From Microscopes to Telescopes: Sensing the ocean's color from Space

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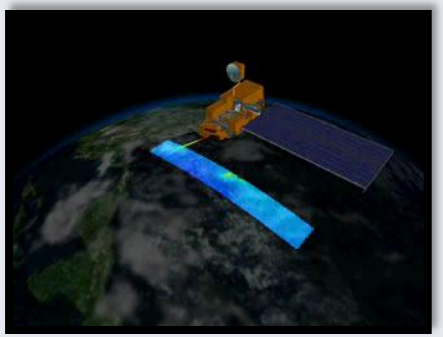
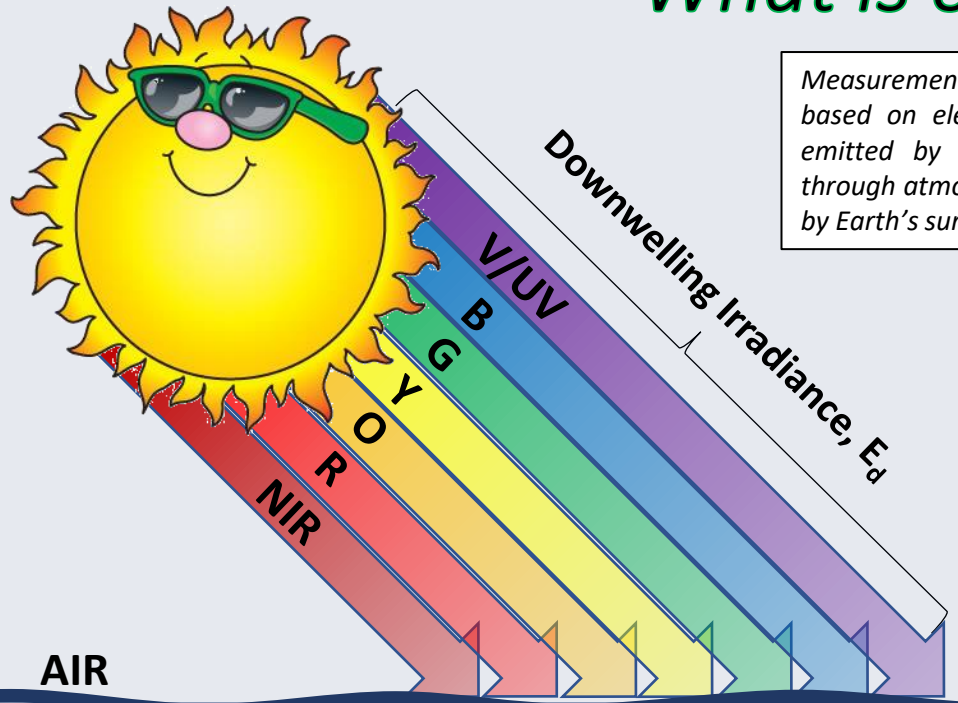
NOAA Fisheries - Office of Science and Technology

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.*



Water-leaving Radiance, L_w

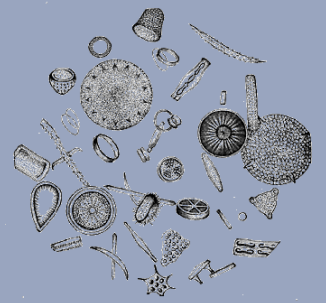


AIR

SEA

There are two possible things that can happen to a photon in water

SCATTERING (b_b)

