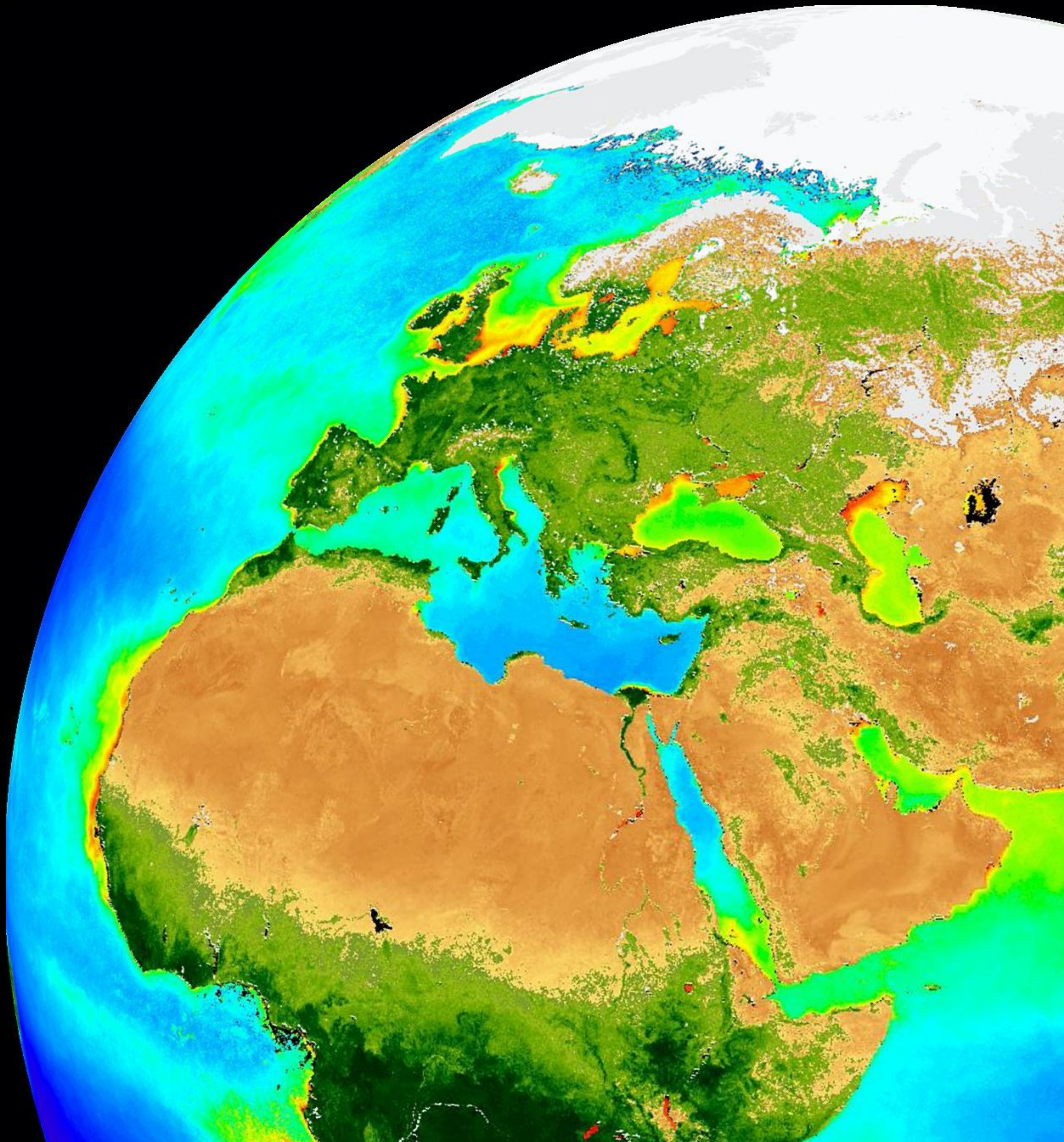
A *very* brief history of ocean color from space



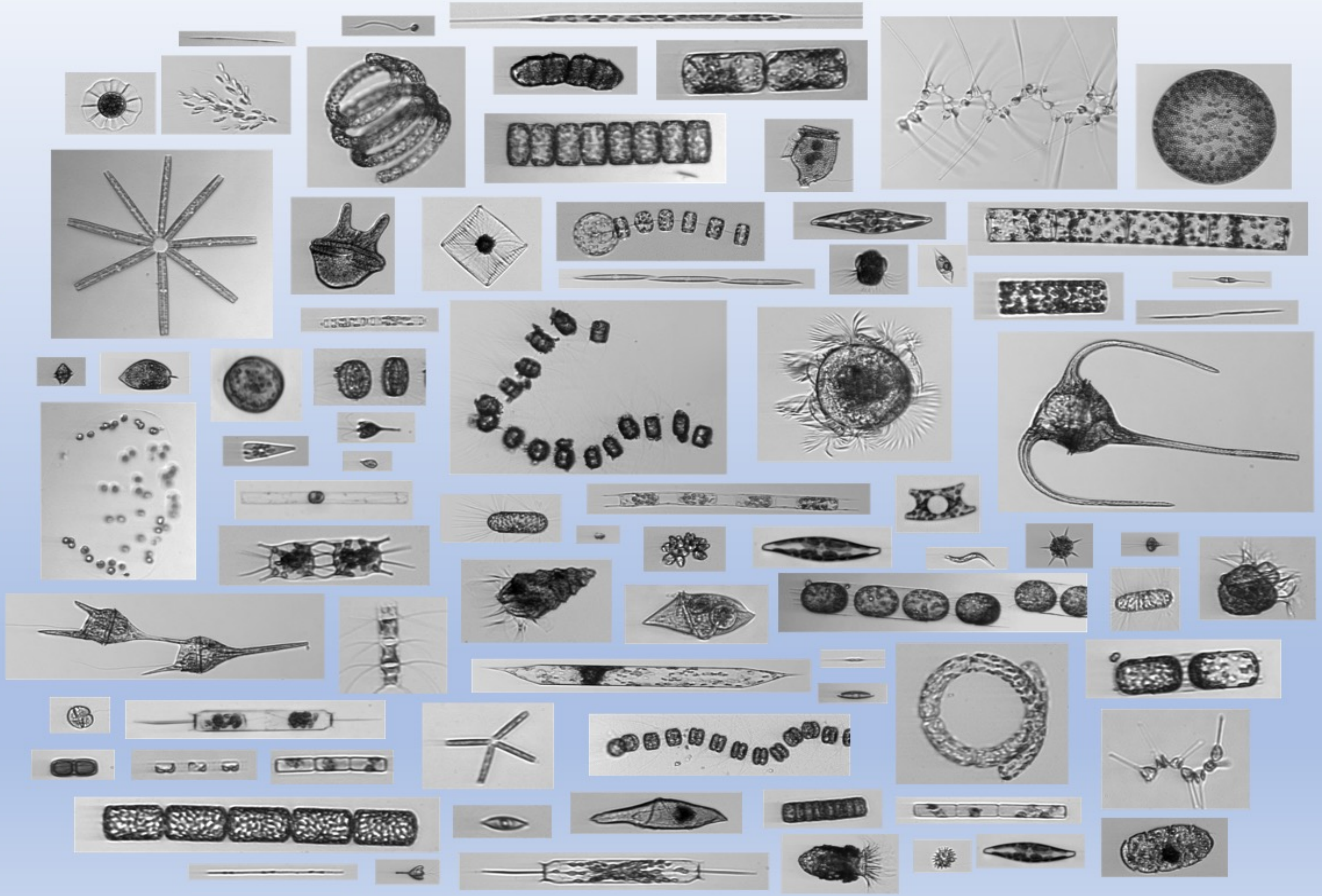
Jeremy Werdell

PACE class @ UMBC
1-5 Aug 2022

GODDARD EARTH SCIENCES

Theme for the next 25 min:

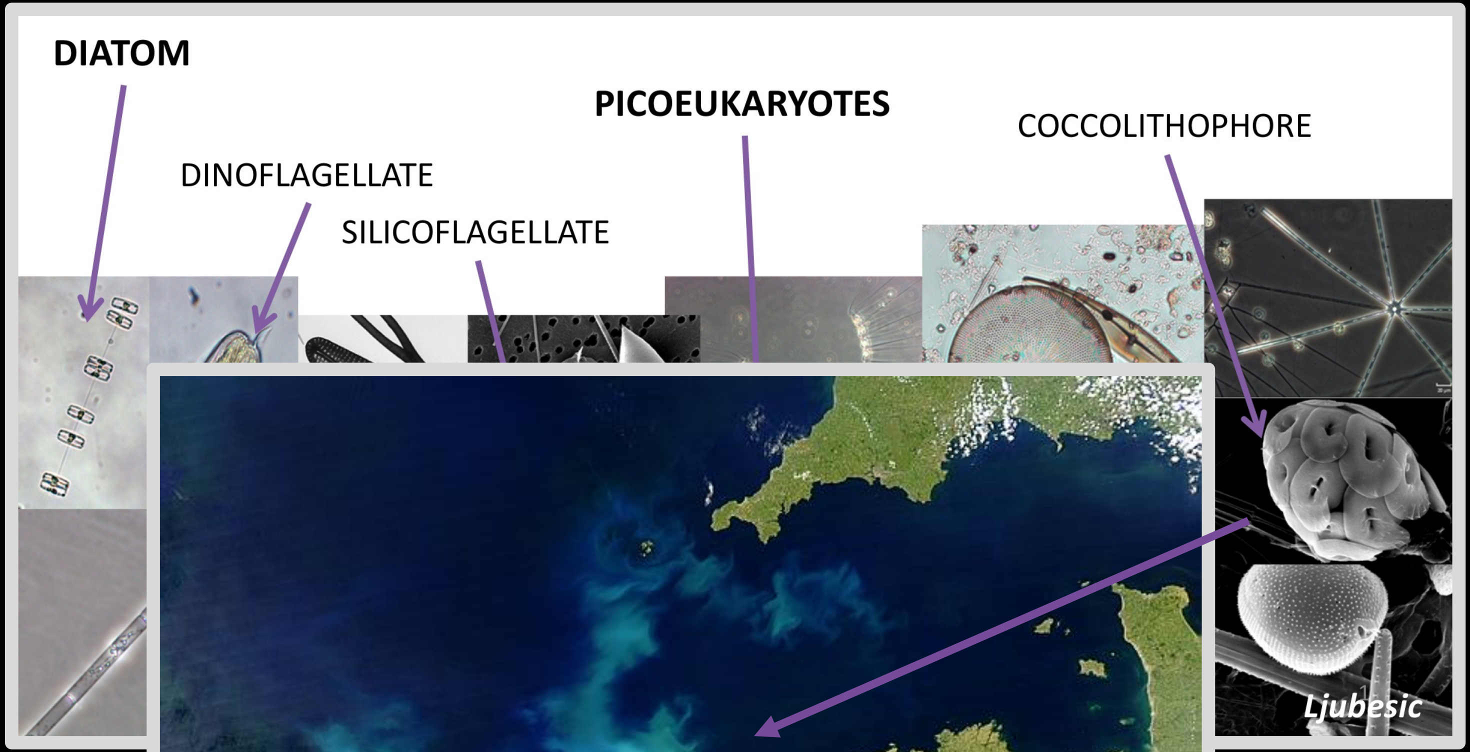
A brief history of the genesis and evolution of satellite "ocean color"

