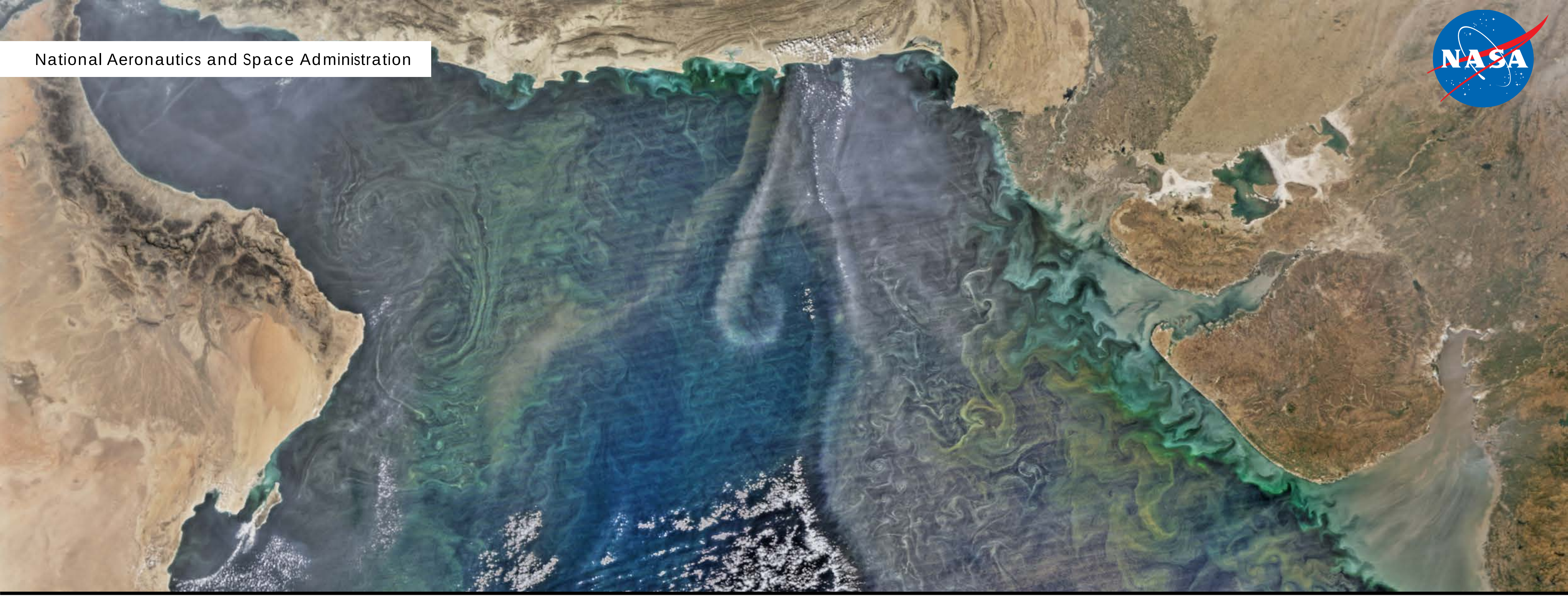
National Aeronautics and Space Administration



Monitoring Water Quality Using Satellite Image Processing

Amita Mehta & Africa Flores (SERVIR Global)

5, 12, and 19 September 2018

Training Objectives

Learn to:

- Monitor water temperature and chlorophyll-a concentrations as harmful algal bloom indicators
- Access MODIS and Landsat data for water quality monitoring
- Perform image processing of MODIS and Landsat data using SeaDAS Software

Prerequisite: Introduction to Remote Sensing of Harmful Algal Blooms

https://arset.gsfc.nasa.gov/water/webinars/HABs17

Course Outline

September 5

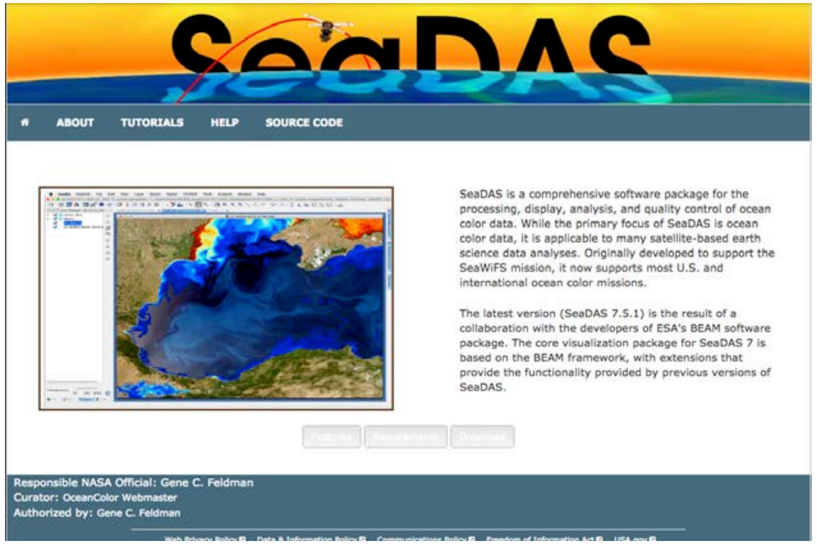
Overview and Analysis of NASA Remote Sensing Data for HAB Monitoring

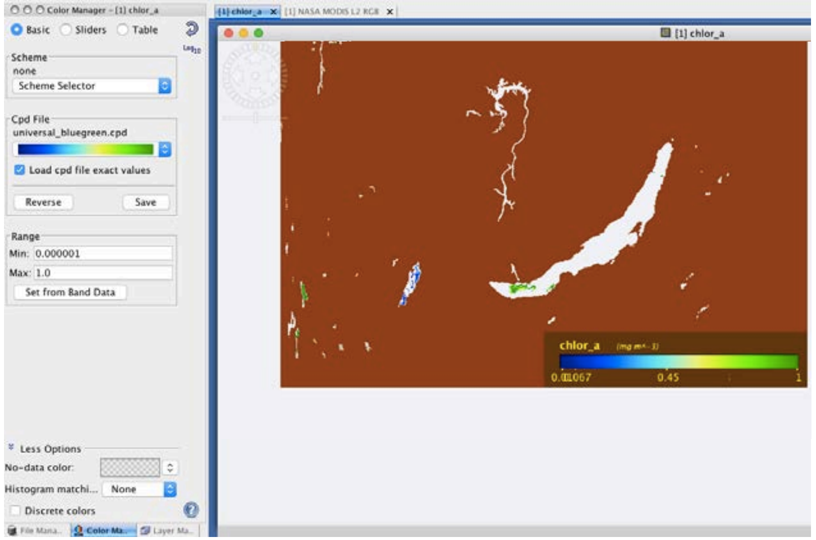
September 12

Introduction to SeaDAS for Image Processing and Data Analysis

September 19

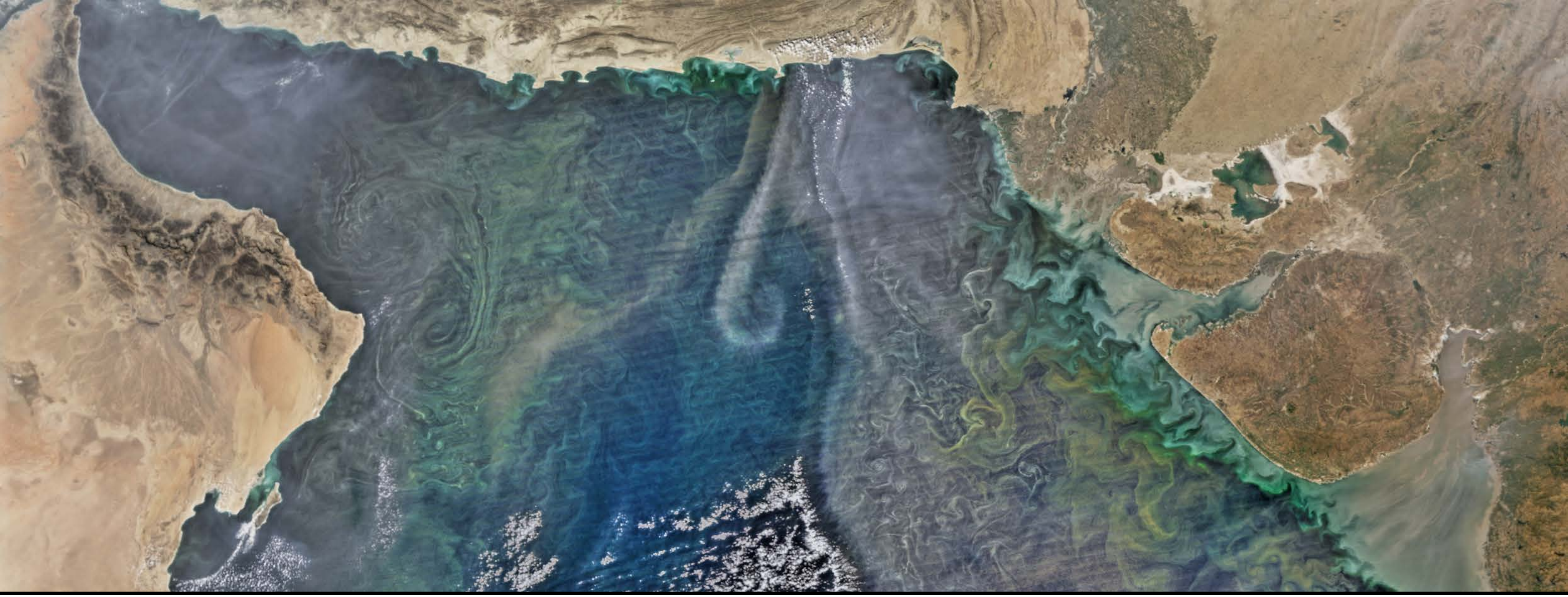
Image Analysis Exercise Using SeaDAS





Outline for Week 1

- About ARSET
- Remote Sensing of Water Quality (WQ)
- Monitoring WQ in Coastal and In-land Waters
- Demonstration of NASA Web-tools for WQ Data Access
  - Focus: Chlorophyll a Concentration (Chlor_a) and Water Surface Temperature (ST) Case Study: Chesapeake Bay, 1-10 May 2018
  - Giovanni: http://giovanni.gsfc.nasa.gov/giovanni/
  - OceanColor: https://oceancolor.gsfc.nasa.gov/
- Exercise: Analyze and Download Chlor_a and ST in Lake Victoria, Africa



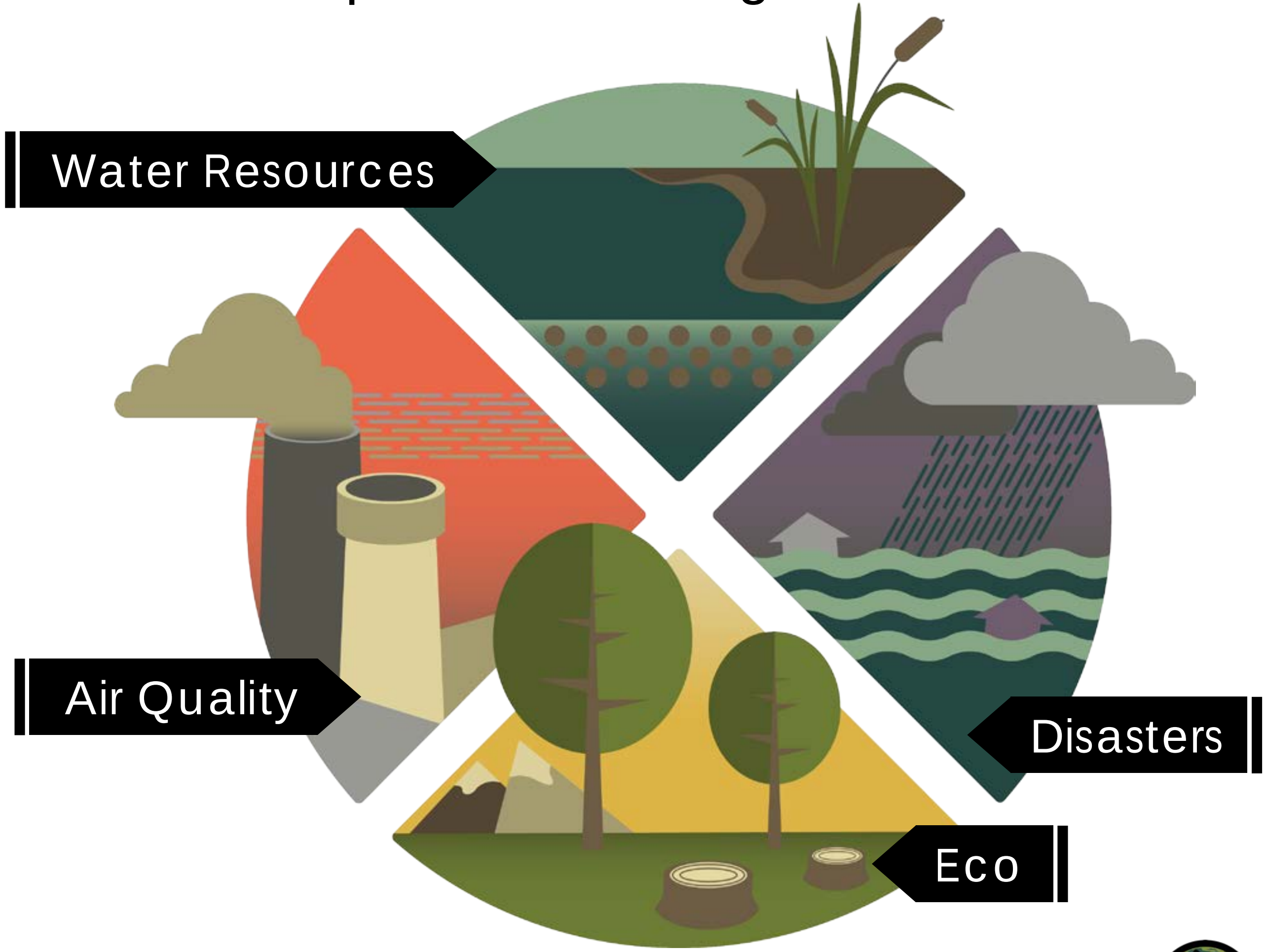
About ARSET

NASA's Applied Remote Sensing Training Program (ARSET)

http://arset.gsfc.nasa.gov/

- Empowering the global community through remote sensing training
- Part of NASA's Applied Sciences Program
- Seeks to increase the use of Earth science in decision-making through training for:
  - policy makers
  - environmental managers
  - other professionals in the public and private sector