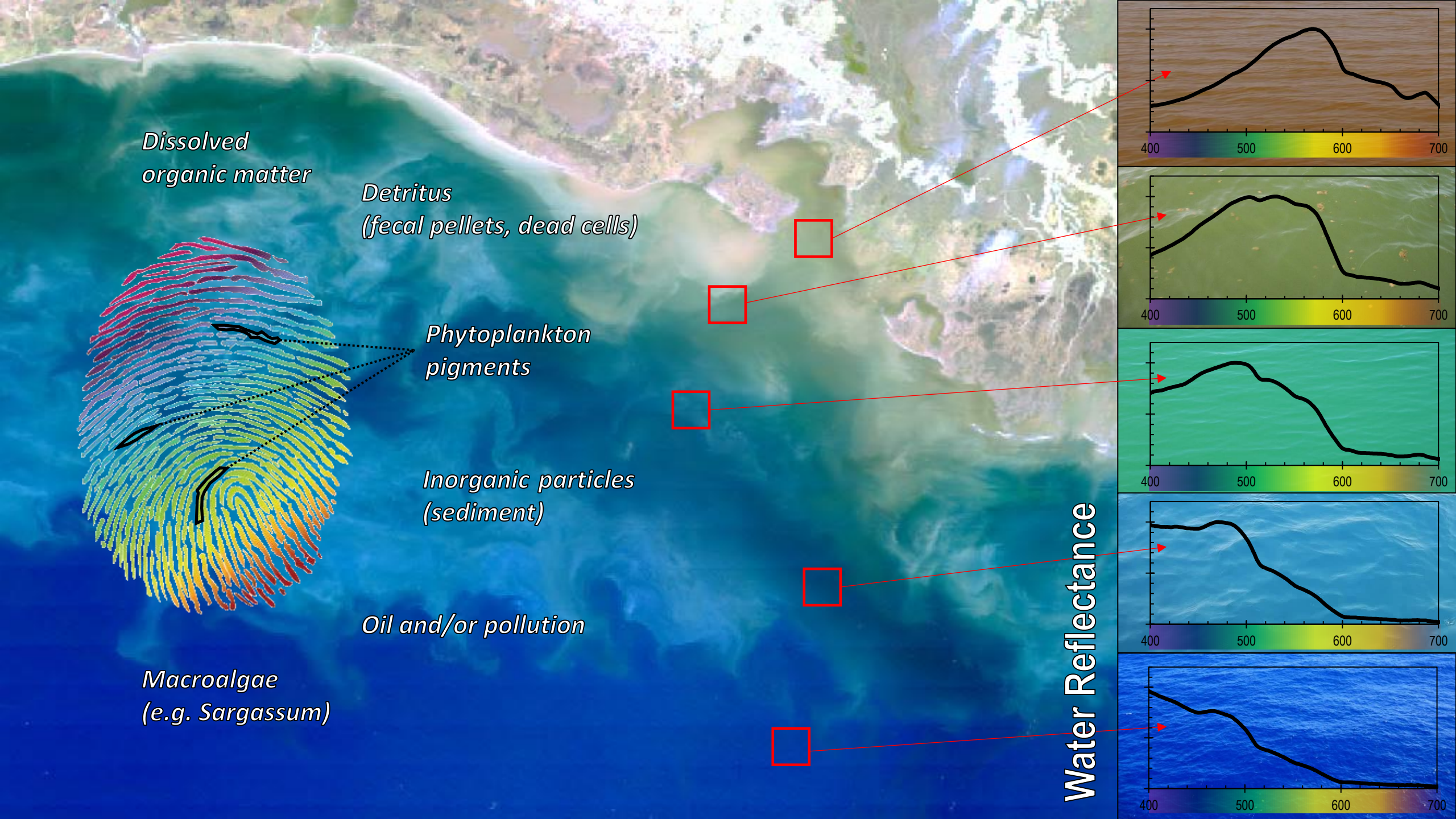


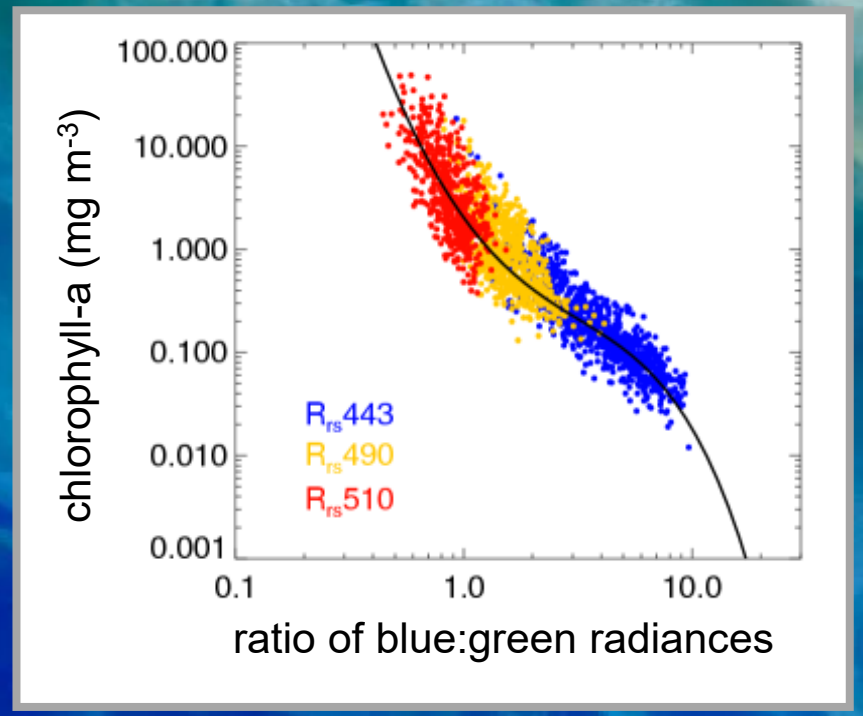
Organic Matter

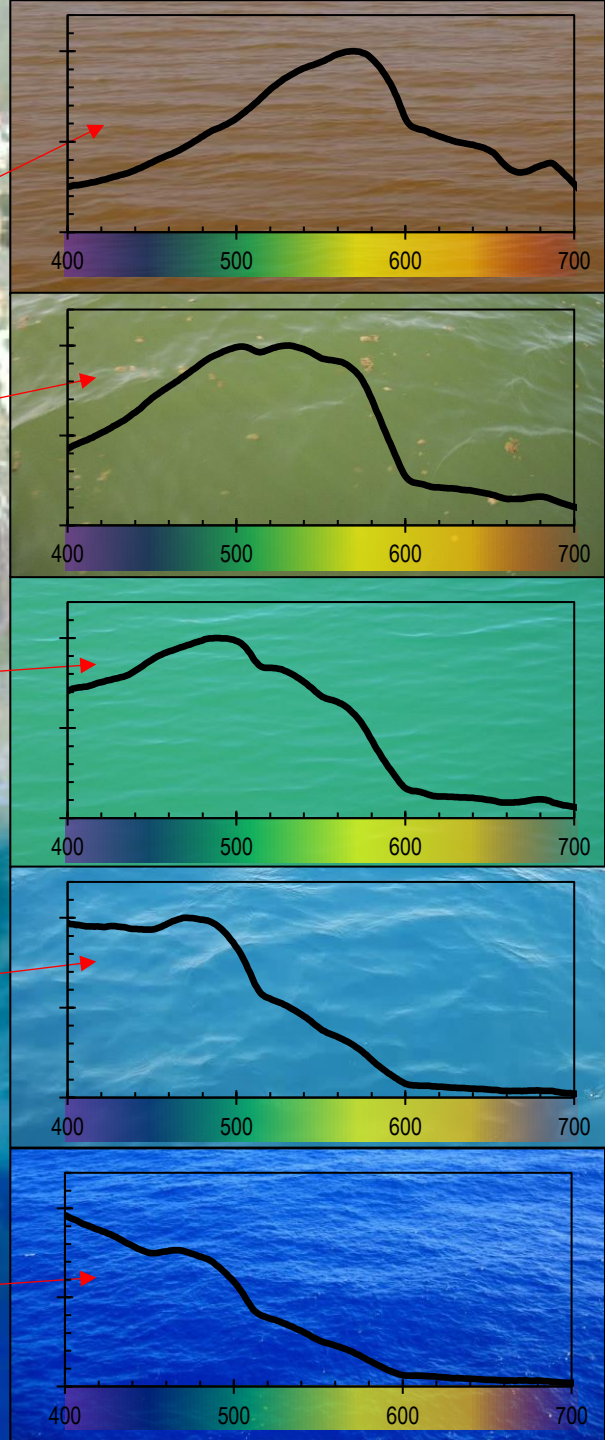
Detritus

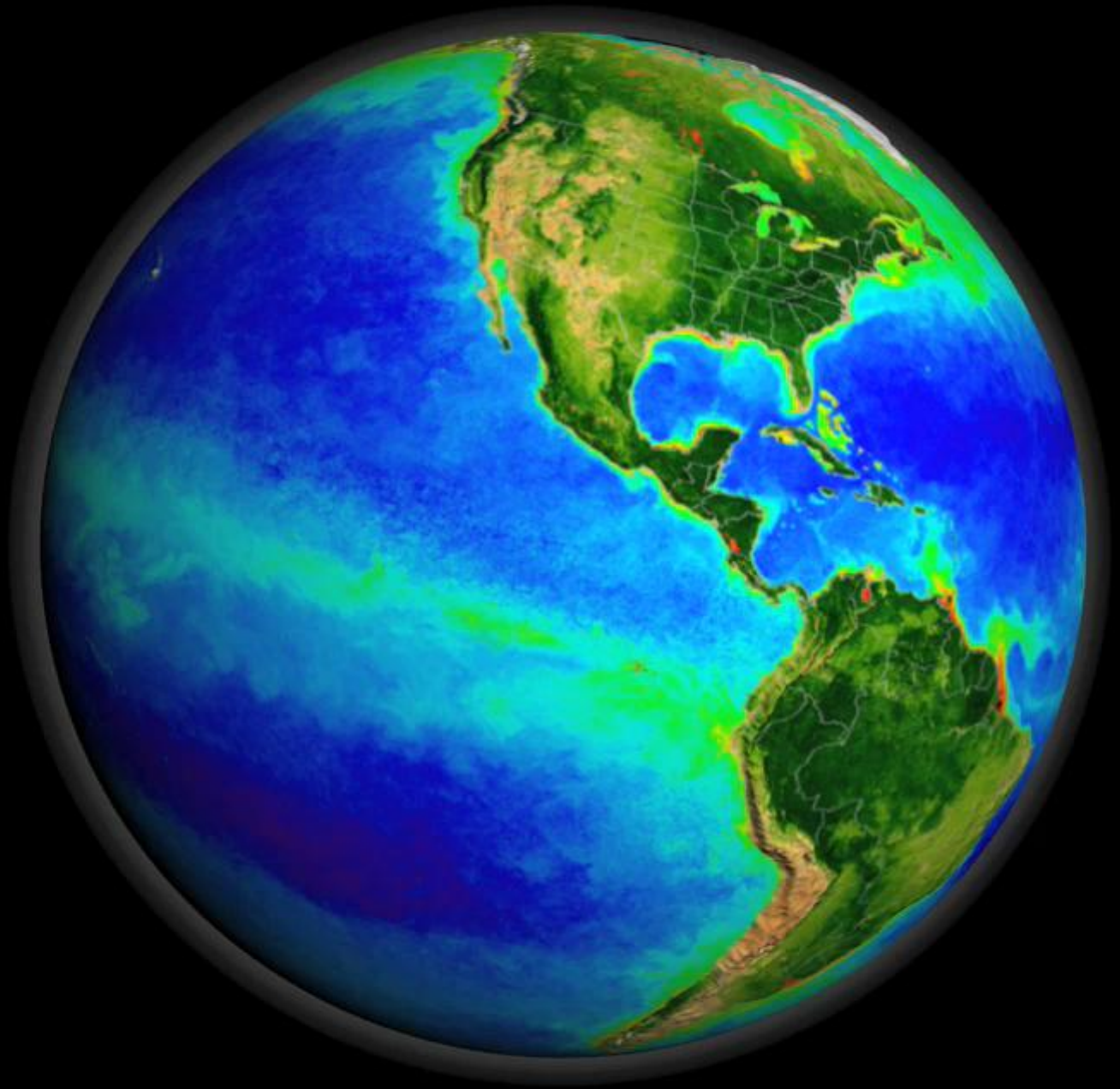
Phytoplankton

ABSORPTION (a)

