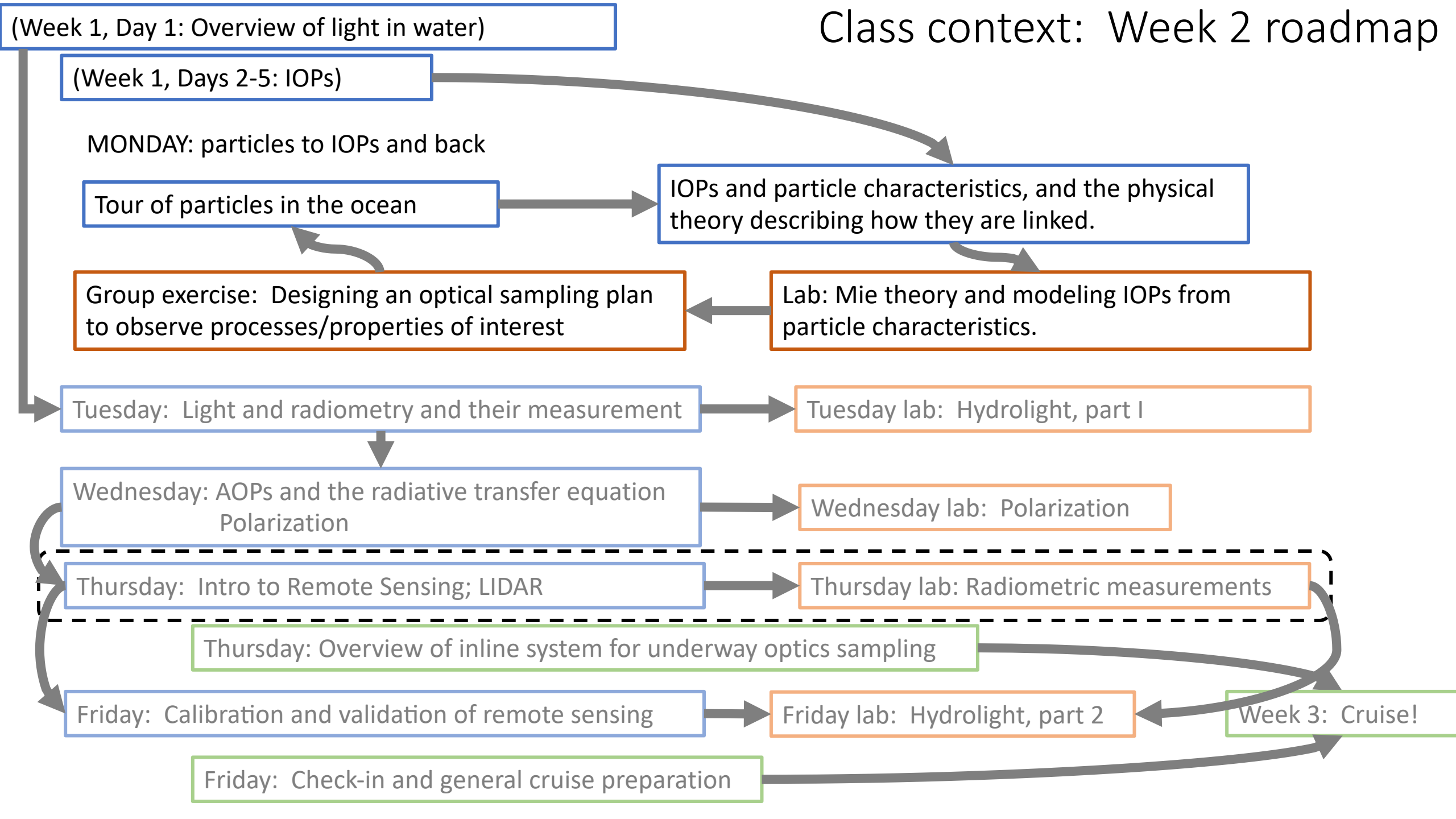
Class context: Week 2 roadmap



Introduction to Remote Sensing

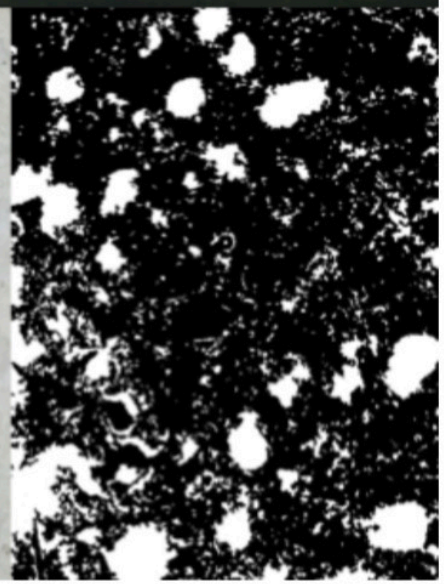
Patrick, Kelsey, with help from others!

What is remote sensing?

What is remote sensing?

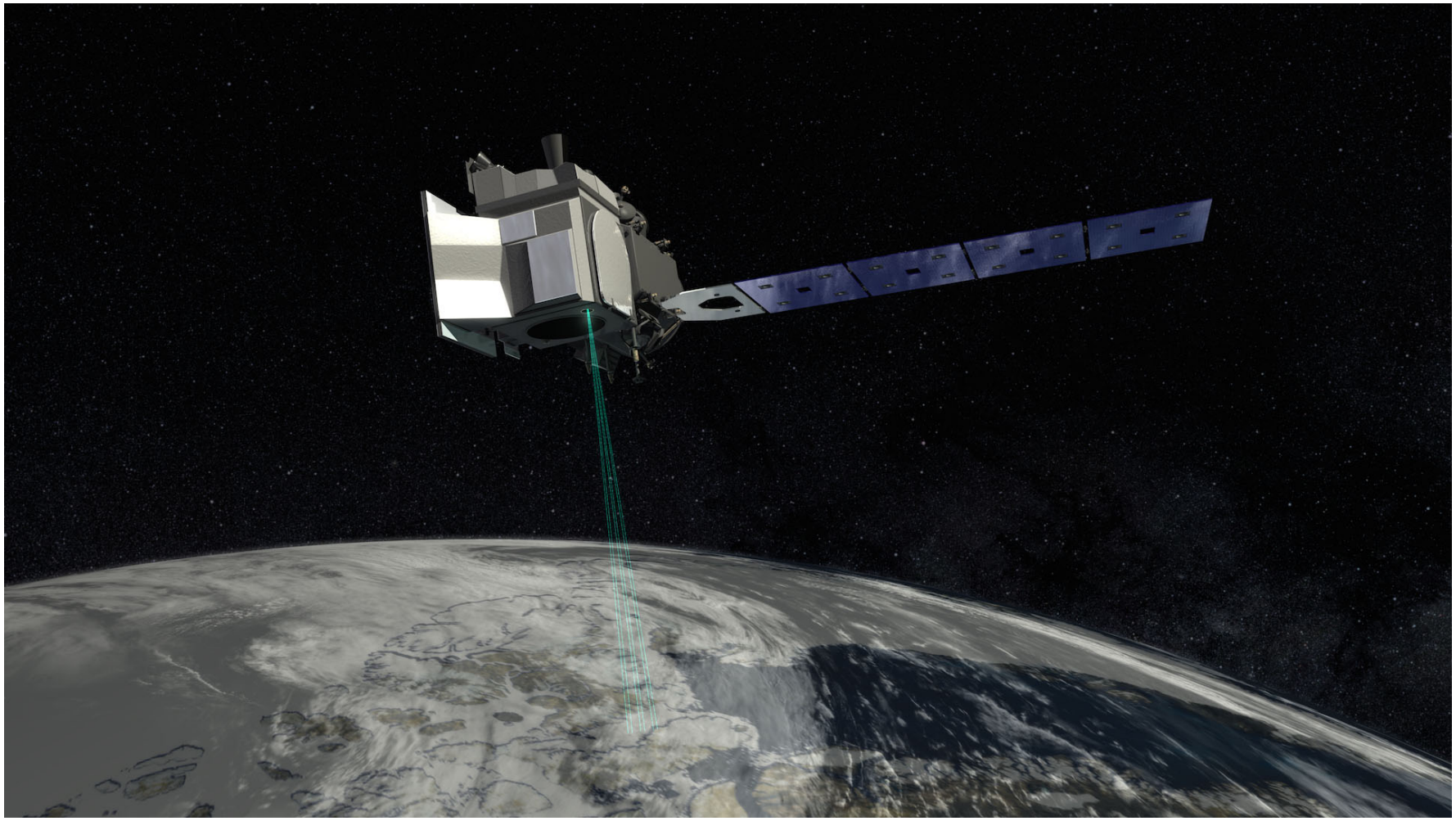
…as simple as an iphone on a fishing pole

Ocean optics side project 2015, ‘Landsat 10’



What is remote sensing?

as complex as a billion dollar mission with over a decade of planning



Remote sensing considerations

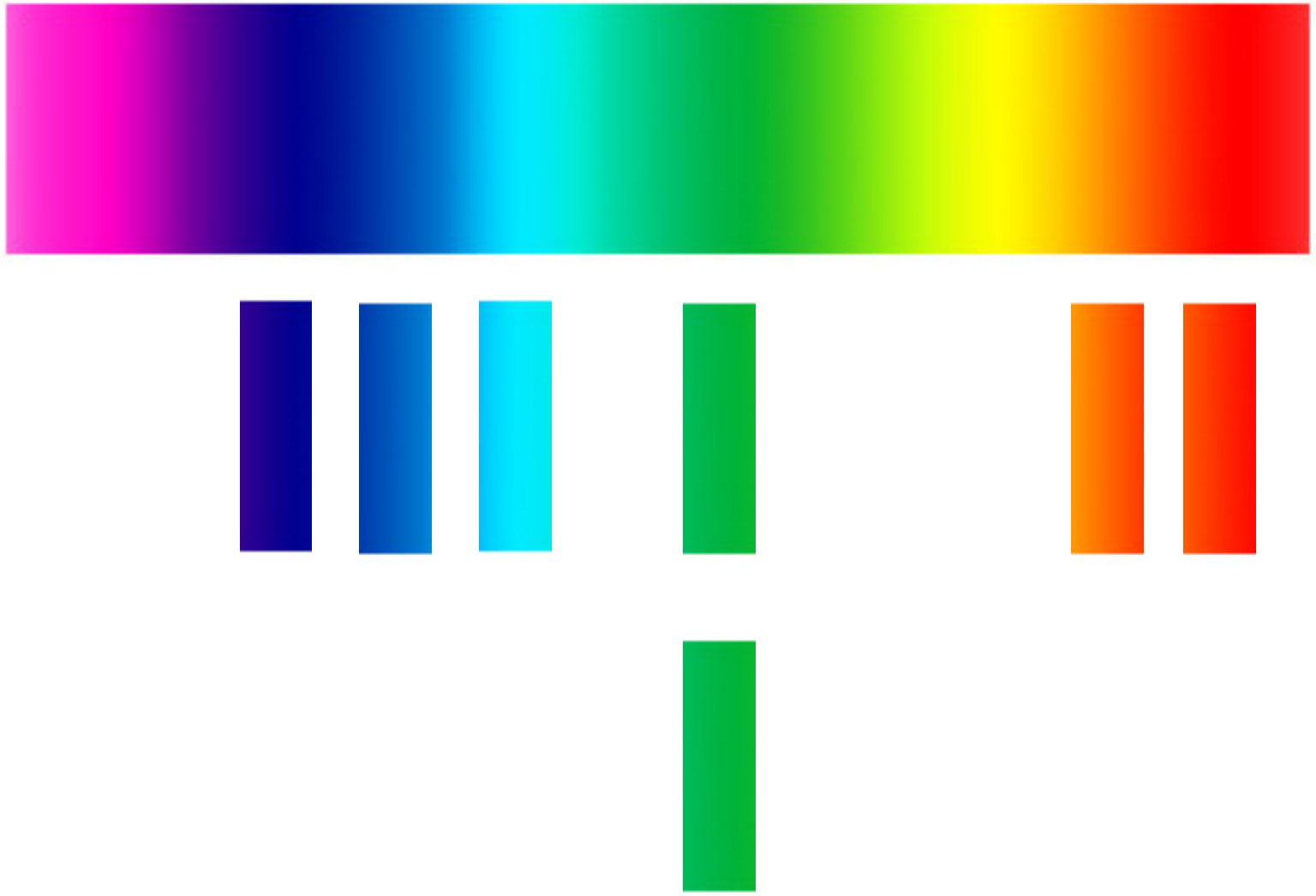
Spectral resolution

Spatial resolution

Time resolution (coverage)

Signal strength (relative to noise)

