The PACE-MAPP algorithm

Simultaneous aerosol and ocean products from combined polarimeter and shortwave infrared measurements

2/27/2023

PACE-MAPP team

❑ PI

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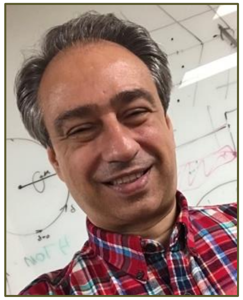
➢ *James Allen*

➢ *Adam Bell*

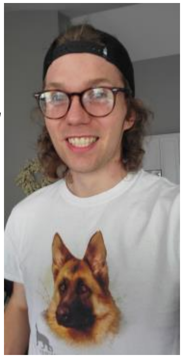
❑ Co-Investigators

➢ *Jacek Chowdhary*



➢ *Ed Chemyakin*

➢ *Michael Jones*



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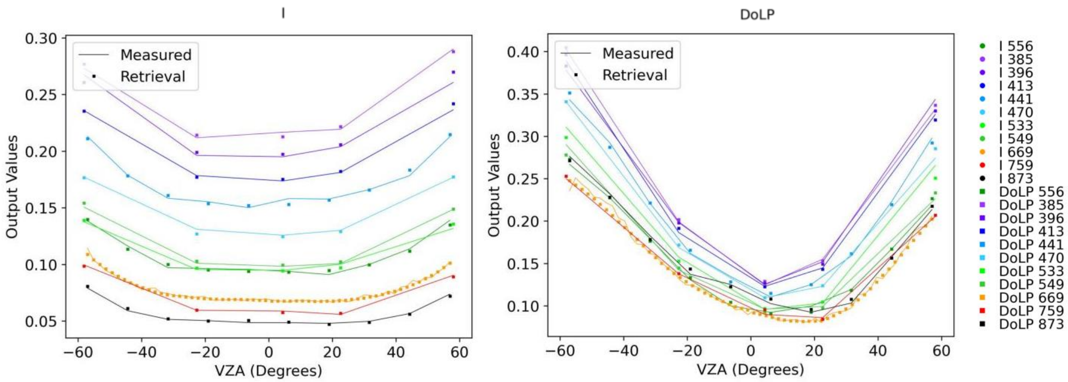
➢ *Yongxiang Hu*

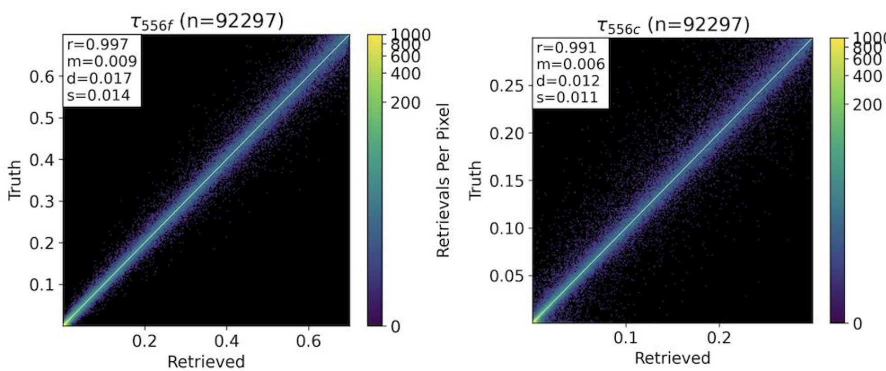
PACE-MAPP collaborative algorithm project

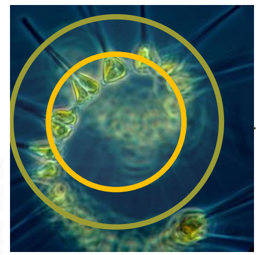
- Produce accurate aerosol optical and microphysical properties and ocean properties
- Use a coupled atmosphere-ocean vector radiative transfer (VRT) model
- Use accurate but fast Mie/SS/T-matrix LUTs
- Use scientific machine learning to speed-up retrievals by 1000x (PACE-MAPP Neural Network)

PACE-MAPP is a multi-instrument polarimeter algorithm for SPEXone, HARP2, OCI shortwave infrared channels

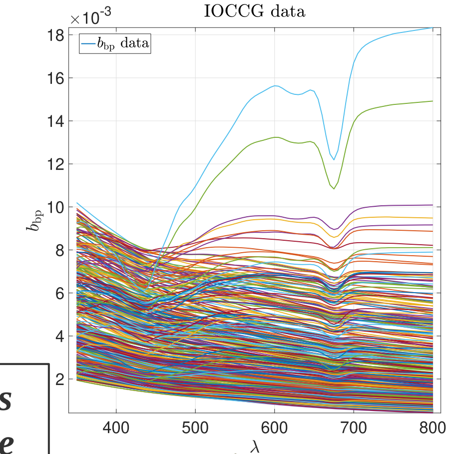


PACE-MAPP uses neural networks to become 1000x faster. 11 channels simulate UV-VIS-NIR at all viewing angles.



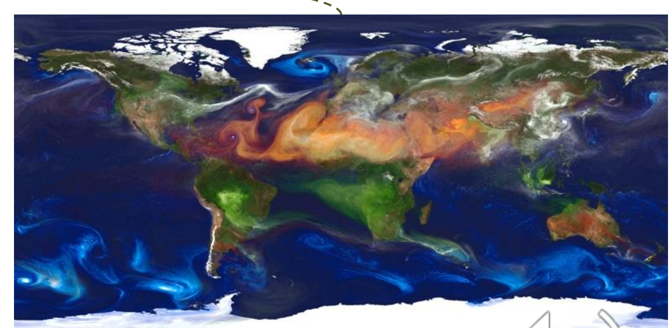


Bio-optical model includes coated particles



Collaborations needed to solve challenges in coastal zones

Thin cirrus correction



Aerosol VIS-NIR-SWIR properties: fine mode (absorbing), sea salt, and dust

Involving interns in PACE

- **Michael Jones (PACE-MAPP neural network)**
  - Mentor: Snorre Stamnes
  - **Goal: Speed-up PACE-MAPP by a factor 1000+**

- **Grant Sims (Coated hydrosol LUT)**
  - Mentors: Snorre Stamnes, Ed Chemyakin, James Allen
  - **Goal: Shrink Coated Hydrosol LUT from 40GB to less than 1GB**

