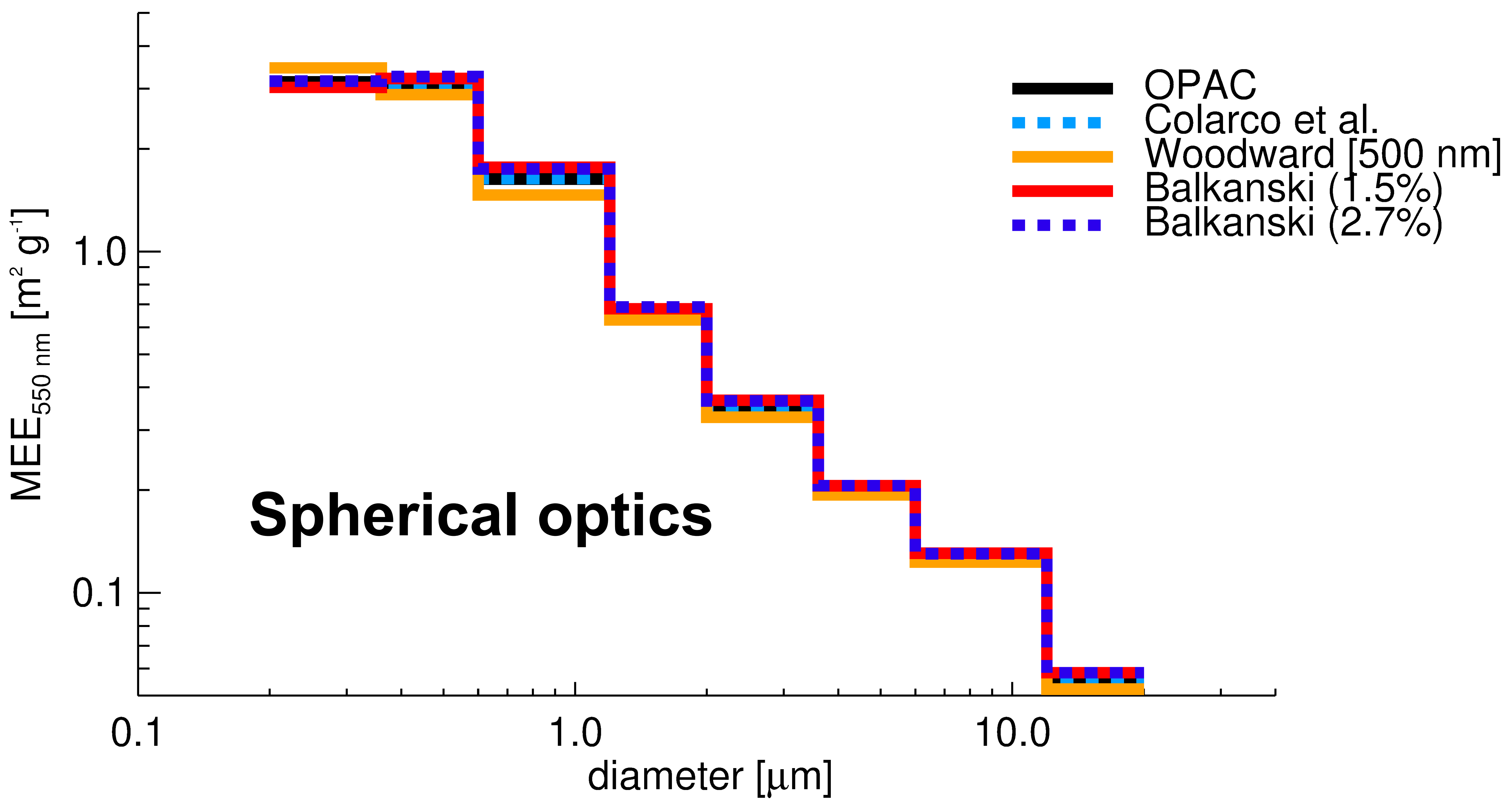
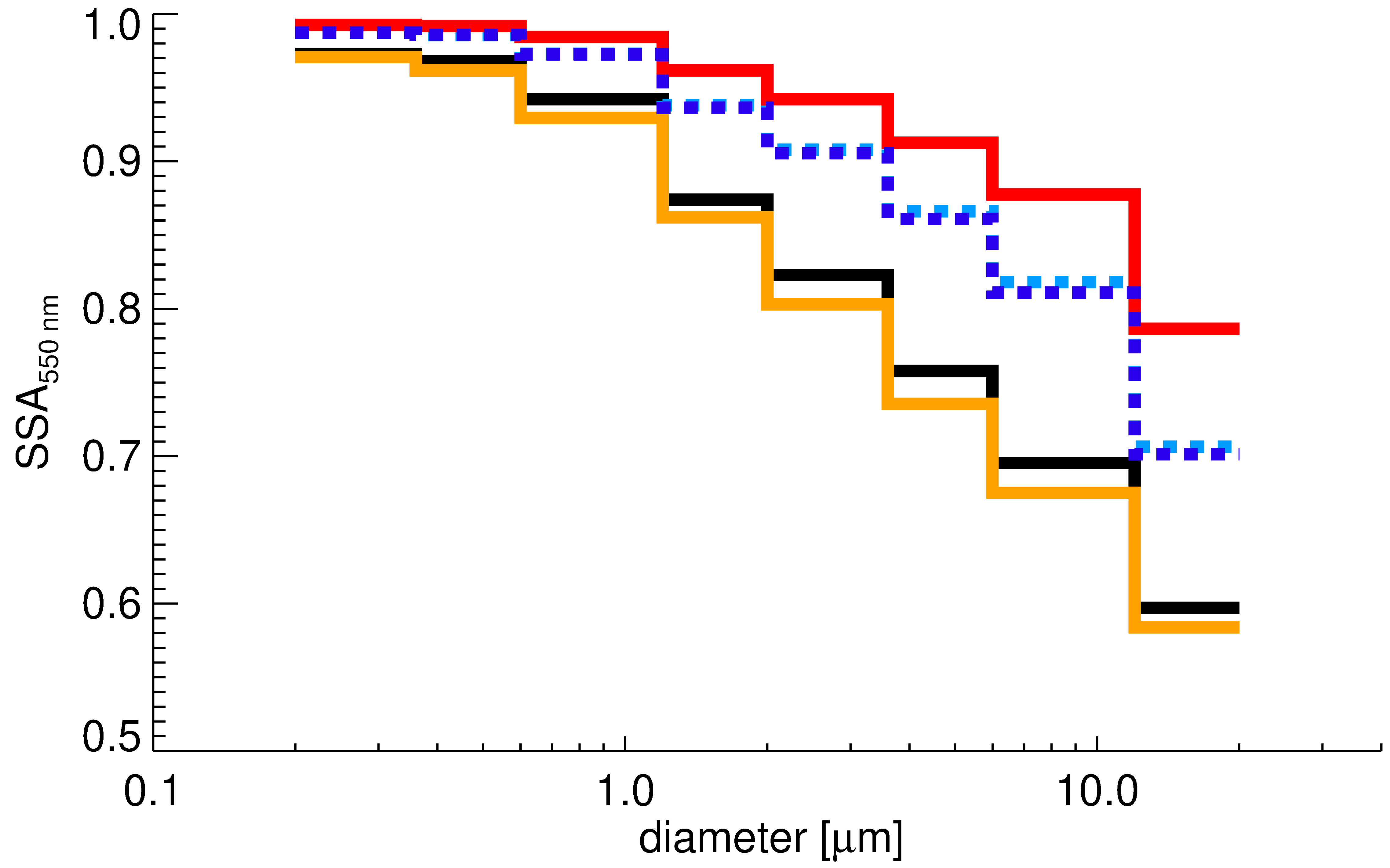
