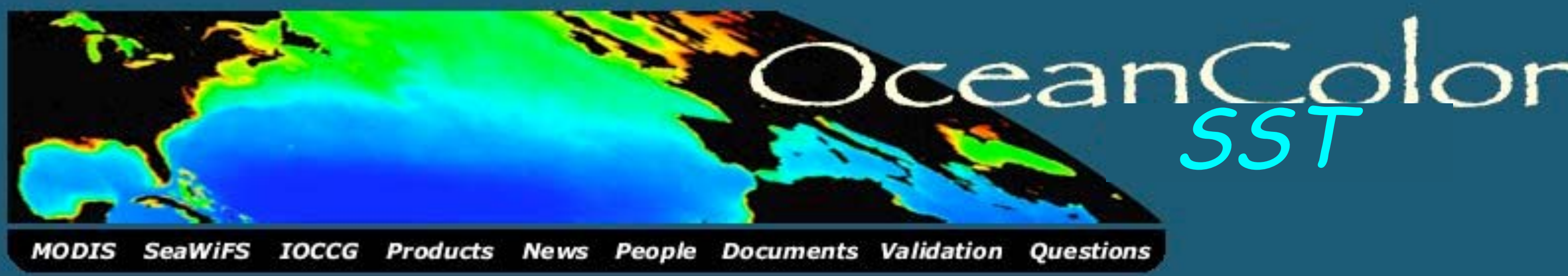


MODIS Ocean Data Processing

Bryan Franz

NASA Ocean Biology Processing Group

Operational MODIS Ocean Band Suite

VIS/NIR

Ocean Color

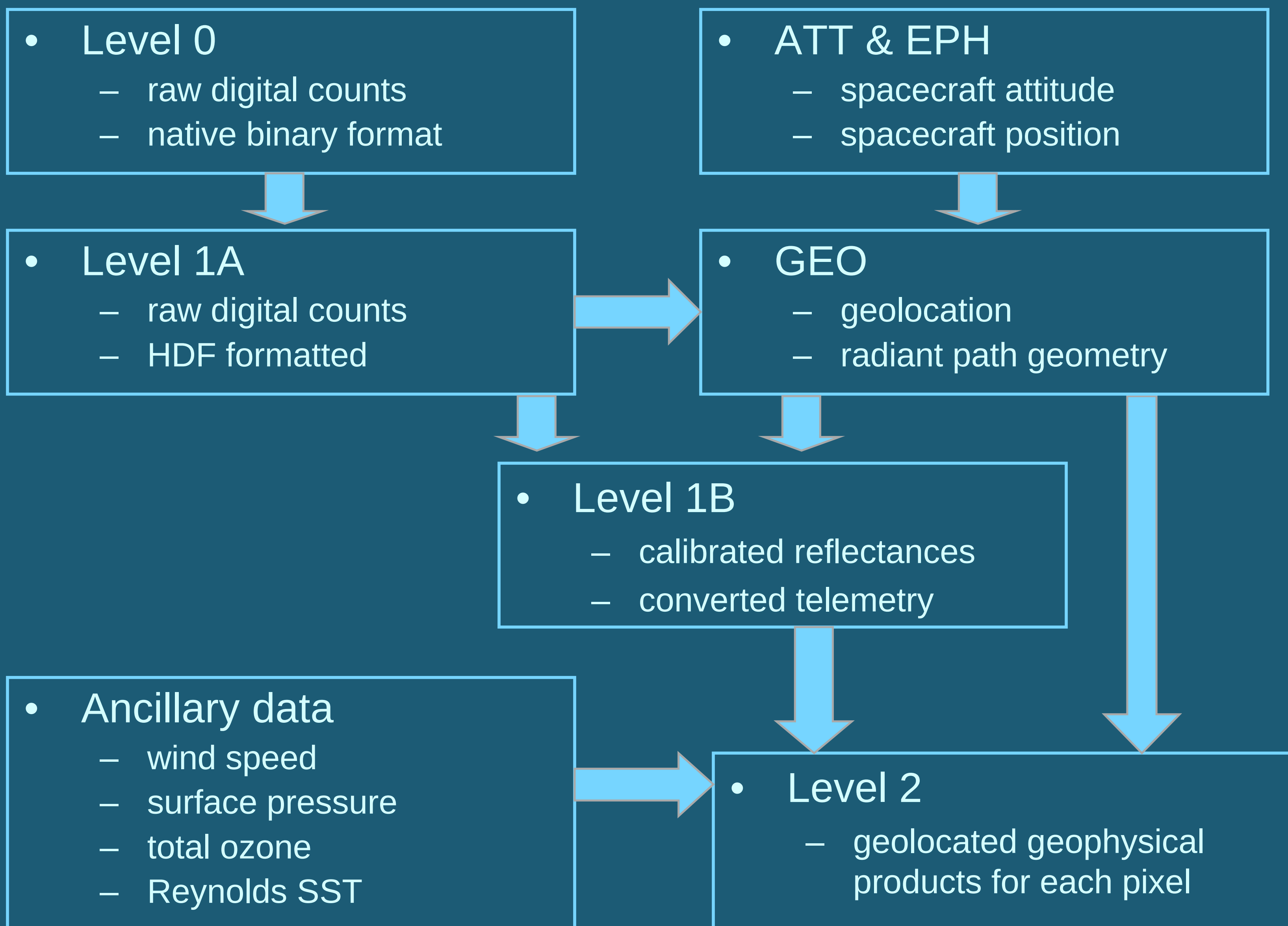
Band Number	Wavelength (nm)	Band Width (nm)	Spatial Resolution (m)	SNR at L_{typ}	L_{typ} mW cm^{-2} μm^{-1} sr^{-1}	L_{max} mW cm^{-2} μm^{-1} sr^{-1}
8	412	15	1000	1773	7.84	26.9
9	443	10	1000	2253	6.99	19.0
10	488	10	1000	2270	5.38	14.0
11	531	10	1000	2183	3.87	11.1
12	551	10	1000	2200	3.50	8.8
13	667	10	1000	1962	1.47	4.2
14	678	10	1000	2175	1.38	4.2
15	748	10	1000	1371	0.889	3.5
16	869	15	1000	1112	0.460	2.5

Thermal

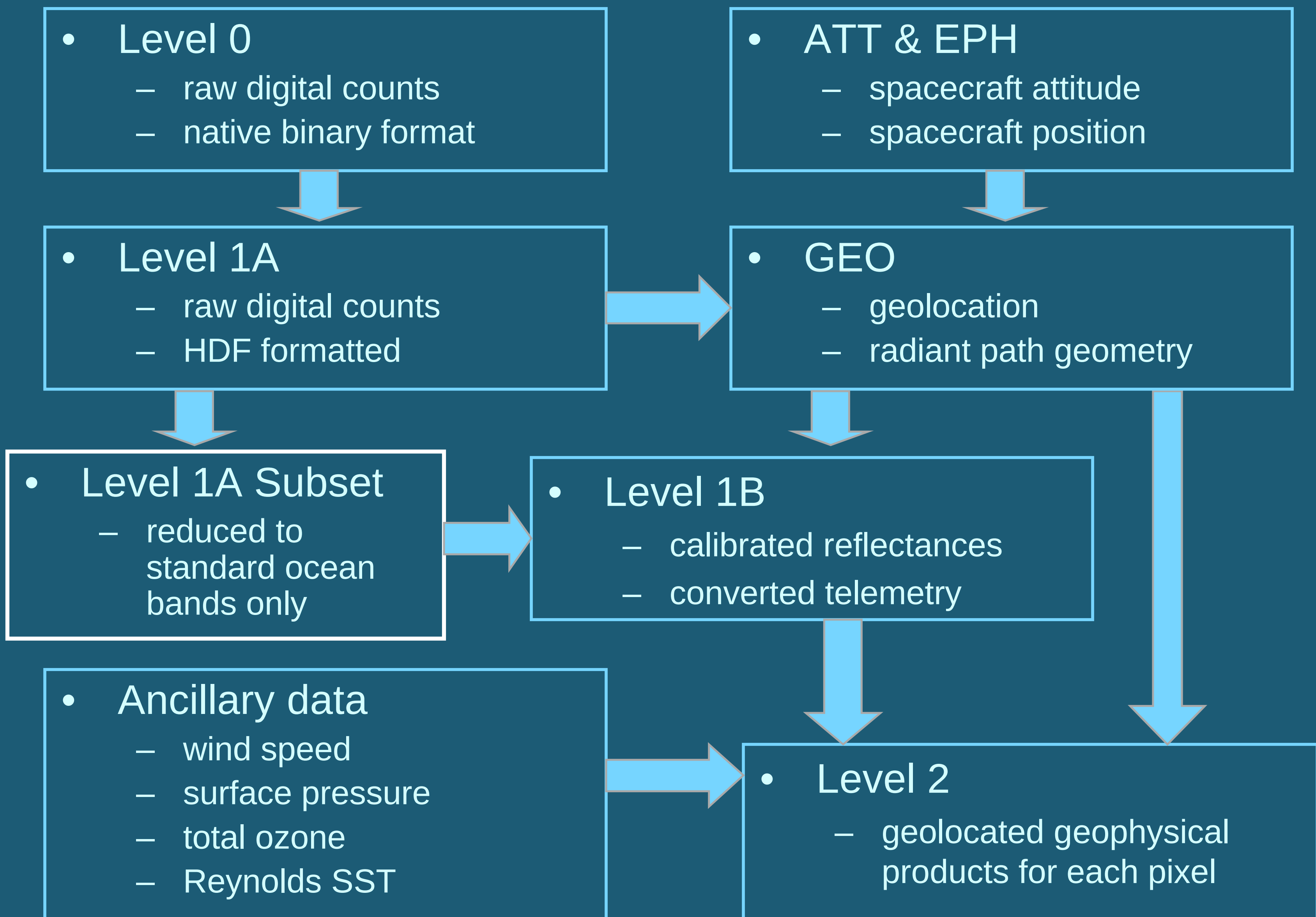
SST

Band Number	Wavelength (nm)	Band Width (nm)	Spatial Resolution (m)	NEdT
22	3959	60	1000	0.07
23	4050	60	1000	0.07
31	11000	60	1000	0.05
32	12000	60	1000	0.05

Data Levels & Flow



Data Levels & Flow



Level-3 Processing

- Level 2
  - geolocated geophysical products for each pixel

- Level 3 binned
  - geophysical products averaged spatially and/or temporally
  - sinusoidally distributed, equal area bins

- Level 3 mapped
  - images created by mapping and scaling binned products
  - user-friendly, cylindrical equiangular projection

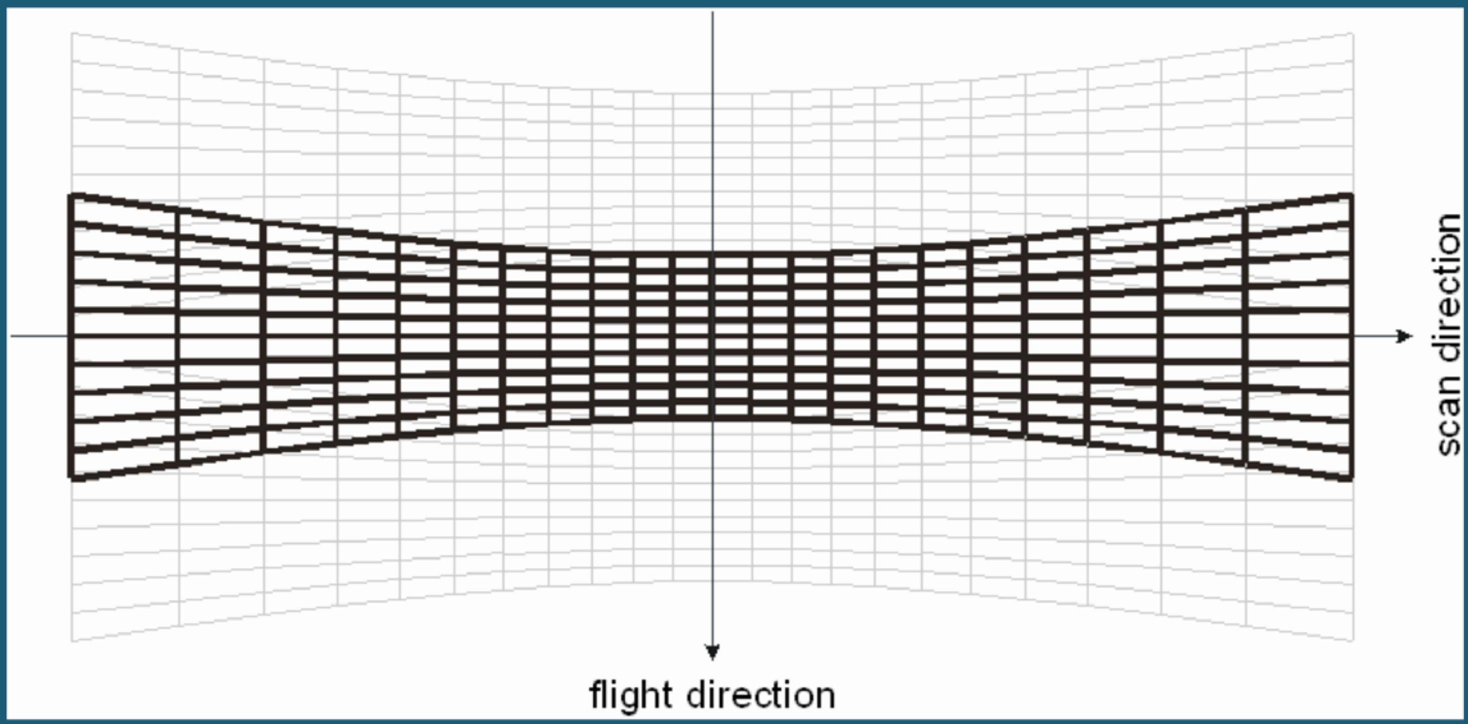
Standard Products

- Bin resolution 4.6 x 4.6 km^2

- Mapped resolution
  - 0.042-deg (4.6 km at equator)
  - 0.084-deg (9.2 km at equator)

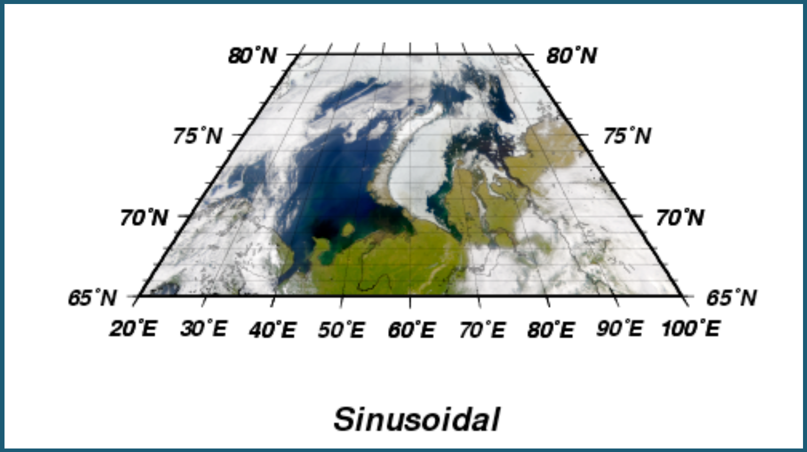
- Composite Periods
  - Daily
  - 8-day
  - Monthly
  - Seasonal
  - Yearly
  - Mission

Increasing Pixel Size



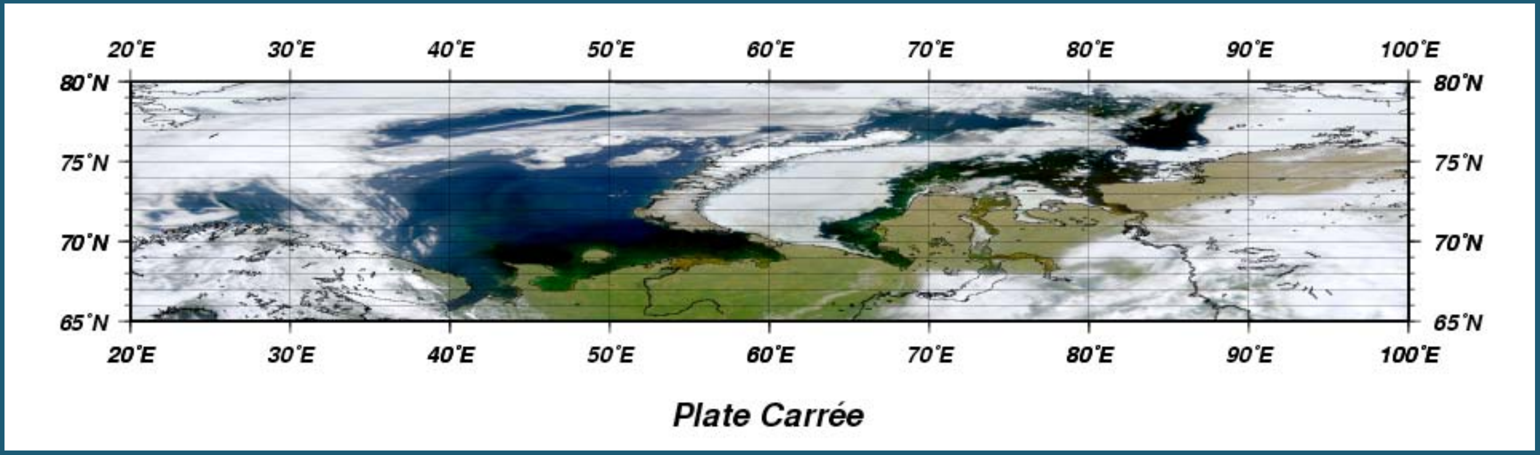
Level-3 Binned vs Mapped

bin file grid



- bin files
  - multiple products
  - stored as float
  - sampling statistics included
- map files
  - single product
  - stored as scaled integer

map file grid



Standard MODIS Ocean Products

- Ocean Temperature
  - Long-wave SST (11-12 μm), day and night
  - Short-wave SST (3.9 - 4.0 μm), night only
  - SST quality level (0-4)

- Ocean Color (day only)
  - Normalized water-leaving radiances, nLw(λ)
  - Chlorophyll, C_a
  - Diffuse attenuation, K_d(490)
  - Aerosol type and concentration
    - Optical thickness, τ_a
    - Ångström exponent
    - Atmospheric epsilon
  - Processing flags
    - Cloud, land, glint, atmfail, atmwarn, chlfail, chlwarn, etc.

Non-standard MODIS Ocean Products

- Ocean Temperature
  - Brightness temperatures

- Ocean Color
  - Alternate C_a and K_d algorithms
  - Chlorophyll fluorescence, FLH
  - Particulate inorganic carbon, Calcite
  - Inherent optical properties (various bio-optical models)
    - absorption (total, phaeophytin, dissolved matter)
    - backscatter (total, particulate)
  - Photosynthetically active radiation, iPAR, PAR (coming)
  - Euphotic depth (Z_{eu}, Z_{sd})
  - Subsurface PAR at 1st optical depth, K_d(PAR)
  - Intermediate atmospheric correction products

MSL12

Multi-Sensor Level-1 to Level-2

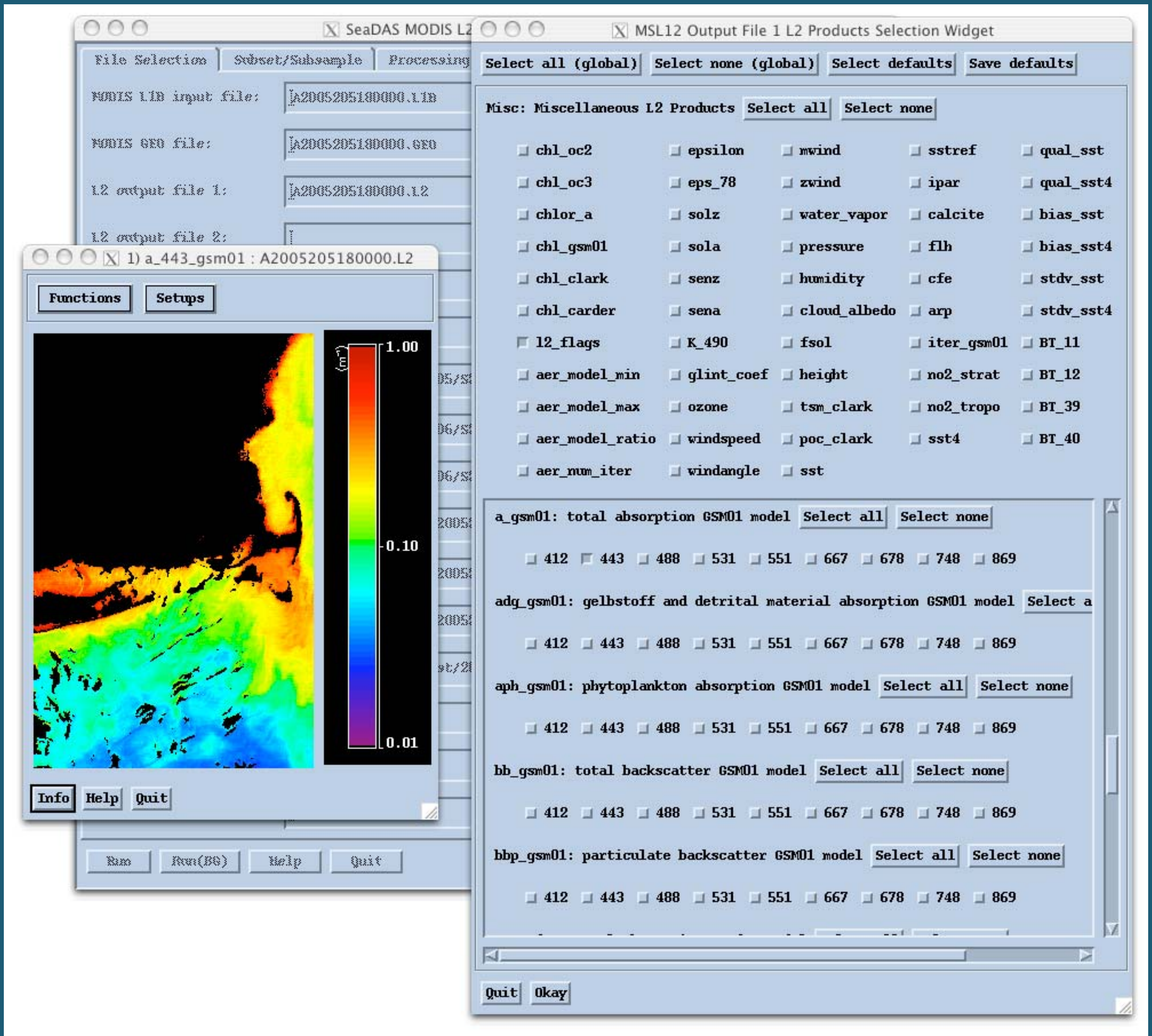
- Common software for Level-2 processing of MODIS, SeaWiFS and other sensors in a consistent manner.