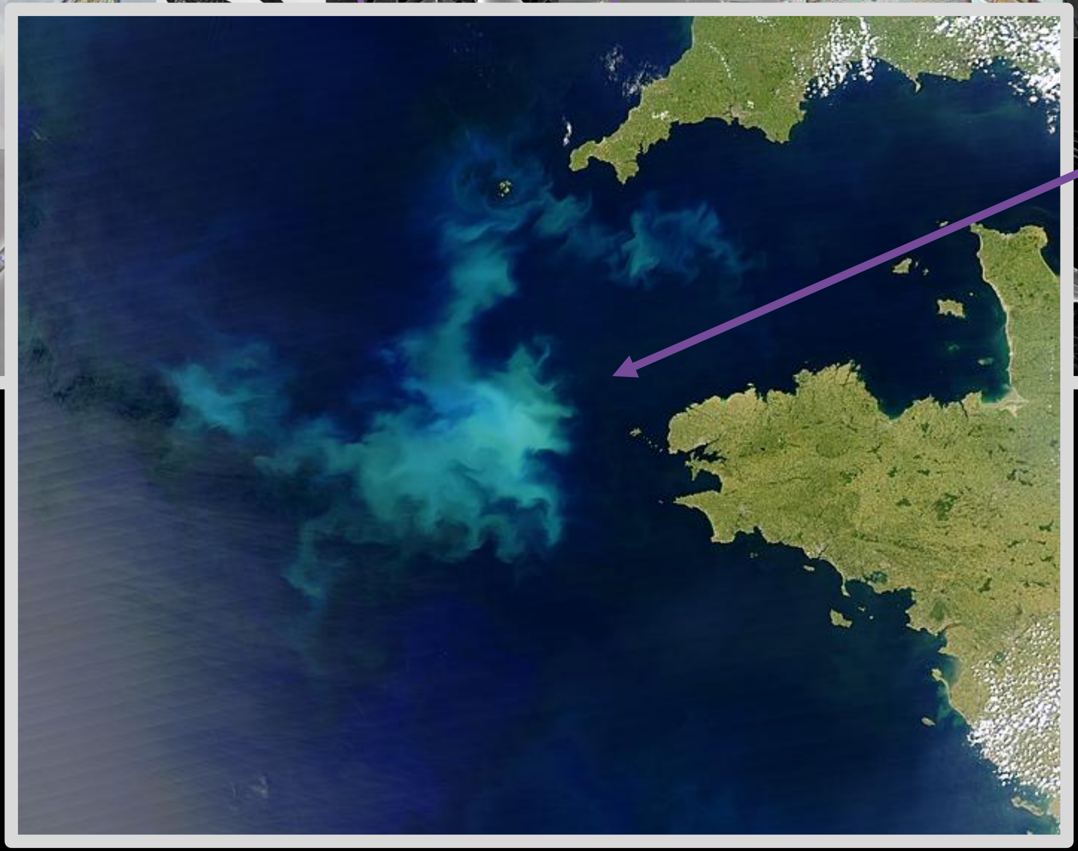


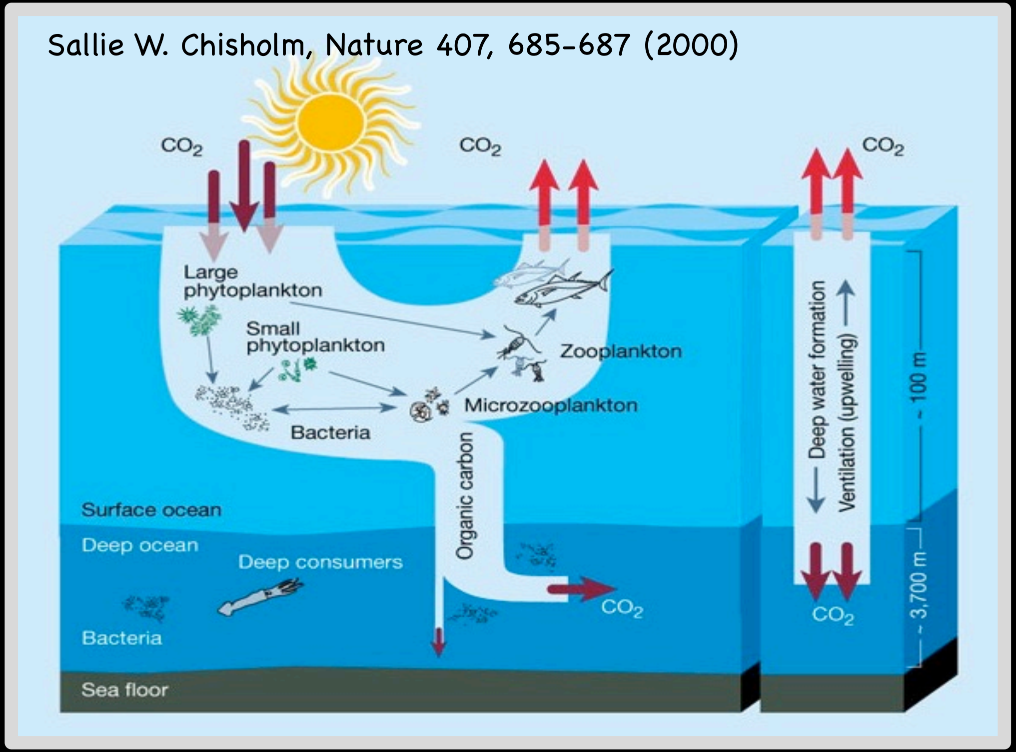
Credit: Heidi Sosik (WHOI)

Part 1 (of 3)

Why phytoplankton?
Why satellites?







<u>one coccolithophore</u>

0.01 mm

1,000 cells/mL

A satellite image from NOAA shows an aerial view of Lake Erie's massive 2011 algae bloom.

PHOTOGRAPH BY NASA/EARTH OBSERVATORY

Algae outbreak suffocates thousands of sardines in Oman

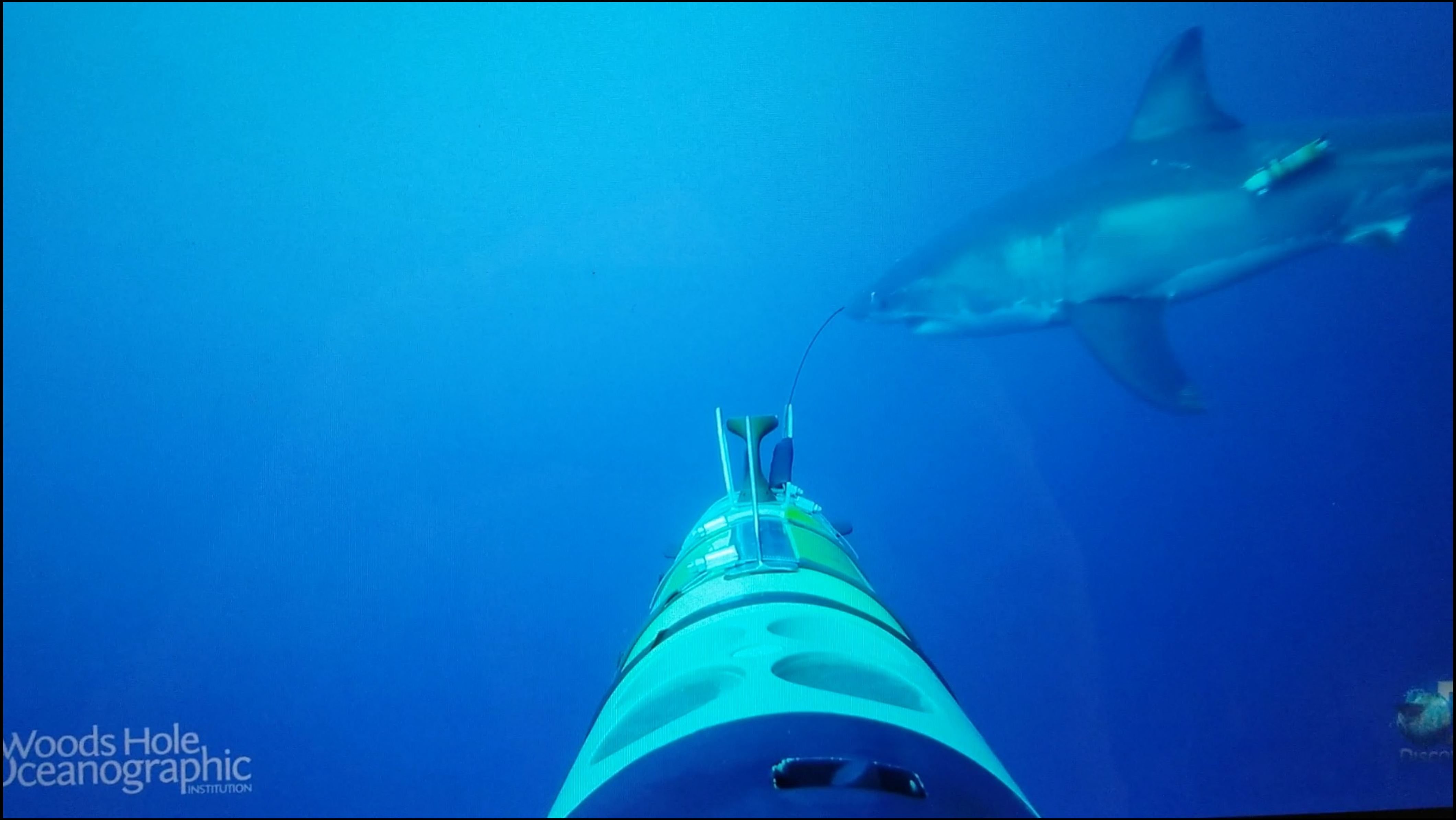
Residents of Sidab village teamed up to clean the area before the smell of dead fish spread

