A brief history of the **P**lankton **A**erosol **C**loud ocean **E**cosystem mission (PACE) and some notes about what is next in Earth System Science remote sensing.

By

Carlos E. Del Castillo, Ph.D

Legal Disclaimer #1: My opinions do not represent those of my employer, but I am right.
Legal Disclaimer #2: This presentation was prepared with my private resources.
Provenance: All the material in this presentation is available in public websites and has been presented elsewhere. Most of the stories told here happened before I was hired by my current employer.

Summary:

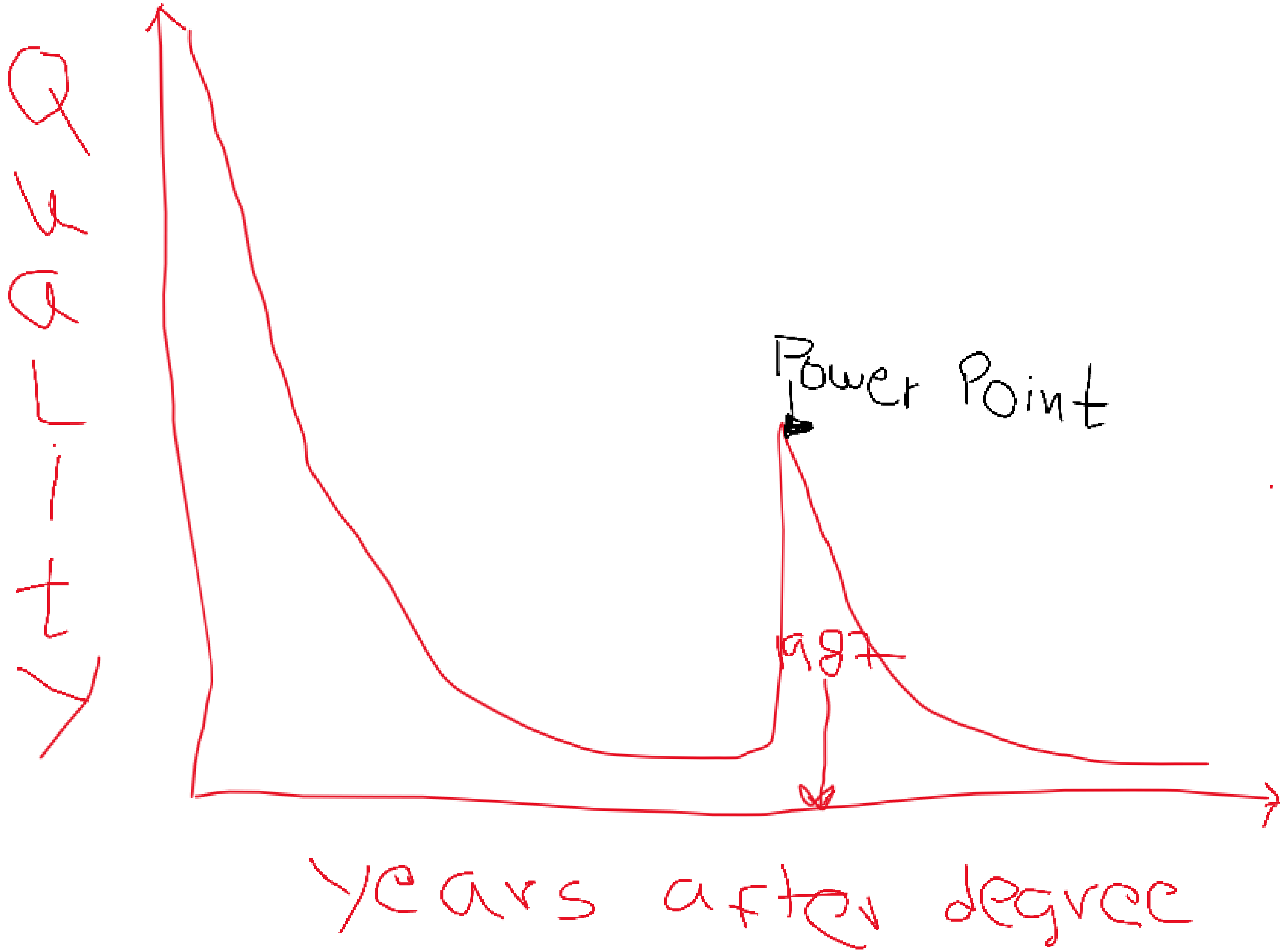
1- What is “ocean color”?

2- A brief history of satellite Ocean Color
- -Why satellites?
- -A few examples of valiant and not-so-valiant efforts

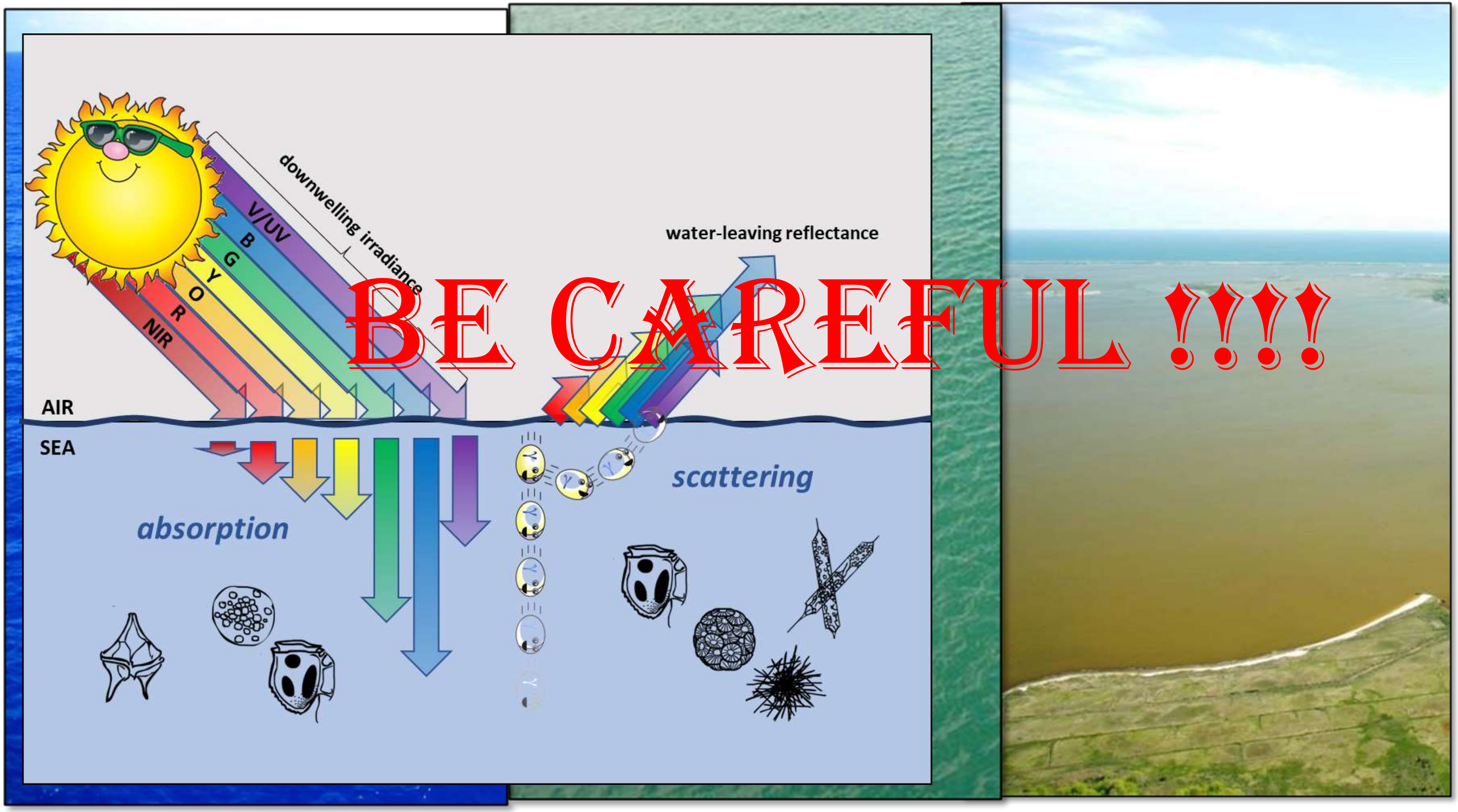
3- ¿Cómo se prepara la morcilla?

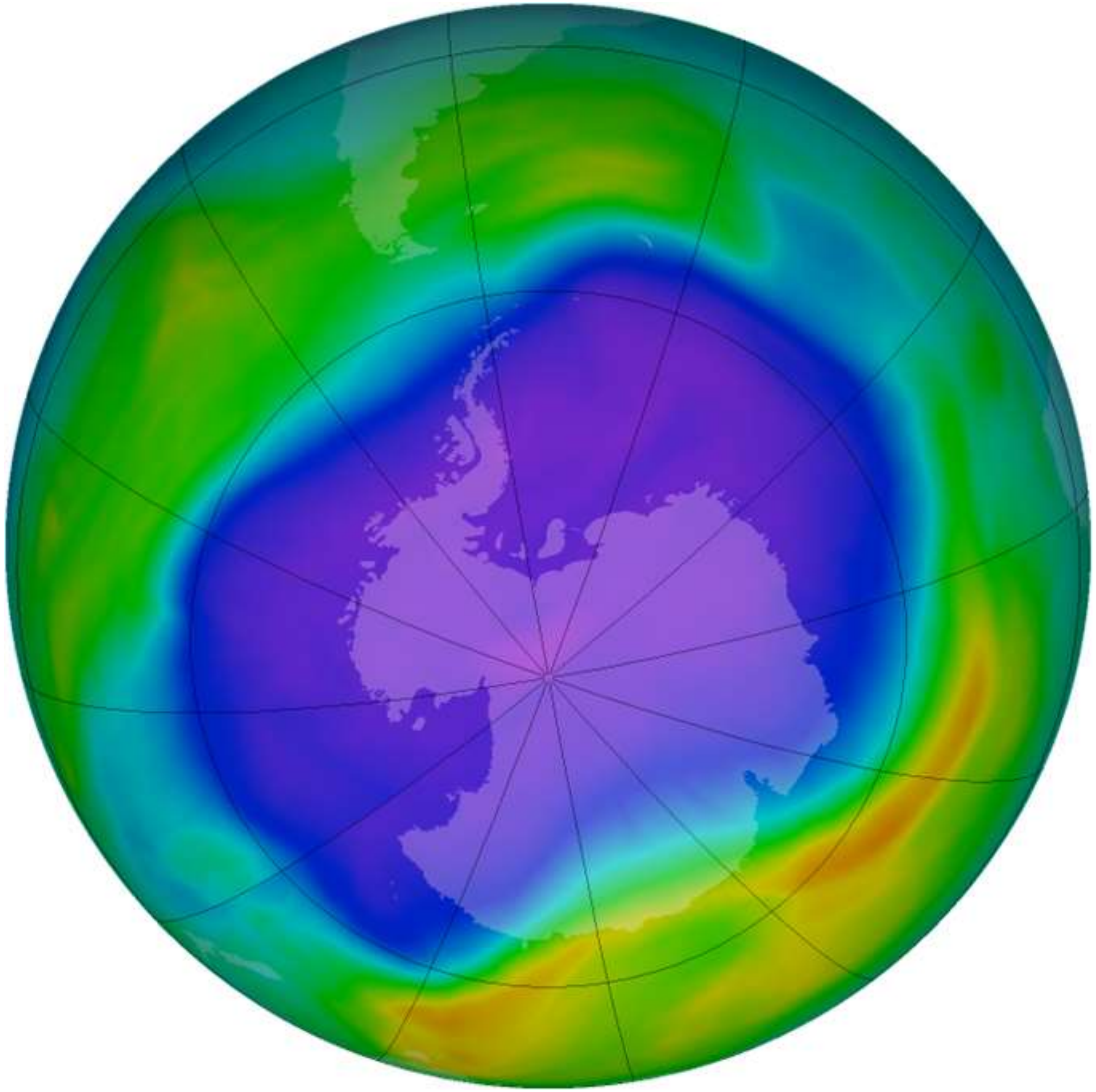
4- PACE (la morcilla)

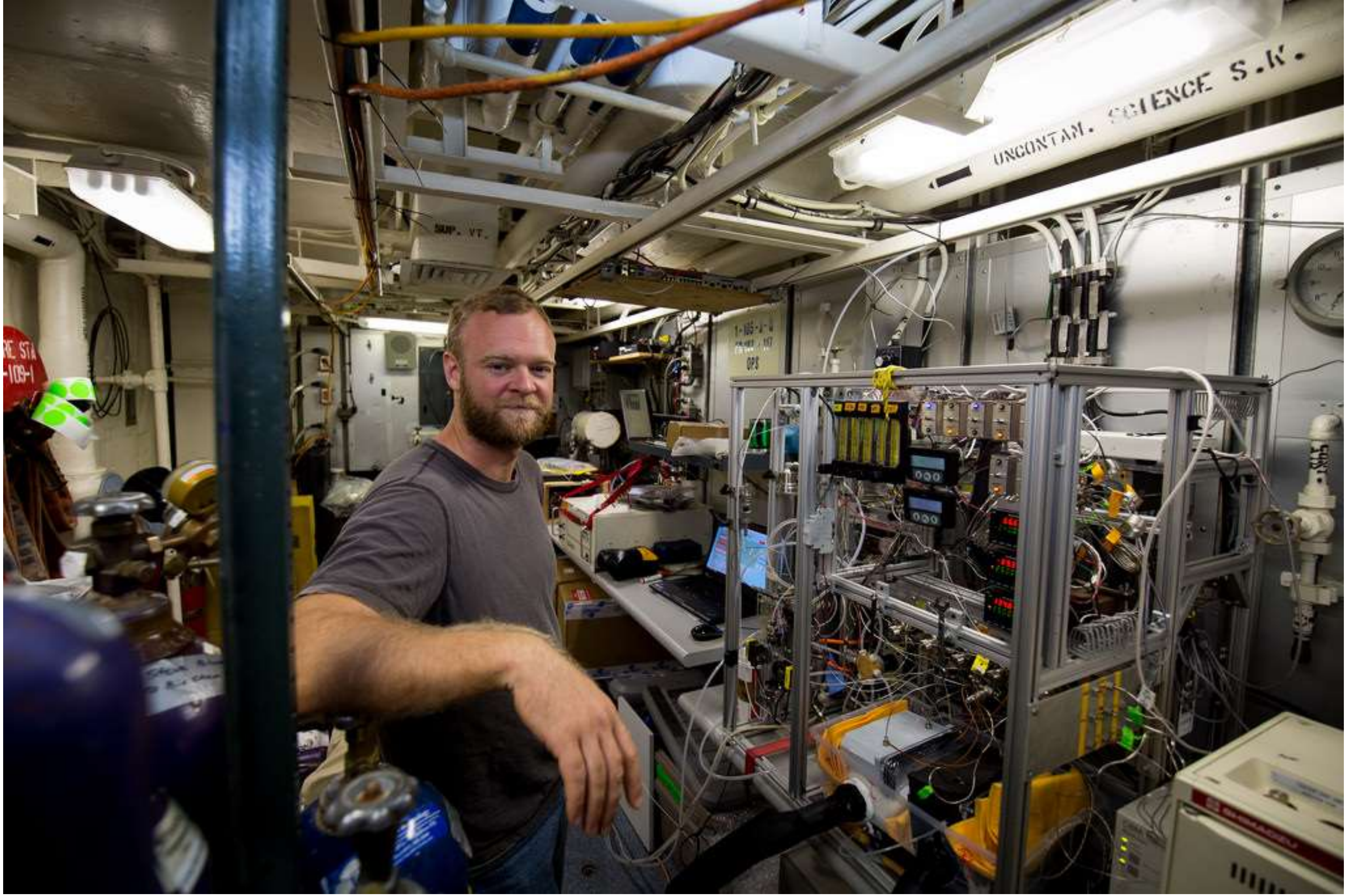
Quality of presentation vs. experience after terminal degree