- Supports a multitude of product algorithms and processing methodologies.
  - standard and non-standard, validated and experimental
  - run-time selection of output product suite

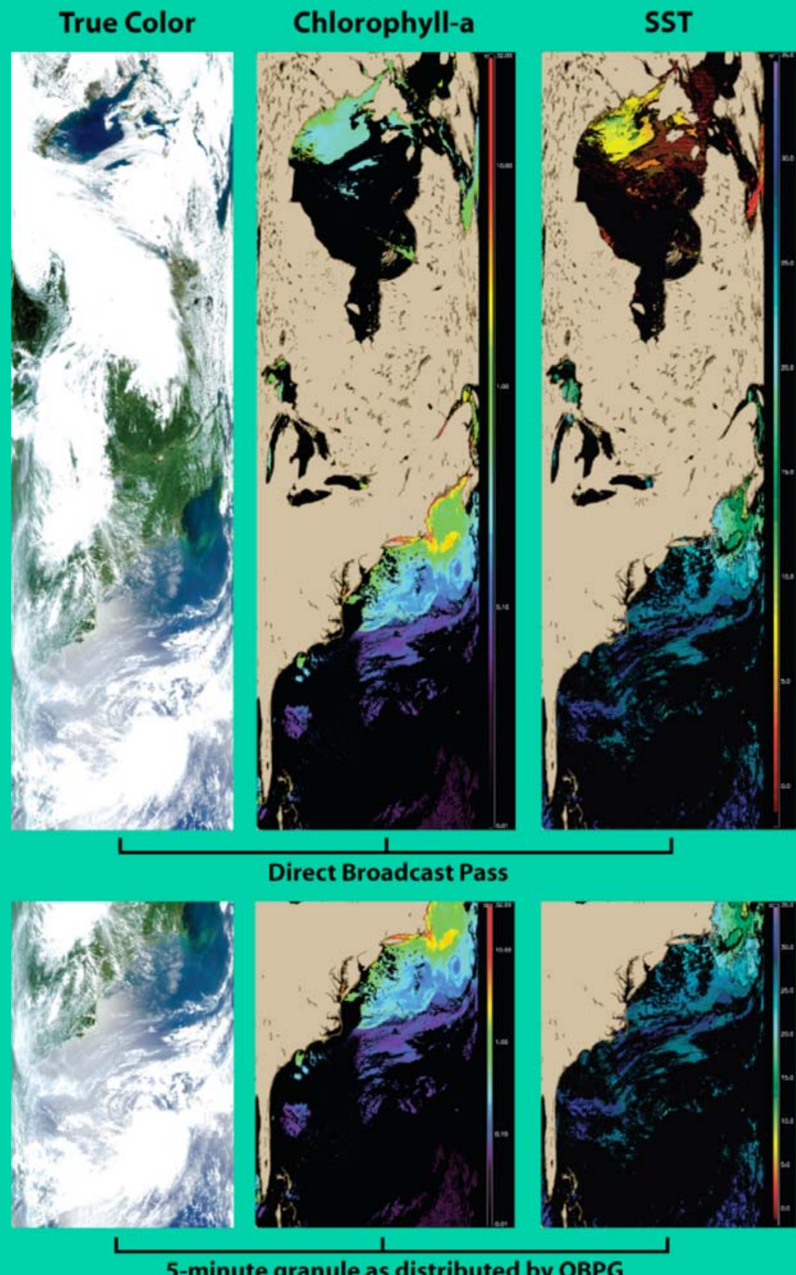
- For MODIS, replaced:
  - PGE09, PGE10
  - products MOD18 - MOD28
  - file types MODOCL2A, MODOCL2B, MODOCQC, MOD28L2, MOD28QC

SeaDAS

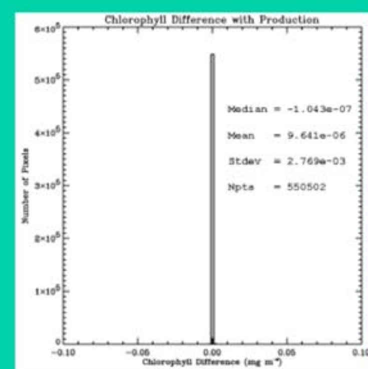
SeaWiFS Data Processing, Analysis, and Display

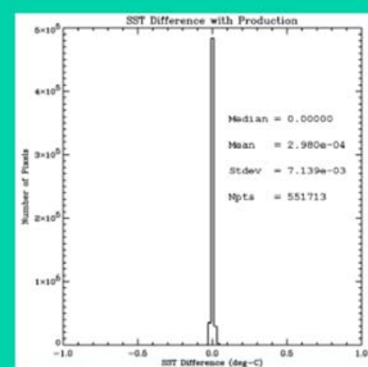


MODIS Direct Broadcast Support



These images and histograms show pixel-for-pixel comparisons between MODIS/Aqua products generated from a Level-0 scene (UWisc DB station) using SeaDAS, and the overlapping 5-minute granule processed by the OBPG. Using SeaDAS, it is possible to exactly reproduce the standard products distributed by the OBPG, as well as a host of additional products.





Level-2 SST Processing

1 Convert observed radiances to brightness temperatures (BTs)

2 Apply empirical algorithm to relate brightness temperature in two wavelengths to SST

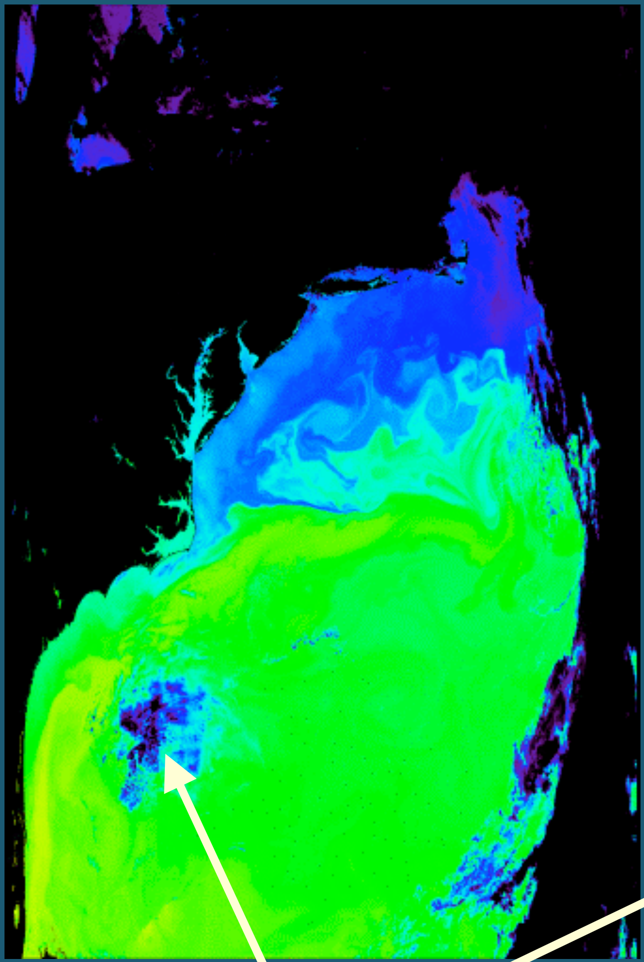
$$sst = a0 + a1 * BT_1 + a2 * (BT_2 - BT_1) + a3 * (1.0/\mu - 1.0)$$

3 Assess quality (0=best, 4=not computed)

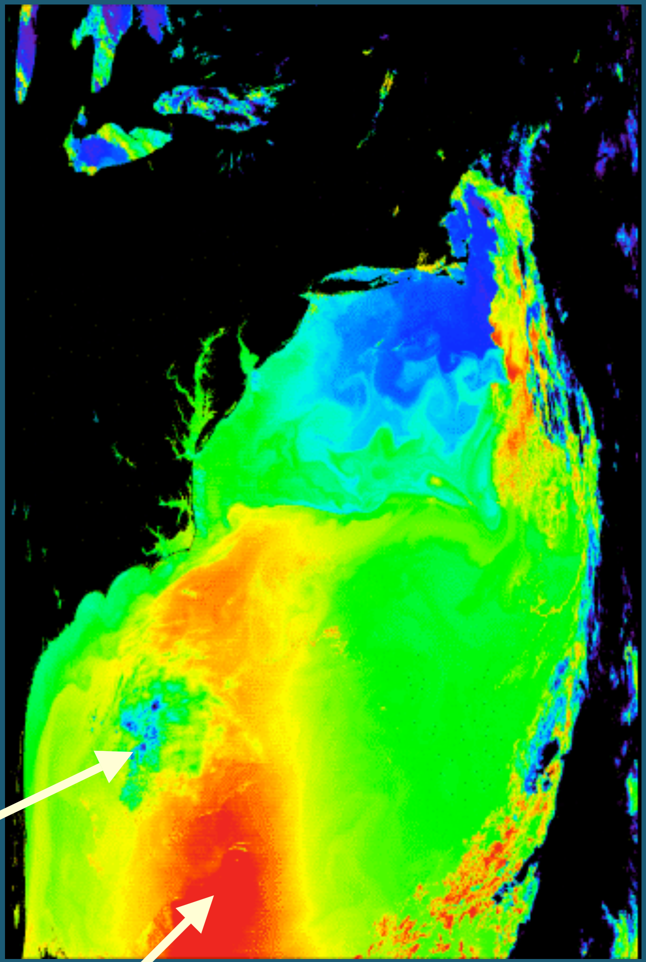
- e.g., cloud or residual water vapor contamination
- no specific “cloud mask”

Daytime SST Products

Longwave SST



Shortwave SST



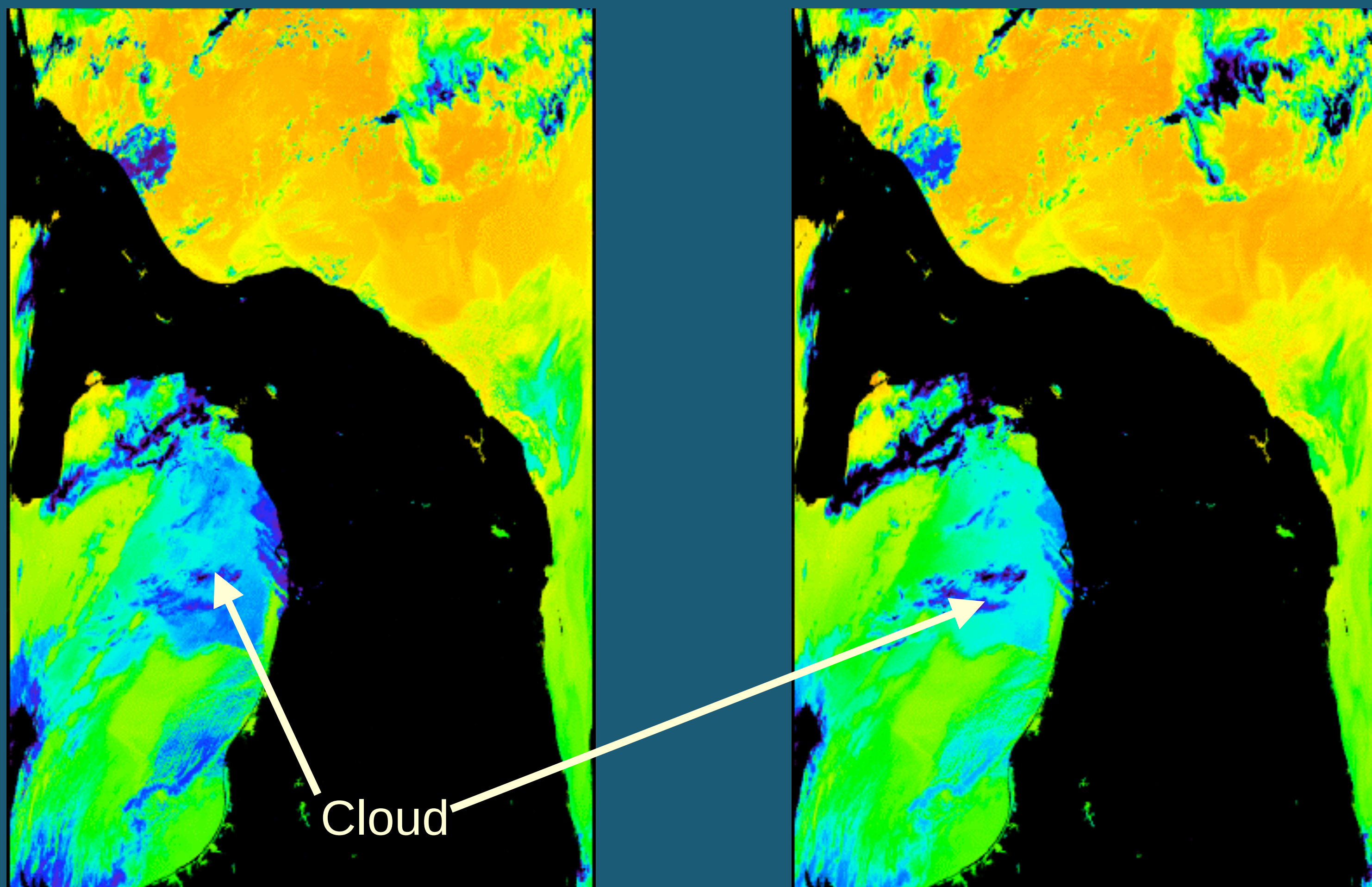
Cloud

Sun glint

Nighttime SST Products

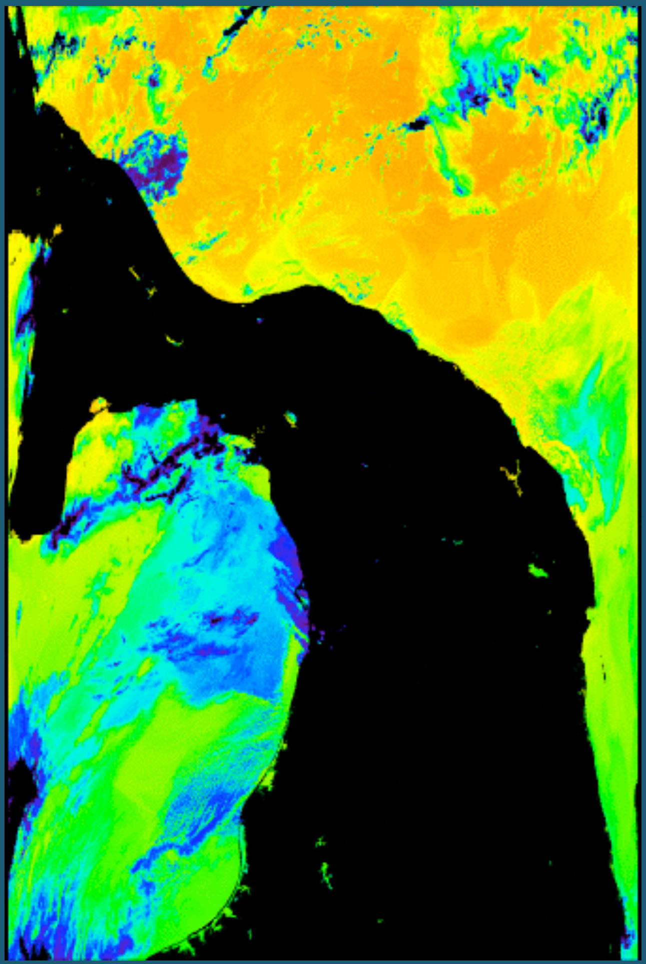
Shortwave SST

Longwave SST

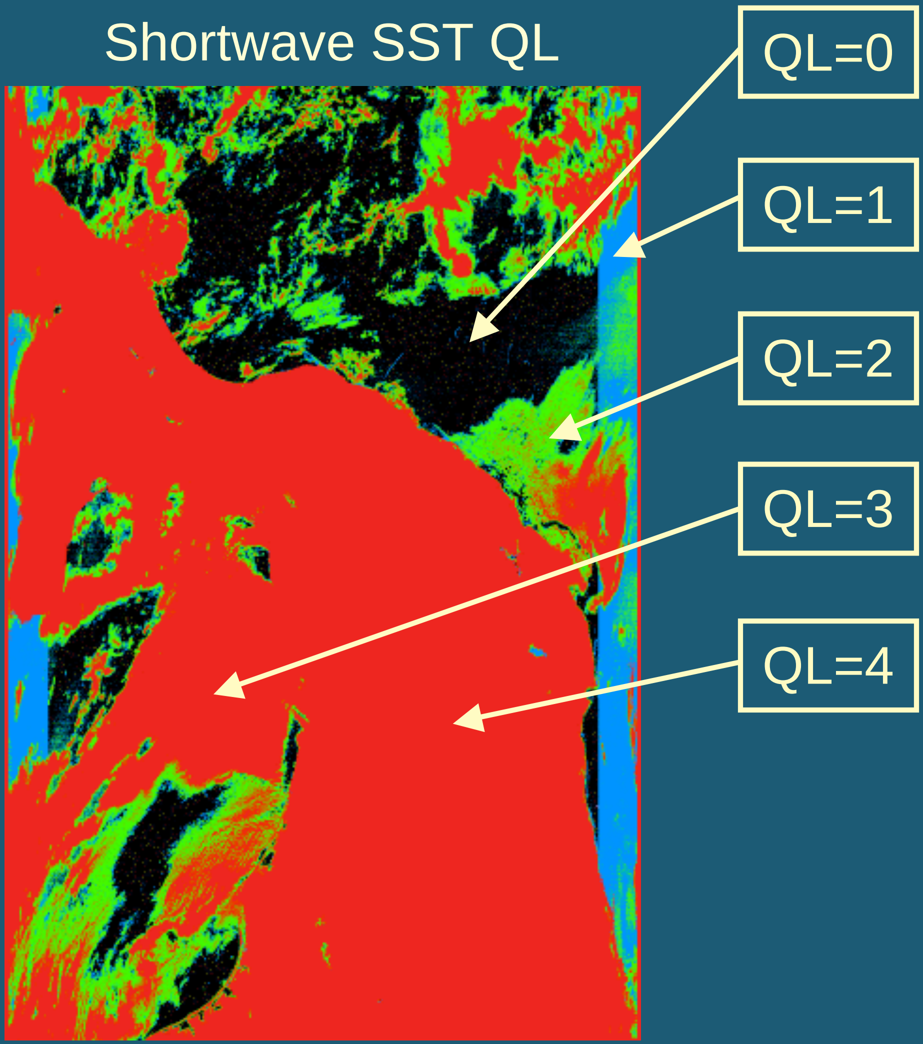


SST Quality Levels

Shortwave SST

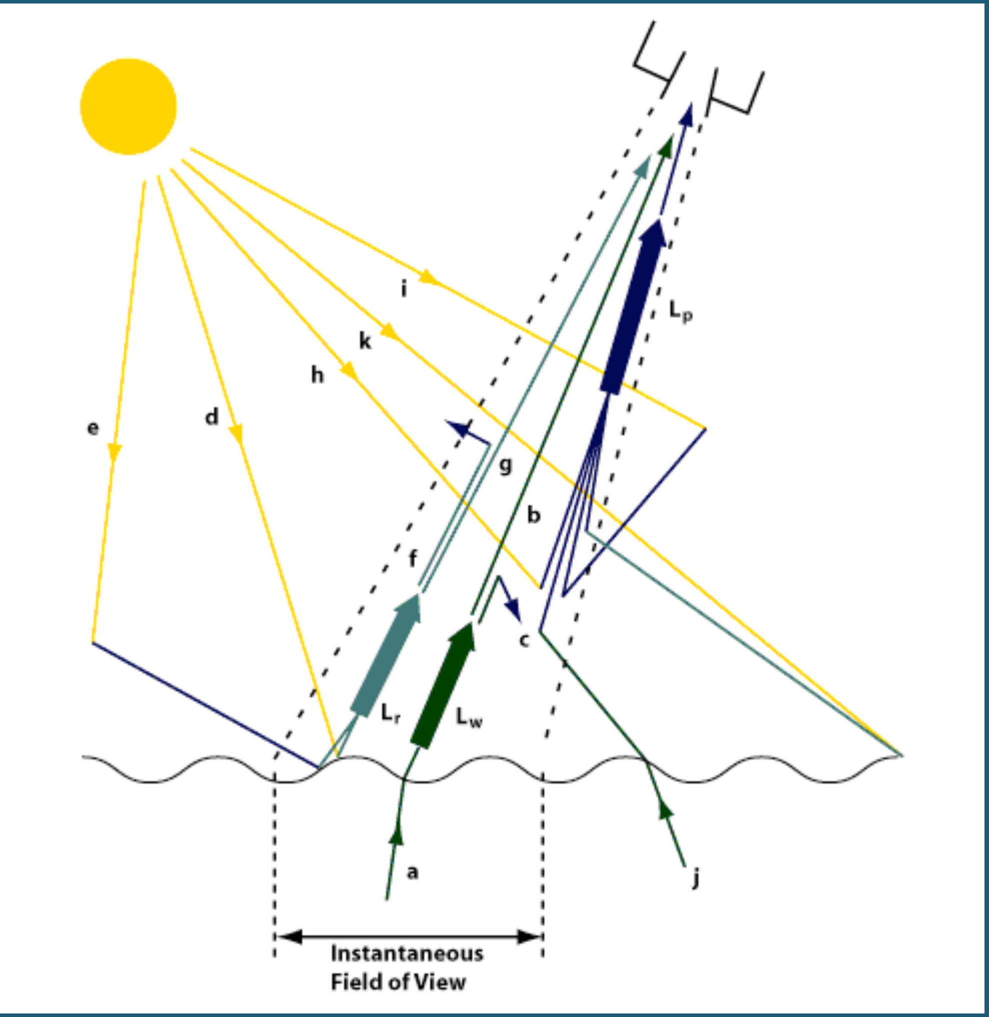


Shortwave SST QL

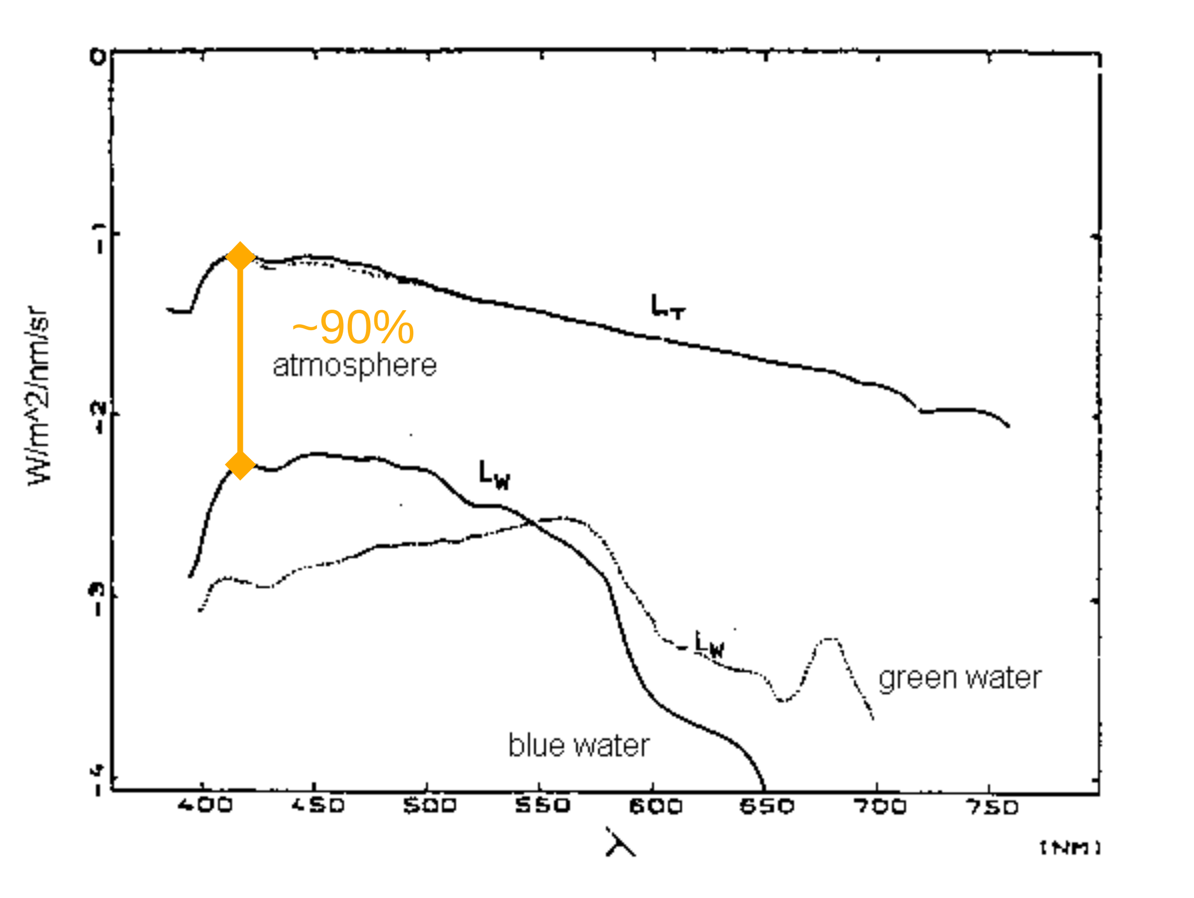


Light Paths to the Sensor

Scattering and Attenuation of Reflected Solar Bands



Ocean Color



1% error in instrument calibration or atmospheric model
~10% error in water-leaving radiance

