Satellite ocean color data products for marine biogeochemical research applications

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18 January 2010 @ NIO

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 use satellites for oceanographic applications?
2. why study ocean color?
3. ocean color @ NASA
4. the NASA Ocean Biology Processing Group (OBPG)
5. international collaborations

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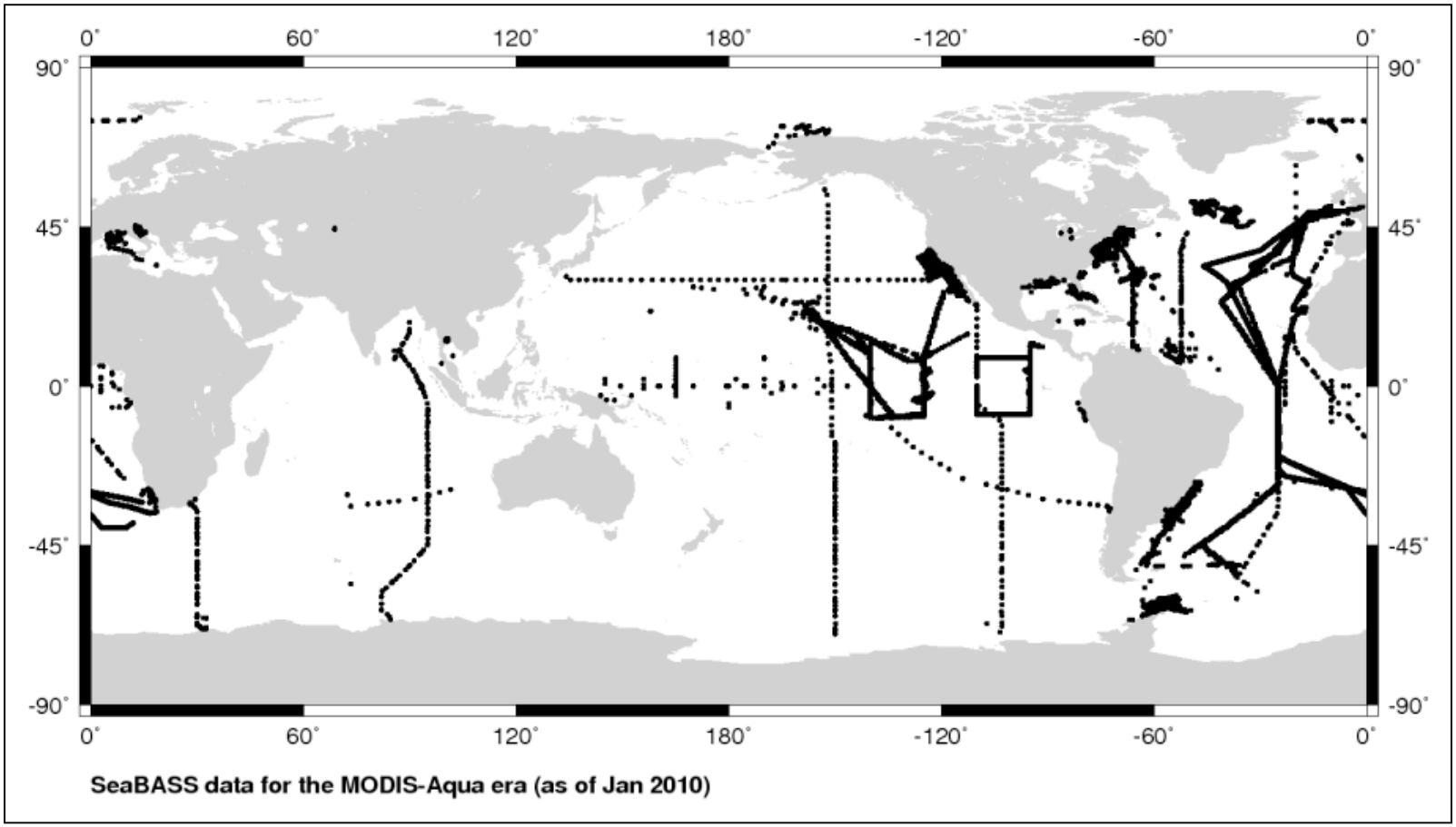
why use satellites?

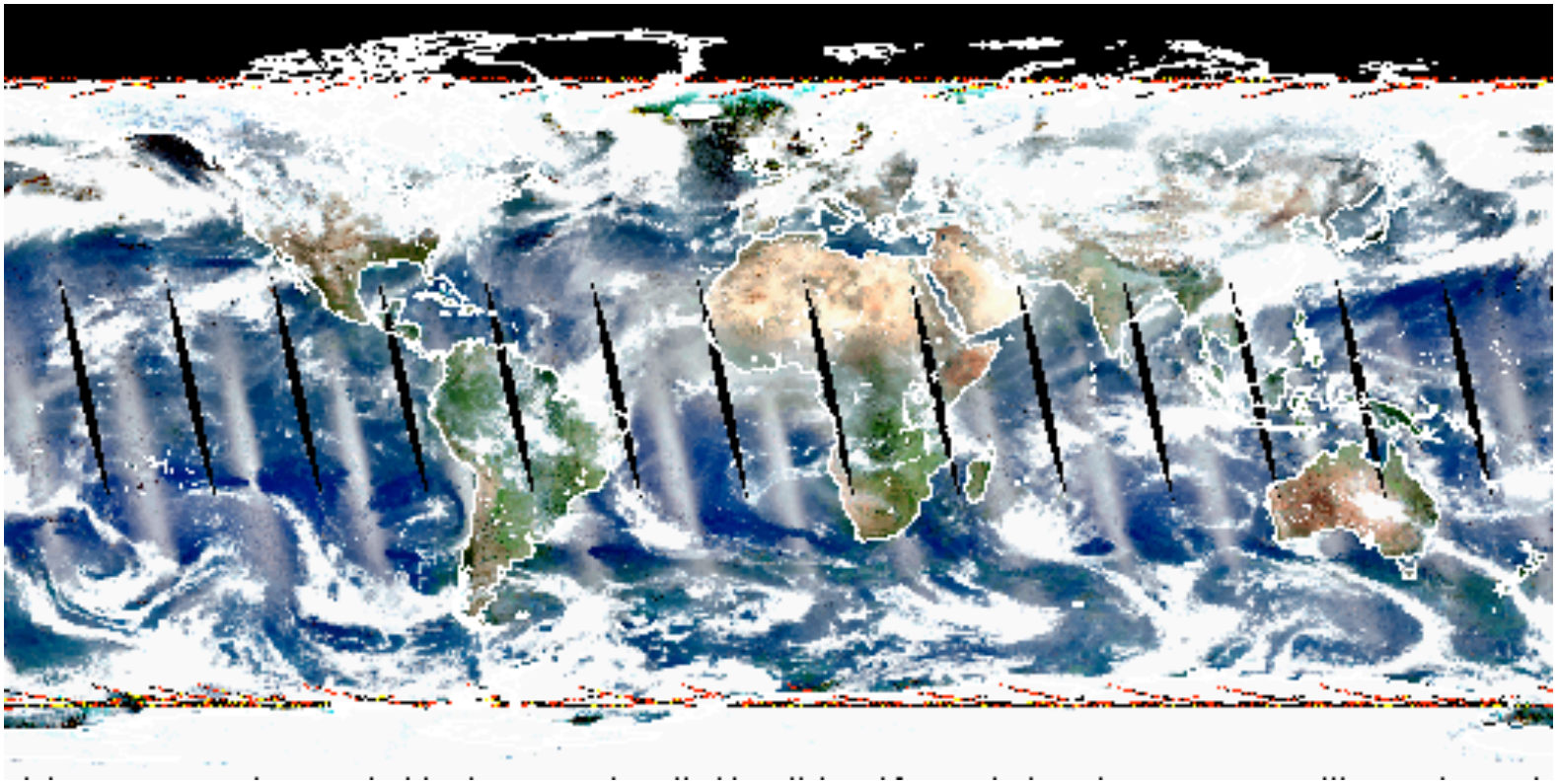
NASA funds *in situ* sampling programs in support of its cal/val programs



bio-optical data collected during the MODIS-Aqua era (June 2002 to present)

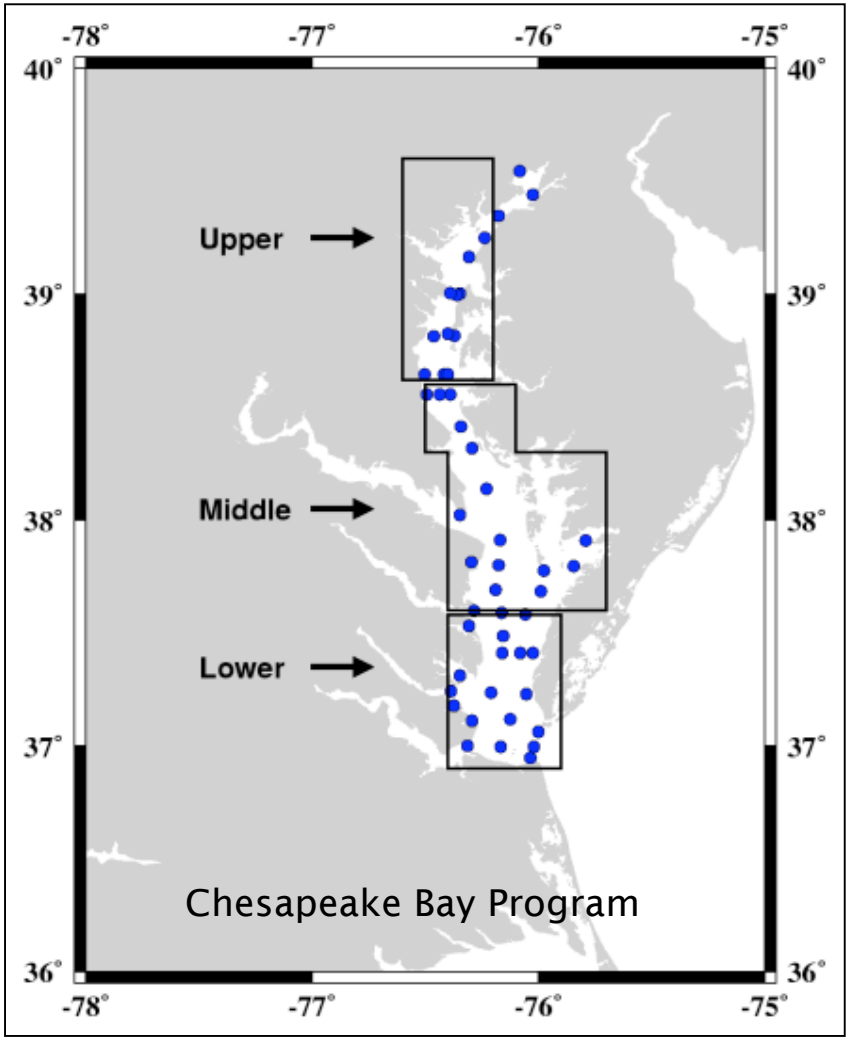
why use satellites?

SeaWiFS, MODIS-Aqua, & others provide a daily, synoptic view of the Earth

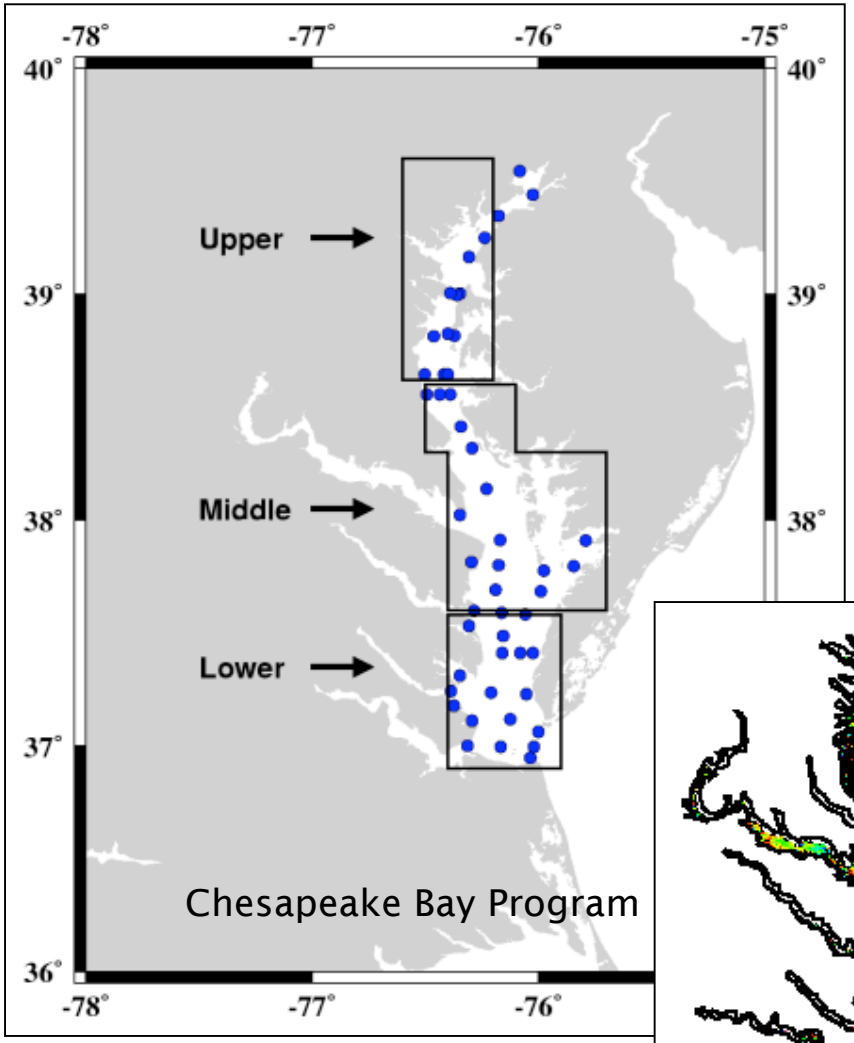


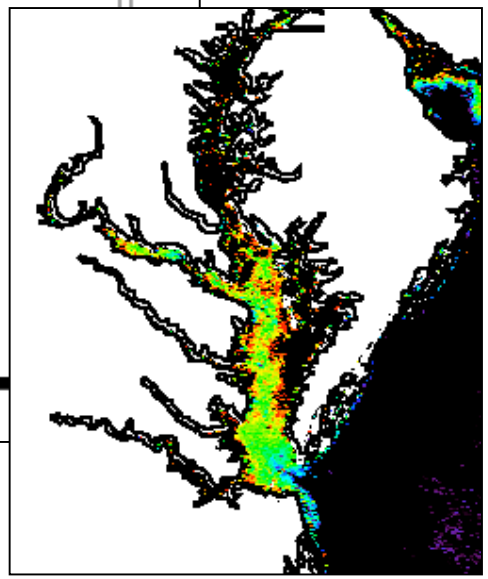
MODIS-Aqua observations for one day (1 February 2008)

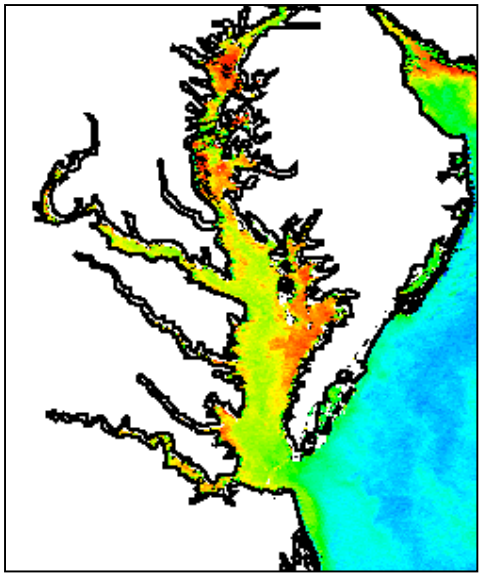
why use satellites?



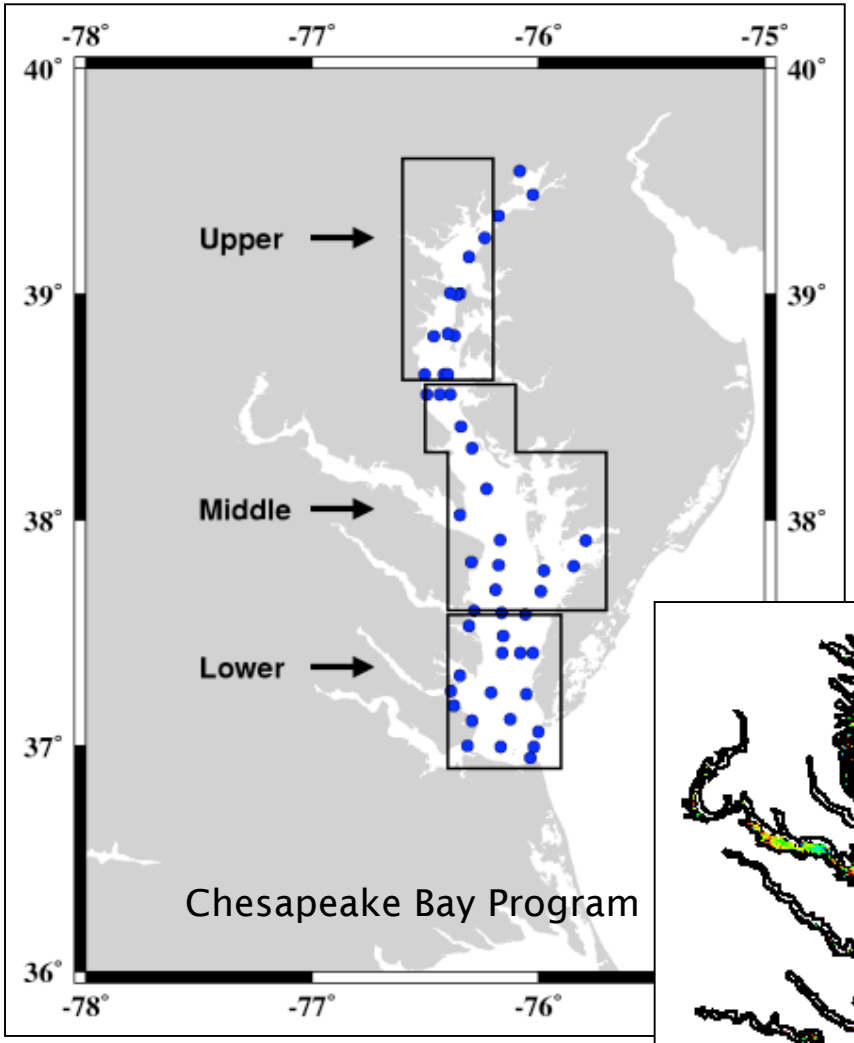
why use satellites?