Topics for Trainings Include:



ARSET Team Members

Program Support

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- Brock Blevins, Training Coordinator (GSFC)
- David Barbado, Spanish Translator (GSFC)
- Annelise Carleton-Hug, Program Evaluator (Consultant)
- Elizabeth Hook, Technical Writer/Editor (GSFC)
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- Amita Mehta, Instructor (GSFC)
- Erika Podest, Instructor (JPL)

Land & Wildfires

- Cynthia Schmidt, Lead (ARC)
- Amber Jean McCullum, Instructor (ARC)

Health & Air Quality

- Pawan Gupta, Lead (GSFC)
- Melanie Cook, Instructor (GSFC)

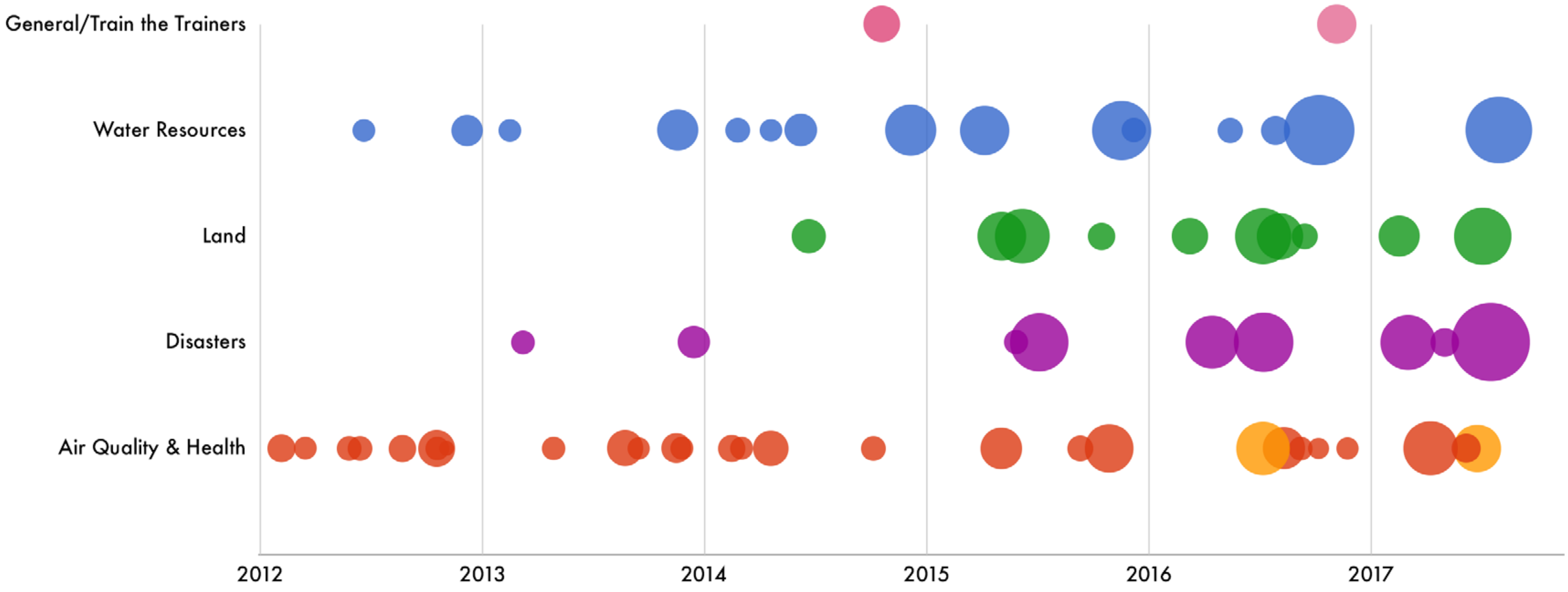
Acknowledgement:

- We wish to thank Nancy Searby for her continued support

ARSET Trainings

Trainings: Introductory and Advanced, On-line and In-person

100 trainings 13,000+ participants 160+ countries 3,700+ organizations



* size of bubble corresponds to number of attendees

ARSET Water Quality Trainings

https://arset.gsfc.nasa.gov/water/

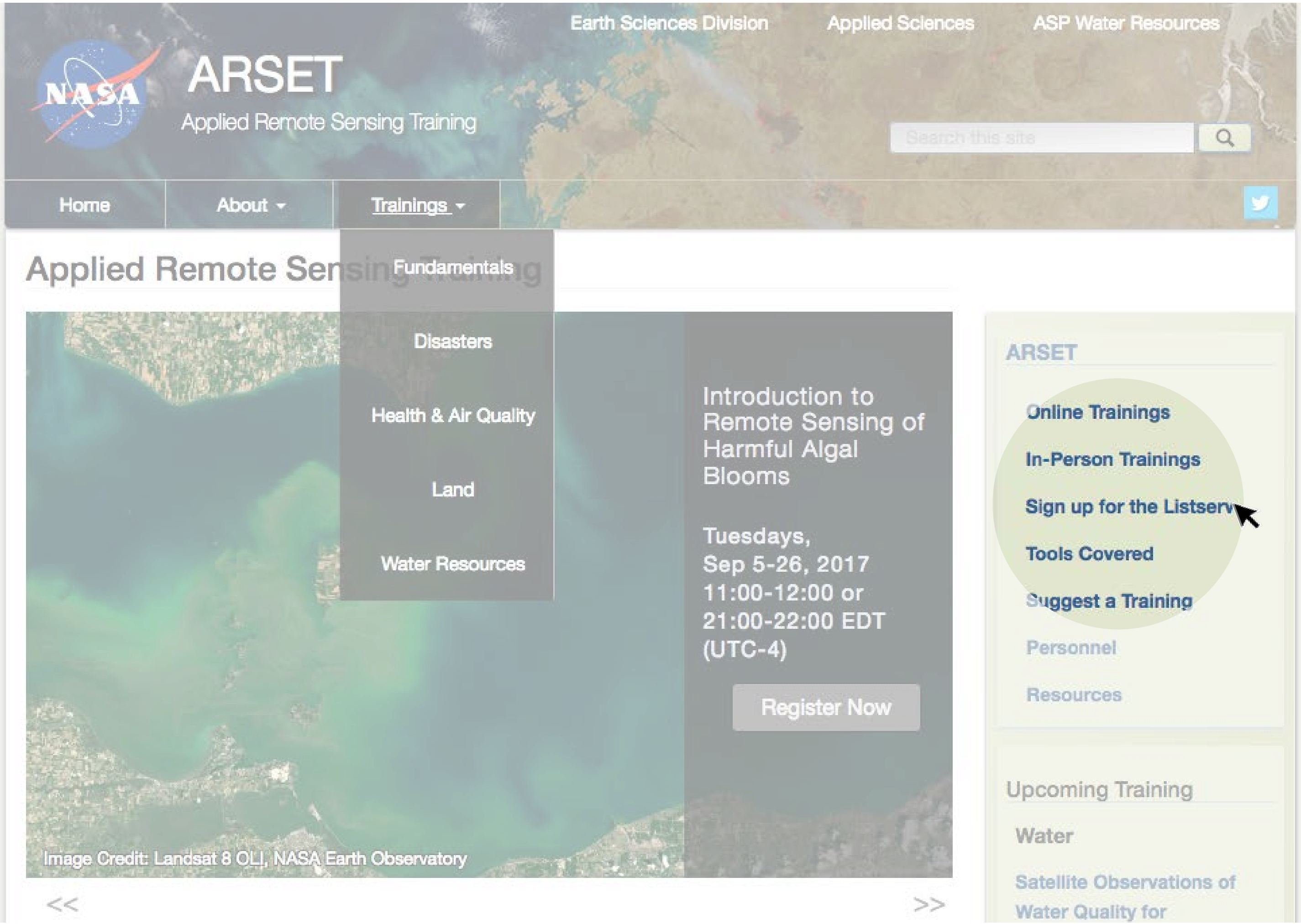
- Introduction to Remote Sensing of Harmful Algal Blooms:
  – https://arset.gsfc.nasa.gov/water/webinars/HABs17

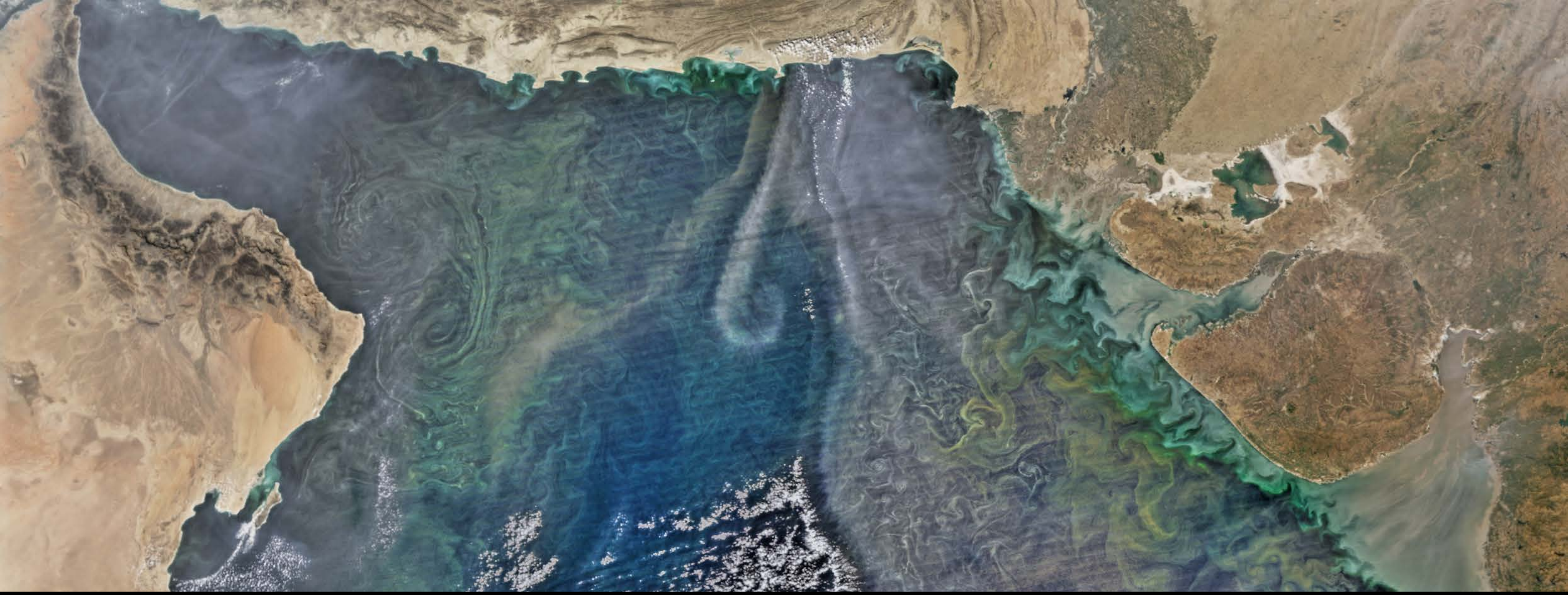
- Introduction to Remote Sensing for Coastal & Ocean Applications:
  – https://arset.gsfc.nasa.gov/land/webinars/coastal-oceans-2016

- Water Quality Monitoring Using Remote Sensing Measurements:
  – https://arset.gsfc.nasa.gov/water/water-quality-2014