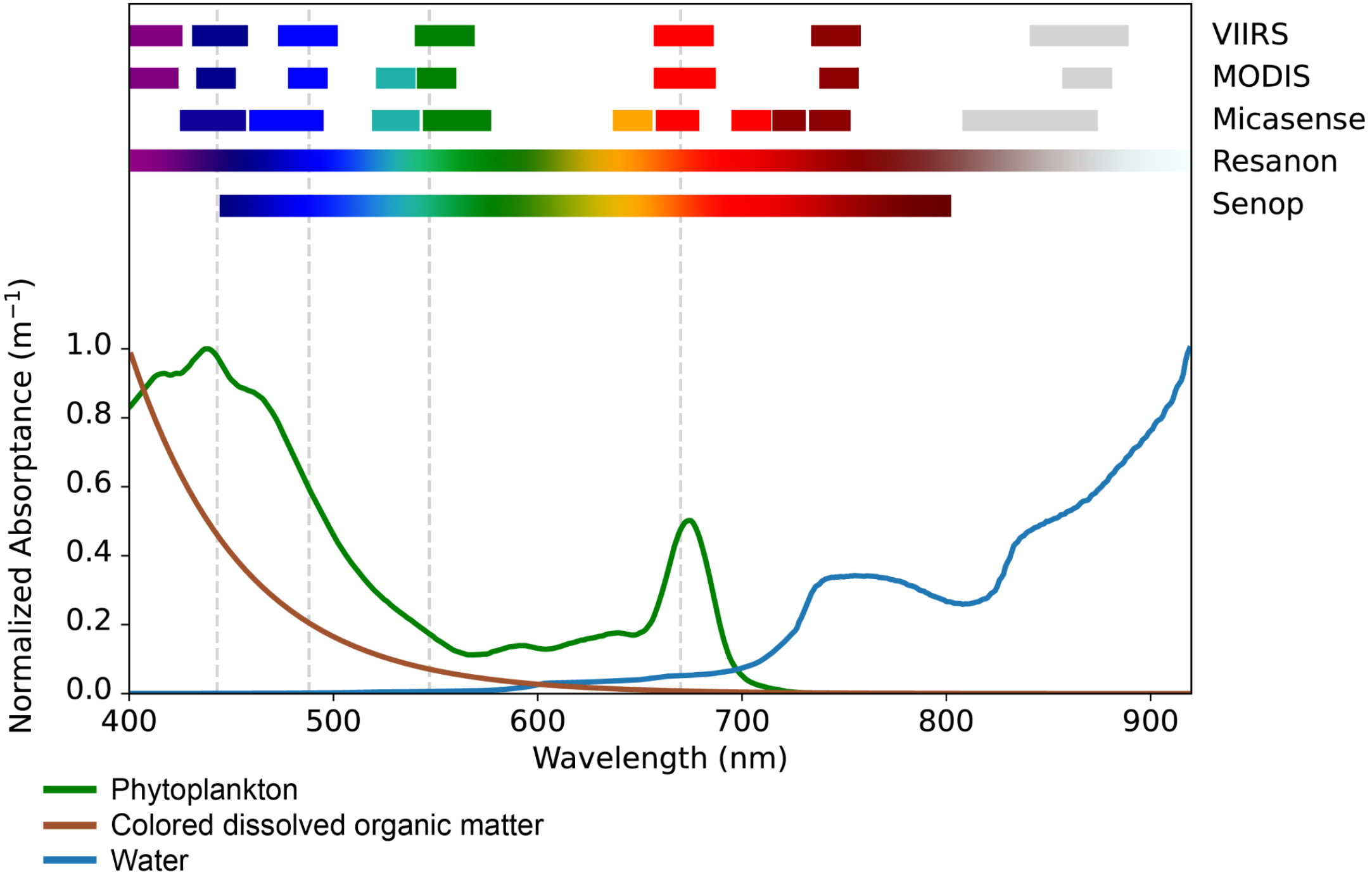
Spectral resolution



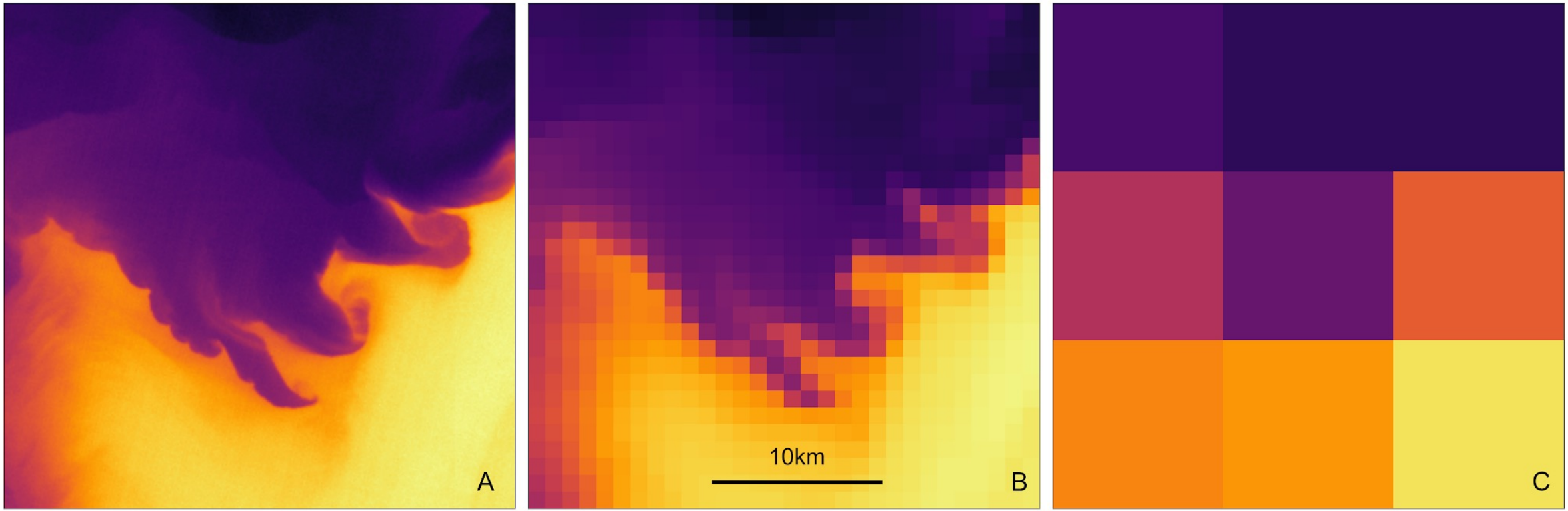
hyperspectral

multispectral

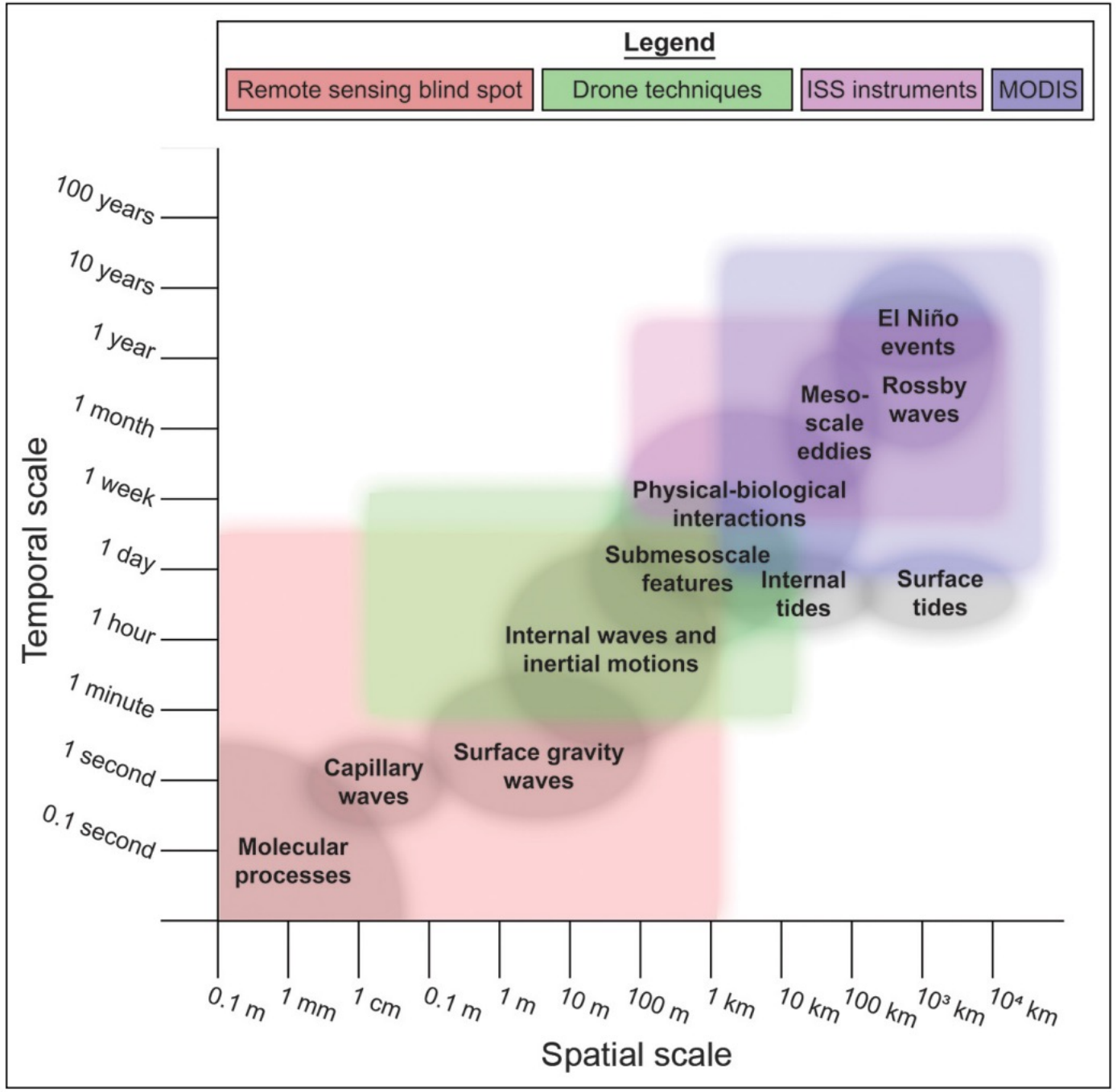
monochromatic

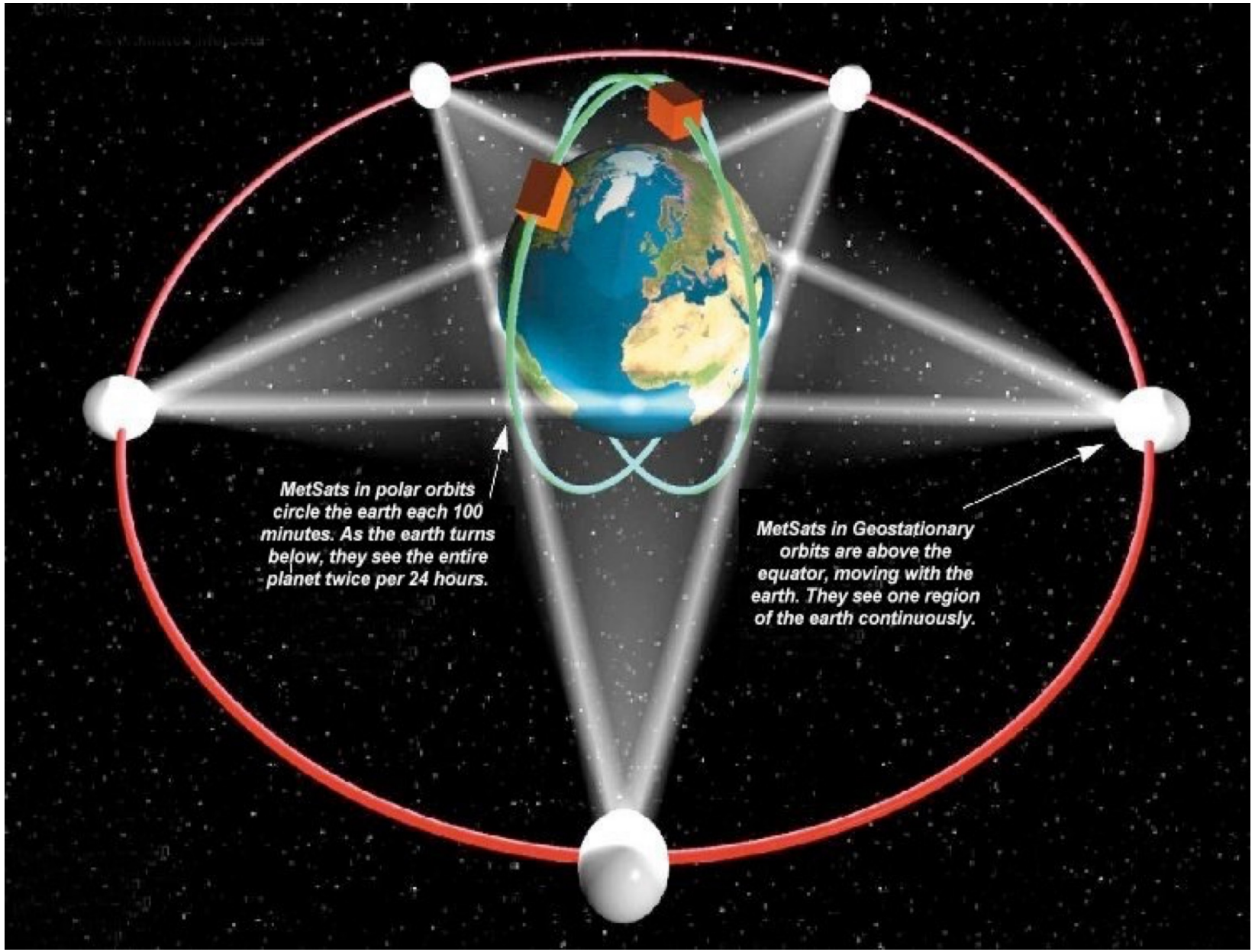

VIIRS
MODIS
Micasense
Resanon
Senop
Normalized Absorptance (m^{-1})
1.0
0.8
0.6
0.4
0.2
0.0
400
500
600
700
800
900
Wavelength (nm)
Phytoplankton
Colored dissolved organic matter
Water

