Part II

Atmospheric Correction over Complex Atmosphere

Atmospheric Correction of Ocean-Color Imagery in the Presence of Absorbing Aerosols

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INTRODUCTION

-Absorbing aerosols are particles that have a refractive index with a non-null imaginary part. In terms of radiation transfer, their single scattering albedo (i.e., the ratio of scattering and extinction coefficients), ω_{aer}, is less than 1.

-There are two basic sources of absorbing aerosols, both of terrestrial origin:

(i) Industrial, as a soot component of small particles present in variable amount in urban-type aerosols, and

(ii) Natural, as small or large mineral particles present in desert dust aerosols

-Variability is large in space and time; Vast oceanic regions are affected.

GEOS Model Aerosol Simulations, Sep-Oct 2006

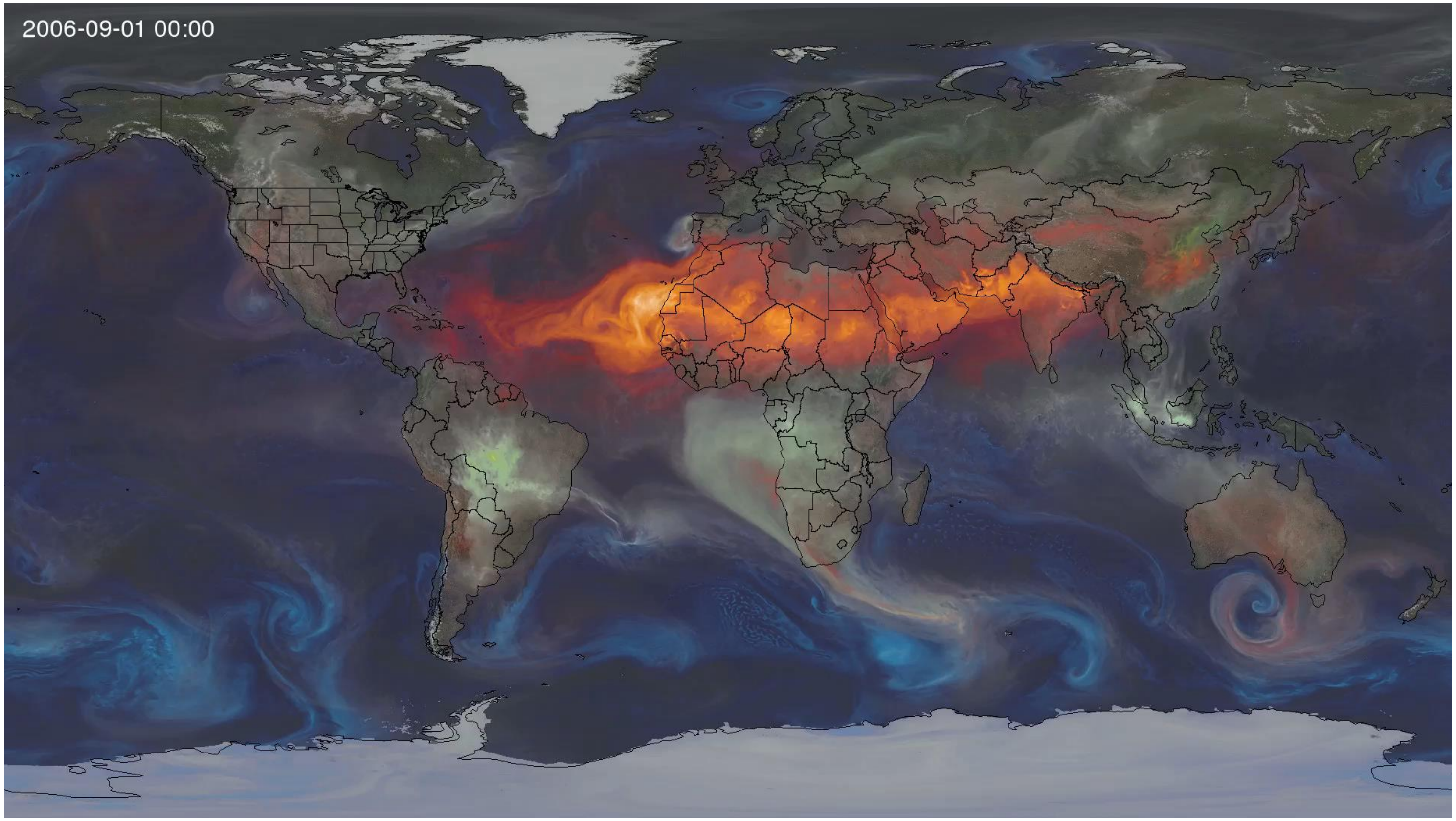

***Figure 2**: Global 10km resolution aerosol simulations from GEOS model, v5. Time period is September-October 2006. The model is driven by observed sea surface temperature and daily fire emissions derived from MODIS fire radiative power. Dust, sea-salt, and carbonaceous aerosols are displayed in orange, blue, and green tones, respectively. (Arlindo Silva, NASA GSFC, 2012.)*

AEROSOL ABSORPTION EFFECT ON TOA SIGNAL

-Aerosol scattering affects the TOA reflectance at all wavelengths. It is better detected as a TOA reflectance increase with decreasing wavelength at large wavelengths, above 700 nm where the ocean reflectance is null or small.

-Aerosol absorption does not influence much the TOA reflectance in the near infrared, but does influence strongly the TOA reflectance at ocean color wavelengths, especially in the blue and UV, where it constitutes a source of error for ocean-color retrievals.

-The effect of aerosol absorption is mainly the result of its interaction with molecular scattering. It depends on the absorption optical thickness and the location of the aerosol layer in the vertical, and increases with the altitude of the aerosol layer. It can be written as (Torres, 2002):

$$\rho_{a\_abs} \approx -(1 - \omega_{aer})\tau_{aer}\, m^*[\rho_w T_a + \rho_{mol}(P_s - P_{aer})/P_s]$$