Learn More About ARSET

http://arset.gsfc.nasa.gov/

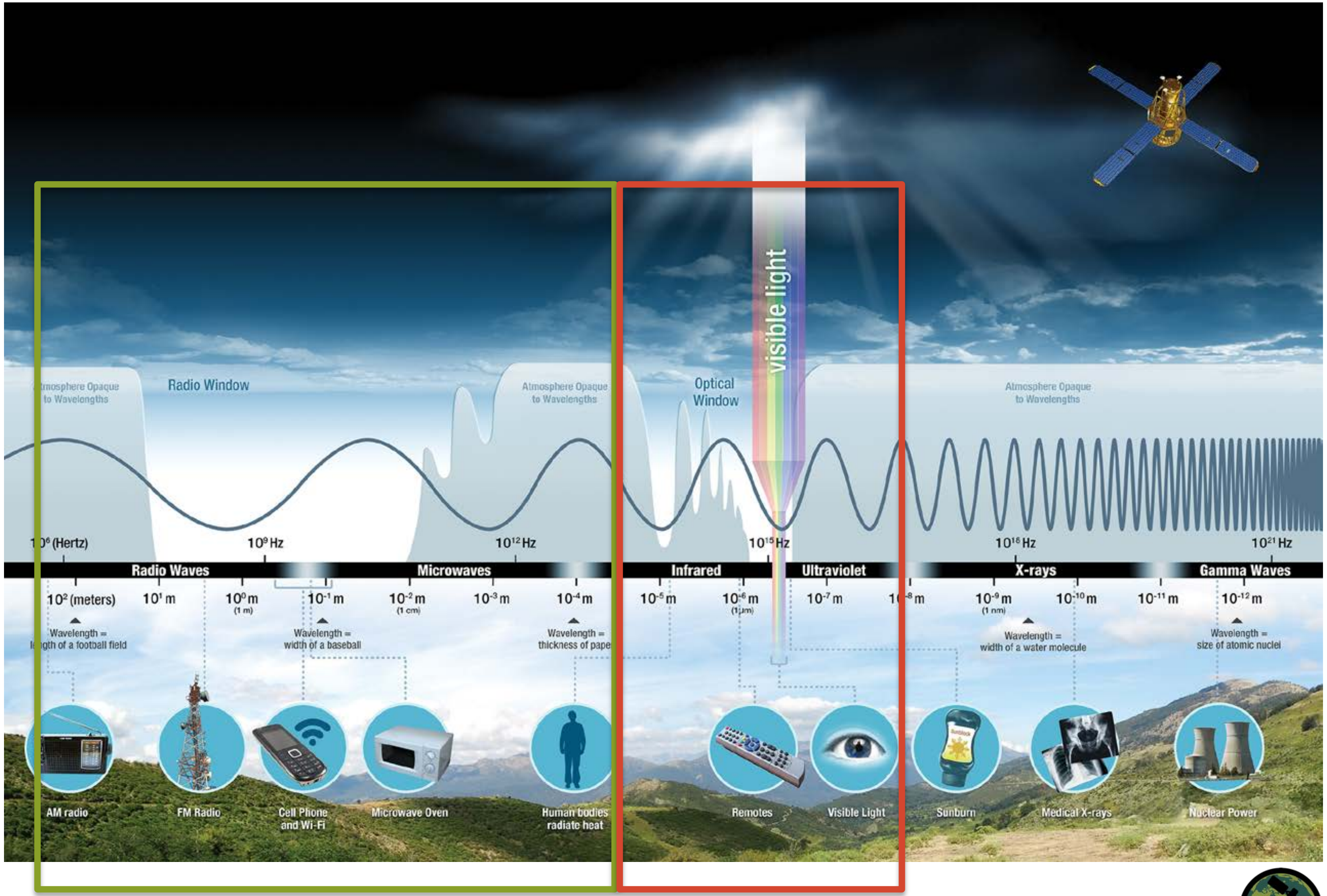




Remote Sensing of Water Quality (WQ)

Remote Sensing of Water Quality

- Satellites carry instruments and sensors to measure:
  - reflected solar radiation
  - emitted infrared and microwave radiation



Water Quality Affects Water Optical Properties

You can use remote sensing to monitor water color, which can be an indicator of water quality:

- dissolved and suspended matter in water change the water's optical property, which changes its color
  - dissolved organic matter includes tannin, which is caused by organic matter coming from leaves, roots, and plant remains
  - suspended matter includes particles of clay, undissolved minerals, planktons, and algal blooms
- some harmful algal bloom (HAB) species have unique properties that affect water color (e.g., red tides)

Color caused by dissolved matter: tannins

Color caused by suspended material: sediment

Image Credit: USGS

Which Factors Cause Change in Water Quality?

- Nutrient loading “eutrophication”
- Pollution
- Water Temperature (warmer water affects Algal Bloom)
- Food web changes
- Introduced species
- Changes in water flow
  – e.g., after major events like hurricanes, drought, or floods

Current Satellite Missions for Water Quality Monitoring

- Landsat 7 (4/15/1999 – present)
- Landsat 8 (2/1/2013 – present)
- Terra (12/18/1999 – present)
- Aqua (5/4/2002 – present)
- Suomi National Polar Partnership (SNPP) (11/21/2011 – present)
- Sentinel-2A (6/23/2015 - present)
- Sentinel-2B (3/7/2017 – present)
- Sentinel-3A (2/16/2016 – present)

Satellites and Sensors for Monitoring Water Quality

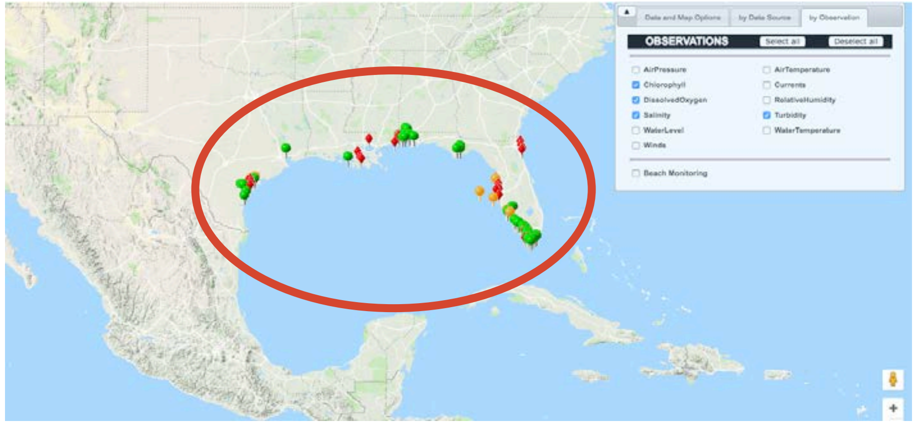
Satellites	Sensors	Resolution
Landsat 7	Enhanced Thematic Mapper (ETM+)	185 km swath; 15 m, 30 m, 60 m; 16 day revisit
Landsat 8	Operational Land Imager (OLI)	185 km swath; 15 m, 30 m, 60 m; 16 day revisit
Terra & Aqua	MODerate Resolution Imaging Spectroradiometer (MODIS)	2330 km swath; 250 m, 500 m, 1 km; 1-2 day revisit
Suomi NPP	Visible Infrared Imaging Radiometer Suite (VIIRS)	3040 km swath; 375 m – 750 m; 1-2 day revisit
Sentinel 2A and 2B	Multi Spectral Imager (MSI)	290 km swath; 10 m, 20 m, 60 m; 5 day revisit
Sentinel 3A	Ocean and Land Color Instrument (OLCI)	1270 km swath; 300 m; 27 day revisit

* See Appendix A for information about the spectral bands

Advantages of Satellite Observations

- Available for large regions
  - only source of global information for some parameters
- Long time series and data continuity
  - tracks progress
  - establishes baselines and trends
- Consistency and comparability
  - among multiple countries
- Diversity of measurements
  - many different physical parameters
- Complements traditional statistical methods
  - cross-check with in situ data
- Mostly free and open access

Limited Water Sampling Locations



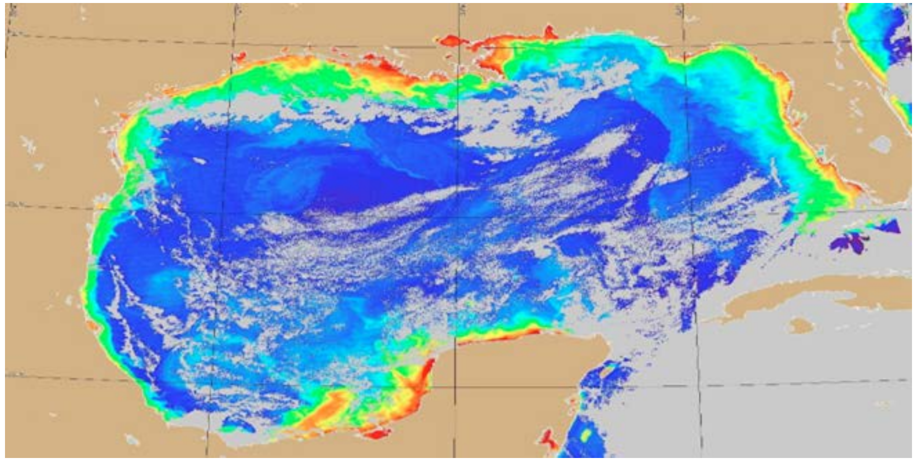


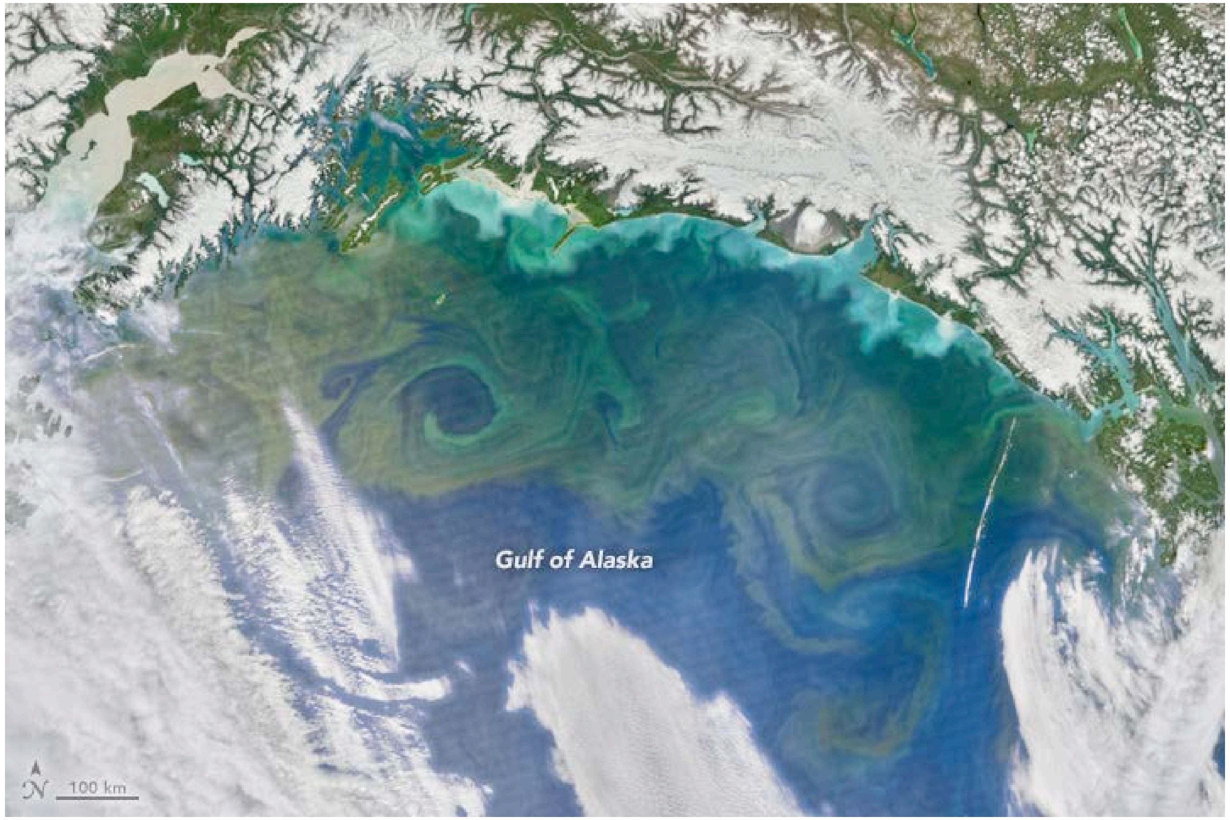
Image Credit (top) http://data.gcoos.org; (bottom) 2013 MODIS Aqua image showing elevated chlorophyll-a levels

Water Quality Indicators Observable from Satellites

- Turbidity and Sediments
- Colored Dissolved Organic Matter (CDOM)
- Sea Surface Temperature (SST)
- Chlorophyll-a (phytoplankton)
- Salinity
- TSS (Total Suspended Solids)
- Fluorescence Line Height
- Euphotic Depth

Phytoplankton Bloom in the Gulf of Alaska

SNPP-VIIRS June 9, 2016



Water Quality Monitoring from Remote Sensing

- Typically optical and infrared spectral bands are used for water quality monitoring
- ETM+, OLI, MODIS, VIIRS, MSI, and OLCI measurements cover optical to infrared spectral ranges in different spectral bands (Appendix A)
- These measurements have been used to monitor water quality over open oceans, coastal waters and estuaries, and inland lakes

