Overview of Atmospheric Correction
(For Global Ocean Color Data Processing)

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Brief History

- Color photographs of the oceans were obtained from spacecraft (Apollo, etc., 1960's).
- Clarke et al. (1970) showed the systematic measurements of radiance spectra of sea (ocean color) from aircraft, demonstrated the possibility of detecting the chlorophyll concentration within the ocean upper layers. They also showed atmospheric effects on the measured signals.
- Tyler & Smith (1970) performed field measurements of upward & downward irradiance spectra in different water bodies. Thereafter, there were many similar in situ water optical measurements.
- Interpretation of in situ reflectance measurements was given in the frame of *radiative transfer* by Gordon *et al.* (1975) and also in terms of optically-significant water substances by Morel and Prieur (1977) and Smith and Baker (1978).
- Gordon (1978; 1980) developed a single-scattering atmospheric correction algorithm for processing the NASA CZCS ocean color data, demonstrating the feasibility of satellite ocean color remote sensing.
- Advanced atmospheric correction algorithm, e.g., Gordon and Wang (1994)-type algorithm has been developed for various more sophisticated ocean color satellite sensors, e.g., OCTS, SeaWiFS, GLI, MODIS, MERIS, VIIRS, OLCI, etc., following the successful CZCS proof of concept mission.
- Other approaches, including the **SWIR**, spectral matching (e.g., **POLYMER**), Neural Network, etc.
- In recent years, atmospheric correction effort has been on dealing with more complex water properties in coastal and inland waters, as well as strongly-absorbing aerosols.

Algorithms for Various Ocean Color Sensors

(Routine Global Ocean Color Data Processing)

Standard Algorithms:

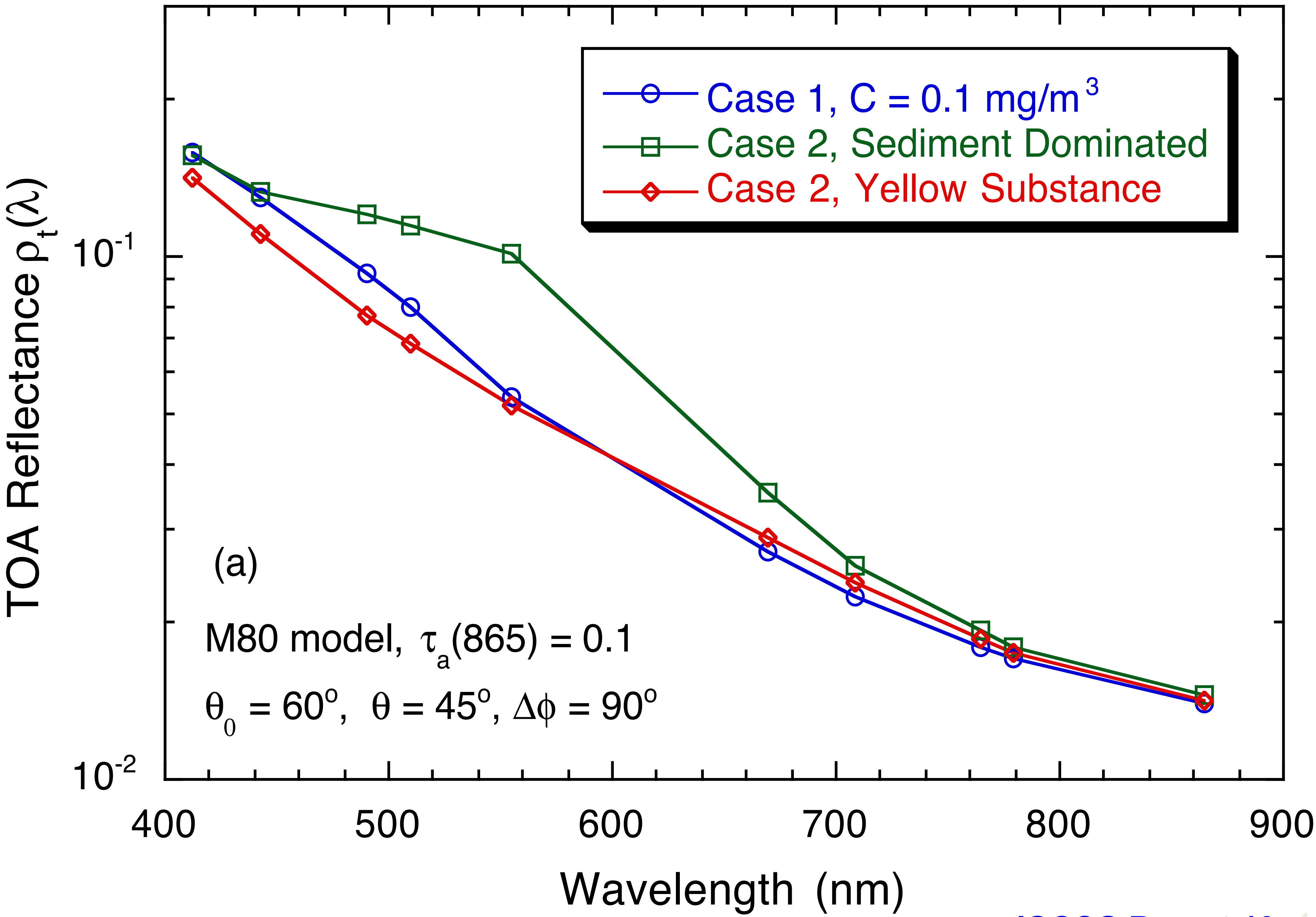
- **Gordon and Wang** (1994) for **SeaWiFS**, **MODIS**, and now **VIIRS** ocean color products.
- **Fukushima** et al. (1998) for **OCTS** and **GLI** ocean color products.
- **Antoine and Morel** (1999) for **MERIS** and now **OLCI** ocean color products.
- **Deschamps** et al. (1999) for **POLDER** ocean color products.

Other approaches:

- Various approaches for dealing with NIR ocean contributions.
- Steinmetz et al. (2011) **POLYMER** for the CCI project.
- Neural Network approach for MERIS and OLCI coastal regions (R. Doerffer), Spectral Match.

IOCCG, Atmospheric Correction for Remotely-Sensed Ocean-Color Products, Wang, M. (ed.), *Reports of International Ocean-Color Coordinating Group*, No. 10, IOCCG, Dartmouth, Canada, 2010.