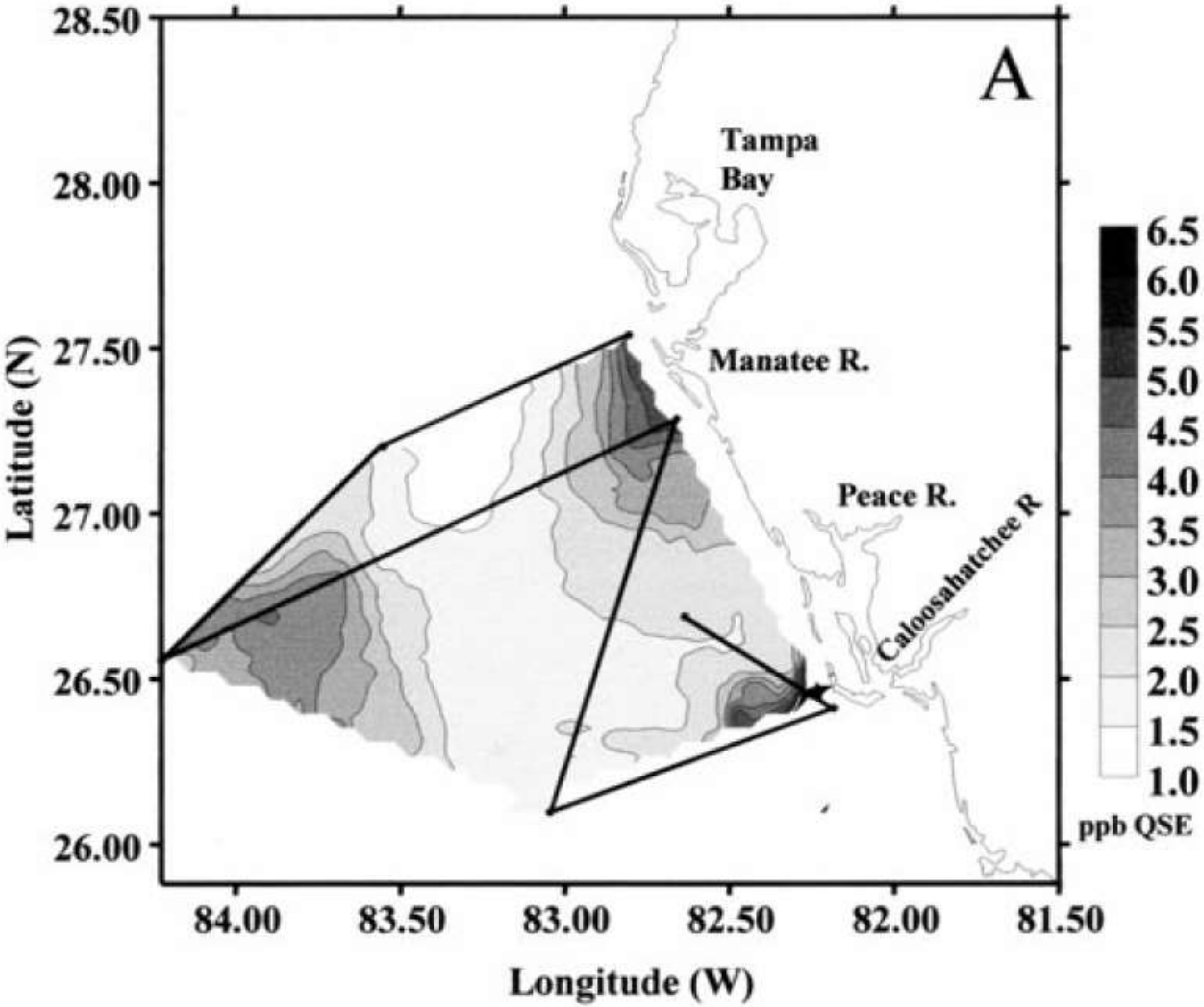


Ocean Color

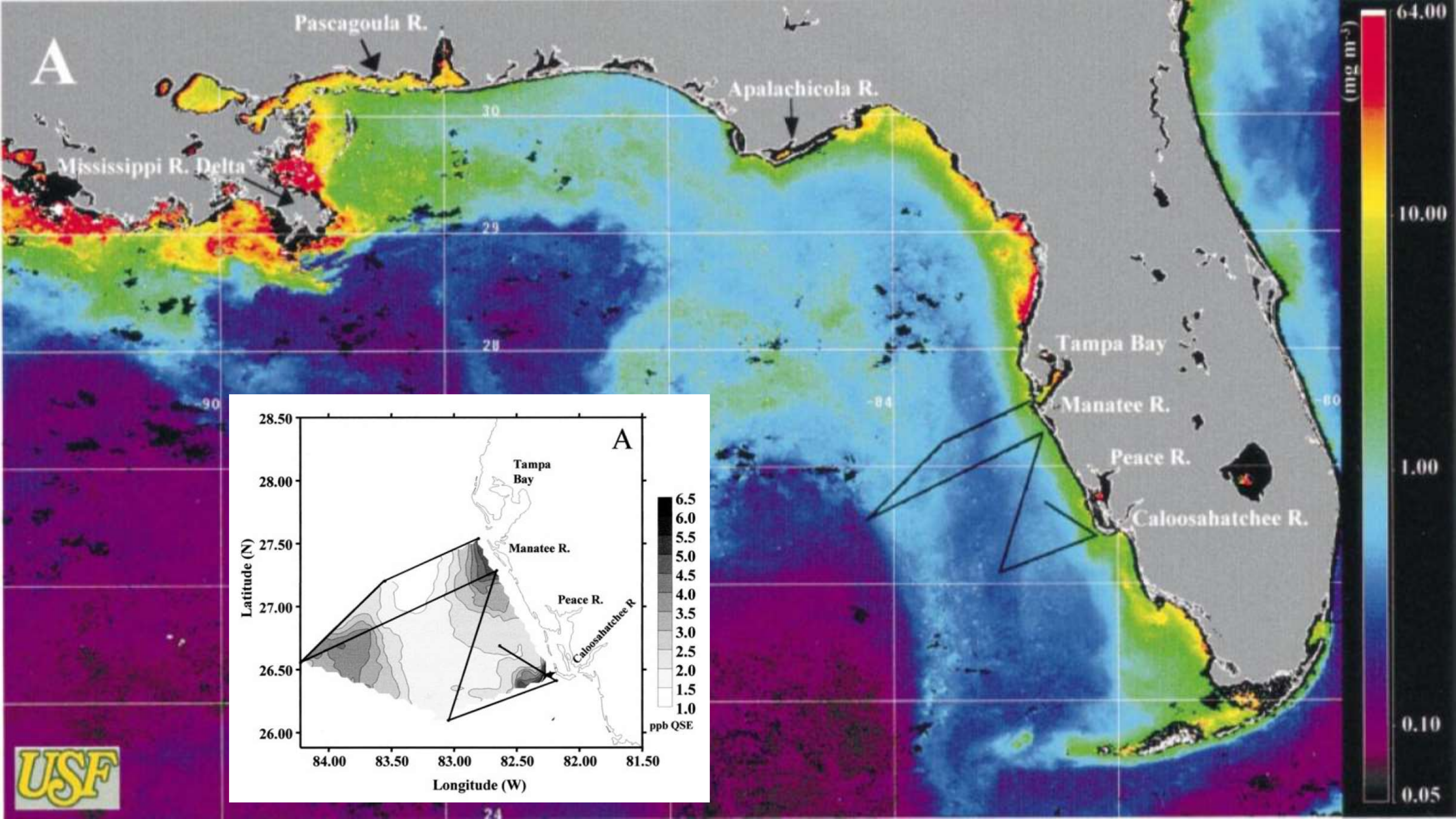

downwelling irradiance
V/UV
B
G
Y
O
R
NIR
water-leaving reflectance
AIR
SEA
absorption
scattering
BE CAREFUL !!!!




UNCONTAM. SCIENCE S.K.



A
Tampa
Bay
Manatee R.
Peace R.
Caloosahatchee R
28.50
28.00
27.50
27.00
26.50
26.00
Latitude (N)
84.00
83.50
83.00
82.50
82.00
81.50
Longitude (W)
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
ppb QSE

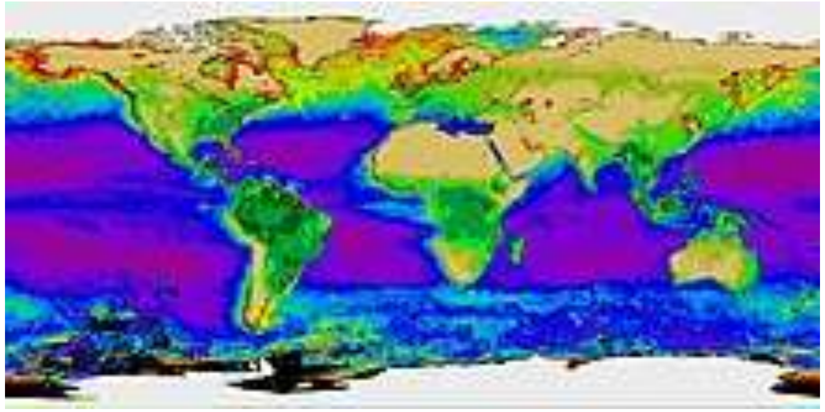


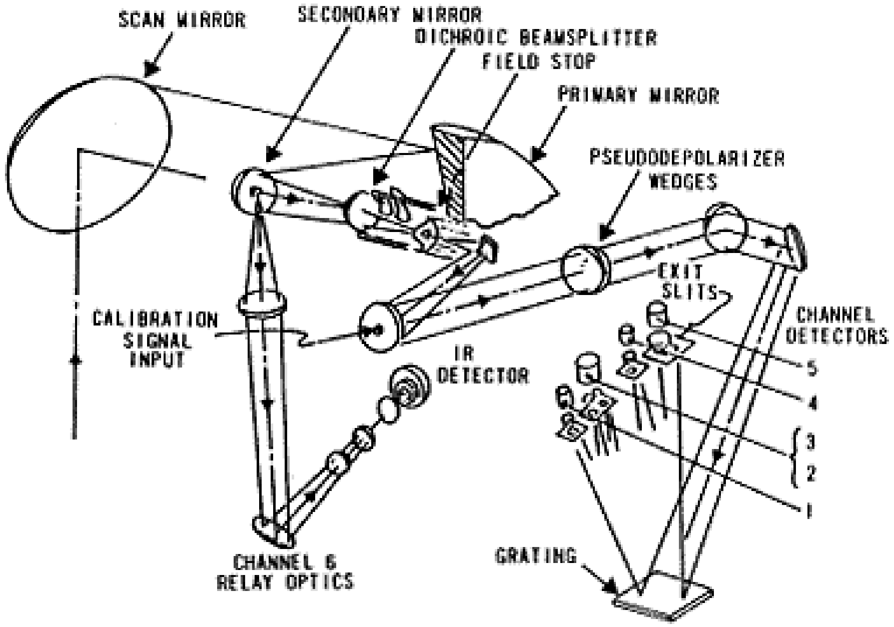
A
Pascagoula R.
Apalachicola R.
Mississippi R. Delta
Tampa Bay
Manatee R.
Peace R.
Caloosahatchee R.
30
29
28
24
-90
-84
-80
(mg m-3)
64.00
10.00
1.00
0.10
0.05
USF
A
Latitude (N)
Longitude (W)
Tampa Bay
Manatee R.
Peace R.
Caloosahatchee R
28.50
28.00
27.50
27.00
26.50
26.00
84.00
83.50
83.00
82.50
82.00
81.50
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
ppb QSE


A painful example….
S. Friedman, 2008

Coastal Zone Color Scanner (CZCS)

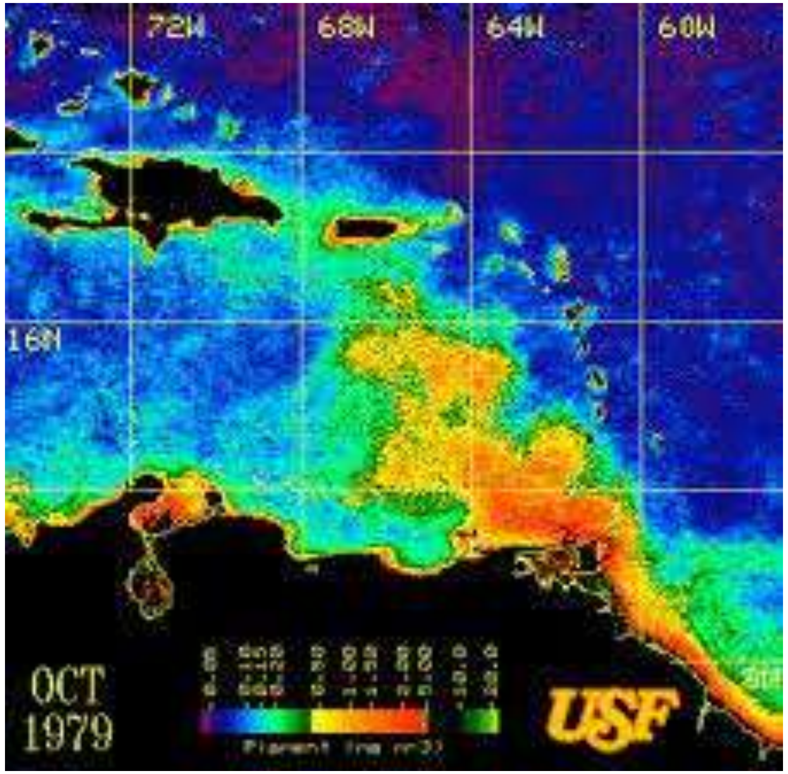
“CZCS was one of eight instruments flown on the Nimbus-7 spacecraft, which was launched on October 24th, 1978. The spacecraft was in a Sun-synchronous orbit, with an inclination of 104.9 degrees, and a nominal altitude of 955 km. It had an equatorial crossing time of noon, in an ascending orbit. Caput June 22,1986.”





Multiple sensors

443 nm
520 nm
550 nm
670 nm
1150 nm



Sea-viewing Wide Field-of-view Sensor (SeaWiFS)

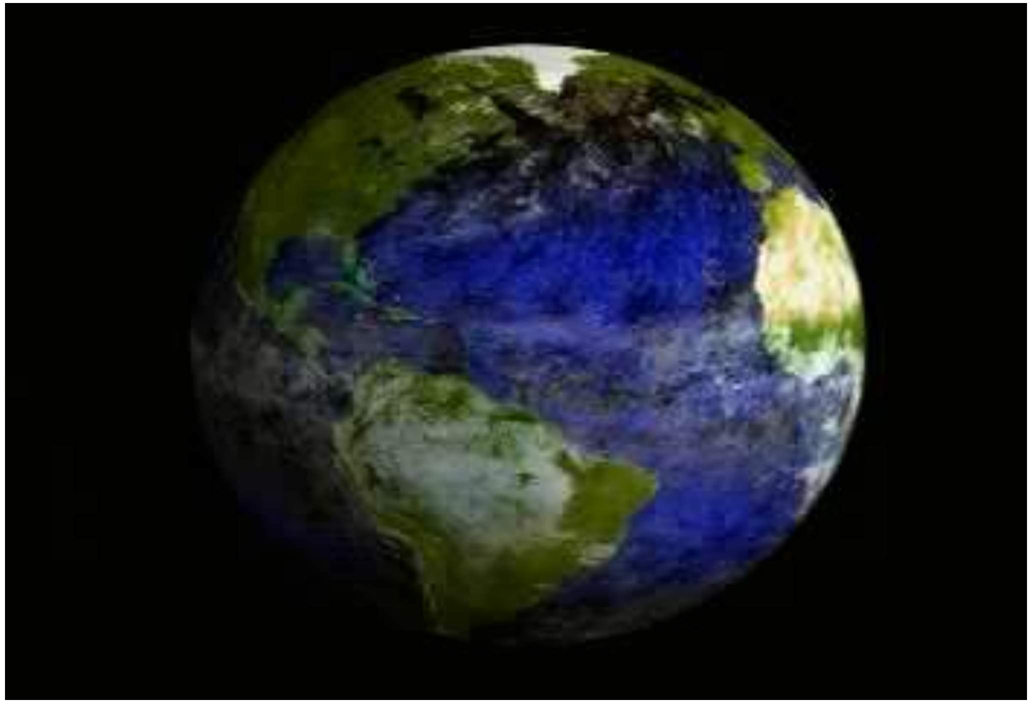
1997-2002

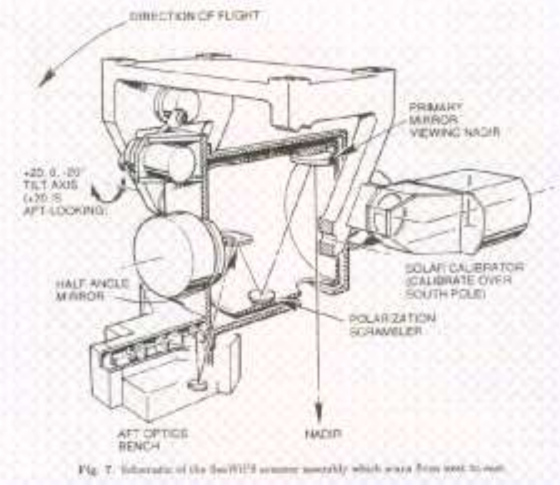
Instrument Bands

Band	Wavelength
1	402-422 nm
2	433-453 nm
3	480-500 nm
4	500-520 nm
5	545-565 nm
6	660-680 nm
7	745-785 nm
8	845-885 nm

Mission Characteristics

Orbit Type	Sun Synchronous at 705 km
Equator Crossing	Noon +20 min, descending
Orbital Period	99 minutes
Swath Width	2,801 km LAC/HRPT (58.3 degrees)
Swath Width	1,502 km GAC (45 degrees)
Spatial Resolution	1.1 km LAC, 4.5 km GAC
Real-Time Data Rate	665 kbps
Revisit Time	1 day
Digitization	10 bits





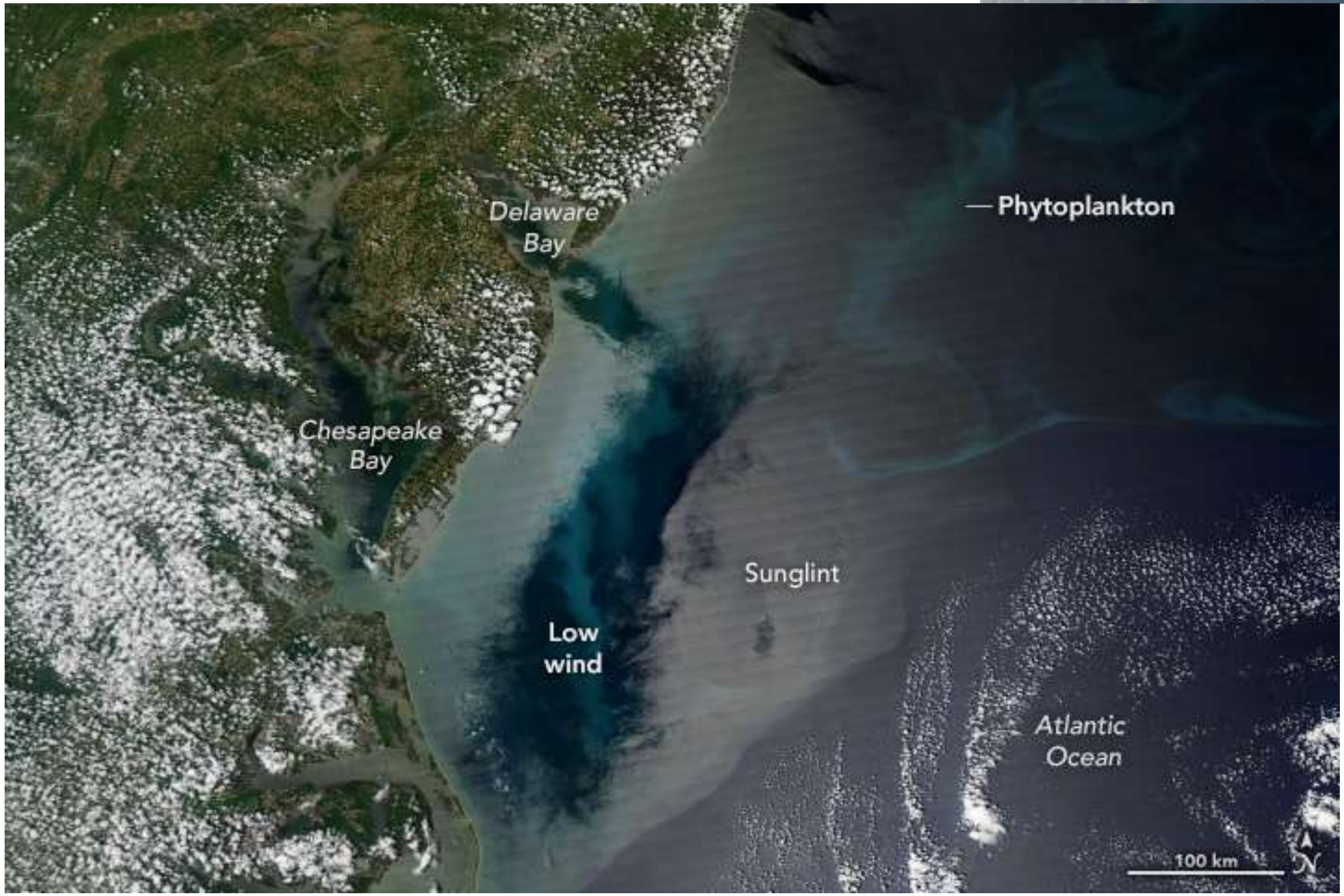
One sensor

Moderate Resolution Imaging Spectroradiometer (MODIS)

The first MODIS instrument, with a 10:30 a.m. equatorial crossing time, was launched aboard Terra in 1999; the second MODIS instrument, with a 1:30 p.m. equatorial crossing time, was launched aboard the Aqua platform in 2002.