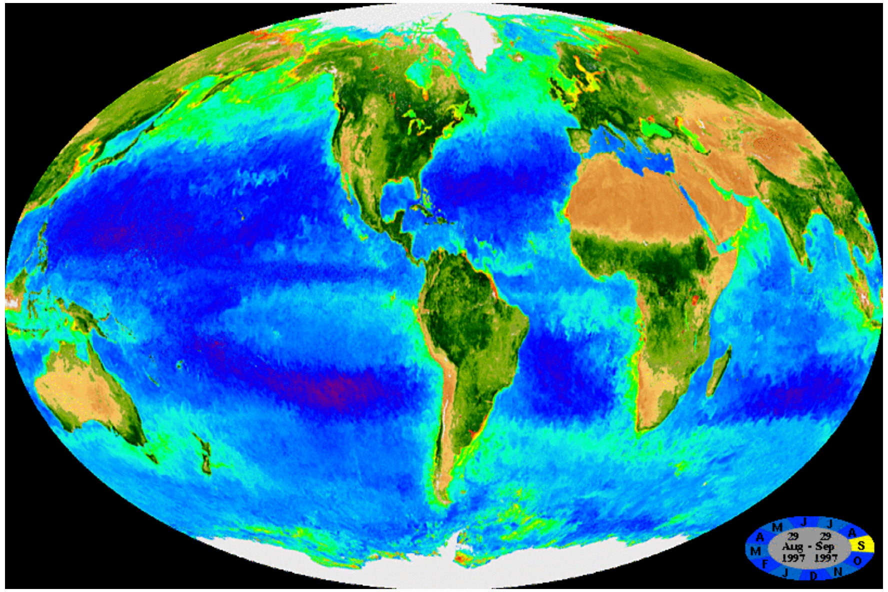
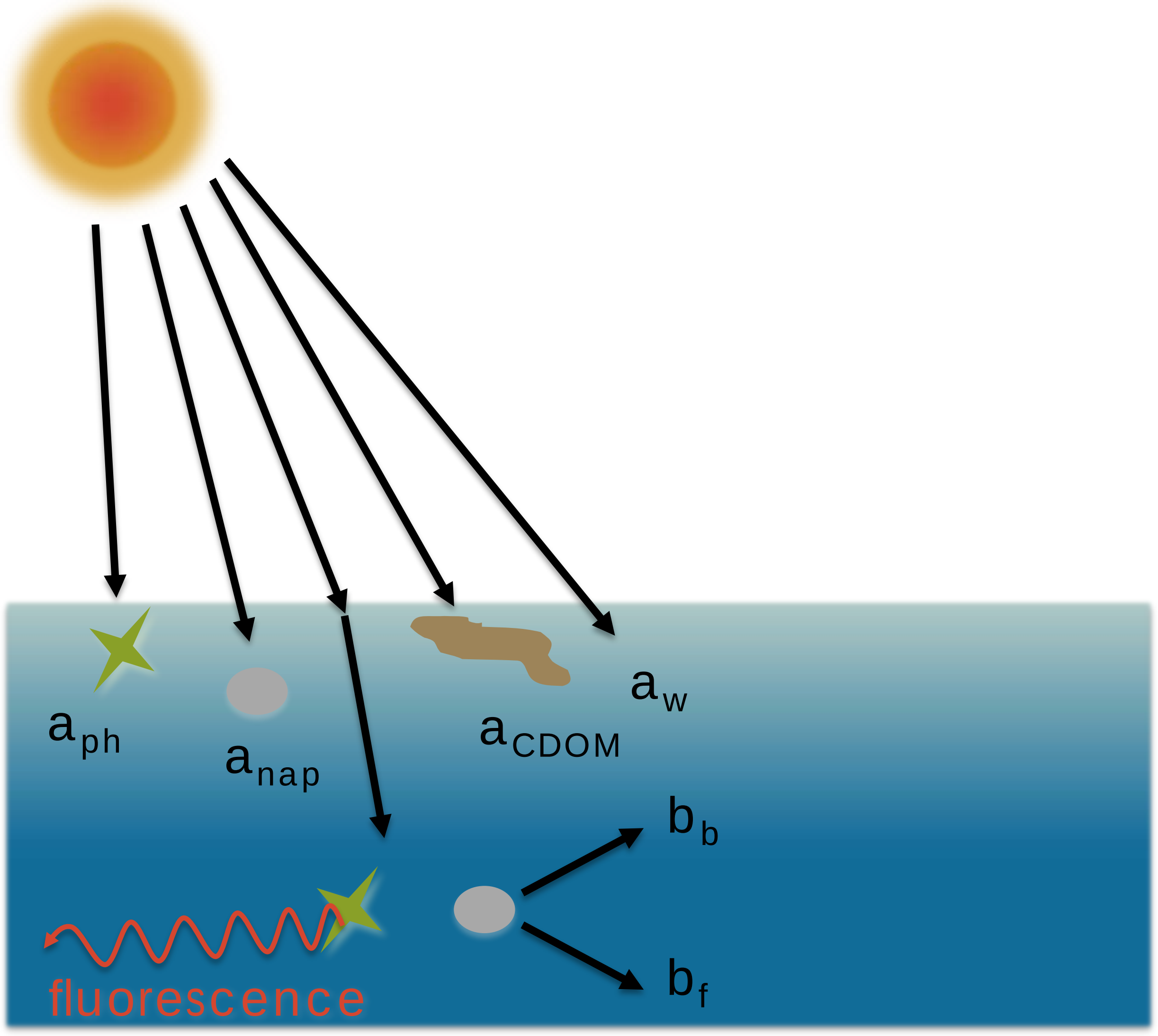


Image Credit: Chlorophyll-a from SeaWIFs

How Light Interacts with Water



$$R_{rs}(\lambda,0^{+}) \cong C \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)}$$

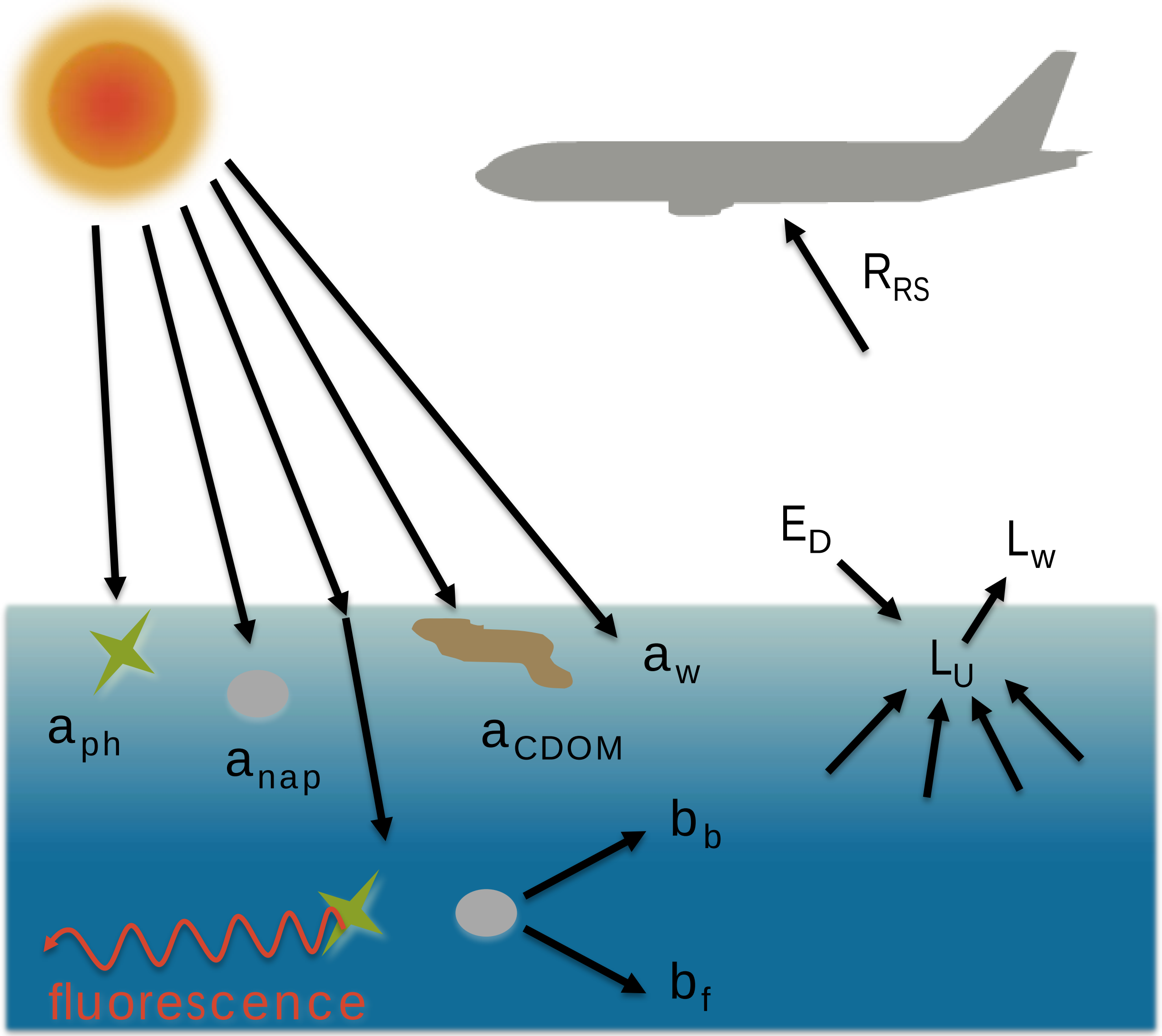
Inherent Optical Properties

a = absorption by...

- phytoplankton (ph)
- non-algal particles (nap)
- colored dissolved organic matter (CDOM)
- water (w)

b = scattering in forward (f) and backward (b) directions

How Light Interacts with Water



$$R_{rs}(\lambda,0^+) \cong C \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)} = \frac{L_w(\lambda)}{E_d(\lambda,0^+)}$$

Inherent Optical Properties

a = absorption

b = scattering

Apparent Optical Properties

L_w = water leaving radiance

L_u = upwelling radiance

E_d = downwelling irradiance

R_{rs} = remote sensing (rs) reflectance

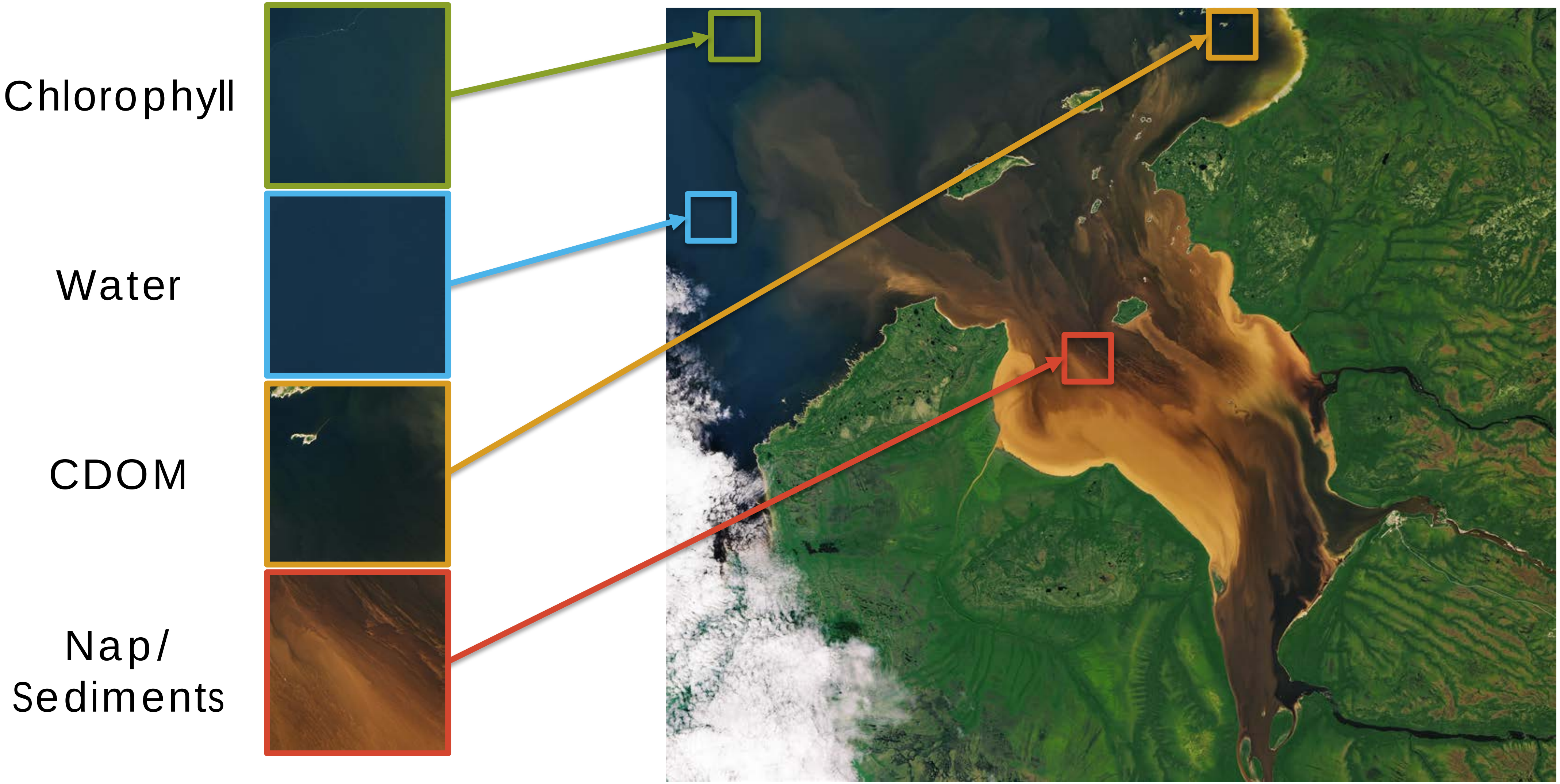
Inherent Optical Properties (IOPs) and the 'Color' of Water

Light absorption (a) by photoplankton (ph), non-algal particles (nap), water (w), and colored dissolved organic matter (CDOM)

$$a = a_{ph} + a_{nap} + a_{CDOM} + a_w$$

Light scattering (b) by particles in forward (b_f) and backward (b_b) direction $b = b_f + b_b$

