The PACE-MAPP algorithm

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

9/20/2021

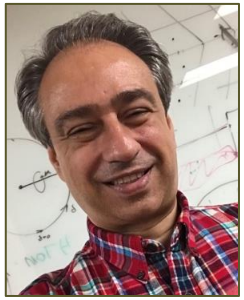
PACE-MAPP team

PI

- Snorre Stamnes

Co-Investigators

- Jacek Chowdhary



- Sharon Burton

- Xu Liu

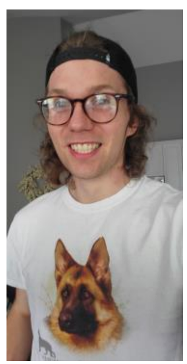
- Bastiaan van Diedenhoven

- James Allen

- Ed Chemyakin

- Adam Bell

- Michael Jones



- Otto Hasekamp

- Johnathan Hair

- Richard Ferrare

Collaborators

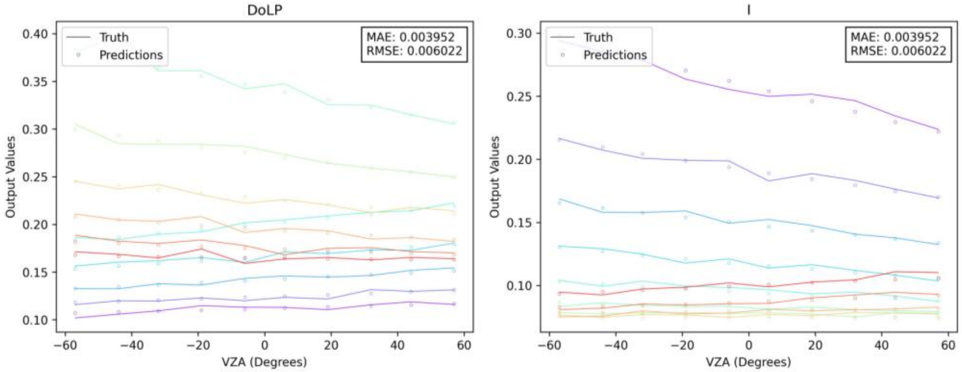
- Chris Hostetler

- Yongxiang Hu

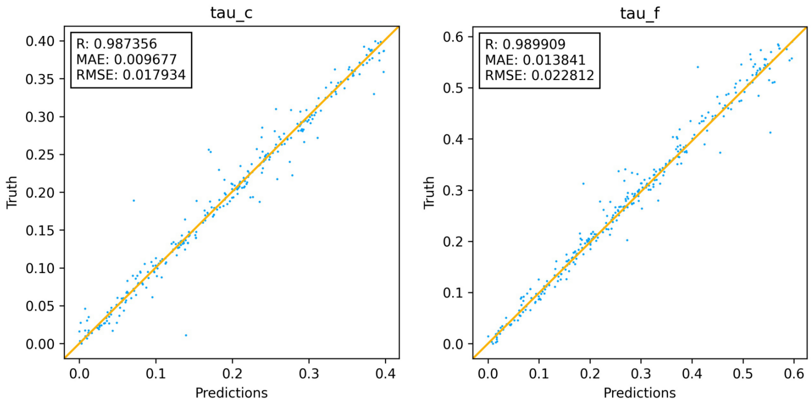
PACE-MAPP collaborative algorithm project

- 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)

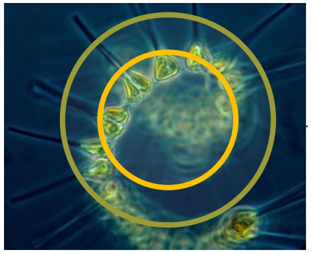
PACE-MAPP is a multi-instrument polarimeter algorithm for SPEXone, HARP2, OCI shortwave infrared channels

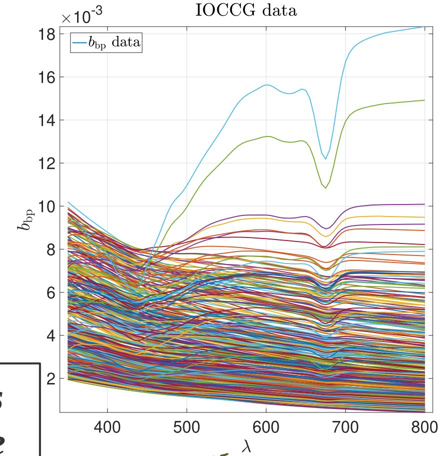


PACE-MAPP uses neural networks to become 1000x faster. 11 channels simulate UV-VIS-NIR at all viewing angles.



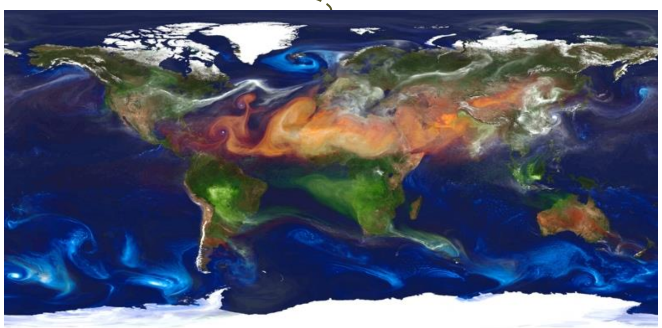
Bio-optical model includes coated particles





Collaborations needed to solve challenges in coastal zones

Thin cirrus correction



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

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			Stamnes et al., 2018.
Numerical model	Thin cirrus model	Atmosphere, ocean, land			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)			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	0.22
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]	1.1	5.9
v [m/s]	0.5	10
Chla [mg/m^3]	0.01	9.9