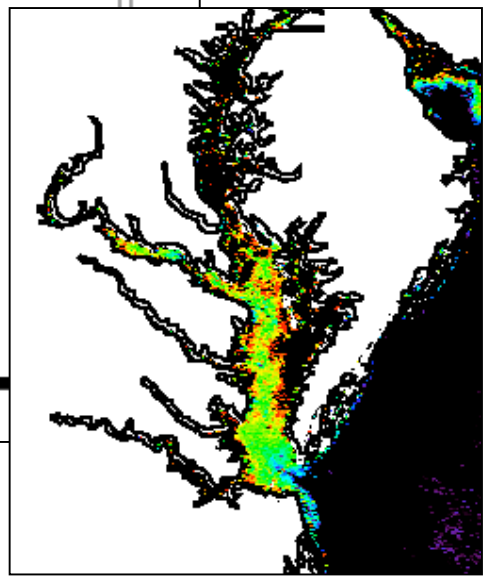


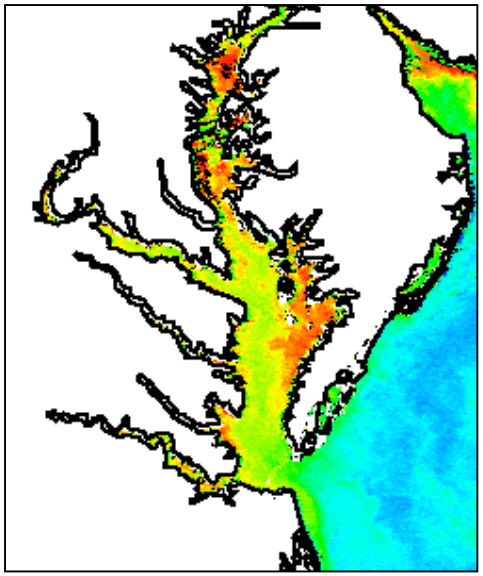


why use satellites?

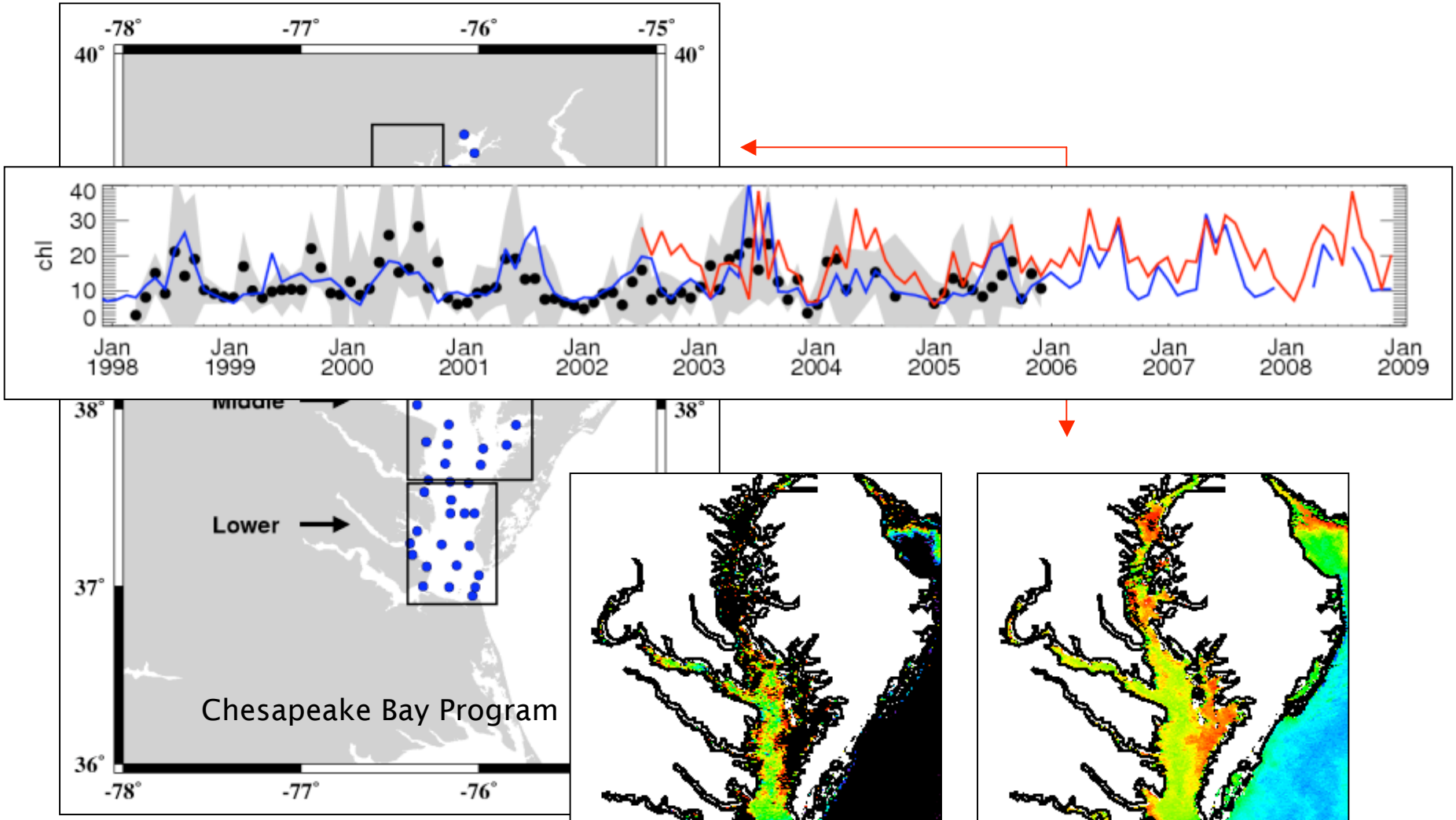


complementary data streams

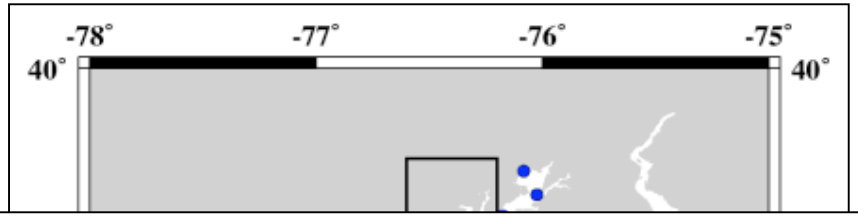


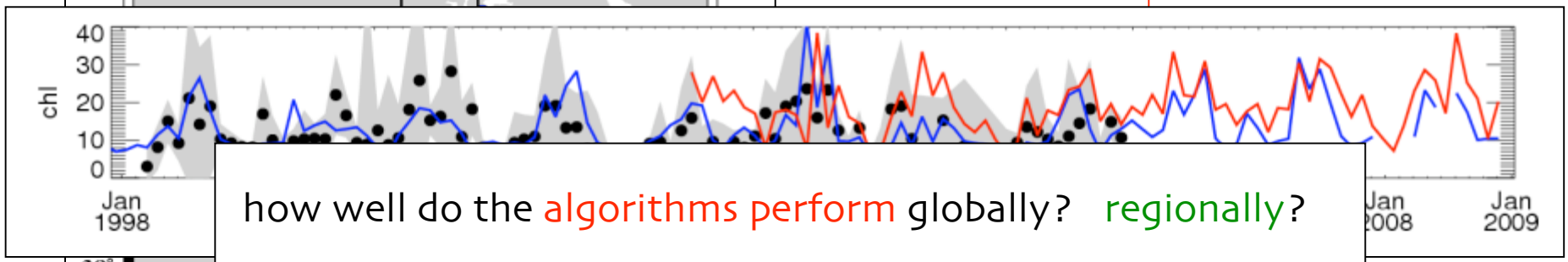


why use satellites?



why use satellites?



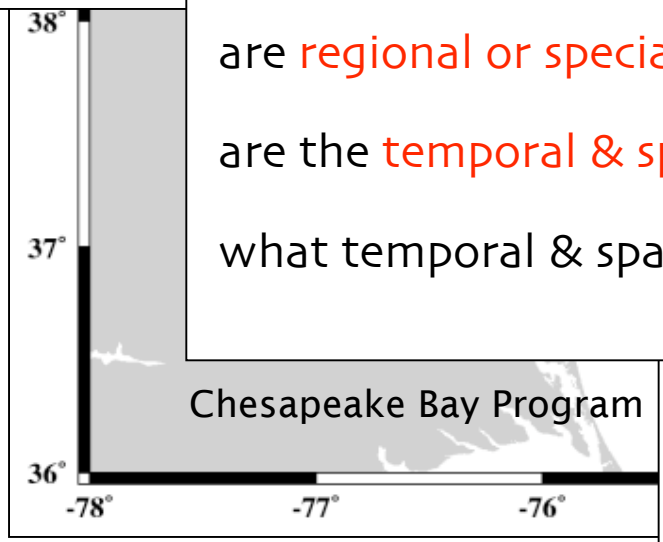


how well do the algorithms perform globally? regionally?

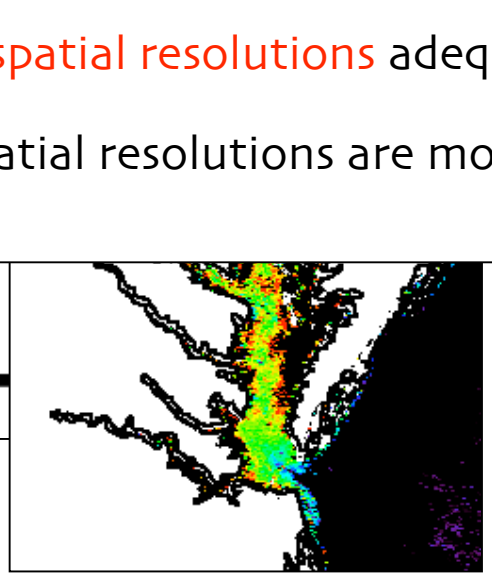
are regional or specially tuned algorithms required?

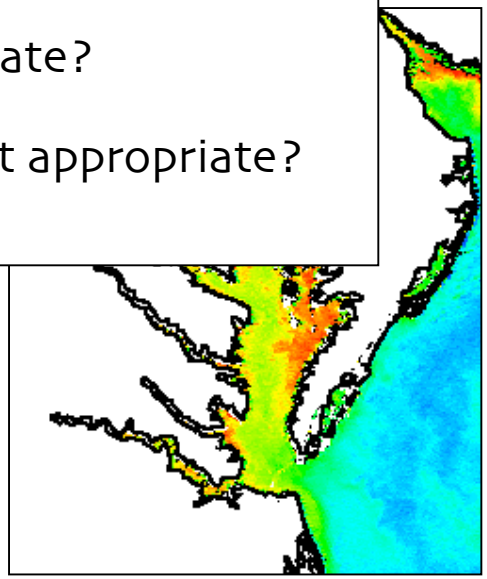
are the temporal & spatial resolutions adequate?

what temporal & spatial resolutions are most appropriate?



Chesapeake Bay Program





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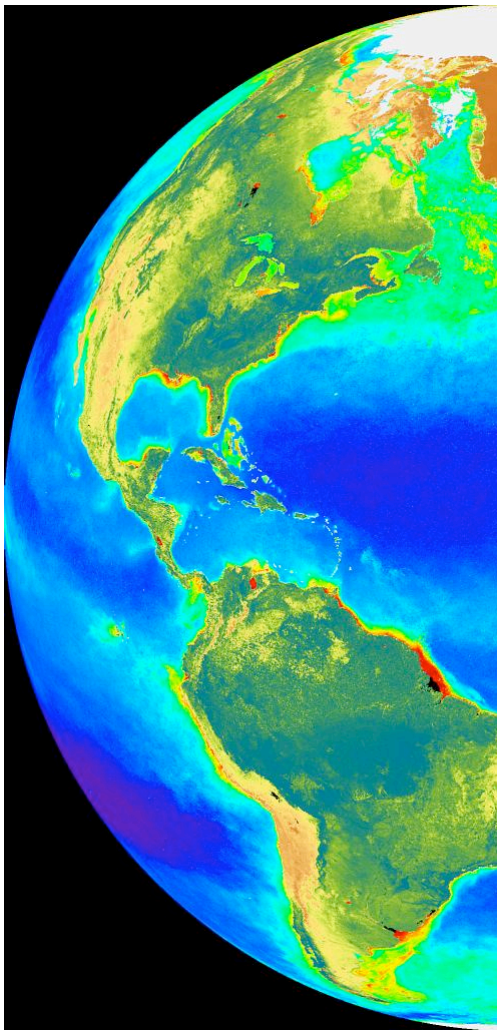
why ocean color?



we want to understand how the Earth is changing & the how these changes impact life on Earth

how is the global Earth system changing?

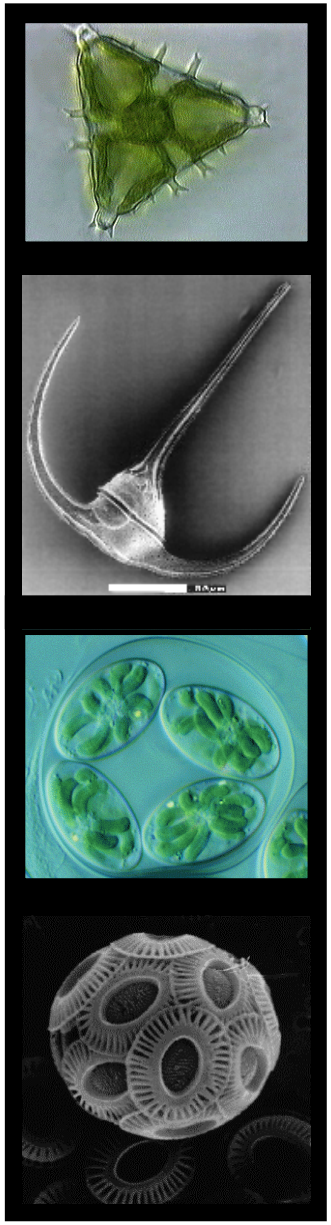
what are the primary forcings of the Earth system?

how does the Earth system respond to natural and human induced changes?

what are the consequences of changes in the Earth system for human civilization?

how well can we predict the changes to the Earth system that will take place in the future?

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)

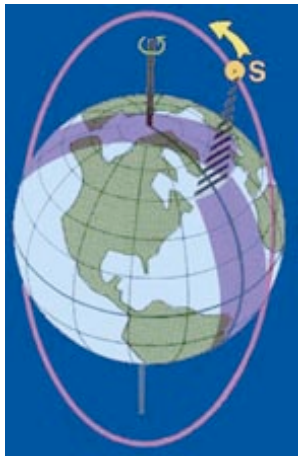
monitor coastal environments

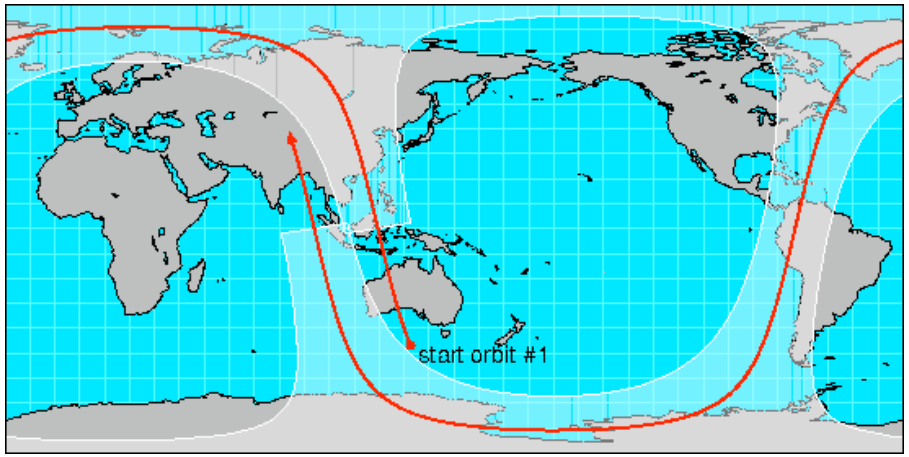
why ocean color?