PACE-MAPP deliverables

Type of Deliverable	Specify Deliverable	Discipline	Applicable PACE Sensor(s)	Input Data for Deliverable	Citation – prior work
Numerical model	Bio-optical model	Ocean color, atmosphere, ocean	OCI HARP2 SPEXone	Multi-Angle Total Radiance and Polarimetry OCI SWIR	Chowdhary et al., 2006, 2012, 2019.
Numerical Model	Aerosol model	Atmosphere, ocean, land	OCI HARP2 SPEXone	Multi-Angle Total Radiance and Polarimetry OCI SWIR	Stamnes et al., 2018.
Numerical model	Thin cirrus model	Atmosphere, ocean, land	OCI HARP2 SPEXone	Multi-Angle Total Radiance and Polarimetry OCI SWIR	Diedenhoven et al., 2012, 2013. Yang et al., 2015.
PACE-MAPP algorithm	Coupled atmosphere-ocean retrieval algorithm for aerosol, thin-cirrus, ocean color ap & bbp spectra	Ocean Color Algorithm, Aerosol Algorithm, Cloud Algorithm, Applications (coastal zones, NPP, AQ, DRE)	OCI HARP2 SPEXone	Multi-Angle Total Radiance and Polarimetry OCI SWIR	Stamnes et al., 2018. Cairns et al., 1999. Chowdhary et al., 2006, 2012, 2019. Diedenhoven et al., 2012, 2013. Yang et al., 2015.

PACE-MAPP aerosol/thin cloud products

❑ Aerosol optical and microphysical properties

- Fine mode AOD (aerosol optical depth), SSA (single-scattering albedo, quantifies absorption), real refractive index, effective radius (size), and effective variance (size distribution width)
- Seasalt AOD, effective radius and effective variance (CRI assumed)
- Dust AOD, effective radius and effective variance (CRI modeled according to Hasekamp/SRON model, with updates from Chowdhary, Schuster and Moosmüller)

❑ Thin cirrus optical and microphysical properties

- Thin cirrus optical depth (< 1.0) and effective radius
- Sensitivity to shape and height will be assessed

Parameter Values

All values randomly selected from a uniform distribution. For VZA 160 angles are generated between 65° and -65° for every observation. Altitude is fixed at top of atmosphere (TOA).

Parameter [Units]	Min	Max
SZA [degrees]	0	60
RAA [degrees]	0	180
n_{rf}	1.39	1.65
n_{if}	1e-5	0.045
r_{nf}	0.075	0.15
r_{nc}	0.5	1.5
τ_{556f}	1e-5	0.7
τ_{556c}	1e-5	0.3
σ_{gf}	log(1.4)	log(2.01)
σ_{gc}	log(1.35)	log(2.01)
FTL Base Height [km]	1.01	7.0
v [m/s]	1.0	13.0
Chla [mg/m^3]	0.01	9.0

PACE-MAPP framework

PACE-MAPP framework for running optimal estimation retrievals:

- Written in 100% Python (no complicated setup).
- Configuration file-based retrievals:
  - Models can be easily interchanged (we have a separate framework to rapidly train neural networks models).
  - Extendable pipeline that supports different modules.
  - Ability to run retrievals using data from multiple instruments at once across different channels.
- Full support to read from PACE Level-1C datafiles.
- Multiprocessing for retrievals across all available cores.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            "../pipeline/handle_model_channels.py:handle_model_channels",
            "../pipeline/l1c/i_dolp_channels.py:l1c_i_dolp_channels",
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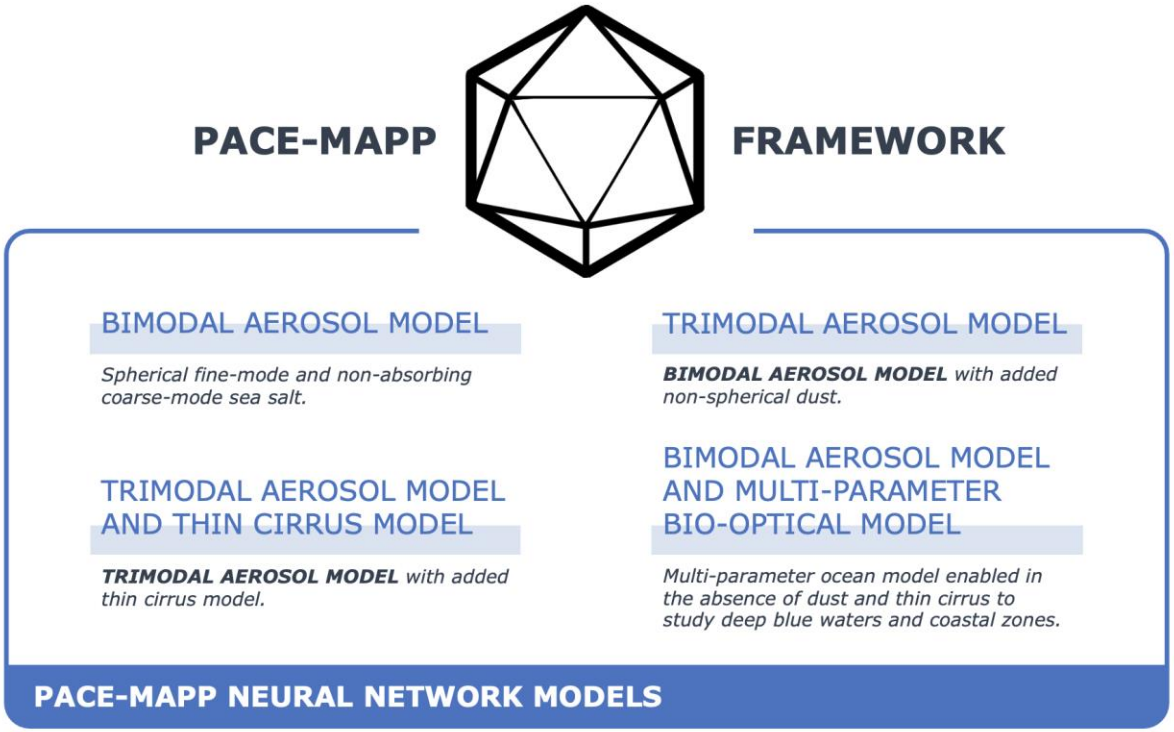
        ]
    }
}
```

PACE-MAPP framework (continued)

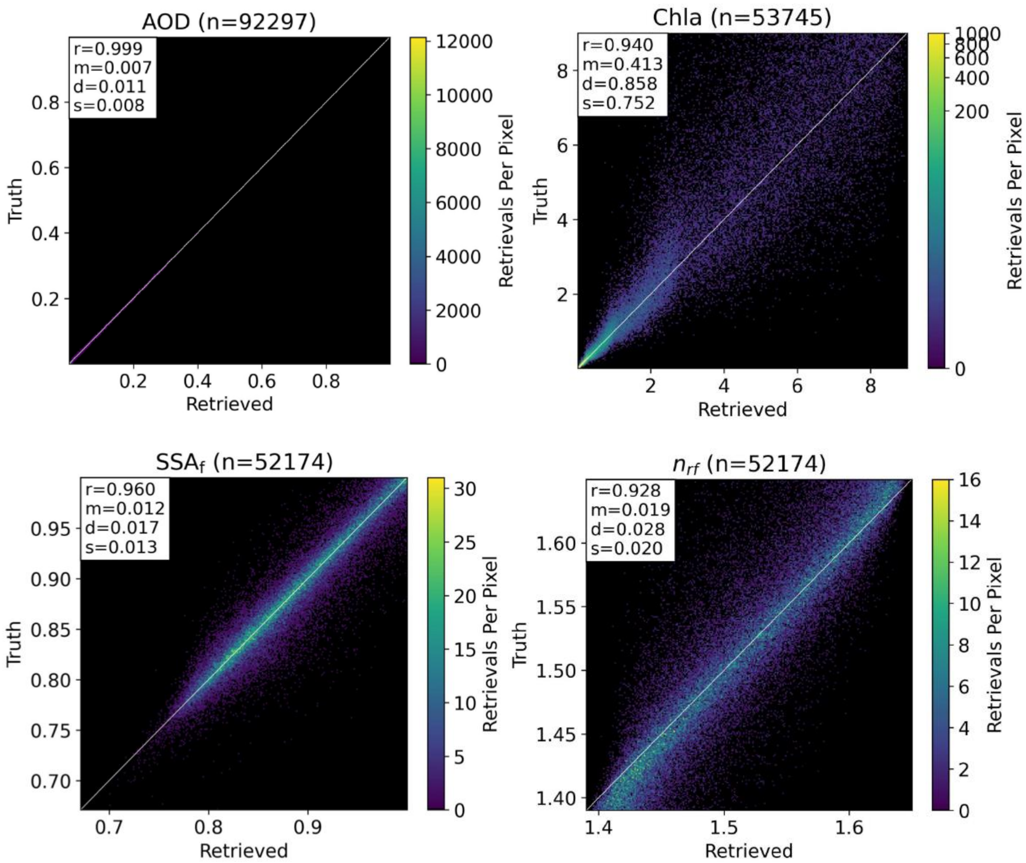


Different PACE-MAPP neural network models can easily be selected inside the PACE-MAPP framework's config file.

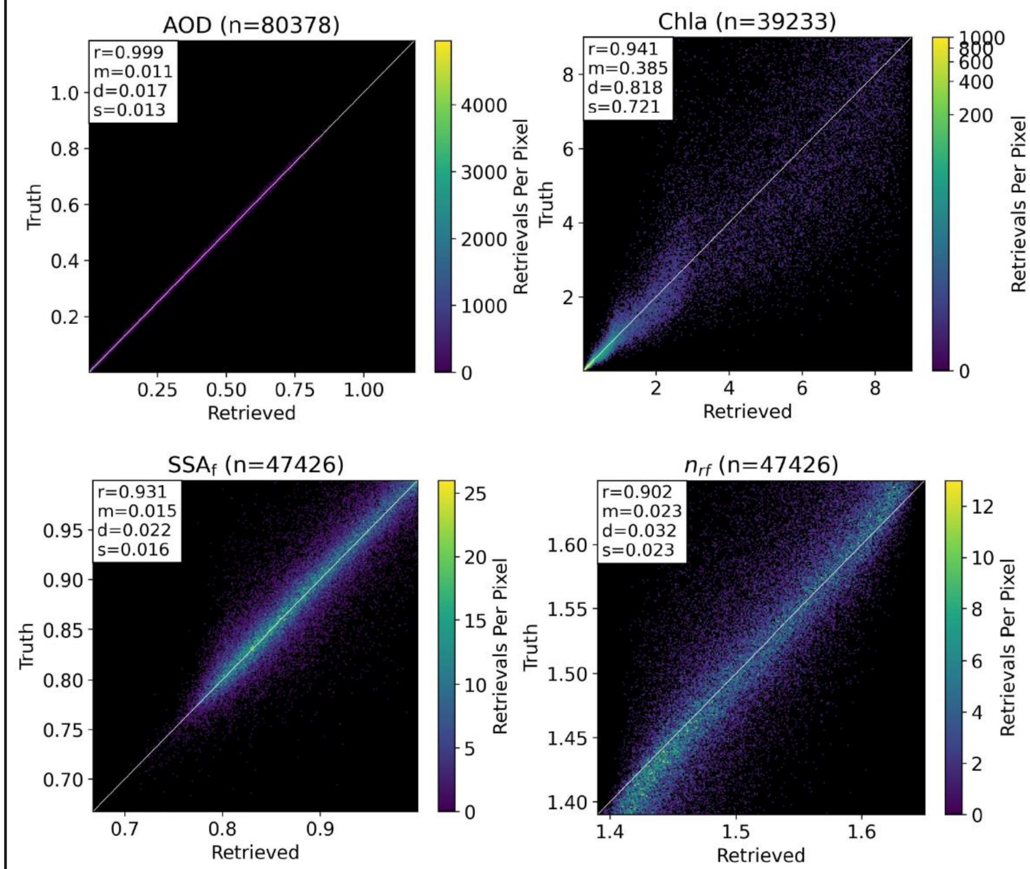
