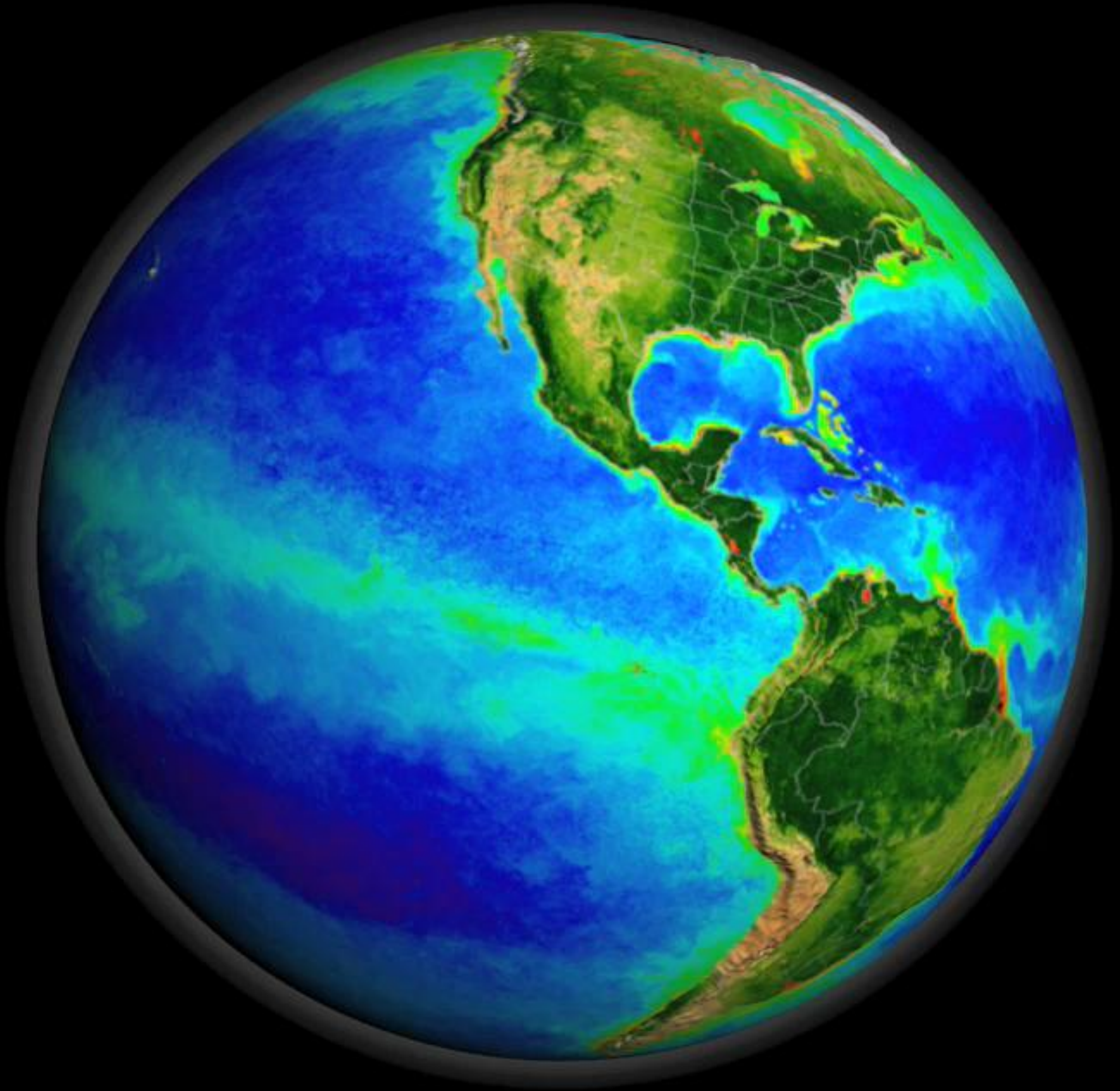
BEYOND CHLOROPHYLL

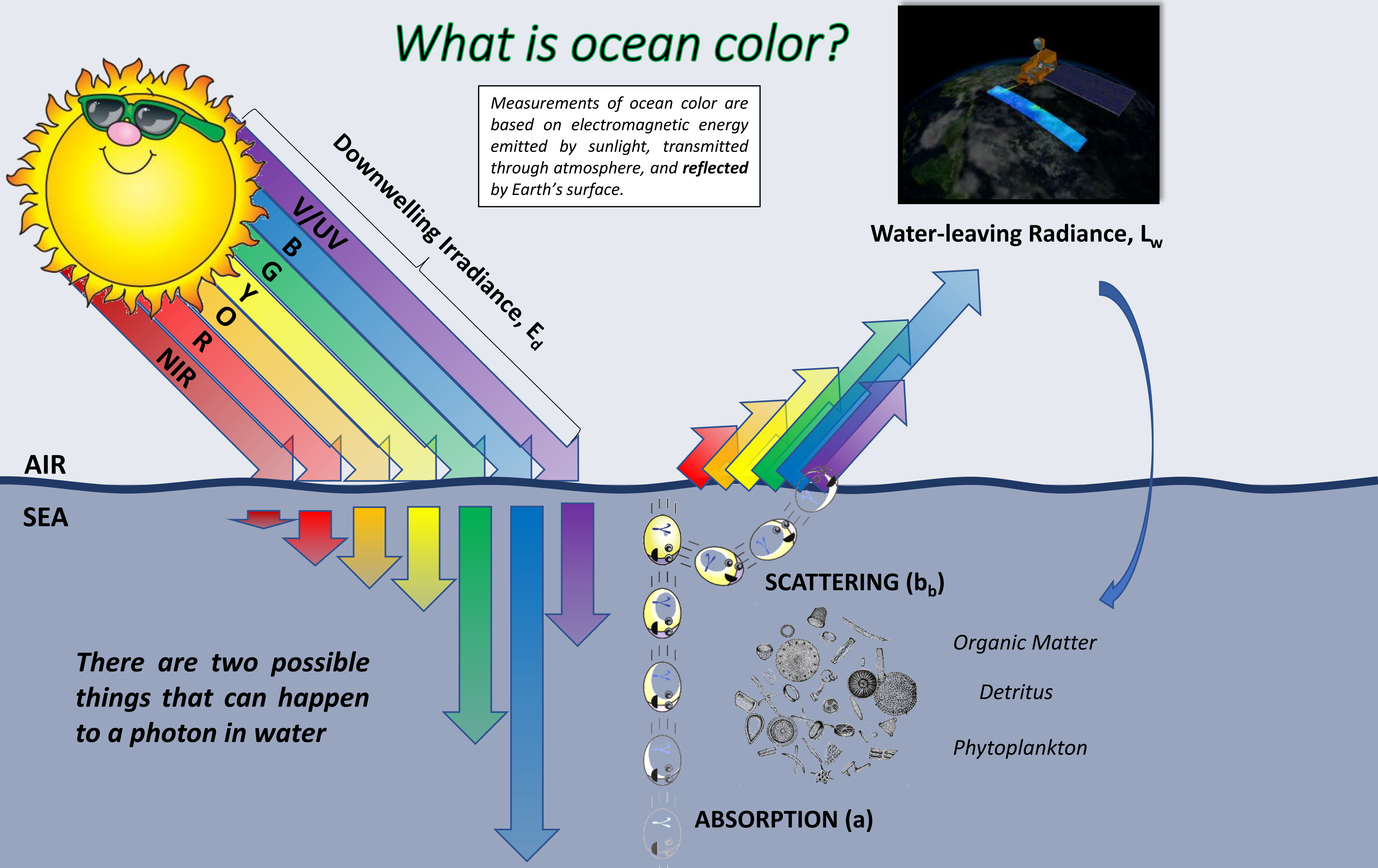
CoastWatch Satellite 201
Summer Lecture Series

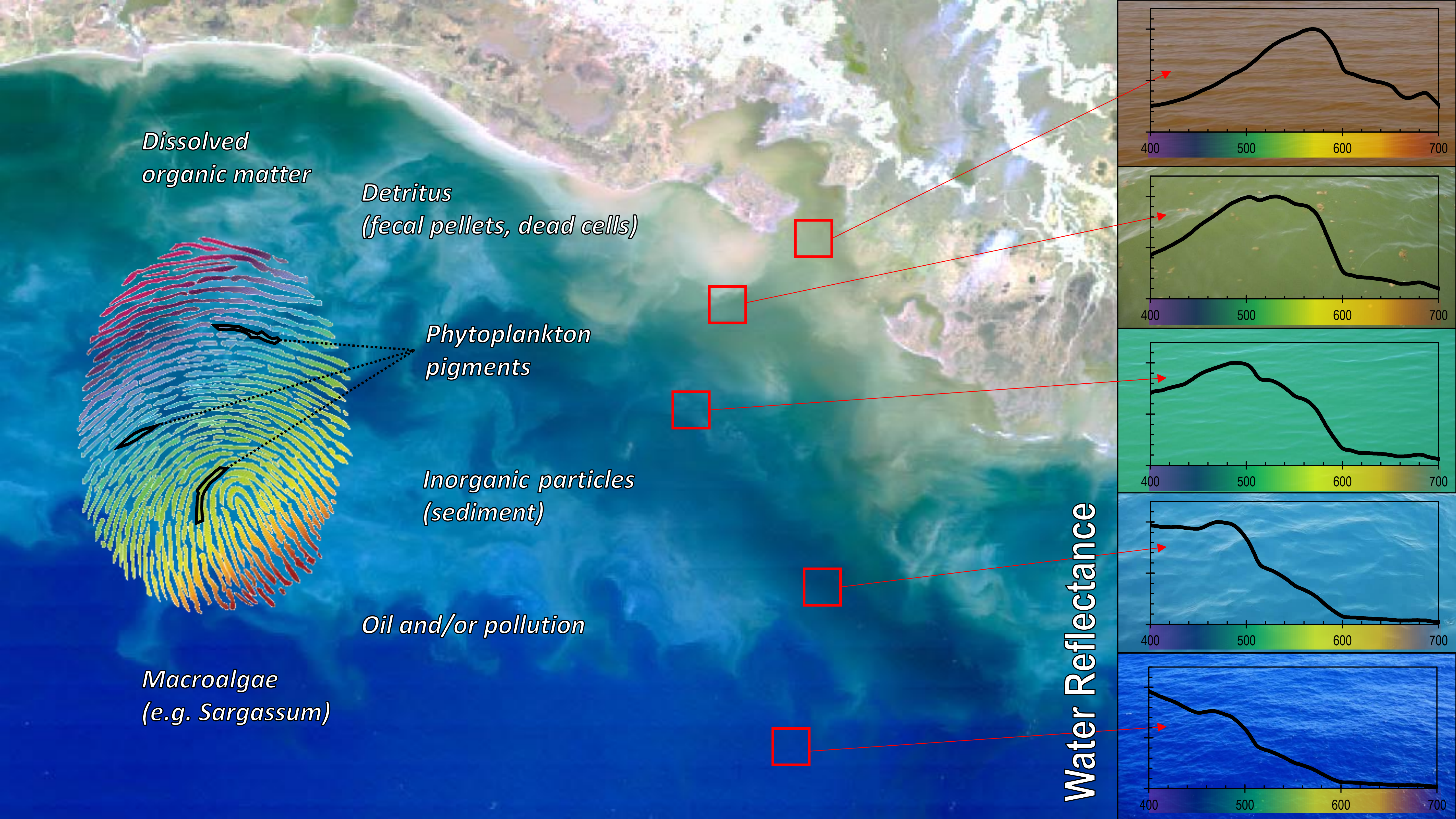
Ryan Vandermeulen
NOAA Fisheries Satellite Coordinator



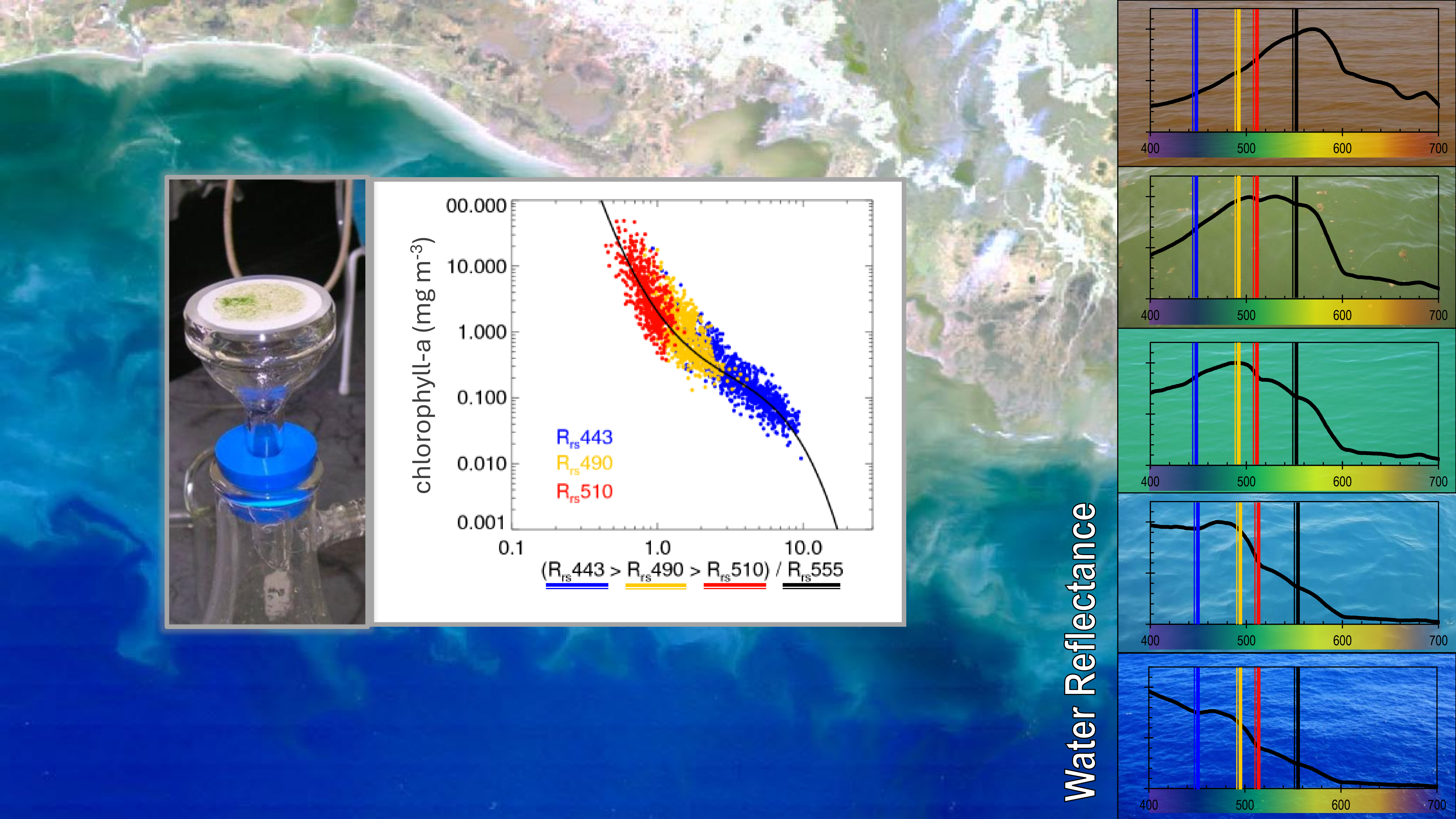
What is ocean color?

