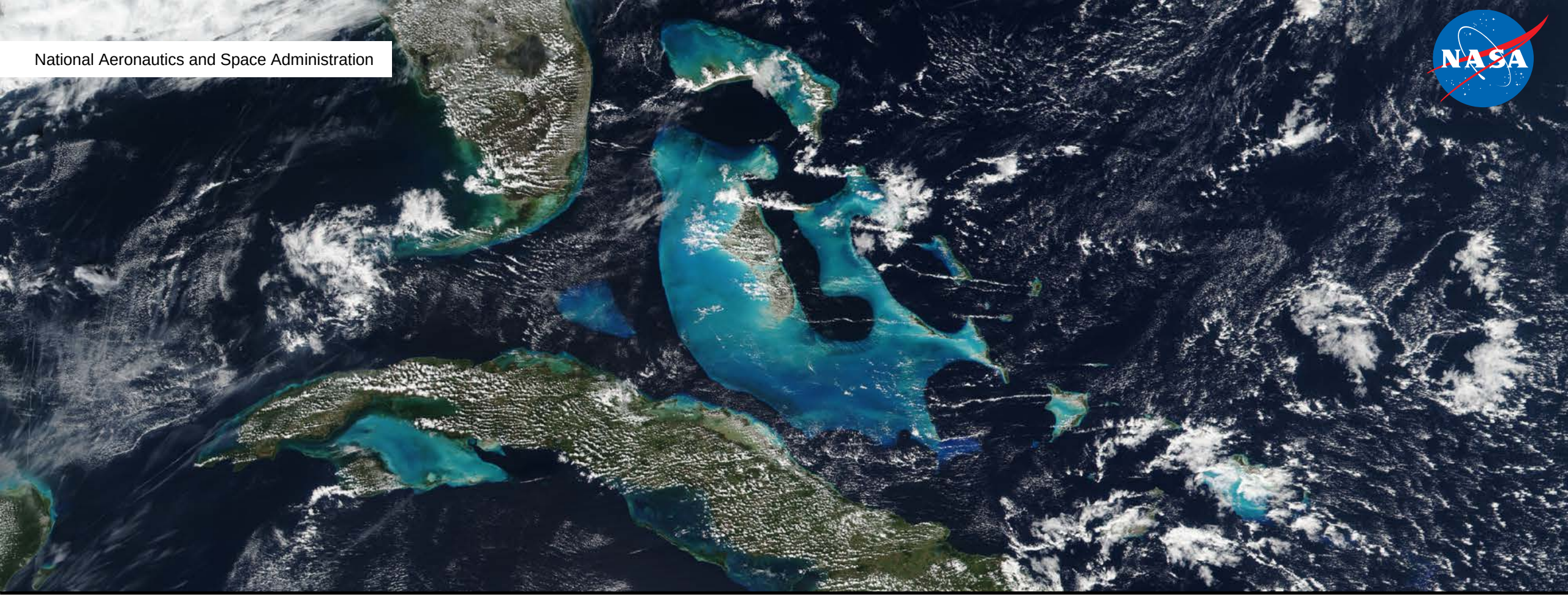
National Aeronautics and Space Administration



Satellite Observations of Water Quality for Sustainable Development Goal 6

Amita Mehta

30 July 2018

Course Objectives

At the end of this session you will obtain:

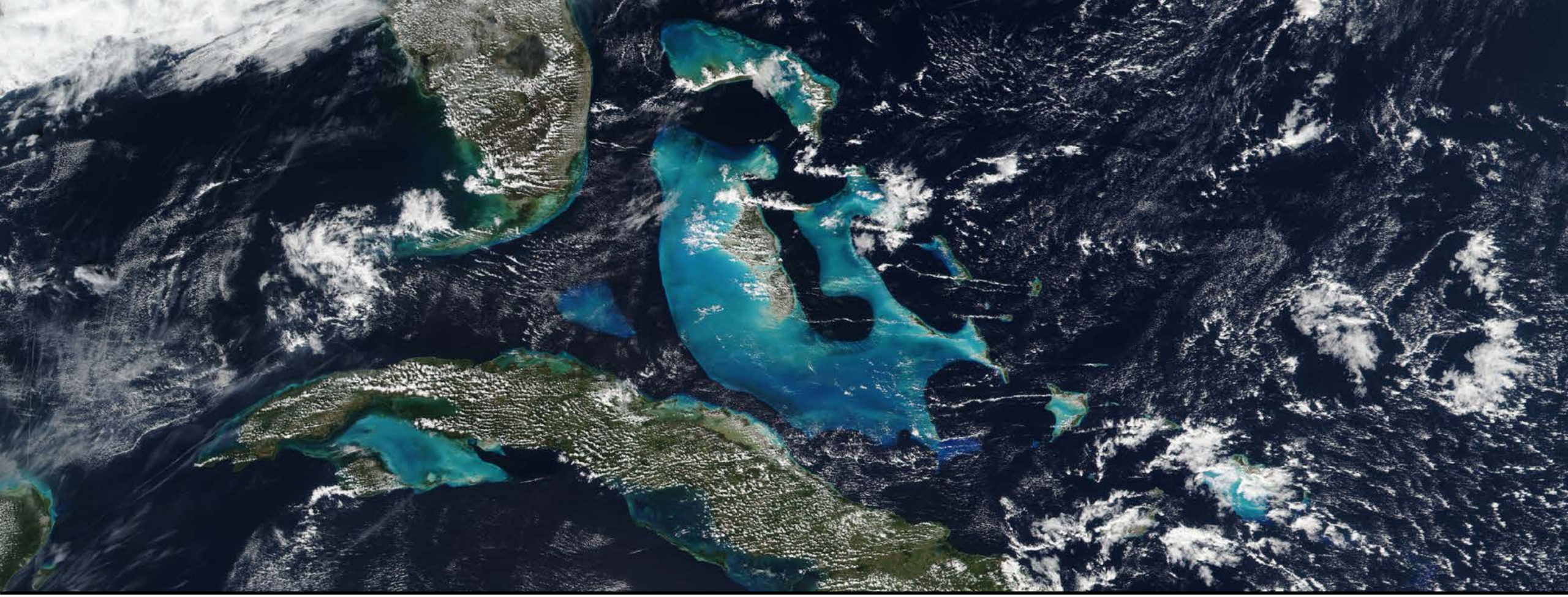
- information about monitoring coastal and inland water quality using satellite observations that can contribute to the United Nations Sustainable Goal 6, related to availability of clean water
- a basic understanding about developing water quality monitoring applications using satellite observations and in situ measurements for your region of interest
- a hands-on exercise for accessing and analyzing selected water quality indicators for Harmful Algal Blooms (HABs), e.g. chlorophyll-a concentration (Ch-a) and sea surface temperature (SST)

Agenda

- Overview of:
  - Applied Remote Sensing Training (ARSET) Program
  - The UN Sustainable Development Goal (SDG) 6
  - Satellite Data Products for Water Quality (WQ) Monitoring For SDG 6.6.1: Sub-Indicator 2 – water quality of lakes and artificial water bodies
- Examples of Monitoring Harmful Algal Boom Indicators
- Demonstration and Hands-on Exercise for **Lake Titicaca**: Chl-a and SST Data Access Using Web-based Tools
- Break-out Groups: Discussion on Data Needs for WQ Monitoring and Decision Support

Materials

- Today's presentation and exercises are available at:
  - http://arset.gsfc.nasa.gov/water/workshops/geoweek-sdg6
- Hard copies of exercises will also be available
- Questions?
  - Amita Mehta: amita.v.mehta@nasa.gov
  - Brock Blevins: brockbl1@umbc.edu
  - Ana Prados: aprados@umbc.edu



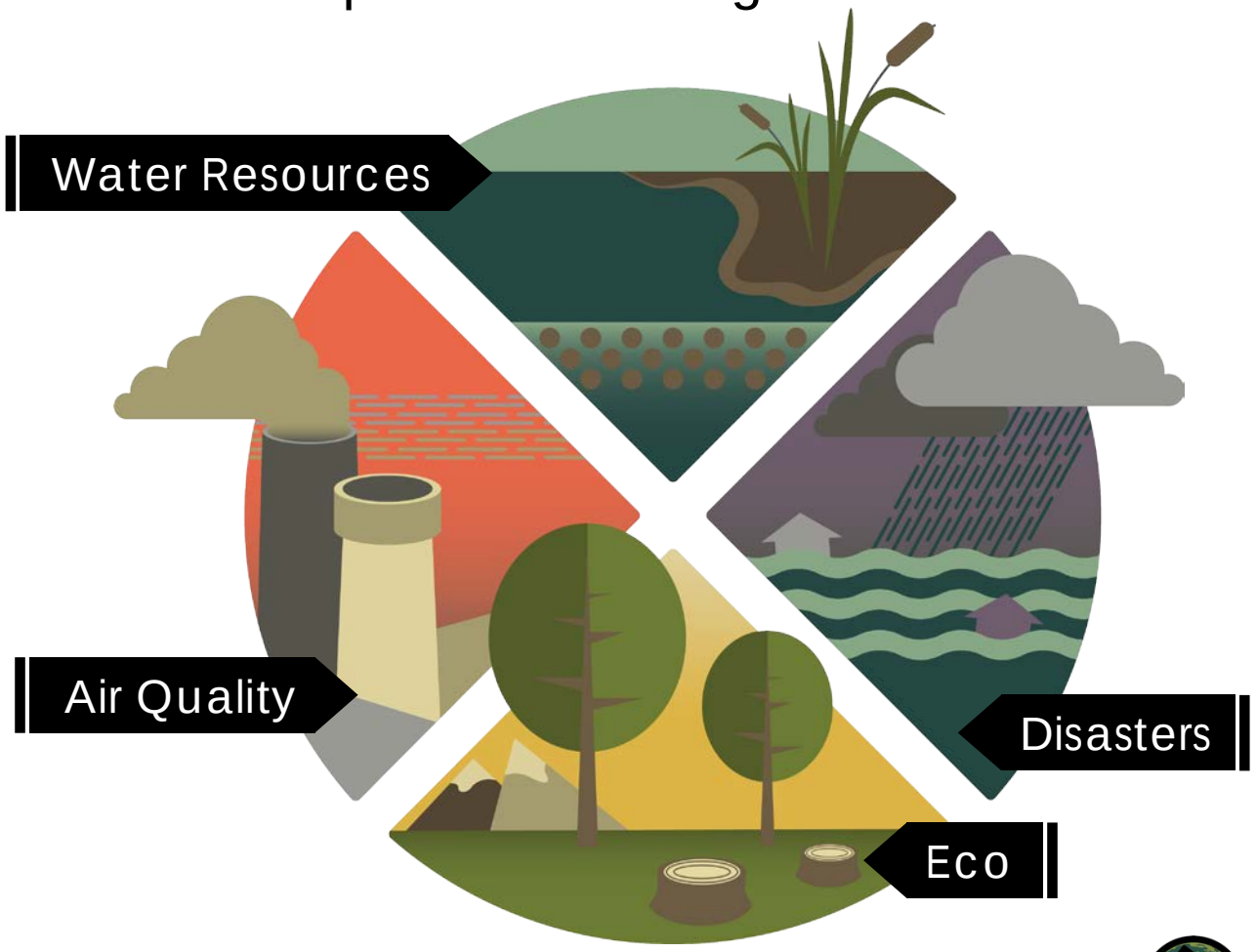
NASA's Applied Remote Sensing Training Program (ARSET)

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 Capacity Building 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

- Ana Prados, Program Manager (GSFC)
- Brock Blevins, Training Coordinator (GSFC)
- David Barbado, Spanish Translator (GSFC)
- Annelise Carleton-Hug, Program Evaluator (Consultant)
- Elizabeth Hook, Technical Writer/Editor (GSFC)
- Selwyn Hudson-Odoi, Training Coordinator (GSFC)
- Marines Martins, Project Support (GSFC)
- Stephanie Uz, Program Support (GSFC)

Disasters & Water Resources

- 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:

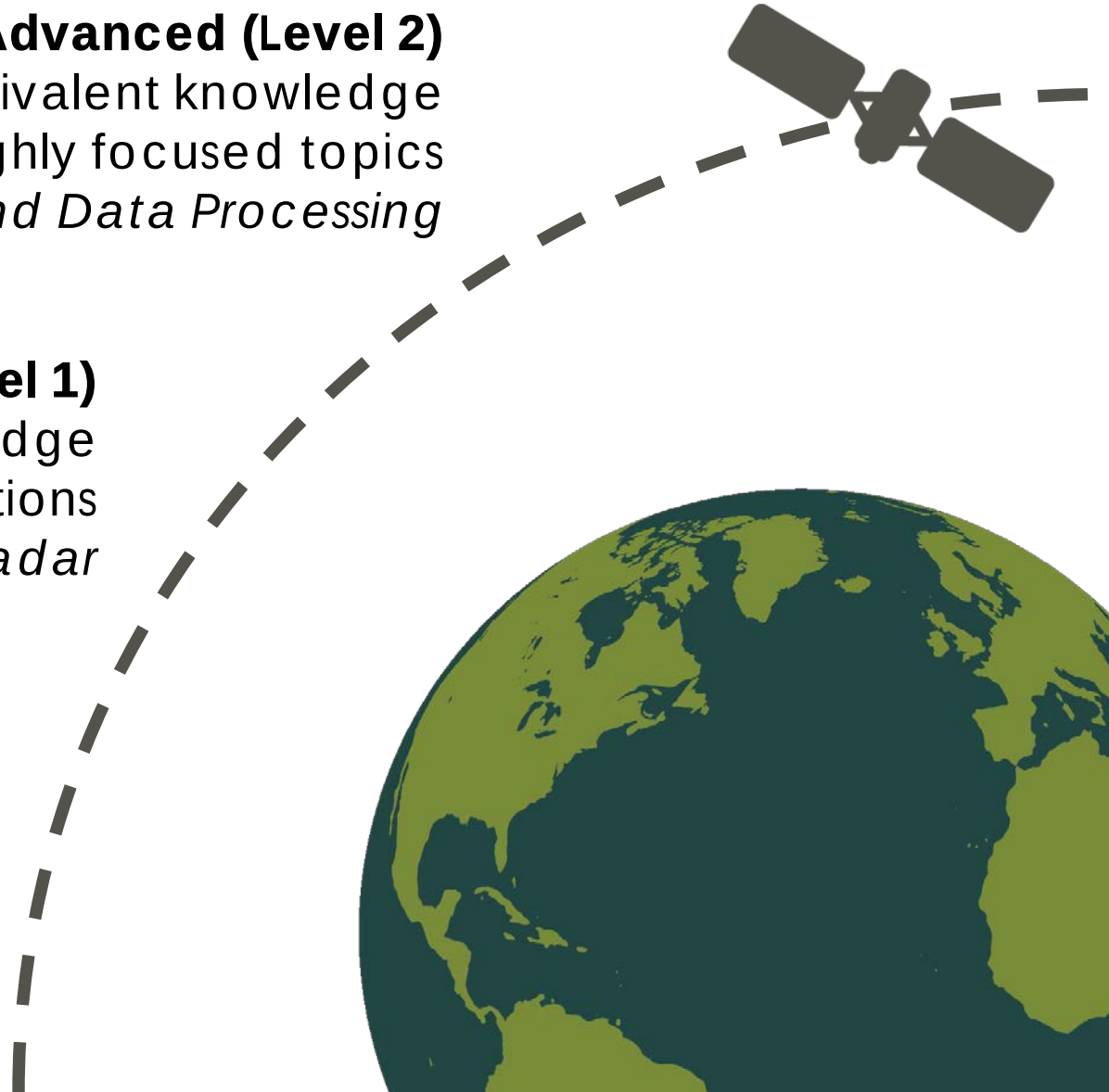
- We wish to thank Nancy Searby for her continued support

ARSET Training Levels

Advanced (Level 2)
Requires level 1 training or equivalent knowledge
In-depth and highly focused topics
Advanced Webinar: SAR Image and Data Processing

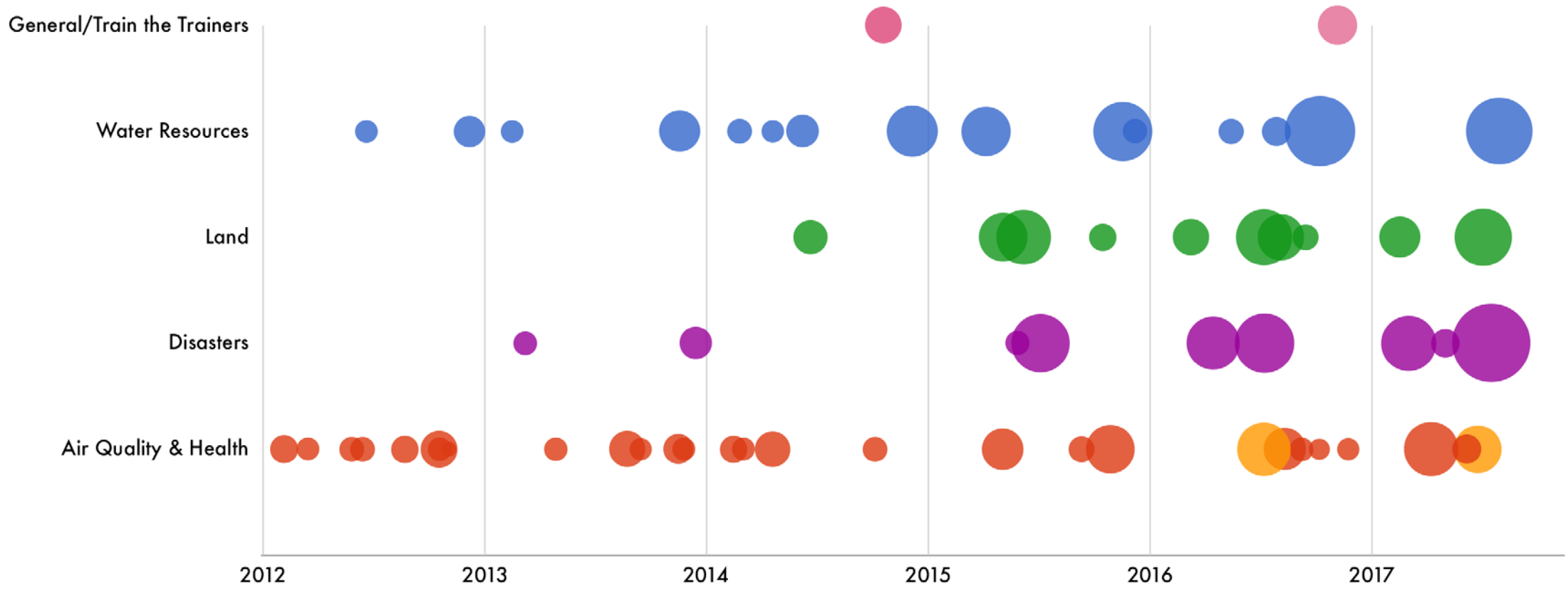
Basic (Level 1)
Requires level 0 training or equivalent knowledge
Covers specific applications
Introduction to Synthetic Aperture Radar