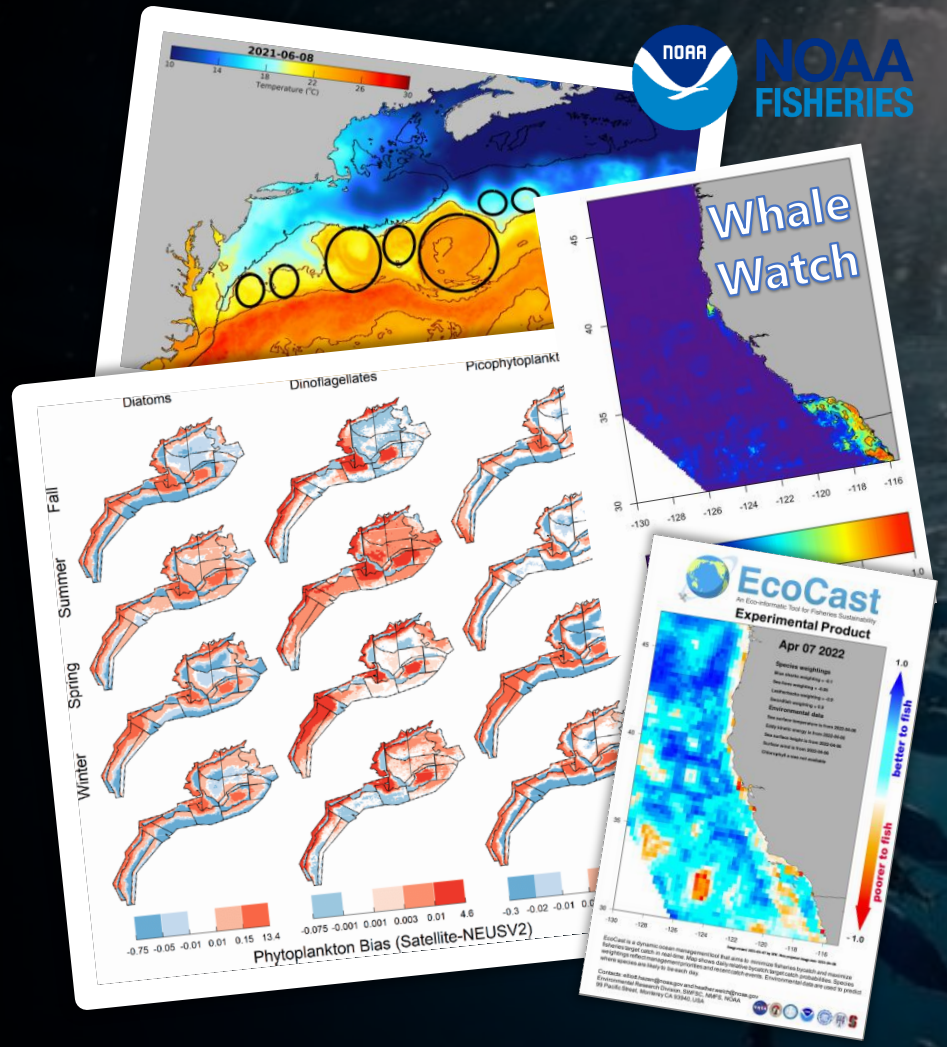

Dissolved
organic matter
Detritus
(fecal pellets, dead cells)
Phytoplankton
pigments
Inorganic particles
(sediment)
Oil and/or pollution
Macroalgae
(e.g. Sargassum)
Water Reflectance
400
500
600
700


chlorophyll-a (mg m-3)
100.000
10.000
1.000
0.100
0.010
0.001
0.1
1.0
10.0
ratio of blue:green radiances
Rrs443
Rrs490
Rrs510


Water Reflectance
400
500
600
700



Uses of satellite-based *chlorophyll-a/productivity* for fisheries



- Annual fish yields (Conti and Scardi 2010);
- Trophic energy potential (Fogarty et al. 2016);
- Recruitment (Woodworth-Jefcoats et al. 2020);
- Zooplankton productivity (Stock and Dunne 2010);
- Zooplankton biomass (Strömberg et al. 2009);
- Ecosystem overfishing (Coll et al. 2008);
- Fish distributions (Salois et al. 2023);
- Species richness (Turner et al. 2003);
- Research track stock assessments (Sculley et al. 2018);
- Marine mammal habitat (Palka et al. 2017);
- By-catch avoidance (Hazen et al. 2018);
- Aquaculture growth variability (Thomas et al. 2011);
- Illegal fishing hotspots (Welch et al. 2022);
- Fisheries ecosystem modeling (Caracappa et al. 2022);

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

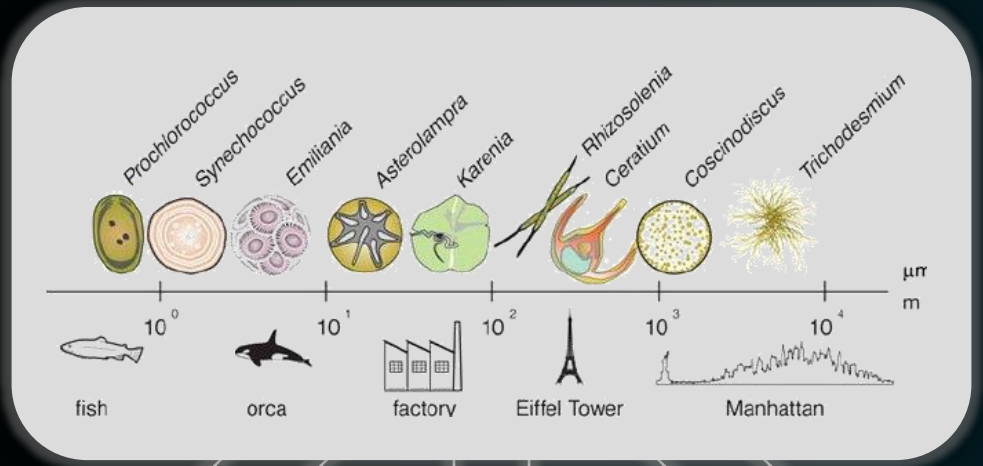
POC
(Particulate Organic Carbon)
Ocean carbon pool (suspended organic matter)

Primary Productivity (PP)
Rate of carbon production (photosynthesis)

Phytoplankton Functional Types / Size Classes (PFTs)
Community composition & size structure (biodiversity)

Carbon & Ecosystem Metrics

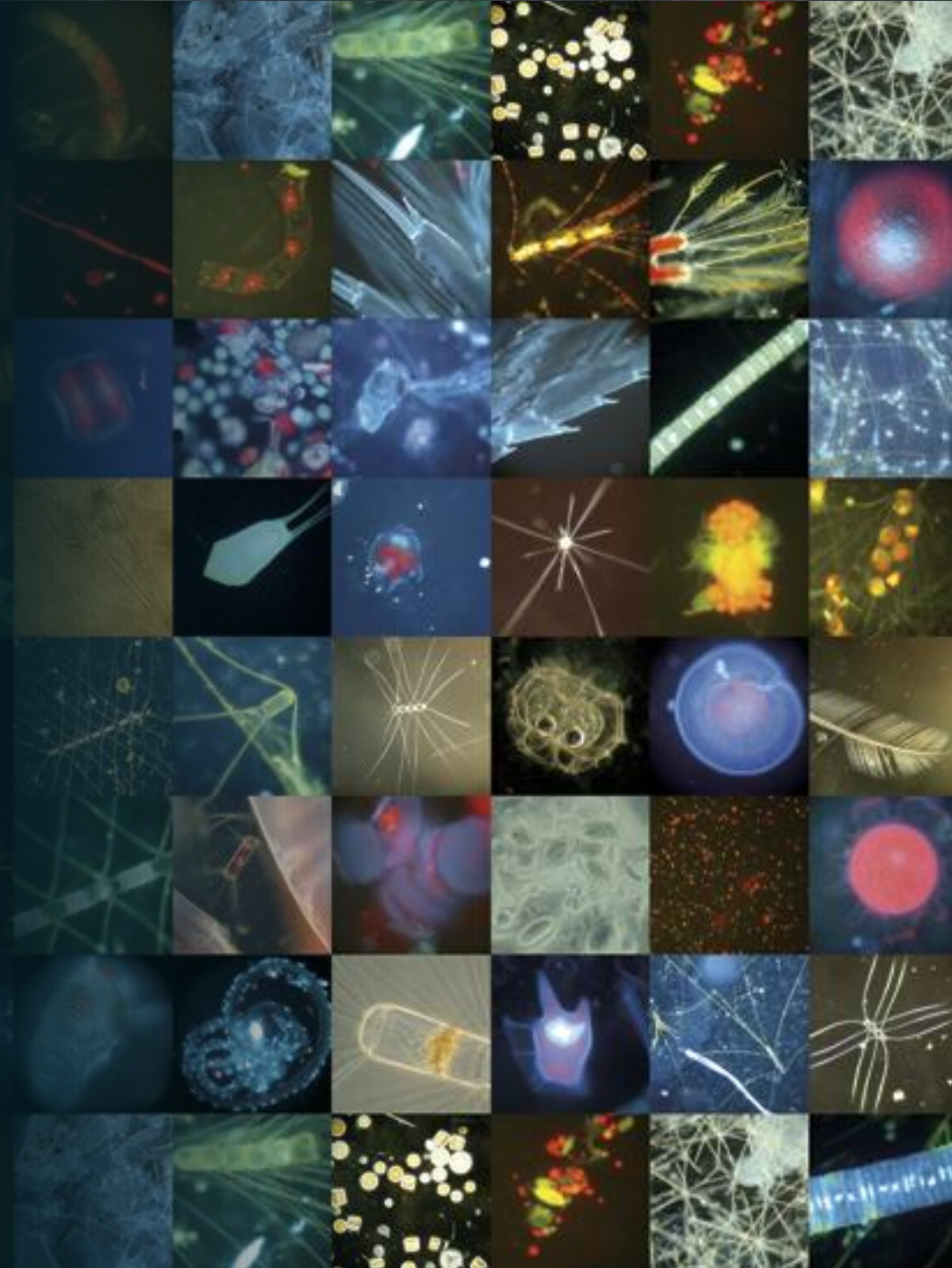
There is more to the story than just chlorophyll-a…