Space/time resolution

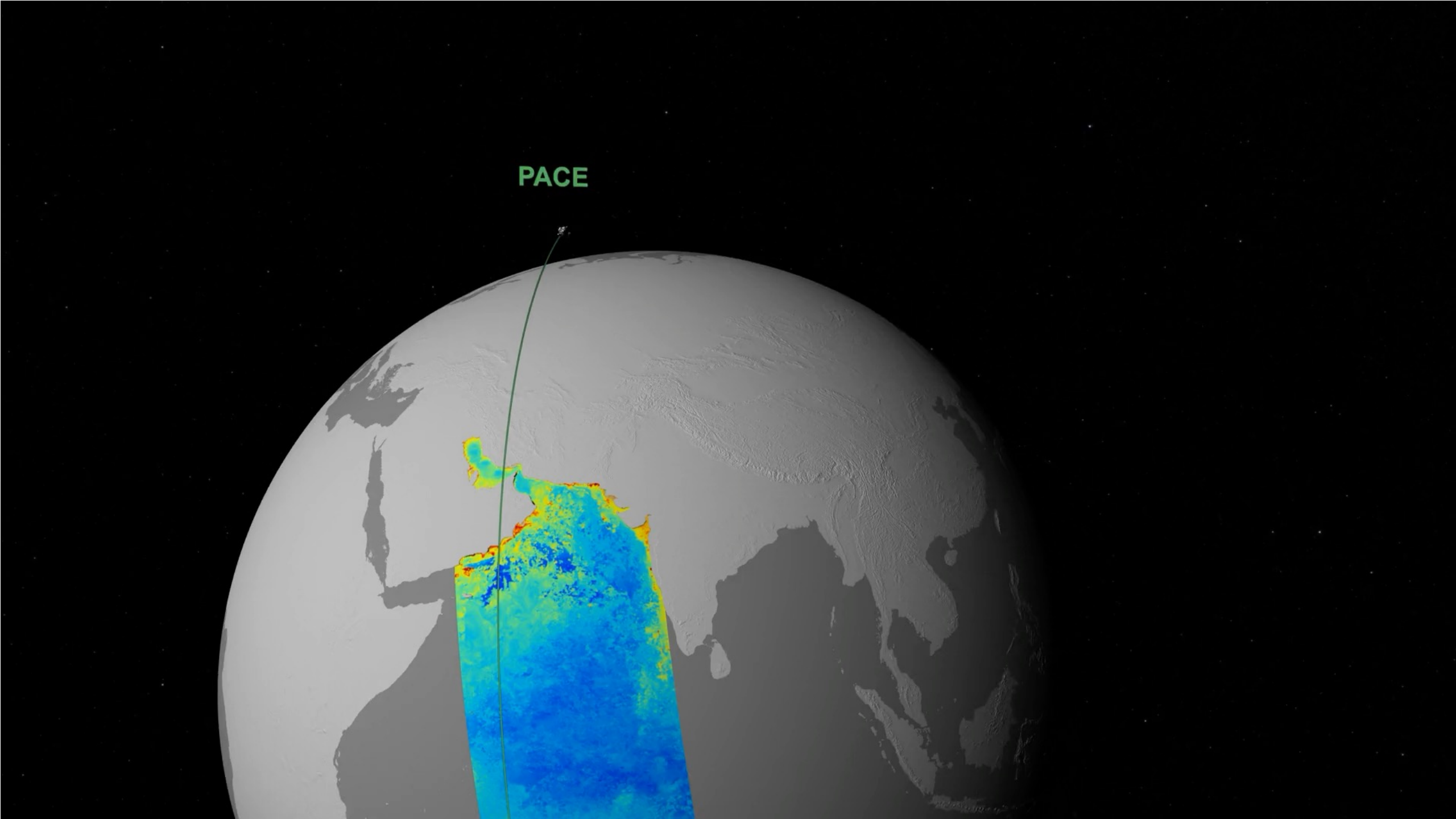


Space/time resolution

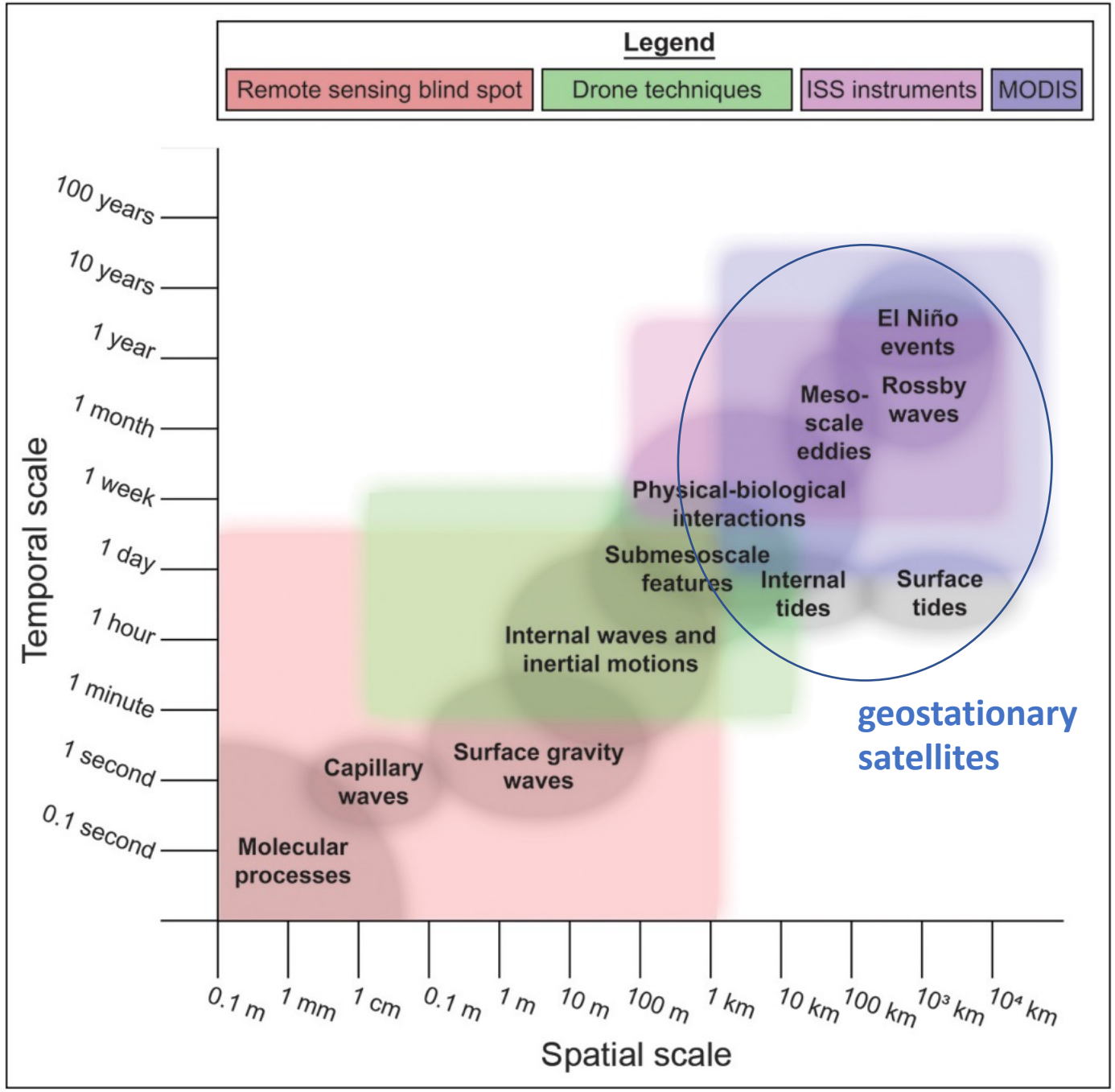


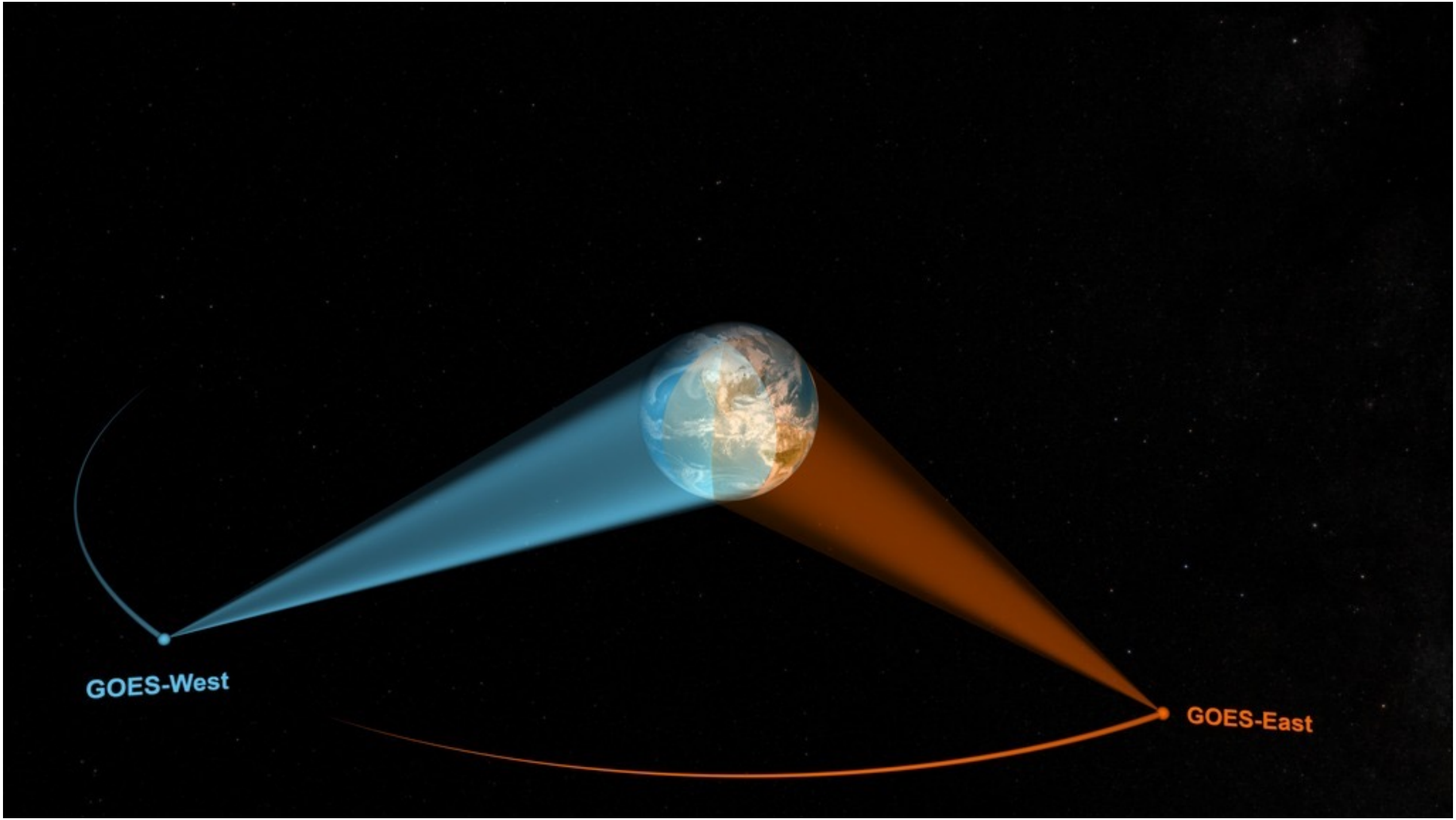


From Bruce Monger

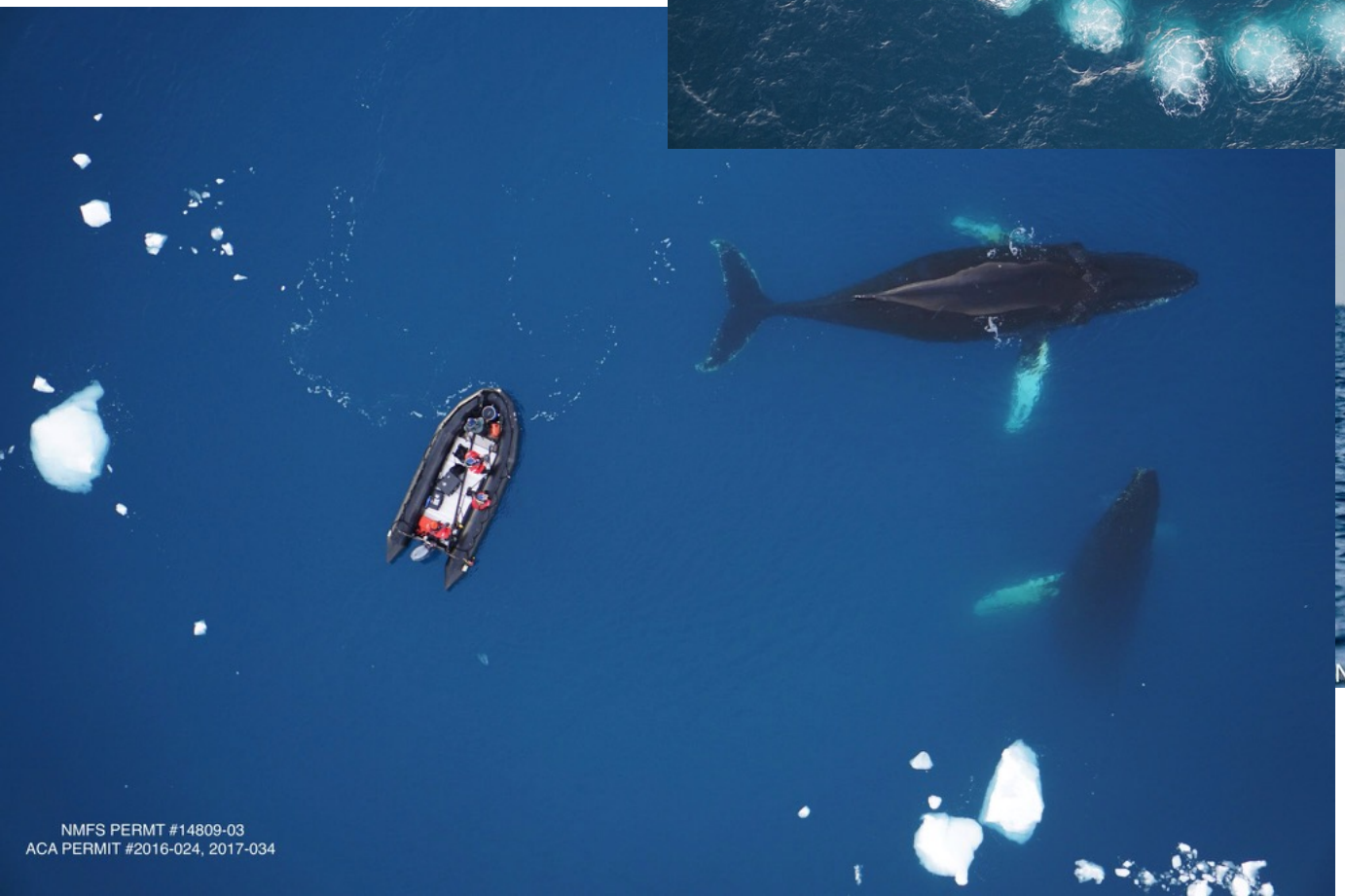

PACE

Space/time resolution



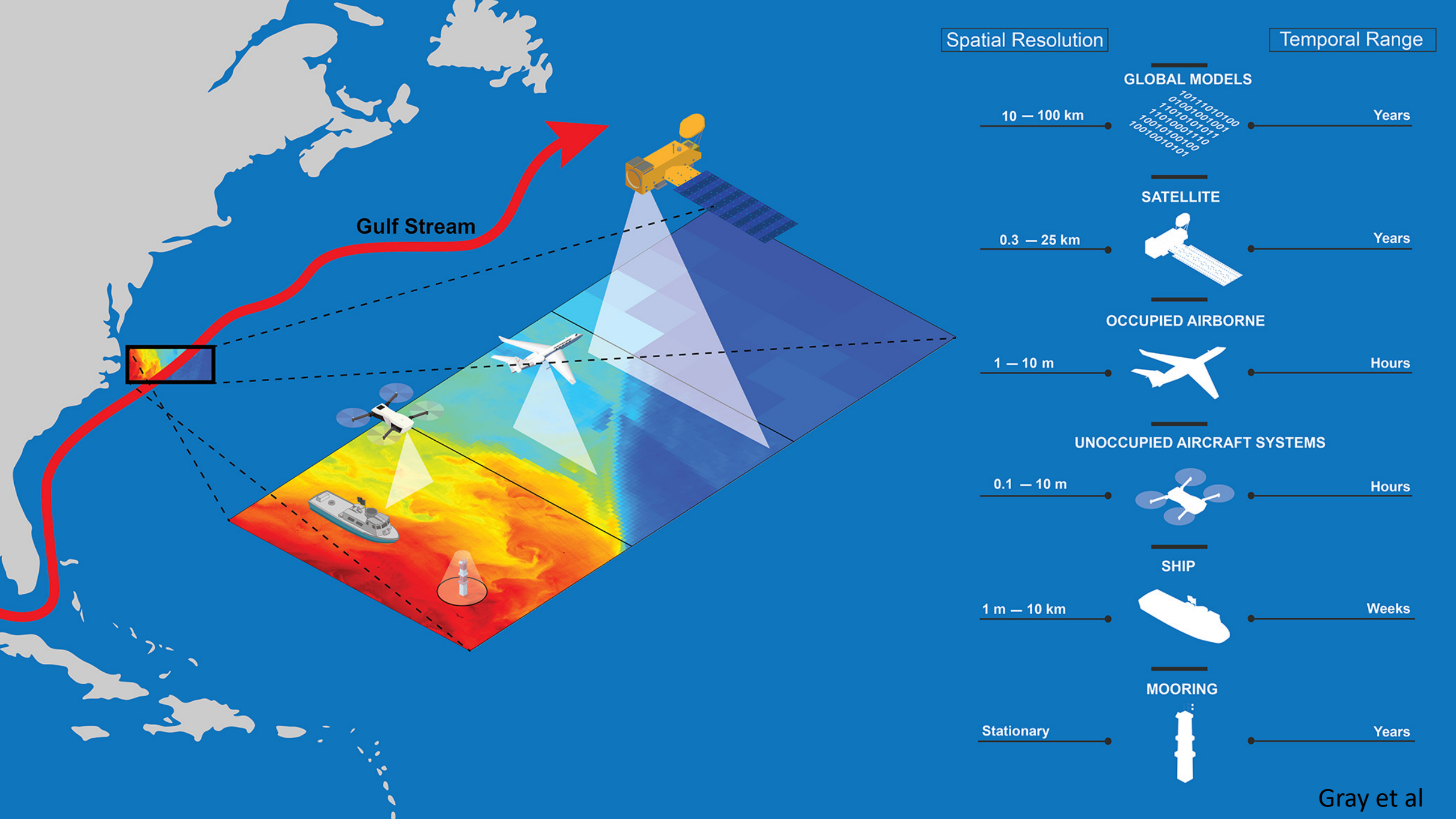

GOES-West
GOES-East

NOAA

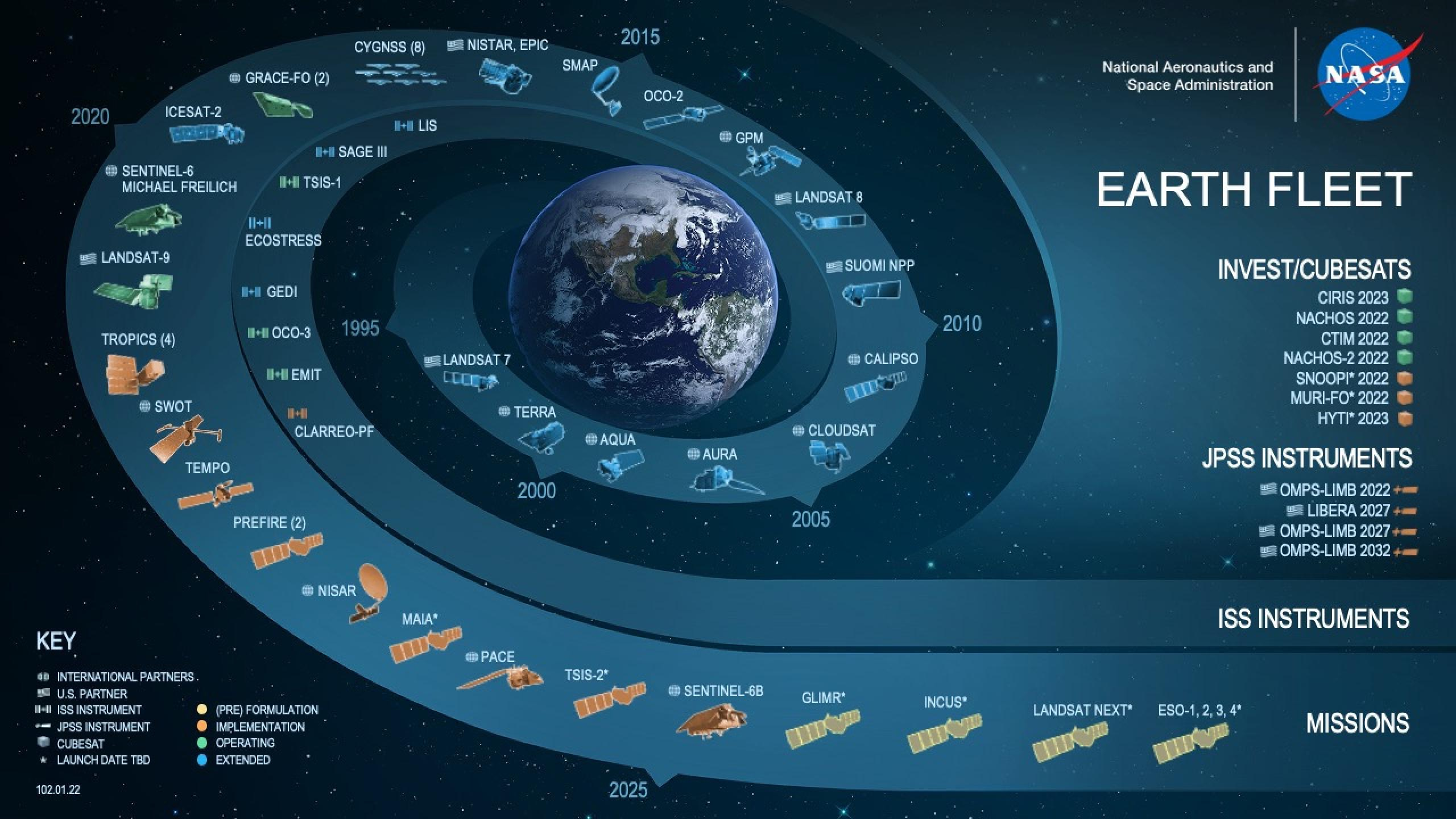


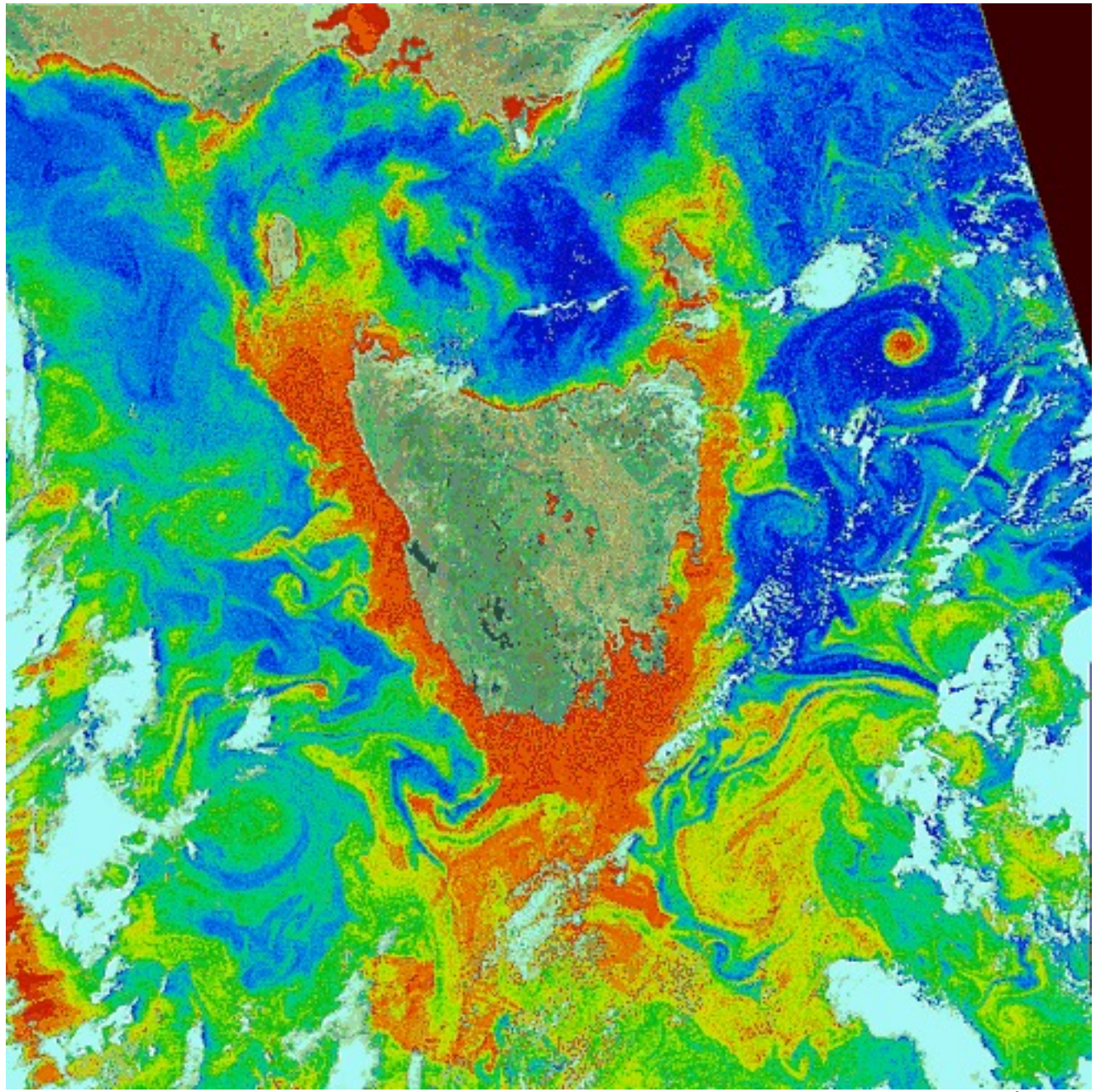
Duke Marine Robotics and Remote Sensing

Aerospace Information Research Institute (AIR)


Gulf Stream
Spatial Resolution
Temporal Range
GLOBAL MODELS
10 — 100 km
Years
SATELLITE
0.3 — 25 km
Years
OCCUPIED AIRBORNE
1 — 10 m
Hours
UNOCCUPIED AIRCRAFT SYSTEMS
0.1 — 10 m
Hours
SHIP
1 m — 10 km
Weeks
MOORING
Stationary
Years

Gray et al


National Aeronautics and Space Administration
NASA
EARTH FLEET
2015
CYGNSS (8)
NISTAR, EPIC
SMAP
OCO-2
GPM
LANDSAT 8
SUOMI NPP
2010
CALIPSO
CLOUDSAT
AURA
AQUA
TERRA
LANDSAT 7
2005
2000
1995
2020
GRACE-FO (2)
ICESAT-2
LIS
SAGE III
TSIS-1
ECOSTRESS
GEDI
OCO-3
EMIT
CLARREO-PF
SENTINEL-6 MICHAEL FREILICH
LANDSAT-9
TROPICS (4)
SWOT
TEMPO
PREFIRE (2)
NISAR
MAIA*
PACE
TSIS-2*
SENTINEL-6B
GLIMR*
INCUS*
LANDSAT NEXT*
ESO-1, 2, 3, 4*
2025
INVEST/CUBESATS
CIRIS 2023
NACHOS 2022
CTIM 2022
NACHOS-2 2022
SNOOPI* 2022
MURI-FO* 2022
HYTI* 2023
JPSS INSTRUMENTS
OMPS-LIMB 2022
LIBERA 2027
OMPS-LIMB 2027
OMPS-LIMB 2032
ISS INSTRUMENTS
MISSIONS
KEY
INTERNATIONAL PARTNERS
U.S. PARTNER
ISS INSTRUMENT
JPSS INSTRUMENT
CUBESAT
LAUNCH DATE TBD
(PRE) FORMULATION
IMPLEMENTATION
OPERATING
EXTENDED
102.01.22



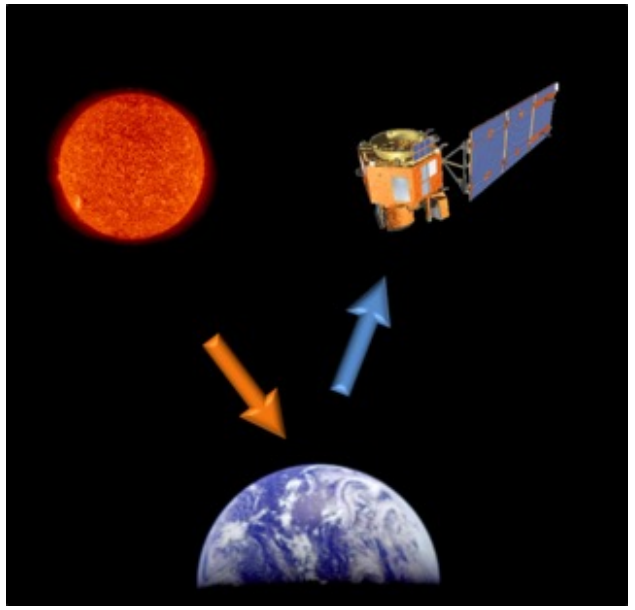
NASA/Wikipedia

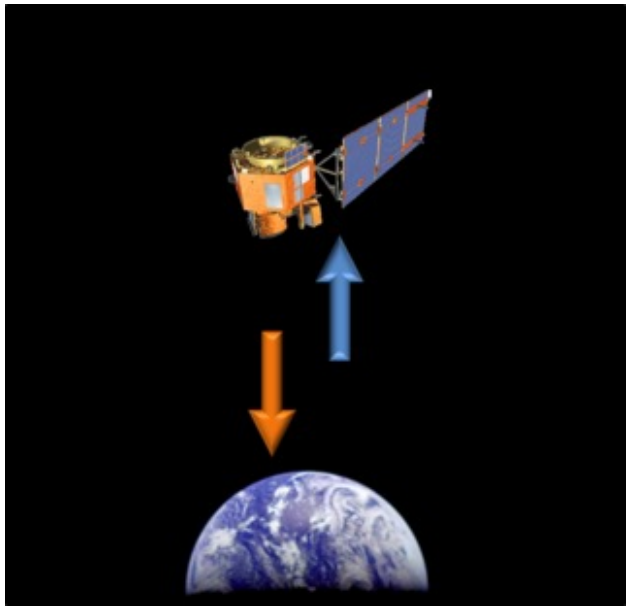
For passive OCR we're measuring Lt and deriving Rrs

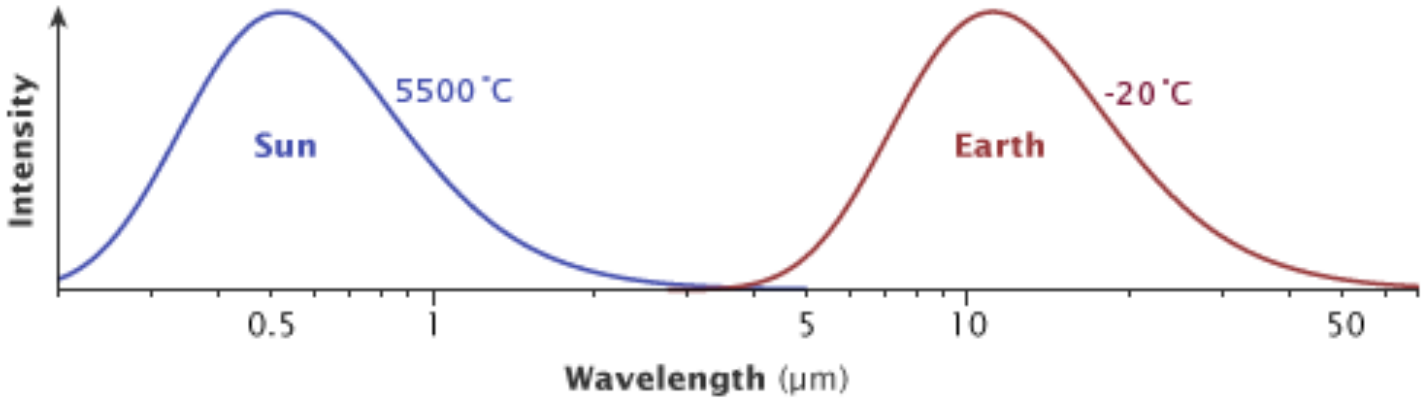
For active systems we're measuring backscatter

For SST we're measuring ~12um and assuming blackbody and using Planck's Law

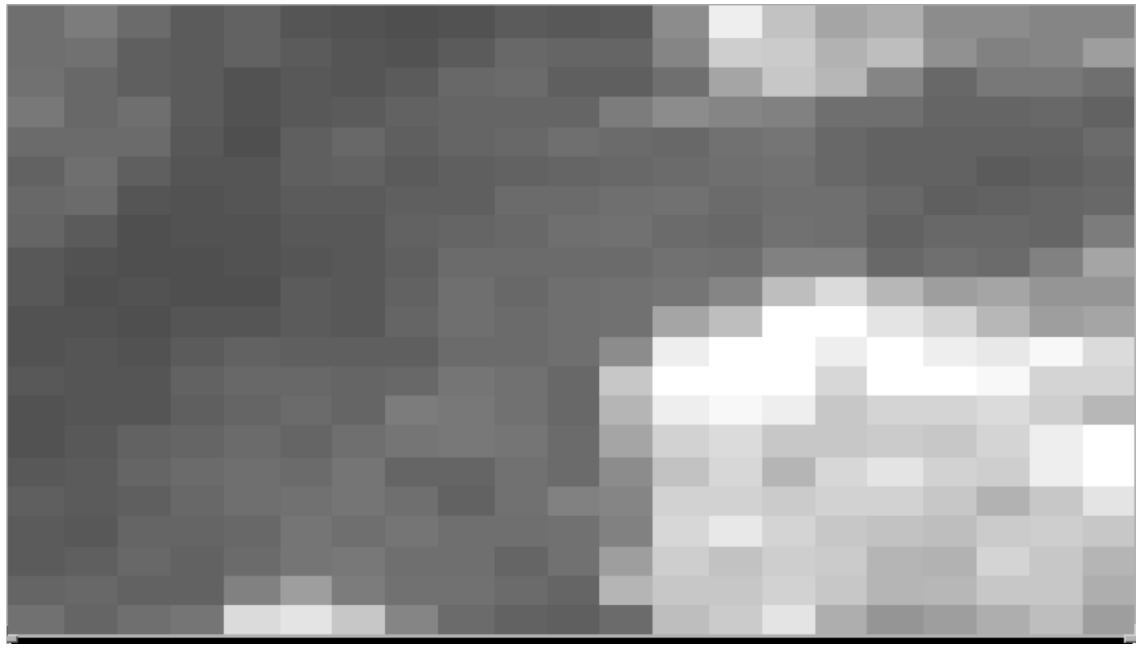
For SSH we're measuring backscatter of radar or lidar backscatter (altimetry)





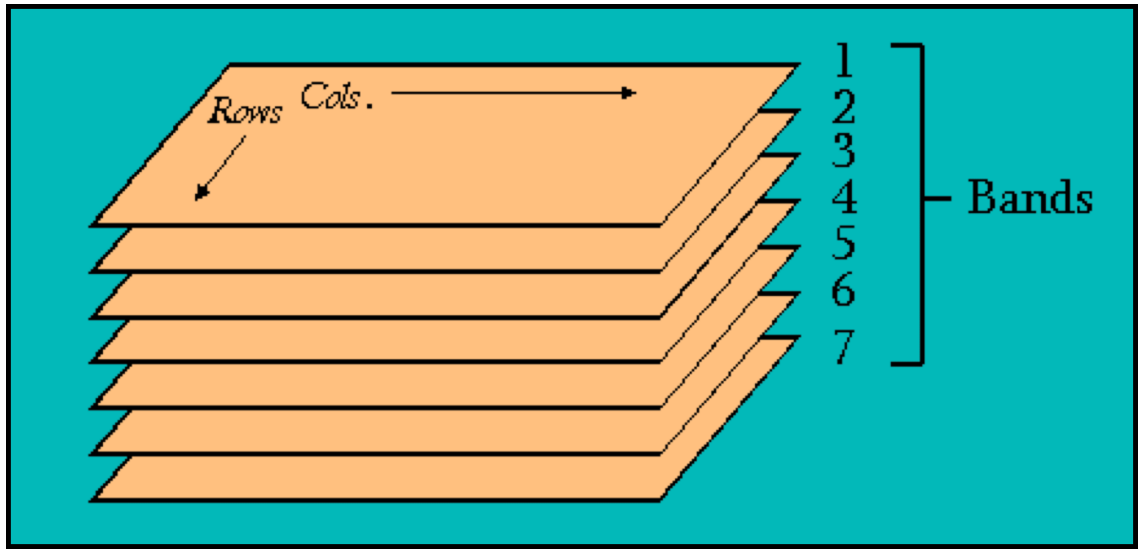


NASA Earth Observatory



=

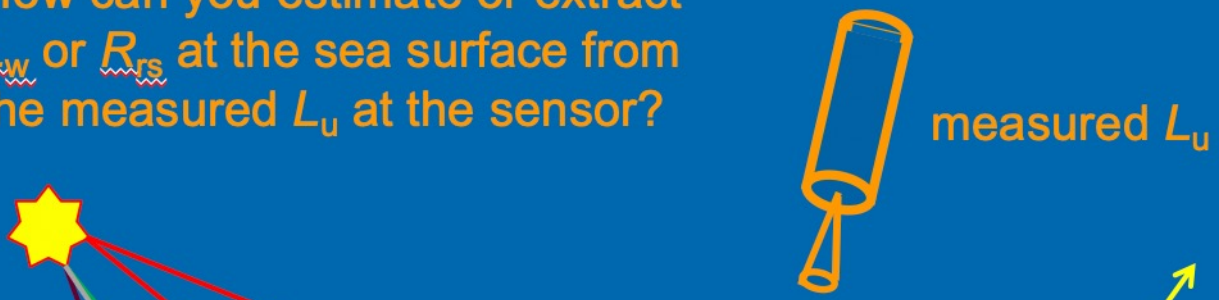
111	124	107	91	98	85	82	79	82	91	88	91	142	238	194	168	171	142	142	136	136
111	113	95	91	98	91	85	82	91	104	101	101	136	206	203	178	187	145	127	136	161
113	104	95	91	82	88	85	91	104	107	95	95	111	165	199	183	133	104	120	120	111
120	104	111	91	82	88	91	98	101	101	101	124	140	136	129	111	111	101	101	104	98
107	107	107	88	79	95	104	95	101	104	111	107	104	113	117	104	98	98	98	98	107
98	111	95	85	85	95	98	91	95	98	101	104	107	111	113	104	98	98	91	95	101
104	107	85	82	85	91	91	95	95	107	107	111	113	107	111	111	104	95	98	101	104
101	91	79	82	82	88	88	98	101	104	111	113	107	104	113	111	98	104	104	101	124
88	82	79	79	82	85	88	95	107	107	107	107	113	111	127	127	104	111	107	129	165
88	79	82	79	79	91	88	98	111	104	111	113	117	133	187	219	183	161	165	152	149
82	82	79	85	85	91	88	101	111	107	111	113	168	190	255	255	228	212	183	161	168
82	85	82	91	98	95	95	95	107	107	111	142	241	255	255	235	255	238	232	248	219
88	85	85	98	104	104	101	104	117	113	104	197	255	255	255	215	255	255	251	212	212
82	85	85	95	101	107	101	124	120	113	104	181	241	251	235	199	212	212	219	206	183
82	88	98	101	107	101	111	117	120	117	107	165	210	219	199	199	203	199	212	241	255
88	91	101	107	111	107	117	101	101	113	107	140	194	215	181	215	226	210	206	241	255
95	91	95	104	111	113	117	111	98	113	129	133	210	210	203	210	210	199	178	199	228
91	88	101	101	104	117	111	117	111	111	113	127	215	232	212	199	194	187	203	206	199
91	95	104	98	107	117	120	111	111	101	113	158	206	194	206	203	181	178	212	199	181
101	104	98	98	129	161	124	113	113	107	101	181	199	197	210	199	181	183	199	199	174
113	101	111	117	219	228	197	133	107	98	95	107	187	203	228	171	149	161	174	190	161