Fundamentals (Level 0)
Assumes no prior knowledge of remote sensing
Fundamentals of Remote Sensing



ARSET Trainings

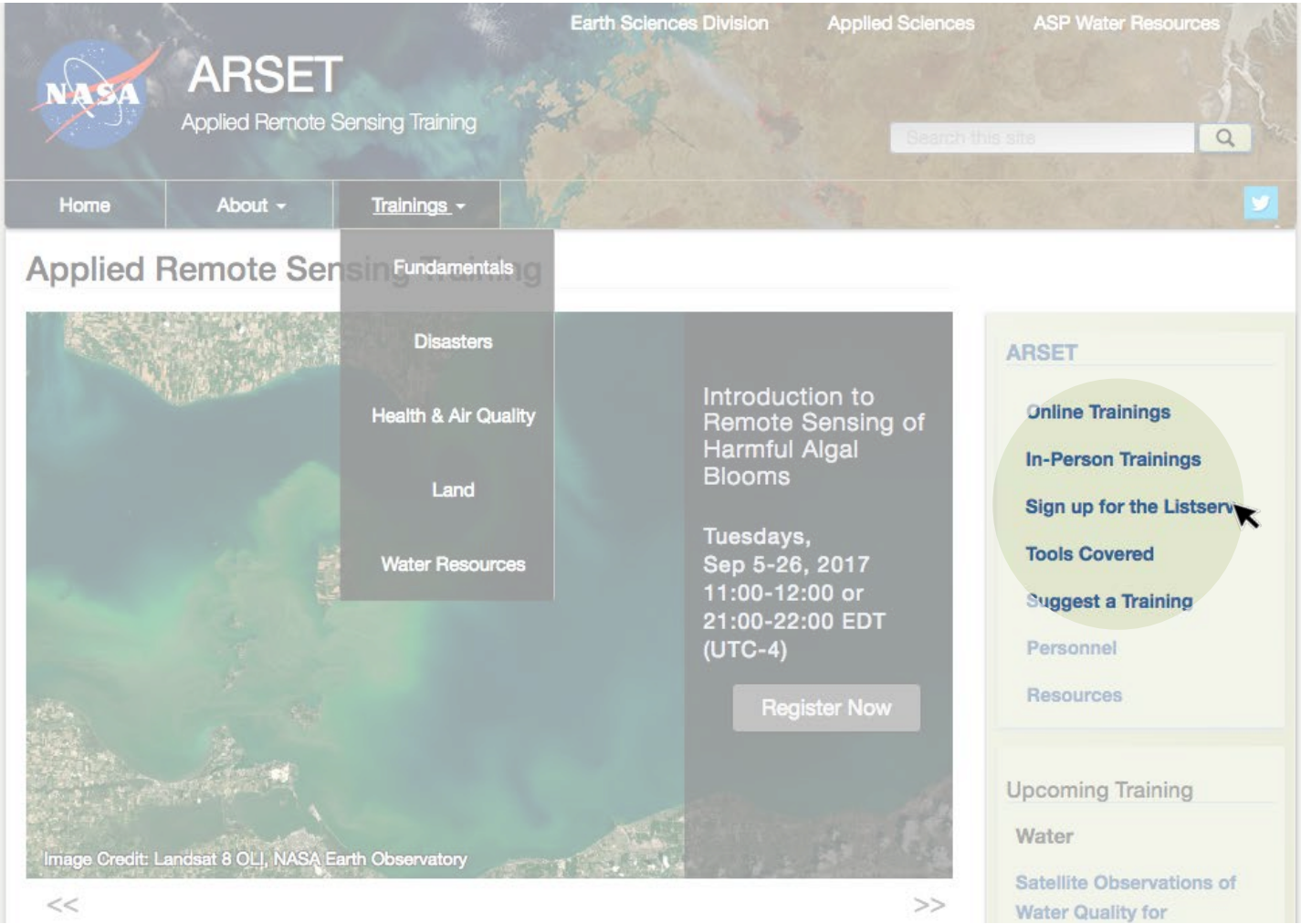
100 trainings | 13,000+ participants | 160+ countries | 3,700+ organizations



* size of bubble corresponds to number of attendees

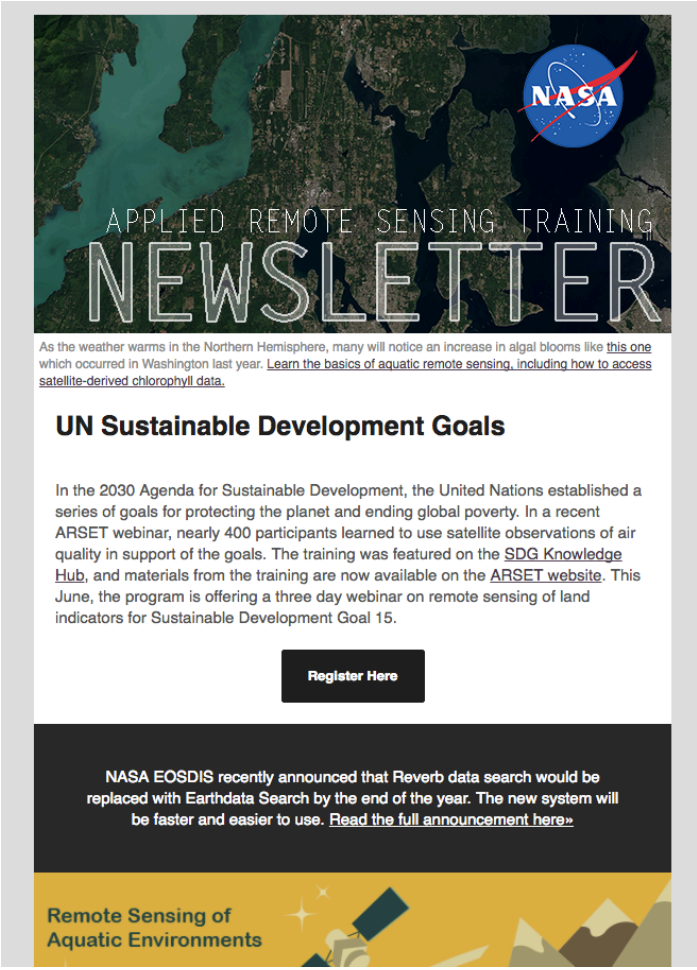
Learn More About ARSET

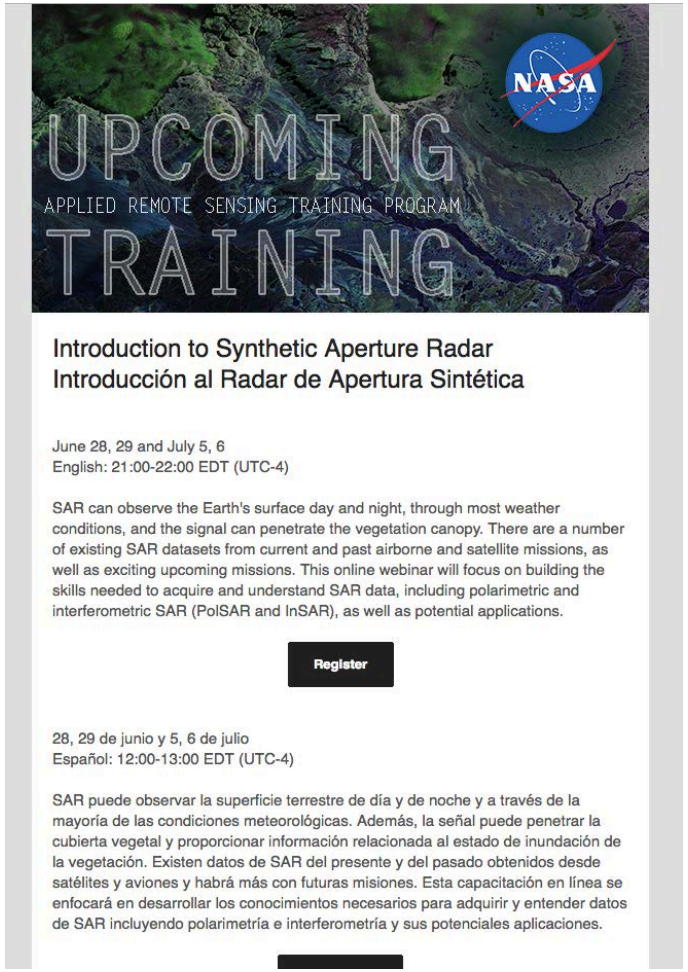
http://arset.gsfc.nasa.gov/

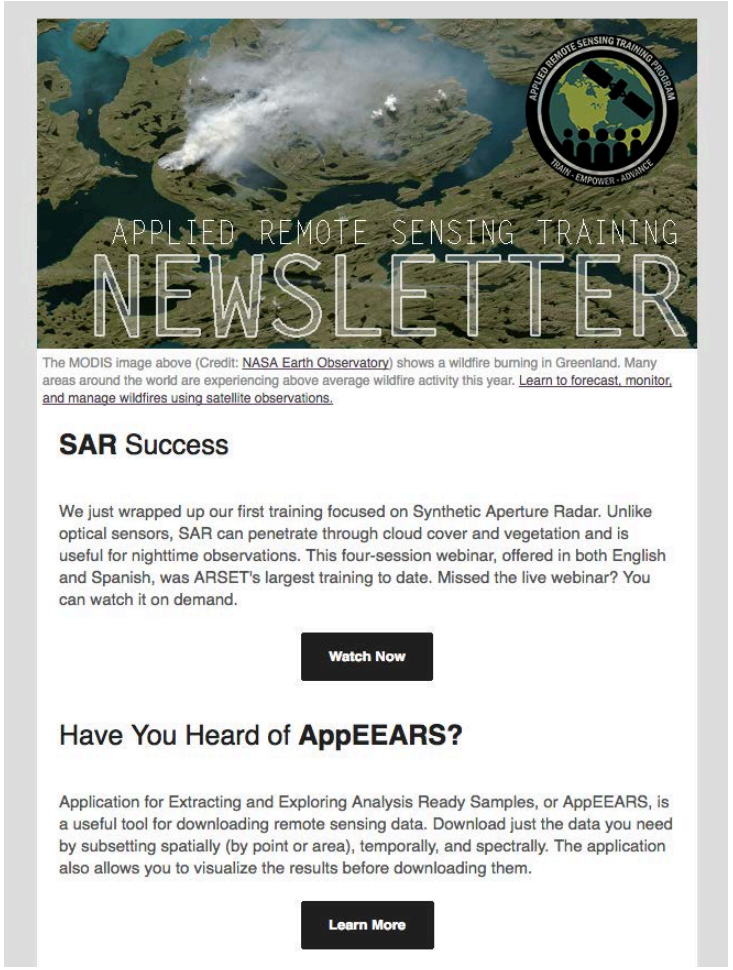


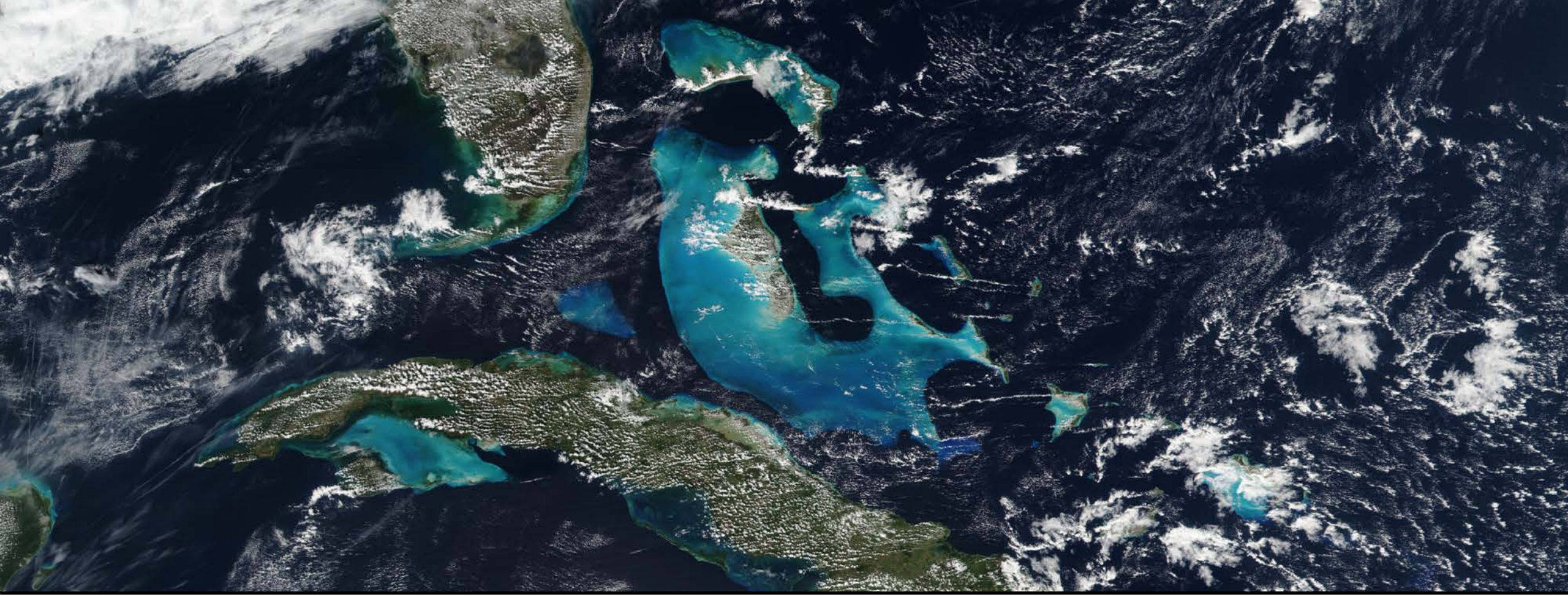
Sign up for the ARSET Listserv

https://lists.nasa.gov/mailman/listinfo/arset









Information about the SDGs and SDG 6

UN Sustainable Development Goals

Transforming Our World: The 2030 Agenda for Sustainable Development

- A plan of action for people, planet and prosperity
- All countries and all stakeholders, acting in collaborative partnership, will implement this plan
- 17 SDGs and 169 targets
- Balance the three dimensions of sustainable development:
  - economic
  - social
  - environmental

Reference: Transforming our world: the 2030 Agenda for Sustainable Development

SDG 6: Clean Water & Sanitation Targets

Ensure Availability and Sustainable Management of Water and Sanitation for All

6.1: By 2030, achieve universal and equitable access to safe and affordable drinking water for all

6.2: By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations

6.3: By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally

6.4: By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity

6.5: By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate

6.6: By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes

6.a: By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies

6.b: Support and strengthen the participation of local communities in improving water and sanitation management

SDG 6: Clean Water & Sanitation Indicators

Ensure Availability and Sustainable Management of Water and Sanitation for All

6.1.1 Proportion of population using safely managed drinking water services

6.2.1 Proportion of population using safely managed sanitation services, including a hand-washing facility with soap and water

6.3.1 Proportion of wastewater safely treated

6.3.2 Proportion of bodies of water with good ambient water quality

6.4.1 Change in water-use efficiency over time

6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources

6.5.1 Degree of integrated water resources management implementation (0-100)

6.5.2 Proportion of transboundary basin area with an operational arrangement for water cooperation

6.6.1 Change in the extent of water-related ecosystems over time

6.a.1 Amount of water- and sanitation-related official development assistance that is part of a government-coordinated spending plan

6.b.1 Proportion of local administrative units with established and operational policies and procedures for participation of local communities in water and sanitation management

SDG 6

- Target 6.6 By 2020 protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes
- **Indicator 6.6.1 Change in the extent of water-related ecosystems over time**

- "Due to the multi-faceted nature of Indicator 6.6.1, a progressive methodology is proposed which promotes country-derived data collection to be complimented by other globally available datasets such as earth observations. Used in conjunction with national knowledge and data, global earth observations which are validated by countries can enhance an understanding of how and why water related-ecosystems are changing"

MONITORING METHODOLOGY FOR SDG INDICATOR 6.6.1

SDG 6.6.1: Change in the extent of water-related ecosystems over time

Sub-Indicators based on globally available data from earth observations which will be validated by countries against their own methodologies and datasets:

- Sub-Indicator 1 – spatial extent of water-related ecosystems
- ***Sub-Indicator 2 – water quality of lakes and artificial water bodies***
- Monitoring parameters of water quality (**chlorophyll *a* and total suspended solids**) from earth observations
- Data for Sub-Indicator 2 generated annually and used to calculate percentage change every 5 years (reported in % and direction of change)

Other ARSET Trainings Related to SDG 6

Remote sensing can be used to monitor and address a variety of issues related to water resource management, including drought, flooding, and reservoir management

Relevant Targets:

6.3, 6.4, 6.5, 6.6,

Level 0

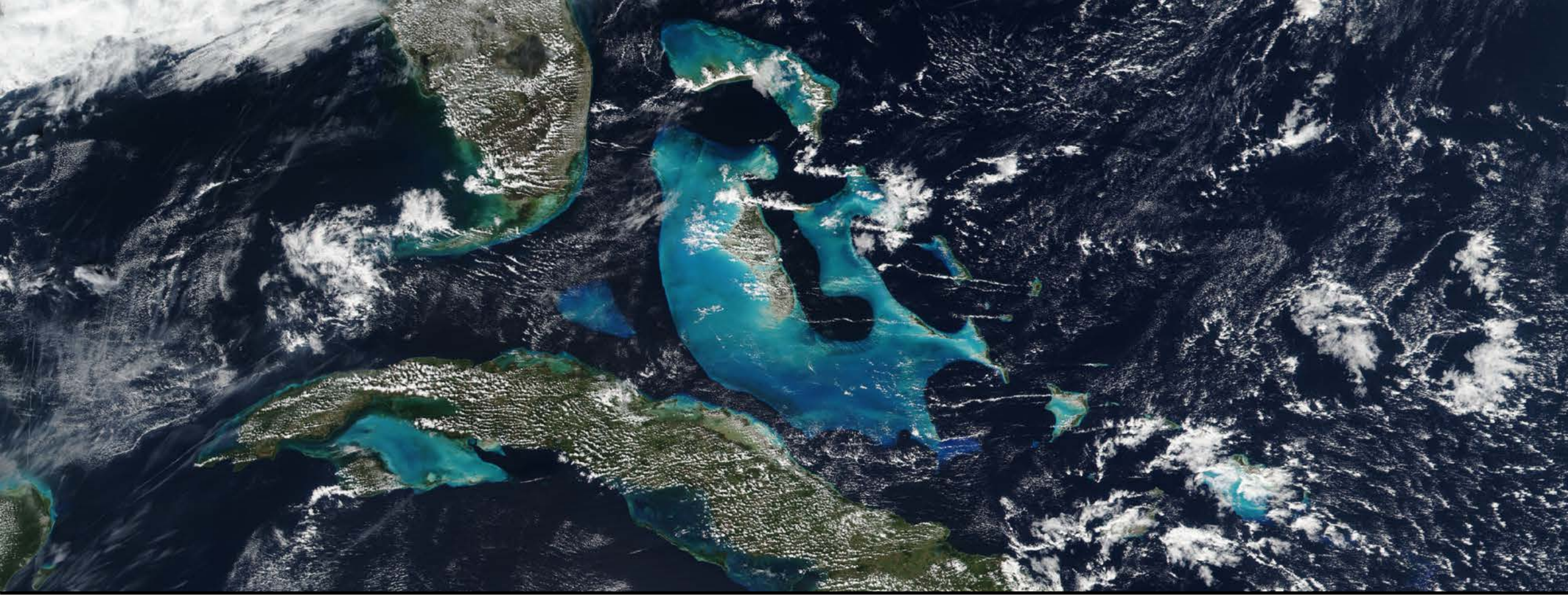
Fundamentals of Remote Sensing for Water Resource Management
http://arset.gsfc.nasa.gov/webinars/fundamentals-remote-sensing#water
1 Hour

Level 1

Water Resource Management Using NASA Earth Science Data
http://arset.gsfc.nasa.gov/water/webinars/water-resources15
5 Hours

Level 1

Applications of Remote Sensing to Soil Moisture & Evapotranspiration
http://arset.gsfc.nasa.gov/water/webinars/apps-et-smap
5 Hours

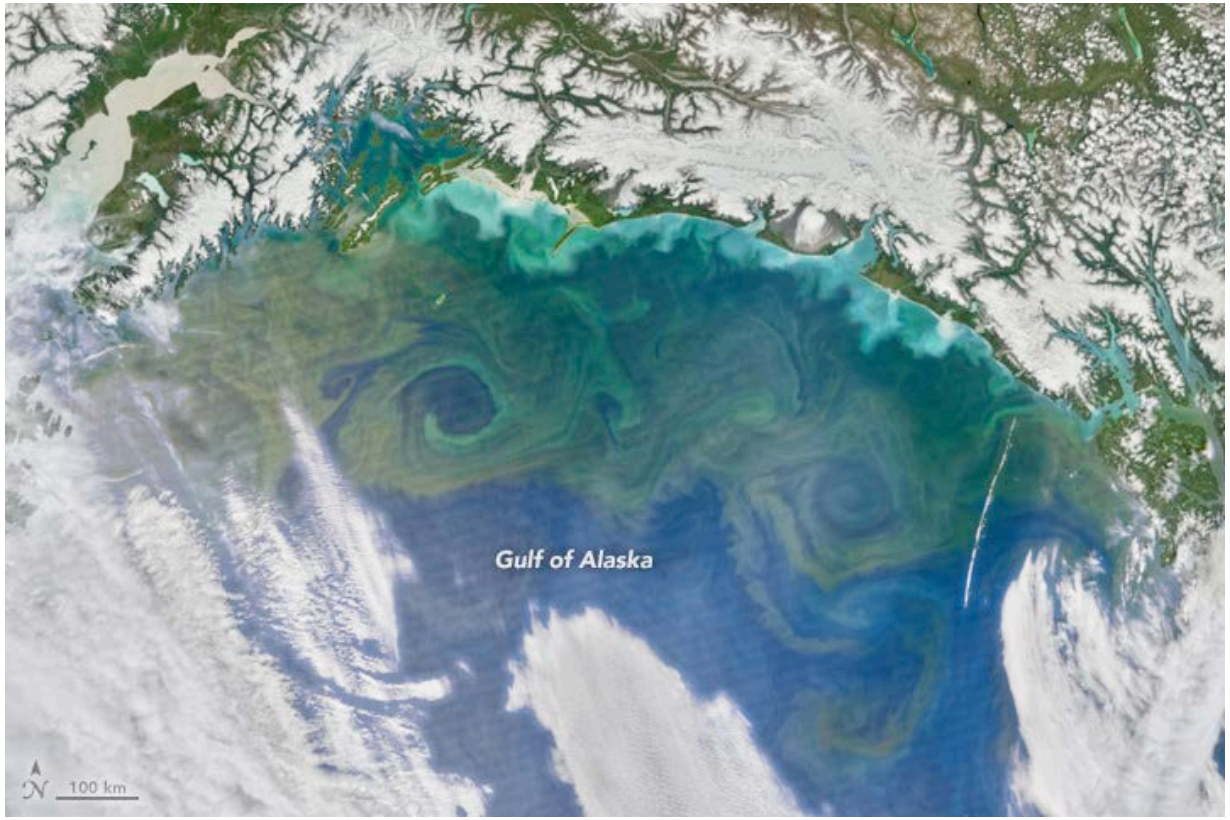


Satellite Data Products for Water Quality Monitoring

Water Quality Indicators Observable from Satellites

- Turbidity / Sediments
- Colored Dissolved Organic Matter (CDOM)
- Sea Surface Temperature (SST)
- Chlorophyll-a (phytoplankton)
- Salinity
- TSS (Total Suspended Solids)

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

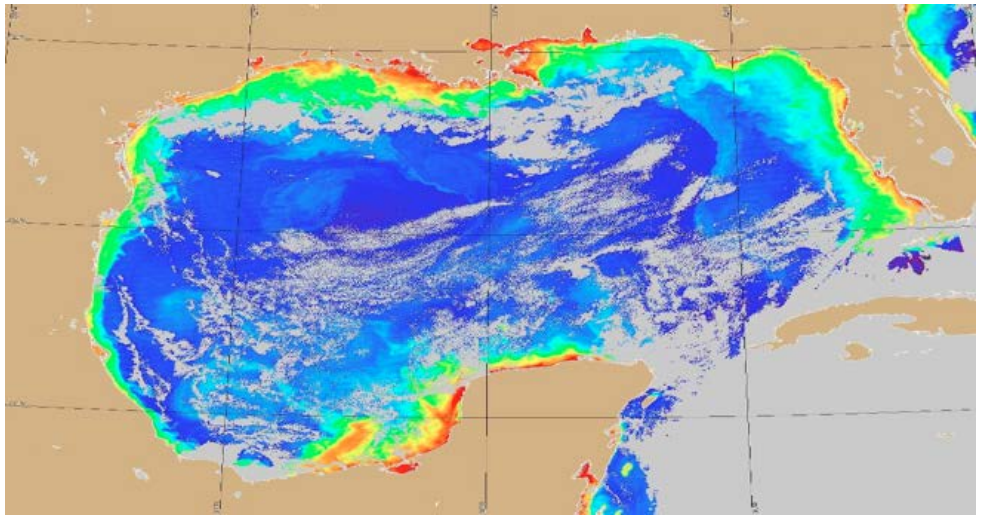


Which Factors Cause Changes in Water Quality?

- 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
- Other, yet unknown, factors

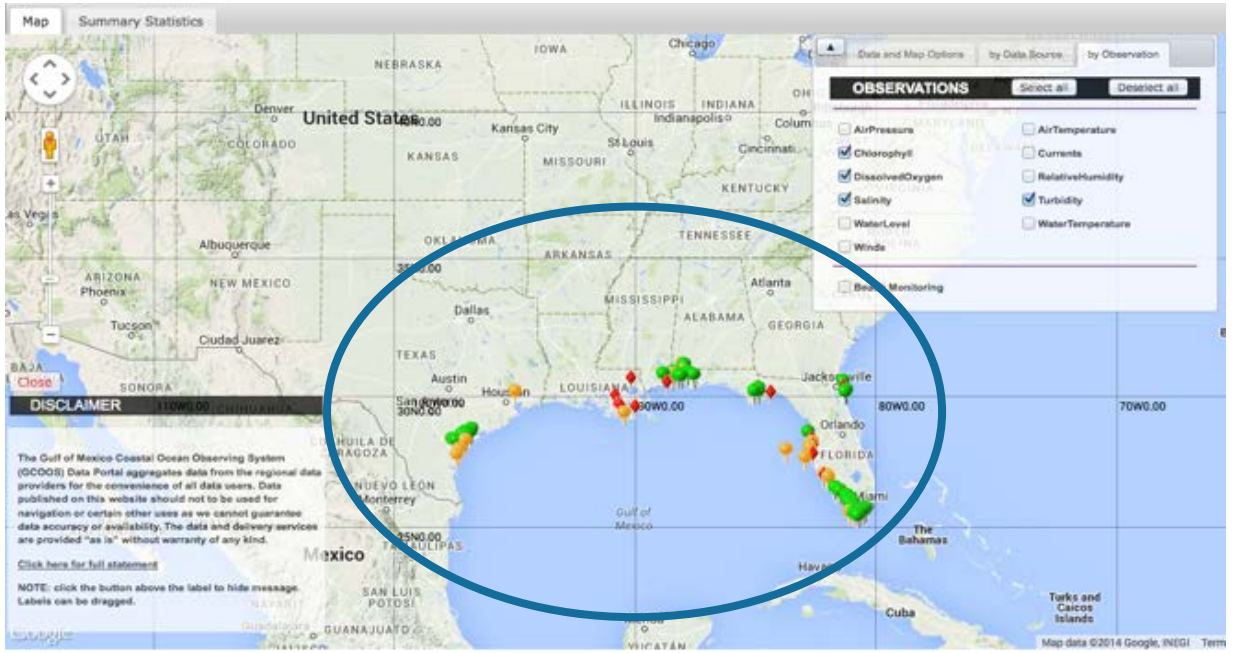
Advantage of Satellite Observations for Water Quality Monitoring

- Provides information where there are no surface-based measurements available
- Global and near-global coverage with consistent observations
- Continuous coverage in comparison to point measurements



Limited Water Sampling Locations

http://data.gcoos.org/



Left: MODIS Aqua satellite image from October 23, 2011, showing areas of elevated chlorophyll a (in red and orange)

Water Quality Affects Water Optical Properties

Remote Sensing can be used to Monitor Water Color, Indicative of Water Quality

- Dissolved and suspended matter in water change optical property and therefore its color

  -Dissolved matter include: tannin, caused by organic matter coming from leaves, roots, and plant remains

  -Suspended matter include: particles of clay, undissolved minerals, planktons and algal bloom

- Some Harmful Algal Bloom (HAB) species have unique properties that affect water color - (e.g., red tides)

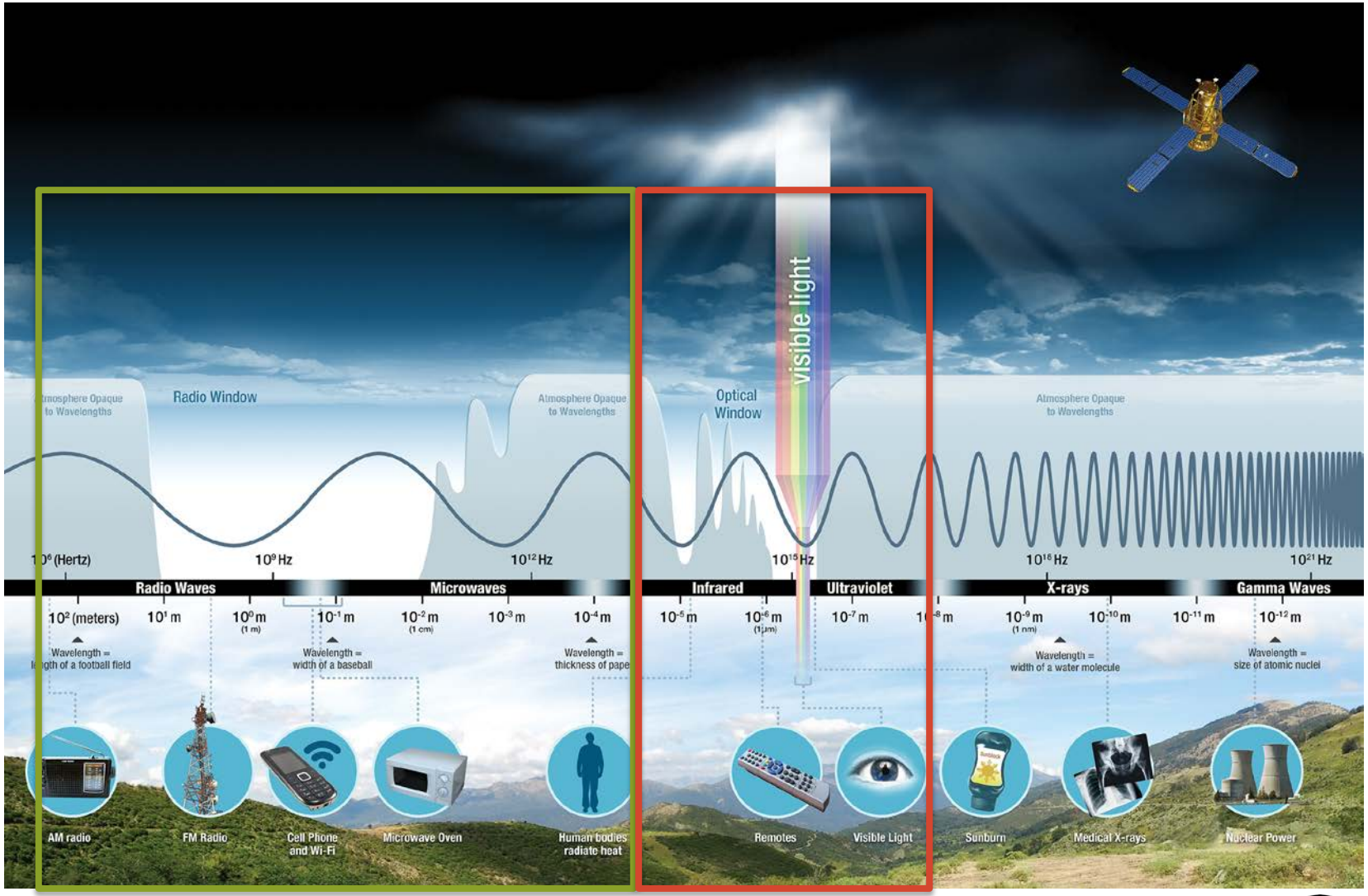
Color caused by dissolved matter: tannins