AOT and absorption effects for urban and dust aerosols

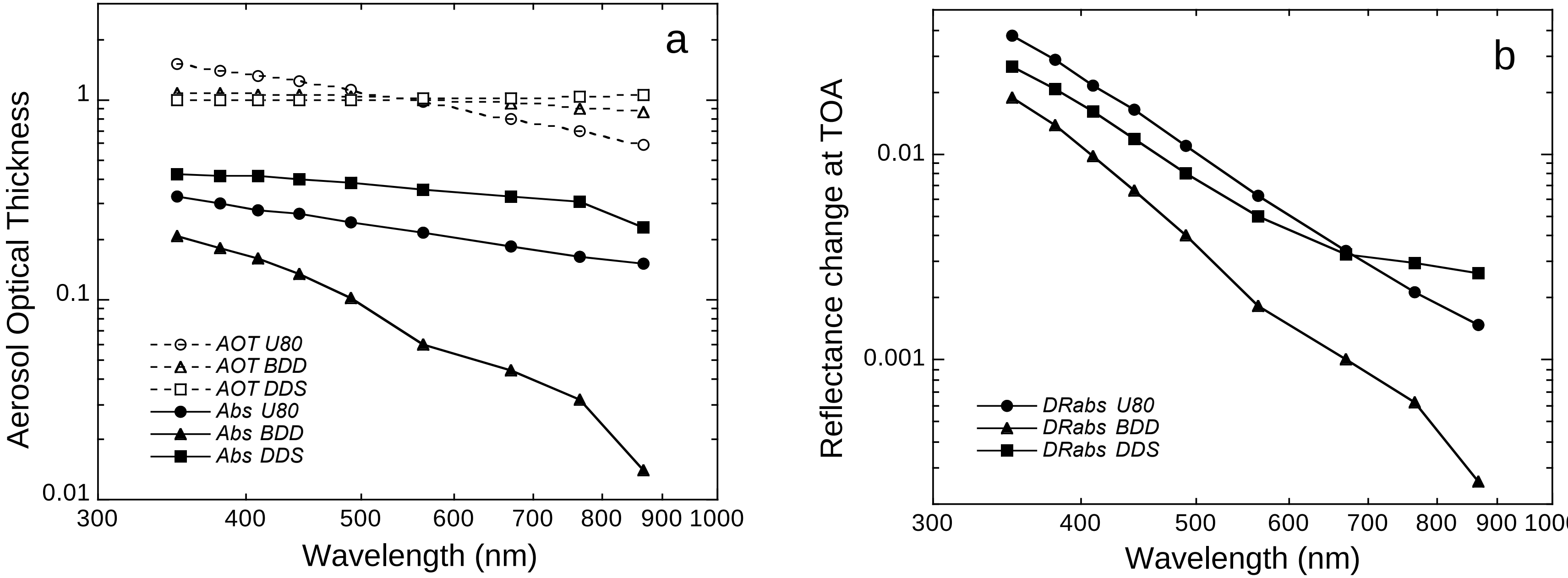

***Figure 1**: (a) Aerosol optical thickness as a function of wavelength for the Urban at 80% humidity (U80) model of Shettle and Fenn (1979) and the Background Desert Dust (BDD) and Desert Dust Storm (DDS) models of Shettle (1984). Open symbols correspond to the total aerosol optical thickness, τ_a, normalized to 550 nm, and solid symbols to the absorption optical thickness. (b) Difference between the top-of-atmosphere reflectance when the aerosol, τ_a = 0.2 at 865 nm, is located near the surface and at the altitude of 3.76 km.*

-Reflectance change at TOA due to absorbing aerosols is above 0.01 in the blue/UV, much larger than accuracy requirement on water reflectance (±0.001).