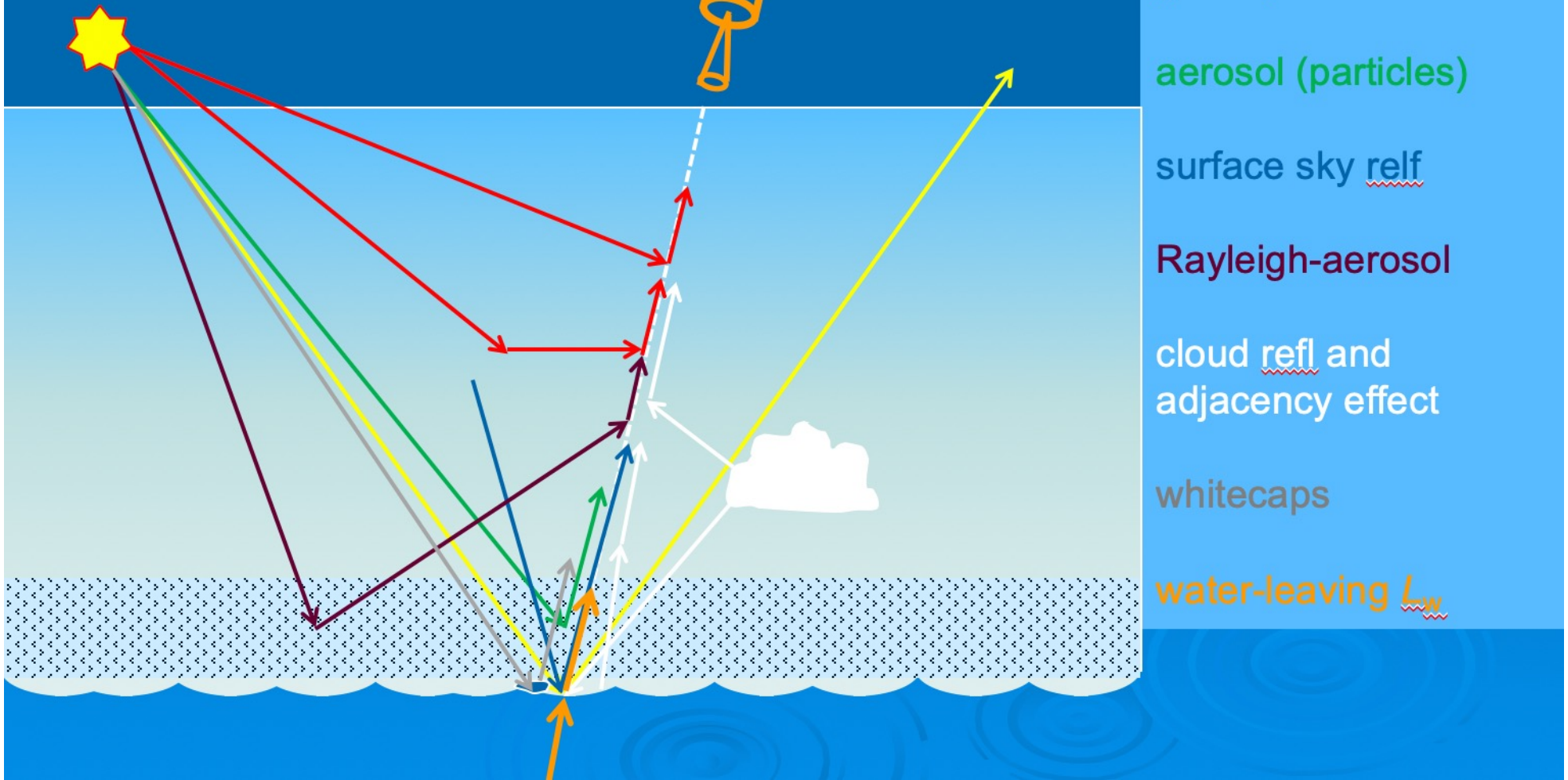
From Bruce Monger

The Atmospheric Correction Problem

How can you estimate or extract L_w or R_{rs} at the sea surface from the measured L_u at the sensor?



measured L_u



contributions to at-sensor radiance

specular reflectance

Rayleigh (atmospheric gases)

aerosol (particles)

surface sky relf

Rayleigh-aerosol

cloud refl and adjacency effect

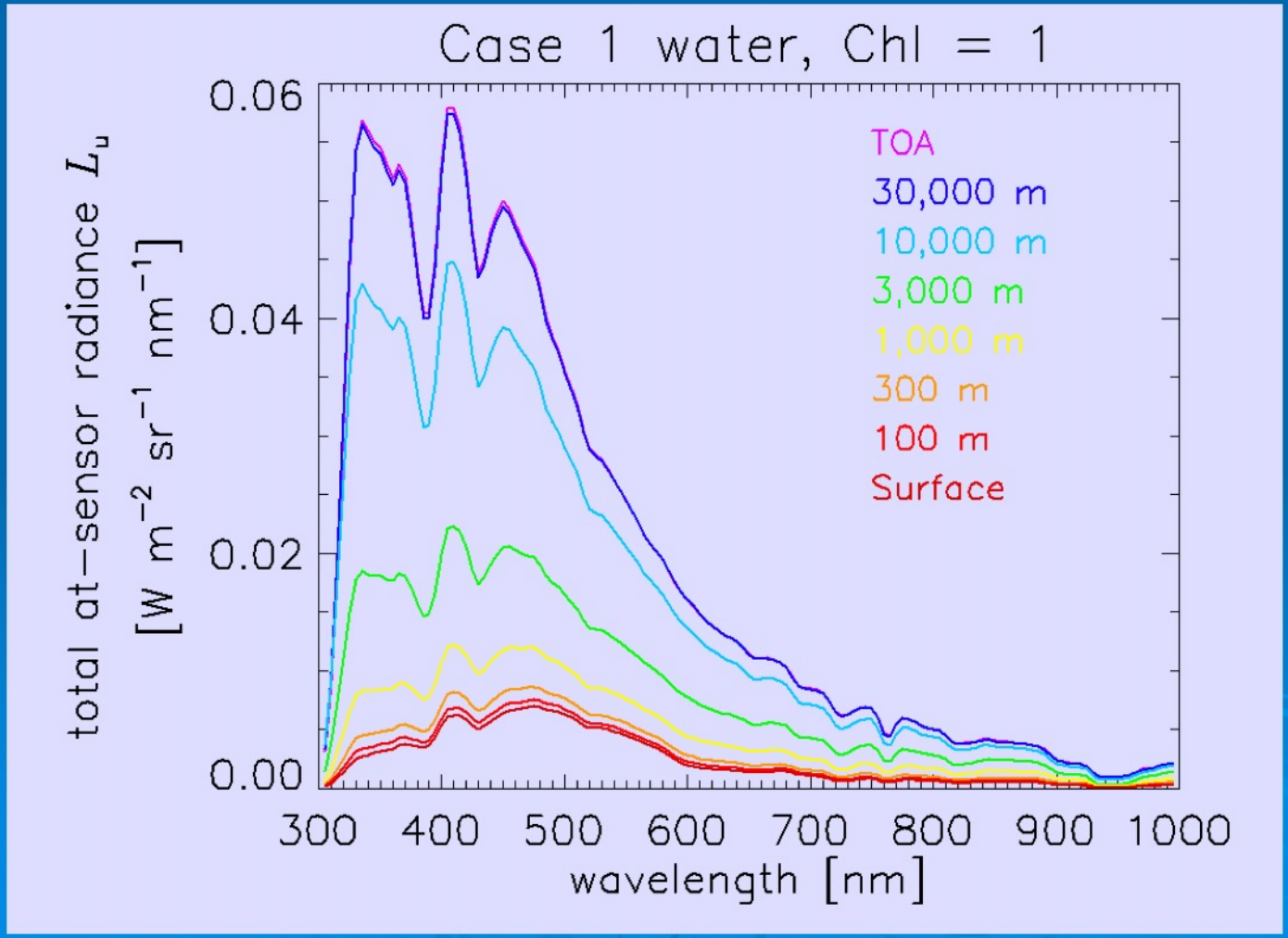
whitecaps

water-leaving L_w

from curt

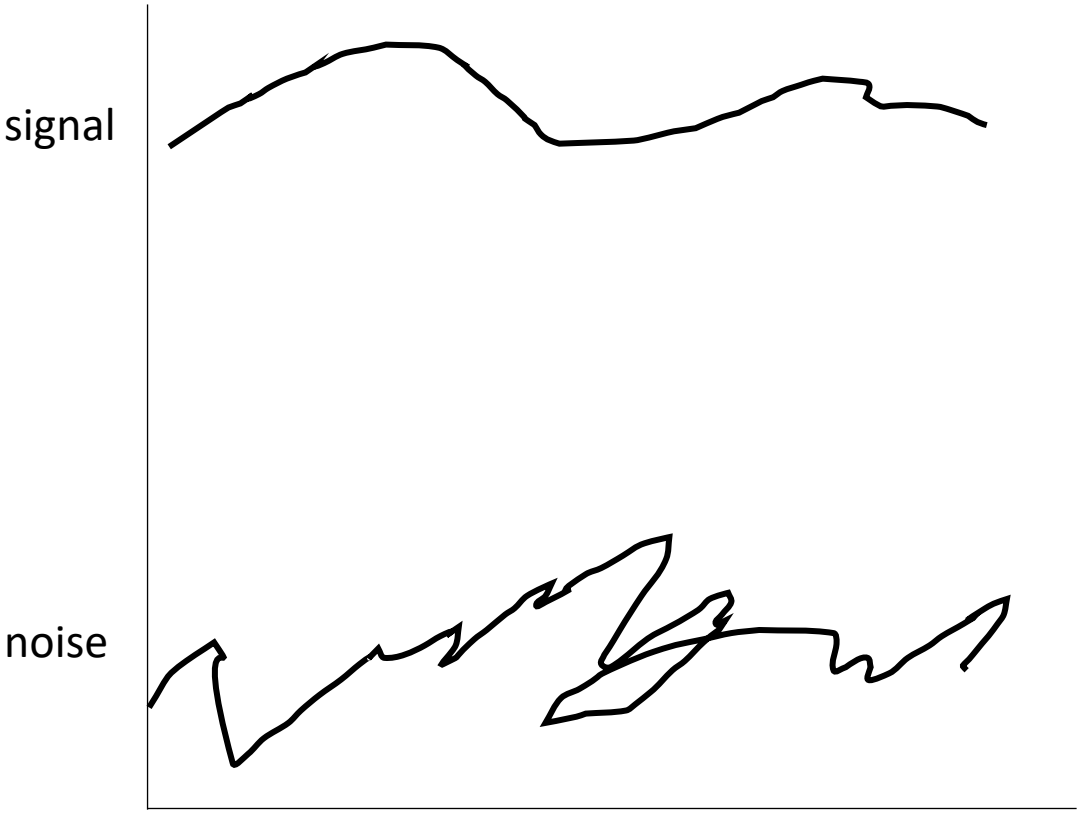
Total At-sensor Radiances at Various Altitudes

Most airborne remote sensing is done from altitudes of 1,000 to 10,000 m. Atmospheric path radiance is very important

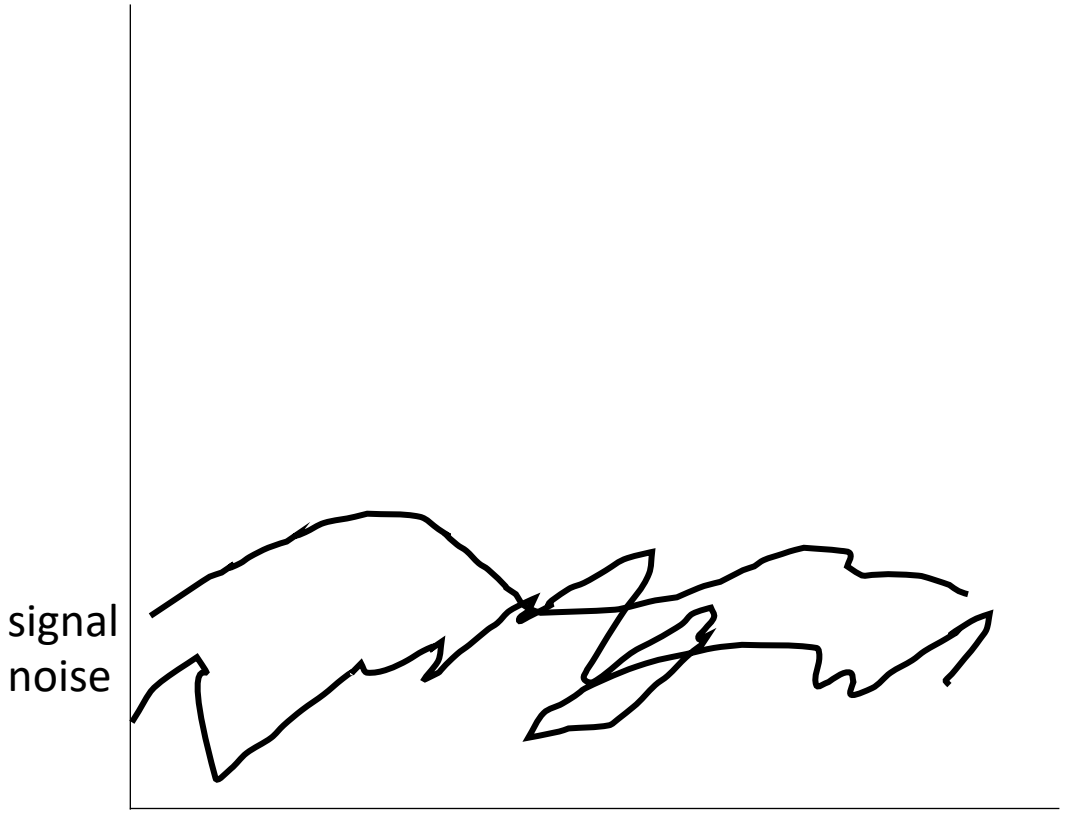


from curt

Signal strength relative to noise



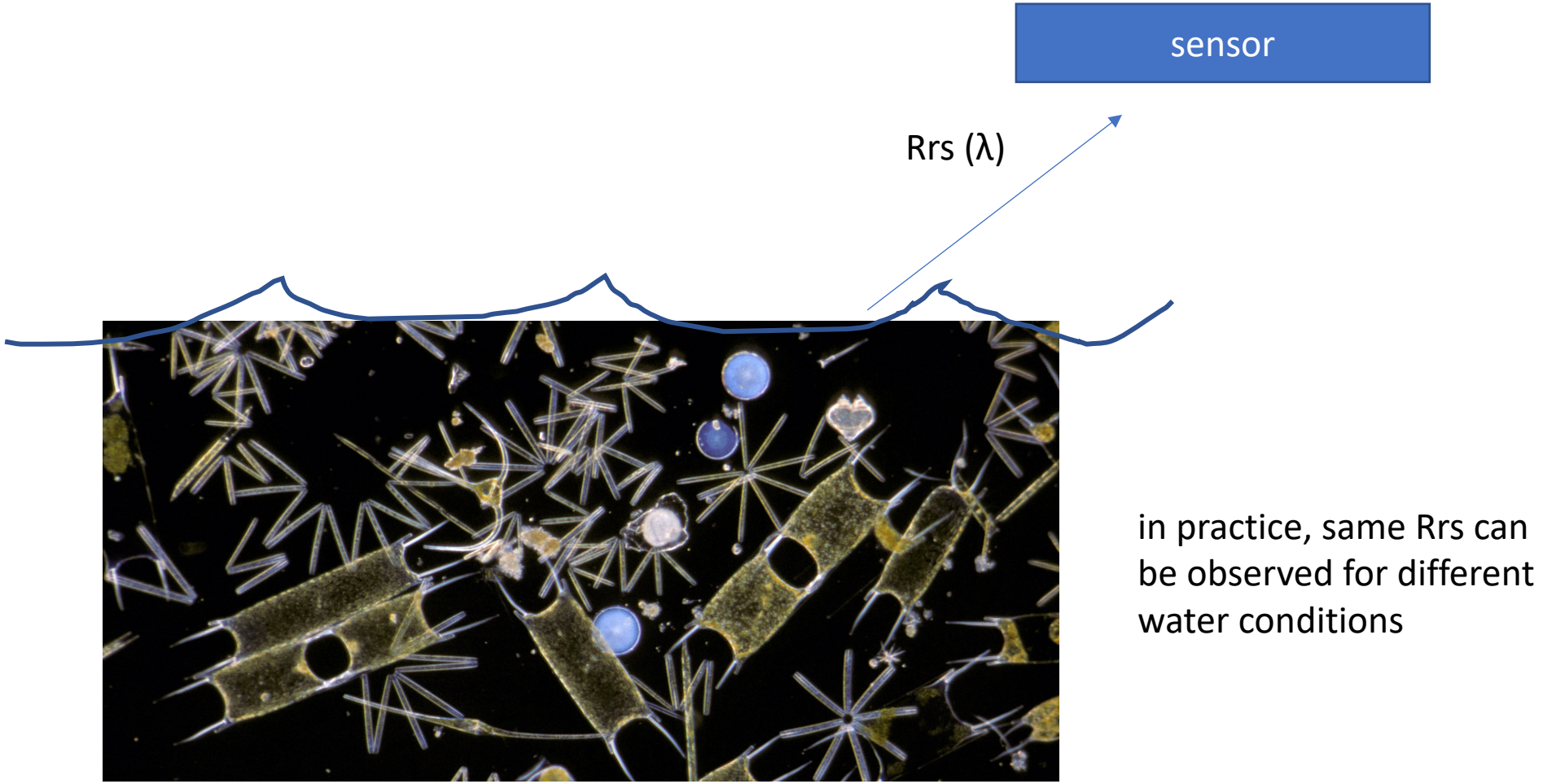
vs



What studies are enabled from the left plot compared to right?

Ocean color remote sensing is an INVERSE PROBLEM

Radiometers observed the combined effects of optical constituents, not the constitutes themselves.

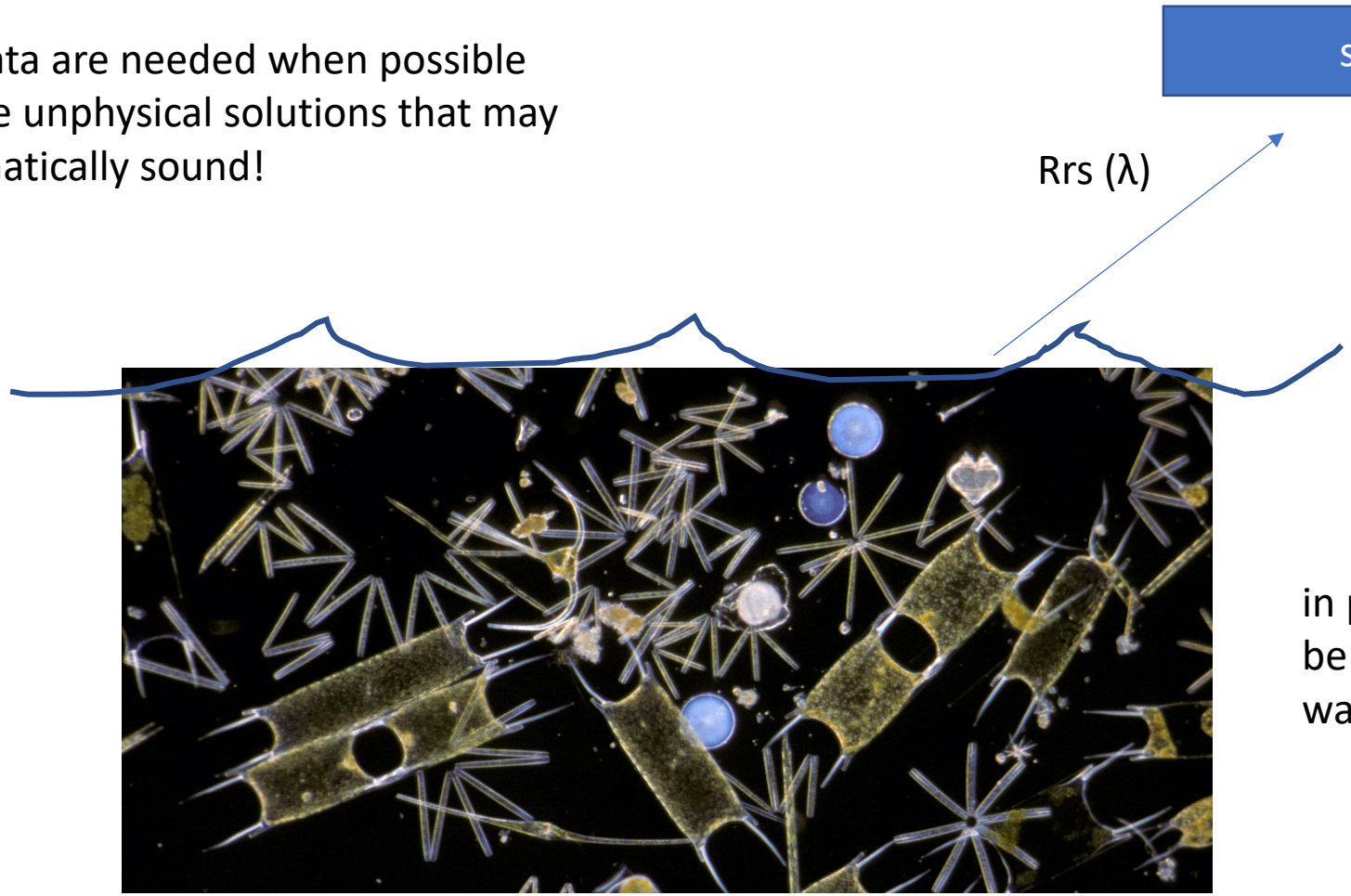


in practice, same Rrs can be observed for different water conditions

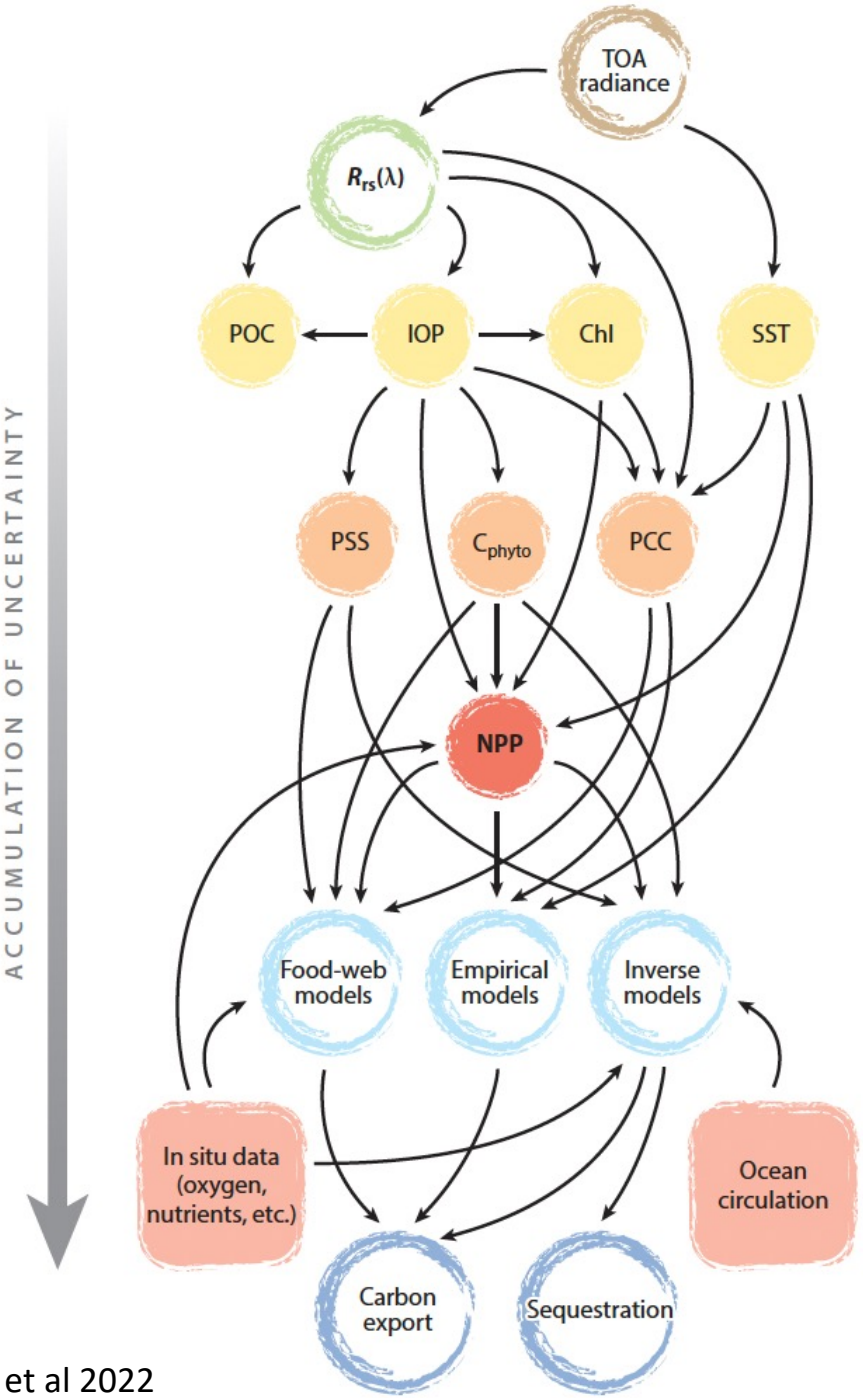
Ocean color remote sensing is an INVERSE PROBLEM

Radiometers observed the combined effects of optical constituents, not the constitutes themselves.