Effects of the Atmosphere

- Gaseous absorption (ozone, water vapor, oxygen)
- Rayleigh scattering by air molecules
- Mie scattering and absorption by aerosols (haze, dust, pollution)
- Polarization (MODIS response varies with polarization of signal)

Rayleigh (80-85% of total signal)

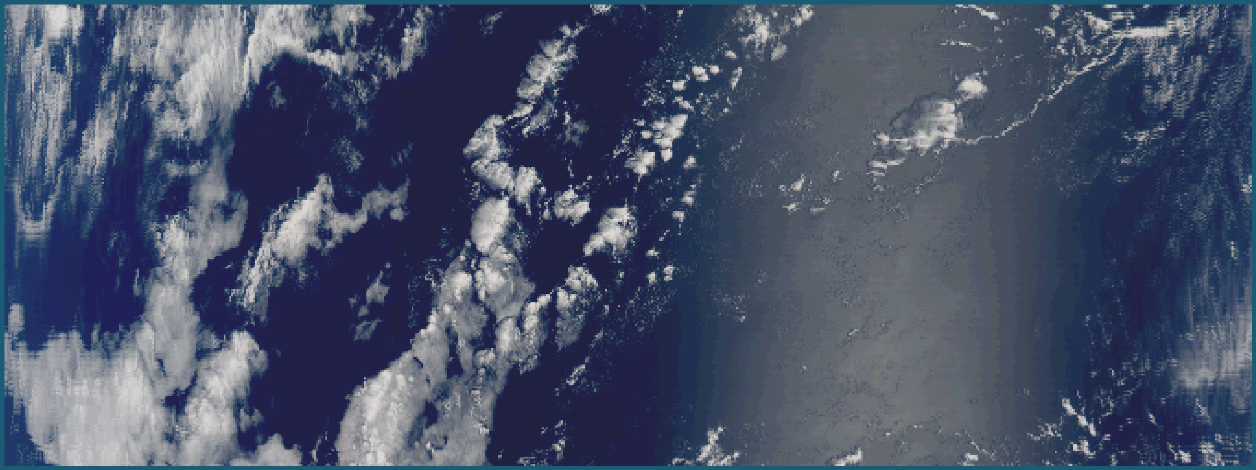
- small molecules compared to nm wavelength, scattering efficiency decreases with wavelength as λ^{-4}
- reason for blue skies and red sunsets
- can be accurately approximated for a given atmospheric pressure and geometry (using a radiative transfer code)

Aerosols (0-10% of total signal)

- particles comparable in size to the wavelength of light, scattering is a complex function of particle size
- whitens or yellows the sky
- significantly varies and cannot be easily approximated

Surface Effects

Sun Glint



White Caps

Corrections based on statistical models (wind & geometry)

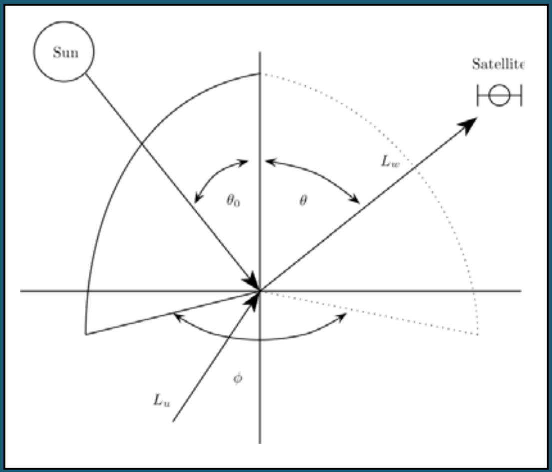
Atmospheric Correction

TOA gas pol glint whitecap air aerosol

$$t_d(\lambda)\ L_w(\lambda) = L_t(\lambda) / t_g(\lambda) / f_p(\lambda) - TL_g(\lambda) - tL_f(\lambda) - L_r(\lambda) - L_a(\lambda)$$

brdf Sun

$$nL_w(\lambda) = L_w(\lambda)\ f_b(\lambda) / t_{d0}(\lambda)\ \mu_0\ f_0$$



But, we need aerosol to get $L_w(\lambda)$

$L_w(\lambda=\mathrm{NIR}) \approx 0$ and can be estimated (model extrapolation from VIS) in waters where C_a is the primary driver of $L_w(\lambda)$.

TOA gas pol glint whitecap air water

$$L_a(\lambda=\mathrm{NIR}) = L_t(\lambda) / t_g(\lambda) / f_p(\lambda) - TL_g(\lambda) - tL_f(\lambda) - L_r(\lambda) - t_d(\lambda)\ L_w(\lambda)$$

Aerosol Determination in Visible Wavelengths

Given retrieved aerosol reflectance at two λ, and a set of aerosol models fn(θ,θ_0,ϕ).

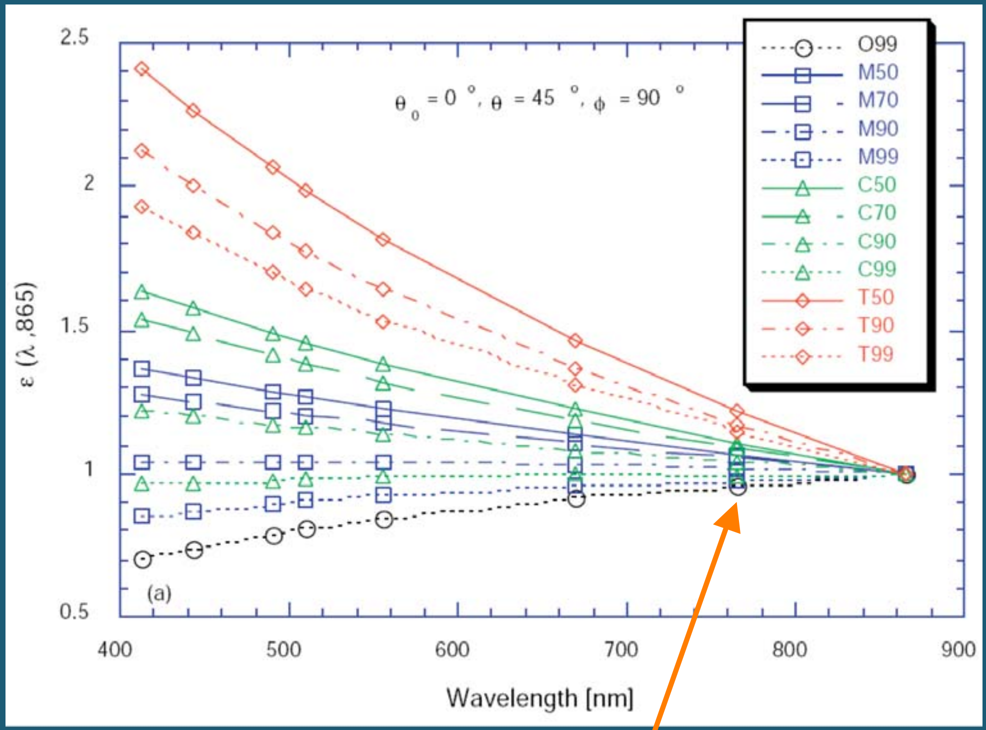
$$\rho = \frac{\pi L}{F_0 \cdot \mu_0}$$

$\rho_a(748)$ & $\rho_a(869)$

$$\rho_a(\mathrm{NIR}) \overset{\text{model}}{\Rightarrow} \rho_{as}(\mathrm{NIR})$$

$$\varepsilon\,(748,869) = \frac{\rho_{as}(748)}{\rho_{as}(869)}$$

$$\varepsilon\,(\lambda,869) = \frac{\rho_{as}(\lambda)}{\rho_{as}(869)}$$



$\varepsilon\,(748,869)$

Iterative Correction for Non-zero L_w(NIR)

1) Assume Lw(NIR) = 0
2) Compute La(NIR)
3) Compute La(VIS) from La(NIR)
4) Compute Lw(VIS)
5) Estimate Lw(NIR) from Lw(VIS) + model
6) Repeat until Lw(NIR) stops changing

Iterating up to 10 times

Level-2 Ocean Color Processing

1. Determine atmospheric and surface contributions to total radiance at TOA and subtract, iterating as needed.

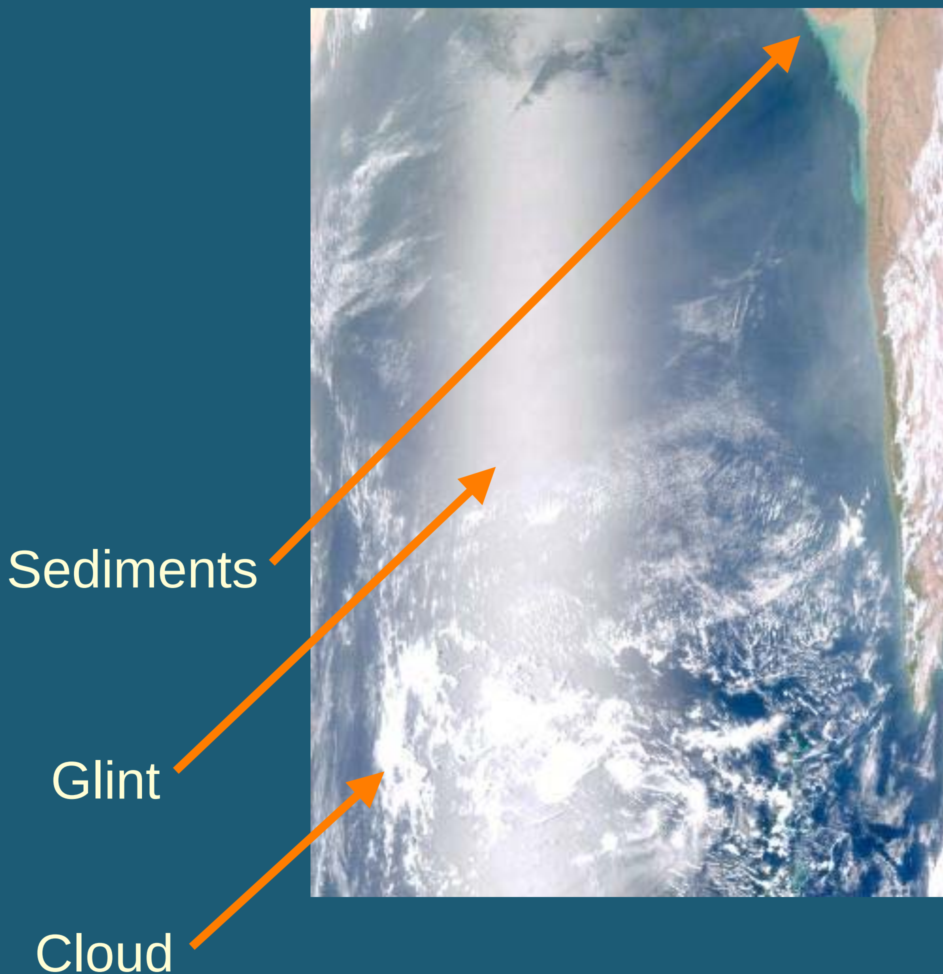
2. Normalize to the condition of Sun directly overhead at 1 AU and a non-attenuating atmosphere (nLw or Rrs = nLw/F_0).

3. Apply empirical or semi-analytical algorithms to relate the spectral distribution of nLw or Rrs to geophysical quantities.

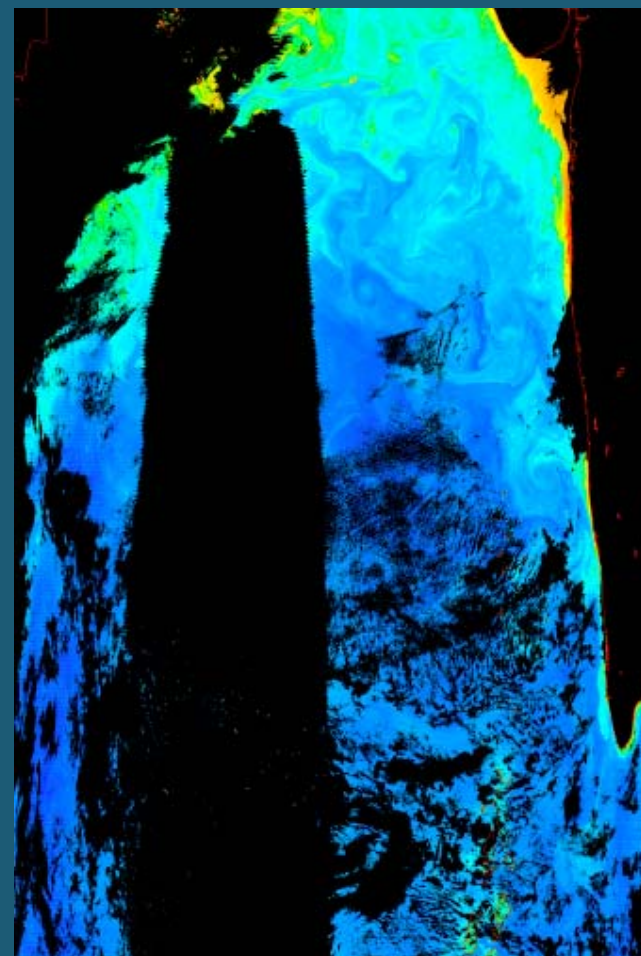
4. Assess quality (set flags) at each step

Level-2 Flags and Masking

RGB Image



Chlorophyll



Level-2 Flags and Masking

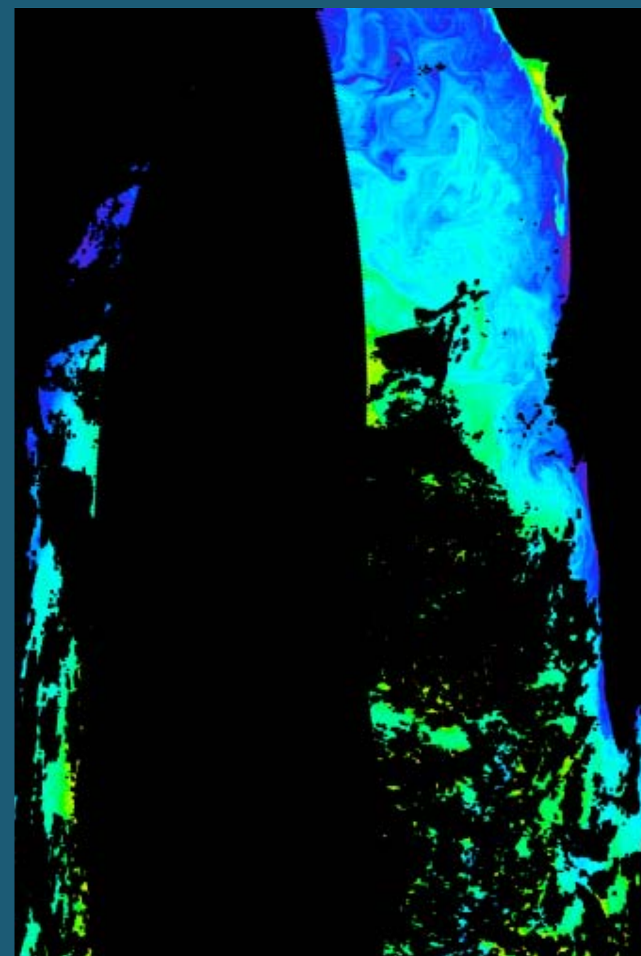
RGB Image

Sediments

Glint

Cloud

nLw (443)



Add masking for straylight

Level-2 Ocean Color Flags

BIT	NAME	DESCRIPTION
01	ATMFAIL	Atmospheric correction failure
02	LAND	Pixel is over land
03	BADANC	Reduced quality of ancillary data
04	HIGLINT	High sun glint
05	HILT	Observed radiance very high or saturated
06	HISATZEN	High sensor view zenith angle
07	COASTZ	Pixel is in shallow water
08	NEGLW	Negative water-leaving radiance retrieved
09	STRAYLIGHT	Straylight contamination is likely
10	CLDICE	Probable cloud or ice contamination
11	COCCOLITH	Coccolithophores detected
12	TURBIDW	Turbid water detected
13	HISOLZEN	High solar zenith
14	HITAU	High aerosol optical thickness
15	LOWLW	Very low water-leaving radiance (cloud shadow)
16	CHLFAIL	Derived product algorithm failure

BIT	NAME	DESCRIPTION
17	NAVWARN	Navigation quality is reduced
18	ABSAER	possible absorbing aerosol
19	TRICHO	Possible trichodesmium contamination
20	MAXAERITER	Aerosol iterations exceeded max
21	MODGLINT	Moderate sun glint contamination
22	CHLWARN	Derived product quality is reduced
23	ATMWARN	Atmospheric correction is suspect
24	DARKPIXEL	Rayleigh-subtracted radiance is negative
25	SEAICE	Possible sea ice contamination
26	NAVFAIL	Bad navigation
27	FILTER	Pixel rejected by user-defined filter
28	SSTWARN	SST quality is reduced
29	SSTFAIL	SST quality is bad
30	HIPOL	High degree of polarization
31	spare	spare
32	OCEAN	not cloud or land

Level-2 flags used as masks in Level-3 processing

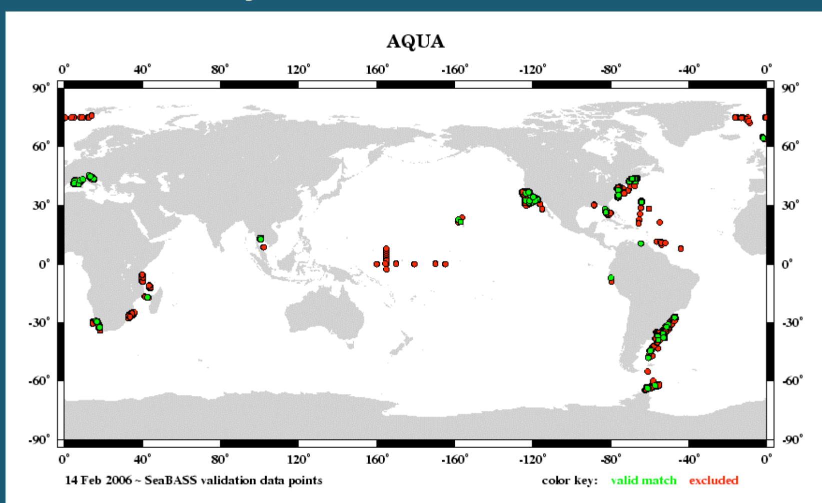
Are the results valid?

SeaBASS

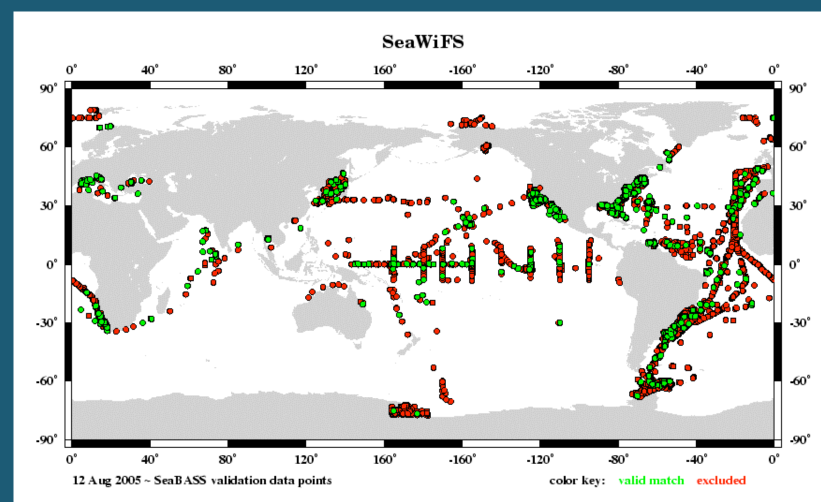
The SeaWiFS Bio–optical Archive and Storage System

