Satellite Ocean Color Remote Sensing for Ocean Coastal and Inland Waters

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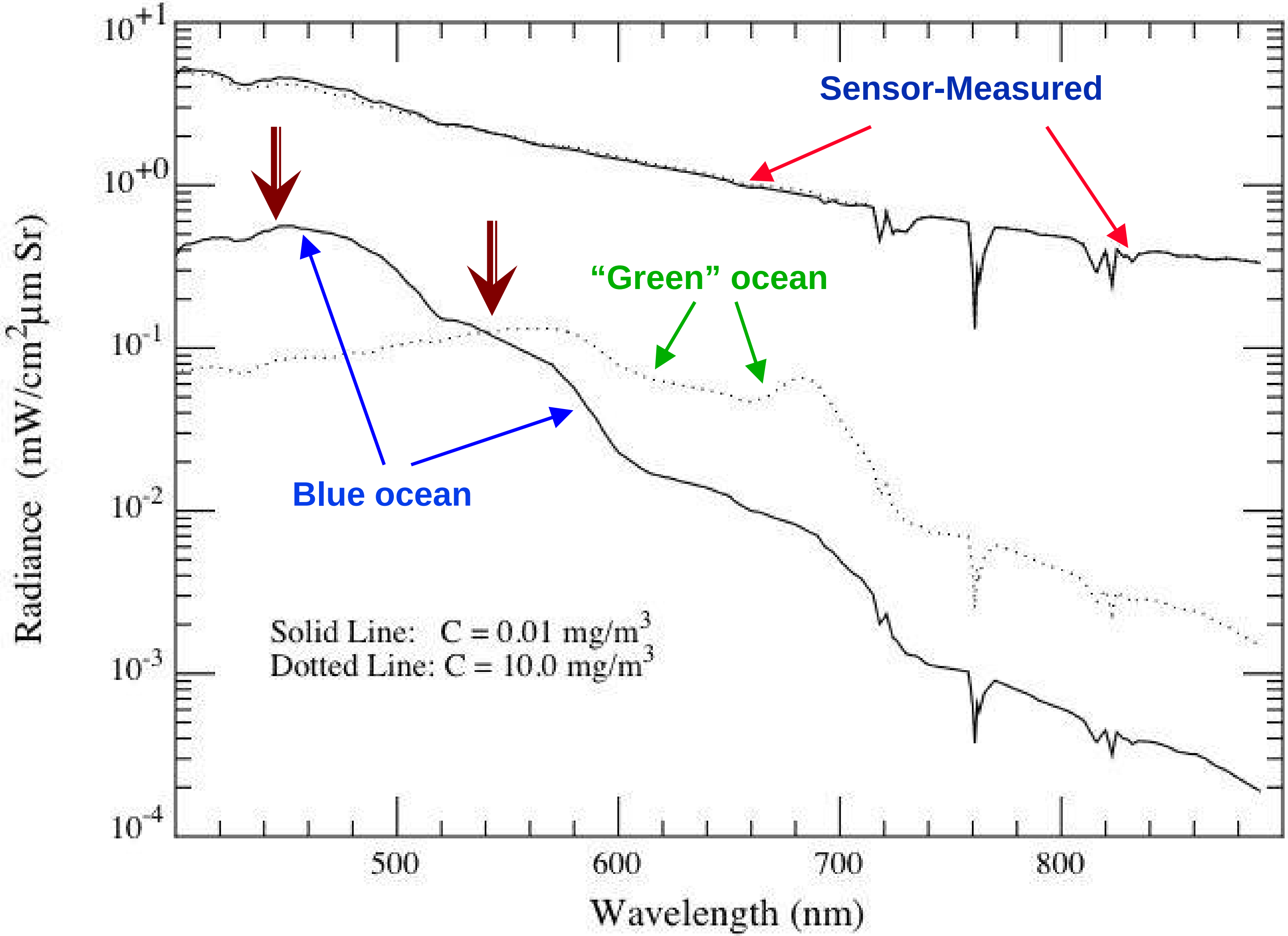
- Dr. **Seung-Hyun Son**, IMSG.
- Dr. **Xiaoming Liu**, SP Systems, Inc.

Works are supported by NOAA and NASA funding and grants.

Lake Taihu

Chesapeake Bay

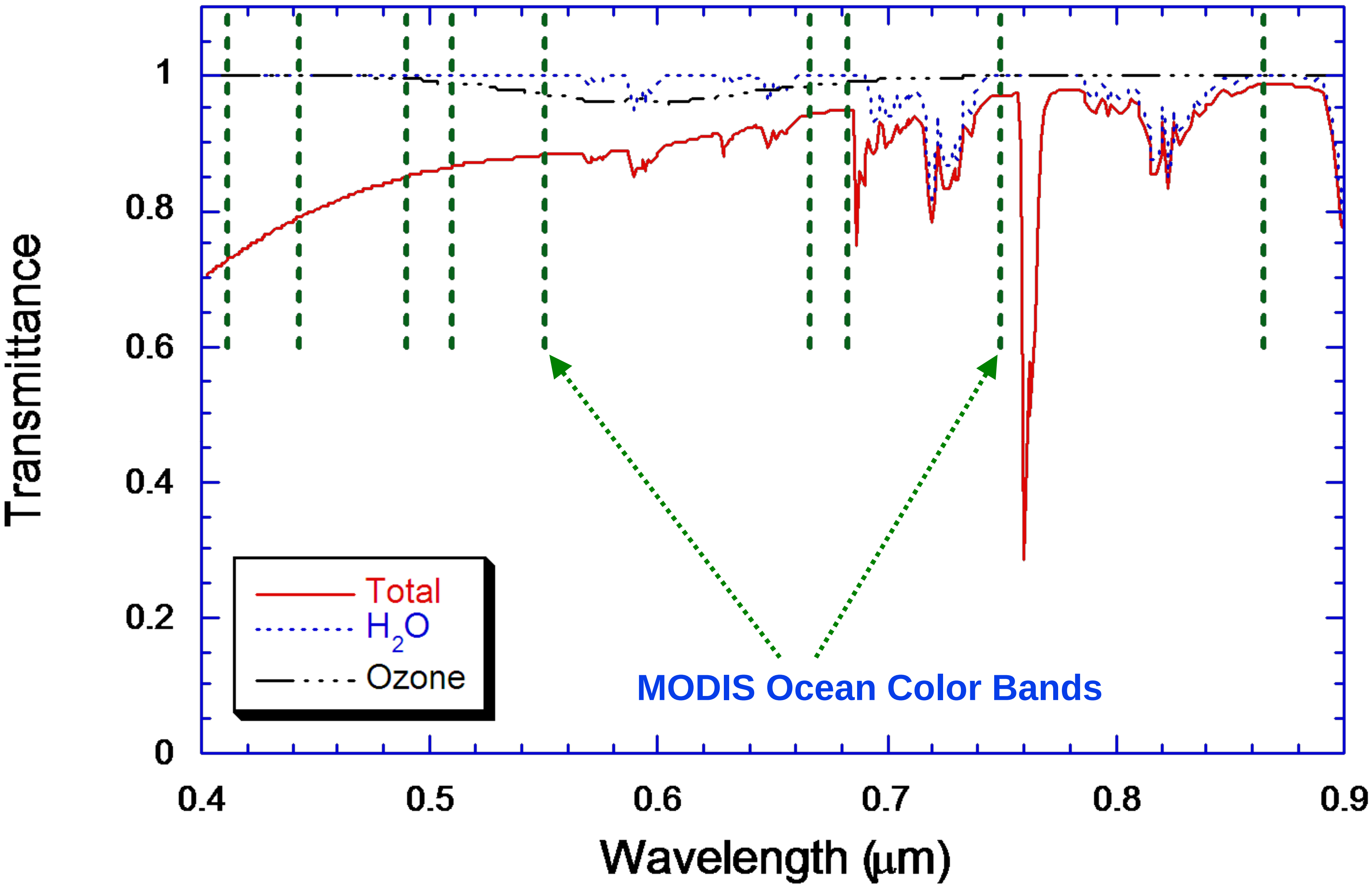
Ocean Color Remote Sensing



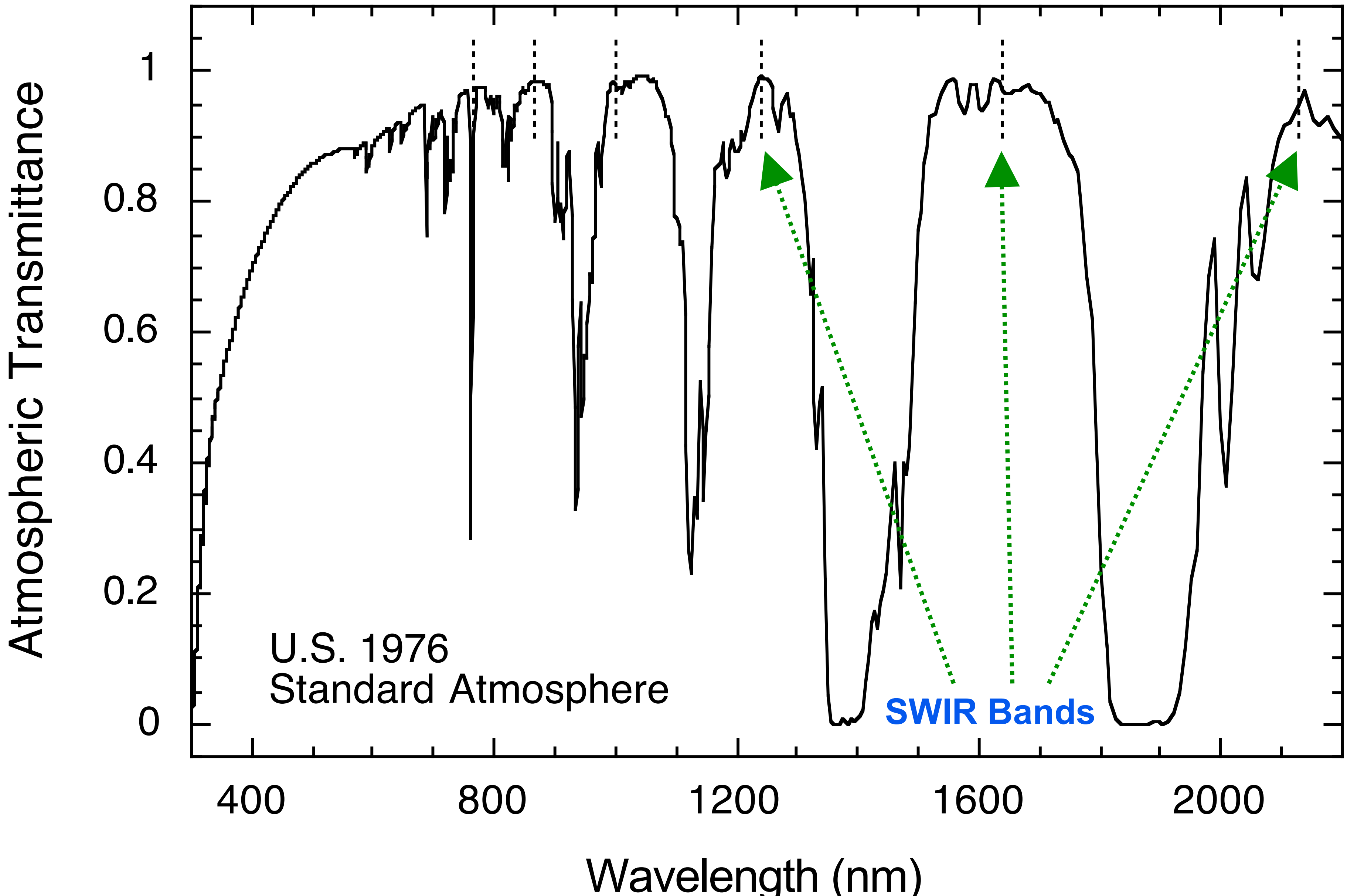
- Atmospheric Correction (removing >90% sensor-measured signals)
- Calibration (0.5% error in TOA >>>> 5% in surface)

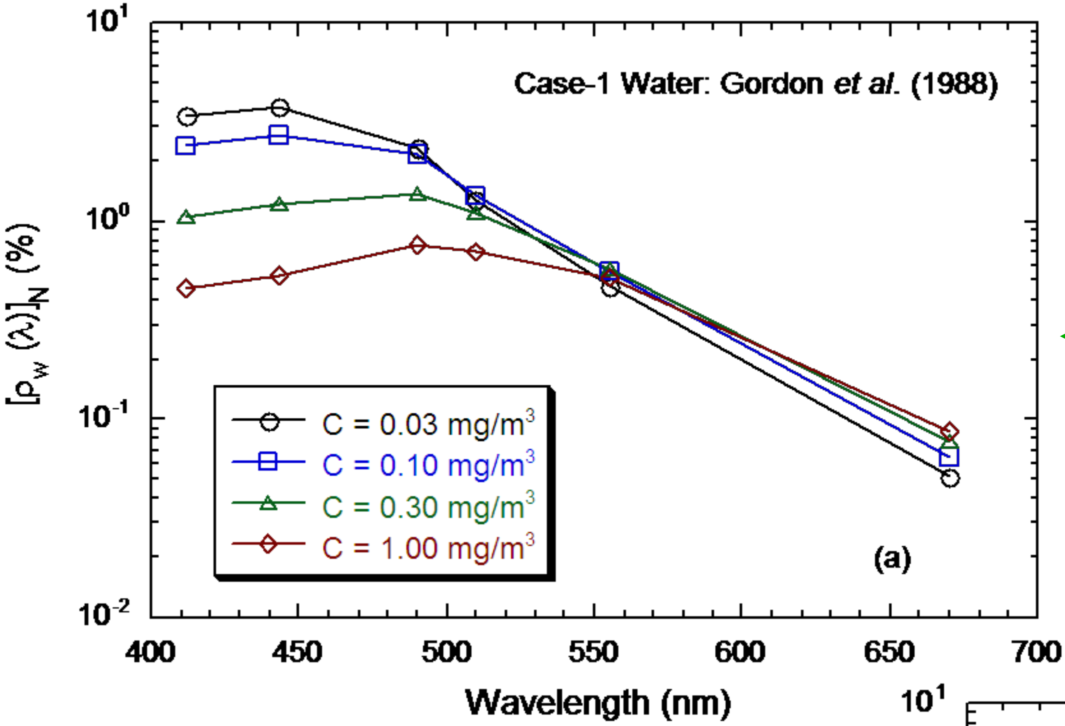
From H. Gordon

Atmospheric Windows (VIS-NIR)