Measurements of ocean color are based on electromagnetic energy emitted by sunlight, transmitted through atmosphere, and ***reflected*** *by Earth's surface.*

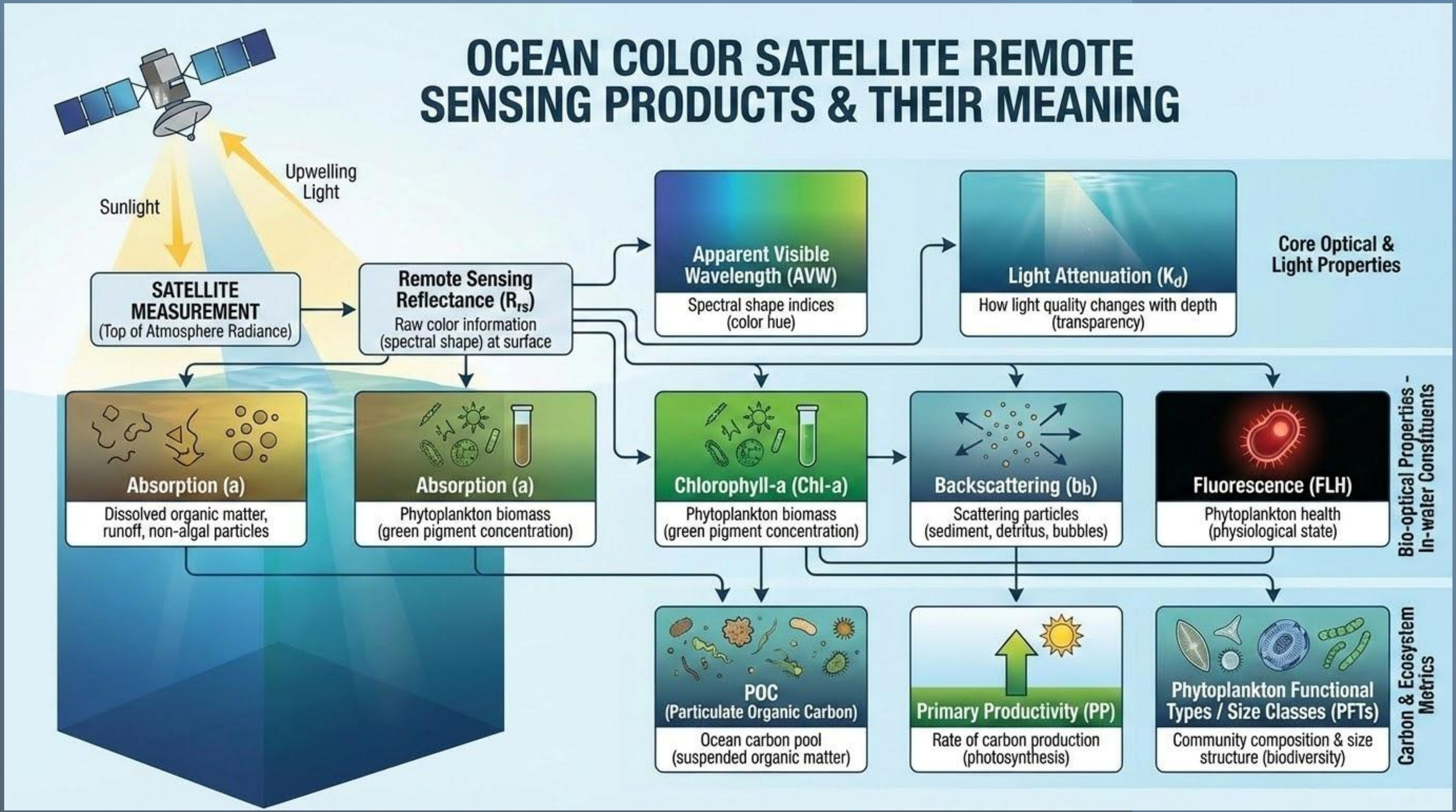




Dissolved
organic matter
Detritus
(fecal pellets, dead cells)
Phytoplankton
pigments
Inorganic particles
(sediment)
Oil and/or pollution
Macroalgae
(e.g. Sargassum)
Water Reflectance
400
500
600
700



chlorophyll-a (mg m-3)
00.000
10.000
1.000
0.100
0.010
0.001
0.1
1.0
10.0
(Rrs443 > Rrs490 > Rrs510) / Rrs555
Rrs443
Rrs490
Rrs510
Water Reflectance
400
500
600
700


OCEAN COLOR SATELLITE REMOTE SENSING PRODUCTS & THEIR MEANING
Sunlight
Upwelling Light
SATELLITE MEASUREMENT
(Top of Atmosphere Radiance)
Remote Sensing Reflectance (R_{rs})
Raw color information (spectral shape) at surface
Apparent Visible Wavelength (AVW)
Spectral shape indices (color hue)
Light Attenuation (K_d)
How light quality changes with depth (transparency)
Core Optical & Light Properties
Absorption (a)
Dissolved organic matter, runoff, non-algal particles
Absorption (a)
Phytoplankton biomass (green pigment concentration)
Chlorophyll-a (Chl-a)
Phytoplankton biomass (green pigment concentration)
Backscattering (b_b)
Scattering particles (sediment, detritus, bubbles)
Fluorescence (FLH)
Phytoplankton health (physiological state)
Bio-optical Properties - In-water Constituents
POC
(Particulate Organic Carbon)
Ocean carbon pool (suspended organic matter)
Primary Productivity (PP)
Rate of carbon production (photosynthesis)
Phytoplankton Functional Types / Size Classes (PFTs)
Community composition & size structure (biodiversity)
Carbon & Ecosystem Metrics

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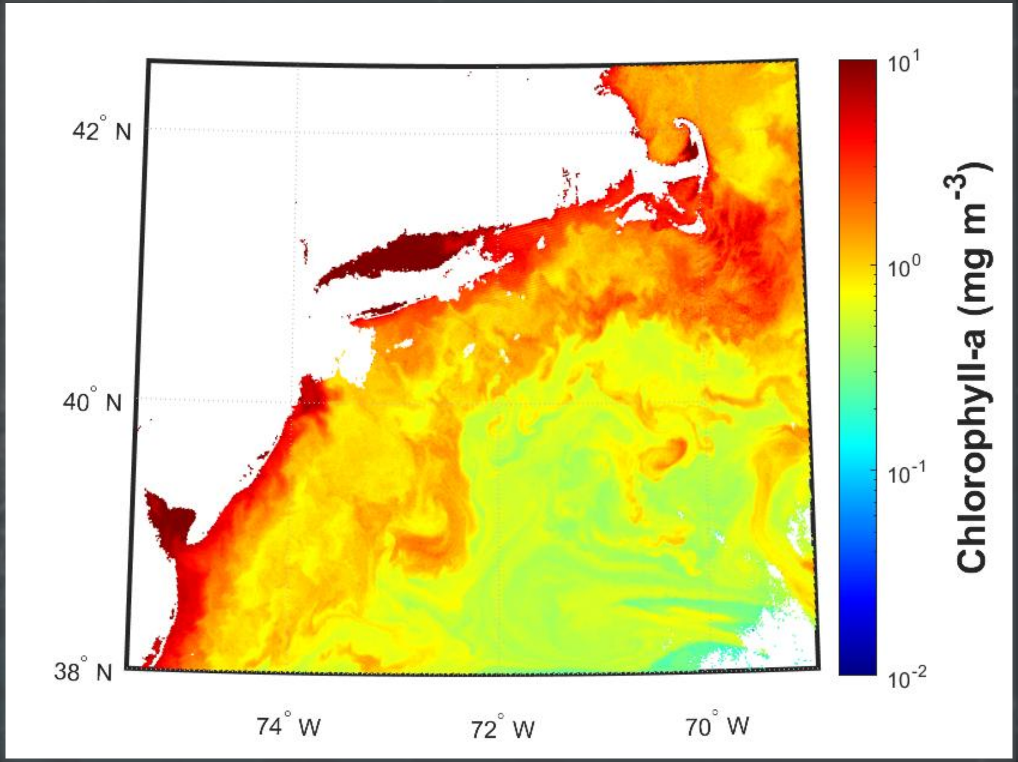
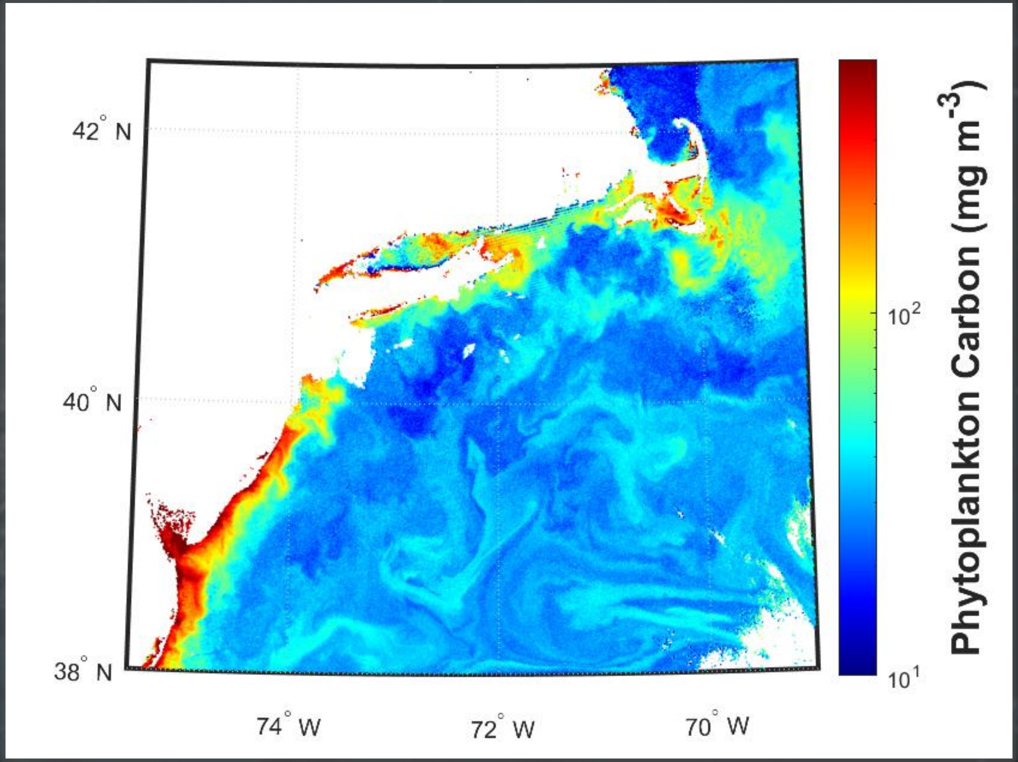
Chlorophyll-a (chlor_a)

- Pigment contained within all phytoplankton and cyanobacteria
- A ubiquitous indicator of phytoplankton biomass, and other… stuff (in coastal waters)
- NOTE: In some cases, increases/decreases in concentration do not explicitly reflect biomass change