Available *In Situ* Match-Ups by Mission

MODIS/Aqua
July 2002 - Present

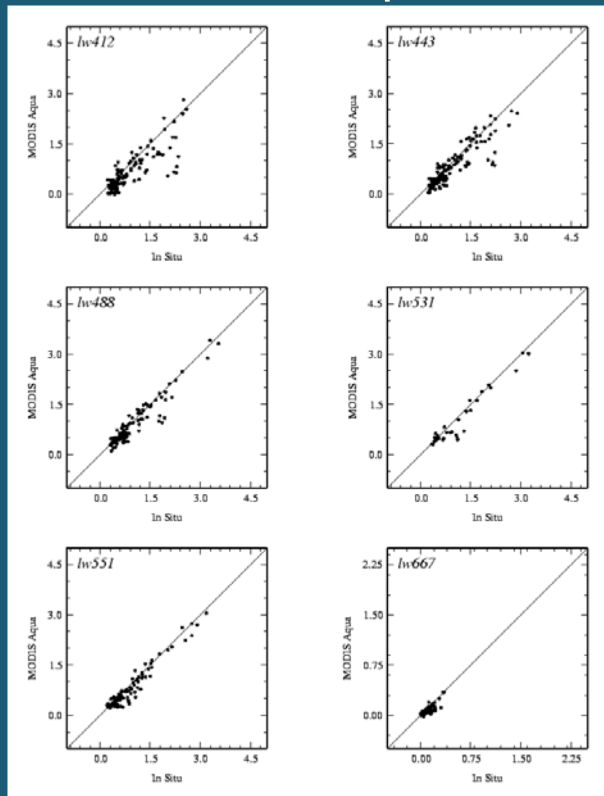


SeaWiFS
Sept 1997 - Present

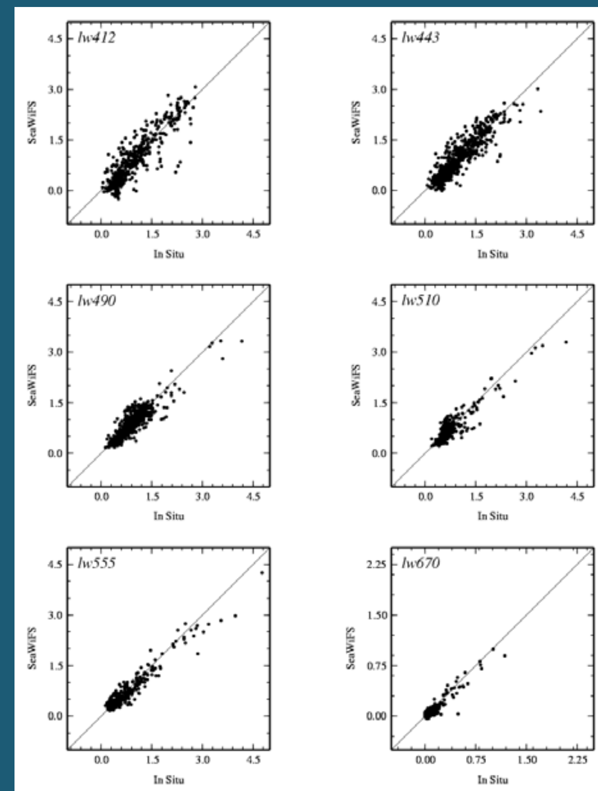


Comparison of Water-Leaving Radiances to *In Situ*

MODIS/Aqua



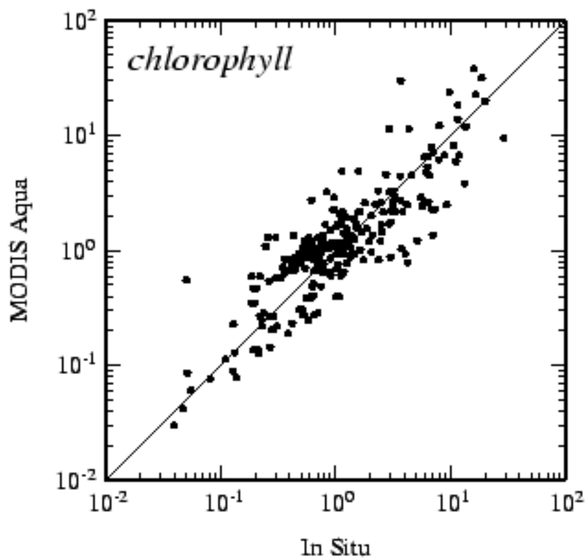
SeaWiFS



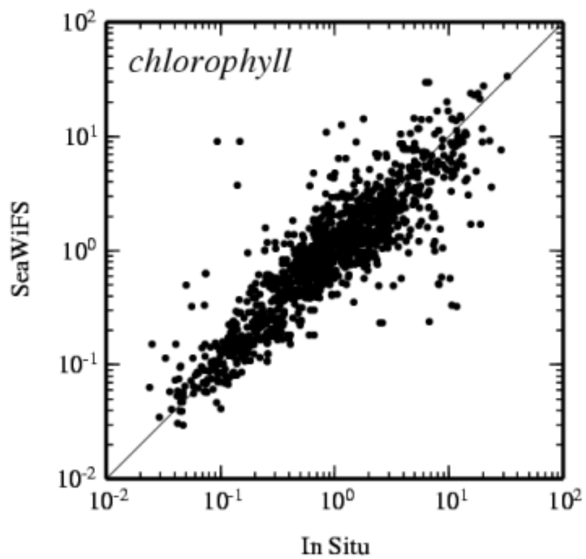
Wavelength		# Matches		Mean Ratio*		% Difference**		r^2	
MODIS	SeaWiFS	MODIS	SeaWiFS	MODIS	SeaWiFS	MODIS	SeaWiFS	MODIS	SeaWiFS
412	412	120	553	0.747	0.905	30.898	24.098	0.742	0.827
443	443	133	702	0.862	0.915	18.811	17.480	0.815	0.830
488	490	109	660	0.923	0.918	14.563	15.101	0.907	0.821
531	510	32	479	0.933	0.918	11.178	13.739	0.934	0.849
551	555	120	702	0.940	0.915	12.255	16.878	0.943	0.931
667	670	107	666	0.682	0.920	36.392	45.717	0.735	0.876

Comparison of Chlorophyll Retrievals to *In Situ*

MODIS/Aqua



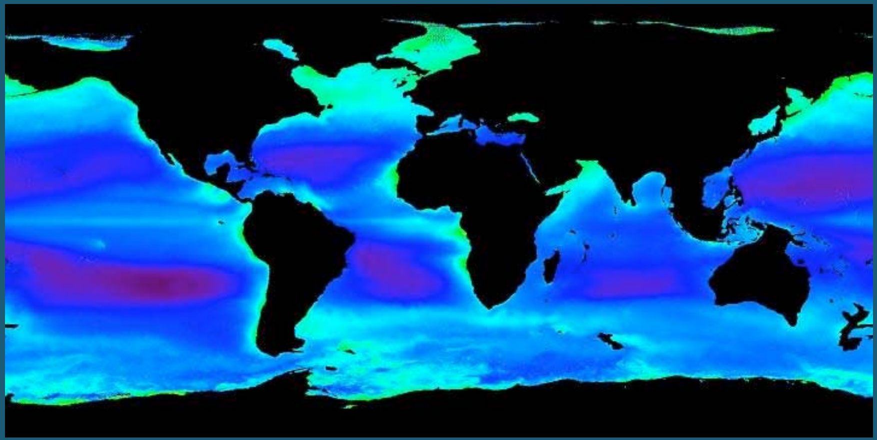
SeaWiFS



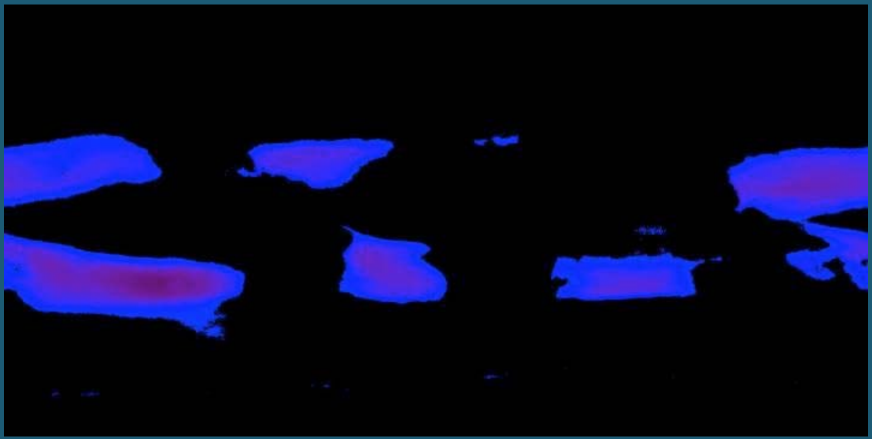
Sensor	# Matches	Mean Ratio	% Diff	r^2
SeaWiFS	1293	0.998	33.1	0.796
MODIS/Aqua	263	1.084	40.4	0.780

Definition of Trophic Subsets

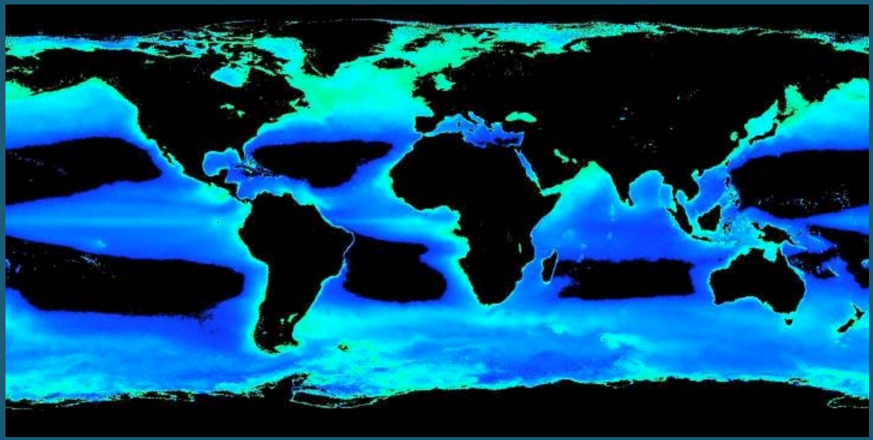
Deep-Water (Depth > 1000m)



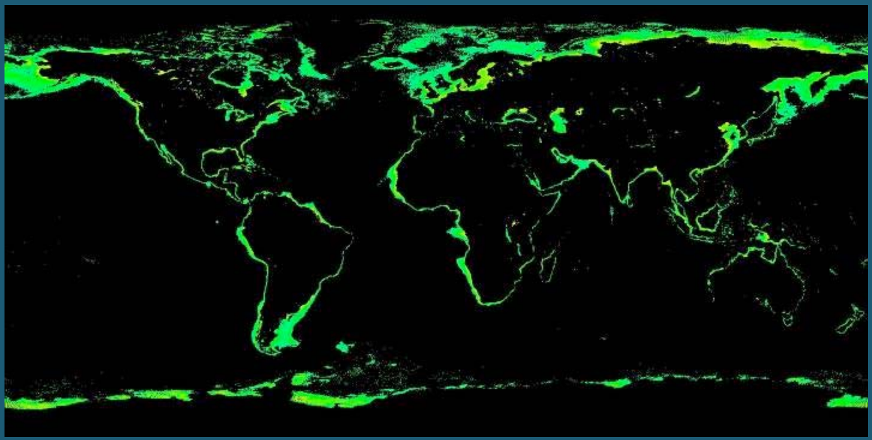
Oligotrophic (Chlorophyll < 0.1)



Mesotrophic (0.1 < Chlorophyll < 1)



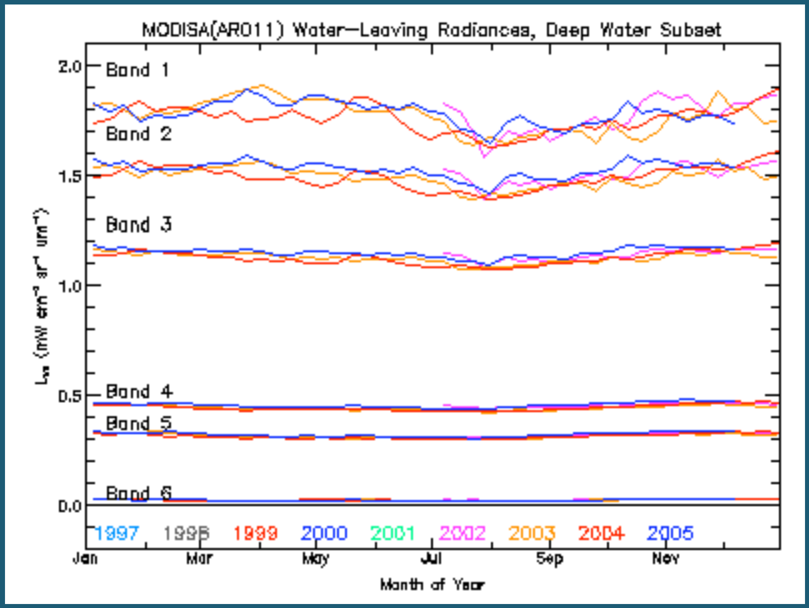
Eutrophic (1 < Chlorophyll < 10)



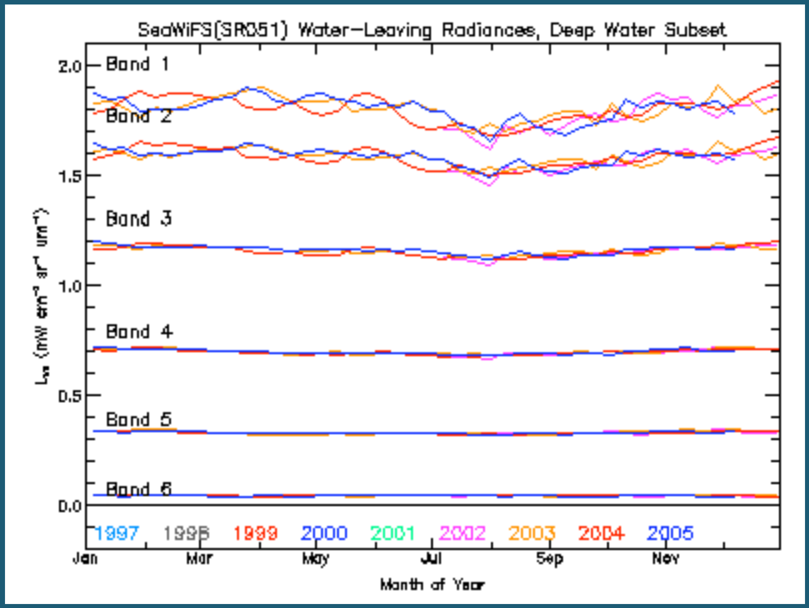
Comparison of Relative Temporal Stability in nLw

Deep-Water, 8-Day Composites, Common Bins

MODIS/Aqua



SeaWiFS

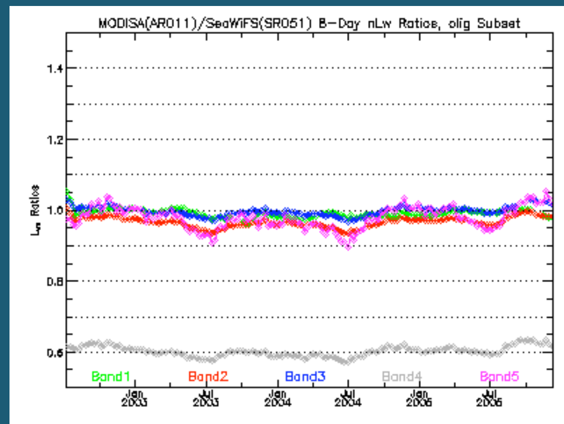


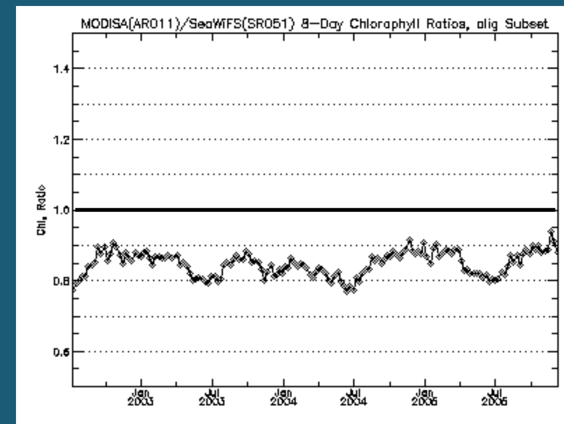
MODIS/SeaWiFS Ratio Trends

nLw Ratios

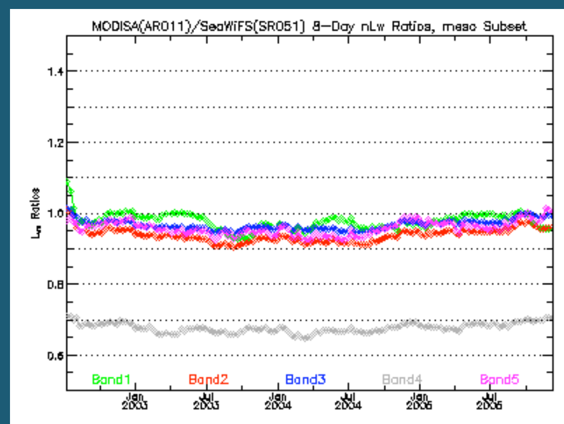
C_a Ratios

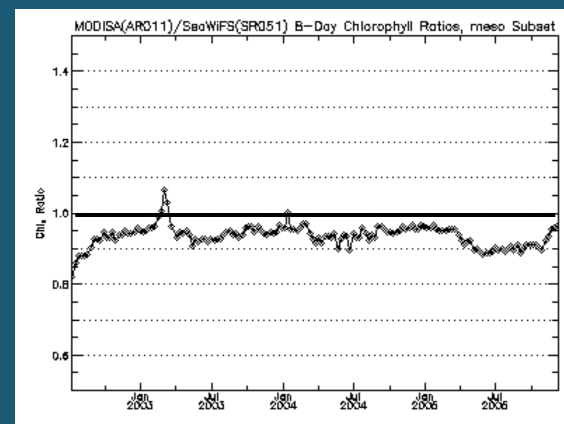
Oligotrophic



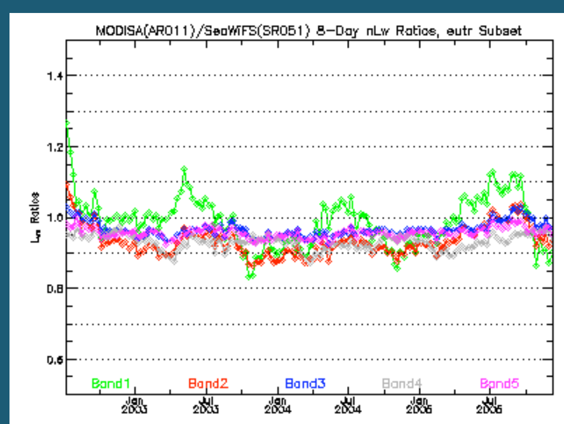


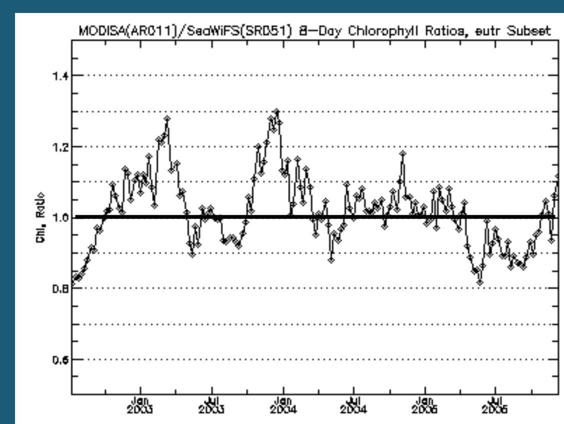
Mesotrophic





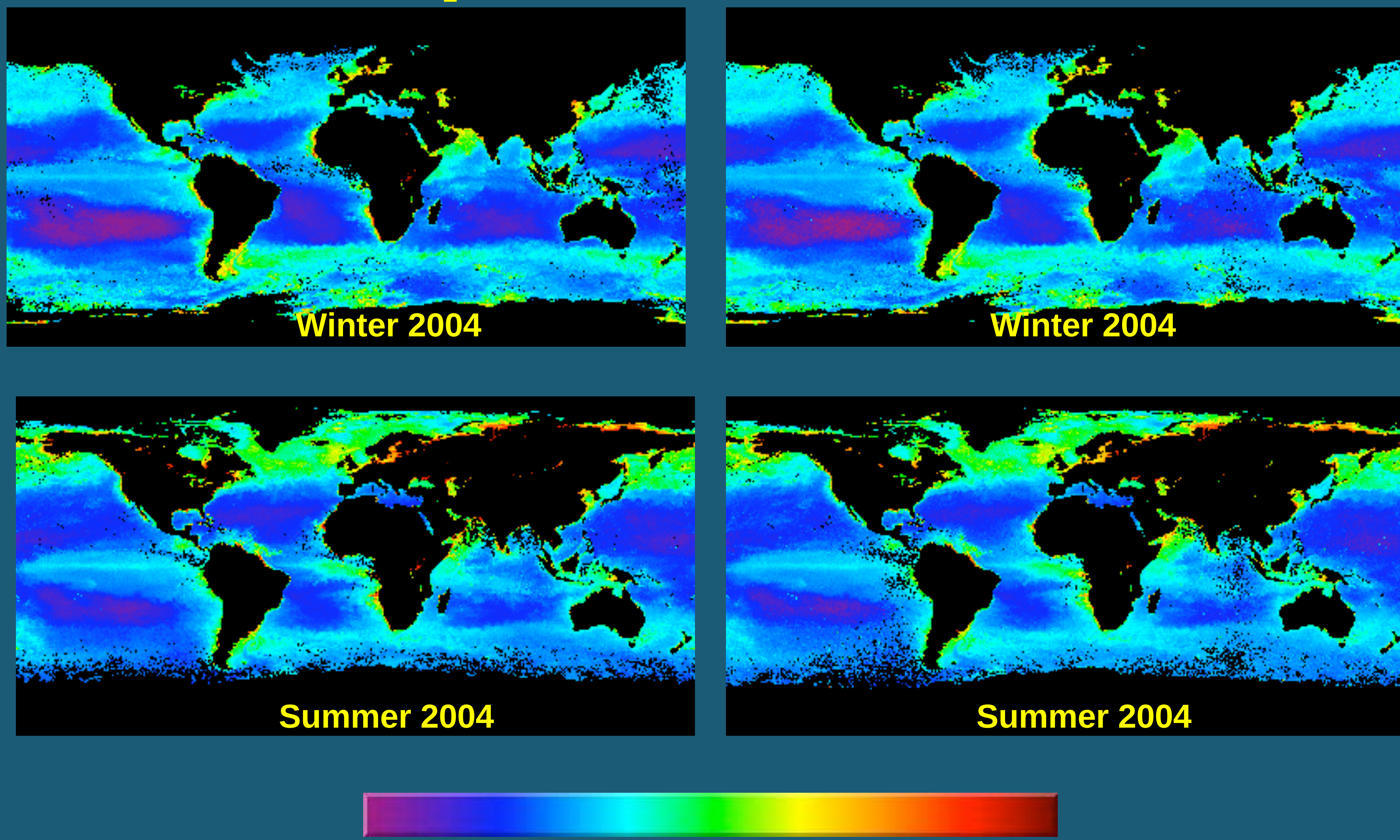
Eutrophic





Seasonal Chlorophyll Images

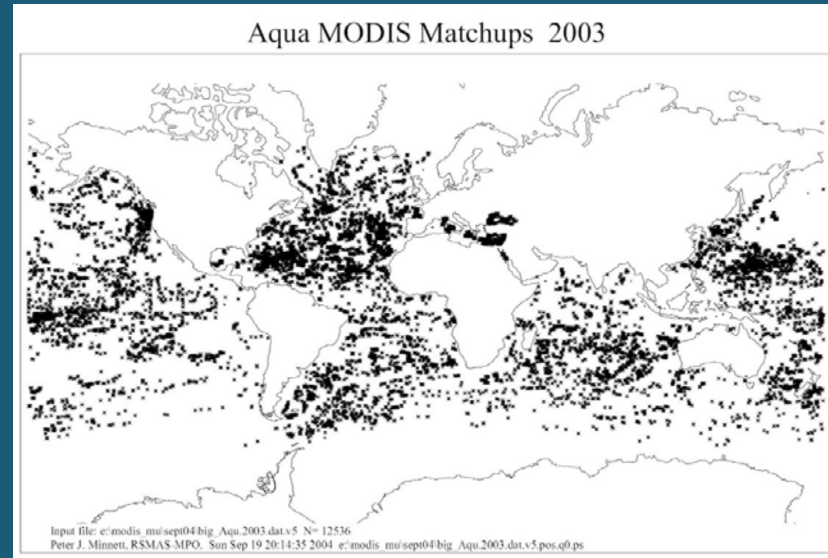
MODIS/Aqua | **SeaWiFS**



0.01-64 mg m^{-3}

SST Validation

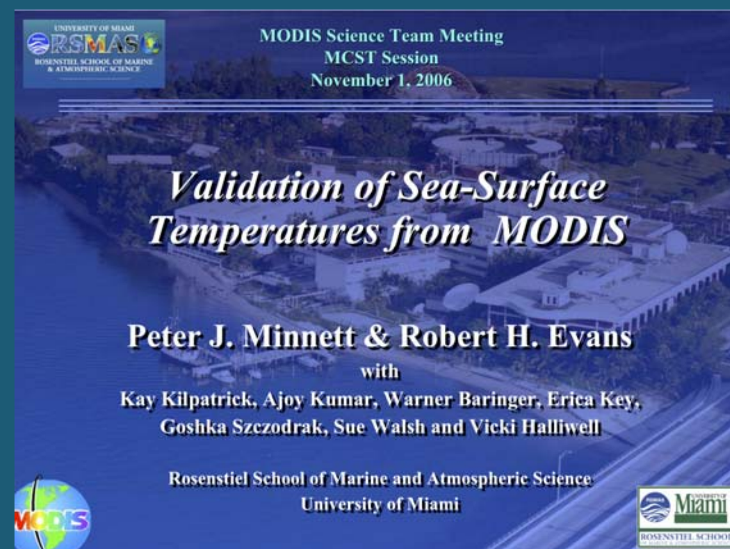
Buoy Measurements



SST 11-12 µm	TERRA					
	day			night		
Year	mean	RMS	Count	mean	RMS	Count
2000	-0.139	0.797	3091	-0.186	0.794	1800
2001	-0.262	1.430	6321	-0.228	0.707	4935
2002	-0.135	0.621	9244	-0.204	0.580	6935
2003	-0.086	0.607	15685	-0.190	0.558	11058
2004	-0.068	0.579	24964	-0.167	0.559	16943
2005	-0.110	0.549	39826	-0.213	0.519	28460
2006	-0.105	0.574	32495	-0.208	0.524	23149
all years	-0.108	0.650	131626	-0.200	0.555	93280