Retrievals using the bimodal aerosol neural network model take ~4.5 sec/core (1,000x speedup).

PACE-MAPP

Bimodal aerosol model with fine-mode absorbing aerosol and coarse-mode, non-absorbing sea salt



Trimodal aerosol model also includes non-spherical coarse-mode dust aerosol



Coated hydrosol LUT. Scale invariance rule

Size parameter

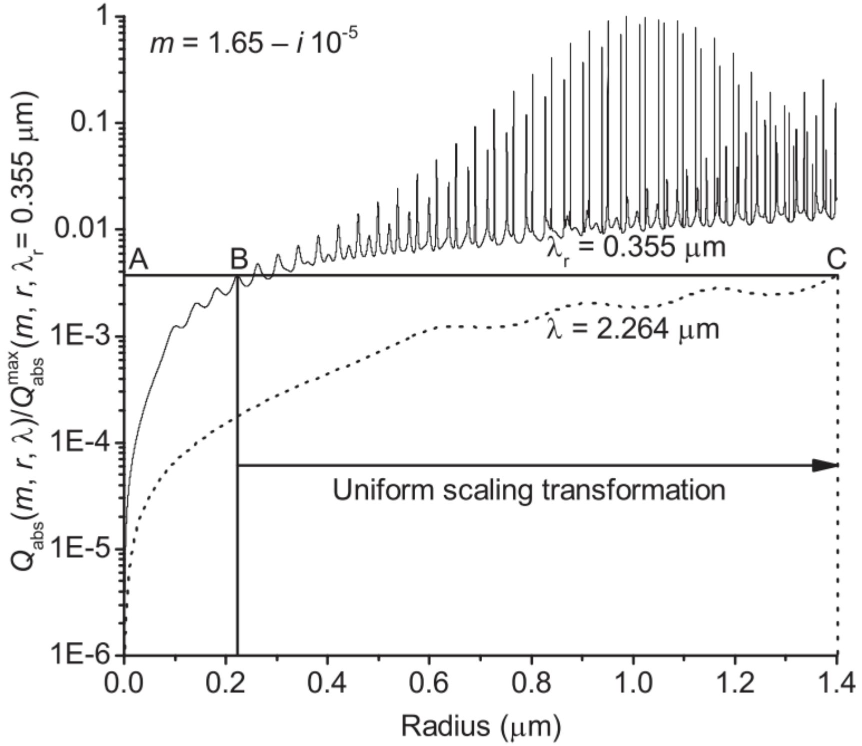
$$x = 2\pi\frac{1.4}{2.264} = 2\pi\frac{r}{\lambda} = 2\pi\frac{\frac{0.355}{2.264}\cdot 1.4}{0.355}$$

Efficiencies

$$Q_p(.,r,\lambda) = Q_p\left(.,\frac{\lambda_r}{\lambda}r,\lambda_r\right)$$

In terms of integrals

$$\int_{r_{\min}}^{r_{\max}} Q_p(.,r,\lambda)\mathrm{d}\ln r = \int_{\frac{\lambda_r}{\lambda}r_{\min}}^{\frac{\lambda_r}{\lambda}r_{\max}} Q_p(.,r,\lambda_r)\,\mathrm{d}\ln r.$$



Normalized absorption efficiencies at wavelengths 0.355 and 2.264 μm are related by a uniform scaling transformation which is a type of Euclidean affinity transformation.

