

NASA support for ocean color research

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NASA Goddard Space Flight Center
Science Systems & Applications, Inc.

21 January 2010 @ SAC

professional background

NASA Goddard Space Flight Center - Jun 99 to present
oceanographer @ Ocean Biology Processing Group
ocean color from all instruments & SST from MODIS & VIIRS
located in Maryland near Washington D.C.

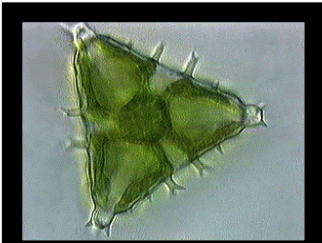
academic background

biology & environmental science @ University of Virginia - 1996
oceanography @ the University of Connecticut - 1998
oceanography @ the University of Maine - Sep 09 to present

1. why ocean color?
2. ocean color @ NASA
3. the NASA Ocean Biology Processing Group (OBPG)
4. calibrating & reprocessing an ocean color mission
5. international collaborations

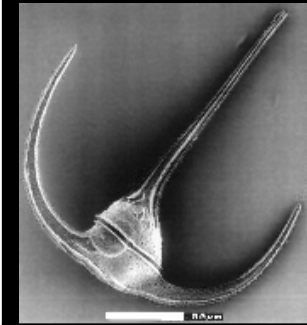
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why ocean color?



ocean color:

ocean monitoring in the visible range of the electromagnetic spectrum



primary (historical) goal:

to extract concentrations of marine phytoplankton



phytoplankton:

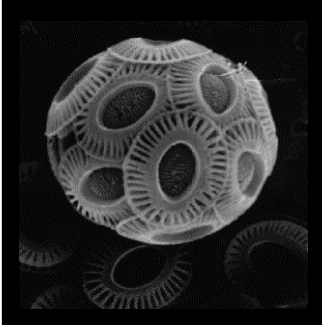
fix carbon dioxide into organic material

play a profound role in the global carbon cycle and climate

responsible for ~half of Earth net primary production

form the basis of the marine food chain

support various industries, primarily fisheries

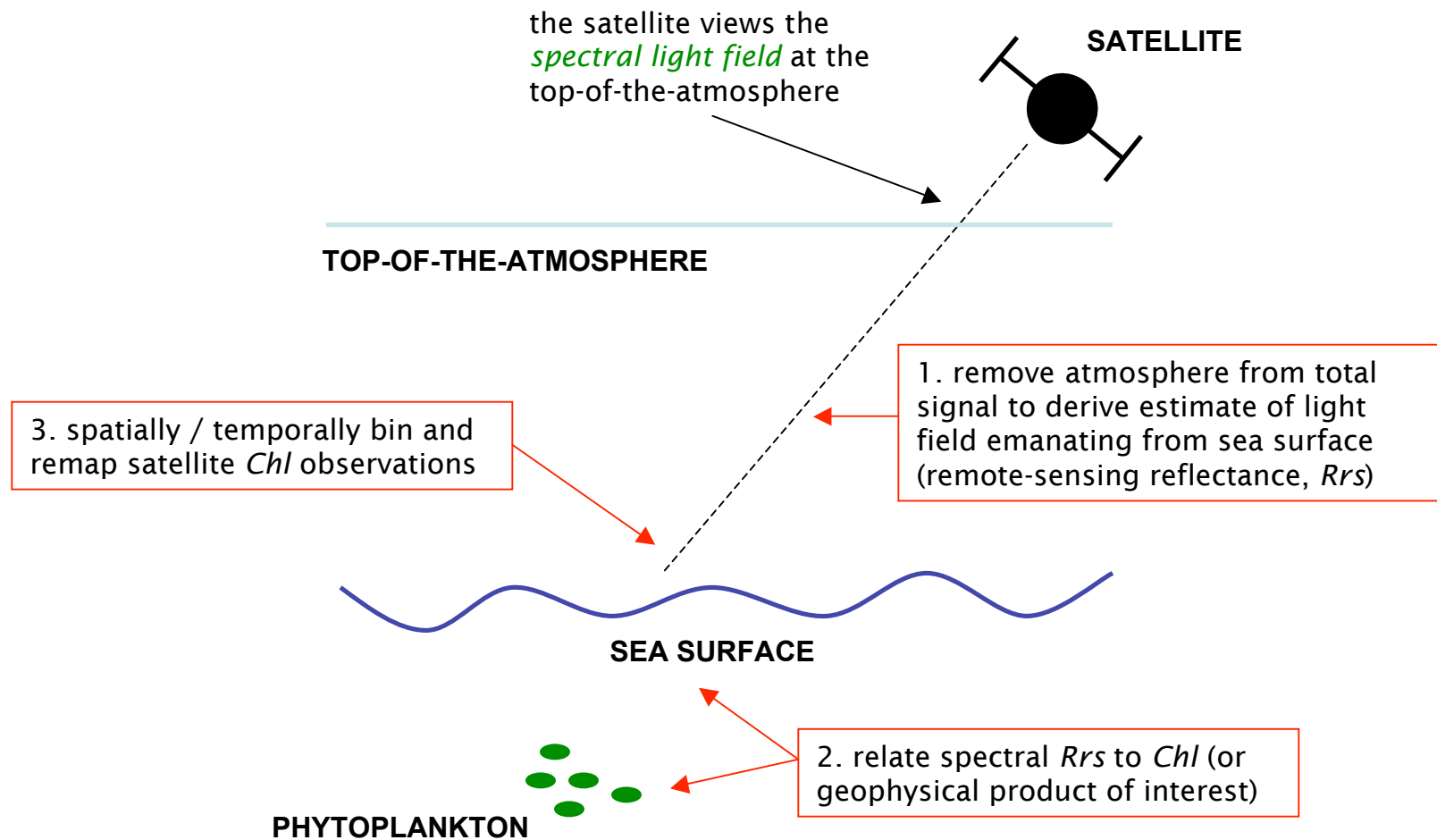


secondary (modern) goals:

separate phytoplankton species (e.g. coccolithophore, harmful algae)

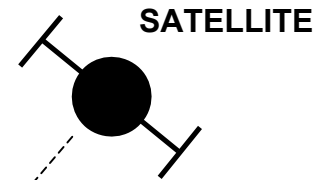
monitor coastal environments

why ocean color?

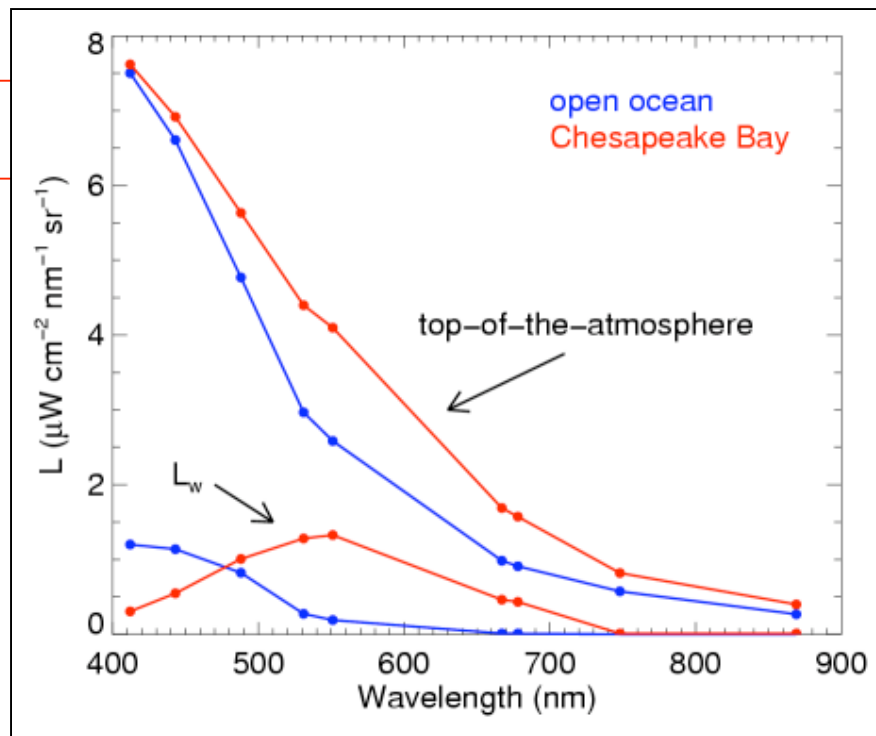


why ocean color?

the satellite views the *spectral light field* at the top-of-the-atmosphere

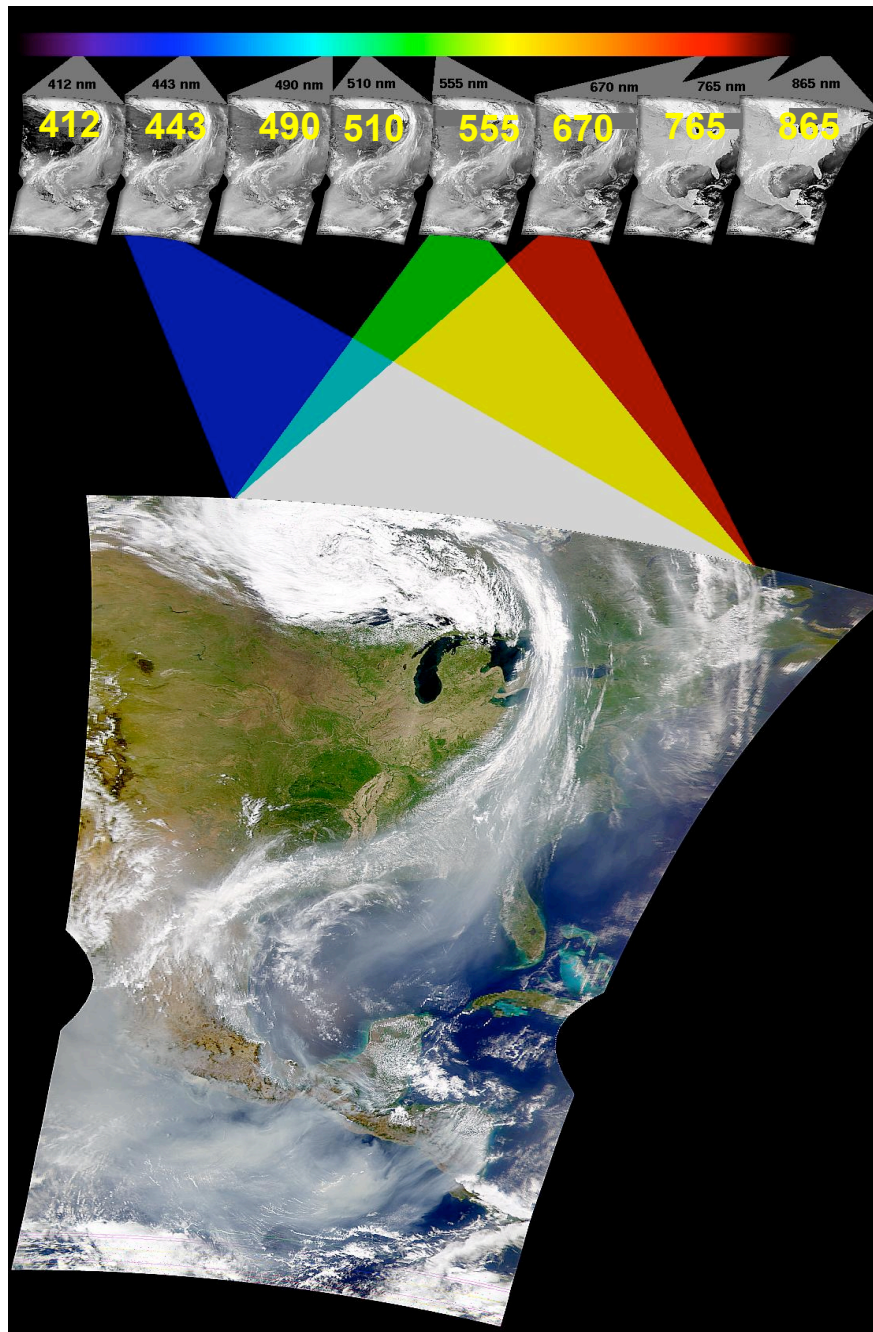


TOP-OF-THE-ATMOSPHERE



1. remove atmosphere from total signal to derive estimate of light field emanating from sea surface (remote-sensing reflectance, R_{rs})

2. relate spectral R_{rs} to Chl (or geophysical product of interest)



ocean color data products

primary optical variable

remote-sensing reflectance (R_{rs} ; units sr^{-1});

the subsurface upwelled radiance that propagates through the sea-air interface, normalized by the downwelled irradiance

primary bio-optical variable

chlorophyll-a concentration (Chl; units $mg\ m^{-3}$);

main photosynthetic pigment of phytoplankton, used as index of phytoplankton biomass;

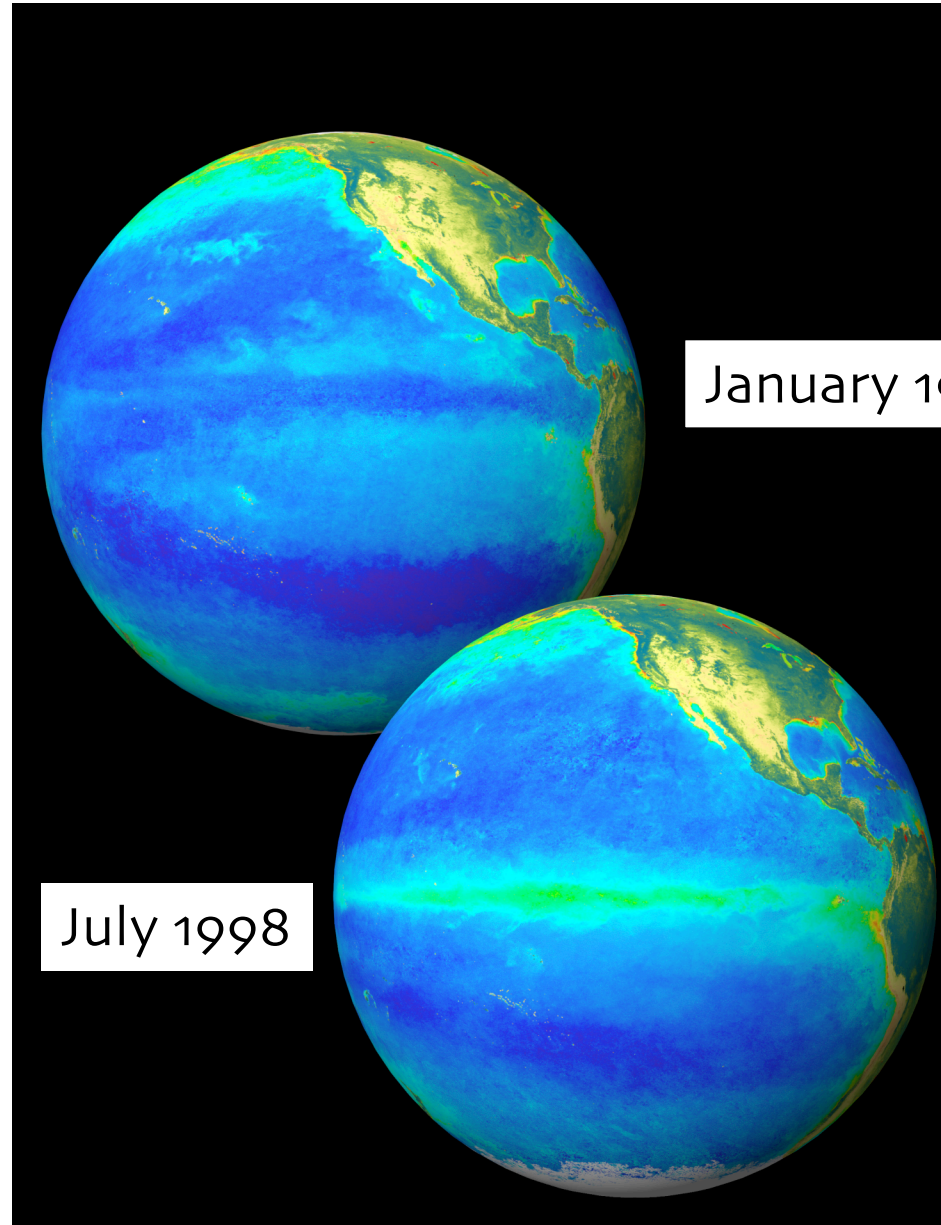
other data products

concentrations of water column constituents, e.g., particulate inorganic & organic carbon, & descriptors of the light field (e.g., PAR, euphotic depth, fluorescence line height & quantum yield)

examples of ocean color applications

SeaWiFS captured
the El Nino / La
Nina transition

see Behrenfeld et al.
"Biospheric primary
production during an
ENSO transition,"
Science 30 (2001)



examples of ocean color applications

climate & productivity are related

see Behrenfeld et al. "Climate-driven trends in contemporary ocean productivity," Nature 444, (2006)

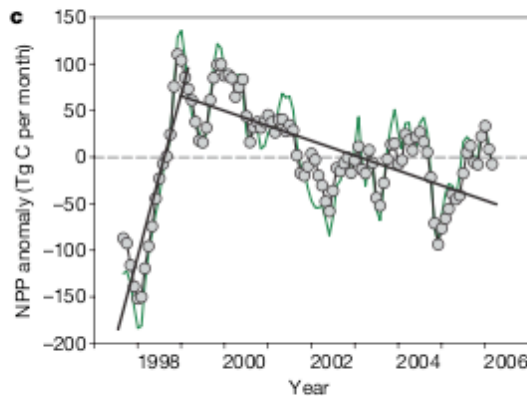
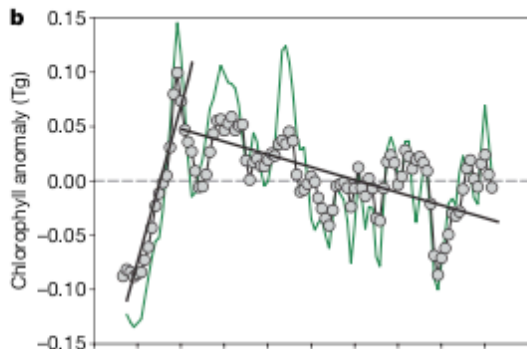
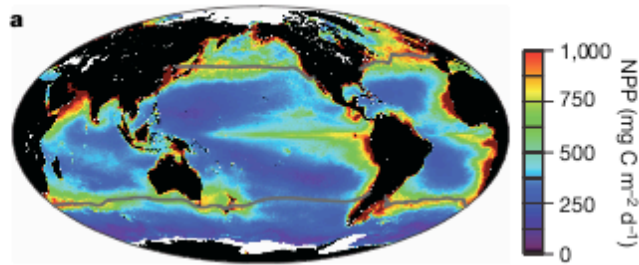


Figure 1 | Distribution and trends in global ocean phytoplankton productivity (NPP) and chlorophyll standing stocks.

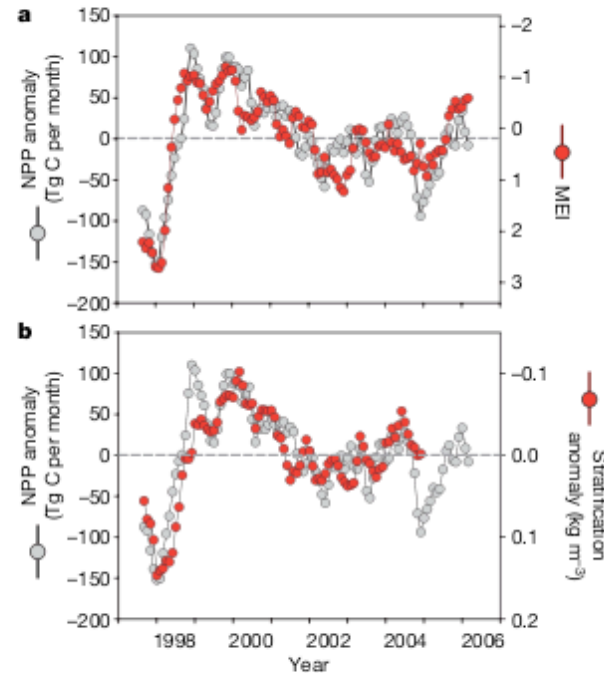



Figure 2 | Ocean productivity is closely coupled to climate variability.

examples of ocean color applications

harmful algal blooms



Gulf of Mexico Harmful Algal Bloom Bulletin
27 October 2005
National Ocean Service
National Environmental Satellite, Data, and Information Service
Last bulletin: October 24, 2005

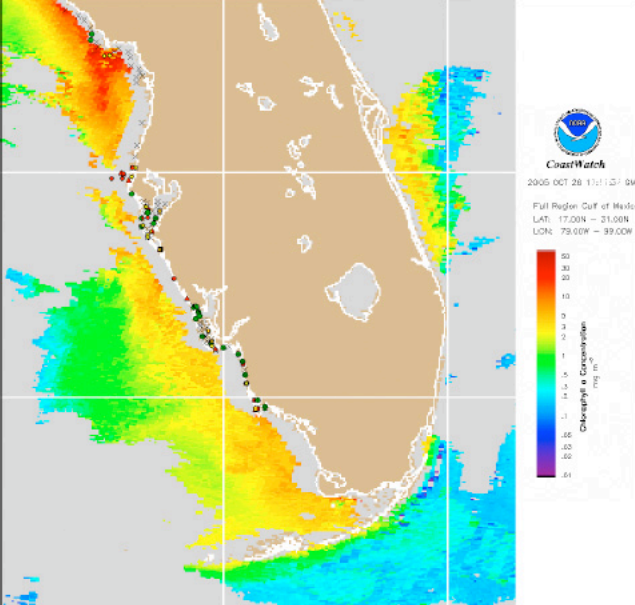
Conditions: Harmful algal blooms have been identified in Pinellas County, Dixie to Levy County and in very small patches from Manatee to Collier County in Florida. A secondary bloom has been identified in patches along Alabama and the Florida Panhandle. No impacts are expected along the coast from Pinellas to Collier County or from Dixie to Levy County today through Sunday. Patchy very low to low impacts are possible from Wakulla to Okaloosa County, FL and Baldwin to Mobile County, AL today through Sunday. Dead fish have been reported in Bay and Okaloosa Counties over the past few days. Dead fish smell, while unpleasant, does not produce the same respiratory irritation as red tide.

Analysis: The harmful algal bloom continues to dissipate along the SW Florida coastline; however very small remnant populations of *K. brevis* may still be present in patches from Pinellas to Collier County. Low *K. brevis* concentrations remain offshore of Bunces Pass in southern Pinellas County. Previous low *K. brevis* concentrations in Sarasota County have decreased to background levels (FWRI 10/20-26). Chlorophyll levels are elevated all along the Florida coast due to resuspension produced by Hurricane Wilma; thus bloom extent analysis is limited. Results of a wind transport model indicate possible bloom movement 20-30km southward since October 24. No recent samples have been reported from Levy to Dixie Counties. Sampling is recommended. Persistent northeasterlies will minimize coastal impacts through Sunday. Continual dissipation of the bloom is expected. Reports of discolored water are likely.

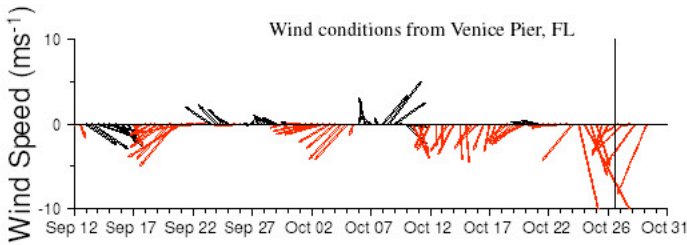
Fisher, Bronder

Please note the following restrictions on all SeaWiFS imagery derived from CoastWatch.

1. These data are restricted to civil marine applications only; i.e. federal, state, and local government use/distribution is permitted.
2. Distribution for military, or commercial purposes is NOT permitted.
3. There are restrictions on Internet/Web/public posting of these data.
4. Image products may be published in newspapers. Any other publishing arrangements must receive OrbImage approval via the CoastWatch Program.