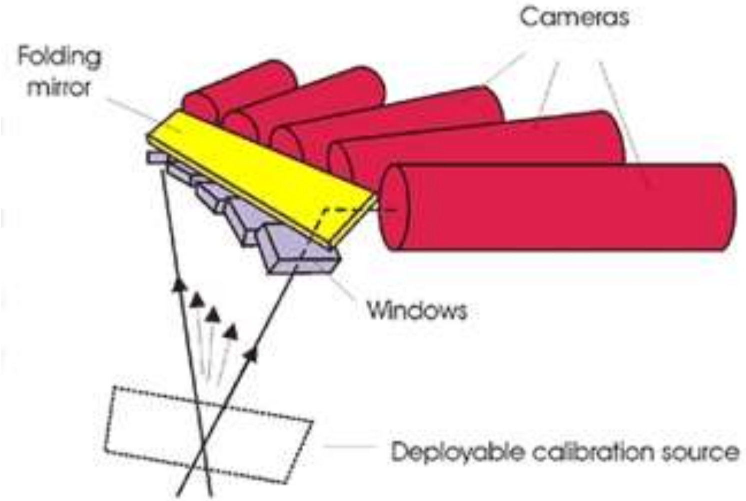
Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required SNR[3]
Land/Cloud/Aerosols Boundaries	1	620 - 670	21.8	128
	2	841 - 876	24.7	201
Land/Cloud/Aerosols Properties	3	459 - 479	35.3	243
	4	545 - 565	29.0	228
	5	1230 - 1250	5.4	74
			7.3	275
			1.0	110
Ocean Color/ Phytoplankton/ Biogeochemistry			44.9	880
			41.9	838
			32.1	802
			27.9	754
			21.0	750
			9.5	910
			8.7	1087
			10.2	586
			6.2	516
Atmospheric Water Vapor			10.0	167
			3.6	57
			15.0	250
Primary Use			Spectral Radiance[2]	Required NE[Δ]T(K)[4]
Surface/Cloud Temperature			0.45(300K)	0.05
			2.38(335K)	0.20
			0.67(300K)	0.07
	23	4.020 - 4.080	0.79(300K)	0.07
Atmospheric Temperature	24	4.433 - 4.498	0.17(250K)	0.25
	25	4.482 - 4.549	0.59(275K)	0.25
Cirrus Clouds Water Vapor	26	1.360 - 1.390	6.00	150(SNR)
	27	6.535 - 6.895	1.16(240K)	0.25
	28	7.175 - 7.475	2.18(250K)	0.25
Cloud Properties	29	8.400 - 8.700	9.58(300K)	0.05
Ozone	30	9.580 - 9.880	3.69(250K)	0.25
Surface/Cloud Temperature	31	10.780 - 11.280	9.55(300K)	0.05
	32	11.770 - 12.270	8.94(300K)	0.05
Cloud Top Altitude	33	13.185 - 13.485	4.52(260K)	0.25
	34	13.485 - 13.785	3.76(250K)	0.25
	35	13.785 - 14.085	3.11(240K)	0.25
	36	14.085 - 14.385	2.08(220K)	0.35

8	405 - 420
9	438 - 448
10	438 - 493
11	526 - 536
12	546 - 556
13	662 - 672
14	673 - 683
15	743 - 753
16	862 - 877



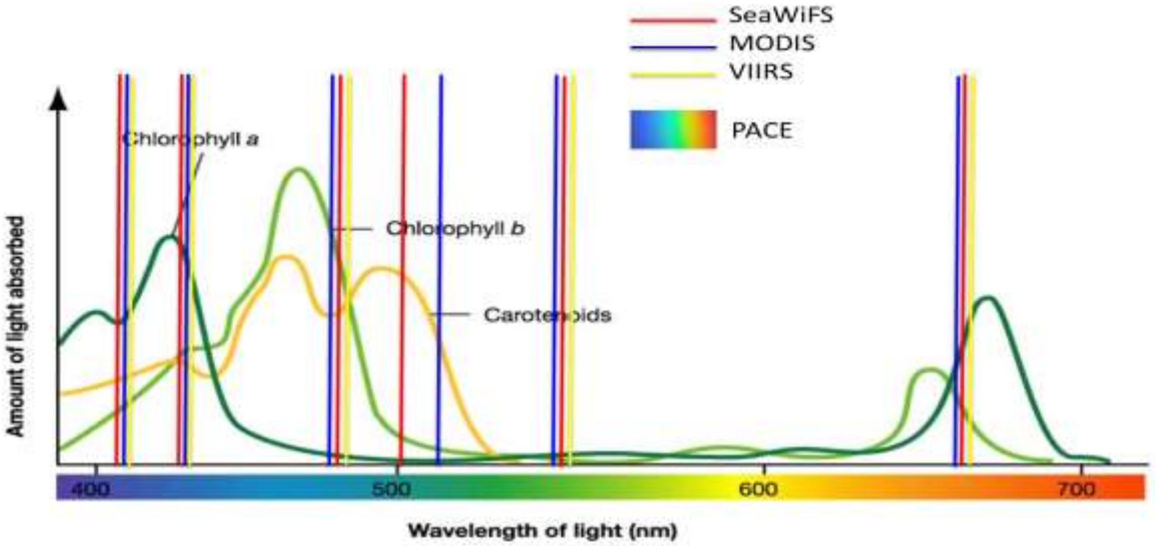
Medium Resolution Imaging Spectrometer (MERIS) 2002-2012

	Band centre	Bandwidth	Potential Applications
1	412.5	10	Yellow substance and detrital pigments
2	442.5	10	Chlorophyll absorption maximum
3	490	10	Chlorophyll and other pigments
4	510	10	Suspended sediment, red tides
5	560	10	Chlorophyll absorption minimum
6	620	10	Suspended sediment
7	665	10	Chlorophyll absorption and fluo. reference
8	681.25	7.5	Chlorophyll fluorescence peak
9	708.75	10	Fluo. Reference, atmospheric corrections
10	753.75	7.5	Vegetation, cloud
11	760.625	3.75	Oxygen absorption R-branch
12	778.75	15	Atmosphere corrections
13	865	20	Vegetation, water vapour reference
14	885	10	Atmosphere corrections
15	900	10	Water vapour, land



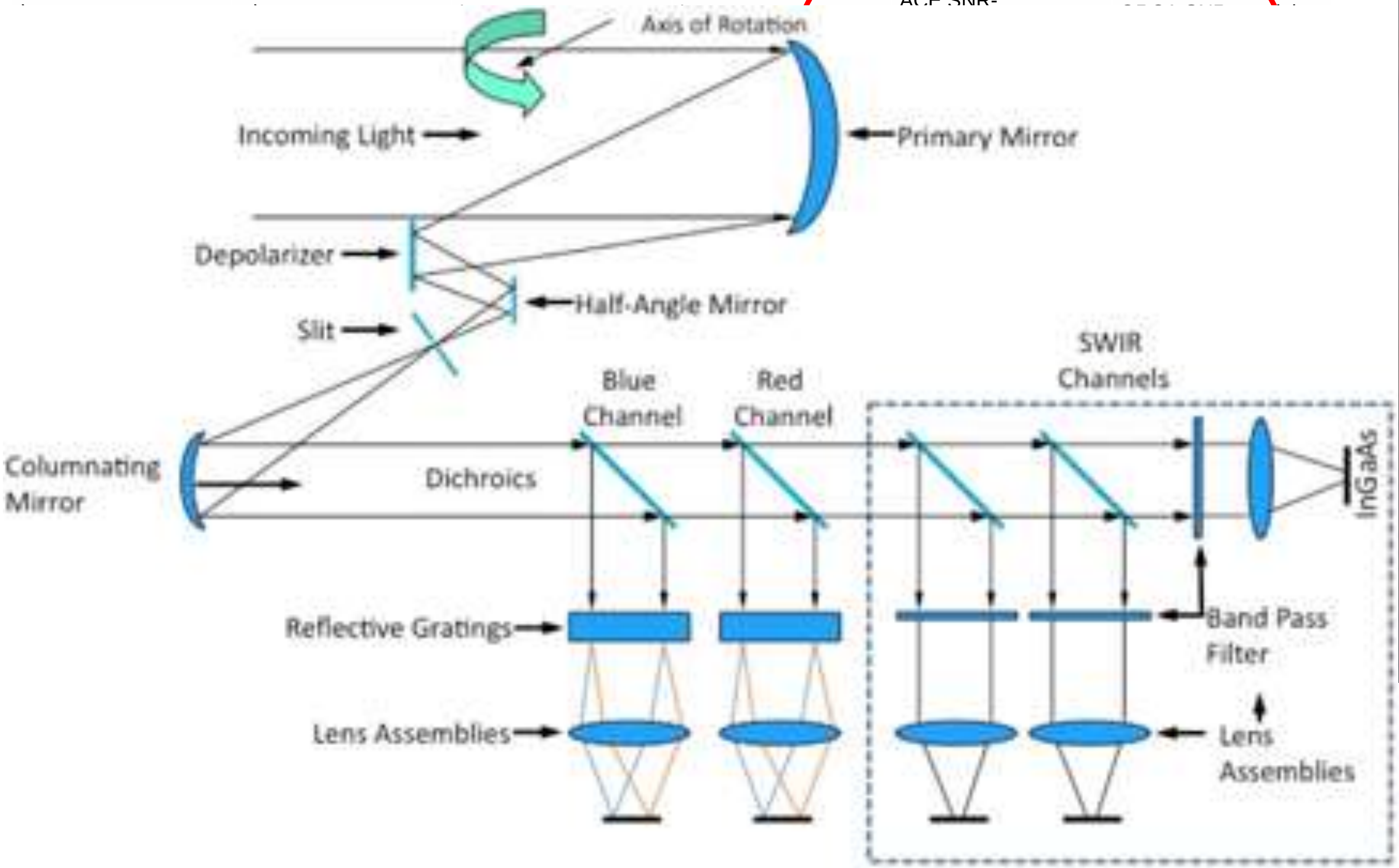
Ocean Radiometer for Carbon Assessment (ORCA)

By late to 1990's –early 2000 it was clear that we needed:
1- More spectral bands (hyperspectral if possible)
2- No artifacts (stripping)
3- High signal-to-noise
4- Sun-glint avoidance
5- Ability to calibrate on orbit
6- Ability to reprocess data

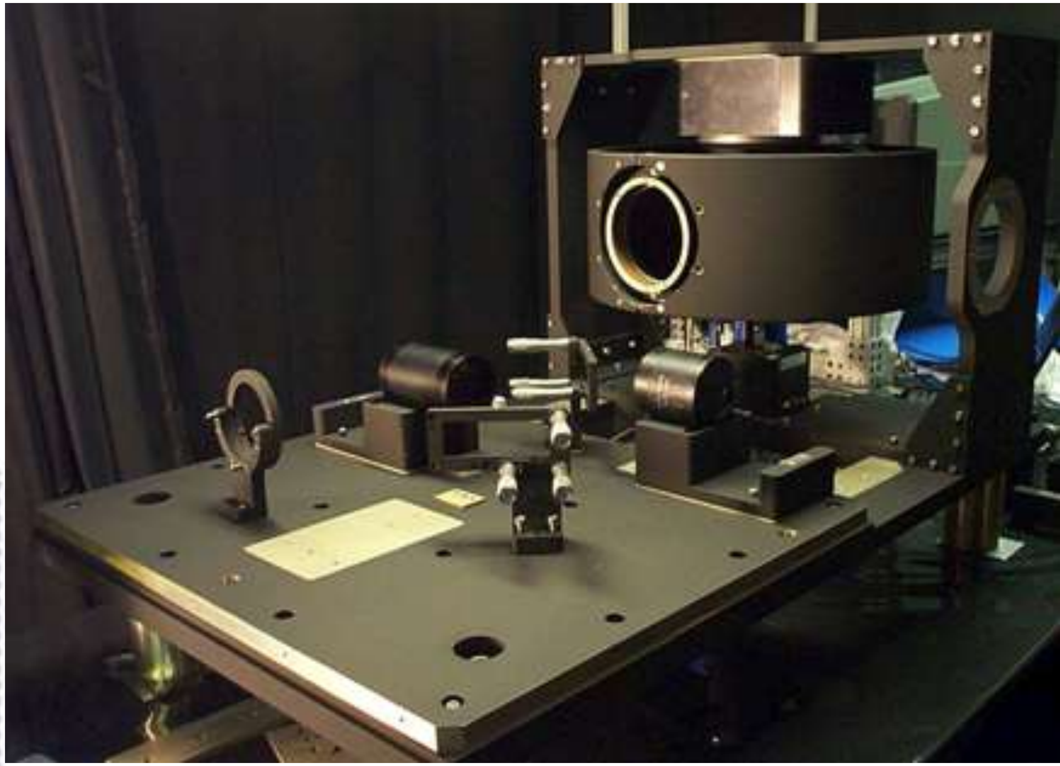


- By 2002, scientists and engineers at NASA GSFC started working on the ORCA concept.
- In 2007, the NRC issued the Decadal Survey for Earth Sciences calling for a new Earth system Science Mission: The Aerosol, Cloud, Ecosystems mission (**ACE**).
- By 2007, GSFC was fairly advanced in the development of ORCA. This was well known in the community.