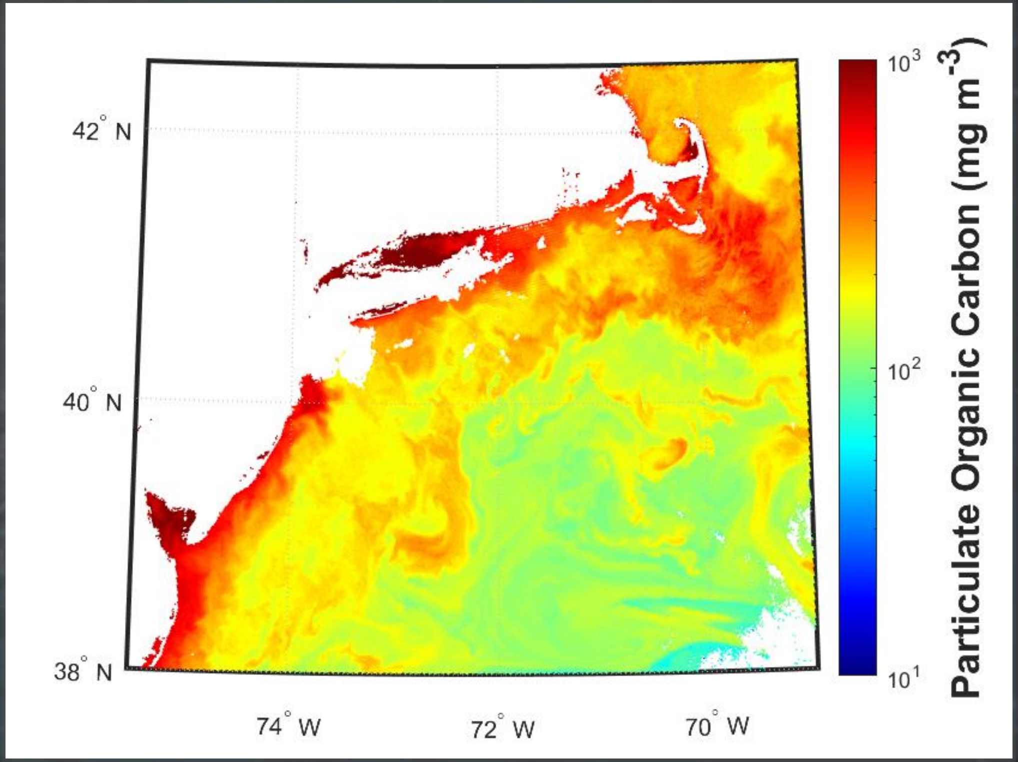
Phytoplankton Carbon (c_phyto)

- The concentration of phytoplankton expressed in terms of *carbon* concentration
- This product is related to particle backscattering
- Arguably, a more direct indicator of phytoplankton biomass, but it hasn't been as well vetted
- [c_phyto ÷ chlor_a] can be useful



Particulate Organic Carbon (poc)

- Organic carbon particles (plankton, detritus, bacteria)
- Particularly relevant for carbon export processes
- Can be overestimated in the presence of minerals
- POC corrected for *non-carbon* particles via CoastWatch (TBD)

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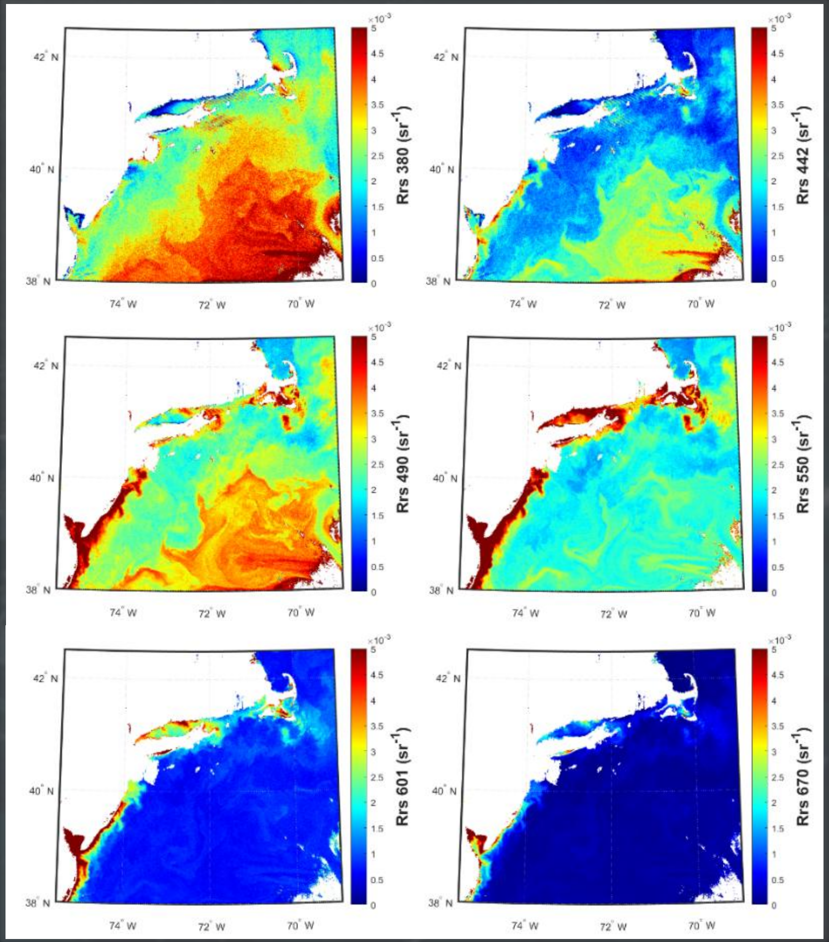
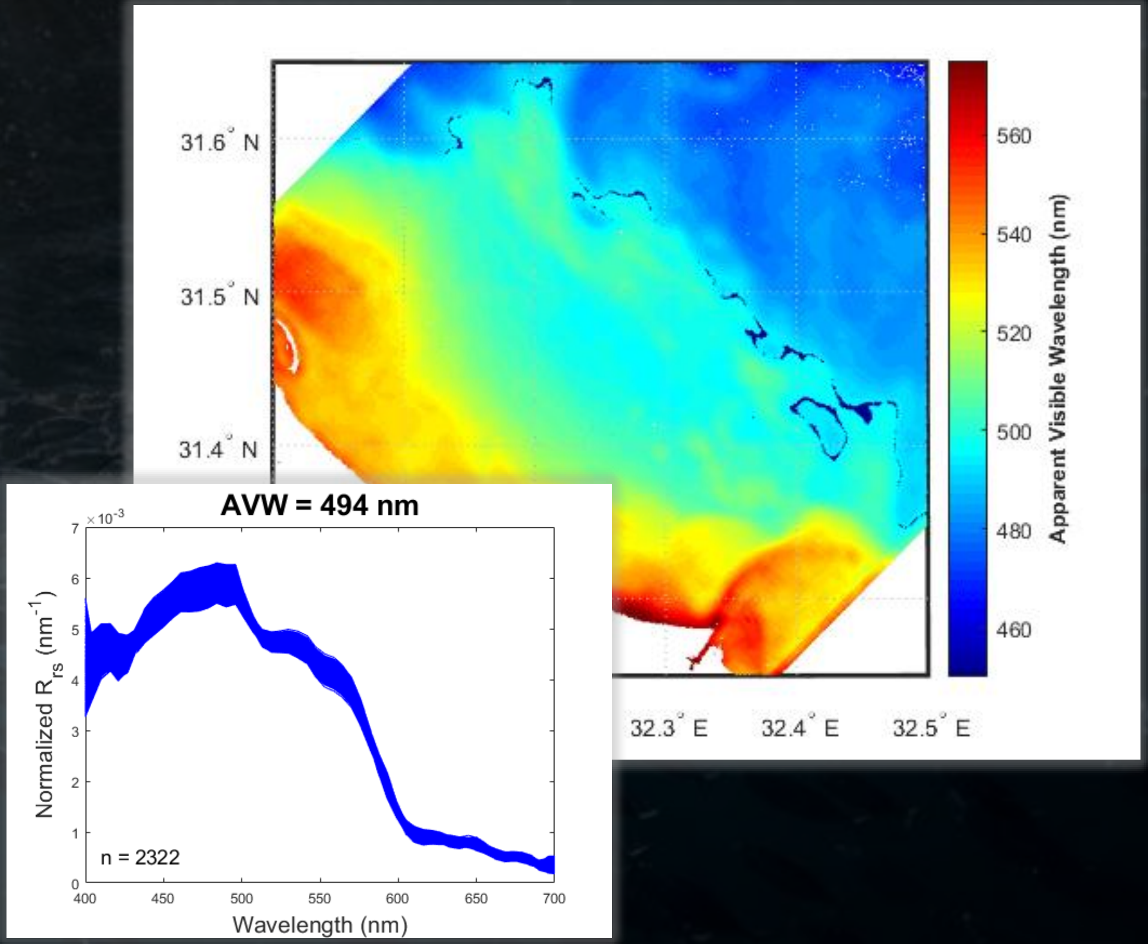
Remote Sensing Reflectance (Rrs)

- The mathematical description of color in the ocean
- This product is the baseline for the construction of most algorithms
- Remote sensing reflectance is subject to uncertainties introduced in the removal of the atmospheric signal



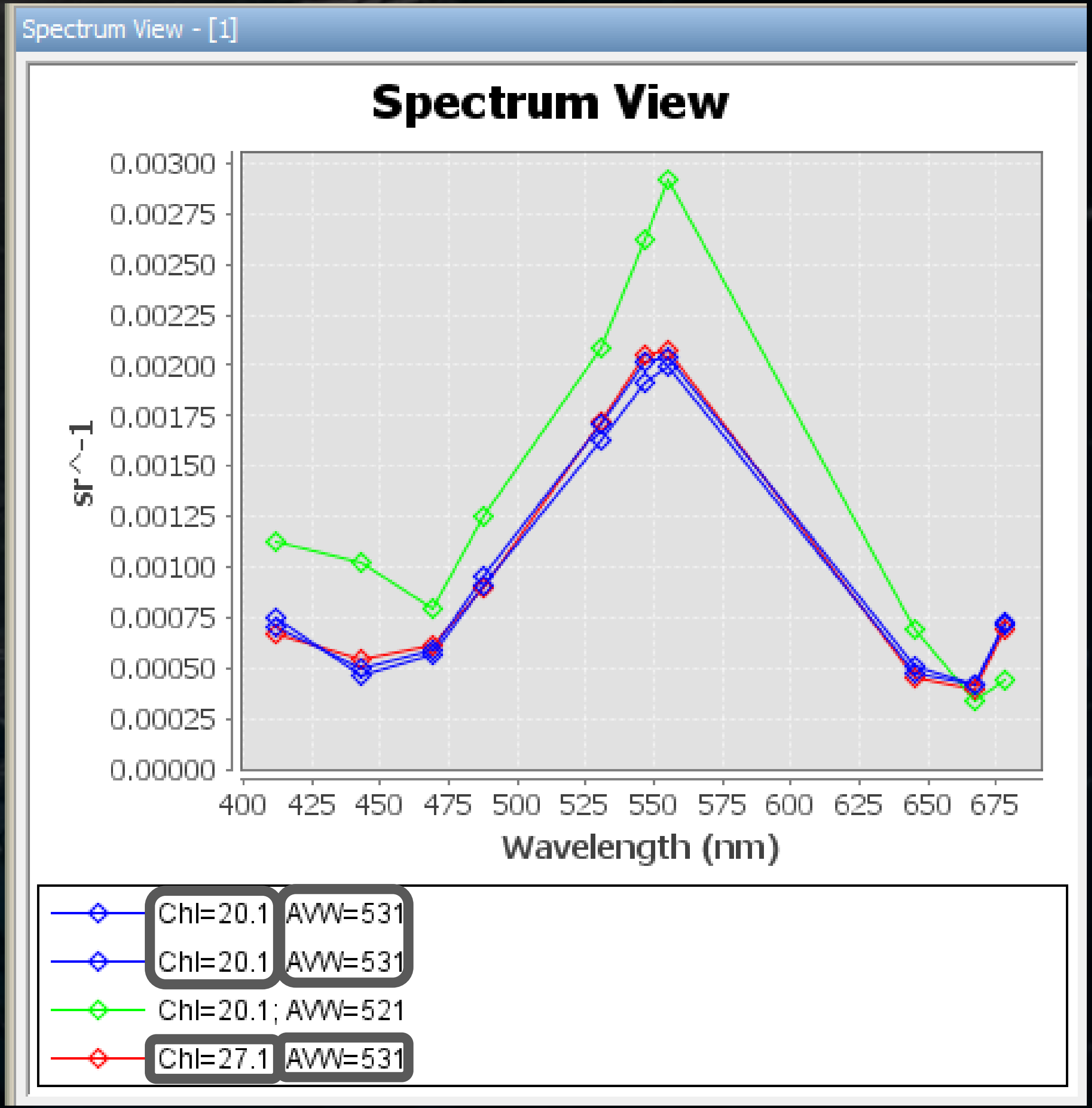
Apparent Visible Wavelength (avw)

- Optical index that is sensitive to changes in water chromaticity
- All wavelengths are used, ensuring any diagnostic signals present are captured
- Describes and analyze subtle shifts in ocean's color
- No bias, but subject to R_{rs} uncertainties



