Using multispectral, multiangle remote sensing observations for ocean color retrievals: Studies performed for the NASA/PACE mission

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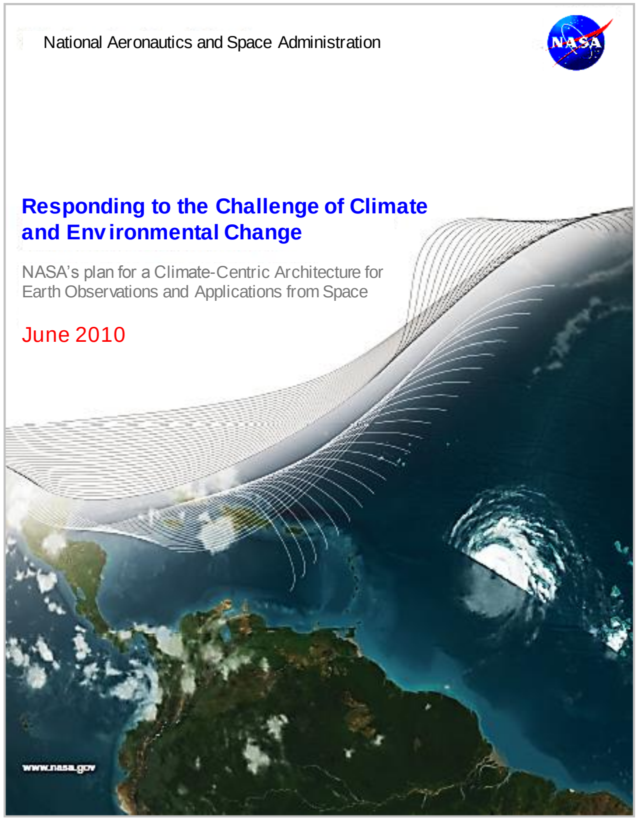
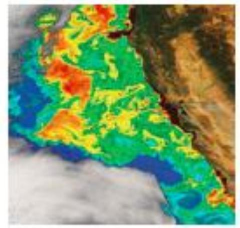
PACE Mission



Pre-Aerosol, Clouds, and ocean Ecosystem (PACE)



The Pre-Aerosol, Clouds, and ocean Ecosystem (PACE) mission will make essential global ocean color measurements, essential for understanding the carbon cycle and how it both affects and is affected by climate change, along with polarimetry measurements to provide extended data records on clouds and aerosols.

"The PACE mission will extend key climate data records whose future was in jeopardy prior to the FY2011 budget request. Global ocean color measurements, essential for understanding the carbon cycle and how it affects and is affected by climate change, will be made by a radiometer instrument on this mission. A polarimeter instrument will extend data records on aerosols and clouds using this approach begun by the French PARASOL mission and expanded upon by NASA's Glory mission, as well as multi-spectral and multi-angle measurements made by NASA's MODIS and MISR instruments on NASA's EOS platforms (MODIS on terra and Aqua, MISR on Aqua)."

- In autumn of 2011 NASA selected a science definition team (SDT) to provide (within 3 years) the science justification and measurement, as well as mission requirements, for the PACE mission
  - *Primary mission:* *Ocean;* *Secondary mission:* *atmosphere*
- In autumn of 2014 NASA selected a science team (ST) to pursue studies on inherent optical properties (IOPs) and Atmospheric Correction (AC)
  - *Atmospheric Correction:* *polarization*

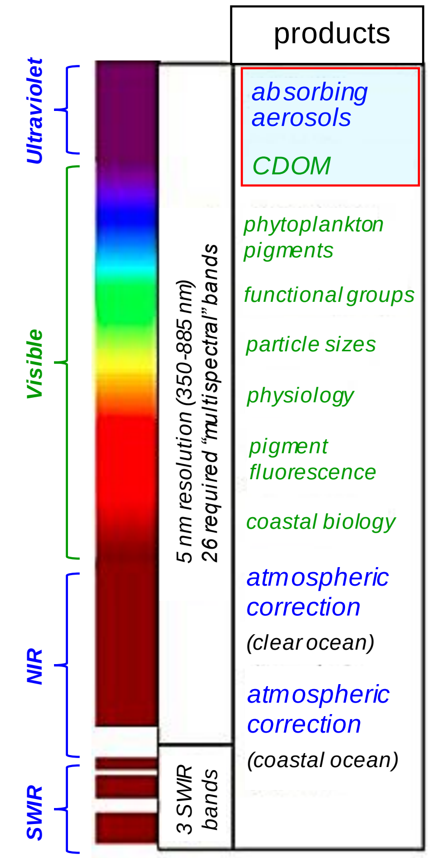
PACE Mission

Ocean Science

Option	Science Threshold and Goal Questions	Brief Instrument Description
OCI †	➢ **Threshold** Ocean Questions SQ 1-7 ➢ Goal Terrestrial Questions TSQ 1-3 *Note*: **Threshold** Questions define required research, i.e. they <u>must</u> be addressed	○ Hyperspectral imager with 5 nm resolution between 350-800 nm ○ 2 NIR bands (incl. 865 nm) ○ 3 SWIR bands (1240, 1640, 2130 nm) ○ spatial resolution = 1 km^2
OCI/OG	➢ OCI Questions (SQ 1-7, TSQ 1-3) ➢ Goal Coastal Questions CSQ 1-4	○ OCI instrument capabilities ○ hyperspectral between 800-900 nm, 1-2 nm subsamples (O_2 A) ○ improved global coverage (1 day) ○ spatial resolution better than 500m × 500m

Atmosphere Science

Option	Science Threshold and Goal Questions	Brief Instrument Description
OCI+	➢ OCI Questions (SQ 1-7, TSQ 1-3) ➢ "**Threshold**" Atmosphere Question ASQ 1	○ OCI instrument capabilities ○ 3 additional NIR and SWIR bands (940, 1378, 2250 nm)
OCI-3M ¶	➢ OCI Questions (SQ 1-7, TSQ 1-3) ➢ Goal Atmosphere Questions ASQ 4,5	○ OCI instrument capabilities ○ a 3M imager ‡ §
OCI/A	➢ OCI+ Questions (SQ 1-7, TSQ 1-3, ASQ 1) ➢ Goal Atmosphere Question ASQ 2	○ OCI+ instrument capabilities ○ selected atmospheric bands at spatial resolution 250m × 250m
OCI/A-3M	➢ OCI-3M & OCI/A Questions (SQ 1-7, TSQ 1-3, ASQ 2,4,5) ➢ Goal Atmosphere Question ASQ 3	○ OCI/A instrument capabilities ○ a 3M imager ‡ §



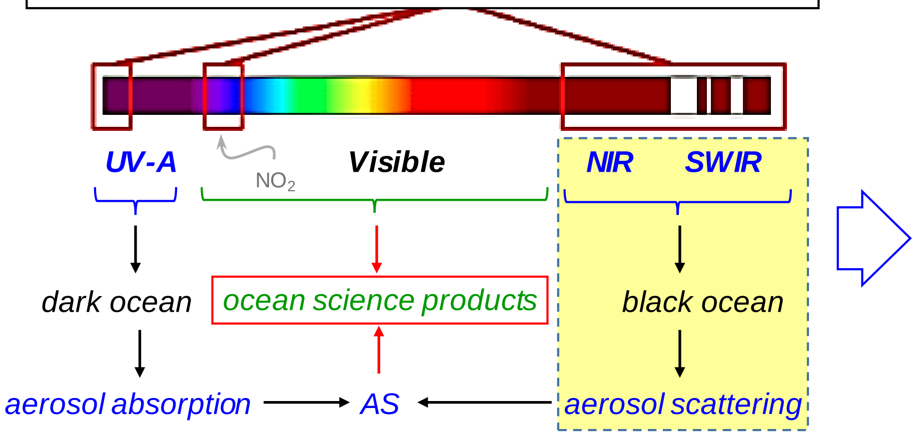
† OCI = Ocean Color Imager
¶ 3M = Multi-directional, Multi-polarization, Multi-spectral

‡ improved atmospheric correction, data continuity for POLDER products
§ data continuity for MISR products, albeit with coarser spatial resolution

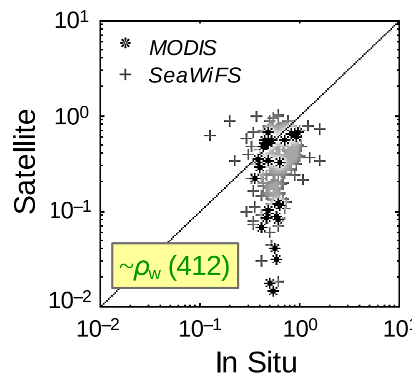
PACE Mission

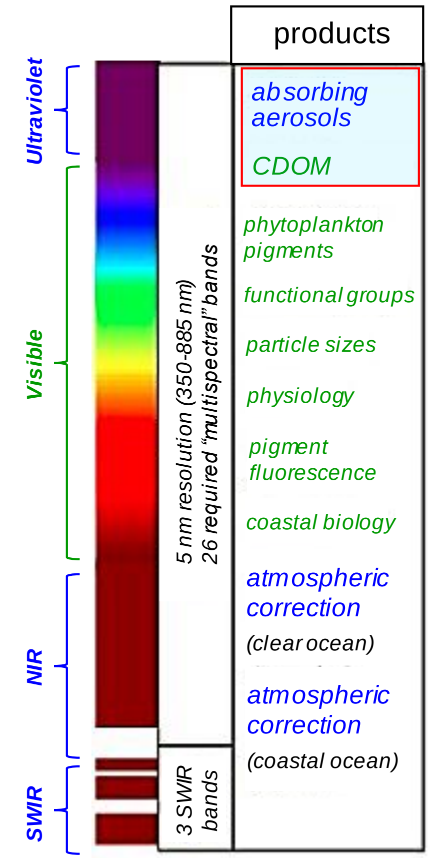
Atmospheric Scattering (AS) estimate

NIR & SWIR band ratios: select aerosol scattering model
UV-A radiance: detect (& constrain?) aerosol absorption