Dust storm out of Libya, 20 June 1997, POLDER imagery

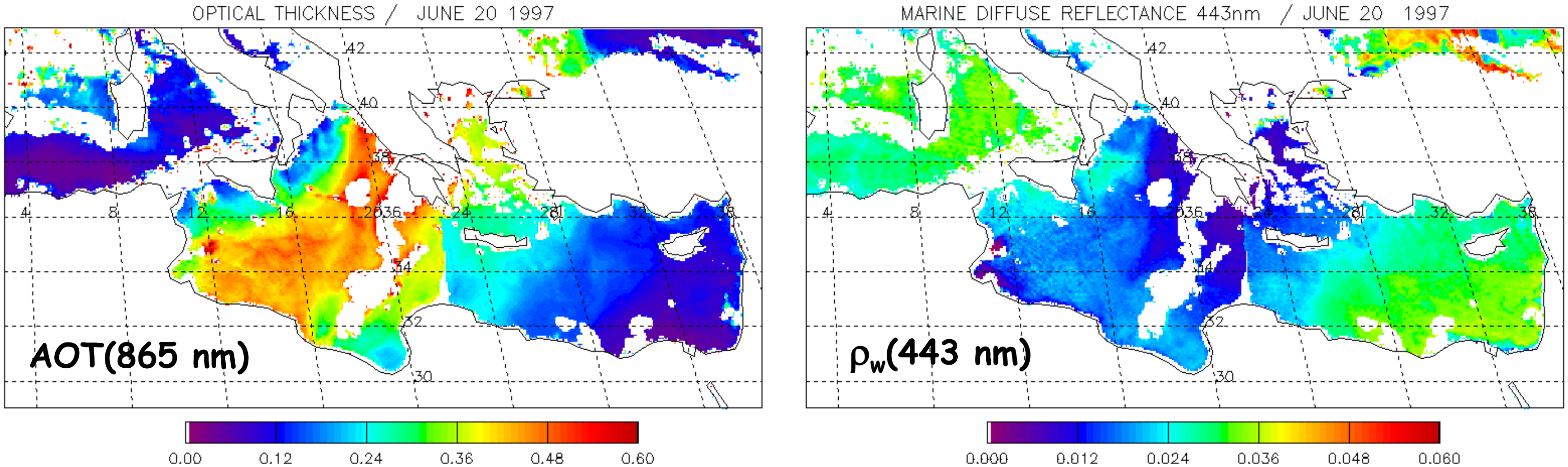

***Figure 3**. Aerosol optical thickness (top) and marine reflectance (bottom) derived from POLDER data on 20 June 1997 using an atmospheric correction scheme that neglects aerosol absorption. The presence of a strong dust storm out of Libya to Greece results in a large underestimation of the marine reflectance.*

-Neglecting aerosol absorption results in a large underestimation of the water reflectance.

DEALING WITH ABSORBING AEROSOLS

1) One may estimate the relevant aerosol properties.