ORCA vs ACE



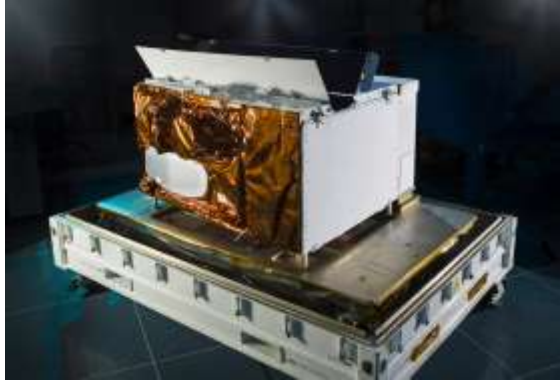
765	40	0.83	43.0	600	2512
820	15	0.59	39.3	600	1200
865	40	0.45	33.3	600	1640
1245	20	0.088	15.8	250	415
1640	40	0.029	8.2	250	273
2135	50	0.008	2.2	100	146



But: ACE was not moving, and we got:

Visible Infrared Imaging Radiometer Suit (VIIRS)

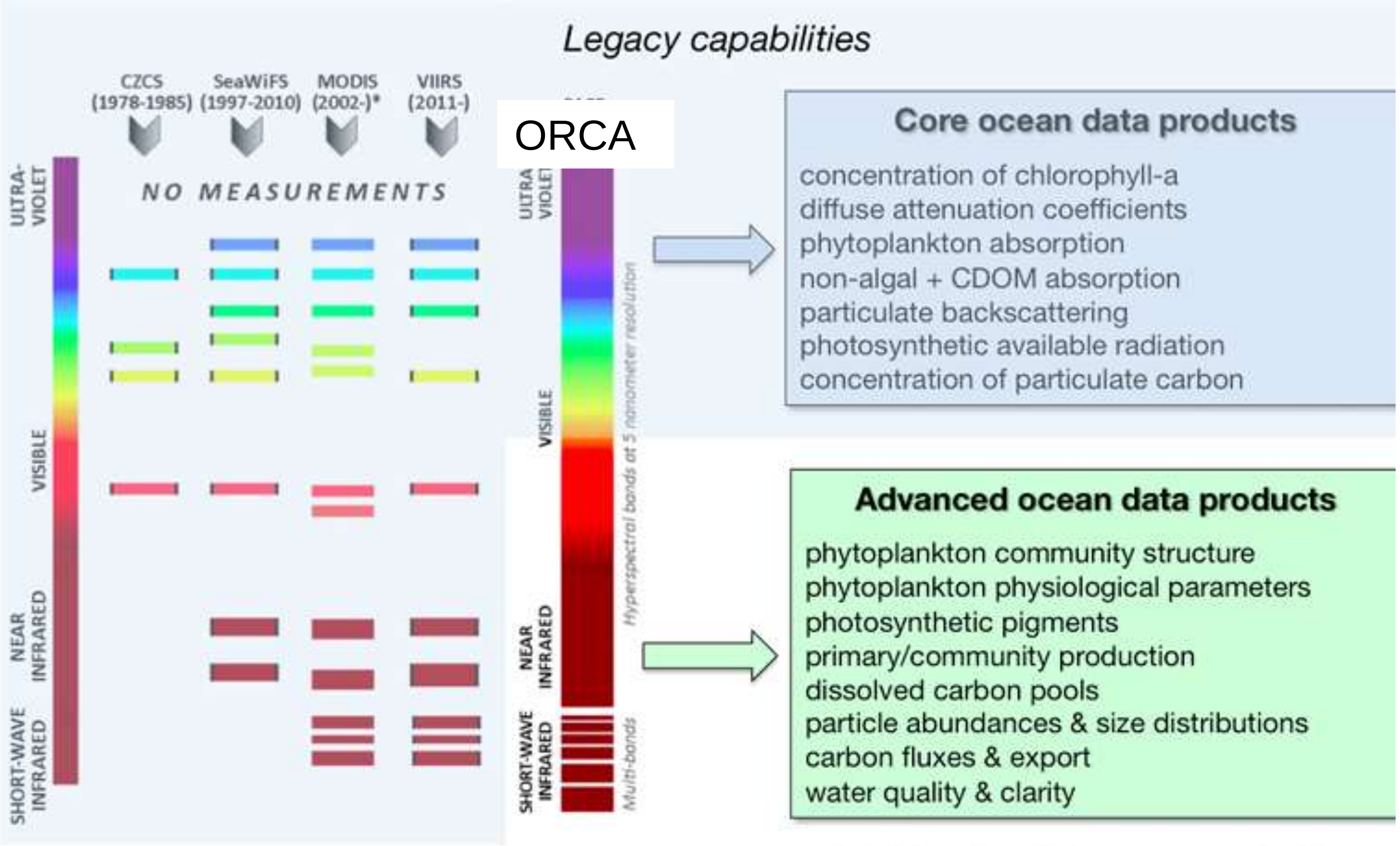
Suomi NPP 2011; NOAA 20 – 2017; NOAA 21- 2022



By late to 1990's –early 2000 it was clear that we needed:

~~1- More spectral bands (hyperspectral if possible)~~
~~2- No artifacts (stripping)~~
3- High signal-to-noise
~~4- Sun-glint avoidance~~
5- Ability to calibrate on orbit
6- Ability to reprocess data

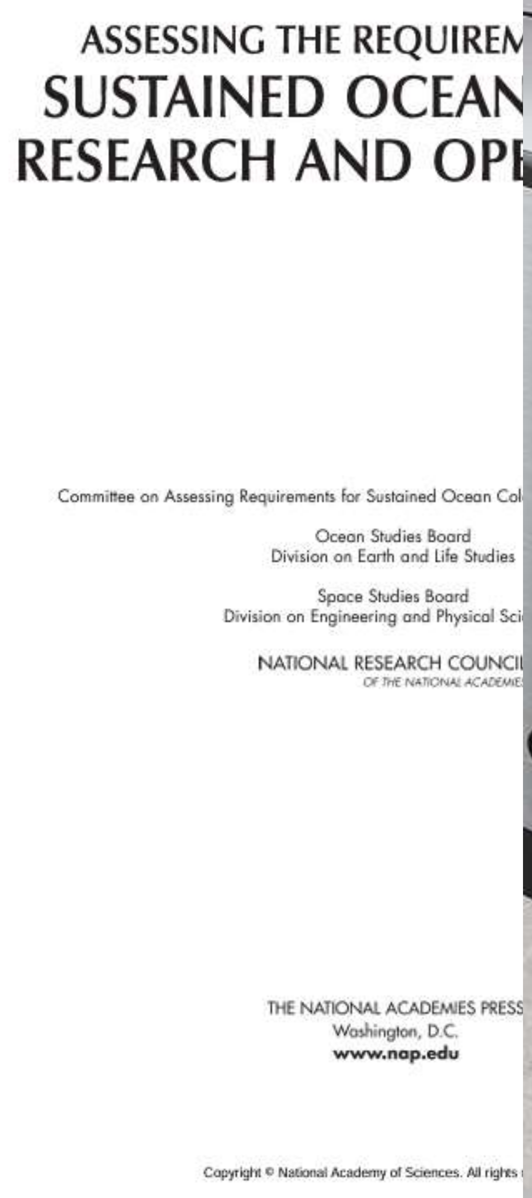
Victims of our success.



From a presentation at Oceans from Space, Venice, Italy, 2012?

“We needed another SeaWiFS, instead we bought a MERIS, two MODIS, and ~~a~~ VIIRS.”

3


ASSESSING THE REQUIREM
SUSTAINED OCEAN
RESEARCH AND OPE

Committee on Assessing Requirements for Sustained Ocean Col

Ocean Studies Board
Division on Earth and Life Studies

Space Studies Board
Division on Engineering and Physical Sci

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIE

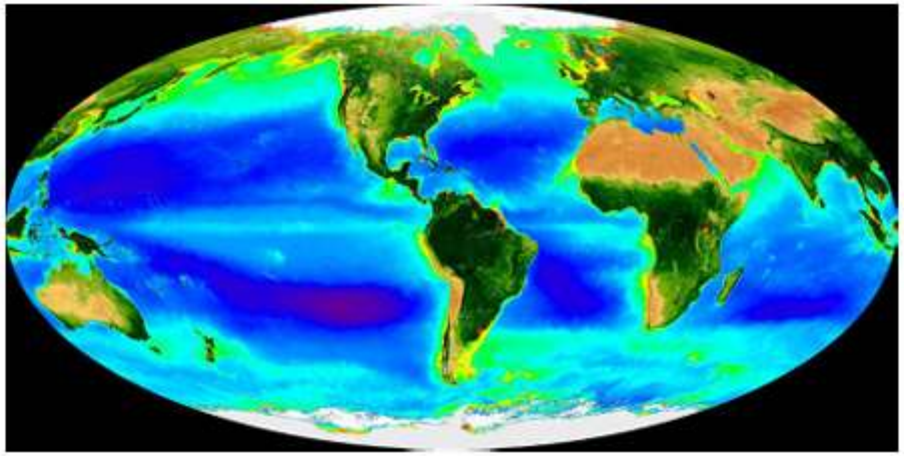
THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

om the community
n general (had QC issues)

nsive)

CE

Pre-Aerosol, Clouds, and ocean Ecosystem (PACE) Mission Science Definition Team Report



October 16, 2012

Whole Mission Concept- constrained budget

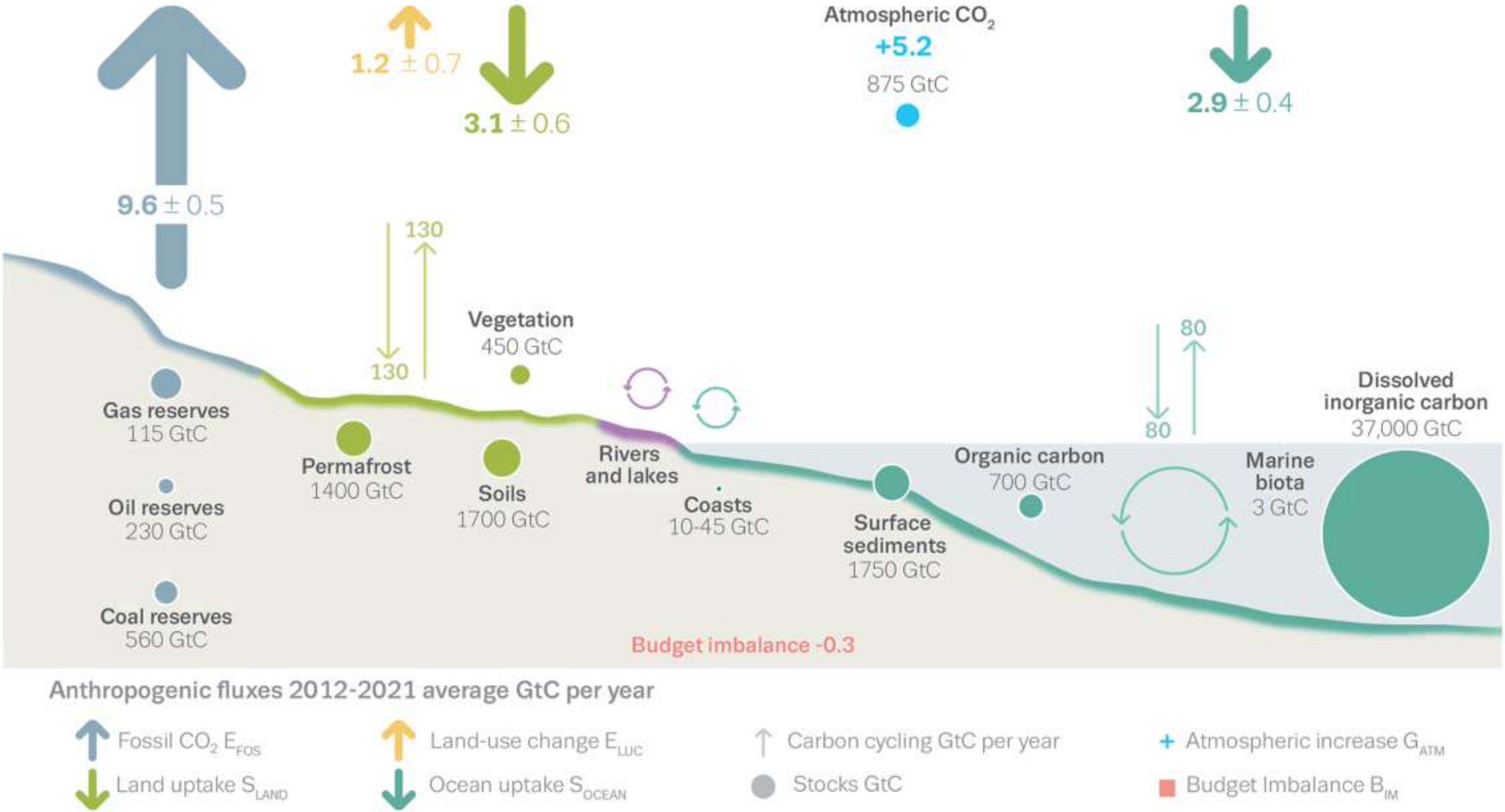
PACE Science Definition Team

By the way…No 3MI!

Chair: Del Castillo, Carlos (Johns Hopkins University Applied Physics Laboratory)
Deputy Chair: Platnick, Steve (NASA Goddard Space Flight Center)

SDT members:
Antoine, David (Laboratoire d'Océanographie de Villefranche, France)
Balch, Barney (Bigelow Laboratory for Ocean Sciences)
Behrenfeld, Mike (Oregon State University)
Boss, Emmanuel (University of Maine)
Cairns, Brian (NASA Goddard Institute for Space Studies)
Chowdhary, Jacek (NASA Goddard Institute for Space Studies)
DaSilva, Arlindo (NASA Goddard Space Flight Center)
Diner, David (NASA Jet Propulsion Laboratory)
Dubovik, Oleg (University of Lille, France)
Franz, Bryan (NASA Goddard Space Flight Center)
Frouin, Robert (University California, San Diego - Scripps Institution of Oceanography)
Gregg, Watson (NASA Goddard Space Flight Center)
Huemmrich, K. Fred (NASA Goddard Space Flight Center [University of Maryland, Baltimore County])
Kahn, Ralph (NASA Goddard Space Flight Center)
Marshak, Alexander (NASA Goddard Space Flight Center)
Massie, Steve (National Center for Atmospheric Research)
McClain, Charles (NASA Goddard Space Flight Center)
McNaughton, Cameron (Golder Associates Ltd. [Canada], University of Hawai`i at Mānoa)
Meister, Gerhard (NASA Goddard Space Flight Center)
Mitchell, Greg (University California, San Diego - Scripps Institution of Oceanography)
Muller-Karger, Frank (University of South Florida)
Puschell, Jeffery (Raytheon)
Riedi, Jerome (University of Lille, France)
Siegel, David (University California, Santa Barbara)
Wang, Menghua (National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service/Center for Satellite Applications and Research)
Werdell, Jeremy (NASA Goddard Space Flight Center)

The global carbon cycle

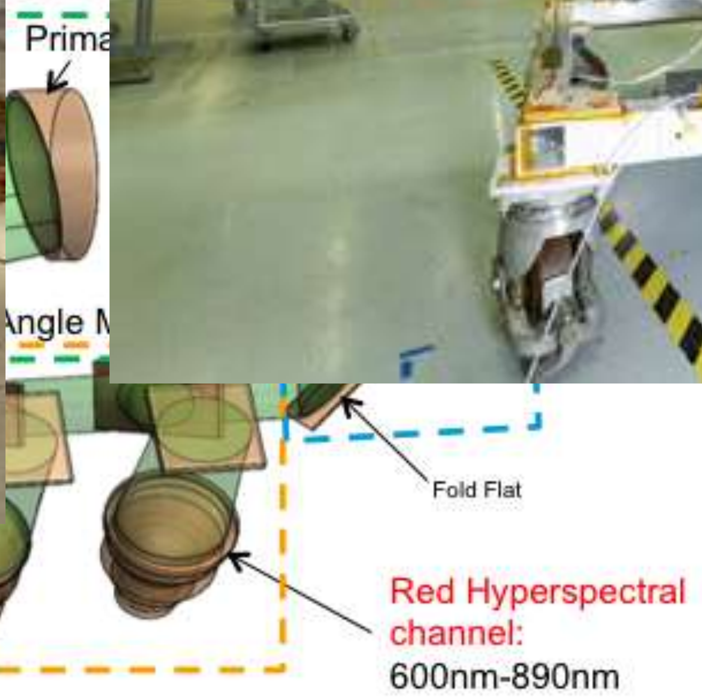


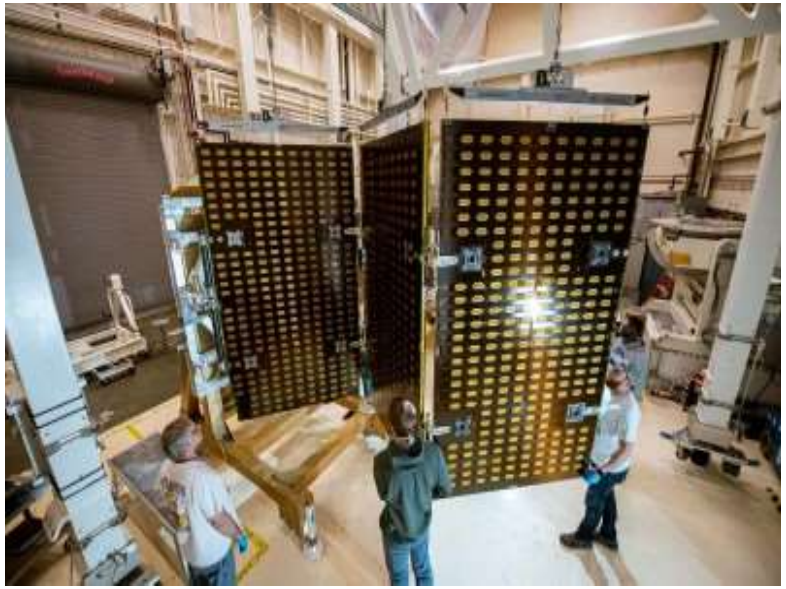
QUESTION: how are the oceans & atmosphere responding CO2 increases and global warming??

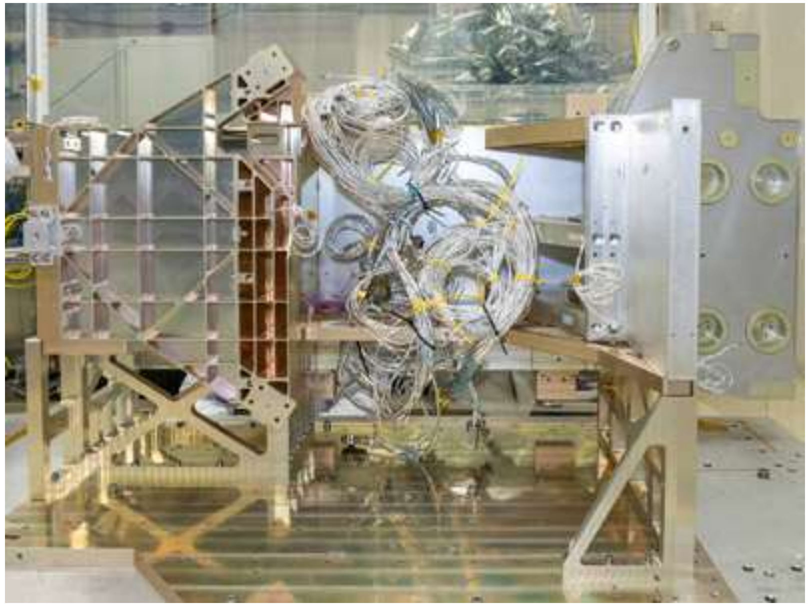
- **Resolving**
  - Why are ecosystems changing?
  - What within the ecosystem drives change?
  - What are the consequences?
  - How will the future Earth look?