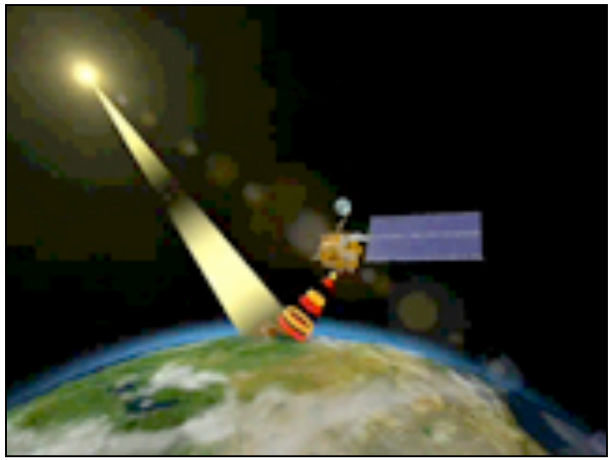
near-polar, sun-synchronous orbits

near-polar orbits enable low-altitude imaging & global daily coverage

sun-synchronous orbits cross the equator at the same local time







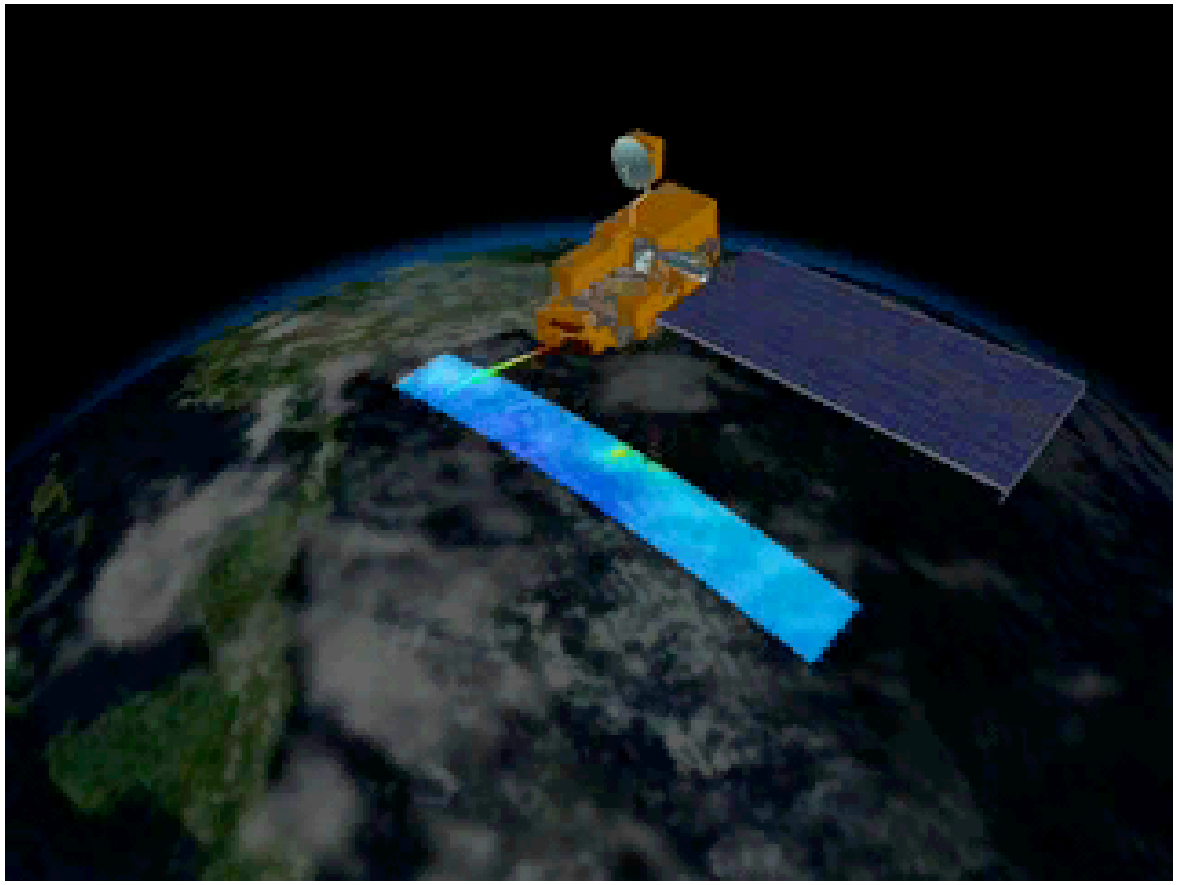
ocean color instruments are passive sensors

they measure electromagnetic radiation reflected or emitted by the Earth surface

MODIS has 20 reflective solar bands from 410 nm – 2.1 μm

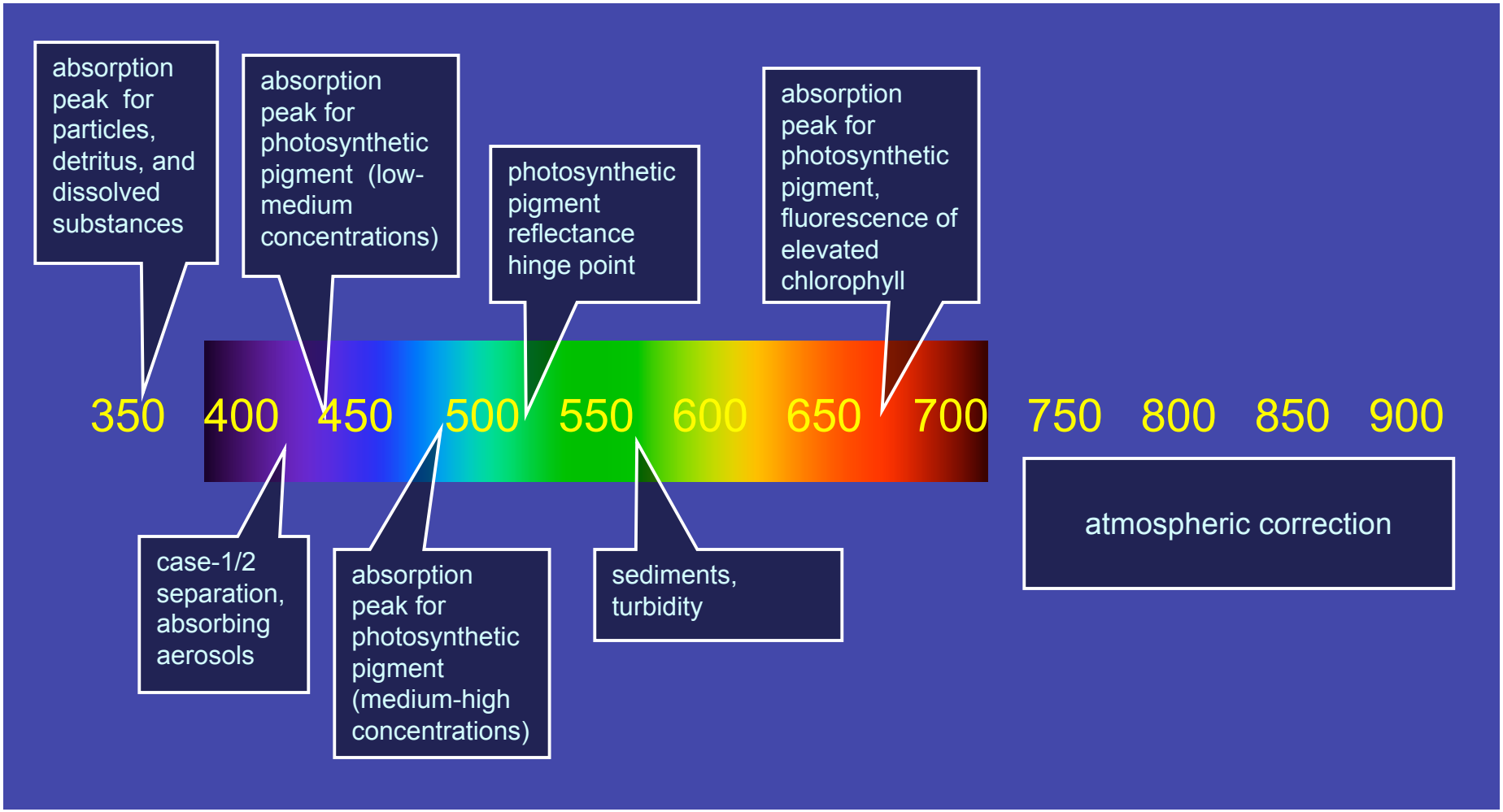
MODIS has 16 thermal emissive bands from 3.7 – 14.4 μm

why ocean color?



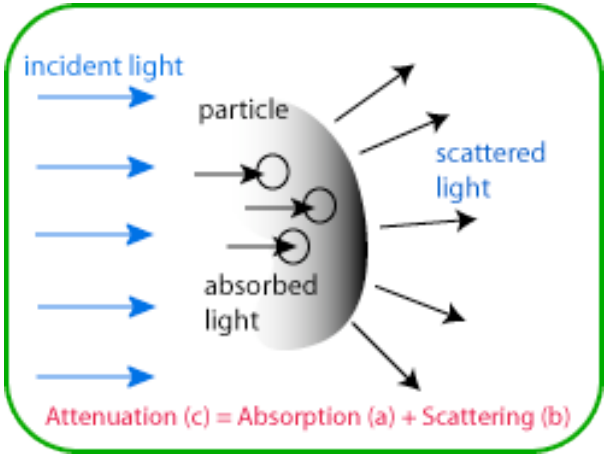
why ocean color?

spectral characteristics of ocean waters



why ocean color?

data products: relative concentrations of water column constituents



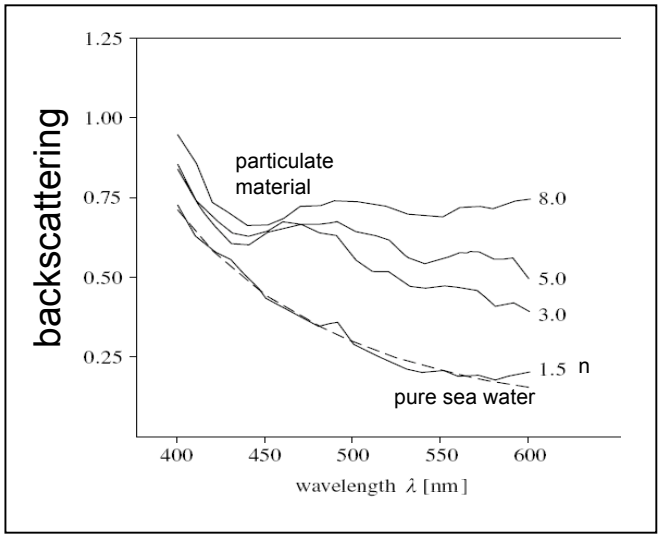
photons have two fates when they travel through a medium:

(1) absorbed, *a*
(2) scattered, *b* (backwards, b_b)

$$R(\lambda) \approx \frac{b_b(\lambda)}{a(\lambda)}$$

why ocean color?

data products: relative concentrations of water column constituents



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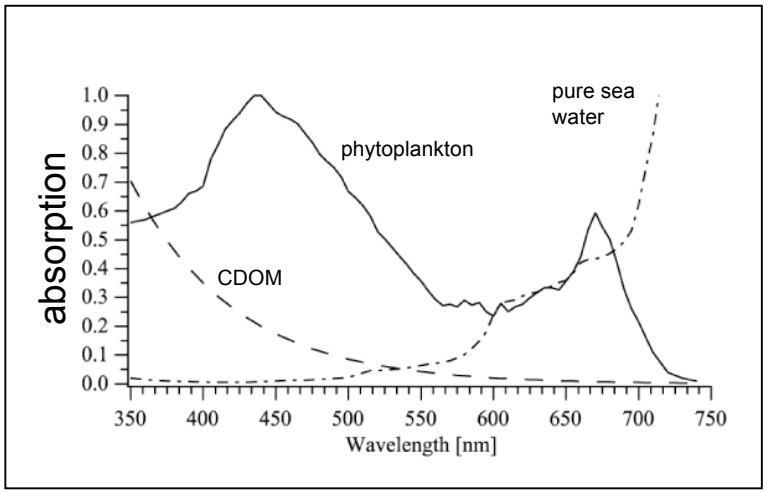

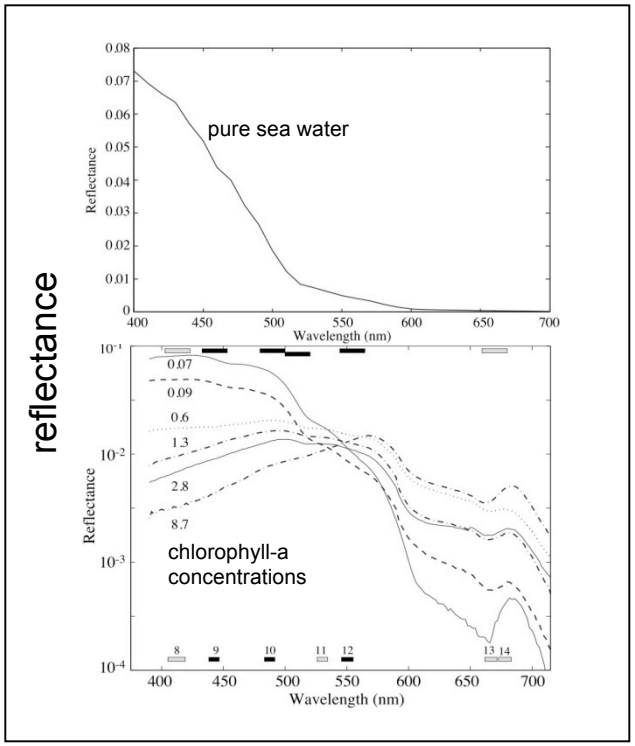

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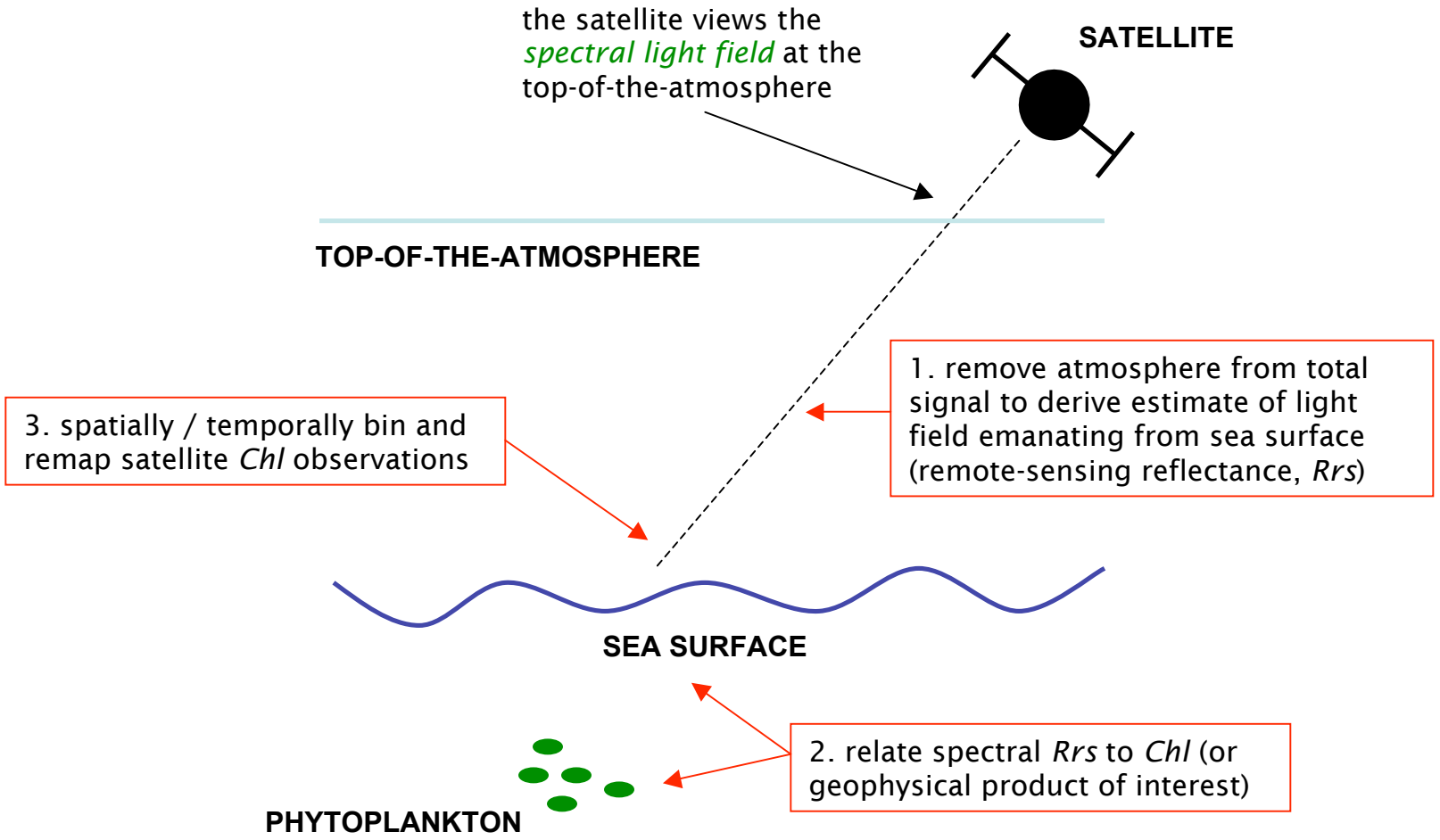
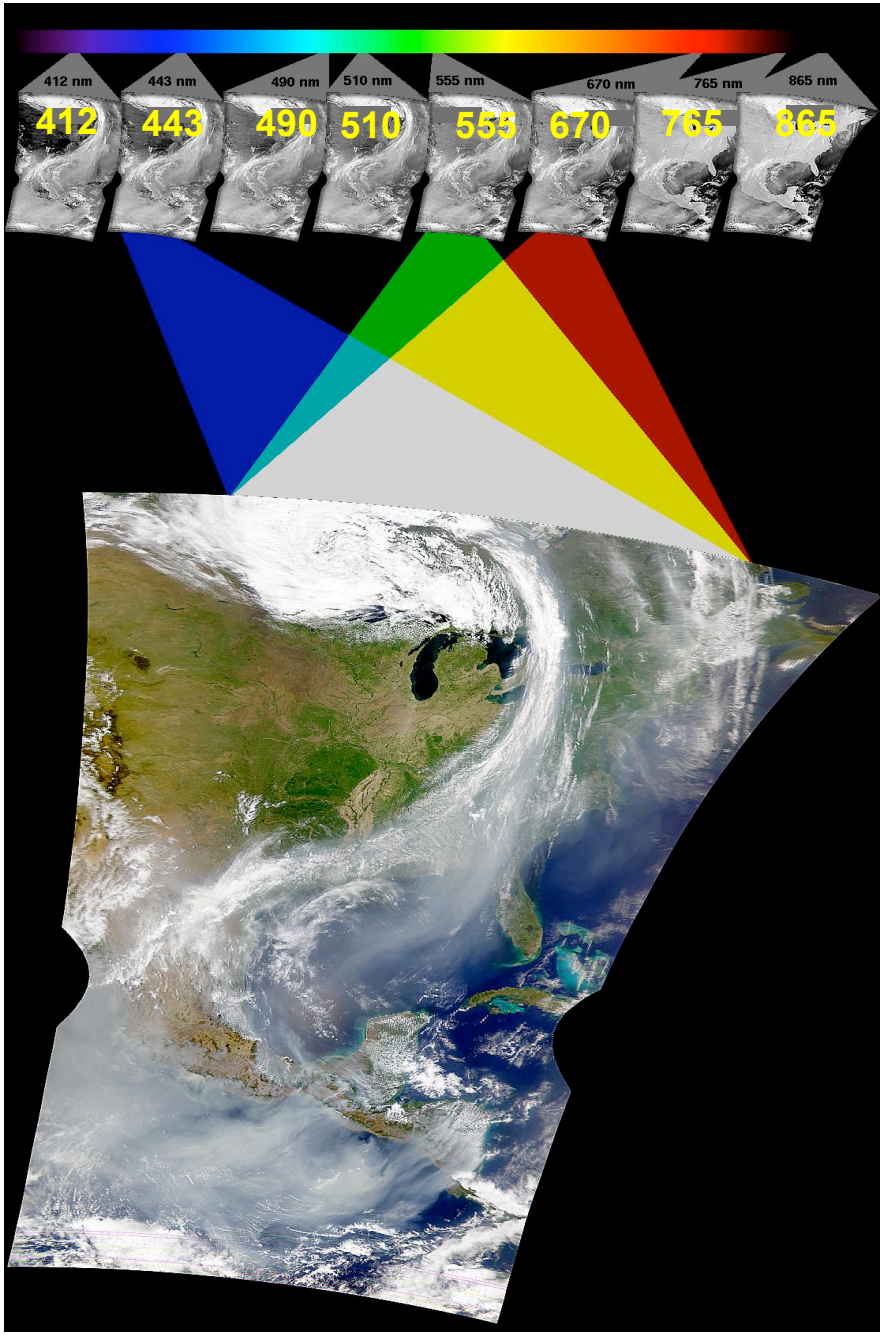




ocean color data products

primary optical variable

remote-sensing reflectance (Rrs; 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)

types of algorithms: operational empirical algorithms

operational empirical (statistical) algorithms typically have a form that resembles

$$log_{10}(C_a) = c_0 + \sum_{i=1}^{N} c_i log_{10}\left(\frac{R_{rs}(\lambda_b)}{R_{rs}(\lambda_g)}\right)$$

including all OC* & KD* algorithms developed by the OBPG, plus POC, TSM, etc. algorithms developed elsewhere