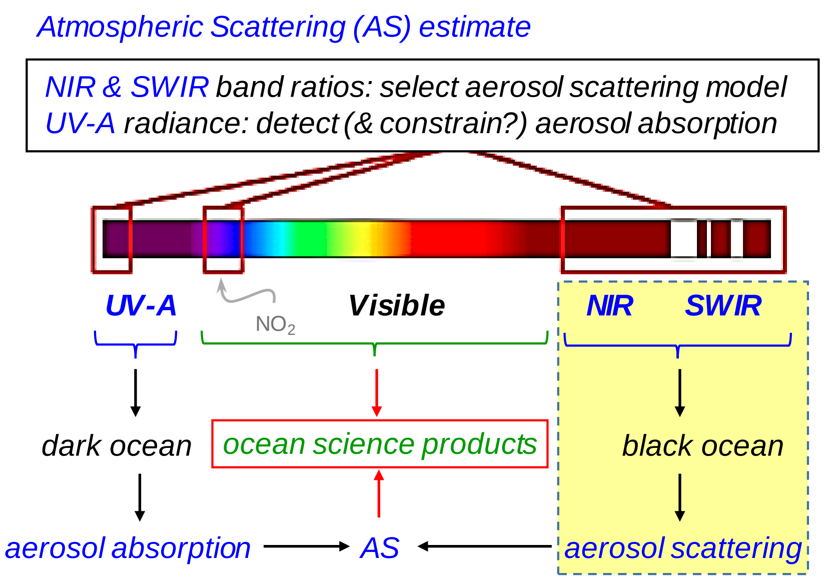


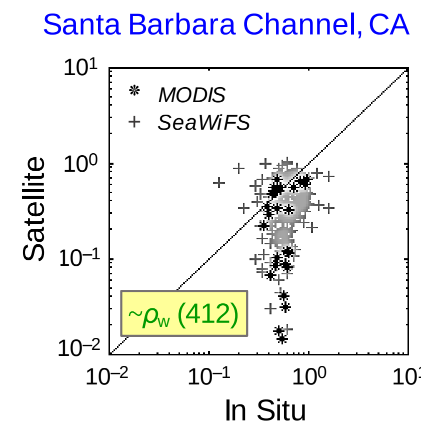
Santa Barbara Channel, CA

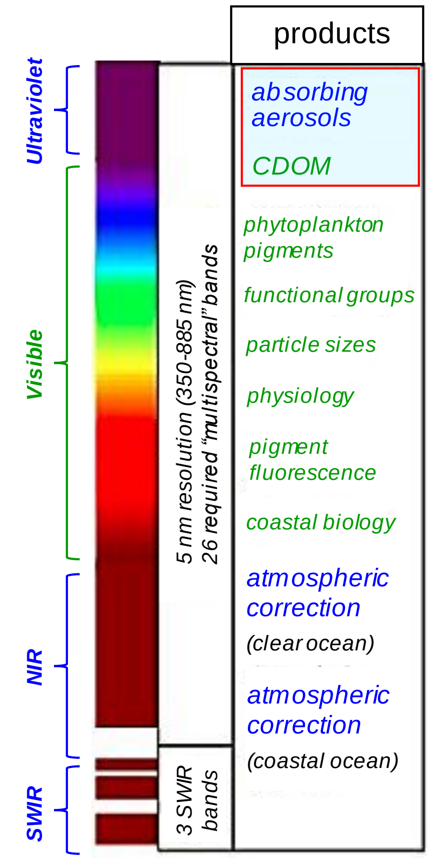




PACE Mission







- When is the ocean dark enough to retrieve variations in aerosol absorption?
- When is the ocean bright enough to retrieve variations in CDOM?

Part I

RT Comparison studies

- Motivation
- Results

1) Accuracy for Stokes parameters *I*, *Q*, *U* emerging from various AOS is better than **10^{-6}**

2) Corresponding accuracy in degree of linear polarization better than 0.1%

RT comparison Studies

Motivation

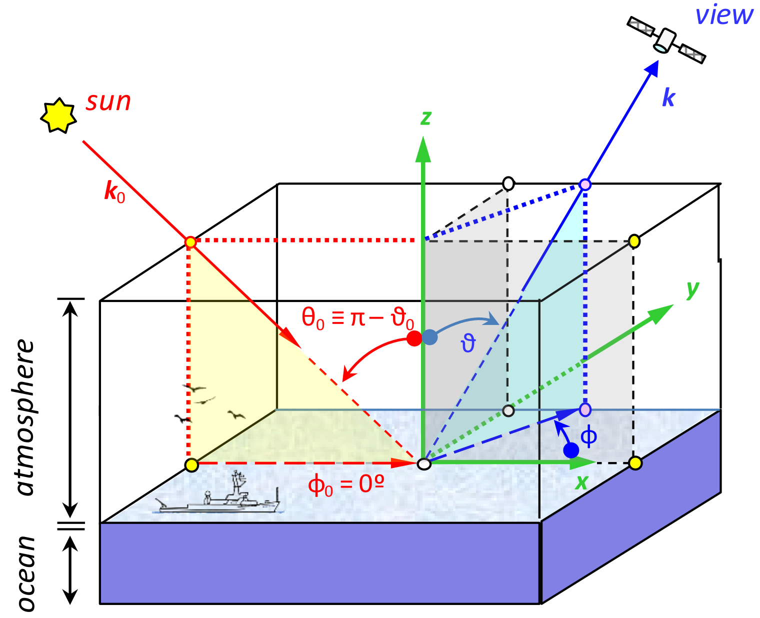
Polarization is an extremely useful tool to retrieve aerosol properties

- provided that it is measured with very high accuracies (0.2%–0.5%)

Simulated aerosol retrieval from space-borne observation over ocean at 865 nm

Synthetic TOA data of *I*, *Q*, & *U*:

- μ_0=0.8; μ=0.2, 0.4, 0.6, 0.8, 1.0
  $\Delta\varphi$=60º & 120º
- Fine mode aerosol, τ = 0.2
  (r_e = 0.4 µm; v_e=0.2; m=1.45
- Rough ocean surface
  (W = 7 m/s)
- Black water body



AOS system

Aerosol candidate models:

- Fine mode aerosol:
  τ = 0.01 – 0.4, $\Delta\tau$ = 0.01
  r_e = 0.01 – 0.8 µm, Δr_e = 0.01
  m = 1.3 – 1.7, Δm = 0.01
  ω = 0.78 – 1.00, $\Delta\omega$ = 0.02
  v_e = 0.2

>350,000 aerosol candidate models

Source: Mishchenko and Travis, JQSRT 102:13,543-13,553 (1997)

Motivation

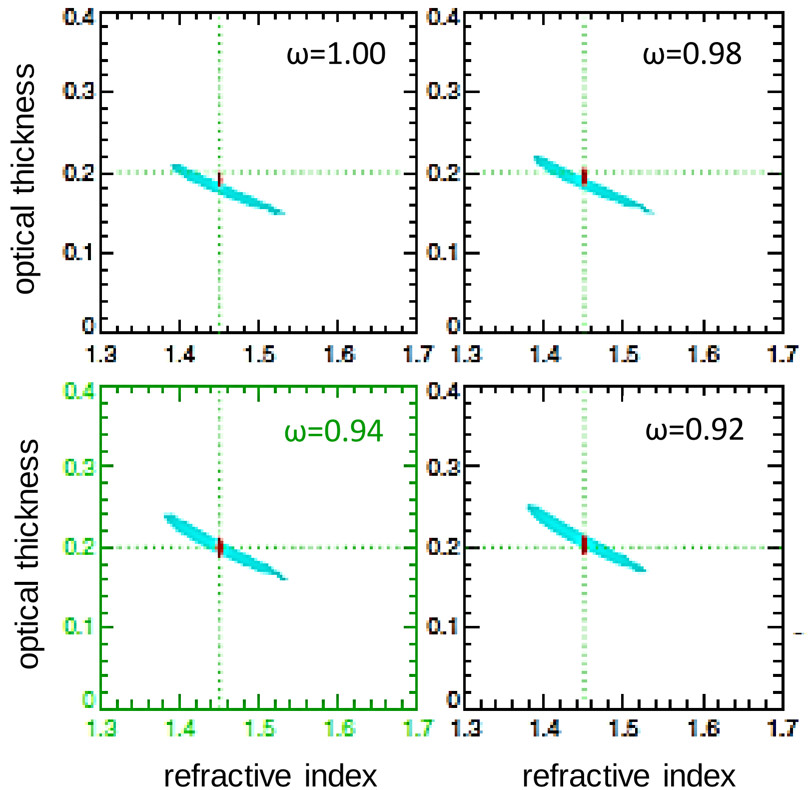
Polarization is an extremely useful tool to retrieve aerosol properties

- provided that it is measured with very high accuracies (0.2%–0.5%)

Simulated aerosol retrieval from space-borne observation over ocean at 865 nm

- radiance I,
- 9 viewing angles
- ΔI = 4%

- polarization Q/I and U/I,
- 9 viewing angles
- ΔP = 0.2%



Aerosol candidate models:

- Fine mode aerosol:

τ = 0.01 – 0.4, $\Delta\tau$ = 0.01
r_e = 0.01 – 0.8 μm, Δr_e = 0.01
m = 1.3 – 1.7, Δm = 0.01
ω = 0.78 – 1.00, Δω = 0.02
v_e = 0.2

>350,000 aerosol candidate models

Source: Mishchenko and Travis, JQSRT 102:13,543-13,553 (1997)

RT comparison Studies

Motivation

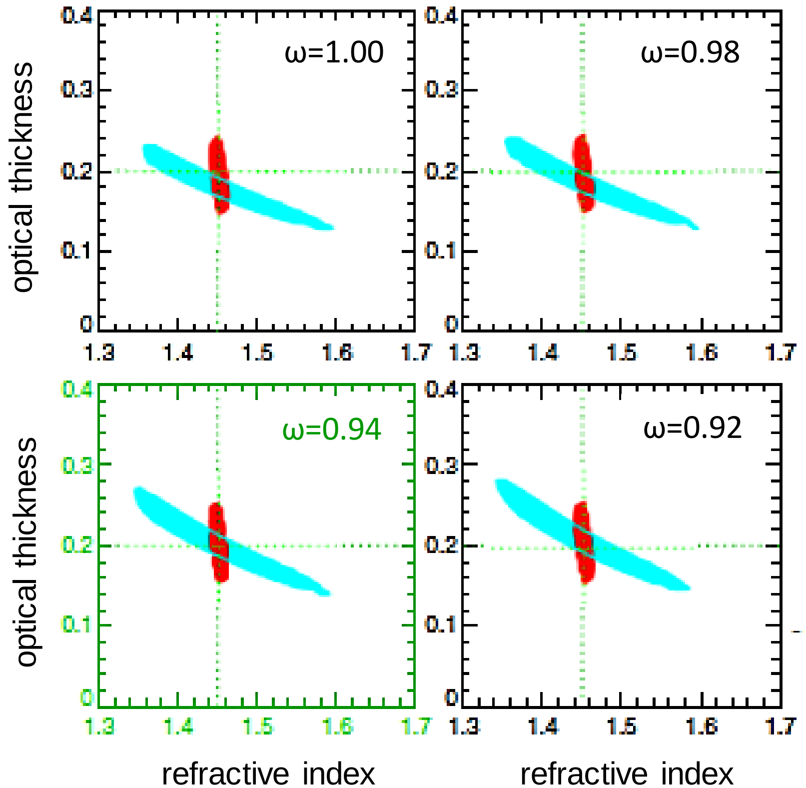
Polarization is an extremely useful tool to retrieve aerosol properties