Color caused by suspended material: sediment

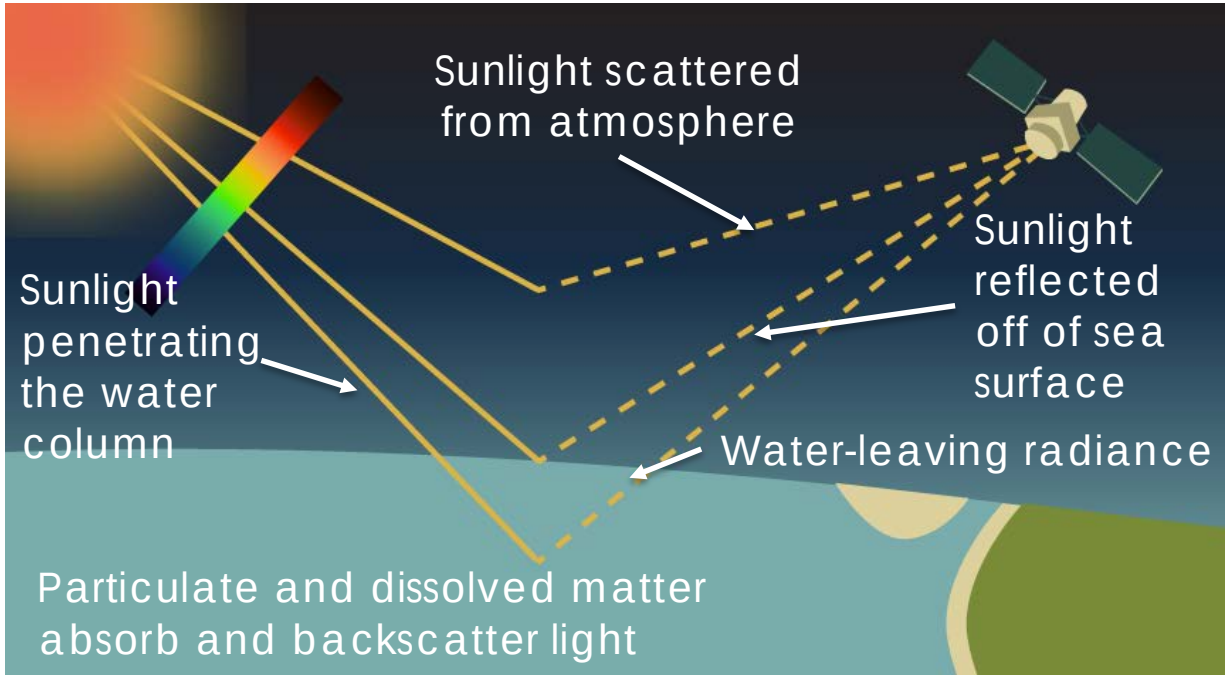
https://water.usgs.gov/edu/color.html

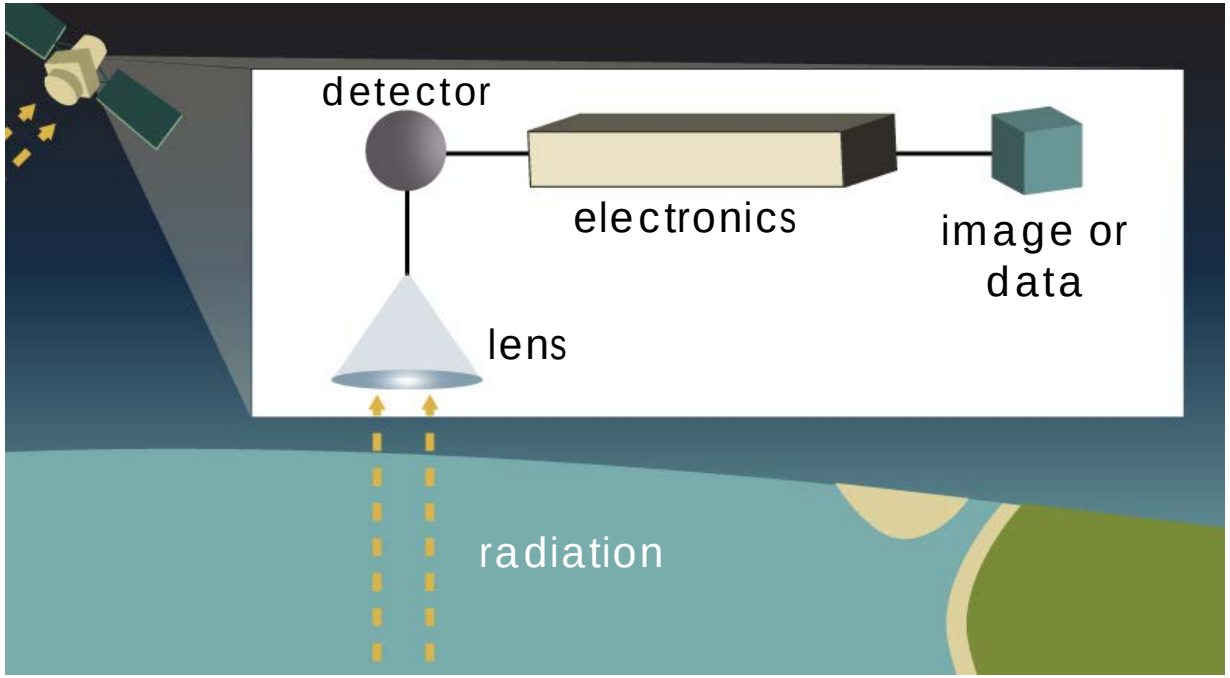
Remote Sensing of Water Quality

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



Remote Sensing of Water Quality





Reflected solar radiation measured by satellite sensors is used to derive optically-active water constituents:

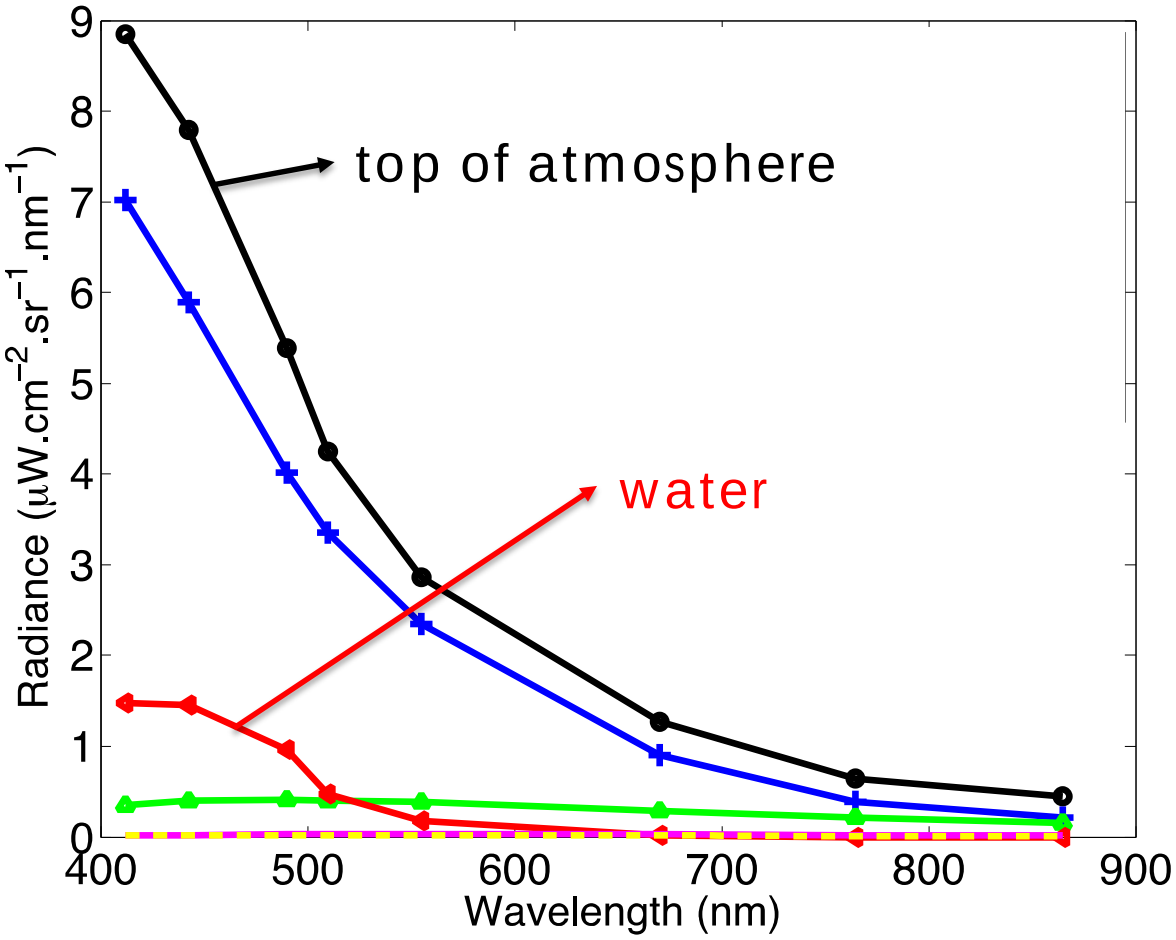
- Turbidity and Suspended Sediments
- Colored Dissolved Organic Matter (CDOM)
- Chlorophyll-a (phytoplankton)

Emitted thermal infrared and microwave radiation measured by satellite sensors is used to derive:

- Surface Temperature
- Salinity

Remote Sensing of Water Quality

- Satellite observations of reflectance has to be corrected for atmospheric effects to derive water quality

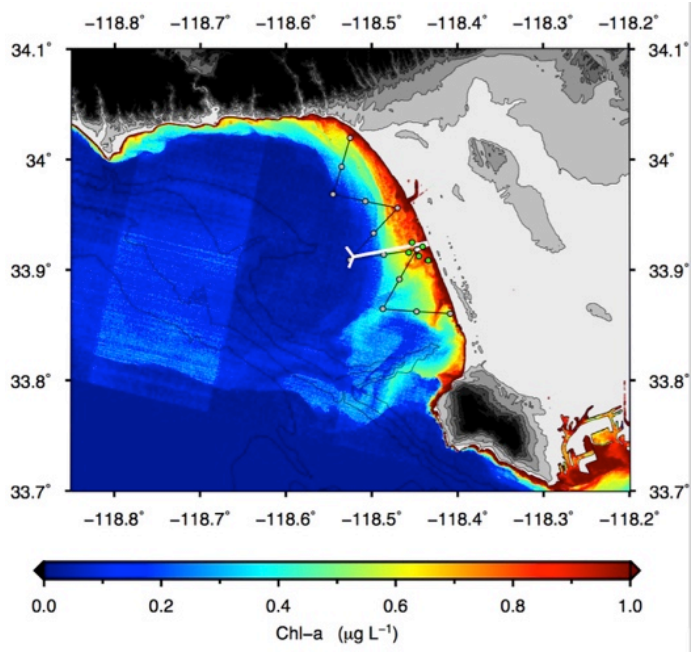


Remote Sensing of Water Bodies

Techniques

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

Use of various types of algorithms combining atmospherically corrected satellite images and in situ measurements to derive **quantitative information** about water quality



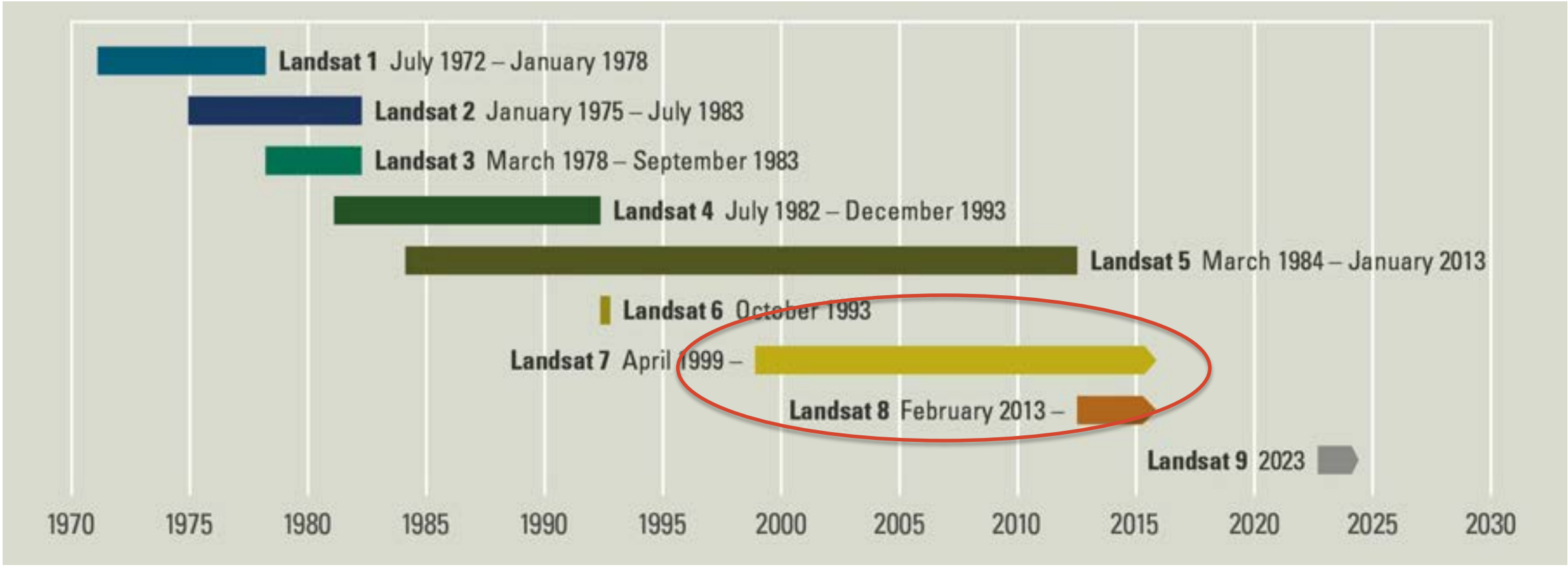
In Situ Observations Required

Satellites for Water Quality Monitoring

- Current Satellite Missions:
  - Landsat 7 & Landsat 8
  - Terra
  - Aqua
  - Suomi National Polar Partnership (SNPP)
  - Sentinel-2 and Sentinel-3

Landsat Satellites and Sensors

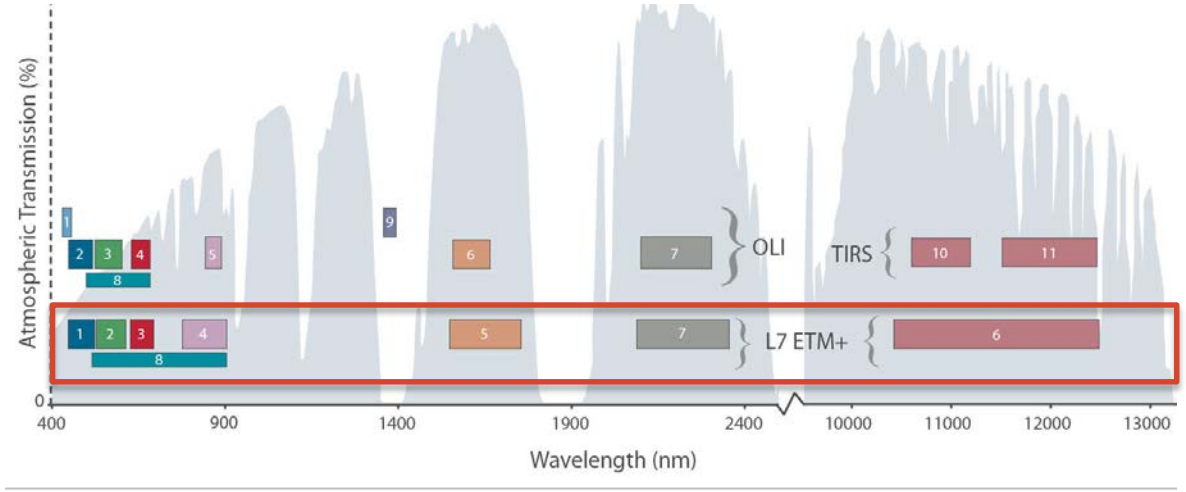
http://landsat.gsfc.nasa.gov/



Enhanced Thematic Mapper (ETM+)

http://landsat.gsfc.nasa.gov/landsat-7/

- Onboard **Landsat 7**
- Polar orbiting satellite
- Spatial Coverage and Resolution:
  - Global, Swath: 185 km
  - Spatial Resolution:
    - 15 m, 30 m, 60 m
- Temporal Coverage and Resolution:
  - April 15, 1999 – present
  - 16-day revisit time



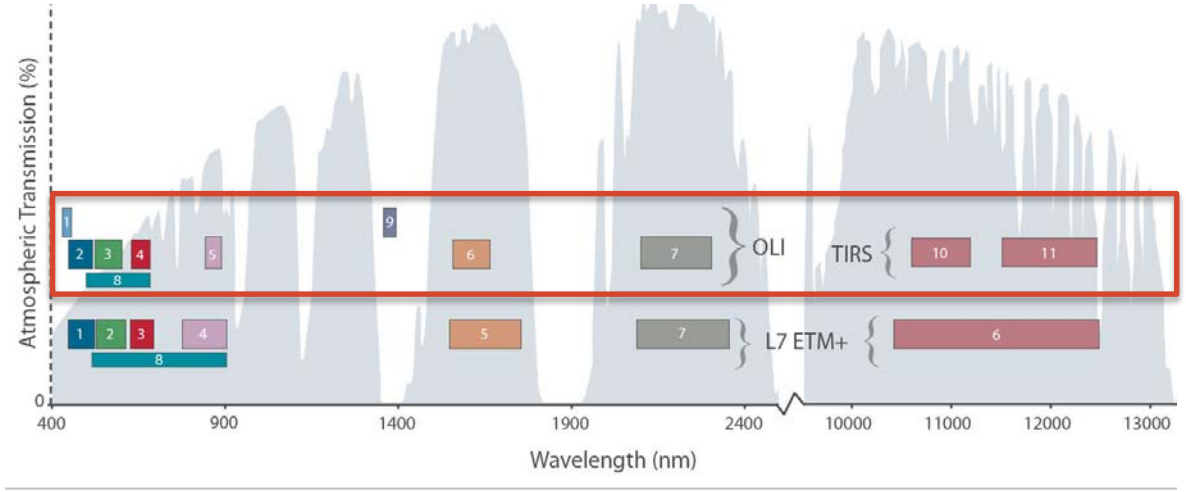
Spectral Bands: 8

- Major Bands: blue-green, green, red, thermal IR, panchromatic
  - Bands 1-5, 7: 30 m
  - Band 6: 60 m
  - Band 8: 15 m

Operational Land Imager (OLI)

http://landsat.gsfc.nasa.gov/landsat-8/

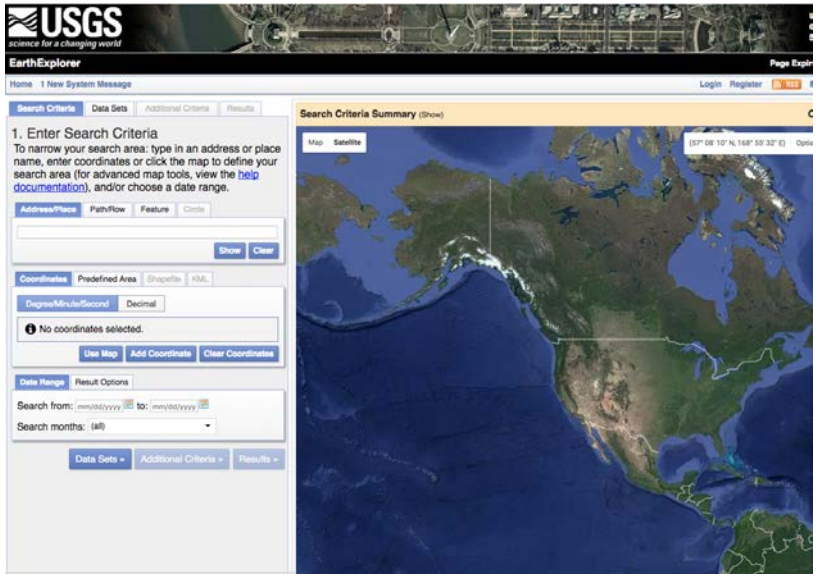
- Onboard **Landsat 8**
- Polar orbiting satellite
- Spatial Coverage and Resolution
  - Global, Swath: 185 km
  - Spatial Resolution: 15 m, 30 m
- Temporal Coverage and Resolution:
  - Feb 11, 2013 – present
  - 16-day revisit time