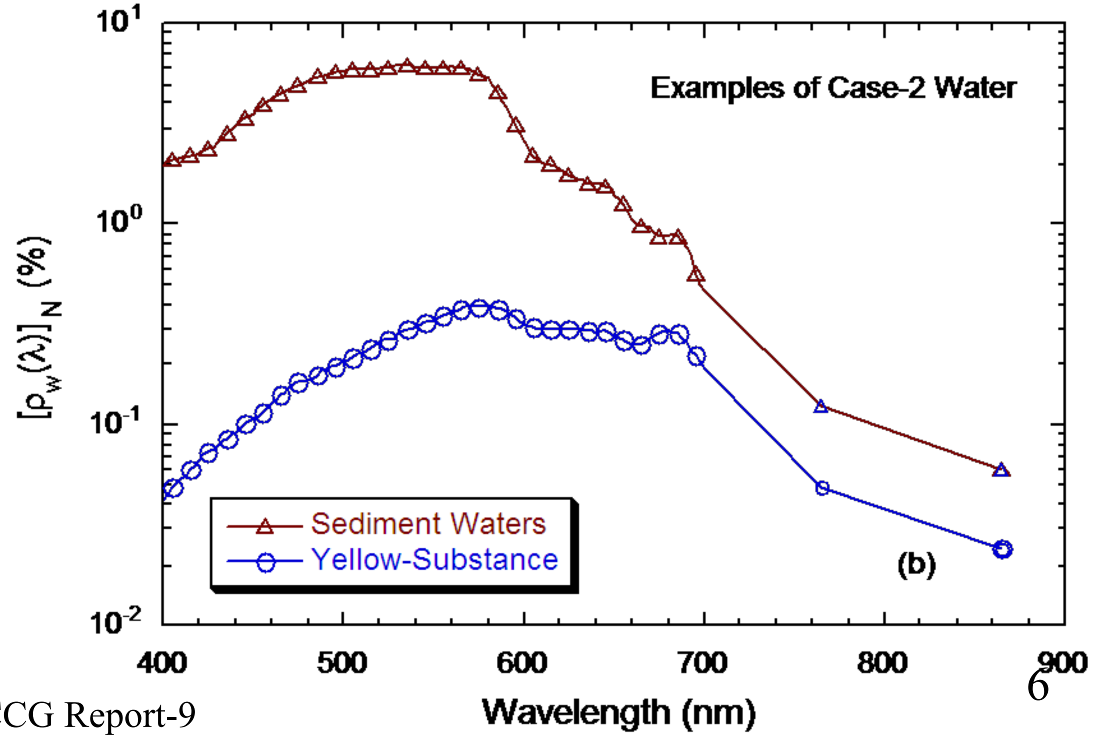
Atmospheric Windows





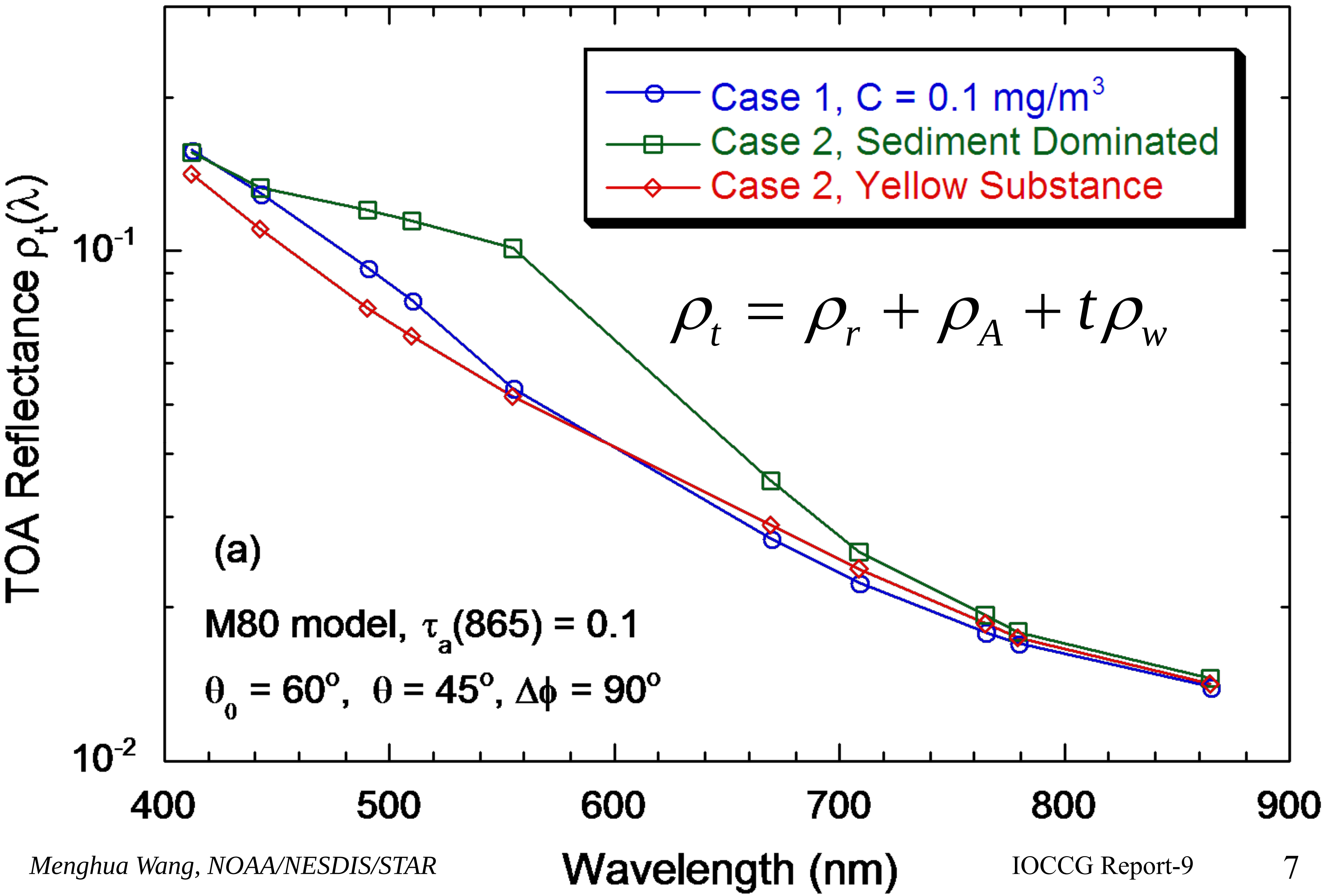
Ocean Contributions: Case-1 Waters

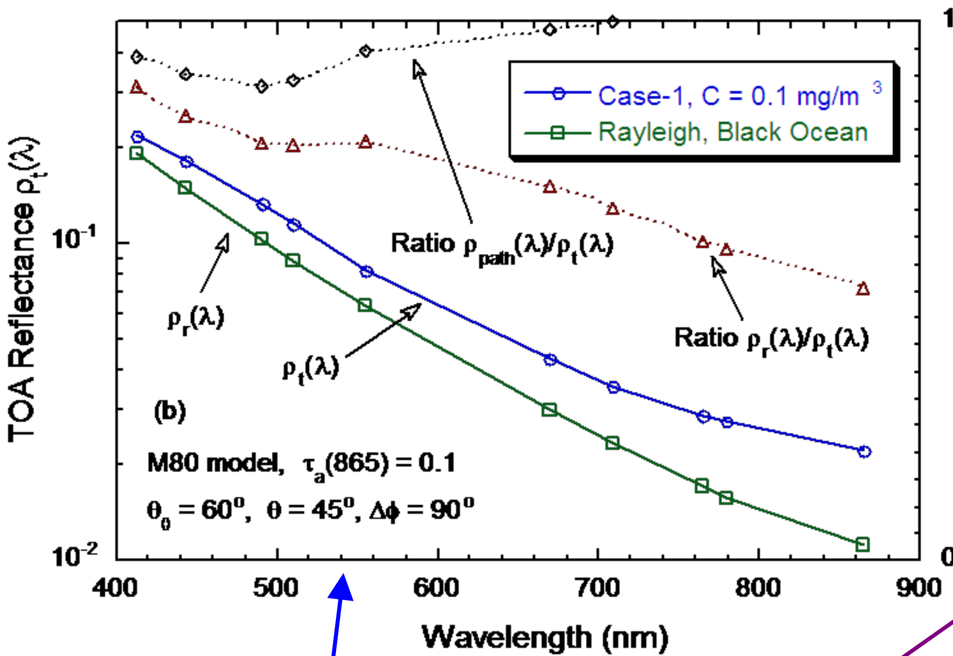
Ocean Contributions: Case-2 Waters

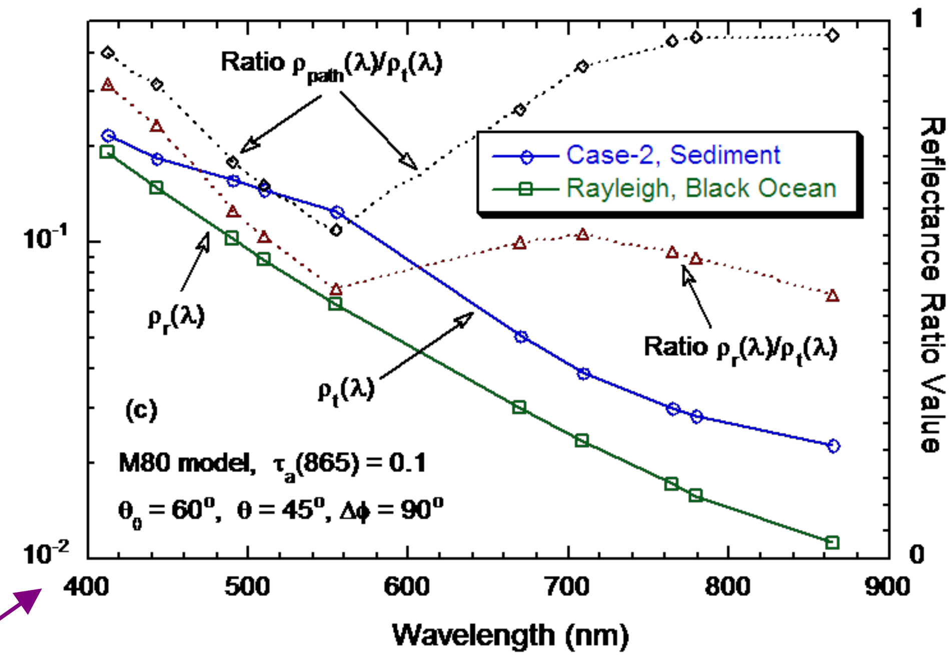


IOCCG Report-9

Satellite Sensor Measured TOA Reflectance Spectra

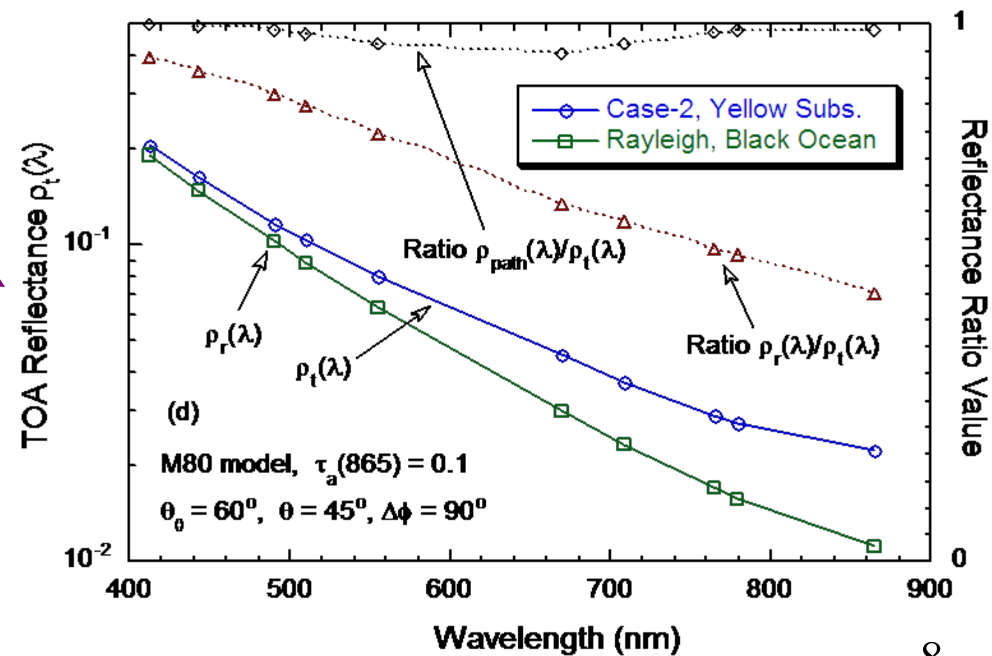






Open Ocean Waters

Case-2 Waters

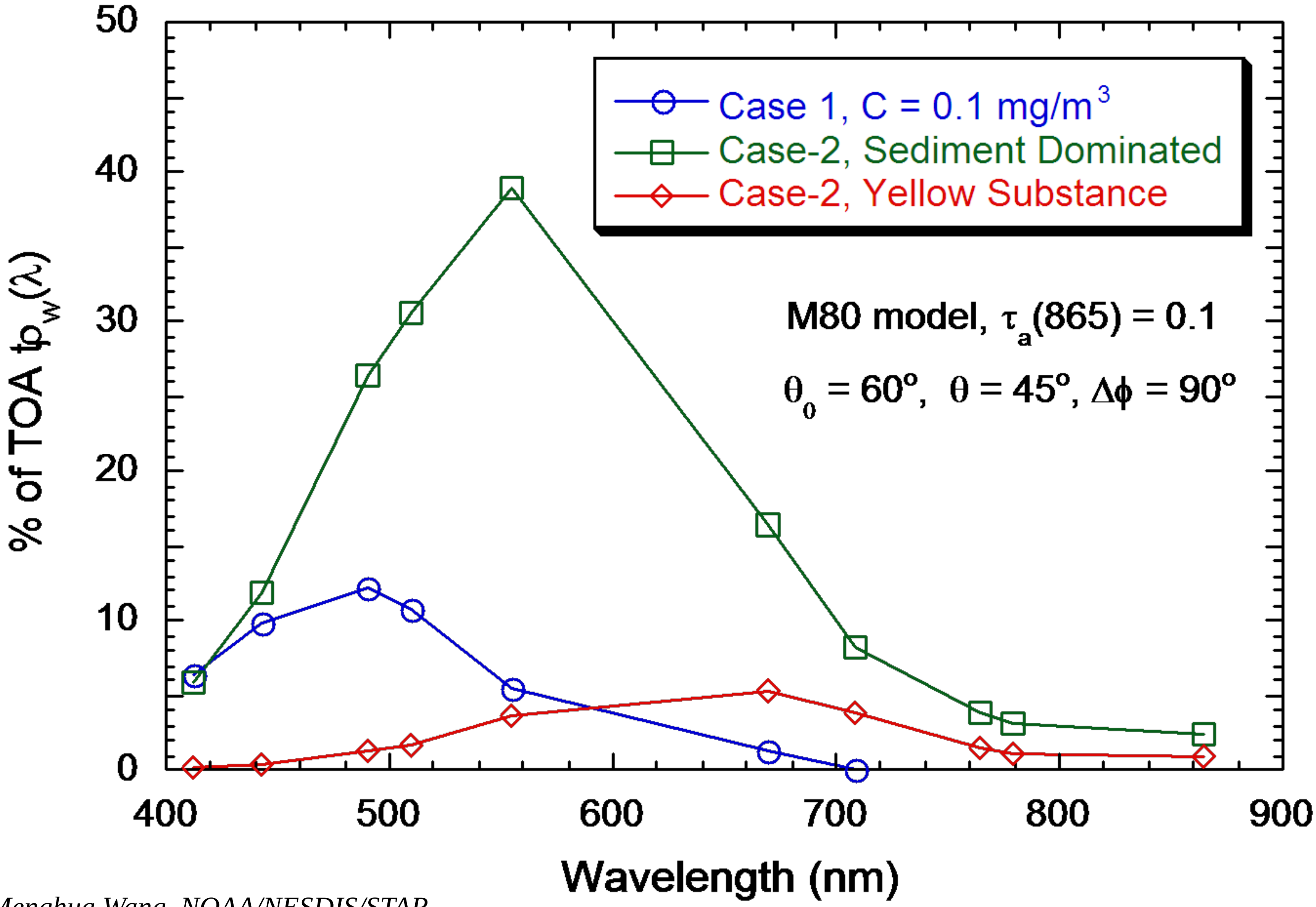


Ocean TOA Radiance Contributions for Case-1 and Case-2 Waters

$$\rho_t = \rho_r + \rho_A + t\rho_w$$

Menghua Wang, NOAA/NESDIS/STAR

The TOA Ocean Contributions



At satellite altitude ~**90%** of sensor-measured signal over ocean comes from the **atmosphere & surface**!

- It is crucial to have accurate **atmospheric correction** and **sensor calibrations**.
- **0.5%** error in atmospheric correction or calibration corresponds to possible of ~**5%** error in the derived ocean water-leaving radiance.
- We need **~0.1%** sensor calibration accuracy.

Ocean Color Remote Sensing: **Derive the ocean water-leaving radiance spectra by accurately removing the atmospheric and surface effects.**

Ocean properties **can be derived from the ocean water-leaving radiance spectra.**

Algorithms for Various Ocean Color Sensors

(Routine Global Ocean Color Data Processing)

- **Gordon and Wang** (1994) for **SeaWiFS** and **MODIS** (USA) ocean color products.
- **Fukushima** et al. (1998) for **OCTS** and **GLI** (Japan) ocean color products.
- **Antoine and Morel** (1999) for **MERIS** (ESA) ocean color products.
- **Deschamps** et al. (1999) for **POLDER** (France) ocean color products.

Atmospheric Correction Algorithm

MODIS and SeaWiFS algorithm (Gordon and Wang 1994)

$$\rho_t = \rho_r + \rho_A + t\rho_{wc} + T\rho_g + t\rho_w, \quad \rho = \pi L / \mu_0 F_0$$

- **ρ_w is the desired quantity in ocean color remote sensing.**
- $T\rho_g$ is the sun glint contribution—avoided/masked/corrected.
- $T\rho_{wc}$ is the whitecap reflectance—computed from wind speed.
- ρ_r is the scattering from molecules—computed using the Rayleigh lookup tables (vector RTE, wind speed, atmospheric pressure dependents).
- $\rho_A = \rho_a + \rho_{ra}$ is the aerosol and Rayleigh-aerosol contributions —estimated using **aerosol models**.
- For Case-1 waters at the open ocean, ρ_w is usually negligible at 750 & 865 nm. ρ_A can be estimated using these two NIR bands. Ocean is usually not black at NIR for the coastal regions.

Characteristics of the Aerosol Models

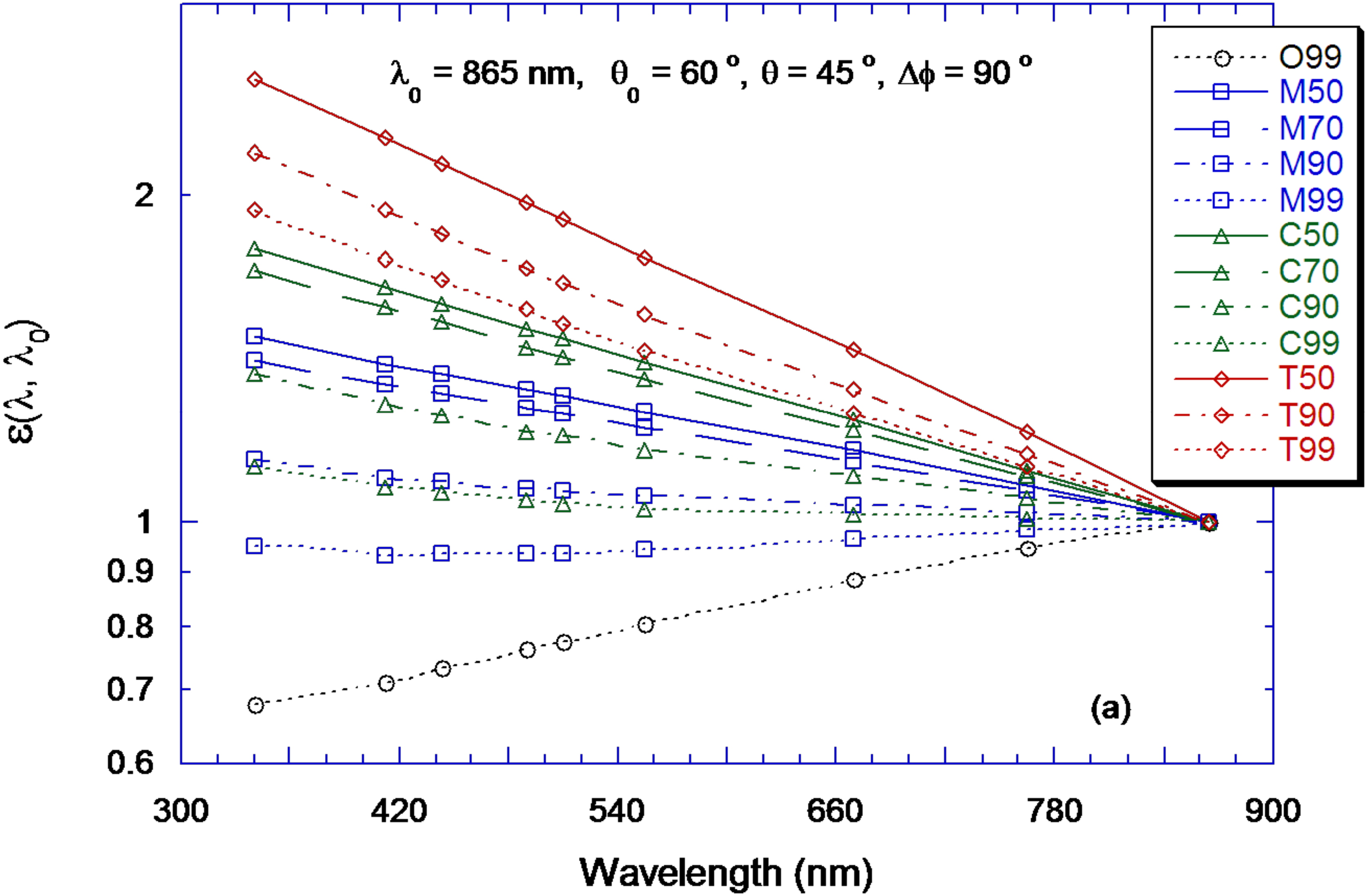
Aerosol Model	Single Scattering Albedo $\omega_a(865)$	Asymmetry Parameter g	Ångström Exponent $\alpha(510, 865)$
Oceanic [=]	1.0	0.724-0.840	-0.087~ -0.016
Maritime [=]	0.982-0.999	0.690-0.824	0.09-0.50
Coastal [==]	0.976-0.998	0.682-0.814	0.23-0.76
Tropospheric [=]	0.930-0.993	0.603-0.769	1.19-1.53
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).