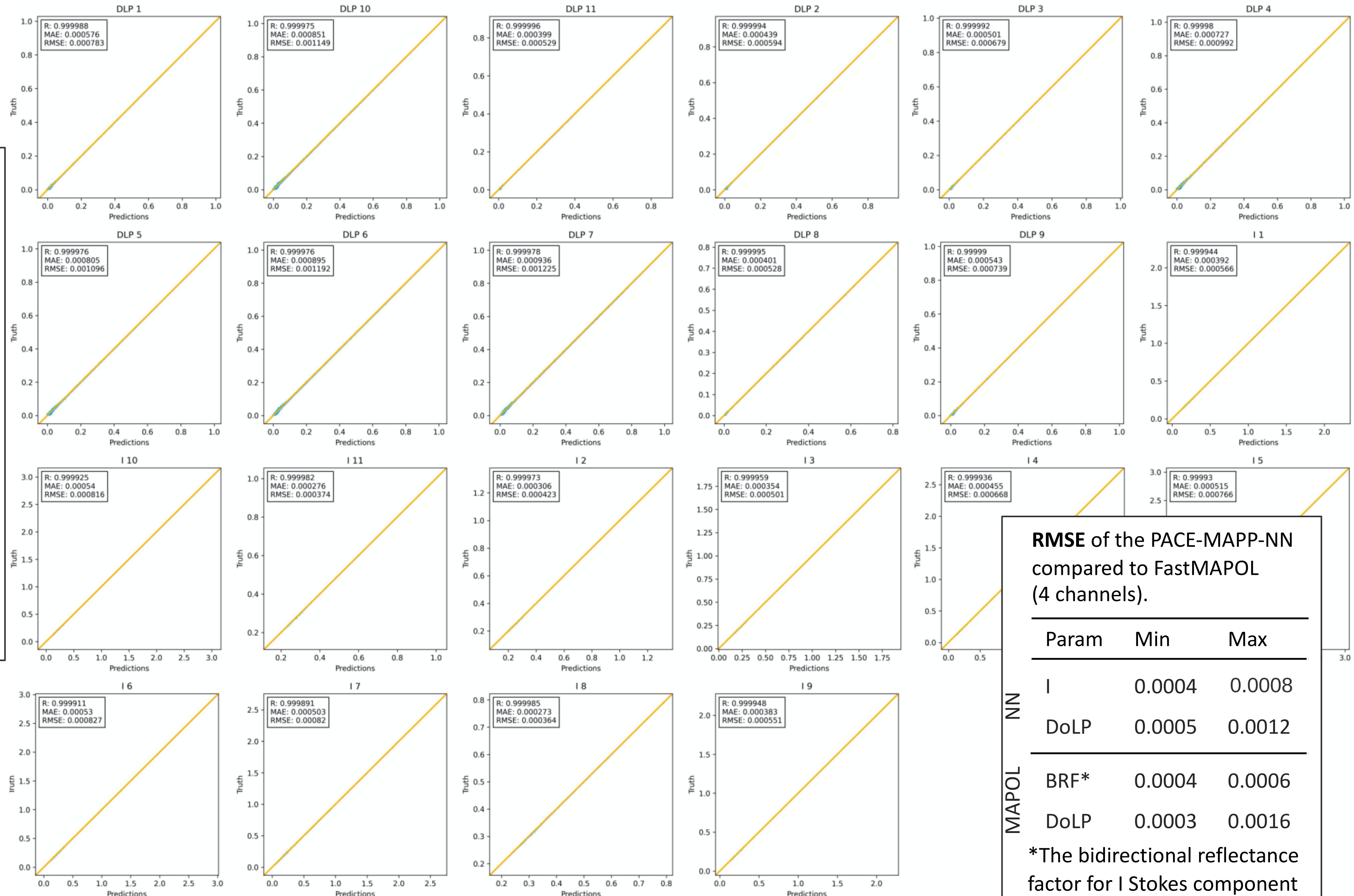
Involving interns in PACE

- **Michael Jones (PACE-MAPP-NN)**
  - 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**
- **Chris Um (integration of Jacek Chowdhary's coupled VRT code)**
  - Mentors: Snorre Stamnes, Adam Bell, Jacek Chowdhary
  - **Goal: Compute water-leaving radiance and Kd products**

PACE-MAPP-NN

Each plot consists of ~2.84 million datapoints.

We have trained a neural network to replace the vector radiative transfer model in PACE-MAPP.