SST 11-12 µm	AQUA					
	day			night		
Year	mean	RMS	Count	mean	RMS	Count
2002	-0.153	0.538	10293	-0.235	0.499	5906
2003	-0.133	0.577	22988	-0.224	0.508	12977
2004	-0.137	0.562	26415	-0.219	-0.484	15471
2005	-0.152	0.539	40941	-0.235	0.461	25083
2006	-0.135	0.550	34687	-0.205	0.452	22187
all years	-0.142	0.553	135324	-0.222	0.475	81624

SST 4µm	TERRA			AQUA		
Year	night			night		
	mean	RMS	Count	mean	RMS	Count
2000	-0.161	0.829	1993			
2001	-0.220	0.663	5397			
2002	-0.191	0.528	7580	-0.224	0.449	6429
2003	-0.176	0.500	12006	-0.217	0.455	14095
2004	-0.178	0.493	18452	-0.214	0.426	16765
2005	-0.178	0.471	31130	-0.223	0.414	27280
2006	-0.174	0.473	25294	-0.208	0.404	24140
all years	-0.179	0.505	101852	-0.216	0.423	88709



Challenges to Remote Sensing of Coastal and Inland Waters

- Temporal and spatial variability
  - Limitations of satellite sensor resolution and repeat frequency
  - Validity of ancillary data (reference SST, wind)

- Straylight contamination from land

- Non-maritime aerosols (dust, pollution)
  - Region-specific models required
  - Absorbing aerosols

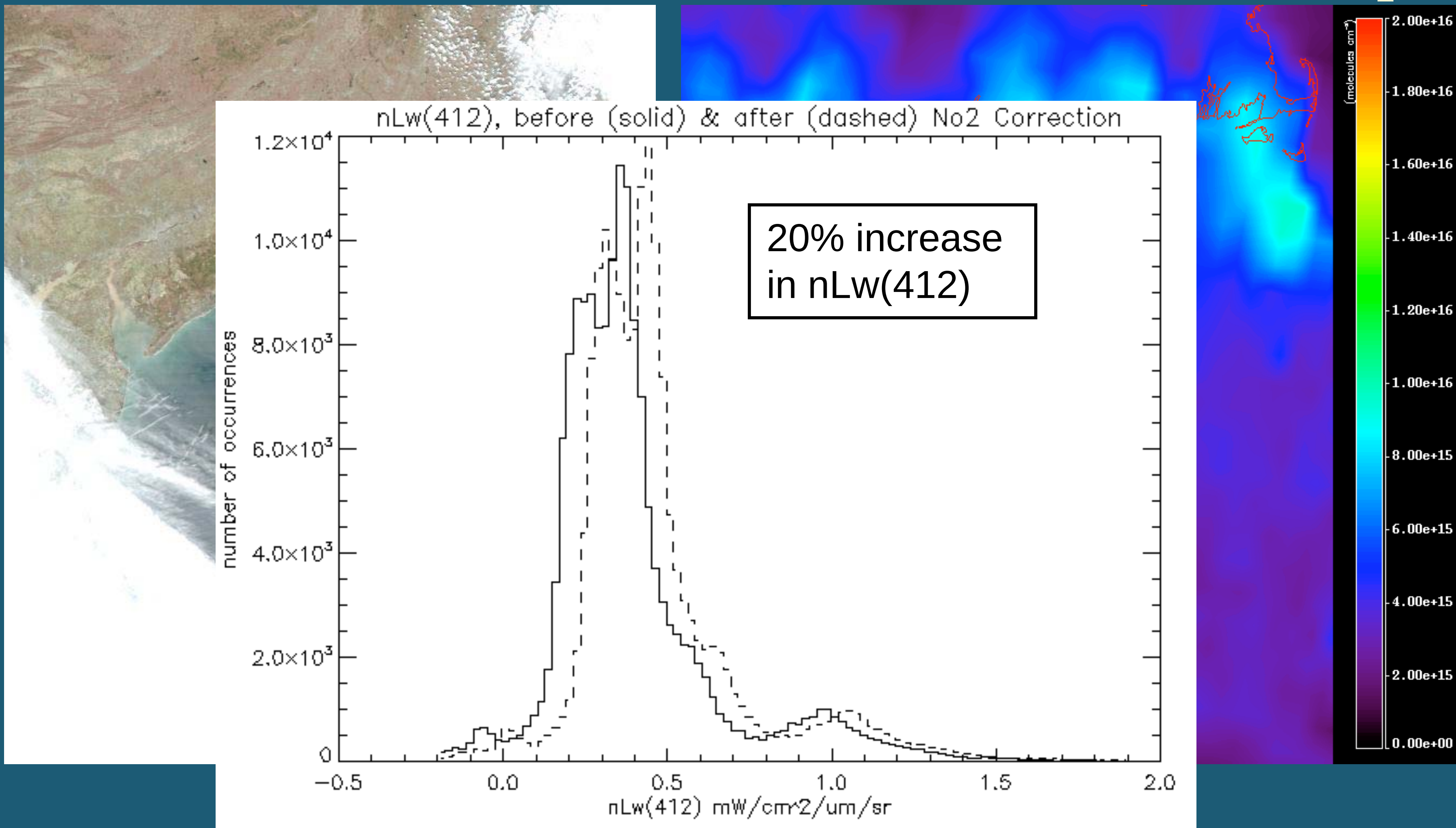
- Anthropogenic emmissions (NO_2 absorption)

- Suspended sediments and CDOM
  - Invalid estimation of Lw(NIR), model not fn(C_a)
  - Saturation of observed radiances

Correction for NO_2 Absorption

MODIS/Aqua RGB

OMI/Aura Tropospheric NO_2



MODIS Land/Atmosphere Bands

Application to Ocean Remote Sensing

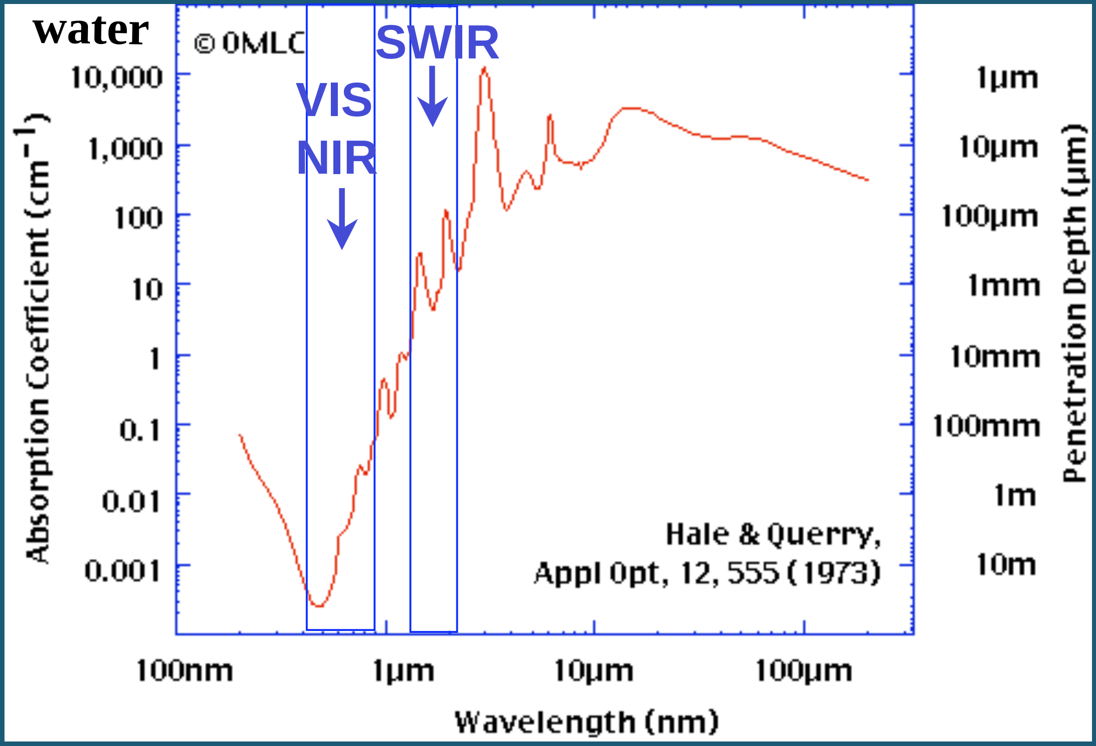
Band	Wavelength	Resolution	Potential Use
1	645 nm	250 m	sediments, turbidity, IOPs
2	859	250	aerosols
3	469	500	C_a, IOPs, $CaCO_3$
4	555	500	C_a, IOPs, $CaCO_3$
5	1240	500	aerosols
6	1640	500	aerosols
7	2130	500	aerosols

Expanded MODIS Ocean Band Suite

Band Number	Wavelength (nm)	Band Width (nm)	Spatial Resolution (m)	SNR at L_{typ}	L_{typ} mW cm^{-2} µm^{-1} sr^{-1}	L_{max} mW cm^{-2} µm^{-1} sr^{-1}
8	412	15	1000	1773	7.84	26.9
9	443	10	1000	2253	6.99	19.0
3	469	20	500	556	6.52	59.1
10	488	10	1000	2270	5.38	14.0
11	531	10	1000	2183	3.87	11.1
12	551	10	1000	2200	3.50	8.8
4	555	20	500	349	3.28	53.2
1	645	50	250	140	1.65	51.2
13	667	10	1000	1962	1.47	4.2
14	678	10	1000	2175	1.38	4.2
15	748	10	1000	1371	0.889	3.5
2	859	35	250	103	0.481	24.0
16	869	15	1000	1112	0.460	2.5
5	1240	20	500	25	0.089	12.3
6	1640	35	500	19	0.028	4.9
7	2130	50	500	12	0.008	1.7

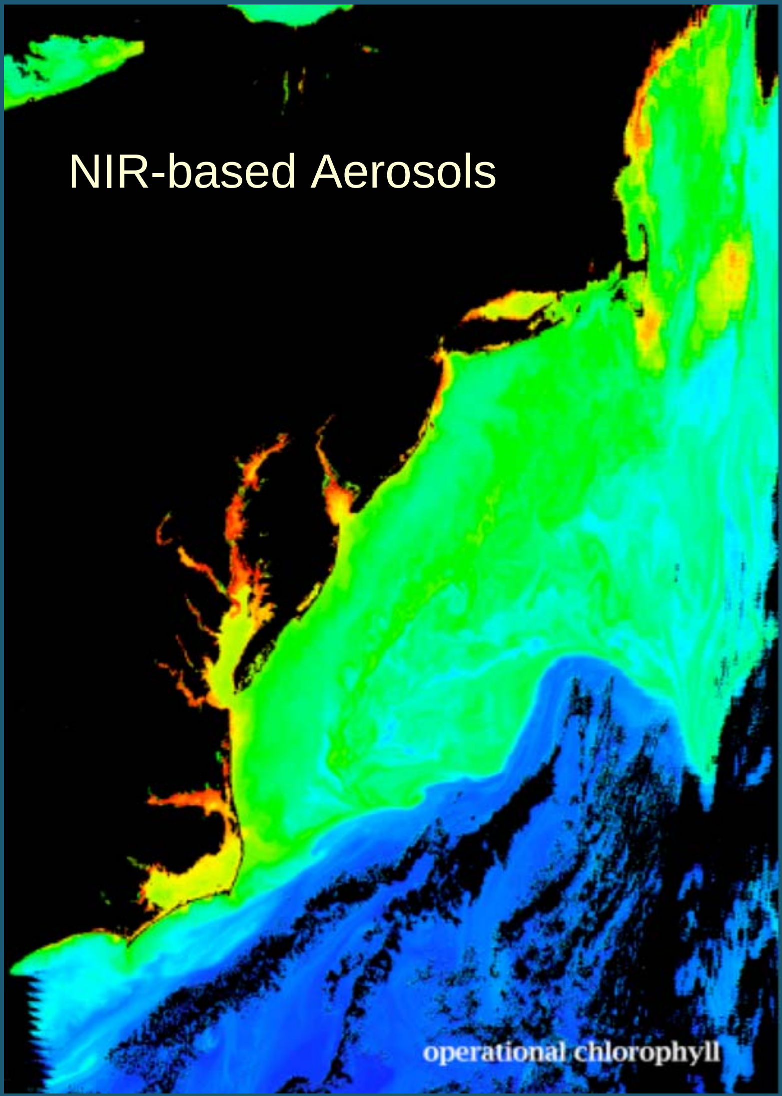
Use of MODIS SWIR bands in coastal waters

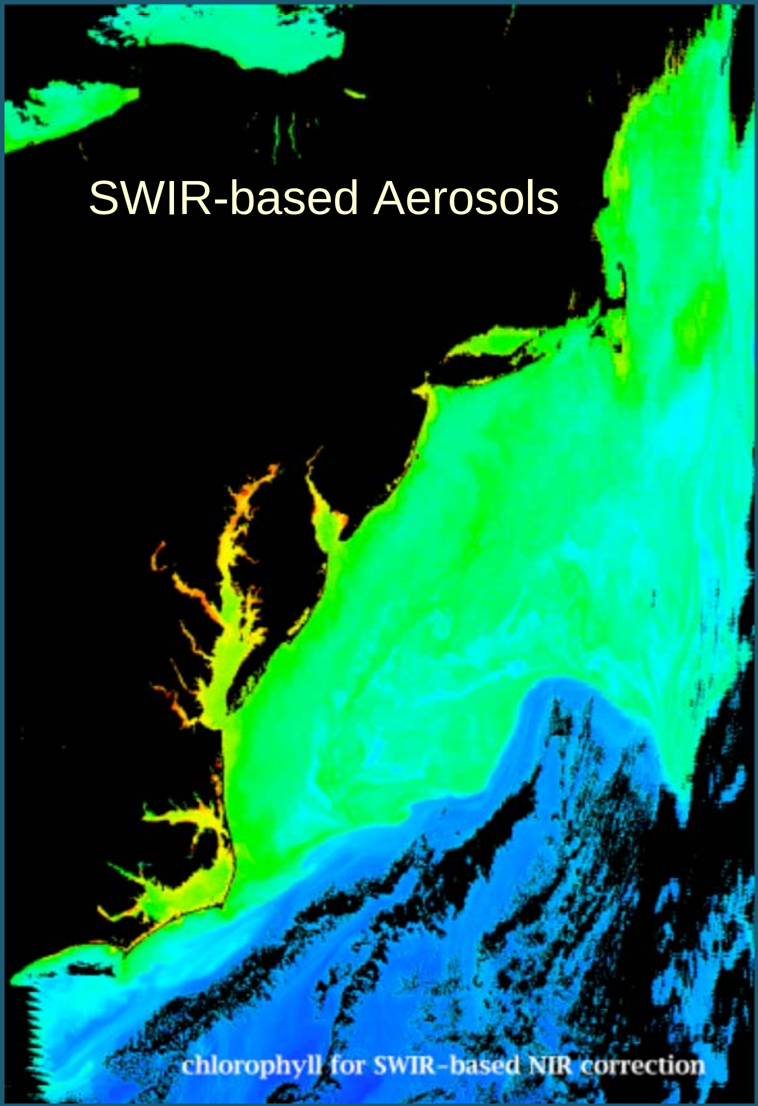
(Wang and Shi, 2005)



- In the SWIR range water has more than one order of magnitude stronger absorption than that at the NIR
- In SWIR ocean is black even in turbid waters, $L_w(SWIR) = 0$

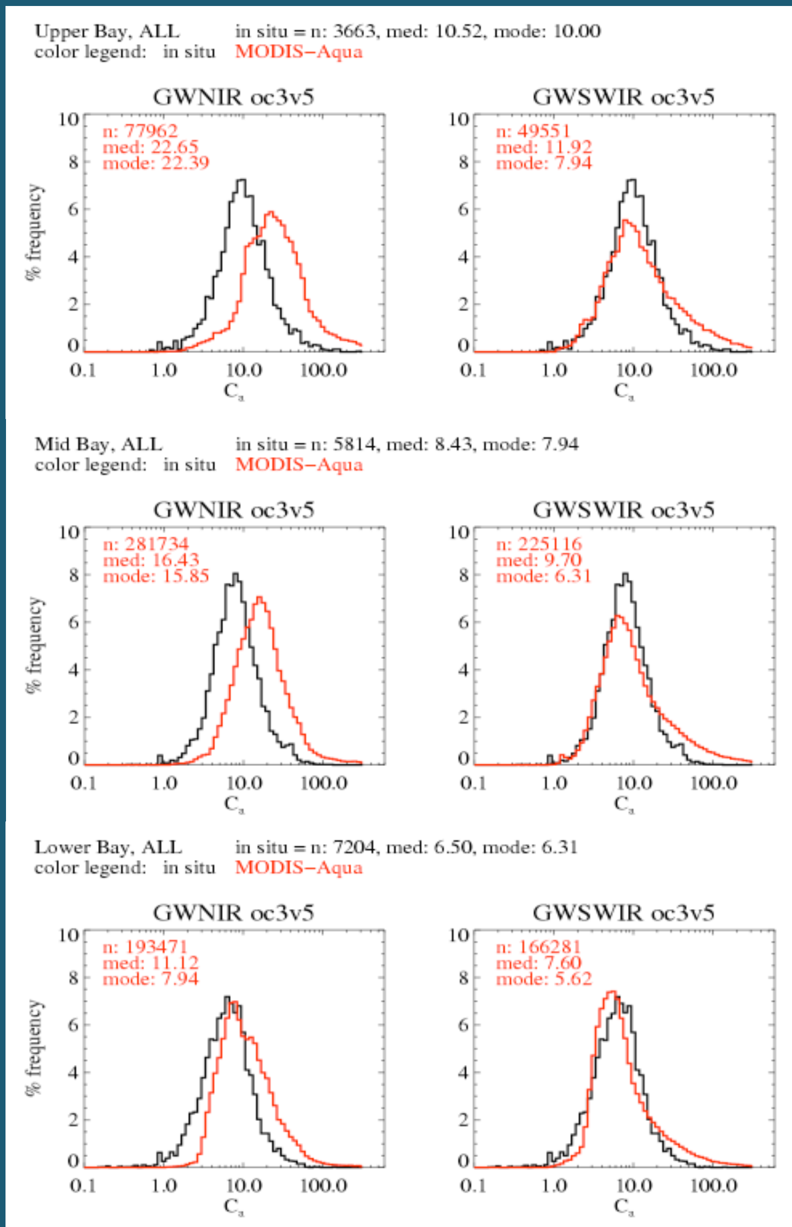
Improved Chlorophyll Retrievals using SWIR bands

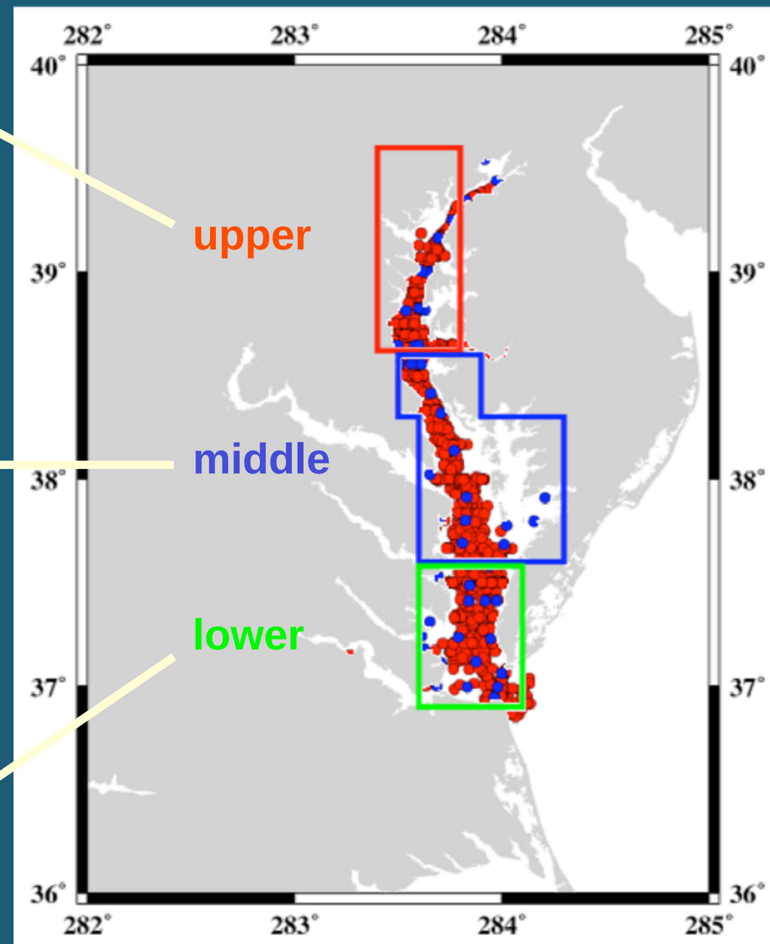




Satellite vs In Situ

NIR SWIR



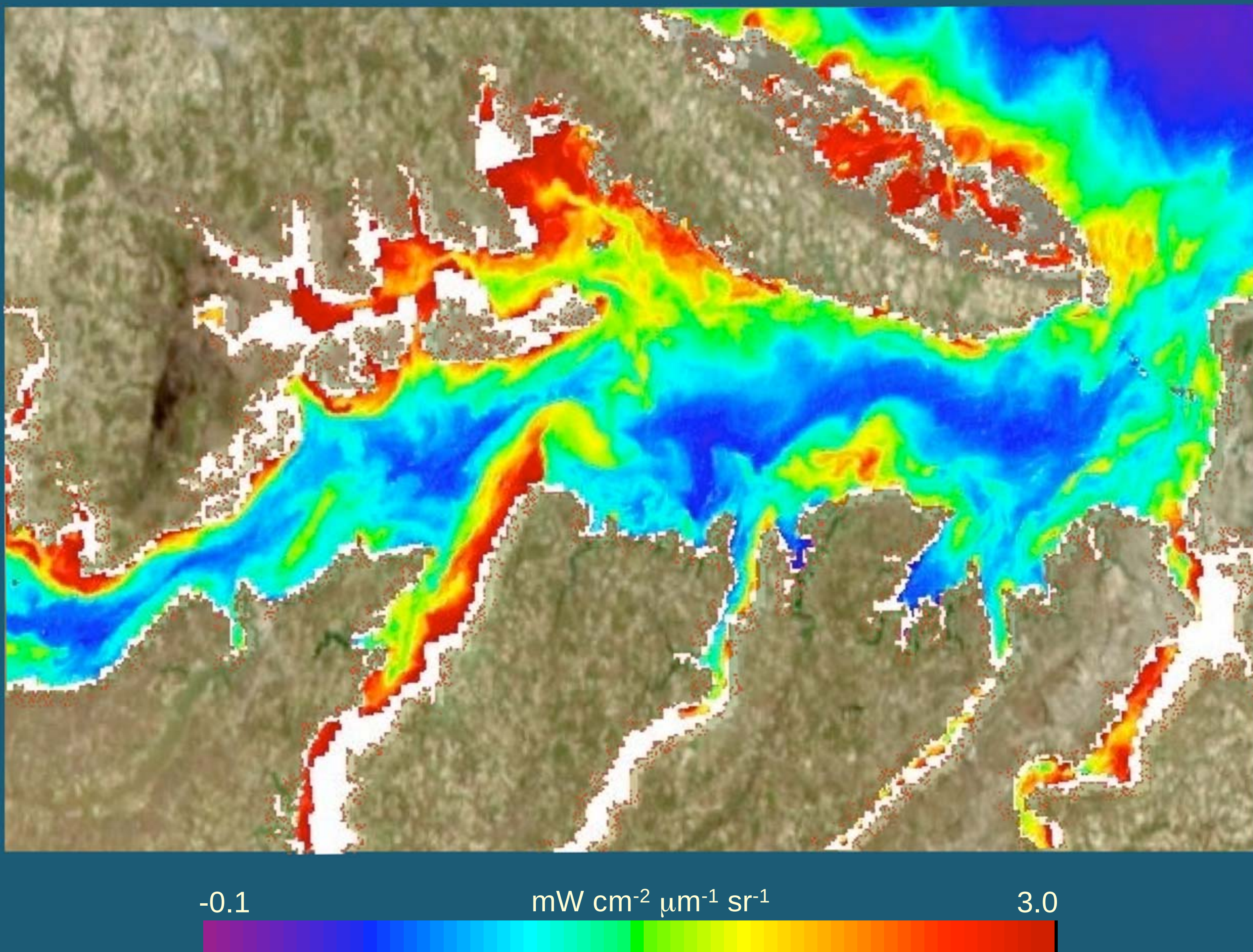


RGB Image: 645, 555, 469

showing river sediments

RGB Image: 250-meter Resolution

nLw(645): 250-meter resolution



Thank You !