- provided that it is measured with very high accuracies (0.2%–0.5%)

Simulated aerosol retrieval from space-borne observation over ocean at 865 nm

- radiance I,
- 9 viewing angles
- ΔI = 6%

- polarization Q/I and U/I,
- 9 viewing angles
- ΔP = 0.8%



Aerosol candidate models:

- Fine mode aerosol:

τ = 0.01 – 0.4, $\Delta\tau$ = 0.01
r_e = 0.01 – 0.8 μm, Δr_e = 0.01
m = 1.3 – 1.7, Δm = 0.01
ω = 0.78 – 1.00, $\Delta\omega$ = 0.02
v_e = 0.2

>350,000 aerosol candidate models

Source: Mishchenko and Travis, JQSRT 102:13,543-13,553 (1997)

Motivation

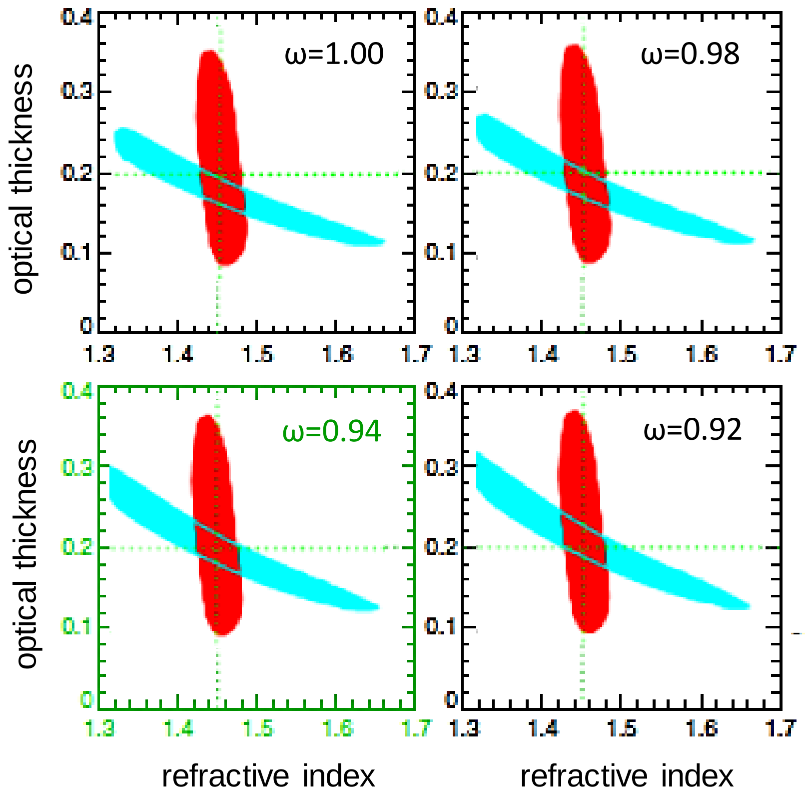
Polarization is an extremely useful tool to retrieve aerosol properties

- provided that it is measured with very high accuracies (0.2%–0.5%)

Simulated aerosol retrieval from space-borne observation over ocean at 865 nm

- radiance I,
- 9 viewing angles
- ΔI = 8%

- polarization Q/I and U/I,
- 9 viewing angles
- ΔP = 2.0%



Aerosol candidate models:

- Fine mode aerosol:

τ = 0.01 – 0.4, $\Delta\tau$ = 0.01
r_e = 0.01 – 0.8 μm, Δr_e = 0.01
m = 1.3 – 1.7, Δm = 0.01
ω = 0.78 – 1.00, $\Delta\omega$ = 0.02
v_e = 0.2

>350,000 aerosol candidate models

Source: Mishchenko and Travis, JQSRT 102:13,543-13,553 (1997)

RT comparison Studies

Motivation

Polarization is an extremely useful tool to retrieve aerosol properties

- provided that it is measured with very high accuracies (0.2%–0.5%)

- our forward RT computations need to match these accuracies!

2015:

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IPRT polarized radiative transfer model intercomparison project – Phase A

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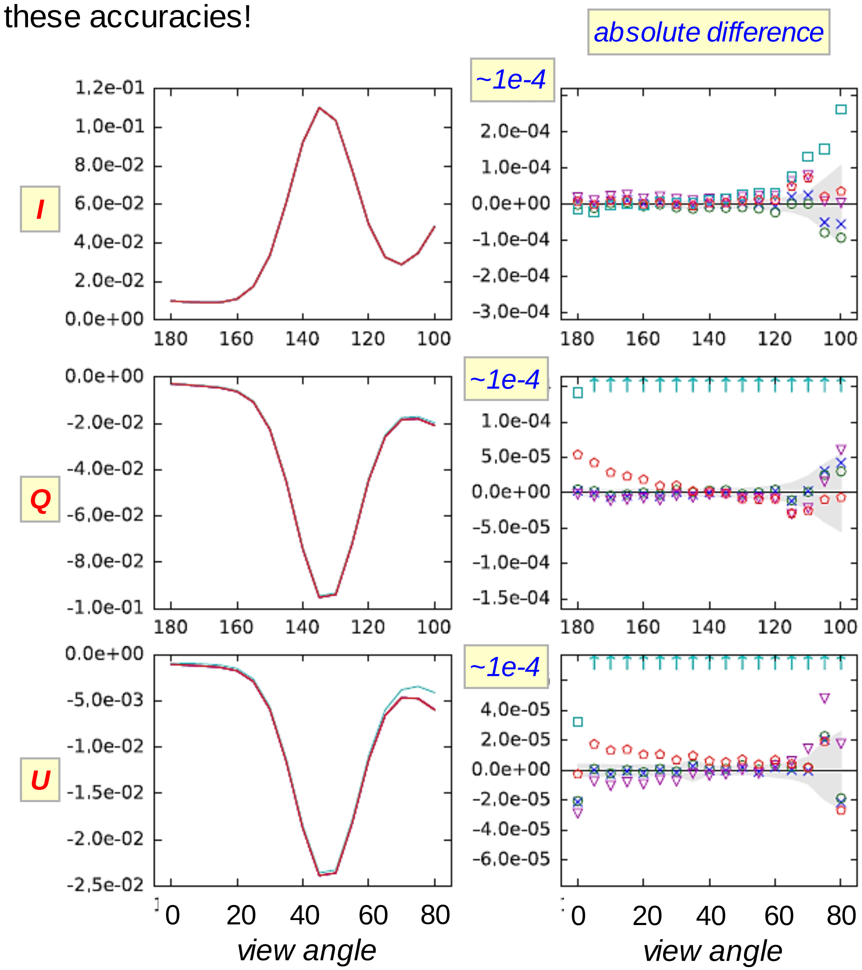
AOS system: molecular atmosphere above ocean surface



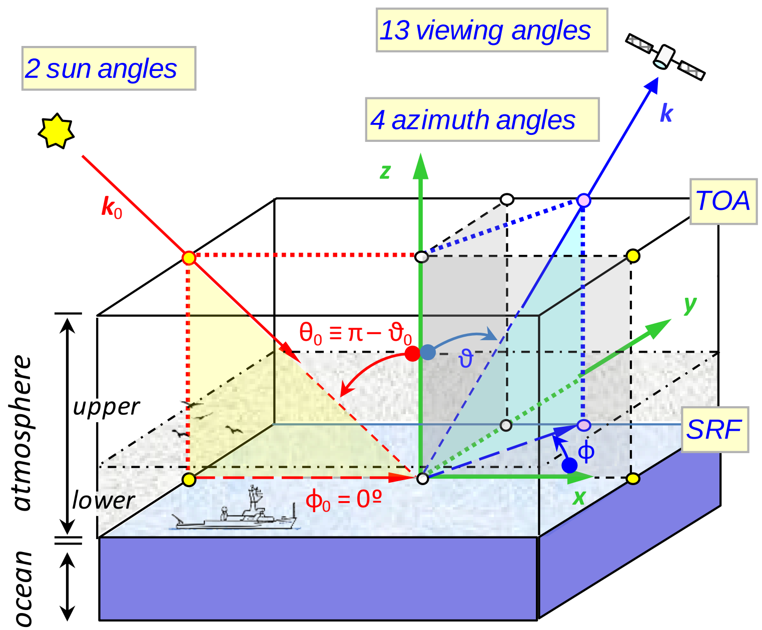
RT comparison Studies

Results

Polarization is an extremely useful tool to retrieve aerosol properties

- provided that it is measured with very high accuracies (0.2%–0.5%)

- our forward RT computations need to match these accuracies!



models	Ocean Body	Ocean Surface	Atmosphere
AOS-I	none	rough • Gaussian isotropic • No foam or shadowing	molecular • Pure Rayleigh scattering
AOS-II	pure water • Pure Rayleigh scattering	rough • Gaussian isotropic • No foam or shadowing	none
AOS-III	pure water • Pure Rayleigh scattering	rough • Gaussian isotropic • No foam or shadowing	molecular • Pure Rayleigh scattering
AOS-IV	pure water & hydrosol • Pure Rayleigh scattering • Detritus-Plankton mix	rough • Gaussian isotropic • No foam or shadowing	molecular • Pure Rayleigh scattering
AOS-V	pure water & hydrosol • Pure Rayleigh scattering • Detritus-Plankton mix	rough • Gaussian isotropic • No foam or shadowing	molecular & aerosol • Pure Rayleigh scattering • Fine-mode aerosol