Inherent Optical Properties (IOPs) and the 'Color' of Water

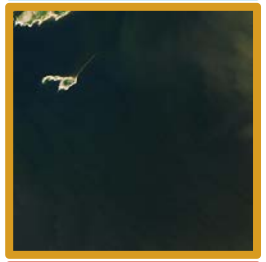


Inherent Optical Properties (IOPs) and the ‘Color’ of Water

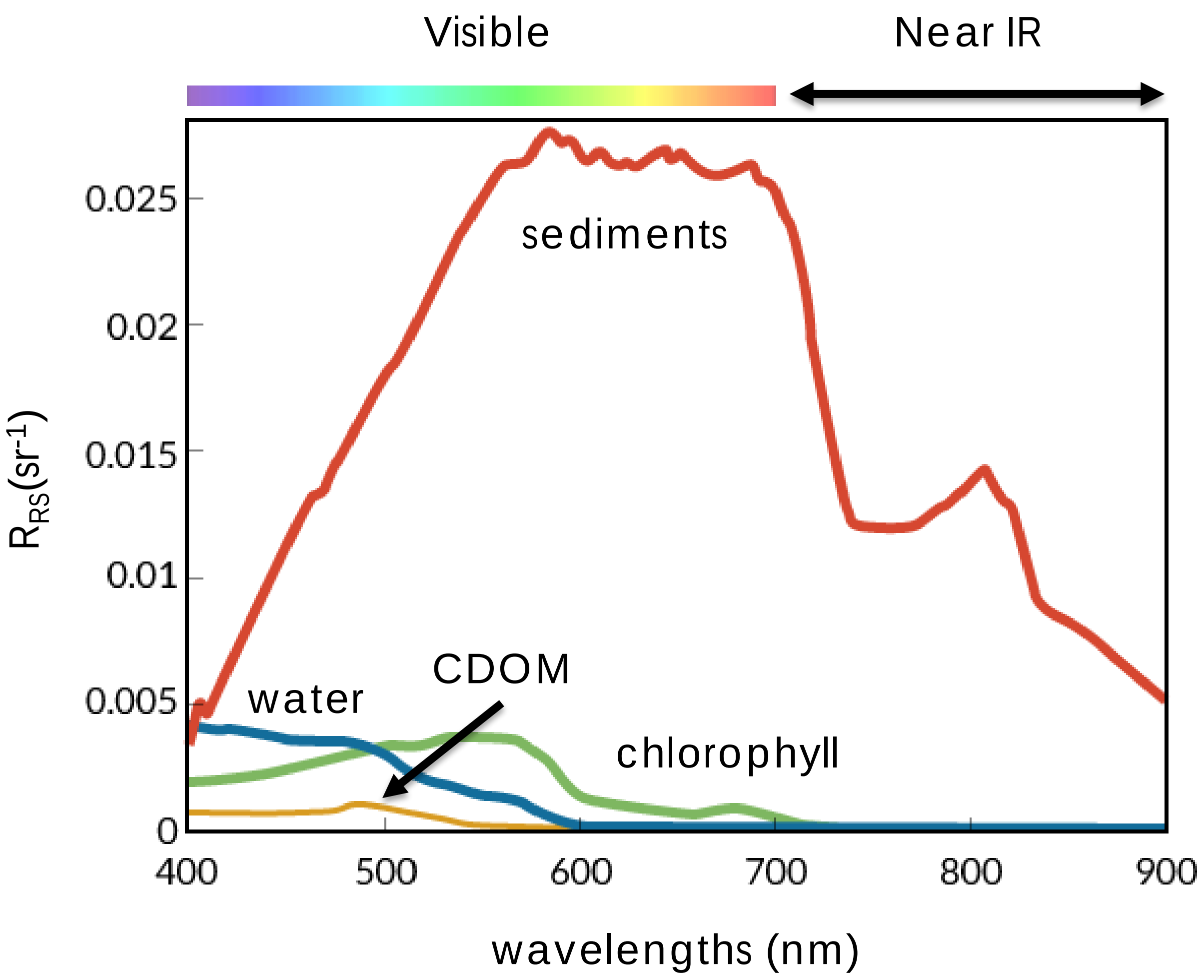
Chlorophyll

Water

CDOM



Nap/
Sediments

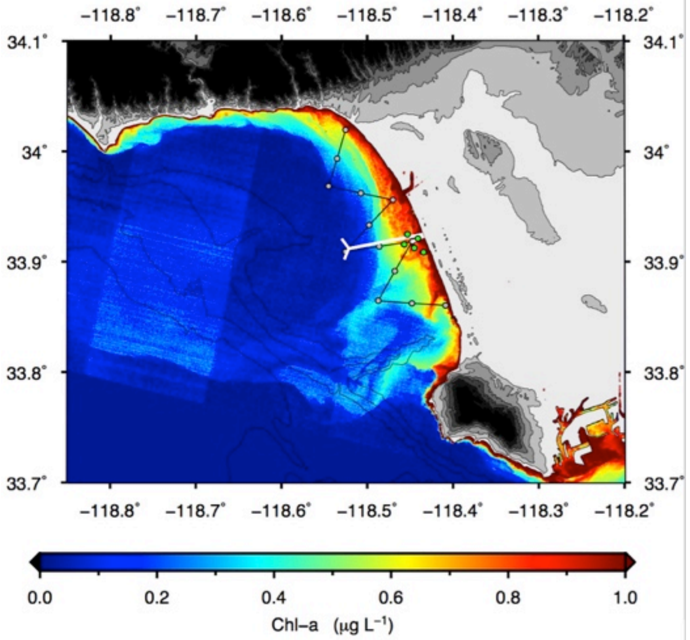


Remote Sensing of Water Bodies

Techniques

1. Simple image interpretation to derive **qualitative information** about water quality

2. Different algorithms combine atmospherically corrected satellite images and in situ measurements to derive **quantitative information** about water quality



In situ observations required

Remote Sensing of Water Bodies

- Satellite sensors measure top-of-atmosphere (TOA) radiances
- The TOA radiances result from a combination of surface and atmospheric conditions, including effects of clouds and aerosol particles
- Water-leaving reflectance depends on:
  - backscattering and absorption of radiation due to water, sediments, phytoplankton, and colored dissolved organic matter (CDOM)

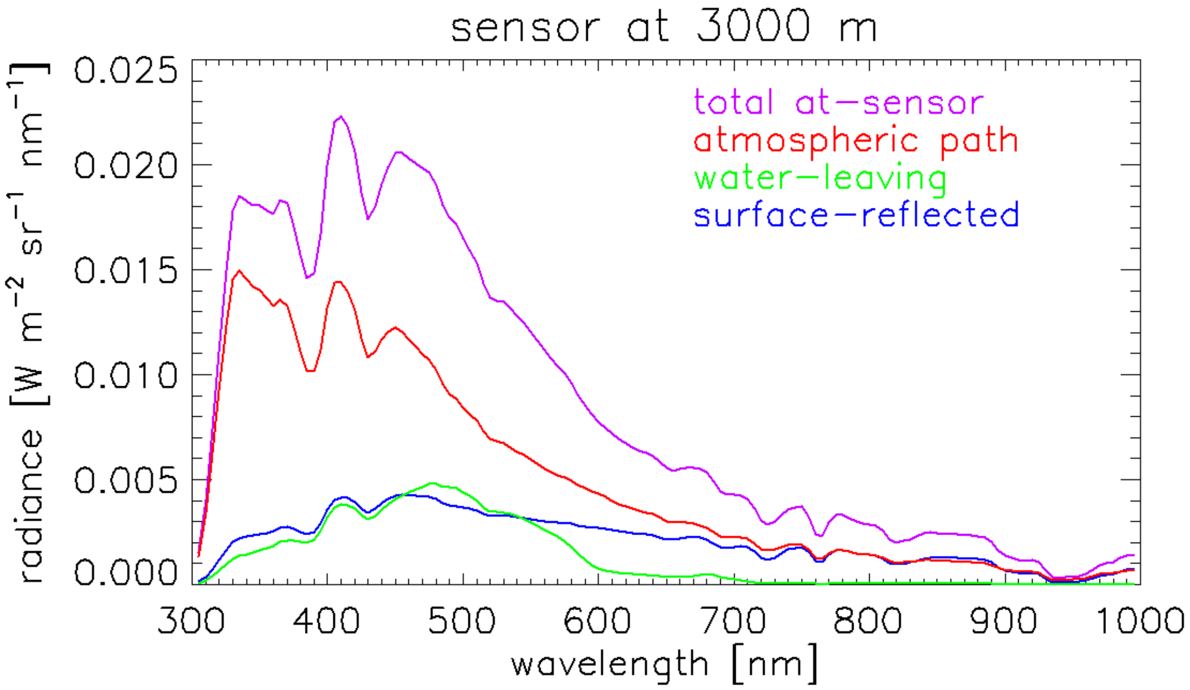


Image Credit: http://www.oceanopticsbook.info/view/remote_sensing/the_atmospheric_correction_problem

Atmospheric Correction for Water Quality Monitoring

- Satellite observations of reflectance have to be corrected for atmospheric effects for getting water surface reflectance
- Various techniques exist for the atmospheric corrections
- Requires raditaive transfer modeling along with atmospheric conditions, clouds, and aerosol information

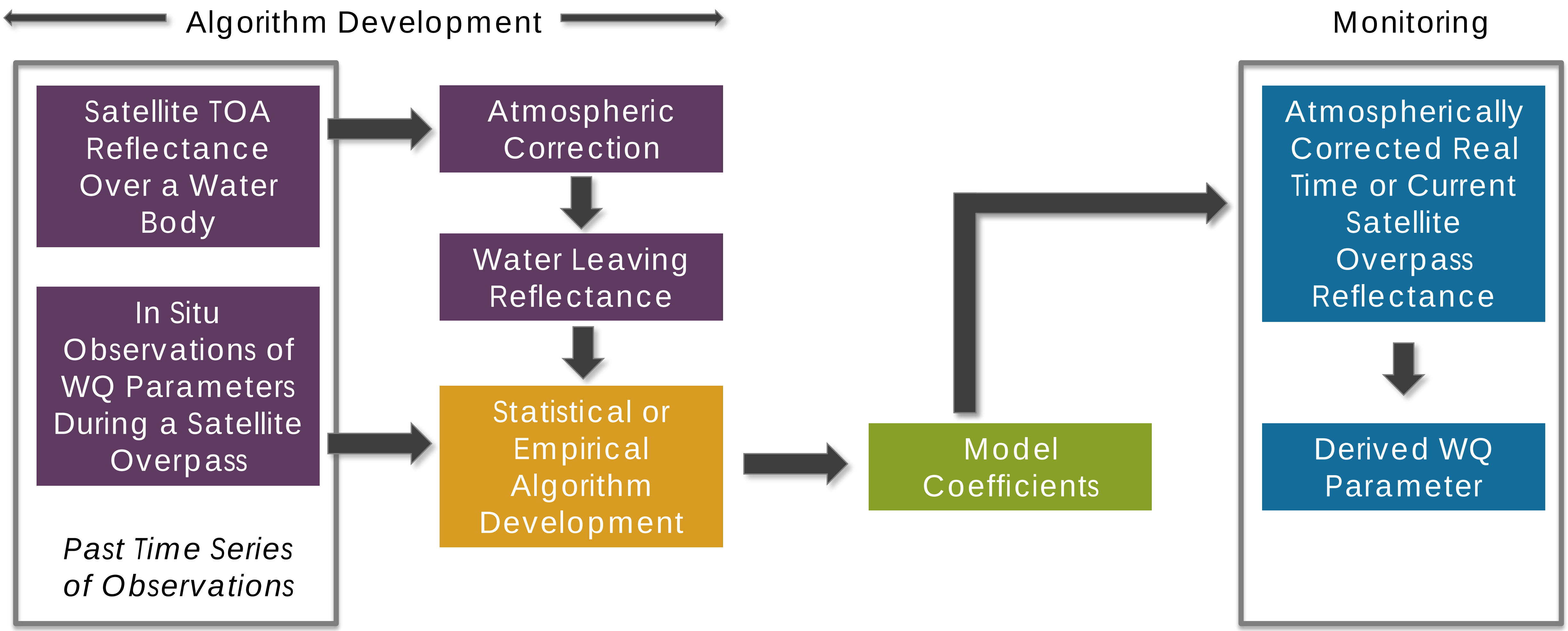
Examples:

- NASA Ocean Biology Processing Group Algorithm: https://oceancolor.gsfc.nasa.gov/docs/technical/NASA-TM-2016-217551.pdf
- ***6S**: **S**econd **S**imulation of the Satellite **S**ignal in the **S**olar **S**pectrum: http://6s.ltdri.org/#
- ACOLITE: https://odnature.naturalsciences.be/remsem/software-and-data/acolite
- HydroLight: http://www.oceanopticsbook.info/view/radiative_transfer_theory/level_2/hydrolight

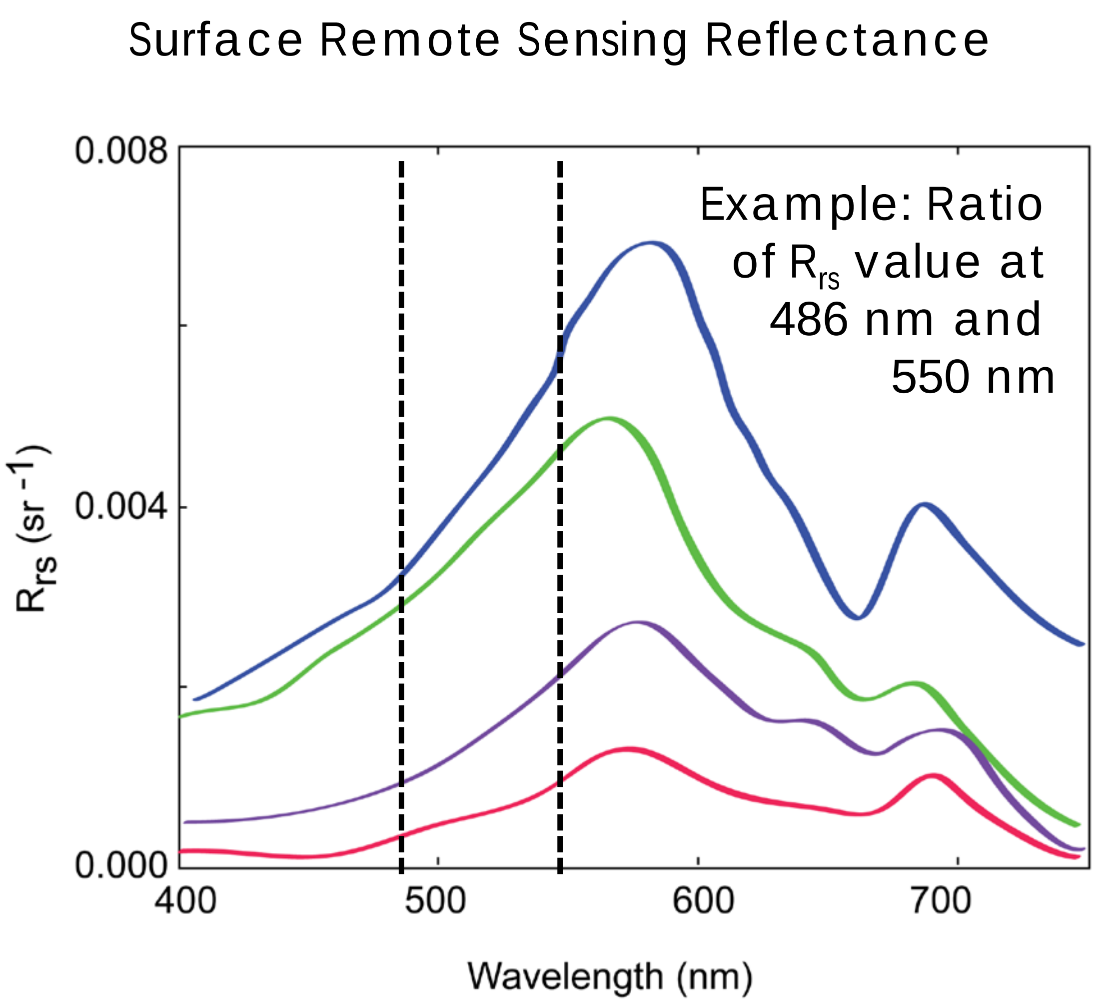
*Vermote, E.E., D. Tanré, J.L. Deuzé, M. Herman and J.-J. Morcrette, Second Simulation of the Satellite Signal in the Solar Spectrum, 6S: An Overview, *IEEE Transactions on Geoscience and Remote Sensing, Vol. 35, No. 3, p. 675-686., 1997.* r12_Stumpf_Tomlinson.pdf