For more details see: E. Chemyakin, S. Stamnes, S. P. Burton, Xu Liu, C. Hostetler, R. Ferrare, B. Cairns, and O. Dubovik, "Improved Lorenz-Mie look-up table for lidar and polarimeter retrievals," Frontiers in Remote Sensing, 2:711106, doi: 10.3389/frsen.2021.711106 (2021).

Coated hydrosol LUT

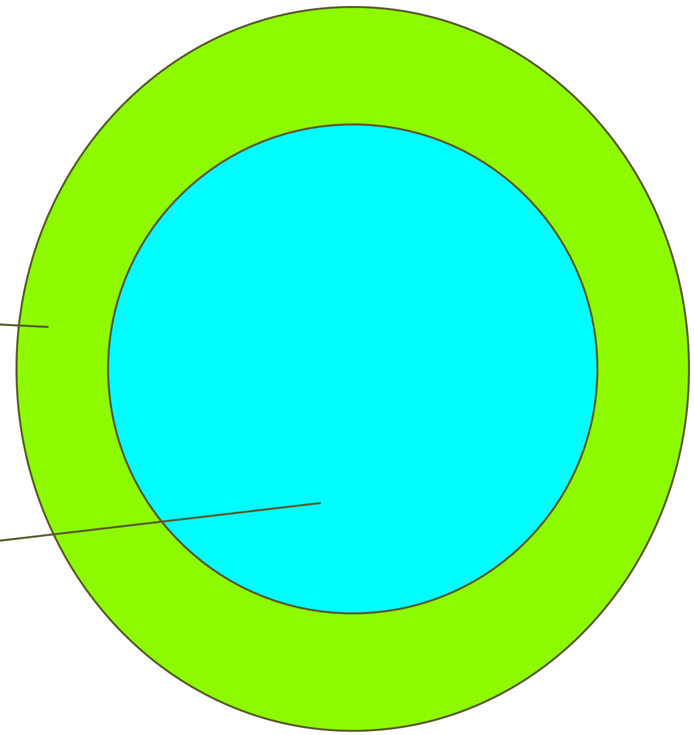
- We have created a coated hydrosol LUT for PACE
- Coated particles can realistically simulate bbp without resorting to tiny sizes as required by solid spheres
- LUT structure based on Chemyakin et al., 2021

Shell real refractive index

Shell imag. refractive index

Core real refractive index

Core imag. refractive index



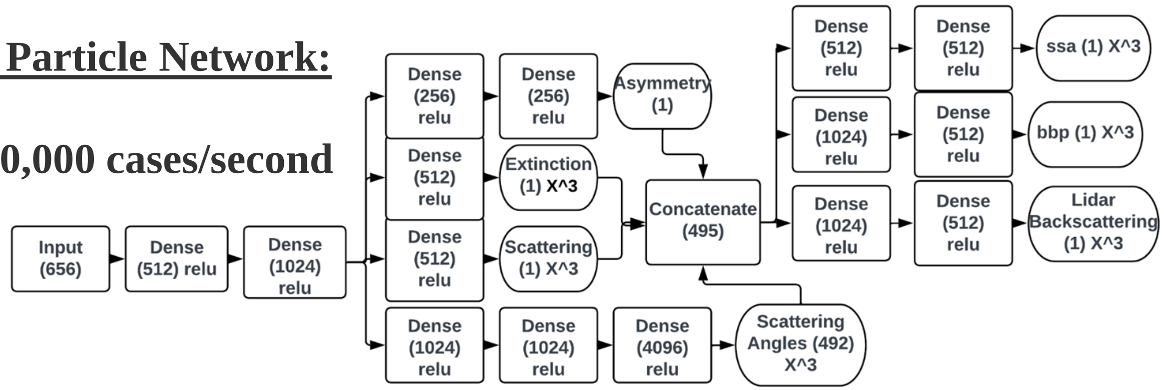
Size distribution:
Effective radius
Effective variance

Core-to-shell ratio: 0.85

Neural Network for Coated/Uncoated Hydrosol Particles

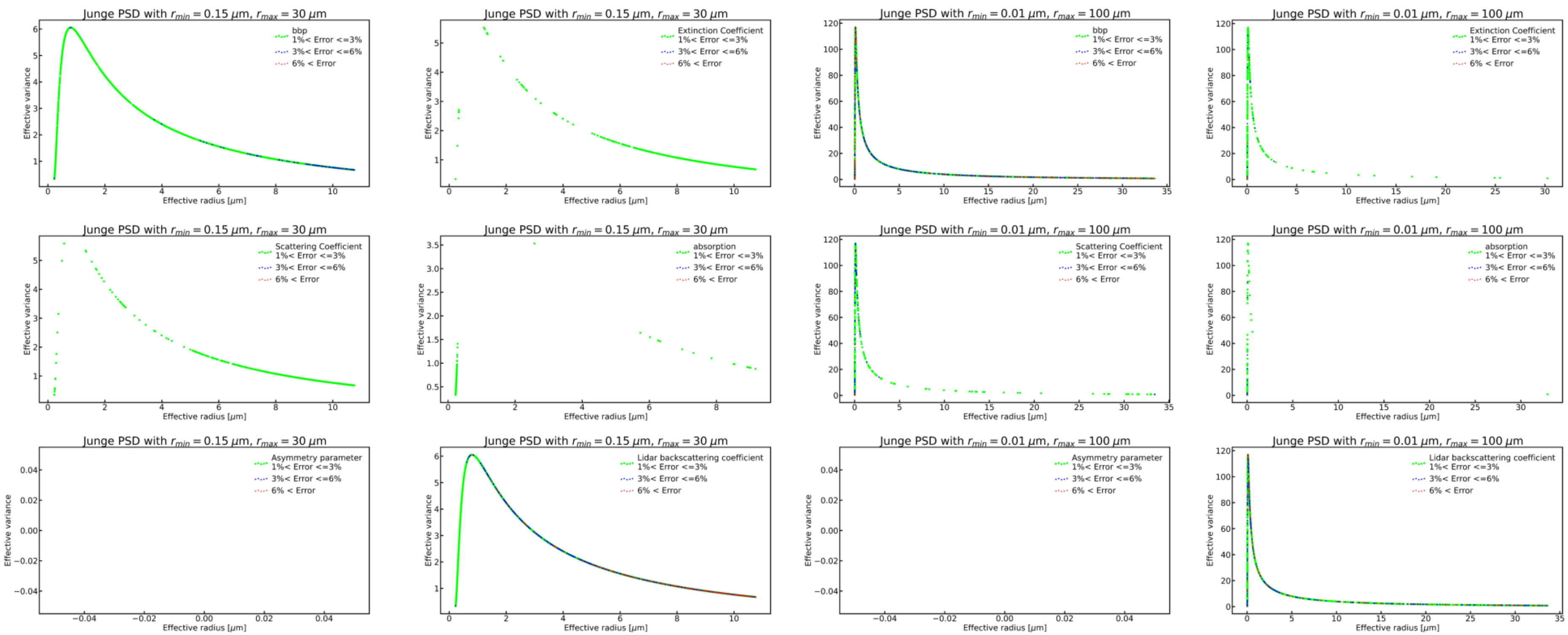
Coated/Uncoated Hydrosol Particle Network:

- Size: 150 MB
- Speed: Approx. 5,000-10,000 cases/second

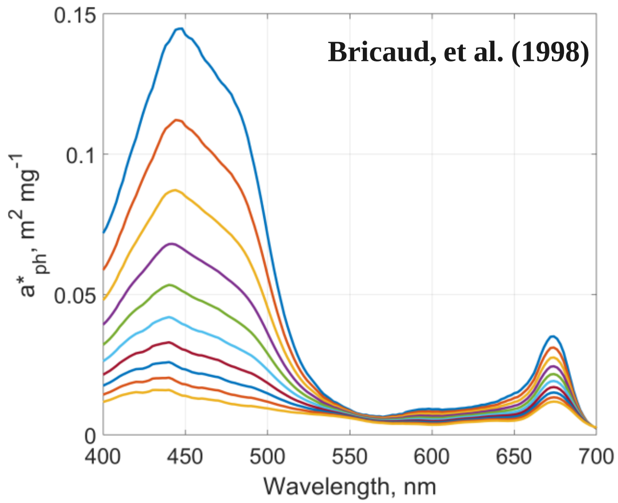


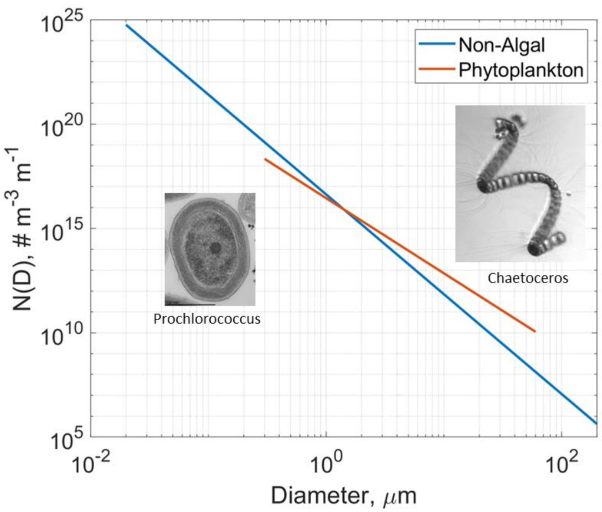