Ancillary data are needed when possible to eliminate unphysical solutions that may be mathematically sound!



in practice, same Rrs can be observed for different water conditions

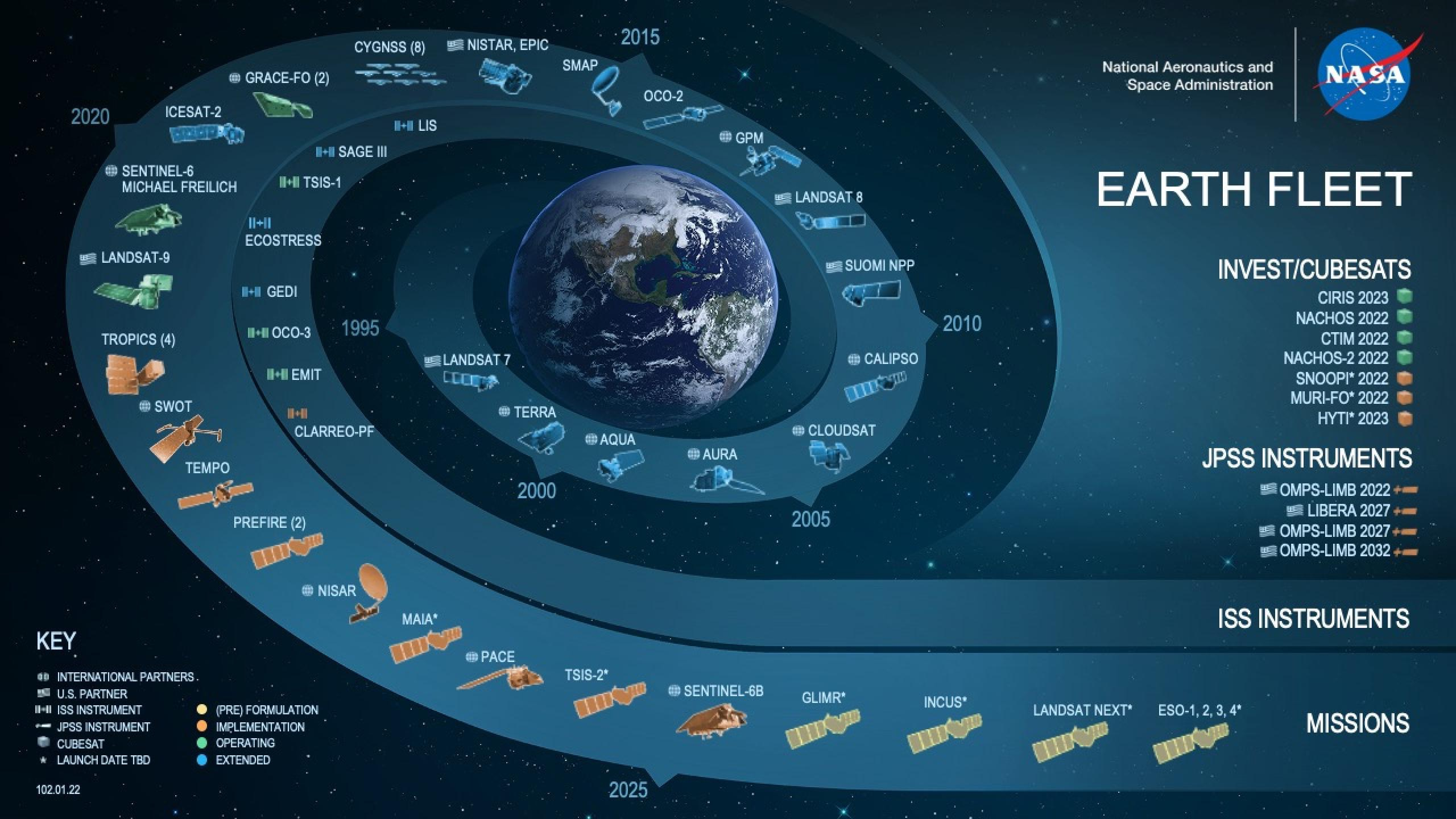


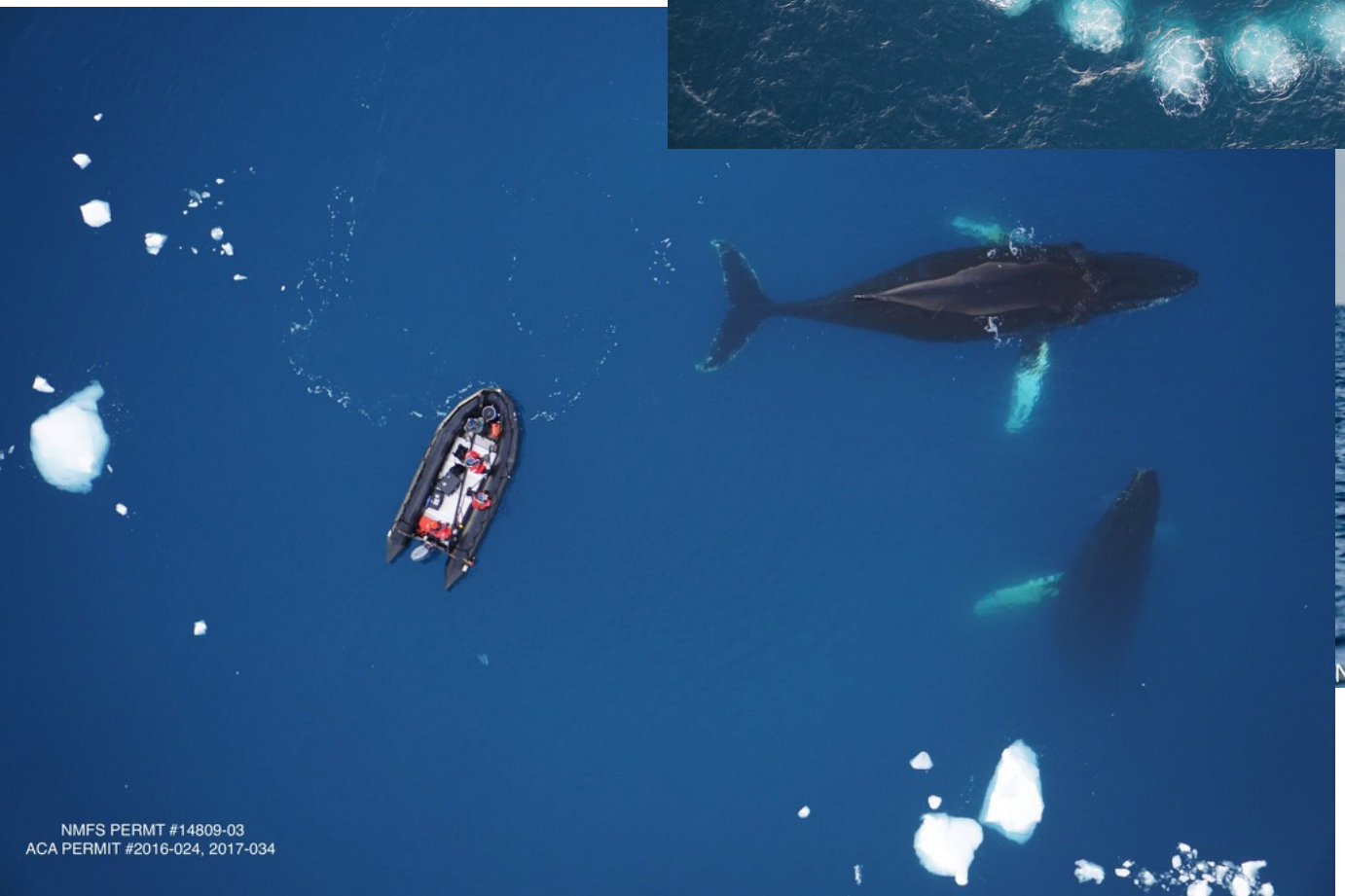
Siegel et al 2022

How independent are RS products?

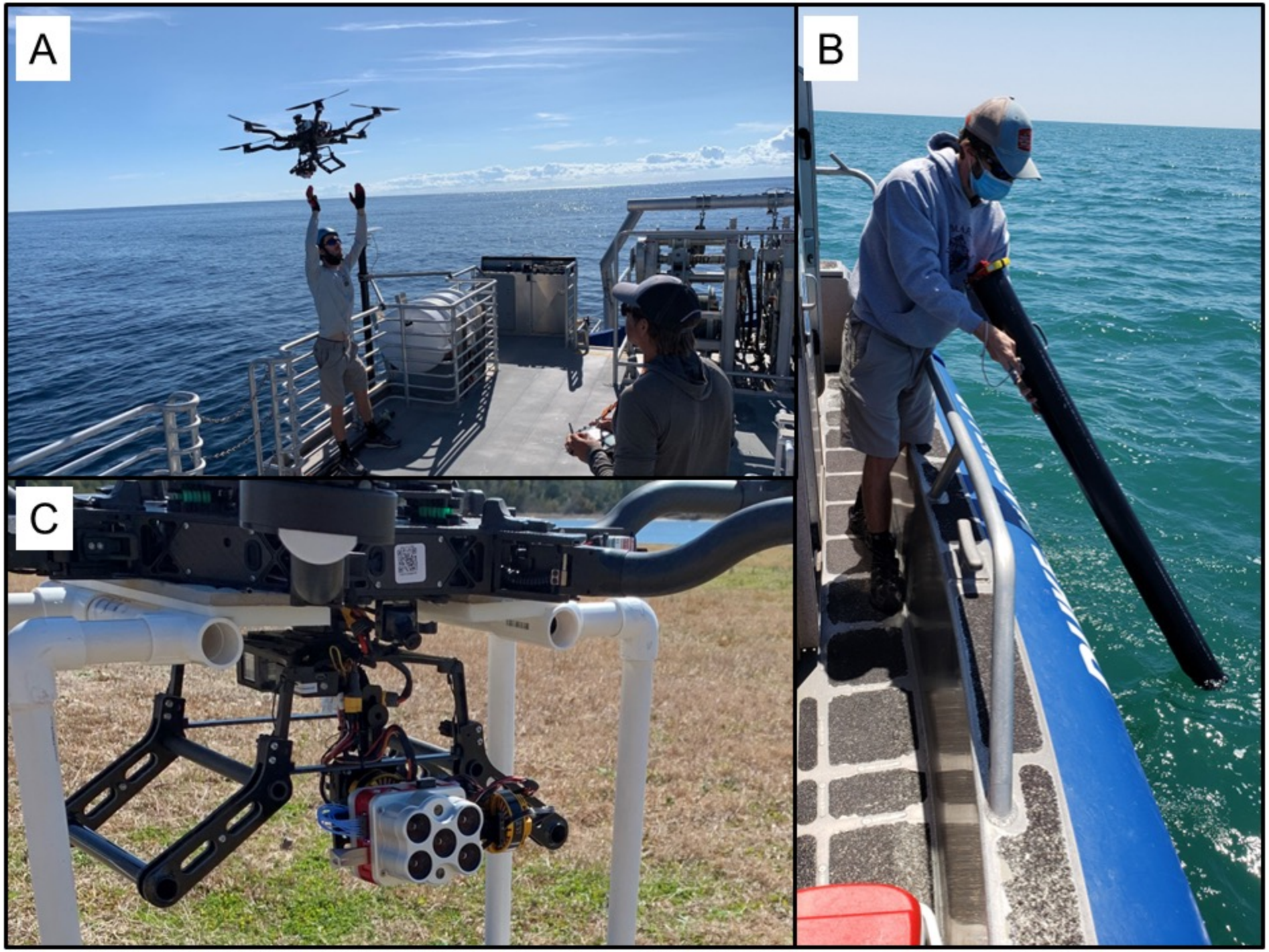
Many products are retrieved from remote sensing that are used by modelers as independent products

However, these products are highly correlated with each other as they are derived from one central product

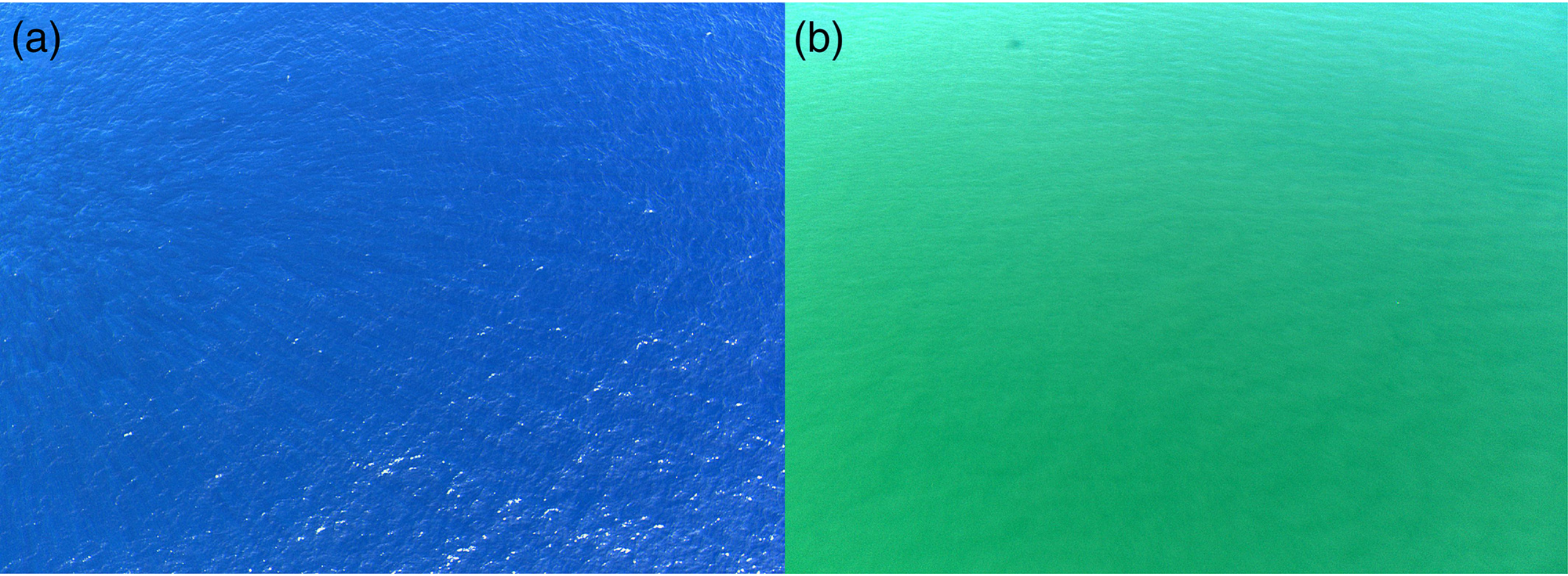

National Aeronautics and Space Administration
NASA
EARTH FLEET
2015
CYGNSS (8)
NISTAR, EPIC
SMAP
OCO-2
GPM
LANDSAT 8
SUOMI NPP
2010
CALIPSO
CLOUDSAT
AURA
AQUA
TERRA
LANDSAT 7
2005
2000
1995
2020
GRACE-FO (2)
ICESAT-2
LIS
SAGE III
TSIS-1
ECOSTRESS
GEDI
OCO-3
EMIT
CLARREO-PF
SENTINEL-6 MICHAEL FREILICH
LANDSAT-9
TROPICS (4)
SWOT
TEMPO
PREFIRE (2)
NISAR
MAIA*
PACE
TSIS-2*
SENTINEL-6B
GLIMR*
INCUS*
LANDSAT NEXT*
ESO-1, 2, 3, 4*
2025
INVEST/CUBESATS
CIRIS 2023
NACHOS 2022
CTIM 2022
NACHOS-2 2022
SNOOPI* 2022
MURI-FO* 2022
HYTI* 2023
JPSS INSTRUMENTS
OMPS-LIMB 2022
LIBERA 2027
OMPS-LIMB 2027
OMPS-LIMB 2032
ISS INSTRUMENTS
MISSIONS
KEY
INTERNATIONAL PARTNERS
U.S. PARTNER
ISS INSTRUMENT
JPSS INSTRUMENT
CUBESAT
LAUNCH DATE TBD
(PRE) FORMULATION
IMPLEMENTATION
OPERATING
EXTENDED
102.01.22