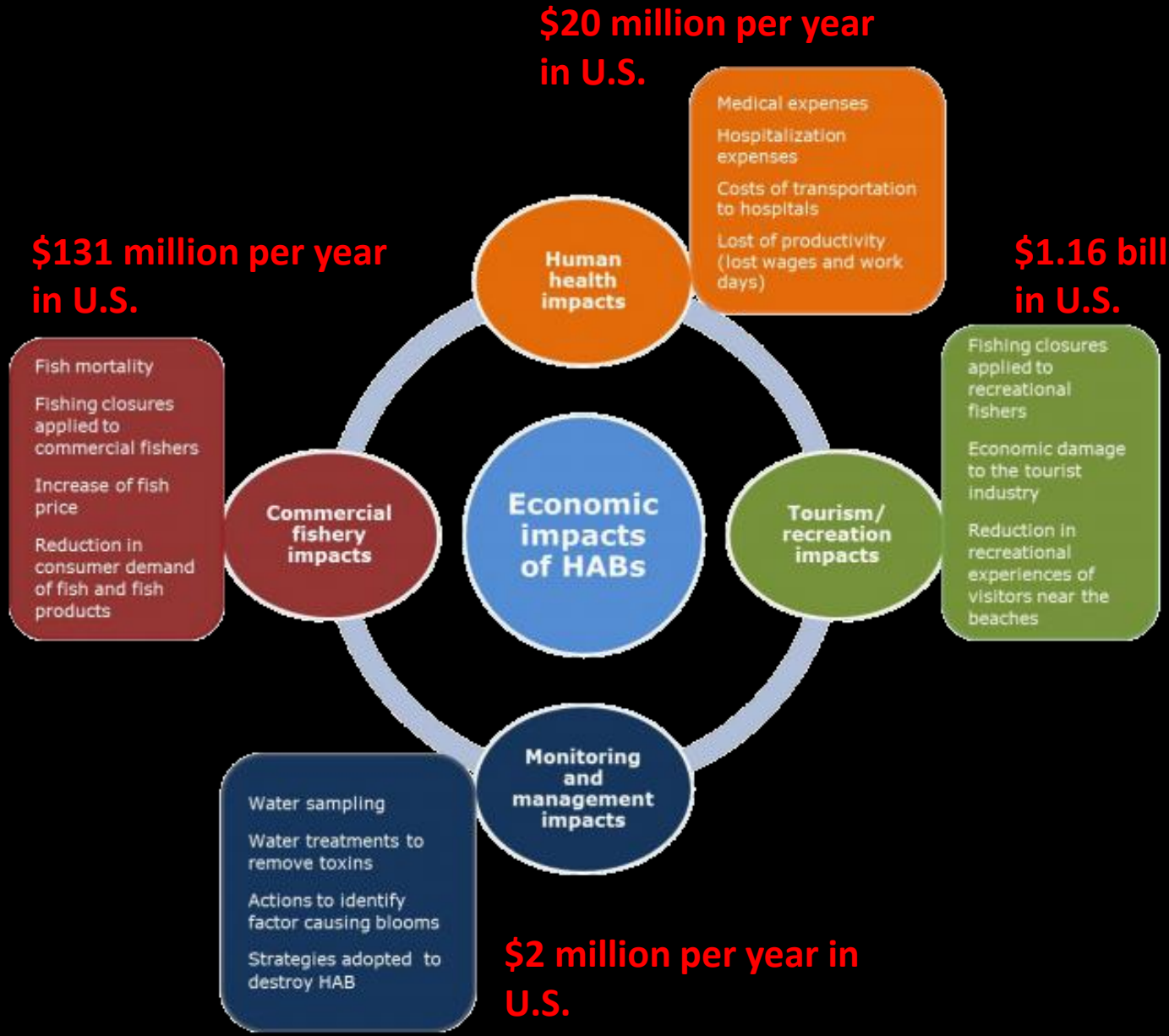


Small copepods

Large copepods

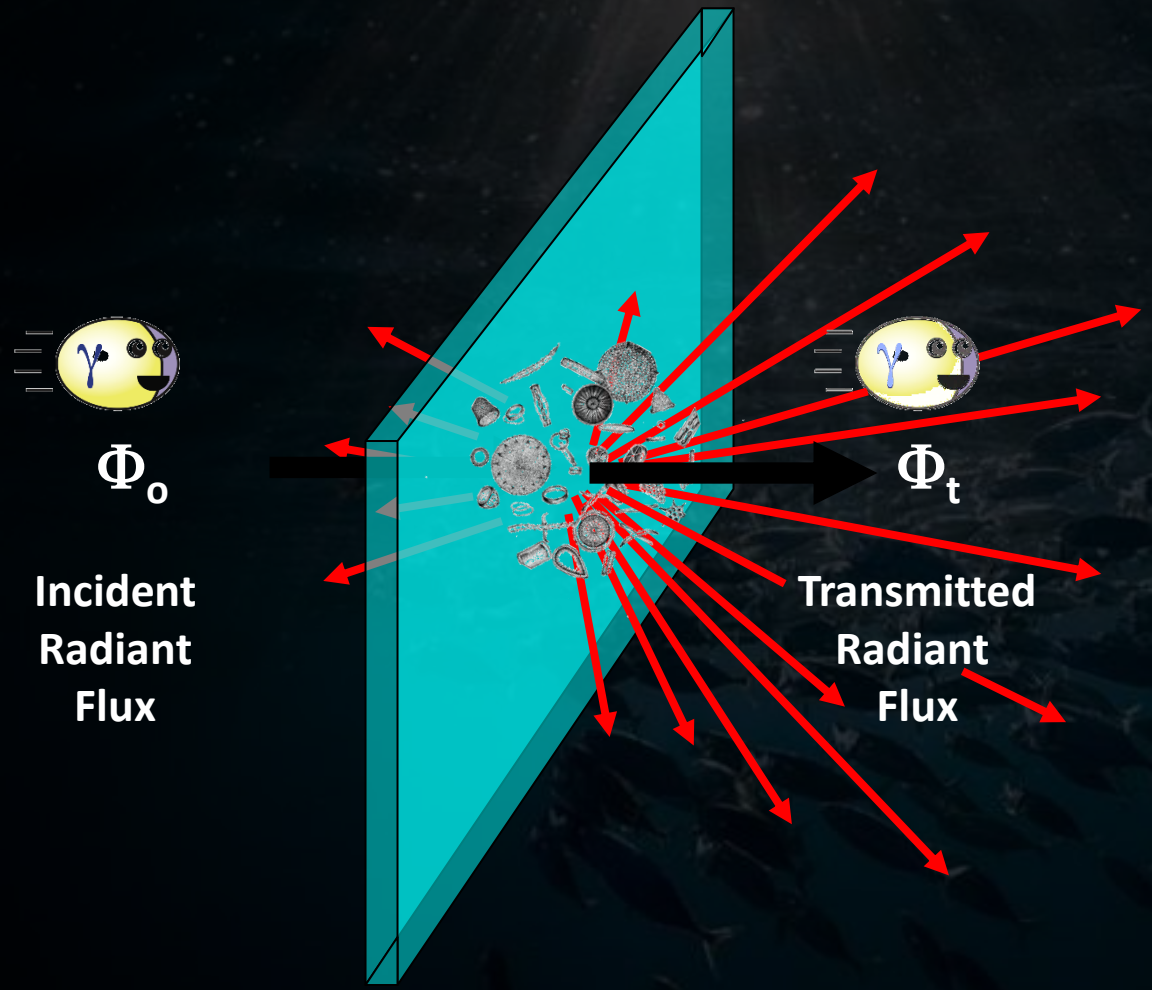
Gelatinous zooplankton





Sanseverino et al. 2016

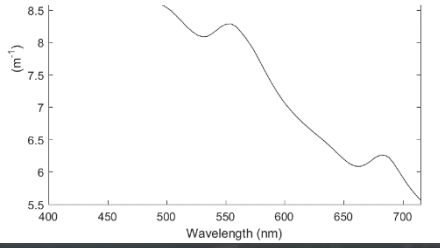
Two things can happen when light interacts with water:



Φ_a – Absorbed Radiant Flux
Φ_b – Scattered Radiant Flux

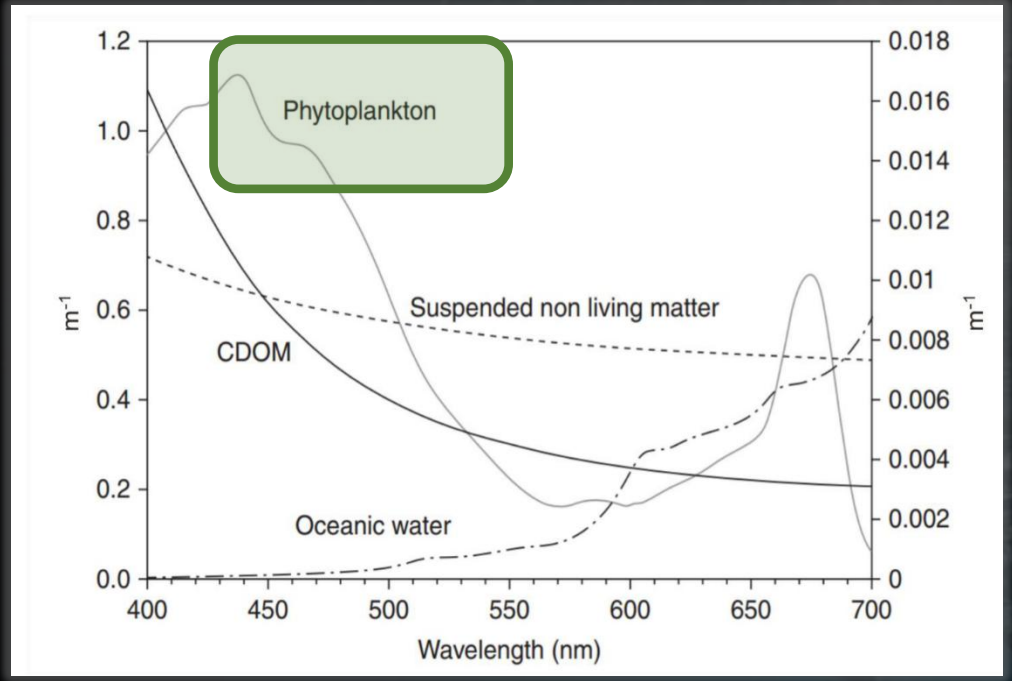
R_{rs} = Remote Sensing Reflectance

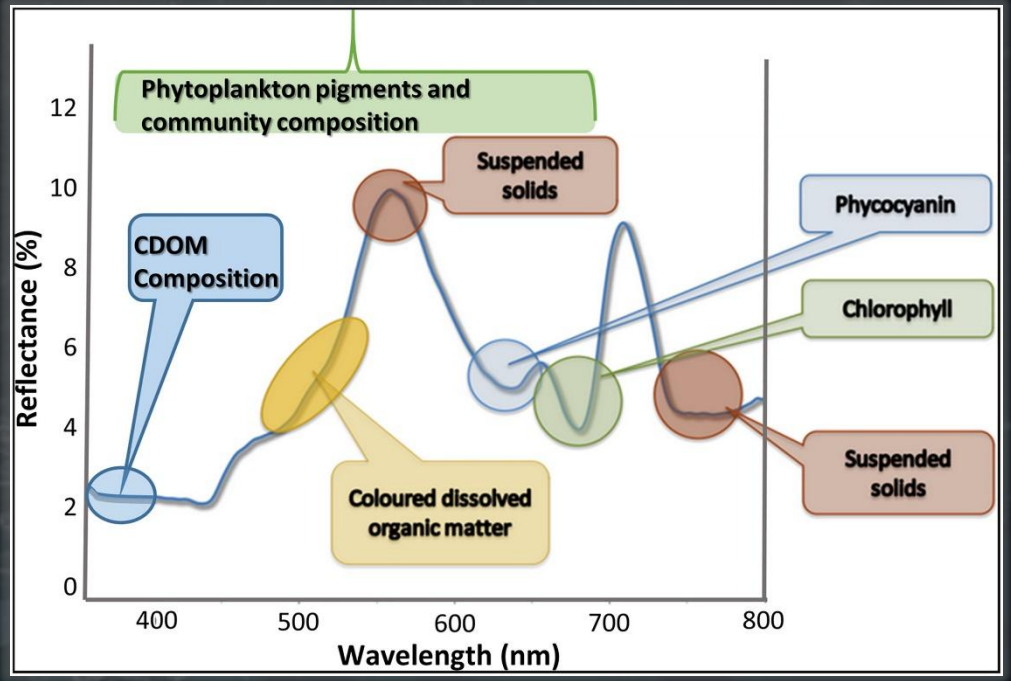
$R_{rs} \approx F\,[bb(\lambda) / a(\lambda) + bb(\lambda))]$



INTENSITY and ***DIRECTION*** of light at different wavelengths will change and can be measured to further define optical properties of water.

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





Absorption

Inherent *optical property*

Reflectance

Apparent *optical property*

A shamefully short history of the evolution of ocean color satellites

1978-1986 1997-2010 1999-pres. 2012-pres.

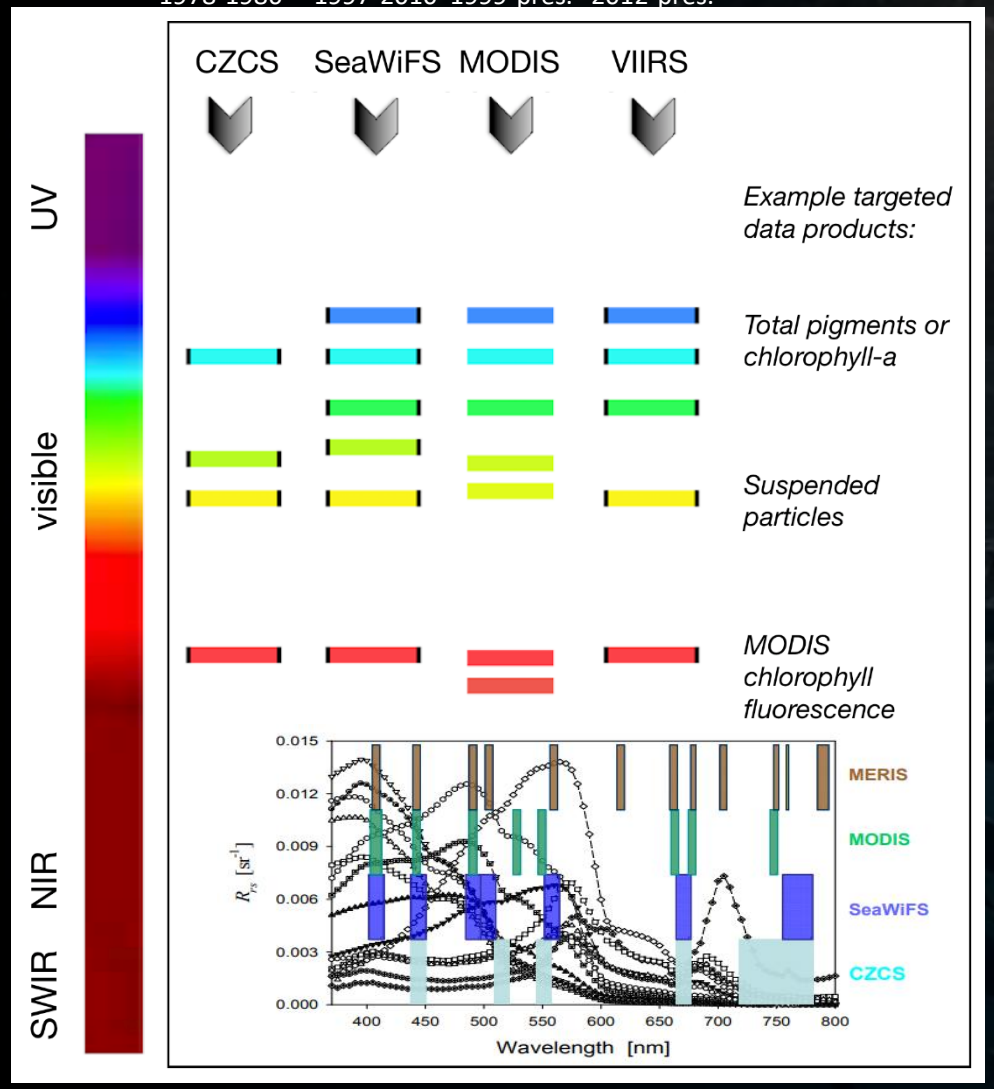
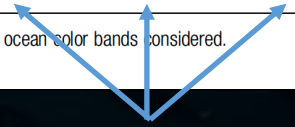


Table 1 A sample of other recent or upcoming Earth observing missions capable of ocean color observations

Mission	*Agency*	*Sensor*	*Launch*	*Bands*[a]	*Resolution (m)*	*Other specifications*
High spatial resolution missions (~100 km swath)						
Landsat-8, –9	USGS/NASA	OLI, OLI-II	2013, 2020	4 VIS	30	16-day revisit
Sentinel 2A, 2B	ESA	MSI	2015, 2017	4 VIS	10	10-day revisit, 5-day in constellation
EnMAP	DLR	EnMAP	2017	UV-SWIR (6.5 nm[b])	30	4-day revisit
Geostationary missions						
Geo-Kompsat 2B	KIOST	GOCI-II	2019	1 UV, 8 VIS	250 local 1000 global	Geostationary over NE Asia
Medium spatial resolution missions (~1000 km swath)						
Nimbus-7	NASA	CZCS	1978–86	5 VIS	1000	Regional coverage
ADEOS	NASDA	OCTS	1996–97	8 VIS	1000	3-day global
Orbview-2	NASA/Orbital	SeaWiFS	1997–2010	8 VIS	1000	2-day global
Terra, Aqua	NASA	MODIS	1999-, 2002-present	9 VIS	1000	2-day global
Envisat	ESA	MERIS	2002–12	8 VIS	350 local 1000 global	3-day global, 15 total tunable bands
Suomi NPP, JPSS-1	NOAA/NASA	VIIRS	2012-,2017-present	5 VIS	750 global	2-day global
Sentinel 3A, 3B	ESA	OLCI	2016, 2018	8 VIS	300 coastal 1000 ocean	4-day global 2-day in constellation
Oceansat-3	ISRO	OCM-3	2018	8 VIS	360	2-day global
GCOM-C	JAXA	SGLI	2018	1 UV, 6 VIS	250 coastal 1000 ocean	2-day global 2 polarized bands