-Hasekamp et al. (2011), Dubovik et al. (2011), multi-angle photo-polarimetry:

$0.1 < \tau_{aer}(550) < 0.3$

$\Delta r_f = 0.036$; $\Delta r_c = 0.24$ (micron); $\Delta\sigma_f = 0.071$; $\Delta\sigma_c = 0.30$;
$\Delta m_{rf} = 0.055$; $\Delta m_{rc} = 0.016$; $\Delta m_{if} = 0.018$; $\Delta m_{ic} = 0.02$;
$\Delta\tau_{aer} = 0.024$; $\Delta\omega_{aer} = 0.02\text{-}0.05$; $\Delta PF_{aer} = 5\text{-}10\%$

-Dubuisson et al. (2009), oxygen A-band technique:

$\Delta h_{aer} = 1\text{-}2$ km ($\Delta P_{aer} = 100\text{-}200$ hPa)

-For BDD aerosols with $\tau_{aer}(550) = 0.2$ and $P_{aer} = 800$ hPa, 5% accuracy on $\rho_w(450)$ requires $\Delta\tau_{aer} = 0.022$, $\Delta\omega_{aer} = 0.05$, and $\Delta P_{aer} = 344$ hPa when [Chl-a] = 0.06 mg/m^3, but 0.003, <0.01, and 40 hPa when [Chl-a] = 2.4 mg/m^3, i.e., accuracy may not be sufficient.

2) One may use the entire information available (e.g., spectral observations from UV to SWIR).

-To estimate simultaneously the key properties of aerosols and water constituents by minimizing an error criterion between the measured reflectance and the output of a RT model (this belongs to the family of deterministic solutions to inverse problems), e.g., Gordon et al., 1997; Chomko and Gordon (1998, 2001).

-To cast atmospheric correction as a statistical inverse problem and to define a solution in a Bayesian context (e.g., estimating based on simulations, a function performing a mapping from the TOA reflectance to the marine reflectance), e.g., Gross et al., 2007; Frouin et al. (2015).