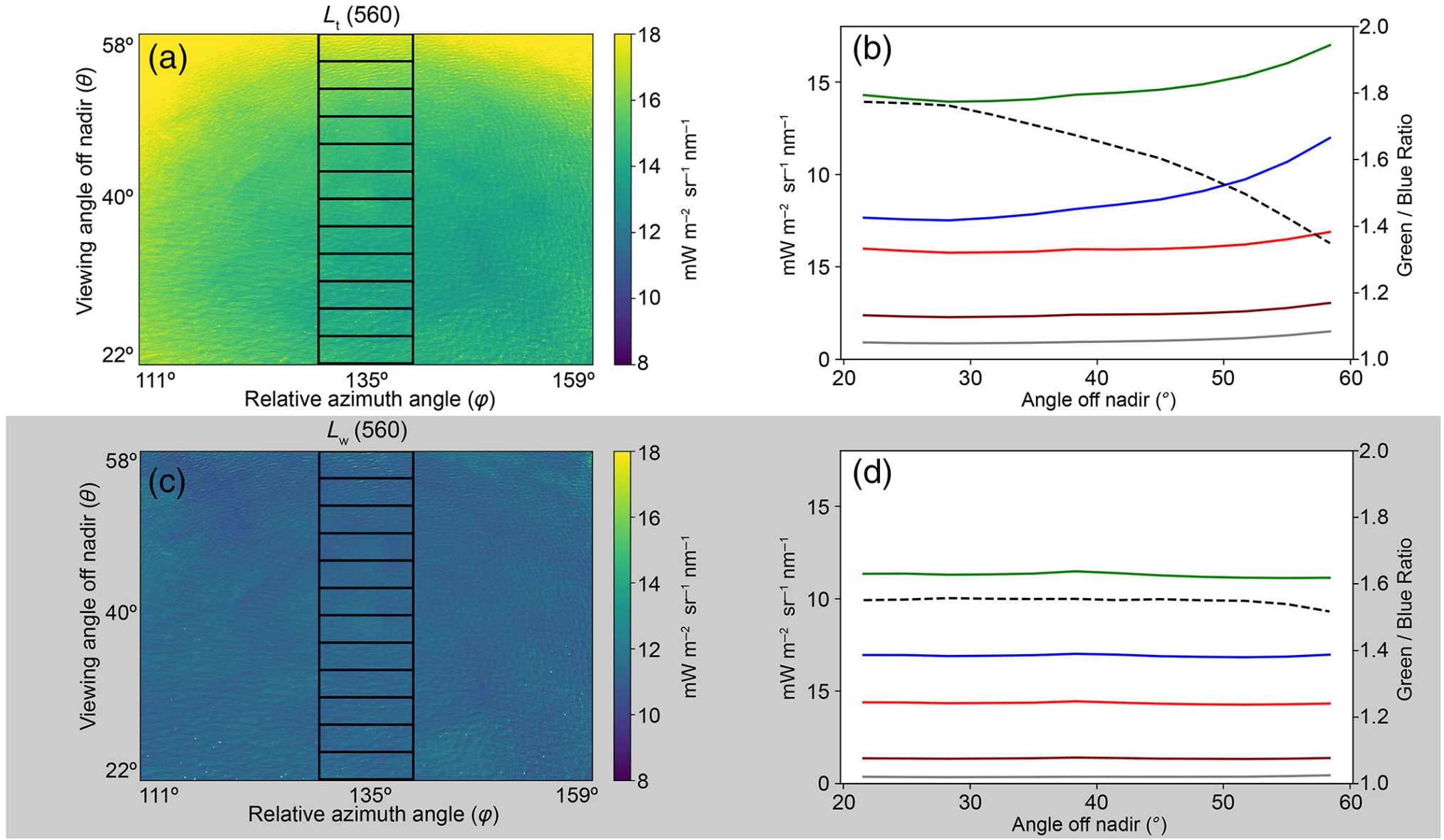
Duke Marine Robotics and Remote Sensing



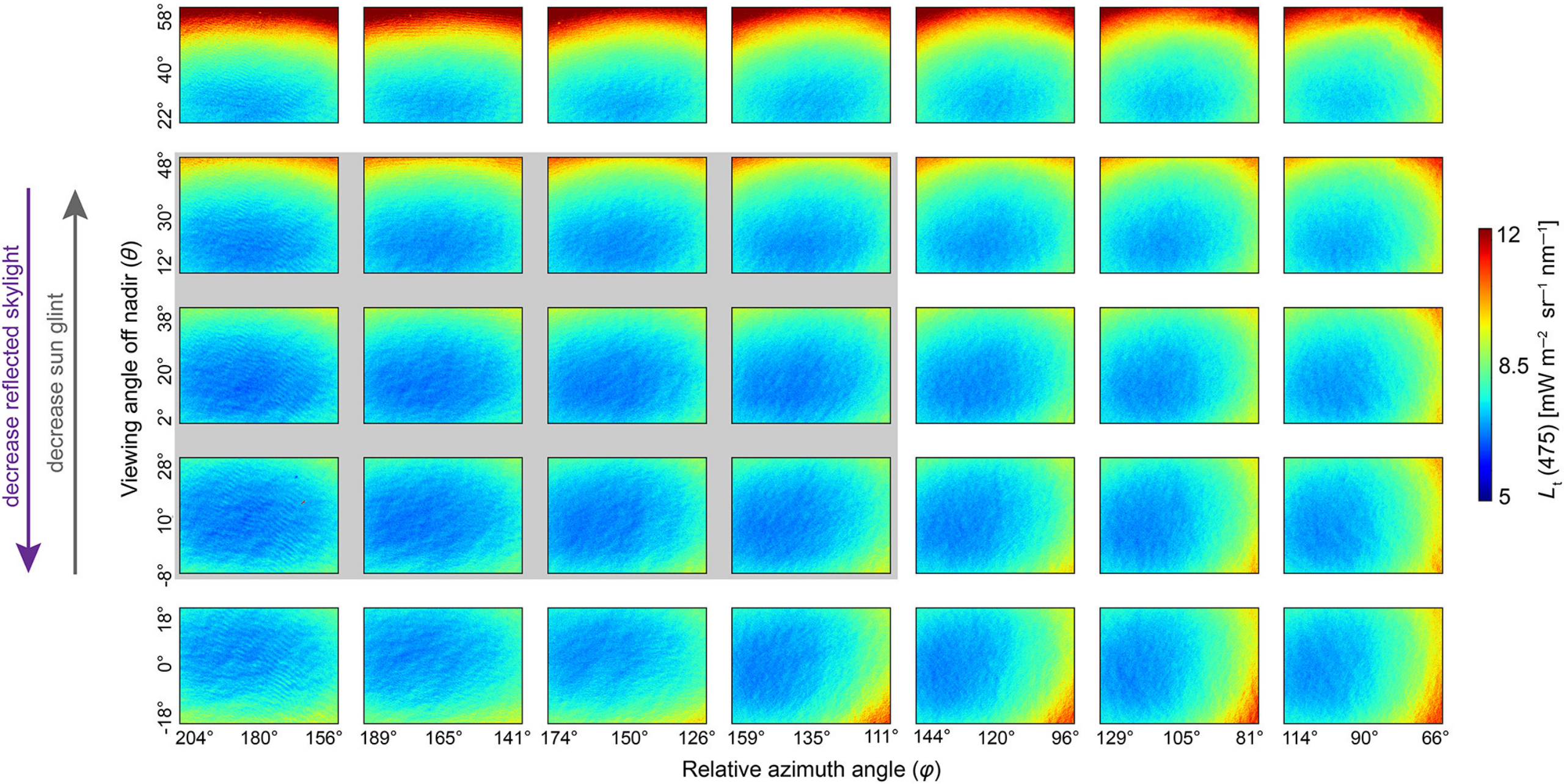
Gray et al



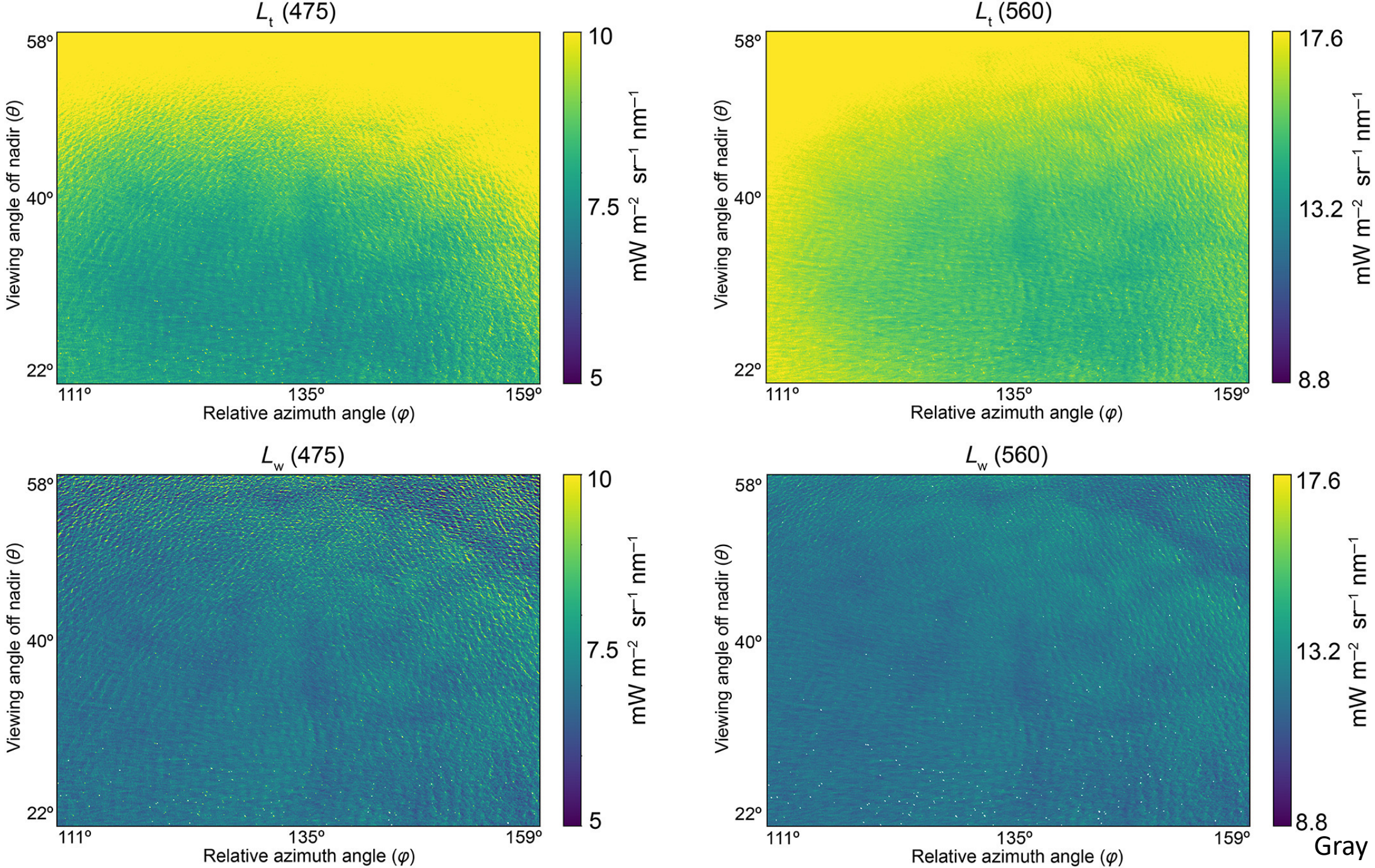
Gray et al


L_t (560)
(a)
58°
40°
22°
Viewing angle off nadir (θ)
111°
135°
159°
Relative azimuth angle (φ)
18
16
14
12
10
8
mW m⁻² sr⁻¹ nm⁻¹
(b)
mW m⁻² sr⁻¹ nm⁻¹
Green / Blue Ratio
Angle off nadir (°)
L_w (560)
(c)
(d)

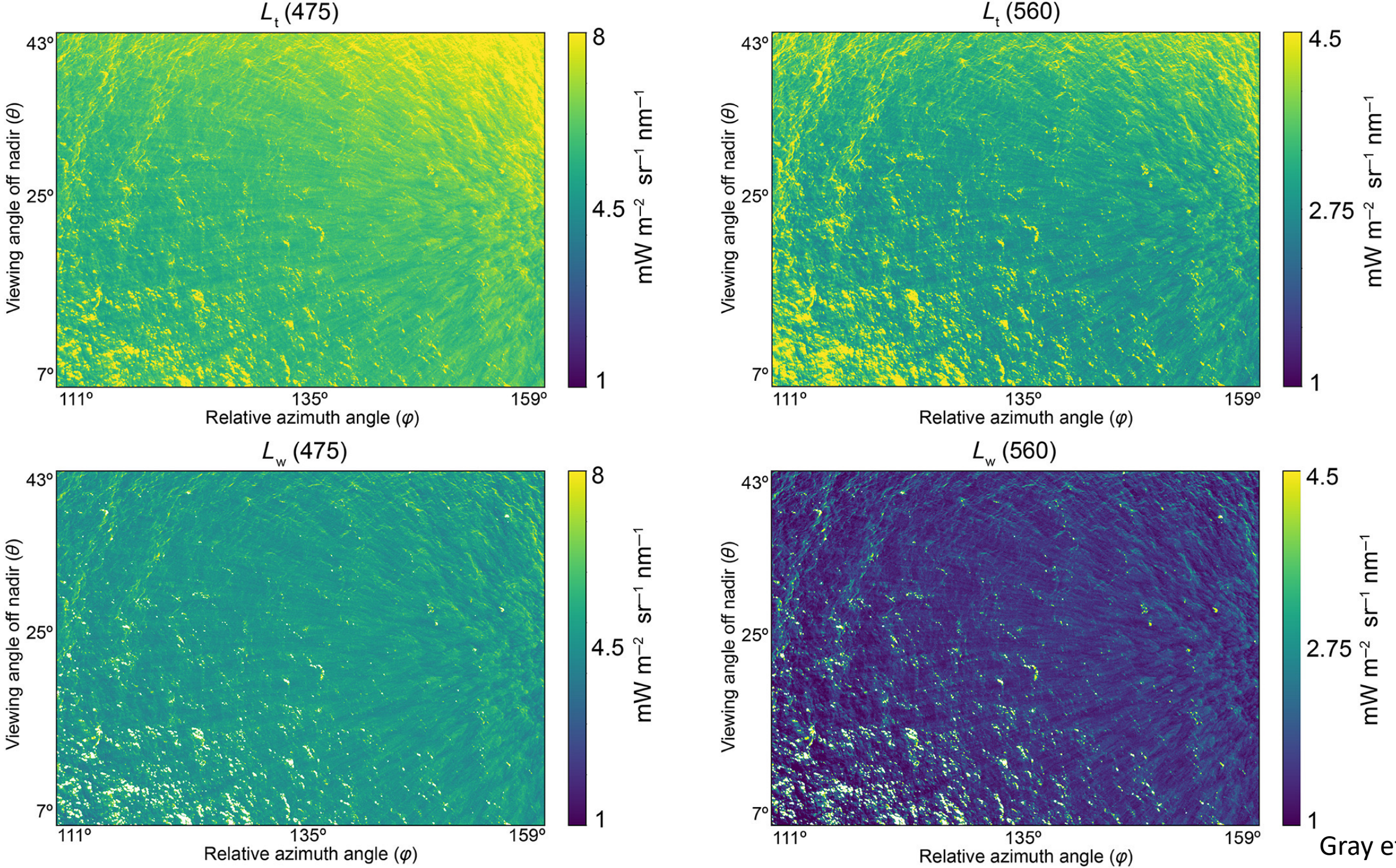
Gray et al


decrease reflected skylight
decrease sun glint
Viewing angle off nadir (θ)
58°
40°
22°
48°
30°
12°
38°
20°
2°
28°
10°
-8°
18°
0°
-18°
204°
180°
156°
189°
165°
141°
174°
150°
126°
159°
135°
111°
144°
120°
96°
129°
105°
81°
114°
90°
66°
Relative azimuth angle (φ)
12
8.5
5
L_t (475) [mW m^{-2} sr^{-1} nm^{-1}]

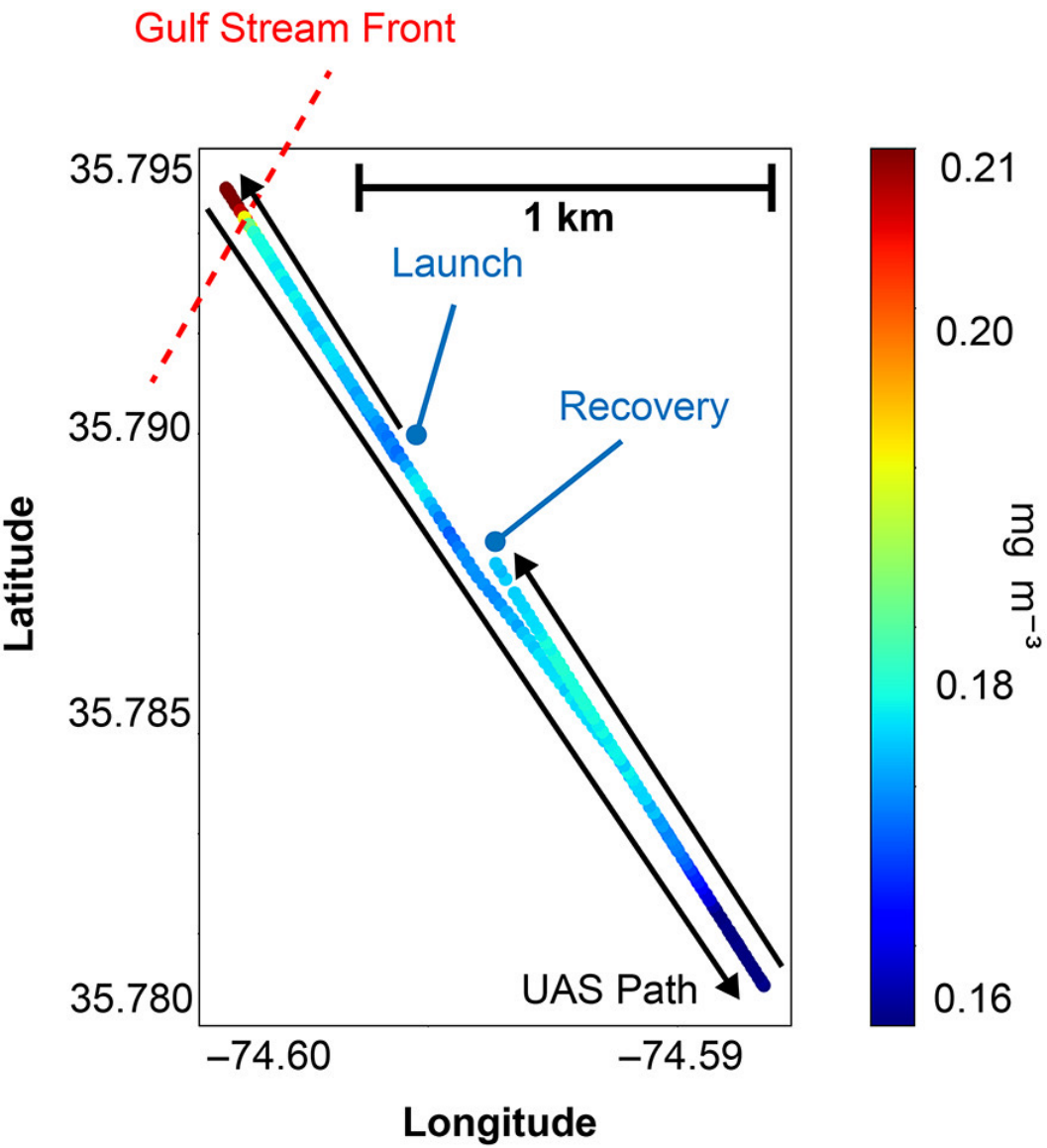
Gray et al

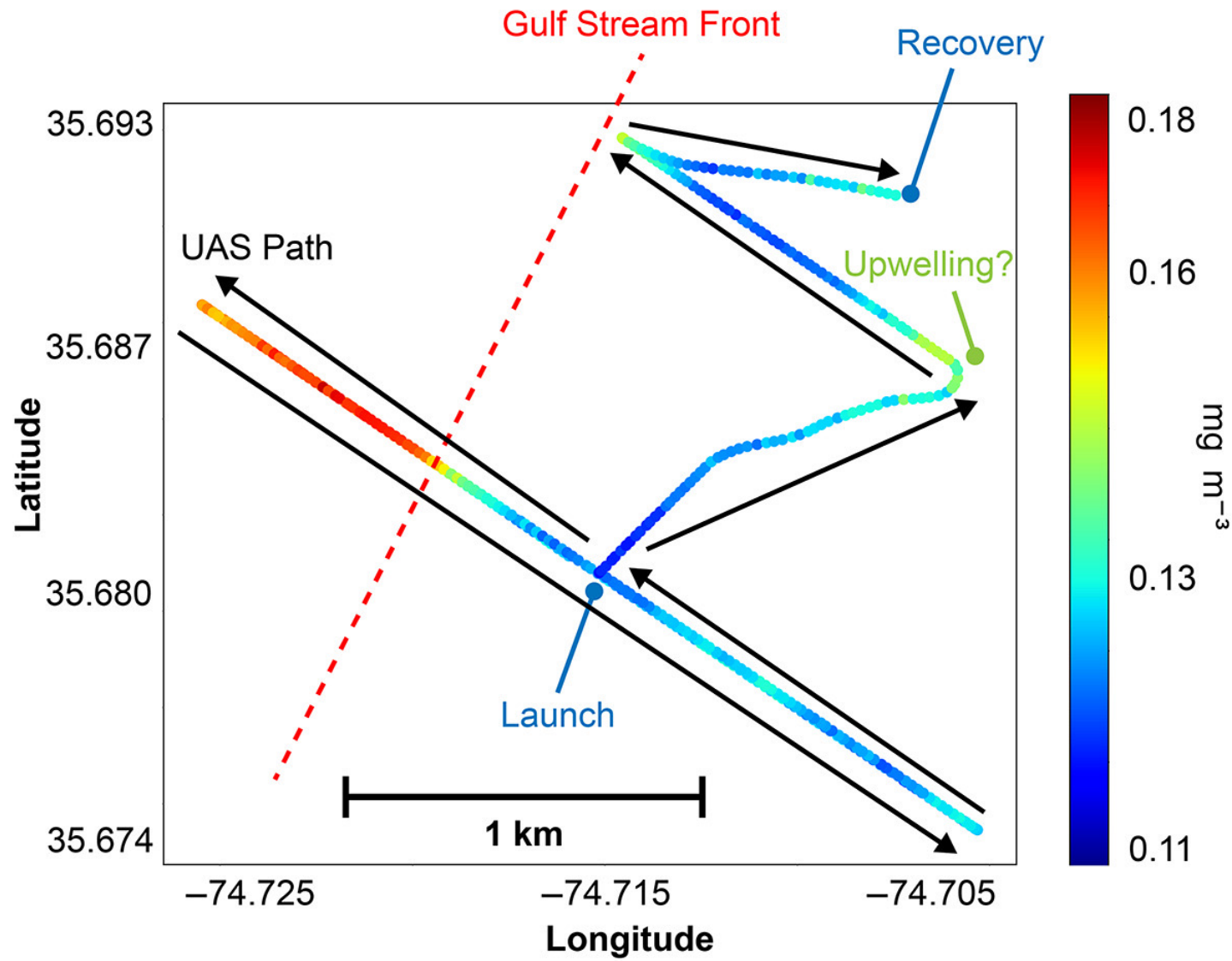

L_t (475)
L_t (560)
L_w (475)
L_w (560)
Viewing angle off nadir (θ)
58°
40°
22°
Relative azimuth angle (φ)
111°
135°
159°
mW m^{-2} sr^{-1} nm^{-1}
10
7.5
5
17.6
13.2
8.8