>100 scattering geometries x 2 altitudes

λ = 350 nm, 450 nm, 550 nm, 650 nm

I, Q, U → $\Delta P \le 0.1\%$

RT comparison Studies

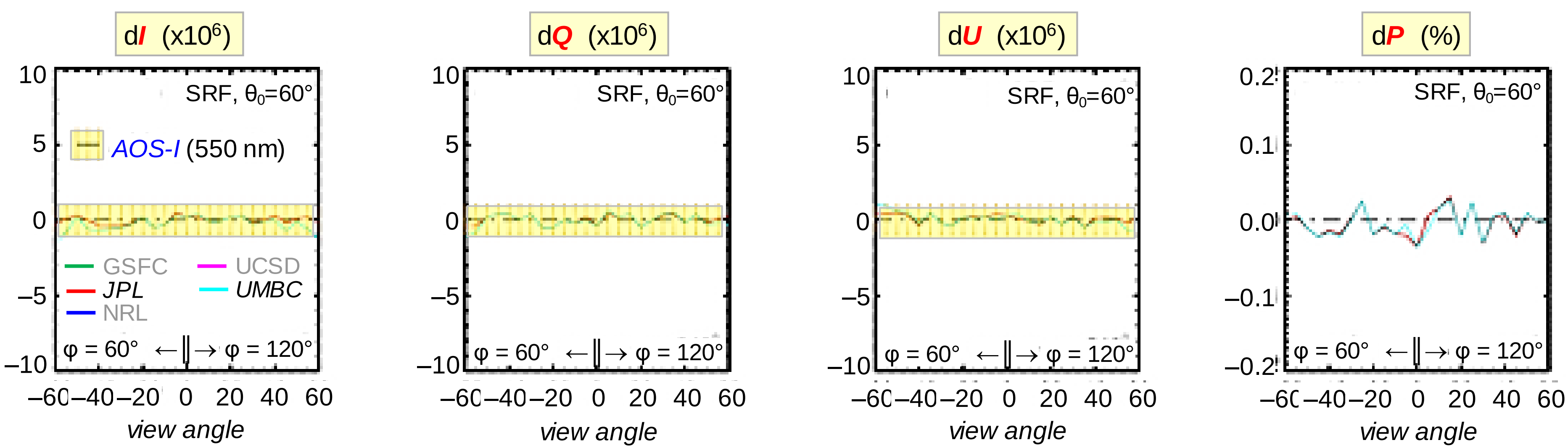
Results

Polarization is an extremely useful tool to retrieve aerosol properties

- provided that it is measured with very high accuracies (0.2%–0.5%)

- our forward RT computations need to match these accuracies!

models	***Ocean Body***	***Ocean Surface***	***Atmosphere***
AOS-I	*none*	rough • *Gaussian isotropic* • *No foam or shadowing*	molecular • *Pure Rayleigh scattering*
AOS-II	pure water • *Pure Rayleigh scattering*	rough • *Gaussian isotropic* • *No foam or shadowing*	*none*
AOS-III	pure water • *Pure Rayleigh scattering*	rough • *Gaussian isotropic* • *No foam or shadowing*	molecular • *Pure Rayleigh scattering*



RT comparison Studies

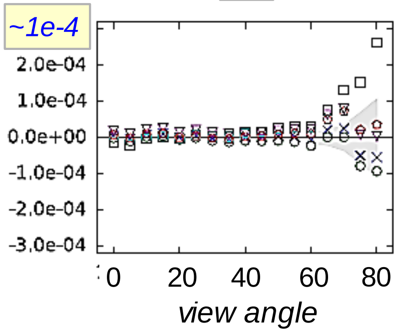
Results

Polarization is an extremely useful tool to retrieve aerosol properties

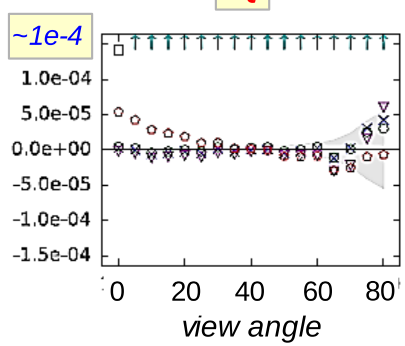
- provided that it is measured with very high accuracies (0.2%–0.5%)

- our forward RT computations need to match these accuracies!

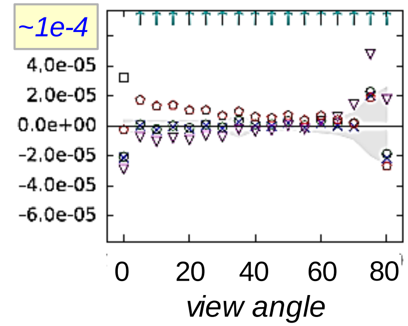
d*I*



d*Q*

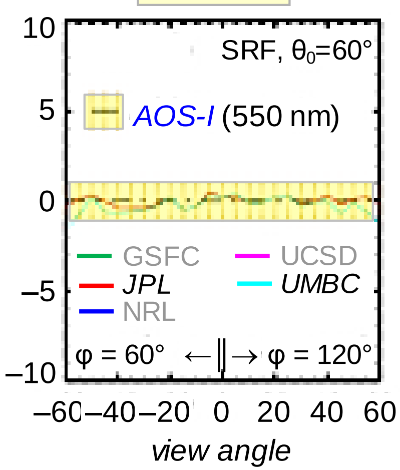


d*U*

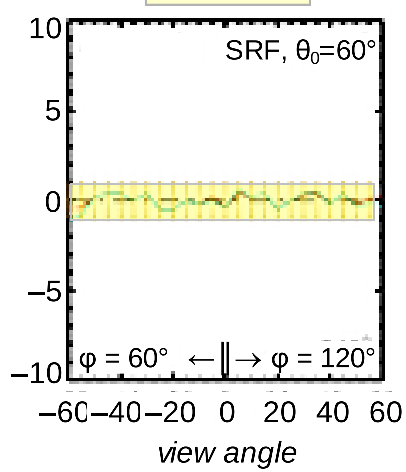


- Benchmarked >magnitude better
- Satisfies polarization accuracy

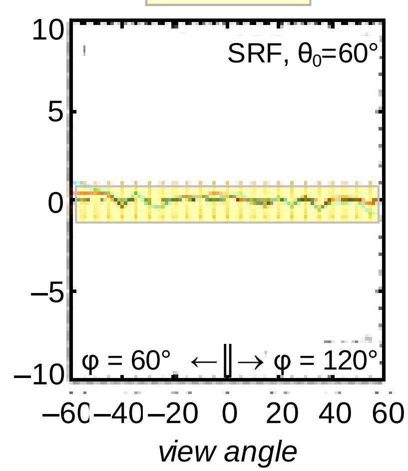
d*I* ($\times 10^6$)



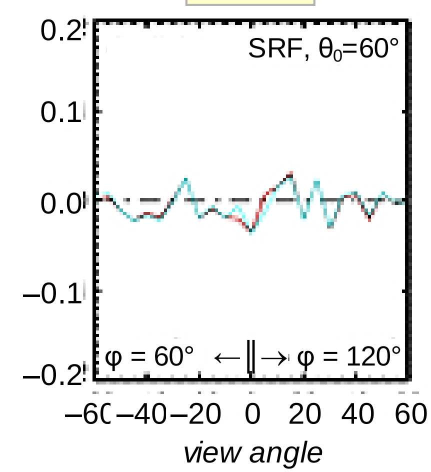
d*Q* ($\times 10^6$)



d*U* ($\times 10^6$)



d*P* (%)



Part II

UV sensitivity Studies

- Motivation
- Results

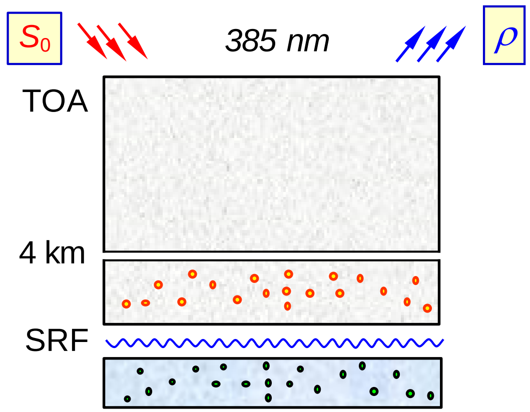
1) TOA polarized reflectance is more sensitive to variations in aerosol height than in ocean or aerosol microphysical properties

2) It varies by (much) more than **0.001** per km change in aerosol height in boundary layer

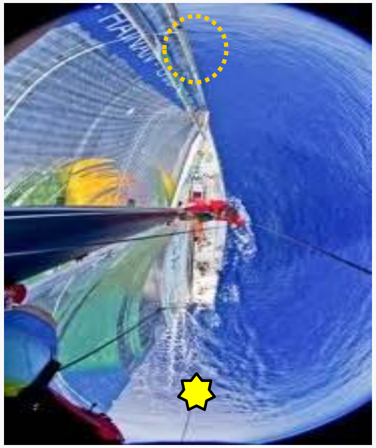
UV Sensitivity Studies

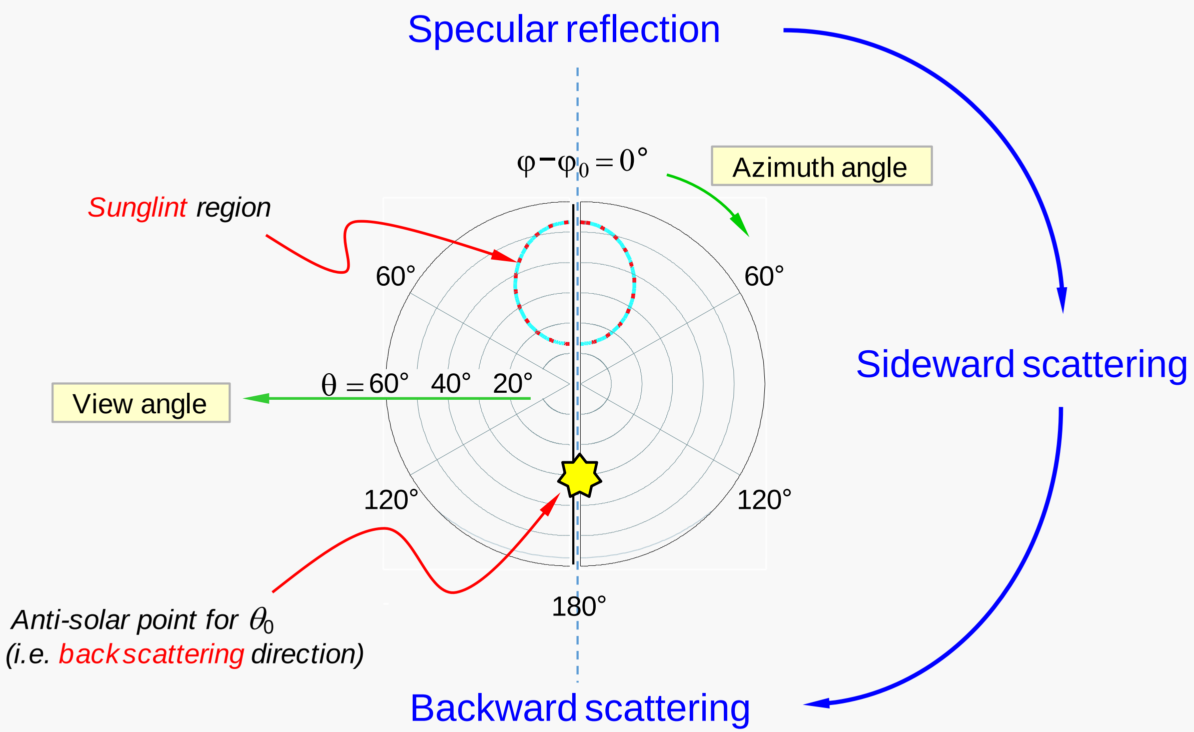
Motivation

- UV polarized reflected light is nearly insensitive to variations in the ocean color
- But is this light sensitive to the presence and variations in aerosols?