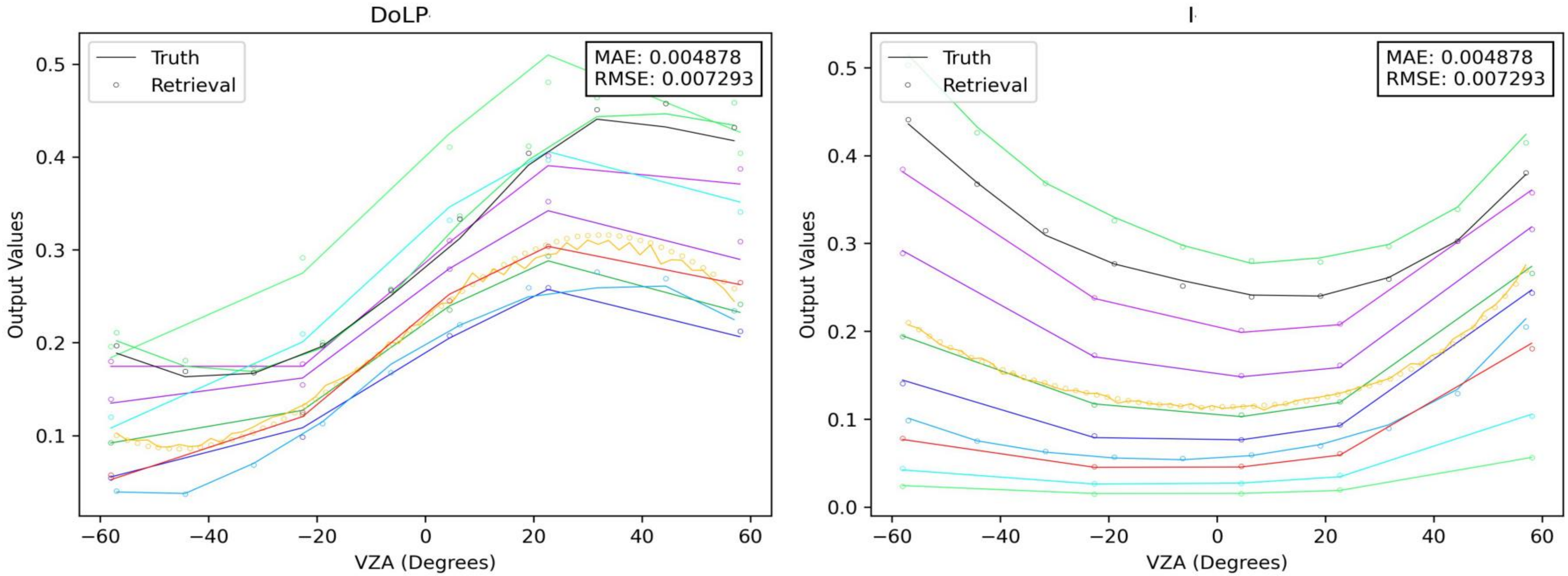


RMSE of the PACE-MAPP-NN compared to FastMAPOL (4 channels).

	Param	Min	Max
NN	I	0.0004	0.0008
	DoLP	0.0005	0.0012
MAPOL	BRF*	0.0004	0.0006
	DoLP	0.0003	0.0016

*The bidirectional reflectance factor for I Stokes component

PACE-MAPP-NN



1000x faster than online VRT

11 channels simulating SPEXone and HARP2 from UV-VIS-NIR

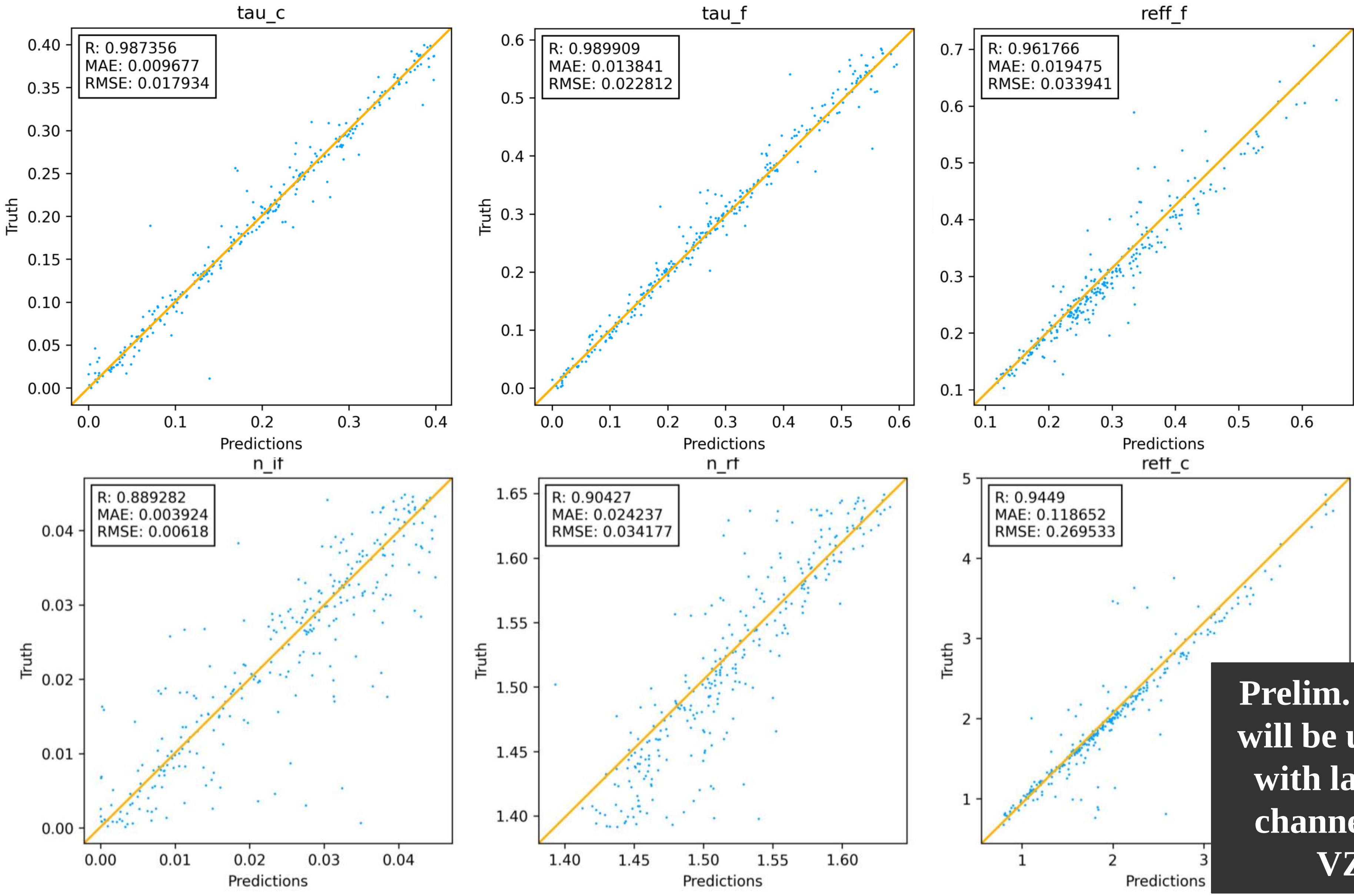
(556, 385, 396, 413, 441, 470, 533, 549, 669, 759, and 873 nm)