Satellite Sensor Measured TOA Reflectance Spectra



IOCCG Report-10

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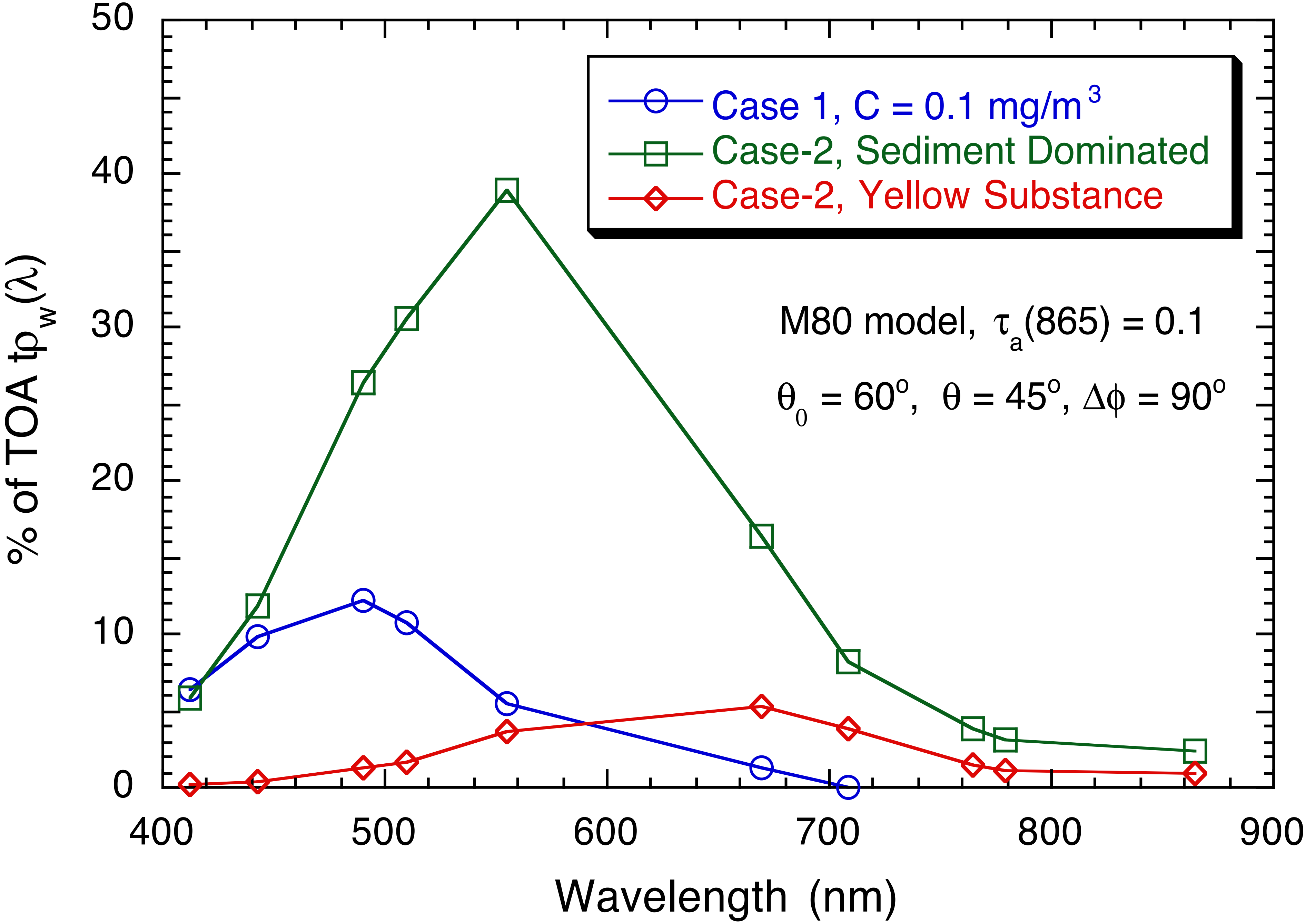
The TOA Ocean Contributions



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Atmospheric Correction

Standard atmospheric correction algorithm (Gordon and Wang 1994)

$$L_t(\lambda) = L_r(\lambda) + L_A(\lambda) + t(\lambda)L_{wc}(\lambda) + T(\lambda)L_g(\lambda) + t(\lambda)t_0(\lambda)\cos\theta_0\, nL_w(\lambda)$$

$$\rho_{wN}(\lambda) = \pi\, nL_w(\lambda)/F_0(\lambda) \text{ and } R_{rs}(\lambda) = nL_w(\lambda)/F_0(\lambda)$$

- ***nL_w* is the desired quantity in ocean color remote sensing.**
- TL_g is the sun glint contribution—avoided/masked/corrected.
- TL_{wc} is the whitecap radiance—computed from wind speed.
- L_r is the scattering from molecules—computed using the Rayleigh lookup tables (vector RTE, wind speed, atmospheric pressure dependents).
- $L_A = L_a + L_{ra}$ is the aerosol and Rayleigh-aerosol contributions — estimated using **aerosol models**.
- For Case-1 waters at the open ocean, nL_w is usually negligible at the NIR 750 & 865 nm, i.e., L_A can be estimated using these two NIR bands, and extrapolated into visible using aerosol models.

- However, the black pixel assumption is usually incorrect at the NIR bands for coastal and inland waters.