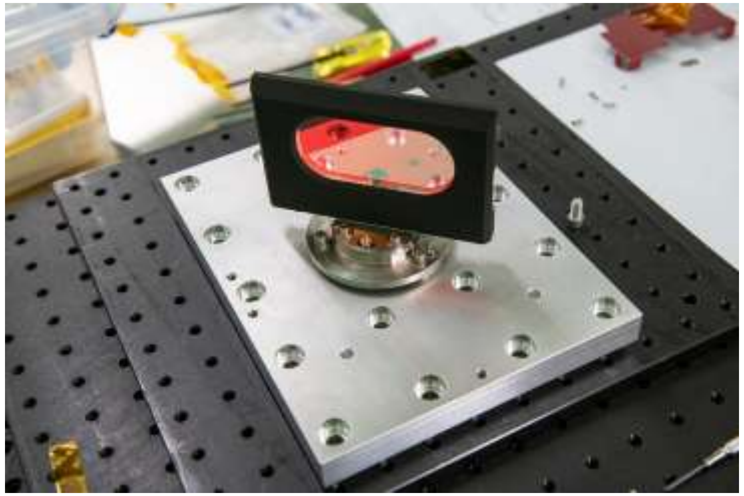
- **Requires coincident measurements of ocean biogeochemical & atmospheric properties to estimate**:
  - Phytoplankton standing stocks & diversity
  - Ocean carbon standing stocks & fates
  - 3-dimensional cloud distributions
  - Aerosol particle compositions & diversity


SAUSAGE MAKER
Make healthy
sausages at home

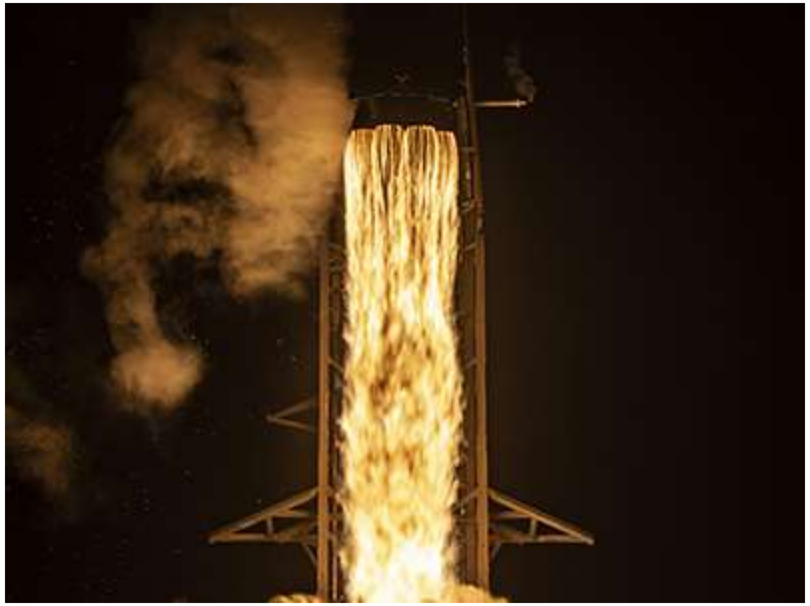
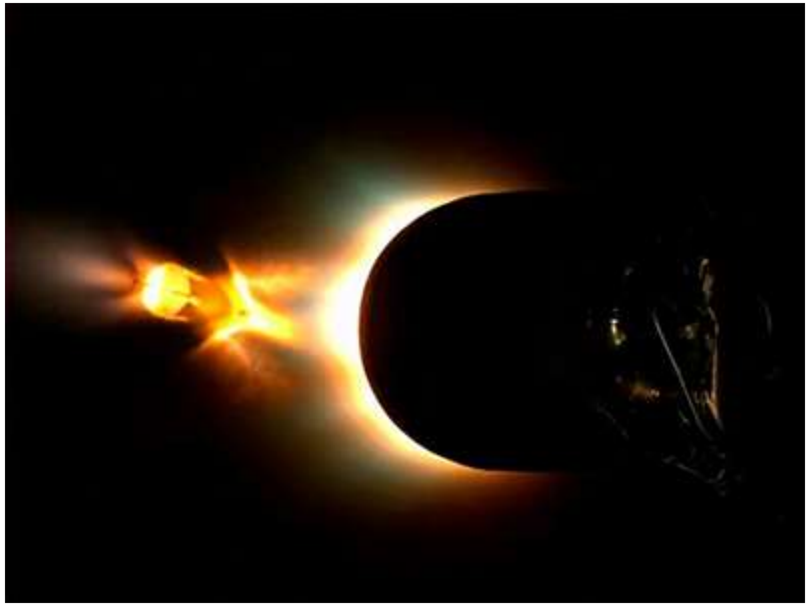
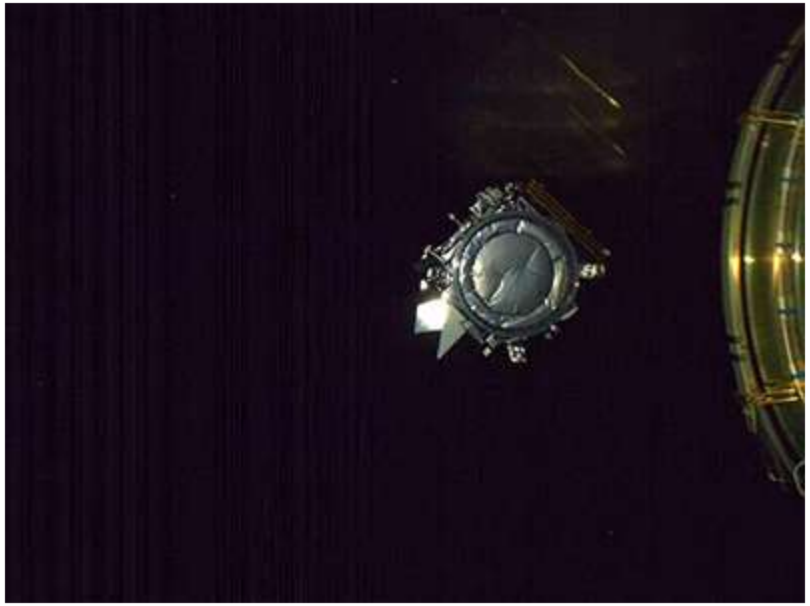

mm
Prima
Angle M
Fold Flat
Collimator
Blue Hyperspectral channel:
340nm-600nm
Red Hyperspectral channel:
600nm-890nm