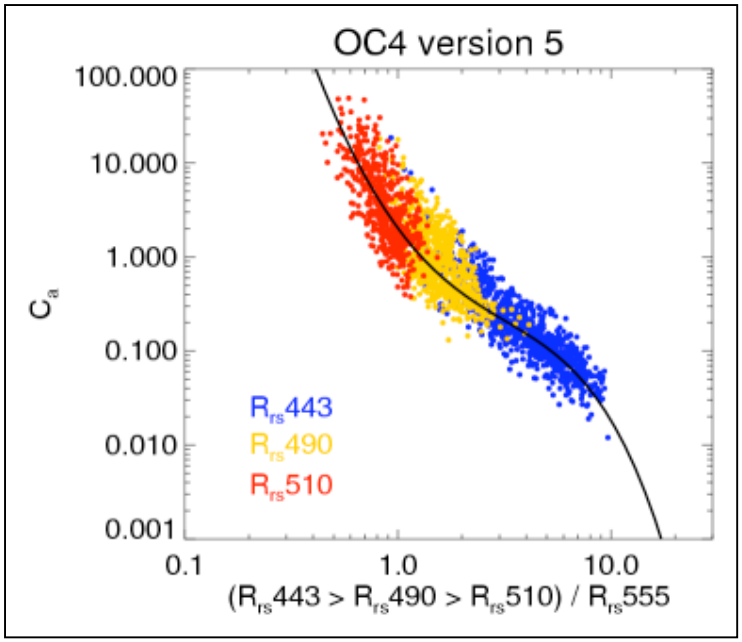


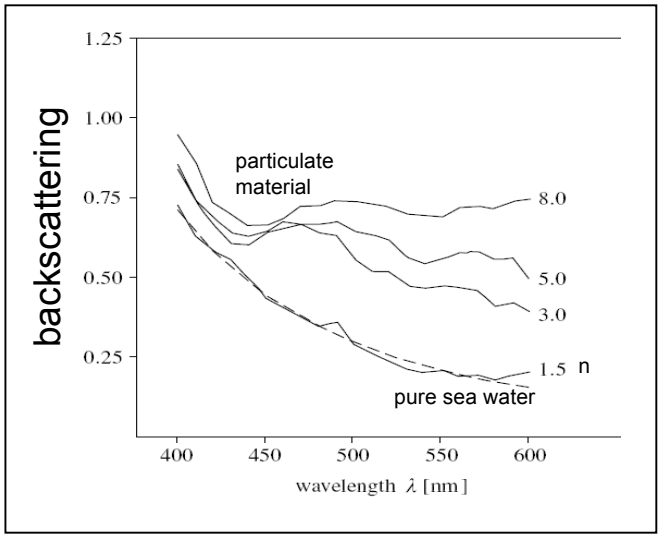
Table 1
Coefficients for the OC version 5 algorithms (O'Reilly, personal communication).

	λ_b	λ_g	c_0	c_1	c_2	c_3	c_4
OC4	443,490,510	555	0.3080	−3.0882	3.0440	−1.2013	−0.7992
OC3S[a]	443,490	555	0.2409	−2.4768	1.5296	0.1061	−1.1077
OC3M[b]	443,488	551	0.2254	−2.6354	1.8071	0.0063	−1.2931

[a] For SeaWiFS.
[b] For MODIS-Aqua.

types of algorithms: "semi-analytical" algorithms

Collin will provide a comprehensive overview in the next talk



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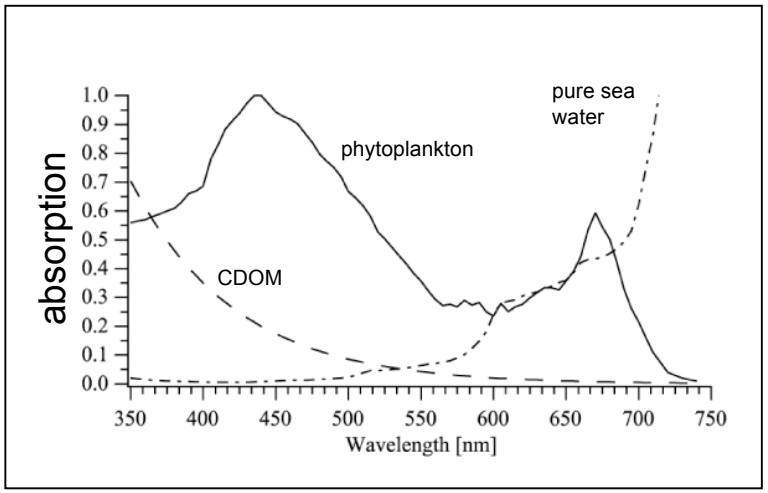
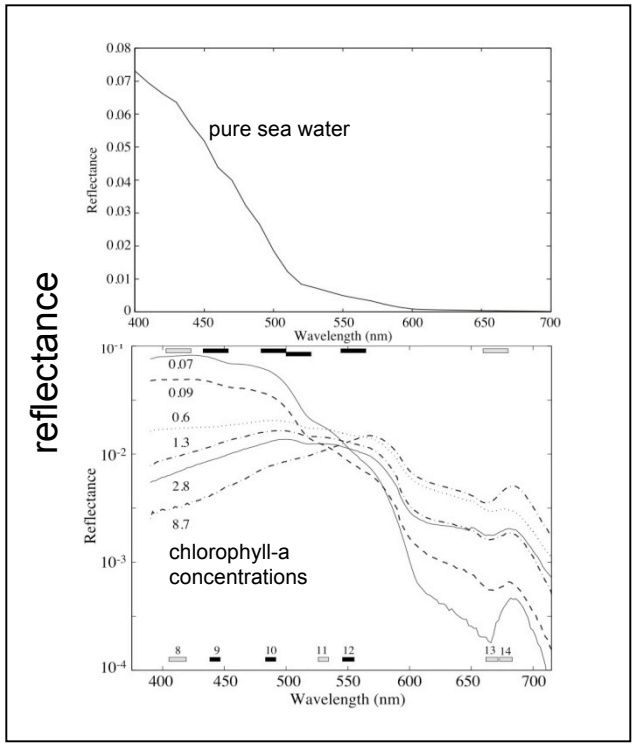
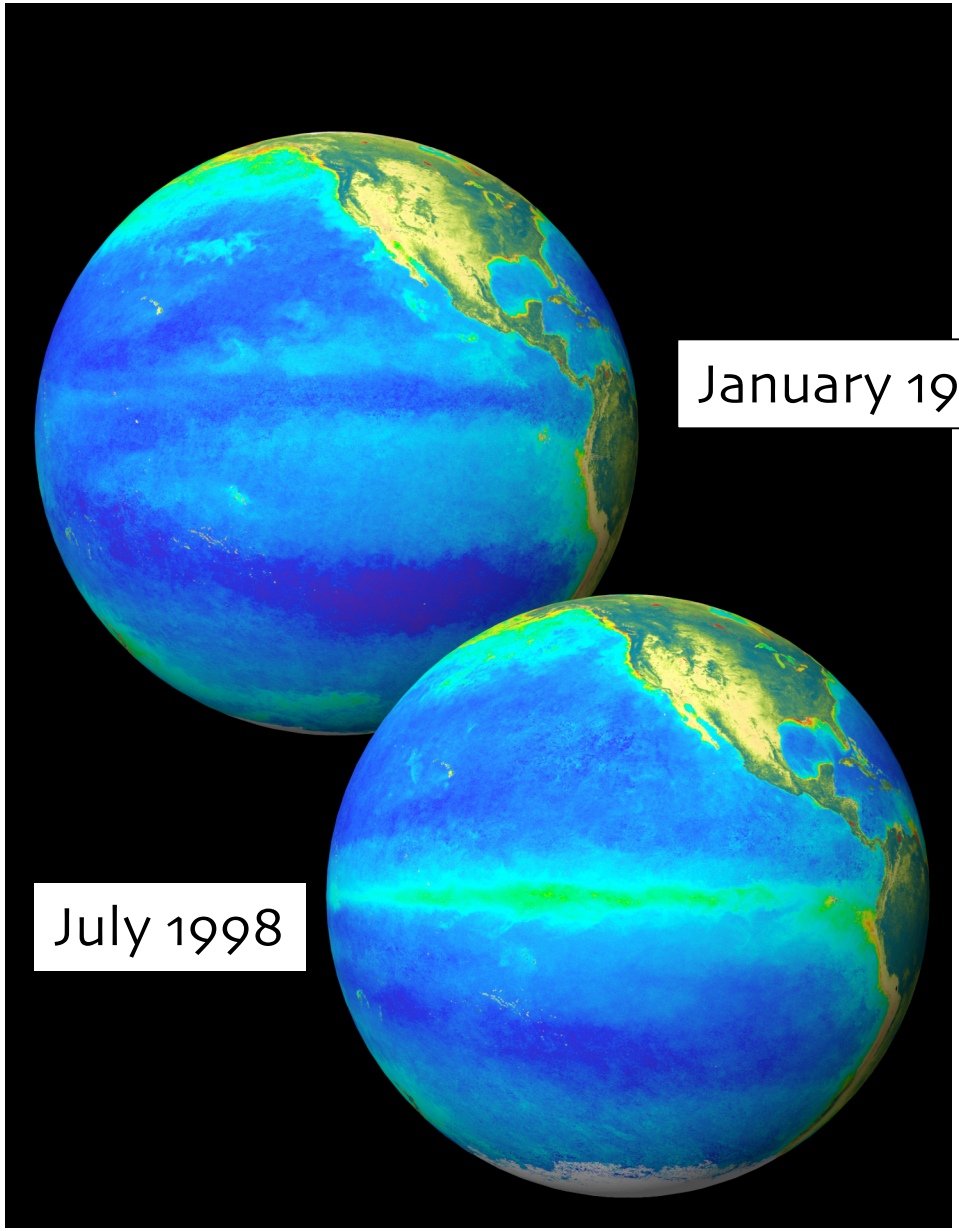




examples of ocean color applications

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)

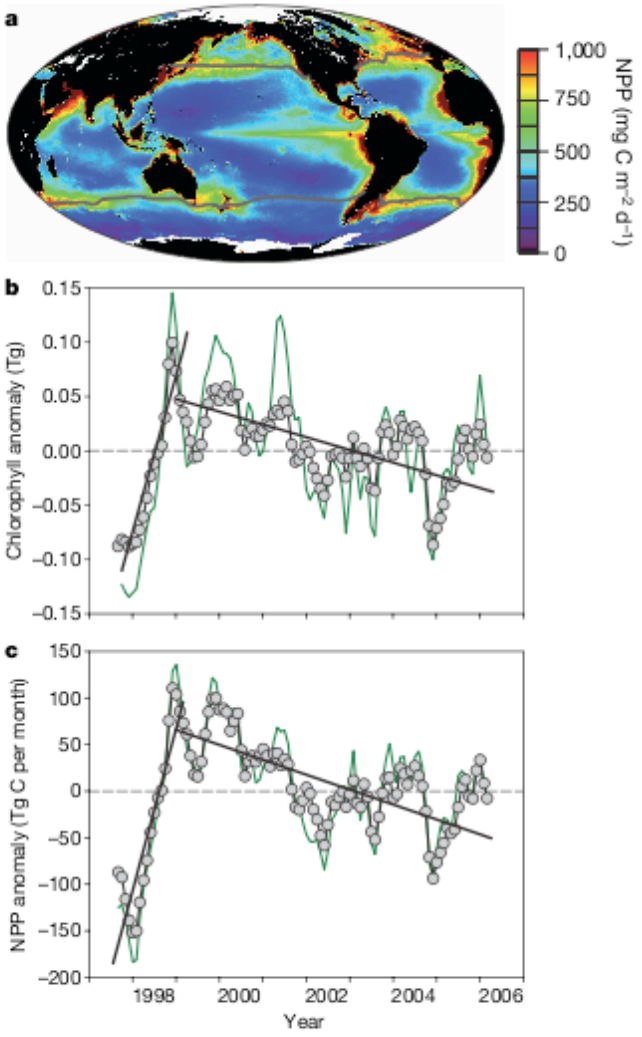


Figure 1 | Distribution and trends in global ocean phytoplankton productivity (NPP) and chlorophyll standing stocks.

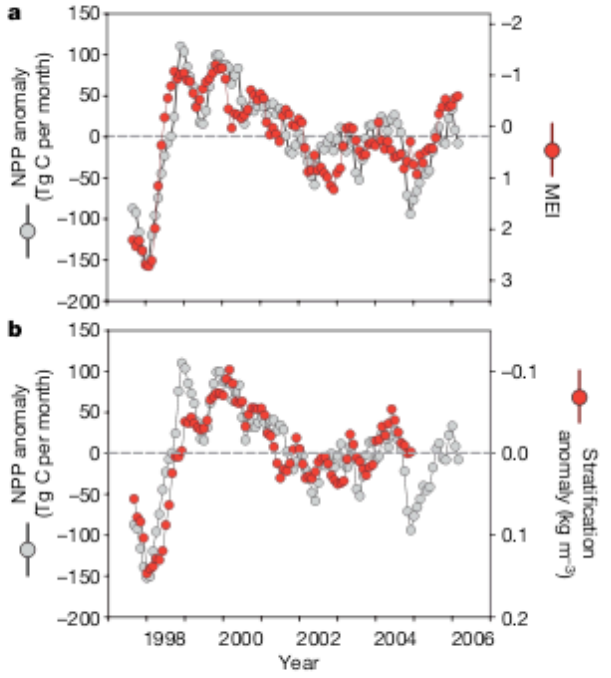
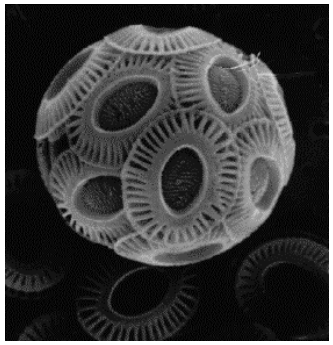


Figure 2 | Ocean productivity is closely coupled to climate variability.

examples of ocean color applications

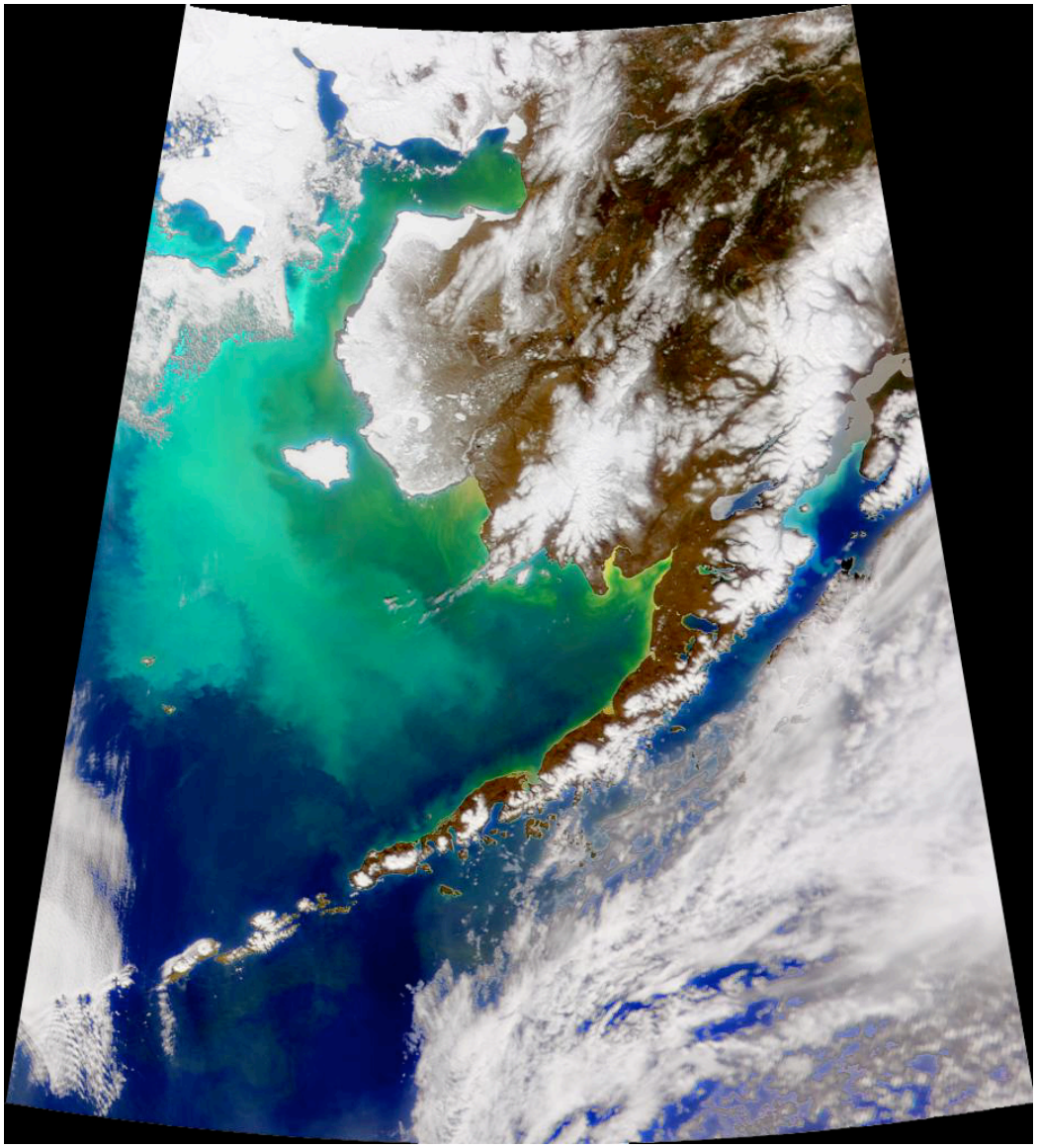
Bering Sea blooms



coccolithophore

reflective carbonate plates shed in water, giving it opaque, milky quality

reduced water clarity affects ecology (birds, fish)