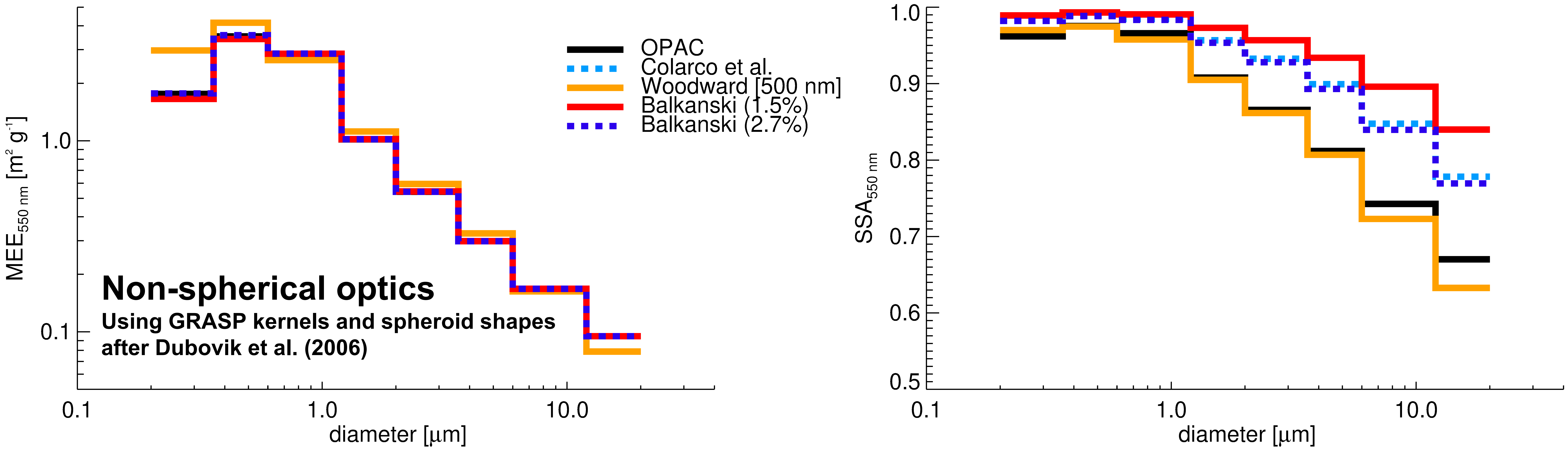
Impact of Refractive Index on Dust Optical Properties