Reflection $\rho = \dfrac{\pi I}{S_0 \cos\theta_0}$





UV Sensitivity Studies

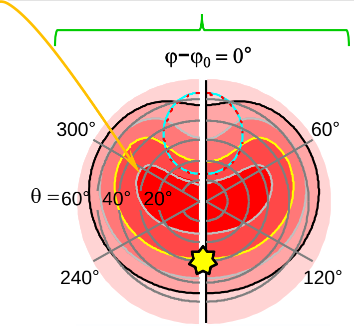
RT results

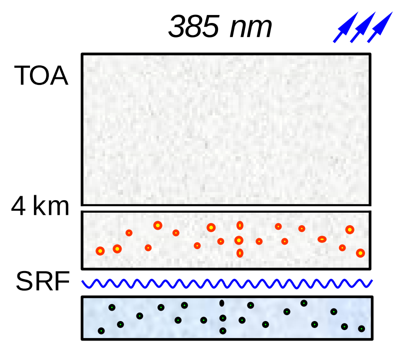
ρ_{ocean} (%) ≡ ρ_{ocean} / ρ_{TOA}

contribution of ocean to TOA reflectance: >13%

average oligotrophic ocean

ρ_{ocean} (%)





Rayleigh scattering

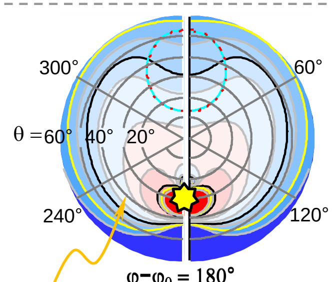
Bodhaine et al. (1999)

Aerosol scattering

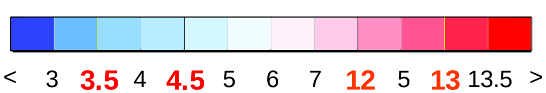
r_e = 0.15 μm, v_e = 0.15, τ_{550} = 0.10

Case I (open) ocean

$\rho_{ocean,P}$ (%)

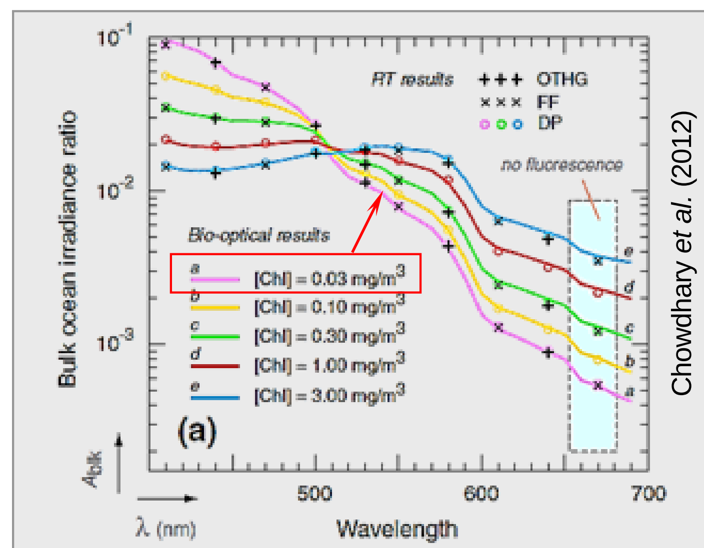


contribution of ocean to TOA polarized reflectance: <5%



ρ_{ocean} (%) (385 nm)

AOT(550) = 0.1, θ_0 = 30°



Chowdhary et al. (2012)

UV Sensitivity Studies

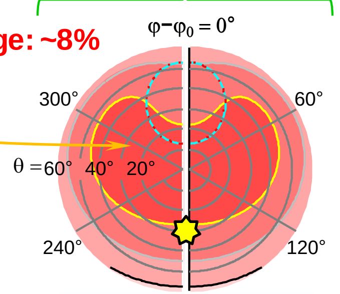
RT results

$\Delta\rho_{TOA}$ (%) $\equiv \Delta\rho_{TOA} / \rho_{TOA}$

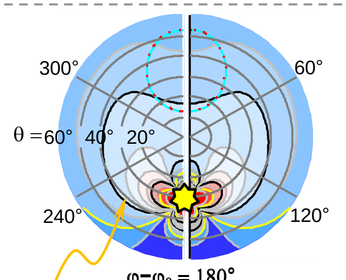
max CDOM variation

TOA reflectance change: ~8%

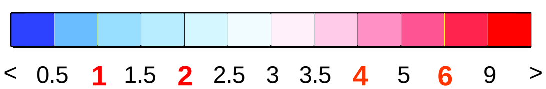
$\Delta\rho_{TOA}$ (%)



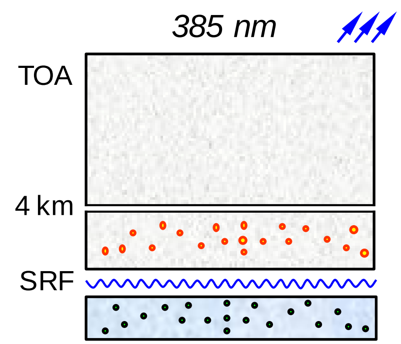
$\Delta\rho_{TOA,\,P}$ (%)



TOA polarized reflectance change: <2%



$\Delta\rho_{TOA}$ (%) (385 nm)



Rayleigh scattering

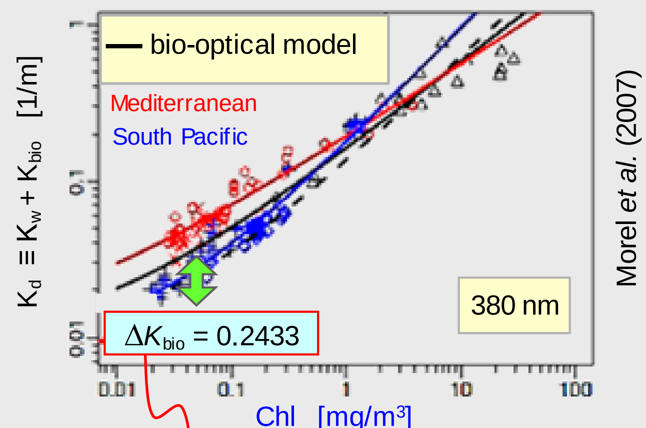
Bodhaine et al. (1999)