Image Credit: Twitter

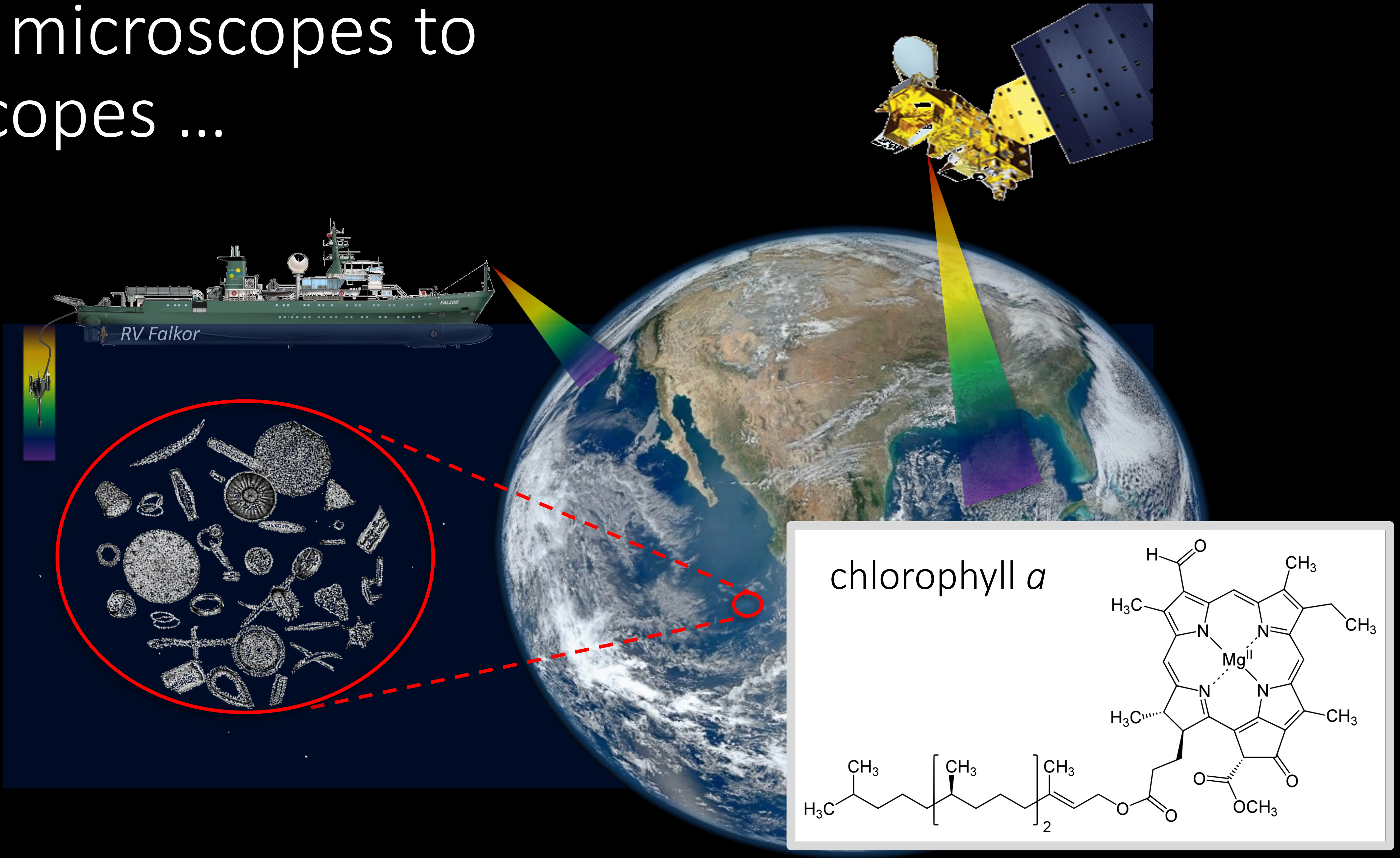
The sardines had choked to death due to the lack of oxygen in the seawater.

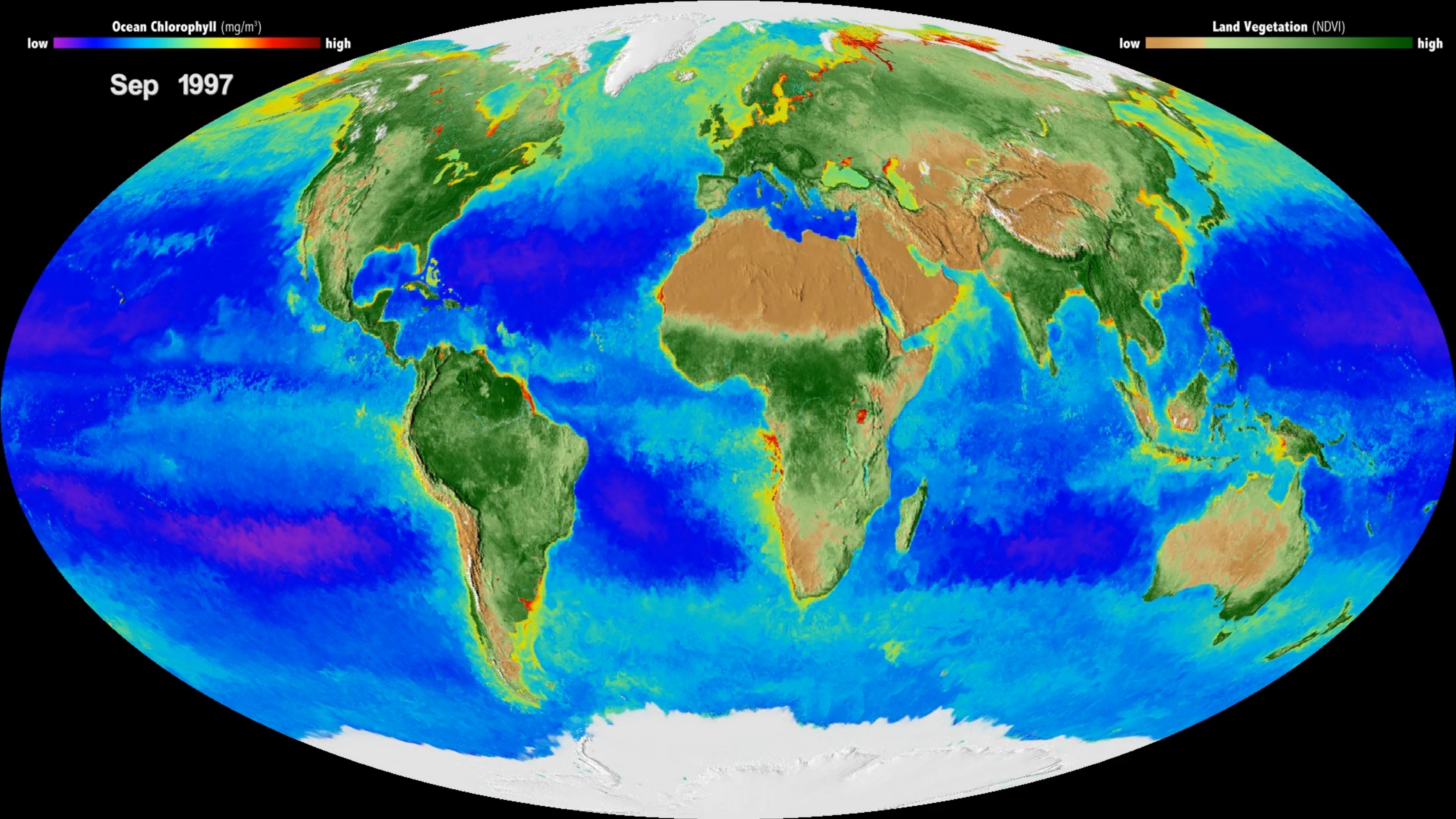
Published: 12:27 May 6, 2017
Gulf News

GULF NEWS


Woods Hole
Oceanographic
INSTITUTION

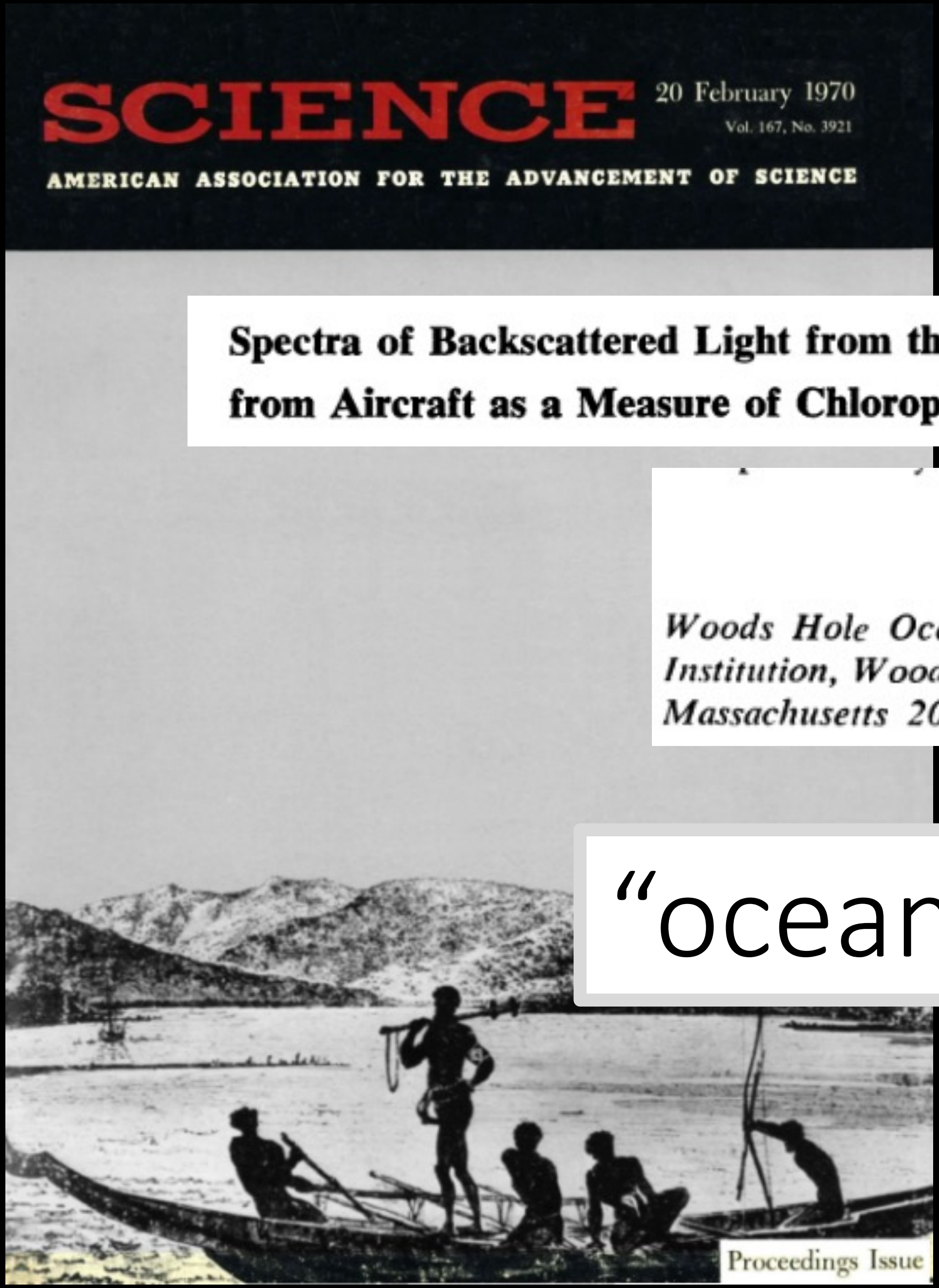
From microscopes to telescopes …




Ocean Chlorophyll (mg/m³)
low
high
Sep 1997
Land Vegetation (NDVI)
low
high

Part 2

How’d we get here?
How does it work?