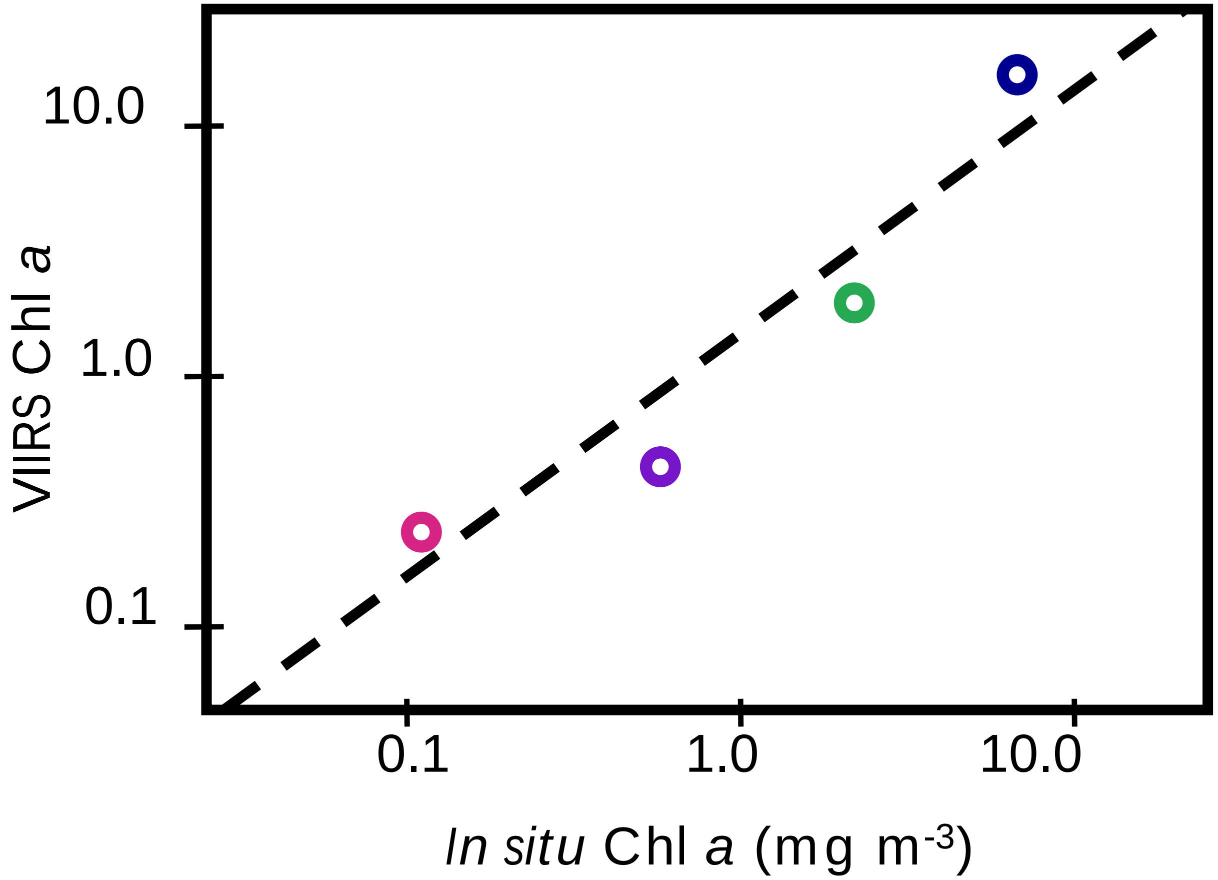
Water Quality Parameters from Remote Sensing Observations

Quantitative Technique

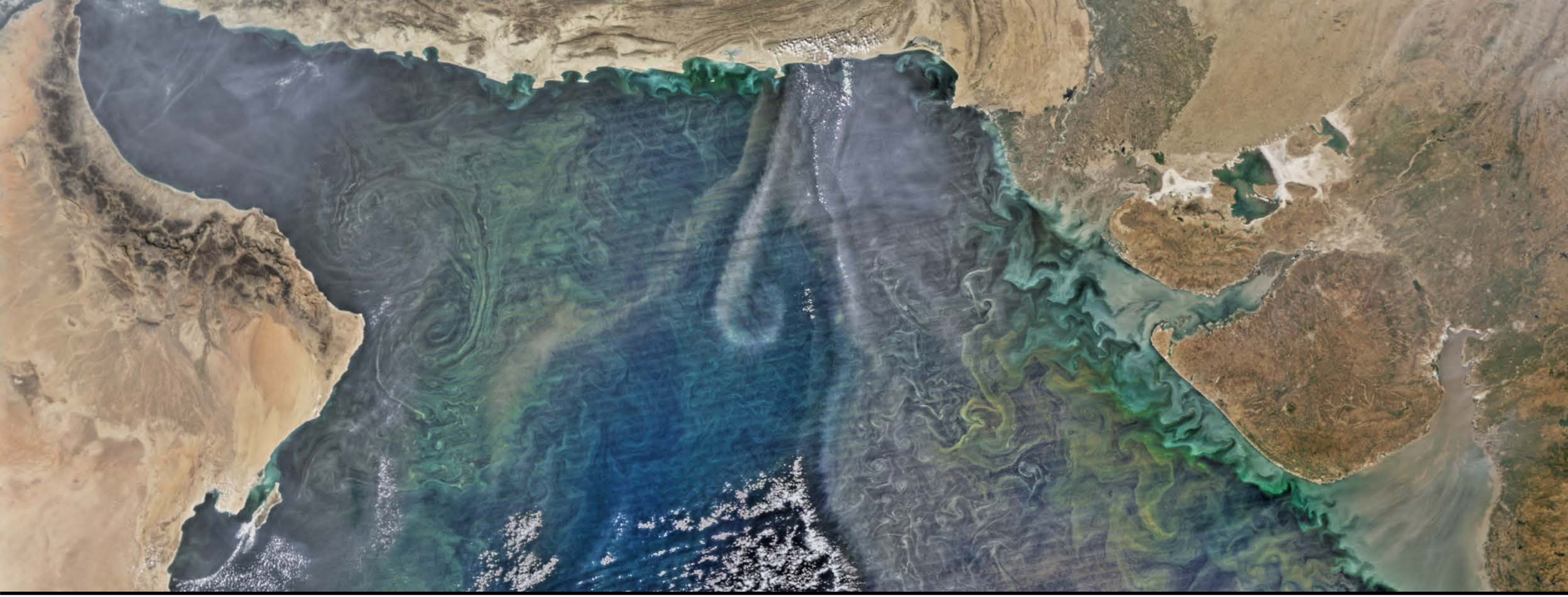


Example: Chlorophyll-a Estimates from Ratios of Reflectance





Algorithm description: http://oceancolor.gsfc.nasa.gov/cms/atbd/chlor_a



Monitoring WQ in Coastal and Inland Waters

Remote Sensing Data Source Considerations

- What **geographical and atmospheric** (especially persistent cloud cover) conditions exist?
- What is the **spatial resolution** of the data and how appropriate is it, relative to the size of the water body to be monitored?
- What is the **temporal resolution** in terms of potential frequency of acquisition of non-cloudy observations compared to the desired frequency of monitoring?
- What are the **spectral regions**, and bands within them, and how do these relate to the potential for distinguishing water quality?
- What is the **longevity of the image archive length** – does this meet the historical mapping needs?
- What are the **cost implications** of these data in terms of purchase and analysis?
- What are the **future satellite development** and launch commitments?

NASA Ocean Color Web from Ocean Biology Processing Group

https://oceancolor.gsfc.nasa.gov/

- Primarily designed for coastal and open oceans
- Useful for monitoring ‘large’ in-land lakes and estuaries
- Provides historical and current data from various satellites and sensors
- Focuses on processing remote sensing imagery to derive **Chlorophyll Concentration (Ch)** and **Sea Surface Temperatures (SST)**

NASA Ocean Color Data Products

https://oceancolor.gsfc.nasa.gov/atbd/

- Algorithms are derived based on spectral band ratios and SeaBASS in situ measurements
  - https://seabass.gsfc.nasa.gov

Standard Ocean Color Products

Chlorophyll *a* (chlor_a; mg m^{-3})

The concentration of the photosynthetic pigment chlorophyll *a*.

Diffuse attenuation coefficient for downwelling irradiance at 490 nm (Kd_490; m^{-1})

The diffuse attenuation coefficient for downwelling irradiance over the first optical attenuation layer.

Inherent Optical Properties (IOPs; m^{-1})

The spectral marine absorption and backscattering coefficients of water column constituents.

Particulate Organic Carbon (POC; mg m^{-3})

The concentration of particulate organic carbon.

Particulate Inorganic Carbon (PIC; mol m^{-3})

The concentration of particulate inorganic carbon.

Photosynthetically Available Radiation (PAR; Einstein m^{-2} d^{-1})

Daily mean photosynthetically available radiation (PAR) at the ocean surface.

Instantaneous Photosynthetically Available Radiation (iPAR; Einstein m^{-2} s^{-1})

PAR the ocean surface at the time of the satellite observation. (MODIS only)

Normalized Fluorescence Line Height (nFLH; mW cm^{-2} μm^{-1} sr^{-1})

Relative measure of water-leaving radiance associated with chlorophyll fluorescence. (MODIS only)

Remote Sensing Reflectance (Rrs; sr^{-1})

The at-surface spectral remote-sensing reflectances observed by the satellite instrument after atmospheric correction. The aerosol optical thickness and Ångstrom data products are also described.

Standard Sea Surface Temperature Products

11 µm Sea Surface Temperature (SST; °C)

Sea surface temperature derived from long-wave (11-12 µm) thermal radiation. (MODIS & VIIRS)

4 µm Sea Surface Temperature (SST4; °C)

Sea surface temperature derived from short-wave (3-4 µm) thermal radiation. (MODIS only)

NASA Ocean Color Data Products Algorithms

https://oceancolor.gsfc.nasa.gov/atbd/

- Algorithms to derive Ocean Color (OC) products from MODIS and VIIRS
- The OC algorithm is a fourth-order polynomial relationship between a ratio of R_{rs} and *chlor_a*

$$log_{10}(chlor\_a) = a_0 + \sum_{i=1}^{4} a_i \left(log_{10} \left(\frac{R_{rs}(\lambda_{blue})}{R_{rs}(\lambda_{green})} \right) \right)^i,$$

- SSTs are derived from infrared window radiances (11 and 4 micron)

- The algorithm for Particulate Organic Carbon (POC) is a power-law relationship between a ratio of R_{rs} from MODIS and POC

$$poc = a \times (R_{rs}(443) / R_{rs}(557))^b$$

- Particulate Inorganic Carbon (PIC)
  - 2-band approach: normalized water-leaving radiances in two bands near 443 and 555 nm
  - 3-band approach: spectral top-of-atmosphere reflectance at three wavelengths near 670, 750, and 870 nm

NASA Ocean Color Data Products Algorithms

https://oceancolor.gsfc.nasa.gov/atbd/

- Kd490, a diffuse attenuation coefficient:
  - Indicates how strongly light intensity at a given wavelength is attenuated within the water column
  - Useful for
    - characterizing water optical properties
    - classifying water types (e.g., Case 1 or 2)
  - Is a critical parameter for accurate estimation of the light intensity at depth
  - Useful for measuring Water Turbidity and Transparency
  - Derived by using an empirical relationship between Kd(490) and the blue-green normalized water-leaving radiance ratio (NASA's Ocean Color Processing Group)

NASA Ocean Color Data Products Algorithms

https://oceancolor.gsfc.nasa.gov/atbd/

- Normalized Fluorescence Line Height (normalized to solar irradiance)
  - A measurement of solar-induced phytoplankton chlorophyll fluorescence emission at ~678 nm
  - Useful to improve ocean photosynthesis estimates
  - Helps resolve climate-phytoplankton interactions
  - Characterize iron stress in the global ocean
- Derived from difference between the observed nLw(678) and a linearly interpolated nLw(678) from two surrounding bands. (NASA's Ocean Color Processing Group)

Water Quality Data Product Algorithms

- Various spectral combinations are used in different algorithms to derive water quality parameters (Gholizadeh et al. 2016)
- In addition to NASA Ocean Color data based on MODIS and VIIRS, several studies have used Landsat 5, 7, and 8 to derive water quality parameters

Gholizadeh, M., Melesse, A., & Reddi, L. (2016). A Comprehensive Review on Water Quality Parameters Estimation Using Remote Sensing Techniques. Sensors, 16(8), 1298. doi:10.3390/s16081298