Chlorophyll concentration from satellite with HAB areas shown by red polygon(s). Cell concentration sampling data from October 19, 2005 shown as red squares (high), red triangles (medium), red diamonds (low b), red circles (low a), orange circles (very low b), yellow circles (very low a), green circles (present), and black "X" (not present).



Wind conditions from Venice Pier, FL

Wind speed and direction are averaged over 12 hours from measurements made on buoys. Length of line indicates speed; angle indicates direction. Red indicates that the wind direction favors upwelling near the coast. Values to the left of the dotted vertical line are measured values; values to the right are forecasts.

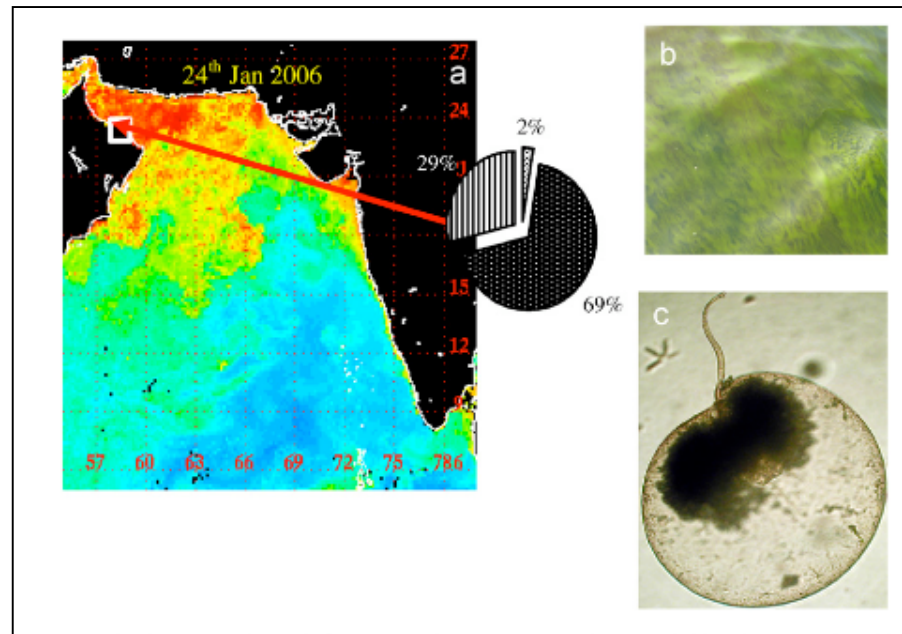
SW Florida: Moderate (10-15kts, 5-8m/s) northeasterly winds today will continue through Sunday; strengthening up to 20kts (10m/s) Saturday and Sunday.

examples of ocean color applications

two (of many) studies of the Arabian Sea that used satellite ocean color

Goes et al., "Warming of the Eurasian landmass is making the Arabian Sea more productive," *Science* 22 (2005)

Gomes et al., "Blooms of *Noctiluca miliaris* in the Arabian Sea - an *in situ* and satellite study," *Deep Sea Research I* 55 (2008)



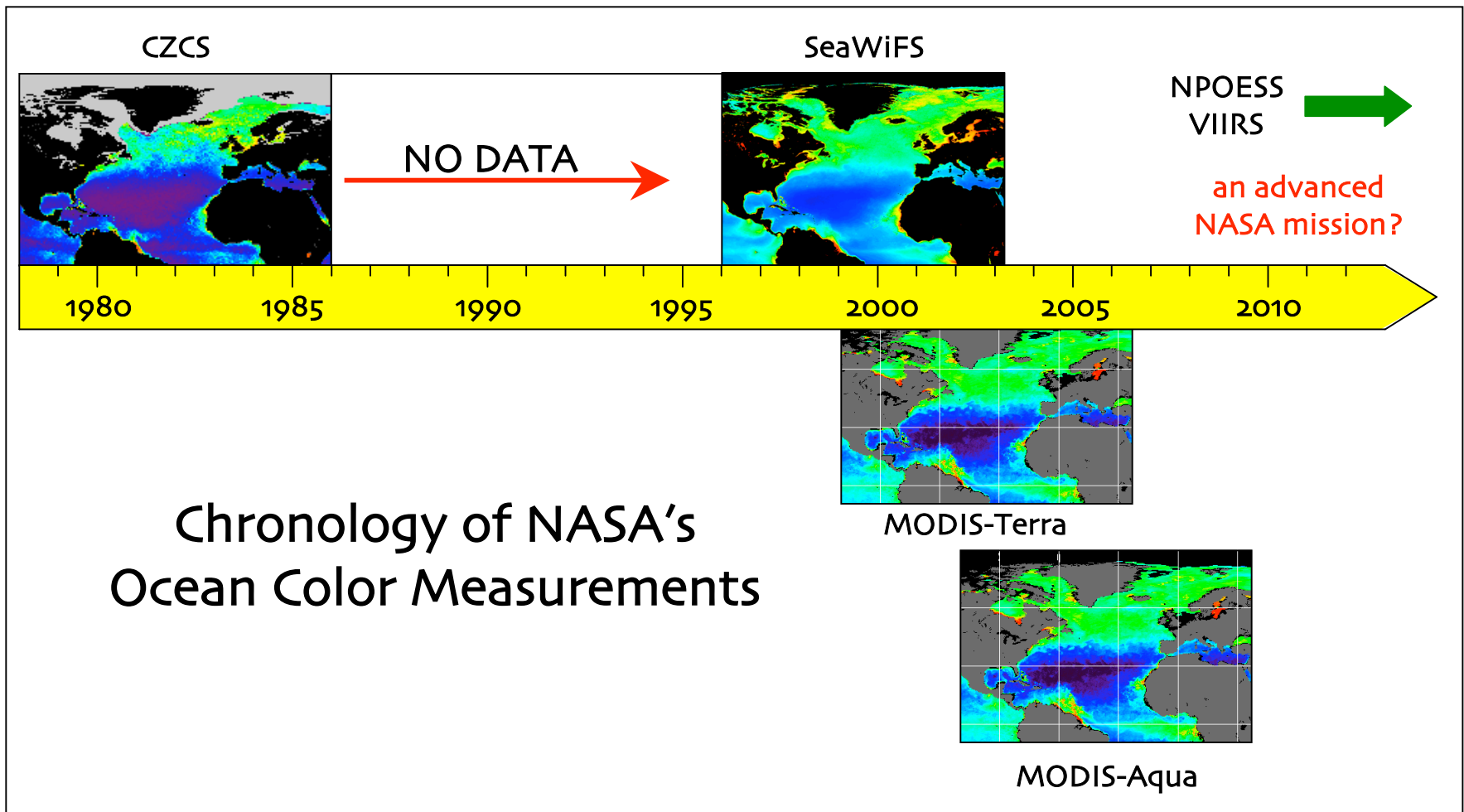
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2. ocean color @ NASA
3. the NASA Ocean Biology Processing Group (OBPG)
4. calibrating & reprocessing an ocean color mission
5. international collaborations

ocean color @ NASA

NASA's goals are to:

make available high quality ocean color data to the broadest user community in the most timely & efficient manner possible

facilitate the continuity & consistency of a long-term ocean color data record for climate research through international collaborations on satellite missions and field campaigns



Chronology of NASA's Ocean Color Measurements

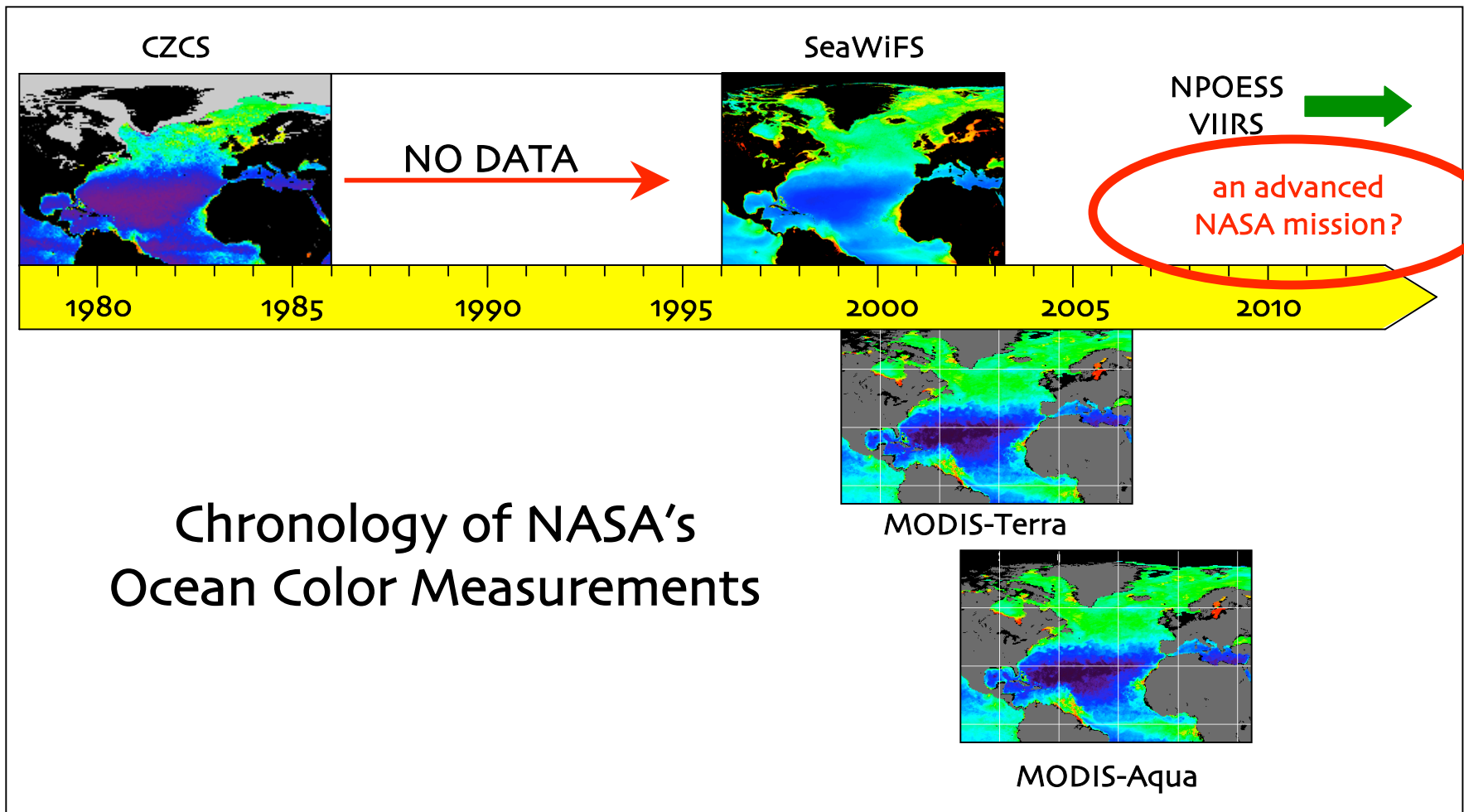
other
satellite data

sea surface temperature: AVHRR, MODIS, VIIRS, ...

winds: SSMI, Nscat, Quikscat, SeaWinds, ...

sea surface topography: TOPEX, Jason, Grace, OSTM, ...

salinity: Aquarius



Chronology of NASA's Ocean Color Measurements

other
satellite data

sea surface temperature: AVHRR, MODIS, VIIRS, ...

winds: SSMI, Nscat, Quikscat, SeaWinds, ...

sea surface topography: TOPEX, Jason, Grace, OSTM, ...

salinity: Aquarius

1. ACE (Aerosols-Clouds-Ecosystems)

mission & payload

low Earth orbit (LEO), polar orbit

sun-synchronous, early-afternoon orbit, with altitude of 500-650 km

instruments and technology

HSR Lidar for assessing the heights of aerosol & cloud properties.

dual frequency Doppler cloud radar for cloud properties & precipitation

multi-angle, swath polarimeter for imaging aerosol & clouds

ocean ecosystem multi-channel spectrometer (OES)

IR multi-channel imager for cloud temperatures & heights

high frequency swath radiometer for cloud ice measurements

low frequency swath radiometer for precipitation measurements

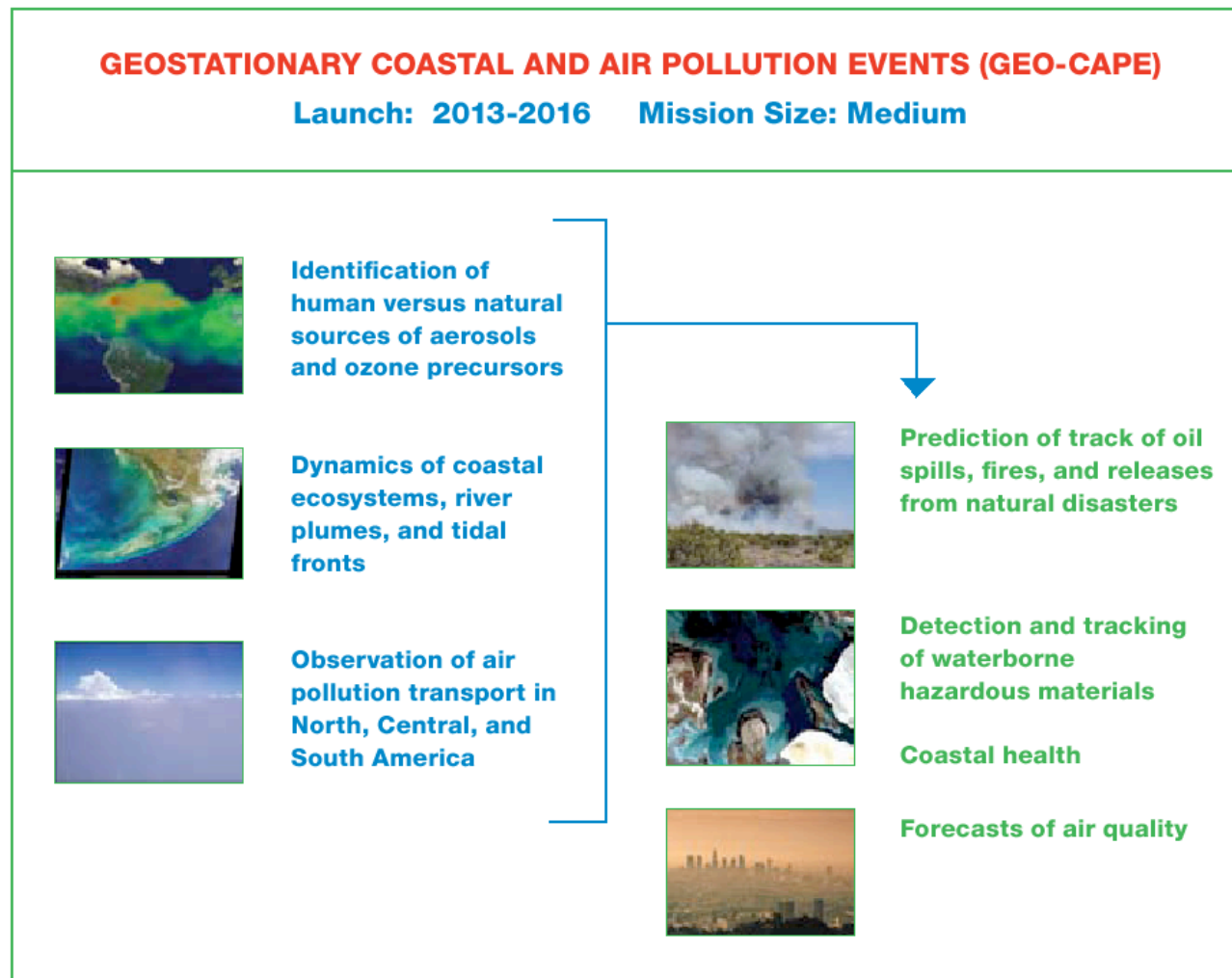
microwave temperature/humidity sounder

the ACE mission – with its advanced instruments – will likely not launch until 2020

black – specified by NAS Decadal Survey & red – Science Definition Team recommendations

2. GEO-CAPE (Geostationary Coastal & Air Pollution Events)

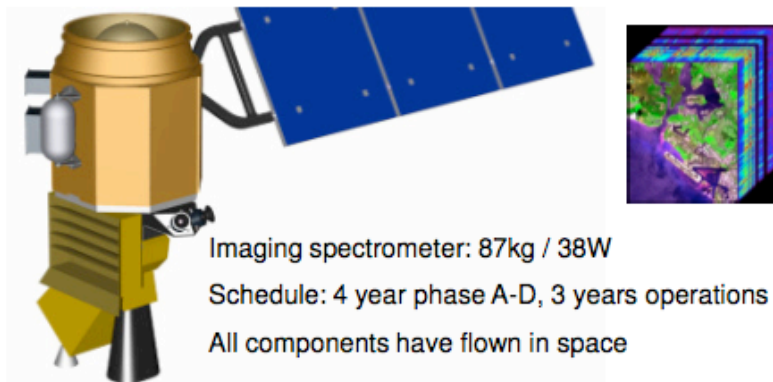
UV-visible-near IR wide area spectrometer covering 45°S to 50°N hourly steerable, high spatial resolution, event-imaging spectrometer
O₃, NO₂, CH₂O, SO₂, aerosols & IR correlation radiometer for CO mapping



3. HypSIIRI (Hyperspectral Infrared Imager)



HypSIIRI Imaging Spectroscopy Science Measurements



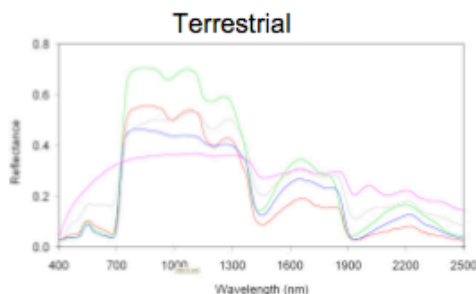
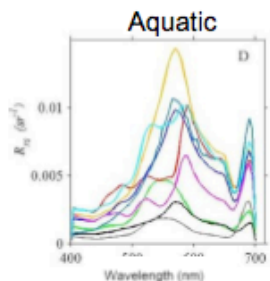
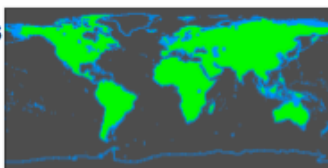
Imaging spectrometer: 87kg / 38W
 Schedule: 4 year phase A-D, 3 years operations
 All components have flown in space

Science Questions:

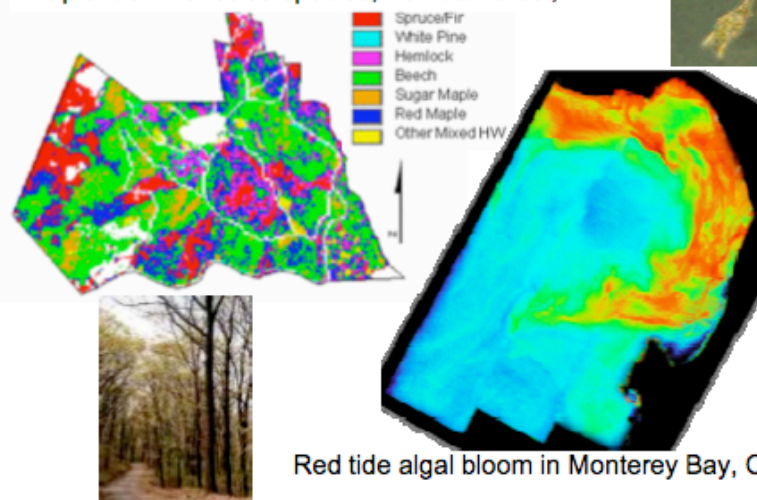
- *What is the composition, function, and health of land and water ecosystems?*
- *How are these ecosystems being altered by human activities and natural causes?*
- *How do these changes affect fundamental ecosystem processes upon which life on Earth depends?*

Measurement:

- 380 to 2500 nm in 10nm bands
- Accurate 60 m resolution
- 19 days revisit
- Global land and shallow water



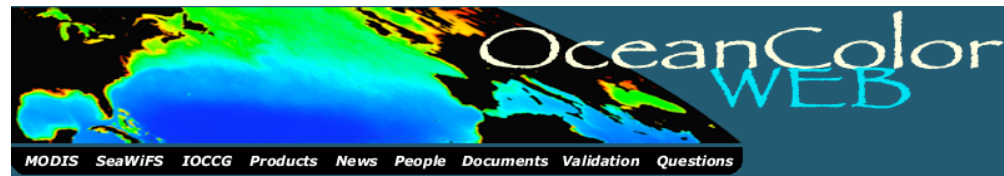
Map of dominant tree species, Bartlett Forest, NH



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the NASA Ocean Biology Processing Group

- Ocean Color (OC)
- SST for MODIS, GHRSSST
- Salinity from Aquarius
- End-to-End Shop for Ocean Color
 - Sensor calibration/characterization
 - Processing software & algorithms
 - Product validation (SeaBASS)
 - Algorithm development (NOMAD)
 - User processing and display (SeaDAS)
 - Data archive and distribution
 - User support (Ocean Color Forum)
- Distributed processing system
 - 400x global reprocessing for MODIS
 - 4000x for SeaWiFS
- Data archive and distribution
 - ~1 PB online storage (RAID)
 - distribution: 34 million files OC (2004-)
 - 9 million files SST



oceancolor.gsfc.nasa.gov

Consolidated data access, information services, and community feedback.

Missions Supported

MODIS/Aqua: 2002-present
MODIS/Terra: 1999-present
SeaWiFS/Orbview-2: 1997-present
OCTS/ADEOS: 1996-1997
MOS/IRS-P3: 1996-2004
CZCS/NIMBUS-7: 1978-1986
VIIRS/NPP: 2011 launch
Glory Data System : 2009 launch
Aquarius / SAC-D : May 2010 launch
New Mission Development (ACE)

the NASA Ocean Biology Processing Group

measurement-based organization

consolidated expertise in ocean color measurements

multi-mission, end-to-end

sensor calibration/characterization, prelaunch & on-orbit

product validation (SeaBASS validation data set)

algorithm development & evaluation (NOMAD)

data processing and distribution (ODPS, OceanColorWeb)

user processing and display (SeaDAS)

user support (Ocean Color Forum)

global processing & distribution

SeaWiFS

MODIS (Aqua & Terra)

CZCS

OCTS (Japan)

the NASA Ocean Biology Processing Group

OceanColor WEB

MODIS SeaWiFS IOCCG Products News People Documents Validation Questions

Data Access

Data Production and Distribution Status

SeaWiFS in safe-haven: data outage

NOTE: FTP connections must be made in PASSIVE mode

Level 1 and 2 Browser

Visually search the ocean color data archive. Directly download or order data from a single file to an entire mission.

Level 3 Browser

Browse the entire global ocean color data set for many parameters and time periods and download PNG images or digital data in HDF format.

Global Time Series

Time series plots of selected SeaWiFS, MODIS and OCTS Standard Mapped Images for a set of selected regions or the entire globe.

Data by FTP

The FTP access to our most popular data products, including the complete Level 3 data archive.

Ocean Productivity

Ocean Net Primary Productivity data products derived from MODIS and/or SeaWiFS data available from Oregon State University.

Giovanni

An easy-to-use, Web-based interface for the visualization and analysis of Earth Science data provided by the GES DISC DAAC.

Ocean Color Web Feature

Recent topics and imagery of interest to the OceanColor community.

The Chatham Rise

The **Chatham Rise**, extending eastward from the Banks Peninsula on New Zealand's South Island, separates two areas of deeper water to the north and south. Tides and other currents flowing over this submarine topography cause **increased mixing** in the water column. That and the location of the rise along the **subtropical front** often results in large blooms of phytoplankton in the area -- particularly during the austral spring and summer. The above image collected by Terra-MODIS on January 5, 2008 shows such blooms coloring the waters above the rise. The view is toward the west.