A simple aerosol correction algorithm (Wang & Gordon, 1994)

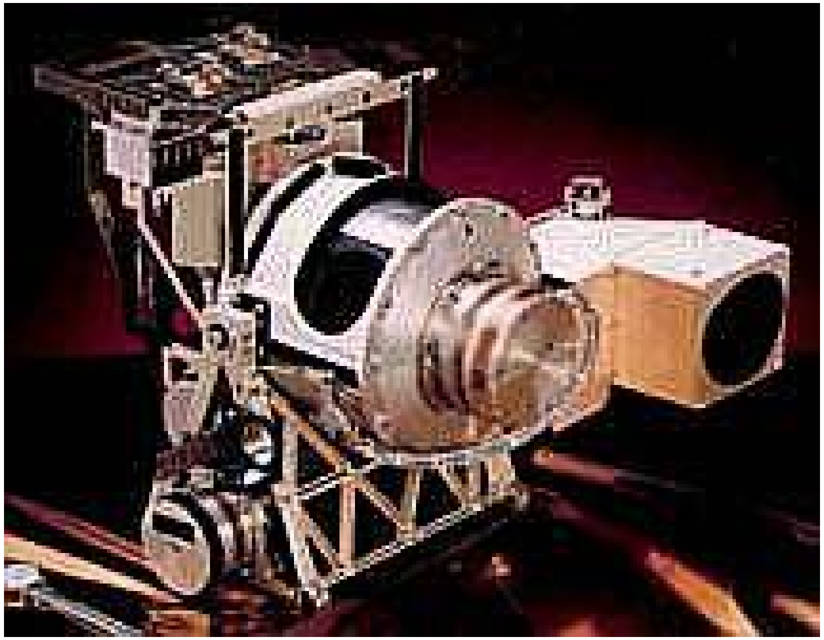
Aerosol Single-Scattering Epsilon (λ_0 = 865 nm)



Example of Satellite Ocean Color Sensor

SeaWiFS

Sea-Viewing **Wi**de-**F**ield-of-view **S**ensor



The Ocean Color and Other Useful Spectral Bands for VIIRS, MODIS, and SeaWiFS

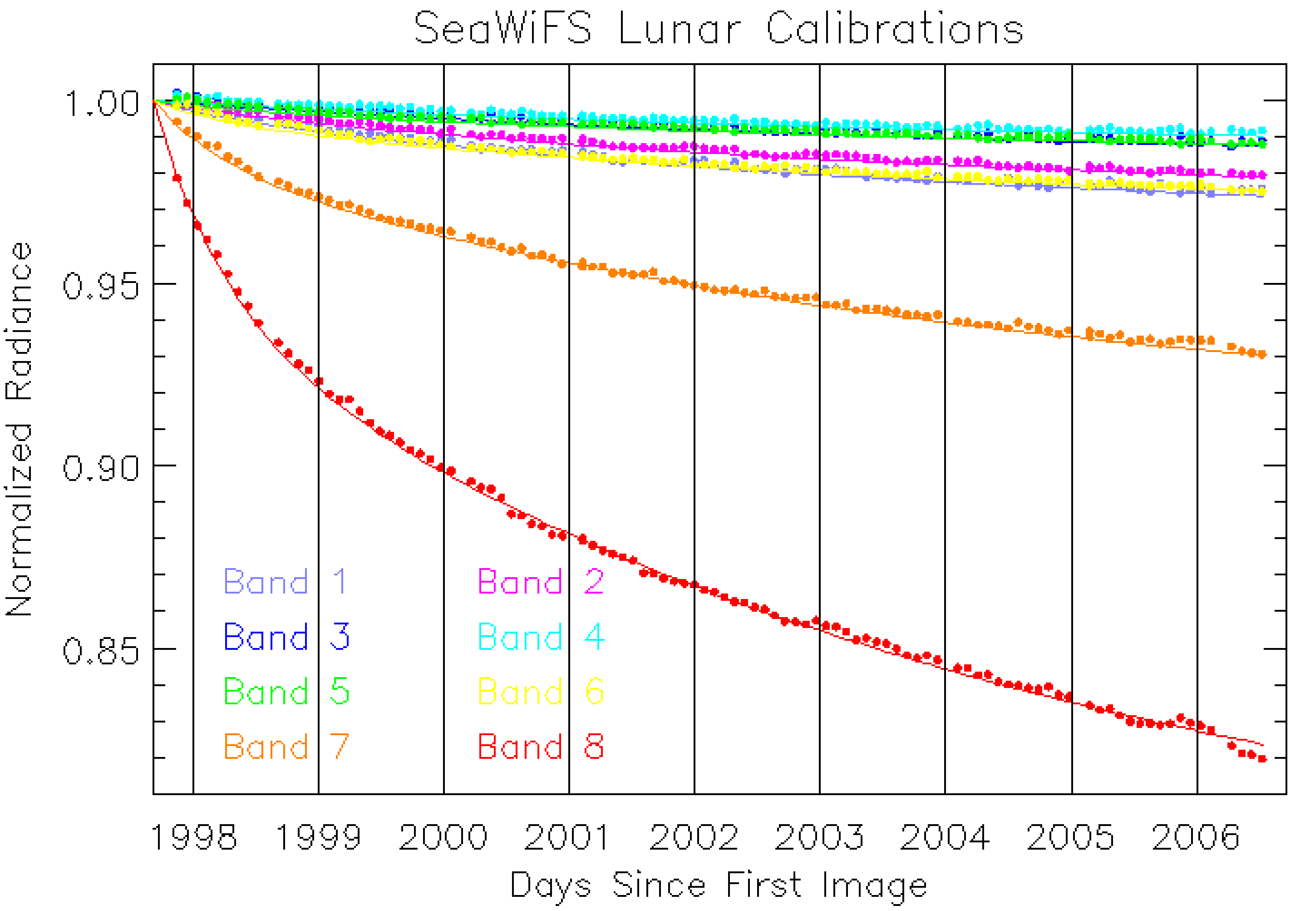
VIIRS		MODIS		SeaWiFS
Ocean Bands (nm)	Other Bands (nm)	Ocean Bands (nm)	Other Bands (nm)	Ocean Band (nm)
412		412	645	412
445		443	859	443
488		488	469	490
Ń		531	555	510
555	*SWIR Bands*	551	*SWIR Bands*	555
672	1240	667	1240	670
746	1610	748	1640	765
865	2250	869	2130	865

VIIRS has similar SWIR bands as **MODIS**

Some Details

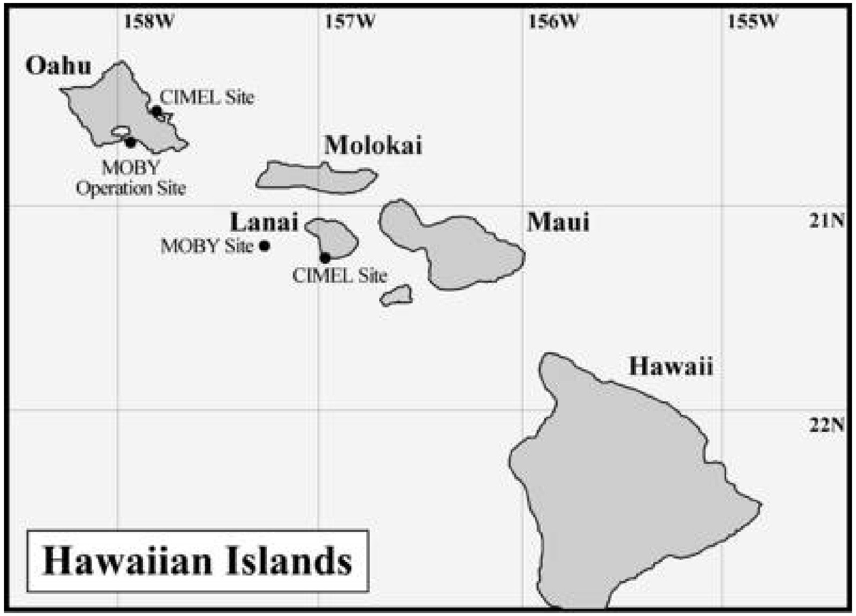
- **Calibrations:** (a)**Lunar calibration** to remove sensor degradation, and (b) **Vicarious calibration** using the in situ MOBY data to set gains. It requires **~0.1%** accuracy.
- **Cloud Masking for SeaWiFS/MODIS:** A simple reflectance threshold technique has been used**,** $(\rho_t - \rho_r) \leq$ **2.7%** at the NIR (865 nm) band as being identified as clear sky.
- **Surface effects:** Ocean is assumed to be black at the NIR bands**,** modifications are made to account for the NIR ocean contributions at the NIR bands for **productive oceans**.
- A flat **Fresnel-reflecting surface** was used in RTE computations for aerosol lookup tables, while the Cox & Monk (1954) surface roughness model (wind dependent) was used for the Rayleigh lookup tables.
- **Sun glint** is avoided/masked and sun glint contamination is corrected using Wang and Bailey (2001).
- **Aerosol Models:** A set of 12 aerosol models from or derived from the work of **Shettle and Fenn** (1979) was used.
- **Validations:** SeaWiFS ocean color and aerosol products have been validated through the NASA SeaWiFS and SIMBIOS projects, and from in situ data acquired from various field campaigns in global open oceans.

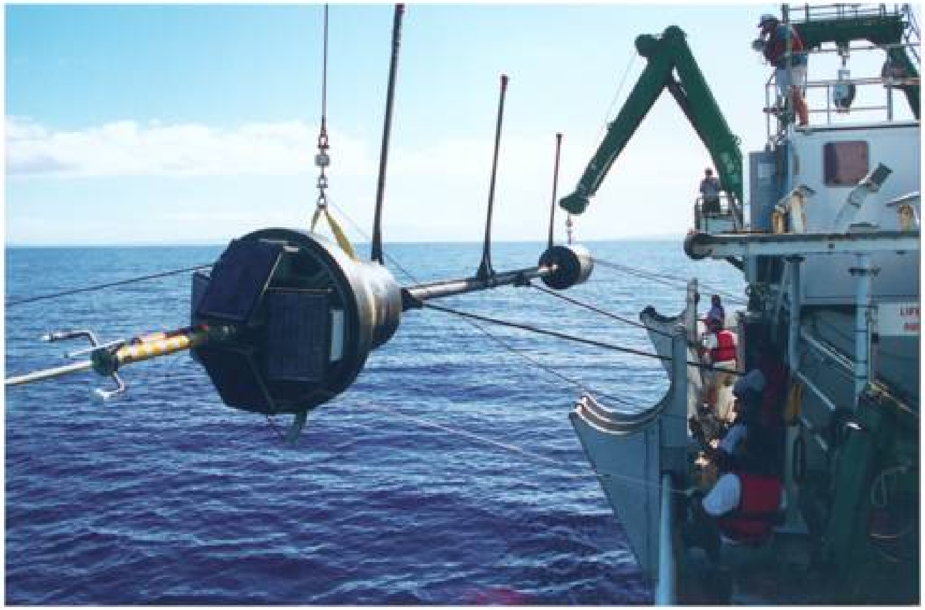
SeaWiFS Looks at the Moon

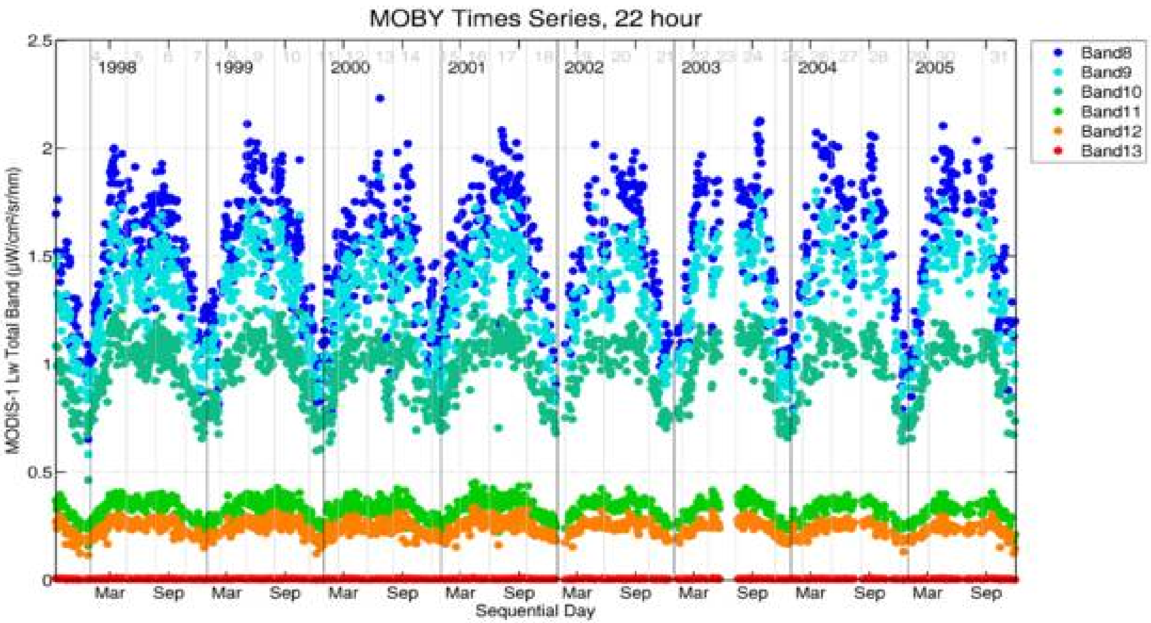


From http://oceancolor.gsfc.nasa.gov

MOBY--Vicarious Calibration Facility for Ocean Color Satellite Sensors



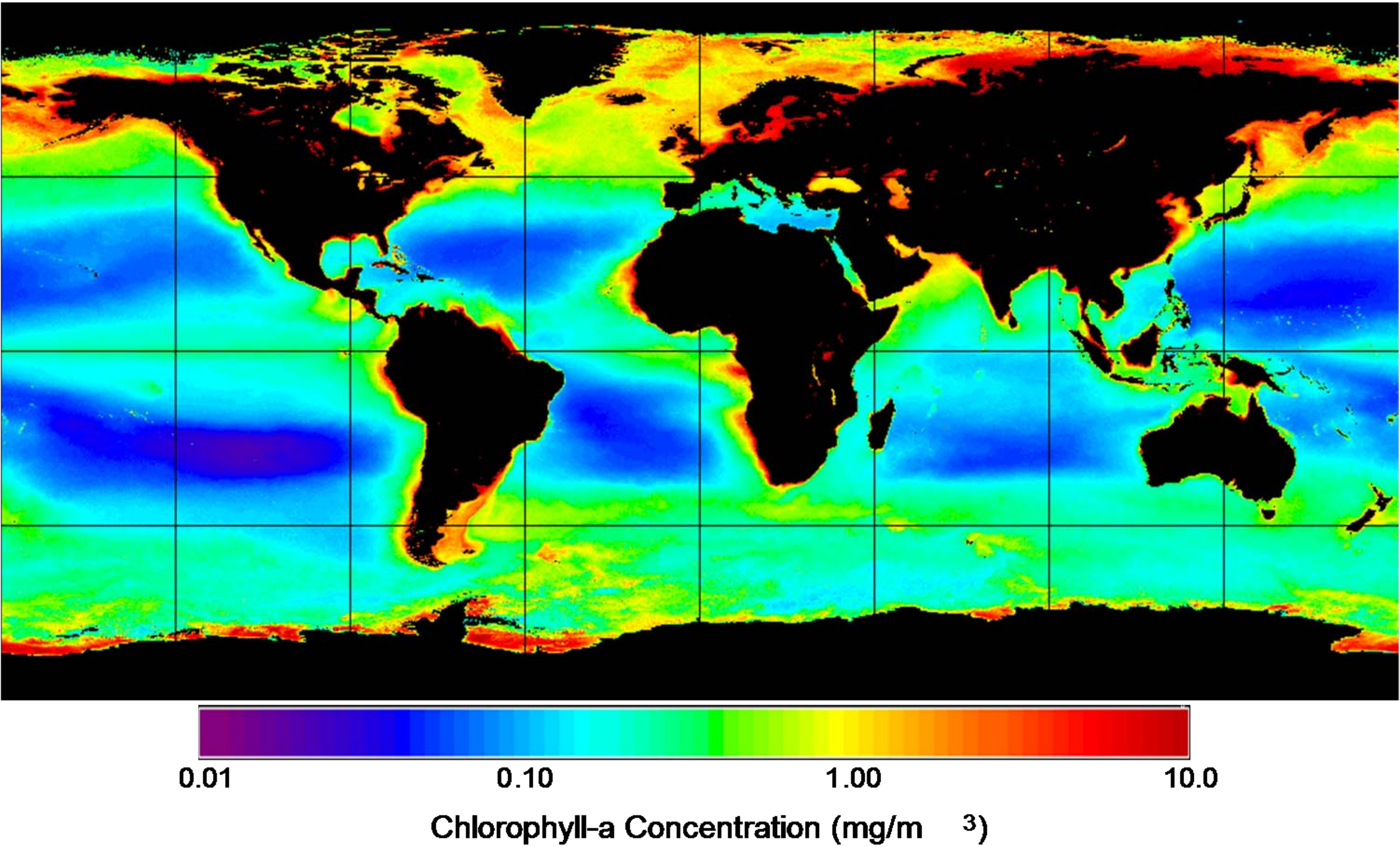




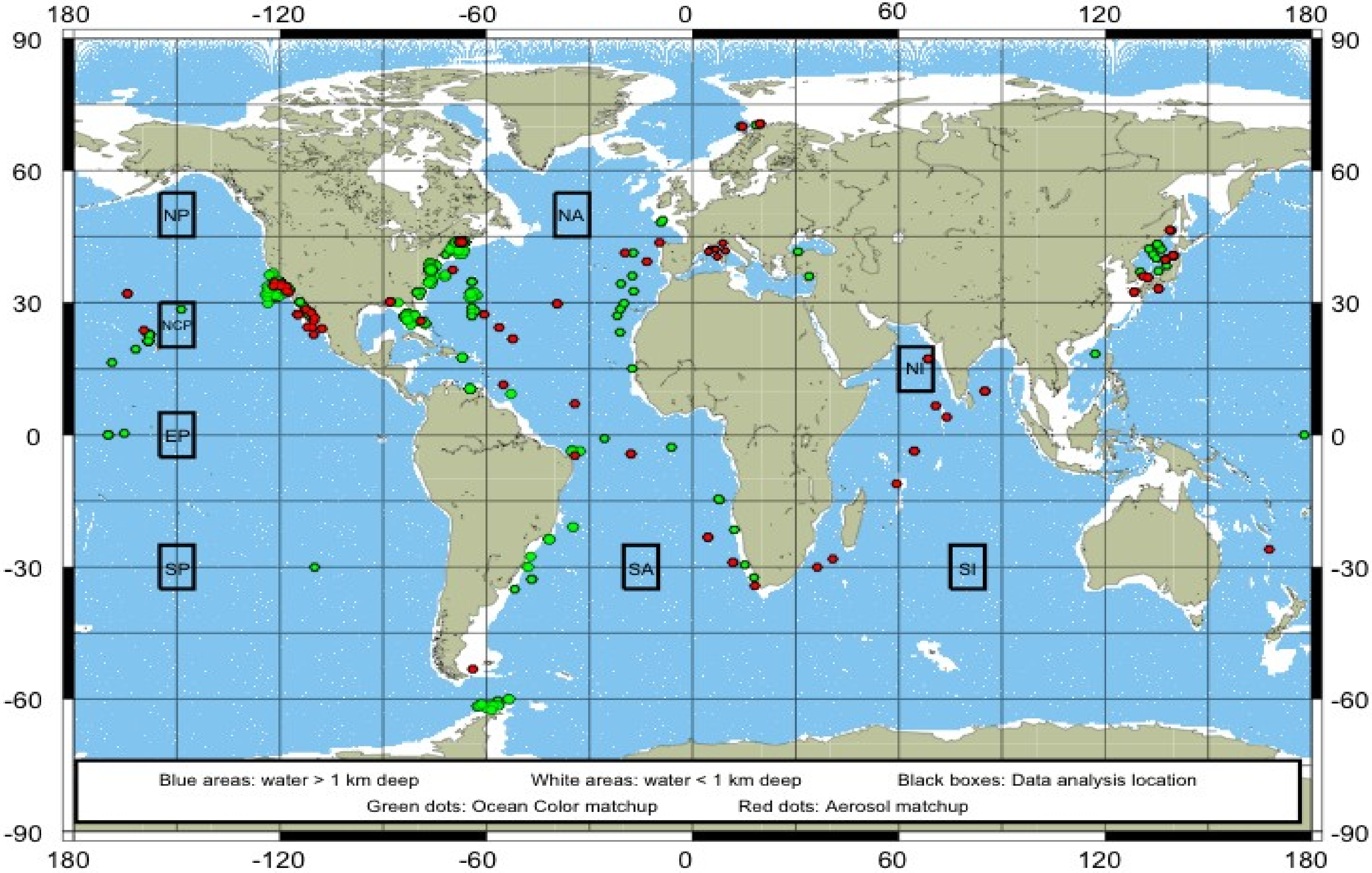
Radiance Measurement Accuracy ~ 5%

From D. Clark

SeaWiFS Chlorophyll-a Concentration (October 1997-December 2003)