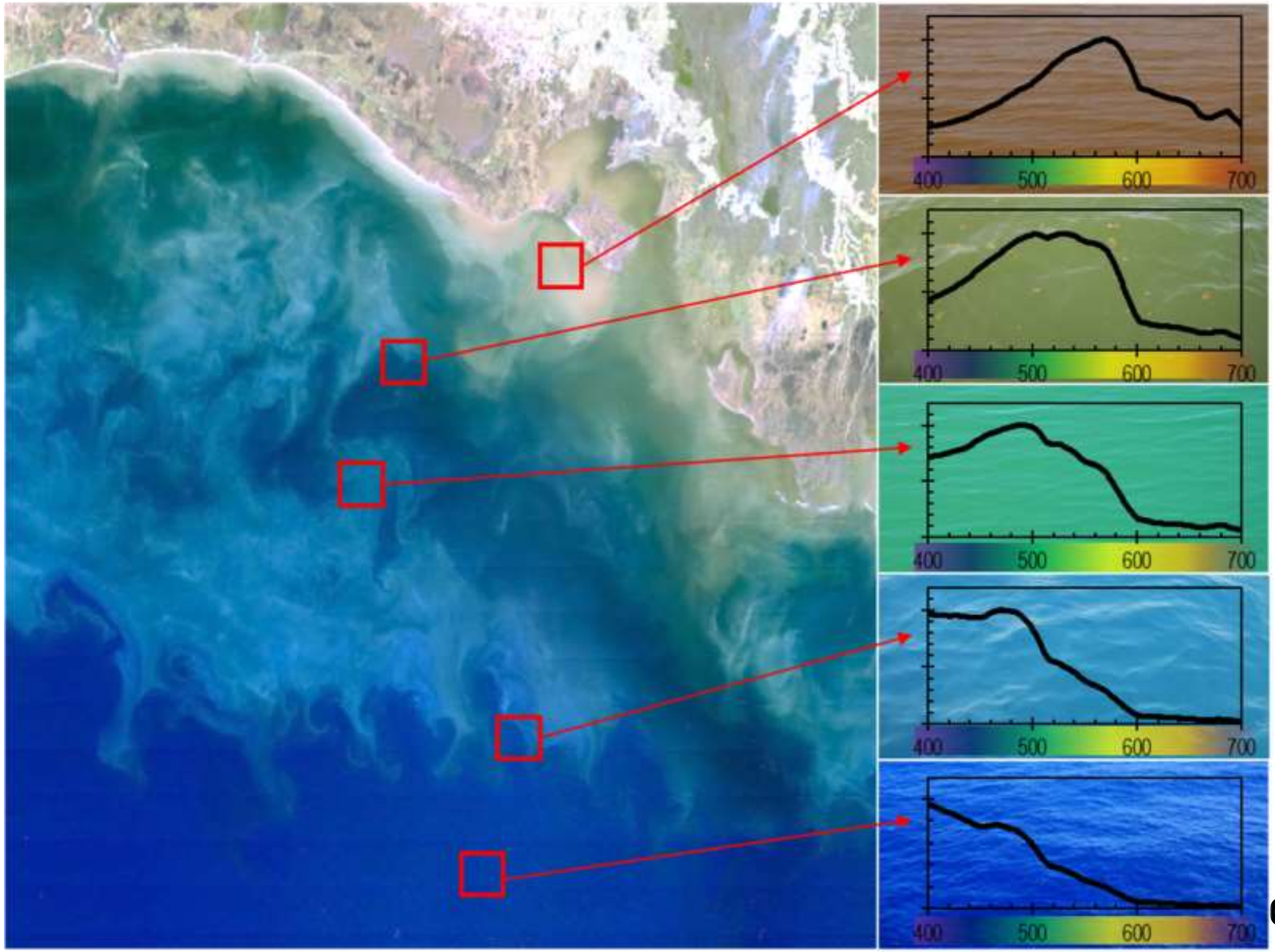




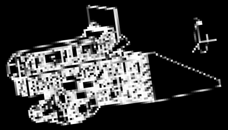





Plankton Aerosol Cloud ocean Ecosystem – PACE February 8, 2024

https://pace.oceansciences.org/

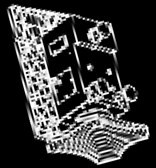


olarimeters



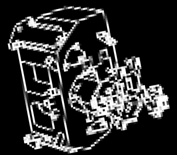
OCI

340-890 nm in 2.5 nm
7 discrete SWIR, 940-
1-2 day coverage ±20



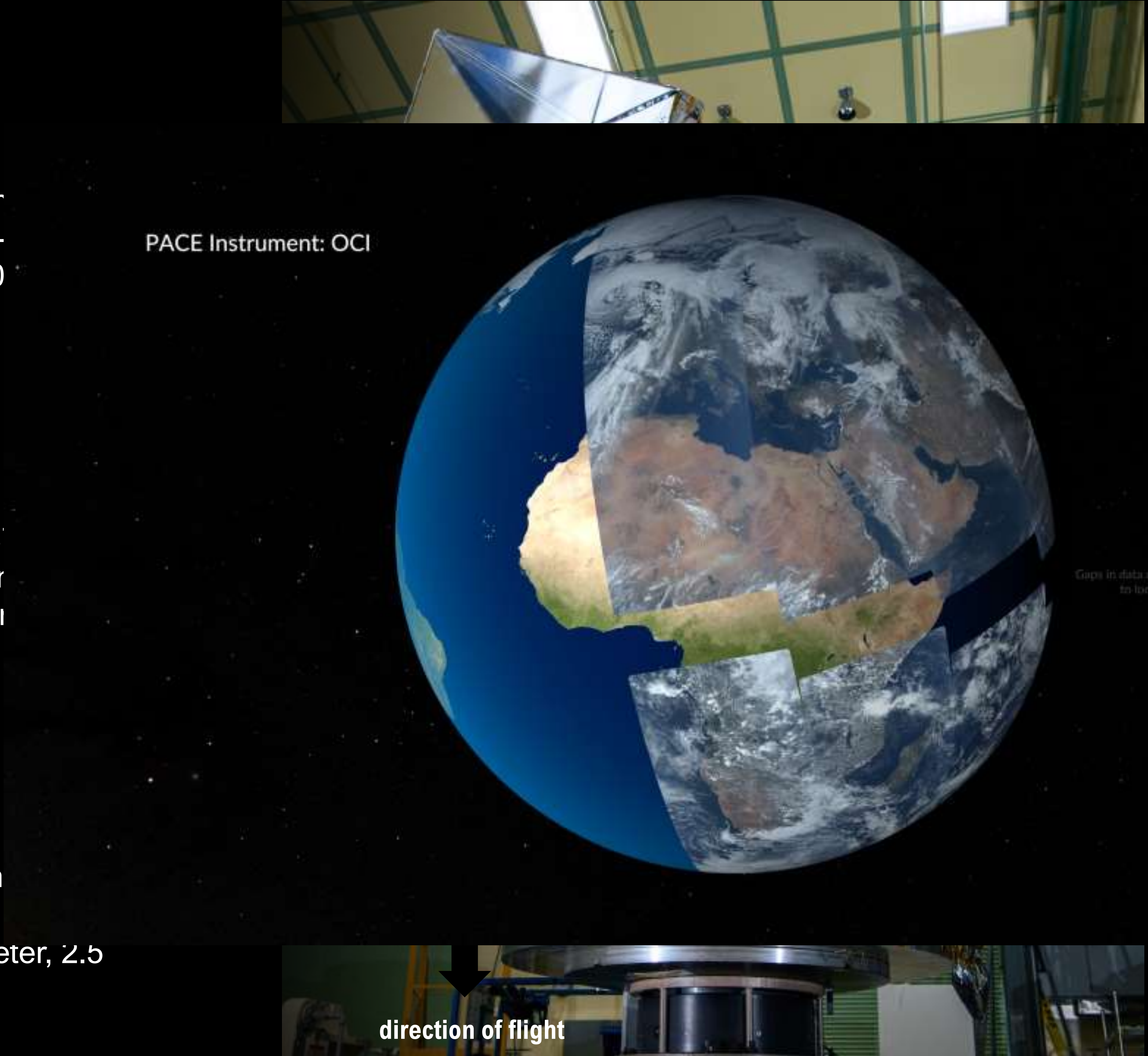
HARP2

440, 550, 670, 8
10-60 viewing ar
wide swath polar



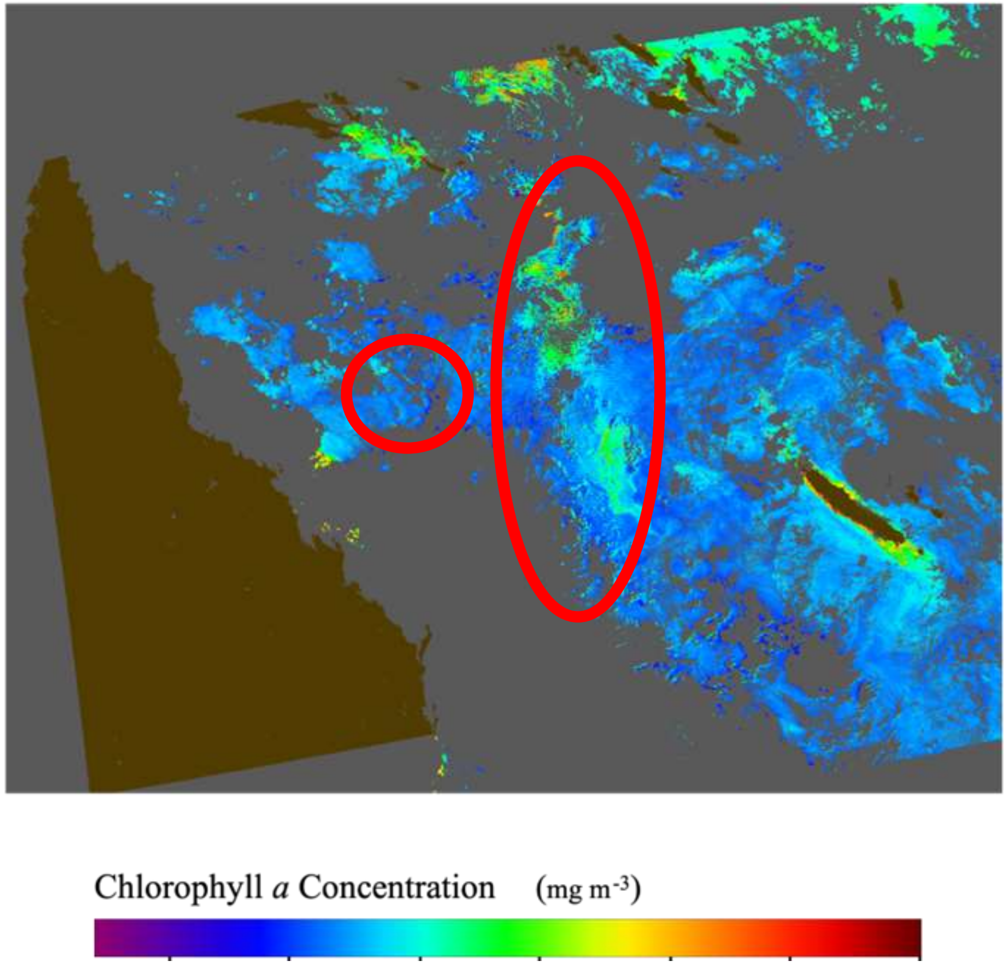
SPEXone

380-770 nm in 2-4 nm
5 viewing angles
narrow swath polarimeter, 2.5

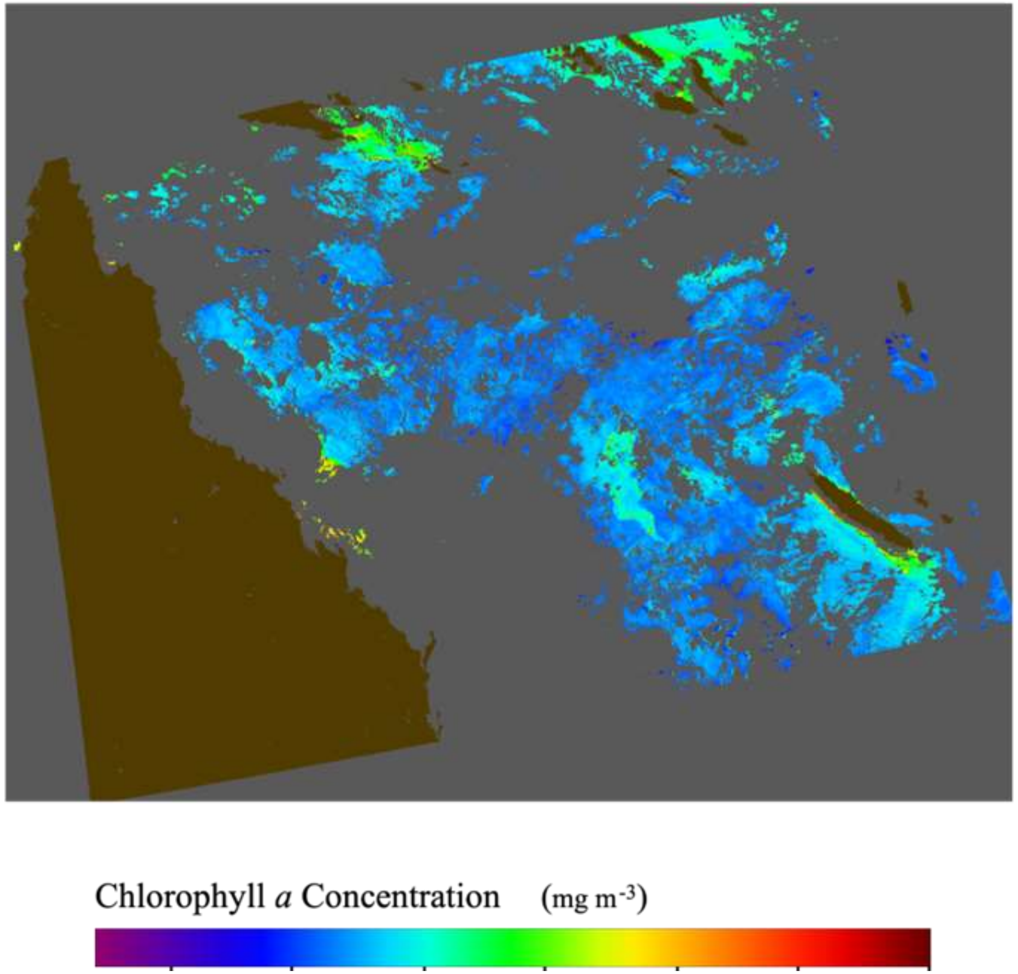


How good is the Ocean Color Instrument (OCI)? – Phytoplankton chlorophyll retrievals, NE Australia – **First light**

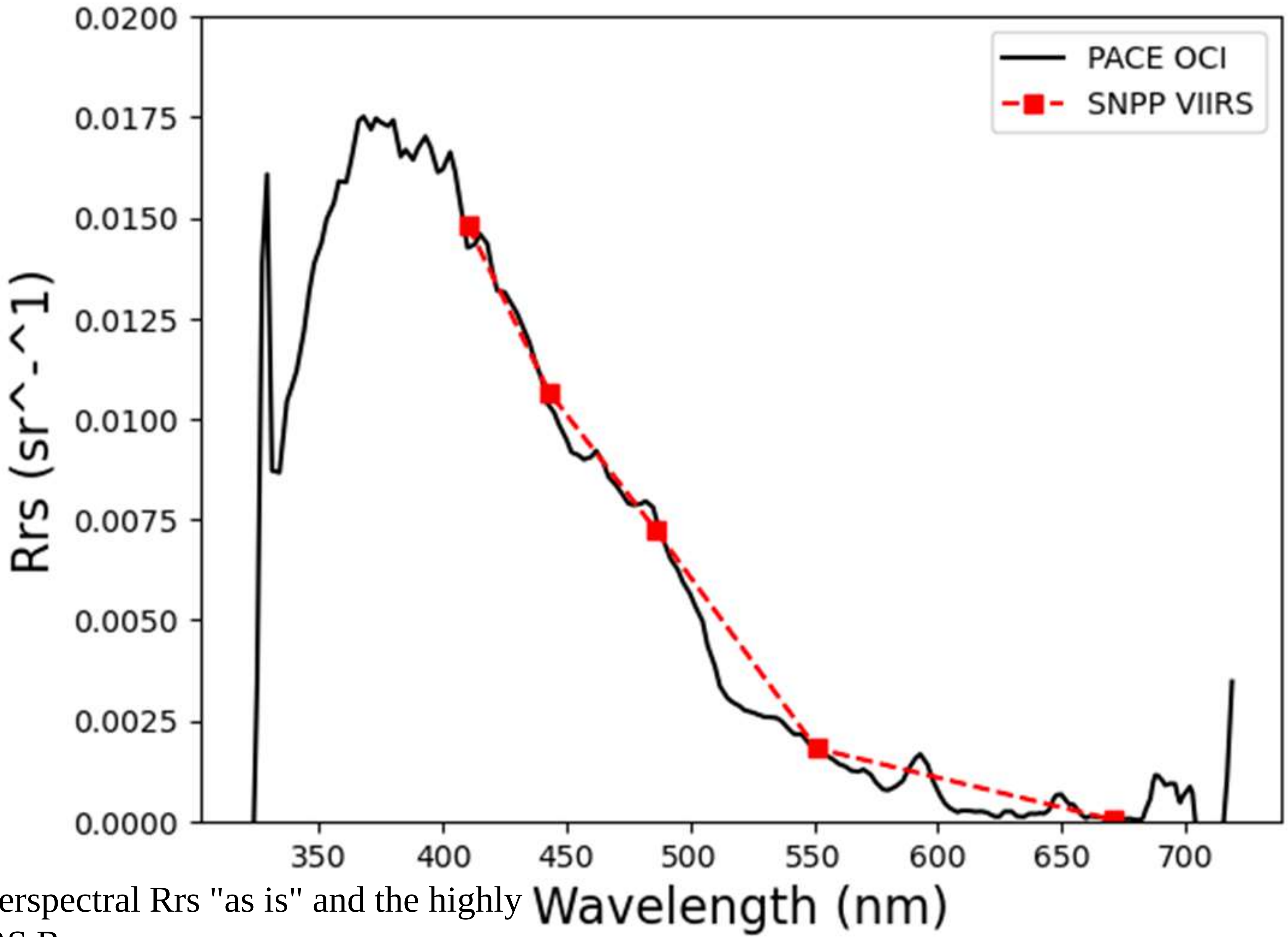
SNPP-VIIRS



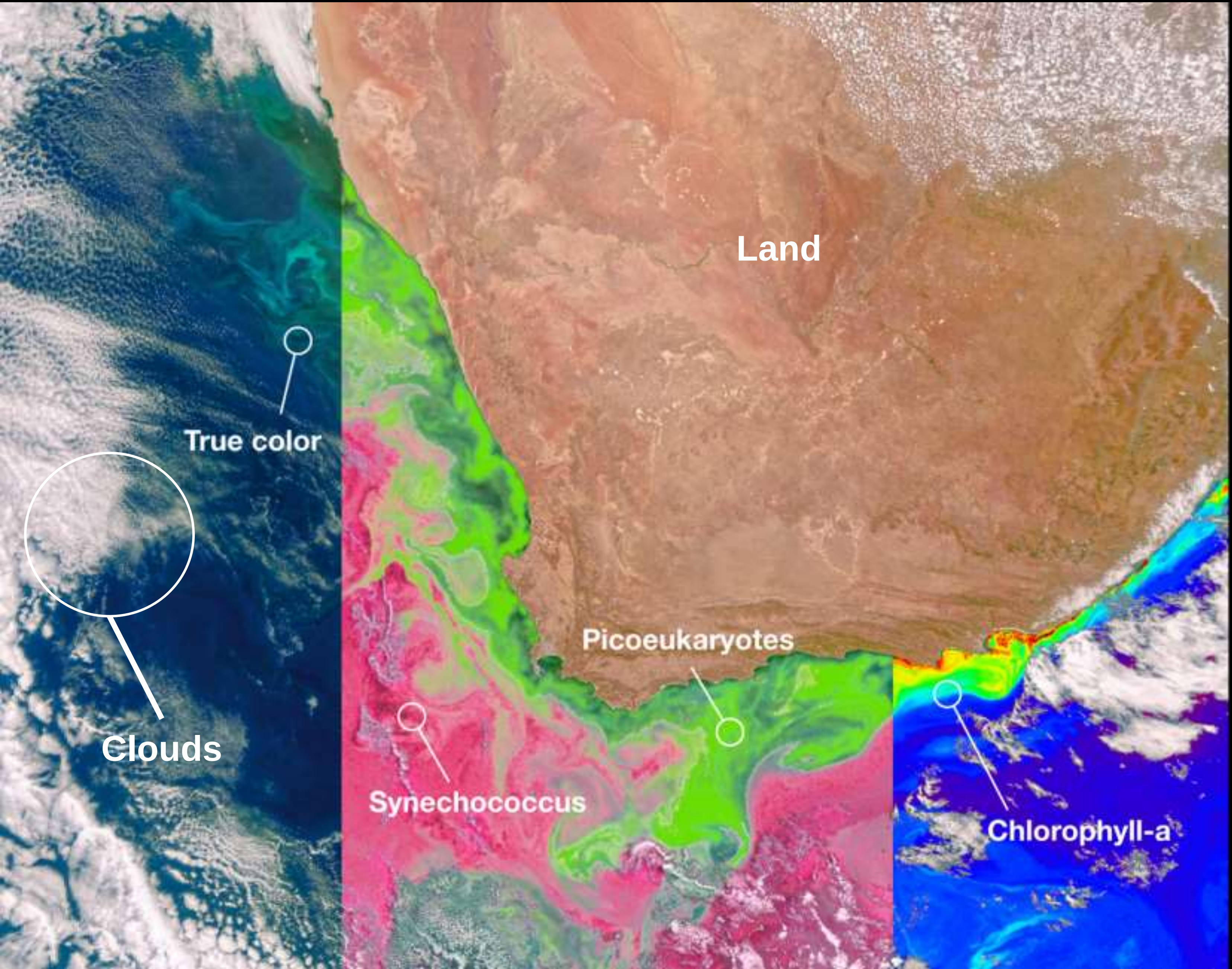
OCI



How good is the OCI?



Agreement between hyperspectral Rrs "as is" and the highly refined, well vetted VIIRS Rrs.



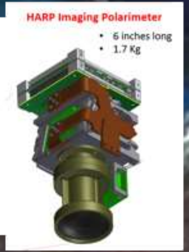
Initial data release on 11 Apr 2024

- Level-1 (radiometry) from all 3 instruments
- Heritage suite of O/C products from OCI

Additional data products to be released pending review by Project and PIs

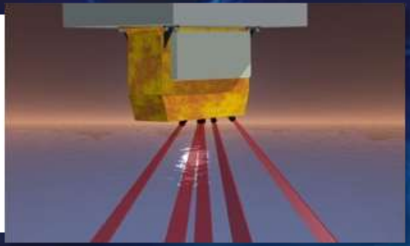
2006-08-17 00:00

UMBC Hyper Angular Rainbow Polarimeter **(HARP-2)**

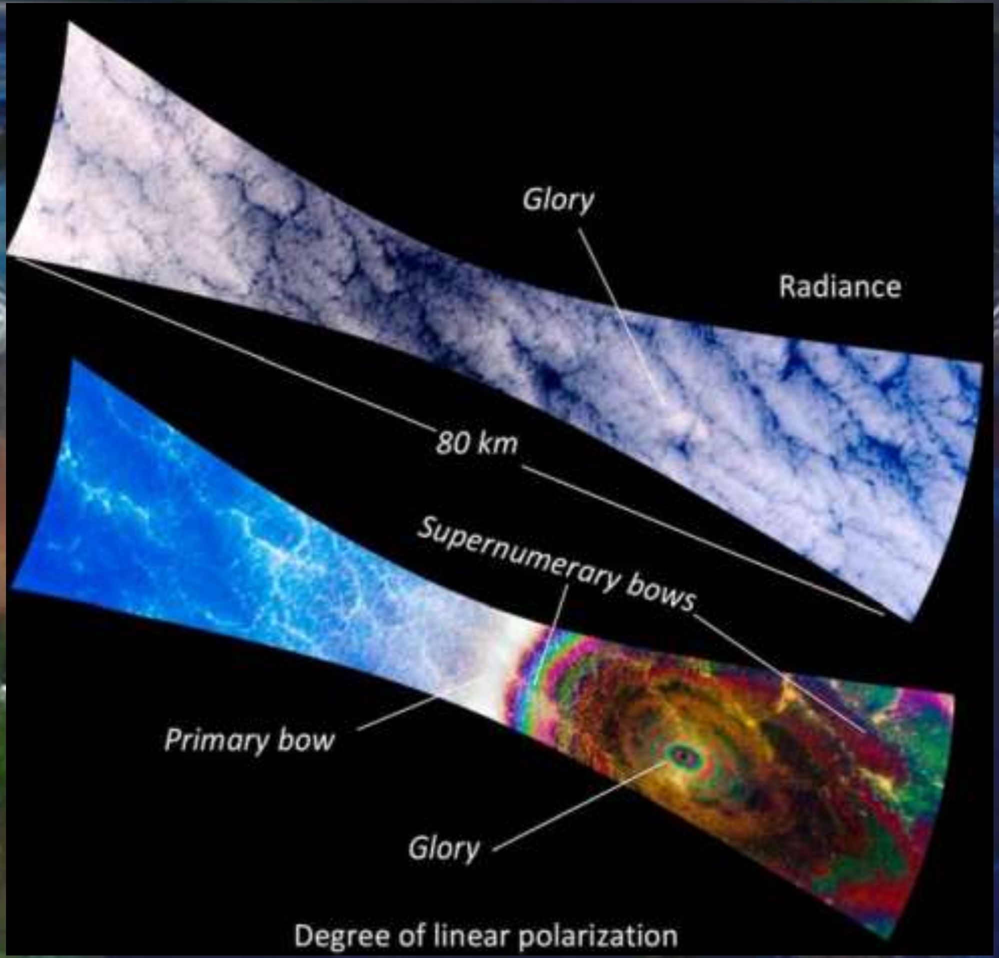


Hyperangular + wide swath

SRON Spectro-polarimeter for Planetary Exploration (**SPEXone**)



Hyperspectral (UV) + narrow swath + high accuracy



From: Xu, F., et al. 2018.

10-km GEOS-5 Aerosol Optical Depth

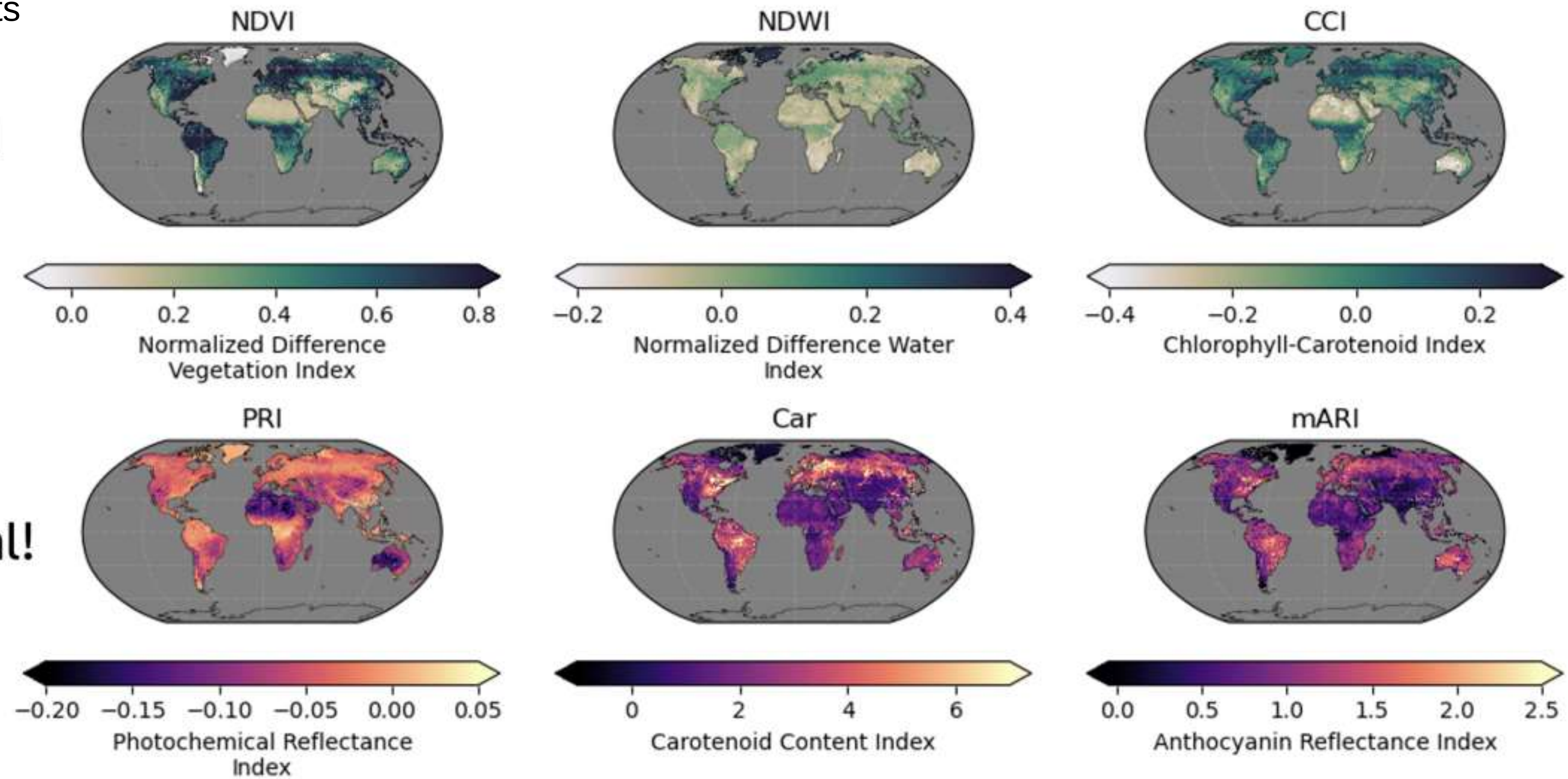
Dust | Organic & Black Carbon | Sulfates | Sea Salt