Spectral Matching Algorithm

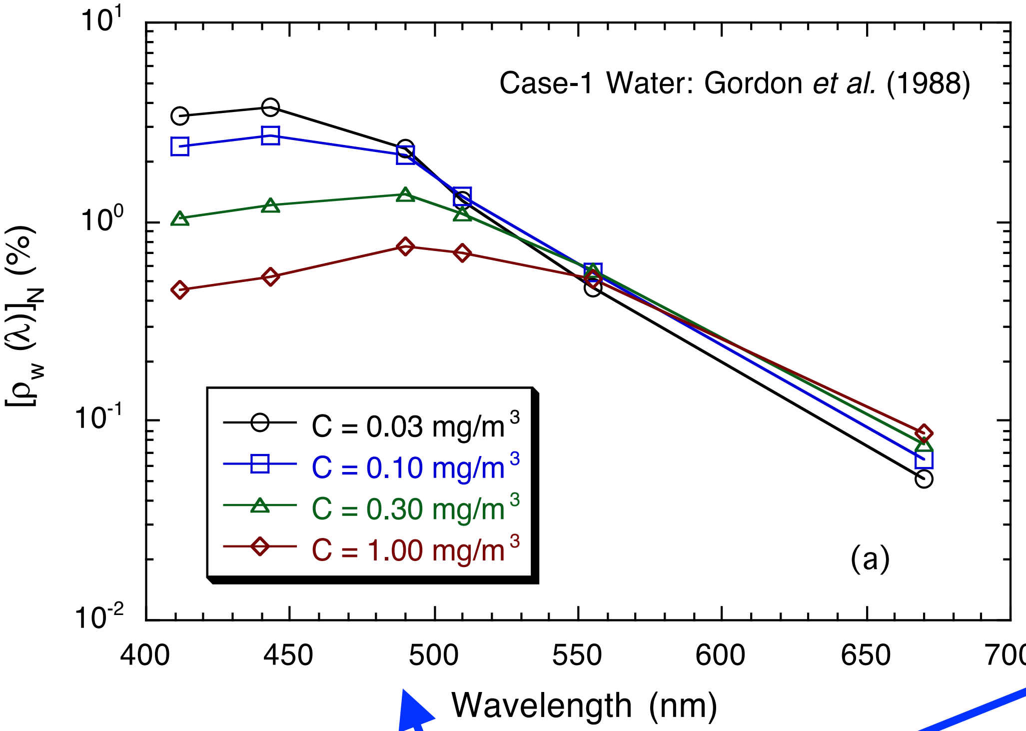
POLYMER (Steinmetz et al., 2011)--- Polynomial based algorithm applied to MERIS, which has been used for the CCI global ocean color data processing for MERIS, SeaWiFS, and MODIS:

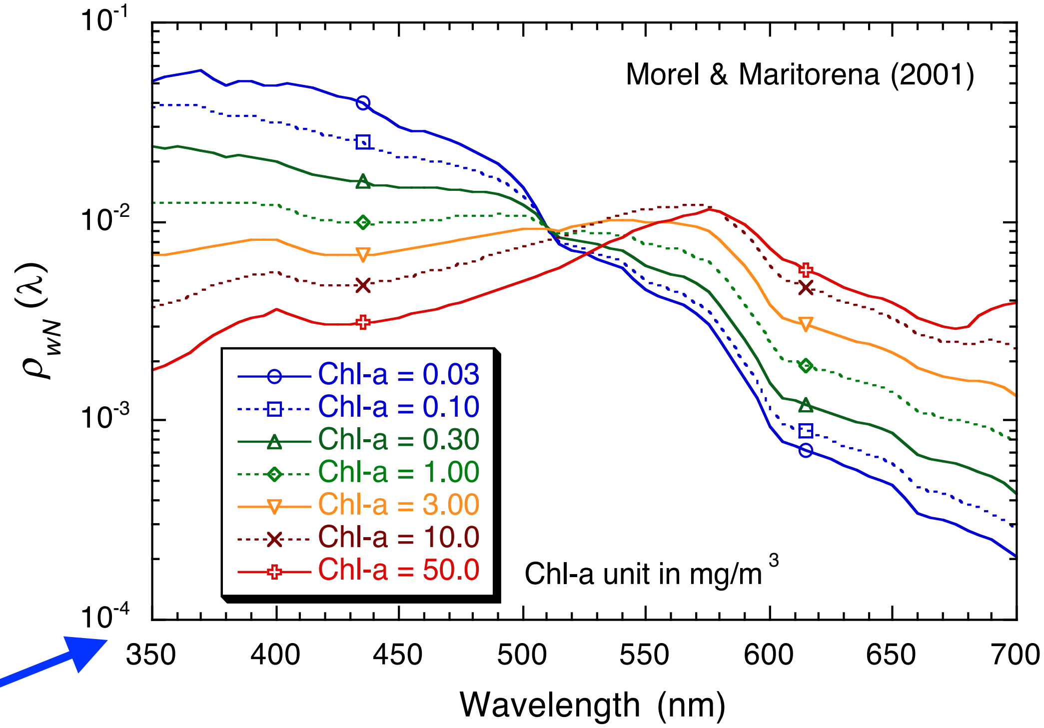
$$L_t(\lambda) = L_r(\lambda) + L_A(\lambda) + t(\lambda)L_{wc}(\lambda) + T(\lambda)L_g(\lambda) + t(\lambda)t_0(\lambda)\cos\theta_0\, nL_w(\lambda)$$

- ***nL_w* spectra are modeled using bio-optical model**.
- The rest of radiance contributions are modeled assuming a polynomial as a function of the wavelength, i.e., **$a_0 + a_1 \lambda^{-1} + a_2 \lambda^{-4}$**
- L_t spectra are then estimated and compared with the sensor-measured values----nL_w spectra with the best fit to the sensor-measured TOA radiance can be derived.

Important Notes:

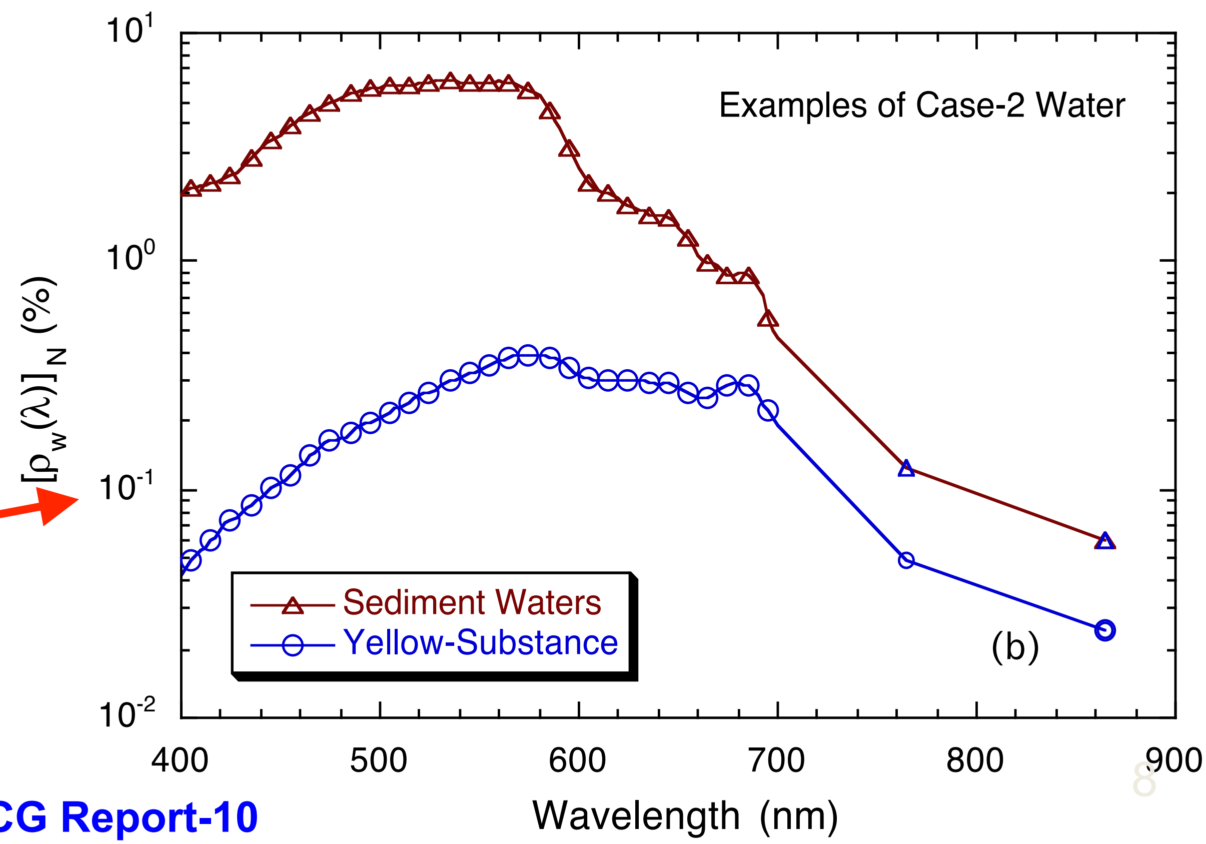
- Require **good in-water model** (results are from in-water model).
- **Aerosol models are not important**, or aerosol spectral reflectance follows: **$c_0 + c_1 \lambda^{-1}$** (simple non-absorbing, power law aerosol size distribution).