Aerosol scattering

r_e = 0.15 μm, v_e = 0.15, τ_{550} = 0.10

Case I (open) ocean

AOT(550) = 0.1, θ_0 = 10°



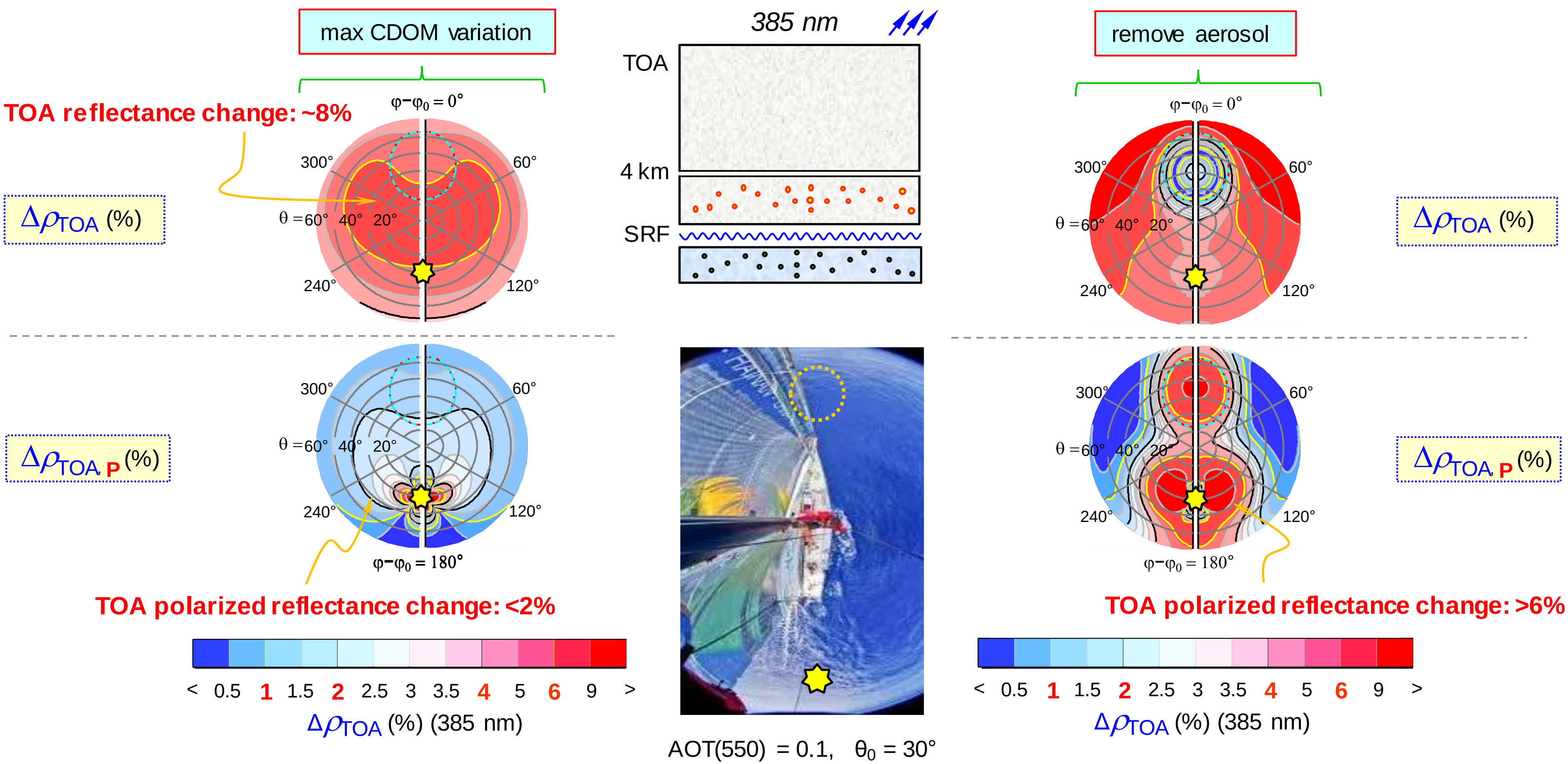
CDOM

$\Delta K_d \approx 1.04(\mu_d)^{-1}(\Delta a + b_b)$

UV Sensitivity Studies

RT results

$\Delta\rho_{TOA}$ (%) $\equiv \Delta\rho_{TOA} / \rho_{TOA}$



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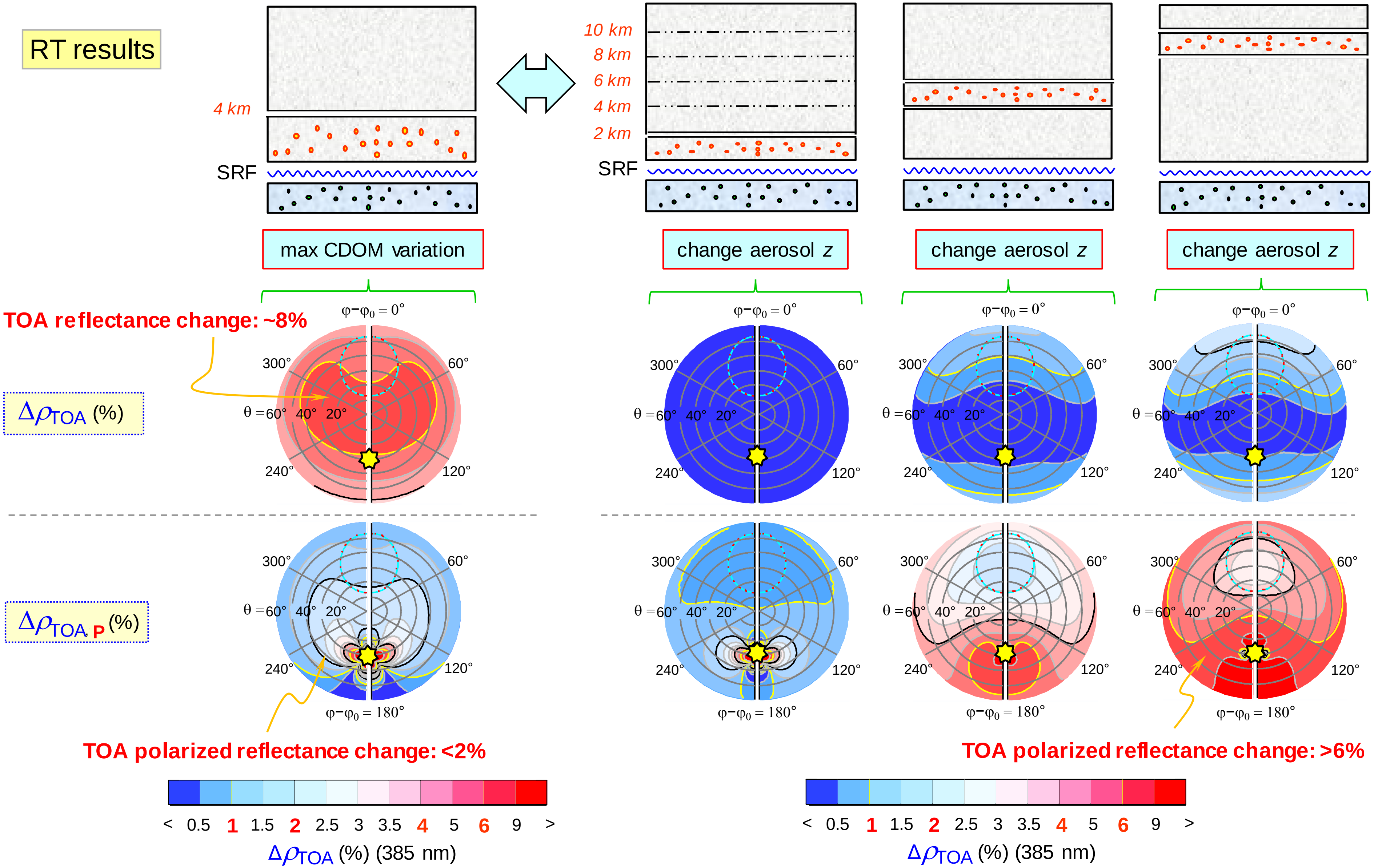
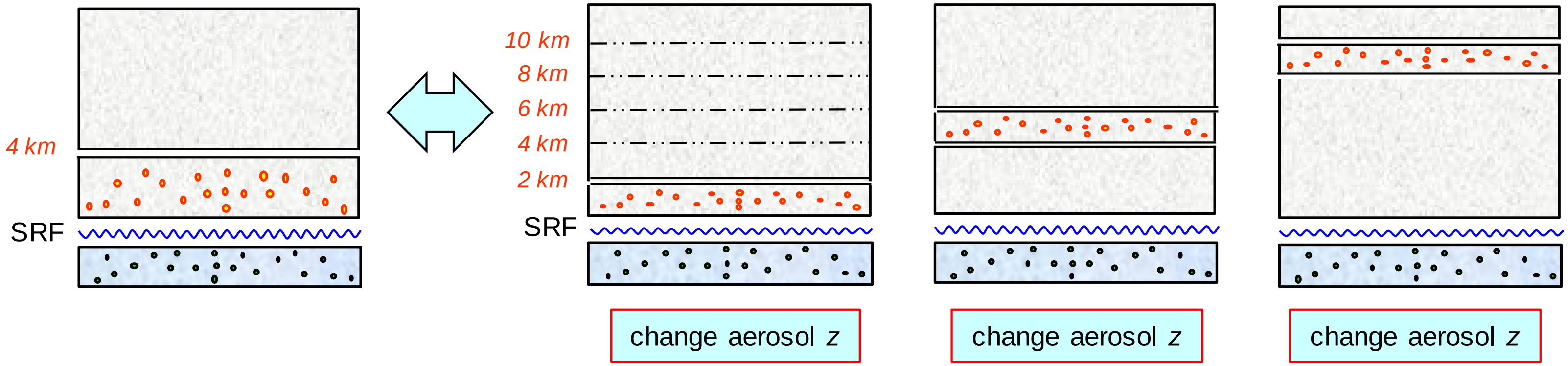
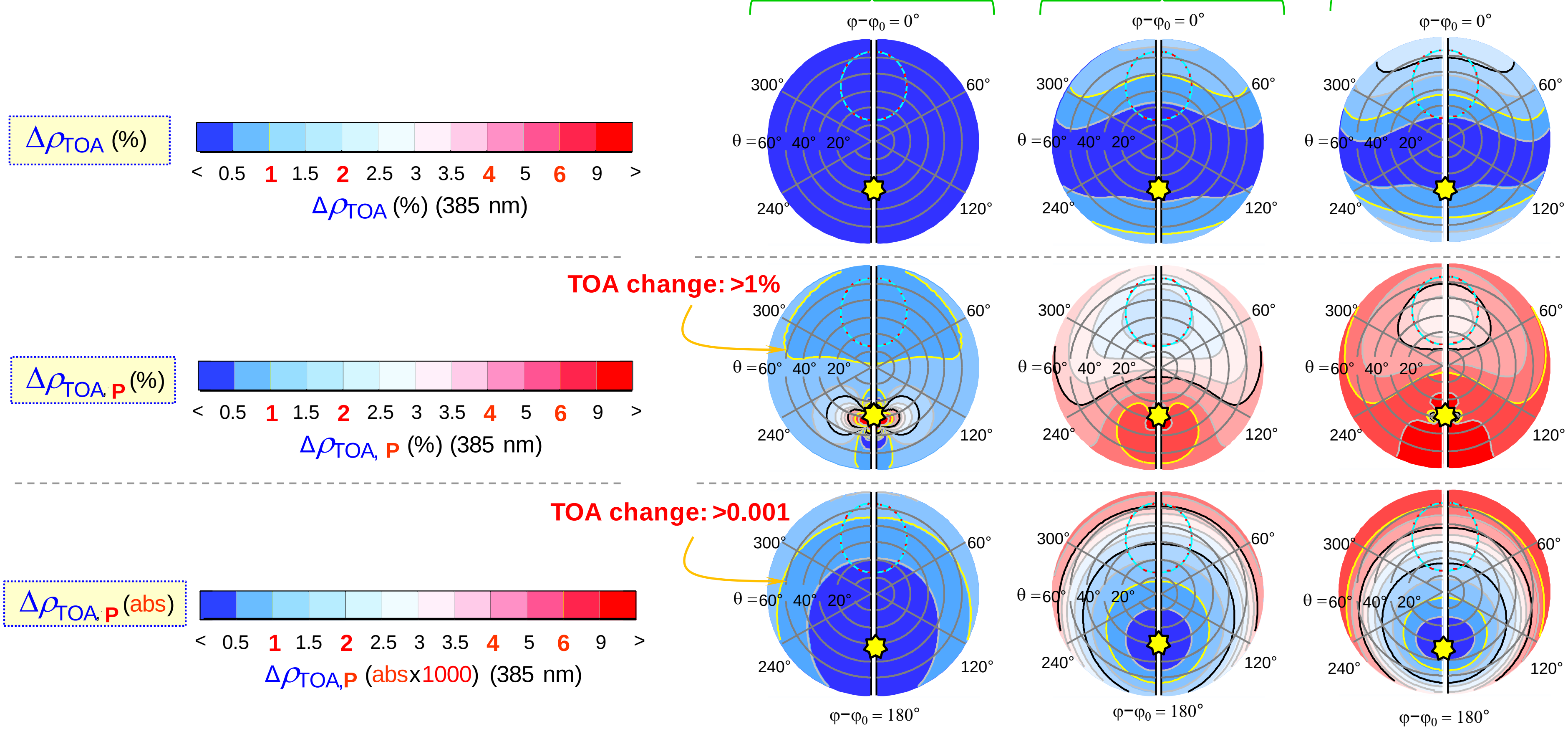
UV Sensitivity Studies