Spectra of Backscattered Light from the Sea Obtained from Aircraft as a Measure of Chlorophyll Concentration

GEORGE L. CLARKE
GIFFORD C. EWING
CARL J. LORENZEN
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 20543

“ocean color”

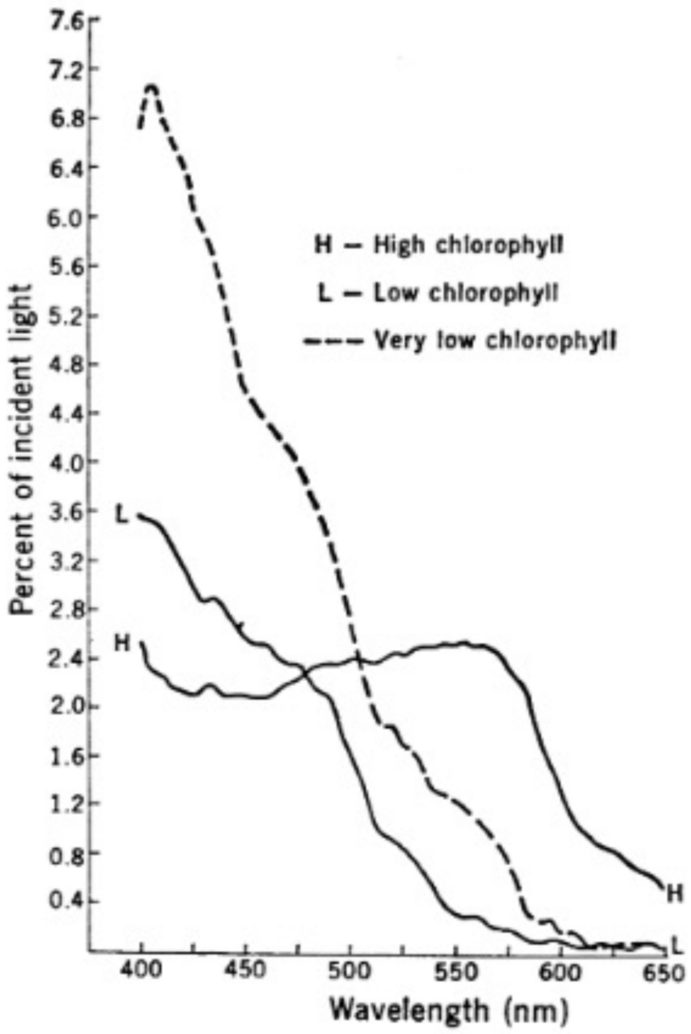


Fig. 3. Data from the high and low chlorophyll curves plotted as percentage of the incident light and compared with data taken on the same day from an area with very low chlorophyll concentration south of the Gulf Stream.

Clear water radiances for atmospheric correction of coastal zone color scanner imagery

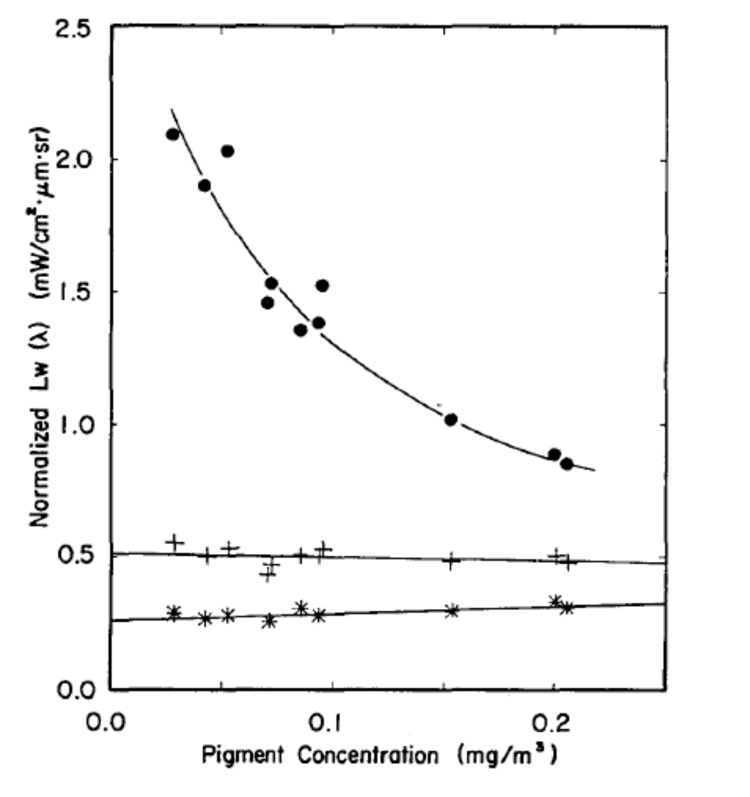
Howard R. Gordon and Dennis K. Clark

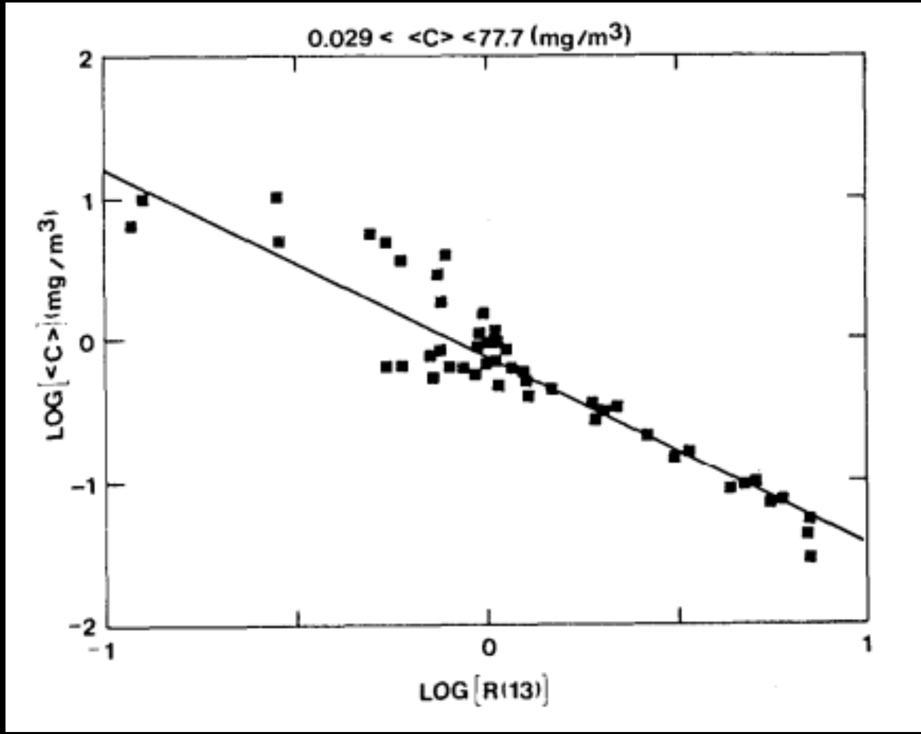
15 December 1981 / Vol. 20, No. 24 / APPLIED OPTICS 4175

Phytoplankton pigment concentrations in the Middle Atlantic Bight: comparison of ship determinations and CZCS estimates

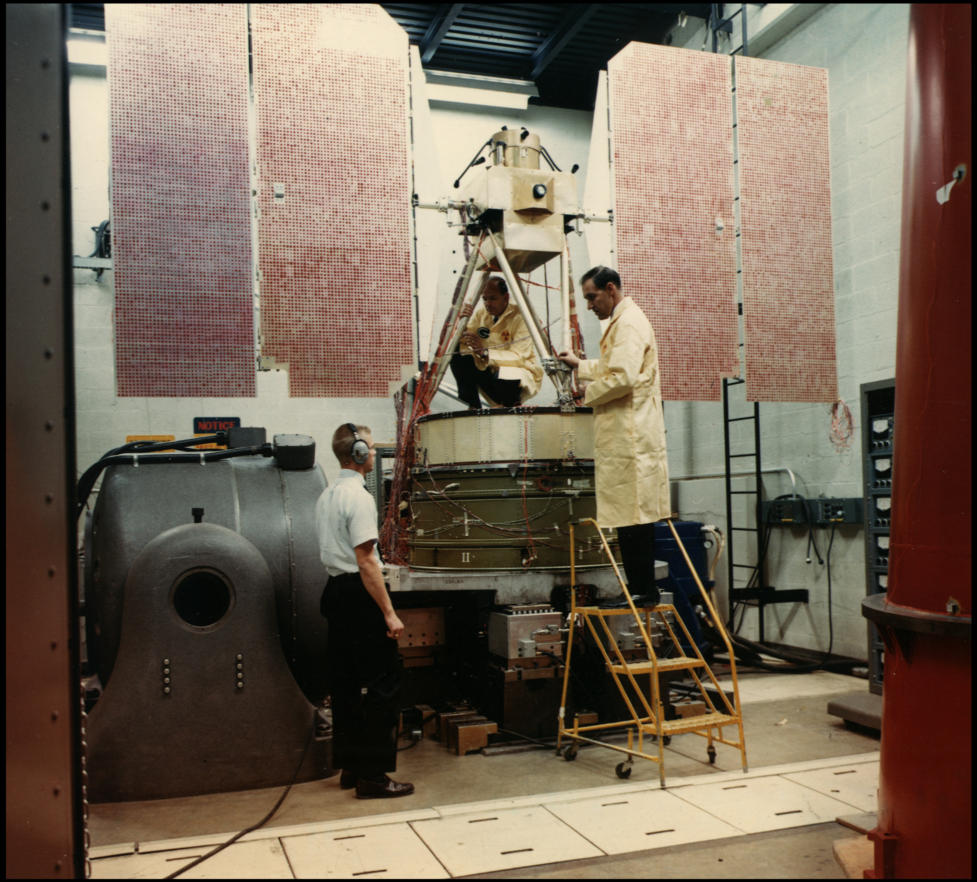
Howard R. Gordon, Dennis K. Clark, James W. Brown, Otis B. Brown, Robert H. Evans, and William W. Broenkow

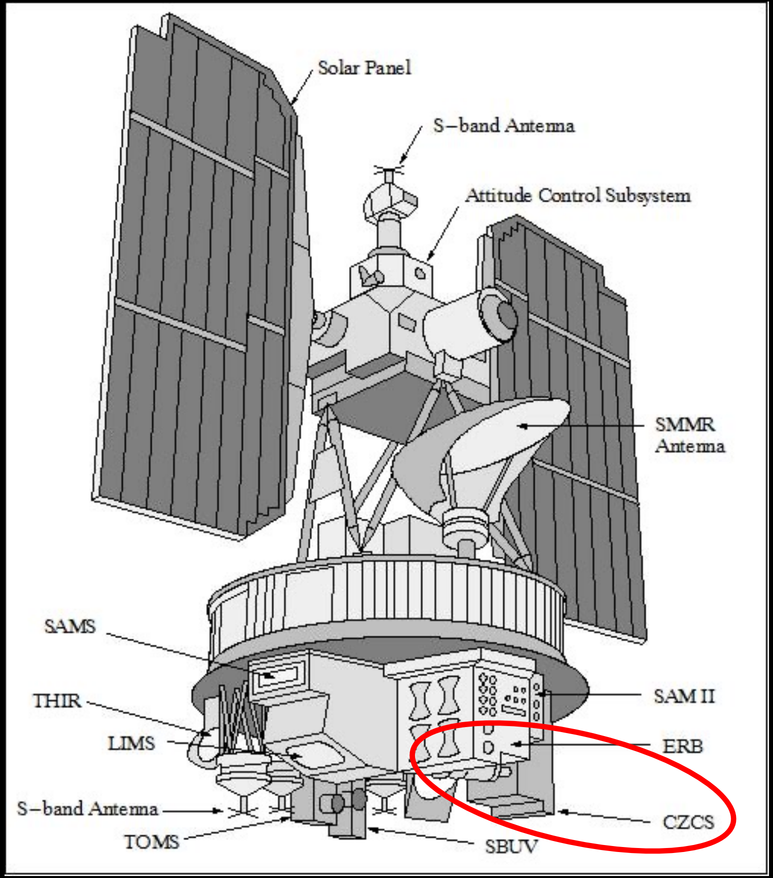
20 APPLIED OPTICS / Vol. 22, No. 1 / 1 January 1983