Ocean Contributions:
Case-1 Waters

Ocean Contributions:
Case-2 Waters



SeaWiFS, MODIS, MERIS, VIIRS Experiences Show:

High quality ocean color products for the global **open oceans** (Case-1 waters).

Significant efforts are needed for improvements of ocean color products in the **coastal & inland regions**:

- **Turbid Waters**
  (violation of the NIR black ocean assumption)
- **Strongly-Absorbing Aerosols**
  (violation of non- or weakly absorbing aerosols)

Algorithm Developments for Productive/Turbid Waters

- **Arnone** et al. (1998) and **Siegel** et al. (2000) to account for the NIR ocean contributions for SeaWiFS and MODIS NIR bands.
- **Hu** et al. (1999) proposed an *adjacent pixel method*.
- **Gordon** et al. (1997) and **Chomko** et al. (2003) *the spectral optimization algorithm*.
- **Ruddick** et al. (2000) for regional Case-2 algorithm using the *spatial homogeneity of the aerosol* in a given area.
- **Lavender** et al. (2004) regional bio-optical model (suspended sediments) for SeaWiFS application.
- **Wang** and **Shi** (2005) derived NIR ocean contributions using the MODIS shortwave infrared (**SWIR**) bands.
- **Doerffer** et al. and others developed Artificial *Neural Network* for coastal Case-2 waters (implemented for MERIS data processing).
- **Wang** (2007) and **Wang** & **Shi** (2007) proposed the SWIR and NIR-SWIR atmospheric correction for the coastal waters.
- **Bailey** et al. (2010) developed an improved NIR model for the NASA standard ocean color data processing (SeaDAS).
- **Wang** et al. (2012) developed an NIR model for western Pacific regions (highly turbid) using the data from the SWIR algorithm for GOCI sensor.
- **Jiang and Wang** (2014) developed BMW algorithm--combined Bailey, Ruddick, and Wang algorithms for VIIRS global ocean color data processing.

The NIR Ocean Contribution Modeling (I)

Various investigators all sought to remove the NIR $nL_w(\lambda)$ contributions from the TOA NIR radiances, so that a "**black pixel**" could be provided to the *Gordon and Wang* (1994) type atmospheric correction:

- **Siegel** et al. (2000) used chlorophyll estimate to determine the NIR $nL_w(\lambda)$.
- **Lavender** et al. (2005) used a sediment estimate to determine the NIR $nL_w(\lambda)$.
- **Ruddick** et al. (2000) fixed the aerosol and backscatter type and then solved for both the NIR $nL_w(\lambda)$ and NIR aerosol reflectance simultaneously.
- **Arnone** et al. (1998) and **Stumpf** et al. (2003) used a bio-optical model for absorption coefficient at the red band and then used that with the red $nL_w(\lambda)$ to find the NIR $nL_w(\lambda)$.
- **Bailey** et al. (2010) developed an improved NIR model for the NASA standard ocean color data processing (SeaDAS).
- **Wang** et al. (2012) developed an NIR model for western Pacific regions (highly turbid) using the data from the SWIR algorithm for GOCI sensor.
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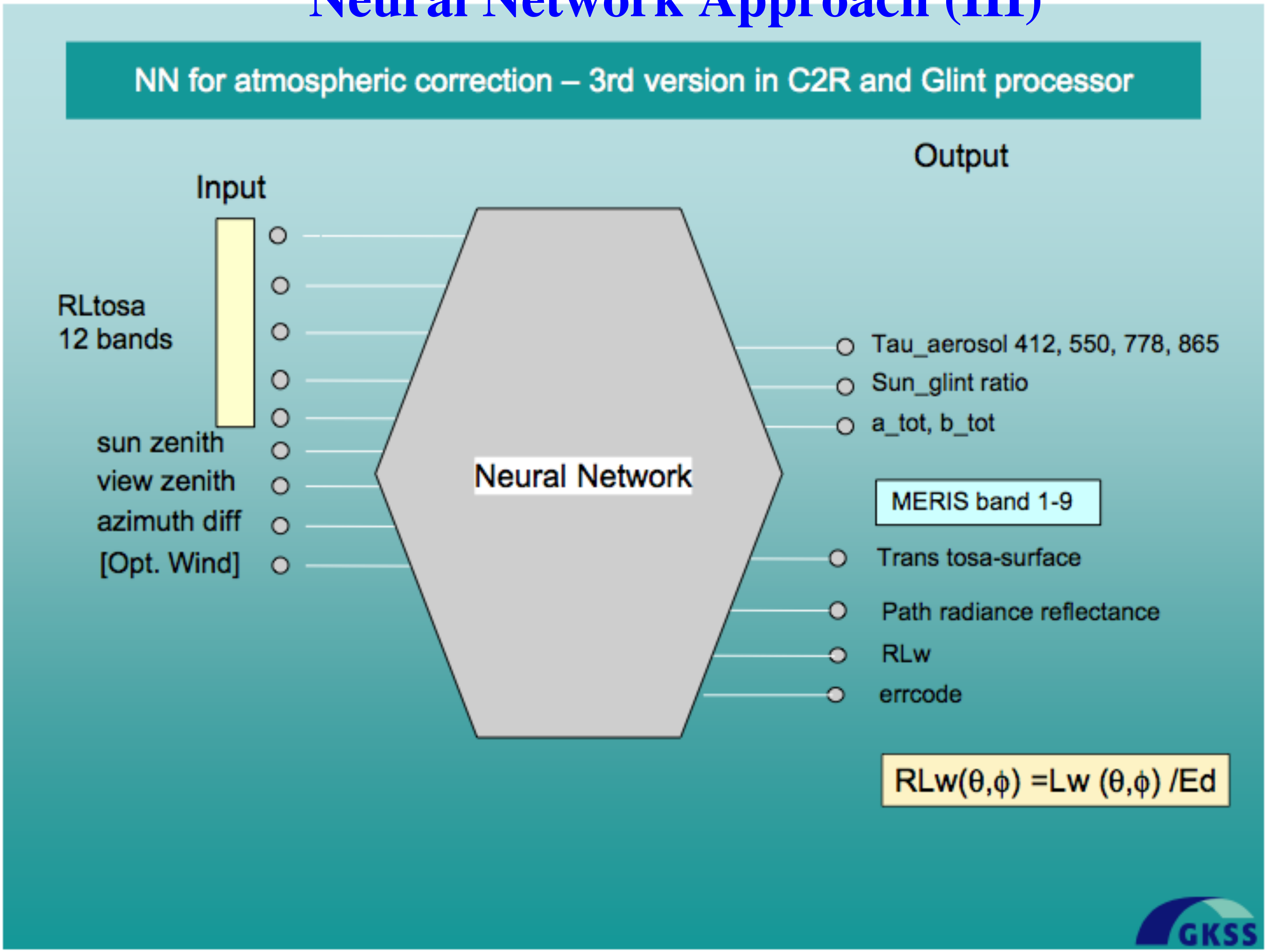
Spectral Optimization Algorithm (II)