UV Sensitivity Studies

RT results





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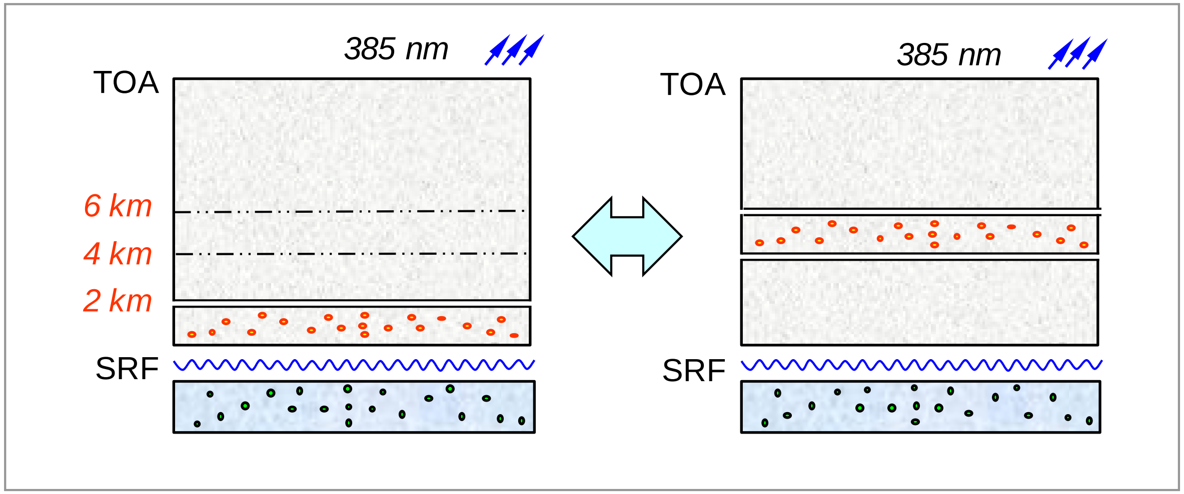
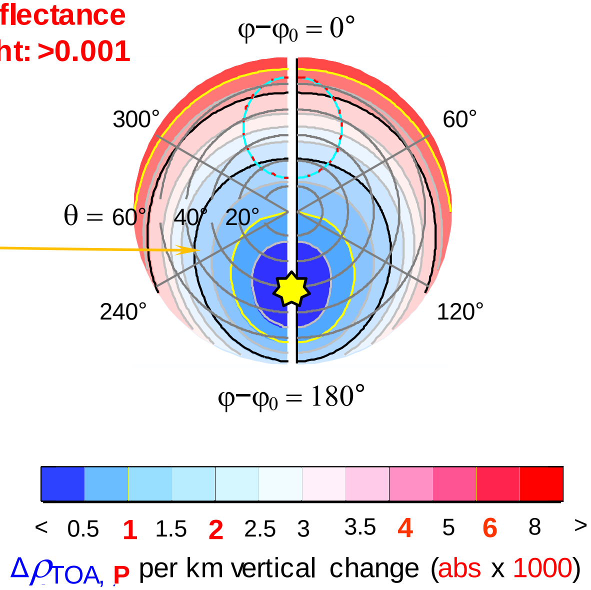
UV Sensitivity Studies

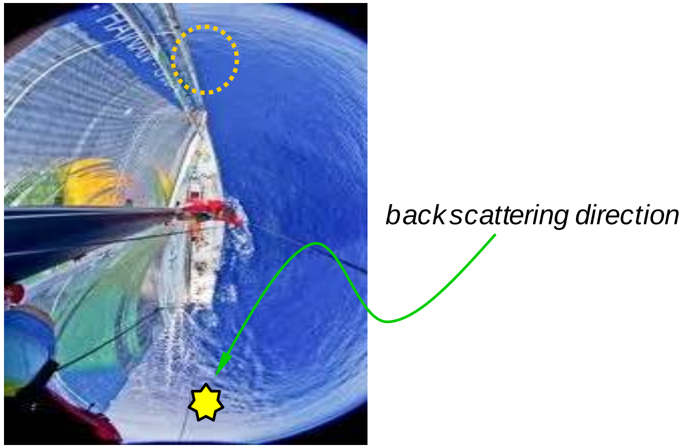
RT results

Changing height of aerosols in lower 5 km



Change in TOA polarized reflectance per km shift in aerosol height: >0.001



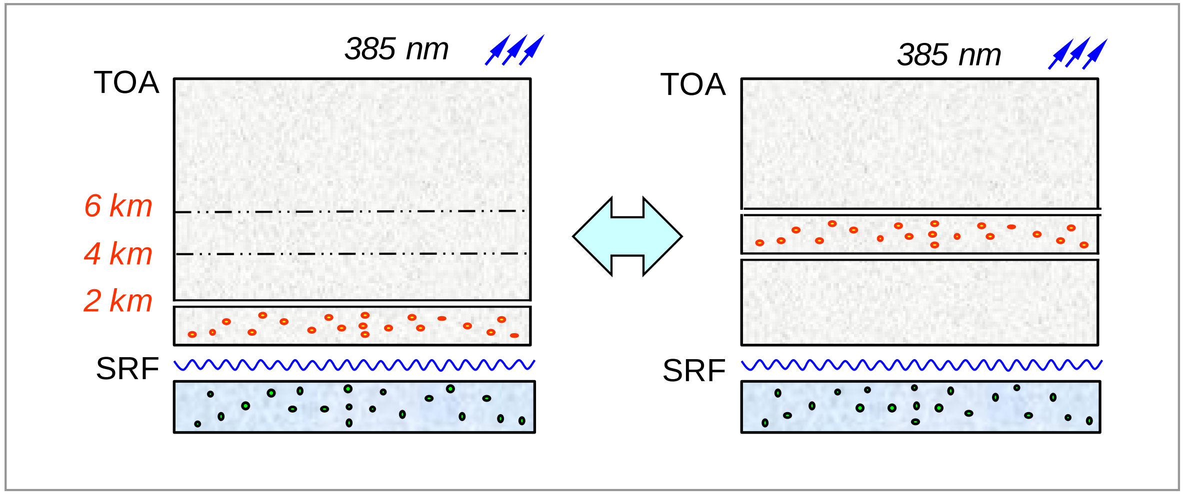


AOT(550) = 0.1, $\theta_0 = 30°$

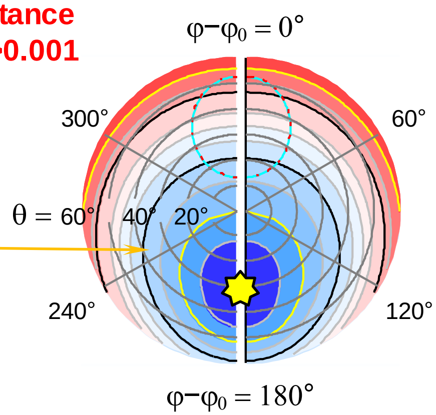
UV Sensitivity Studies

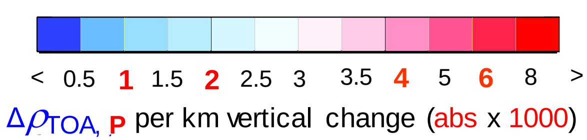
RT results

Changing height of aerosols in lower 5 km

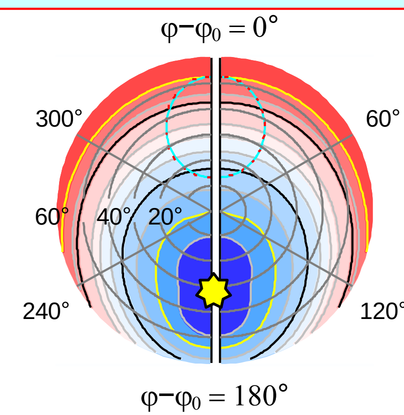


Change in TOA polarized reflectance per km shift in aerosol height: >0.001





absorbing aerosol: $\omega_{550} = 0.91$



case for absorbing aerosol remains ~same!

Conclusions

Part I

RT Comparison studies

1) Accuracy for Stokes parameters *I*, *Q*, *U* emerging from various AOS is better than **10^{-6}**

2) Corresponding accuracy in degree of linear polarization better than 0.1%

Part II

UV sensitivity Studies

1) TOA polarized reflectance is more sensitive to aerosol height than to aerosol microphysical properties

2) It varies by (much) more than **0.001** per km change in aerosol height in boundary layer

Backup slides

Hydrosol models

1) Approximate, but not a substitute for, real ocean color spectra

1) Allow for simultaneous retrieval of aerosol and ocean color spectra from polarimetric data

Backup Slides

aerosol model variations

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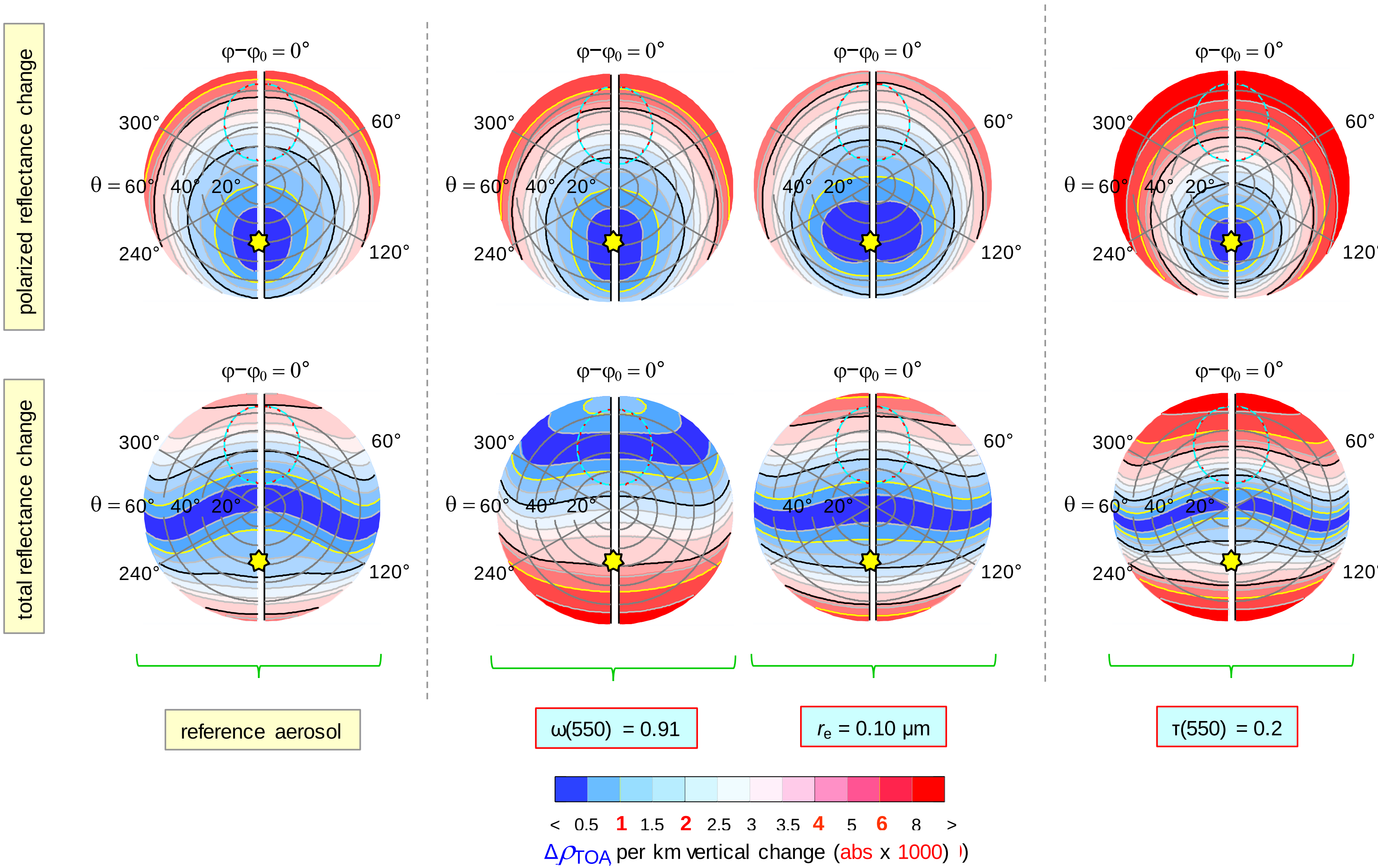
UV Sensitivity Studies