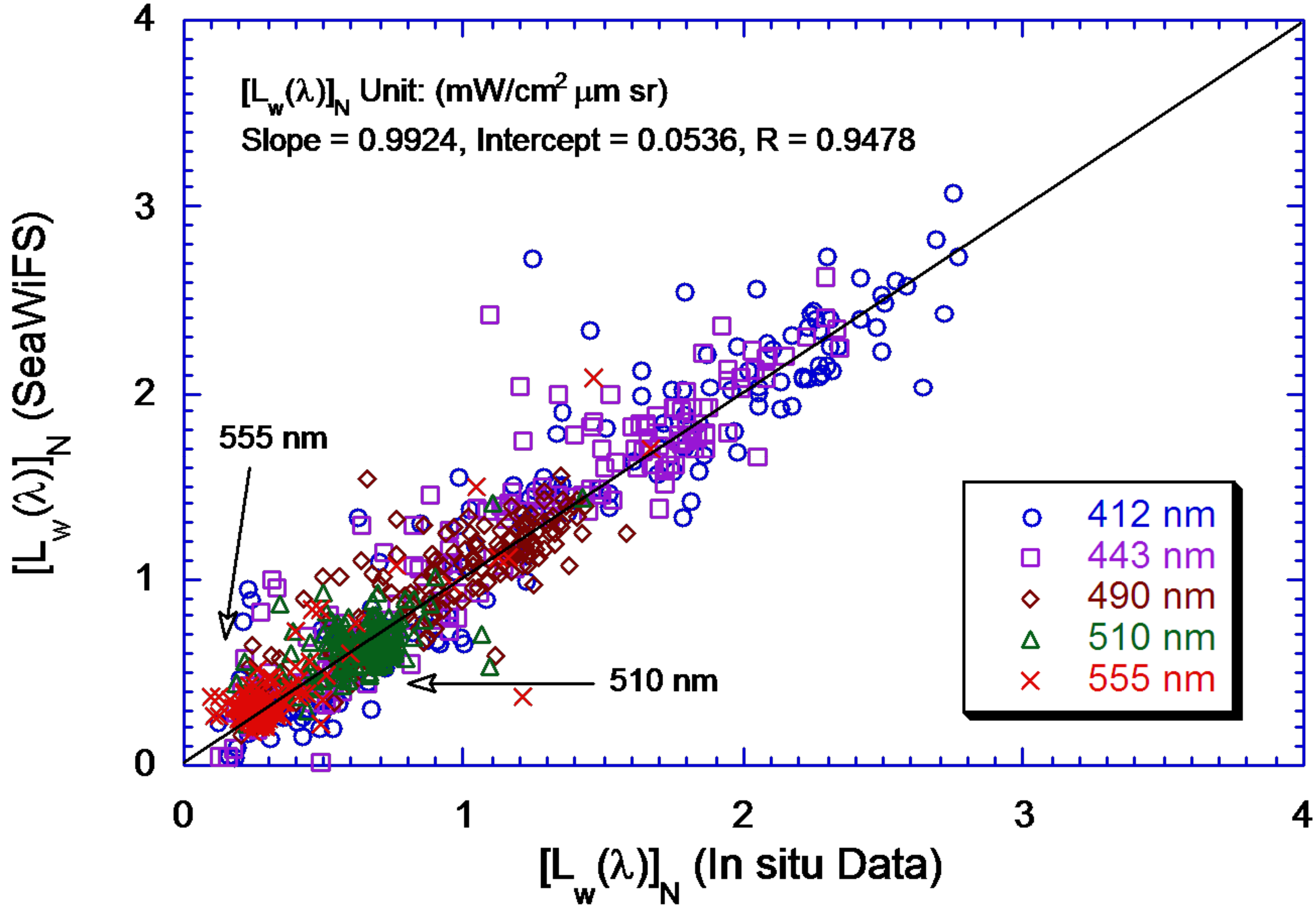


Some In Situ Measurements

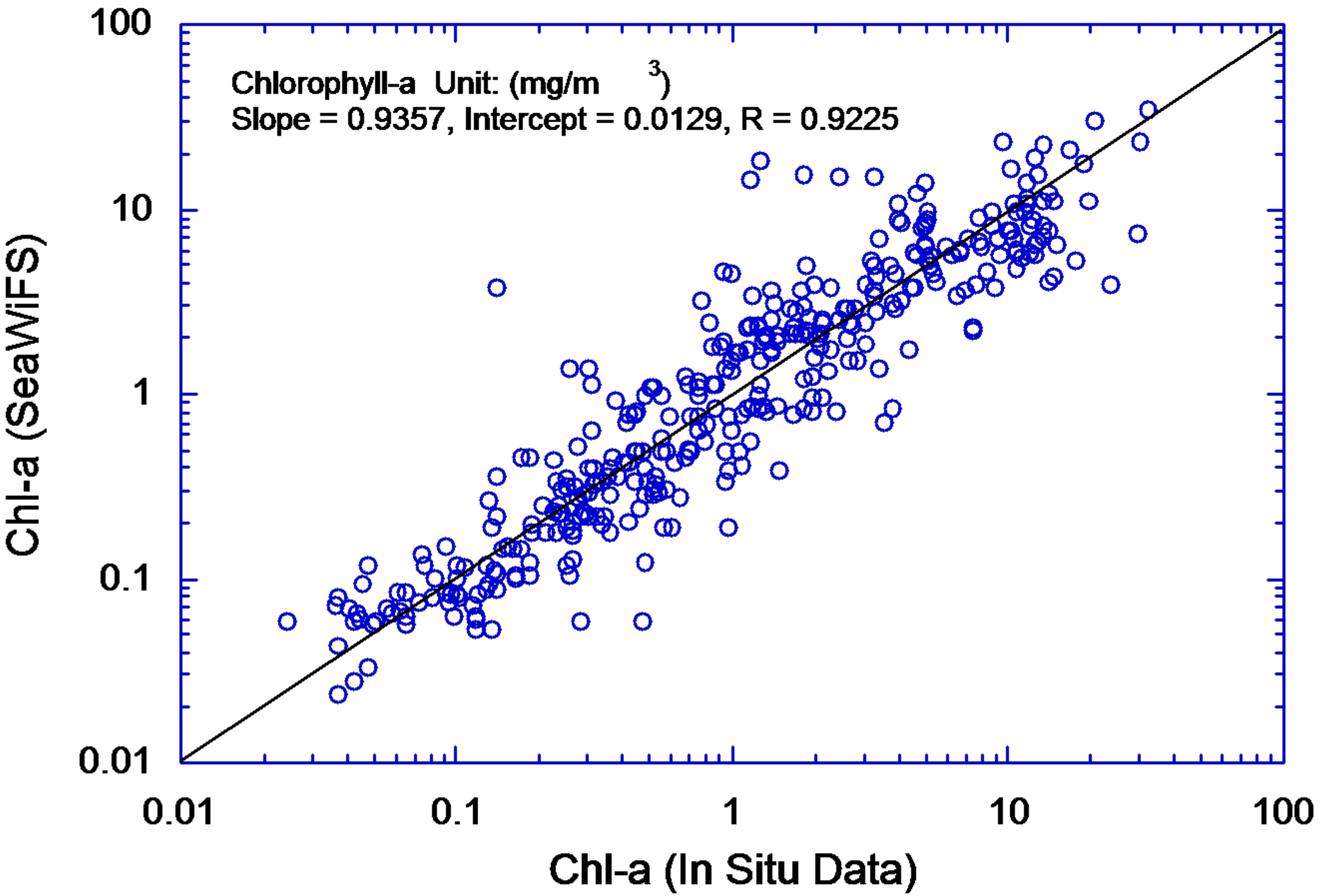


Wang, M., K. Knobelspiesse, and C. R. McClain (2005), "Study of the SeaWiFS aerosol optical property data over ocean in combination with the ocean color products," *J. Geophys. Res.*, 110, D10S06, doi:10.1029/2004JD004950.

SeaWiFS experiences demonstrate that the atmospheric correction works well in the **open oceans**

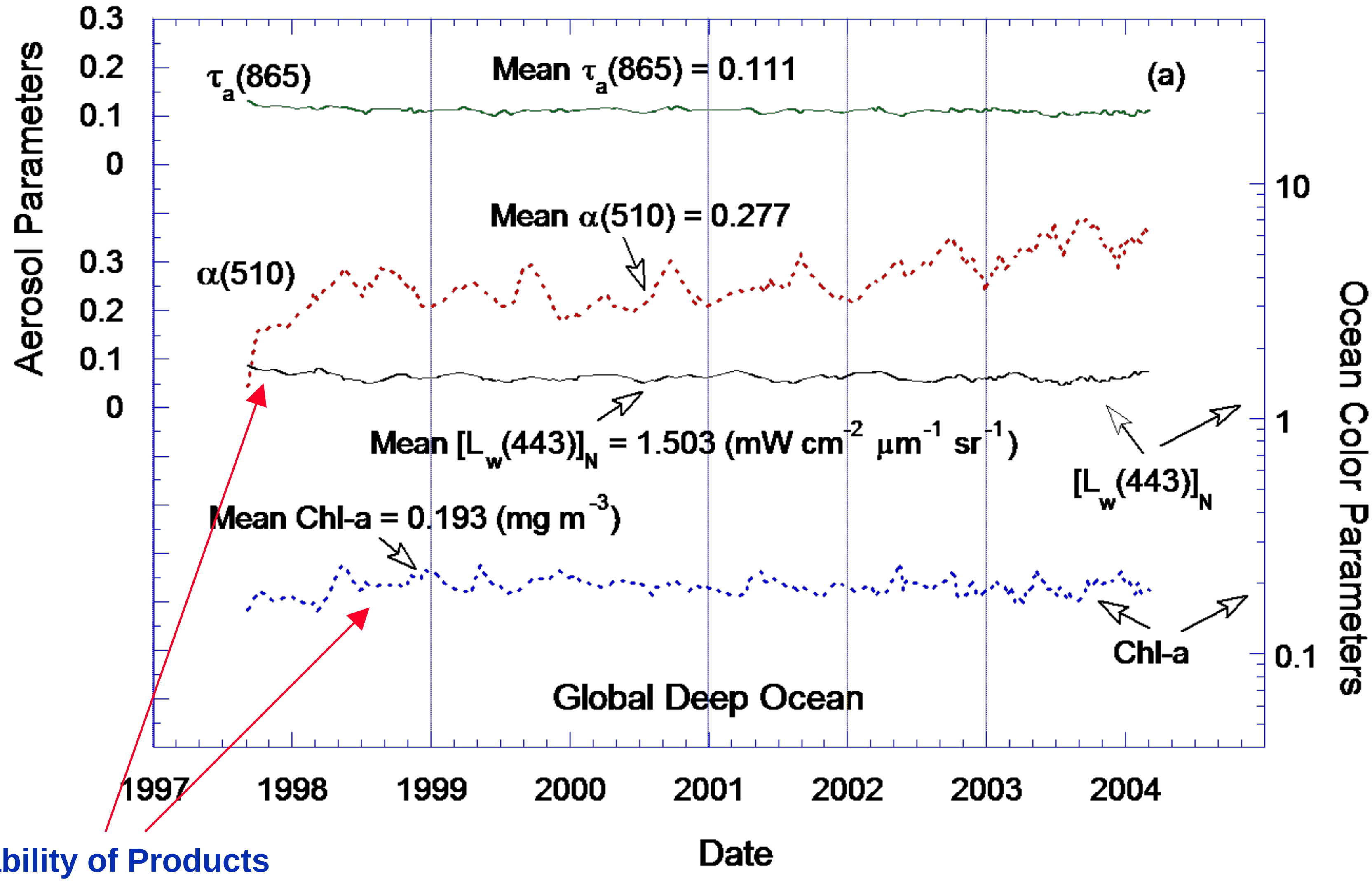


SeaWiFS Chlorophyll-a Comparison



SeaWiFS Global Deep Ocean Results

(Wang et al., 2005)



Stability of Products

SeaWiFS and MODIS Experiences Show:

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

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

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

Algorithm Developments for Productive 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 IR (SWIR) bands.
- **Doerffer** et al. and others developed Artificial *Neural Network* for coastal Case-2 waters (implemented for MERIS data processing).
- **Wang** (2007) proposed atmospheric correction using the SWIR bands for the turbid coastal waters.

The NIR Ocean Contribution Modeling

Various investigators all sought to remove the NIR *nLw*(λ) 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 *nLw*(λ).
- **Lavender** et al. (2005) used a sediment estimate to determine the NIR *nLw*(λ).
- **Ruddick** et al. (2000) fixed the aerosol and backscatter type and then solved for both the NIR *nLw*(λ) and NIR aerosol reflectance simultaneously.
- **Stumpf** et al. (2003) used a bio-optical model for absorption coefficient at the red band and then used that with the red *nLw*(λ) to find the NIR *nLw*(λ).

Atmospheric Correction: SWIR Bands

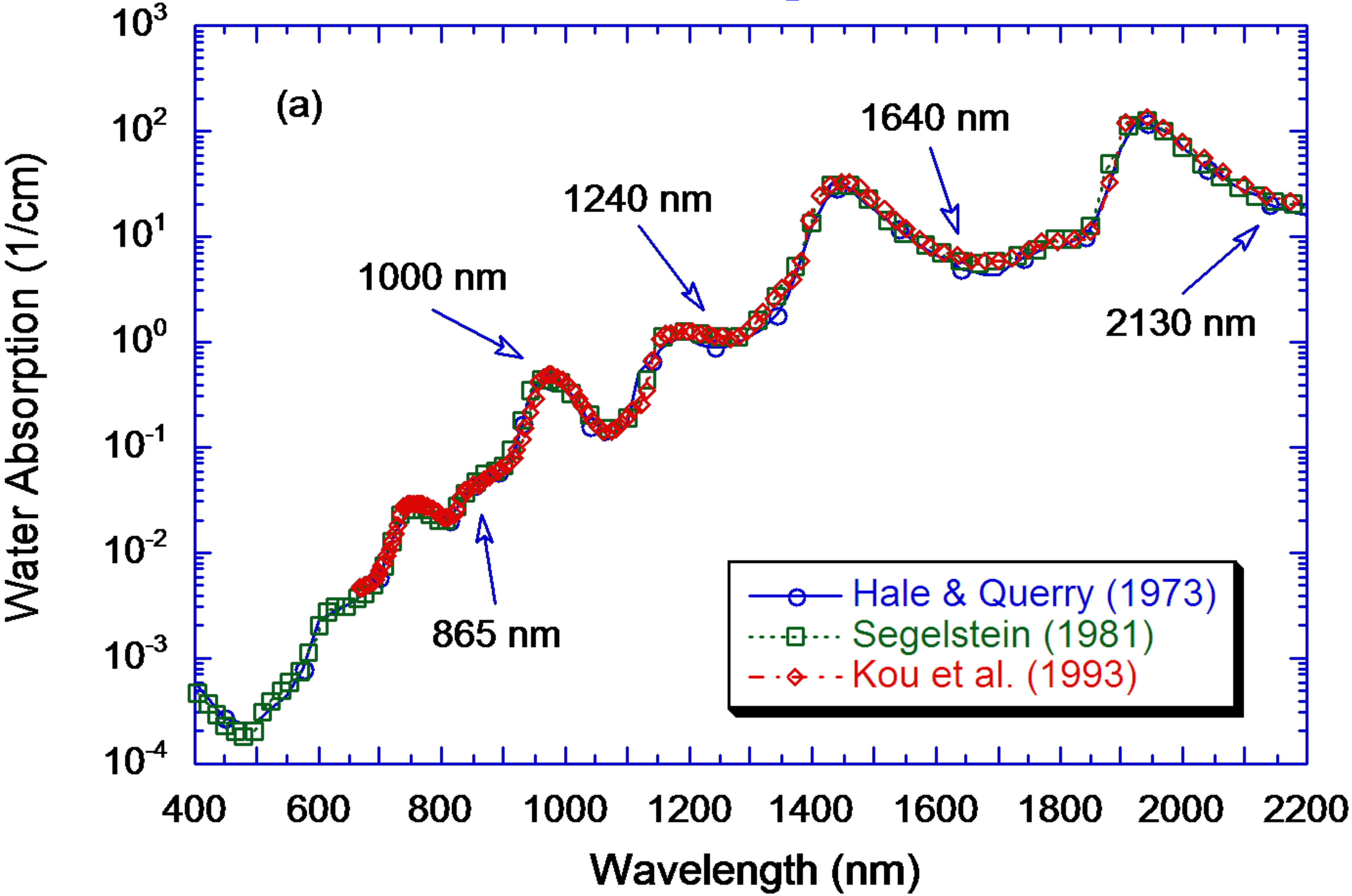
(Wang & Shi, 2005; Wang, 2007)

- At the shortwave IR (SWIR) wavelengths (>~1000 nm), ocean water has much strongly absorption and ocean contributions are significantly less. Thus, atmospheric correction can be carried out for coastal regions **without using the bio-optical model**.
- Water absorption for 869 nm, 1240 nm, 1640 nm, and 2130 nm are 5 m^{-1}, 88 m^{-1}, 498 m^{-1}, and 2200 m^{-1}, respectively.
- Examples using the MODIS Aqua **1240** and **2130 nm** data to derive the ocean color products are provided.