- The **Spectral Optimization Algorithm (SOA)** (Chomko and Gordon, 1998) derives the properties of the ocean and atmosphere simultaneously using sensor-measured TOA radiance from the blue to NIR (entire radiance spectra from visible to NIR). However, the algorithm has no attempt to use **realistic aerosol models**.
  - Use a simple power-law size distribution aerosol model
  - Use the Garver-Siegel-Maritorena (GSM) ocean bio-optical model
  - Some studies with SeaWiFS data show improved results over the coastal productive waters (Kuchinke et al., 2009).

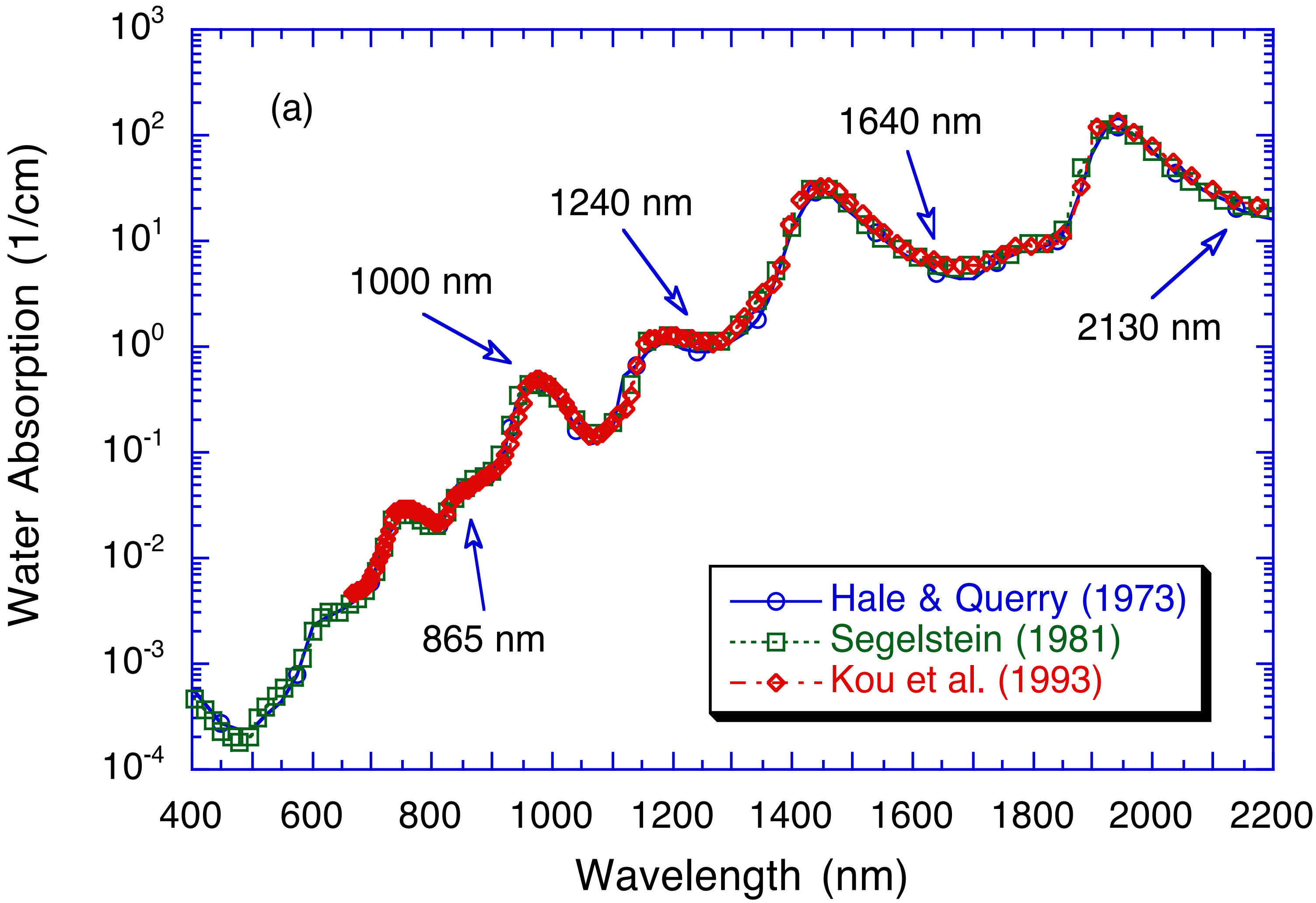
✓ The SOA approach with simultaneously ocean and atmosphere properties retrieval (one-step) requires **robust ocean bio-optical model** (e.g., over complex turbid waters).