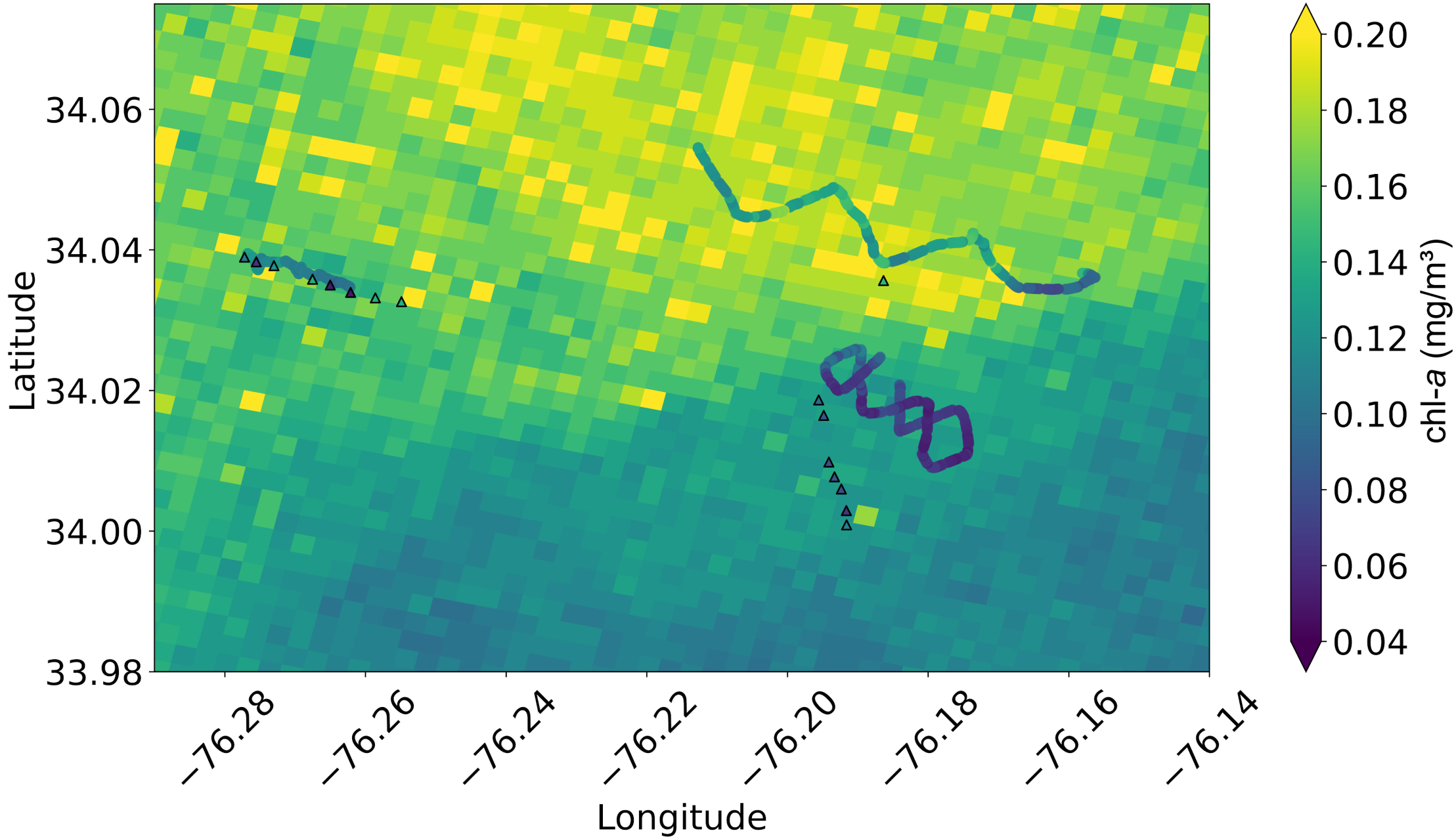
Gray et al

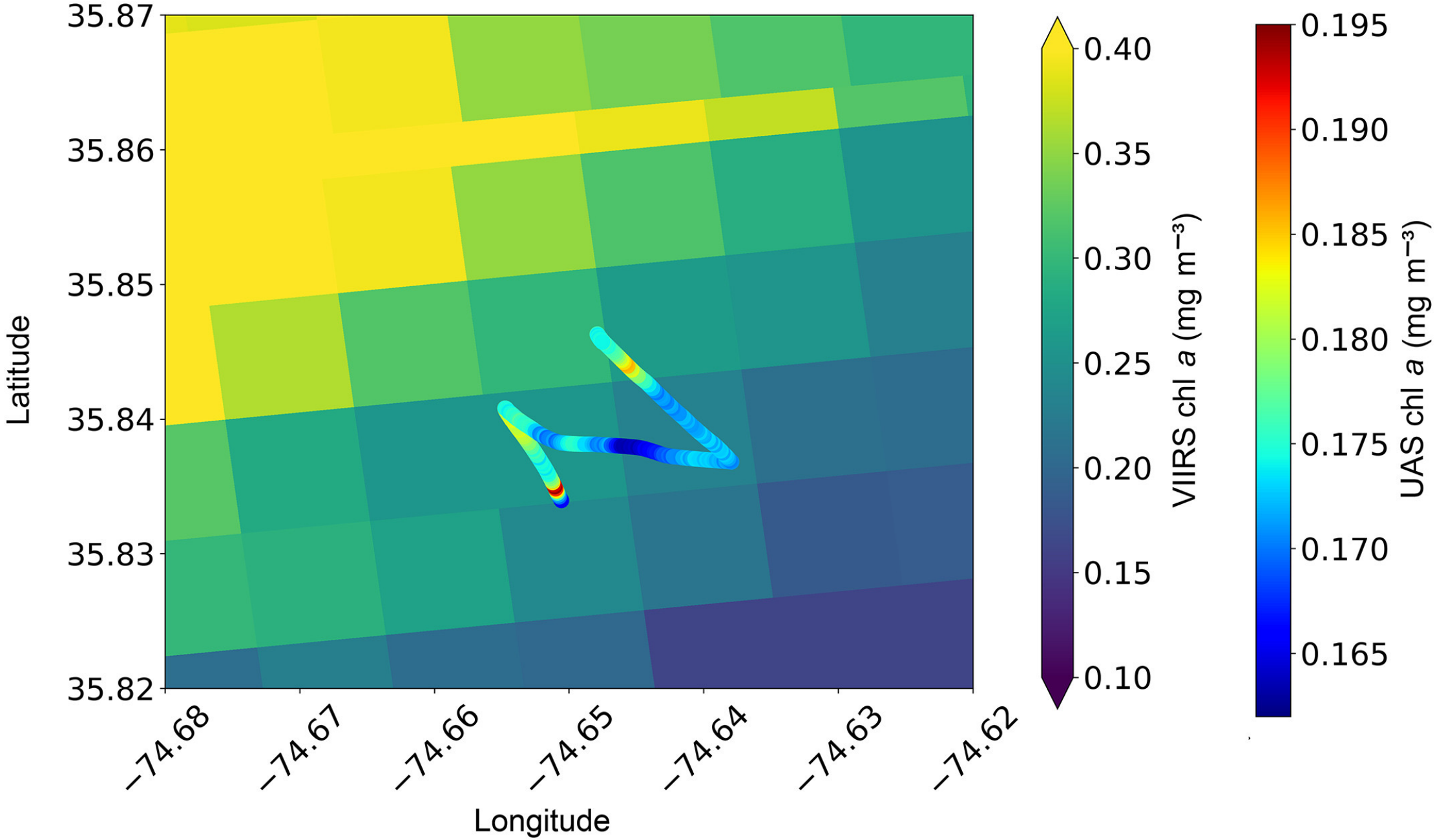

L_t (475)
L_t (560)
L_w (475)
L_w (560)
Viewing angle off nadir (θ)
43°
25°
7°
111°
135°
159°
Relative azimuth angle (φ)
8
4.5
1
2.75
mW m^{-2} sr^{-1} nm^{-1}

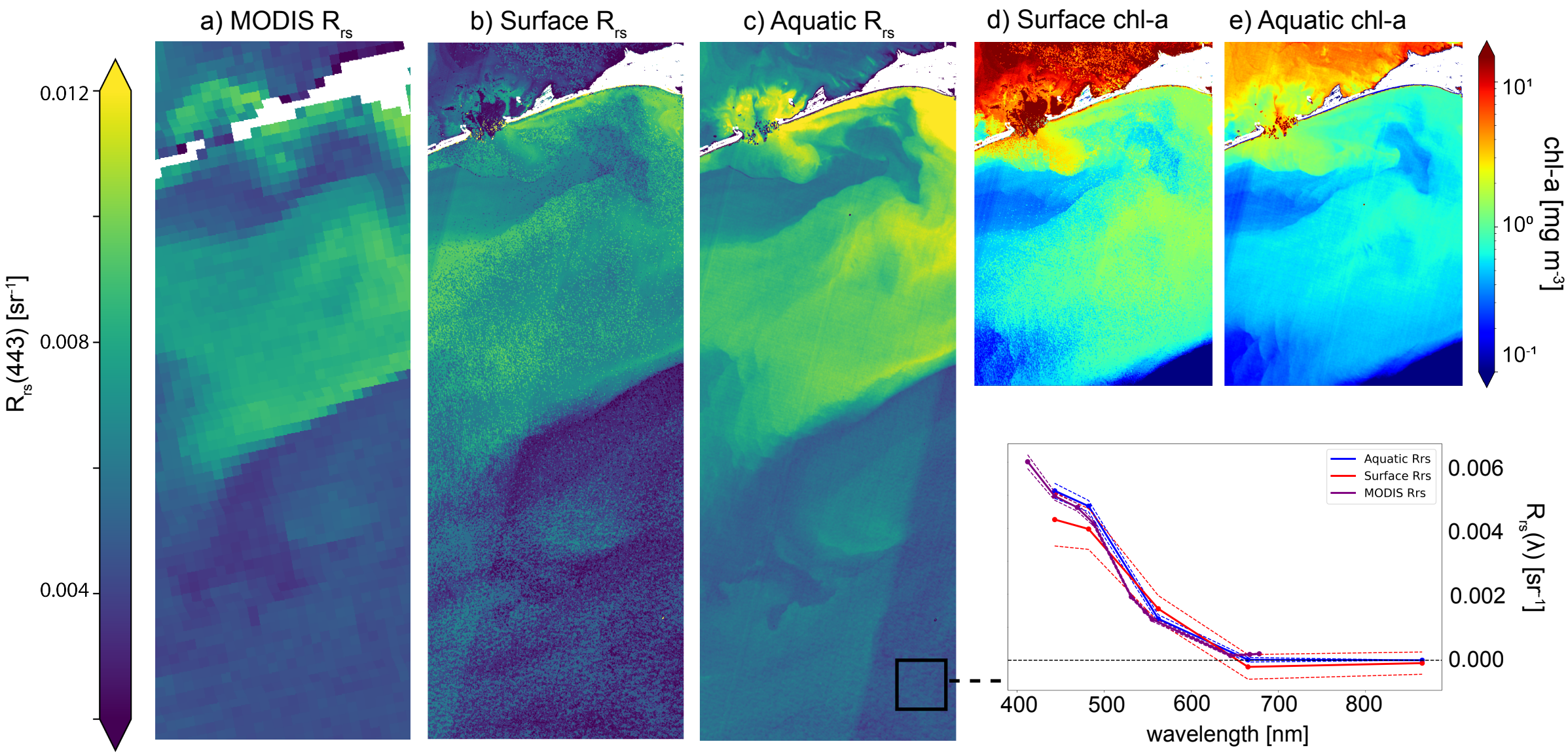
Gray et al


Gulf Stream Front
35.795
35.790
35.785
35.780
1 km
Launch
Recovery
UAS Path
–74.60
–74.59
Longitude
Latitude
0.21
0.20
0.18
0.16
mg m⁻³


Gulf Stream Front
Recovery
35.693
35.687
35.680
35.674
UAS Path
Upwelling?
Launch
1 km
–74.725
–74.715
–74.705
Longitude
Latitude
0.18
0.16
0.13
0.11
mg m⁻³

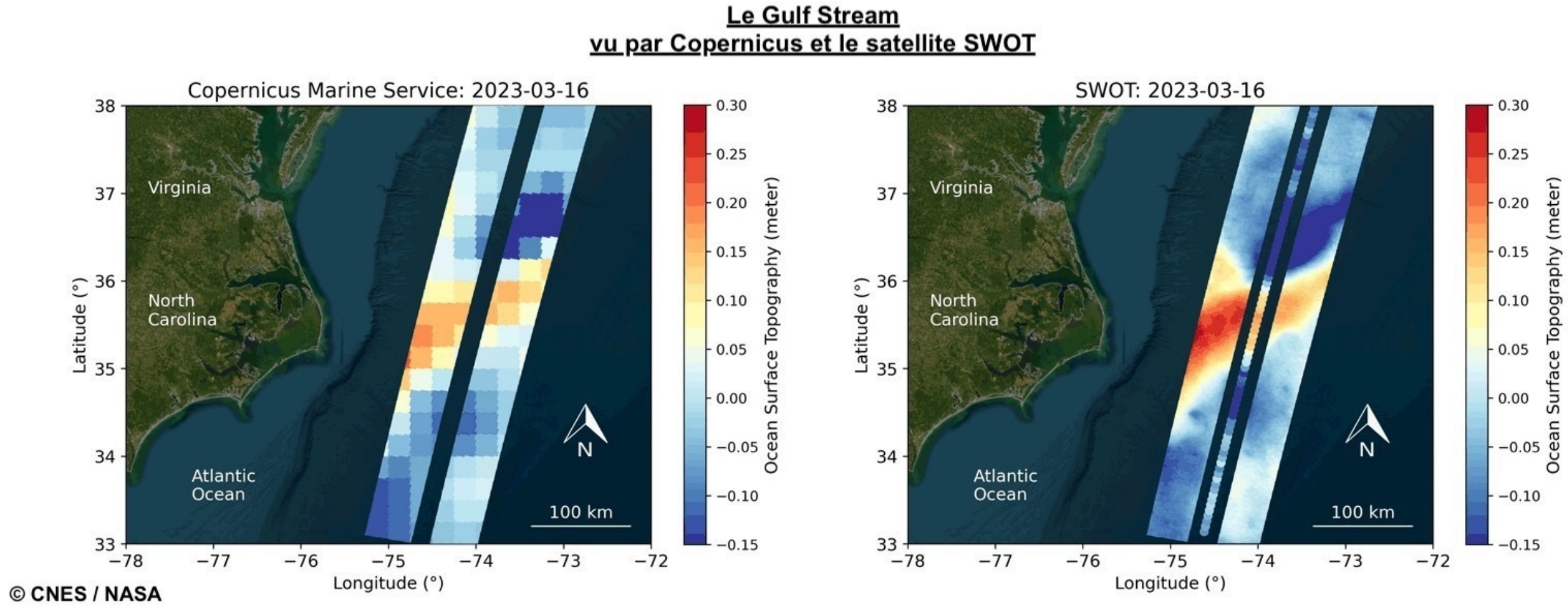

Latitude
34.06
34.04
34.02
34.00
33.98
−76.28
−76.26
−76.24
−76.22
−76.20
−76.18
−76.16
−76.14
Longitude
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
chl-a (mg/m³)


35.87
35.86
35.85
35.84
35.83
35.82
Latitude
−74.68
−74.67
−74.66
−74.65
−74.64
−74.63
−74.62
Longitude
0.40
0.35
0.30
0.25
0.20
0.15
0.10
VIIRS chl a (mg m⁻³)
0.195
0.190
0.185
0.180
0.175
0.170
0.165
UAS chl a (mg m⁻³)

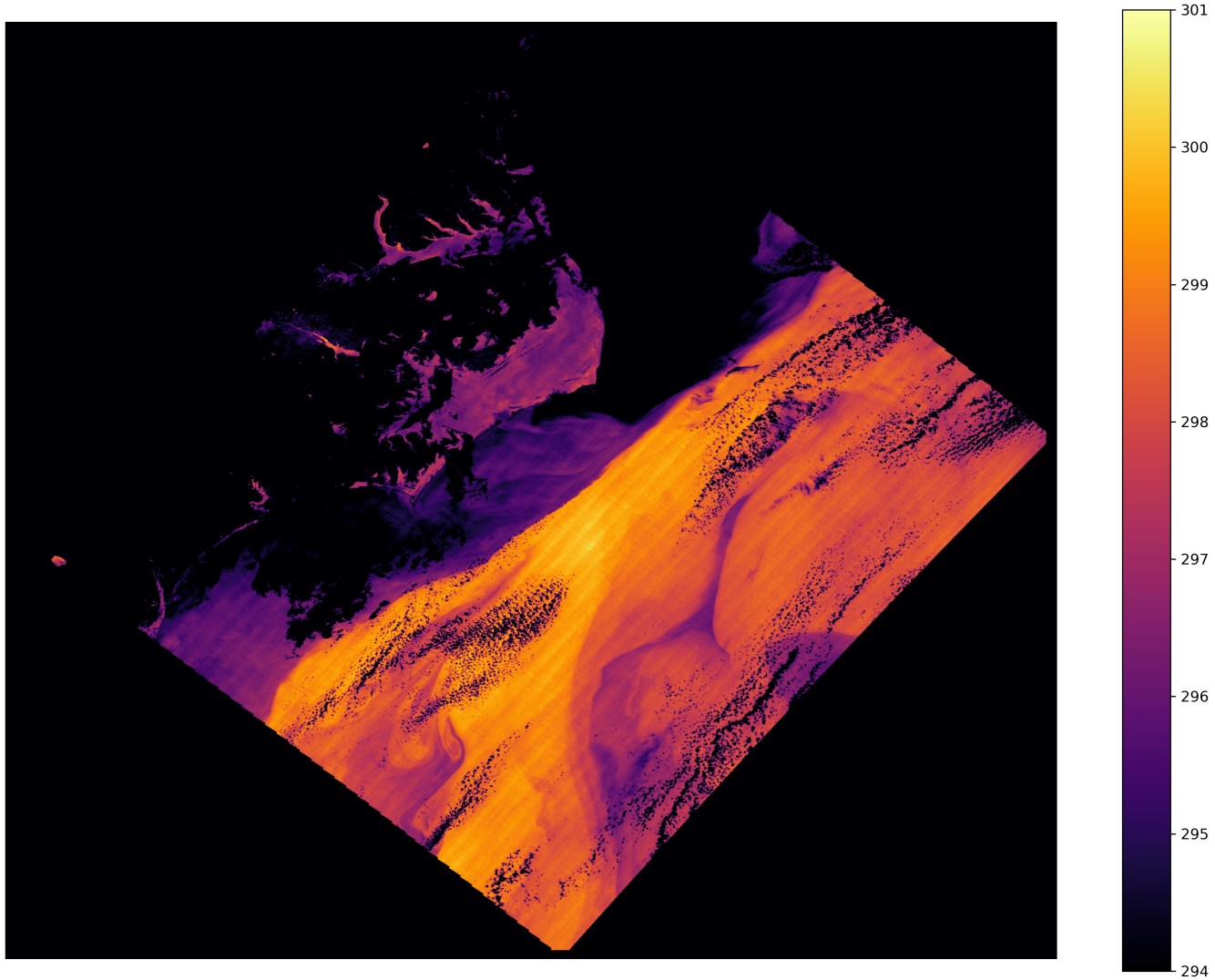

a) MODIS R_{rs}
b) Surface R_{rs}
c) Aquatic R_{rs}
d) Surface chl-a
e) Aquatic chl-a
$R_{rs}(443)$ [sr^{-1}]
0.012
0.008
0.004
chl-a [mg m^{-3}]
10^{1}
10^{0}
10^{-1}
Aquatic Rrs
Surface Rrs
MODIS Rrs
0.006
0.004
0.002
0.000
$R_{rs}(\lambda)$ [sr^{-1}]
400
500
600
700
800
wavelength [nm]

Tavora et al

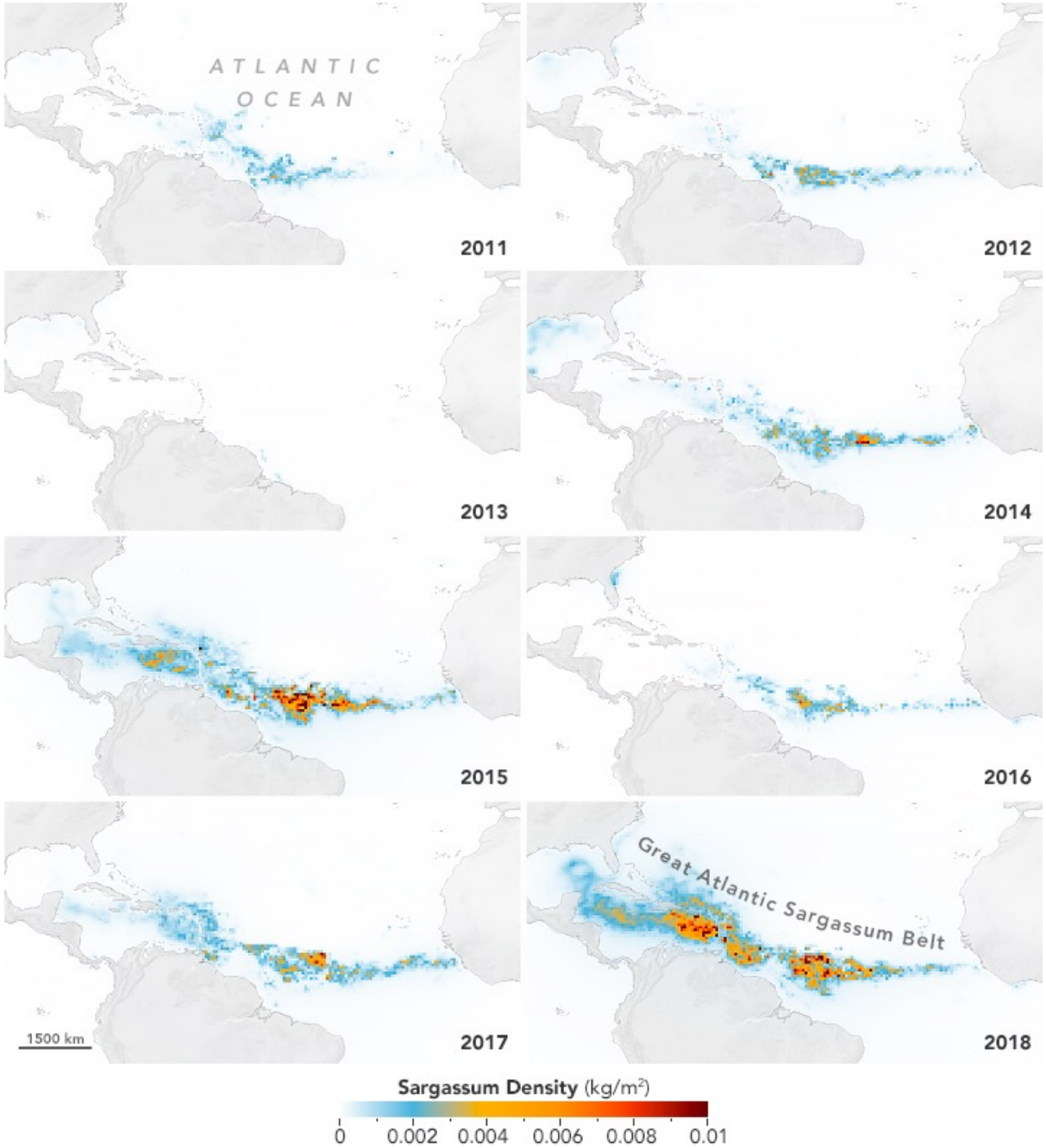
Complementary Satellites to OCR



Complementary Satellites to OCR



Relevancy of remote sensing for societal challenges



Work by Mengqiu Wang and Chaumin Hu

“New normal’ of sargassum blooms??

NASA Earth Observatory

Detection of algal blooms can lead to health benefits and financial savings

GeoHealth

Research Article | Open Access

Quantifying the Human Health Benefits of Using Satellite Information to Detect Cyanobacterial Harmful Algal Blooms and Manage Recreational Advisories in U.S. Lakes

Signe Stroming, Molly Robertson, Bethany Mabee, Yusuke Kuwayama, Blake Schaeffer

First published: 18 June 2020 | https://doi.org/10.1029/2020GH000254 | Citations: 26

MODIS-Aqua's 20th birthday

Previously it was thought 30 years were needed to detect climate change trend (separate from natural interannual variability)….