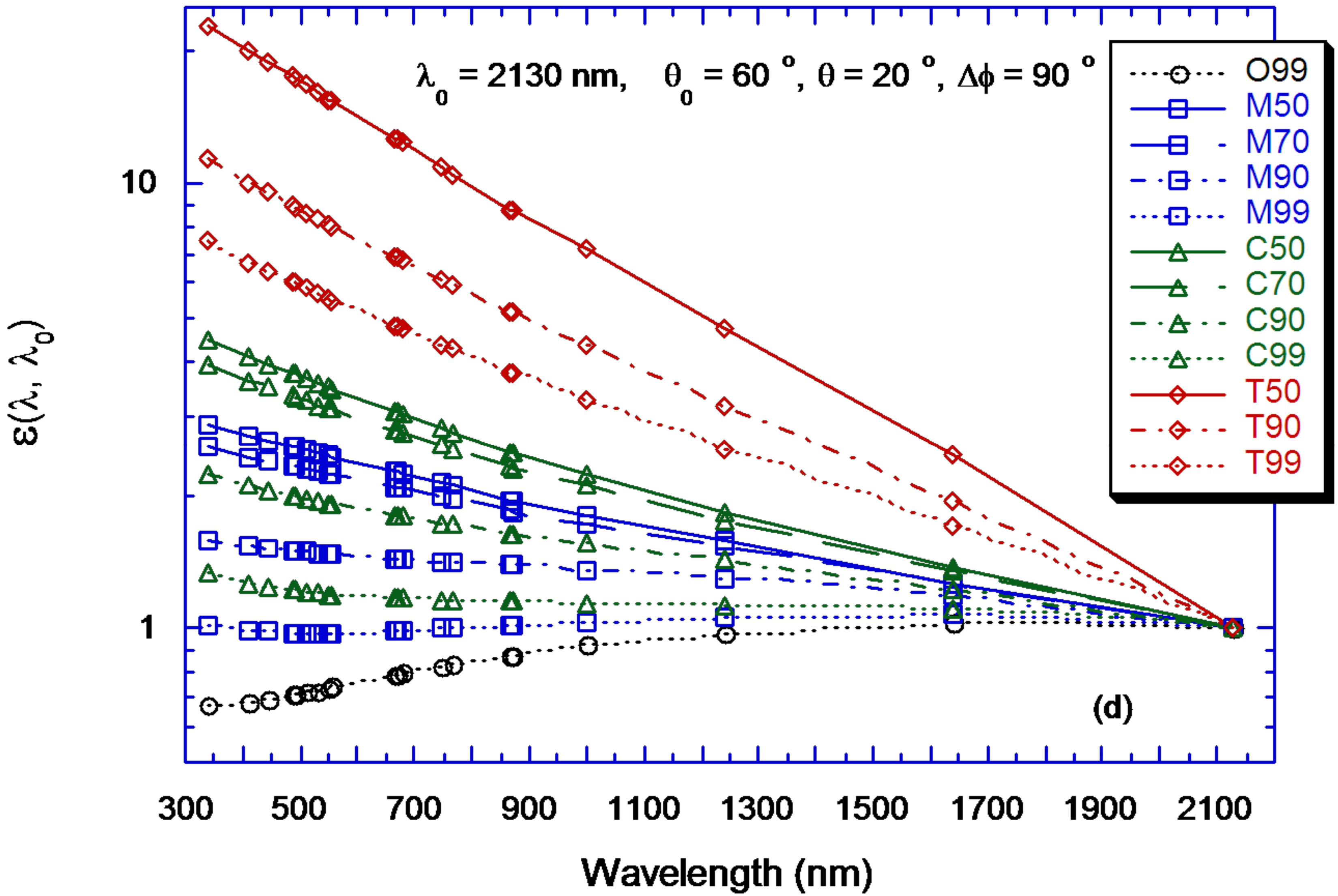
➢ We use the SWIR band (1240 nm) for the cloud masking. This is necessary for coastal region waters.

✓ Require sufficient **SNR** characteristics for the SWIR bands and the SWIR atmospheric correction has slight larger noises at the short visible bands (compared with those from the NIR algorithm).

Water Absorption



Aerosol Single-Scattering Epsilon (λ_0 = 2130 nm)

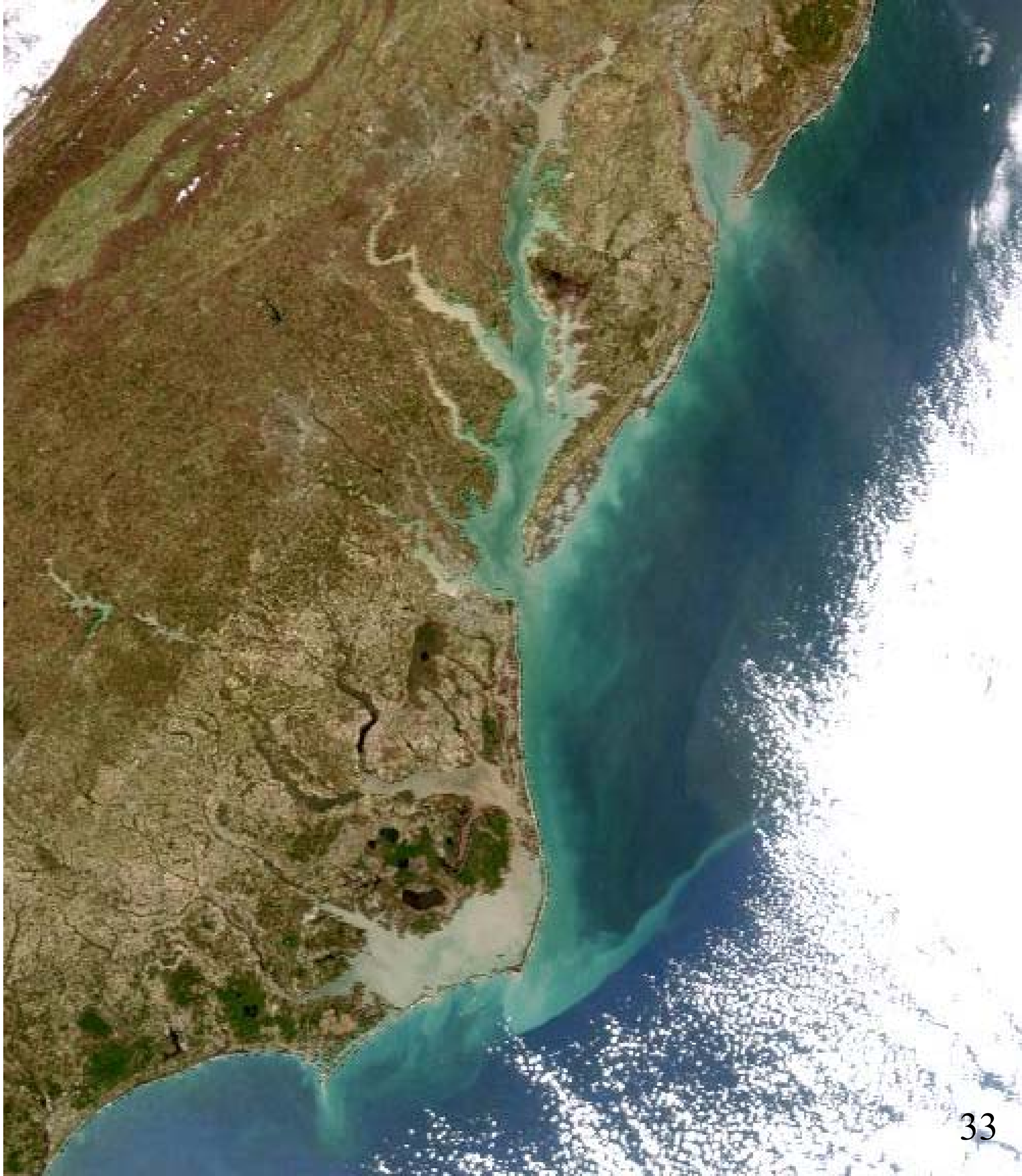


Results from SWIR Atmospheric Correction for turbid ocean waters in US east coastal

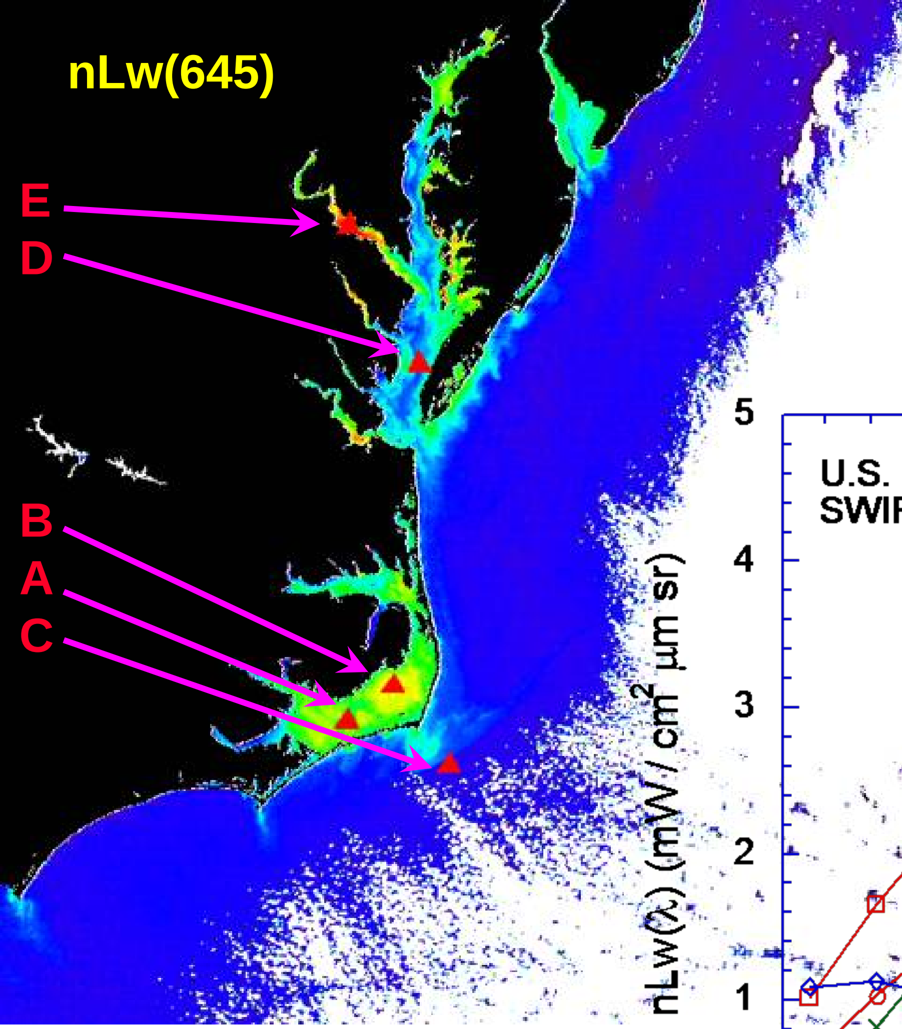
MODIS-Aqua True Color Image

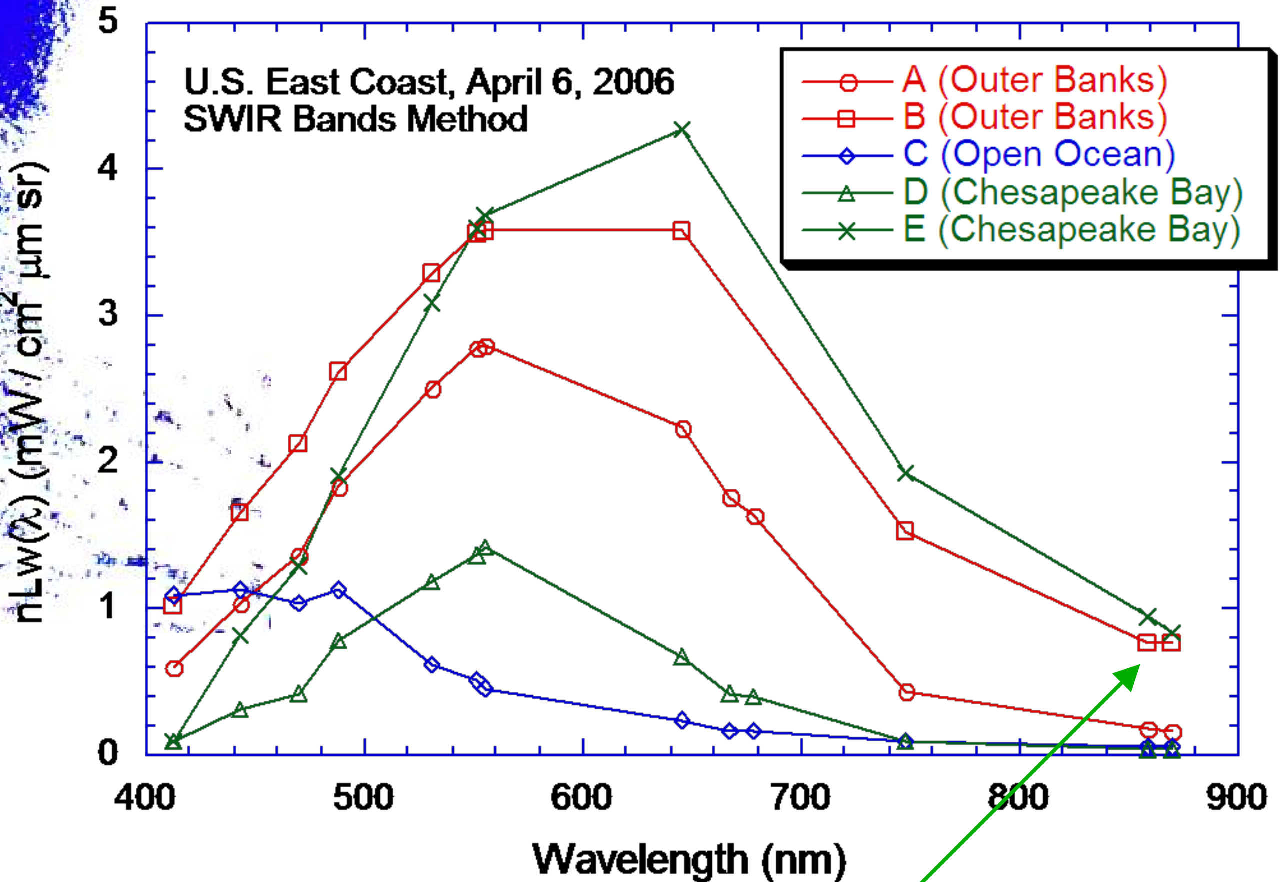
U.S. East Coastal

April 6, 2004



Ocean Spectra from Visible to NIR for Various Ocean Waters



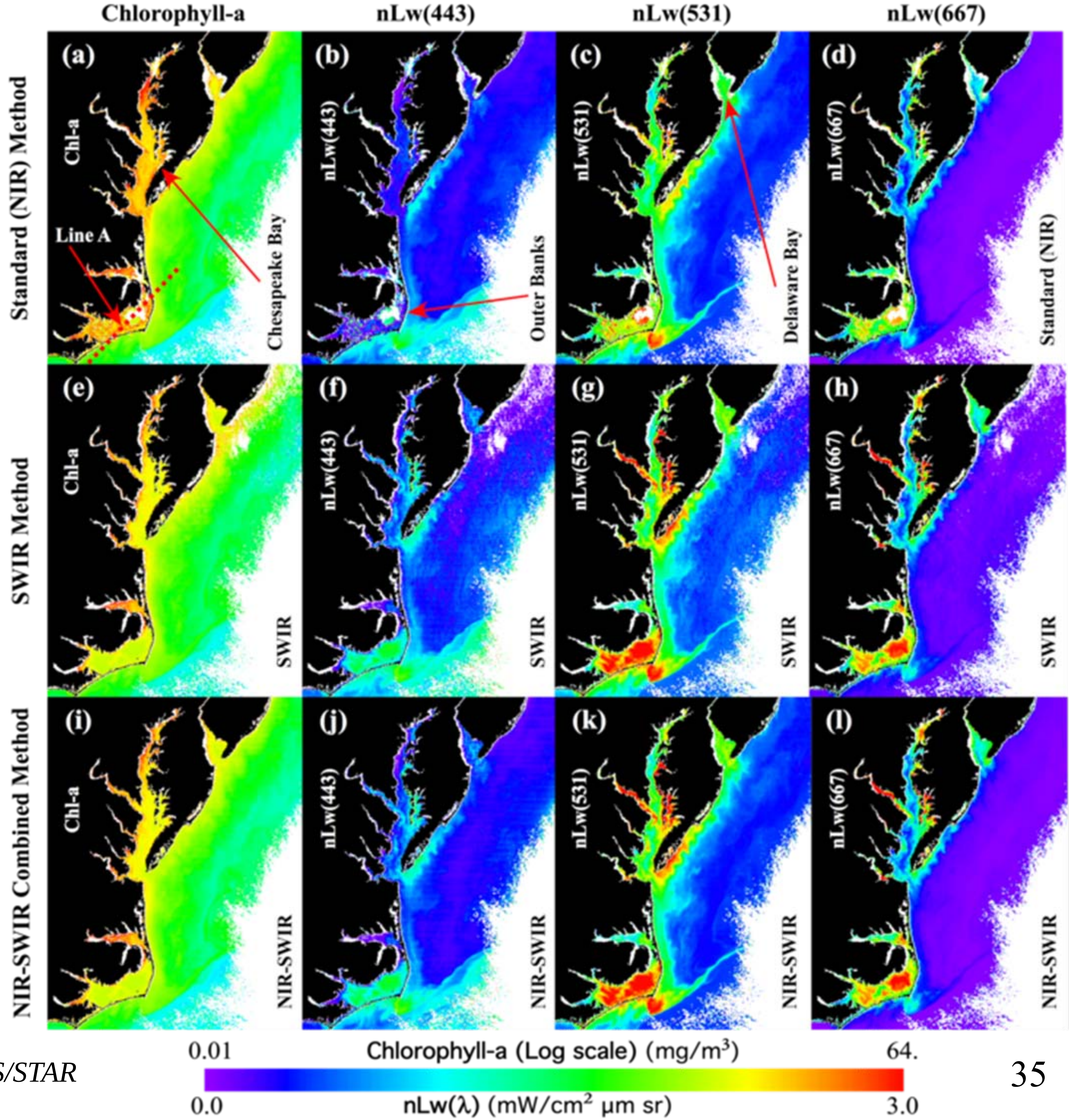


$\tau_a(869) \sim 0.3$

Comparisons of MODIS Ocean Color Products from NIR, SWIR, and NIR-SWIR Combined Methods