Neural Network Approach (III)



From R. Doerffer

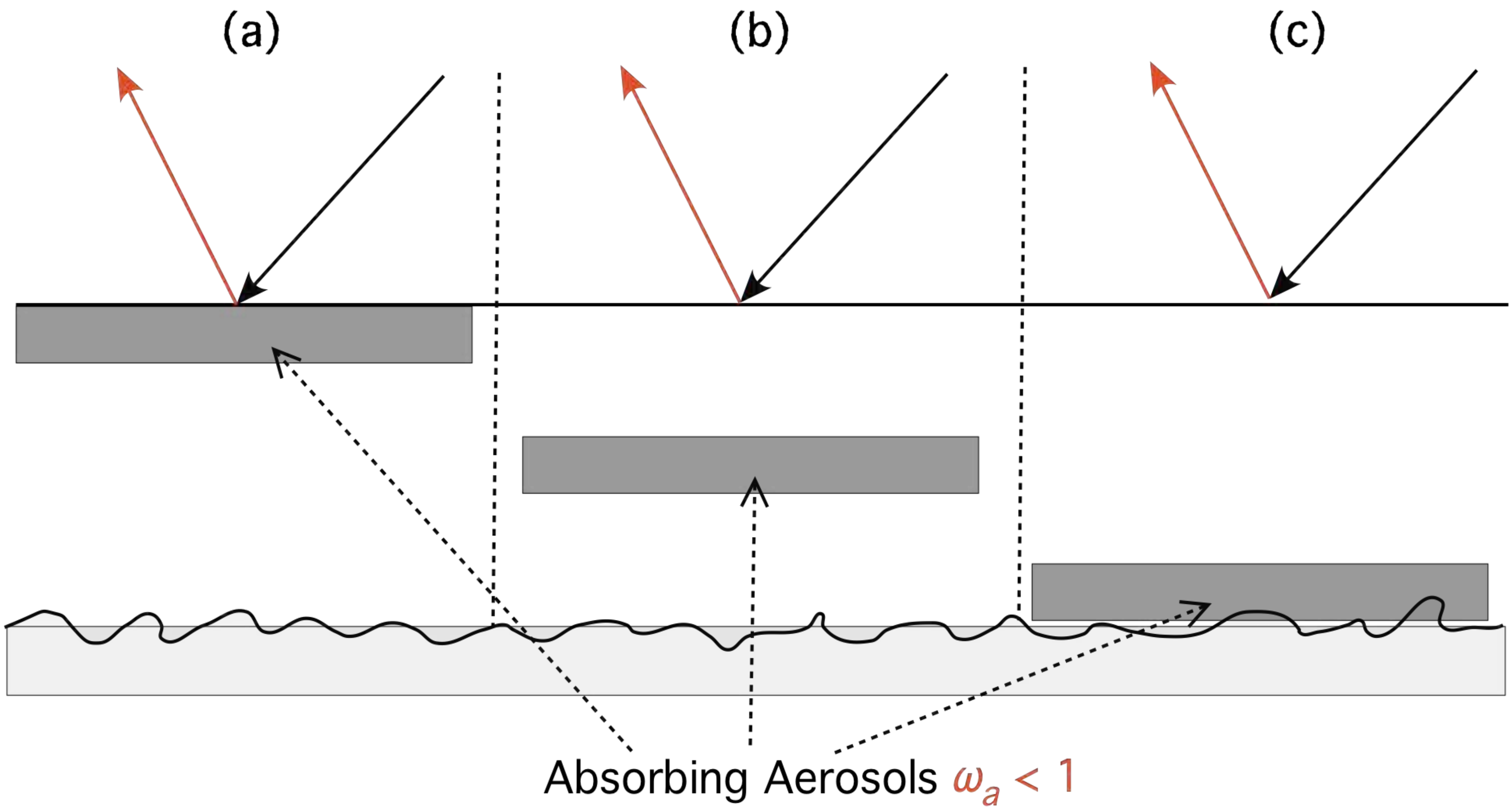
The SWIR Approach



Black ocean at the SWIR bands: Absorption at the SWIR bands is at least an order larger than that at the NIR 865 nm!

The shortwave infrared (**SWIR**) algorithm can be operated the same way as the NIR approach for turbid coastal/inland waters with the black pixel assumption. Require high SWIR **SNR** performance (MODIS and VIIRS SWIR bands do not meet the requirement).

Simply Cases with Strongly-absorbing aerosols:
Which upward radiance is largest and smallest?