Image Gallery

NOTE: All SeaWiFS images presented here are for research and educational use only. All commercial use of SeaWiFS data must be coordinated with **GeoEye**

Ocean Color Distribution Statistics

Support Services

SeaDAS

A comprehensive image analysis package for the processing, display, analysis, and quality control of ocean color data.

SeaBASS

An archive of *in situ* oceanographic and atmospheric data for use in algorithm development and satellite data product validation.

Registration for support services:

- Data access and Subscriptions
- Forgotten password
- Email change
- SeaWiFS Access Authorization

Near Real-Time (NRT) Services:

- NRT Data Subscriptions

Subscriptions allow users to specify regions for NRT data to be continually staged on our FTP server for download.

Information Services:

- Ocean Color Forum
- Ocean Color Mailing List

Other Services:

- Satellite Overflight Predictions
- SeaWiFS LAC scheduling
- Data subscription status
- L1/L2 browser order status
- Ocean Data Processing System

Information related to the ocean color data production system.

<http://oceancolor.gsfc.nasa.gov/>

data
documentation
analyses
software
support services
public forum

the NASA Ocean Biology Processing Group

data distribution

free & open data distribution policy

all data available on-line

Web-based browsing & direct FTP access

automated ordering system

subscription services

geographic & parameter sub-setting

the NASA Ocean Biology Processing Group

SeaWiFS

GAC LAC MLAC

OCTS (ADEOS) MODIS (Terra) MODIS (Aqua) CZCS (Nimbus-7)

Day
 Night

Radius (km) about map click or about typed-in location:

72
 400
 800
 1200
 1500

Select swaths containing (at least):

any part
 25 %
 50 %
 75 %
 all

Select only scenes having in situ matchups.

Monday, 30 October 1978 through Friday, 18 January 2008

Chlorophyll

Display results at a time.

Select one or more regions:

- AdriaticSea
- AegeanSea
- Antarctica
- ArabianSea
- AralSea
- Arctic
- Australia
- AustraliaCoast
- Azores
- Bahamas
- BalticSea

or specify boundary coordinates or a single location:

N:

W: :E

S:

M i s s i o n	1978	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																					
	1979	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																					
	1980	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																					
	1981	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																					
	1982	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																					
	1983	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																					
	1984	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																					
	1985	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																					
	1986	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																					
	1996	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																					
	1997	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																					
	1998	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																					
1999	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																						
2000	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																						
2001	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																						
2002	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																						
2003	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																						
2004	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																						
2005	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																						
2006	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																						
2007	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																						
2008	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec																						

<http://oceancolor.gsfc.nasa.gov/>

the NASA Ocean Biology Processing Group

standard ocean products

observed radiance (uncalibrated)

ocean color

- remote-sensing reflectances, $R_{rs}(\lambda)$

- chlorophyll, Chl

- diffuse attenuation, $K_d(490)$

- aerosol type & concentration

- FLH, FQY, iPAR, PAR, POC, PIC, Morel CDOM index

ocean temperature (MODIS only)

data types (online archive)

- Level-0 or Level-1A: uncalibrated radiances

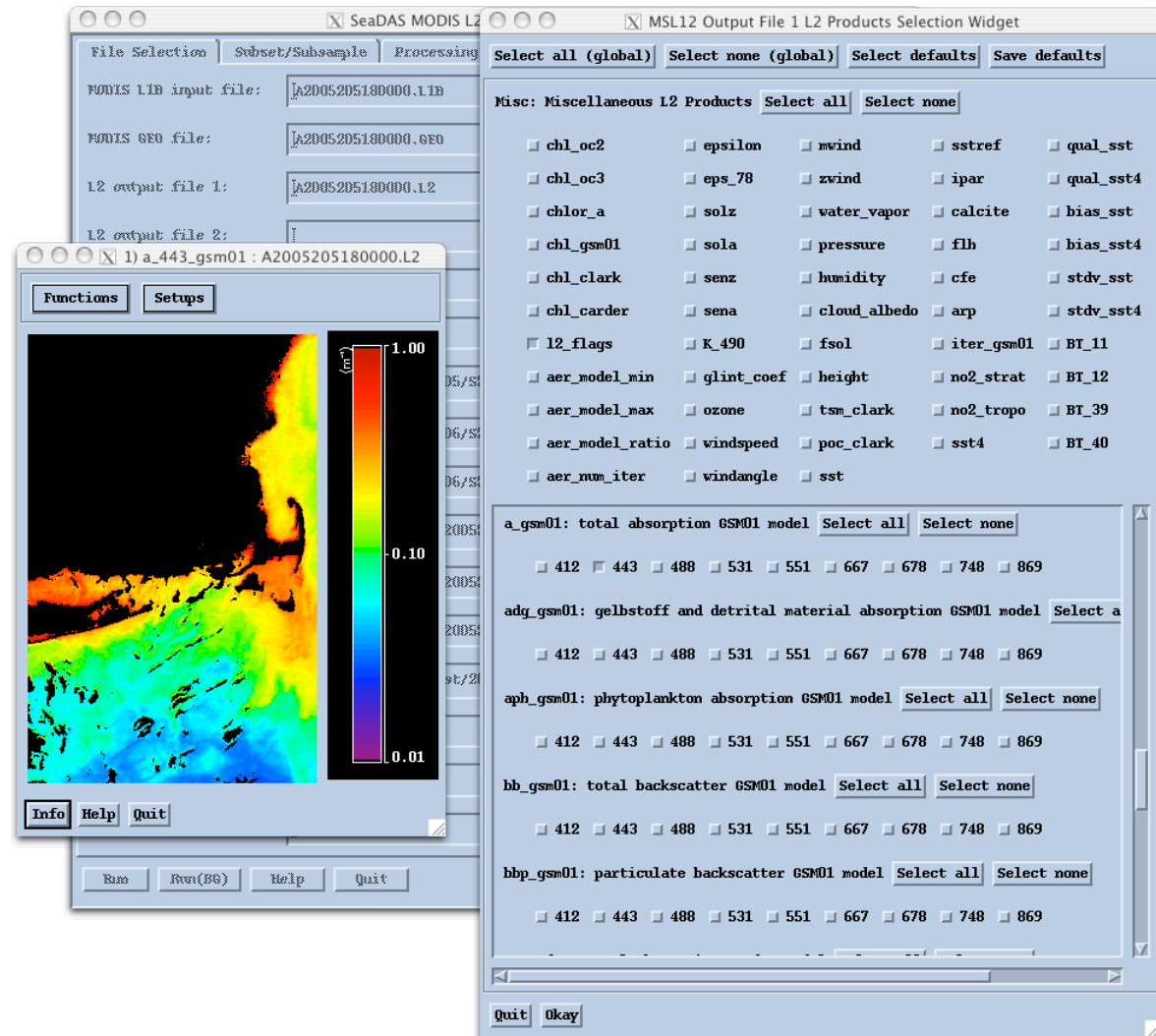
- Level-2: retrieved geophysical parameters

- Level-3: global gridded composites - daily, 8-day, monthly, merged

the NASA Ocean Biology Processing Group

SeaDAS

- free
- multi-mission
- display tools
- analysis tools
- processing
- open source



reprocessing algorithms in latest SeaDAS

The screenshot displays the SeaDAS software interface on a Mac OS X desktop. The main window shows a satellite image of a coastal area with a color scale overlay. A menu is open, listing various processing algorithms under the 'Process' tab, including '11gen_modis', 'geogen_modis', '11aextract_modis', '11bgen_modis', '11brsgen', '12gen,4', '12extract,4', '12bin', '13bin', 'smigen', 'b12map', and 'b13map'. A histogram plot window titled '1) Histogram Plot' shows the distribution of chlorophyll-a data values (mg m⁻³) with a peak around 0.5 mg m⁻³. A terminal window shows the following command-line output:

```
palapa:modis_data mike$ seadas
IDL Version 7.0, Mac OS X (darwin ppc #32). (c) 2007, ITT Visual Information
Solutions
Installation number: 17915.
Licensed for use by: NASA/GSFC SeaWiFS Project

SeaDAS Version 5.3.0 (pid = 58254)
SeaDAS> load, 'A2004080182010.png', ftype='png'
SeaDAS> display
SeaDAS> load, 'A2004080182010.L2', prod_name='chlor_a', ftype='modis'
grp_name=Geophysical Data
Getting - "chlor_a" data from HDF file...
SeaDAS> display, fbuf=2
SeaDAS> loadpal, '$SEADAS/config/color_luts/standard/02-standard_chl.lut'
SeaDAS> loadgp, color=2, red=75, green=75, blue=55
SeaDAS> landmask, color=2
SeaDAS> grid, grdcol=7, lblcol=7, latdel=0.5, lonel=0.5
SeaDAS> cbar
SeaDAS>
```

The desktop also shows a dock with various application icons and a system tray with the date and time (Wed 5:30:40 PM).

15 years in distribution, free, open-source, linux/os-x/solaris/windows(vm), international training
~1400 downloads in 2009 alone

the NASA Ocean Biology Processing Group

examples of non-standard ocean products

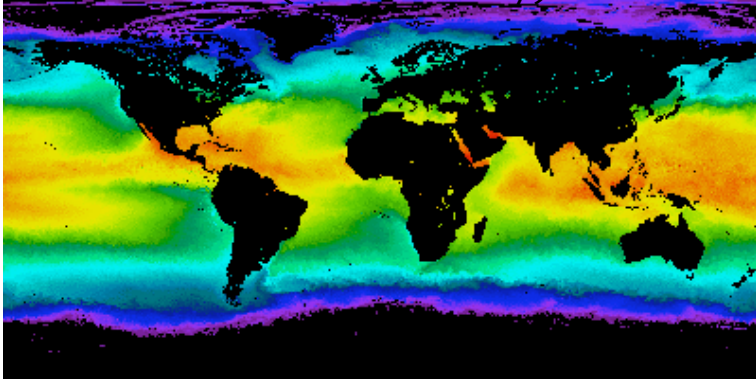
alternate C_a and K_d algorithms

inherent optical properties (various bio-optical models)
absorption (total, phytoplankton, dissolved material)
backscatter (total, particulate)

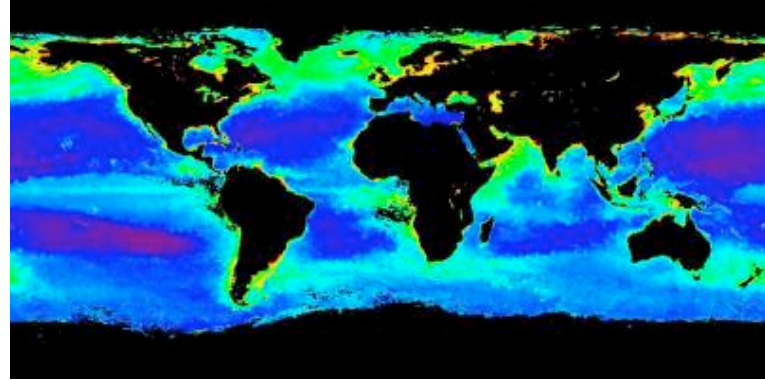
euphotic depth (Z_{eu} , Z_{sd})

spectrally integrated diffuse attenuation, $K_d(\text{PAR})$

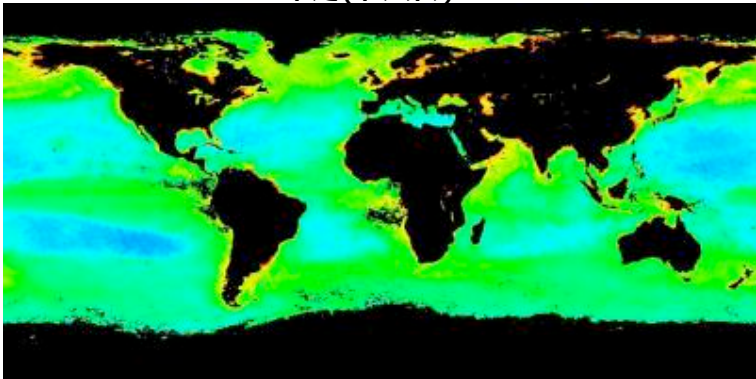
SST (11-12mm day)



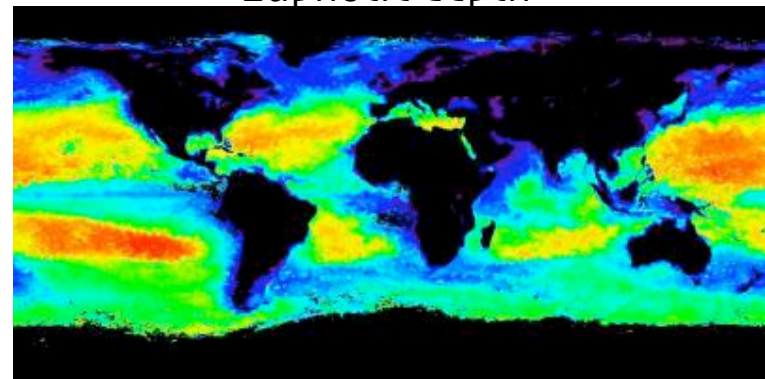
Chlorophyll



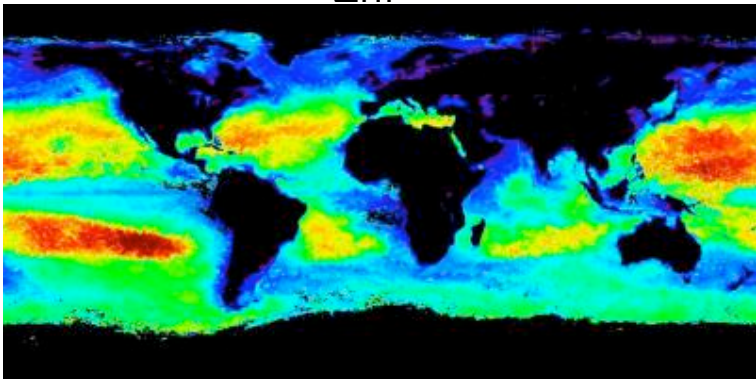
Kd(PAR)



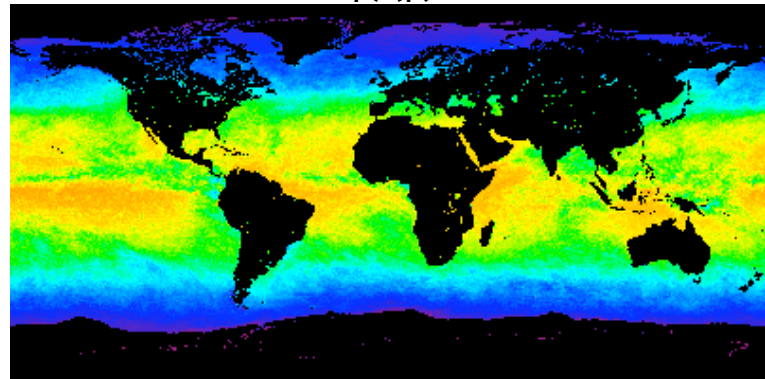
Euphotic depth



Zhl

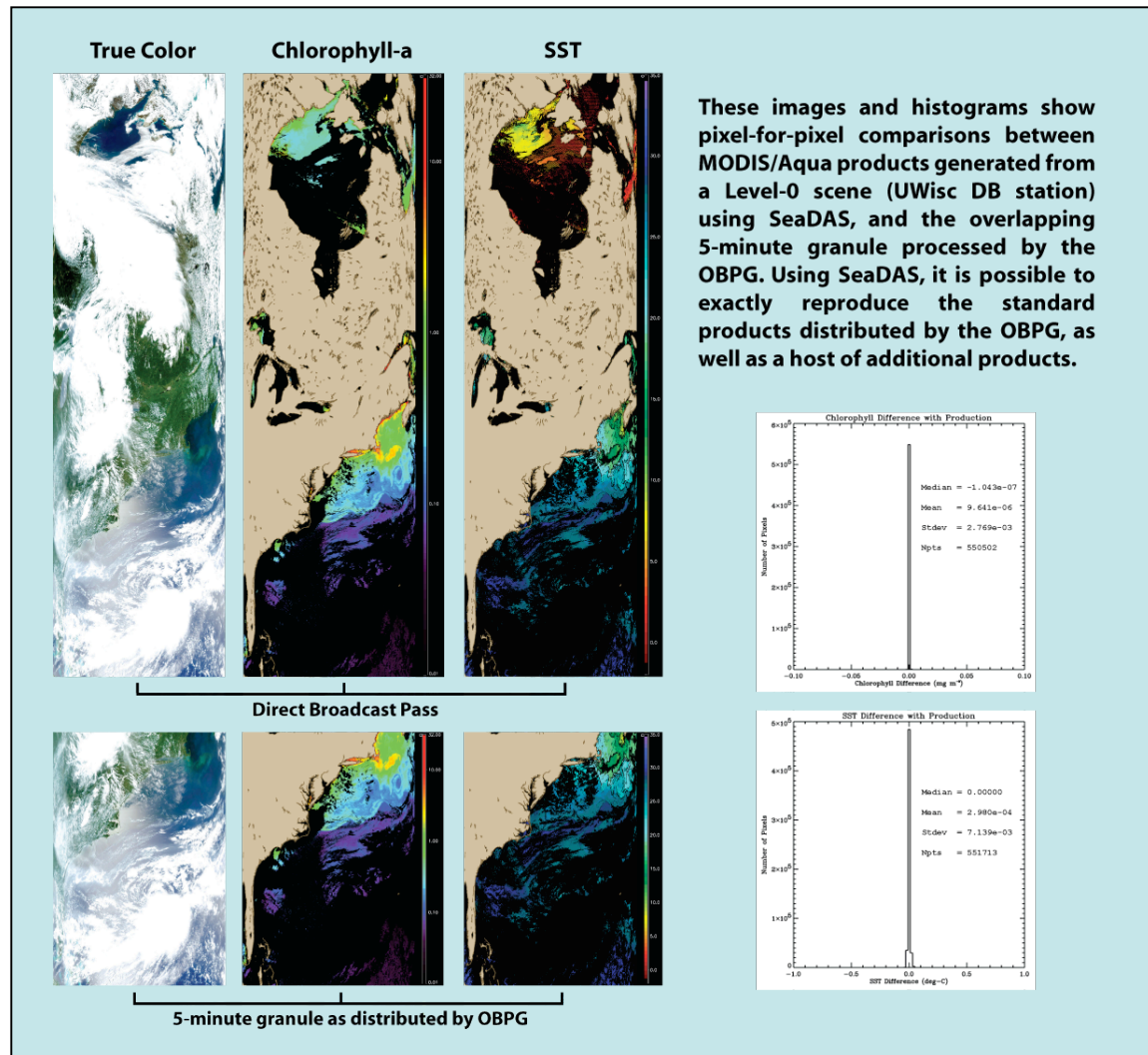


PAR




the NASA Ocean Biology Processing Group

MODIS direct broadcast support



the NASA Ocean Biology Processing Group



Ocean Color Forum - Welcome, gene

Forum Ocean Color Home Help Search Options Logout

Forum

Mark Old Mark Read New Posts Unread Posts ToDo Feeds Info

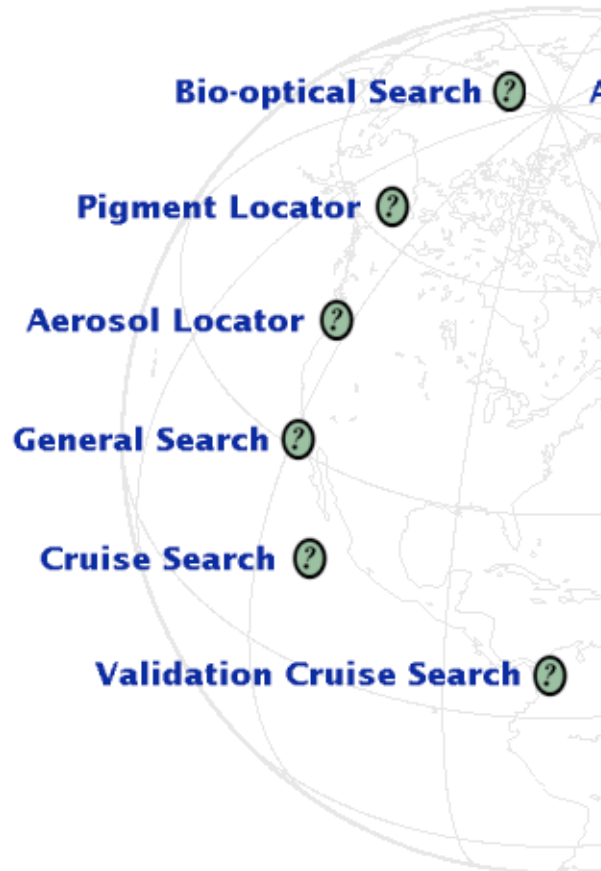
	Posts	Last Post
Announcements		
<input checked="" type="checkbox"/> Ocean Color Announcements	76 (2 new)	2008-01-14 18:59
<input type="checkbox"/> SeaDAS Announcements	53	2008-01-04 16:53
Frequently Asked Questions		
<input checked="" type="checkbox"/> General Forum Information	7	2007-12-10 20:00
<input checked="" type="checkbox"/> SeaDAS FAQ	36	2007-12-18 19:01
<input checked="" type="checkbox"/> Data Products & Algorithms FAQ	29 (2 new)	2008-01-18 13:55
<input checked="" type="checkbox"/> Data Access FAQ	16	2007-11-28 02:02
Products and Algorithms		
<input type="checkbox"/> Satellite Data Products & Algorithms	1732 (14 new)	2008-01-18 13:01
<input type="checkbox"/> Satellite Data Access	1029 (4 new)	2008-01-16 16:38
<input checked="" type="checkbox"/> Field Data	21	2007-07-23 12:19
SeaDAS		
<input type="checkbox"/> SeaDAS General Questions	5362 (26 new)	2008-01-18 00:47
<input checked="" type="checkbox"/> MODIS Direct Broadcast Support	99	2007-12-05 20:14
<input type="checkbox"/> Non-SeaDAS Packages (e.g. MATLAB, ENVI, GIS, etc)	107 (1 new)	2008-01-14 07:42
Ocean Color Features Discussion		
<input checked="" type="checkbox"/> Madagascar Plumes	11	2007-04-26 14:02

Forum Go

http://oceancolor.gsfc.nasa.gov/forum/oceancolor/forum_show.pl

the NASA Ocean Biology Processing Group

SeaBASS - *in situ*
data archive



NASA NOMAD - Galeon

File Edit View Tab Settings Go Bookmarks Tools Help

Back Stop 110 http://seabass.gsfc.nasa.gov/cgi-bin/nomad.cgi

Search engine

LIMIT BY DATE

Start: Dec 1 1991 End: Apr 6 2005

LIMIT BY LOCATION
(positive values are north of the equator and east of the Prime Meridian)

North (+/- 90.0) : 90.0 South (+/- 90.0) : -90.0
West (+/- 180.0) : -180.0 East (+/- 180.0) : 180.0

LIMIT BY ETOPO2 WATER DEPTH
(depth is increasing positive)

Minimum : 0.0 Maximum : 6300.0

LIMIT BY CRUISE or EXPERIMENT
(cruises names are for specific field campaigns, as cataloged in SeaBASS)
(experiments names are those listed in Table 2 of the above citation)

Cruise keyword(s):
Experiment: ALL

SELECT OUTPUT PARAMETERS
(metadata and chlorophyll a concentrations always output)

Lw Es Kd oisst etopo2

LIMIT RESULTS BY CHL AVAILABILITY

everything only valid fluorometry only valid HPLC require both valid fluorometry and HPLC

SEARCH CLEAR

Done.

the NASA Ocean Biology Processing Group

lessons learned

on-line direct access to data & “one-stop shopping” assures wide use & active participation of the research community.

distribution of low-level data (Lo or L1A) & calibration software reduces data distribution & storage costs.

open source software for localized data processing allows for community participation in new product development, enhances user understanding & confidence, & facilitates community feedback & support. (no black boxes!)

on-line forum allows knowledgeable staff to share the load of user support, which is vital to advancing research

1. why ocean color?
2. ocean color @ NASA
3. the NASA Ocean Biology Processing Group (OBPG)
4. calibrating & reprocessing an ocean color mission
5. international collaborations

calibrating & reprocessing an ocean color mission

“A climate data record is a time series of measurements of sufficient length, **consistency**, & continuity to determine climate variability & change.”