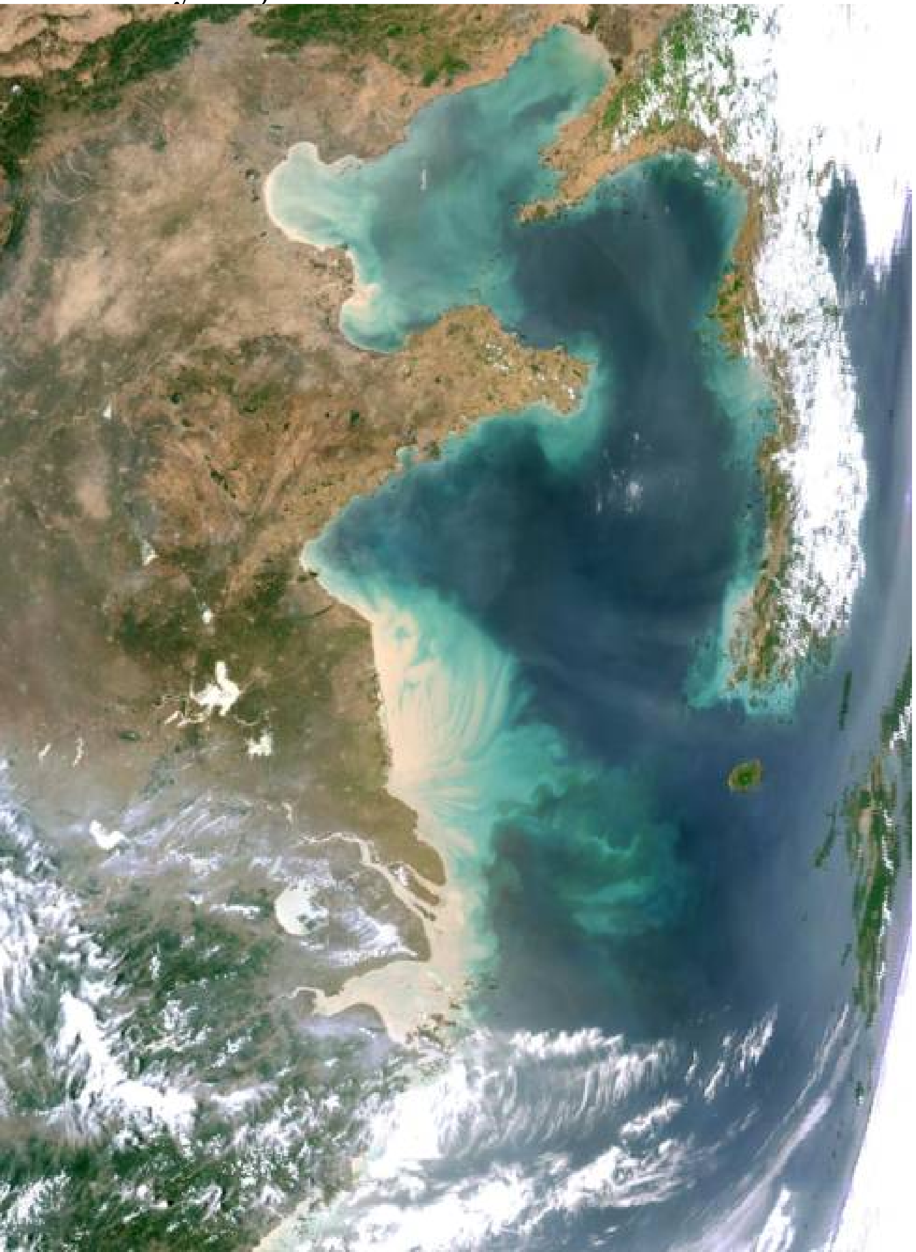
Example: U.S. East Coast

Wang, M. and W. Shi (2007), "The NIR-SWIR combined atmospheric correction approach for MODIS ocean color data processing," *Optics Express*, **15**, 15722-15733.

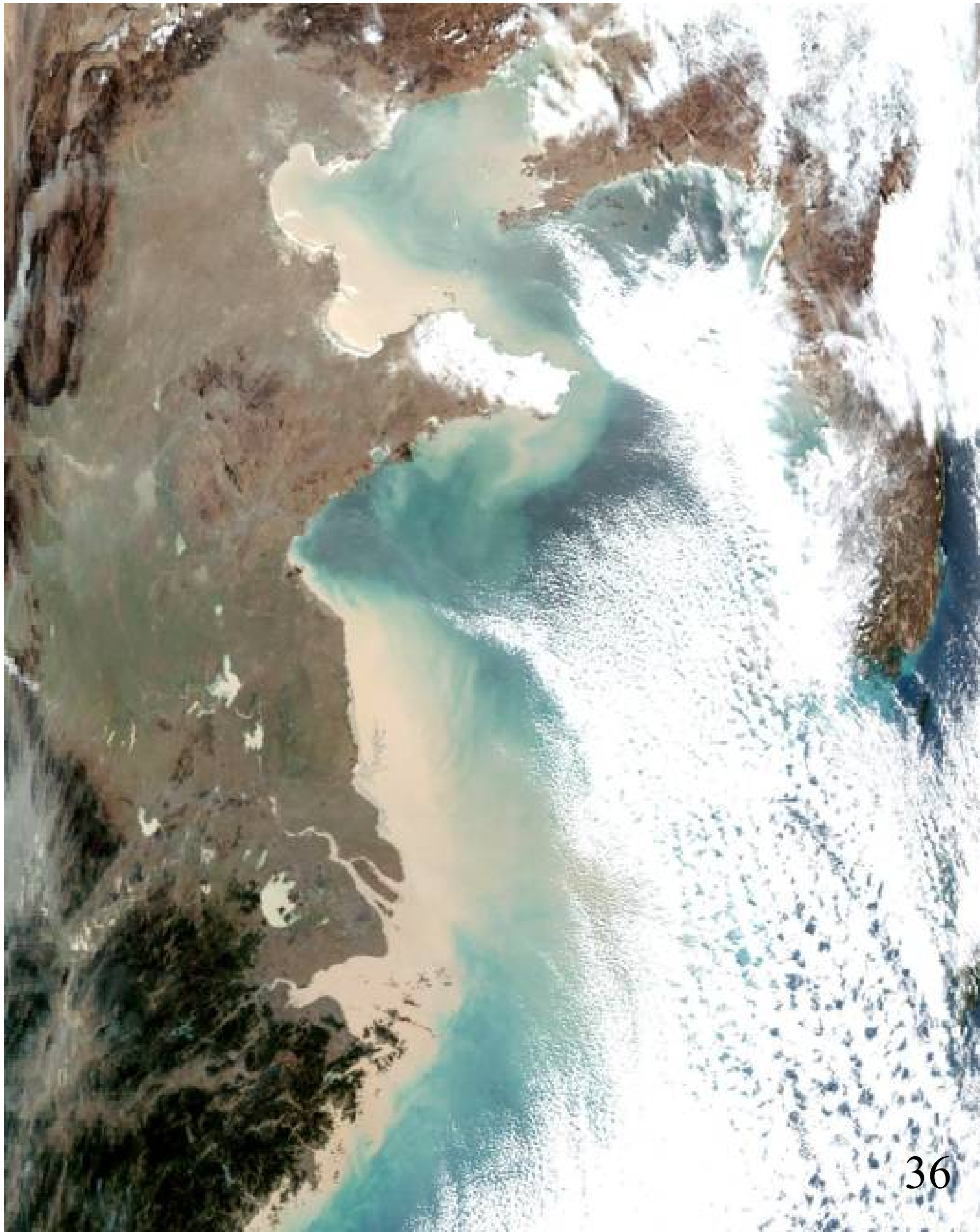


MODIS-Aqua True Color Image
China East Coastal Regions

May 23, 2004

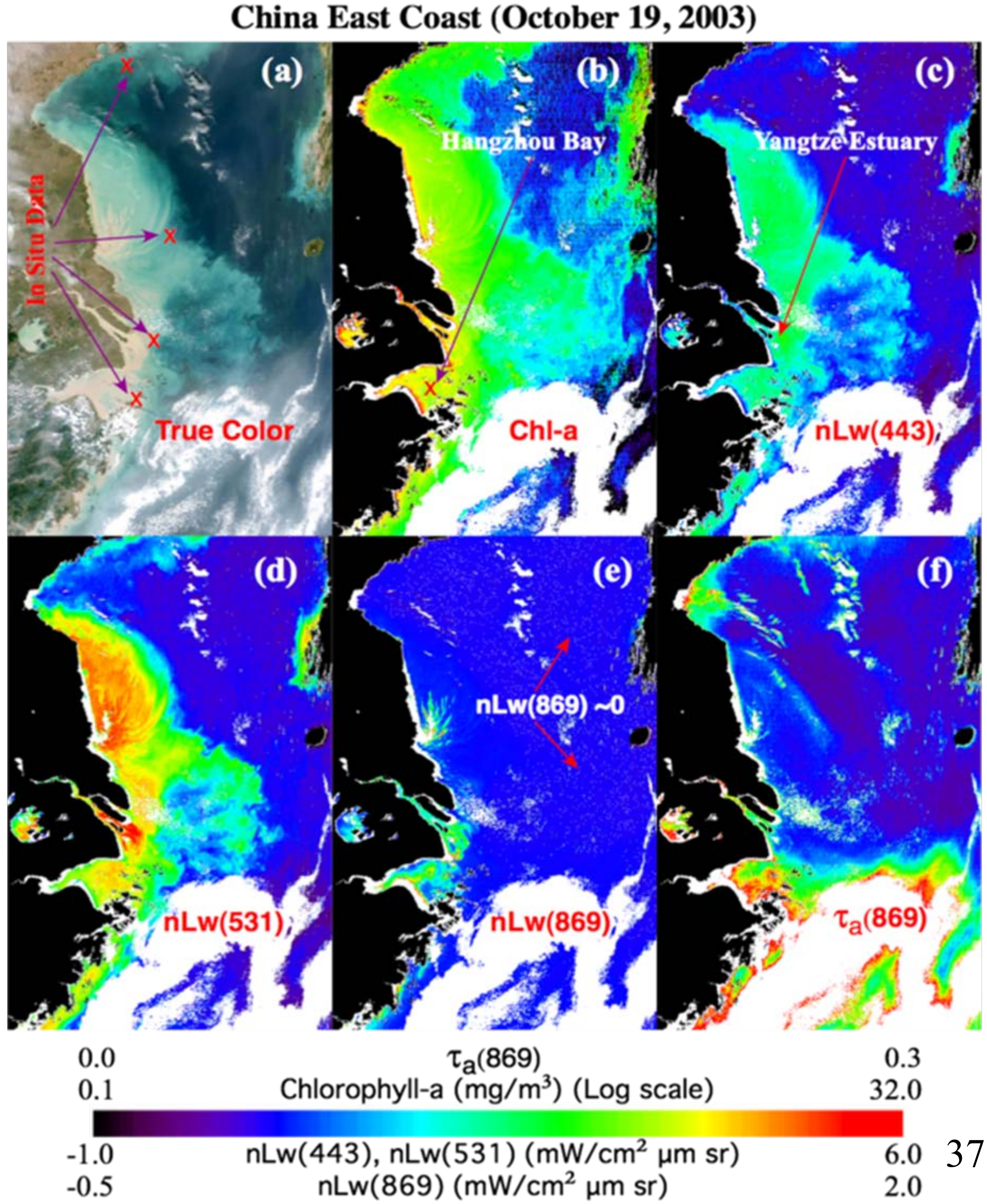


December 22, 2005



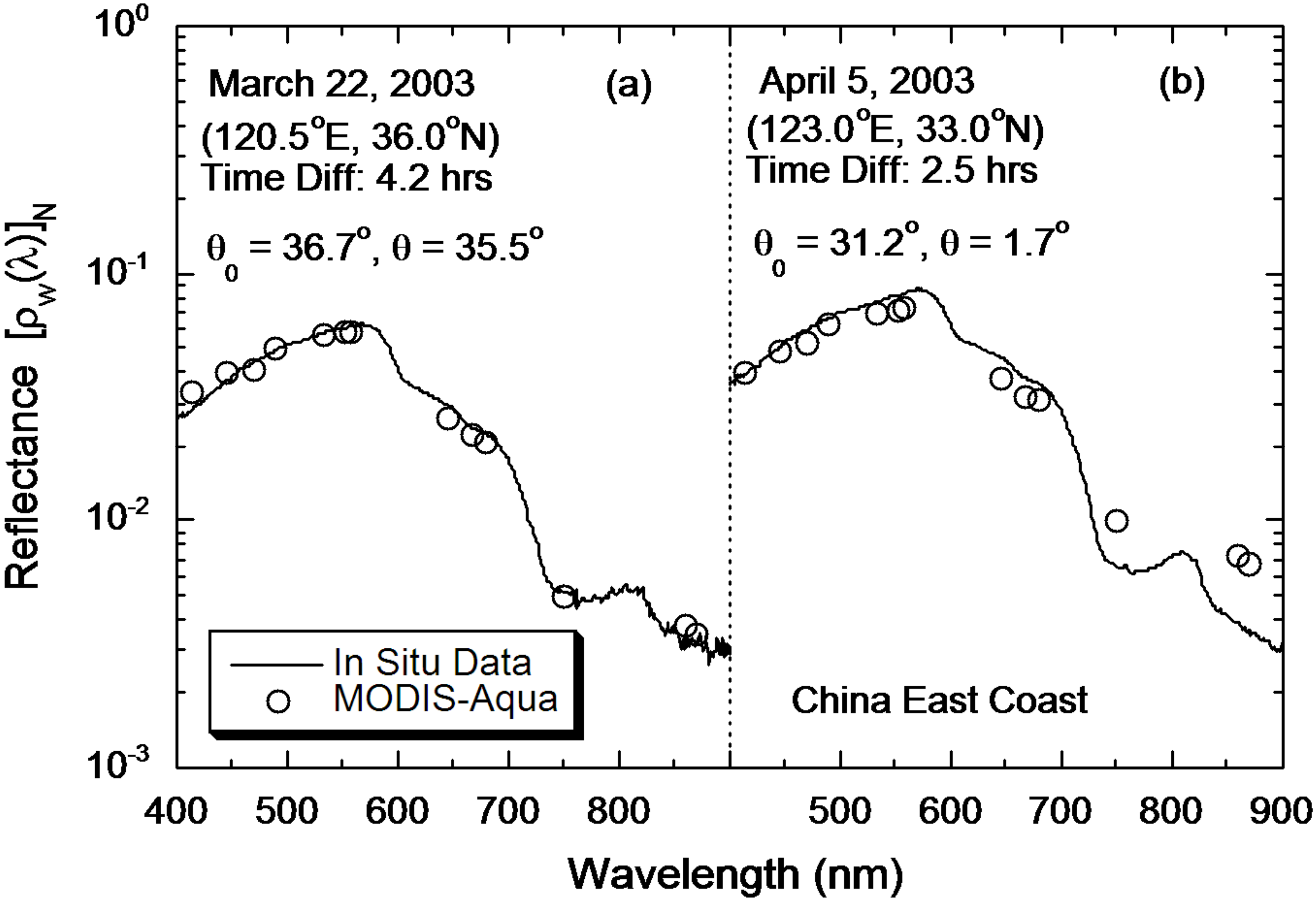
Results from SWIR Atmospheric Correction for **turbid** ocean waters

Standard algorithm often fail to produce valid values in very turbid waters, e.g., Hangzhou Bay, Yangtze Estuary.

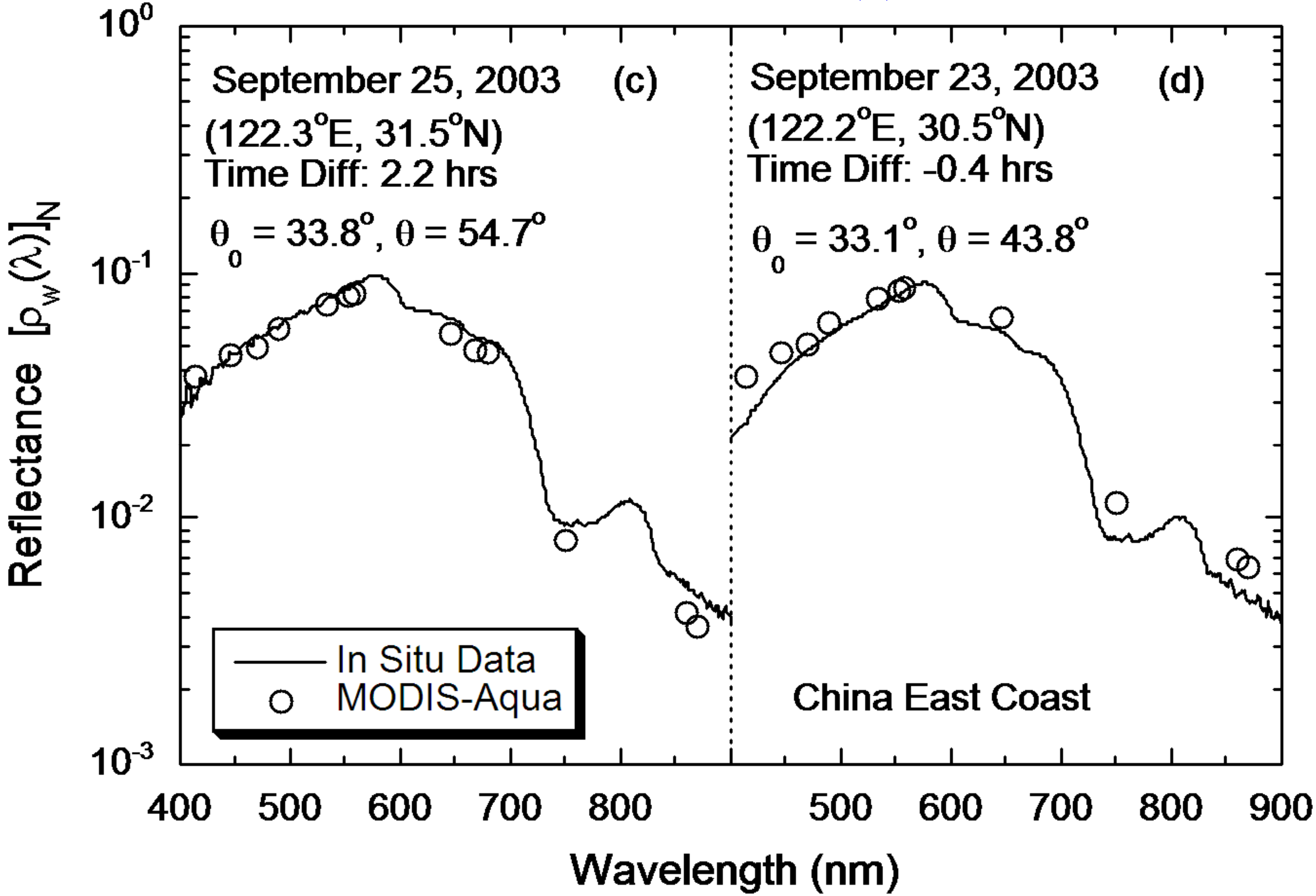


Wang, M., J. Tang, and W. Shi (2007), "MODIS-derived ocean color products along the China east coastal region," *Geophys. Res. Lett., 34,* L06611, doi:10.1029/2006GL028599.