Global Modeling and Assimilation Office - William.M.Putman@nasa.gov

PACE land products

Multispectral

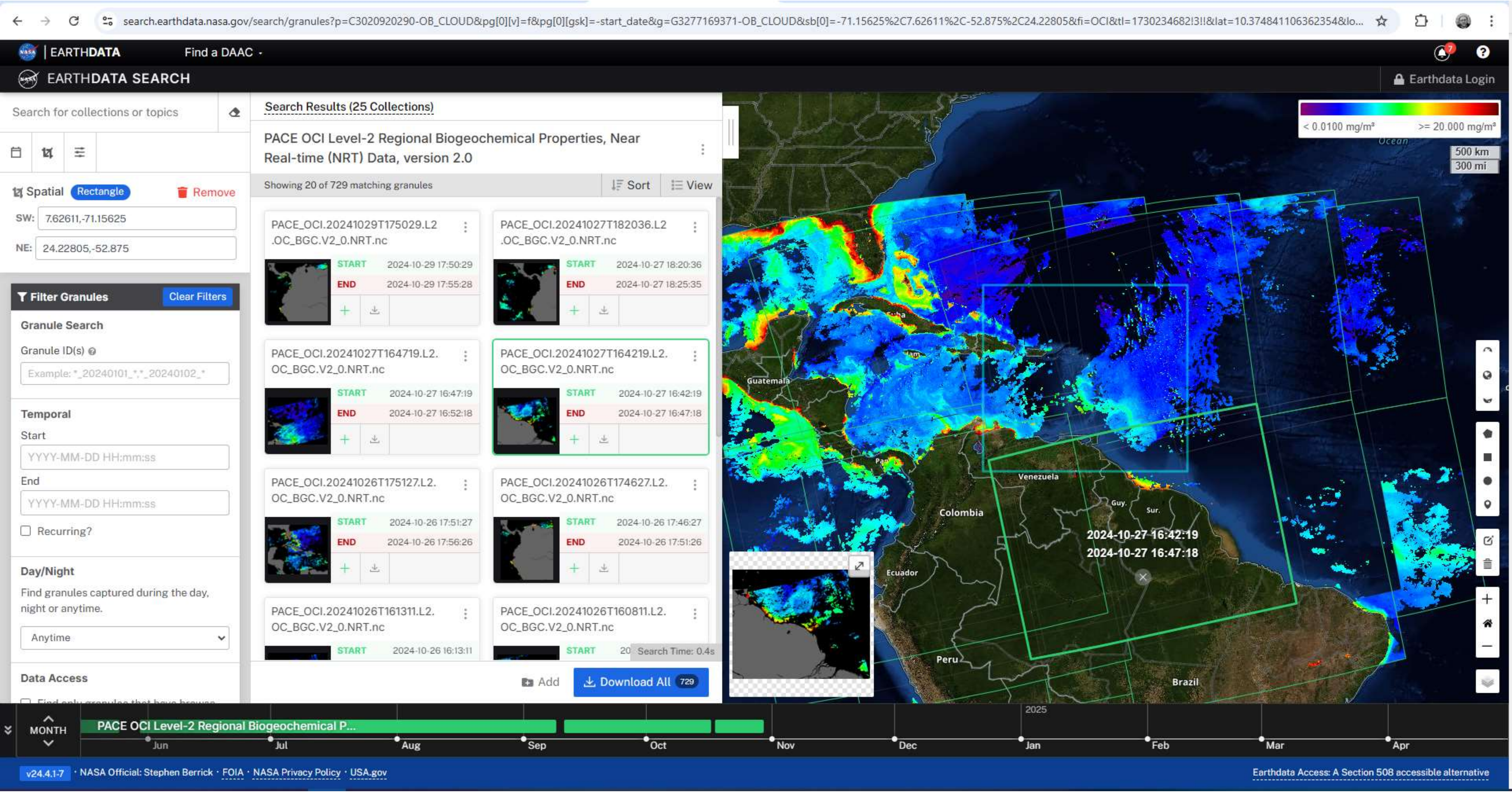
Hyperspectral!

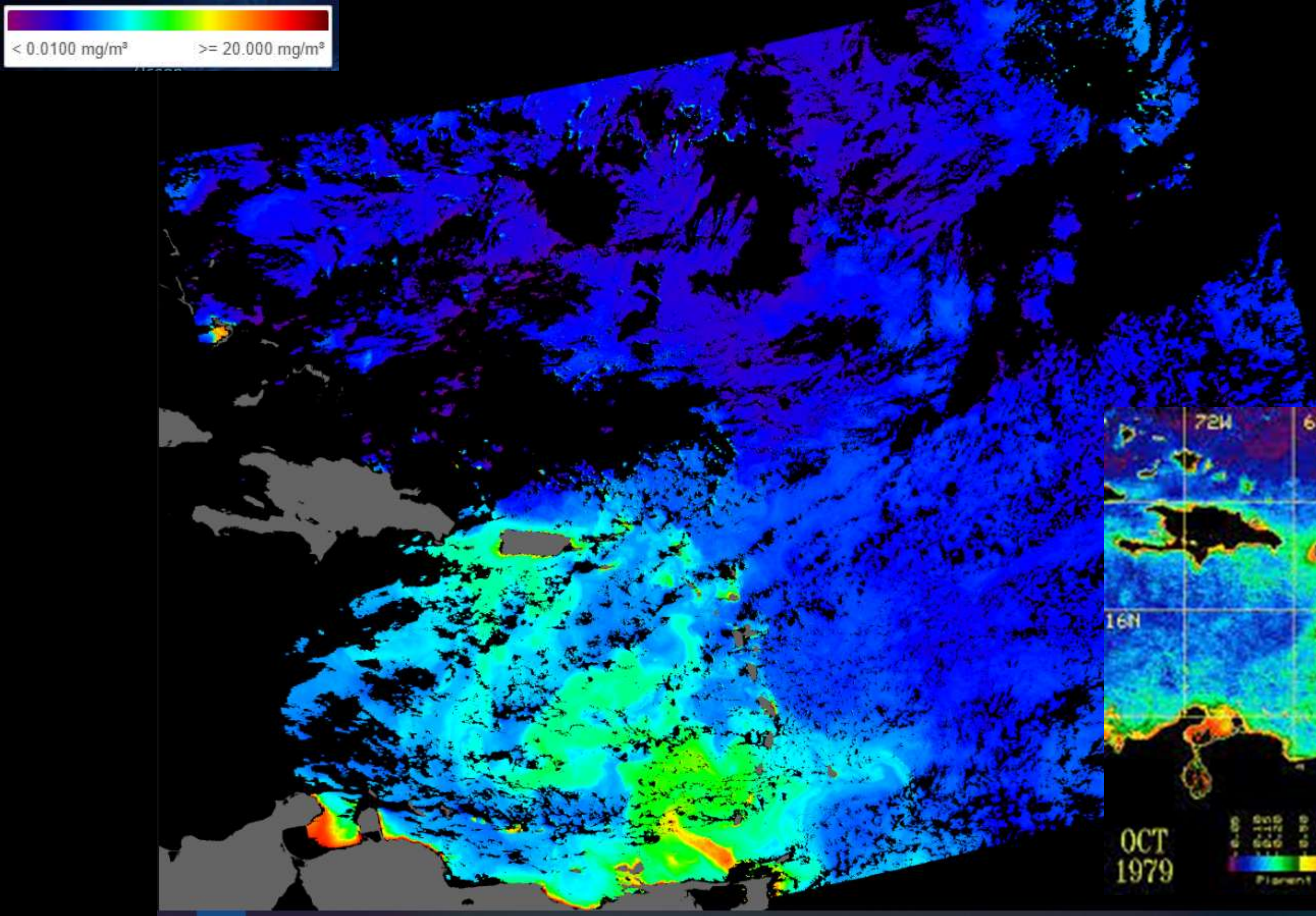


Index	Equation
PRI	$(\rho_{530}-\rho_{570}) / (\rho_{530}+\rho_{570})$
CIRE	$(\rho_{800}/\rho_{705})-1$
Car	$[(1/\rho_{495})-(1/\rho_{705})] * \rho_{800}$
mARI	$[(1/\rho_{550})-(1/\rho_{705})] * \rho_{800}$

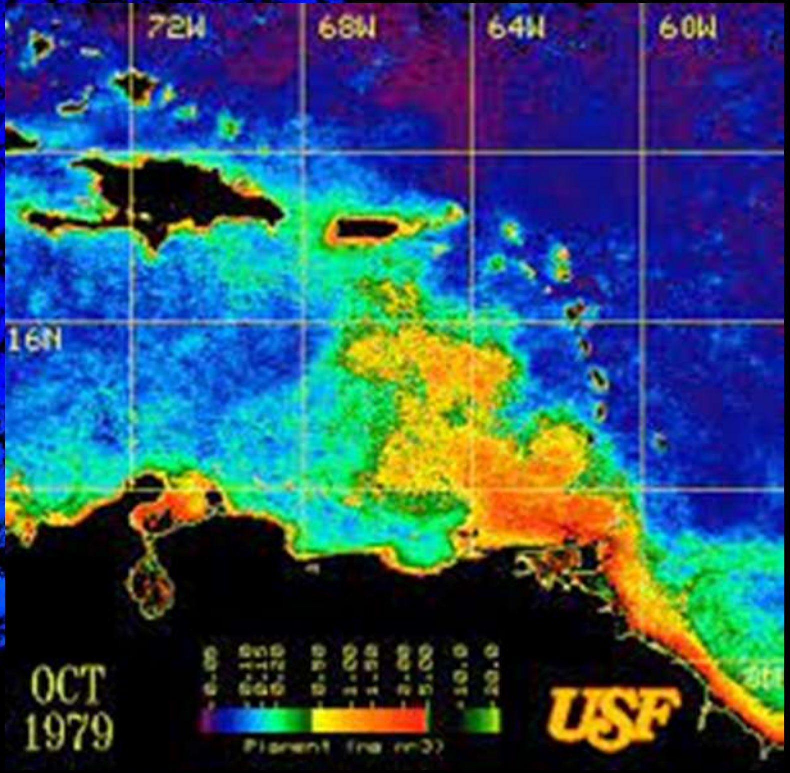
PRI: Photochemical Reflectance Index
CIRE: Chlorophyll Index Red Edge
Car: Carotenoid Content Index
mARI: Modified Anthocyanin Reflectance Index

Where to get PACE data

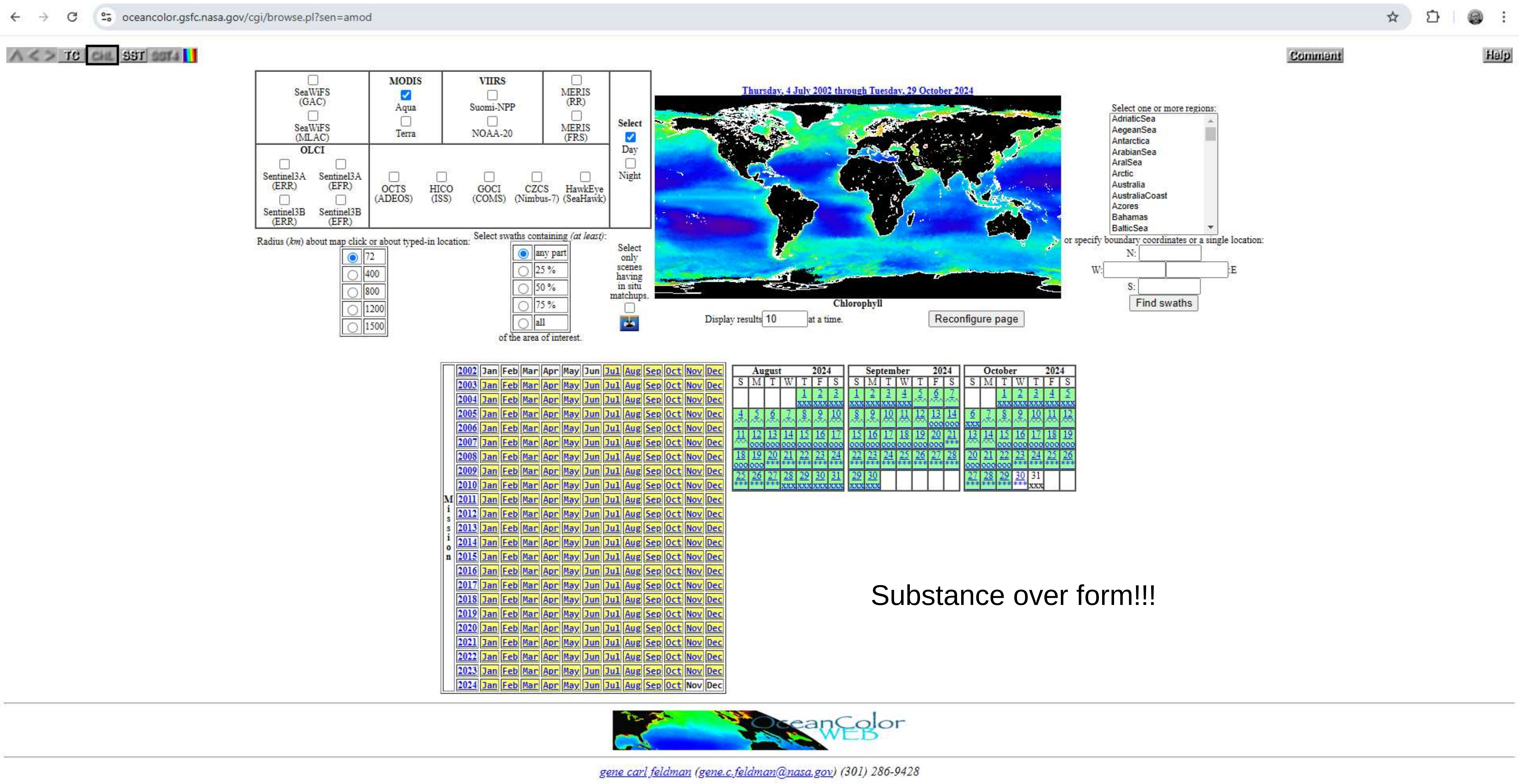

search.earthdata.nasa.gov/search/granules?p=C3020920290-OB_CLOUD&pg[0][v]=f&pg[0][gsk]=-start_date&g=G3277169371-OB_CLOUD&sb[0]=-71.15625%2C7.62611%2C-52.875%2C24.22805&fi=OCI&tl=1730234682!3!!&lat=10.374841106362354&lo...
EARTHDATA
Find a DAAC
EARTHDATA SEARCH
Earthdata Login
Search for collections or topics
Spatial
Rectangle
Remove
SW: 7.62611,-71.15625
NE: 24.22805,-52.875
Filter Granules
Clear Filters
Granule Search
Granule ID(s)
Example: *_20240101_*,*_20240102_*
Temporal
Start
YYYY-MM-DD HH:mm:ss
End
YYYY-MM-DD HH:mm:ss
Recurring?
Day/Night
Find granules captured during the day, night or anytime.
Anytime
Data Access
Search Results (25 Collections)
PACE OCI Level-2 Regional Biogeochemical Properties, Near Real-time (NRT) Data, version 2.0
Showing 20 of 729 matching granules
Sort
View
PACE_OCI.20241029T175029.L2.OC_BGC.V2_0.NRT.nc
START 2024-10-29 17:50:29
END 2024-10-29 17:55:28
PACE_OCI.20241027T182036.L2.OC_BGC.V2_0.NRT.nc
START 2024-10-27 18:20:36
END 2024-10-27 18:25:35
PACE_OCI.20241027T164719.L2.OC_BGC.V2_0.NRT.nc
START 2024-10-27 16:47:19
END 2024-10-27 16:52:18
PACE_OCI.20241027T164219.L2.OC_BGC.V2_0.NRT.nc
START 2024-10-27 16:42:19
END 2024-10-27 16:47:18
PACE_OCI.20241026T175127.L2.OC_BGC.V2_0.NRT.nc
START 2024-10-26 17:51:27
END 2024-10-26 17:56:26
PACE_OCI.20241026T174627.L2.OC_BGC.V2_0.NRT.nc
START 2024-10-26 17:46:27
END 2024-10-26 17:51:26
PACE_OCI.20241026T161311.L2.OC_BGC.V2_0.NRT.nc
START 2024-10-26 16:13:11
PACE_OCI.20241026T160811.L2.OC_BGC.V2_0.NRT.nc
START
Search Time: 0.4s
Add
Download All 729
< 0.0100 mg/m³
>= 20.000 mg/m³
500 km
300 mi
Guatemala
Venezuela
Colombia
Guy.
Sur.
Ecuador
Peru
Brazil
2024-10-27 16:42:19
2024-10-27 16:47:18
MONTH
PACE OCI Level-2 Regional Biogeochemical P...
2025
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
v24.4.1-7
NASA Official: Stephen Berrick · FOIA · NASA Privacy Policy · USA.gov
Earthdata Access: A Section 508 accessible alternative