U.S. National Research Council, 2004

consistency:

consistency between different sensors can be achieved through standardization of processing algorithms, calibration sources & methods, & validation techniques

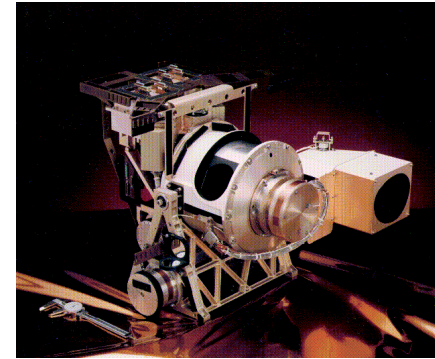
calibrating & reprocessing an ocean color mission

MODIS



- 36 bands, 9 for OC (412-869nm)
- rotating scan mirror
- solar, lunar, bb, sdsms, srca
- polarization sensitivity ~3%
- no tilting capability
- 12 bit digitization
- 10 detectors per band along track
- higher SNR in most bands

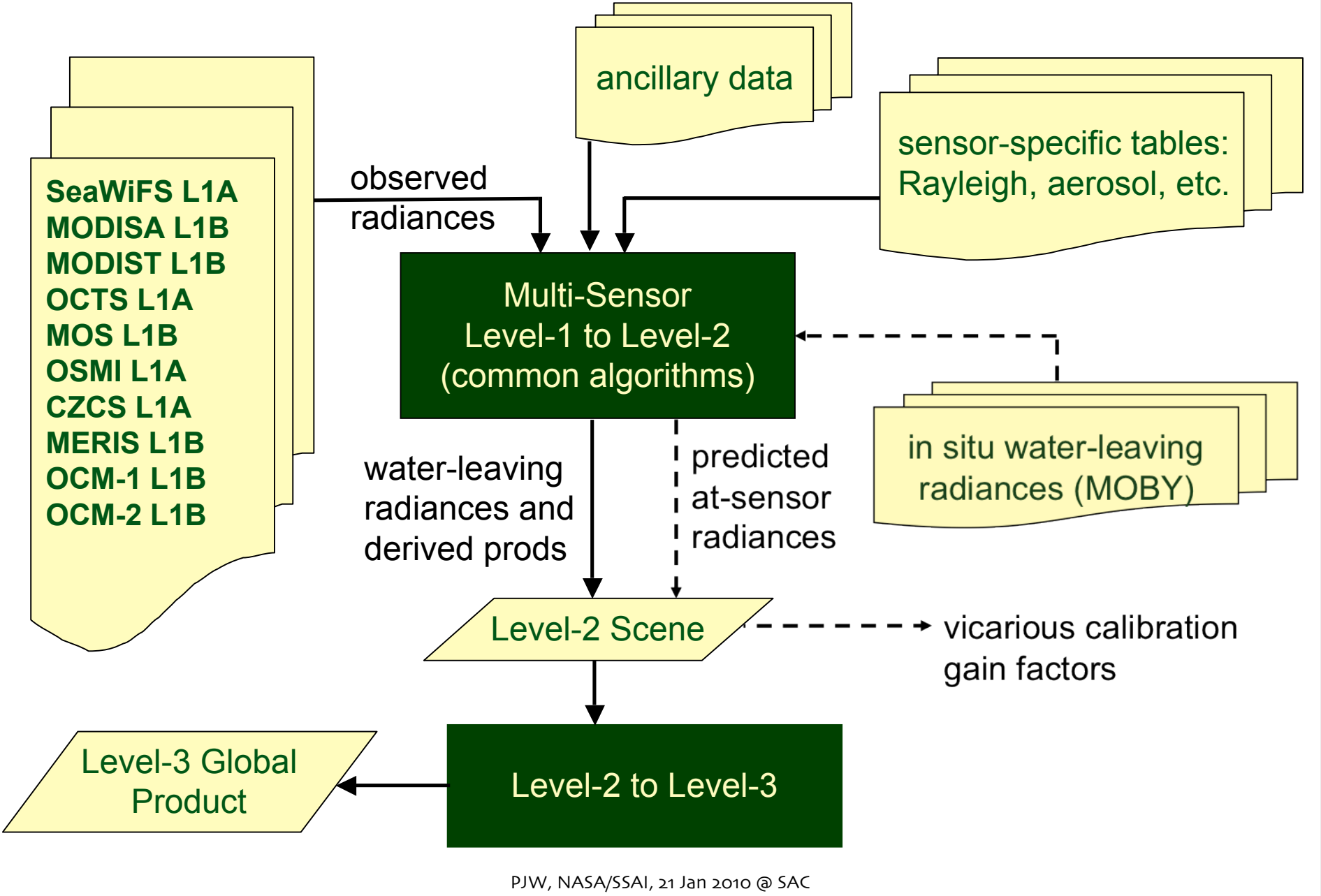
SeaWiFS



- 8 bands for OC (412-865nm)
- rotating telescope
- solar and lunar calibration
- polarization scrambler
- tilting to avoid sun glint
- 12-bit truncated to 10-bit
- 4 detectors averaged to 1 sample
- higher dynamic range (bilinear gain)

sensor design & performance varies

common processing framework



calibrating & reprocessing an ocean color mission

the Great Ocean Color Reprocessing of 2009/2010

scope:

sensors: SeaWiFS, MODISA, MODIST, OCTS, CZCS

highlights:

sensor calibration updates (instrument aging, new insights)

new aerosol models based on AERONET

improved turbid-water atmospheric correction

accounting for atmospheric NO₂ absorption

updated chlorophyll and K_d algorithms based on NOMAD v2

expanded product suite

improved agreement between SeaWiFS and MODISA

improved agreement with in situ ocean color

improved agreement with AeroNET

calibrating & reprocessing an ocean color mission

analysis topics related to reprocessing

temporal calibration

Level-2 satellite-to-*in situ* “match-ups”

applied flags

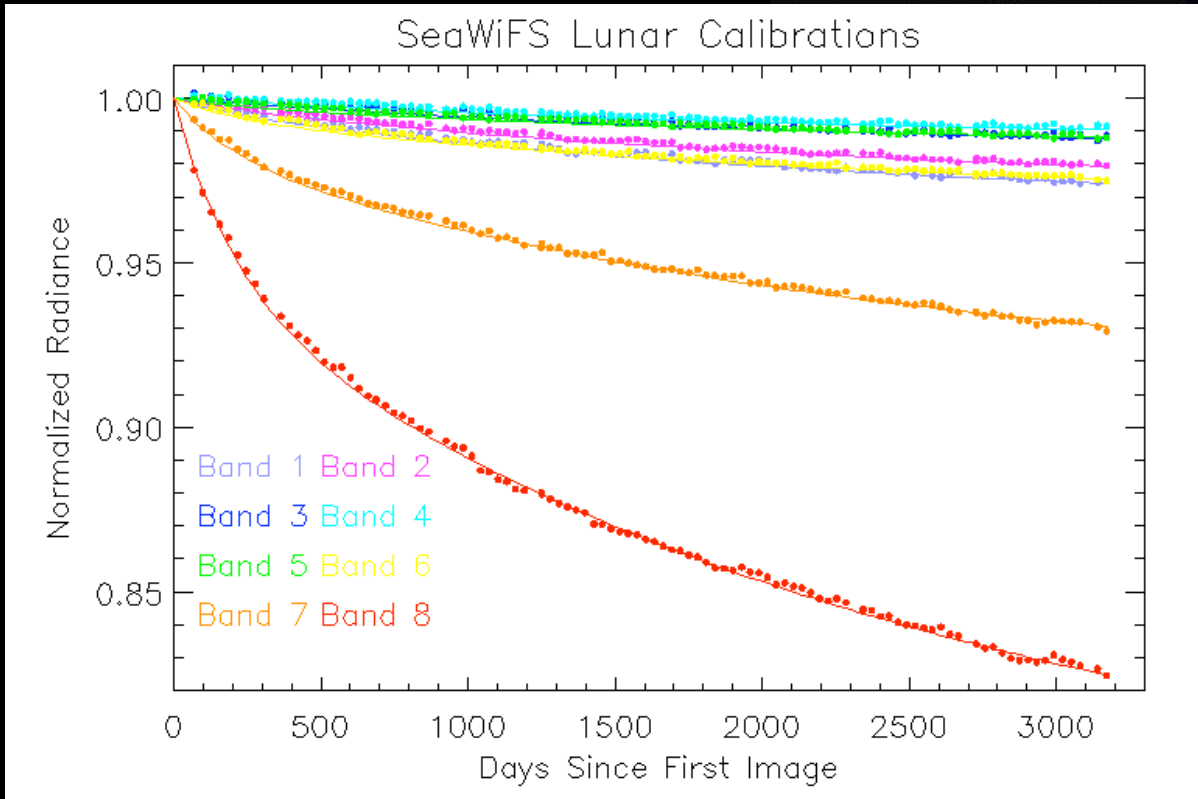
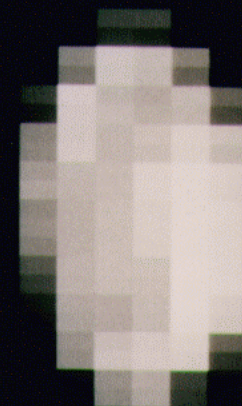
residual detector dependence

residual scan dependence

Level-3 time-series

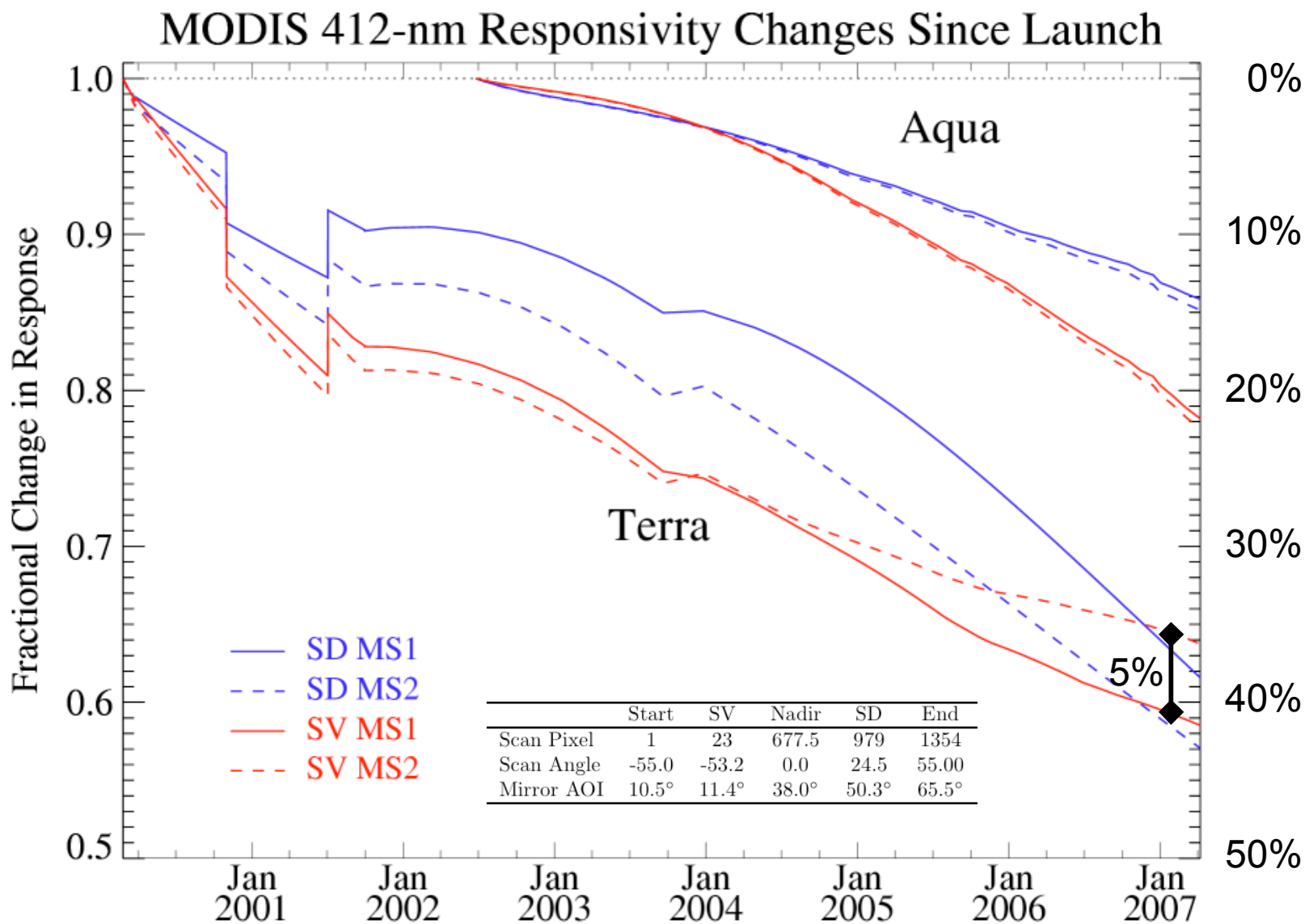
temporal anomalies

Temporal Calibration



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

MODIS temporal degradation @ 412 nm - lunar & solar calibration trends

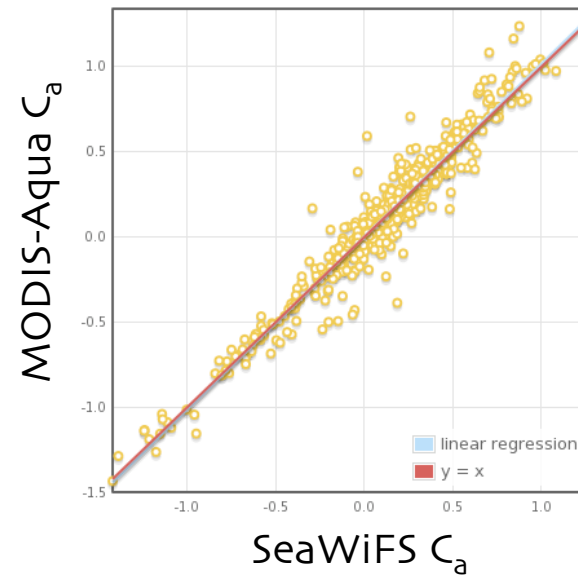
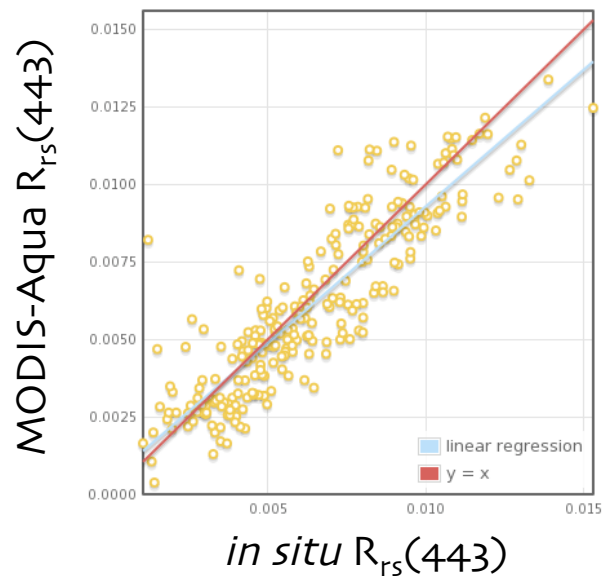


calibrating & reprocessing an ocean color mission

example of Level-2 satellite-to-*in situ* “match-ups”

highlights

- analyze match-ups for satellite-to-*in situ* & satellite-to-satellite
- search by date, location, water depth, or specific cruise
- customize exclusion criteria
- all operational data products



S.W. Bailey and P.J. Werdell, “A multi-sensor approach for the on-orbit validation of ocean color satellite data products,” Remote Sensing of Environment 102, 12-23 (2006)

calibrating & reprocessing an ocean color mission

Level-2 satellite-to-*in situ* “match-ups”

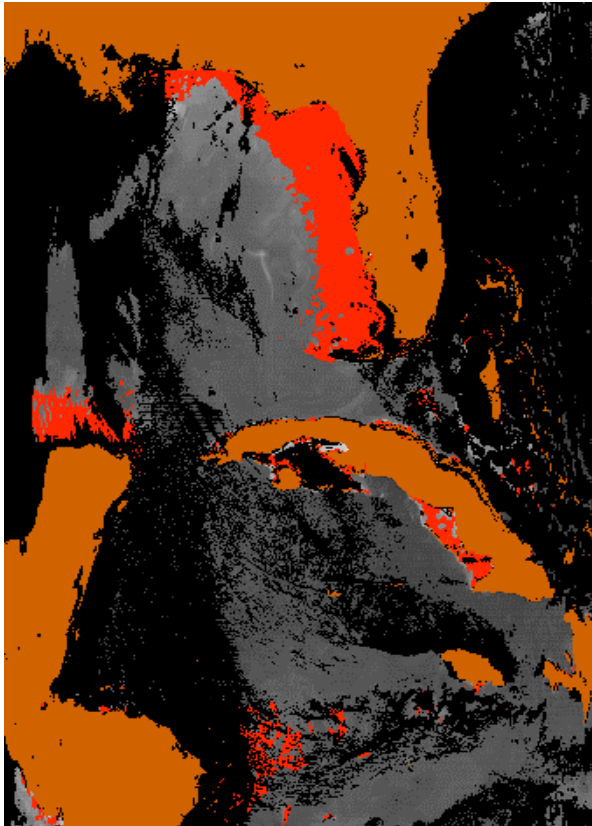
- strengths:
 - the only truly independent validation of the science data products using ground truth measurements.
- limitations:
 - quality of *in situ* data is highly variable and difficult to assess.
 - coverage for OC *in situ* data is limited, both geographically & temporally.
 - assumes that highly localized (~meters) measurements are representative of pixel (km) area.
 - *in situ* measurements require discipline expertise to analyze & compare with satellite values
 - generally useful only for assessing static biases in final products.
 - availability of *in situ* data in future (e.g., VIIRS) is unknown

calibrating & reprocessing an ocean color mission

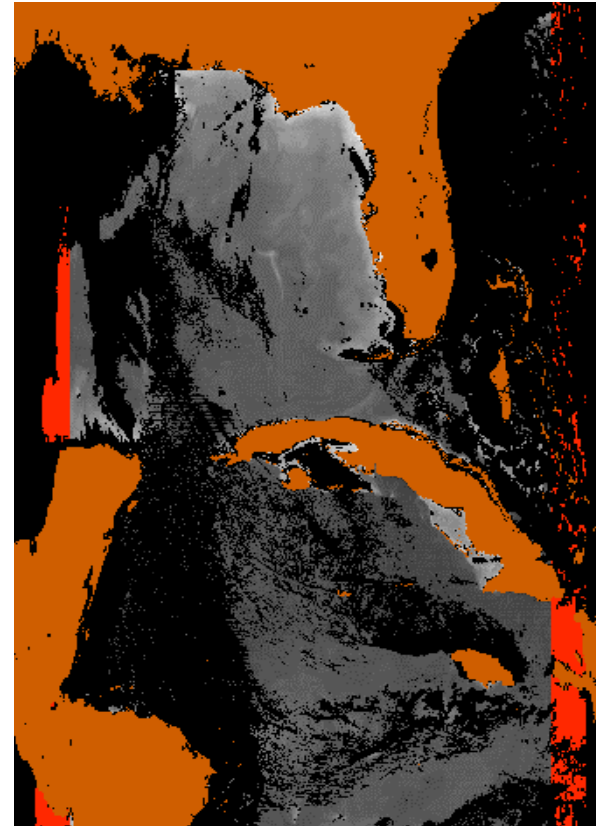
flag analyses

- determine loss of coverage resulting from each flag
- verify effectiveness of flags at removing invalid or questionable data

50-meter depth

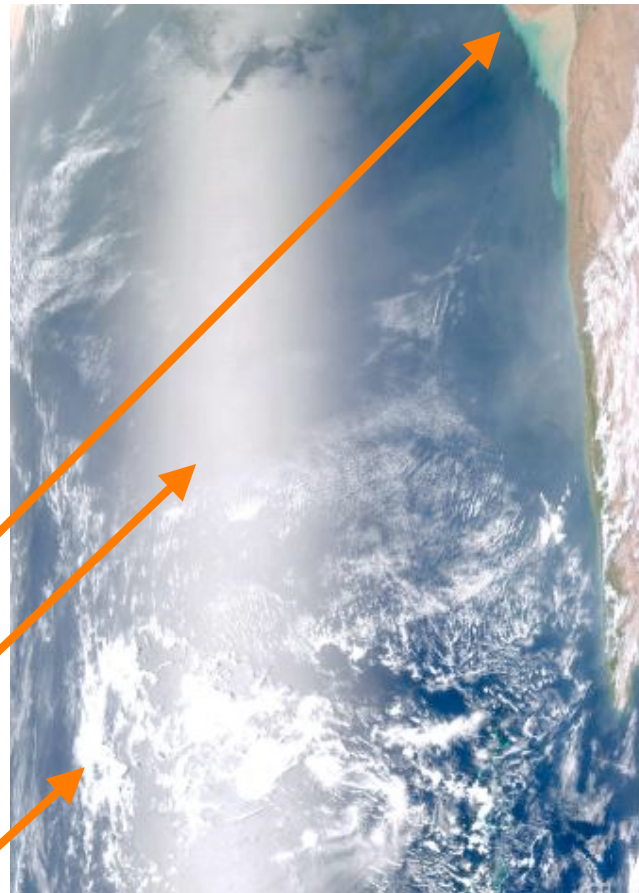


Sensor zenith

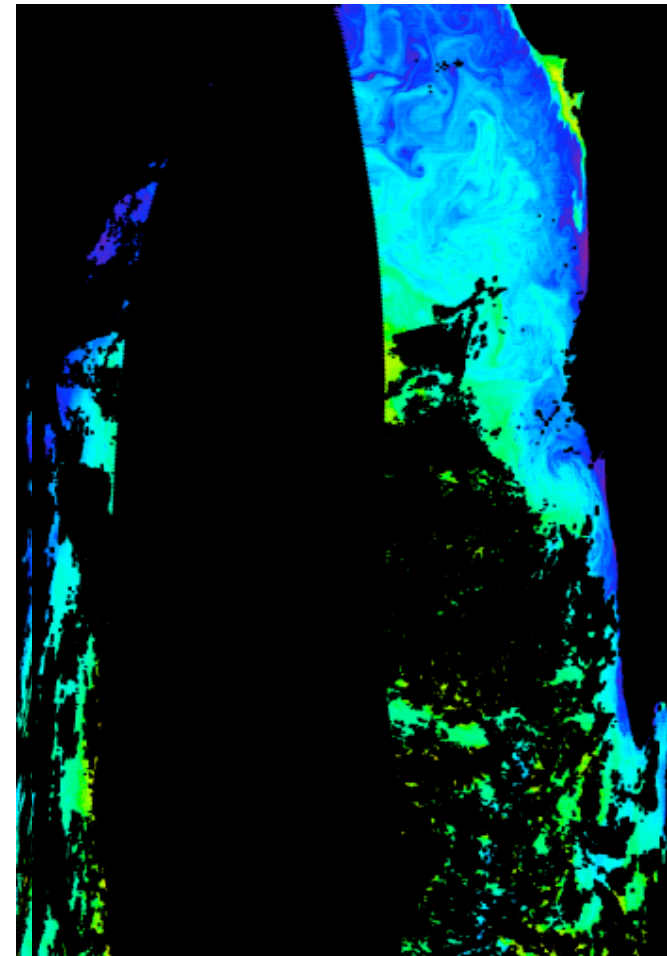


calibrating & reprocessing an ocean color mission

RGB image



$nLw(443)$



sediments

glint

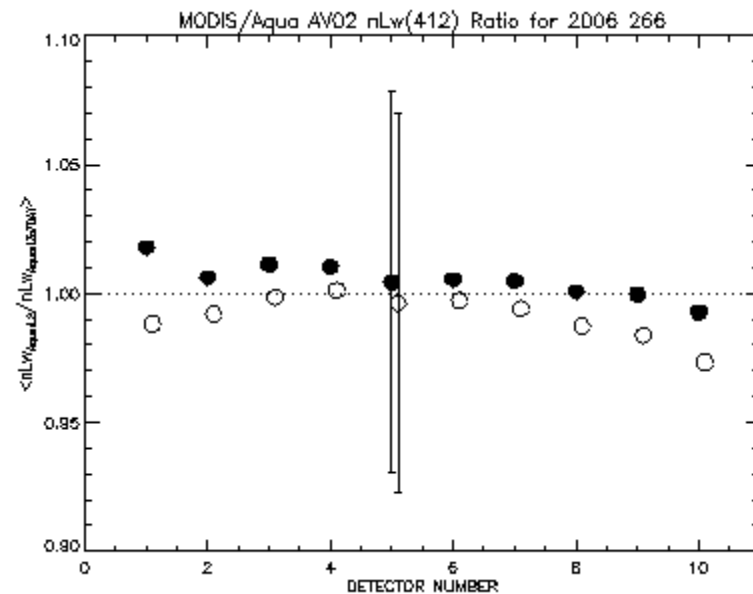
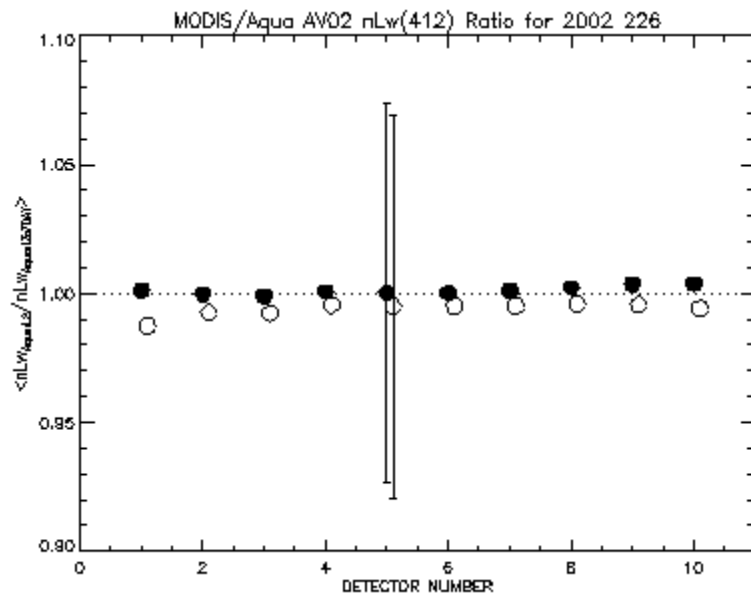
cloud