Changing height of aerosols in boundary layer by 1 km



Backup Slides

Hydrosol models

Hydrosol models

ACROSS → *Update hydrosol model* → couple atmosphere & ocean in atmospheric correction

- Retrieve aerosol model/properties *while accounting for underwater light scattering* → requires an ocean model

✓ "−" below surf

(§) $\rho^{-}_{\text{w, model}} = \{I, Q, U\}(\text{view, IOPs})$

- *NIR total radiance*
- *NIR polarized radiance*
- *VIS total radiance*
- *VIS polarized radiance*
- *UV total radiance*
- *UV polarized radiance*
- *Ocean model assumptions* (§)

aerosol properties

- Retrieve water-leaving radiance in the VIS part of the spectrum

✓ "+" above surf

(¶) $\rho_{\text{TOA}} = \rho_{\text{atm-srf}} + t^{\uparrow}_{\text{atm}}\, \rho^{+}_{\text{w,retrieve}}$

- *VIS total radiance* (¶)

Note: $\rho^{-}_{\text{w,model}}$: *approximates* the ocean in aerosol retrieval

↓

spectral residual in fit of ρ_{TOA} cannot be resolved with aerosol

↓

$\rho^{+}_{\text{w,retrieve}}$: *extracted* from ρ_{TOA} using the retrieved aerosol

spectral residual fit

$$\underbrace{\rho^{-}_{\text{w,model}}}_{\textit{ocean model}} + \overbrace{\Delta\rho^{-}_{\text{w}}}^{\textit{spectral residual fit}} \Longrightarrow \underbrace{\rho^{+}_{\text{w,retrieve}}}_{\textit{retrieval}}$$

ocean model

retrieval

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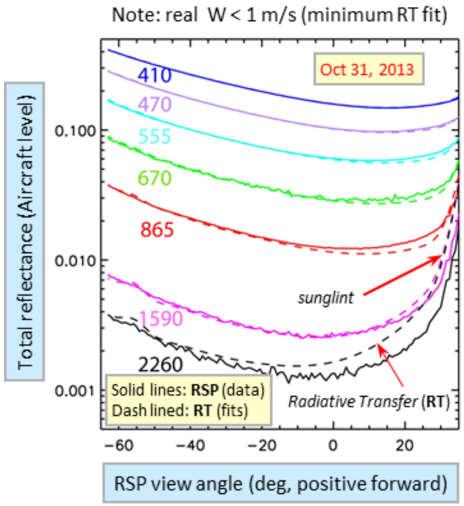
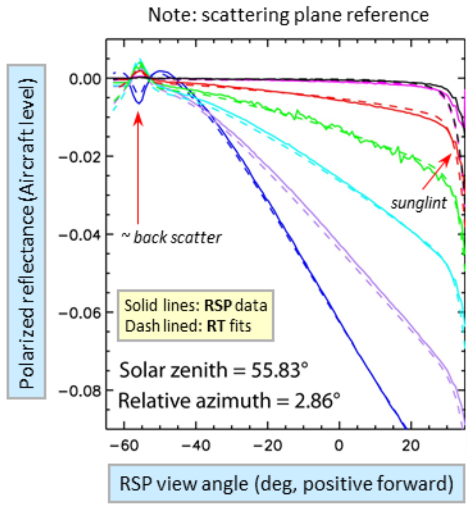
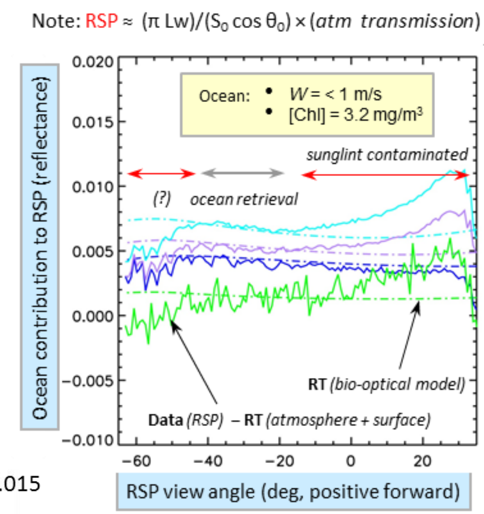
Hydrosol models

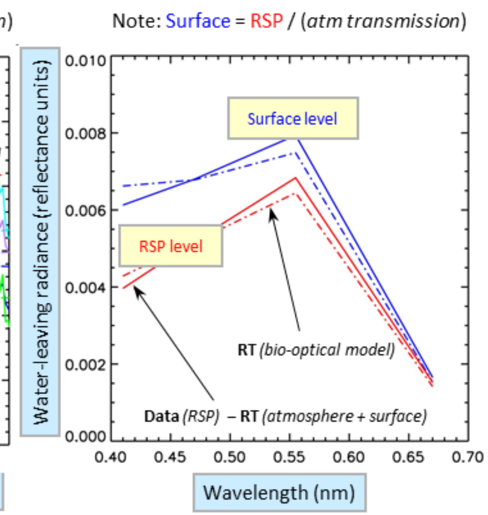
ACROSS → *Update hydrosol model* → couple atmosphere & ocean in atmospheric correction

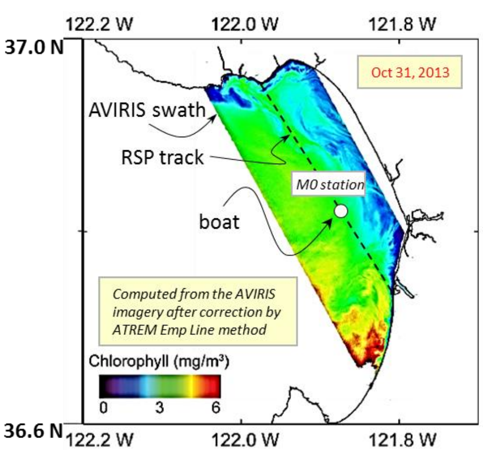


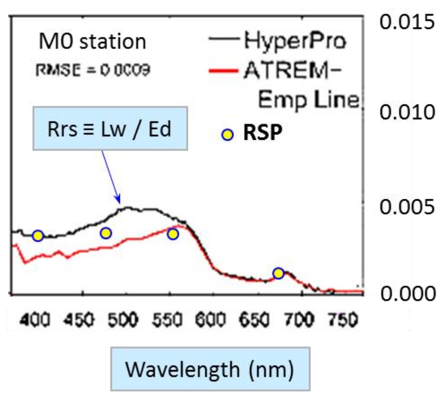


RSP ocean retrieval









Validation ocean retrieval

Hydrosol models

ACROSS → *Update hydrosol model* → couple atmosphere & ocean in atmospheric correction

Hydrosol model	*Free parameters*	*[Chl]-driven parameters*	*Optimized a-priori*
D–P model	• [Chl]	• $a_{blk}(\lambda)$ [see Eq. (5b)] • $b_p(\lambda_0)$ [see Eq. (7a)] • k [see Eq. (7b)] • $\tilde{b}_{bp}$ [see Eq. (8)]	-
ACROSS model	• [Chl] • $a_{cdm}(\lambda_0)$ • $b_{bp}(\lambda_0)$	• $\tilde{b}_{bp}$ [see Eq. (8)]	• S_{cdm} • $\hat{a}_{ph}(\lambda)$ • η (=k)
ACROSS-II model	• [Chl] • $a_{cdm}(\lambda_0)$ • $b_{bp}(\lambda_0)$	• $\hat{a}_{ph}(\lambda)$ [see Eq. (15)] • k [see Eq. (7b)] • $\tilde{b}_{bp}$ [see Eq. (8)]	• S_{cdm}
c-model	• [Chl] • $a_{cdm}(\lambda_0)$ • $a_{dm}(\lambda_0)$ § • $c_p(\lambda_0)$	• $\hat{a}_{ph}(\lambda)$ [see Eq. (15)] • k' (≈k) [see Eq. (7b)] • $\tilde{b}_{bp}$ [see Eq. (8)]	• S_{cdm}

§ Becomes *[Chl]-driven* if retrieved from $a_p(\lambda) - a_{ph}(\lambda)$ and if $a_p(\lambda)$ is *[Chl]-driven* (*Bricaud et al.*, 1998)

IOCCG5 model
(back-up slides)

Free parameter	*[Chl]-driven parameter*	*[Chl]-driven parameter range*	*fixed parameter range*	*Assumed a-priori*
[Chl]	$\hat{a}_{ph}(\lambda)$	$a_{dm}(\lambda_0)$, $a_g(\lambda_0)$, $c_{ph}(\lambda_0)$, $b_{dm}(\lambda_0)$, $n1$, $n2$	S_{dm}, S_g §	$\tilde{b}_{b,ph}$, $\tilde{b}_{b,dm}$ ‡

§ $S_{dm} \in [0.007, 0.015]$ and $S_g \in [0.01, 0.02]$; ‡ $\tilde{b}_{b,ph}$=0.01 and $\tilde{b}_{b,dm}$=0.0183