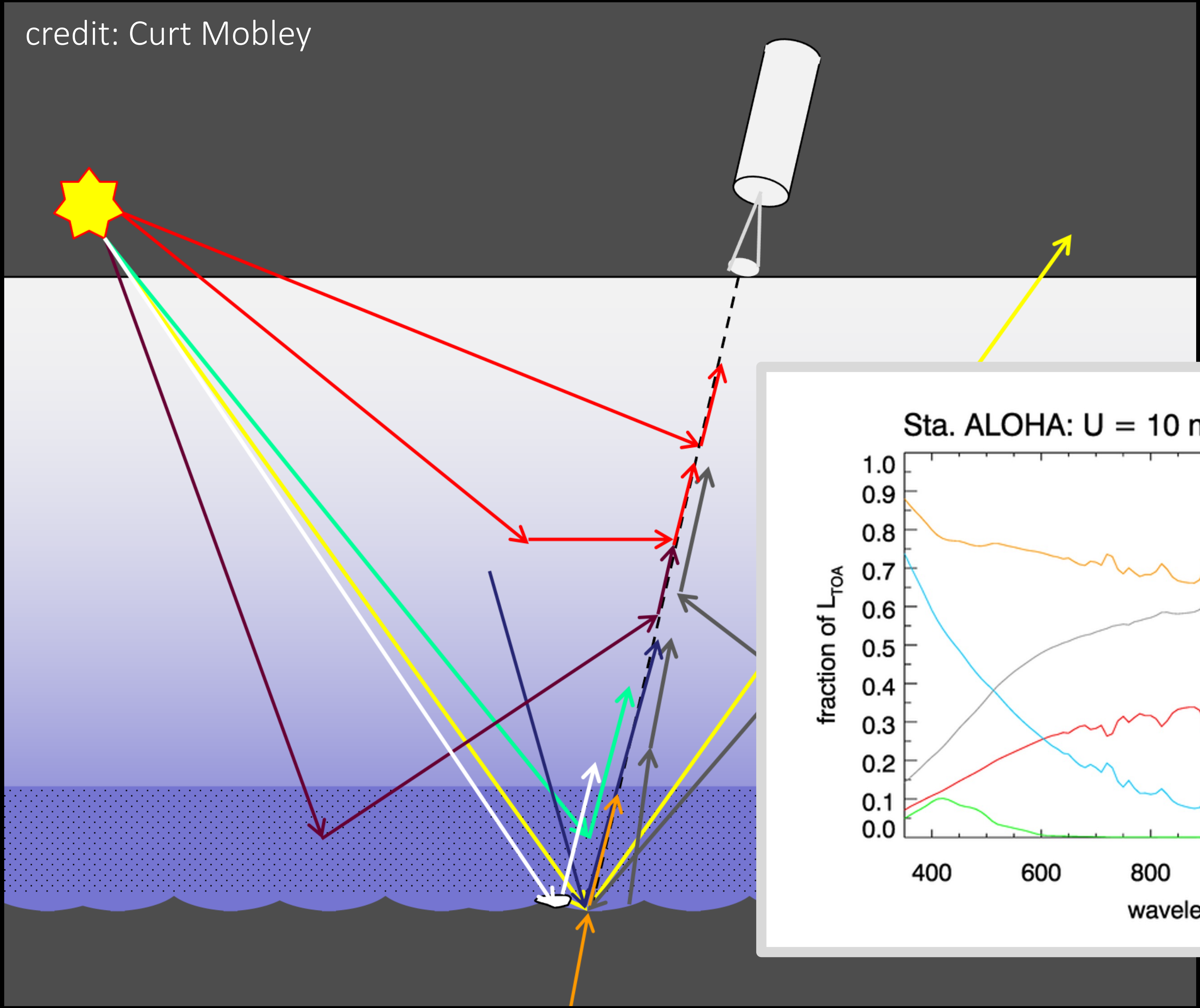


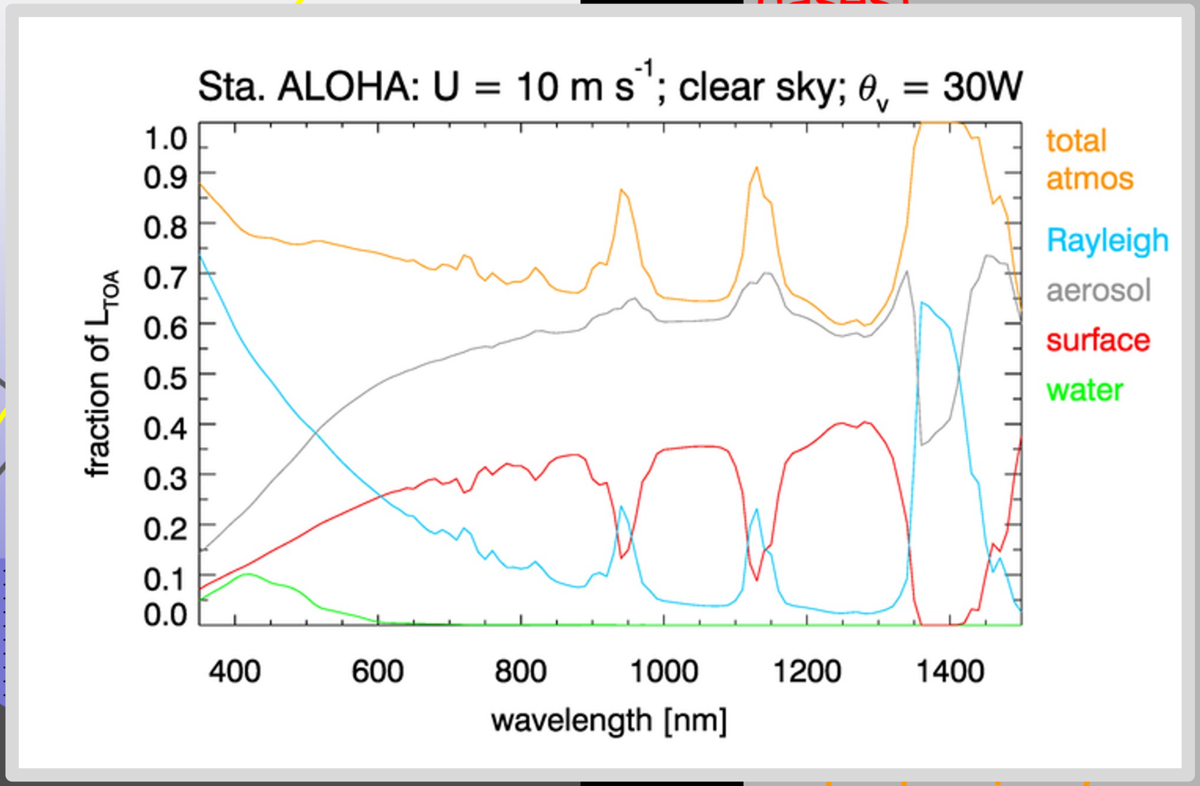
Coastal Zone Color Scanner
1978-1986





metric	CZCS
primary ocean bands (nm)	443, 520, 550, 670
○ chl-a + phaeopigments ○ diffuse attenuation at 490 nm	
nadir res.	825 m
nadir swath	1636 km discontinuous operation
tilt	$\pm 20^{o}$ in 2^{o} increments
det. per band	1
digitization	8 bits





contributions to at-sensor radiance

specular reflectance

Rayleigh (atmospheric gases)

water-leaving L_w

credit: Curt Mobley

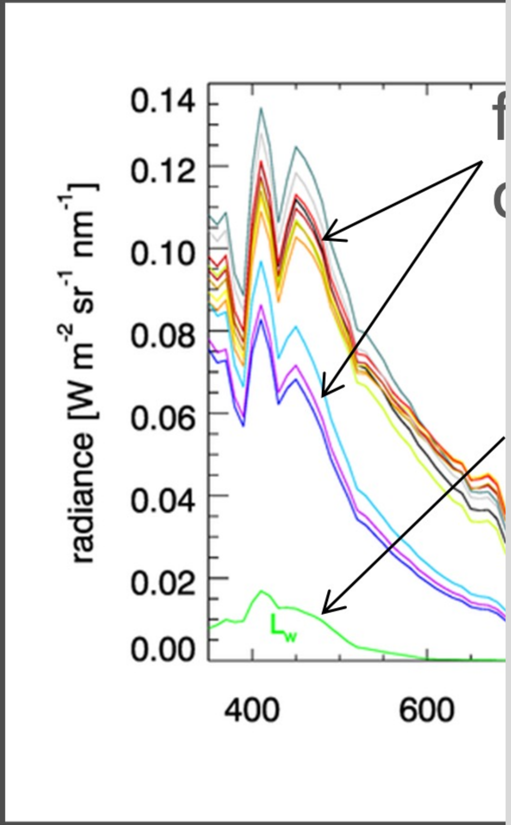
How can you estimate or extract L_w surface from the measured L_u at the

3 approaches:

1) the "black pixel" assumption + extrapolation (Case 1, deep waters only)

2) empirical line fit

3) radiative transfer modeling



A PRELIMINARY ASSESSMENT OF THE NIMBUS-7 CZCS ATMOSPHERIC CORRECTION ALGORITHM IN A HORIZONTALLY INHOMOGENEOUS ATMOSPHERE

Howard R. Gordon

Department of Physics
University of Miami
Coral Gables, Florida 331

Gordon 2021 recounts the development & validation of the methodologies

1. THE CORRECTION ALGORITHM

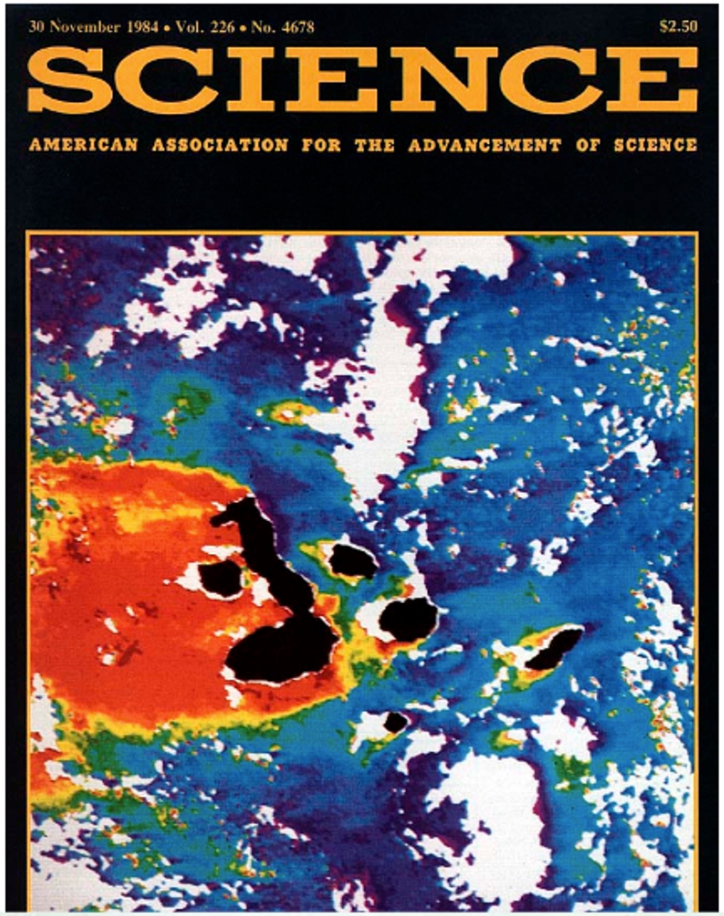
In order to employ the Nimbus-7/CZCS to estimate the concentration of phytoplankton pigments in the oceans, it is necessary to remove the effects of the intervening atmosphere from the satellite imagery. The principal effect of the atmosphere is a loss in contrast caused by the addition of a substantial amount of radiance (path radiance) to that scattered out of the water. Although image enhancement techniques can be used to regain some of the contrast for pattern recognition purposes, the extraction of pigment concentrations requires that the radiance originating from beneath the sea surface be accurately extracted from the imagery (Gordon and Clark, 1980). A technique has been developed (Gordon, 1978) which shows considerable promise (Gordon et al, 1980) for removal of these atmospheric effects and is presently being implemented into the NASA processing system. The basic idea of this atmospheric correction algorithm is two-fold. First, it is noted that to an excellent approximation the total radiance L_T^λ at the sensor at a wavelength λ can be partitioned into a Rayleigh scattering component L_R^λ, an aerosol scattering component L_A^λ, and a component $t^\lambda L_W^\lambda$ backscattered out of the ocean and transmitted through the atmosphere, i.e.