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

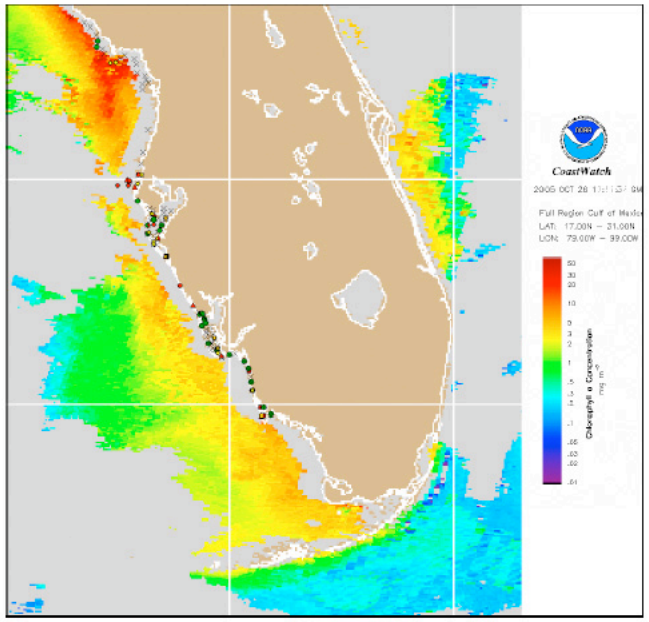
Conditions: Harmful algal blooms have been identified in Pinellas County, Dixie to Levy County and in very small patches from Manatee to Collier County in Florida. A secondary bloom has been identified in patches along Alabama and the Florida Panhandle. No impacts are expected along the coast from Pinellas 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.

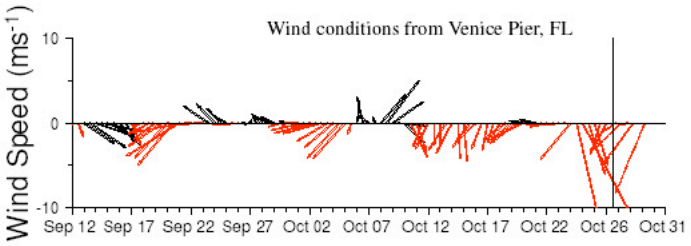
~Fisher, Bronder

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 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.

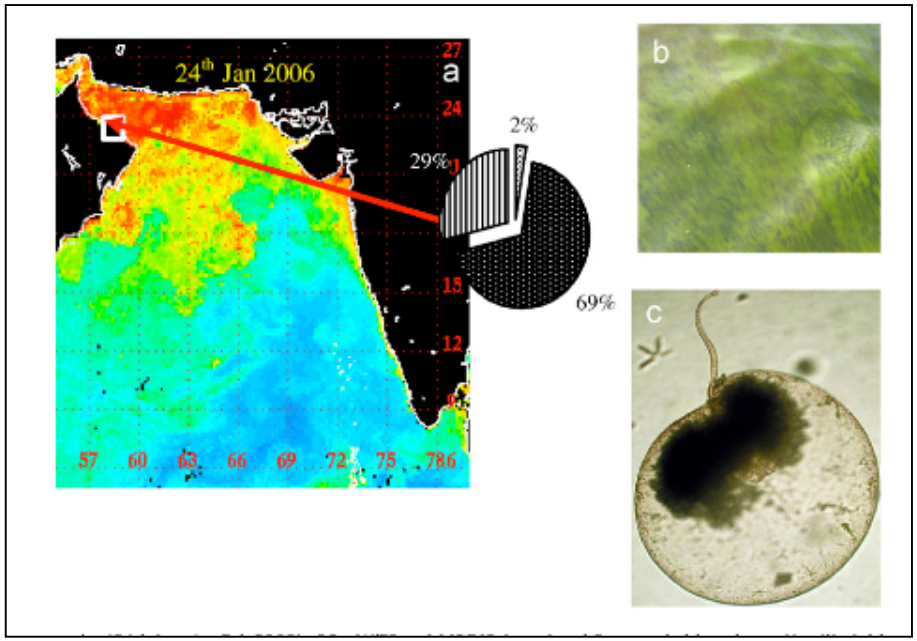
SW Florida: Moderate (10-15kts, 5-8m/s) northeasterly winds today will continue through Sunday; strengthening up to 20kts (10m/s) Saturday and Sunday.

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)



examples of ocean color applications

impacts of natural disasters

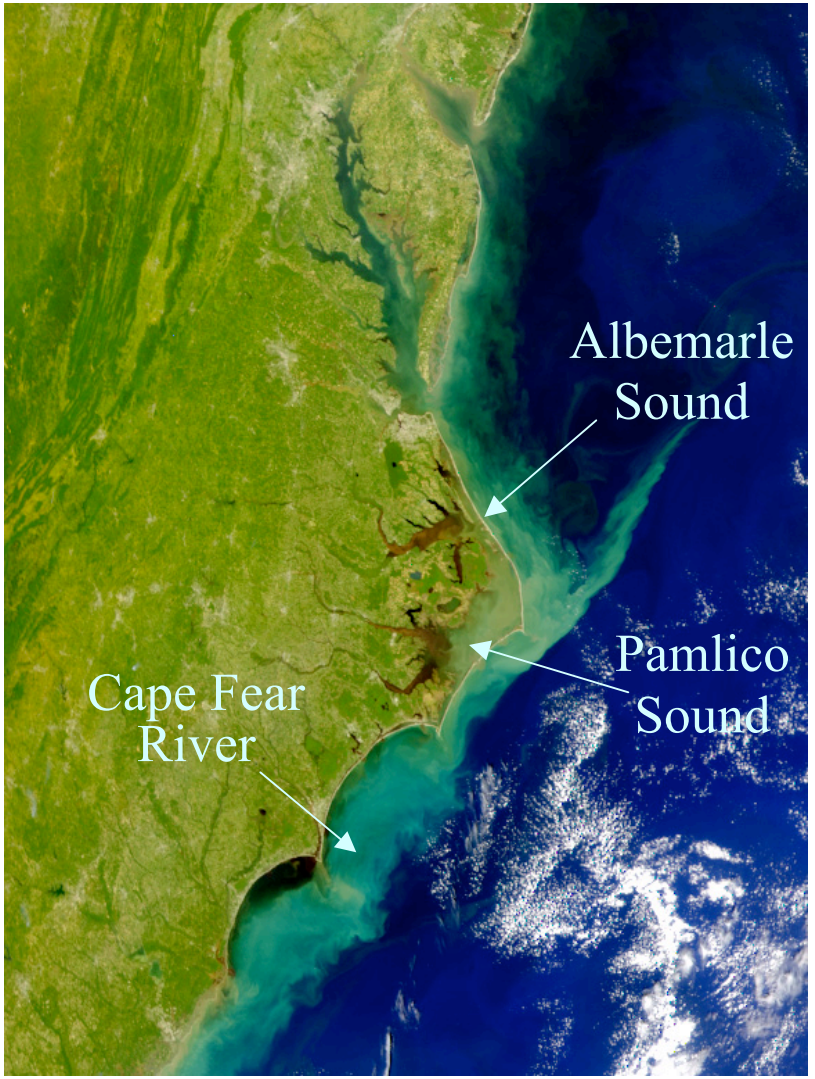
Hurricane Floyd

23 September 1999

massive flooding

rivers carried sediment & sewage discharge into coastal areas

resulted in anoxic conditions in bays



Sept. 23, 1999

examples of ocean color applications

SeaWiFS coral reef activities

collaborative effort between NASA, NOAA & WCMC to create the most accurate global map of potential coral reef habitats

accurate to 1 km; improved coral reef maps - nearly 2K reef groups corrected in ReefBase

nearly 44K images processed

online web-based tool

http://seawifs.gsfc.nasa.gov/reefs

examples of ocean color applications

SeaWiFS depth classification

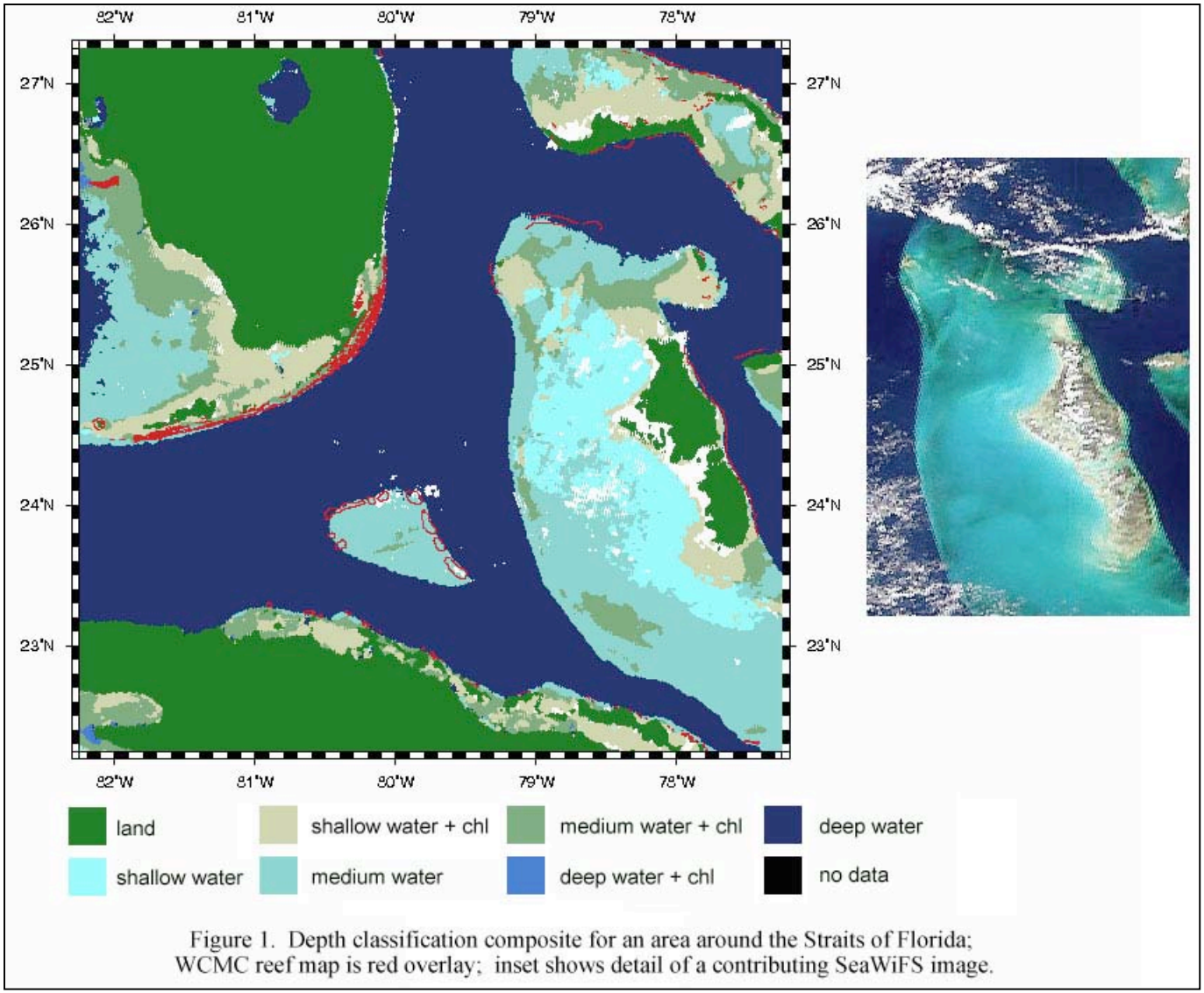


Figure 1. Depth classification composite for an area around the Straits of Florida; WCMC reef map is red overlay; inset shows detail of a contributing SeaWiFS image.

examples of ocean color applications

IOCCG Report 7 (2008)

"Why Ocean Colour? The Societal Benefits of Ocean-Colour Technology"

http://www.ioccg.org

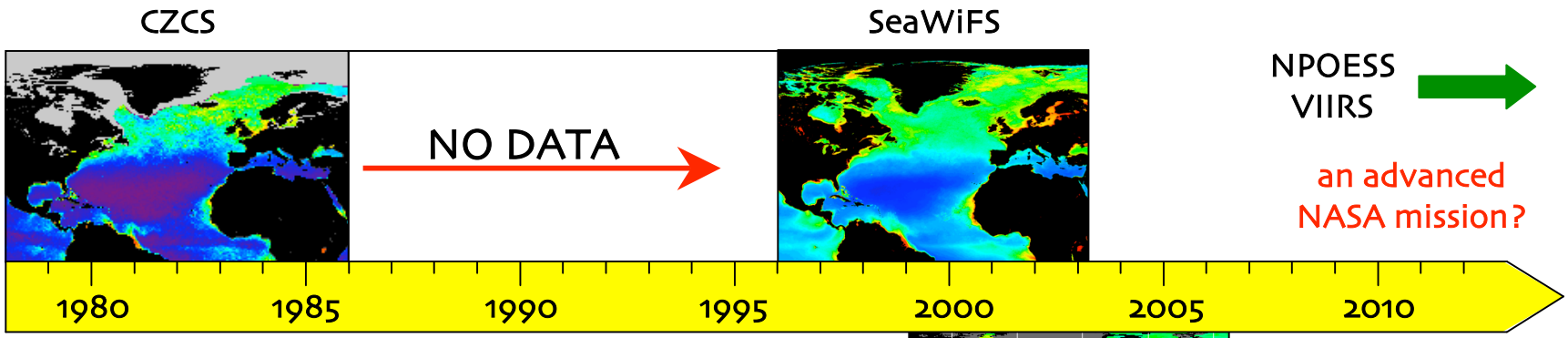
1. why use satellites for oceanographic applications?
2. why study ocean color?
3. ocean color @ NASA
4. the NASA Ocean Biology Processing Group (OBPG)
5. international collaborations

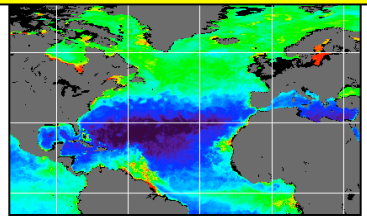
ocean color @ NASA

NASA's goals are to:

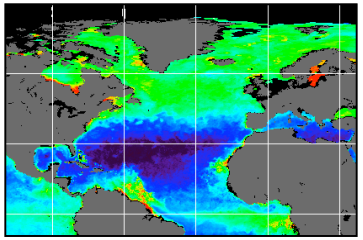
make available high quality ocean color (& sst) data to the broadest user community in the most timely & efficient manner possible

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





MODIS-Terra



MODIS-Aqua

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

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

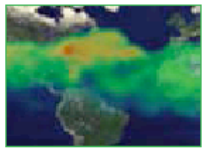
black – specified by NAS Decadal Survey & red – Science Definition Team recommendations

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

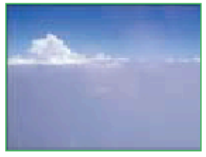
GEOSTATIONARY COASTAL AND AIR POLLUTION EVENTS (GEO-CAPE)

Launch: 2013-2016 Mission Size: Medium



Identification of human versus natural sources of aerosols and ozone precursors

Dynamics of coastal ecosystems, river plumes, and tidal fronts



Observation of air pollution transport in North, Central, and South America

Prediction of track of oil spills, fires, and releases from natural disasters

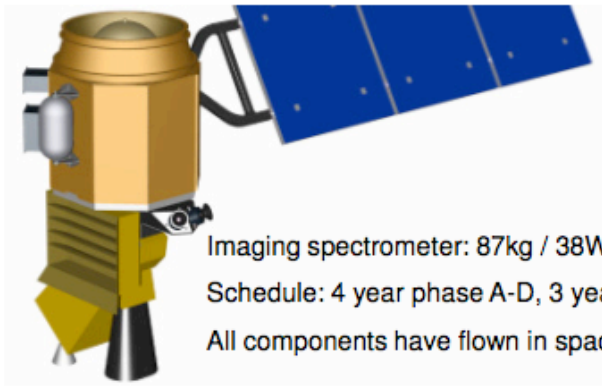
Detection and tracking of waterborne hazardous materials

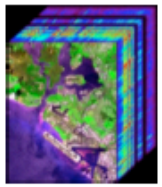
Coastal health

Forecasts of air quality

3. HyspIRI (Hyperspectral Infrared Imager)

HyspIRI Imaging Spectroscopy Science Measurements





Imaging spectrometer: 87kg / 38W

Schedule: 4 year phase A-D, 3 years operations

All components have flown in space

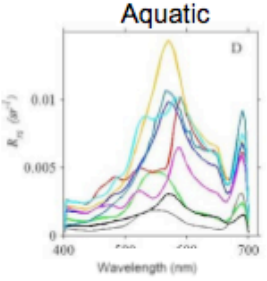
Science Questions:

- *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?*

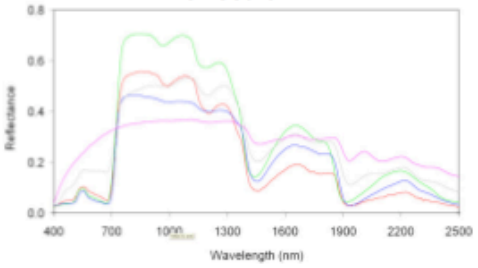
Measurement:

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

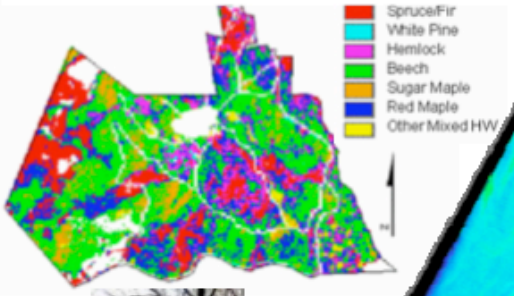
Aquatic

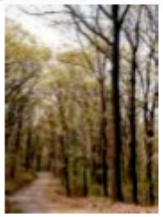


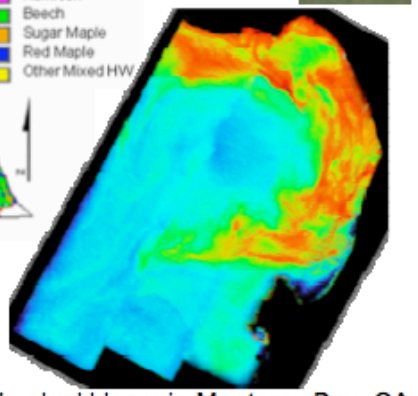
Terrestrial



Map of dominant tree species, Bartlett Forest, NH





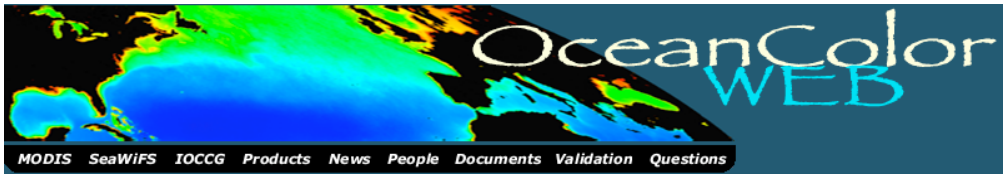


Red tide algal bloom in Monterey Bay, CA

1. why use satellites for oceanographic applications?
2. why study ocean color?
3. ocean color @ NASA
4. the NASA Ocean Biology Processing Group (OBPG)
5. international collaborations

the NASA Ocean Biology Processing Group

- Ocean Color (OC)
- SST for MODIS, GHRSST
- Salinity from Aquarius



oceancolor.gsfc.nasa.gov

- 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

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)

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standard ocean products

observed radiance (uncalibrated)

ocean color
- remote-sensing reflectances, Rrs(λ)
- chlorophyll, Chl
- diffuse attenuation, Kd(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

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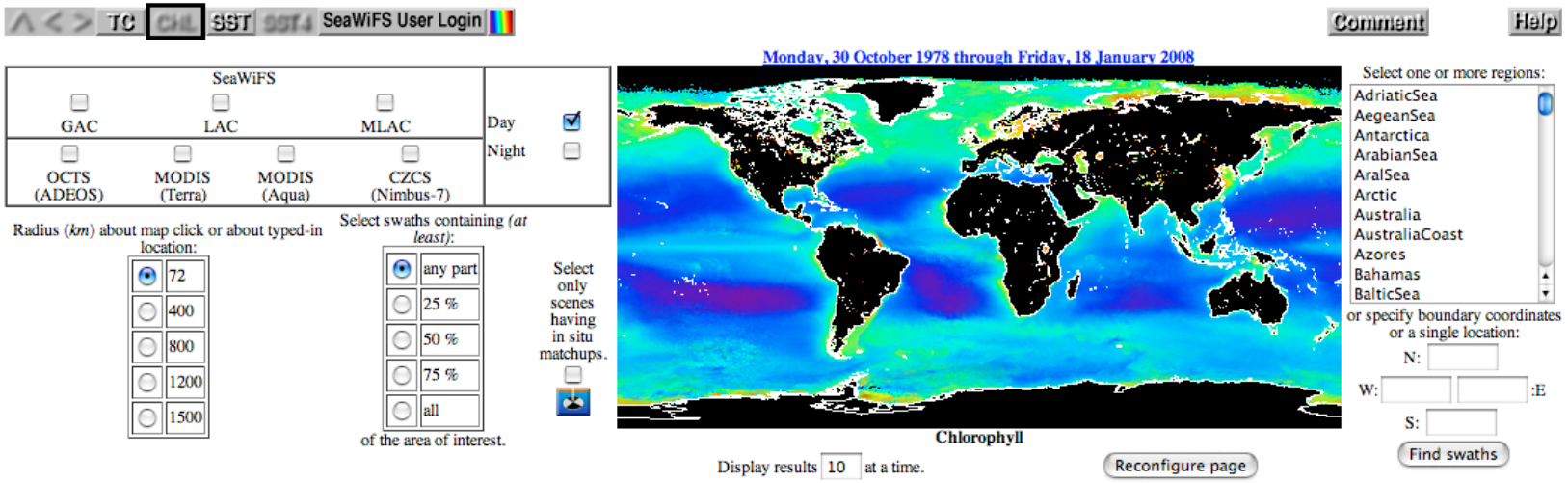
data distribution

- 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



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

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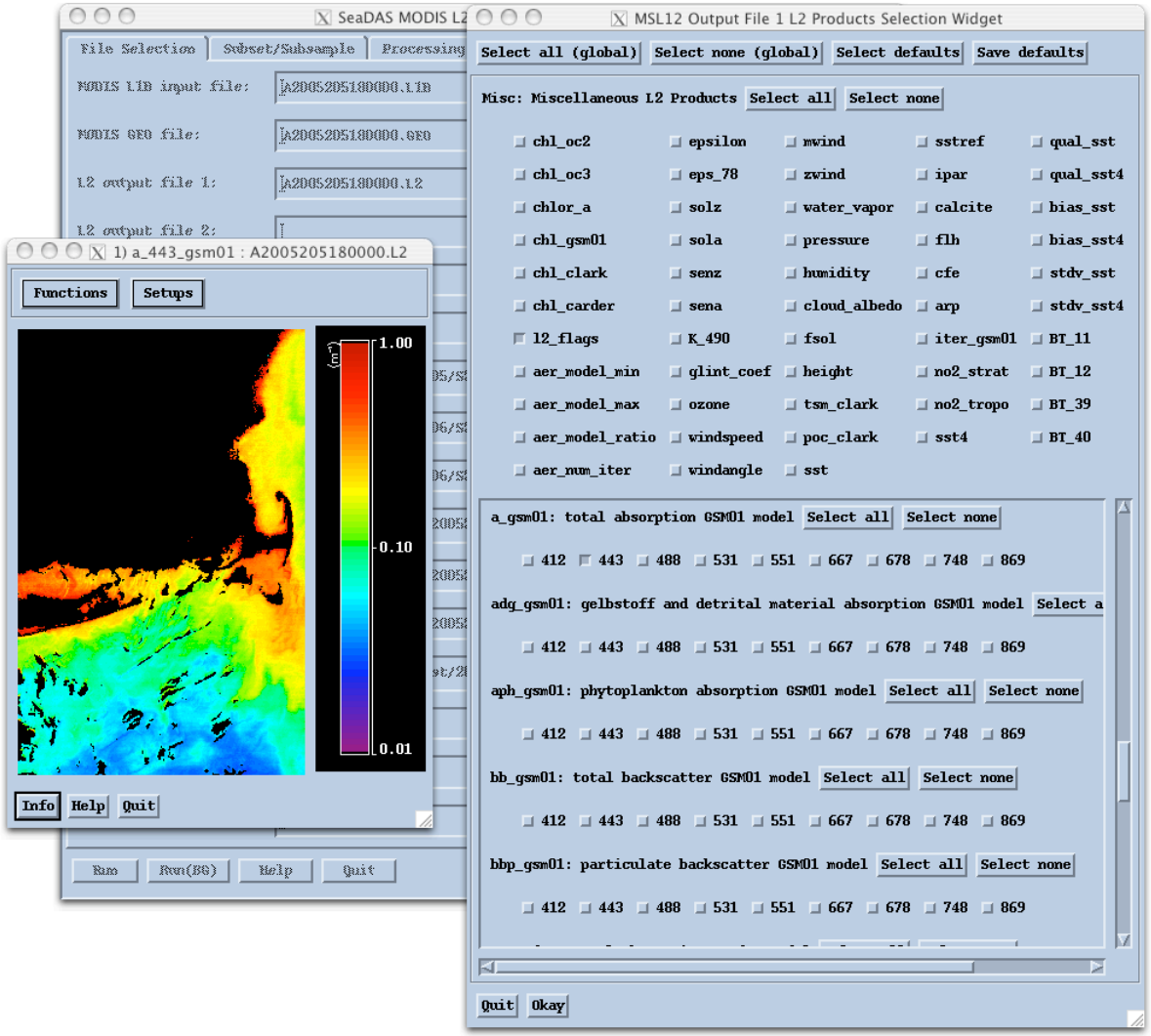
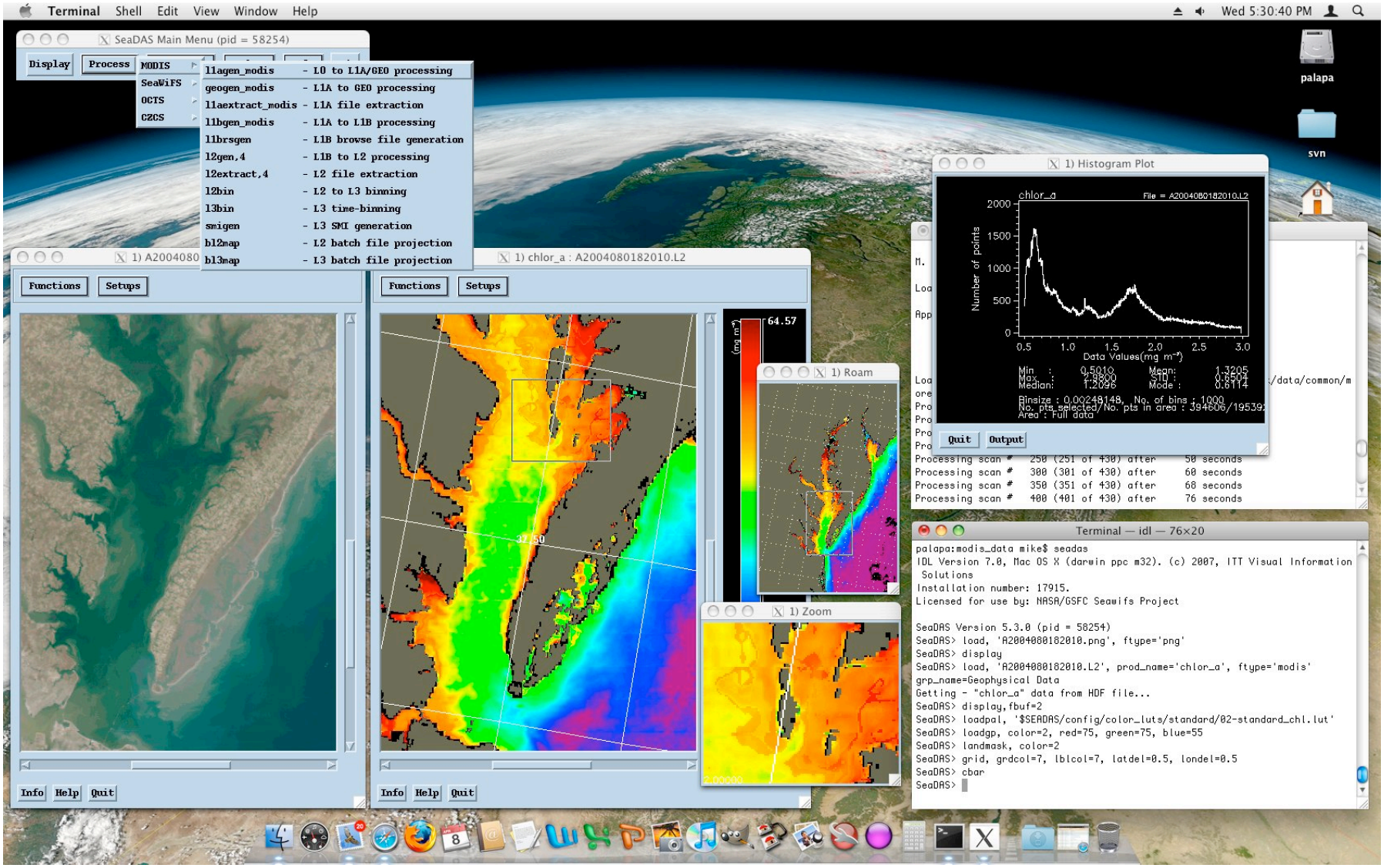
SeaDAS

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



reprocessing algorithms in latest SeaDAS



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

examples of non-standard ocean products

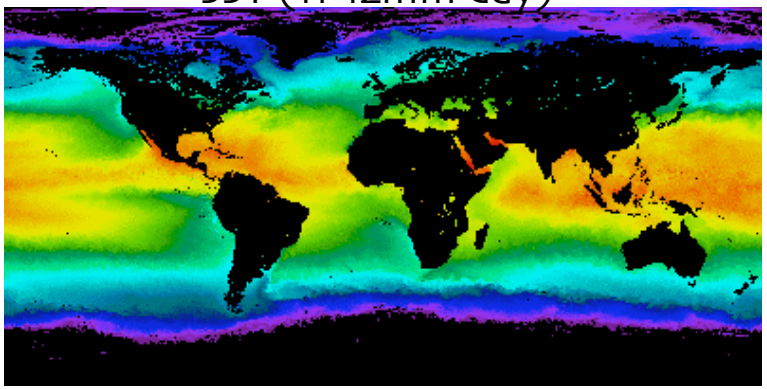
alternate C_a and K_d algorithms

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

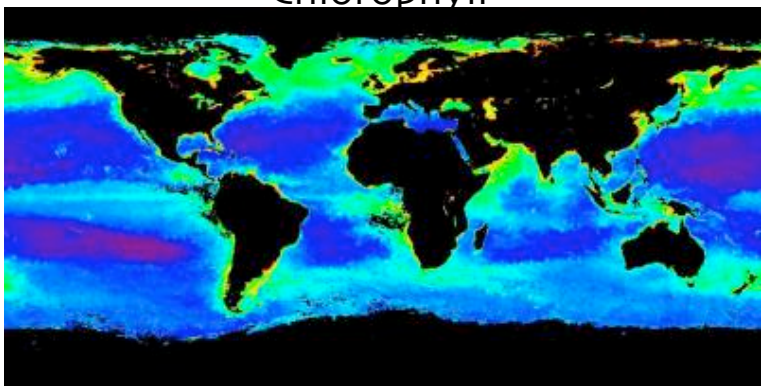
euphotic depth (Z_{eu}, Z_{sd})

spectrally integrated diffuse attenuation, K_d(PAR)

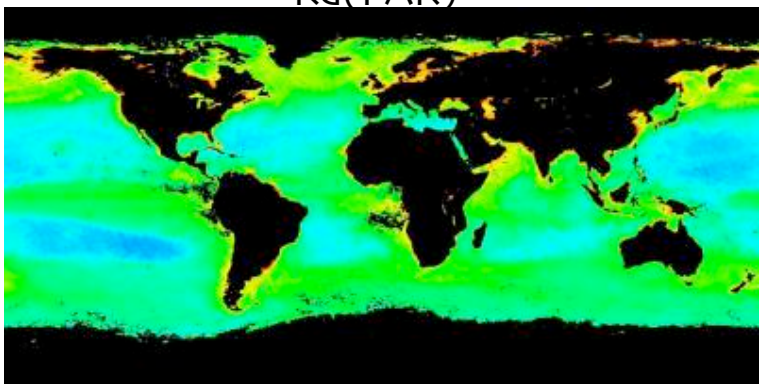
SST (11-12mm day)



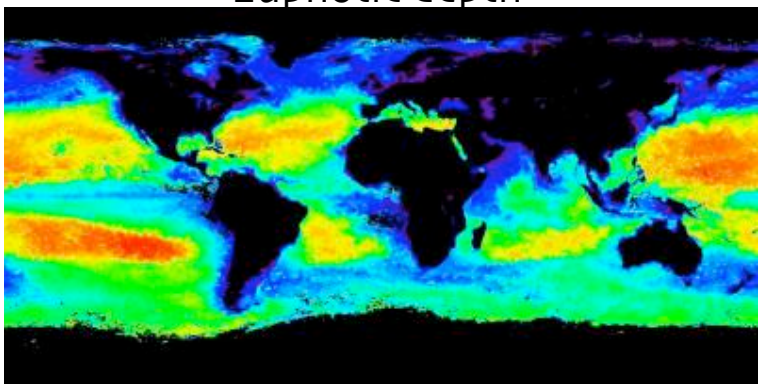
Chlorophyll



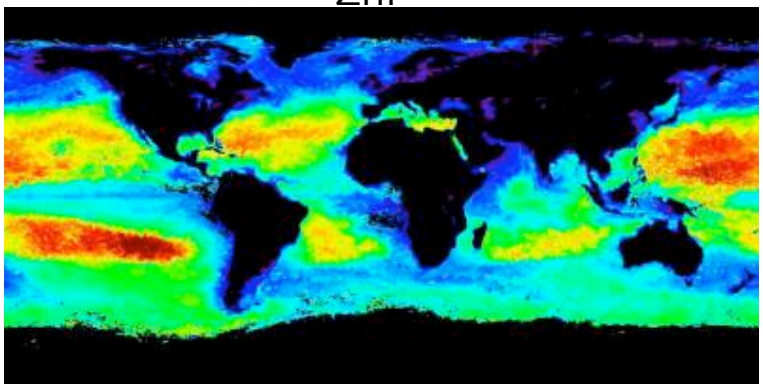
Kd(PAR)