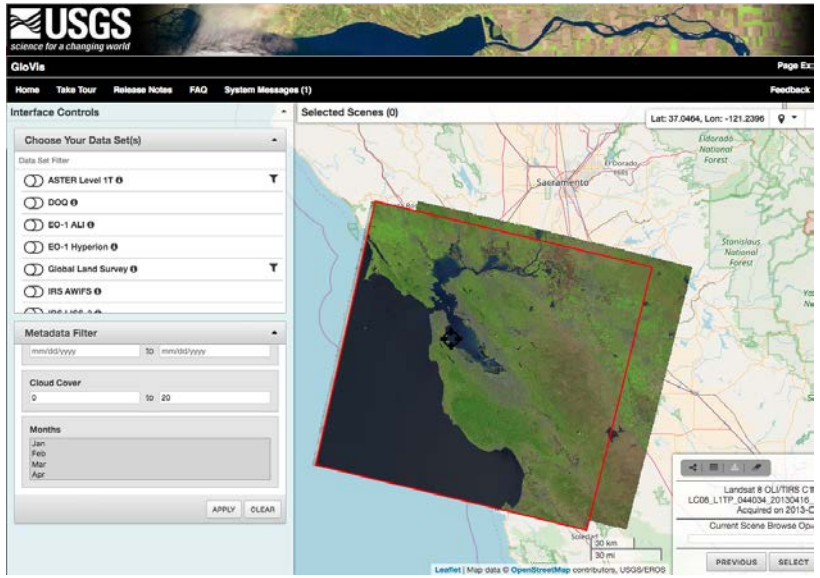


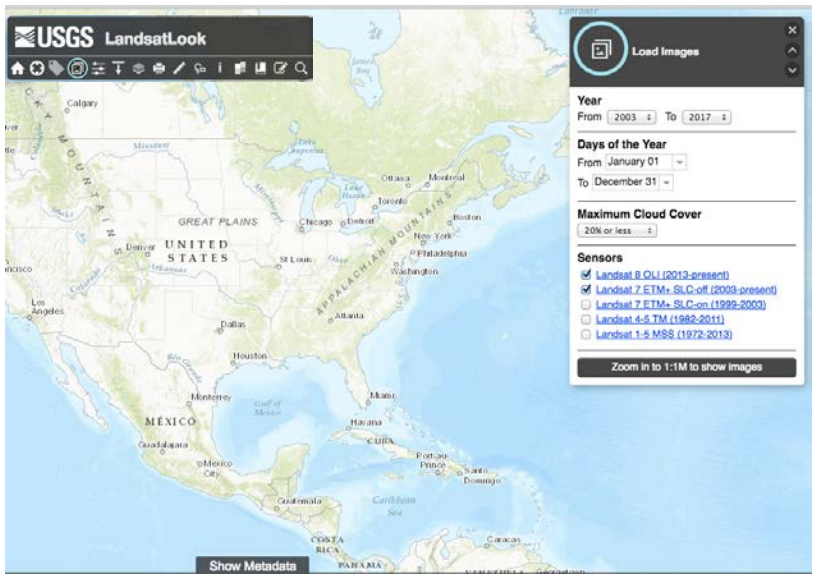
Spectral Bands: 9

- Major Bands: blue, blue-green, red, near IR, shortwave, panchromatic
  - Bands 1-7, 9: 30 m
  - Band 8: 15 m

Get Landsat Images and Band Reflectance Data







Earth Explorer:

http://earthexplorer.usgs.gov/

GloVis

http://glovis.usgs.gov/

LandLook Viewer:

https://landlook.usgs.gov

Terra and Aqua Satellites and Sensors

Terra

http://terra.nasa.gov

- Polar orbit, 10:30 a.m. equator crossing time
- Global Coverage
- December 18, 1999 – Present
- 1-2 observations per day
- Sensors:
  - ASTER, CERES, MISR, MODIS, MOPITT

Aqua

http://aqua.nasa.gov/

- Polar orbit, 1:30 p.m. equator crossing time
- Global Coverage
- May 4, 2002 – Present
- 1-2 observations per day
- Sensors:
  - AIRS, AMSU, CERES, MODIS, AMSR-E

MODerate Resolution Imaging Spectroradiometer (MODIS)

http://modis.gsfc.nasa.gov/

- Onboard **Terra** and **Aqua**
- Designed for land, atmosphere, ocean, and cryosphere observations
- Spatial Coverage and Resolution:
  - Global, swath: 2,330 km
  - Spatial resolution varies: 250 m, 500 m, 1 km
- Temporal Coverage and Resolution:
  - 2000 – present, 1–2 times per day

Spectral Bands: 36

- Reflection and Emission Bands (Major Bands: red, blue, IR, NIR, MIR)
- Bands 1-2: 250 m; Bands 3-7: 500 m; Bands 8-36: 1,000 m

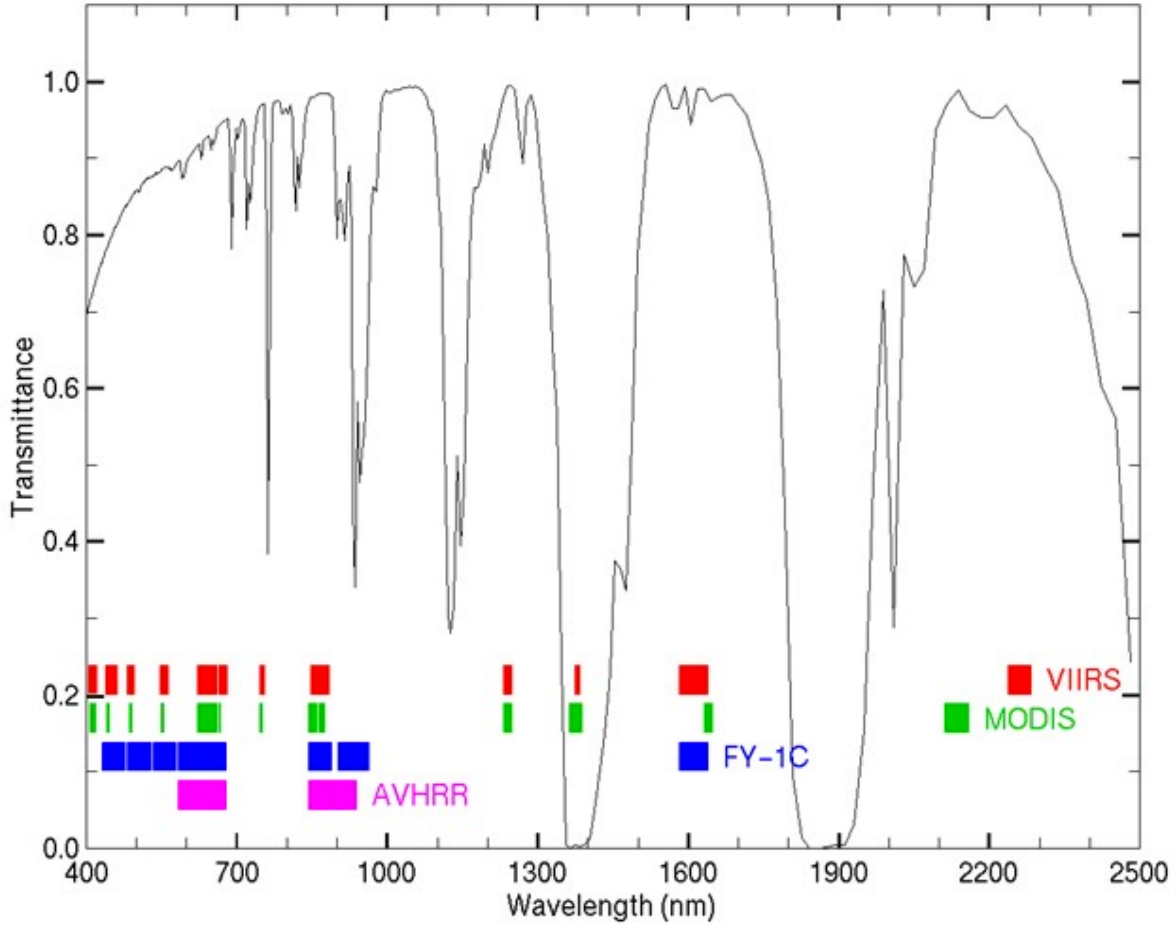
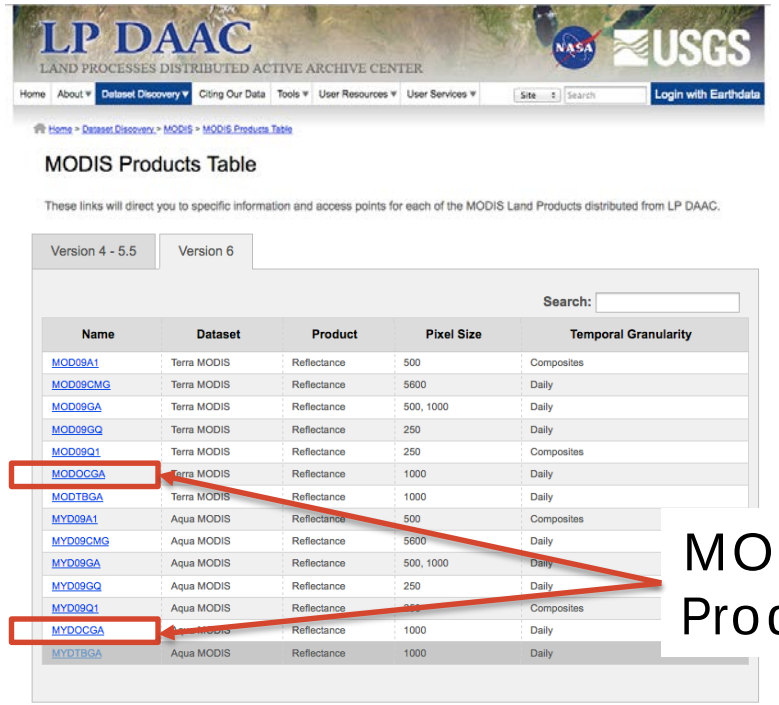


Image Credit: Li, J. (2001 Dec 18) *Atmospheric Temperature, Moisture, Ozone, and Motion-Infrared (MOD-07)*. CIMSS

Get MODIS Band Reflectance Data

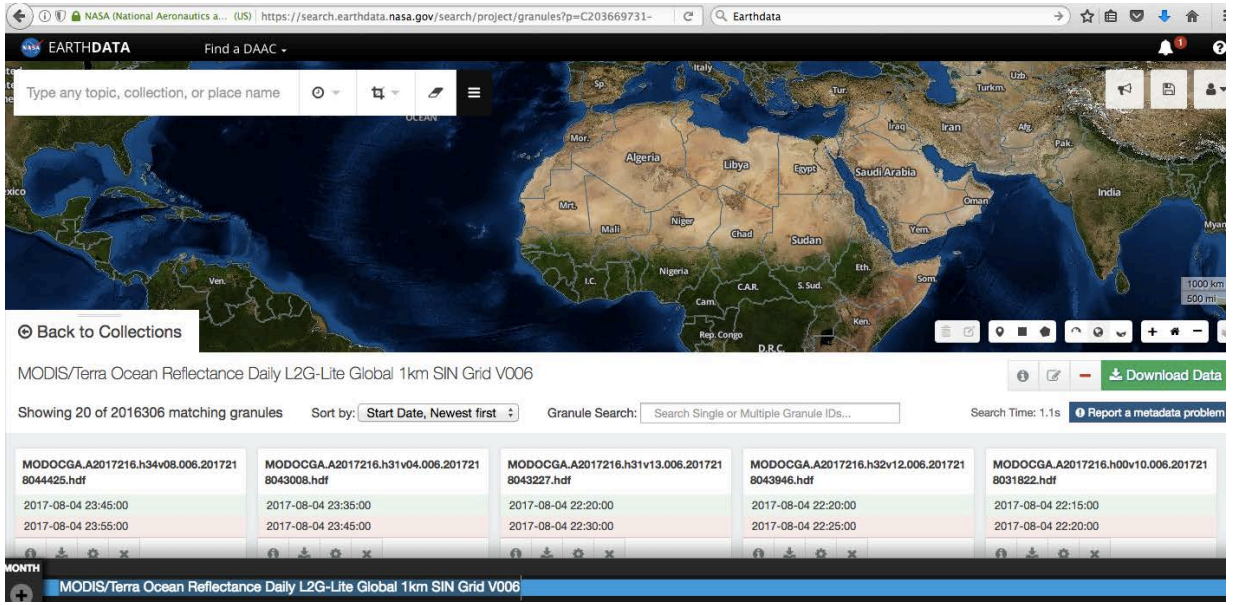
Land Processing Distributed Active Archive Center

http://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/



NASA Earthdata

http://earthdata.nasa.gov/

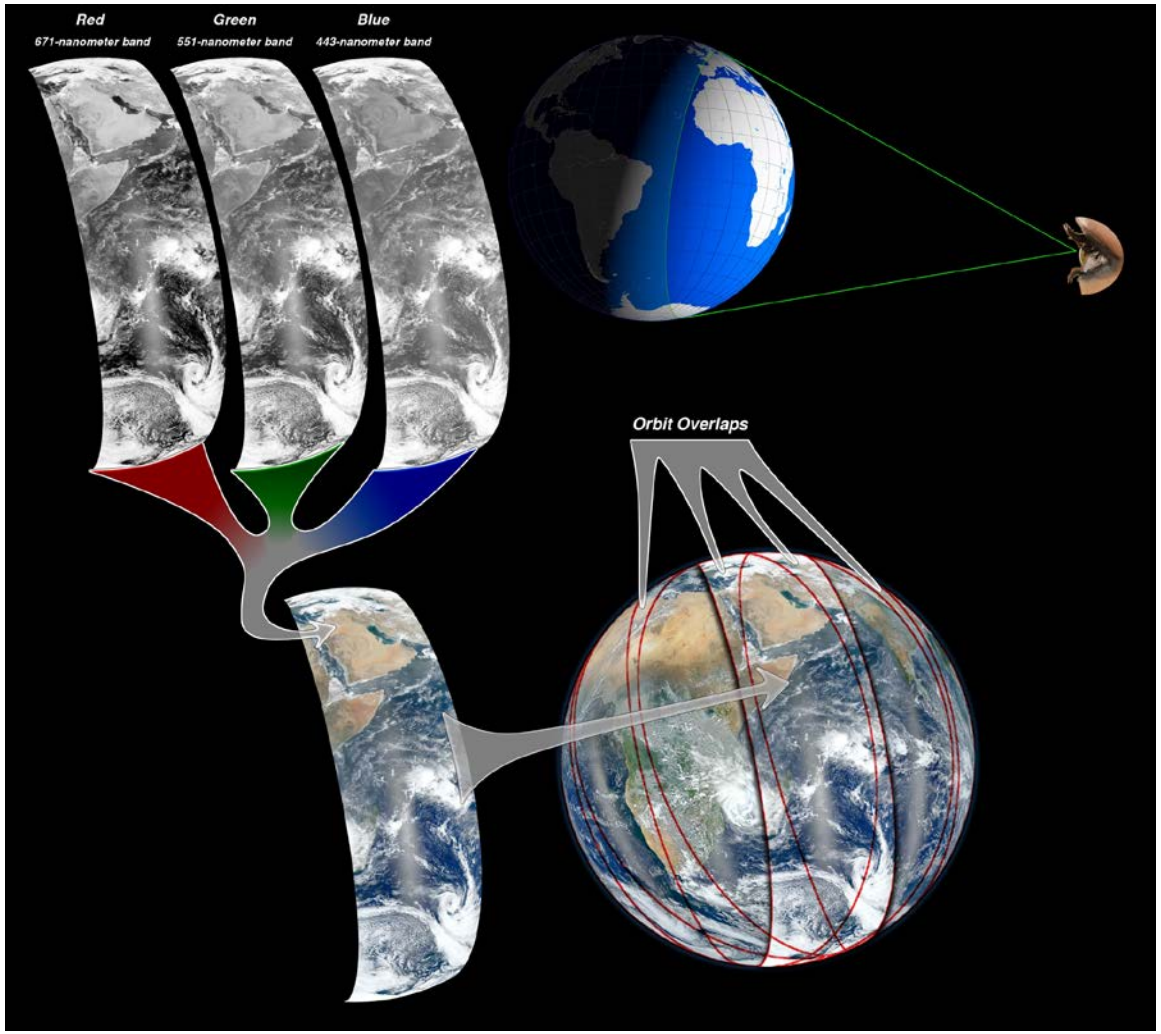


MODIS Band Reflectance for Oceans, Bands 8-16
Product Name: MODOCGA (Terra), MYDOCGA (Aqua)

Suomi National Polar Partnership (SNPP)

http://nasa.gov/mission_pages/NPP/

- Polar orbit, 1:30 p.m. equator crossing time
- Global coverage
- November 21, 2011 – present
- Sensors:
  - VIIRS, ATMS, CrIS, OMPS, CERCES



Visible Infrared Imaging Radiometer Suite (VIIRS)

http://jointmission.gsfc.nasa.gov/viirs.html

- Onboard **Suomi NPP**
- Polar orbiting satellite
- Functionality similar to MODIS
- Spatial Coverage and Resolution:
  - Global, Swath Width: 3,040 km
  - Spatial Resolution: 375 – 750 m
- Temporal Coverage and Resolution:
  - Oct 2011 – present
  - 1-2 times per day