$$L_T^\lambda = L_R^\lambda + L_A^\lambda + t^\lambda L_W^\lambda \quad (1)$$

where L_W^λ is the radiance backscattered out of the ocean and t^λ is the diffuse transmittance of the atmosphere. t^λ is used rather than the direct transmittance to take into account the fact that when the sensor is viewing a given pixel some of the radiance it receives originated from neighboring pixels. t^λ is given by

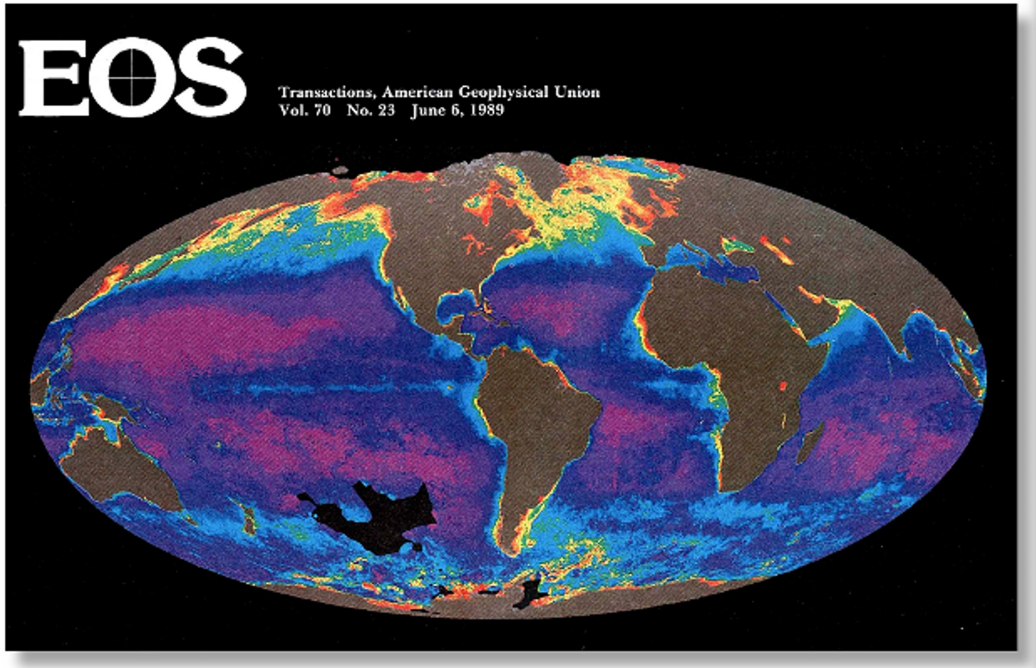
J. F. R. Gower (ed.), *Oceanography from Space*

revolutionized perceptions of the ocean



Satellite Color Observations of the Phytoplankton Distribution in the Eastern Equatorial Pacific During the 1982–1983 El Niño

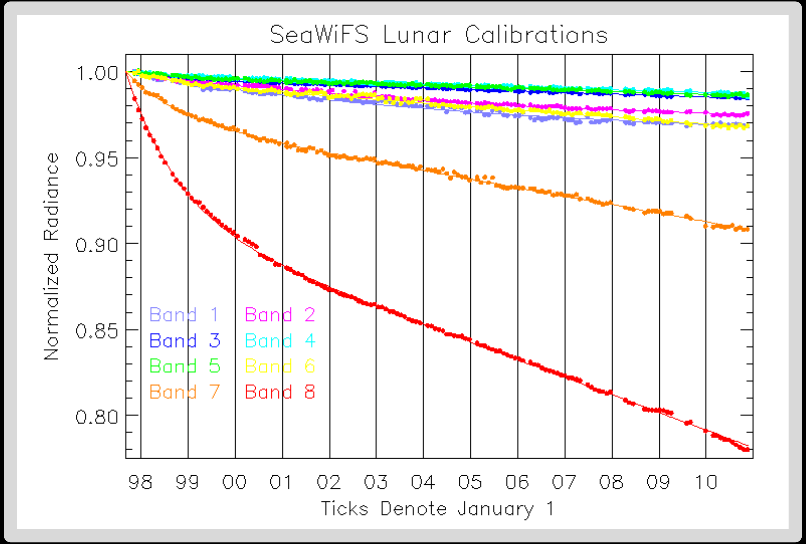
first ever look at global distribution of marine phytoplankton, ocean productivity

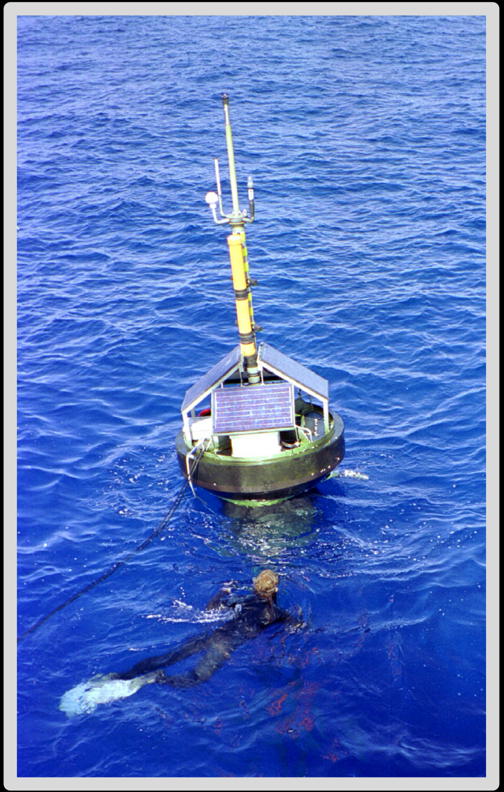


Feldman et al. 1984 and 1989

SeaWiFS 1997-2010

- lunar calibration
- system vicarious calibration





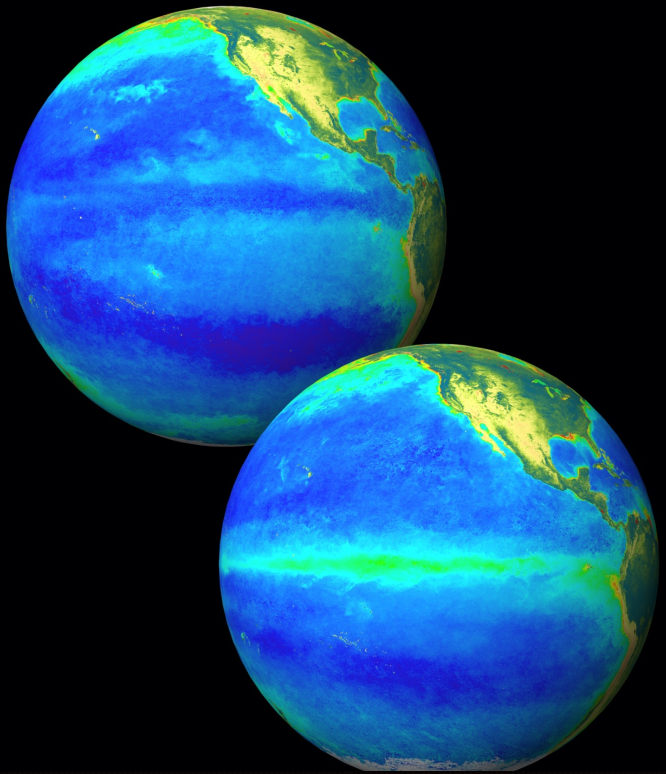
- black pixel assumption revisited
- spectral inversion modeling
- coupled atmosphere-ocean retrievals
- wind speed dependent Sun glint mask
- ocean bidirectional reflectance

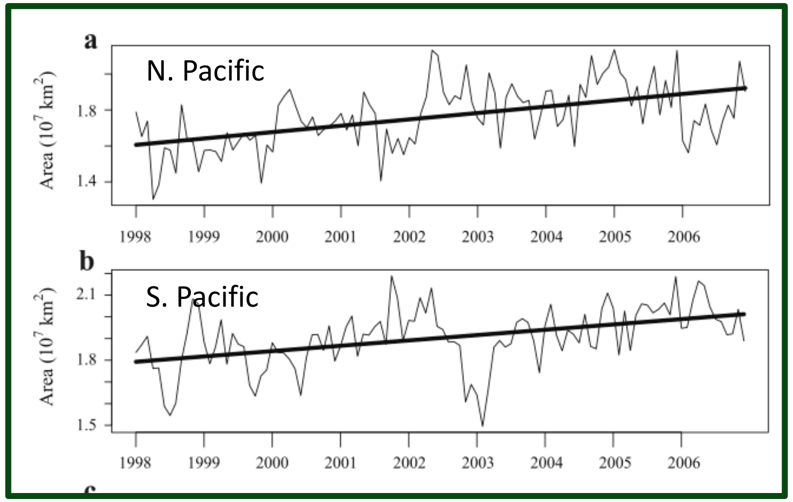
metric	CZCS	SeaWiFS
primary ocean bands (nm)	443, 520, 550, 670	412, 443, 490, 510, 555, 670, 765, 865
nadir res.	825 m	1100 m
nadir swath	1636 km discontinuous operation	1500 km GAC (2-day global) 2875 km LAC
tilt	$\pm 20^{o}$ in 2^{o} increments	$\pm 20^{o}$
det. per band	1	4 (TDI) = 1
digitization	8 bits	10 bits GAC 12 bits LAC

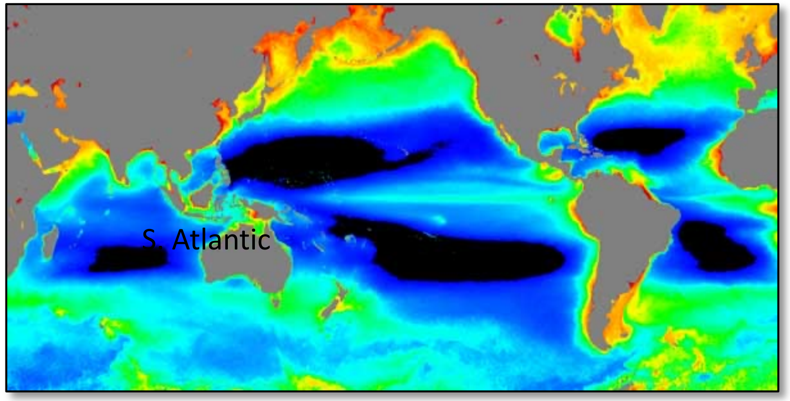
+ aquatic inherent optical properties
+ carbon: POC, PIC
+ photosynthetically available radiation