Bayesian vs. Standard AC, Sea of Japan, April 7, 2001

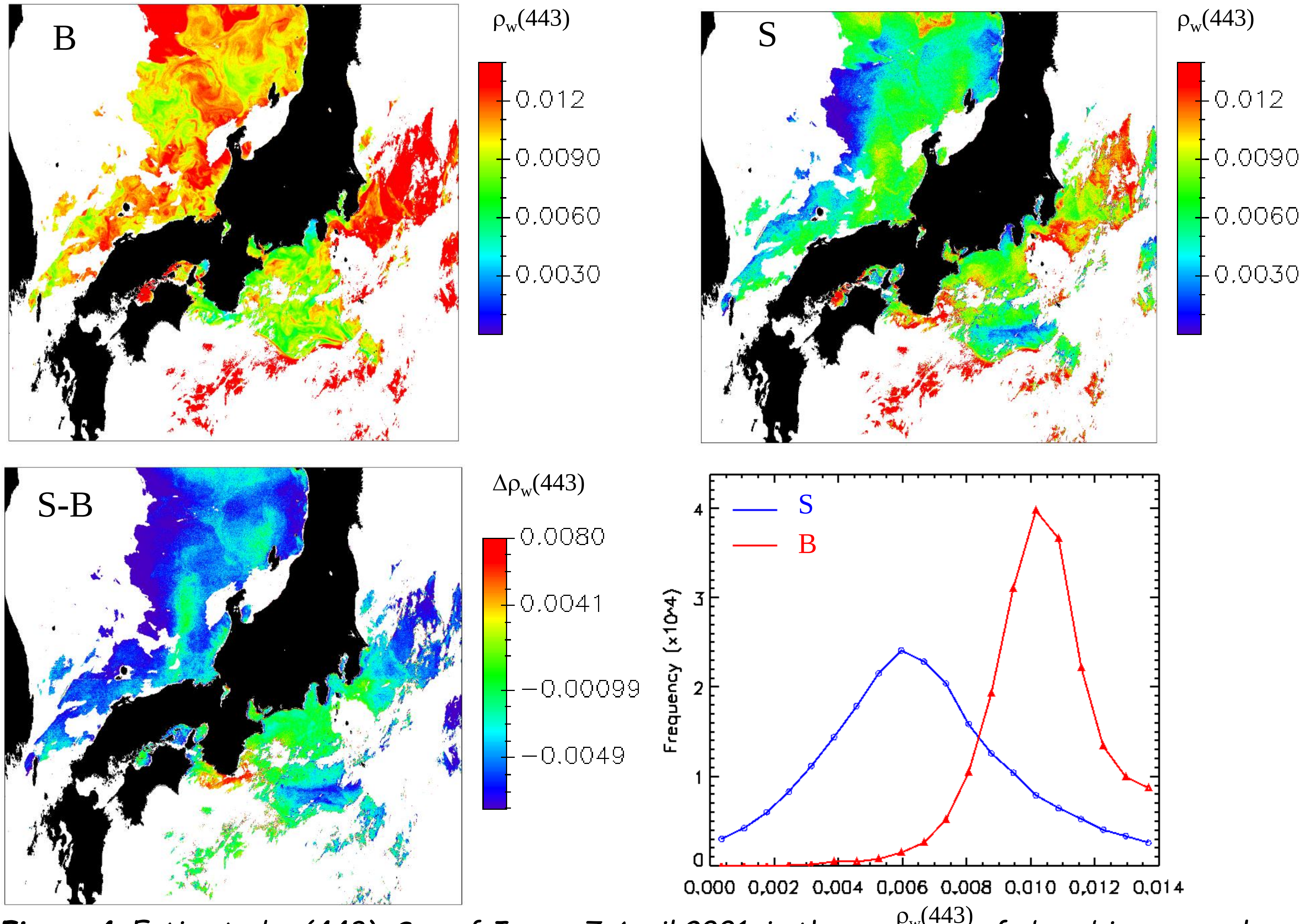

***Figure 4**: Estimated $\rho_w(443)$, Sea of Japan, 7 April 2001, in the presence of absorbing aerosols.*

3) One may exploit some properties of aerosol absorption on TOA reflectance (e.g., dependence on molecular scattering, therefore angular geometry).

-After removing the atmospheric scattering effects (first step), the TOA reflectance becomes approximately :

$$\rho_{TOA}' \approx -(P_s - P_{aer})/P_s\, \tau_{abs} m^* \rho_{mol} + \rho_w T_a (1 - \tau_{abs} m^*)$$

-By regressing ρ_{TOA}' versus $m^*\rho_{mol}$ (depends on geometry) one may get an estimate of the marine reflectance ρ_w (e.g., Thieuleux, 2002). In practice, the problem is non-linear, and one my use different absorption predictors, such as the absorption effect for a typical aerosol.

-The aerosol variables that govern the absorption effect, i.e., absorption optical thickness and vertical distribution, do not need to be determined.