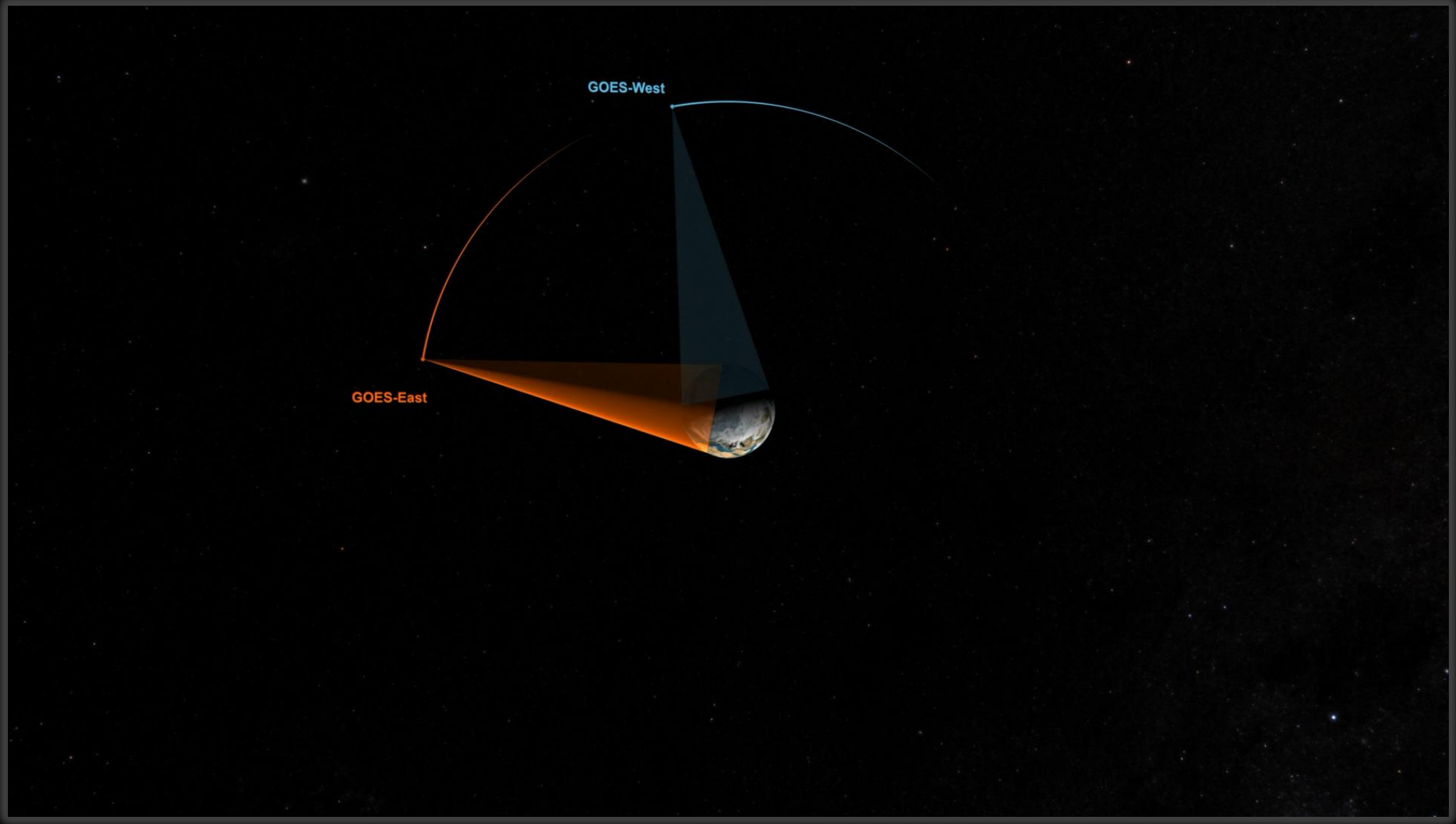
[a] *UV*, Ultraviolet (350–400 nm); *VIS*, visible (400–900 nm); *SWIR*, shortwave infrared (900–2300 nm); only ocean color bands considered.
[b] Indicates continuous resolution from UV-VIS at the wavelength step listed.



Physics & current (space-ready) technologies impede our ability to improve on **all of these simultaneously** with a single instrument concept

GEO (geostationary) vs. LEO (polar, low earth orbit)

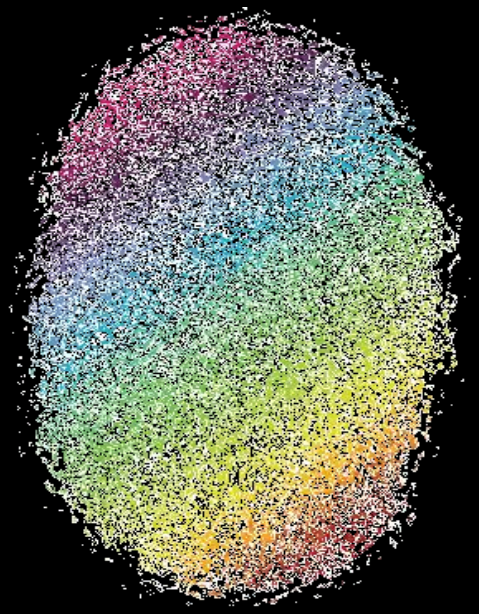
GEO (geostationary) vs. LEO (polar, low earth orbit)