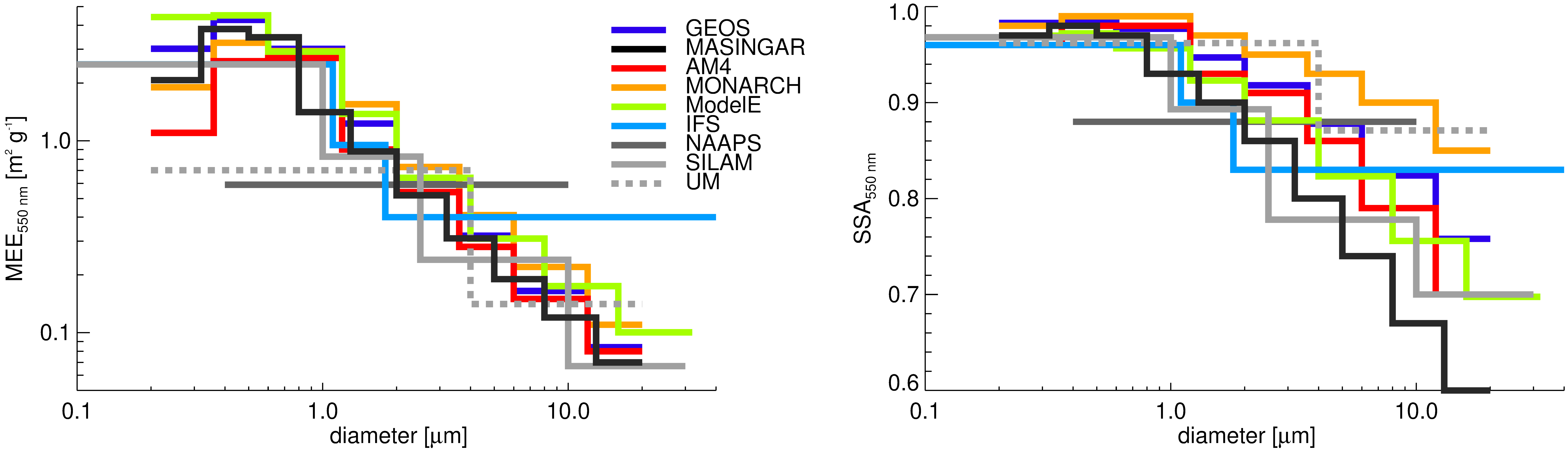
- Calculate dust optical properties assuming GEOS framework, testing different refractive indices
- Low sensitivity in MEE to refractive index choice, expected because n_{real} approximately the same
- Much greater sensitivity to size-resolved SSA that tracks with n_{imag}