Add masking for straylight

calibrating & reprocessing an ocean color mission

residual detector dependence

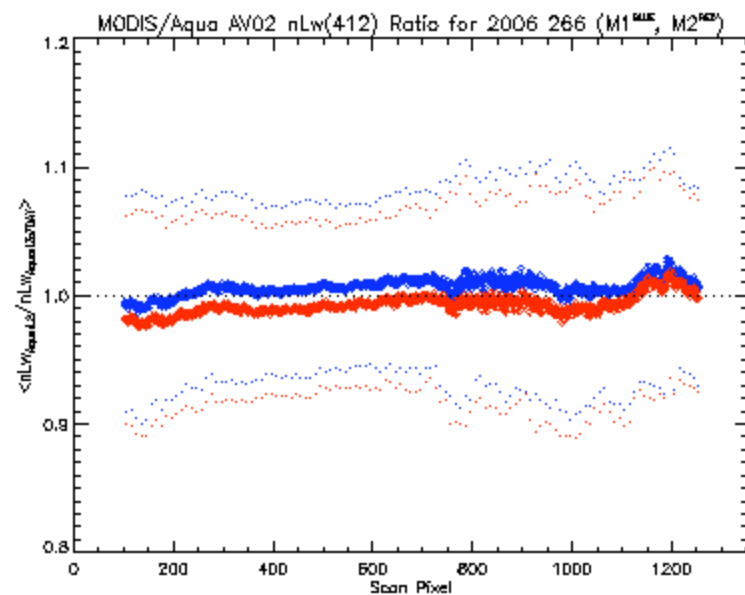
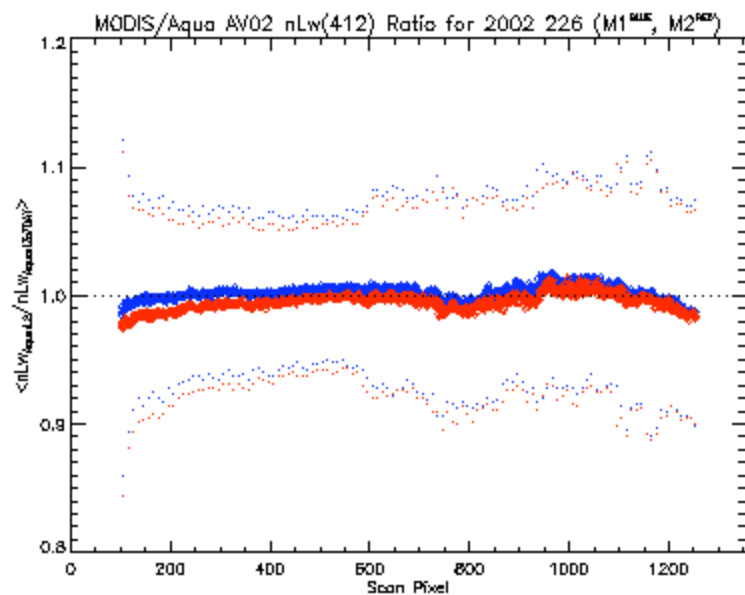
- Level-3 multi-day products (same or different sensor) are resampled to generate values at Level-2 resolution.
- comparisons are performed by detector & mirror side to evaluate residual detector response errors



calibrating & reprocessing an ocean color mission

residual scan dependence

- Level-3 multi-day products (same or different sensor) are resampled to generate values at Level-2 resolution.
- comparisons are performed by pixel number and mirror side to evaluate residual response-vs-scan (RVS) errors



calibrating & reprocessing an ocean color mission

residual detector / scan dependence

- strengths:
 - provides evaluation of response vs. detector, scan angle & mirror side independent of onboard calibration
 - can also be used to evaluate errors in other sensor characteristics
- limitations:
 - works well mainly in temporally stable areas
 - noise levels may be large compared with residual errors

Franz, B.A., E.J. Kwiatkowska, G. Meister, and C. McClain, "Moderate Resolution Imaging Spectroradiometer on Terra: limitations for ocean color applications," *J. Appl. Rem. Sens* (2008)

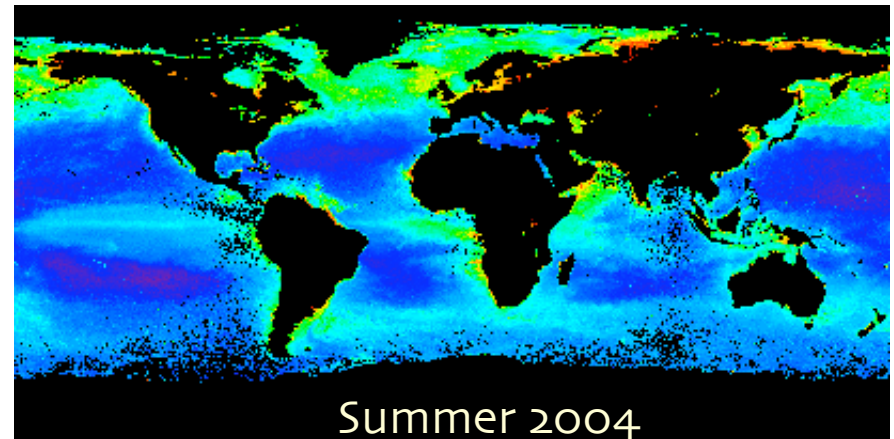
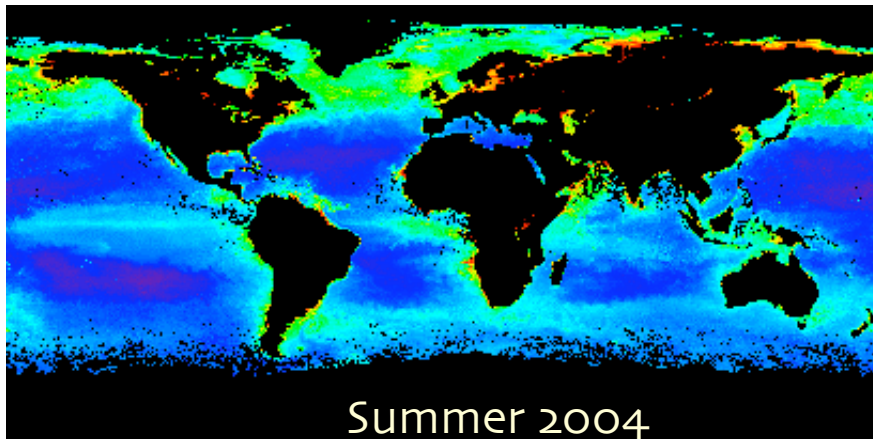
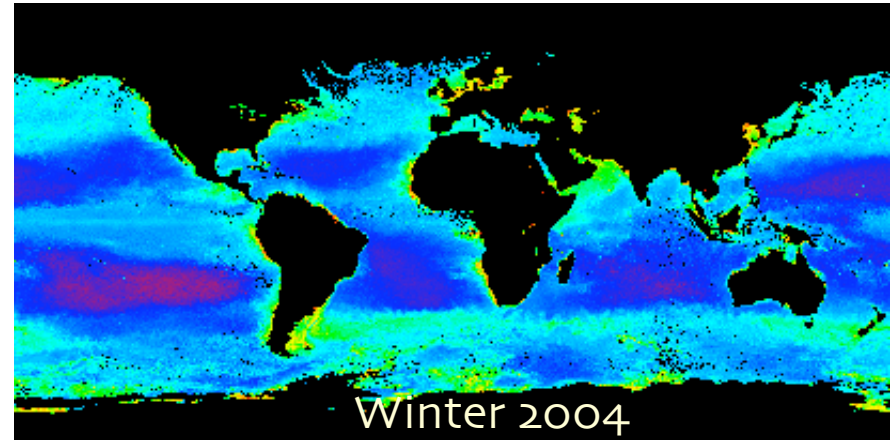
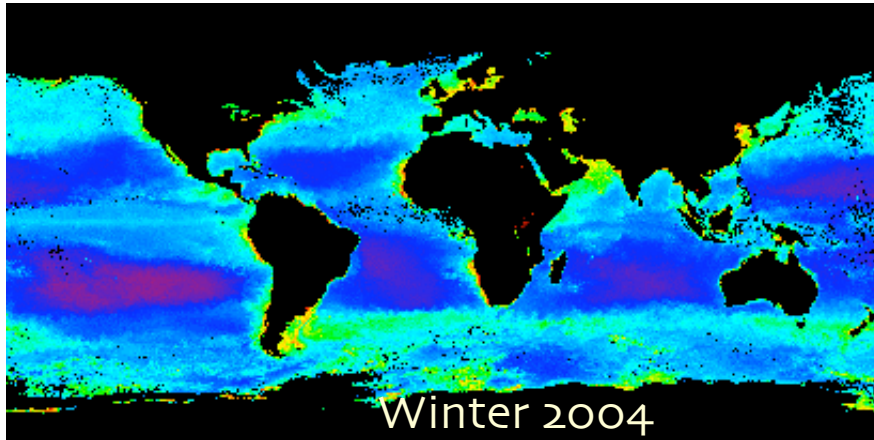
Kwiatkowska, E.J., B.A. Franz, G. Meister, C. McClain, and X. Xiong, "Cross-calibration of ocean-color bands from Moderate Resolution Imaging Spectroradiometer on Terra platform," *Appl. Opt.* (2008)

calibrating & reprocessing an ocean color mission

Seasonal Chlorophyll Images

MODIS/Aqua

SeaWiFS



0.01-64 mg m⁻³

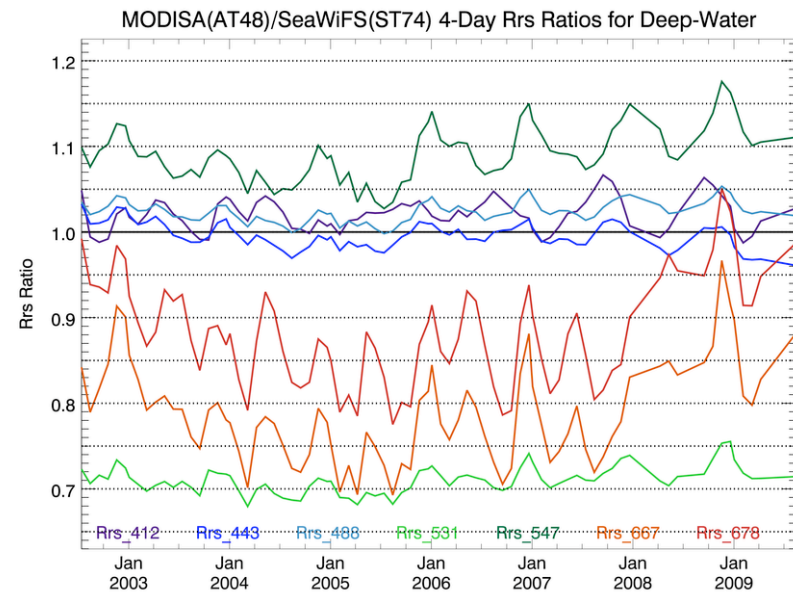
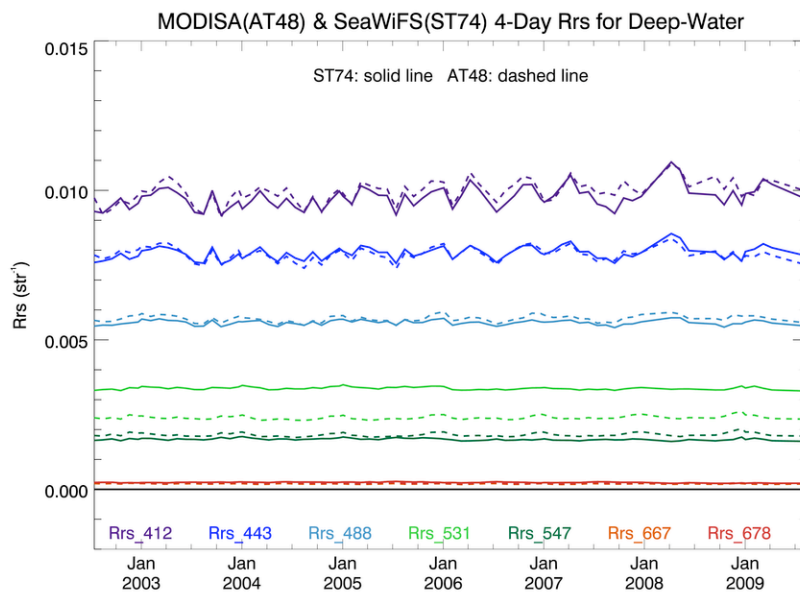
calibrating & reprocessing an ocean color mission

sensor & algorithm comparisons

Level-3 parameters (e.g., Rrs) compared for common spectral bands

common bins extracted & compared over the period of overlap between the sensors

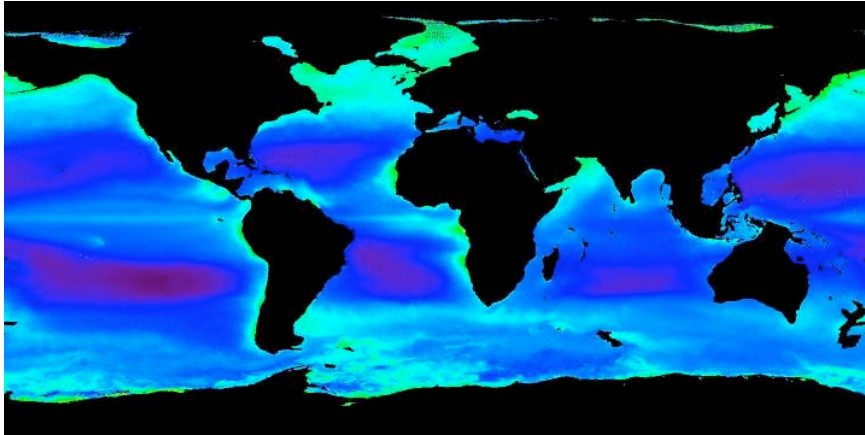
comparisons performed globally, tropically, zonally & for specified regions



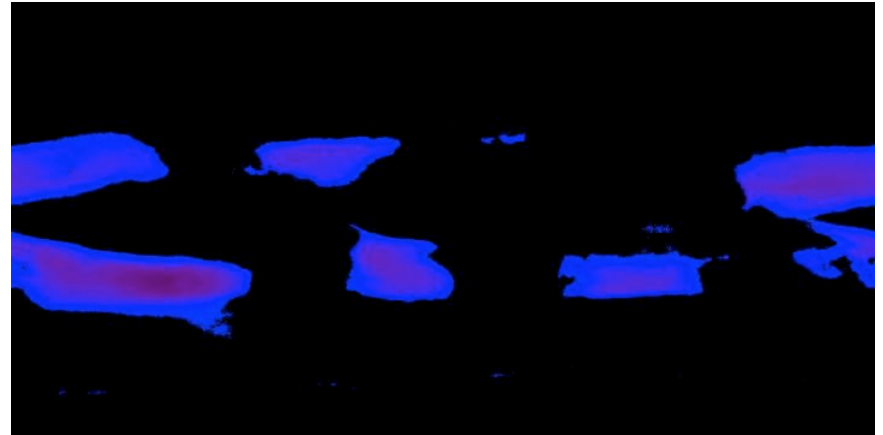
calibrating & reprocessing an ocean color mission

definitions of trophic subsets

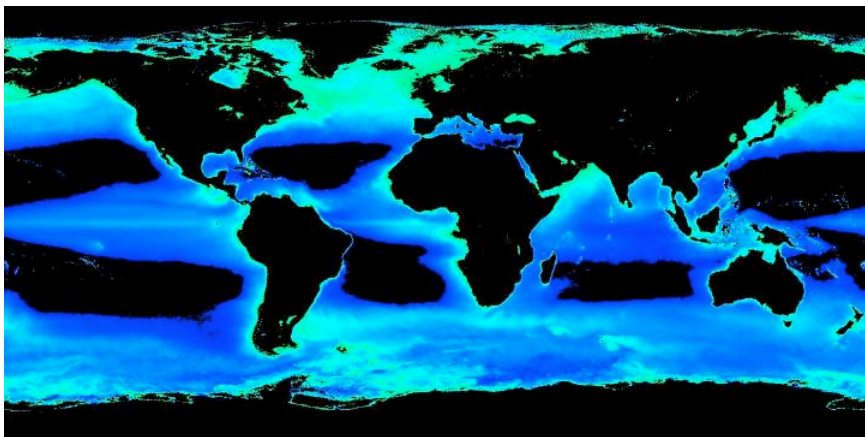
Deep-Water (Depth > 1000m)



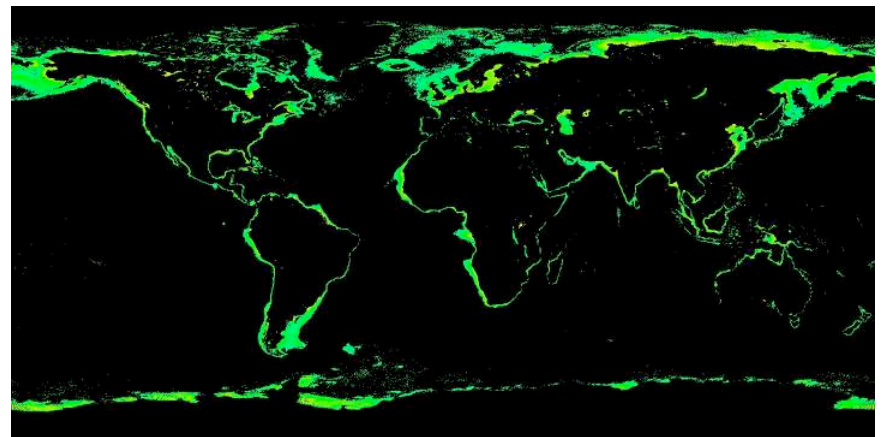
Oligotrophic (Chlorophyll < 0.1)



Mesotrophic (0.1 < Chlorophyll < 1)



Eutrophic (1 < Chlorophyll < 10)