Biospheric Primary Production During an ENSO Transition

Michael J. Behrenfeld,[1*] James T. Randerson,[2] Charles R. McClain,[1] Gene C. Feldman,[1] Sietse O. Los,[3] Compton J. Tucker,[1] Paul G. Falkowski,[4] Christopher B. Field,[5] Robert Frouin,[6] Wayne E. Esaias,[1] Dorota D. Kolber,[4] Nathan H. Pollack[7]





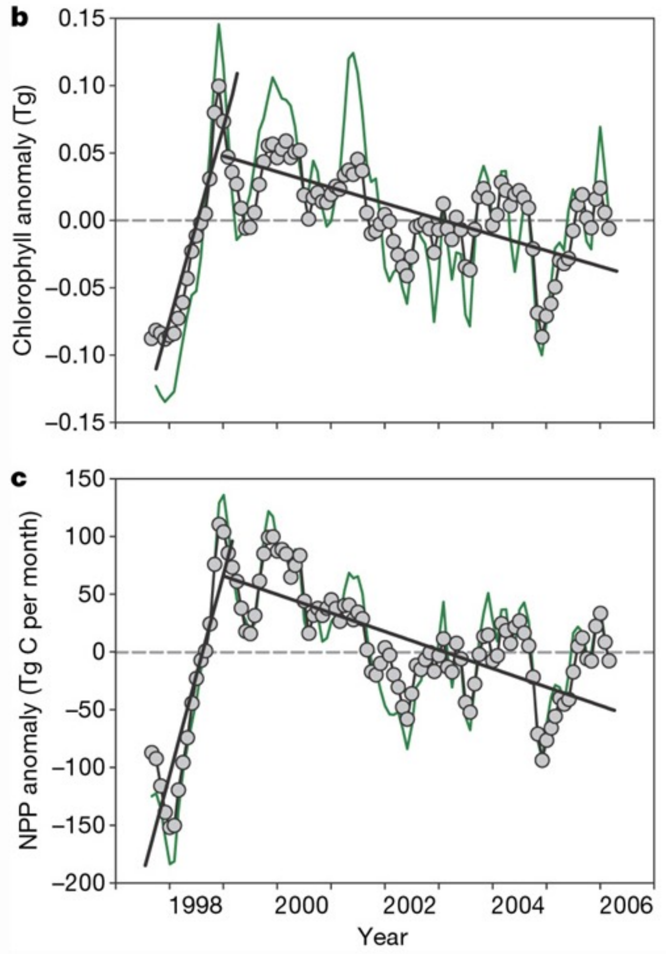


Polivina et al. 2008, Geophy. Res. Letters

Climate-driven trends in contemporary ocean productivity

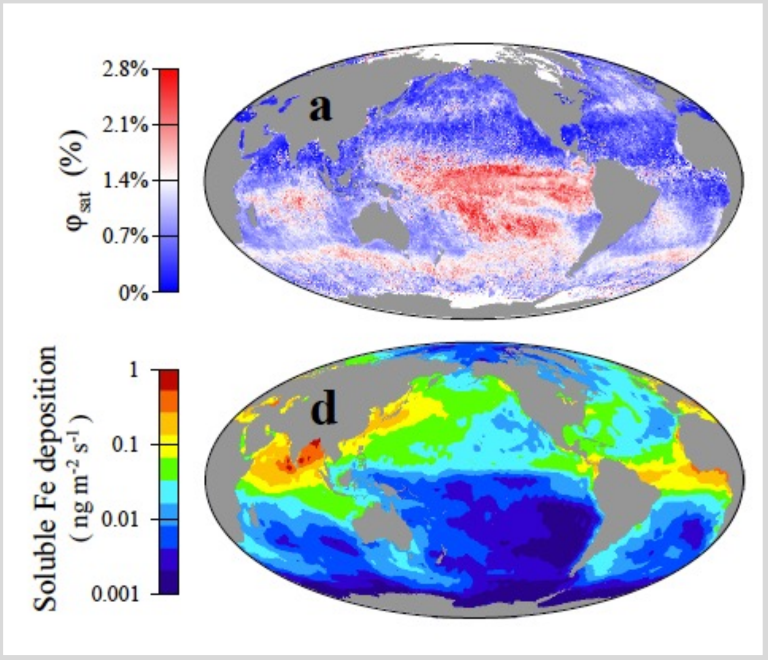
nature

Michael J. Behrenfeld[1], Robert T. O'Malley[1], David A. Siegel[3], Charles R. McClain[4], Jorge L. Sarmiento[5], Gene C. Feldman[4], Allen J. Milligan[1], Paul G. Falkowski[6], Ricardo M. Letelier[2] & Emmanuel S. Boss[7]



MODIS
1999-present

- Fluorescence band
- SWIR for turbid water
- 250 & 500 m atmosphere & land bands



Behrenfeld et al. 2009, BGS

metric	CZCS	SeaWiFS	MODIS
primary ocean bands (nm)	443, 520, 550, 670	412, 443, 490, 510, 555, 670, 765, 865	412, 443, 488, 531, 547, 667, 678, 748, 869, plus SWIR
nadir res.	825 m	1100 m	1000 m
nadir swath	1636 km discontinuous operation	1500 km GAC (2-day global) 2875 km LAC	2230 km (2-day global)
tilt	$\pm 20^{o}$ in 2^{o} increments	$\pm 20^{o}$	none
det. per band	1	4 (TDI) = 1	10
digitization	8 bits	10 bits GAC 12 bits LAC	12 bits

+ fluorescence line height
+ photosynthetic quantum yield
+ turbidity index

SGLI 2017-present

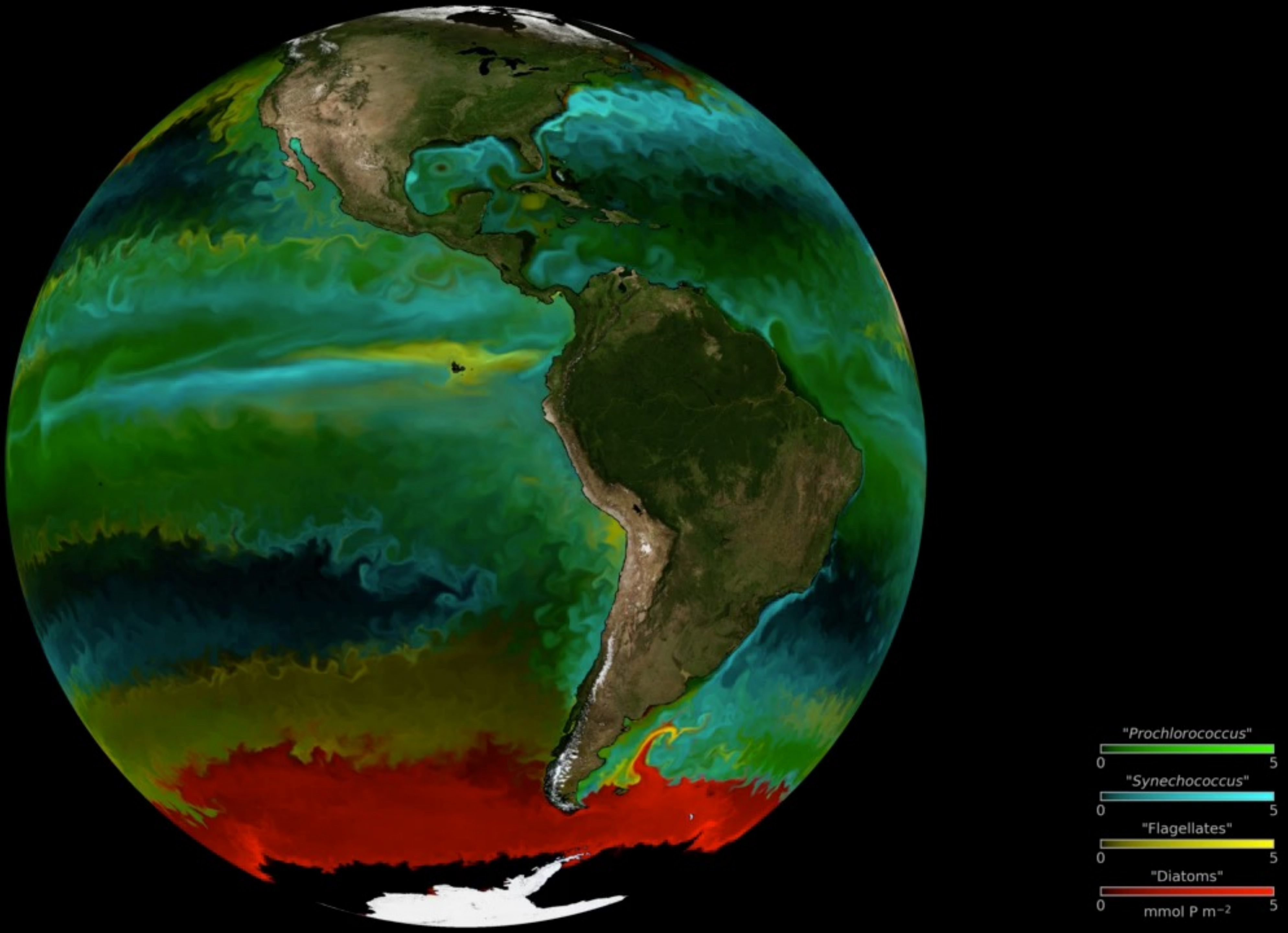
OLCI 2016-present

+ GOCI, HICO, MERIS, MOS, OCM, OSMI, SeaHaWK, VIIRS, others …

metric	CZCS	SeaWiFS	MODIS	SGLI	OLCI
primary ocean bands (nm)	443, 520, 550, 670	412, 443, 490, 510, 555, 670, 765, 865	412, 443, 488, 531, 547, 667, 678, 748, 869, plus SWIR	380, 412, 443, 490, 529, 566, 672(P), 763, 867(P), 1055, SWIR (IRS)	400, 412, 443, 490, 510, 560, 620, 665, 674, 682, 709, …, 765, …, 866, 1013
nadir res.	825 m	1100 m	1000 m	250 m full 1000 m red.	300 m full 1200 m red.
nadir swath	1636 km discontinuous operation	1500 km GAC (2-day global) 2875 km LAC	2230 km (2-day global)	1150 km (3+day global)	1270 km (3+day global)
tilt	$\pm 20^{o}$ in 2^{o} increments	$\pm 20^{o}$	none	none	none
det. per band	1	4 (TDI) = 1	10	pushbroom	pushbroom
digitization	8 bits	10 bits GAC 12 bits LAC	12 bits		

Part 3

Where are we going?