Characteristics of the Aerosol Models

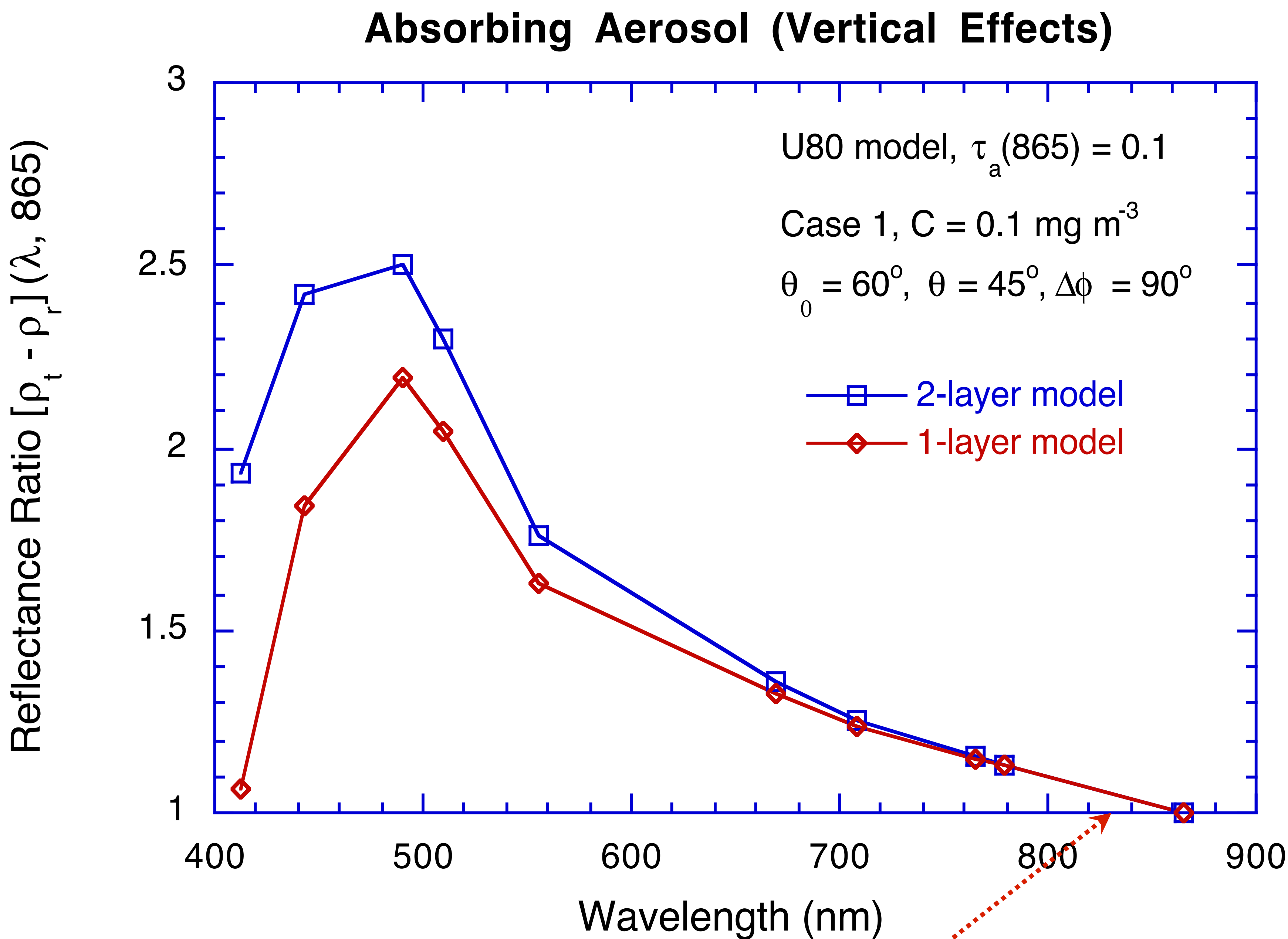
Aerosol Model	Single Scattering Albedo $\omega_a(865)$	Asymmetry Parameter g	Ångström Exponent $\alpha(510, 865)$
Oceanic[†]	1.0	0.724-0.840	-0.087~ -0.016
Maritime[†]	0.982-0.999	0.690-0.824	0.09-0.50
Coastal[††]	0.976-0.998	0.682-0.814	0.23-0.76
Tropospheric[†]	0.930-0.993	0.603-0.769	1.19-1.53
Urban[†]	0.603-0.942	0.634-0.778	0.85-1.14
Dust[†††]	0.836-0.994	0.662-0.763	0.29-0.36

[†] Shettle and Fenn (1979) aerosol models. [††] Gordon and Wang (1994)

[†††] Shettle (1984) and Moulin et al. (2001).