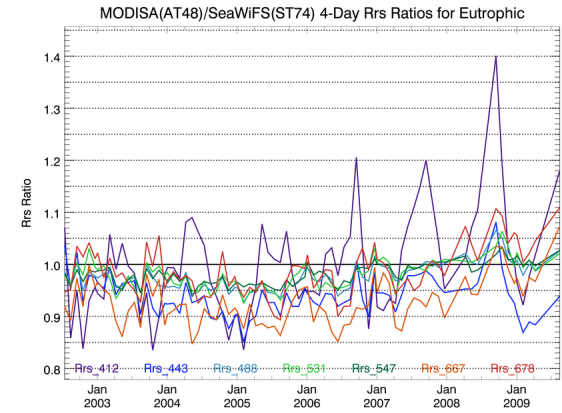
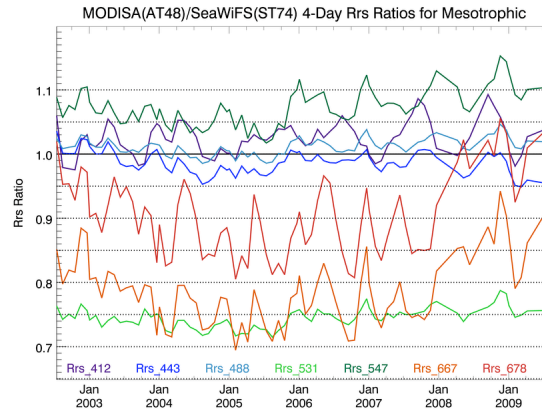
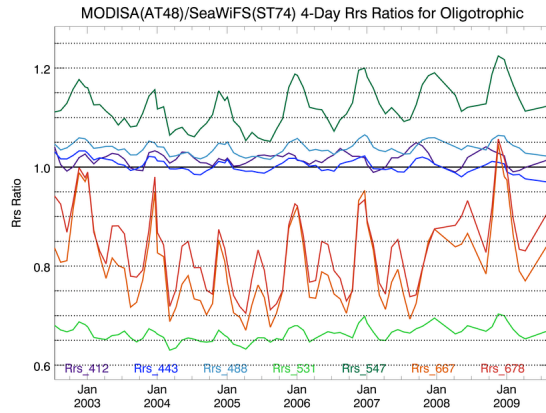
calibrating & reprocessing an ocean color mission

oligotrophic

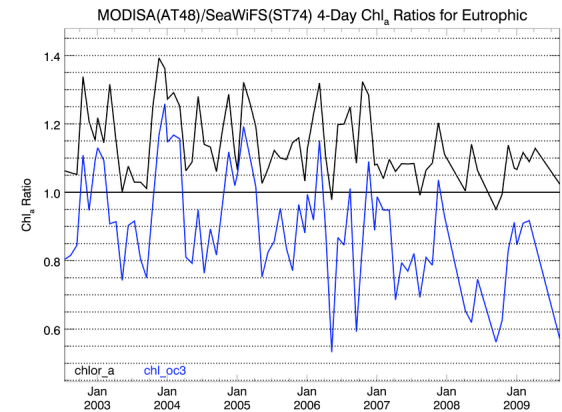
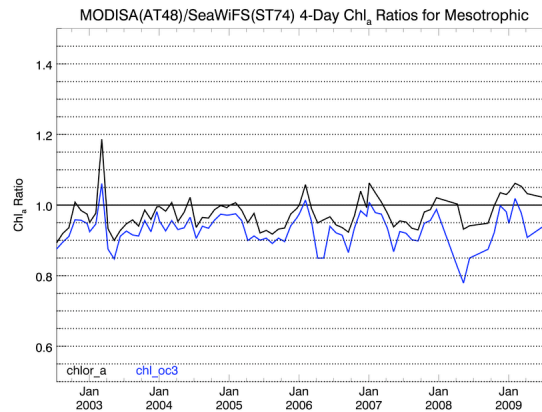
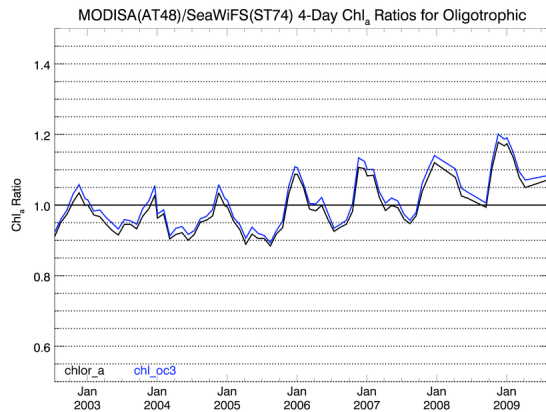
mesotrophic

eutrophic

Rrs



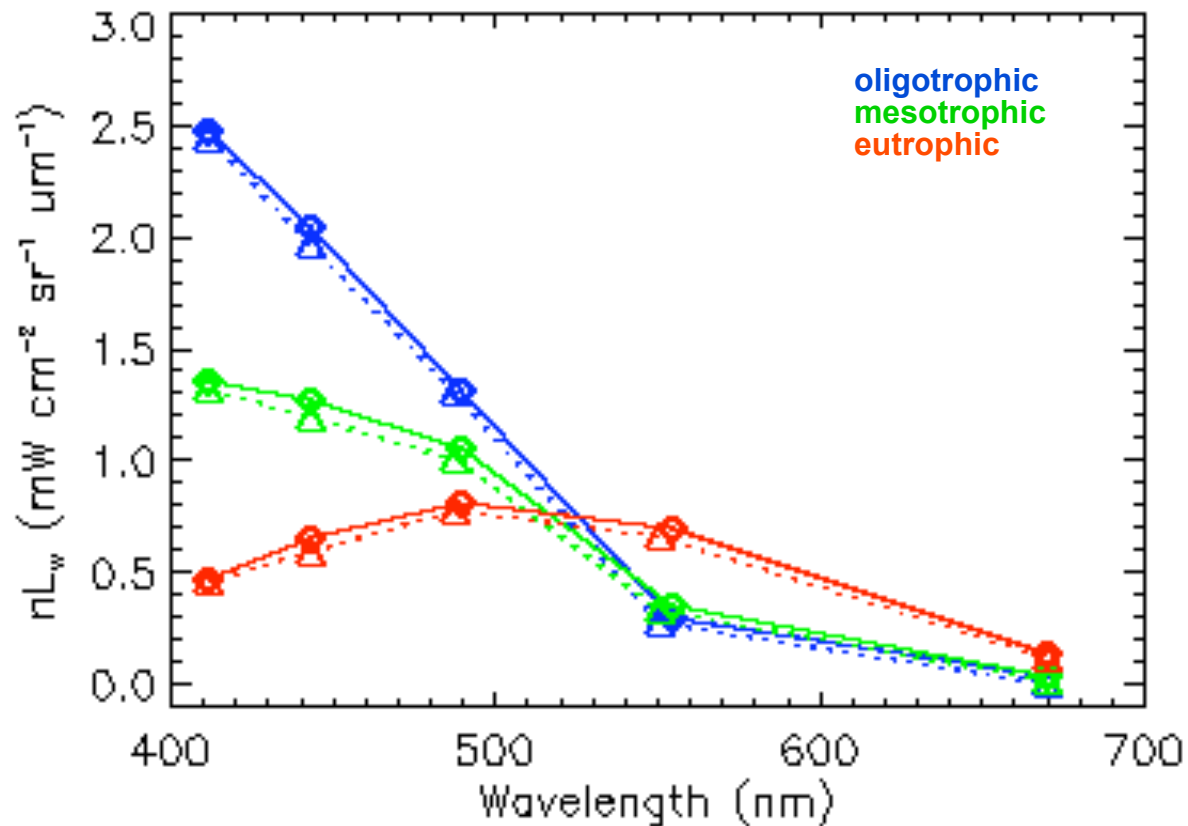
chlorophyll-a



calibrating & reprocessing an ocean color mission

comparison of spectral distribution trends

MODIS & SeaWiFS mean nL_w



calibrating & reprocessing an ocean color mission

Level-3 comparisons

- strengths:
 - sensitive to small differences in products from different sensors or algorithms
 - excellent coverage available, both temporal & geographic
 - can assess continuity among data sets (Climate Data Records)
- limitations:
 - no obvious truth in comparisons.
 - sensitive to band-pass differences.
 - may be affected by time-of-observation differences.
 - availability of other sensors for comparison (SeaWiFS or MODIS) is unknown; climatology is available as an alternative

calibrating & reprocessing an ocean color mission

temporal anomaly evaluations

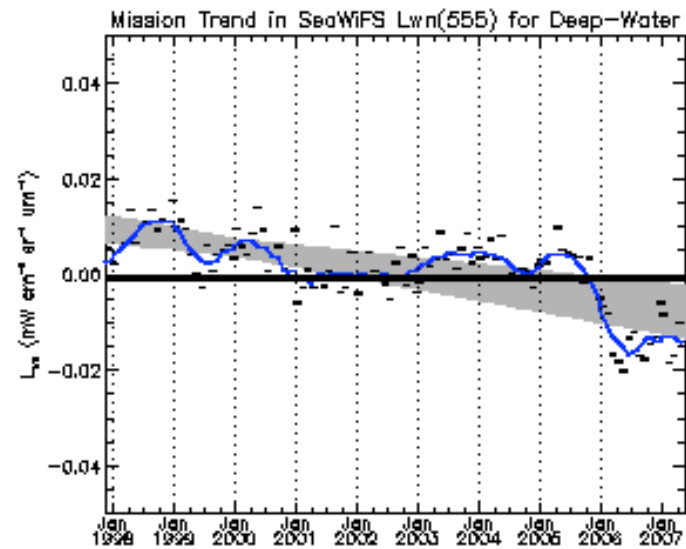
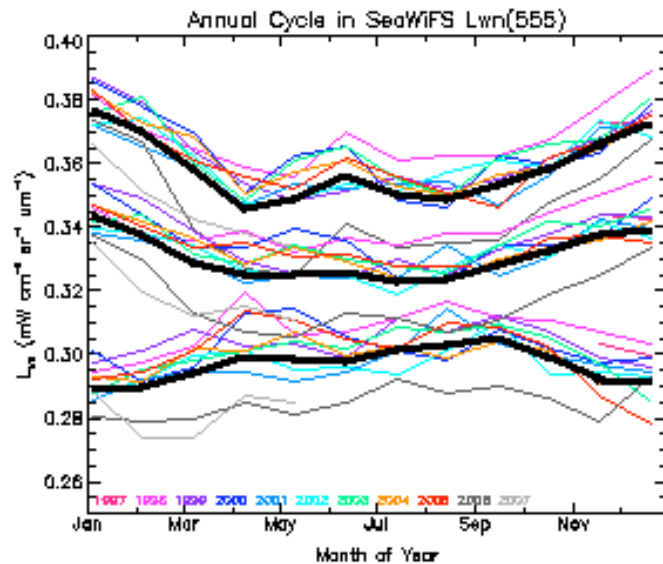
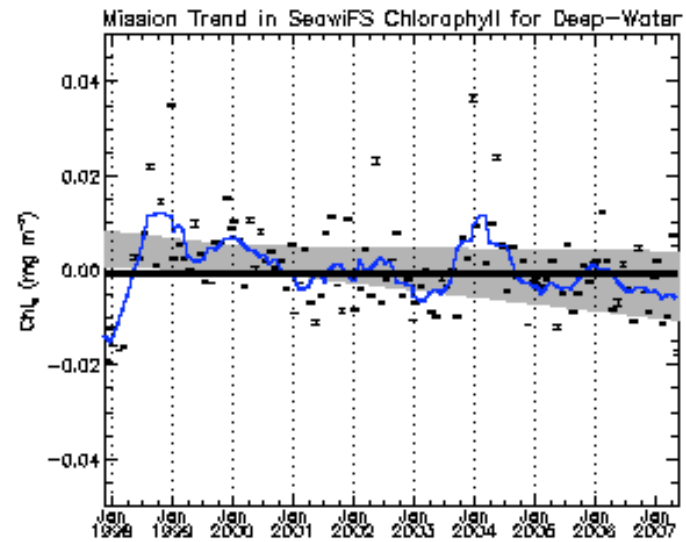
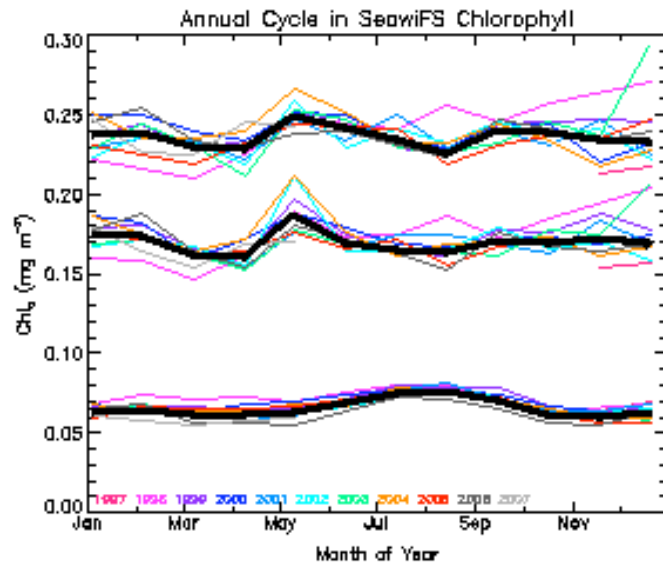
Level-3 global averages for the entire mission are fit to a periodic function to remove natural annual variability

the differences between the global averages & the annual cycle are then plotted over the mission

the results show both geophysical variations & any unexpected changes due to uncharacterized instrument effects or algorithm artifacts

calibrating & reprocessing an ocean color mission

temporal anomaly example



calibrating & reprocessing an ocean color mission

temporal anomaly evaluations

- strengths:
 - very sensitive to small changes in sensor performance
- limitations:
 - difficult to distinguish sensor from real geophysical changes
 - can be affected by sampling variations.

calibrating & reprocessing an ocean color mission

the problem with recovering MODIS-Terra ocean color

- Overheating event in pre-launch testing "smoked" the mirror
 - pre-launch characterization may not adequately represent at-launch configuration (mirror-side ratios, RVS, polarization sensitivities)
- Substantial temporal degradation of instrument response
 - degradation varies with mirror-side and scan-angle
 - temporal change in polarization sensitivity, RVS
- On-board calibration capabilities (lunar, solar) CANNOT assess
 - changes in polarization sensitivities, or
 - changes in RVS "shape"

calibrating & reprocessing an ocean color mission

reprocessing plans for MODIS-Terra

well documented issues with radiometric stability

Franz, B.A., E.J. Kwiatkowska, G. Meister, and C. McClain, "Moderate Resolution Imaging Spectroradiometer on Terra: limitations for ocean color applications," *J. Appl. Rem. Sens* (2008)

vicarious on-orbit recharacterization of RVS & polarization

Kwiatkowska, E.J., B.A. Franz, G. Meister, C. McClain, and X. Xiong, "Cross-calibration of ocean-color bands from Moderate Resolution Imaging Spectroradiometer on Terra platform," *Appl. Opt.* (2008)

analysis to be repeated and results fully implemented once SeaWiFS & MODIS-Aqua reprocessing is completed.

MODIS-Terra full mission will then be available through ocean color web browse & ordering system.

calibrating & reprocessing an ocean color mission

lessons learned

sensor pre-launch characterization is critical (e.g., *cross-scan response, polarization sensitivity, spectral out-of-band response, stray-light*). Post-launch characterization may not be possible.

evaluation of advances in on-orbit calibration & processing algorithms requires the capacity for rapid reprocessing, e.g.:

- 10-year SeaWiFS mission can be reprocessed in ~1 day
- SeaWiFS has been reprocessed & redistributed 8 times
- to facilitate new algorithm & calibration evaluations, global SeaWiFS mission has been reprocessed ~100 times

common (sensor-independent) software eliminates potential for algorithm & implementation differences between missions.

consolidated measurement-based team with strong international ties facilitates progress in product development and data quality

1. why ocean color?
2. ocean color @ NASA
3. the NASA Ocean Biology Processing Group (OBPG)
4. calibrating & reprocessing an ocean color mission
5. international collaborations

international collaborations

cost-free, **open data policy** for all NASA ocean color missions

open source software (SeaDAS - the SeaWiFS Data Analysis System)

SIMBIOS Program

sensor intercomparison studies, data merging algorithms, instrument pools & data processing round robins, & coordinated field data collection

visiting scientists and engineers

Antoine & Morel (f/Q algorithm evaluation), Tanaka (OCTS & GLI, cal/val & processing), Hagolle (POLDER implementation in SeaDAS), Kim (OSMI implementation in SeaDAS), Neumann (IRS-P₃/MOS processing stream)

MOS/IRS-P₃ Receiving Station at Wallops

OCTS/ADEOS reprocessing & distribution

MODIS SST data for GHRSSST

international collaborations

ESA / NASA MERIS collaborations

Bryan Franz & Gerhard Meister are participating members of the MERIS Quality Working Group

SeaDAS enhanced to support display & analysis of standard MERIS Level-2 products

MERIS processing capability incorporated into NASA software & released via SeaDAS

participation in the ESA CoastColour Program forthcoming

MERIS Level-2 data displayed in SeaDAS

The screenshot displays the SeaDAS software interface on a Mac OS X system. The main window, titled "1) Mapped - algal_1 : MER_FR_2PNEPA20030714_102918_00000982018_00094_07162_0053.N1", shows a satellite image of the North Atlantic Ocean with a color scale on the right ranging from 0.01 to 64.57. A red box highlights a specific region of the map.

Surrounding the main window are several utility windows:

- Band List Selection:** Shows loaded bands: 1. reflc_6 : MER_FR_2PNEPA20030, 2. algal_1 : MER_FR_2PNEPA200307, 3. Mapped - algal_1 : MER FR 2PN. It also displays current product information such as dimensions (600 x 800) and scale type (LIN).
- Cursor Position:** Shows display mode (Interactive), pixel/line (465 / 279), and current data/geo values (59.11).
- Zoom:** Provides a magnified view of the selected region.
- Product Selection For MERIS File:** A dialog box for selecting products from a MERIS file. It lists various parameters like latitude, longitude, and various reflectance and algal indices.
- Terminal:** Shows the command line execution of SeaDAS, including version information and a progress log for processing the selected bands.

```
palapa:meris mike$ seadas
IDL Version 7.0, Mac OS X (darwin ppc m32). (c) 2007, ITT Visual Information Solutions
Installation number: 17915.
Licensed for use by: NASA/GSFC SeaWiFS Project

SeaDAS Version 5.3.0 (pid = 96310)
SeaDAS>
GENERIC_FILE_TYPE detected a non-HDF file.
GENERIC_FILE_TYPE detected a MERIS file.
SeaDAS>
Getting MERIS - "reflec_6" data from HDF file...
Getting MERIS - "algal_1" data from HDF file...
SeaDAS>
SeaDAS Projection -      128 out of      800 lines processed
SeaDAS Projection -      256 out of      800 lines processed
SeaDAS Projection -      384 out of      800 lines processed
SeaDAS Projection -      512 out of      800 lines processed
SeaDAS Projection -      640 out of      800 lines processed
SeaDAS Projection -      768 out of      800 lines processed
SeaDAS Projection -      800 out of      800 lines processed
SeaDAS>
```

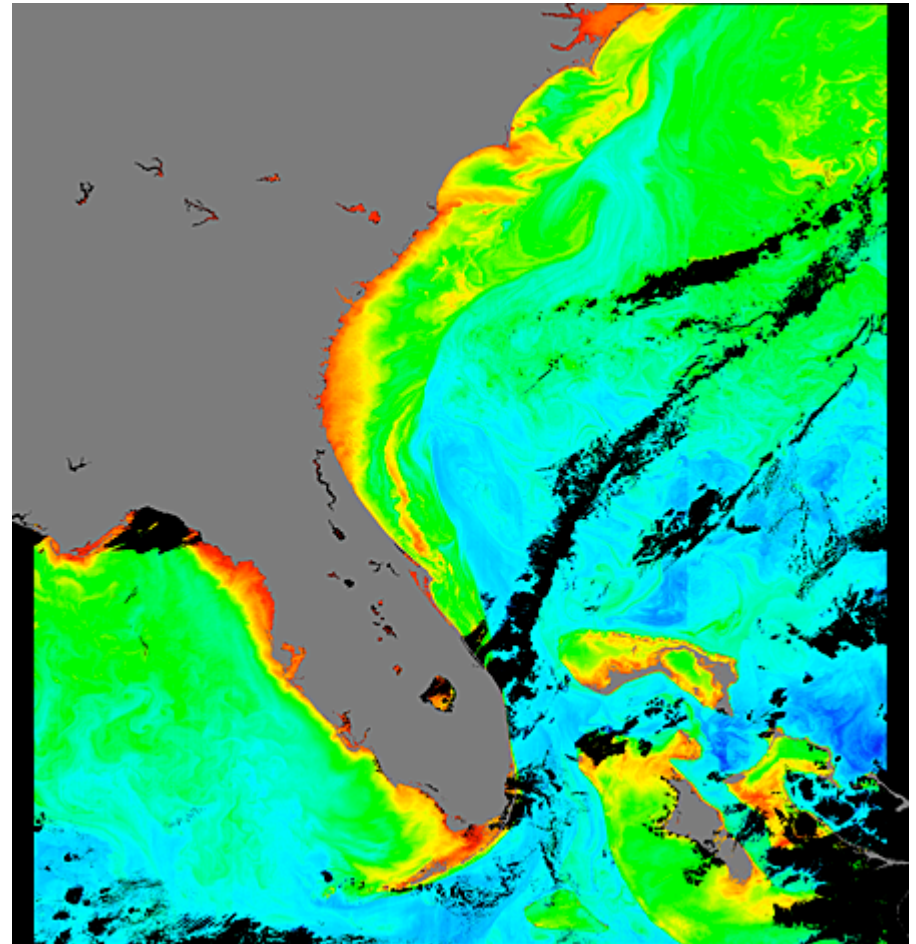
international collaborations

MERIS FRS processed with NASA OC algorithms

RGB



OC4 Chlorophyll

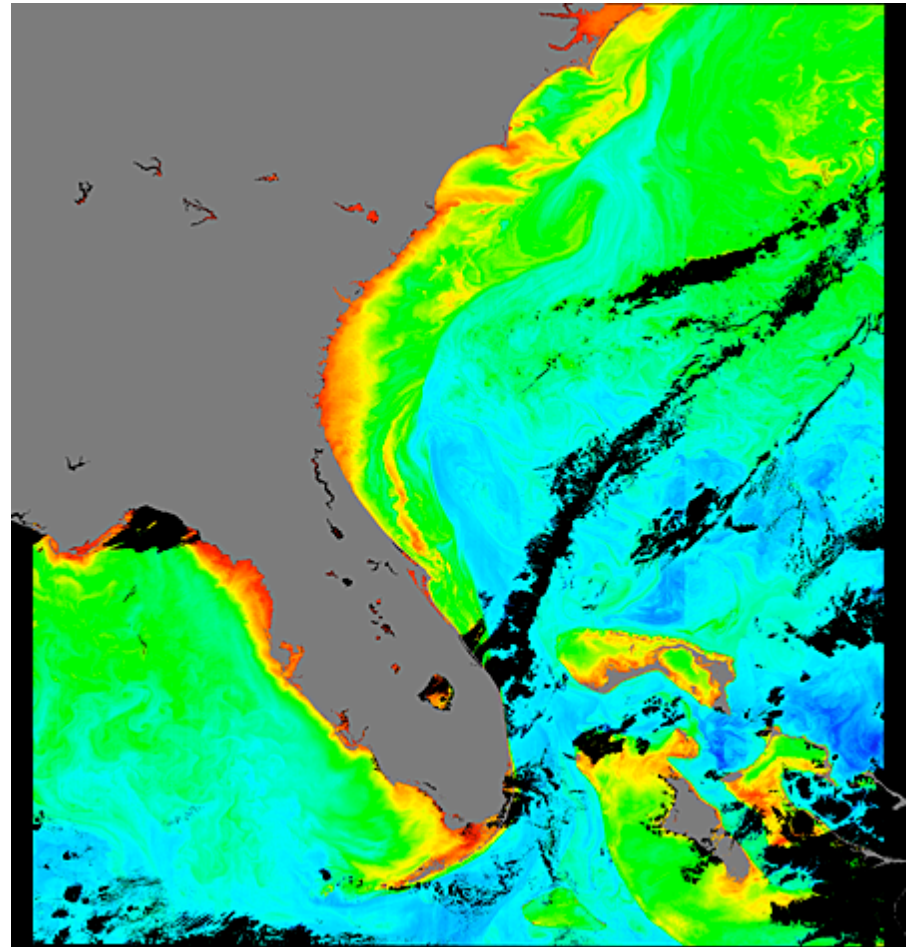
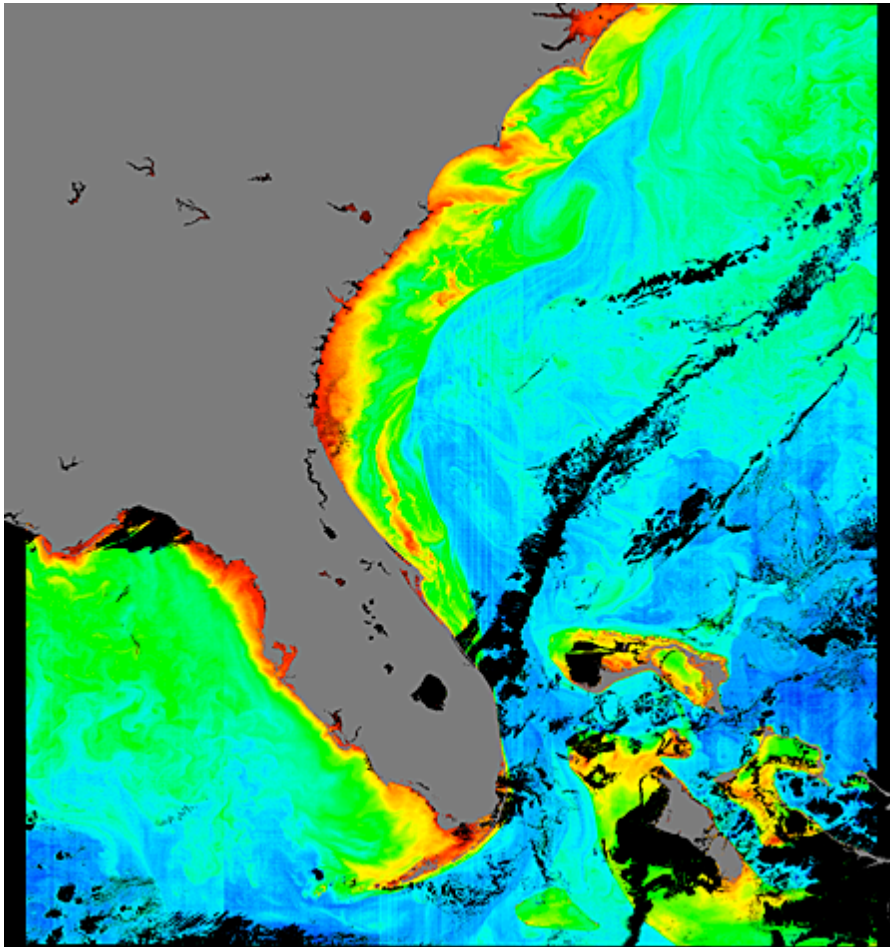


international collaborations

MERIS processing comparison

MERIS Algal1 (ESA/Kiruna)