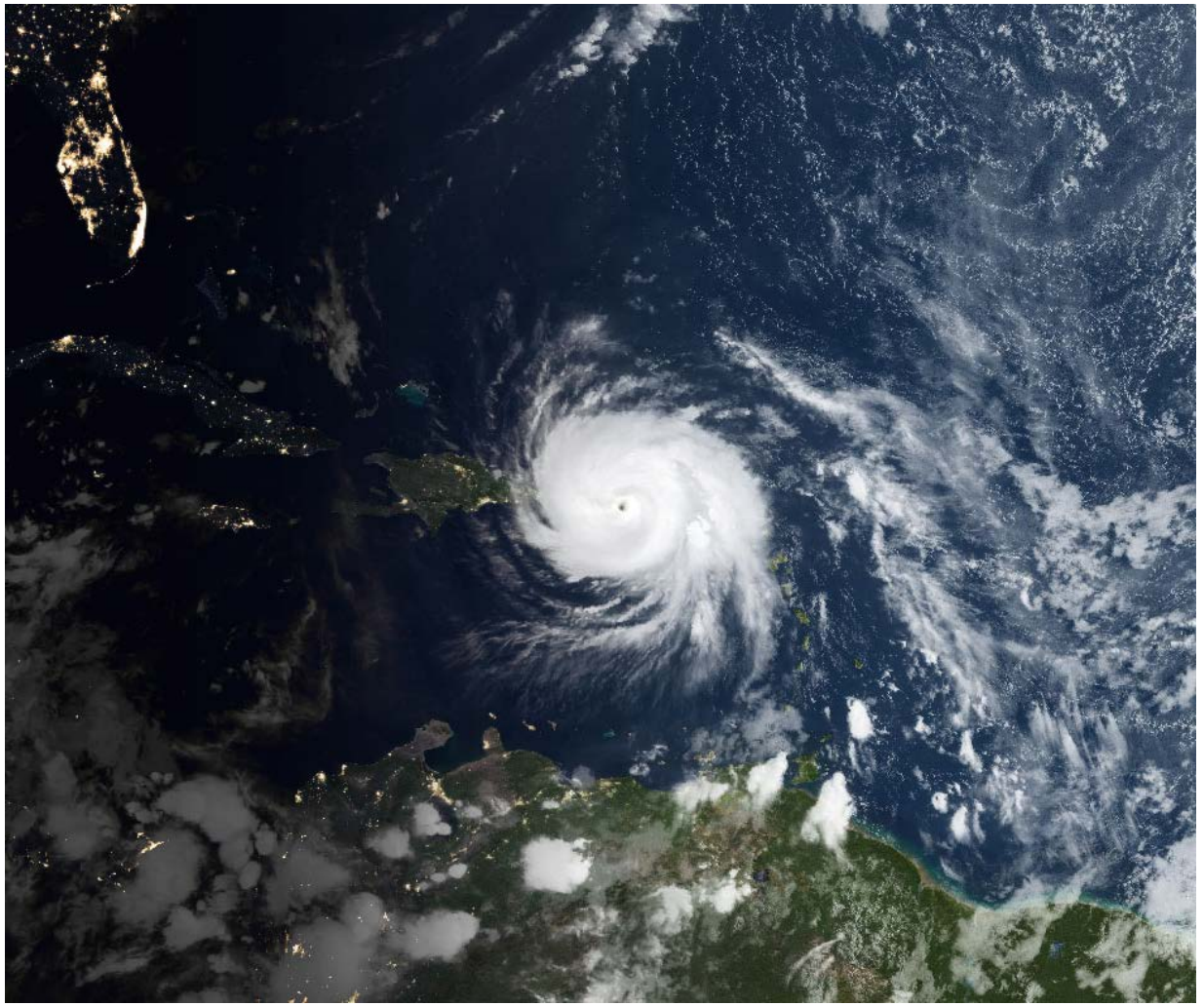
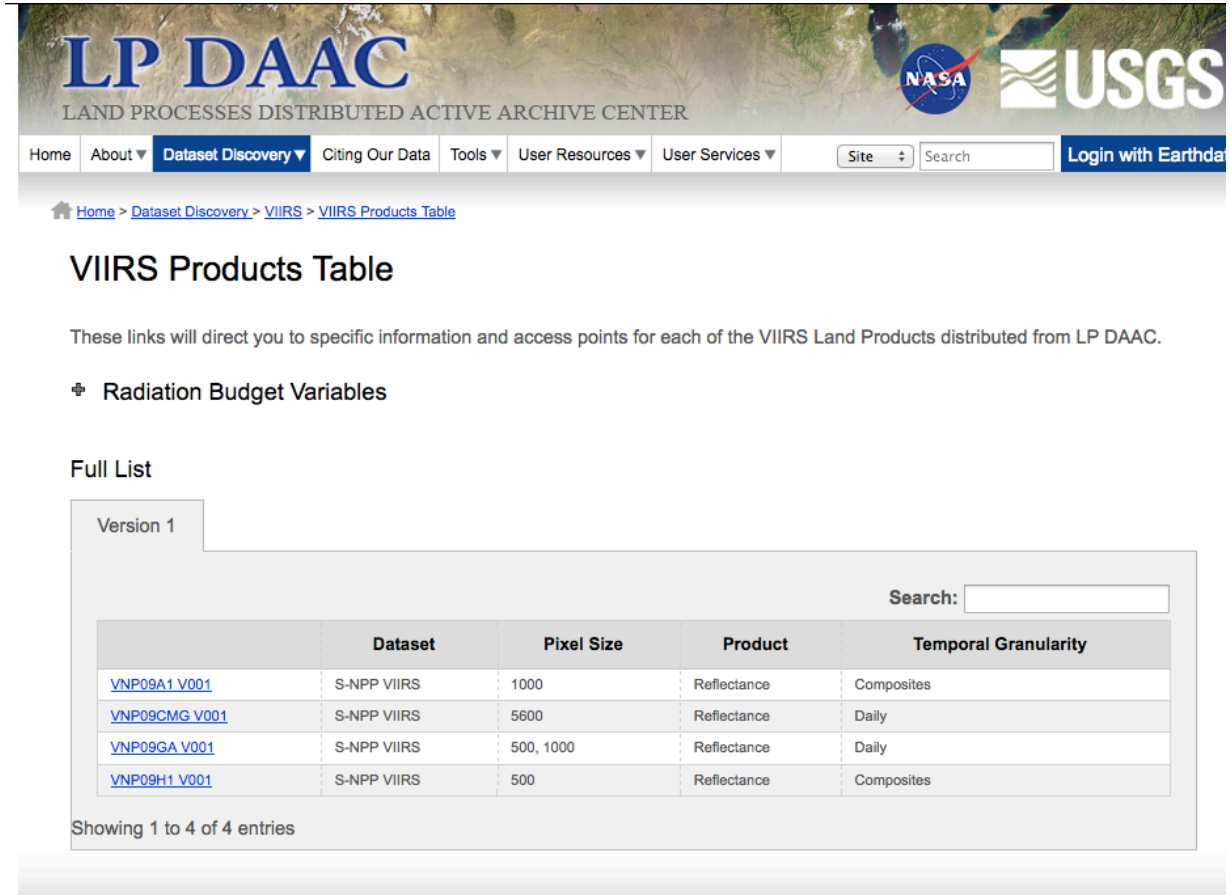


Image: Hurricane Maria as it makes landfall over Yabucoa. EarthObservatory

Get VIIRS Band Reflectance Data

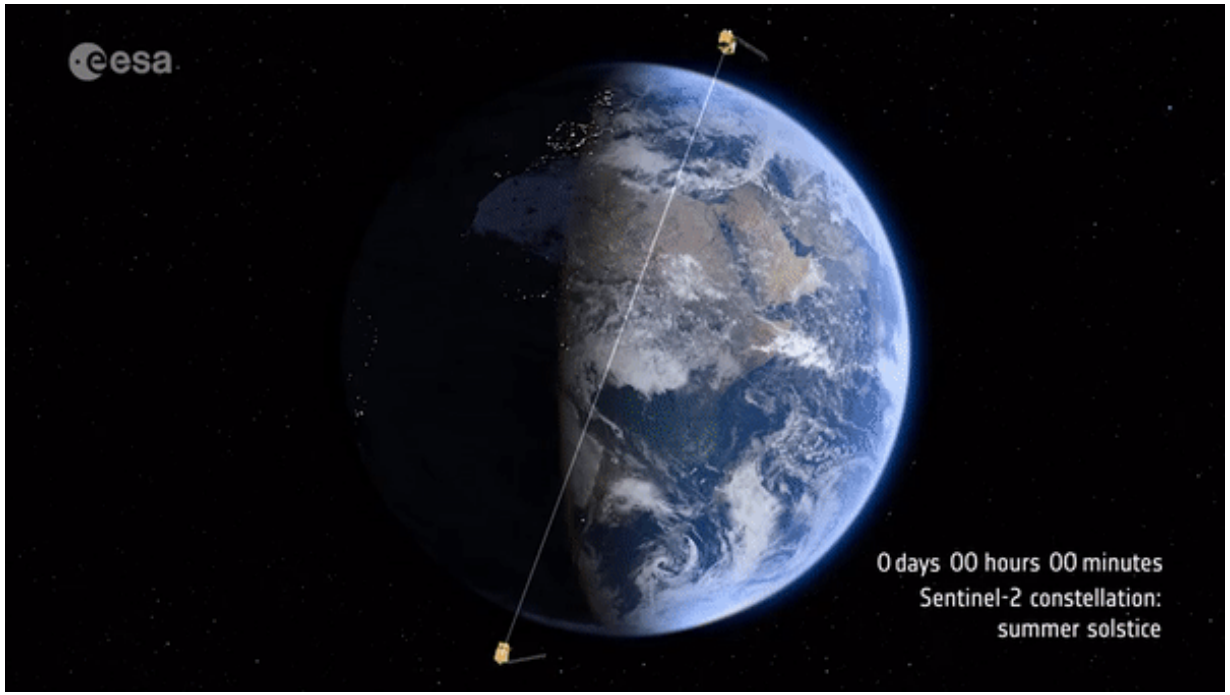


- Land Process Distributed Active Archive Center
- https://lpdaac.usgs.gov/dataset_discovery/viirs/viirs_products_table
- Product Name: VNP09GA_V001

Sentinel-2A and Sentinel-2B

http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-2/

- Launched by **ESA**
- Two satellites, 180° apart, both in polar orbit
- Global coverage
- Temporal Coverage:
  - Sentinel-2A: June 23, 2015 – present
  - Sentinel-2B: March 7, 2017 – present
- 5 day revisit time
- Sensors
  - Multispectral Imager (MSI)

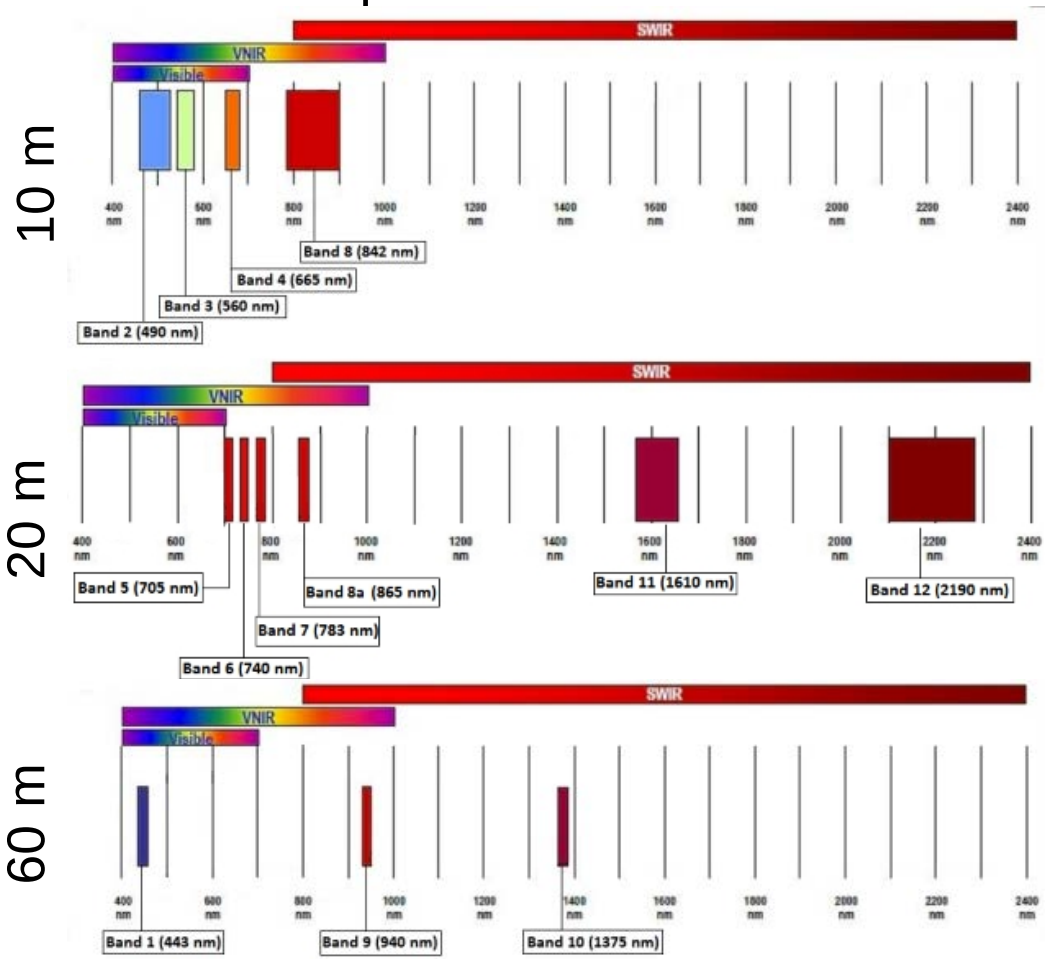


Multispectral Imager (MSI)

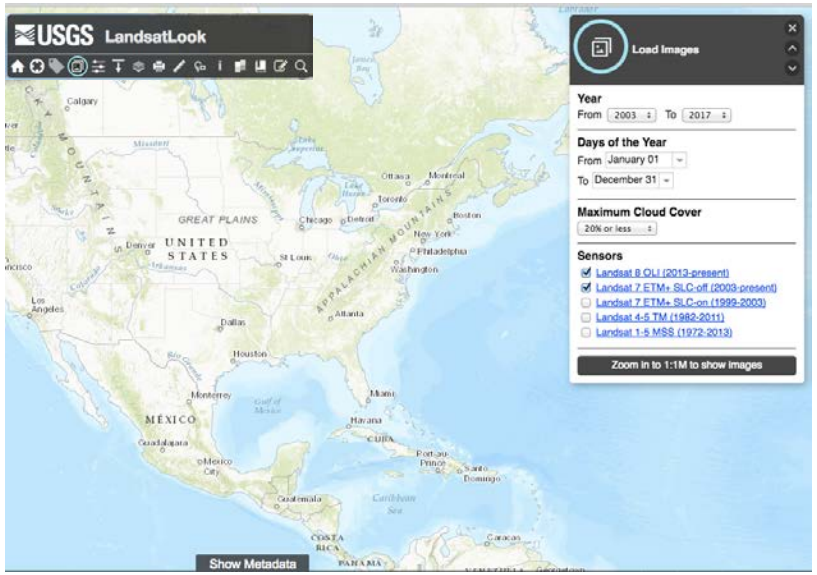
https://earth.esa.int/web/sentinel/user-guides/sentinel-2-msi

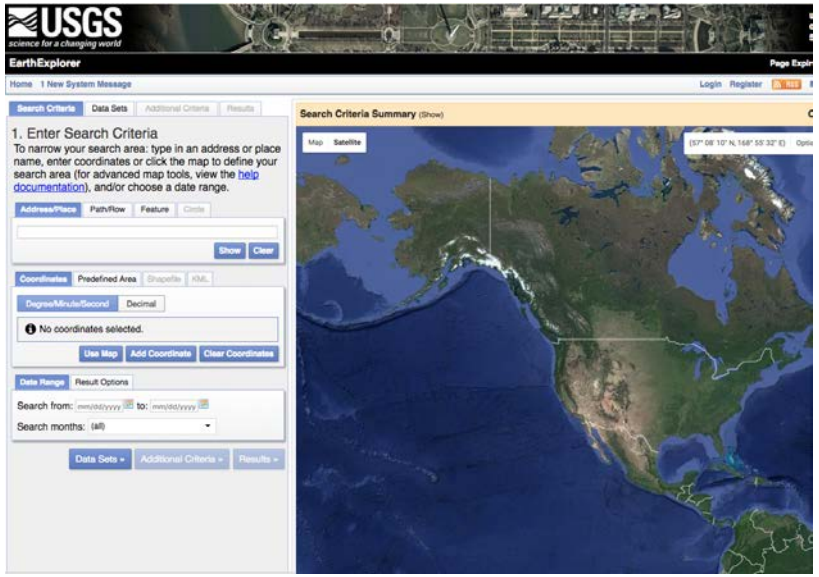
- Onboard **Sentinel-2**
- Land and ocean surface observations
- Spatial Coverage and Resolution:
  - Global, swath: 290 km
  - Spatial resolution varies: 10 m, 20 m, 60 m
- Temporal Coverage and Resolution:
  - June 2015 & March 2017 – present
  - 5 day revisit time
- **Spectral Bands: 13**
  - 4 visible and NIR: 10 m
  - 6 red-edge/shortwave infrared: 20 m
  - 3 atmospheric correction: 60 m