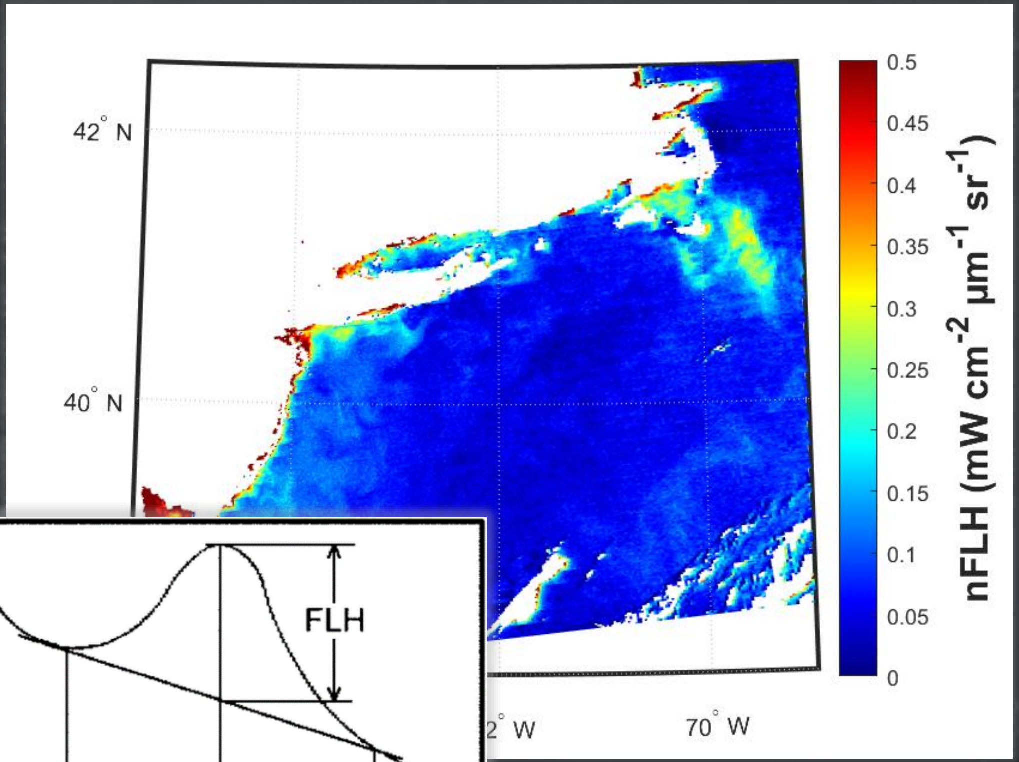
Apparent Visible Wavelength (avw)

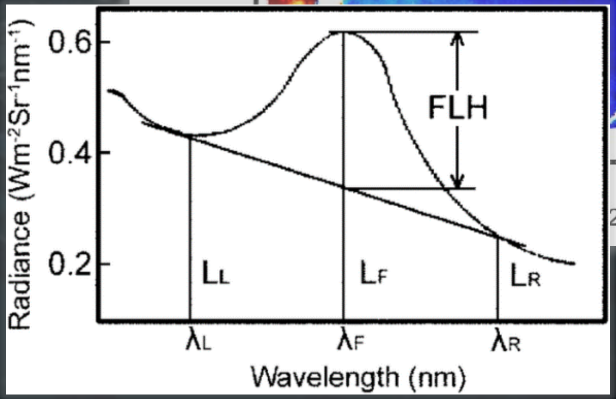
- AVW is the only algorithm to utilize the entire visible spectrum of R_{rs} and is useful for assessing spectral deviations.
- Two **identical** chl-a values can exhibit vastly different spectral shapes
  - green v. blue lines
- Two very **different** chl-a values can exhibit very similar spectral shapes
  - red v. blue lines
- AVW can elucidate specific information about the *behavior* of R_{rs}.

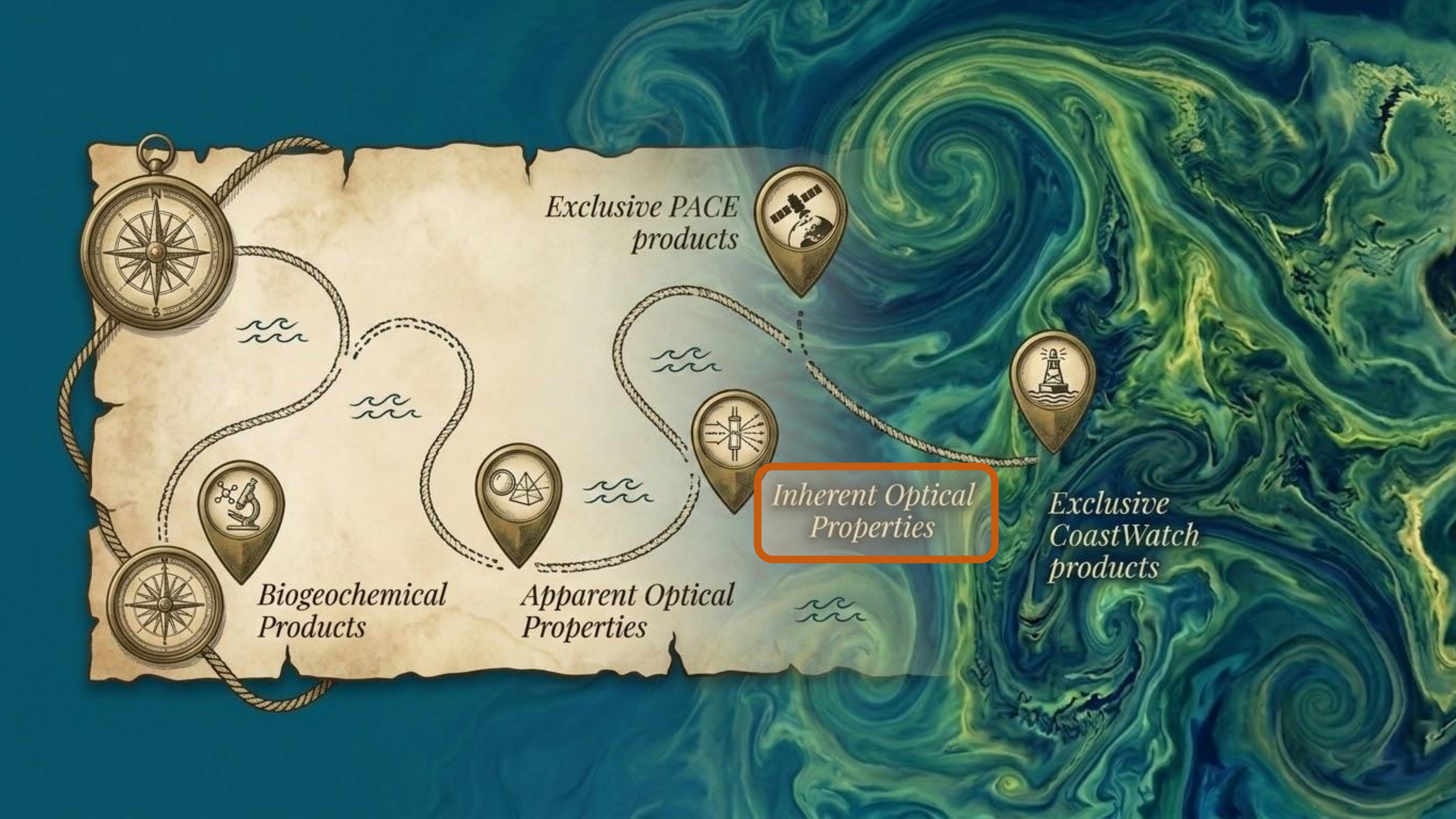


Normalized Fluorescence Line Height (nflh)

- Light leaving the ocean surface due to sun-induced chlorophyll fluorescence
- Provides an indicator of phytoplankton physiology/ nutrient stress
- FLH has multiple dependencies on cellular pigment packaging and light saturation (NPQ)







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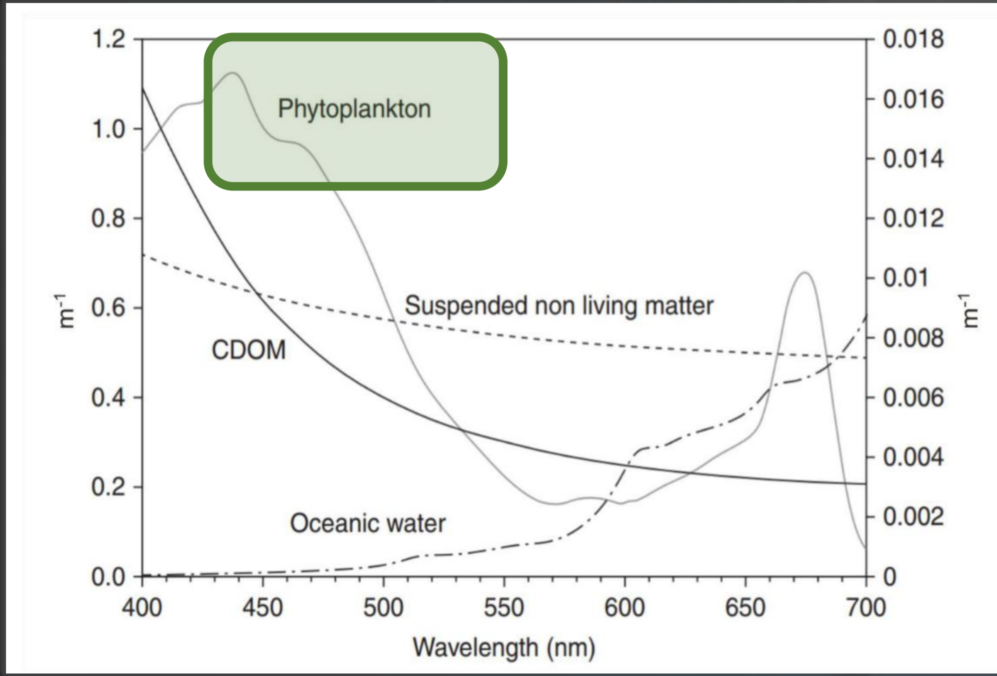
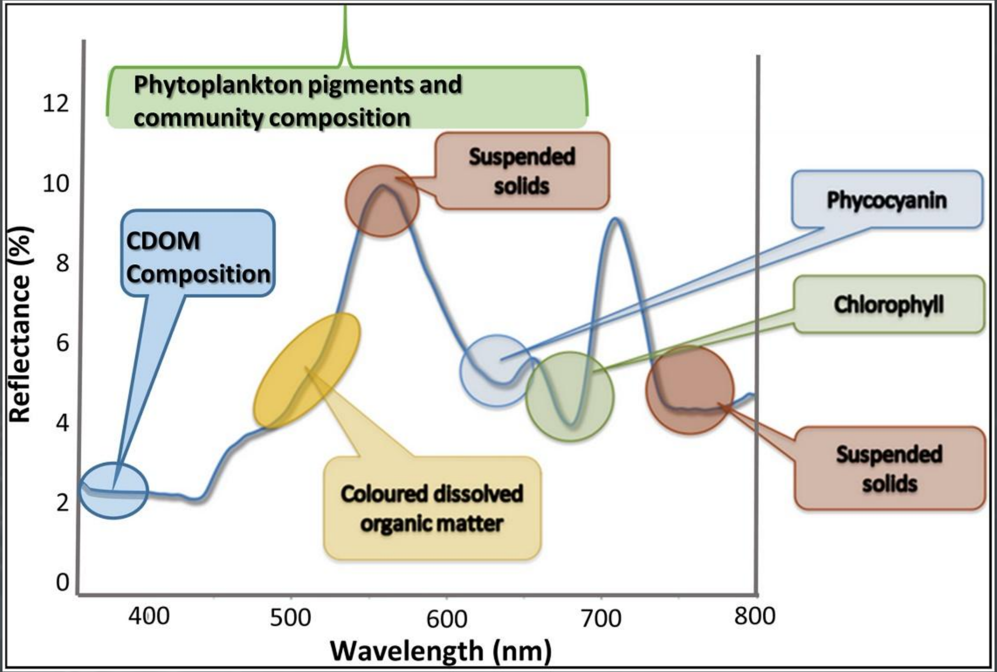
IOPs vs. AOPs: What's in the Water vs. What the Satellite Sees