All viewing angles

Performance goal for retrievals:

1 second per L1C pixel

PACE-MAPP-NN

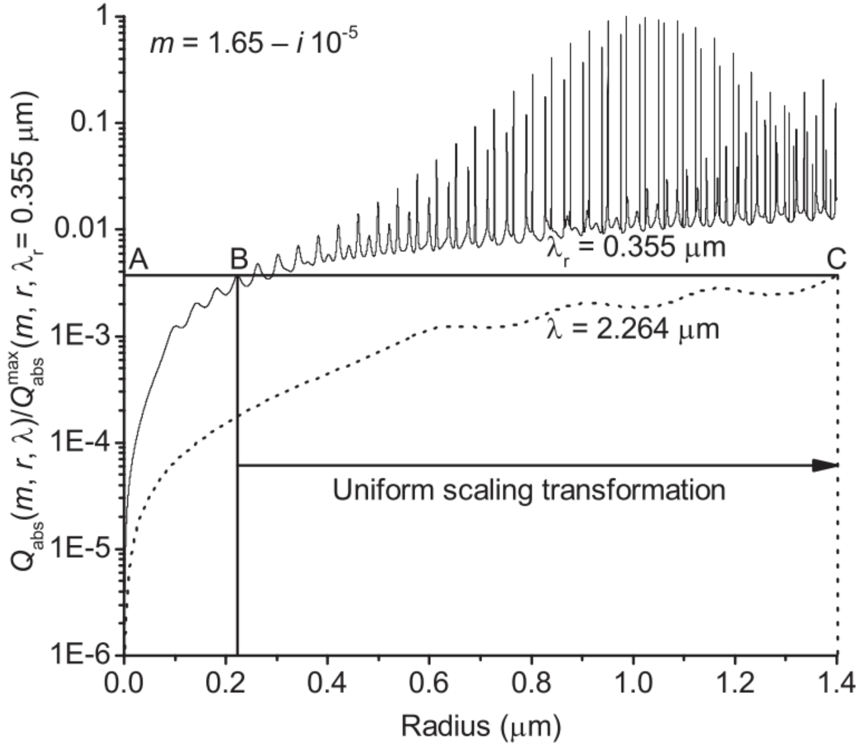


Prelim. results, will be updated with latest 11 channels and VZA

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



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.

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

Coated hydrosol LUT

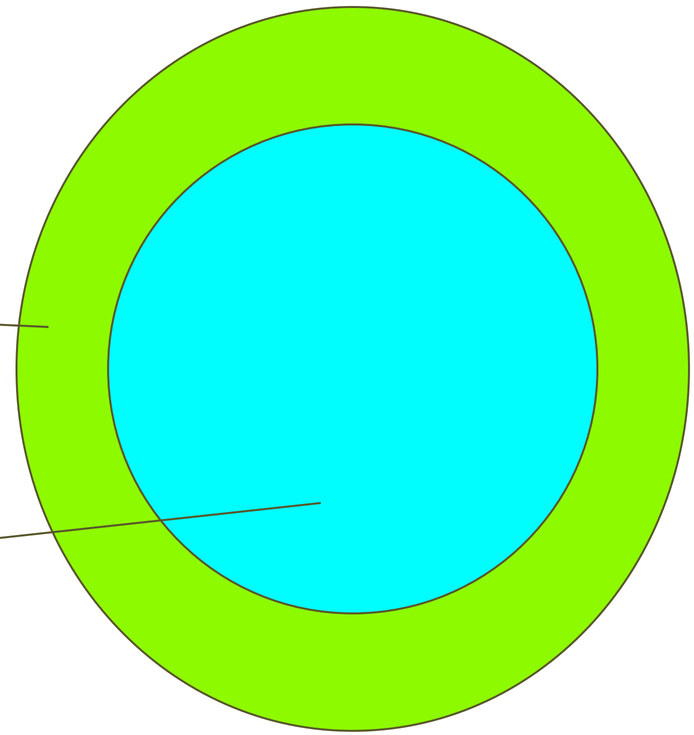
- We have created a coated hydrosol LUT for PACE
- Coated particles can realistically simulate bbp without resorting to tiny sizes as required by solid spheres
- LUT structure based on Chemyakin et al., 2021