< 0.0100 mg/m³
>= 20.000 mg/m³

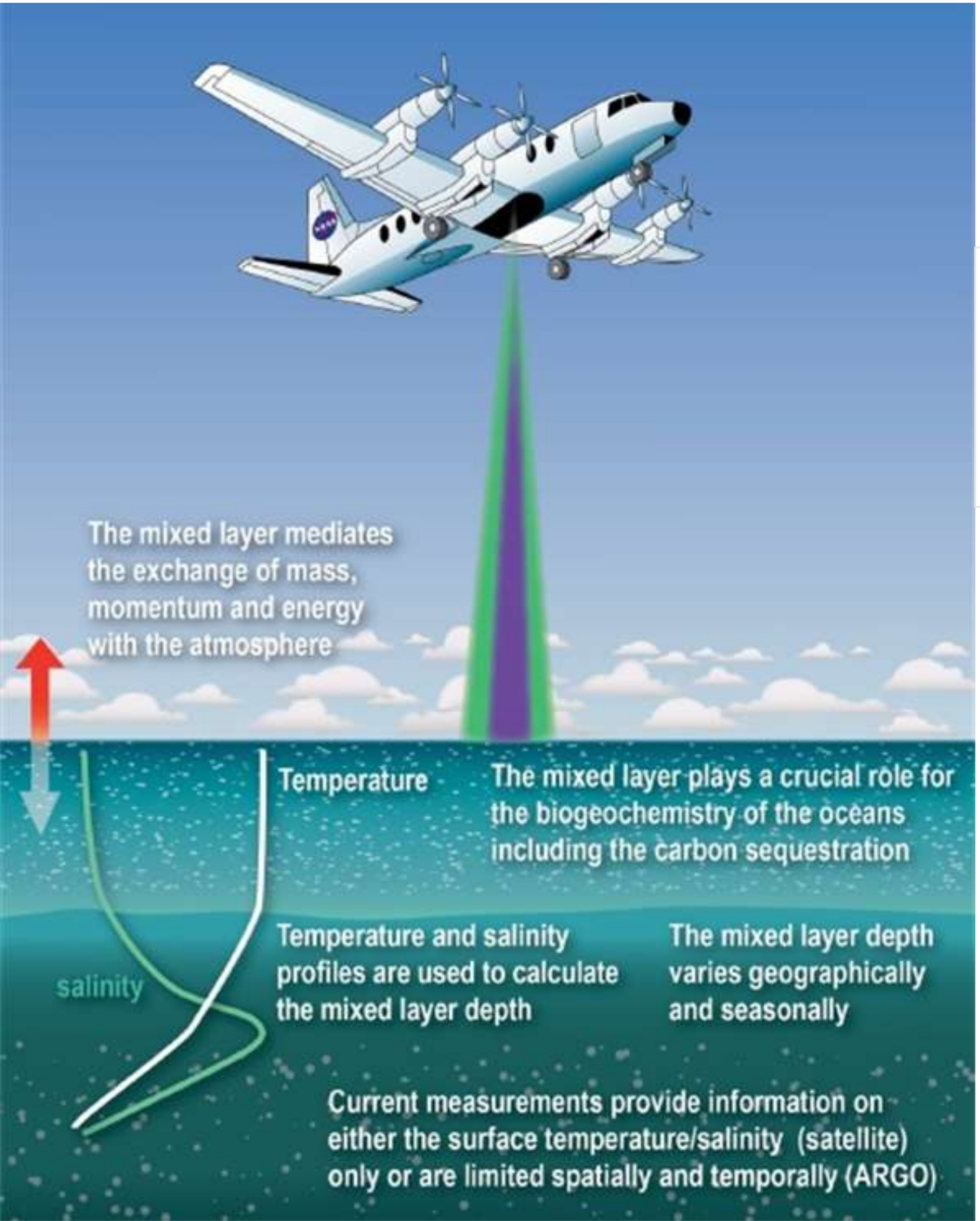


72W
68W
64W
60W
16N
OCT
1979
USF



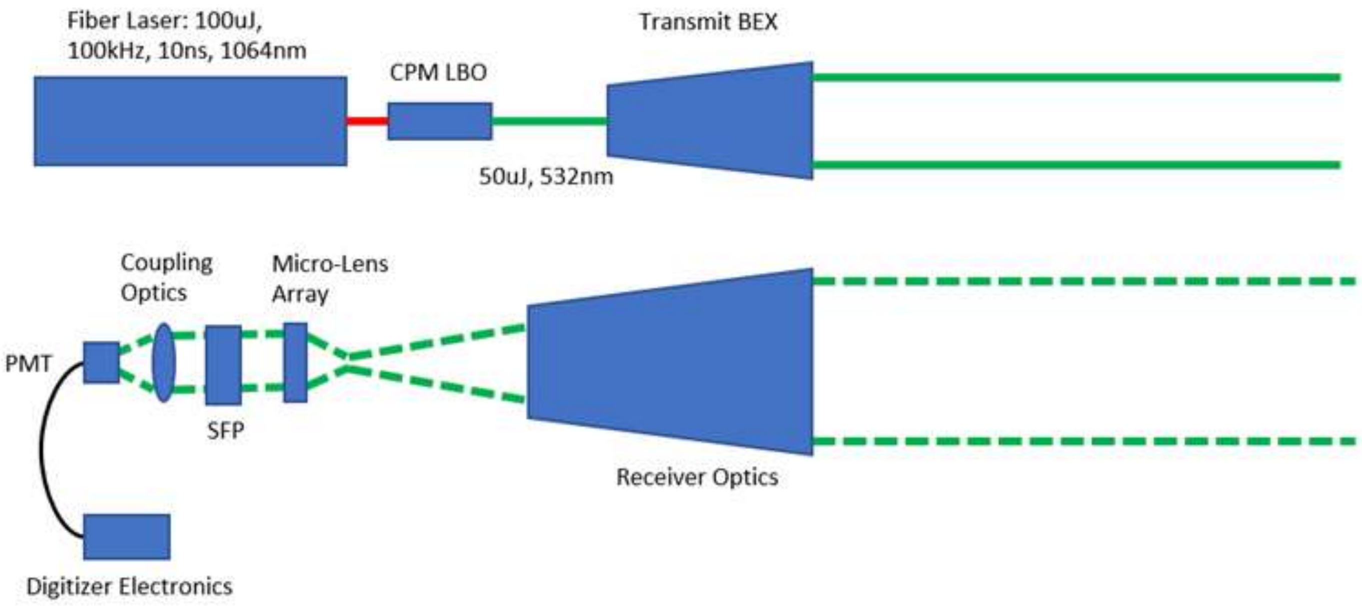
Substance over form!!!

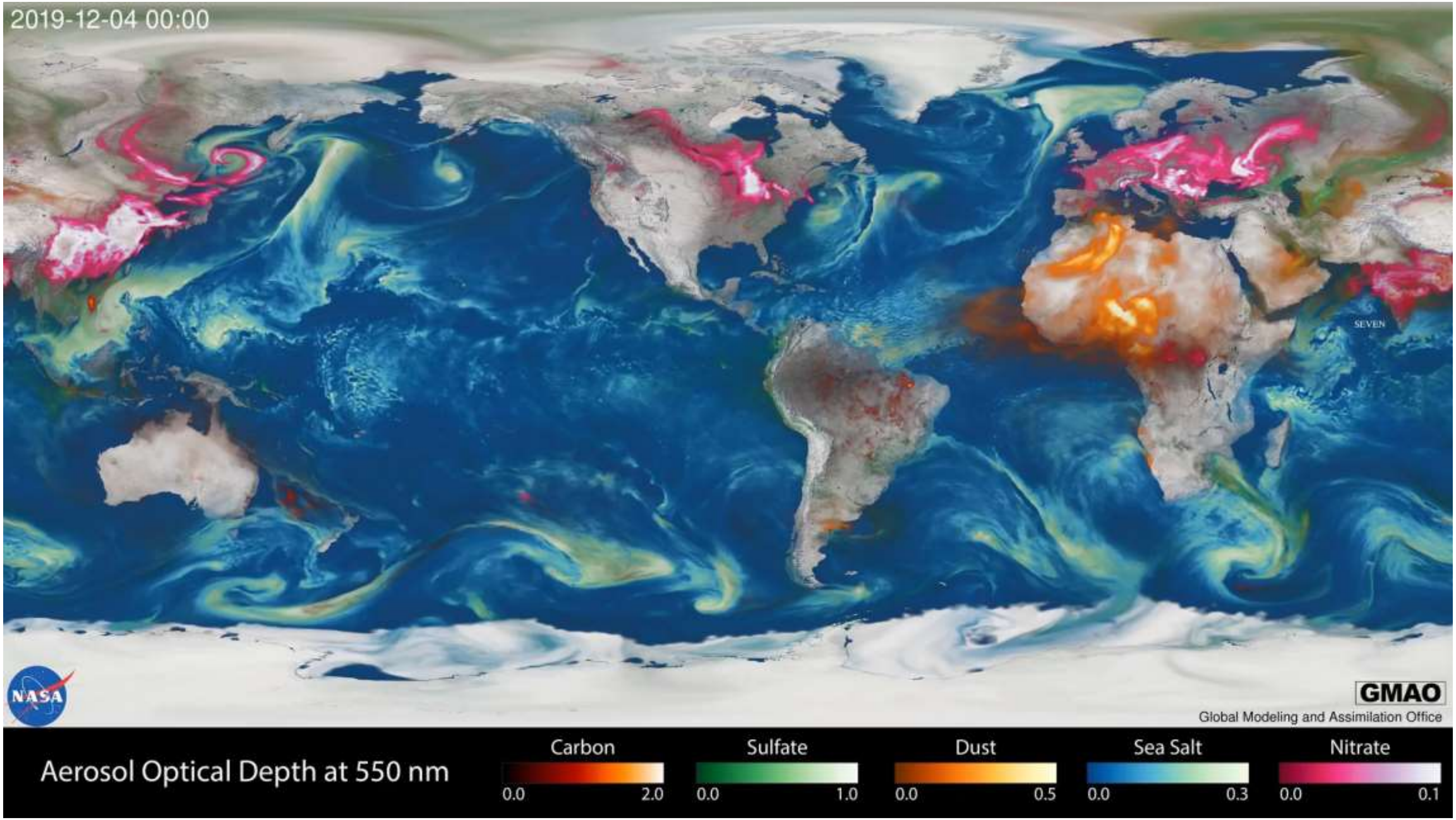
What is next?



Lidar System to measure Ocean Sub-surface Temperature and Salinity Profiles

- Currently evaluating a spectral grating to spread the spectral distribution of the scattered return to a photo-multiplier tube (PMT) array against a hyperfine spectrometer designed for measurement of Brillouin line shapes at 532nm




2019-12-04 00:00
SEVEN
GMAO
Global Modeling and Assimilation Office
Aerosol Optical Depth at 550 nm
Carbon
0.0
2.0
Sulfate
0.0
1.0
Dust
0.0
0.5
Sea Salt
0.0
0.3
Nitrate
0.0
0.1

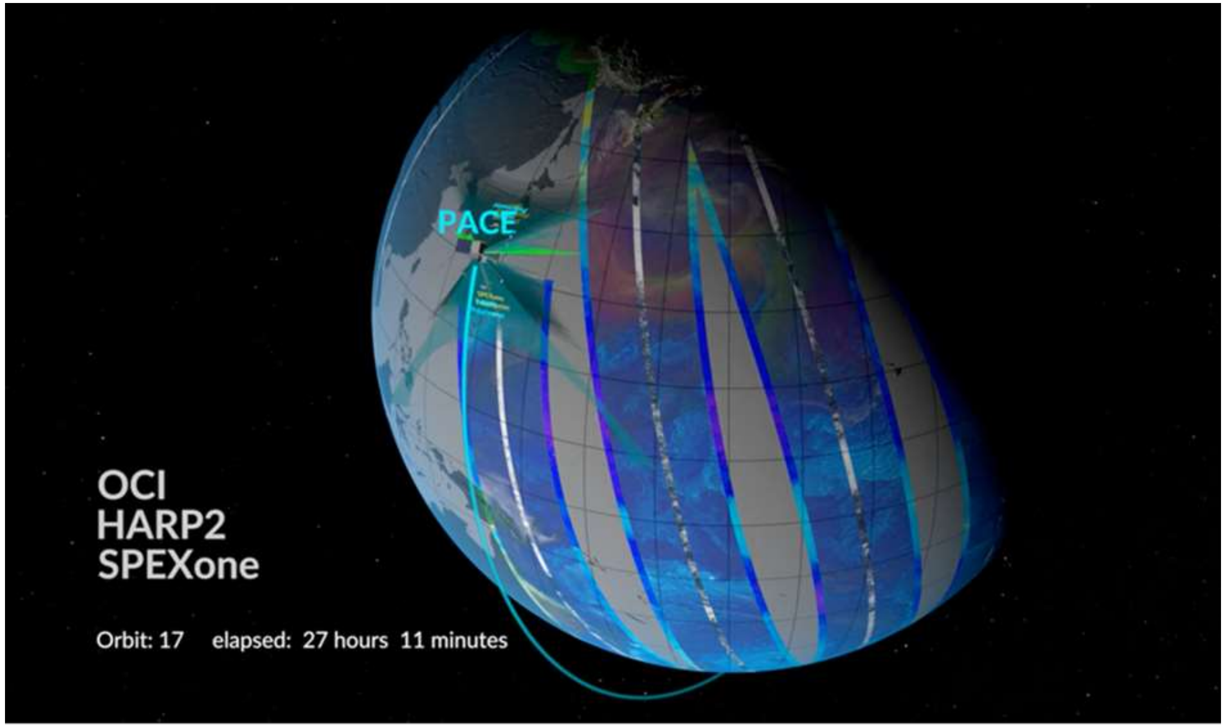
ML-AI Driven Algorithms

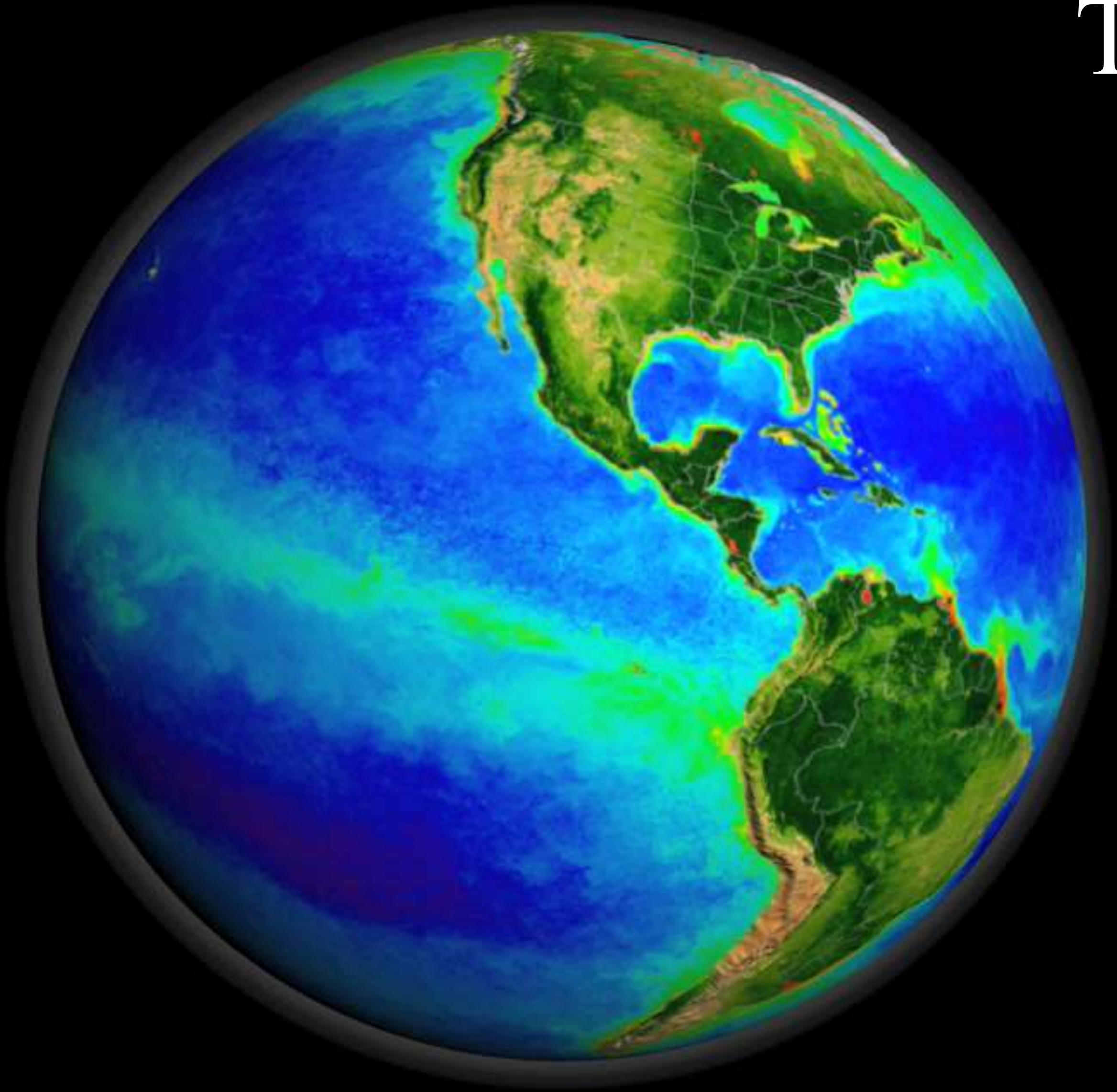
Novel hyper-spectral, hyper-angular inputs to ML retrievals:
-Water clarity as the diffuse attenuation coefficient
-Phytoplankton (including cyanobacteria) in complex waters
-Carbon fixed by diatoms, a globally abundant phytoplankton
-Phytoplankton composition (e.g. big, little, and tiny ones)
-3D representation of clouds
-Coupled ocean-atmospheres from multiple sensors

Surpass computational barriers by replacing radiative transfer models with emulators reducing the computational cost of prohibitively expensive products.

Rapid application of legacy data products, e.g. transfer of cloud mask capability from MODIS solar bands to OCI.

Co-located, high-dimensional data from three sensors





The End….Questions???