MERIS OC4 (NASA/OBPG)



international collaborations

Letter of Intent & Proposed Responsibilities between NASA & ISRO (also NOAA & ISRO) signed 18 November 2009 regarding the OCM-2 & scatterometer instruments onboard the ISRO Oceansat-2 satellite

highlights:

ISRO to provide online access to global OCM-2 data (4-km) at Level-1B for research use to all international users at no cost

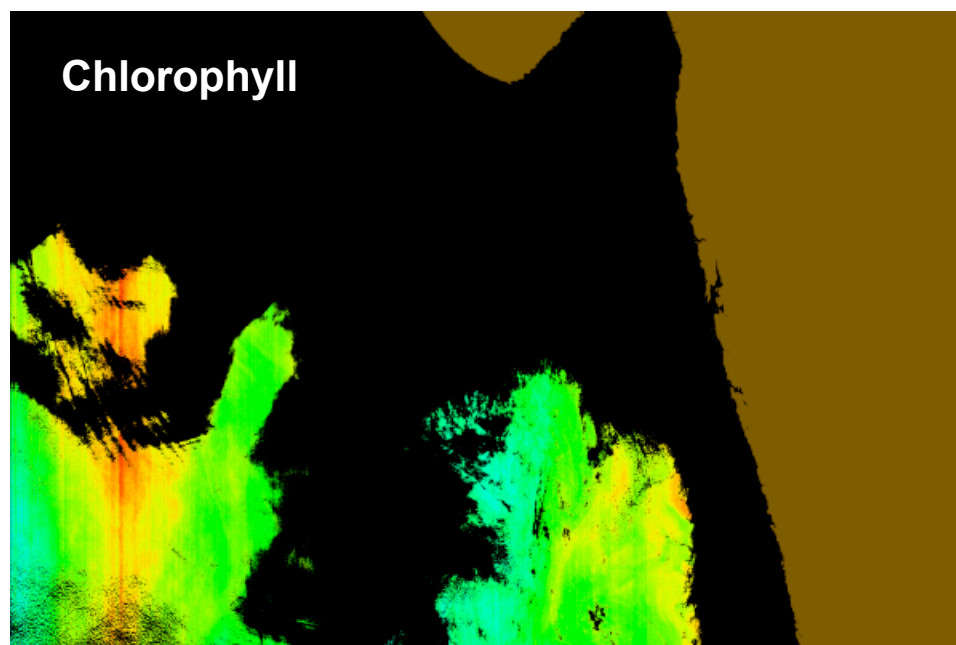
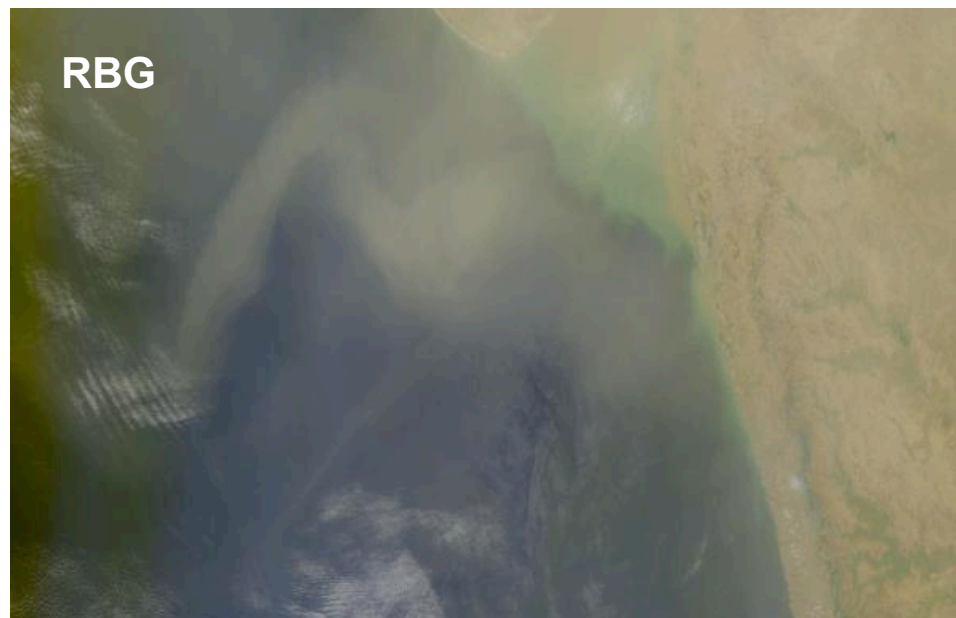
NASA to provide processing capability (Level-1B through Level-3) for use by ISRO & the international community

- distributed via SeaDAS
- preliminary capability based on OCM already implemented
- need ISRO to finalize Level-1B format

NASA & NOAA to participate in Joint Cal/Val Team

preliminary OCM-2 Level-1B
format, simulated from OCM-1

sample OCM processing via
NASA OBPG software & common
SeaWiFS/MODIS algorithms.



Thank
you



OceanColor
People

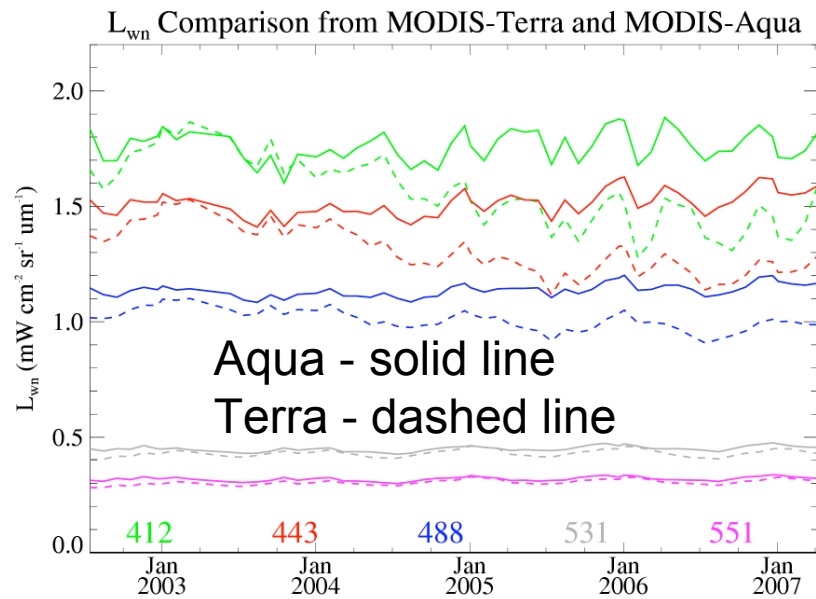


thank you!

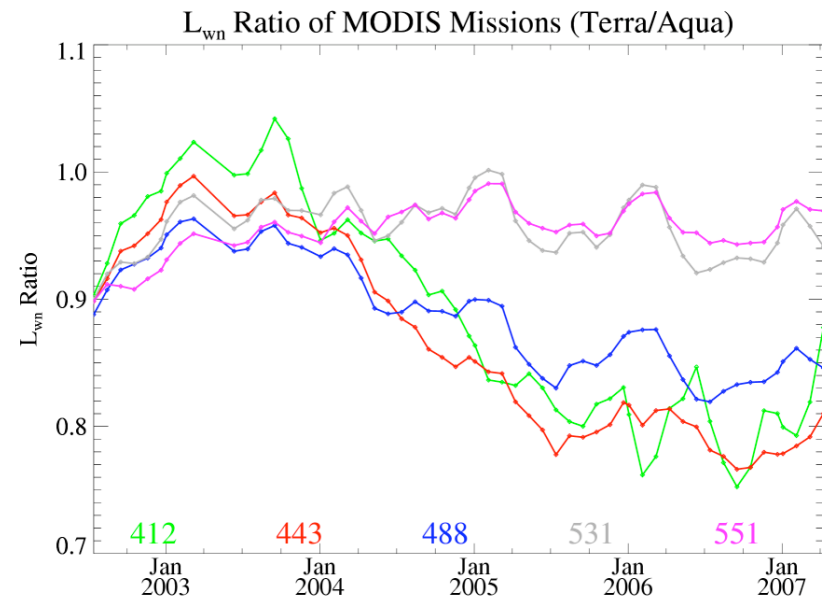
MODIS/Aqua vs MODIS/Terra "as-is"

Temporal Trends in Global Deep-Water nLw

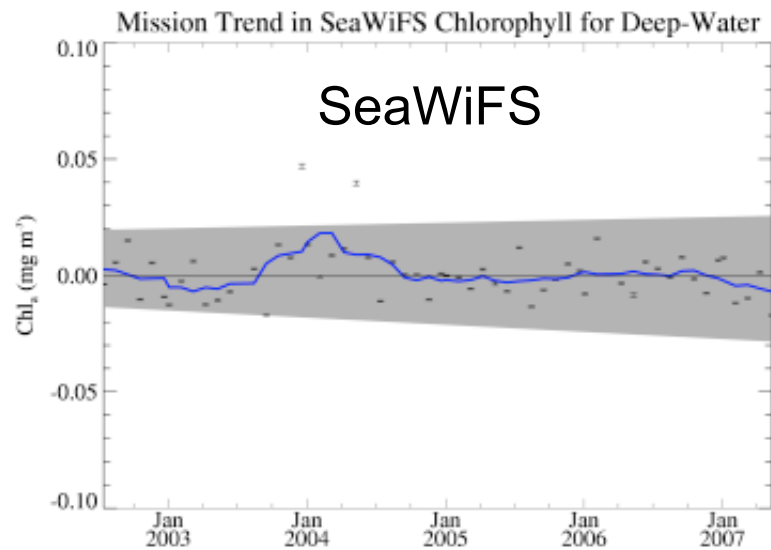
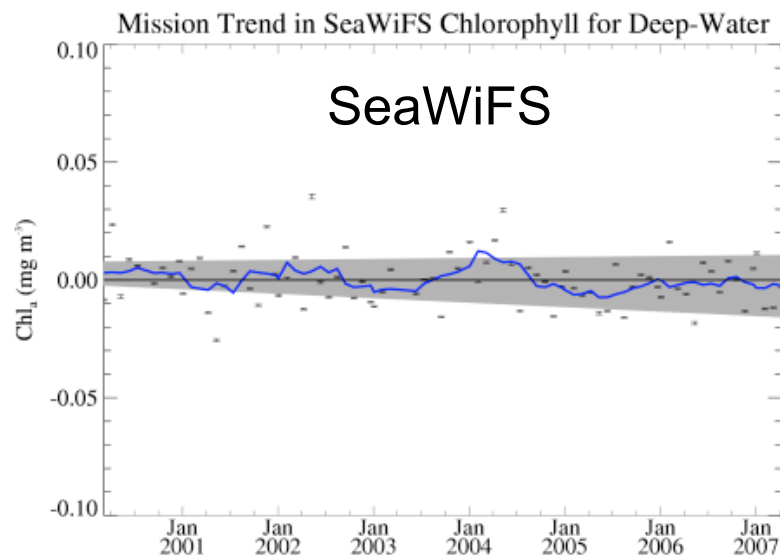
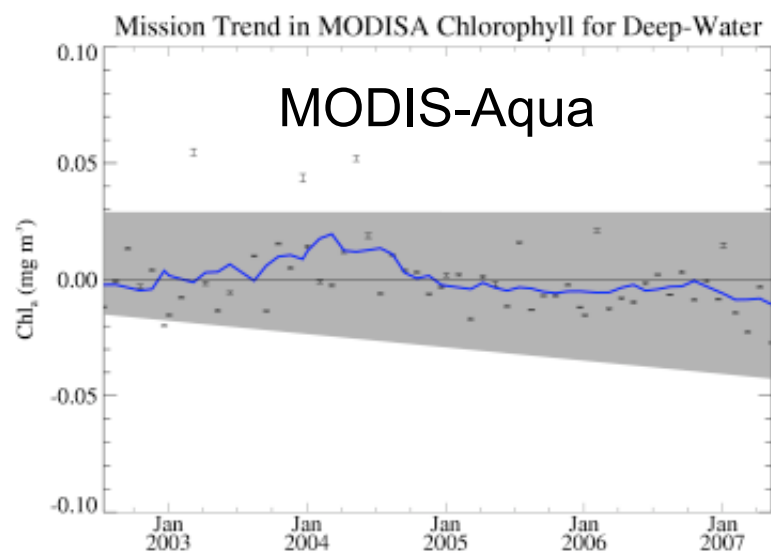
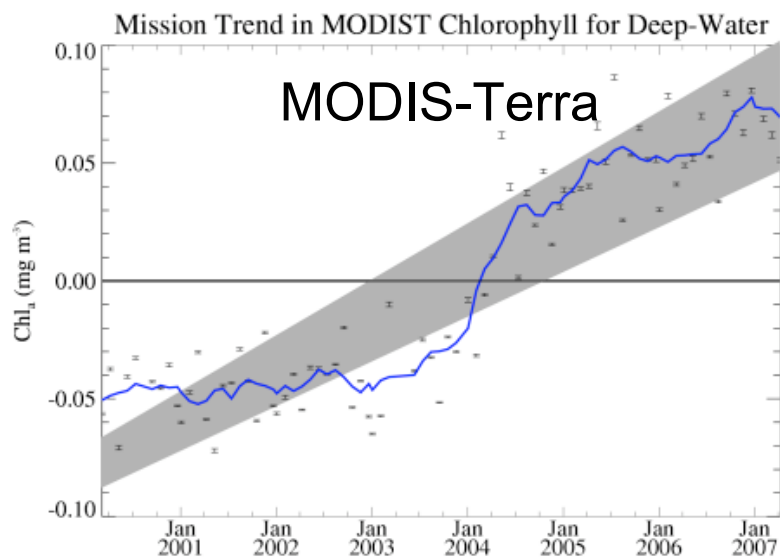
MODIST & MODISA



MODIST / MODISA



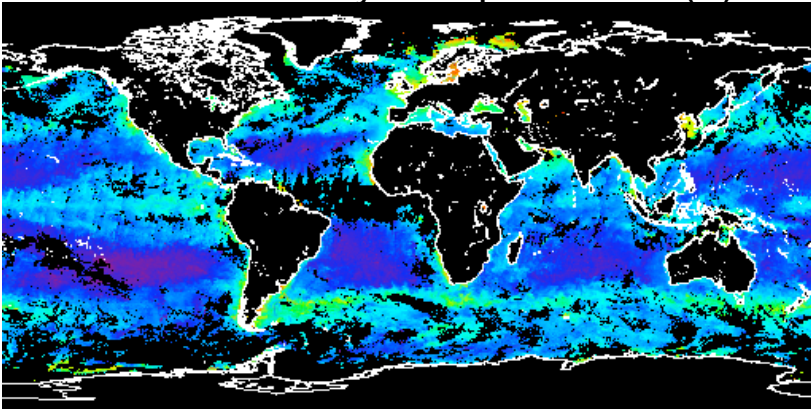
Deep-Water Seasonal Anomaly in Chlorophyll



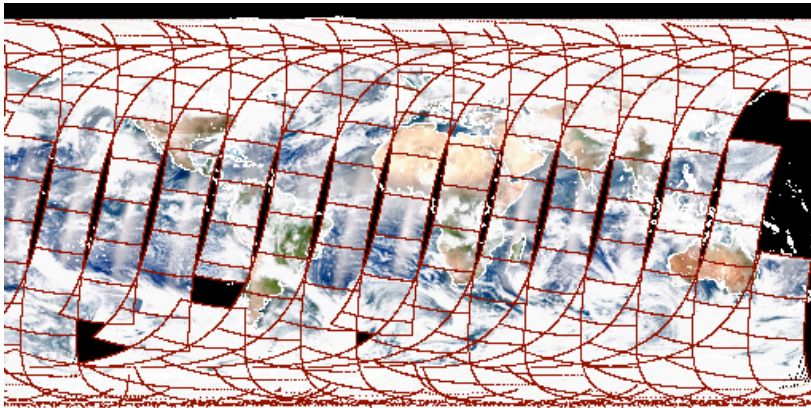
Recovering MODIS/Terra for Ocean Color Use on-orbit characterization of instrument RVS and polarization

$$L_m(\lambda) = \mathbf{M}_{11}L_t(\lambda) + \mathbf{M}_{12}Q_t(\lambda) + \mathbf{M}_{13}U_t(\lambda)$$

SeaWiFS 9-Day Composite nLw(λ)



MODIS Observed TOA Radiances



Vicarious calibration:

given $L_w(\lambda)$ and MODIS
geometry, we can predict $L_t(\lambda)$

Global optimization:

find best fit M_{11} , M_{12} , M_{13} to
relate $L_m(\lambda)$ to $L_t(\lambda)$

where $M_{xx} = \text{fn}(\text{mirror aoi})$

per band, detector, and m-side

Vicarious Characterization of RVS and Polarization

MODIS – vicarious TOA radiance (unpolarized)

$$L_I(\lambda) = [L_r(\lambda) + L_a(\lambda) + tL_f(\lambda) + TL_g(\lambda) + t_d(\lambda)L_w(\lambda)] \cdot t_g(\lambda)$$

from MODIS NIR
assumes MCST NIR band characterization

$\lambda' \rightarrow \lambda, (0,0,0) \rightarrow (\theta_0, \theta, \Delta\phi)$
Morel model, f/Q, etc.

SeaWiFS
9-day mean

$nL_w(\lambda')$

Vicarious Characterization of RVS and Polarization

MODIS – vicarious TOA radiance (unpolarized)

$$L_I(\lambda) = [L_r(\lambda) + L_a(\lambda) + tL_f(\lambda) + TL_g(\lambda) + t_d(\lambda)L_w(\lambda)] \cdot t_g(\lambda)$$

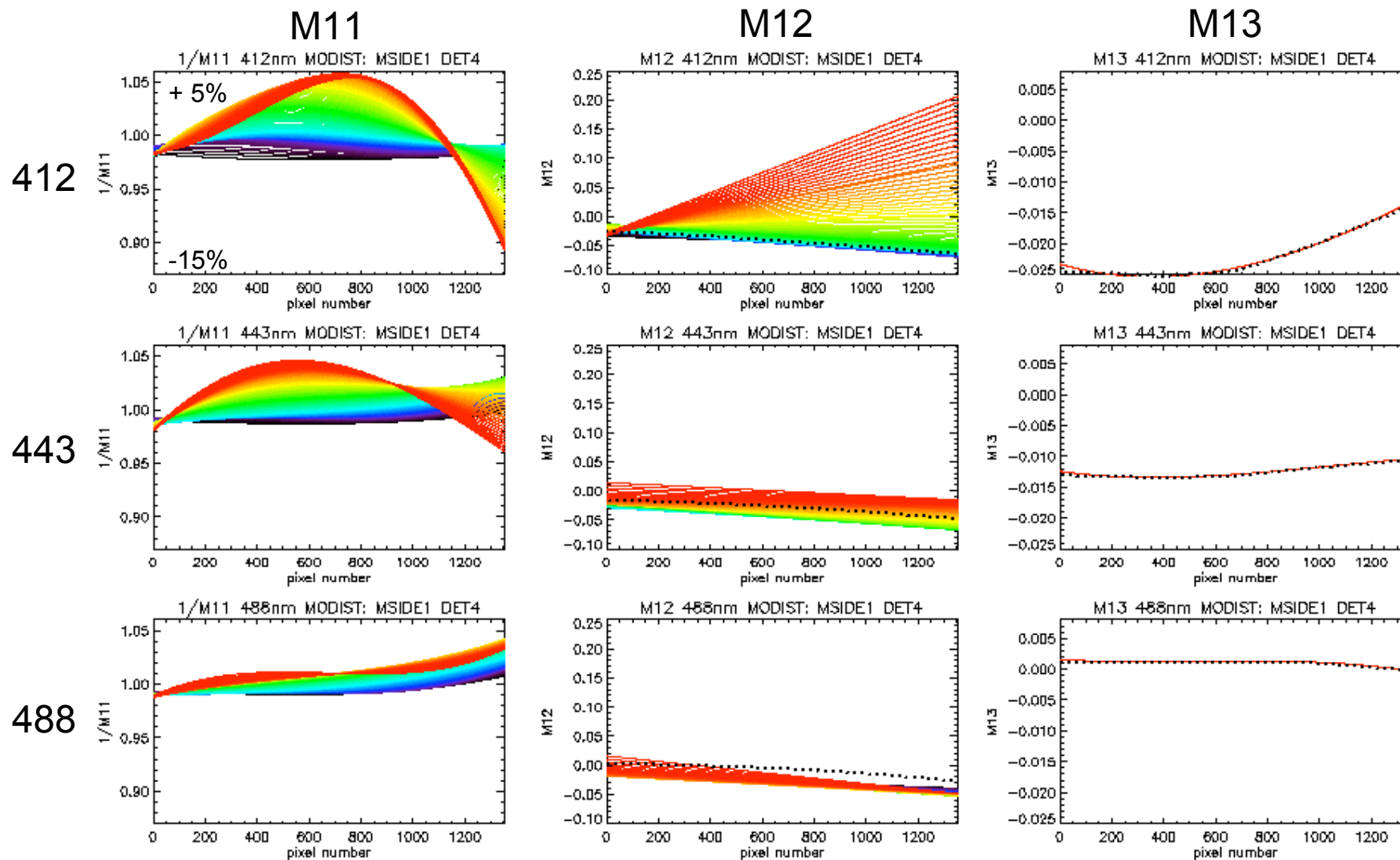
air
aerosol
whitecap
glint
water
gas

$$\sum L_t(\lambda) - [M_{11}L_I(\lambda) + M_{12}L_Q(\lambda) + M_{13}L_U(\lambda)]$$

minimize over global distribution of path geometries to find best M_{11} , M_{12} , M_{13} per band, detector, and mirror-side