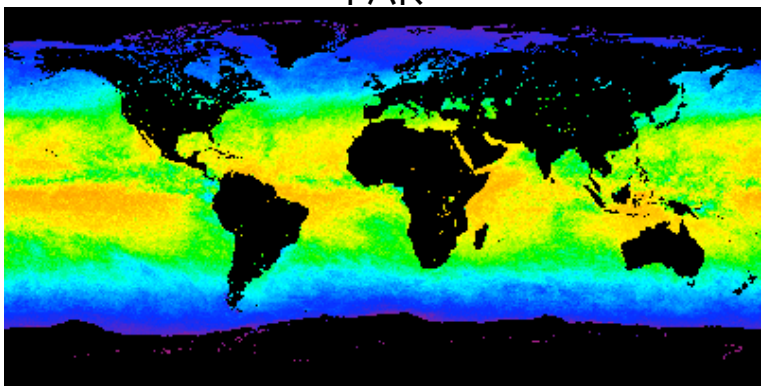
Euphotic depth



Zhl

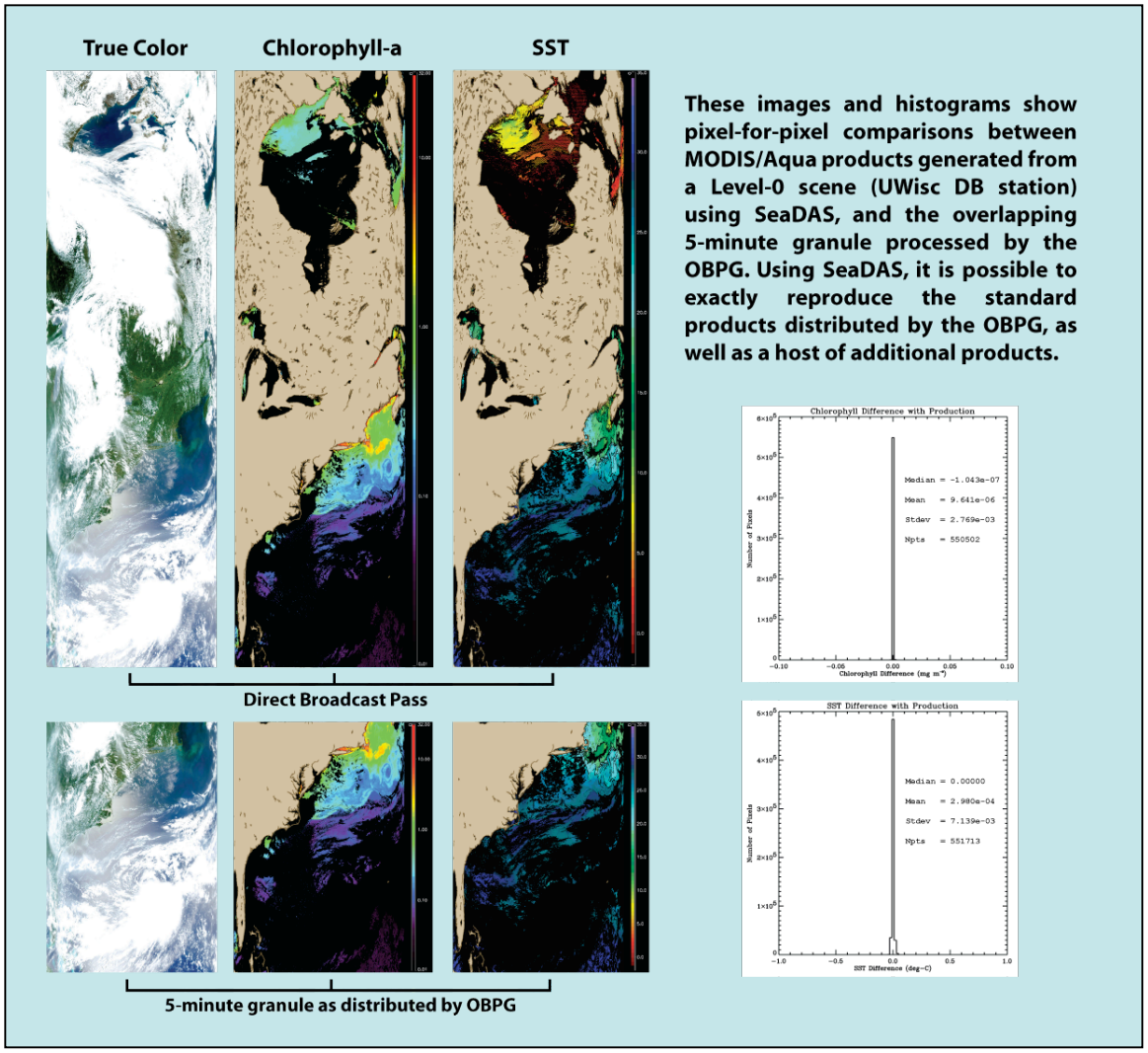


PAR

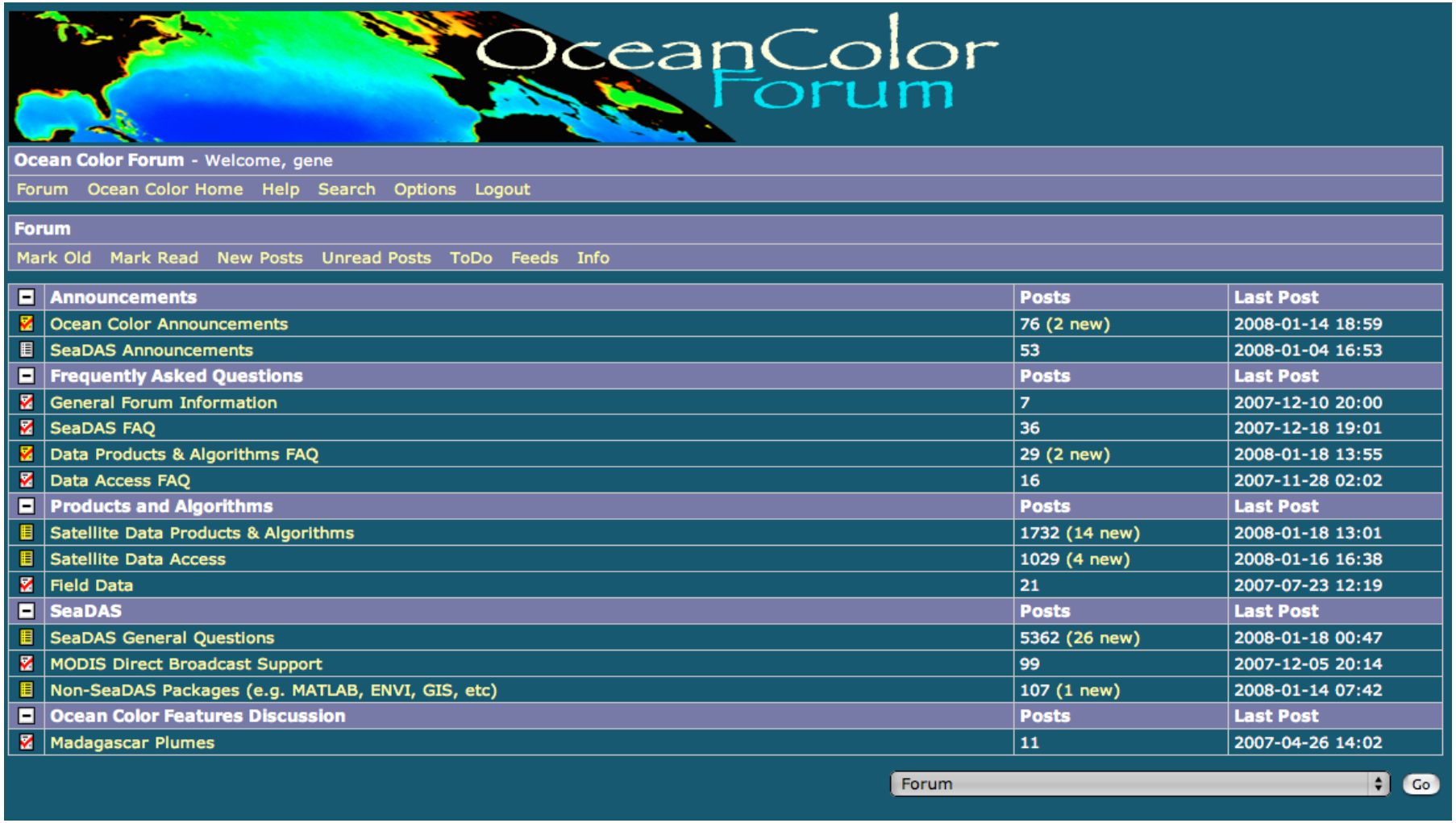


PJW, NASA/SSAI, 18 Jan 2010 @ NIO

MODIS direct broadcast support



the NASA Ocean Biology Processing Group



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

the NASA Ocean Biology Processing Group

SeaBASS

Bio-optical Search

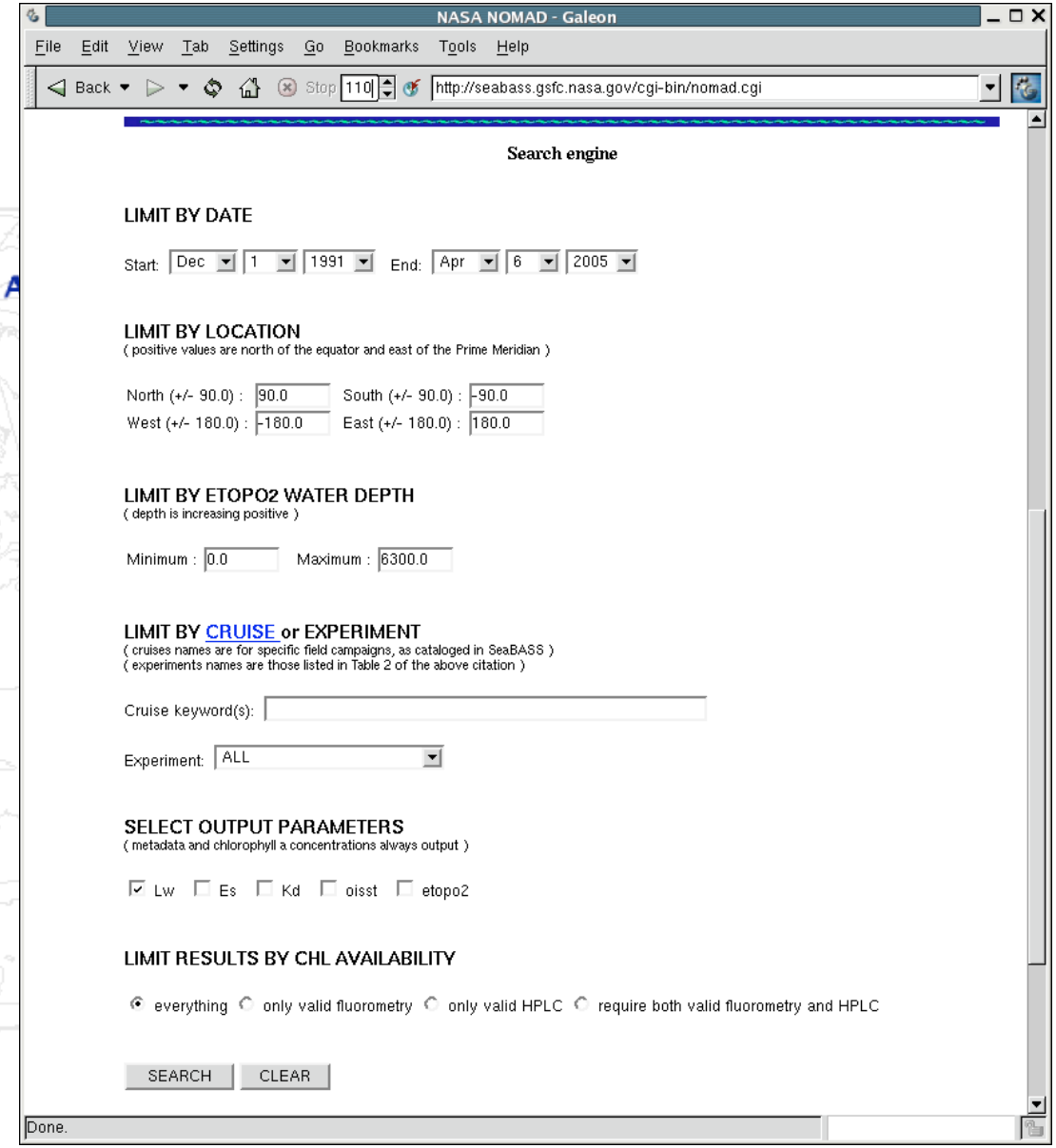
Pigment Locator

Aerosol Locator

General Search

Cruise Search

Validation Cruise Search



the NASA Ocean Biology Processing Group

the SeaWiFS Bio-optical Archive & Storage System (SeaBASS)

archive for bio-optical data & related oceanographic / atmospheric measurements

data contributed by research groups from ~50 institutions in 15 countries

50,000 data files from over 2,000 field campaigns, as of January 2010, including:

- 40,000 radiometric (AOP) stations
- 70,000 pigment (CHL) stations
- 25,000 spectroscopy (IOP) stations
- 17,000 aerosol optical thickness (AOT) stations

all data are publicly accessible online: http://seabass.gsfc.nasa.gov

consolidated processing of high performance liquid chromotography (HPLC) samples at the University of Maryland

comprehensive series of community-vetted protocol documents

P.J. Werdell and S.W. Bailey, "The SeaWiFS Bio-optical Archive and Storage System (SeaBASS): Current architecture and implementation," NASA/TM-2002-211617, NASA Goddard Space Flight Center, 45 pp. (2002).

the NASA Ocean Biology Processing Group

data submission policy

- permanent archive for NASA Ocean Biology & Biogeochemistry (OB&B) data
- data submitted to archive within 1-year of date of collection (DOC)
- periodic release to NOAA National Oceanographic Data Center
- planned periodic release to WHOI BCO-DMO

data access policy

- follows NASA Earth Science Data & Information Policy
- all data publicly available for research and education use
- original contributors to be offered authorship for 3-years of DOC
- contributors, NASA, & SeaBASS always to be acknowledged

benefits of a centralized archive

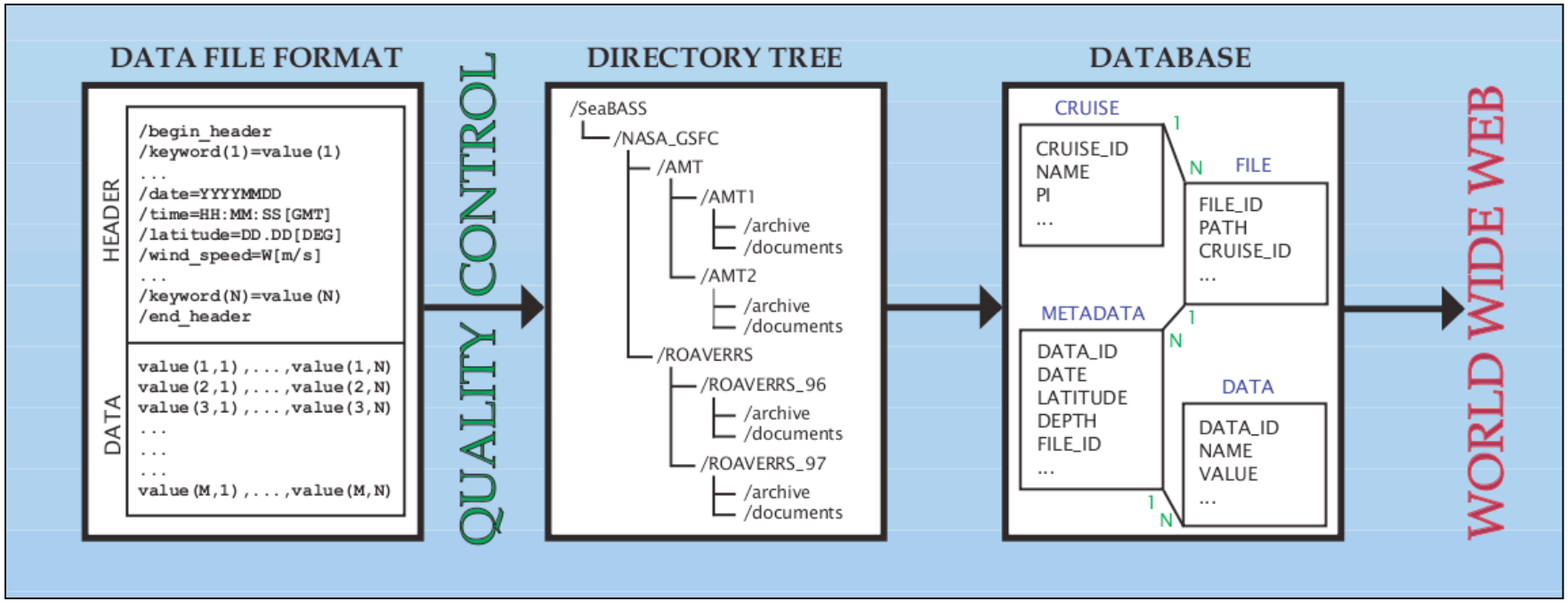
consolidated …

- data acquisition by community members
- file formats
- quality control & quality assurance
- permanent (redudant) archival