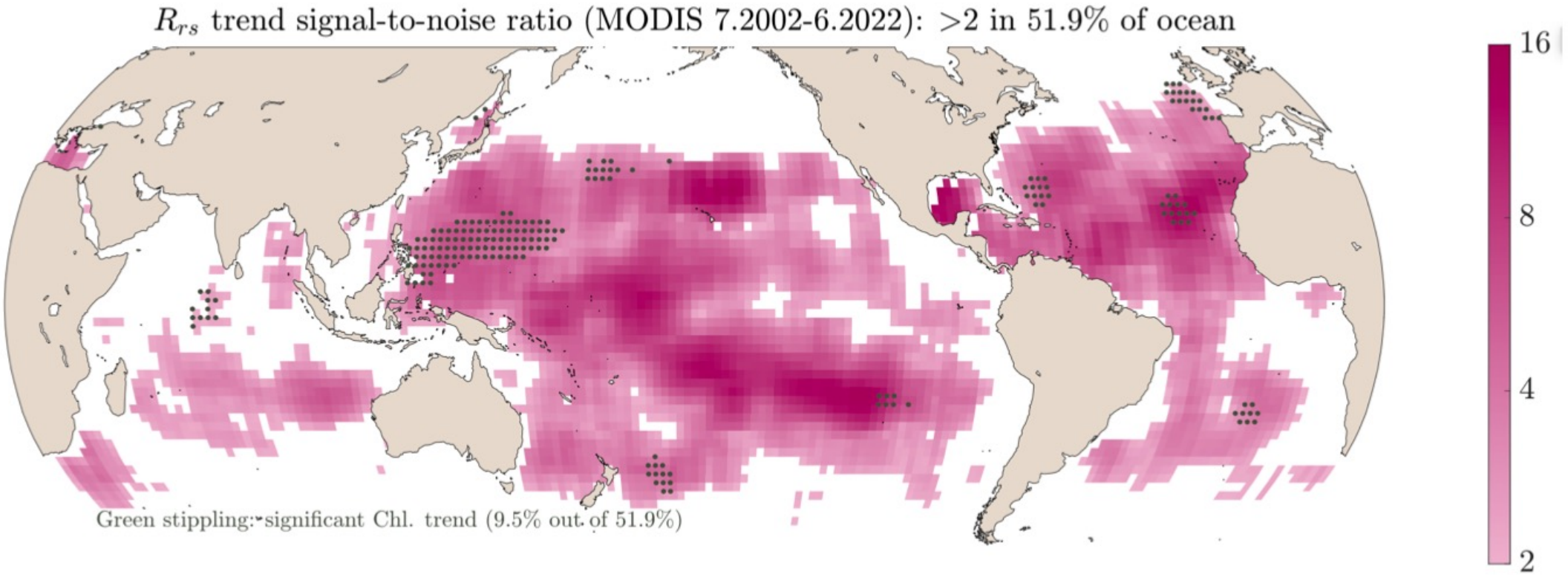


Figure 1: Map of locations where ocean color trend signal-to-noise ratio (SNR) is >2 for 20-year annual time series. Intensity of purple color indicates the SNR. Green stippling indicates regions with significant chlorophyll trends.

Cael et al 2023

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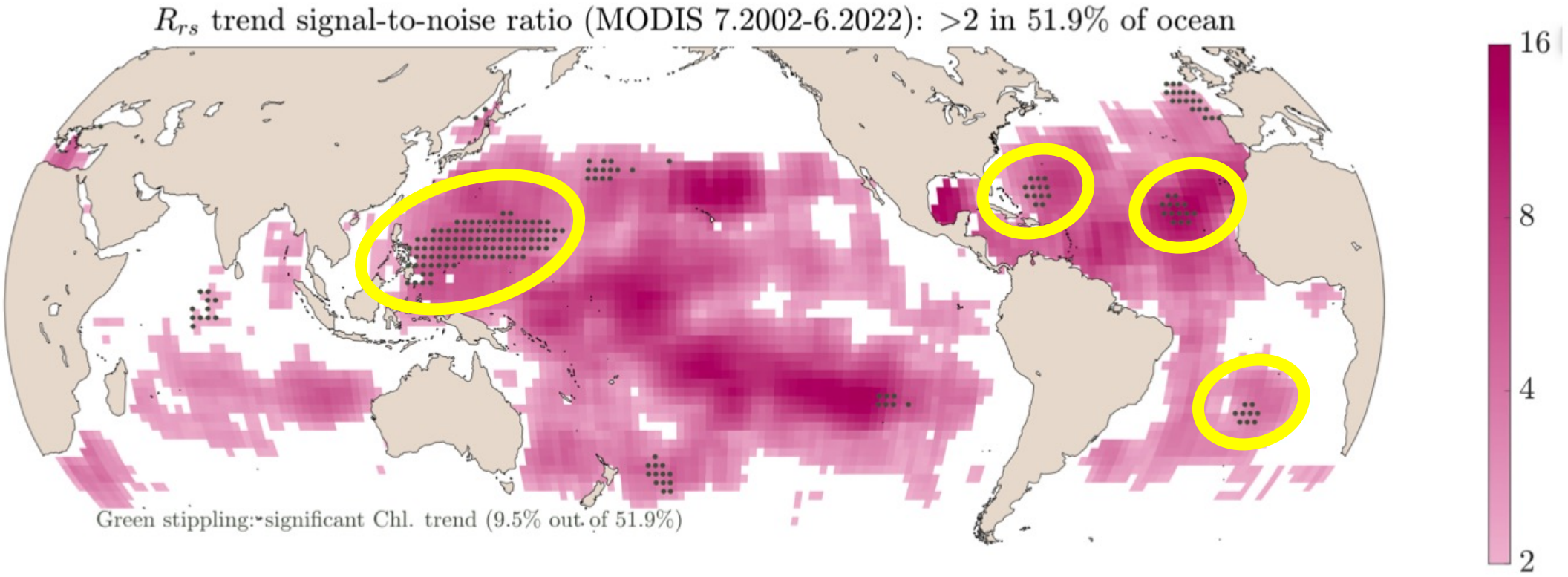

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Cael et al 2023

MODIS-Aqua's 20th birthday

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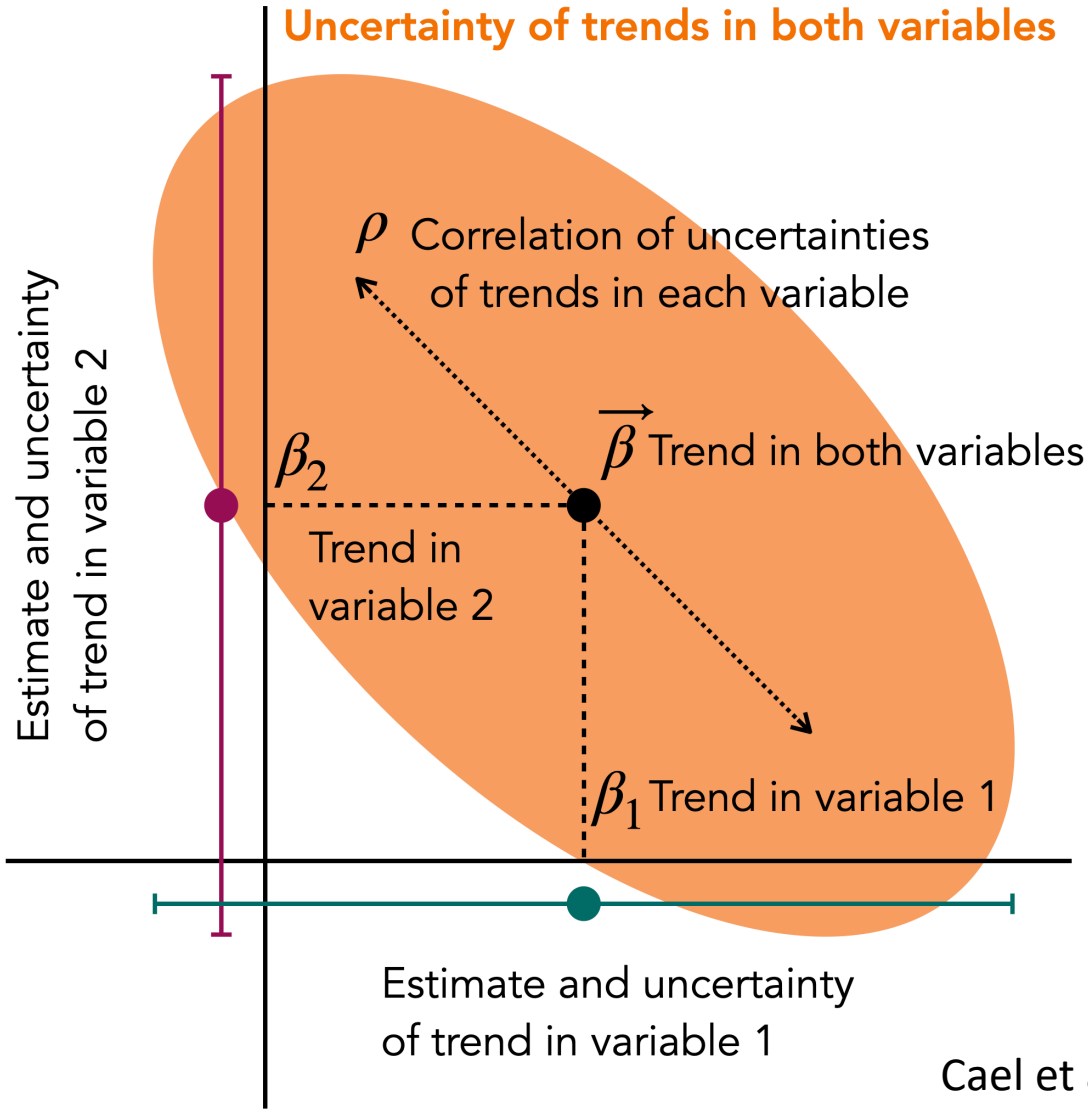
Multivariate trend analysis has more information than univariate (chl)!



Cael et al 2023

>50% of ocean has detectable climate change (in multivariate Rrs) trend after 20 years.

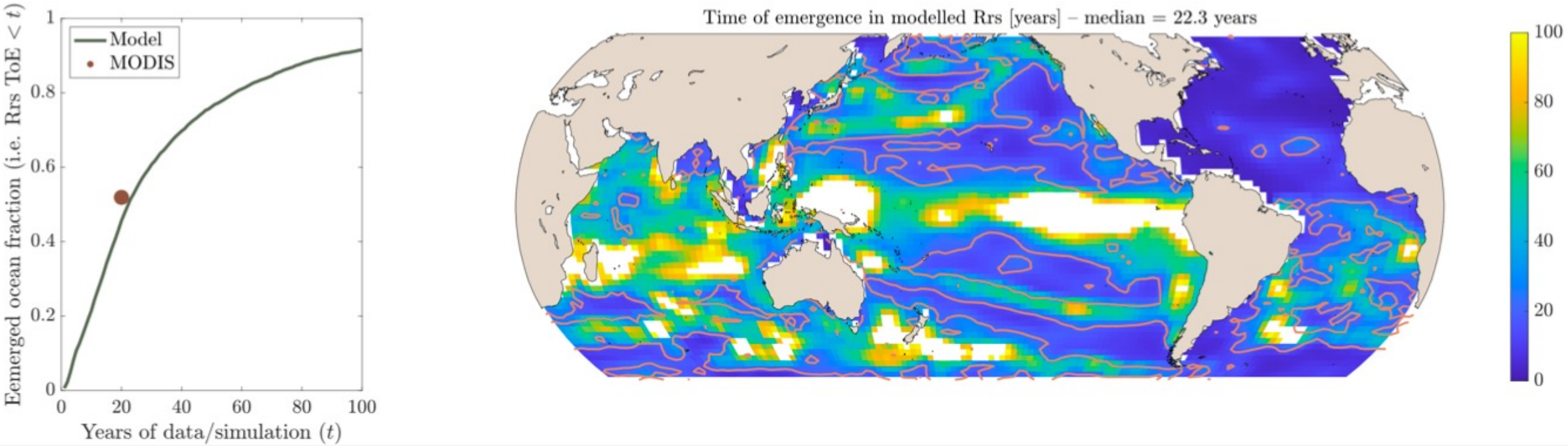
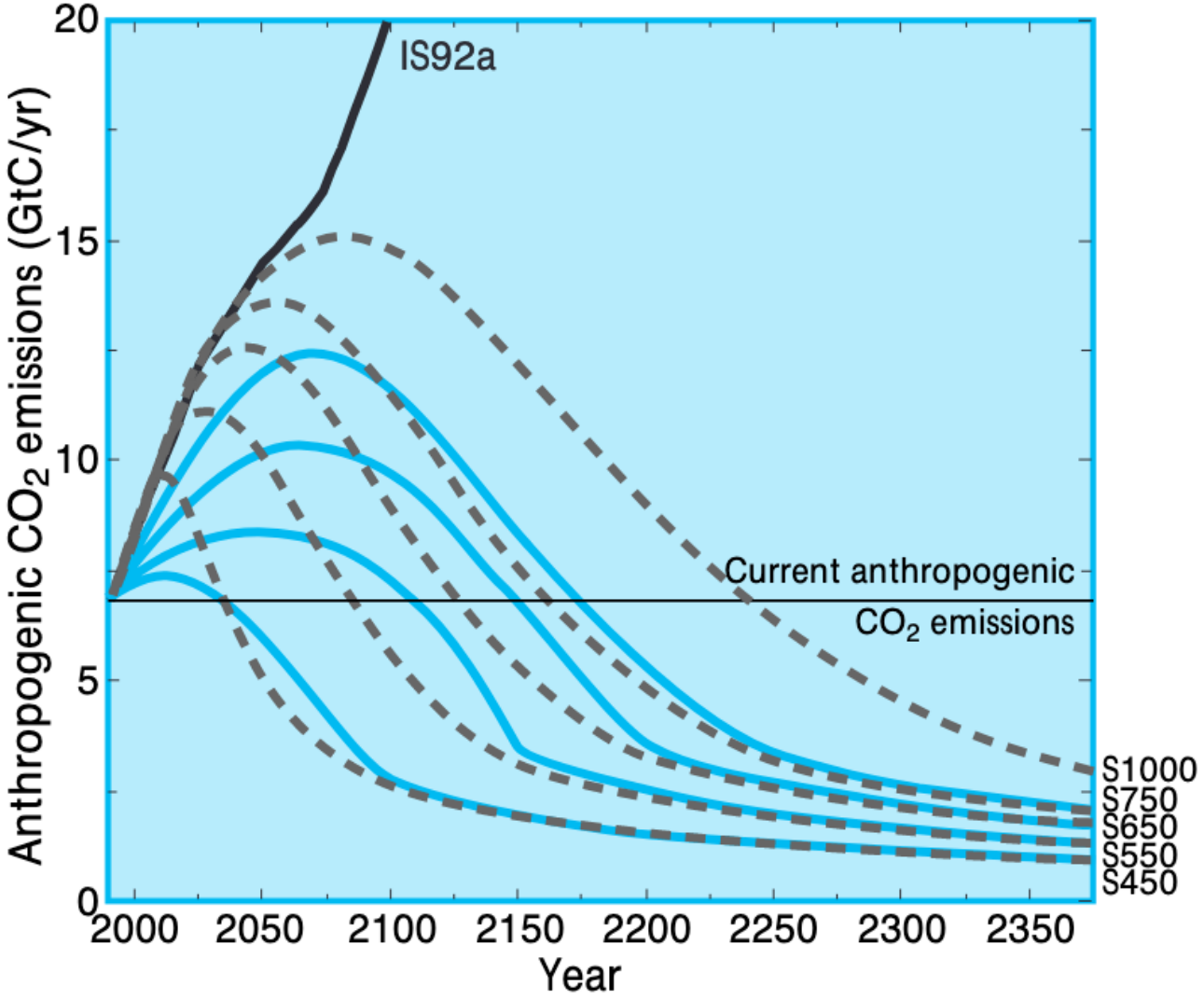


Figure 2: Left: cumulative distribution function of the time of emergence (ToE) of the ocean color trend in the model simulation. Orange point indicates fraction of total surface ocean area with a significant trend in the 20-year MODIS-Aqua time-series. Right: map of ToE in the model simulation. Orange lines are the 20-year ToE contour. See [11] for a similar plot for Chl.

Cael et al 2023

LIFE ON A RAPIDLY CHANGING EARTH

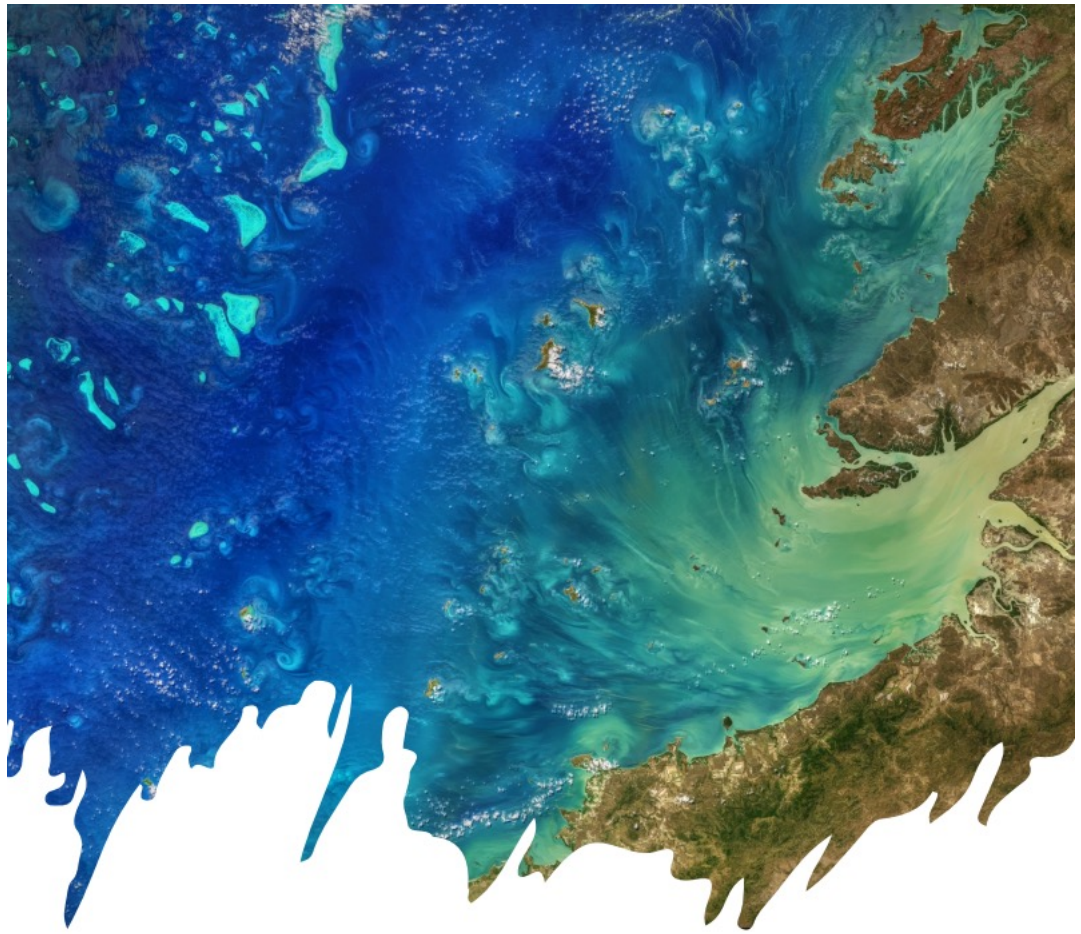
Significance for future PIs



(from Dave Schimel, With appreciation to Lovenduski and Bonan)

Missions and analyses we design now will be measuring peak periods of CO2 and unprecedented temperature changes

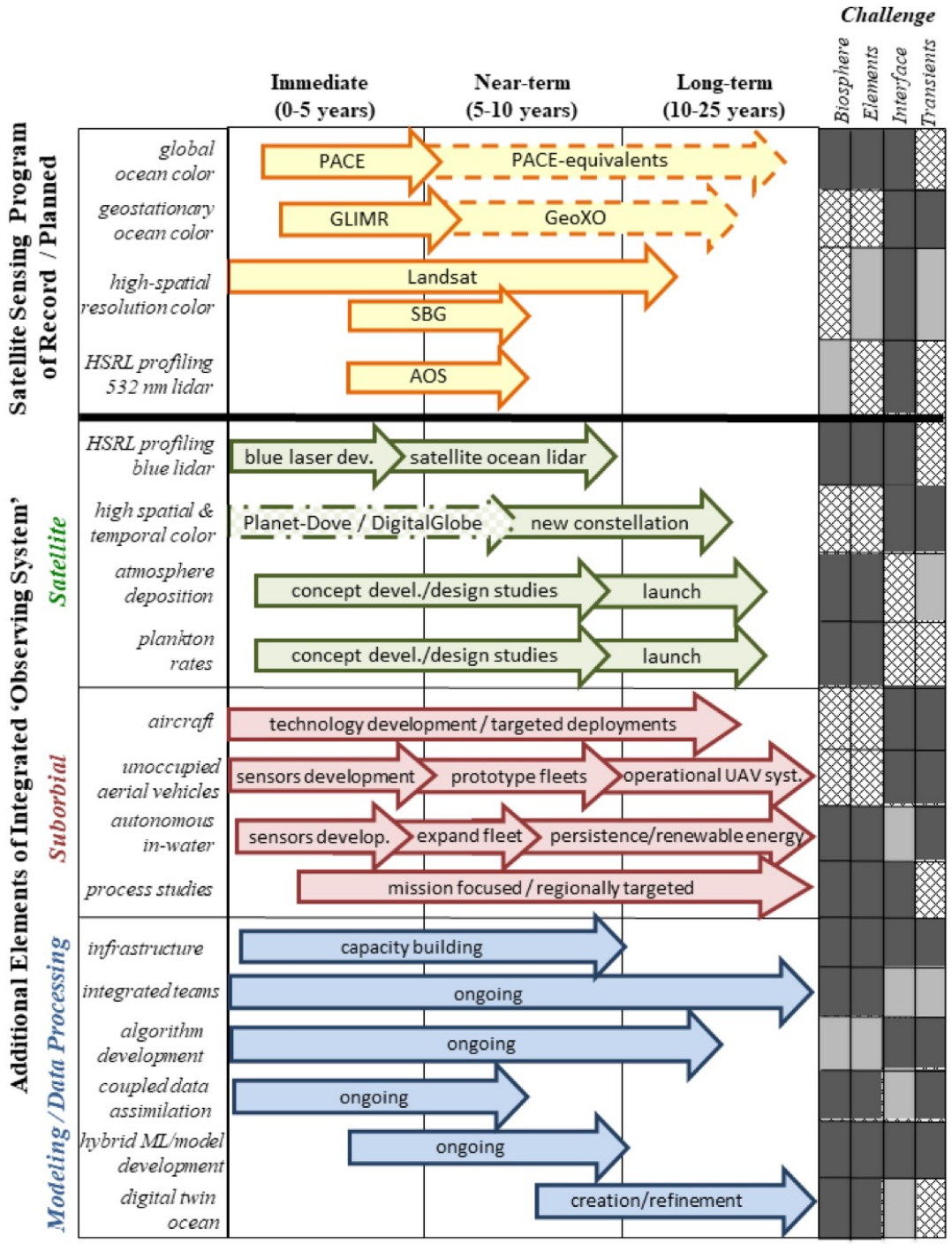
We may be close to tipping points



Earth's Living Ocean:
Vast, Dynamic, Essential to Humanity

Decadal strategic vision released by NASA for ocean biology and biogeochemistry community

5 grand challenges



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