Absorption

Inherent *optical property*

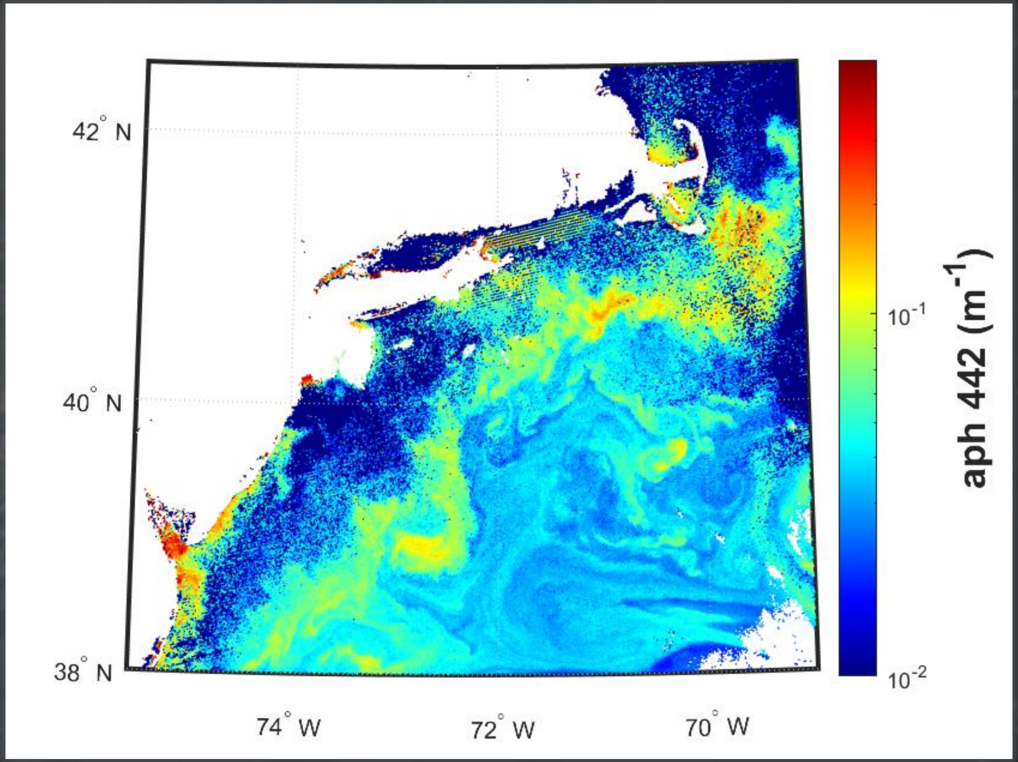


Reflectance

Apparent *optical property*

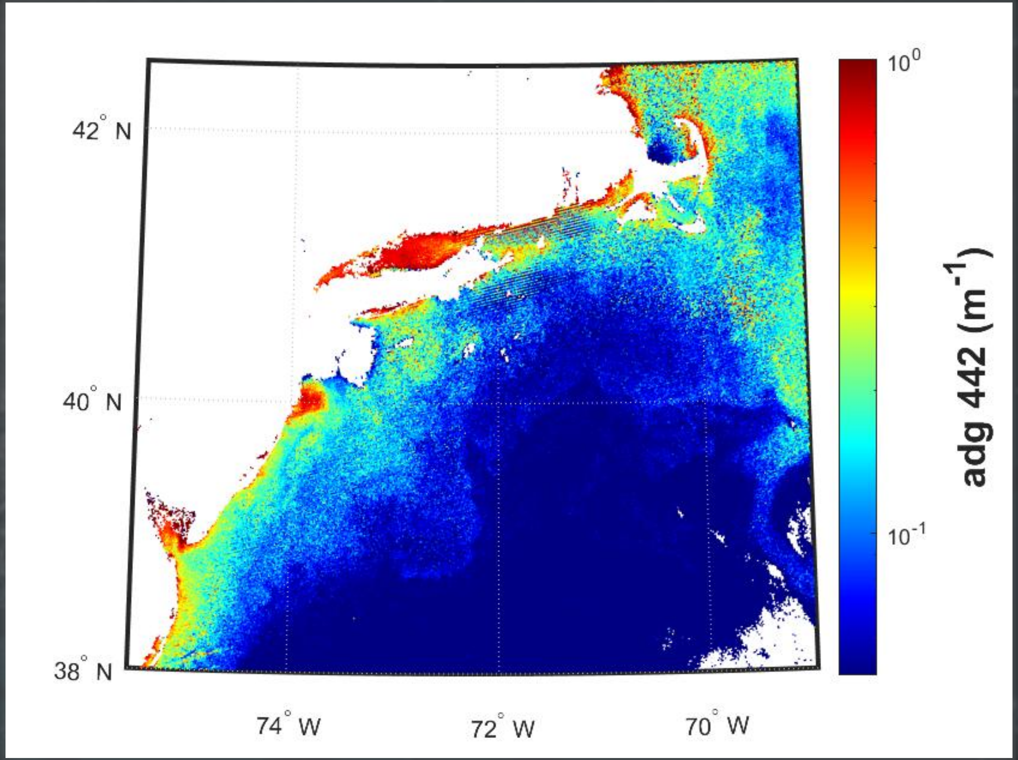
Phytoplankton absorption coefficient (aph)

- Isolates the light absorbed by phytoplankton from total light absorption
- Complements chlorophyll by providing additional ecological information
- Useful for understanding phytoplankton photosynthetic potential



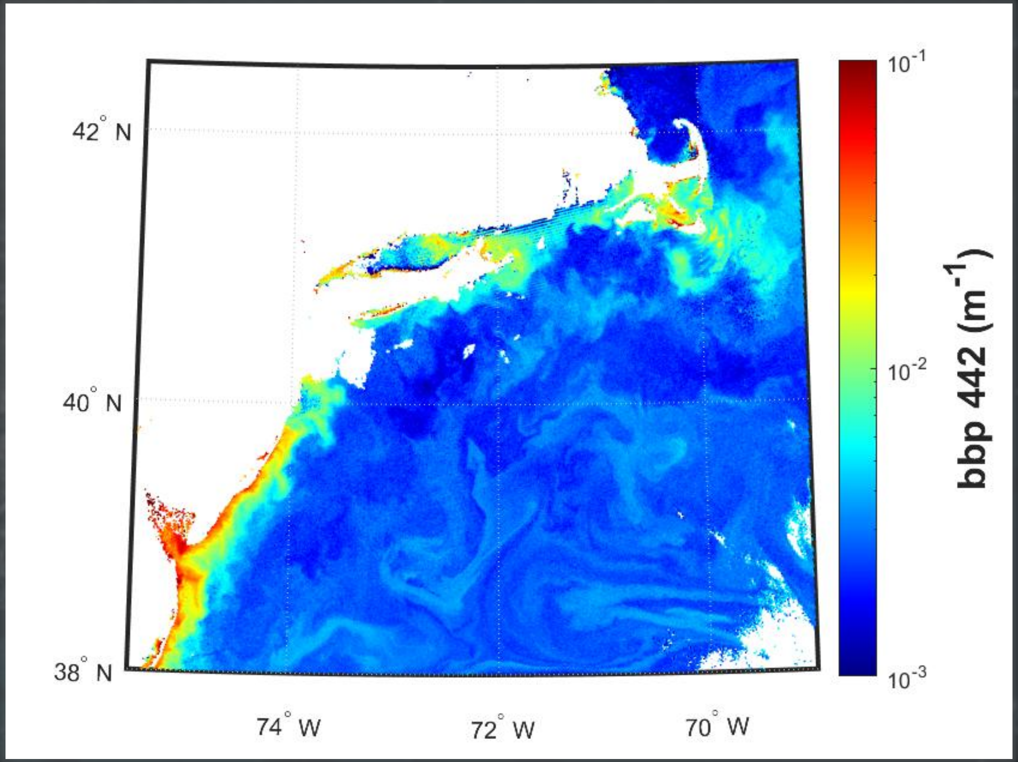
Detrital/gelbstoff absorption coefficient (adg, adg_s)

- Absorption of light by detritus + gelbstoff (aka colored dissolved organic matter aka CDOM)
- Can indicate a declining bloom, or river runoff.
- The slope (S) parameter is a separate product used to estimate a_{dg} at any wavelength
- $a_{dg}(\lambda) = a_{dg}(\lambda_0) \cdot e^{-S(\lambda - \lambda_0)}$



Particle backscatter coefficient (bbp, bbp_s)

- Defines how light is scattered in the backwards direction by particles in the water
- This product provides an indicator of particle density
- The slope (γ) parameter is a separate product that can relate to particle size
- $b_{bp}(\lambda) = b_{bp}(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-\gamma}$



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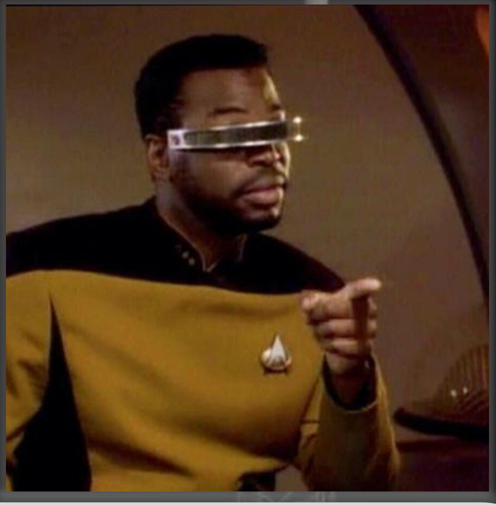
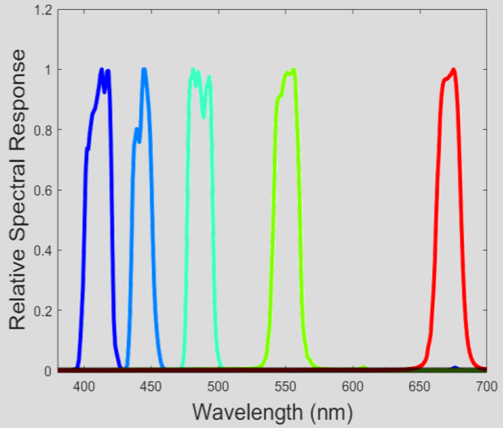
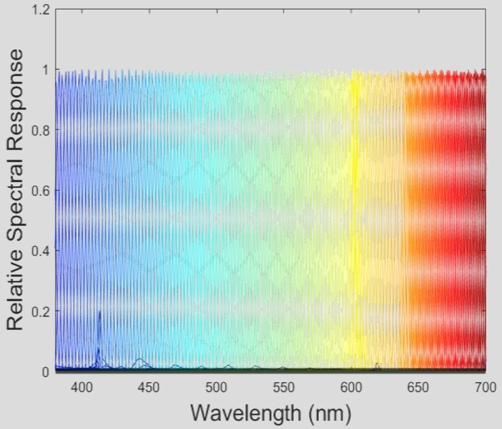
Multispectral Resolution (e.g. VIIRS)

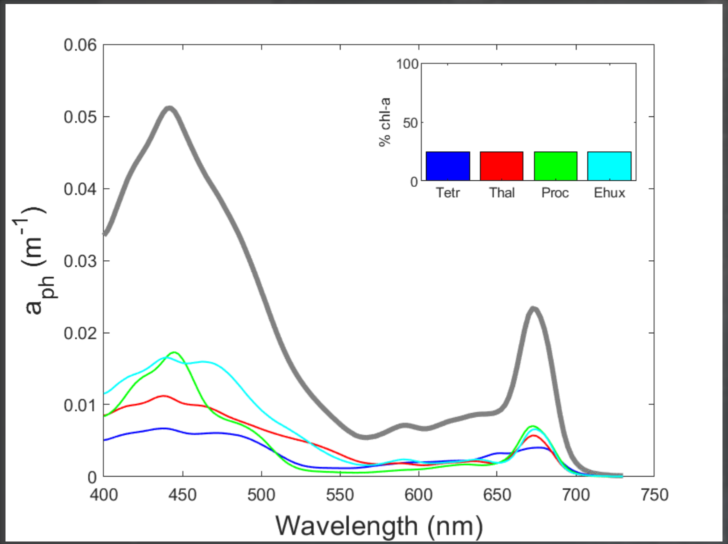
Hyperspecrtal Resolution (e.g. PACE)



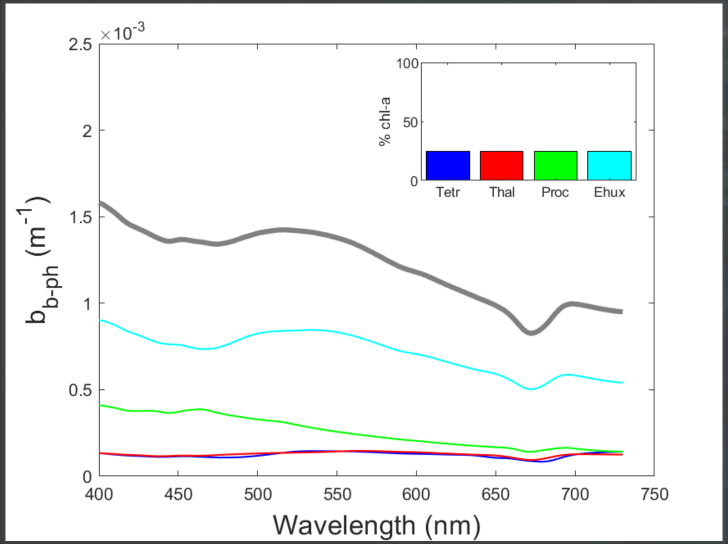


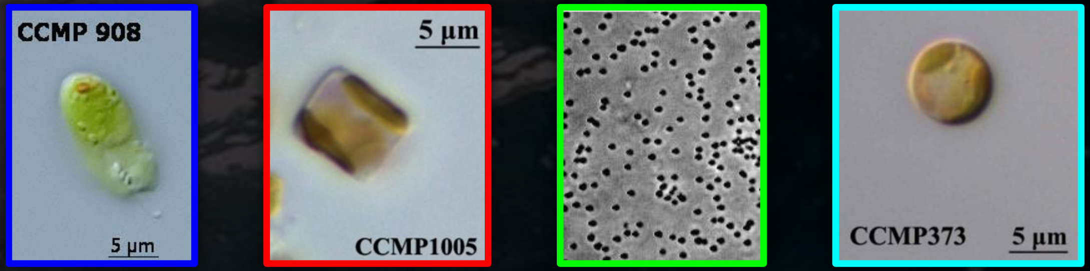


Absorption



Scattering





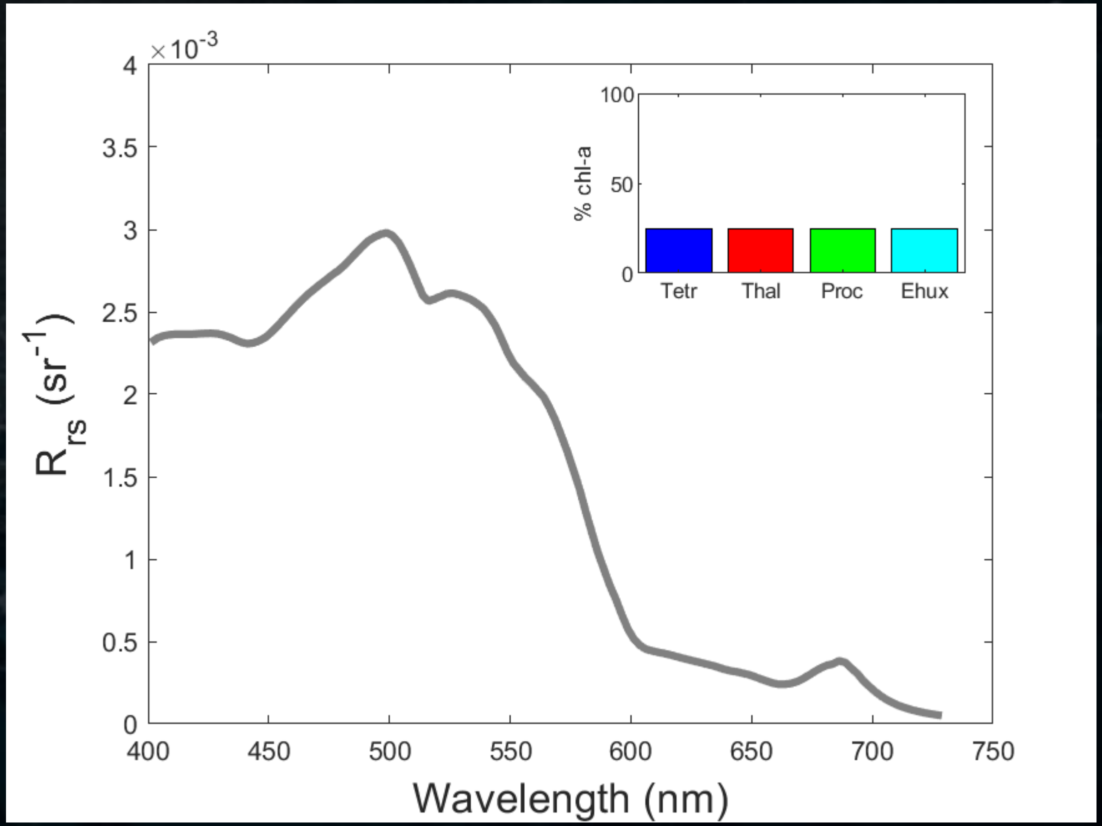
Tetraselmis sp.