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

Coated hydrosol LUT neural network

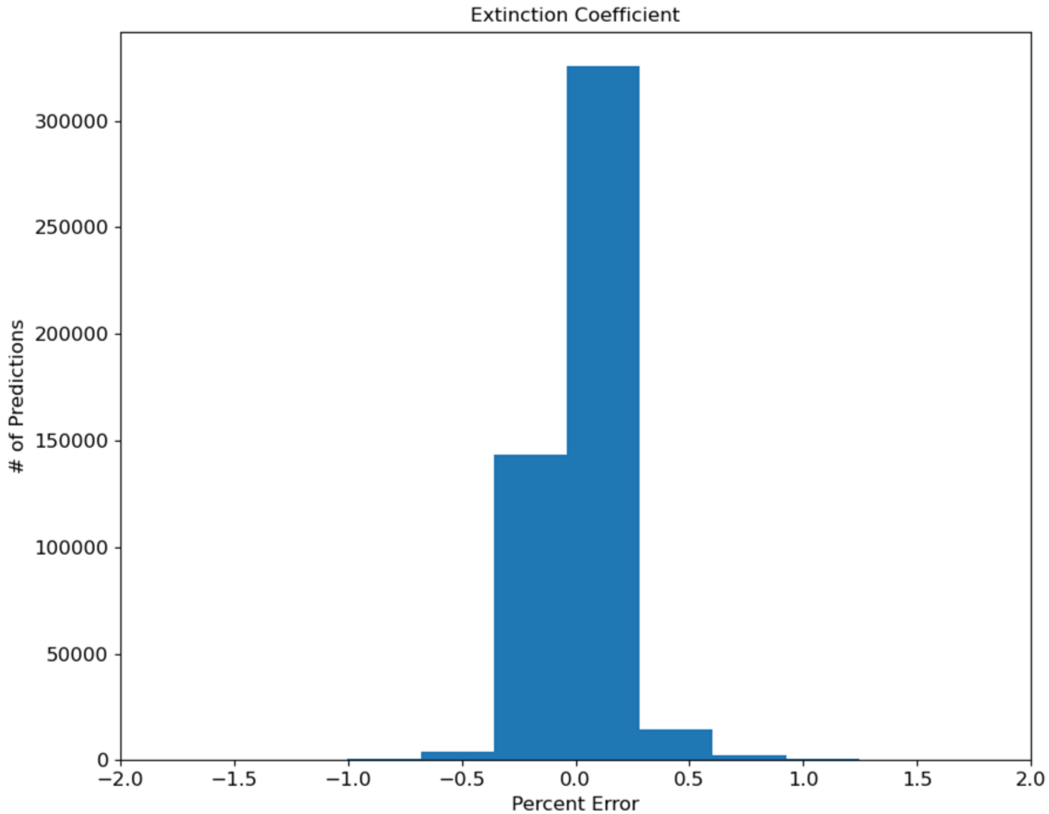
% of dataset within 1% error:

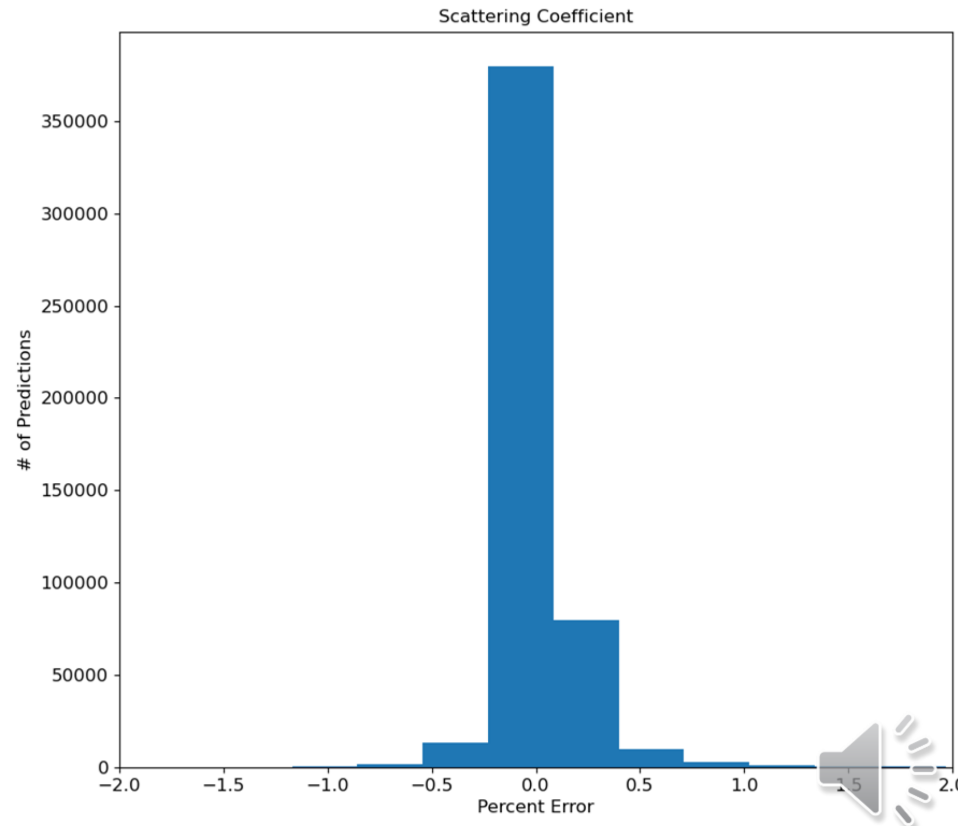
- Extinction: 99.7%
- Scattering: 99.3%

Total Size (Model + Weights): 12.4 MB

Speed: 10,000 – 100,000 cases/second (estimated)

TBD: Scattering matrix elements (p11, p12, p33, p34)