Coated Particles Network	Below 1% Error	Below 2% Error	Uncoated Particles Network	Below 1% Error	Below 2% Error
Extinction Coefficient	97.2%	2.8%	Extinction Coefficient	92.4%	6.4%
Scattering Coefficient	95.4%	4.4%	Scattering Coefficient	89.8%	7.4%
Lidar Backscattering Coefficient	74.1%	20.0%	Lidar Backscattering Coefficient	70.0%	18.3%
Asymmetry Parameter	100.0%	0.0%	Asymmetry Parameter	100.0%	0.0%
Bbp	87.5%	10.7%	Bbp	79.3%	12.5%
Absorption Coefficient	99.8%	0.2%	Absorption Coefficient	97.0%	2.5%

Coated hydrosol LUT neural network



Phytoplankton as Coated Hydrosols



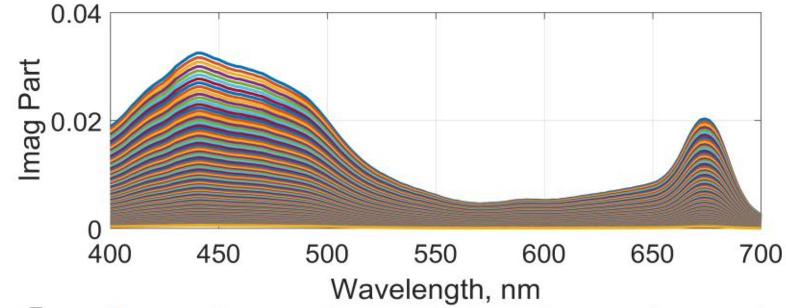


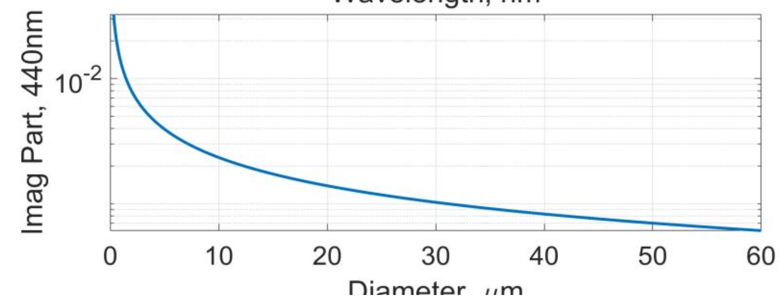
Package Effect

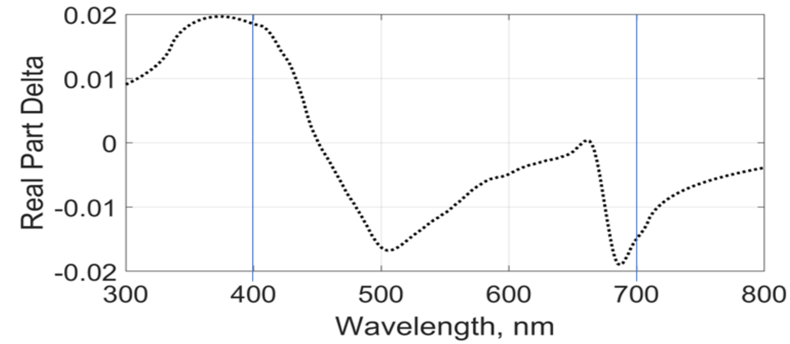
$$Q^* = a_{ph}^*/a_{sol}^*$$

Anomalous Diffraction Approximation (2-layer)

$$Q^* = f(a_{sol}^*, C_i, D, \text{imagCore})$$







Chl Conc

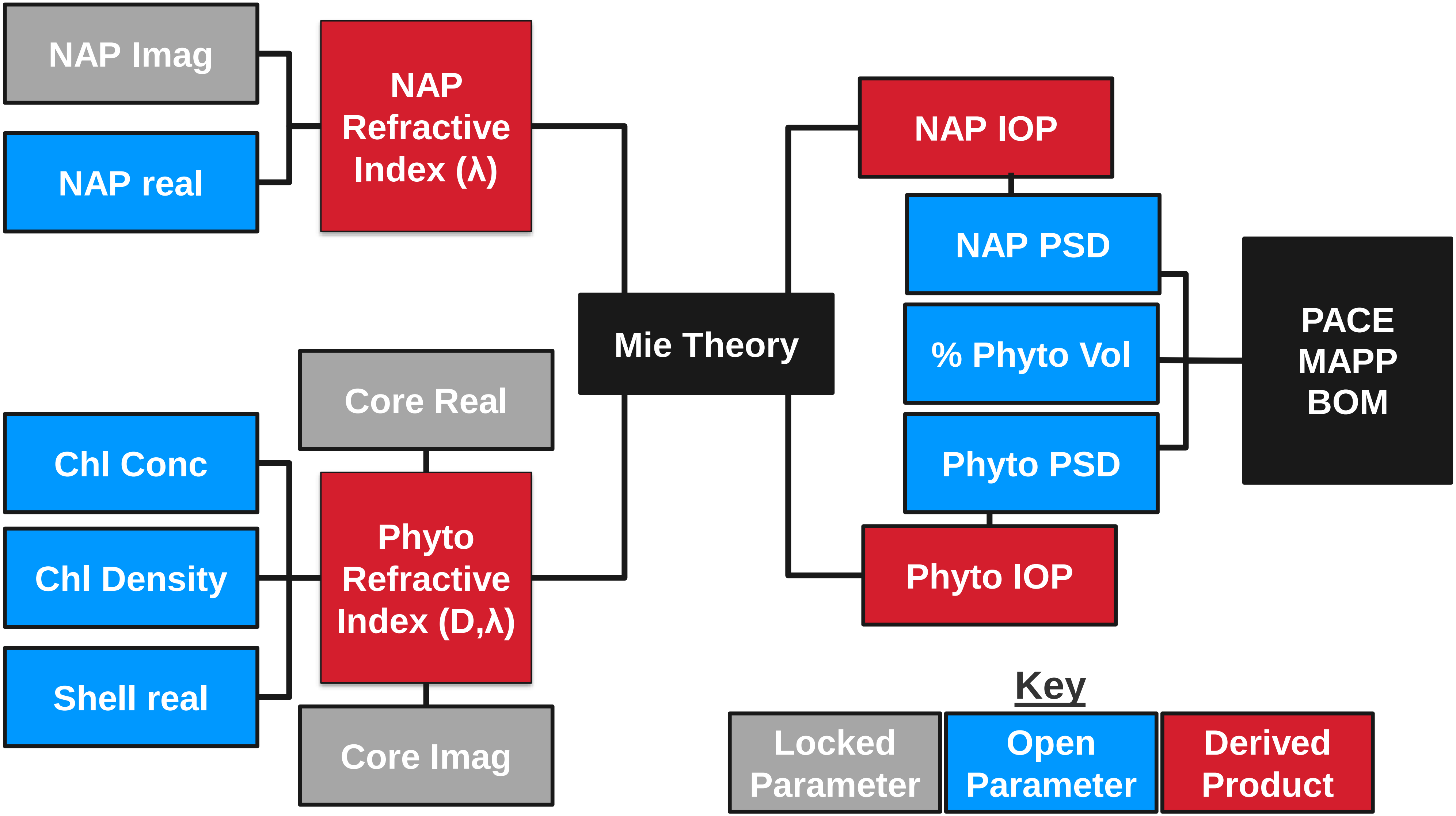
Core Imag

Phyto PSD

Chl Density

Phyto Refractive Index (D,λ)

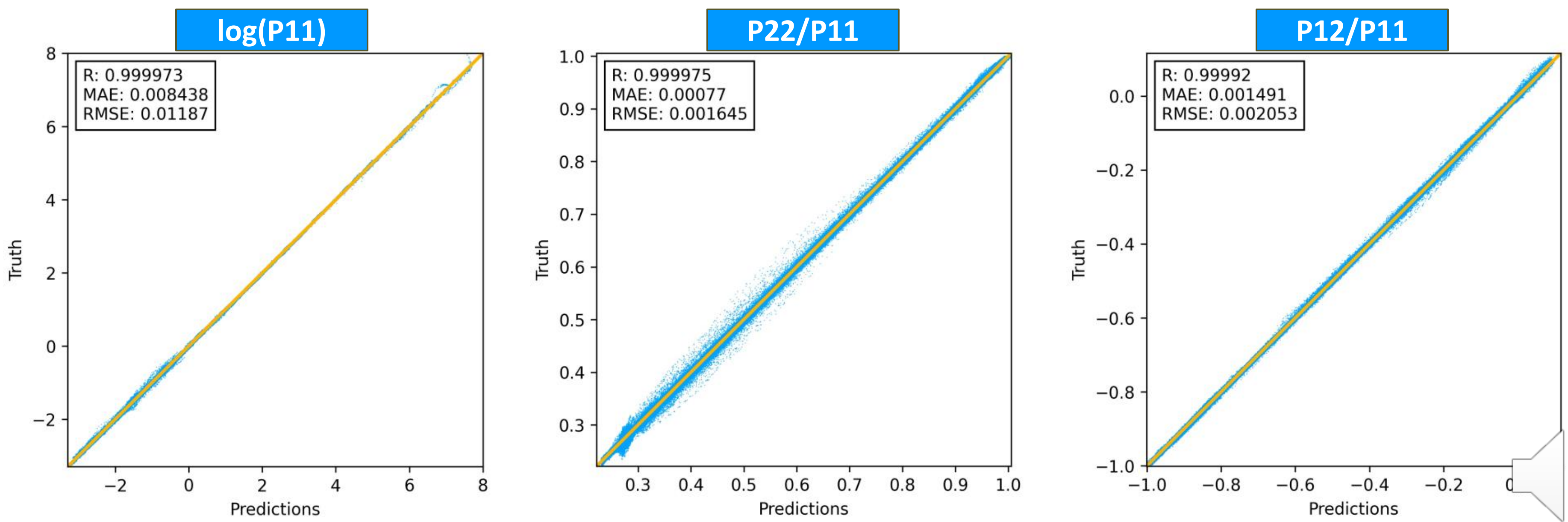
Bio-Optical Model Workflow