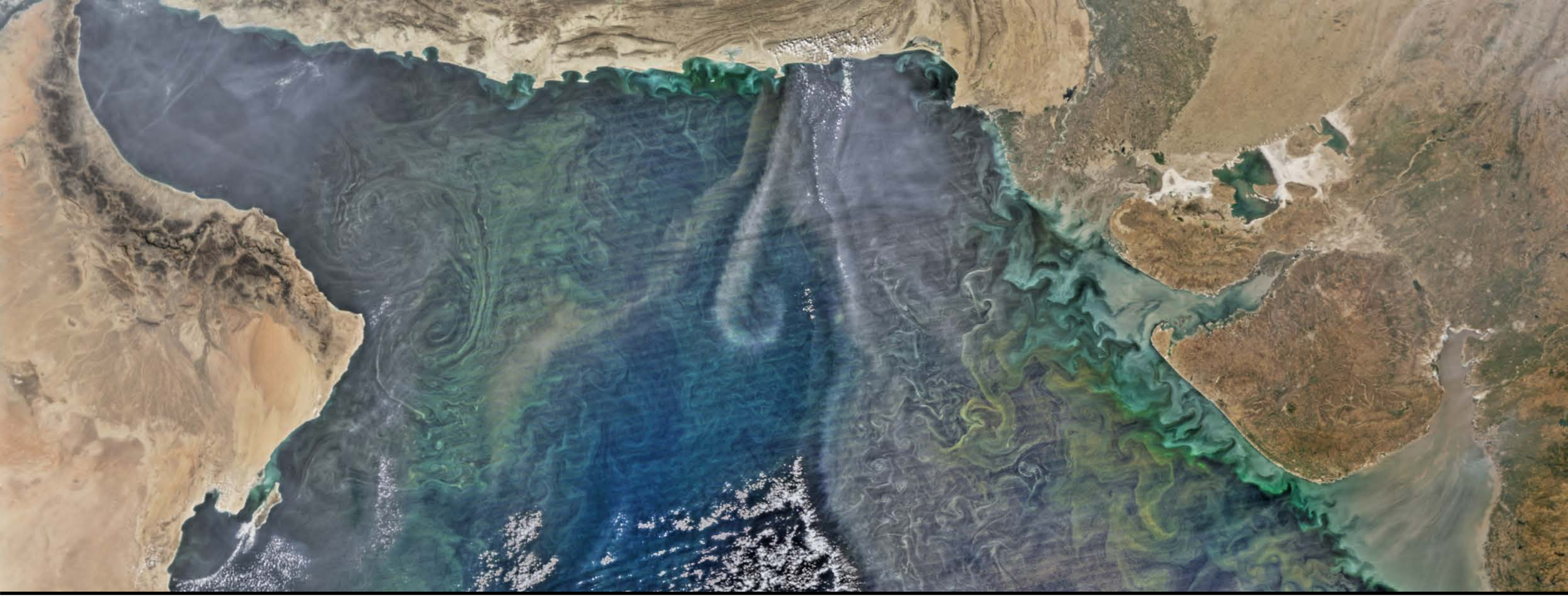
Harmful Algal Blooms (HABs)

https://arset.gsfc.nasa.gov/water/webinars/HABs17

- HABs occur when colonies of algae grow out of control
  - algae: simple fresh and sea water plants
- HABs:
  - Produce toxins
  - Cause economic losses
  - Contaminate drinking water
  - Smother benthic organisms
  - Deplete oxygen
  - Attenuate light to submerged aquatic vegetation or corals

- Generally, chlor_a is used as an indicator for HABs
- Chlor_a anomalies (departure from mean value), and inherent optical properties can also be used an indicator of HABs

Image: Landsat 8 (OLI) Aug 1, 2014



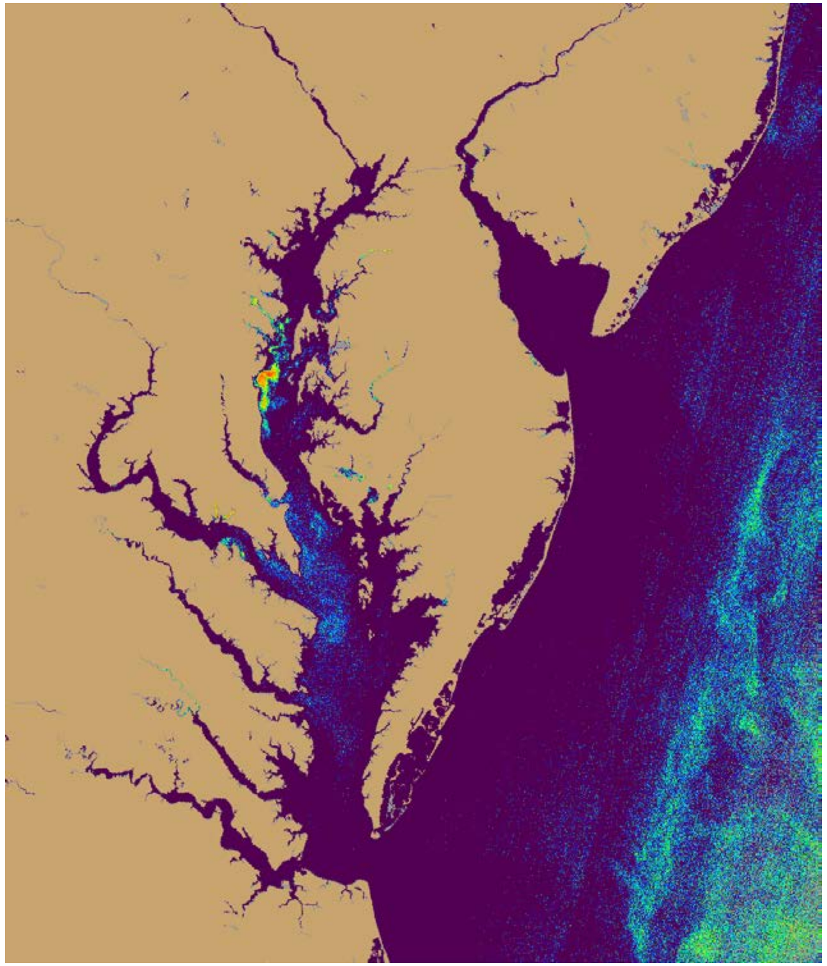
Demonstration of NASA Web Tools for Water Quality Data Access

Web Tools

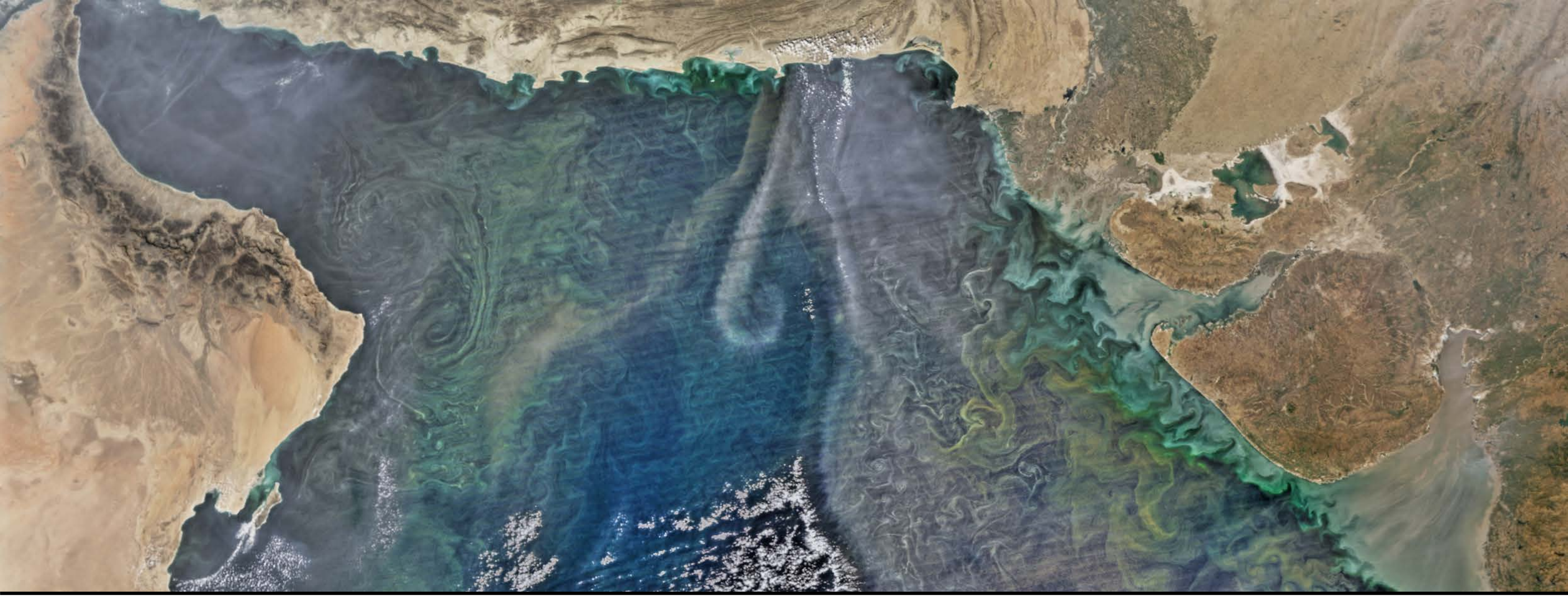
- Data search, spatial and temporal subsetting, analysis, and visualization:
  - Giovanni: http://giovanni.gsfc.nasa.gov/giovanni/
  - OceanColor Web: https://oceancolor.gsfc.nasa.gov/

Case Study: Chesapeake Bay Spring Algal Bloom 2018

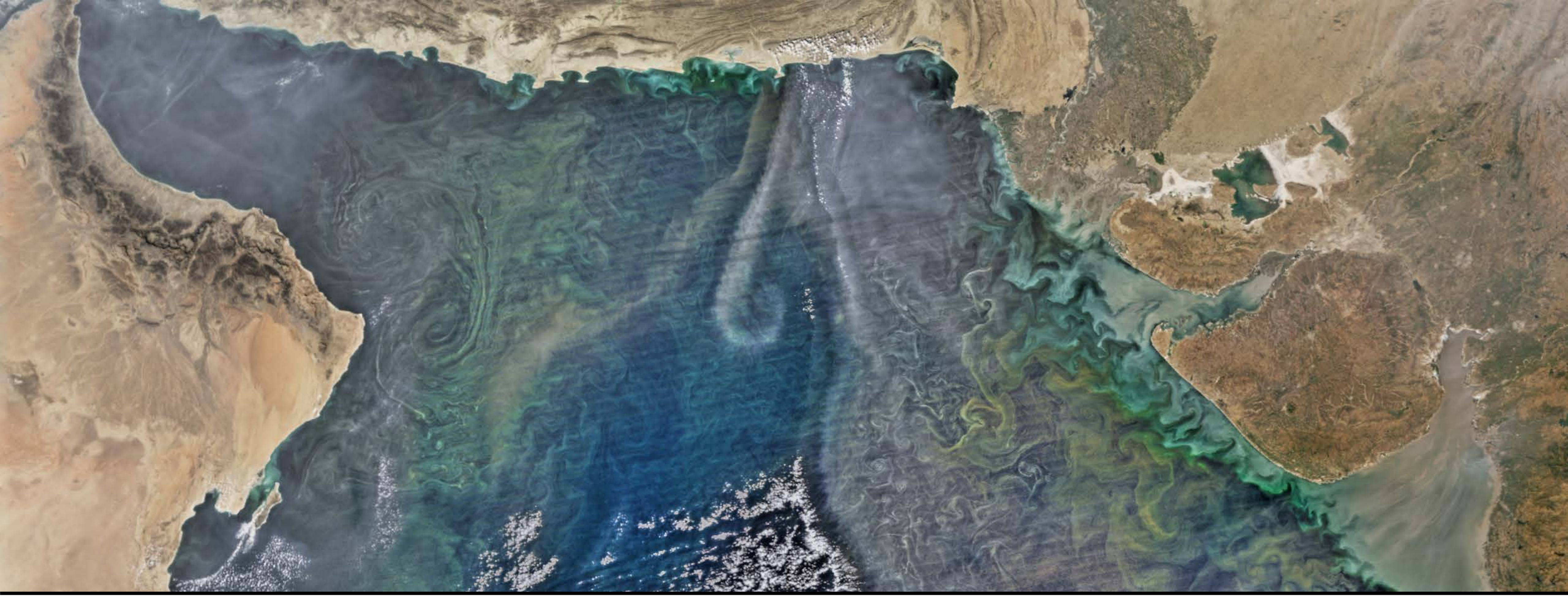
http://eyesonthebay.dnr.maryland.gov/eyesonthebay/habs.cfm



Satellite detection of algal bloom in the Chesapeake Bay on May 1, 2018. Source NOAA, Sentinel 3



Exercise: Lake Victoria



Appendix A

Landsat Bands

Landsat 7 ETM+

Band	Band Range (µm)	Spatial Resolution (m)
1	0.45 – 0.515	
2	0.525 – 0.605	
3	0.63 – 0.69	30
4	0.775 – 0.90	
5	1.55 – 1.75	
6	10.4 – 12.5	60
7	2.08 – 2.35	30
8	0.52 – 0.9	15