Thalassiosira oceanica

Prochlorococcus marinus

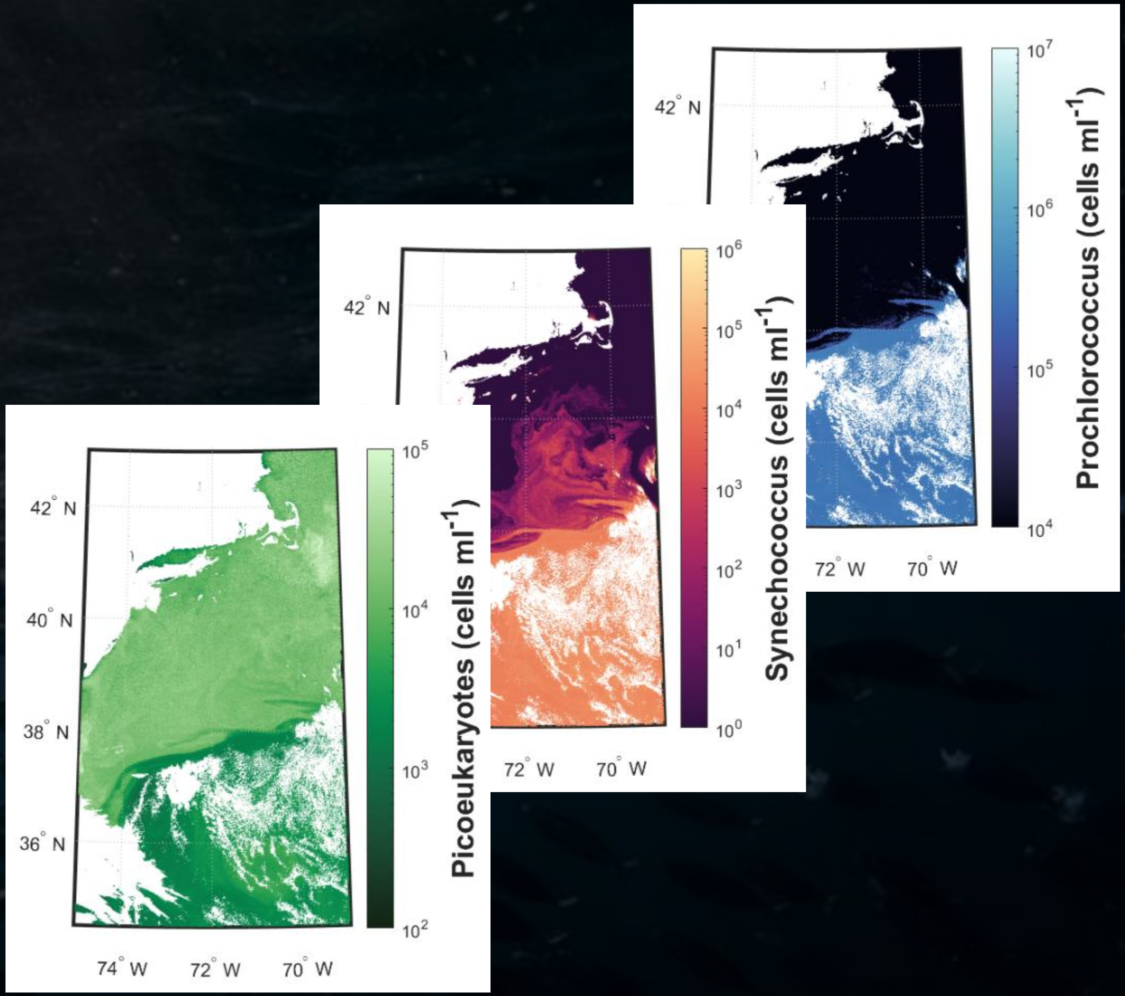
Emiliania huxleyi

What PACE sees



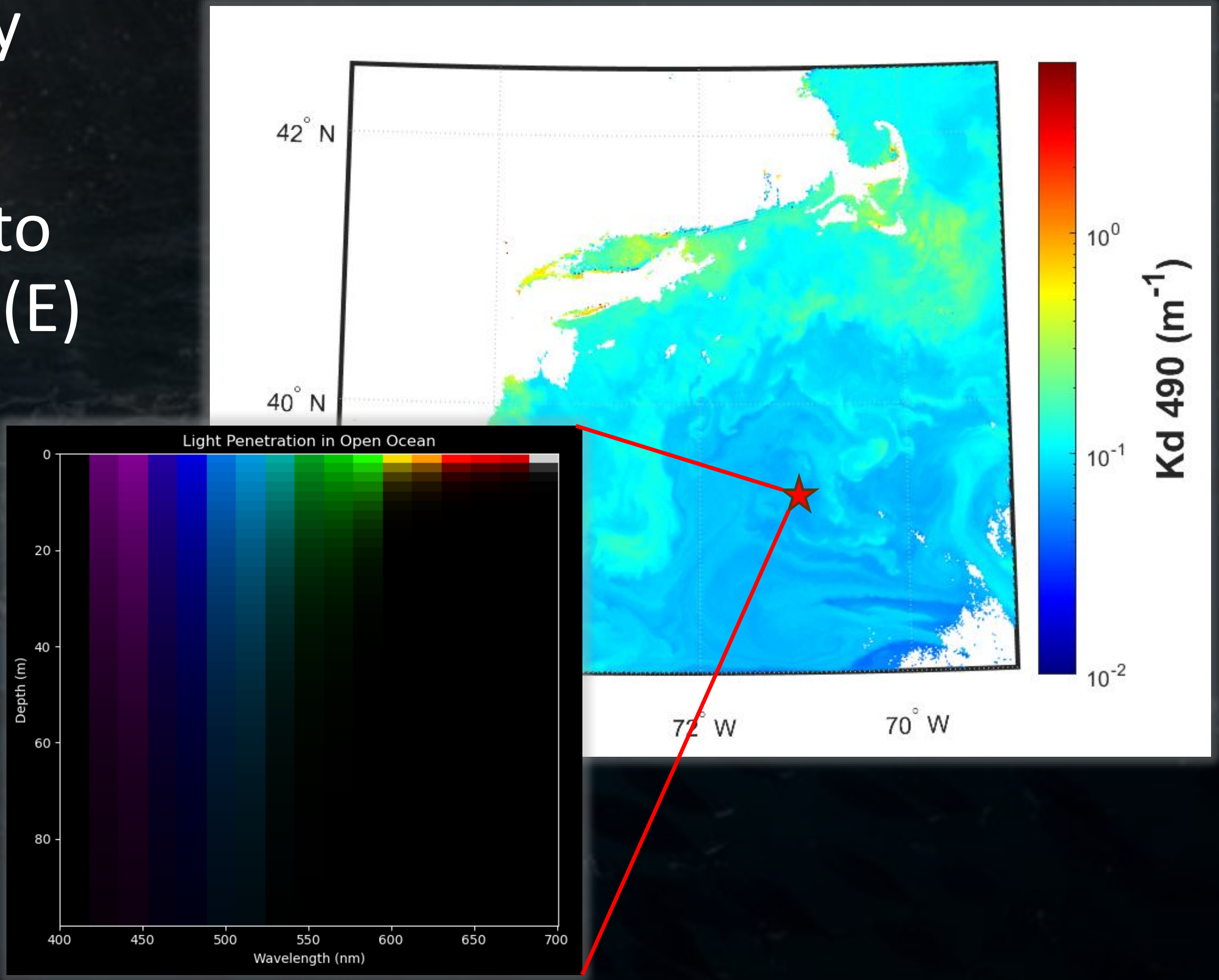
Multiple Ordination ANAlysis (MOANA)

- The first phytoplankton community composition algorithm for PACE
- Resolved the concentration of Prochlorococcus, Synechococcus, and Pico-eukaryotes
- These products are intended for open ocean (Atlantic only), not coastal applications



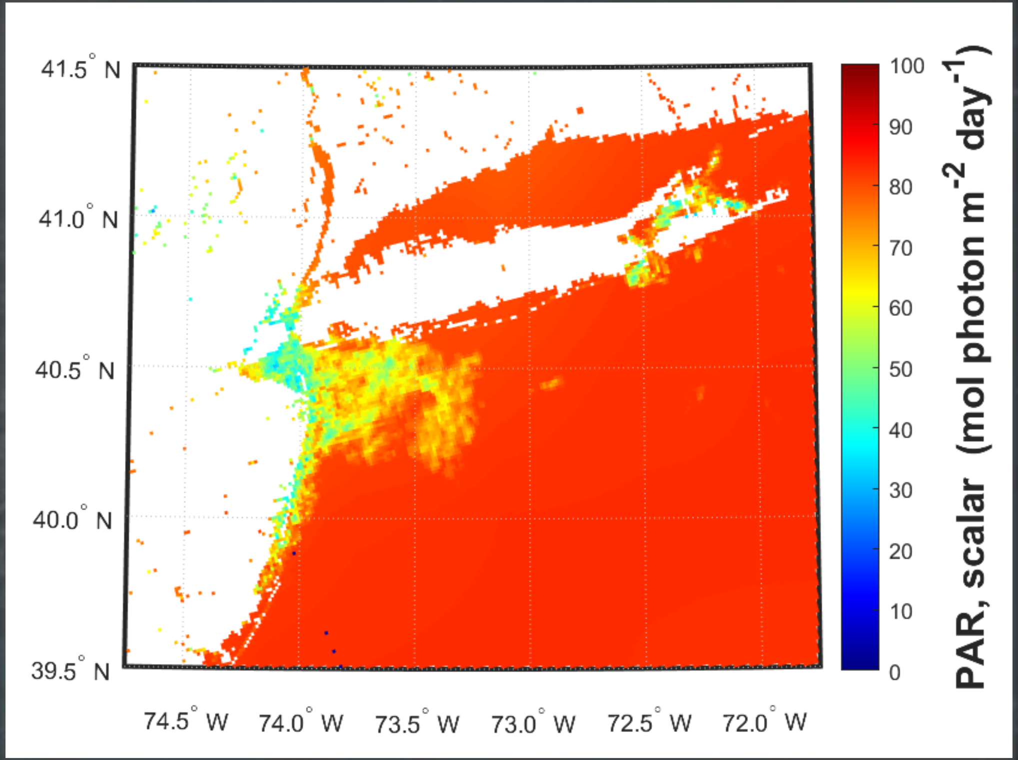
Spectral Diffuse Attenuation Coefficients (Kd)

- A direct indicator of how rapidly light diminishes with depth.
- These coefficients can be used to directly estimate light intensity (E) at any depth (z)
- Widely used to estimate euphotic depth and characterize water clarity
- $E_d(z) = E_d(0^-) \cdot e^{-K_d(z)}$