Impact of Refractive Index on Dust Optical Properties



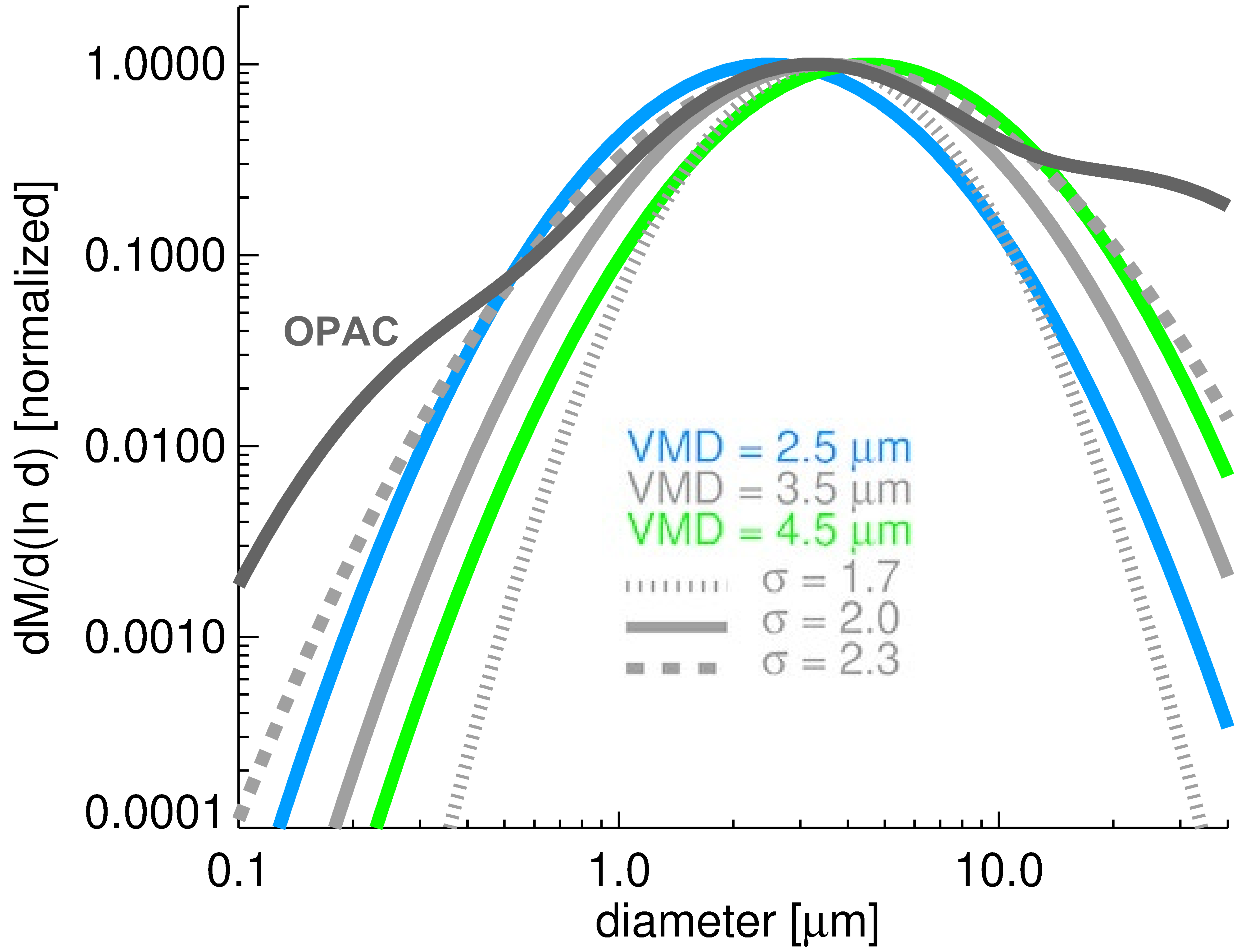
- Non-spherical optics results in a higher MEE and higher SSA versus spherical case
- Low sensitivity in MEE to refractive index choice, expected because n_{real} approximately the same
- Much greater sensitivity to size-resolved SSA that tracks with n_{imag}

Reported Dust Optical Properties



- Here's what was reported by the surveyed models
- Even given the mass loading and particle size distribution a diversity of resulting AOD and SSA will emerge because of structural choices in how the optical properties are computed
- Can we resolve these structural choices?