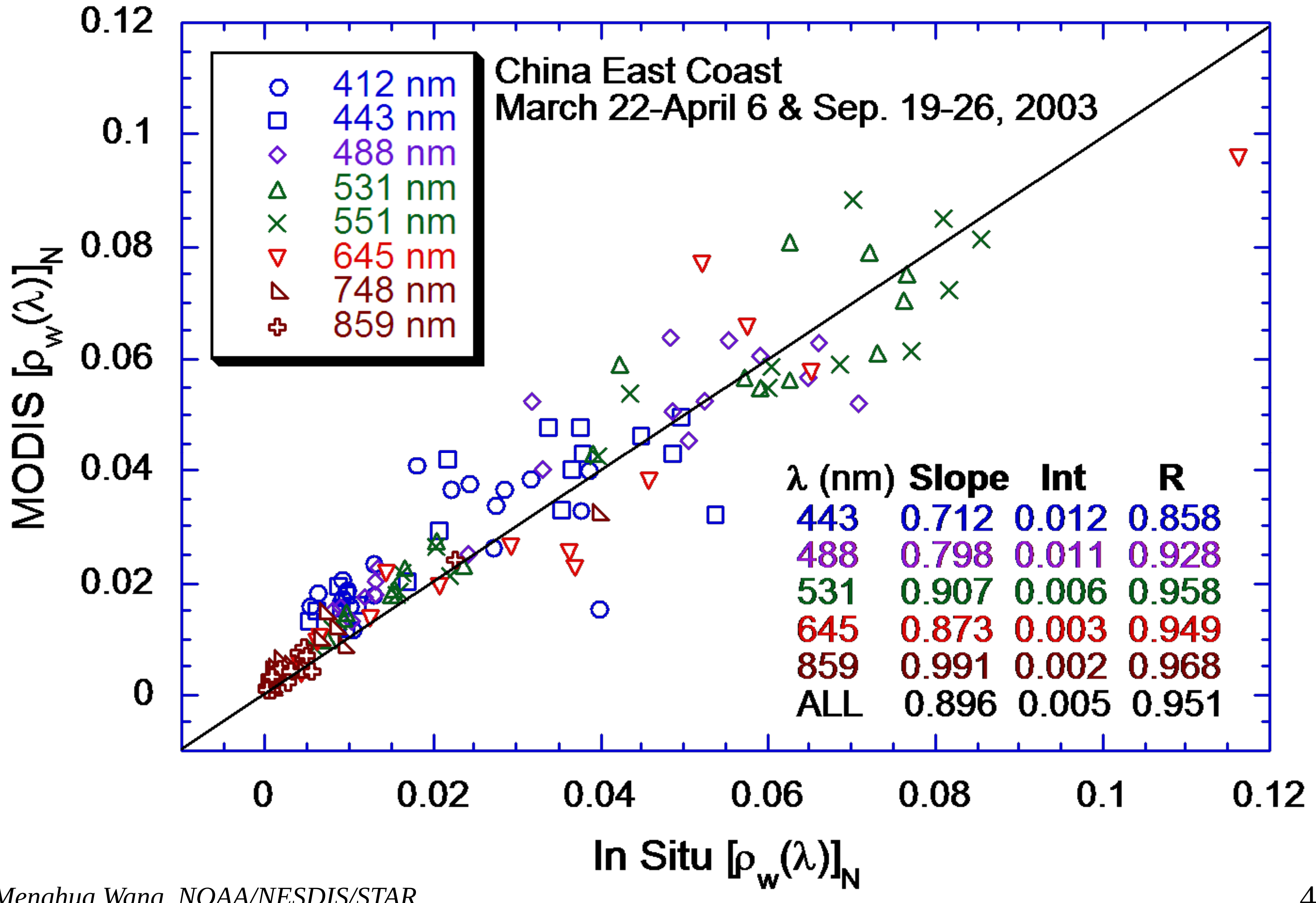
Validation Results (1)



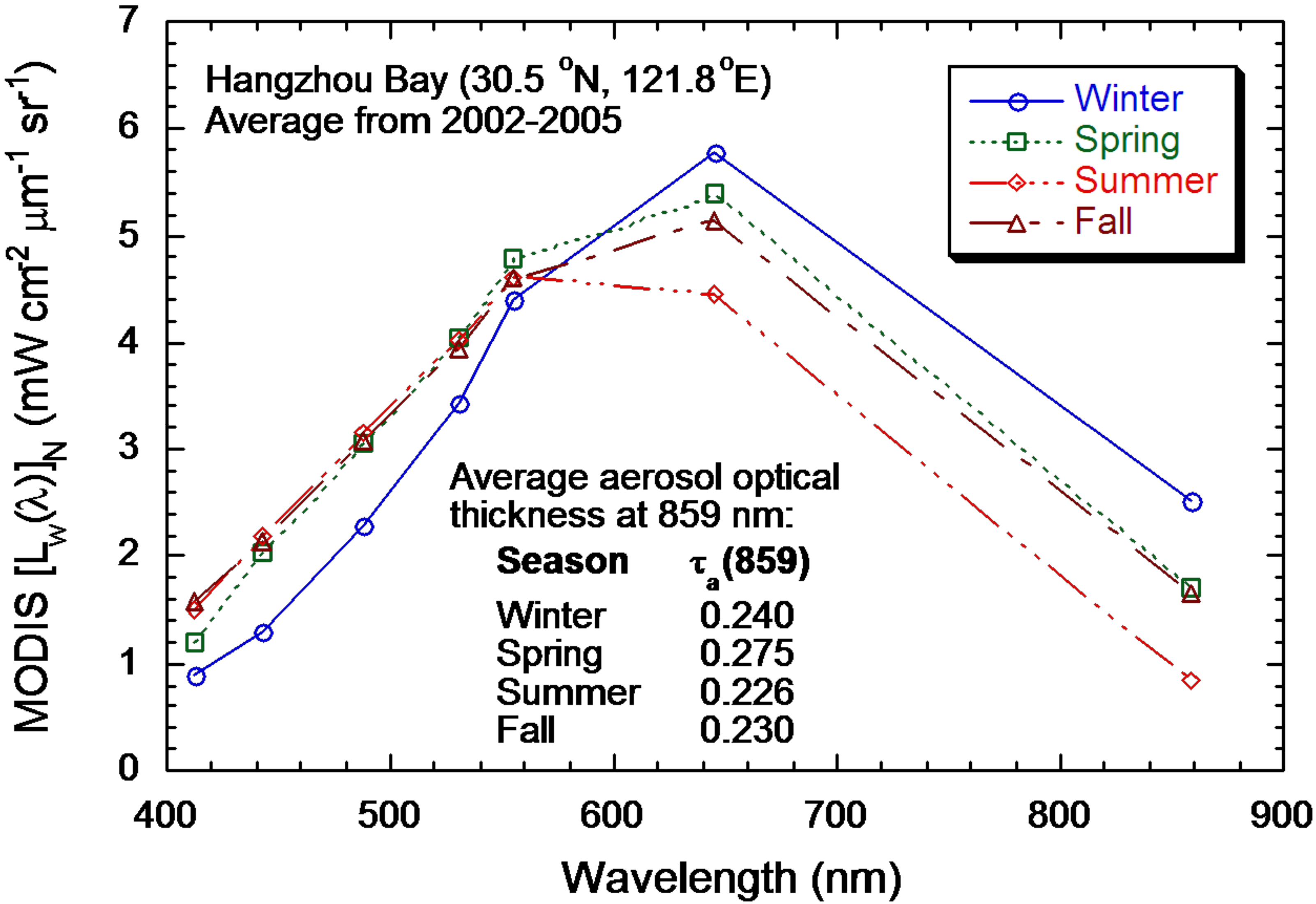
Validation Results (2)



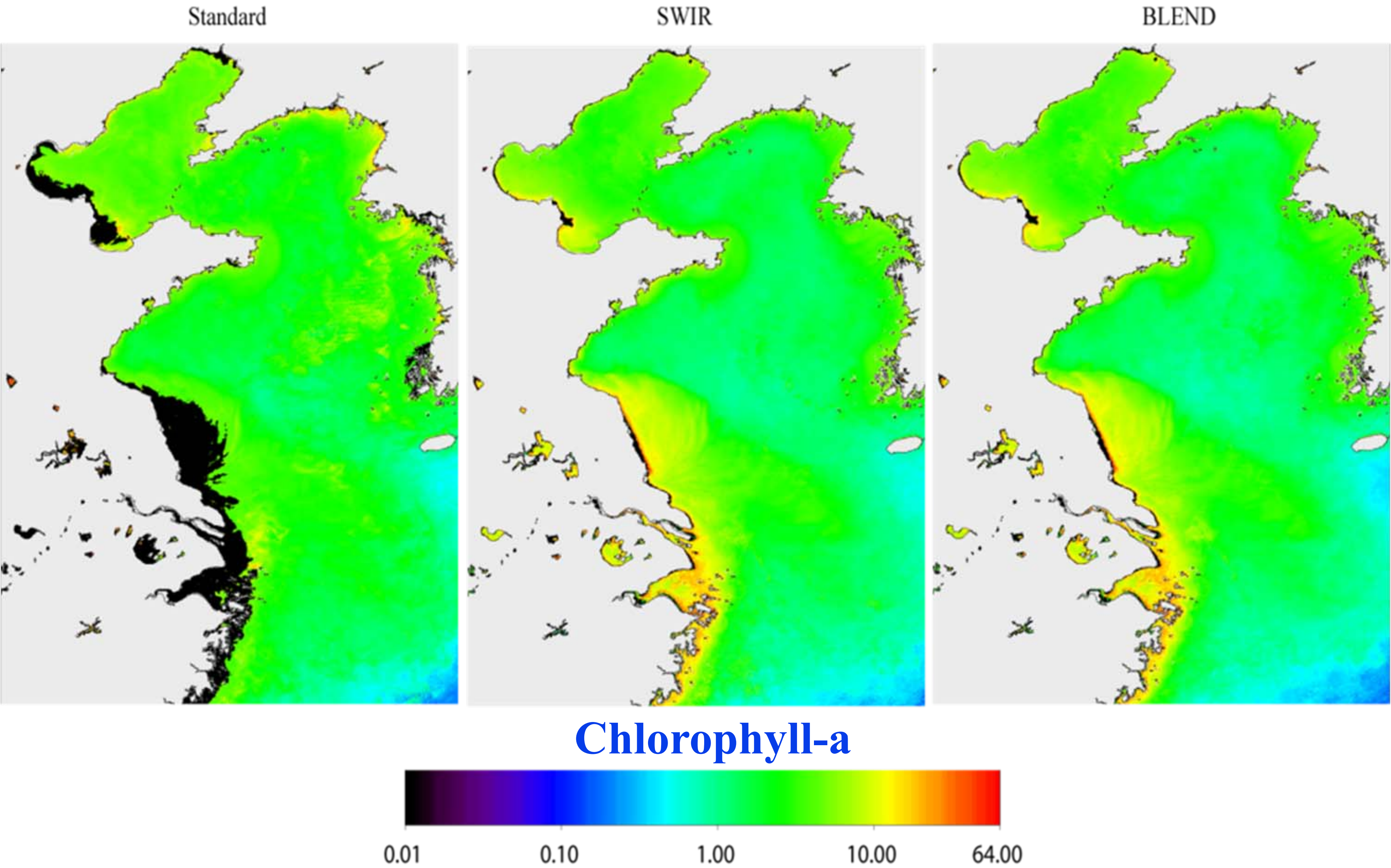
Validation Results (3)



Water-leaving Radiance Spectra in Hangzhou Bay



MODIS-Aqua Climatological Monthly Chl-a Images in YECS (April)



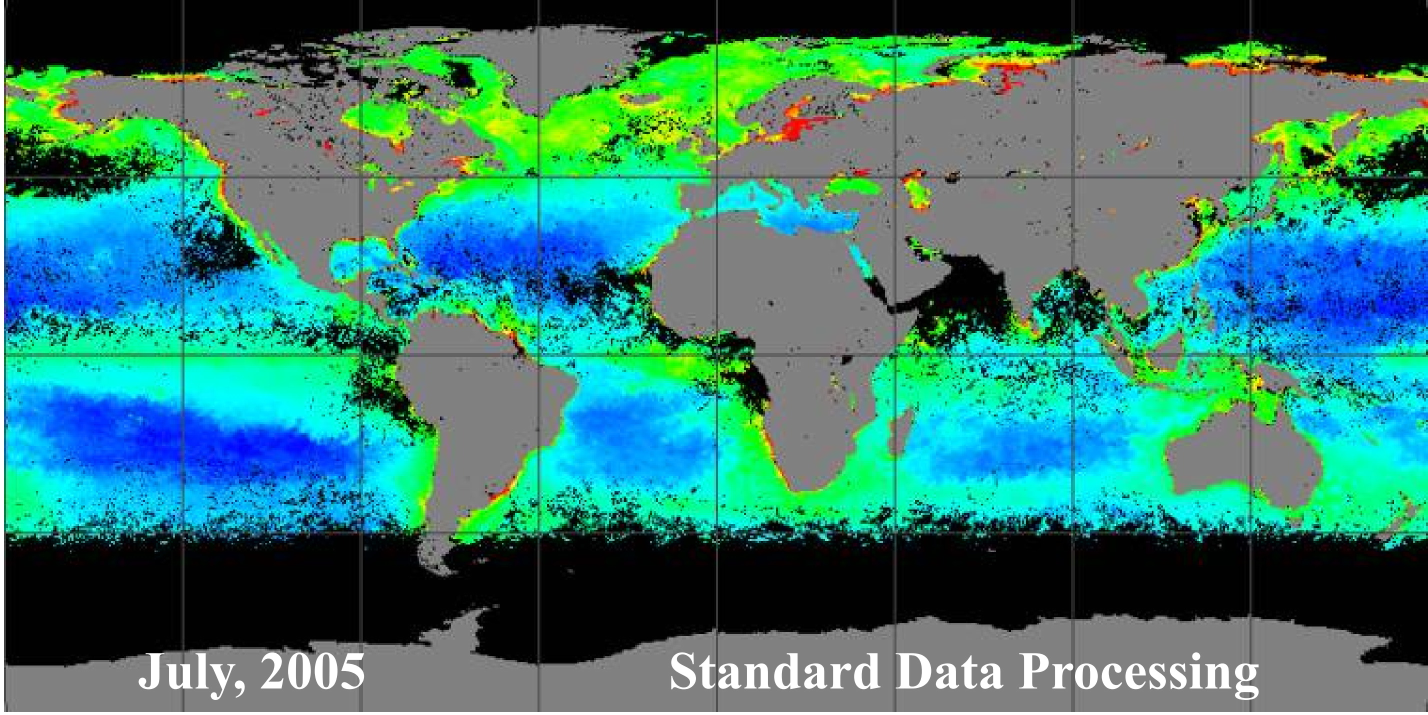
Composite from April 2002-2007 Data

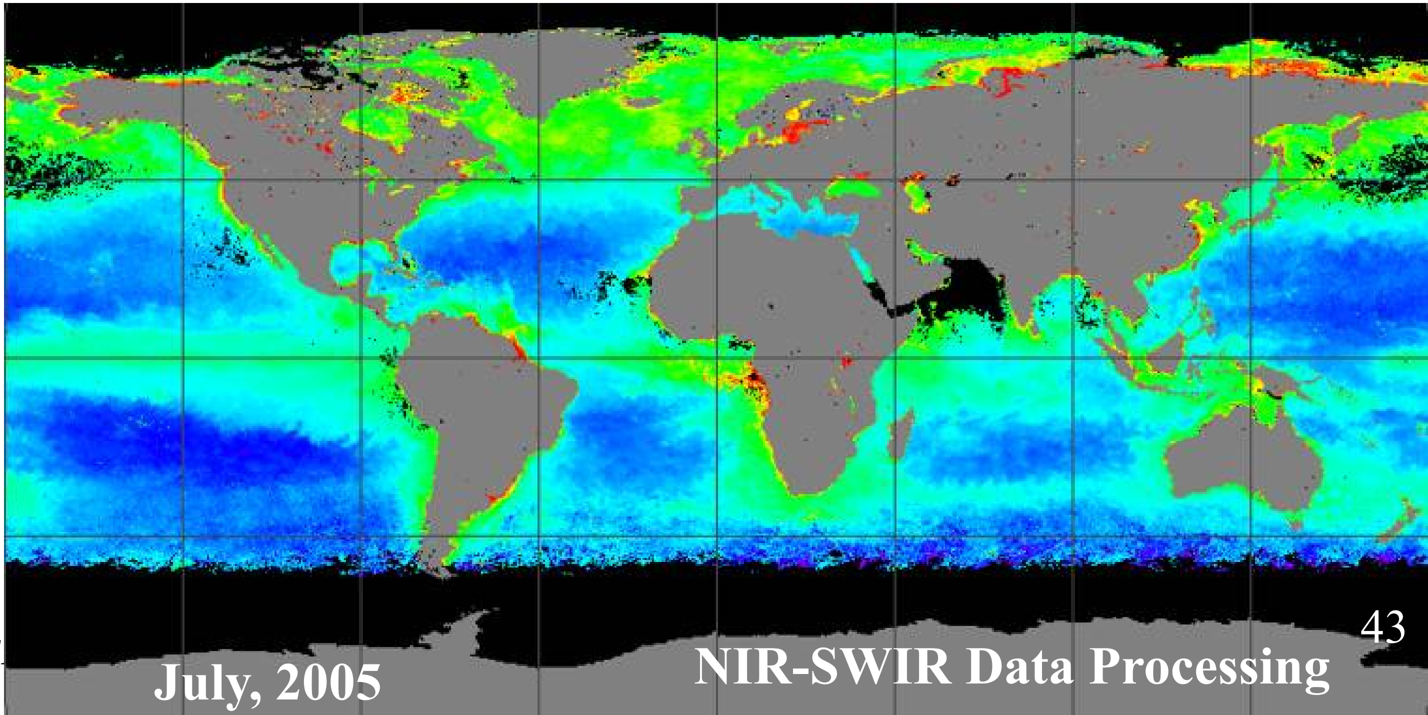
SWIR-based Global Ocean Color Data Processing at NOAA/STAR

Chlorophyll-a

0.01-10 (mg/m^3)

(Log scale)





Wang, M., S. Son, and W. Shi (2009), "Evaluation of MODIS SWIR and NIR-SWIR atmospheric correction algorithms using SeaBASS data," *Remote Sens. Environ.*, **113**, 635-644.