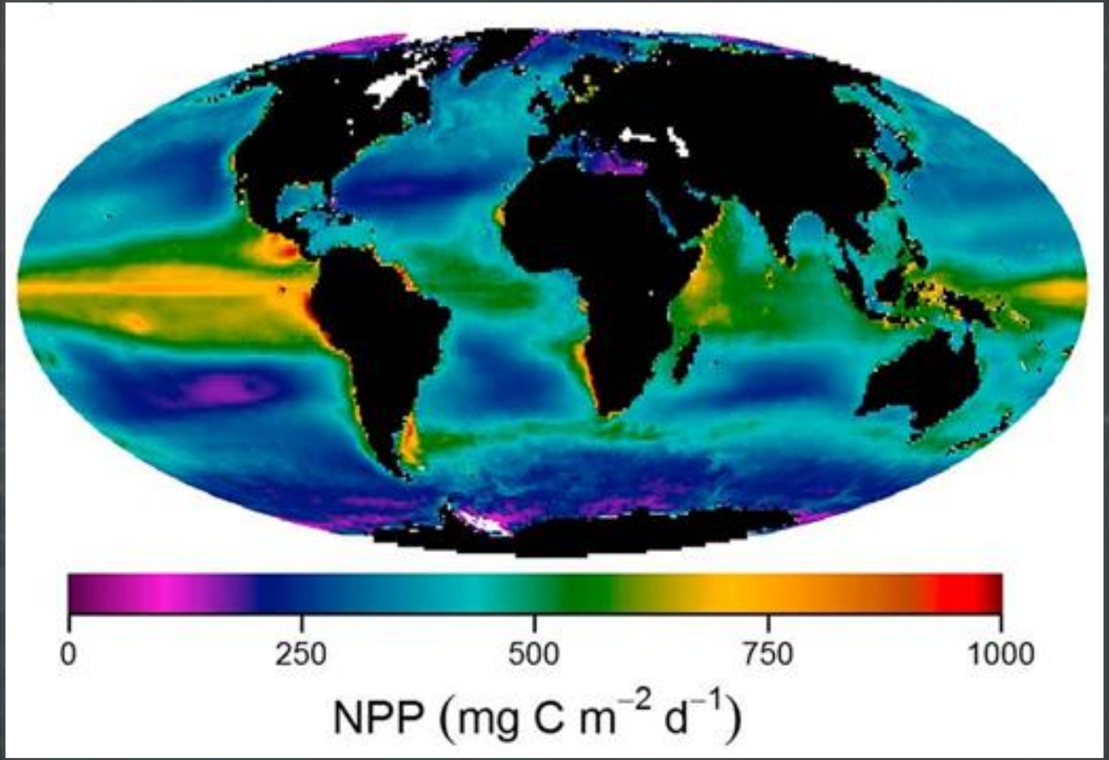
Photosynthetically Available Radiation (PAR)

- Quantum energy flux from the Sun in the 400 - 700 nm range
- Impacts photosynthetic activity (how much light is actually converted to carbon)
- For PACE: If you are modeling phytoplankton growth as a function of light, look for ***par_day_scalar_below***



Net Primary Productivity (npp_cafe)

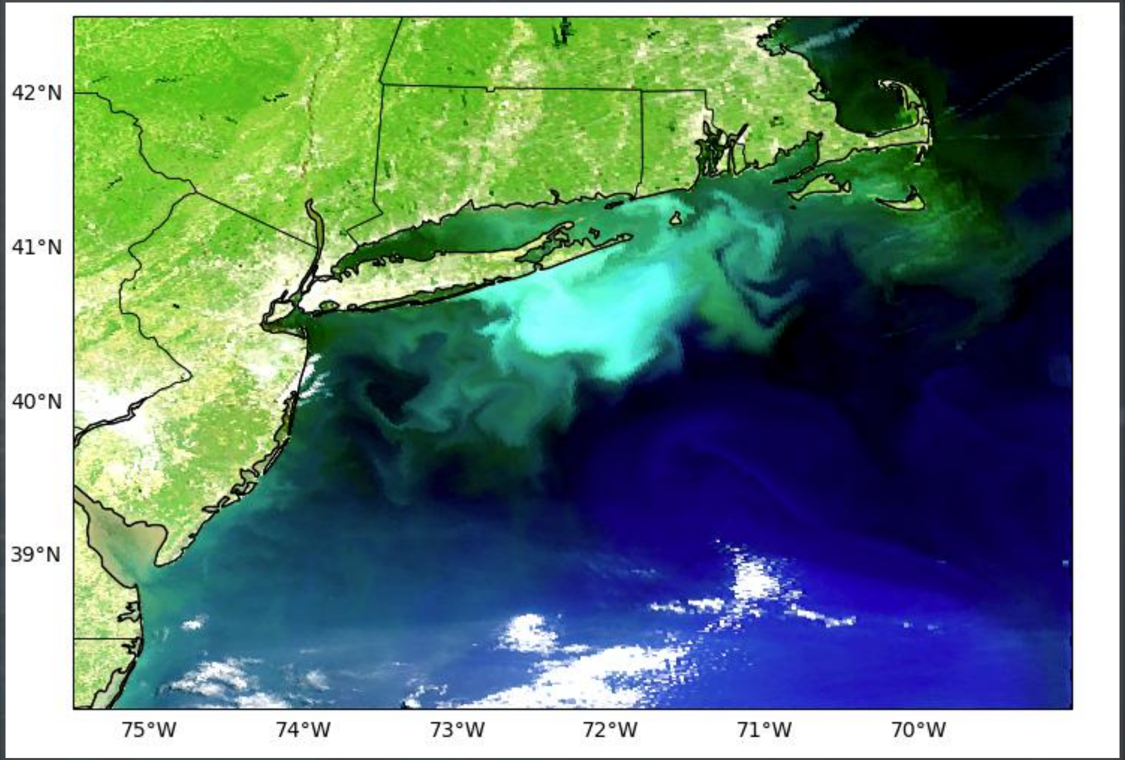
- ***Rate*** at which phytoplankton convert sunlight and CO_2 into new organic matter through photosynthesis
- CAFE (Carbon, Absorption, and Fluorescence Euphotic-resolving) is a mechanistic model based on absorption instead of chlor_a
- Produces global NPP estimates with higher accuracy and lower model bias



QPAR * ϕ_{μ}^{max} * tan (E_k/E(t,z,λ))

Surface Reflectance (rhos)

- The is radiance corrected for the angular effects of Rayleigh scattering, as 90% of signal is atmosphere.
- The basis for “true color” imagery.
- Can also be used as ocean color indicator in areas where atmospheric correction is shoddy



What else can we expect from PACE?

Coming soon

- **Pigments** (GPig): Phytoplankton pigments chlorophyll-a, -b, and -c along with photoprotective and carotenoids. https://github.com/max-danenhower/pace-rrs-inversions-pigments
- **Diatom carbon** (Chase): Satellite-based diatom carbon estimates.
- **Taxonomic groups** (SDP): Phytoplankton pigments https://github.com/max-danenhower/rrs-SDP-pigments

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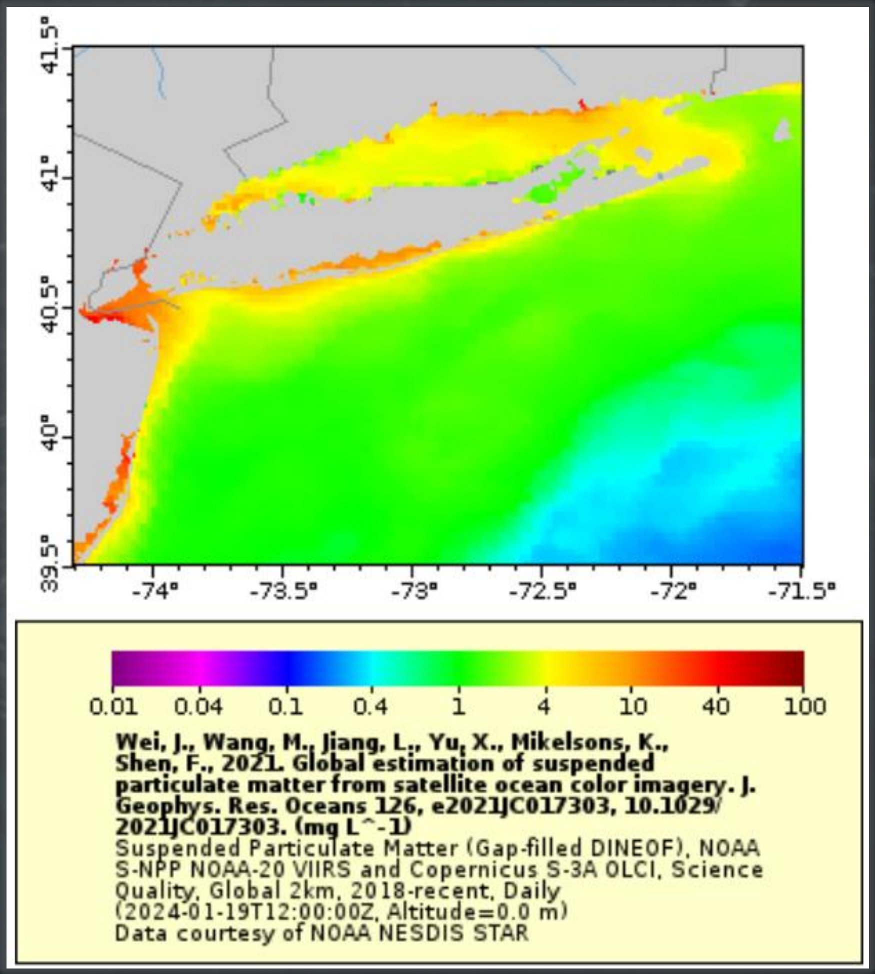
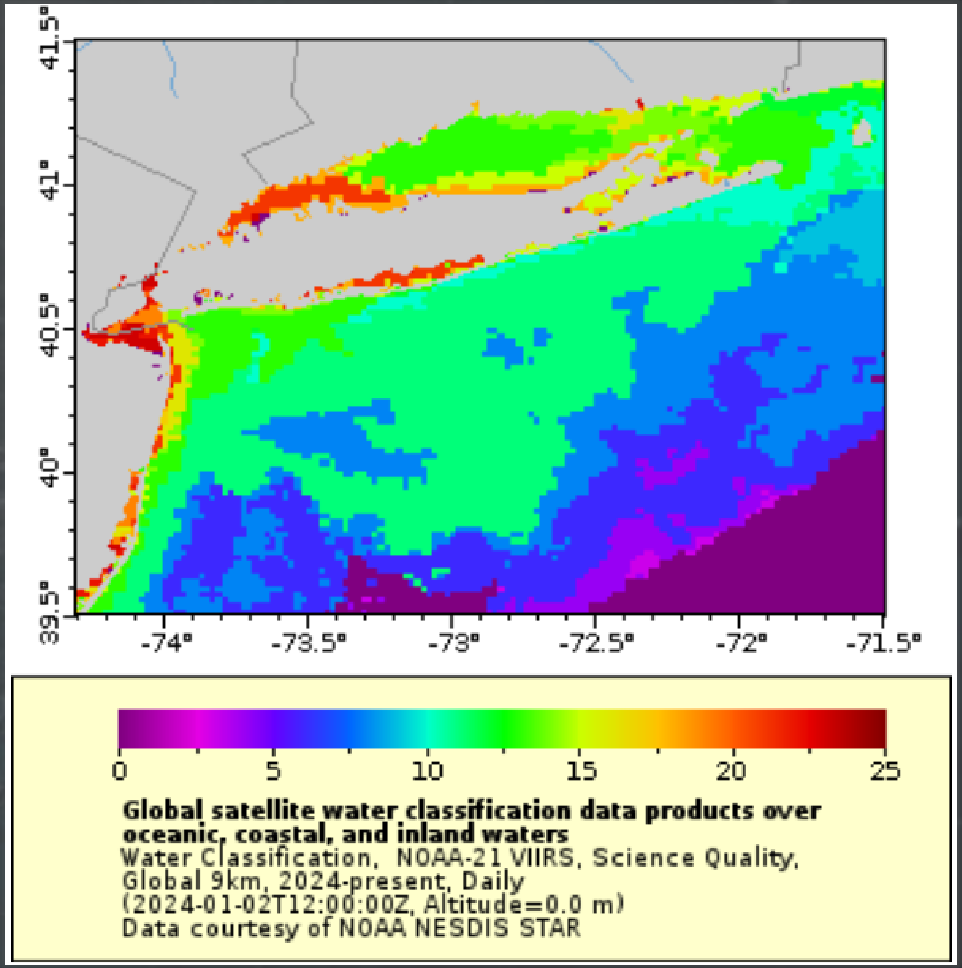
Suspended Particulate Matter (spm)

- Estimates the concentration of all suspended particles in the water
- Includes phytoplankton, detritus, and mineral sediments
- Useful for studying water quality, river plumes, and sediment transport



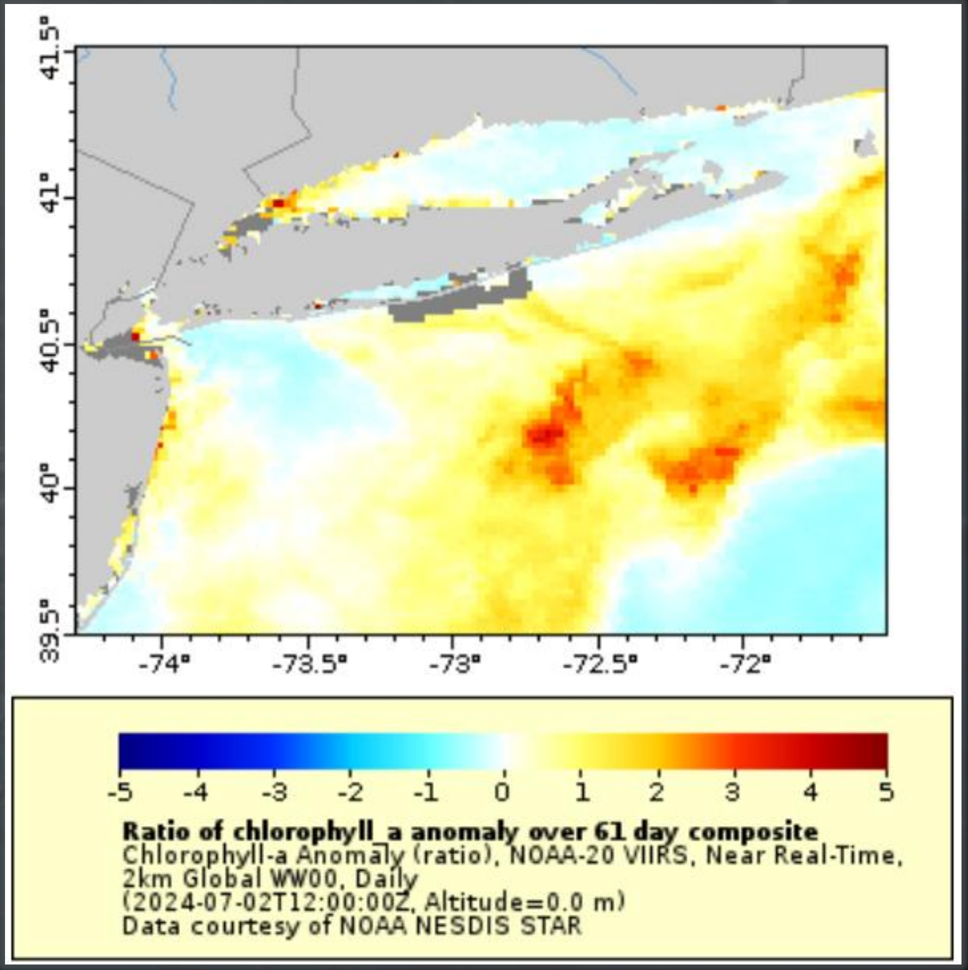
Optical Water Mass Classification

- Categorizes waters according to their observed color and optical properties
- Integrates information across the visible spectrum
- Useful for tracking water masses and ecosystem variability
- Supports selection of appropriate algorithms and interpretation of ocean color data