Multi-angular AC concept

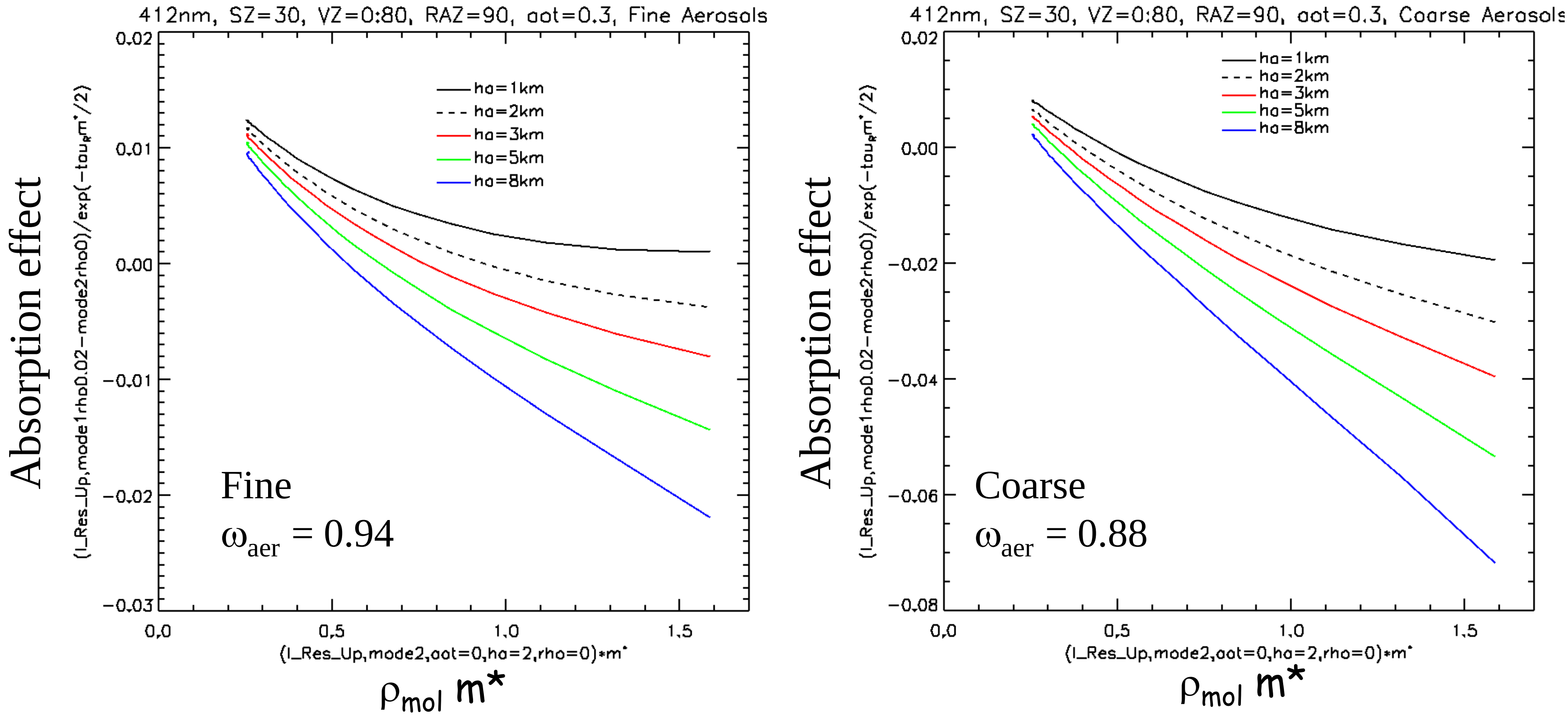

***Figure 5**: SOS simulations of ρ_{TOA}'/T_{mol}, versus ρ_{mol} m* for fine aerosols (left) and coarse aerosols (right). Wavelength is 412 nm and aerosol optical thickness is 0.3. Wind speed is 5 m/s and marine reflectance is 0.02. Solar zenith angle is 30 deg., viewing azimuth angle varies between 0 and 80 deg., and relative azimuth angle is 90 deg. Aerosol scale height varies from 1 to 8 km (8 km correspond to mixed aerosols and molecules). The fine aerosols are defined by r_f = 0.1 µm , σ_f = 0.20, and m_f = 1.40 - 0.010i (single scattering albedo of 0.94), and the coarse aerosols by r_c = 2.0 µm , σ_c = 0.30, and m_c = 1.55 - 0.002i (single scattering albedo of 0.88).*

4) One may detect the presence of absorbing aerosols and, in the standard AC algorithm, shift to a set of absorbing aerosol models.

-Detection may be accomplished using a threshold on water reflectance first retrieved using standard aerosol models (Antoine and Morel, 1999), or using the spectral contrast in TOA reflectance at two UV wavelengths (Torres et al., 1998). Information about aerosol altitude is needed to compute aerosol signal, e.g., Duforet et al. (2007); Dubuisson et al., (2009); Remer et al., (2019).

-Output of atmospheric global climate models, e.g., NASA GEOS-5, may be used to constrain the aerosol model.

SUMMARY

-Neglecting aerosol absorption in standard AC schemes may yield large errors on water reflectance estimates (e.g., 10 times larger than acceptable errors). Thus, the aerosol absorption effect on TOA reflectance needs to be corrected, all the more as absorbing aerosols are highly variable and present over vast oceanic regions.

-Standard AC schemes that use NIR-SWIR to estimate atmospheric signal cannot handle absorbing aerosols properly, since there is little sensitivity to aerosol absorption at those wavelengths.

-The problem can be addressed by 1) estimating the relevant properties (e.g., using multi-angle photo-polarimetry), 2) using deterministic/statistical schemes that use information at all the wavelengths (in particular those sensitive to aerosol absorption, i.e., UV), and 3) using multi-angle information (allows one to avoid determining separately the relevant variables).

SUMMARY (cont.)

-Identifying the presence of absorbing aerosols (e.g., using criteria on water reflectance, UV absorption index, or information from transport models) may also help to constrain the aerosol model.

-For current missions, it will be difficult to handle absorbing aerosols efficiently, unless appropriate atmospheric correction schemes are applied instead of the standard AC scheme (they exist) or a proper set of possible aerosol models identified (probably less accurate).

-For PACE, solutions 1) and 2) can be implemented, but it will be difficult to use solution 3), because of the sensor limitations (SPEX has limited multi-angle capability, HARP does not measure below 440 nm where coupling between aerosol absorption and molecular scattering is effective).