Parametric Experiment

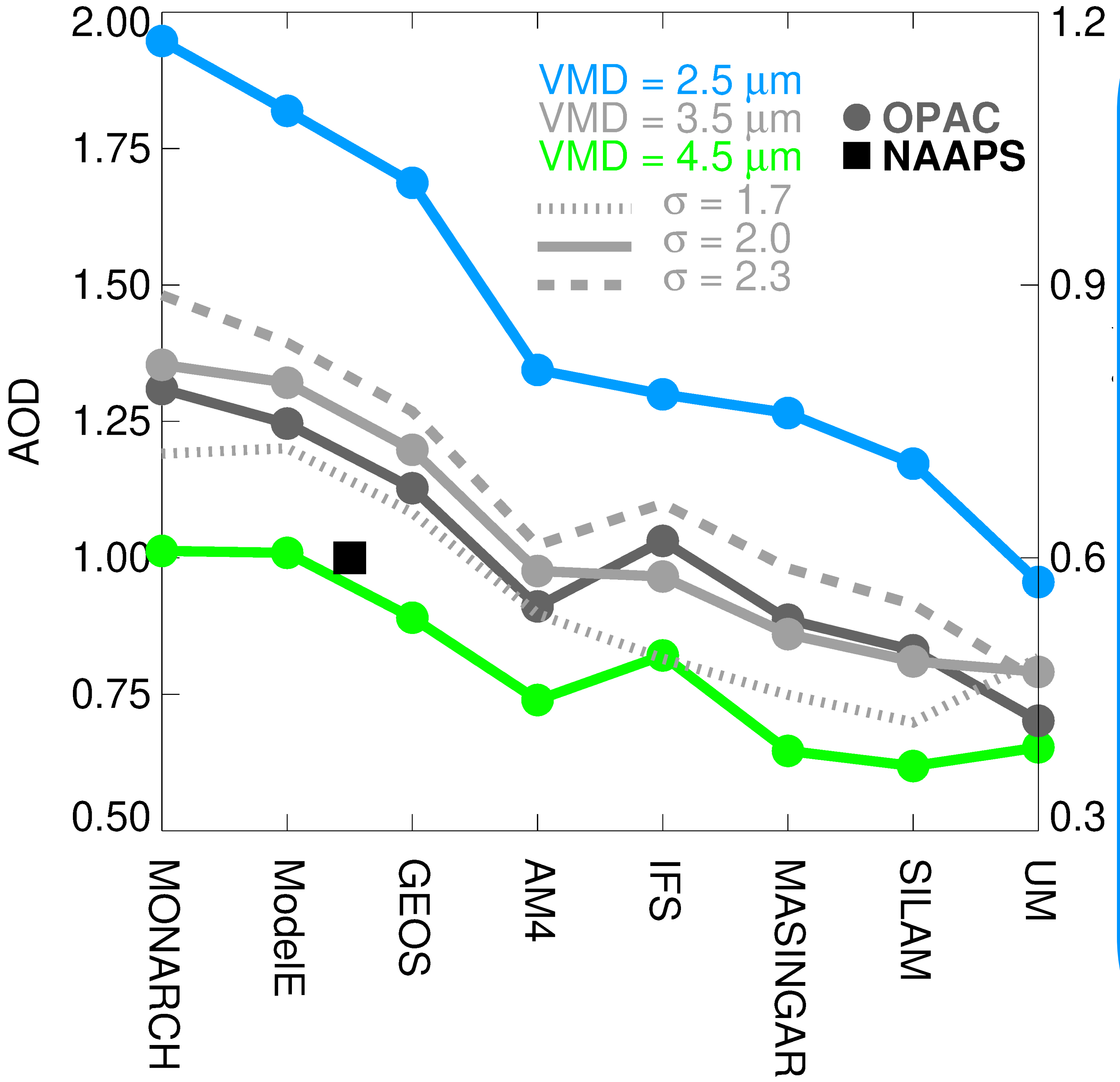


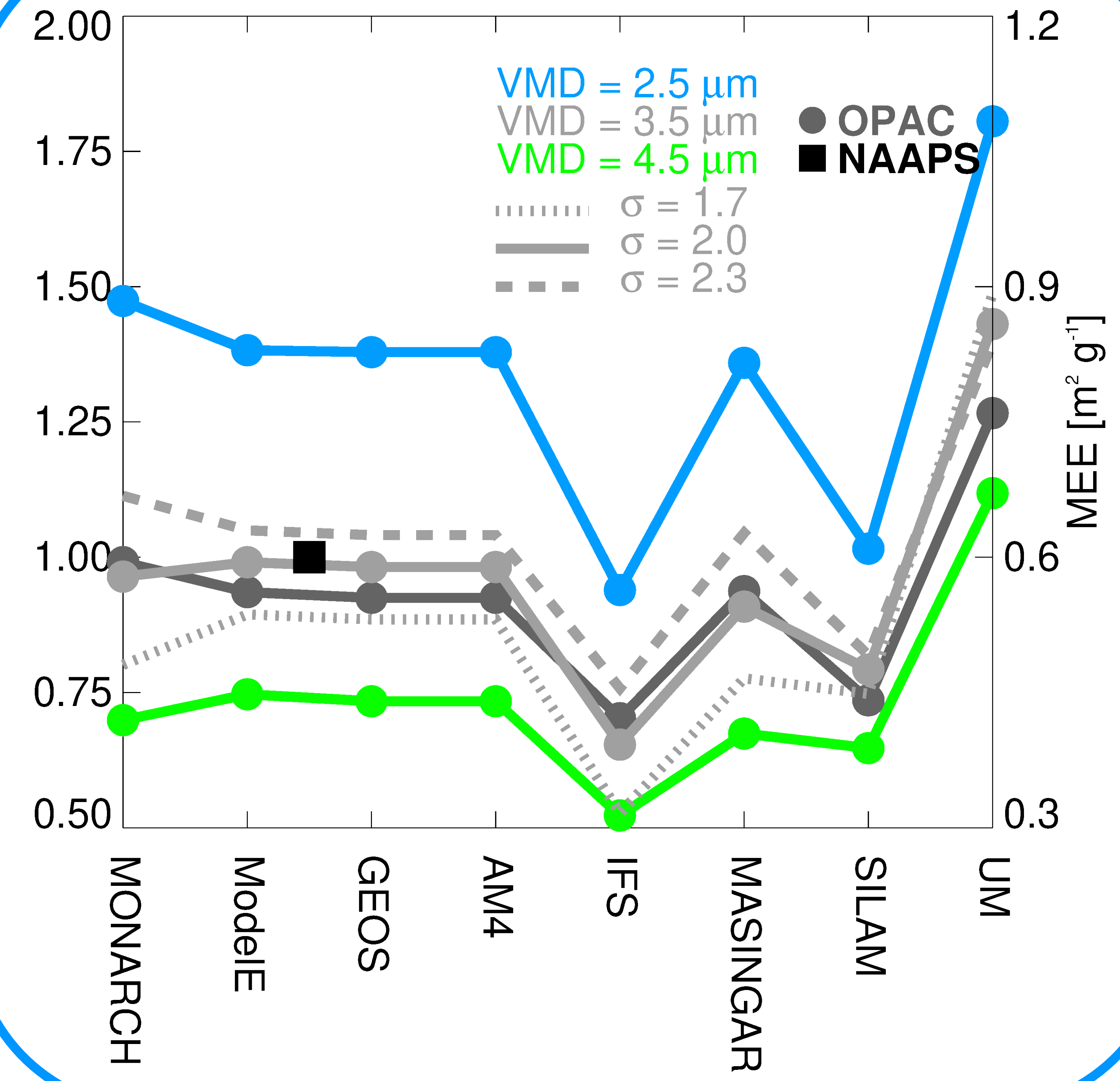
Prescribe the dust mass loading and particle size distribution and compute the AOD, SSA, forcing