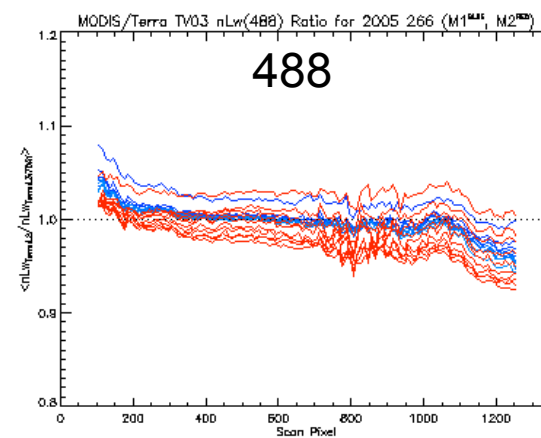
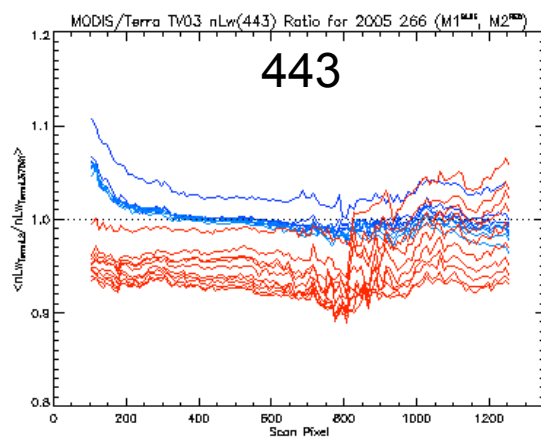
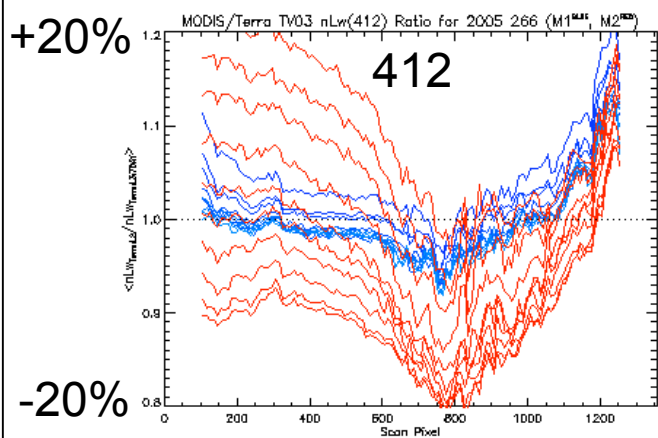
do this for one day per month over the mission lifespan

MODIS-Terra Vicarious Characterization

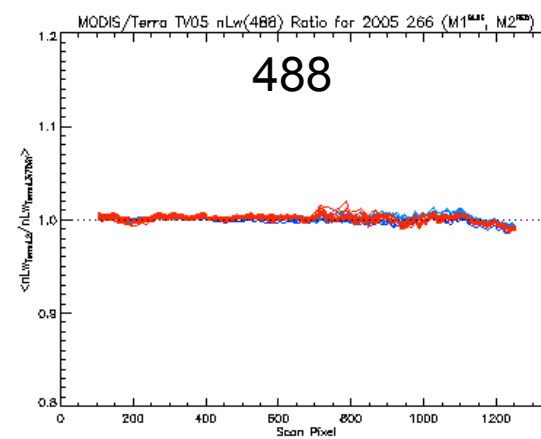
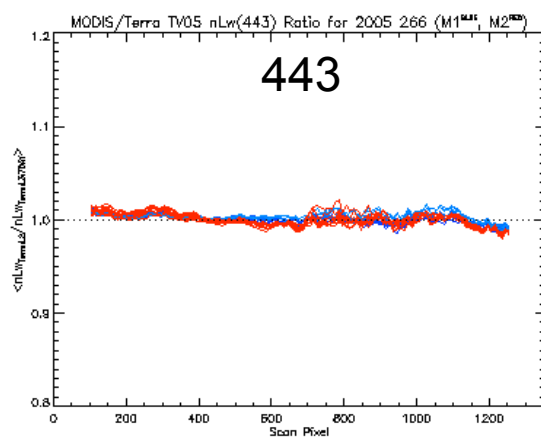
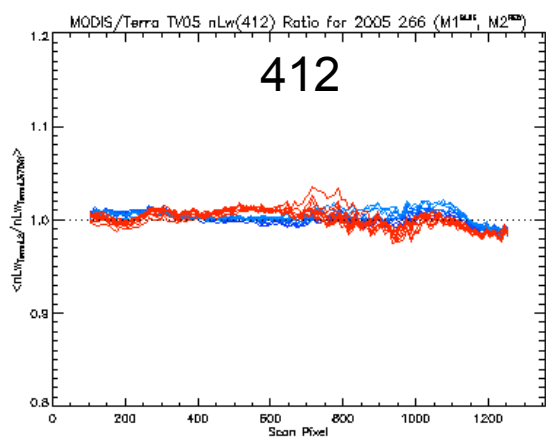


MODIS-Terra Scan-Dependent Variability in nLw

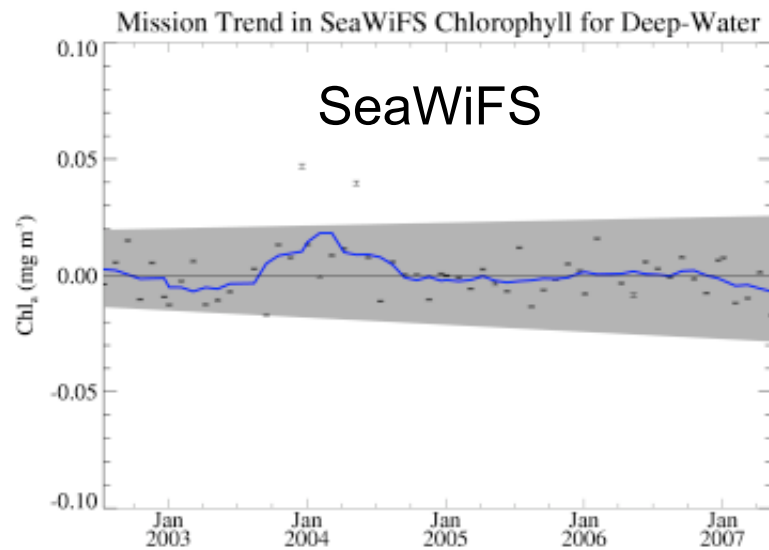
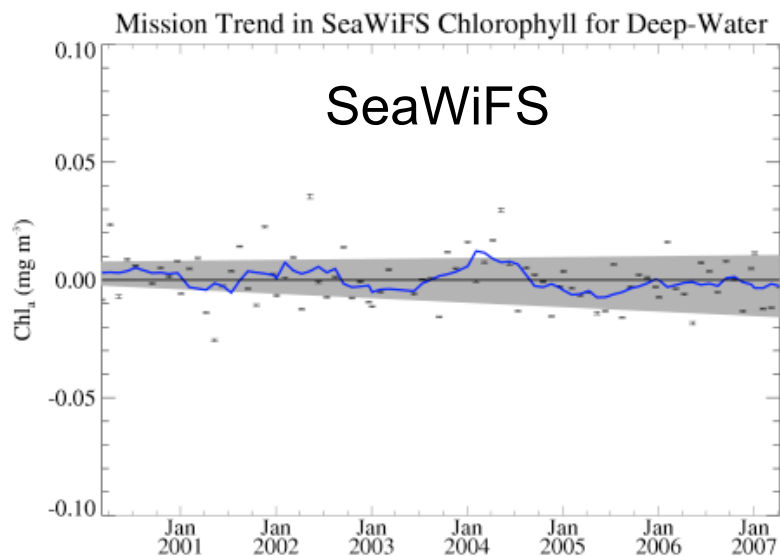
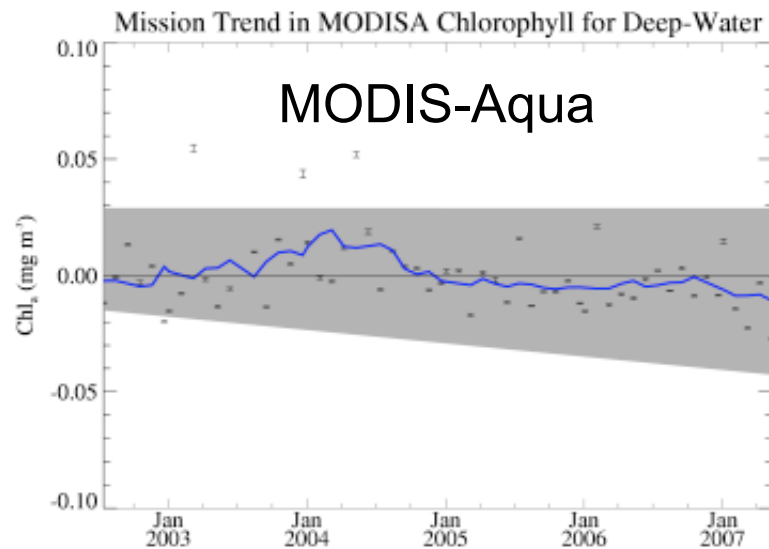
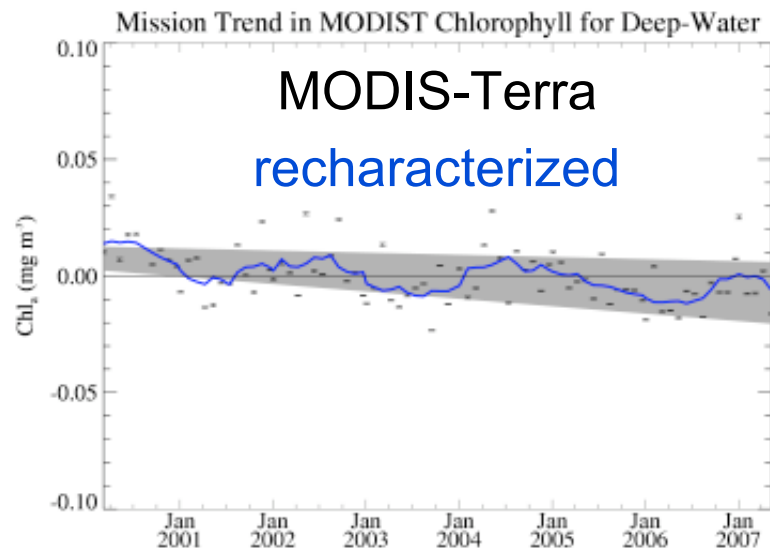
Before Vicarious Characterization



After Vicarious Characterization

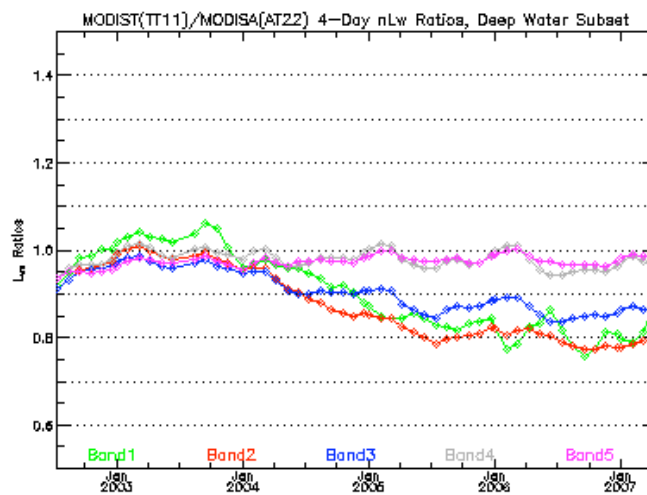
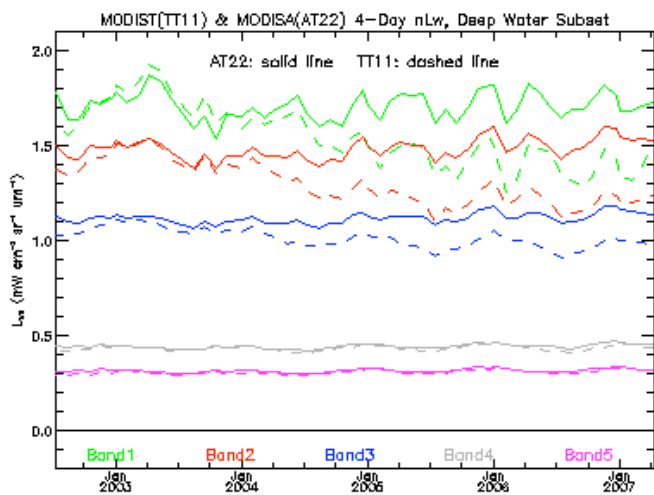


Deep-Water Seasonal Anomaly in Chlorophyll

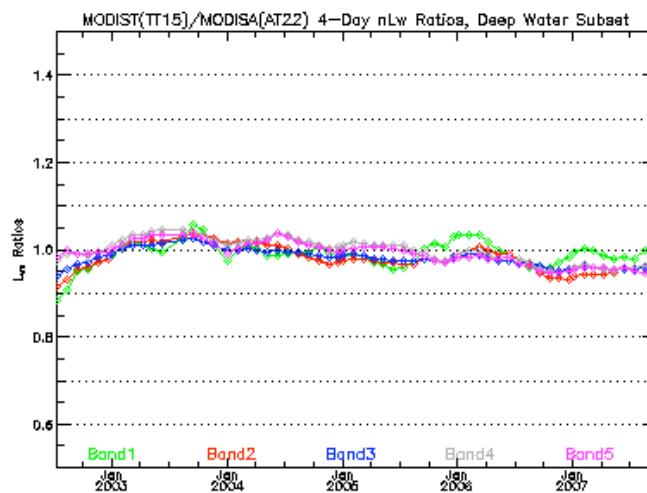
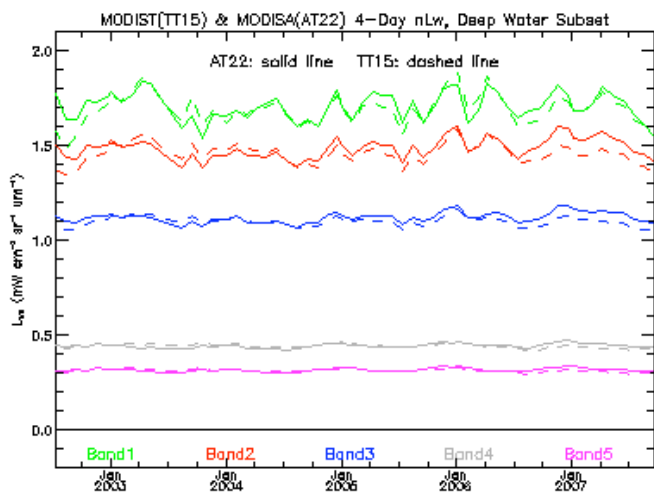


MODIS-Terra and MODIS-Aqua nLw

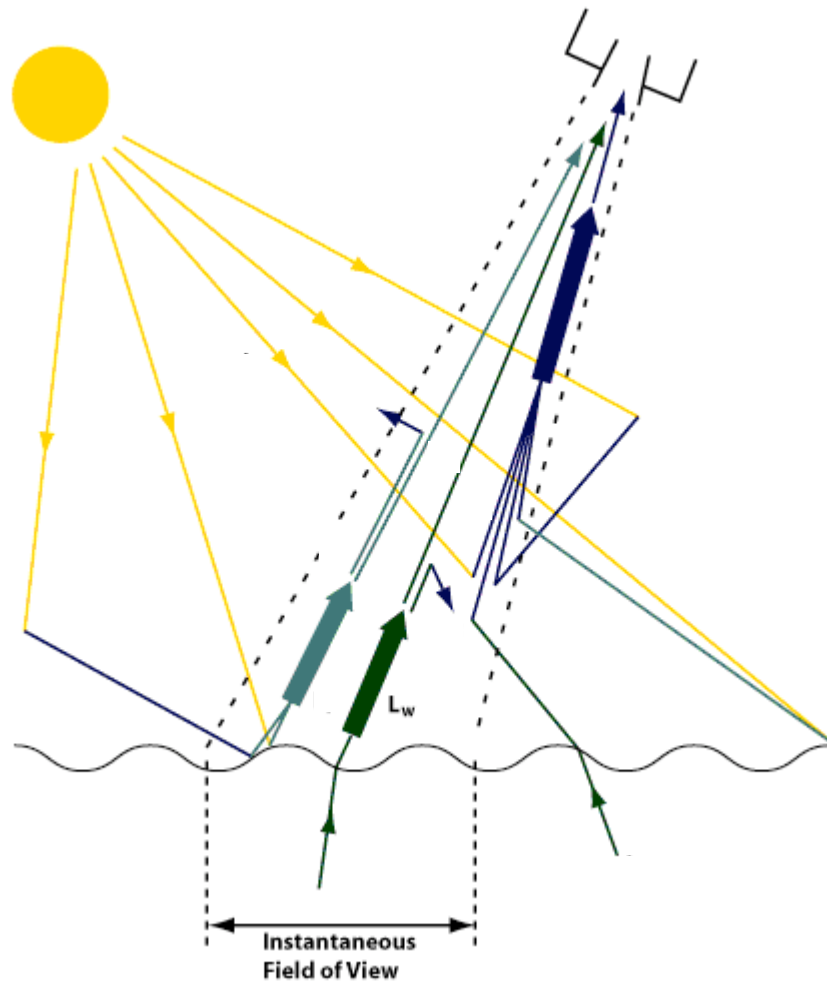
Before Vicarious Characterization



After Vicarious Characterization



Light paths to the sensor



the satellite observes both the **ocean** and the **atmosphere**

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)

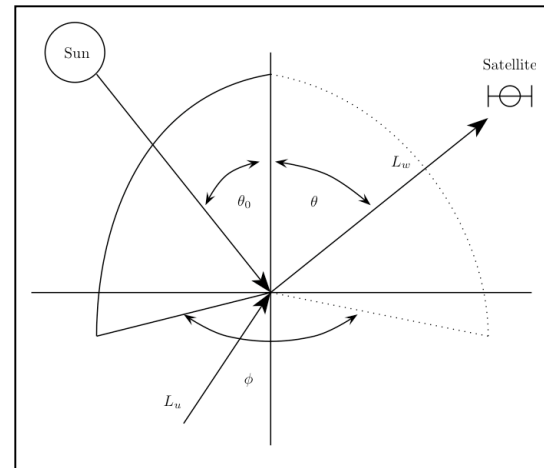
- particles comparable in size to the wavelength of light, scattering is a complex function of particle size
- whitens or yellows the sky
- significantly varies and cannot be easily approximated

Atmospheric correction

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

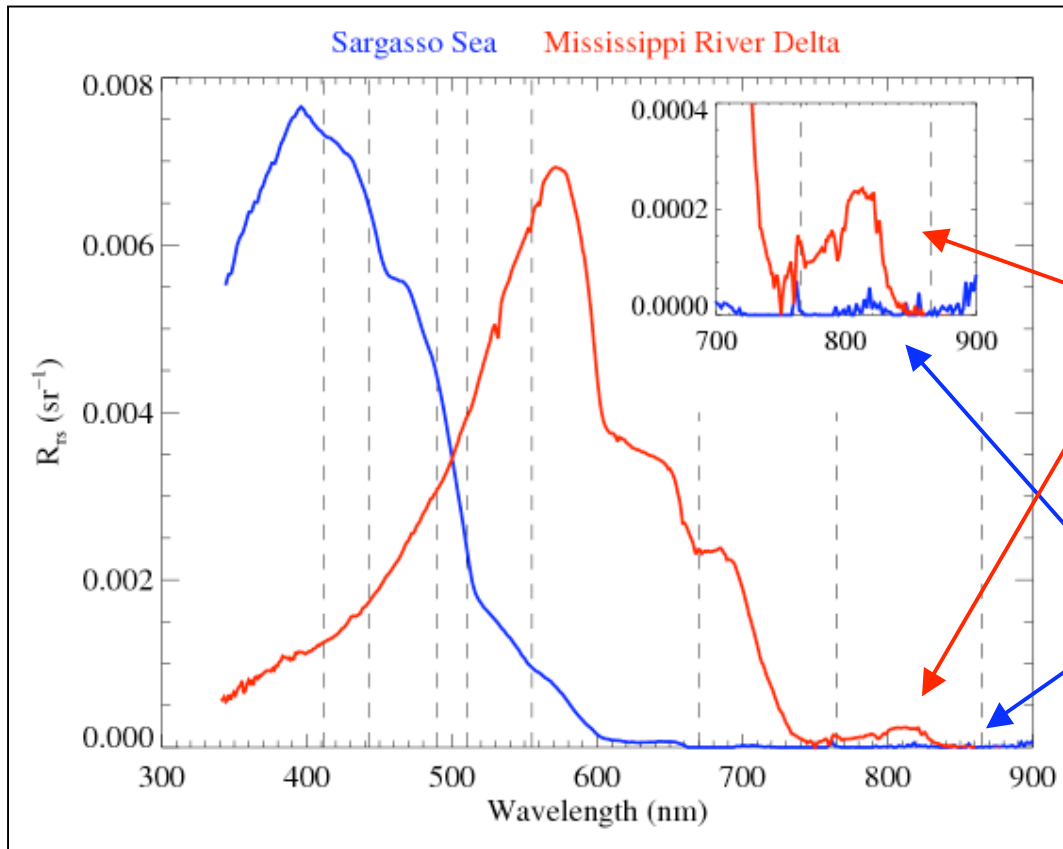
$$nL_w(\lambda) = L_w(\lambda) f_b(\lambda) / t_{d0}(\lambda) \mu_0 f_0$$

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



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

Magnitudes of $L_w(\text{NIR})$



$L_w(\text{NIR}) \neq 0$ (turbid or highly productive water)

$L_w(\text{NIR}) = 0$ (clear water)

Aerosol determination in visible wavelengths

Given retrieved aerosol reflectance at two λ ,
and a set of aerosol models $fn(\theta, \theta_0, \phi)$.

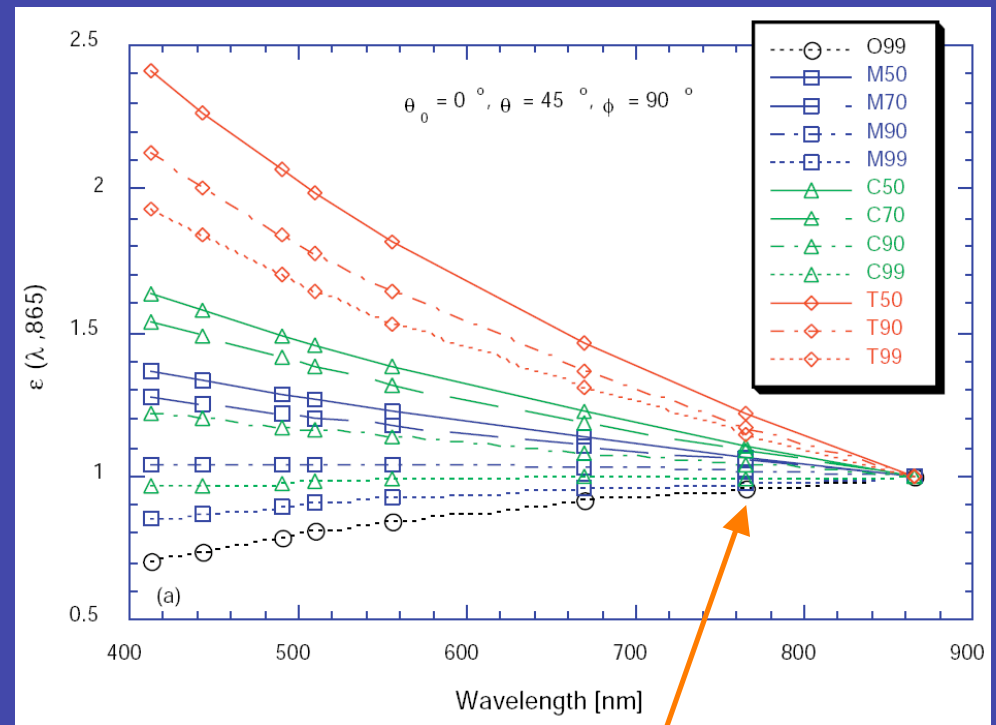
$$\rho = \frac{\pi L}{F_0 \cdot \mu_0}$$

$$\rho_a(748) \text{ \& \ } \rho_a(869)$$

$$\rho_a(\text{NIR}) \xRightarrow{\text{model}} \rho_{as}(\text{NIR})$$


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

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



$\varepsilon(748, 869)$

Iterative correction for non-zero $L_w(\text{NIR})$

- 
- (1) assume $L_w(\text{NIR}) = 0$
 - (2) compute $L_a(\text{NIR})$
 - (3) compute $L_a(\text{VIS})$ from $L_a(\text{NIR})$
 - (4) compute $L_w(\text{VIS})$
 - (5) estimate $L_w(\text{NIR})$ from $L_w(\text{VIS}) + \text{model}$
 - (6) repeat until $L_w(\text{NIR})$ 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