The SWIR-based Ocean Color Products for Various Applications

- **Coastal Phytoplankton Bloom Studies:** Observations of Hurricane Katrina-induced phytoplankton bloom in the Gulf of Mexico (Shi and Wang, 2007; Liu et al., 2009).
- **Ecosystem Responses to Major Weather Event:** Three-dimension observations from MODIS and CALIPSO for ocean responses to Cyclone Nargis in the Gulf of Martaban (Shi and Wang, 2008).
- **River Estuary, River Dynamics and River Plume:** Satellite observations of flood-driven Mississippi River plume in the spring 2008 (Shi and Wang, 2009).
- **Stormwater Plume Detection:** Stormwater plume detection in the southern California coastal ocean (Nezline et al., 2008).
- **Coastal and Inland-water Hazard Monitoring:** Satellite-observed blue-green algae blooms in China's Lake Taihu (Wang and Shi, 2008).

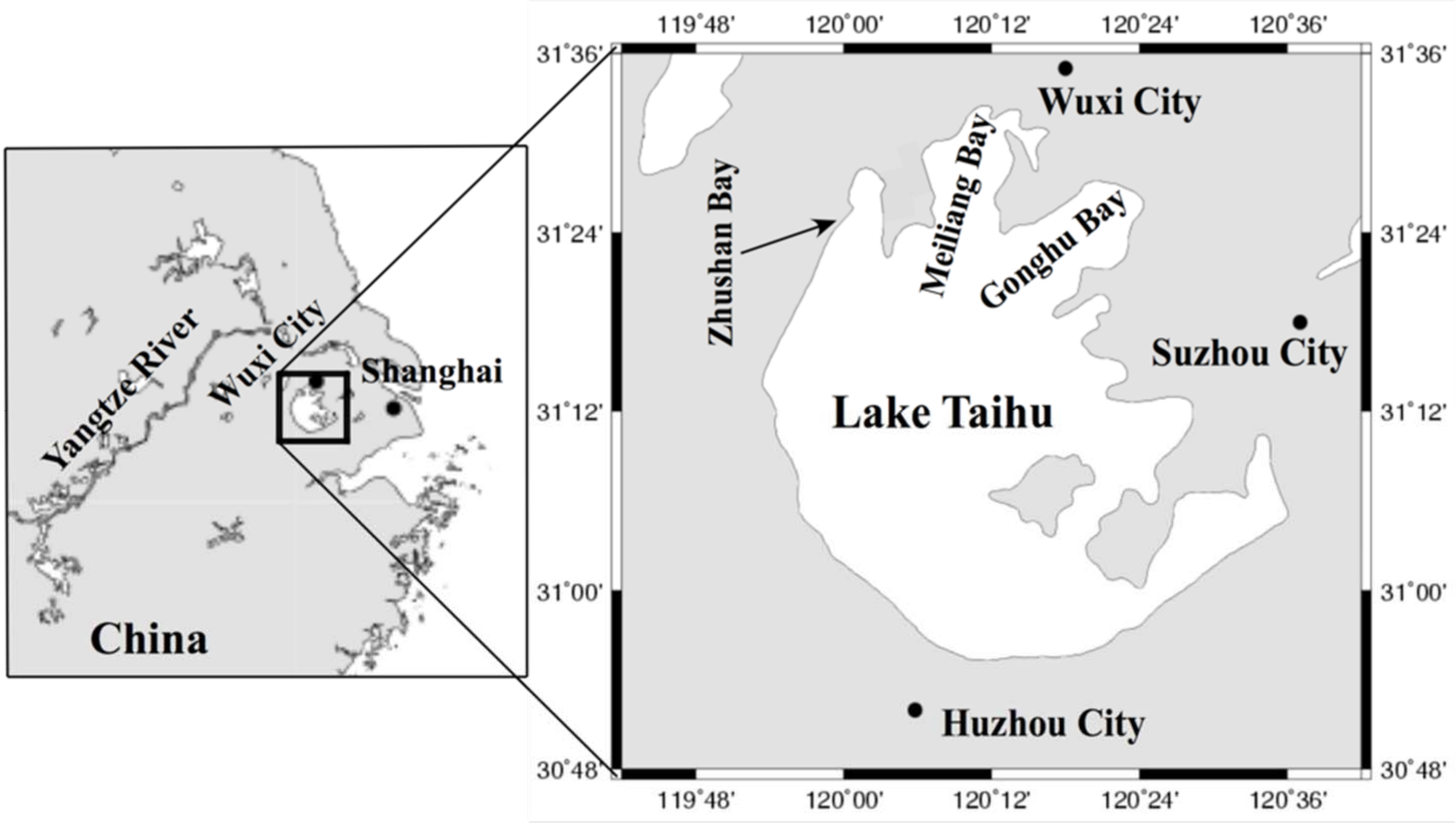
Results from Inland Lake Taihu

Using the **SWIR** algorithm, we have derived the water optical properties over the Lake Taihu using the **MODIS-Aqua** measurements during the spring of 2007 for monitoring a **massive blue-green** algae bloom, which was a major natural disaster affecting several millions residents in nearby Wuxi city.

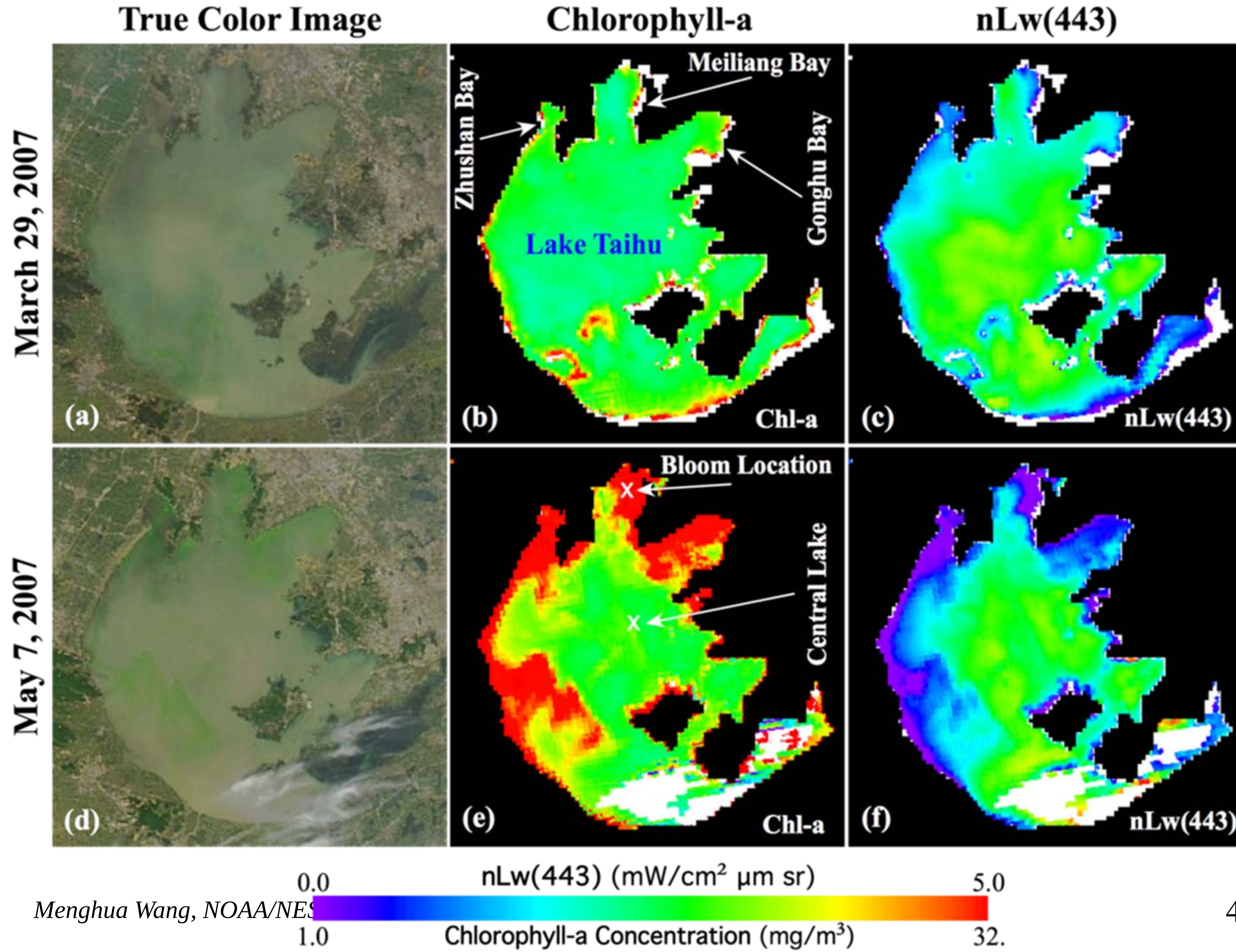
Wang, M. and W. Shi, "Satellite observed algae blooms in China's Lake Taihu", *Eos, Transaction, American Geophysical Union*, **89**, p201-202, May 27 (2008).

- The work has been featured in the NASA 2008 **Sensing Our Planet** (http://nasadaacs.eos.nasa.gov/articles/2008/2008_algae.html)

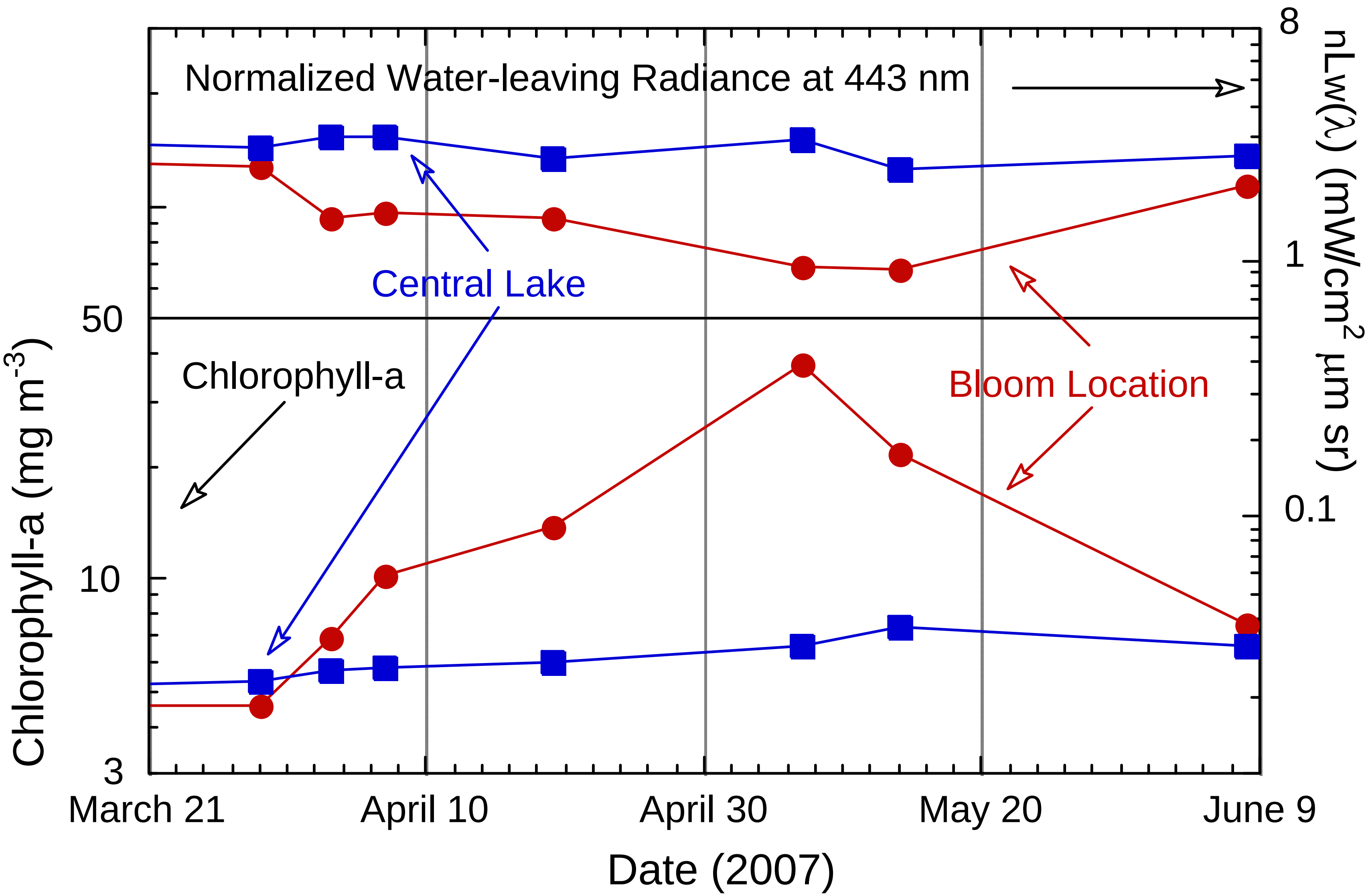
Geo-location of Lake Taihu



Blue-Green Algae (Microcystis) Bloom Crisis in Lake Taihu (Spring 2007)


True Color Image
Chlorophyll-a
nLw(443)
March 29, 2007
May 7, 2007
Meiliang Bay
Zhushan Bay
Gonghu Bay
Lake Taihu
(a)
(b)
Chl-a
(c)
nLw(443)
Bloom Location
Central Lake
(d)
(e)
Chl-a
(f)
nLw(443)
nLw(443) (mW/cm² μm sr)
0.0
5.0
1.0
32.
Chlorophyll-a Concentration (mg/m³)

Time Series of Chlorophyll-a (index) and *nLw*(443) at Wuxi Station (bloom) and Central Lake (non-bloom)



Transition of Research to Operational for the SWIR-Based Algorithms

- Working with the NOAA data operational partners (OSDPD), we have been working on transferring the SWIR-based ocean color data processing system into the NOAA operational data processing system.

- Near real time ocean color products will be produced using the SWIR-based algorithms for the U.S. coastal regions in NOAA CoastWatch Program.

The SWIR Algorithm Related Publications (1)
(Algorithms and Validations)

Wang, M., S. Son, and L. W. Harding Jr., "Retrieval of diffuse attenuation coefficient in the Chesapeake Bay and turbid ocean regions for satellite ocean color applications," *J. Geophys. Res.* (Submitted).

Zhang, H. and M. Wang, "Evaluations of Sun glitter models using MODIS measurements," *Appl. Opt.* (Submitted).

Wang, M. and W. Shi, "Detection of ice and mixed ice-water pixels for MODIS ocean color data processing," *IEEE Trans. Geosci. Remote Sensing* (In press).

Shi, W. and M. Wang, M., "An assessment of the ocean black pixel assumption for the MODIS SWIR bands," *Remote Sens. Environ.* (In press).

Wang, M., S. Son, and W. Shi, "Evaluation of MODIS SWIR and NIR-SWIR atmospheric correction algorithms using SeaBASS data," *Remote Sens. Environ.*, **113**, 635-644, 2009.

Wang, M. and W. Shi, "The NIR-SWIR combined atmospheric correction approach for MODIS ocean color data processing," *Optics Express*, **15**, 15722-15733, 2007.

Wang, M., J. Tang, and W. Shi, "MODIS-derived ocean color products along the China east coastal region," *Geophys. Res. Lett.*, **34**, L06611, doi:10.1029/2006GL028599, 2007.

Shi, W. and M. Wang, "Detection of turbid waters and absorbing aerosols for the MODIS ocean color data processing," *Remote Sens. Environ.*, **110**, 149-161, 2007.

Wang, M., "Remote sensing of the ocean contributions from ultraviolet to near-infrared using the shortwave bands: simulations," *Appl. Opt.*, **46**, 1535-1547, 2007.

Wang, M. and W. Shi, "Cloud masking for ocean color data processing in the coastal regions," *IEEE Trans. Geosci. Remote Sensing*, **44**, 3196-3205, 2006.

Wang, M. and W. Shi, "Estimation of ocean contribution at the MODIS near-infrared wavelengths along the east coast of the U.S.: Two case studies," *Geophys. Res. Lett.*, **32**, L13606, doi:10.1029/2005GL022917, 2005.

The SWIR Algorithm Related Publications (2)

(Various Applications)

Shi, W. and M. Wang, M., "Satellite observations of flood-driven Mississippi River plume in the spring of 2008," *Geophys. Res. Lett.*, **36**, L07607, doi:10.1029/2009GL037210, 2009.

Liu, X, M. Wang, and W. Shi, "A study of a Hurricane Katrina-induced phytoplankton bloom using satellite observations and model simulations," *J. Geophys. Res.*, **114**, C03023, doi:10.1029/2008JC004934, 2009.

Shi, W. and M. Wang, "Three-dimensional observations from MODIS and CALIPSO for ocean responses to Cyclone Nargis in the Gulf of Martaban," *Geophys. Res. Lett.*, **35**, L21603, doi:10.1029/2008GL035279, 2008.

Nezlin, N. P., P. M. DiGiacomo, D. W. Diehl, B. H. Jones, S. C. Johnson, M. J. Mengel, K. M. Reifel, J. A. Warrick, and M. Wang,"Stormwater plume detection by MODIS imagery in the southern California coastal ocean," *Estuarine, Coastal and Shelf Science*, **80**, 141-152, 2008.

Wang, M. and W. Shi, "Satellite-observed blue-green algae blooms in China's Lake Taihu", *Eos, Transactions, American Geophysical Union*, **89**, p201-202, May 27, 2008.

Shi, W. and M. Wang, "Observations of a Hurricane Katrina-induced phytoplankton bloom in the Gulf of Mexico," *Geophys. Res. Lett.*,**34**, L11607, doi:10.1029/2007GL029724, 2007.

Conclusions

- Both SeaWiFS and MODIS have been providing high quality ocean color products in the global open oceans.
- At the coastal regions, however, not only the ocean is usually Case-2 waters, but also the aerosols are often absorbing.
- For the turbid waters in coastal regions, shortwave infrared (SWIR) bands can be used for atmospheric correction because of significantly strong ocean absorption at the SWIR bands.
- Future ocean color sensors need to include the **SWIR** bands with **sufficient SNR** values for coastal and inland turbid waters.
- It is crucial we have on-orbit vicarious calibration.

Thank You!