Large Intermodel Diversity in AOD and Forcing

Use models' own reported MEE and SSA

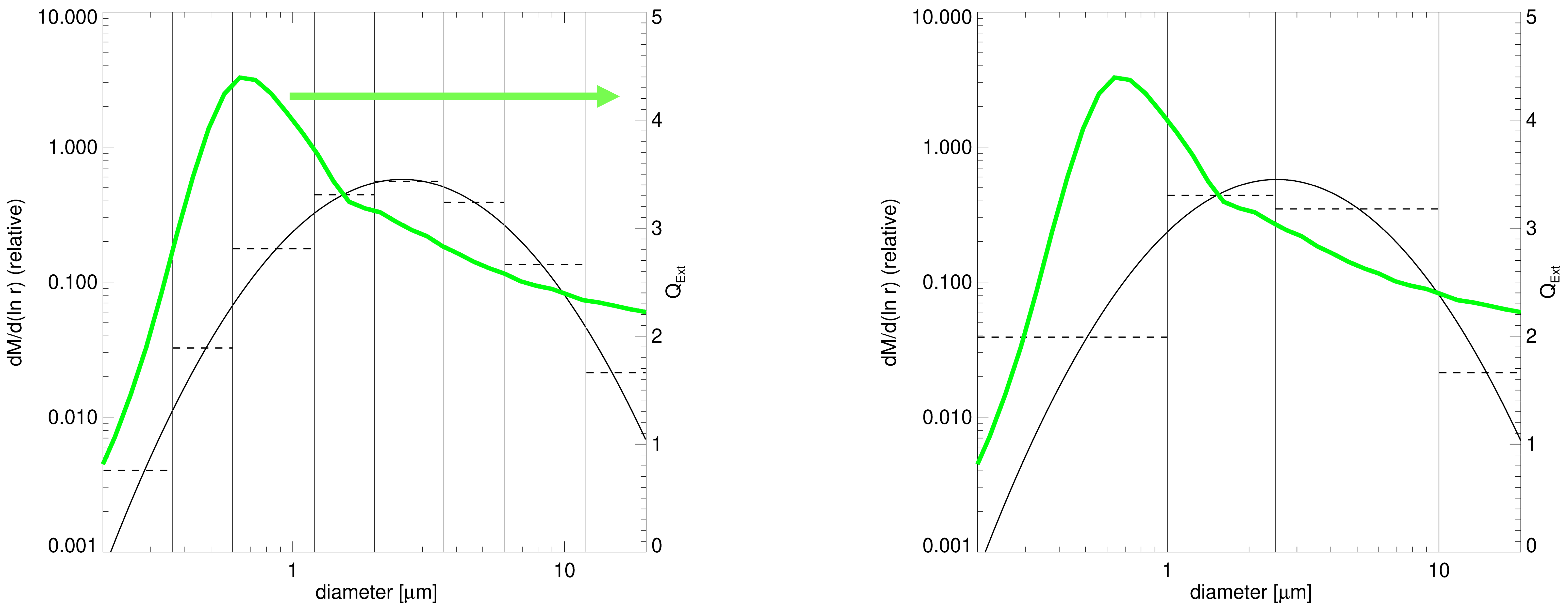
Diversity Reduced Using Consistent Approach





Using the GEOS model infrastructure and refractive index but the individual models' size bins

Discretization of the Sub-bin Particle Size Distribution



The strong size dependence of the extinction efficiency means our choice of how to discretize the particle size distribution across size bins matters

Changed Sub-bin Particle Size Distribution

Changing to lognormal sub-bin particle size distribution removes most of residual diversity

Using Models' Preferred Refractive Indices

Finally, using the smooth particle sub-bin distribution and the models' own choices of refractive indices we see that they mostly resolve the same AOD given the same mass and particle size distribution, with residual diversity due to choices of absorption