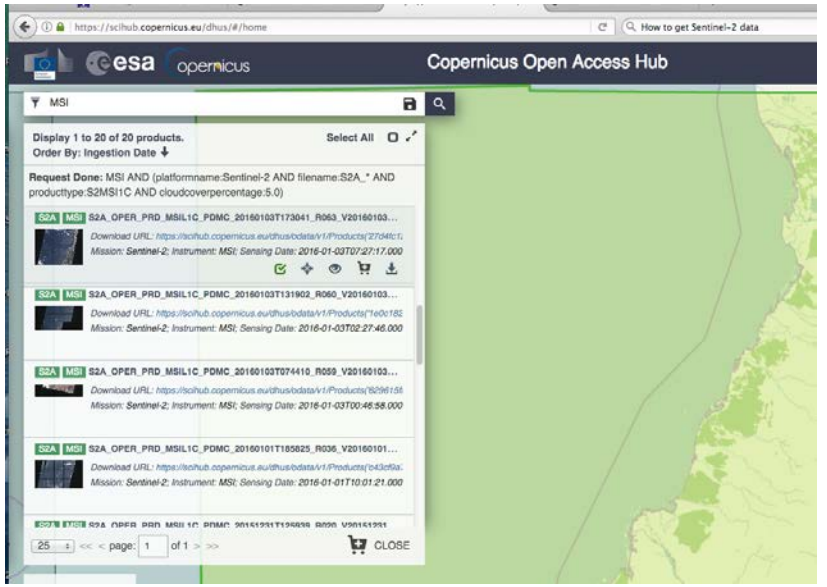
Spatial Resolution



Get MSI Data







LandLook Viewer:
https://landlook.usgs.gov/viewer.html

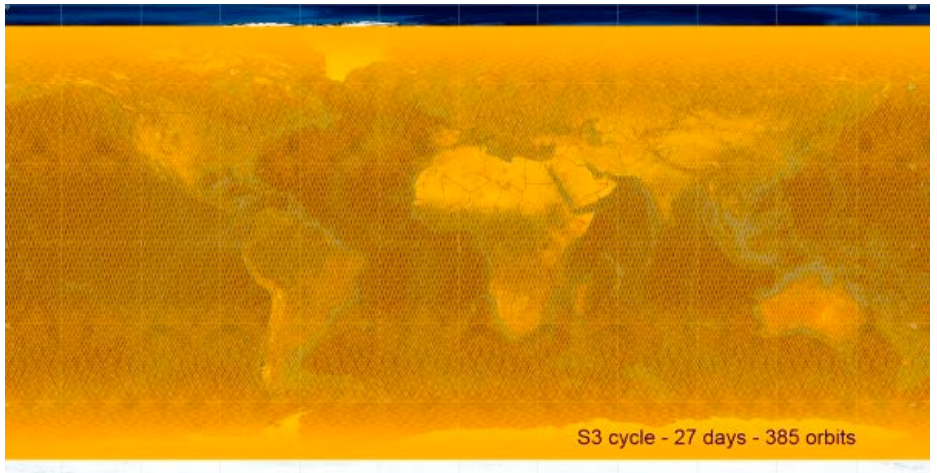
Earth Explorer:
http://earthexplorer.usgs.gov/

ESA Copernicus Open Hub:
http://sentinel.esa.int/web/sentinel/sentinel-data-access

Sentinel-3

www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-3/

- Launched by **ESA**
- Will consist of a two satellite system
  - Sentinel-3A: Feb 16, 2016 - present
  - Sentinel-3B: To be launched
- Global coverage
- 27 day revisit time
- Sensors:
  - **OCLI**, SLSTR, SRAL, MWR



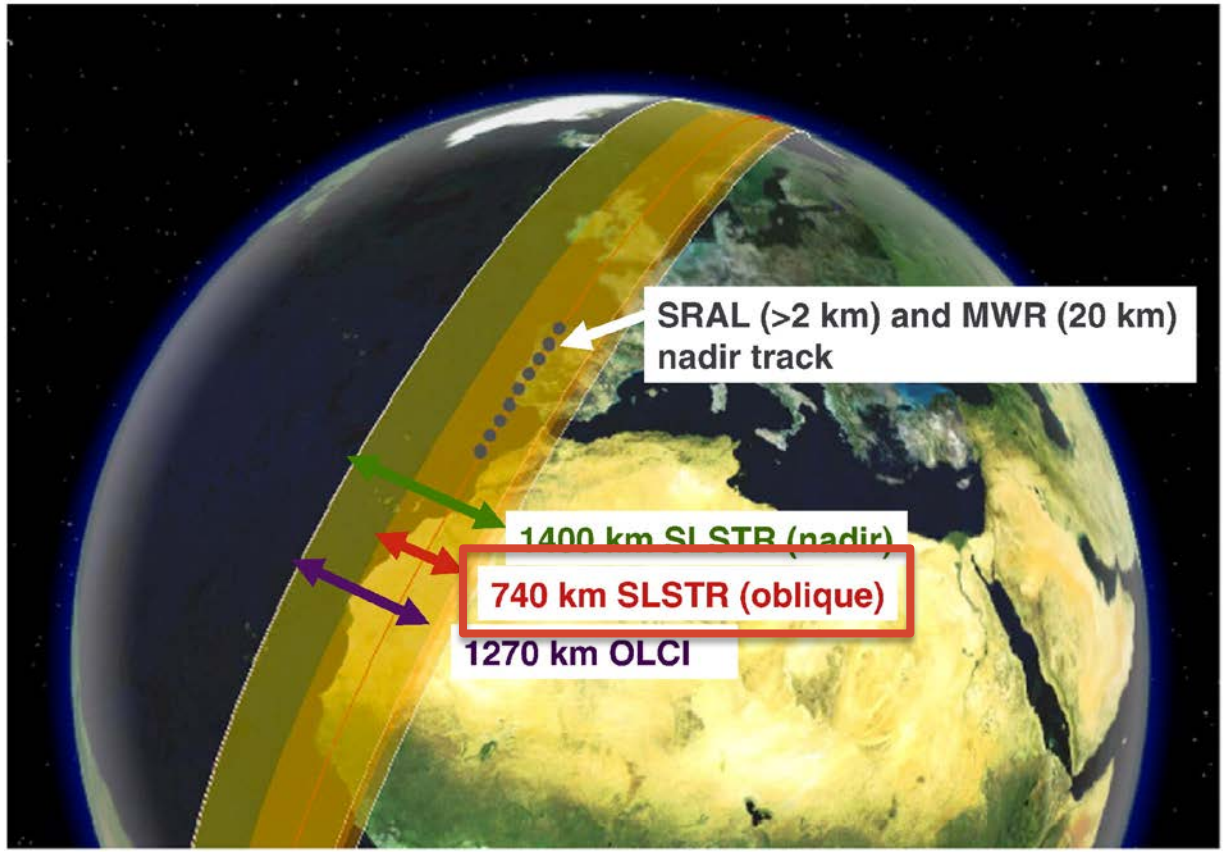
Ocean and Land Color Instrument (OLCI)

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

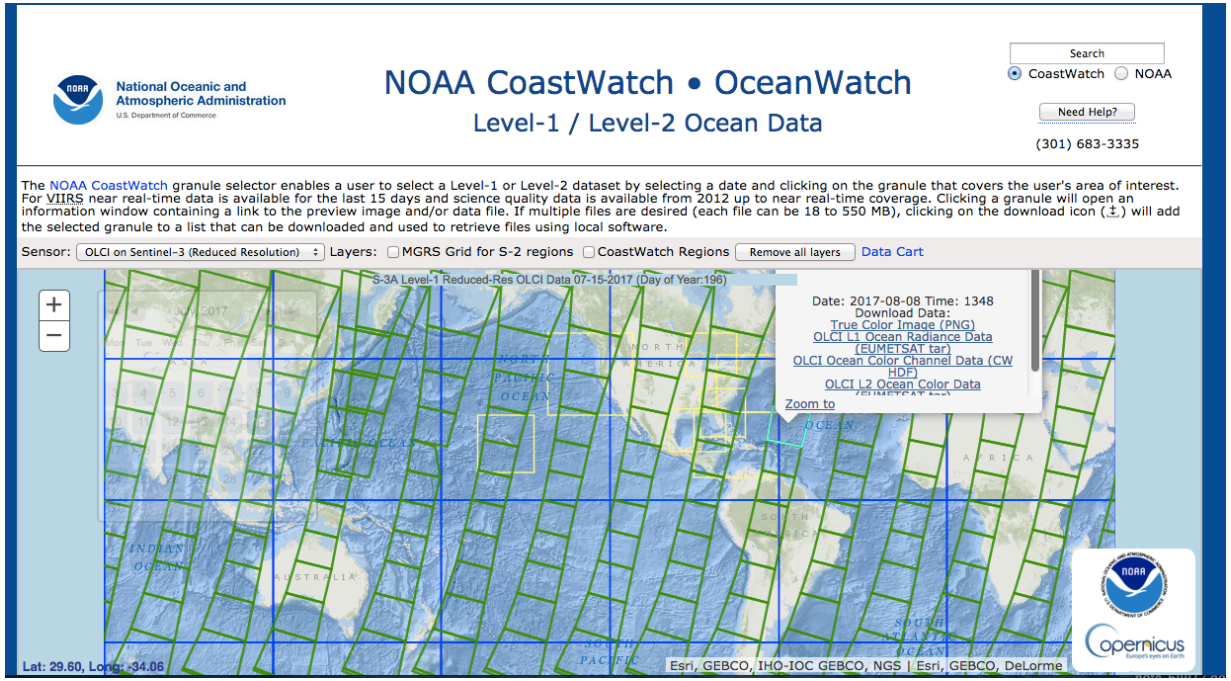
- Onboard **Sentinel-3**
- Based on heritage from ENVISAT satellite Medium Resolution Imaging Spectrometer (MERIS)
- Spatial Coverage and Resolution:
  - Global, swath: 1,270 m
  - Spatial resolution: 300 m, also available at 1.2 km
- Temporal Coverage
  - Feb 2016 – present
  - 27 day revisit time

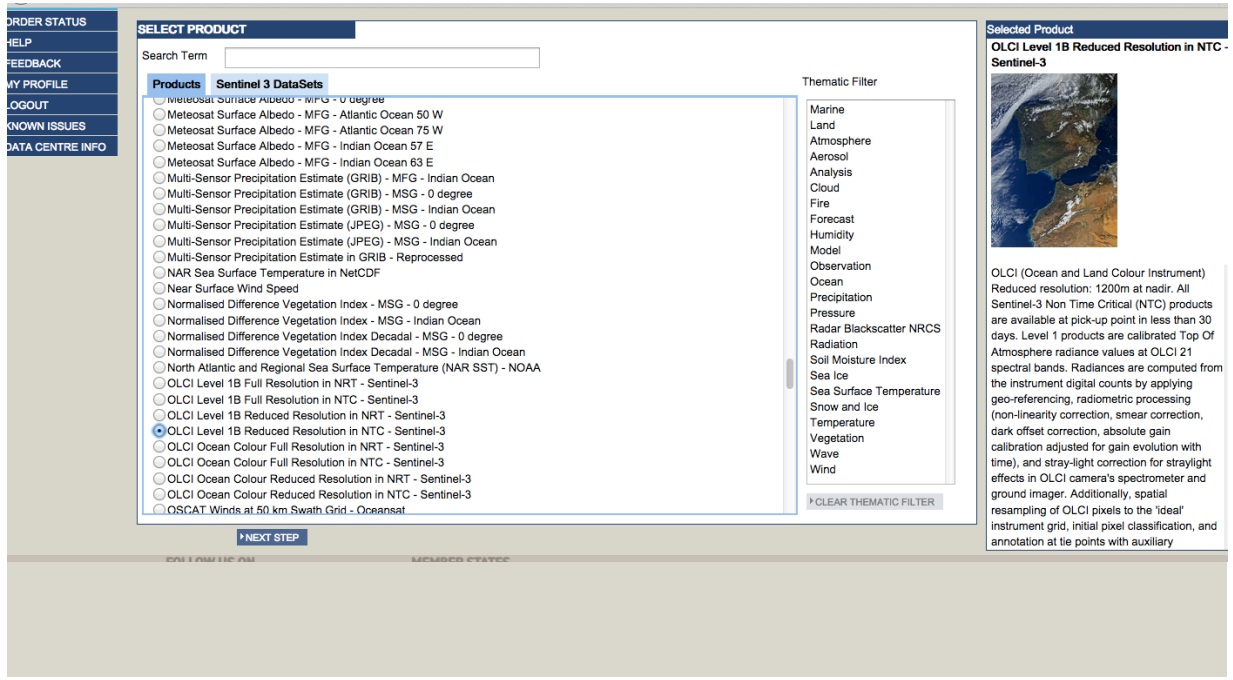
Spectral Bands: 21

- 4 visible to near-infrared: 300 m



Get OLCI Data





NOAA CoastWatch

https://coastwatch.noaa.gov/cw_html/cw_granule_selector.html?sensor=OLCI

EUMETSAT

http://archive.eumetsat.int/usc/#sp:;delm=O;noti=1;udsp=OPE;qqov=ALL;seev=0

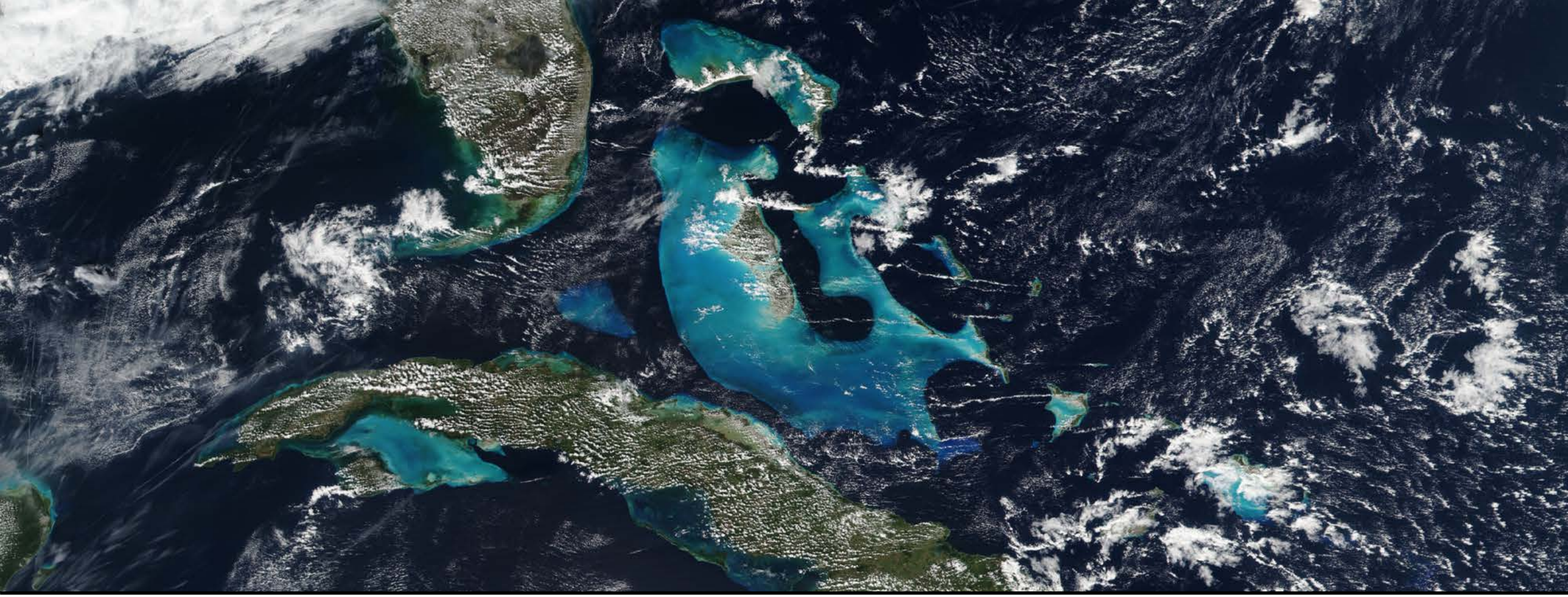
Challenges in Monitoring WQ for SDG 6

- For accurate and quantitative WQ monitoring analysis of spatially and temporally co-located, *in situ* measurements and satellite observations are required
- Feasibility of WQ monitoring in coastal and inland water bodies depends on spatial, temporal, and spectral resolutions of remote sensing observations
- Difficult to separate WQ parameters when sediments, dissolved matter, and Chl-a all are present
- It is not possible to characterize algal types or toxins only from remote sensing observations
- Remote sensing reflectance has to be corrected to account for contributions from atmospheric constituents such as aerosols
- Optical remote sensing observations cannot view the surface in the presence of clouds

Summary of Resources for Monitoring WQ for SDG 6

- Studies use optical and NIR remote sensing observations for qualitative and quantitative WQ monitoring in lakes, rivers, and coastal regions (see a review in Golizadeh et al., 2016 for techniques and case studies)
  - Landsat
  - Terra/Aqua MODIS
  - SNPP VIIRS
  - Sentinel-2 MSI
  - Sentinel-3 OLCI
- Several web tools use satellite-derived Chl-a and SST to monitor Harmful Algal Blooms
  - Landsat can monitor close to 170, 240 lakes
  - MODIS/OLCI would resolve ~1,862 lakes (Wilson Salls, EPA)

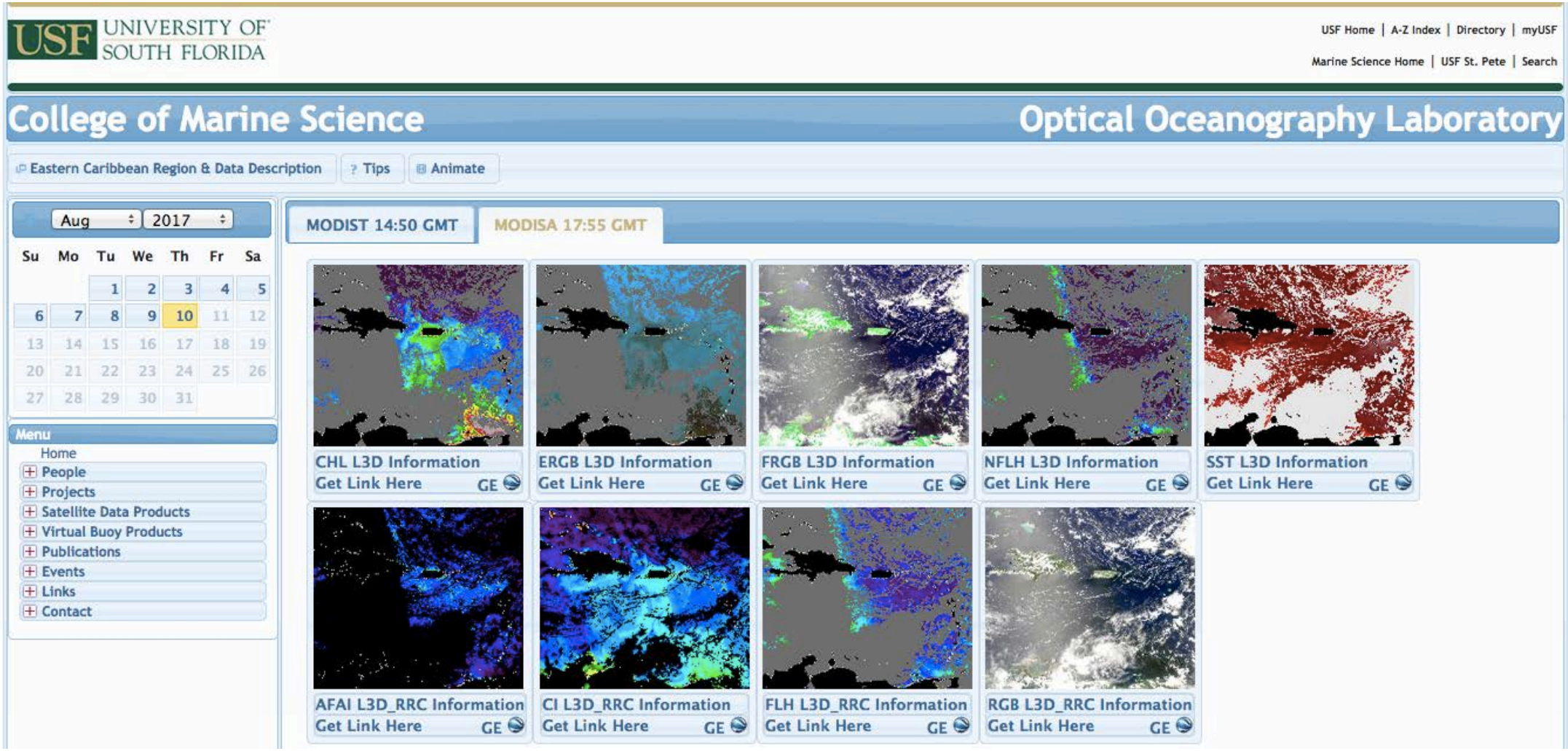
Reference: Gholizadeh, M. H., A. M/ Melesse, L. Reddy, 2016: Spaceborne and airborne sensors in water quality assessment, International J. of Remote Sensing, 37, 3143-3180.