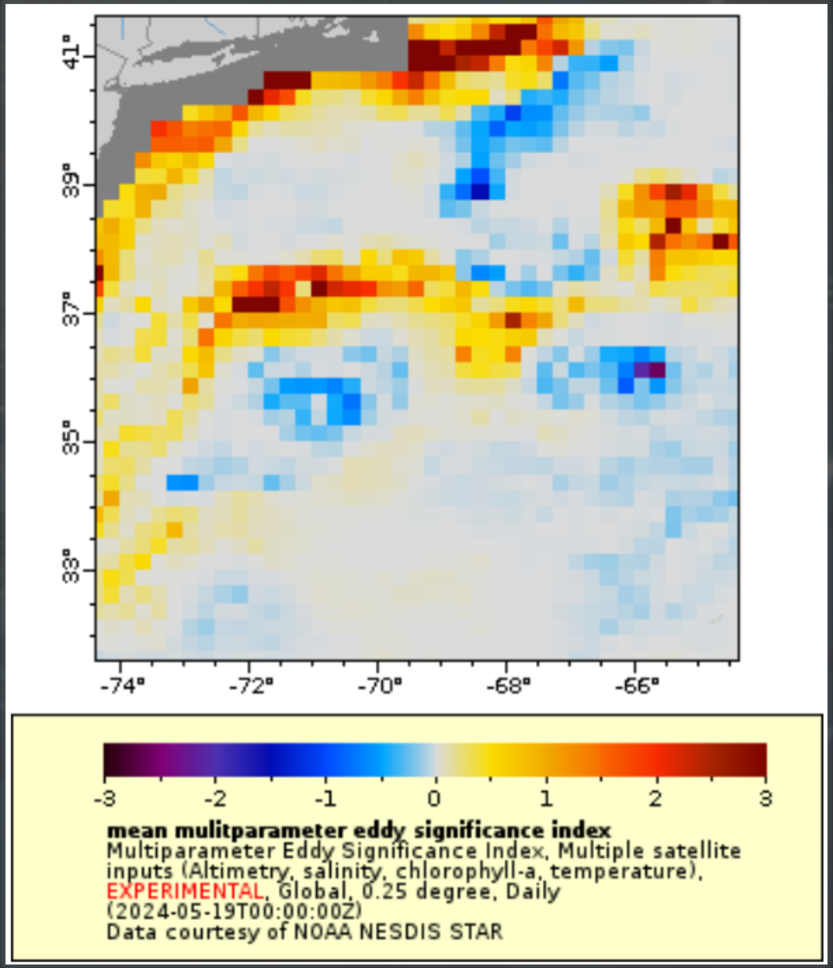
Chlorophyll-a anomaly ratio

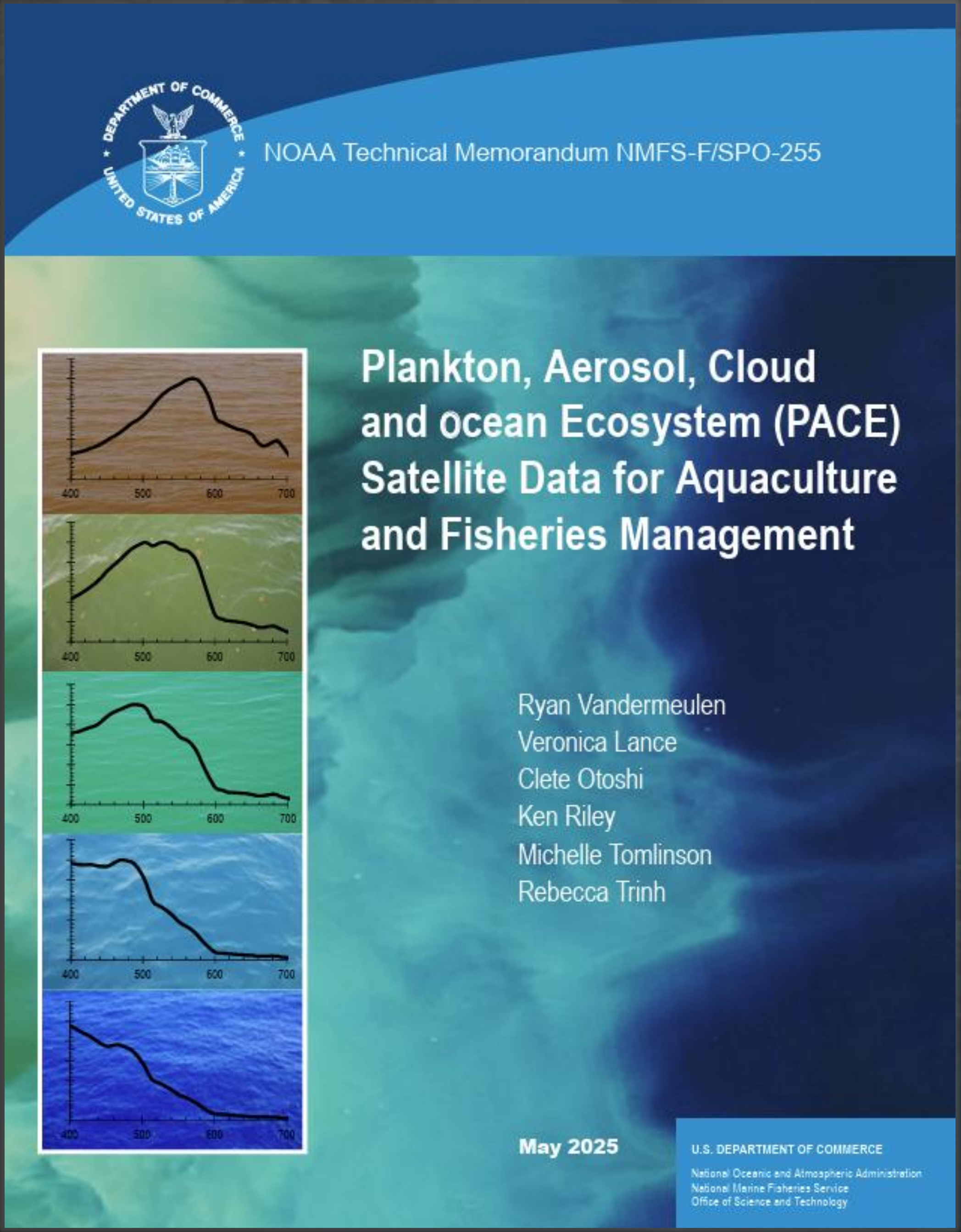
- Compares current chlorophyll concentrations to the previous 60-day average
- Highlights short-term increases or decreases in chlorophyll relative to recent conditions
- Useful for detecting emerging blooms and rapid ecosystem changes



Multiparameter Eddy Significance Index (MESI)

- Combines sea surface height, temperature, salinity, and chlorophyll into a single index
- Highlights biologically significant ocean eddies
- Demonstrates the value of integrating ocean color with other satellite observations
- Coarse (0.25º) resolution





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Product 6: Spectral particle backscattering coefficients (b_{bp})

What is it?

- These backscatter coefficients specifically define how light is scattered in the backwards direction by particles in the water. This product provides an indicator of the concentration of particles in the ocean and a proxy indicator of particulate carbon concentrations.

How does it impact Aquaculture/Fisheries?

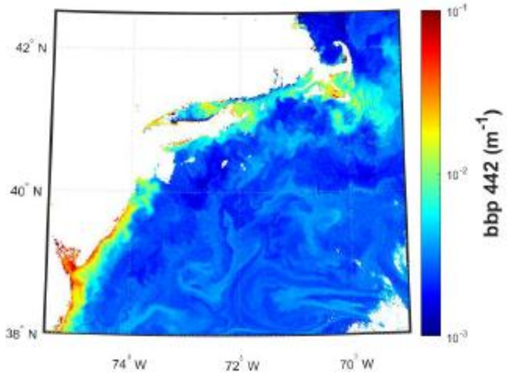
- Many phytoplankton exhibit unique backscattering characteristics[65], primarily as a function of cell size[66], and sometimes composition (e.g. Coccolithophore blooms[67]). Backscatter is also used to derive Particulate Inorganic Carbon (PIC)[68] estimates from satellites. Particle backscatter is a particularly useful tool to determine high sediment loads in nearshore environments, which tends to heavily scatter light. High sediment loads can cause gill saturation[69] in certain oyster species, and some fish species exhibit hypersensitivity to suspended sediment[70]. While not a direct measurement of suspended particulate matter (SPM), it can be used to develop those products.

What are the limitations/caveats?

- The backscatter product is one of the most robust products offered in the "inherent optical property (IOP)" suite of ocean color products. The only caveat is that the IOP algorithms can sometimes fail to arrive at a solution (i.e. no data) in waters with extreme scattering or CDOM concentrations. Nearshore environments present challenges in disentangling phytoplankton backscatter from other optical constituents (re-suspended sediment, SPM, etc.).

Does HYPERSPECTRAL directly improve/enable this product?

- Operational improvements to IOP products using hyperspectral data are anticipated, but still in development (at the time of this publication). PACE Science and Applications Team members are actively working to improve this product using new approaches and techniques.



Product(s) 2: Harmful Algal Blooms (HABs)

What is it?

- Harmful algal blooms, or HABs, occur when colonies of phytoplankton produce toxic or harmful effects on people, fish, shellfish, marine mammals and birds. Various spectral techniques have been used to remotely identify different HABs from ocean color[100]. While not all-inclusive, some examples of HAB detection are listed below.
  - ***Microcystis aeruginosa*** (CyAN[101]): Freshwater algae that can produce a toxin known as microcystin, which causes fish kills and contamination of drinking water.
  - ***Karenia brevis*** (Craig[102], Soto[103]): Ubiquitous red tide species occurring on the Florida coast, causing fish kills and human respiratory issues.
  - ***Pseudo-nitchzia*** (Anderson[104], Smith[105]): Diatom that produces domoic acid, accumulates in shellfish, invertebrates, and sometimes fish, leading to mammal illness and death.
  - ***Alexandrium cantenella*** (Bucci[106]): Dinoflagellate that produces a saxitoxin and causes Paralytic Shellfish Poisoning (PSP).
  - ***Cocholodinium polykrikoides*** (Ahn[107], Kim[108]): Dinoflagellate causing "rust tides" that are toxic to finfish and shellfish.
  - ***Noctiluca scintillans*** (Qi[109]): Large dinoflagellate that can cause disruptions to trophic energy dynamics, even impacting fish yield[110].
  - **Floating algae index** (Hu[111], Sargassum Watch[112]): Used to detect surface slicks, including nuisance algae such as *Sargassum*.
  - **Red-band difference, RBD** (Amin[113]): A generalized indicator frequently used to detect a variety of HABs.
  - **Maximum chlorophyll index, MCI** (Gower[114]): A generalized indicator frequently used to detect high biomass blooms.
  - **Regional Forecast systems:** NCOOS and external partners supply operational forecast systems for various regions of the U.S., including Gulf of Mexico & Florida[115], Gulf of Maine[116], Lake Erie[117], Pacific Northwest[118], and California[119].

How does it impact Aquaculture/Fisheries?

- The impact of HABs can be economically and ecologically disruptive, owing to direct mortality of fish and marine mammals, seafood contamination and crop loss, fisheries and aquaculture closures, trophic-food web disruptions, drinking water contamination, human health impacts, clean-up costs, tourism losses, and even long-term losses in property values.

What are the limitations/caveats?

- With some exceptions, these classes of algorithms and products are not typically supplied by agencies on an operational basis, leaving the burden of implementation on the user. It should be considered that some toxic species are not always producing toxins, and that some species may become toxic at concentrations below detection limits. Tracking of HABs from satellites is often most effective when paired with in situ ground verification and monitoring.

Does HYPERSPECTRAL directly improve/enable this product?

- Hyperspectral data enables the detection of subtle pigment signatures associated with specific phytoplankton, and can thus help determine the likelihood of toxicity.

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Thank you!

Ryan.Vandermeulen@noaa.gov