Back-up Slides

SST Quality Tests

Bit	Name	Description
00	ISMASKED	Pixel was aready masked
01	BTBAD	Brightness temperatures are bad
02	BTRANGE	Brightness temperatures are out-of-range
03	BTDIFF	Brightness temperatures are too different
04	SSTRANGE	SST outside valid range
05	SSTREFDIFF	SST is too different from reference
06	SST4DIFF	Longwave SST is different from shortwave SST
07	SST4VDIFF	Longwave SST is very different from shortwave SST
08	BTNONUNIF	Brightness temperatures are spatially non-uniform
09	BTVNONUNIF	Brightness temperatures are very spatially non-uniform
10	BT4REFDIFF	Brightness temperatures differ from reference
11	REDNONUNIF	Red-band spatial non-uniformity or saturation
12	HISENZ	Sensor zenith angle high
13	VHISENZ	Sensor zenith angle very high
14	Spare	Spare
15	Spare	Spare

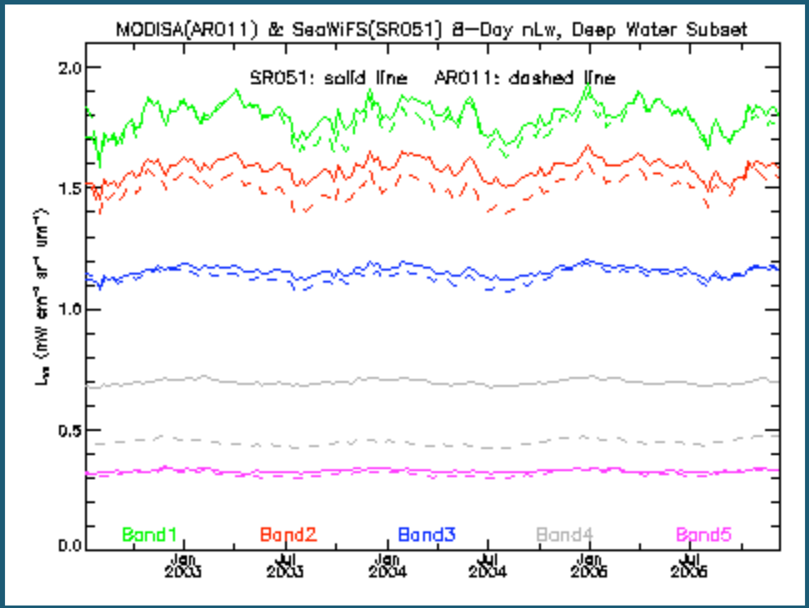
SST Quality Levels

Quality Bit	Minimum Quality Level
ISMASKED	4
BTBAD	4
BTRANGE	3
SSTRANGE	3
BT4REFDIFF	3
SSTREFVDIFF	3
BTVNONUNIF	2
SST4VDIFF	2
VHISENZ	2
SSTREFDIFF	1
BTNONUNIF	1
SST4DIFF	1
HISENZ	1
	0

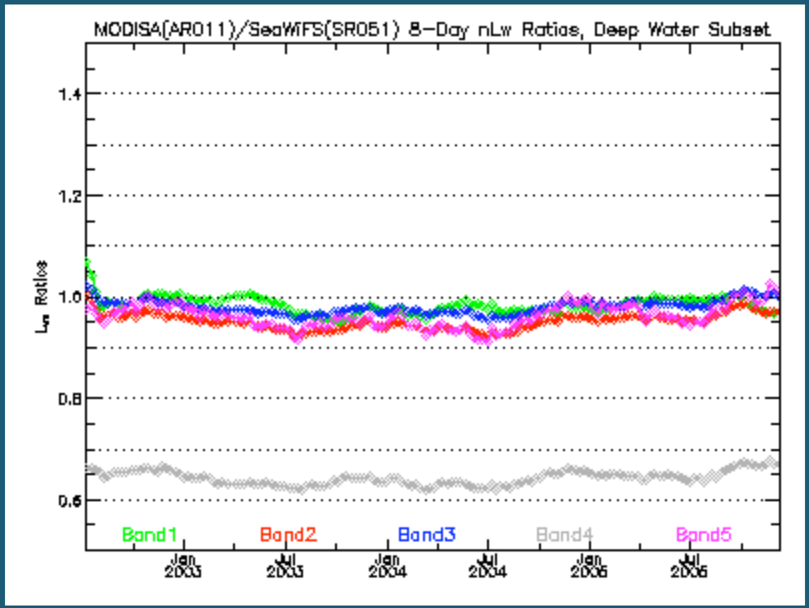
Direct Comparison of Satellite nLw Retrievals

Deep-Water, 8-Day Composites, Common Bins

SeaWiFS & MODIS



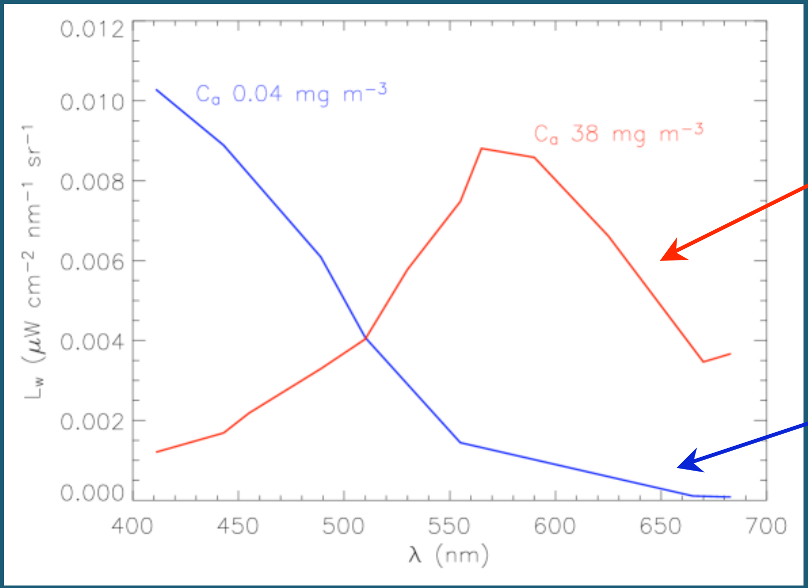
MODIS / SeaWiFS



Coastal waters

- In case-2 waters (colored dissolved organic matter and suspended particles: sediments and phytoplankton), there can be a substantial water-leaving radiance in the NIR

- $L_w(NIR) \neq 0$



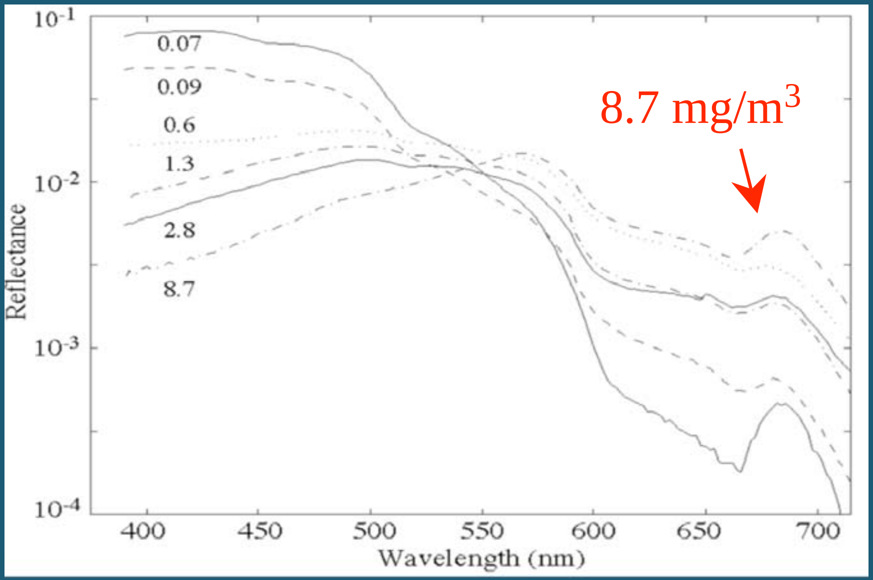
radiance in case-2 waters
- absorption by CDOM the blue
- reflectance by sediments in NIR
- Chesapeake Bay

radiance in clear waters
- phytoplankton only
- around MOBY

- With standard processing, excess NIR radiance is wrongly attributed to the atmosphere
- Overestimation of L_a causes underestimation of L_w and elevated chlorophyll levels

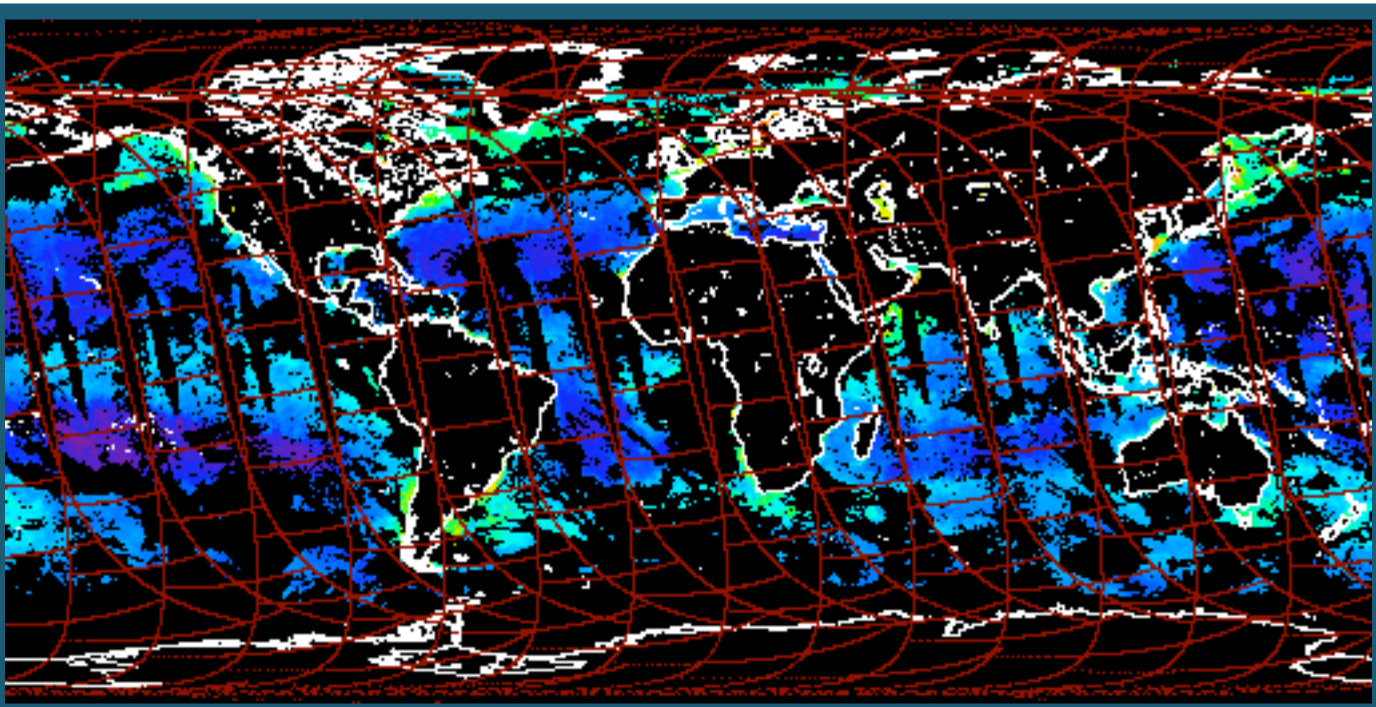
Aerosol Determination in High Chlorophyll

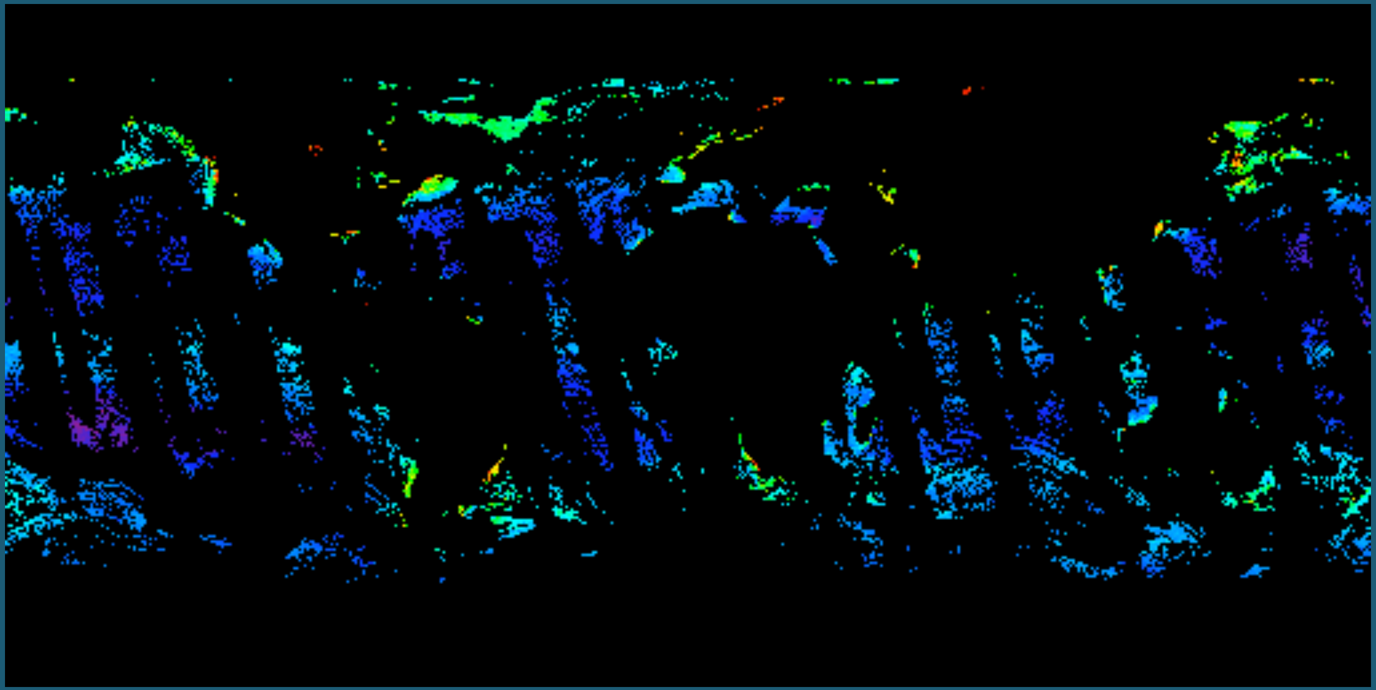
- High chlorophyll waters (or turbid coastal water) may contain significant L_w contribution in the NIR

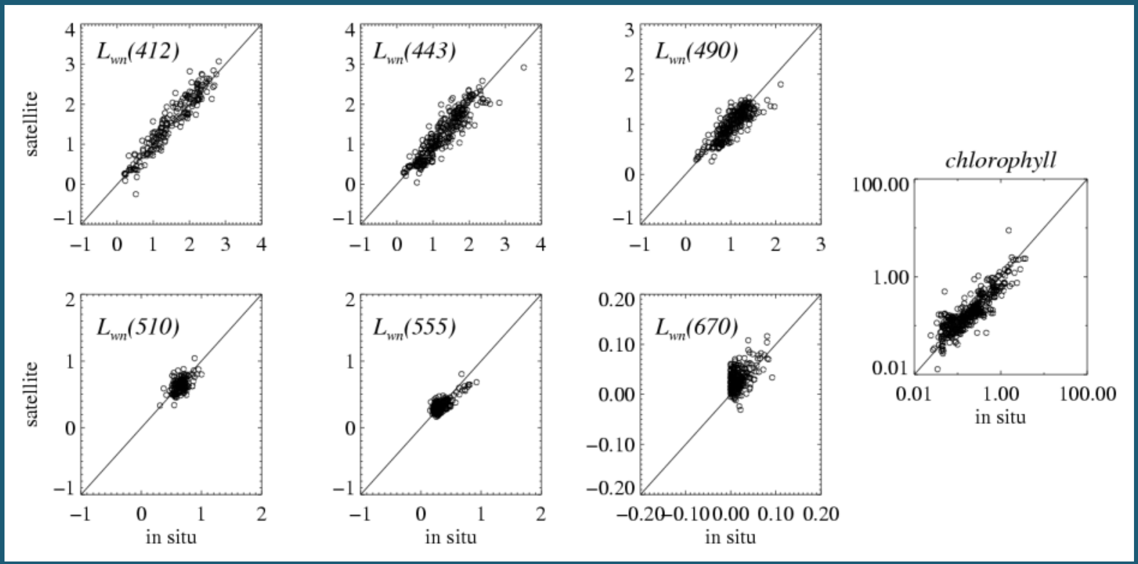


- Atmospheric correction is applied iteratively using NIR reflectance modeling based on consecutive chlorophyll and reflectance retrievals (green & red)

- The modeling assumes
  - NIR absorption to be due to water only, and
  - NIR backscatter to be a function of particulates, colored dissolved organic matter, and detritus







$L_{wn}(412)$
$L_{wn}(443)$
$L_{wn}(490)$
$L_{wn}(510)$
$L_{wn}(555)$
$L_{wn}(670)$
chlorophyll
satellite
in situ

Short-wave SST

$$sst4 = a0 + a1*BT39 + a2*dBT + a3*(1.0/\mu - 1.0)$$

where:

BT39 = brightness temperature at 3.959 um, in deg-C

BT40 = brightness temperature at 4.050 um, in deg-C

μ = cosine of sensor zenith angle

dBT = BT39 - BT40

a0, a1, a2, a3 - fit coefficients derived

- derived by regression of MODIS BTs with *in situ* buoys
- vary seasonally (probably due to residual water-vapor effects)
- determined by science team PI (Peter Minnett and Univ. Miami staff)

Long-wave SST

dBT <= 0.5

sst = a00 + a01*BT11 + a02*dBT*bsst + a03*dBT*(1.0/μ-1.0)

dBT >= 0.9

sst = a10 + a11*BT11 + a12*dBT*bsst + a13*dBT*(1.0/μ-1.0)

0.5 < dBt < 0.9

sstlo = a00 + a01*BT11 + a02*dBT*bsst + a03*dBT*(1.0/μ-1.0)

ssthi = a10 + a11*BT11 + a12*dBT*bsst + a13*dBT*(1.0/μ-1.0)

sst = sstlo + (dBT-0.5)/(0.9-0.5)*(ssthi-sstlo)

where:

BT11 = brightness temperature at 11 um, in deg-C

BT12 = brightness temperature at 12 um, in deg-C

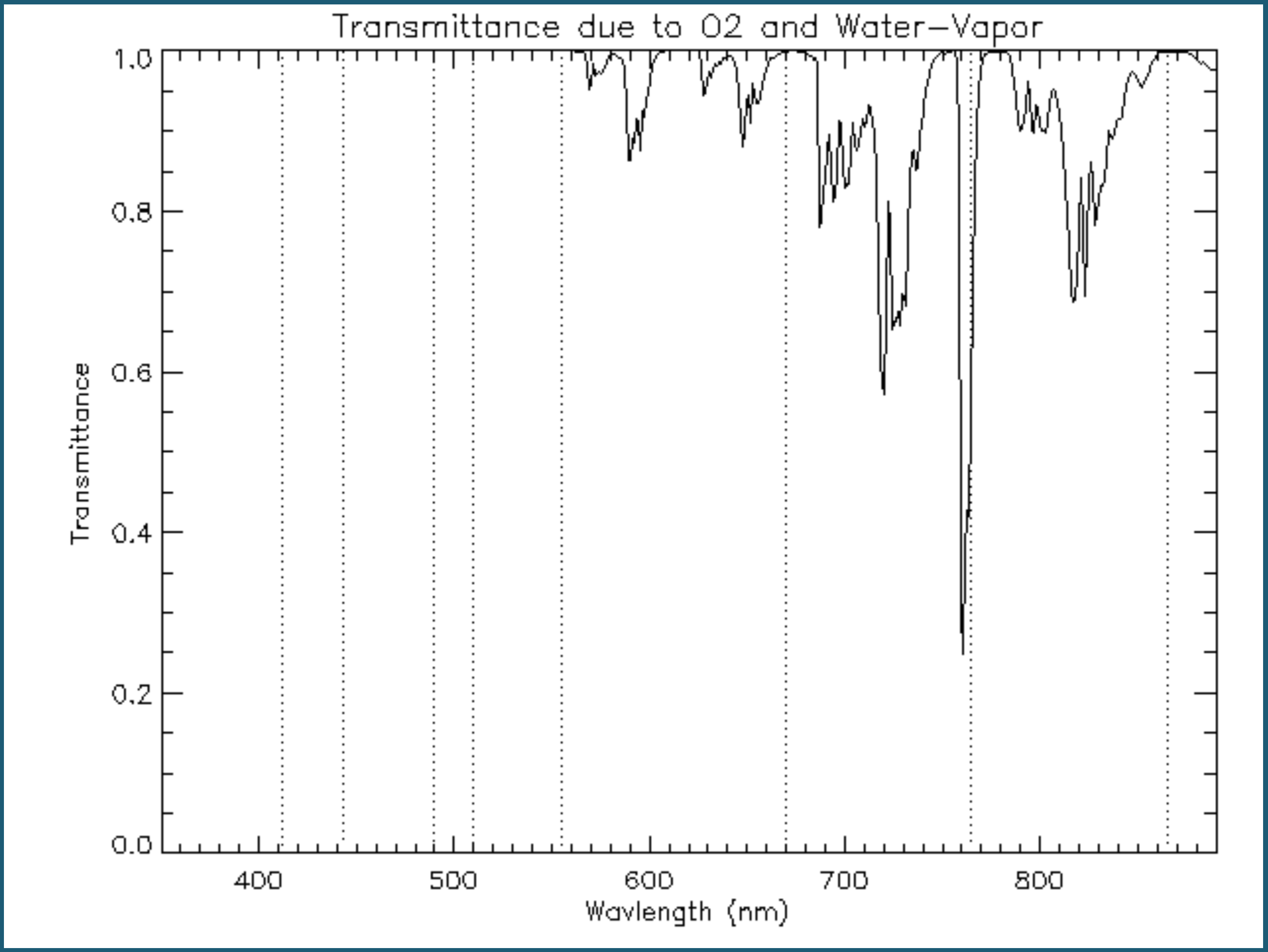
bsst = baseline SST, which is either sst4 (if valid) or sstref (from oisst)

dBT = BT11 - BT12

μ = cosine of sensor zenith angle

Gaseous Absorption

Transparency Windows



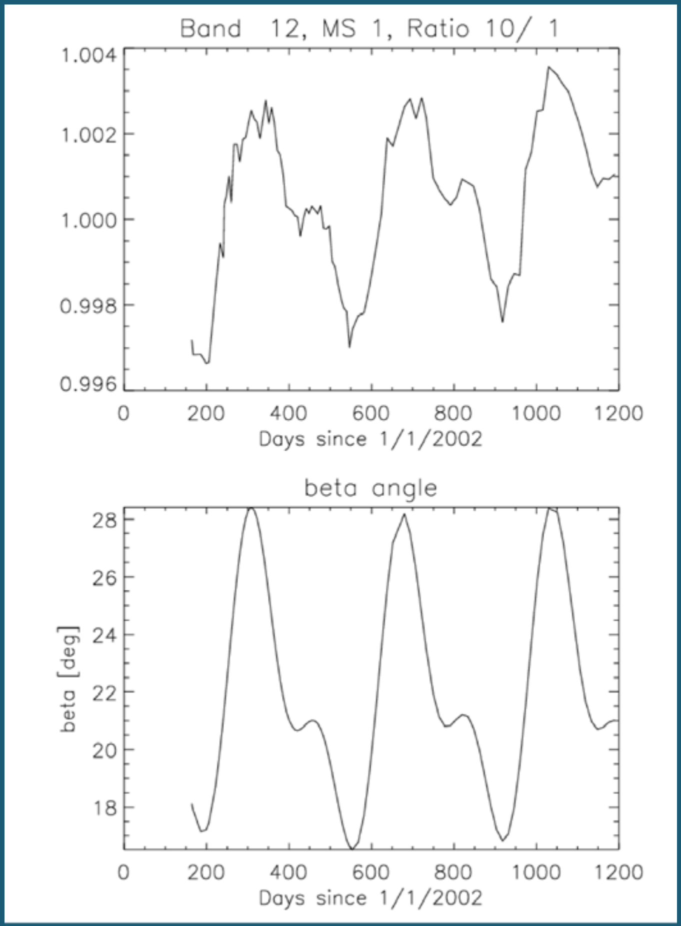
Atmospheric Correction Equation

$$L_t = L_r + (L_a + L_{ra}) + tL_{wc} + TL_g + t\,L_w$$

- L_w is the quantity we wish to retrieve at each wavelength.
- TL_g is Sun glint, the direct reflectance of the solar radiance from the sea surface. Function of geometry and wind.
- tL_{wc} is the contribution due to "white"-capping, estimated from statistical relationship with wind speed.
- L_r is the contribution due to molecular (Rayleigh) scattering, which can be accurately computed.
- $L_a + L_{ra}$ is the contribution due to aerosol and Rayleigh-aerosol scattering, estimated in NIR from measured radiances and extrapolated to visible using aerosol models.

Revised Temporal Calibration
Reflected Solar Bands

- In collaboration with MCST
- Reanalyzed Onboard Calibration (OBC) Data (solar, lunar)
- Removed residual correlations with diffuser screen geometry
- Refit solar diffuser trends to double exponential model
- Improved LUT extrapolation



Multi-Mission Approach

- Common software for Level-1 through Level-3
  - reduces potential for algorithm and implementation differences
  - sensor-specific issues consolidated in i/o function and external tables
- Mission-independent, distributed processing system
  - controls staging/sequencing of processing jobs for max through-put
  - 150x global reprocessing for MODIS, 1600x for SeaWiFS
- Standard procedures for calibration and validation
  - temporal calibration via On-Board Calibration system (OBC)
  - vicarious calibration to MOBY (instrument + algorithm calibration)
  - validation against SeaBASS *in situ* archive
  - temporal trending analysis of Level-3 products

Aerosol modeling

- Shettle and Fenn (1979) introduced a set of basic aerosol models
  - tropospheric
  - coastal
  - maritime, and
  - urban
- Each model consists of a mixture of dry aerosol particles that will grow when exposed to a humid environment
- Tropospheric, coastal, and maritime models defined for different humidity ranges are used in ocean color atmospheric correction

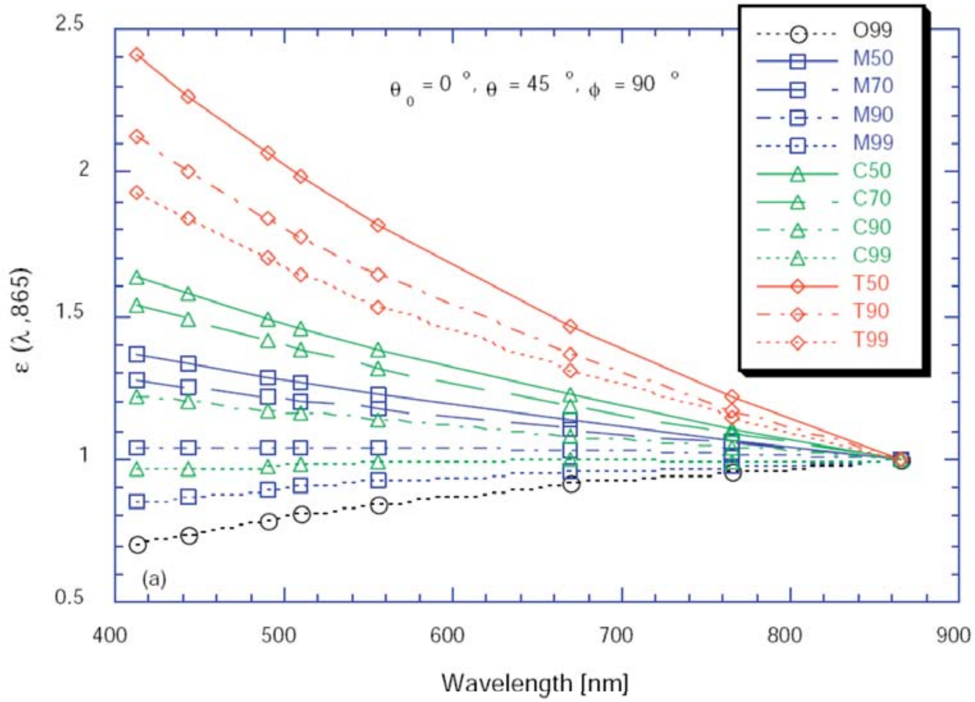
Operational aerosol models

(Gordon and Wang, 1994)

- There are 12 aerosol models used in the current atmospheric correction

- The models are tabulated per sensor wavelength
  - albedo
  - extinction coefficient
  - phase function value per scattering angles
  - quadratic equation coefficients per θ_0, θ, ϕ for conversion from single scattering to multiple scattering reflectance
  - Rayleigh-aerosol diffuse transmittance coefficients, a and b

		AEROSOL MODELS
1	O99	oceanic 99% humidity
2	M50	maritime 50% humidity
3	M70	maritime 70% humidity
4	M90	maritime 90% humidity
5	M99	maritime 99% humidity
6	C50	coastal 50% humidity
7	C70	coastal 70% humidity
8	C90	coastal 90% humidity
9	C99	coastal 99% humidity
10	T50	tropospheric 50% humidity
11	T90	tropospheric 90% humidity
12	T99	tropospheric 99% humidity



Model parameters

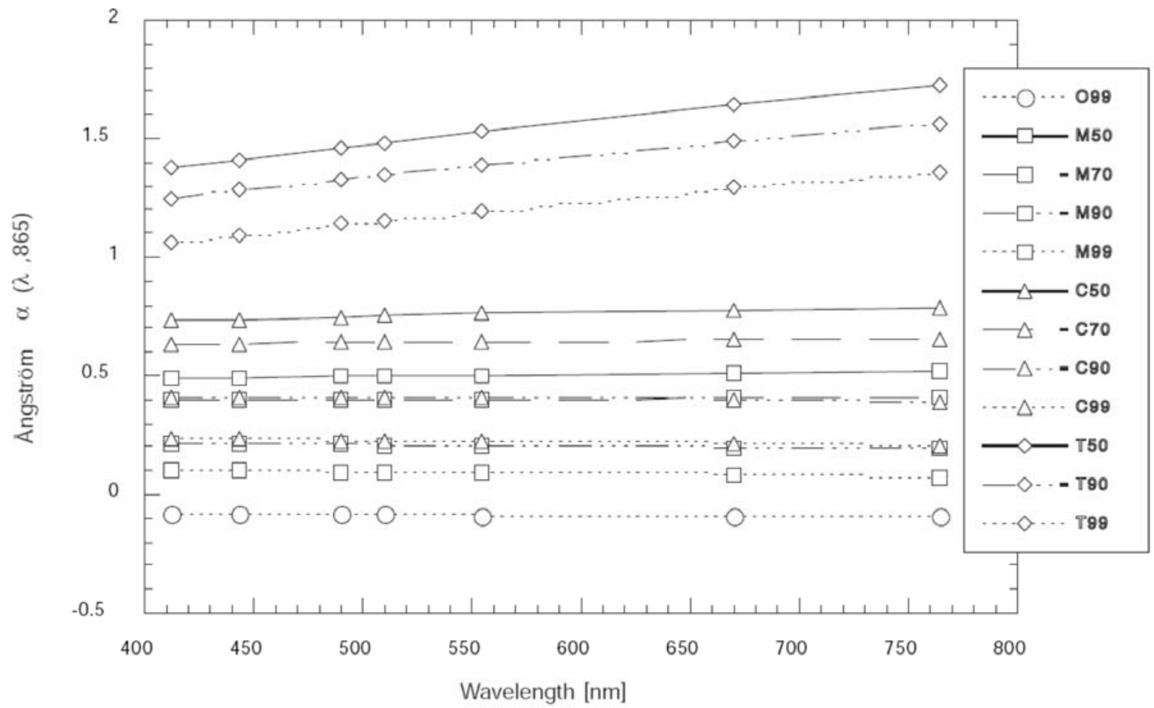
Single scattering reflectance ratio

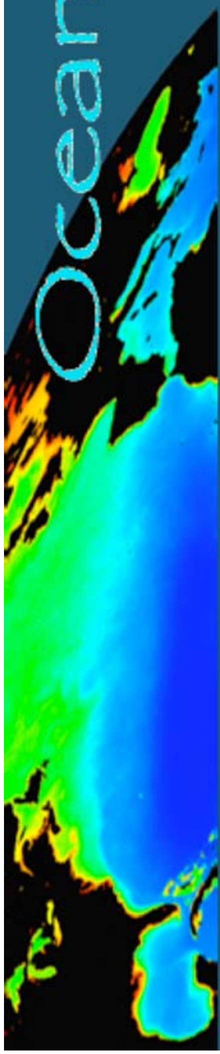
$$\varepsilon(\lambda, 865) = \frac{\rho_{as}(\lambda)}{\rho_{as}(865)}$$

Ångström exponent

$$\alpha = \frac{\ln\left(\tau(\lambda)/\tau(865)\right)}{\ln\left(865/\lambda\right)}$$

flat slope ⇒ weak wavelength dependence ⇒ large particles





Sequence of operations

(Gordon and Wang, 1994)

- Obtain L_a from the top-of-the-atmosphere NIR radiances

$$L_a = [(L_t - tL_{wc}) / t_{oz\_sol} / t_{oz\_sen} / polcor - L_r] / t_{o_2} - TL_g$$

- Select the tabulated aerosol model which two-band relative NIR reflectances are the closest to satellite-derived reflectances
- Using this aerosol model estimate aerosol contribution in the visible bands
- Remove aerosol radiance in the visible bands
- Calculate VIS water-leaving radiances

	SeaWiFS Band	SeaWiFS λ (nm)
	1	412
	2	443
	3	490
	4	510
	5	555
	6	670
NIR {	7	765
	8	865

Use of ε in atmospheric correction

- ε is used in selection of aerosol models and in propagating model reflectance from the NIR to VIS wavelengths
- ε is a ratio of single scattering aerosol reflectance

$$\varepsilon(\lambda, 865) = \frac{\rho_{as}(\lambda)}{\rho_{as}(865)}, \qquad \text{where } \rho = \frac{\pi L}{F_0 \cdot \mu_0}$$

- ε is assumed known for any type of aerosol and geometry

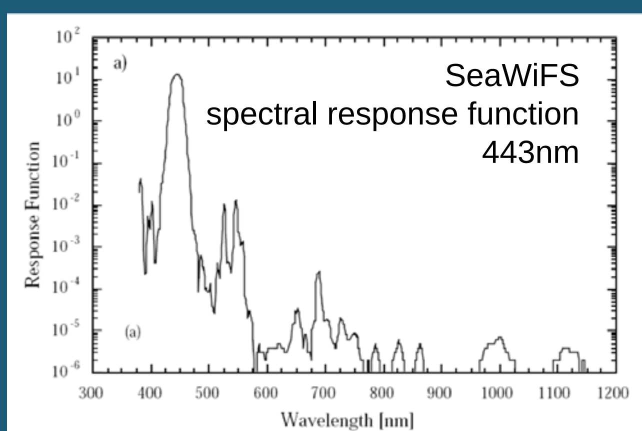
- $L_t(NIR) \Rightarrow L_a(NIR) \Rightarrow \rho_a(NIR) \Rightarrow \rho_{as}(NIR) \Rightarrow \varepsilon(765, 865)$
- Find two aerosol models which theoretical ε brackets the ε calculated from the data
- Get modeled ε for the two models for VIS wavelengths
- Extrapolate ρ_{as} to VIS for the two models

$$\rho_{as}(\lambda) = \rho_{as}(865) \cdot \varepsilon(\lambda, 865)$$

- $\rho_{as}(\lambda) \Rightarrow \rho_a(\lambda)$
- Average $\rho_a(\lambda)$ between the two models $\Rightarrow L_a(\lambda) \Rightarrow tL_w(\lambda)$

nLw calculation

- $nL_w = \dfrac{L_w \cdot brdf}{t_{sol} \cdot t_{oz\_sol} \cdot \mu_0 \cdot f_{sol}}$
  - nL_w - the radiance that would be measured exiting the flat surface of the ocean with the Sun at zenith (directly overhead) and with the atmosphere absent
- $nL_w(VIS) \Rightarrow nL_w(VIS_{10nm})$
  - correction of the retrieved nL_w from the full bandpass averaged value to a 10-nm square bandpass centered on the sensor nominal wavelength



θ_0 – solar zenith angle, θ – sensor zenith, ϕ – relative azimuth
$\mu_0 = \cos(\theta_0)$, $\mu = \cos(\theta)$
f_{sol} – solar distance correction factor
t_{oz_sen} – diffuse transmittance from surface to sensor through ozone layer
t_{oz_sen} – diffuse transmittance from Sun to surface through ozone layer
brdf – bidirectional reflectance correction at surface

Chlorophyll algorithms

- Each sensor has a default empirical chlorophyll algorithm
  - MODIS-Aqua default, OC3 algorithm

$$C_a = 10^{0.283-2.753R+1.457R^2+0.659R^3-1.403R^4}, \text{ where } R = log_{10}\left(\frac{R_{rs}443 > R_{rs}488}{R_{rs}551}\right)$$

  - SeaWiFS default, OC4 algorithm

$$C_a = 10^{0.366-3.067R+1.930R^2+0.649R^3-1.532R^4}, \text{ where } R = log_{10}\left(\frac{R_{rs}443 > R_{rs}490 > R_{rs}510}{R_{rs}555}\right)$$

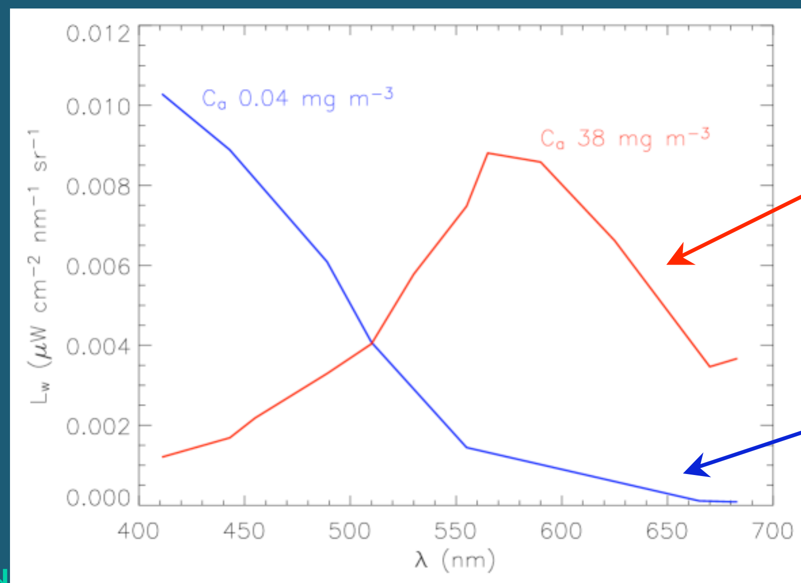
- There are other optional empirical and semi-analytical algorithms (inversion of $R_{rs} = \frac{f}{Q} \frac{b_w + b_{ph} + b_d}{a_w + a_{ph} + a_d + a_g}$), e.g. Garver, Siegel, Maritorena, 2001
- There are optional IOP algorithms, e.g. Z.P. Lee, Carder

remote sensing reflectance $R_{rs} = nL_w / F_0$, w – water, ph – phytoplankton, d – suspended particulate matter, g – colored dissolved organic matter

Uncertainties in the operational atmospheric correction

Coastal waters

- In case-2 waters (colored dissolved organic matter and suspended particles: sediments and phytoplankton), there can be a substantial water-leaving radiance in the NIR
- $L_w(NIR) \neq 0$

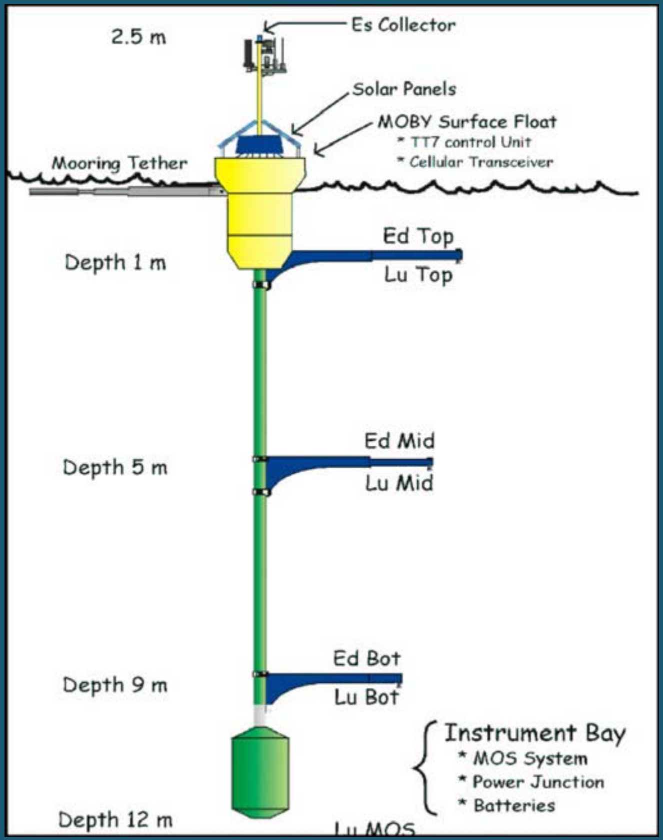


radiance in case-2 waters
- absorption by CDOM in the blue
- reflectance by sediments in the NIR
- Chesapeake Bay

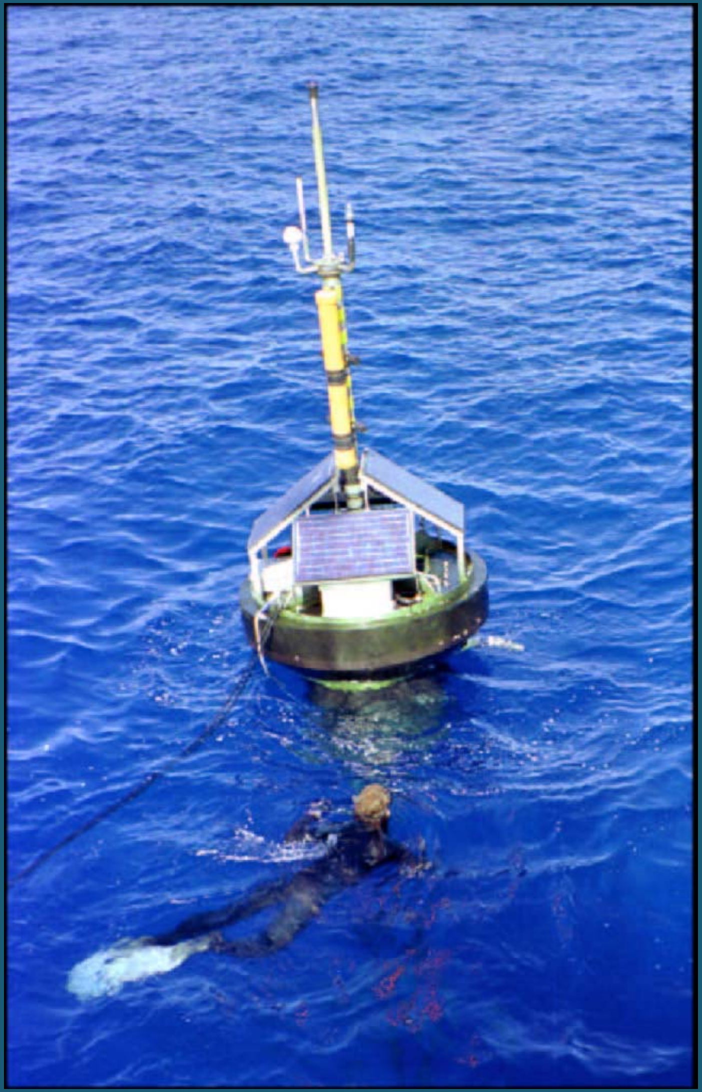
radiance in clear waters
- phytoplankton only
- around MOBY

- With standard processing, excess NIR radiance is wrongly attributed to the atmosphere
- Overestimation of L_a causes underestimation of L_w and elevated chlorophyll levels

Vicarious Calibration



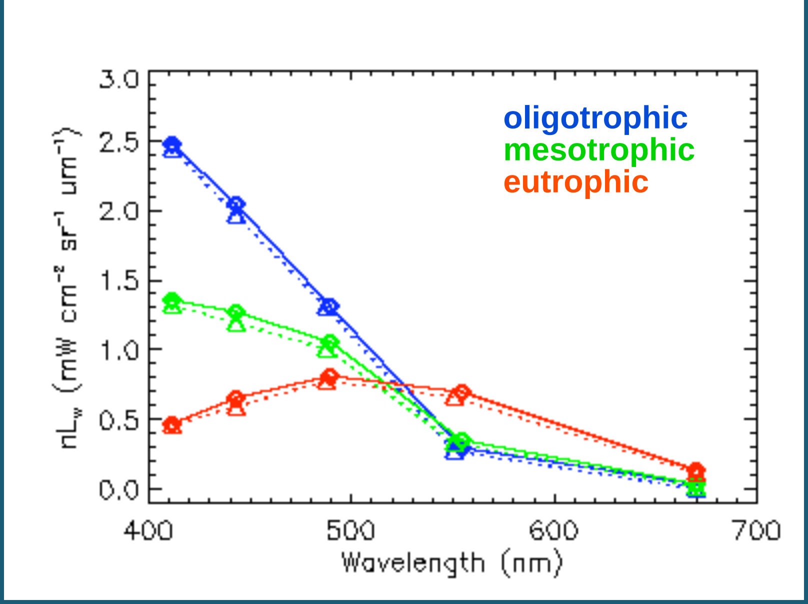
MOBY



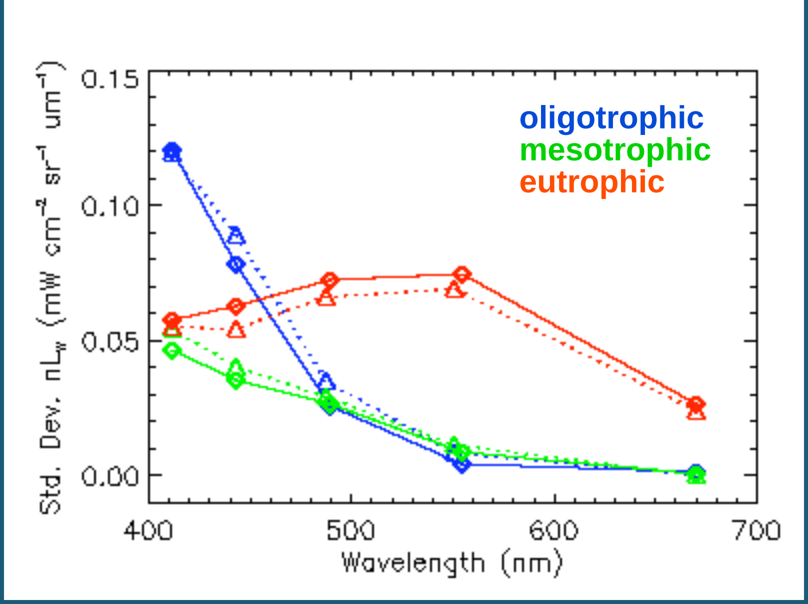
MOBY used to adjust prelaunch calibration gains for visible bands using satellite-buoy comparisons.