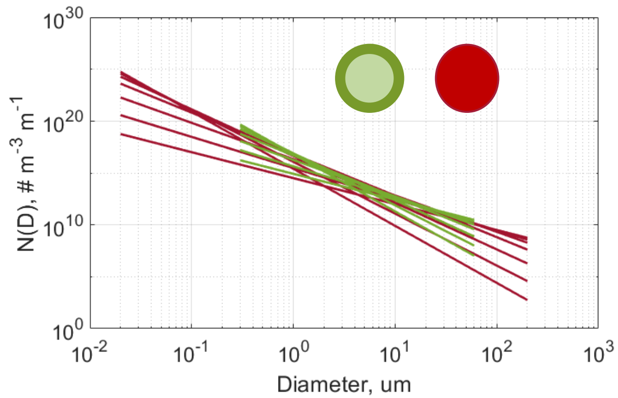


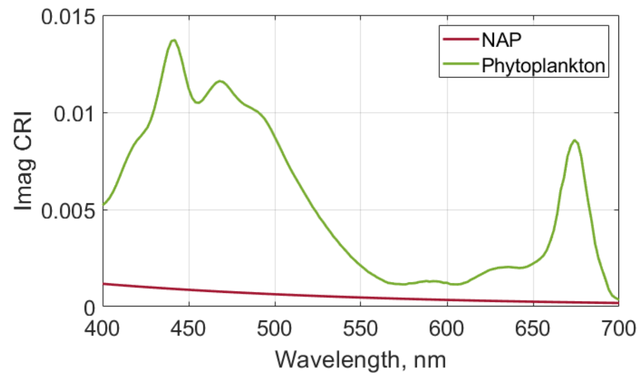
The Bio-Optical Model

Single Particle Optical Efficiencies

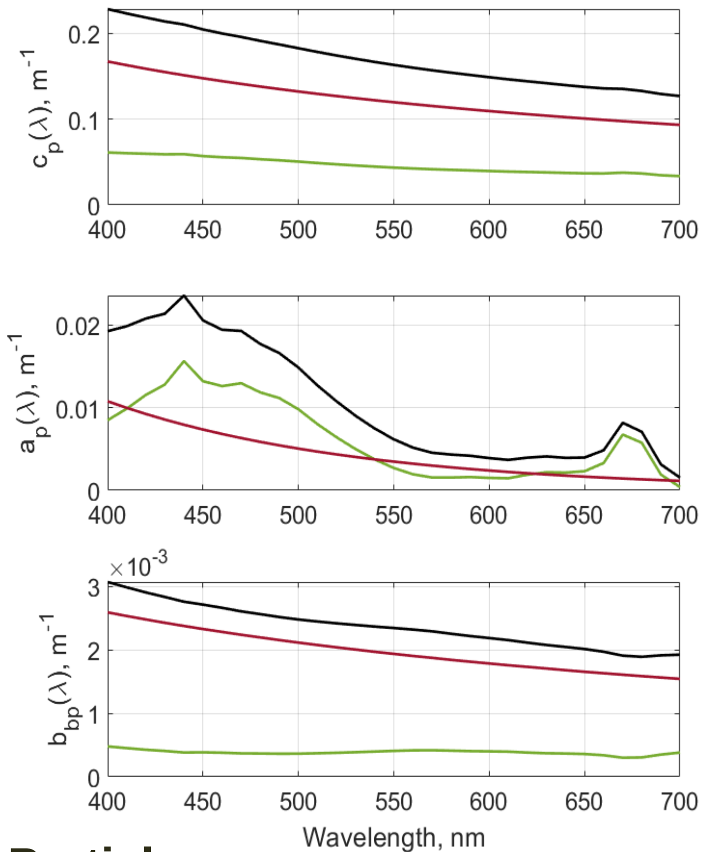
Model Inputs	
Chlorophyll	0.01-10mg m^3
Chl Density	1-10kg m^3
Phyto Shell n	1.05-1.2
NAP n	1.02-1.2
NAP n' slope	0.005-0.02
NAP n' intercept	0.004-0.009
Junge PSD	2.5-6
% Phyto Volume	0.05-0.95