Landsat 8 OLI

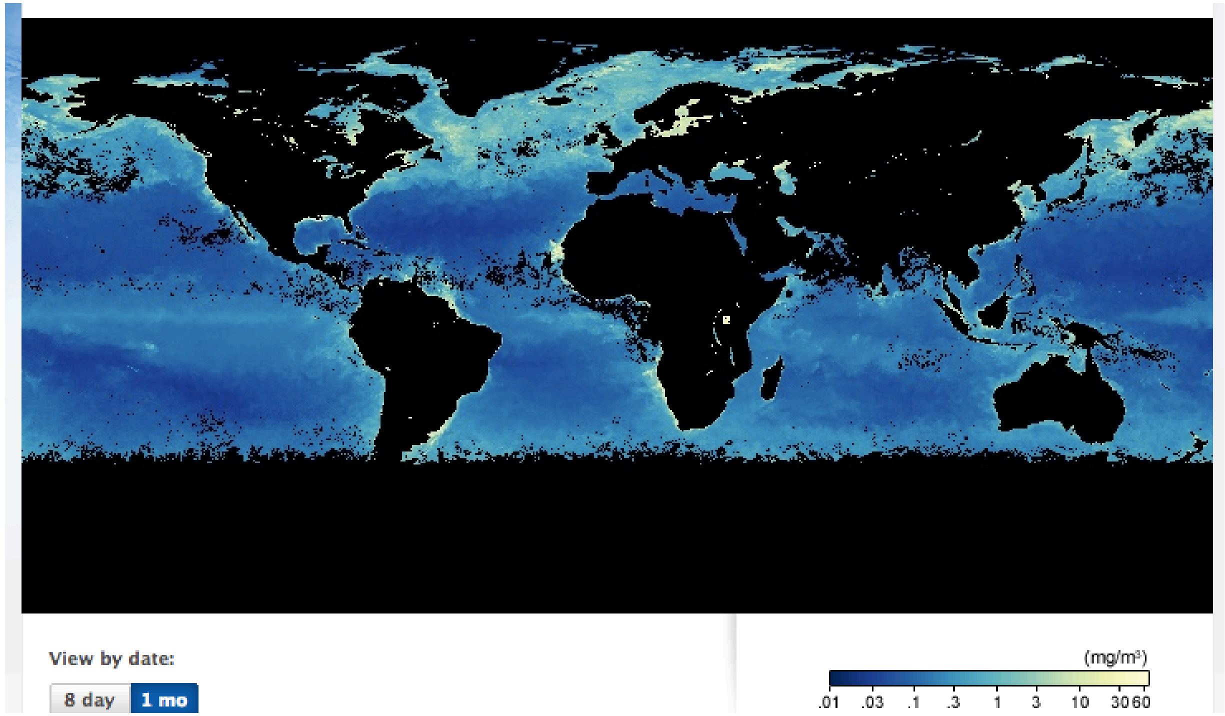
Band	Band Range (µm)	Spatial Resolution (m)
1	0.433 – 0.453	
2	0.450 – 0.515	
3	0.525 – 0.60	
4	0.630 – 0.680	30
5	0.845 – 0.885	
6	2.10 – 2.30	
7	0.500 – 0.680	
8	2.08 – 2.35	15
9	1.36 – 1.39	30

MODIS Bands Relevant for HAB Monitoring

Band	Band Range µm
8	0.405-0.420
9	0.438-0.448
10	0.483-0.493
11	0.526-0.536
12	0.546-0.556
13	0.662-0.672
14	0.673-0.683
15	0.743-0.753

Spatial resolution: 1 km

Chlorophyll Concentration from Aqua MODIS, June 2017

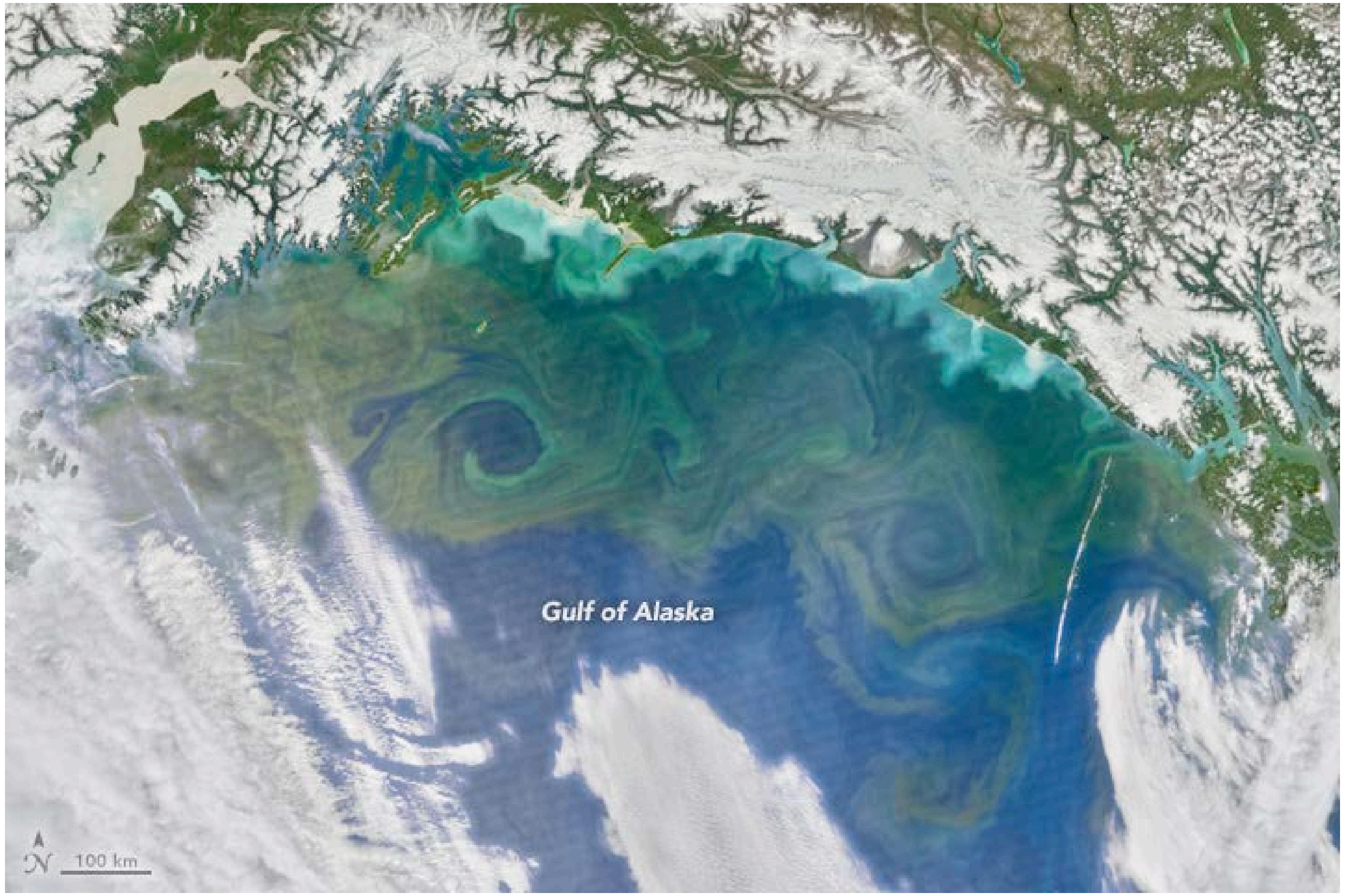


VIIRS Bands Relevant for HAB Monitoring

Band	Band Range µm
M1	0.402-0.422
M2	0.436-0.454
M3	0.478-0.488
M4	0.545-0.565
M5	0.662-0.682
M6	0.739-0.745

Spatial Resolution: 750 m

Phytoplankton Bloom in the Gulf of Alaska, from VIIRS, June 9, 2016

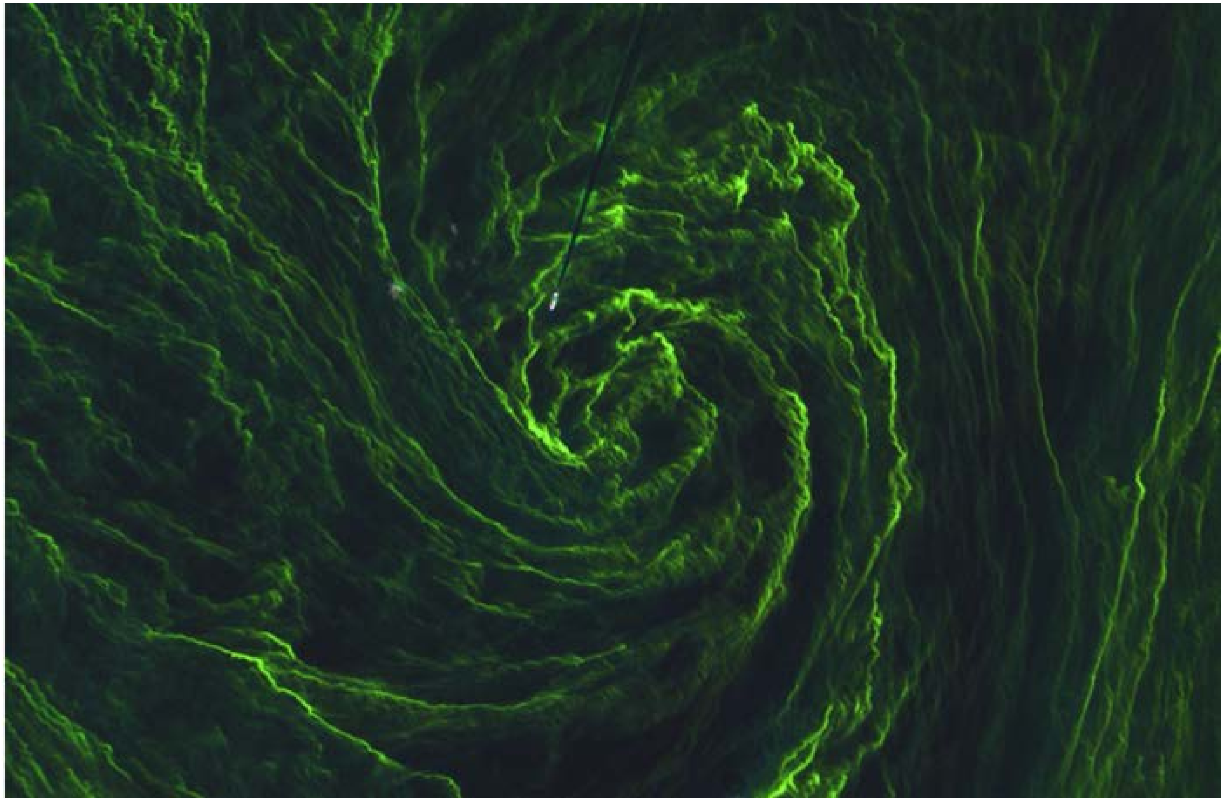


MSI bands

https://earth.esa.int/web/sentinel/user-guides/sentinel-2-msi

	S2A		S2B		
Band Number	Central wavelength (nm)	Bandwidth (nm)	Central wavelength (nm)	Bandwidth (nm)	Spatial resolution (m)
1	443.9	27	442.3	45	60
2	496.6	98	492.1	98	10
3	560.0	45	559	46	10
4	664.5	38	665	39	10
5	703.9	19	703.8	20	20
6	740.2	18	739.1	18	20
7	782.5	28	779.7	28	20
8	835.1	145	833	133	10
8a	864.8	33	864	32	20
9	945.0	26	943.2	27	60
10	1373.5	75	1376.9	76	60
11	1613.7	143	1610.4	141	20
12	2202.4	242	2185.7	238	20

Algal Bloom in the Middle of the Baltic Sea, Sentinel-2 MSI, Aug 7, 2015



OLCI Bands

https://sentinel.esa.int/web/sentinel/user-guides/sentinel-3-olci

Band	λ centre (nm)	Width (nm)
Oa1	400	15
Oa2	412.5	10
Oa3	442.5	10
Oa4	490	10
Oa5	510	10
Oa6	560	10
Oa7	620	10
Oa8	665	10
Oa9	673.75	7.5
Oa10	681.25	7.5
Oa11	708.75	10
Oa12	753.75	7.5

Band	λ centre (nm)	Width (nm)
Oa13	761.25	2.5
Oa14	764.375	3.75
Oa15	767.5	2.5
Oa16	778.75	15
Oa17	865	20
Oa18	885	10
Oa19	900	10
Oa20	940	20
Oa21	1 020	40

Sentinel-3 OCL-Based Chlorophyll Concentration

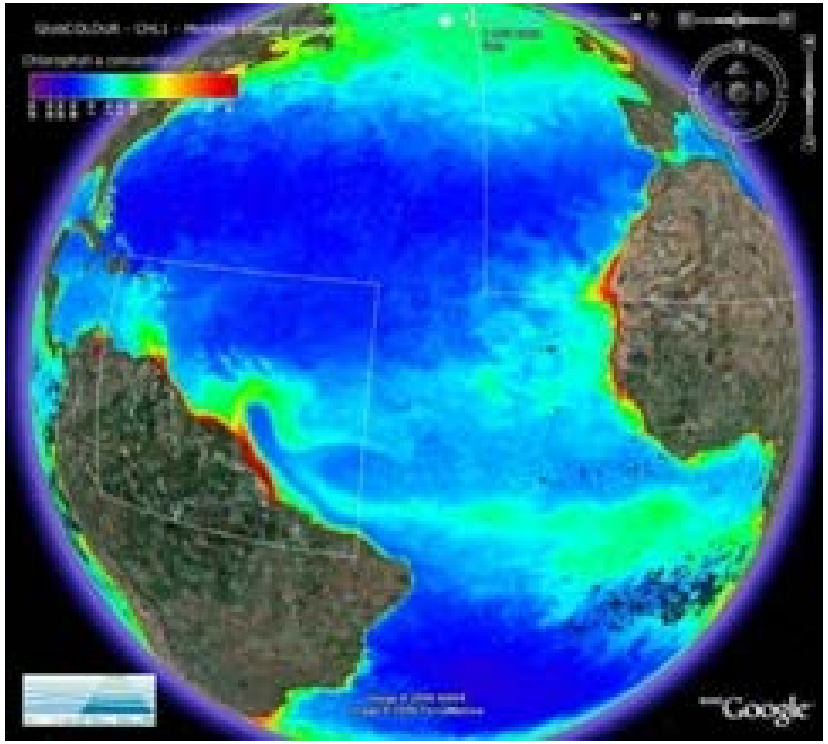


Image Credit: ESA/ACRI-ST

Thank You