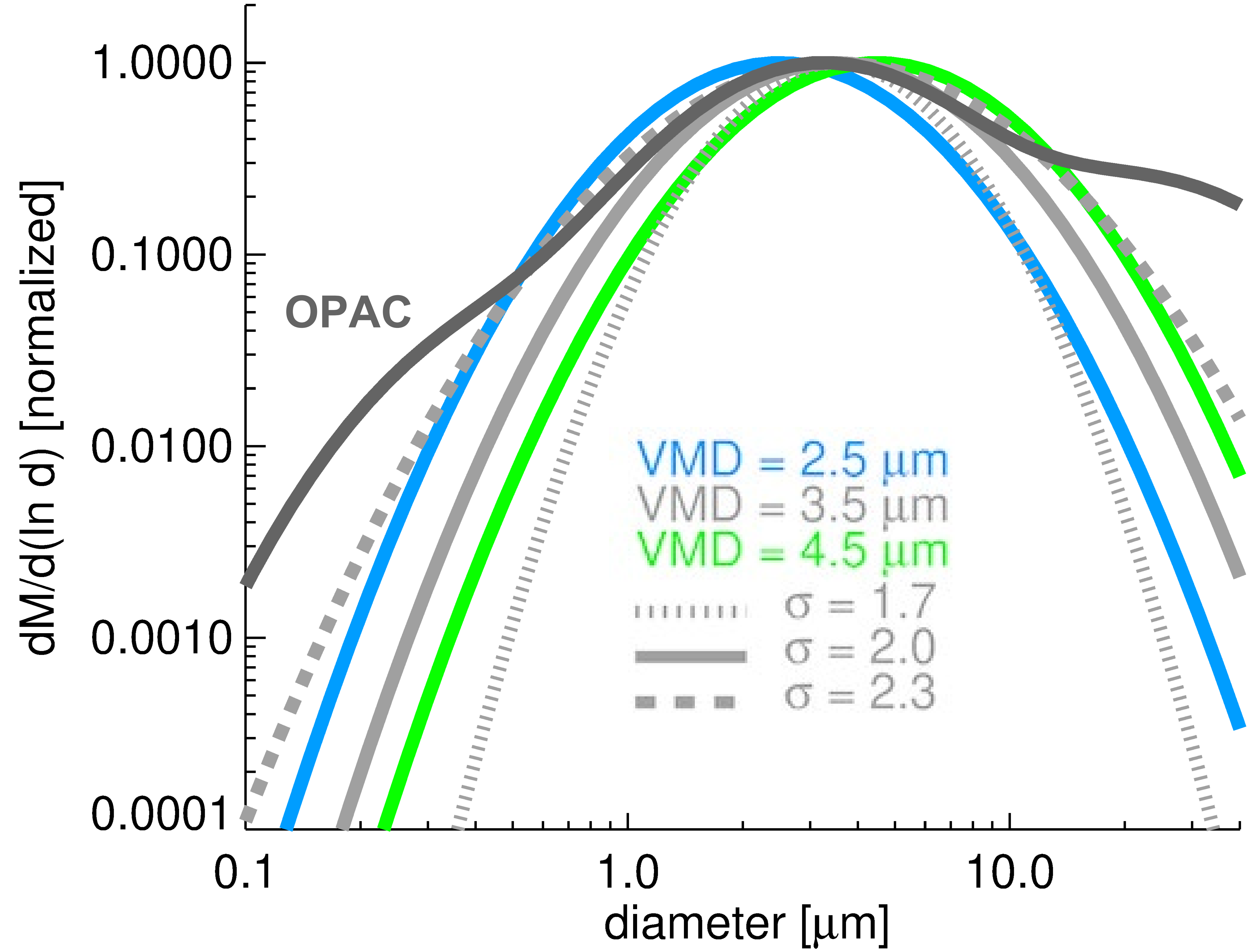
Conclusions

- Models surveyed adopt a sectional approach to partitioning aerosol mass
  - Models that explicitly represent particles out 20 µm diameter (all but one) are notionally able to represent > 99% of the globally averaged dust aerosol mass
- Choice of size section placement and resolution has large impact on AOD
  - AOD computed by the individual models can vary by 40% depending on the assumptions of the dust PSD
  - This is not a consequence of the assumption of the refractive index
  - Dust absorption variability due PSD is somewhat smaller (<30%), with intermodal variability driven by refractive choice
- Models with the finer resolution of the size distribution have greater sensitivity in computed optical properties to variation in the PSD
  - Implications for observational need to constrain fine mode portion of dust
  - Implications for estimates of radiative forcing from models
  - Implications for data assimilation -> possible error in AOD to mass translation

Parametric Experiment

Prescribe the dust mass loading and particle size distribution and compute the integrated AOD, SSA, forcing

- Use the model-provided size bins, MEE and SSA
- Impose a mass loading so that the NAAPS-provided MEE gives a unit of AOD
  - MEE = 0.59 $m^2\ g^{-1}$ => Mass = 1.695 $g\ m^{-2}$
- Explore a plausible range of dust particle size distributions, following Reid et al. (2008)
  - vmd = 1.5 - 5.0 μm; σ = 1.5 - 2.5
  - OPAC particle size distribution of desert dust



Simple SW Dust Forcing Estimate after Chylek & Wong (1995)

$\Delta F_R \sim 2(1-a)^2 \cdot \beta \cdot \tau_{sca} - 4 \cdot a \cdot \tau_{abs}$, where:

a = albedo = 0.06 (ocean), β = upscattering fraction ~ 0.31, τ_{sca} = scattering optical depth, τ_{abs} = absorption optical depth