Bulk Particle Optics





Model Outputs

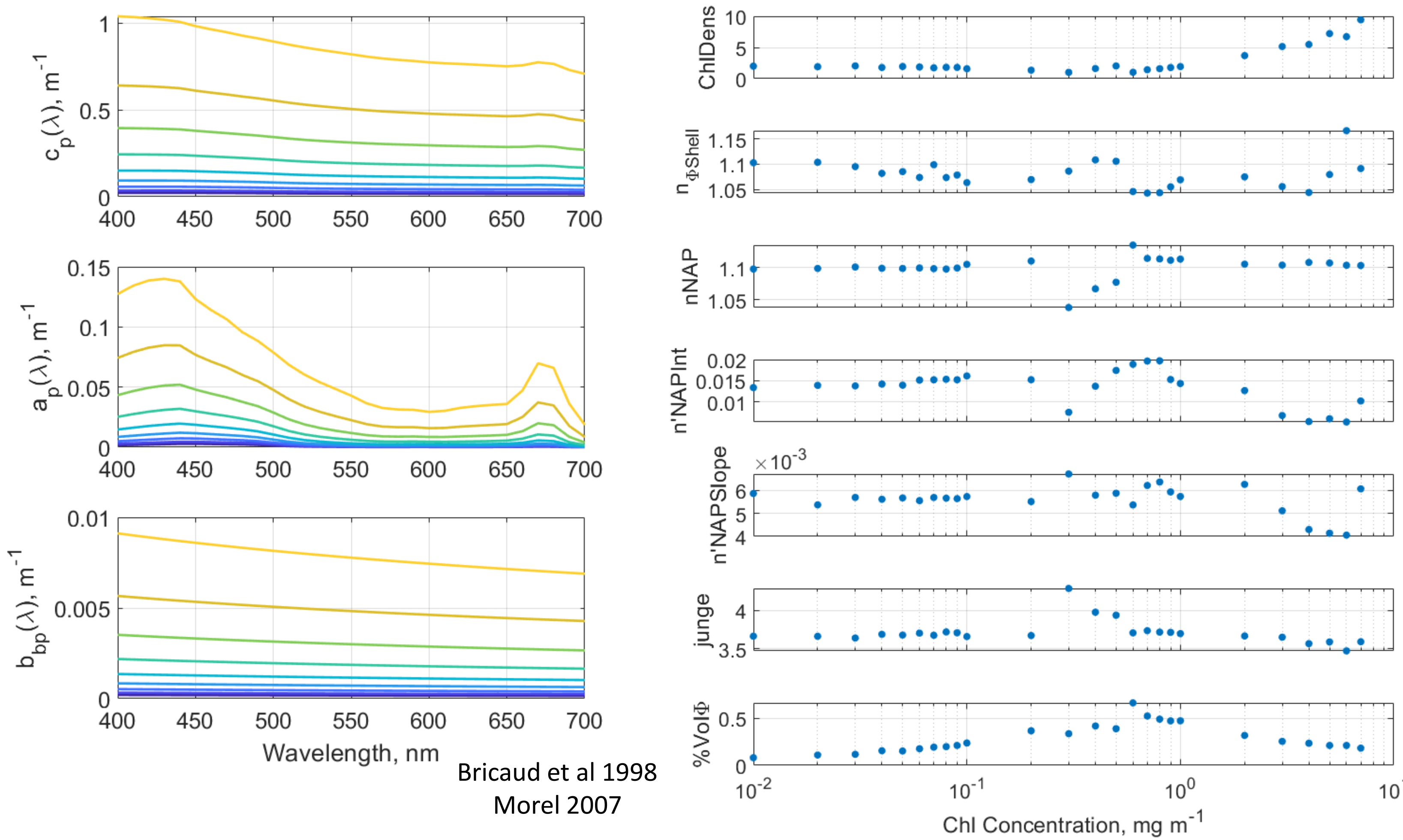


Model Coated Phytoplankton and Homogenous Non-Algal Particles

Chl and relative volume concentration scale to bulk particle population

Forward model realistic biological ranges for Phyto coated spheres and NAP spheres

Theoretical BOM Test



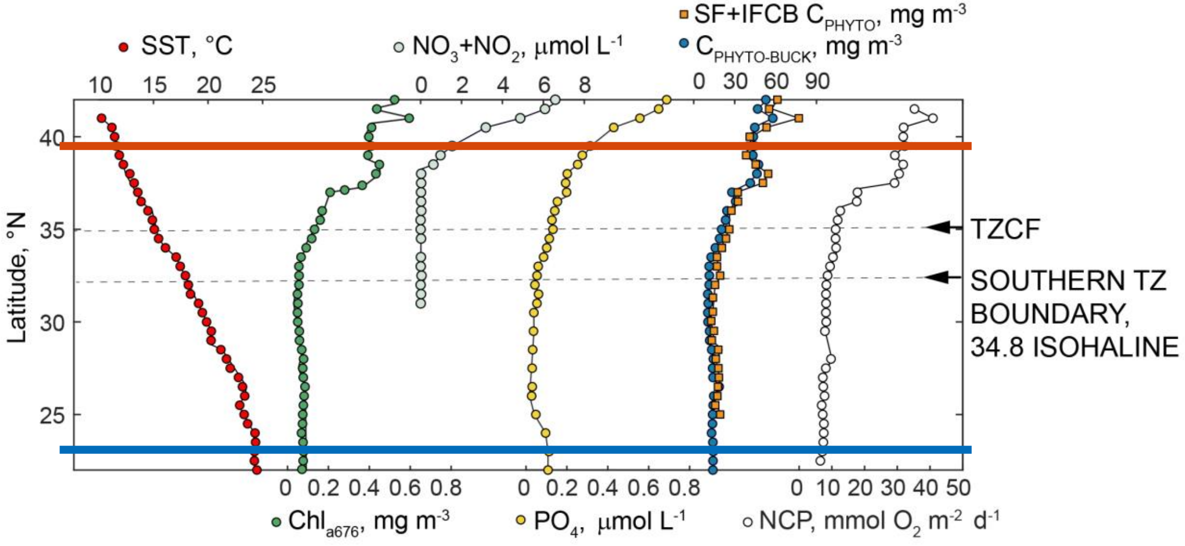
Bricaud et al 1998
Morel 2007

Can test for retrievals using established relationships with chlorophyll

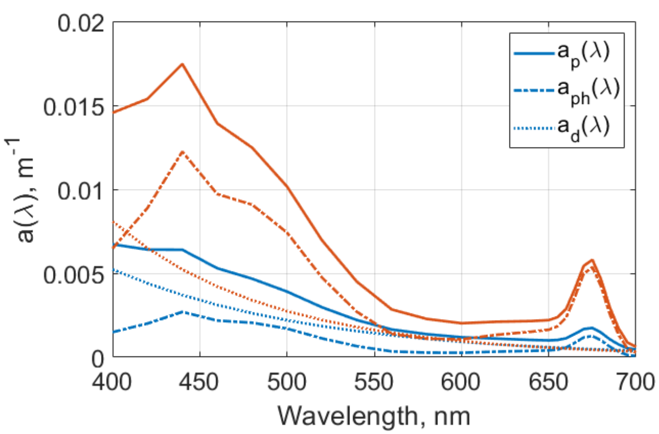
Function minimizes difference between ap, aph, bbp, and cp

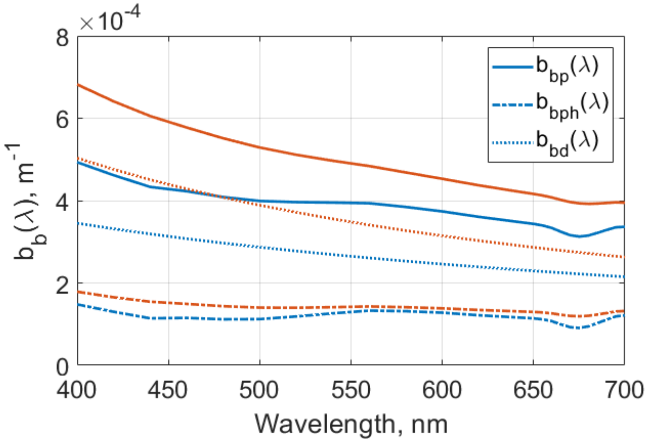
Chl density and relative phytoplankton volume the most important