Summary Statistics for Global Trend Comparisons
Water-Leaving Radiances

MODIS & SeaWiFS Mean nLw



MODIS & SeaWiFS Std. Dev nLw

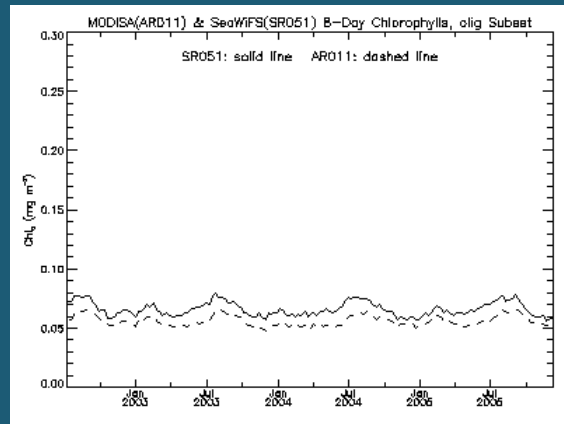


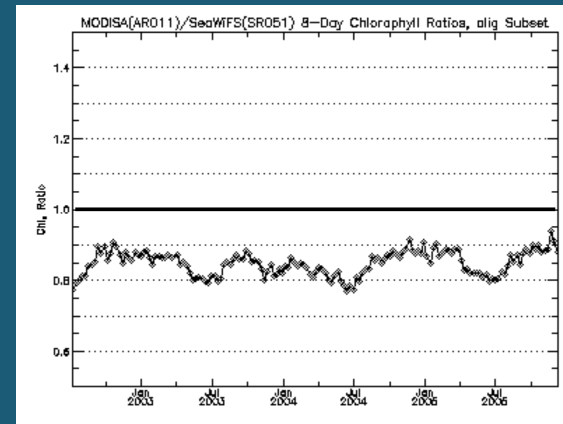
Chlorophyll Comparisons

MODIS & SeaWiFS

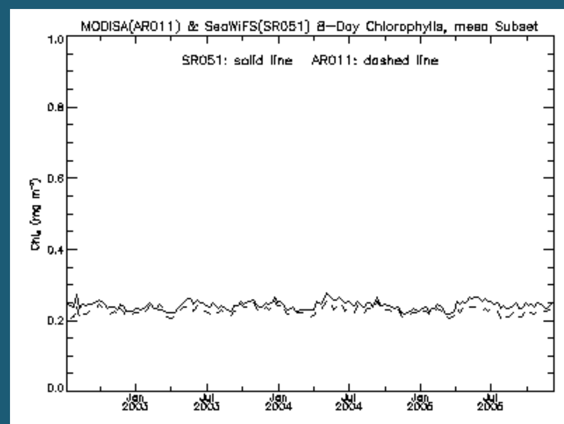
MODIS / SeaWiFS

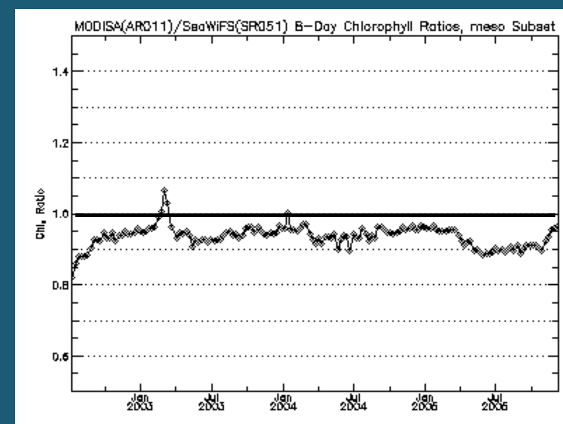
Oligotrophic



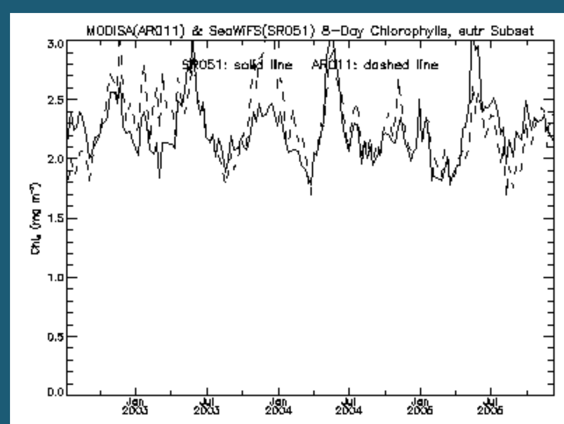


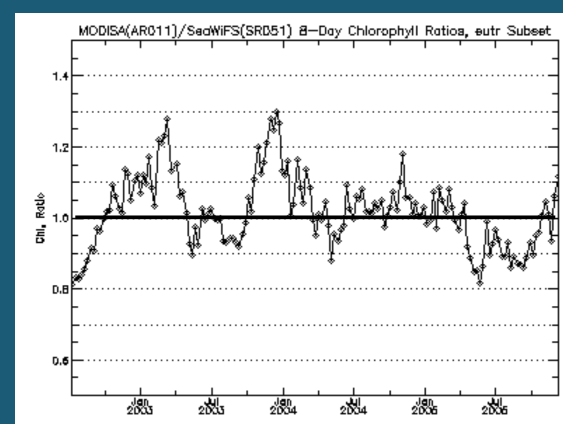
Mesotrophic





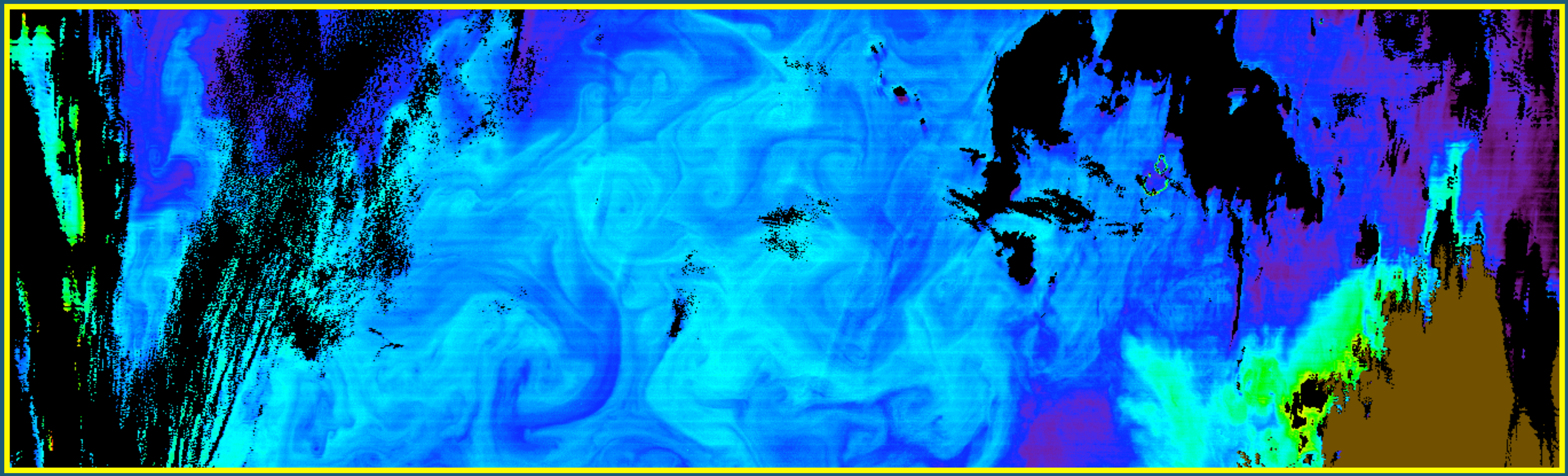
Eutrophic



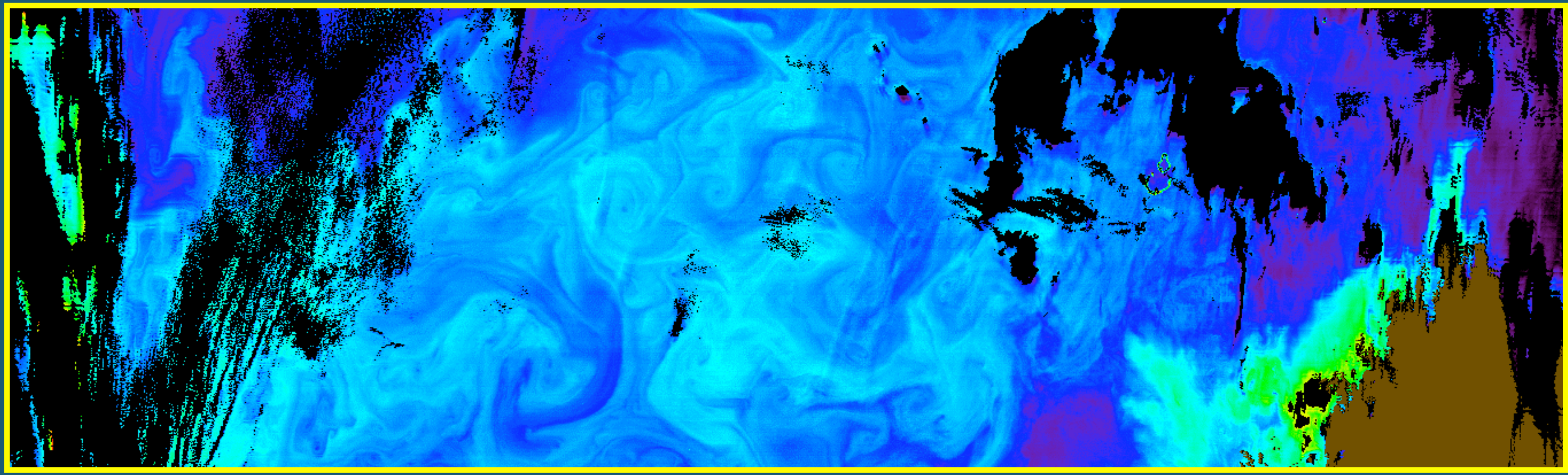


Residual Detector Striping

nLw(412) Before Correction



nLw(412) After Correction

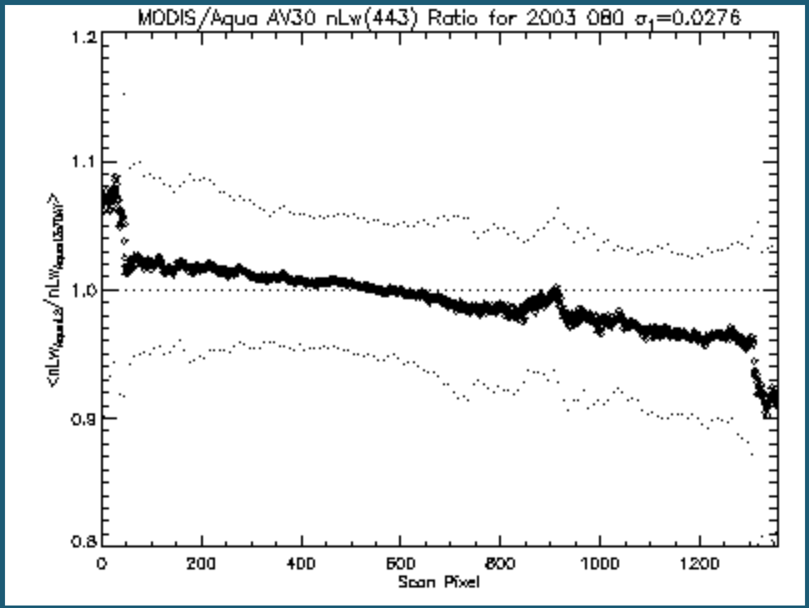


Bidirectional Reflectance at Surface

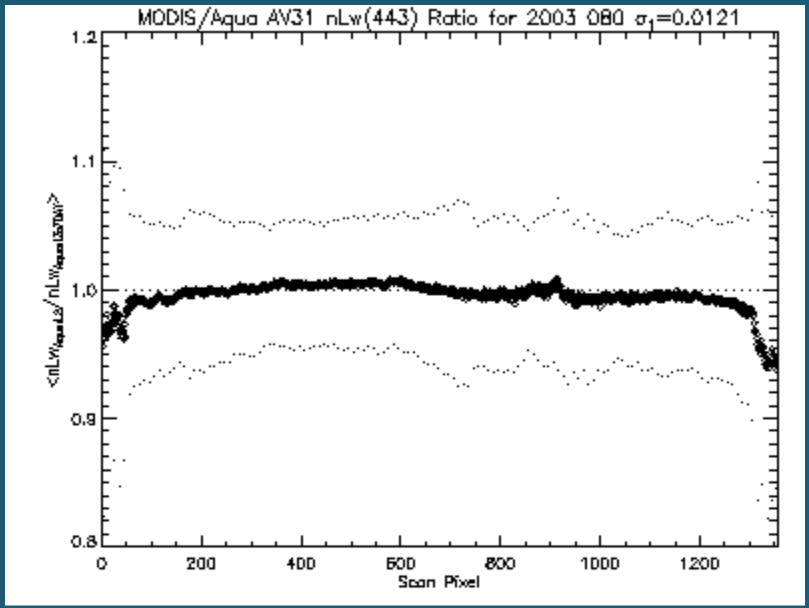
- Each sensor views the same location on earth from different view angle and at different time of day (solar angle).
- The angular distribution of upwelling radiance varies with solar illumination angle and the scattering properties of the water body.
- A. Morel developed a correction for this effect, which was incorporated into the common processing software for both sensors.

Residual Scan Dependence in MODIS nLw(443)

Before BRDF



After BRDF

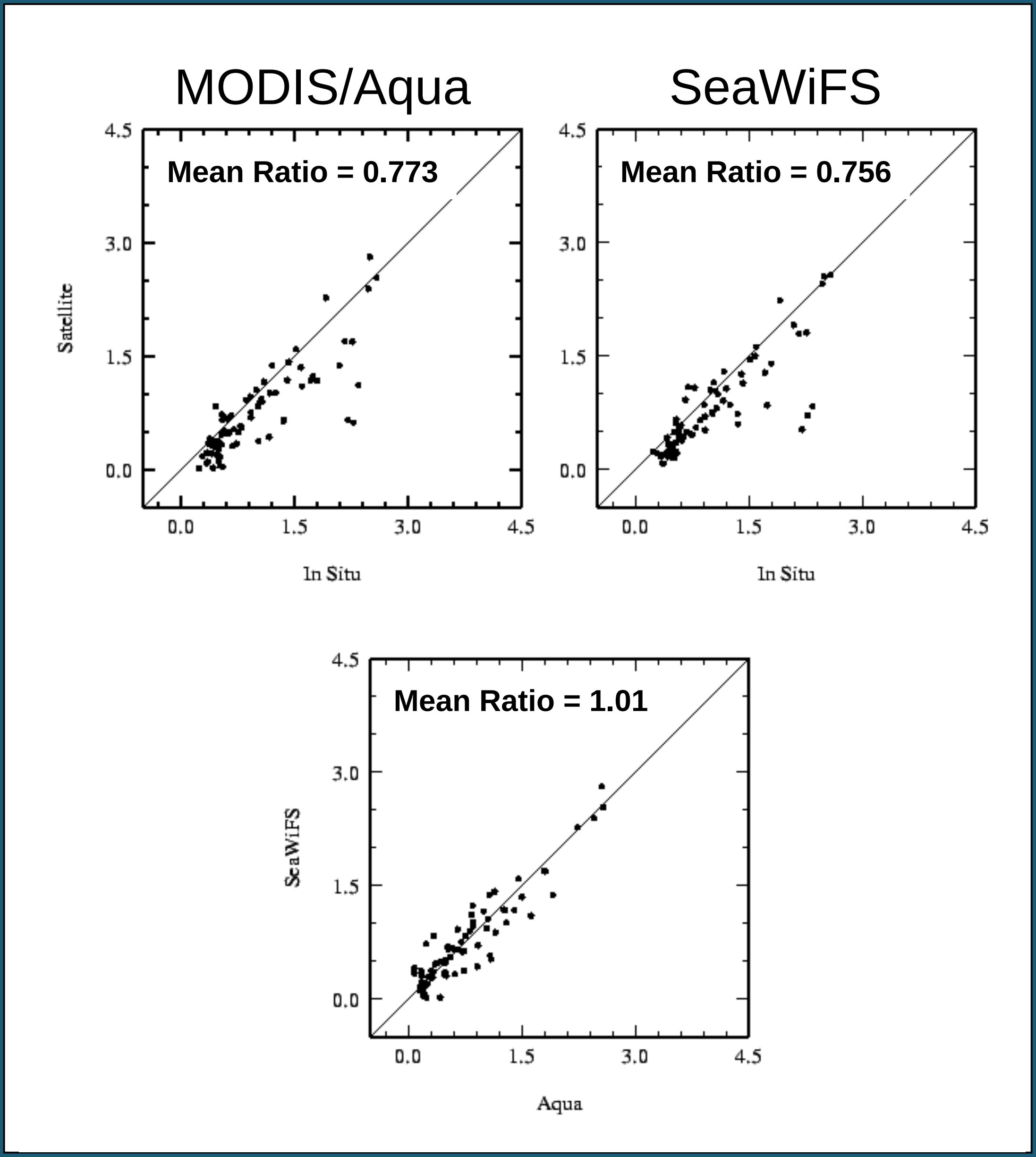


Artifacts and Issues

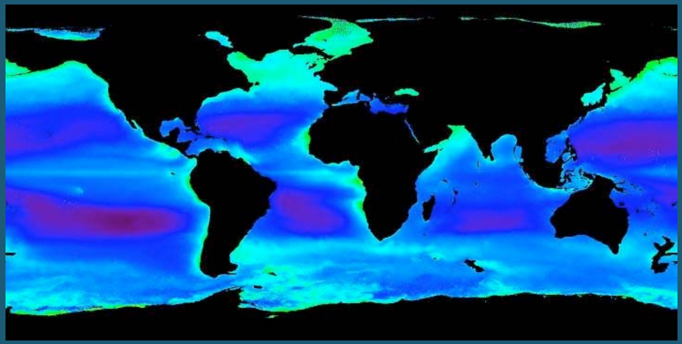
Operational MODIS Ocean Band Suite

Band Number	Wavelength (nm)	Band Width (nm)	Spatial Resolution (m)	SNR at L_{typ}	L_{typ} mW cm^{-2} µm^{-1} sr^{-1}	L_{max} mW cm^{-2} µm^{-1} sr^{-1}
8	412	15	1000	1773	7.84	26.9
9	443	10	1000	2253	6.99	19.0
10	488	10	1000	2270	5.38	14.0
11	531	10	1000	2183	3.87	11.1
12	551	10	1000	2200	3.50	8.8
13	667	10	1000	1962	1.47	4.2
14	678	10	1000	2175	1.38	4.2
15	748	10	1000	1371	0.889	3.5
16	869	15	1000	1112	0.460	2.5
22	3959		1000			
23	4050		1000			
31	11000		1000			
32	12000		1000			

nLw(412) versus *In Situ* for Common Match-ups



Deep-Water (Depth > 1000m)



Deep Water Only

Band	N	Median Ratio*	% Difference**	r^2	Bias	rms+	In Situ Range	Satellite Range
lw412	13	1.023	5.618	0.966	0.045	0.178	0.240 - 2.586	0.017 - 2.812
lw443	17	0.998	10.858	0.929	-0.044	0.224	0.251 - 2.232	0.124 - 2.337
lw488	17	1.040	5.967	0.844	-0.035	0.180	0.307 - 1.415	0.260 - 1.474
lw531	5	0.930	6.961	0.882	-0.028	0.037	0.338 - 0.480	0.302 - 0.456
lw551	13	1.140	14.020	0.574	0.032	0.058	0.217 - 0.440	0.283 - 0.388
lw667	17	1.813	81.317	0.591	0.011	0.017	0.000 - 0.050	0.010 - 0.049
chlorophyll	28	0.956	28.282	0.740	-0.027	0.709	0.039 - 7.258	0.030 - 2.287
kd488	12	1.149	14.864	0.997	0.015	0.029	0.021 - 0.147	0.022 - 0.224
aot869	14	1.552	55.187	0.646	0.043	0.058	0.018 - 0.171	0.047 - 0.256

* median of all satellite / in situ ratios
** median absolute percent difference
\+ sqrt (Σ(satellite - in situ)^2 / n)