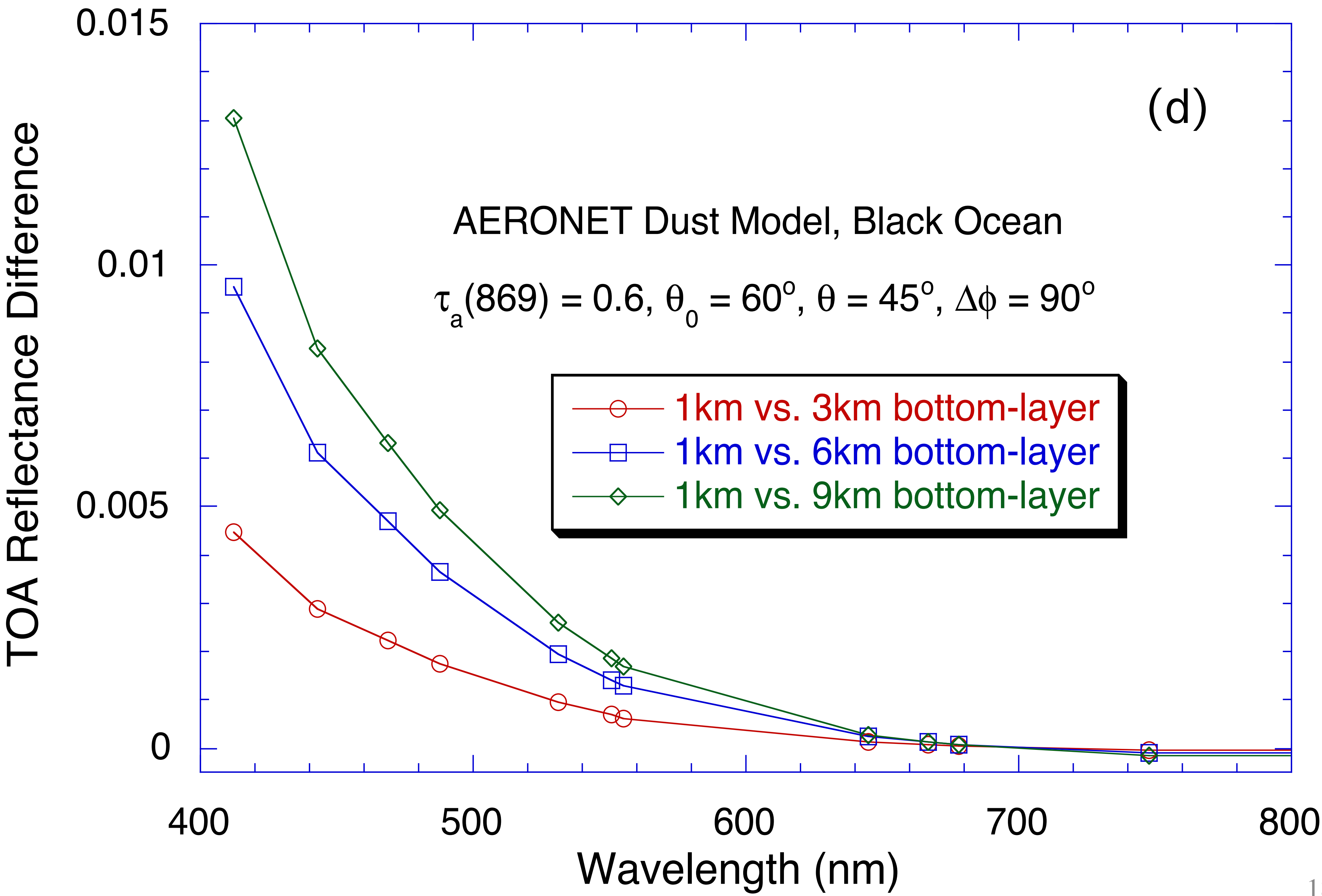
Strongly-absorbing aerosols

Strongly-absorbing aerosols: Urban Aerosols



NIR reflectances are not enough to retrieve absorbing aerosol properties

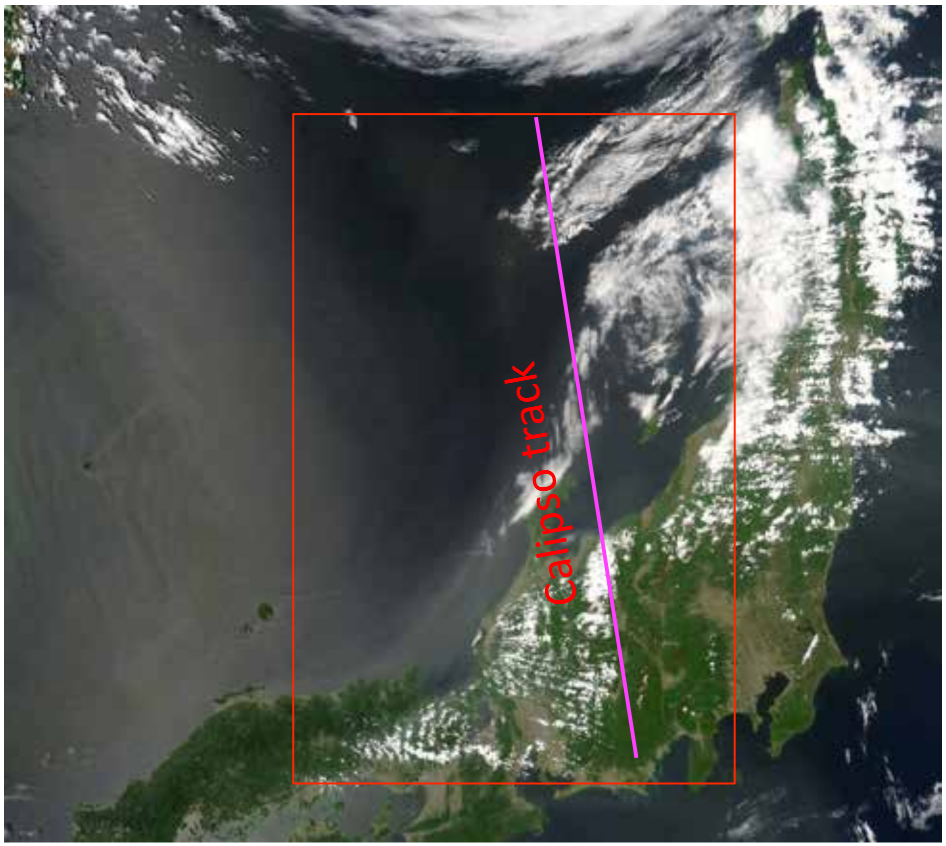
Effects of Dust Aerosol Vertical Distribution



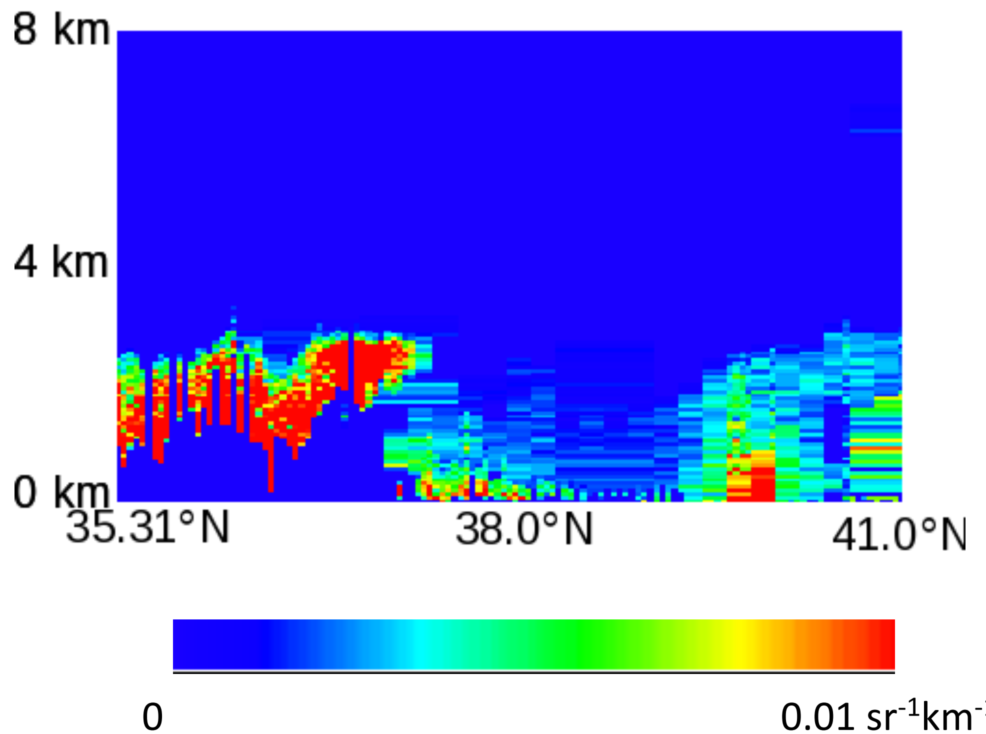
CASE ONE : Dust In Japan/East Sea on 5/26/2007

MODIS Granule (2007146)

MODIS True Color Image and CALIPSO Track



532 nm total attenuated backscatter



Dust height 0–2.5 km

Dealing with Strongly Absorbing Aerosols

For dealing with the strongly absorbing aerosols, it is necessary to first **detect the presence** of the strongly absorbing aerosols (e.g., using measurements in the **UV** bands where the TOA signal is sensitive to the aerosol absorption), and to derive the **aerosol vertical profile** (e.g., from Lidar measurements) with sufficient accuracy for atmospheric correction.

We also need realistic absorbing aerosol models (e.g., dust model).

Summary

- For highly turbid coastal and inland waters, we need the **SWIR** bands with high SNR performance (over ocean, low signal), i.e., at ~100-200.
- For strongly absorbing aerosols (usually over coastal and inland regions):
  - ✓ We would like to have UV bands for **absorbing aerosol detection**, and
  - ✓ It is required to have **aerosol vertical profile information** (e.g., accuracy to ~100-500 m) for carrying out atmospheric correction.
  - ✓ We also need **realistic absorbing aerosol models**, e.g., dust model, for generating proper aerosol lookup tables.