facilitates …

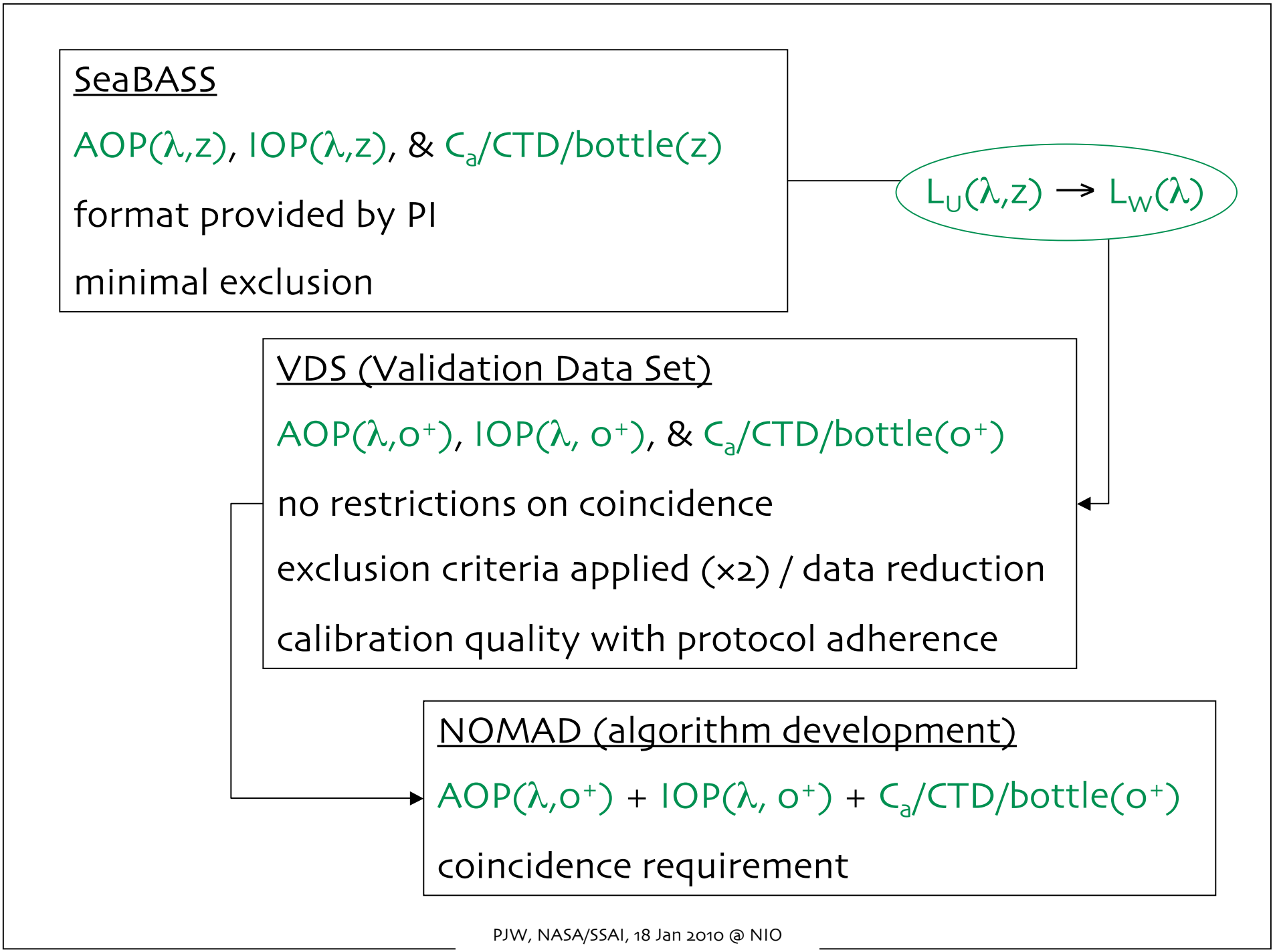
- systematic post-processing
- rigorous quality control & quality assurance
- development of algorithm development & validation data sets
- centralized cal/val activities

the NASA Ocean Biology Processing Group



physical storage at NASA Goddard Space Flight Center

relational database management system (MySQL)

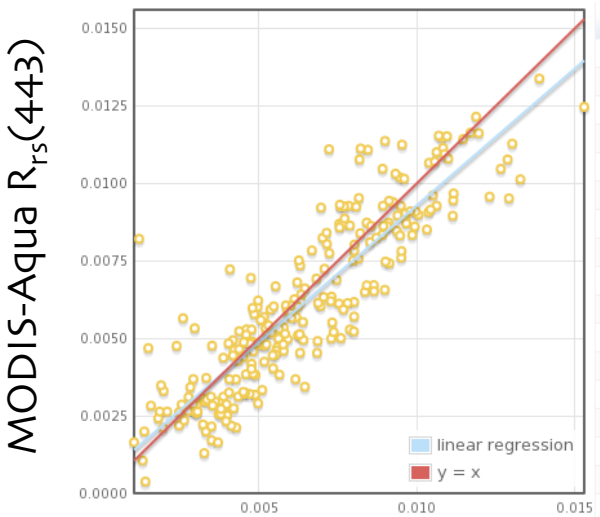

SeaBASS
AOP(λ,z), IOP(λ,z), & Ca/CTD/bottle(z)
format provided by PI
minimal exclusion
LU(λ,z) → LW(λ)
VDS (Validation Data Set)
AOP(λ,o+), IOP(λ, o+), & Ca/CTD/bottle(o+)
no restrictions on coincidence
exclusion criteria applied (x2) / data reduction
calibration quality with protocol adherence
NOMAD (algorithm development)
AOP(λ,o+) + IOP(λ, o+) + Ca/CTD/bottle(o+)
coincidence requirement

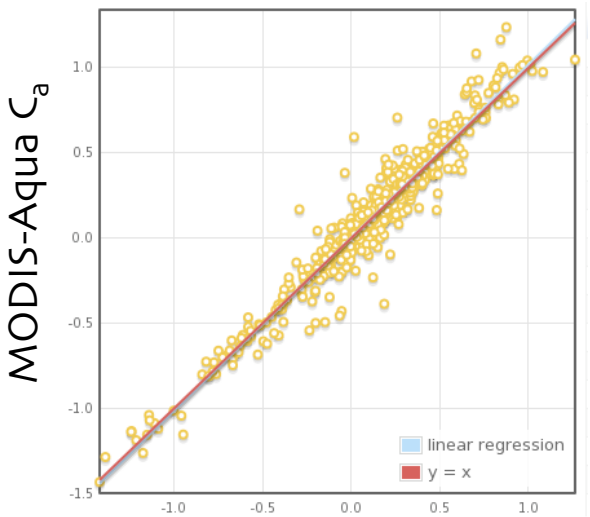
the NASA Ocean Biology Processing Group

Level-2 validation ("match-up") results publicly posted online at:
http://seabass.gsfc.nasa.gov/seabasscgi/validation_search.cgi

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)

1. why use satellites for oceanographic applications?
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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)

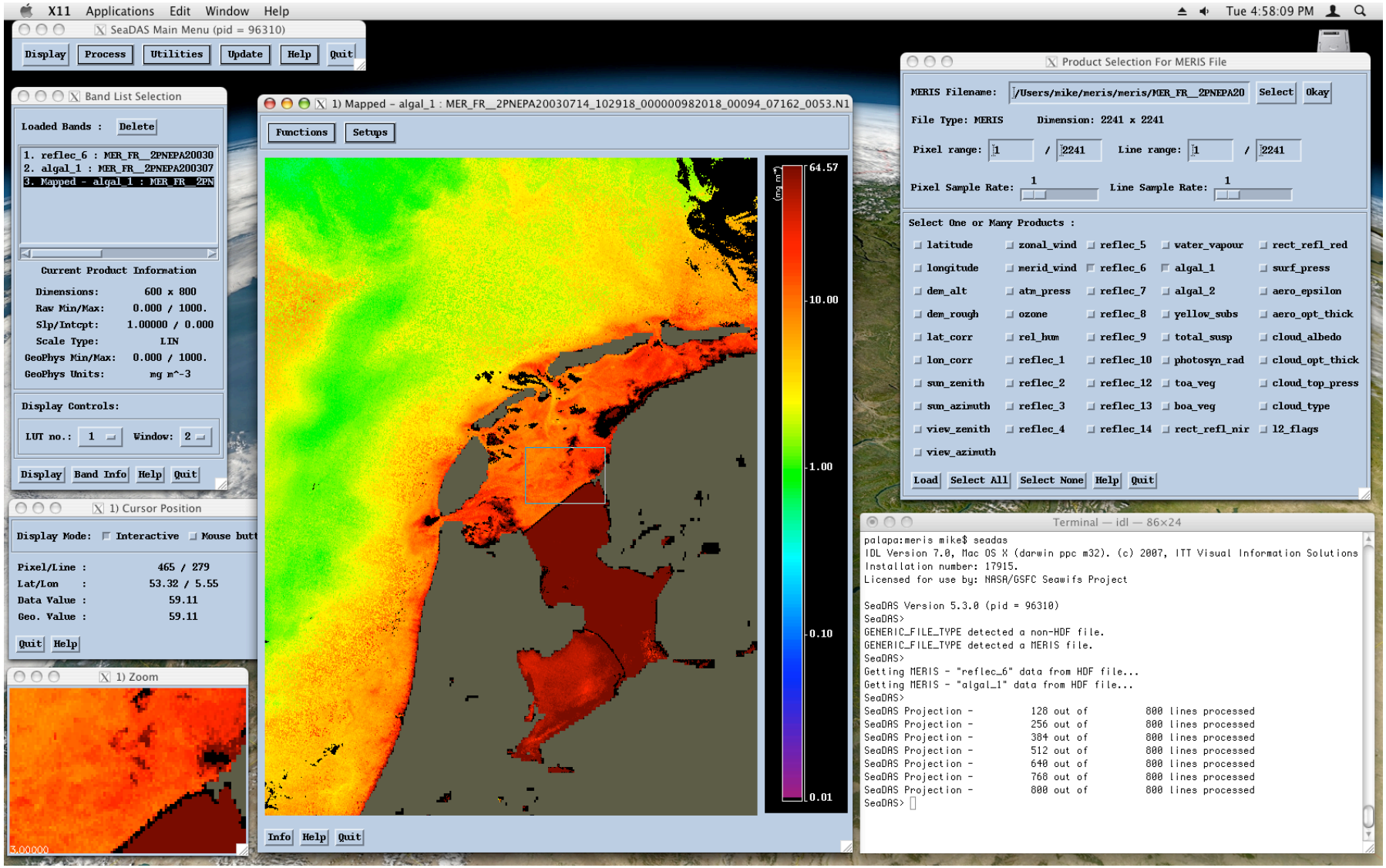
MOS/IRS-P3 Receiving Station at Wallops

OCTS/ADEOS reprocessing & distribution

MODIS SST data for GHRSST

MERIS/ESA - participation in Quality Working Group and (proposed) CoastColour

MERIS Level-2 data displayed in SeaDAS



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

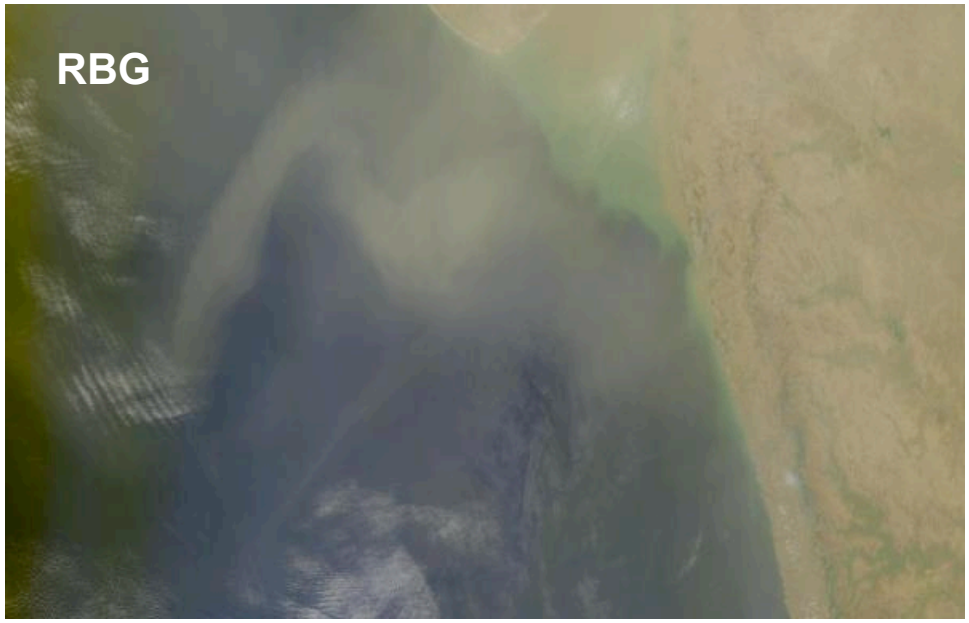
NASA to provide processing capability (Level-1B through Level-3) for use by ISRO & the international community

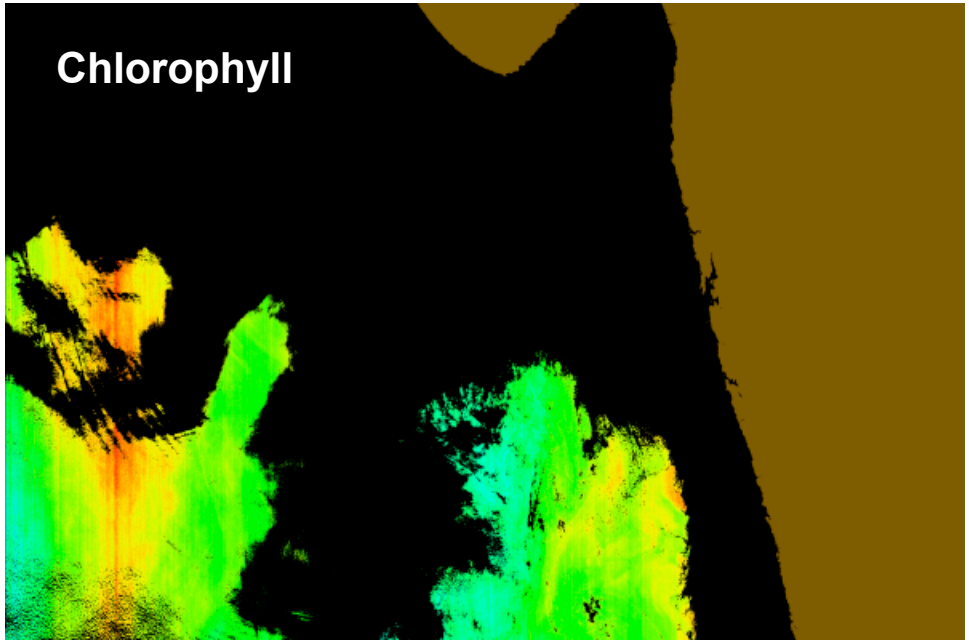
- distributed via SeaDAS
- preliminary cabability based on OCM already implemented
- need ISRO to finalize Level-1B format

NASA & NOAA to participate in Joint Cal/Val Team

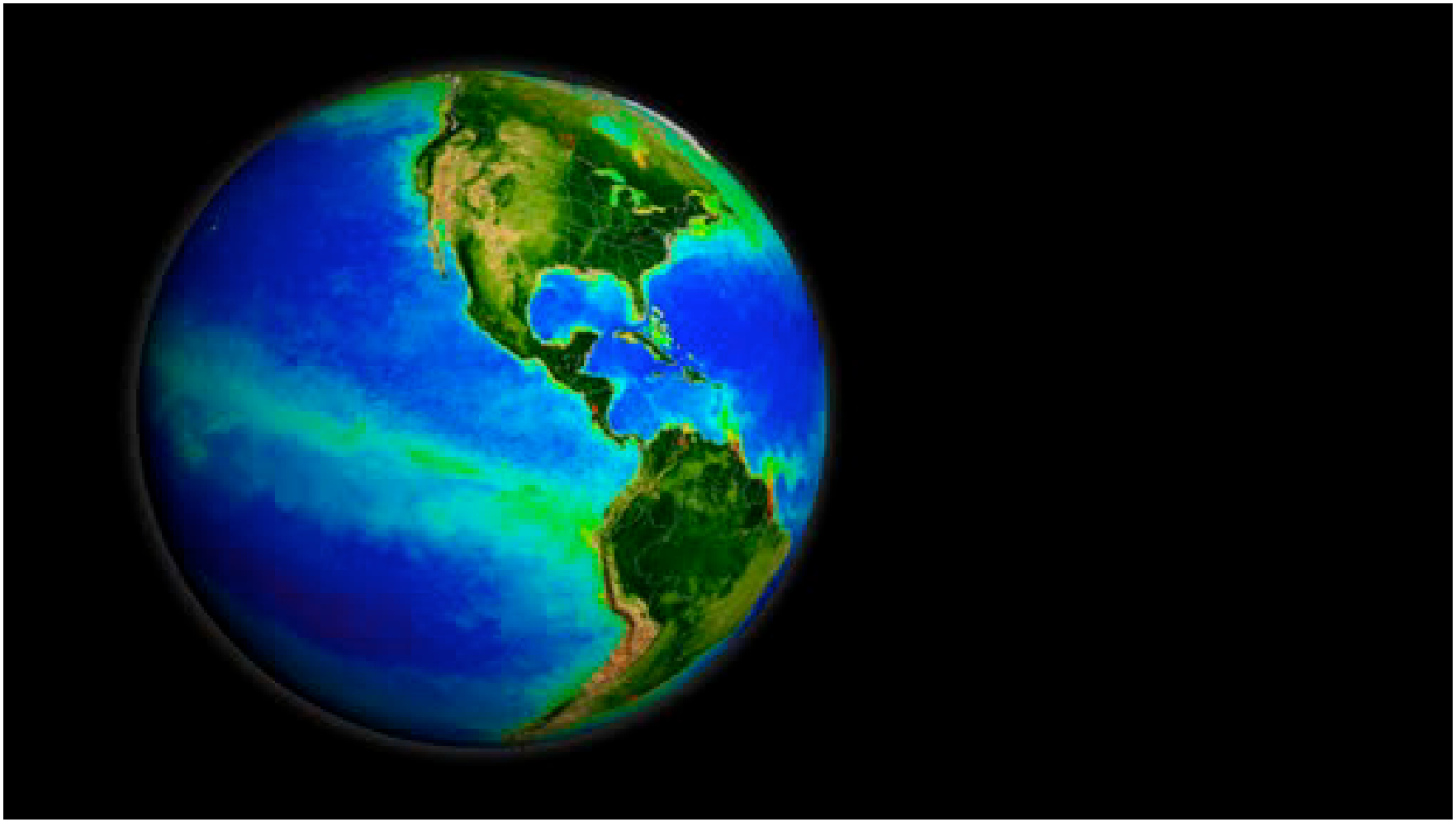
preliminary OCM-2 Level-1B format, simulated from OCM-1

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





thank you



ocean color @ NASA

missions to measurements:

a consistent series of systematic ocean color measurements from **multi-instrument, multi-platform, and multi-year** observations based on accurate and **uniform calibration and validation** over the lifetime of the measurement

global accuracy goals for climate data records:

Rrs(443): ± 5% absolute uncertainty in clear water

Chl: ± 35% over a range of 0.05 - 50 mg m-3