The battle for the photon

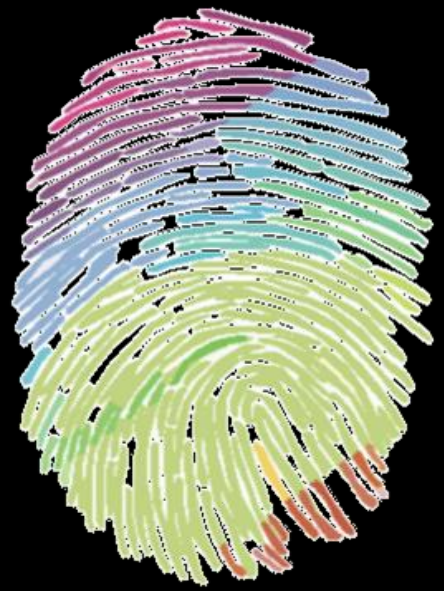
Ideal fingerprint

Too much random noise



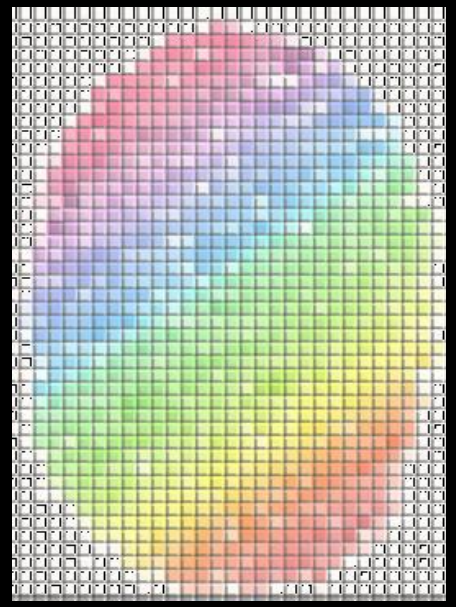
Need longer dwell time

Got the details, but the colors are lumped together



Need better spectral resolution

Captured the color gradient, but not the print details

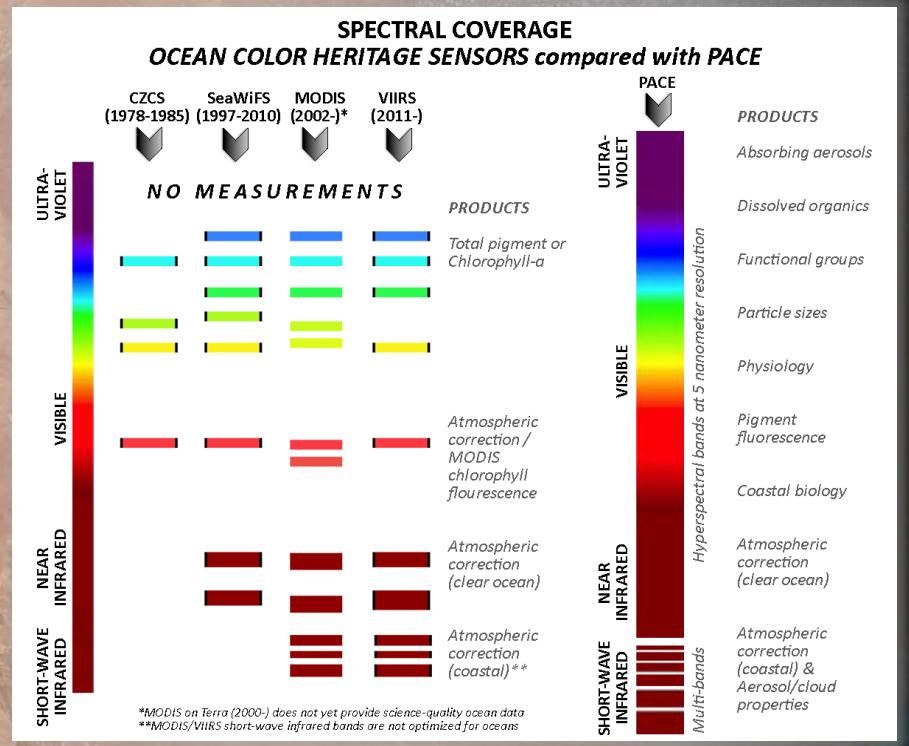


Need better spatial resolution

Got a partial print, degraded over time

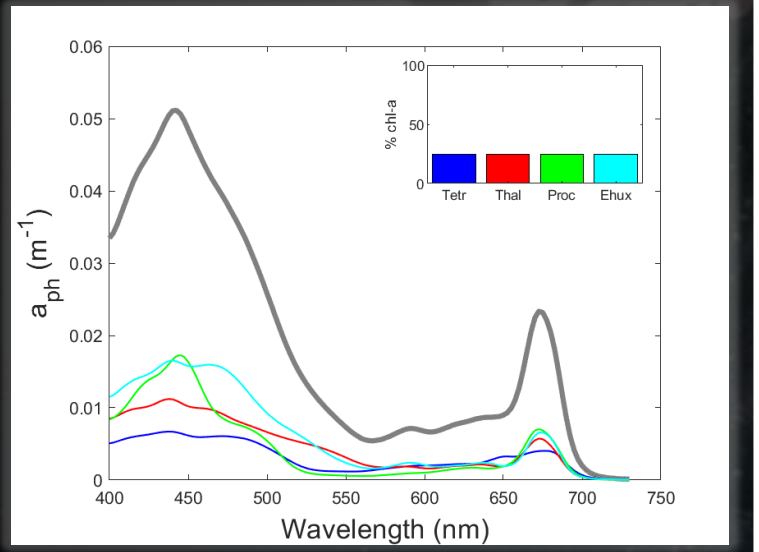
Need better temporal resolution

A step beyond chlorophyll-a

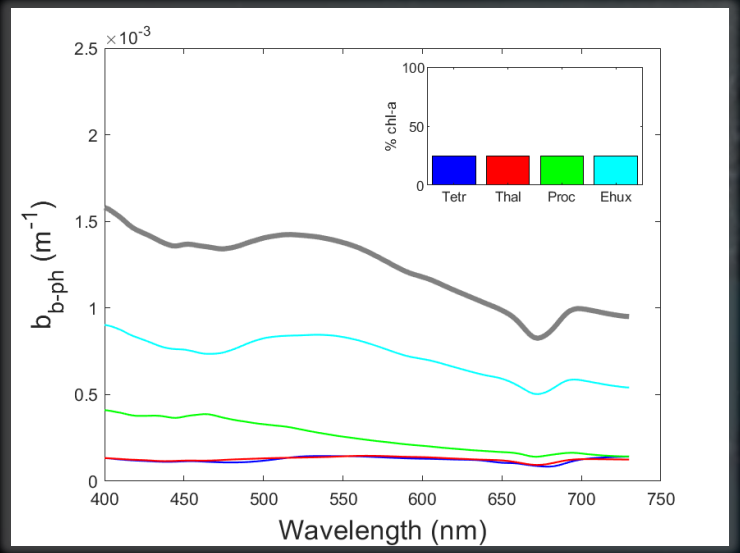


- **P**lankton, **A**erosol, **C**loud, and ocean **E**cosystem (**PACE**) mission
- First global “hyper” spectral ocean mission (the whole rainbow!).
- Providing critical insights into the optical environment that we have been blind to for 25 years.
- Likelihood of toxicity and relevant size-class information for food web dynamics

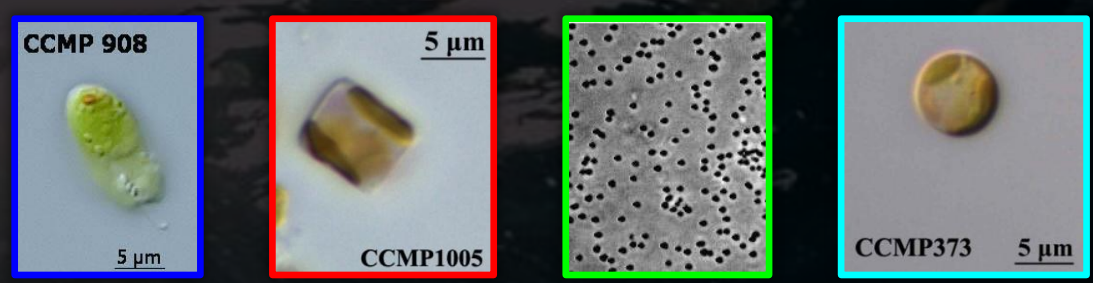
Absorption



Scattering



What PACE sees

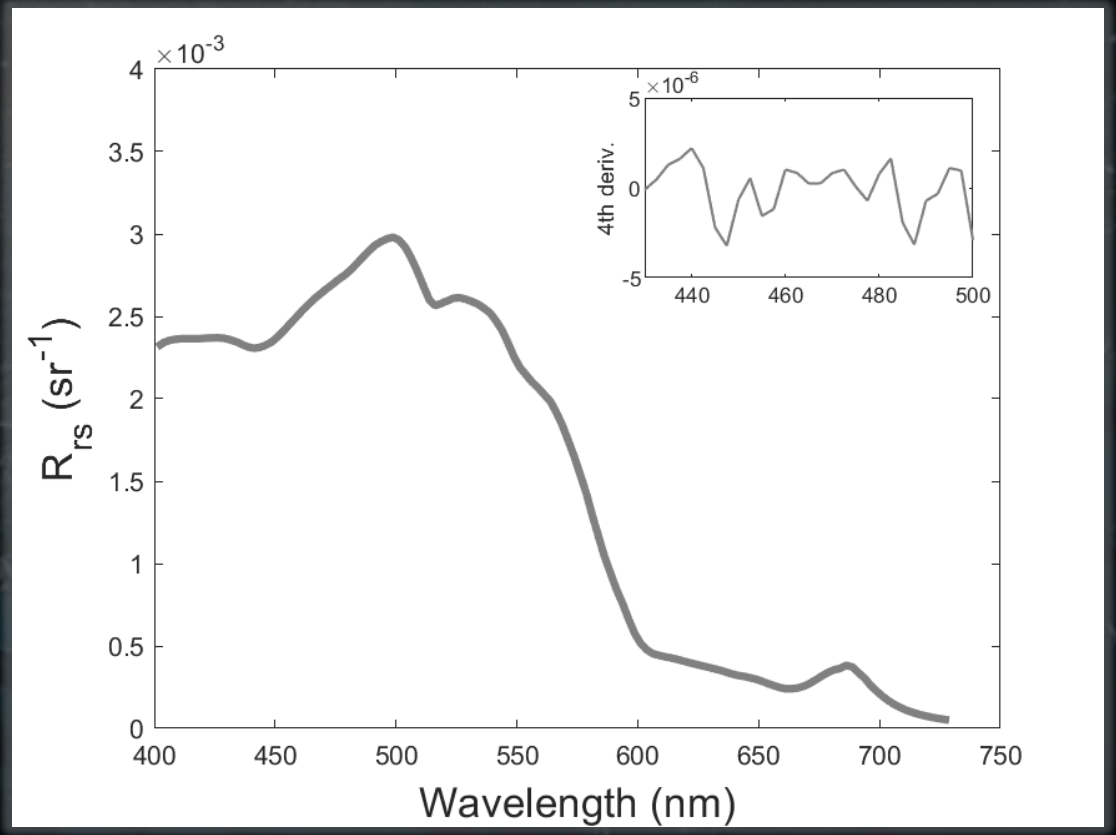


Tetraselmis sp.