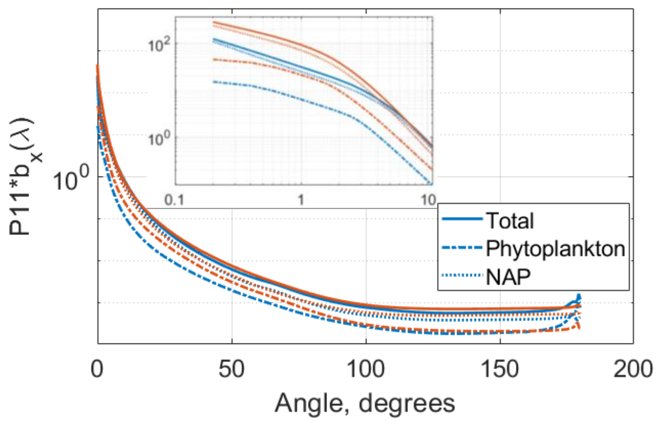
In situ BOM Test



Model Inputs:
Chl
ap(lambda)
cp(lambda)
bbp(700)







Retrievals show expected results just from total particle optics

Scattering processes still dominated by NAP

Future work will improve the Imaginary CRI for the phytoplankton shell

Vector Radiative Transfer Code (VRT) Updates in PACE-MAPP

Integrate Atmosphere-Ocean System model: *eGAP* (*Chowdhary et al.*, 2020)

- Calculates total and polarized (*I, Q,* and *U*) reflectance of radiation emerging from top of an atmosphere-ocean system
- Extended to include underwater light computations of:
  - Upwelling radiance (L_u) at four user-specified ocean depths
  - Upwelling irradiance (E_d) at four user-specified ocean depths
  - Diffuse irradiance attenuation coefficient (K_d) at three user-specified ocean depths
  - Remote sensing reflectance values just above the ocean surface (R_{rs})
- Incorporate new coated hydrosol LUT bio-optical model
  - Compute water leaving contributions to total and polarized reflectance measurements
- Modeling of optically thin cirrus cloud properties (alone or coincident with aerosols) to aid in:
  - Cirrus cloud detection
  - Quantify bias in retrieved aerosol properties due to thin cirrus

Why we care about thin cirrus

❑ The ubiquity of cirrus clouds

- CAMP2Ex above-aircraft cirrus fraction (shown in table)
- For all CAMP2Ex flights, 61% of the time cirrus is present above the aircraft

Flight	Cirrus	No cirrus	Incloud
	P3	P3	P3
20190824	0.75	0	0.25
20190827	0.61	0.24	0.15
20190829	0.64	0.07	0.29
20190830	0.71	0.18	0.11
20190904	0.87	0.03	0.10
20190906	0.83	0.03	0.14
20190908	0.56	0.22	0.22
20190913	0.81	0.13	0.05
20190915	0.77	0.10	0.13
20190916	0.59	0.24	0.17
20190919	0.79	0.12	0.09
20190921	0.70	0.26	0.04
20190923	0.34	0.61	0.05
20190925	0.24	0.74	0.02
20190927	0.32	0.66	0.01
20190929	0.92	0.04	0.05
20191001	0.57	0.35	0.08
20191003	0.42	0.57	0.01
20191005	0.23	0.87	0.05
All Flights	**0.61**	**0.28**	**0.11**

❑ Impacts on aerosol radiative forcing

- Aerosols + thin cirrus shown to be more radiatively important than those with optically thick cirrus clouds
- Aerosols below thin cloud occur with greater frequency and are more impactful on aerosol DRE than aerosols above clouds

❑ Thin cirrus aliasing of aerosol property retrievals

- Impact retrievals of aerosol optical depth (AOD) and aerosol physical properties like shape, size, and single-scattering albedo (SSA)
- How does the presence of thin cirrus impact our goal to retrieve AOD and SSA to ~0.02?

Ongoing and future work

- **Leverage the VRT updates to:**
  - Quantify/correct the bias of retrieved aerosol properties (AOD, SSA, etc.) in the presence of thin cirrus clouds
  - Simultaneously retrieve cloud optical depth and ice cloud particle size and aerosol/ocean properties
- **Neural network (NN) training with thin cirrus:**
  - NN training motivated by the necessity to increase streams in radiative transfer calculations of ice clouds, due to enhanced forward scattering and cloudbow features for large ice particles, as compared to aerosols
- **Additional science questions to address:**
  - Under what cirrus type (i.e., ice crystal habit/orientation), aerosol type, total column optical depth conditions, and to what degree are aerosol retrievals aliased?
    - ”*Microwave and submillimeter wave scattering of oriented ice particles*” Brath et al., 2020
    - The Atmospheric Radiative Transfer Simulator (ARTS) [https://www.radiativetransfer.org]
  - Given spectrally dependent phase functions of the ice crystal habit(s) and aerosol particles, how well can we separate the contributions from clouds and aerosols?
  - Can cirrus contamination create an angularly dependent bias on retrieved aerosol properties?

Conclusion

- **We are working to submit paperwork to request PACE-MAPP be included in the PACE data processing system**
  - Aerosol, Hydrosol, Coated Hydrosol LUTs can be made available to community
- **Working on papers for PACE-MAPP, Coated Hydrosol LUT, Bio-Optical Model using Coated and Uncoated Hydrosols with in-situ data, and thin cirrus detection**
  - PACE special topic due in October
  - We have also submitted three AGU Fall 2021 presentations
- **Questions or suggestions welcome!**