"Prochlorococcus"
0
5
"Synechococcus"
0
5
"Flagellates"
0
5
"Diatoms"
0
mmol P m⁻²
5

global *hyper*spectral

cubesats

LIDAR

polarimetry

geostationary

high spatial resolution

L8 tomorrow:

"PACE in a consumer's market"

NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission

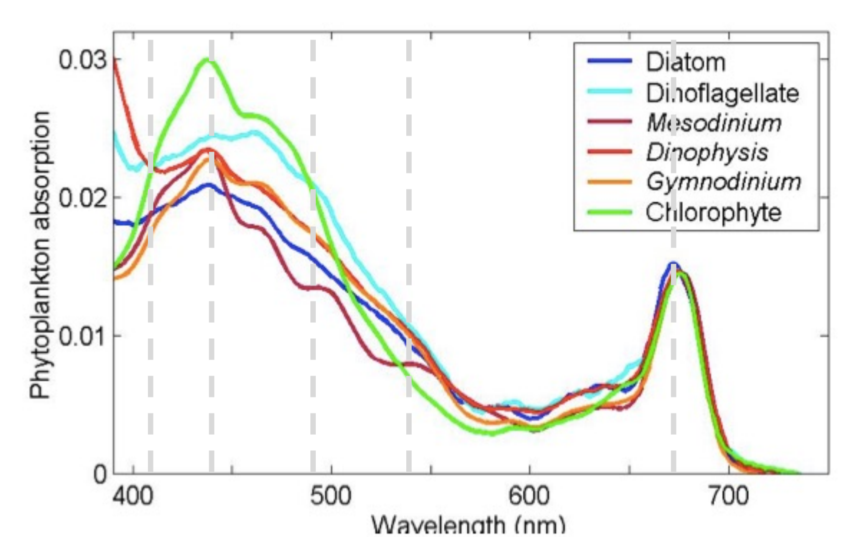
The PACE Ocean Color Instrument (OCI):

- (320) 340 – 890 nm, 5 nm resolution, 2.5 nm steps
- plus, 940, 1038, 1250, 1378, 1615, 2130, and 2250 nm
- *single science pixel to mitigate image striping*
- 1 – 2 day global coverage
- ground pixel size of 1 km^2 at nadir
- ± 20^o fore/aft tilt to avoid Sun glint
- twice monthly lunar calibration
- January 2024 launch

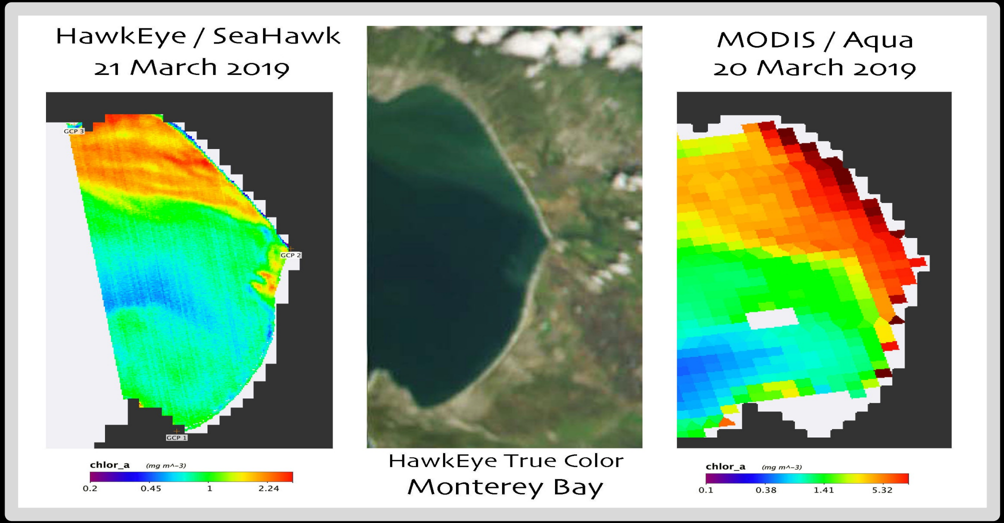
2 contributed multi-angle polarimeters:

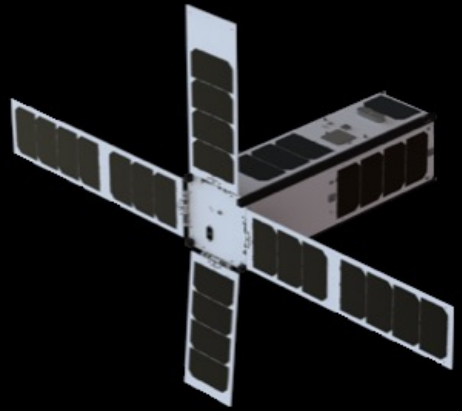
- HARP-2 (UMBC)
  4 visible-NIR bands
  Wide swath and hyper-angular
  2.5-km at nadir
- SPEXone (SRON/Airbus)
  Hyperspectral UV-NIR and narrow swath
  5 angles
  3 km at nadir

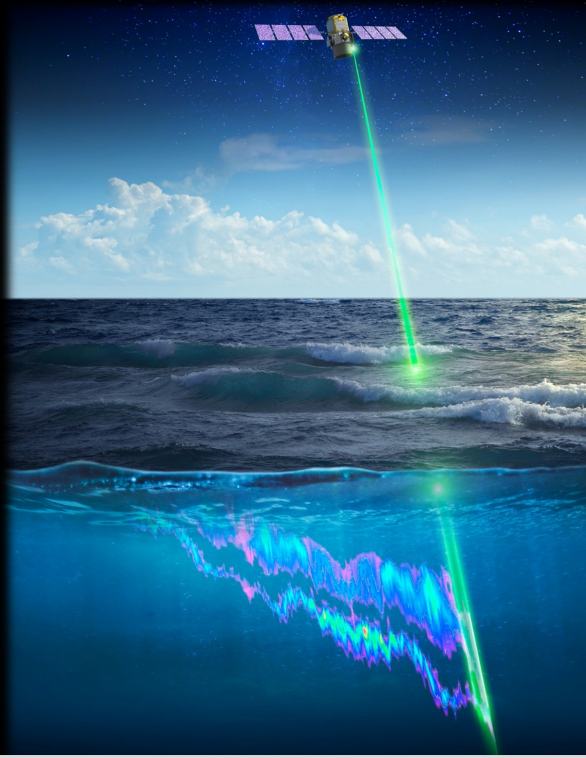
https://pace.gsfc.nasa.gov
@NASAOcean



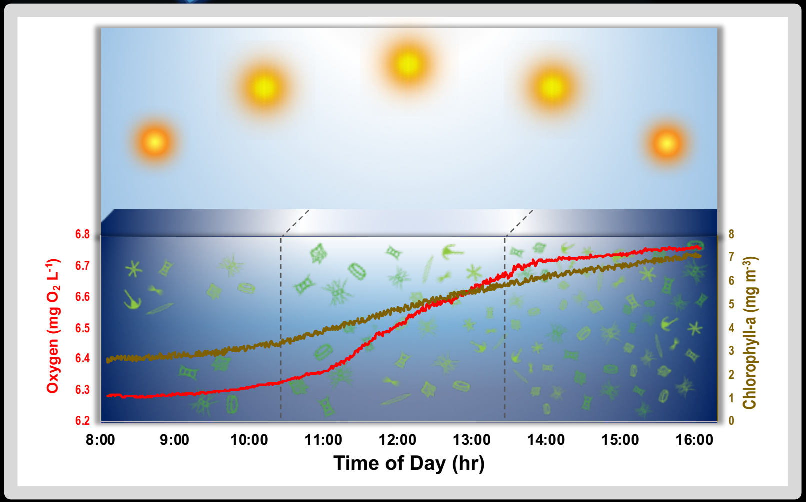
Looking forward

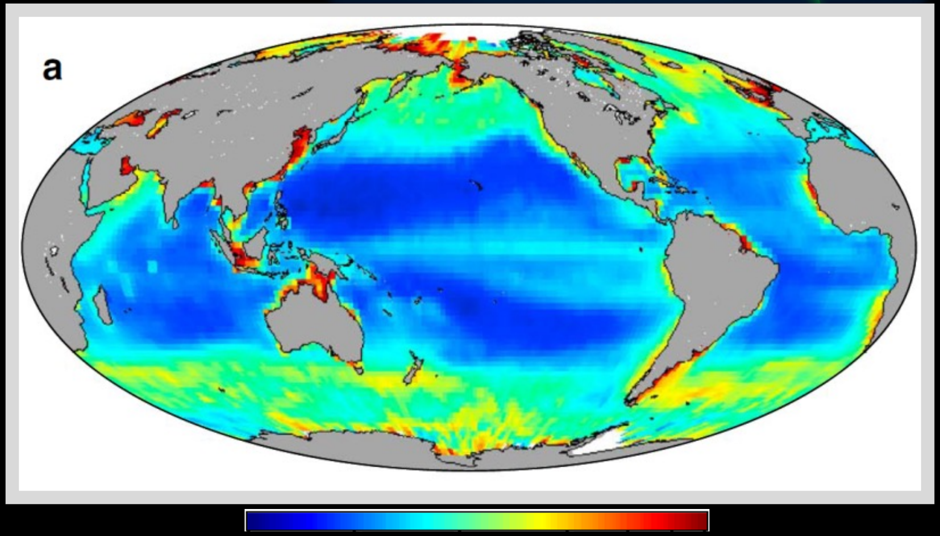




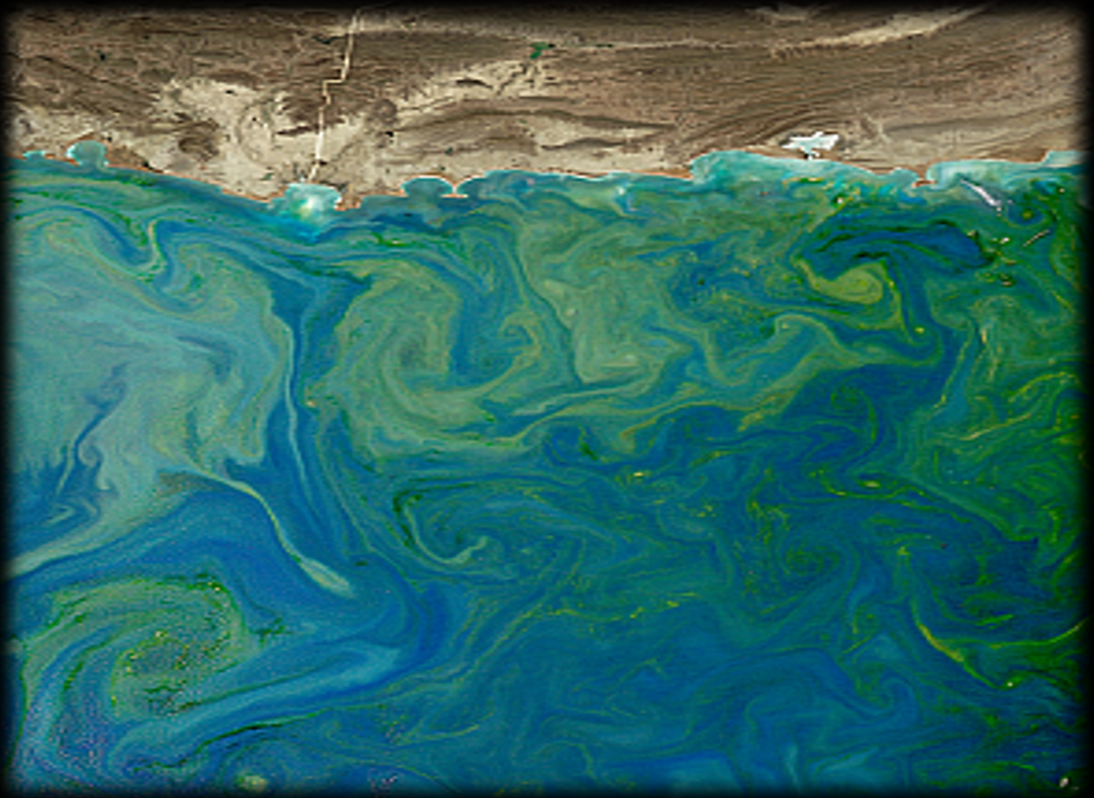


GLIMR





Phytoplankton Carbon (mg m^{-3})



see also: McClain et al. 2022, Frontiers in Remote Sensing