Thalassiosira oceanica

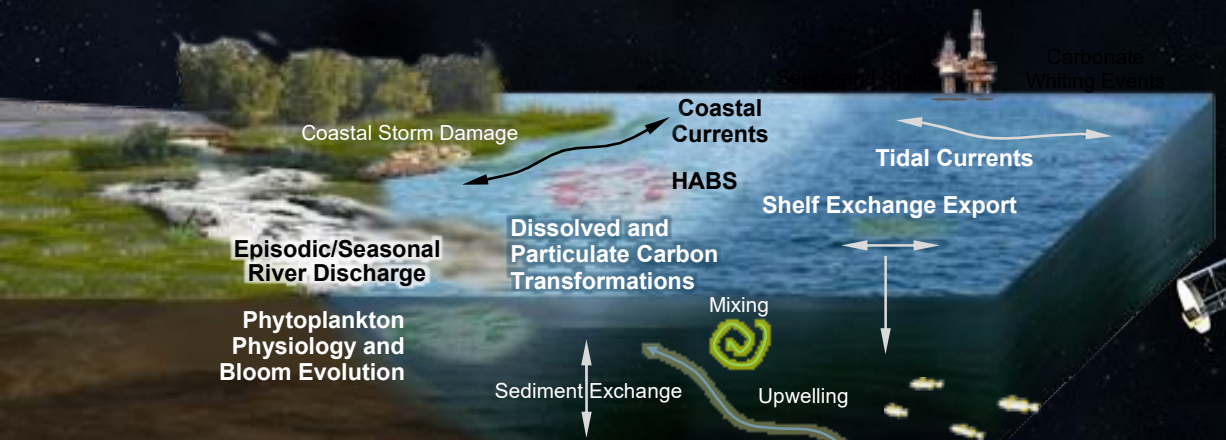
Prochlorococcus marinus

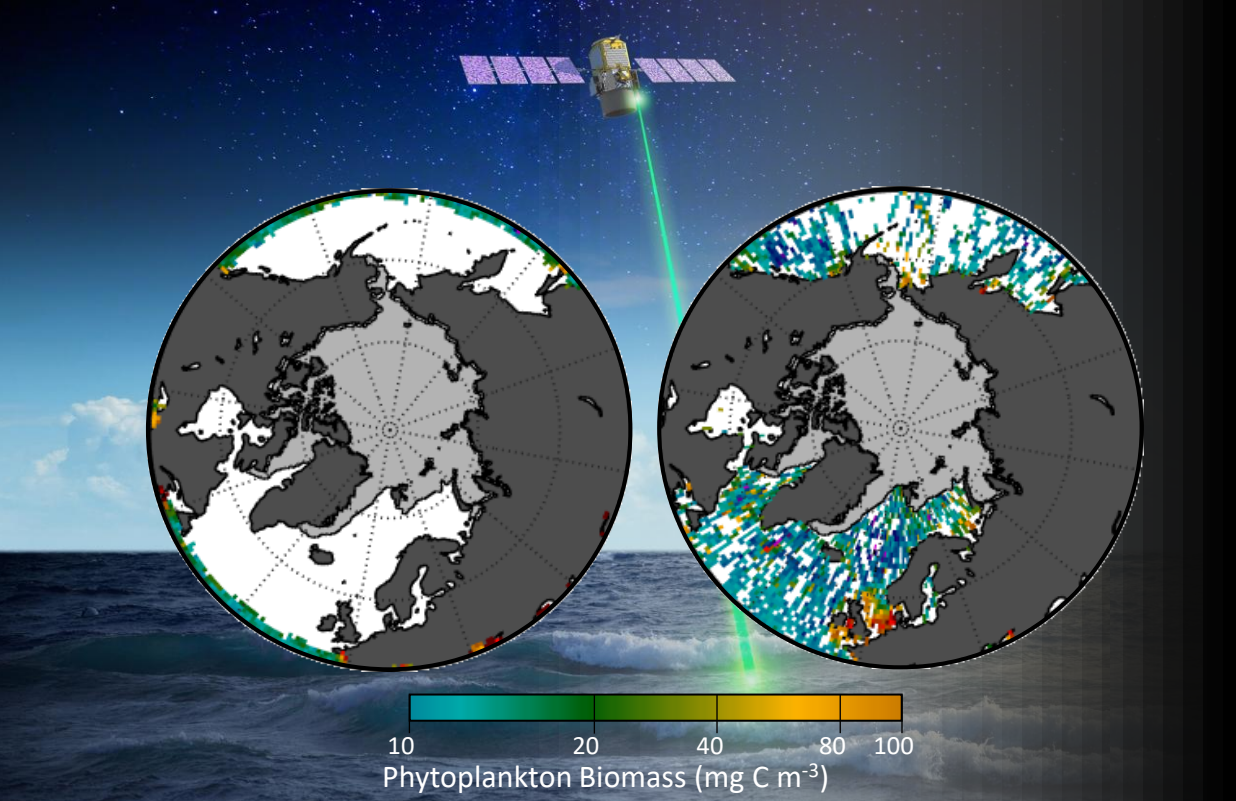
Emiliania huxleyi

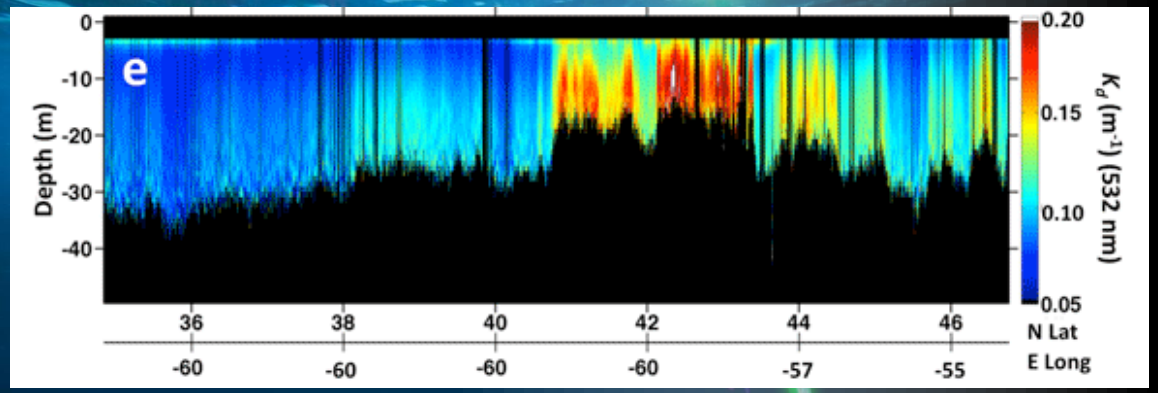


Weather forecast analogues for the ocean

- **G**eostationary **L**ittoral **I**maging and **M**onitoring **R**adiometer (**GLIMR**) launching in 2028
- Near-real time monitoring of the ocean
- Cloud mitigation = 2.5 – 3X more imagery
- Capture an *order of magnitude* more transient events (harmful algae, Sargassum, oil spills, marine debris, coastal currents).
- GOCI (Korea) and AHI (JAXA) also in orbit!





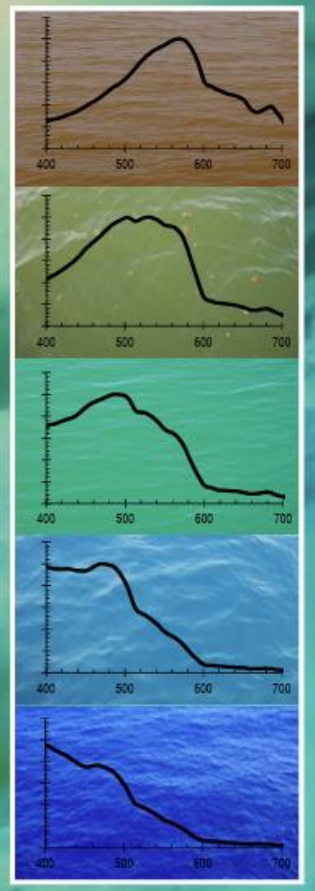


Vertical structure from space-borne sensors

- Pulsed laser (LIDAR) can see:
  - through thin clouds/fog,
  - low-light conditions (high latitudes)
  - ocean particle concentration
  - day/night cycle of particles
  - de-polarizing layers below surface
  - chlorophyll-a fluorescence (*future*)
  - 3.75 meter vertical resolution (*future*)

- **C**loud **A**erosol **LI**DAR for **G**lobal Scale **O**bservations of the Ocean-**L**and **A**tmosphere System (**CALIGOLA**) launching in 2031-2032.

NOAA Technical Memorandum NMFS-F/SPO-255



Plankton, Aerosol, Cloud and ocean Ecosystem (PACE) Satellite Data for Aquaculture and Fisheries Management

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May 2025

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Office of Science and Technology

Table of Contents

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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?

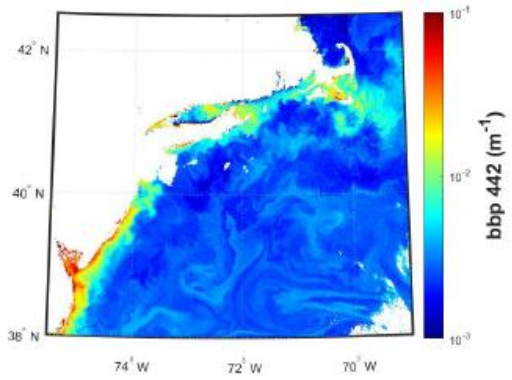
- Many phytoplankton exhibit unique backscattering characteristics[65], primarily as a function of cell size[66], and sometimes composition (e.g. Coccolithophore blooms[67]). Backscatter is also used to derive Particulate Inorganic Carbon (PIC)[68] estimates from satellites. Particle backscatter is a 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).
  - ***Cochlodinium 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!