Thin Cirrus Model: Tools

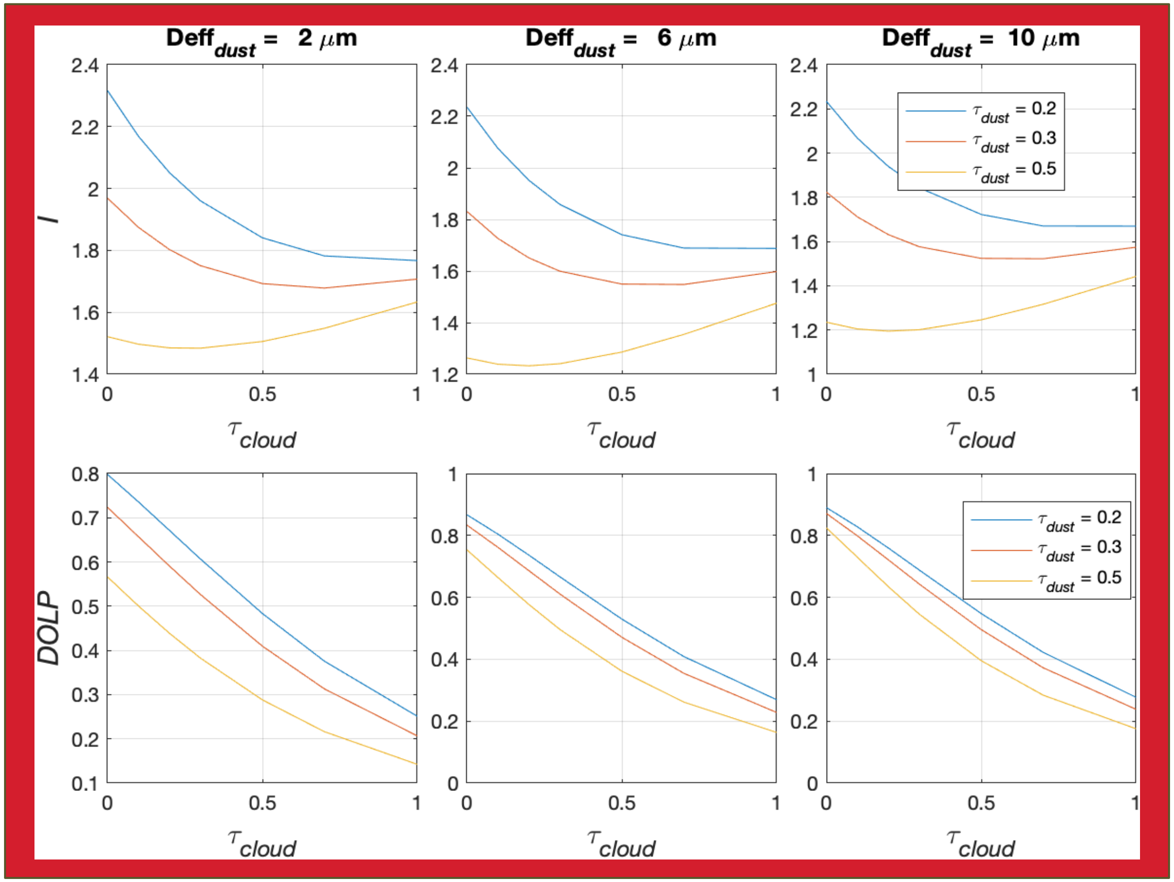
To understand the impacts of optically thin cirrus clouds on aerosol/ocean property retrievals we:

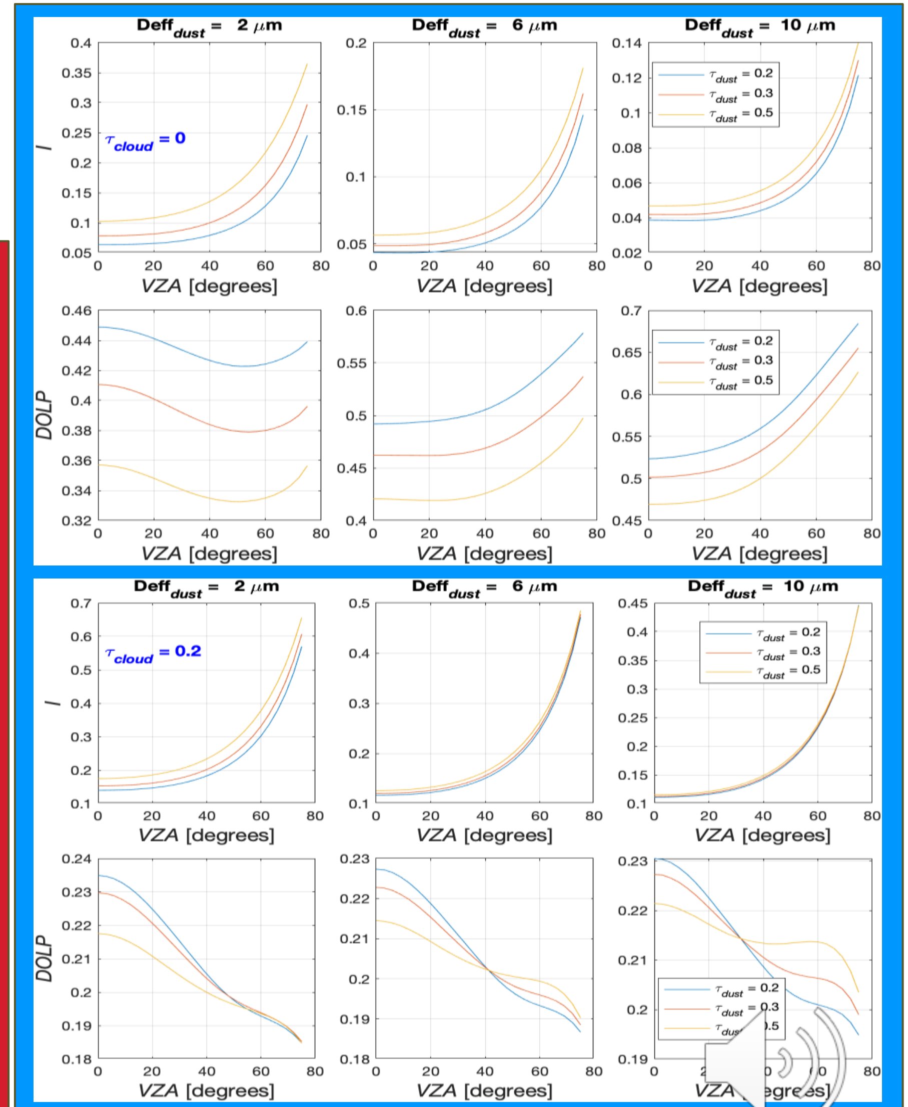
- Incorporated a **Coupled Atmosphere-Ocean Vector** Radiative Transfer solver into the PACE-MAPP retrieval framework (*Chowdhary et al., 2000*)
- Trained a Neural Network to reproduce ice particle optical properties (*Yang, et al., 2015*)
  - **inputs:** wavelength (200-1500 nm), effective diameter (0.6-590 µm), scattering angle
  - **outputs:** log(P11), P22, P33, P44, P12, P43, Qext, Qsca, albedo



Thin Cirrus Model: Next Steps

We can now get a better physical understanding of how thin cirrus clouds impact aerosol property retrievals as a function of optical depth and viewing geometry:





SZA fixed at 60°, Dust properties (*Saito et al., 2021*)

Conclusion

- PACE-related papers
  - Stamnes et al., "The PACE-MAPP algorithm: Simultaneous aerosol and ocean polarimeter products using coupled atmosphere-ocean vector radiative transfer" (submitted)
  - Chemyakin et al., "Improved Lorenz-Mie look-up table for lidar and polarimeter retrievals," Frontiers in Remote Sensing, 2:711106, doi: 10.3389/frsen.2021.711106 (2021).
  - Chemyakin et al., "Efficient single-scattering look-up table for lidar and polarimeter water cloud studies," Opt. Lett. 48, 13–16, doi: 10.1364/OL.474282 (2023).
  - Chemyakin et al., "Efficient single-scattering look-up table for lidar and polarimeter phytoplankton studies," Opt. Lett., to be submitted in 2023.
  - Allen et al., Bio-optical model using coated and uncoated hydrosols (in progress)
  - Bell et al., Simultaneous thin cirrus property retrievals using polarimetry (in progress)
- Working with the PACE SOT for PACE-MAPP to be included in the PACE data processing system
  - Aerosol, Cloud, Hydrosol, Coated Hydrosol IOP LUTs are freely available at **https://science.larc.nasa.gov/polarimetry**
- Questions or suggestions welcome! Email **snorre.a.stamnes@nasa.gov**