Examples of Monitoring Harmful Algal Boom Indicators: Chlorophyll-a Concentration and Water Surface Temperature

Ch-a and SST Data from Aqua and Terra MODIS

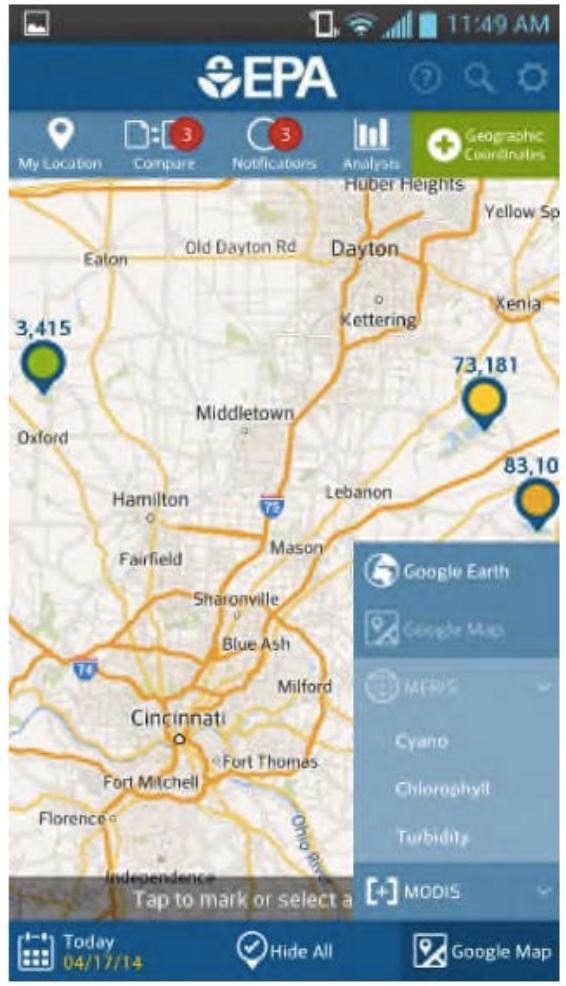
http://optics.marine.usf.edu/cgi-bin/optics_data?roi=ECARIB&current=1/



Cyanobacteria Assessment Network (CyAN)

https://www.epa.gov/water-research/cyanobacteria-assessment-network-cyan#decision%20support

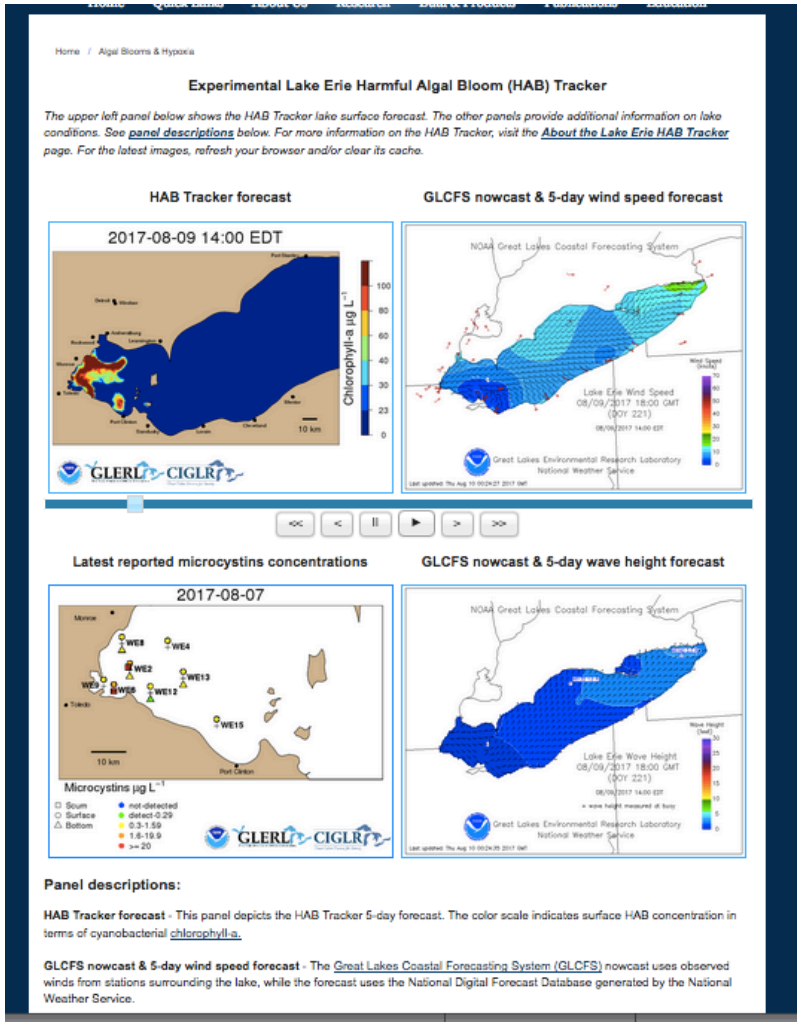
- A collaborative program among EPA, NOAA, NASA, and USGS
- Focused on an early and uniform approach to algal bloom identification using satellite remote sensing from Landsat, Sentinel-2, and Sentinel-3
- Develop a decision support system for stakeholders



Lake Erie HAB Tracker

https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/habTracker.html

- A forecast model based on:
  - MODIS satellite images
  - Weather forecast information
  - Modeled currents in Lake Erie
- Provides:
  - HAB measurements based on in situ water sample collection
  - Near real-time and 5 day HAB forecasts in terms of cyanobacterial chl-a



Lake Erie HAB Tracker

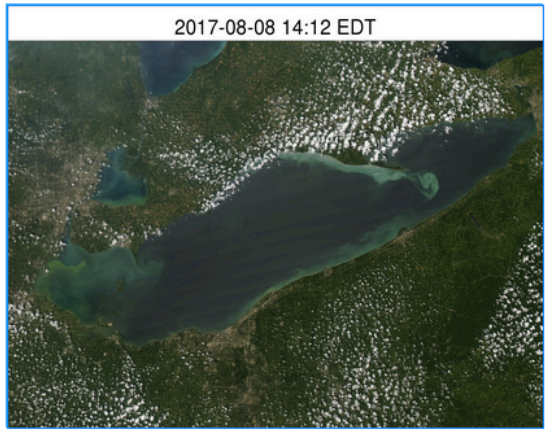
https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/habTracker.html

MODIS-Derived Cyanobacterial Density

Latest satellite-derived data used by the HAB Tracker

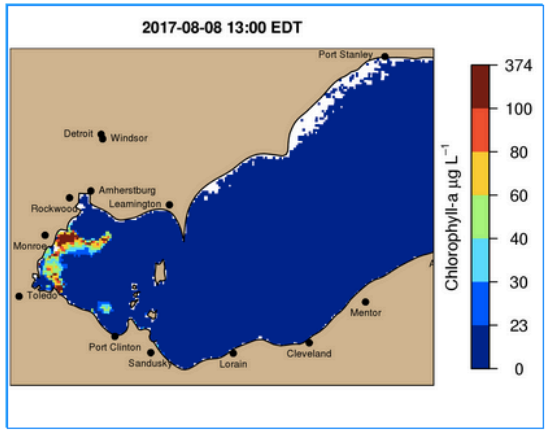
Sensors attached to satellites gather data, which is processed into the cyanobacterial index, an indicator of the abundance, or biomass, of the cyanobacteria associated with HABs. Processed satellite imagery is provided by the NOAA HAB Operational Forecasting System. The cyanobacterial index scale is converted to a cyanobacterial chlorophyll scale for use in the HAB Tracker, a similar indicator of cyanobacterial abundance.

True-color satellite image of Lake Erie



Latest usable (relatively cloud-free) satellite image of Lake Erie. For additional satellite imagery of Lake Erie, visit the NOAA Great Lakes CoastWatch webpage.

HABs extent analysis



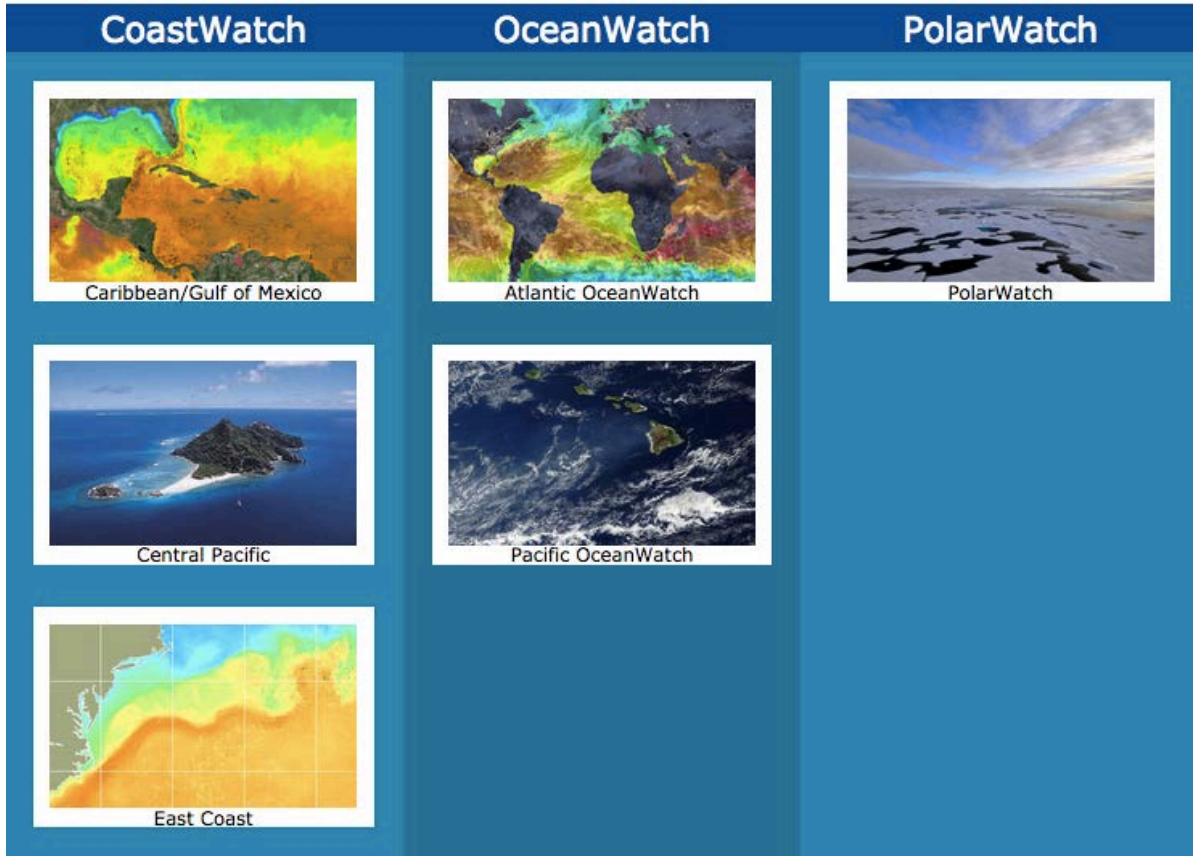
Latest HAB extent analysis from valid satellite imagery above used to update the bloom location in the model.

Photo Credit: NOAA GLERL

NOAA Coast Watch

https://coastwatch.noaa.gov/cw_html/index.html

- Information provided for multiple coastal areas

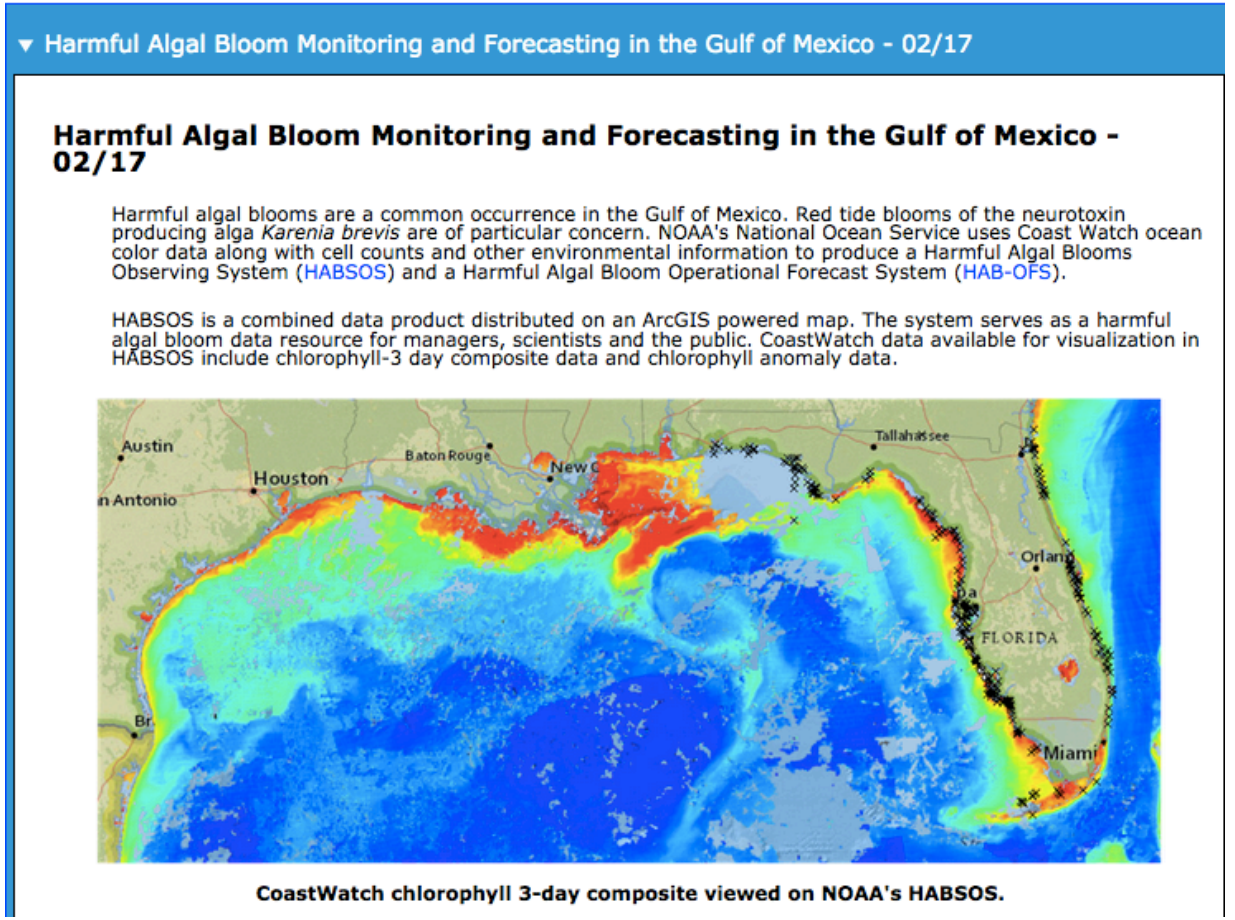


- Satellite products used
  - True-color Imagery
  - Ocean Color – Radiances and Chlorophyll-a Concentration
  - Sea Surface Temperatures
  - Sea Surface Height
  - Sea Surface Salinity
  - Sea Surface Winds

NOAA Coast Watch

https://coastwatch.noaa.gov/cw_html/OceanColor.html

- Satellite-based HAB monitoring
- Near real-time remote sensing data used from:
  - MODIS Aqua
  - VIIRS S-NPP
  - OLCI Sentinel-3

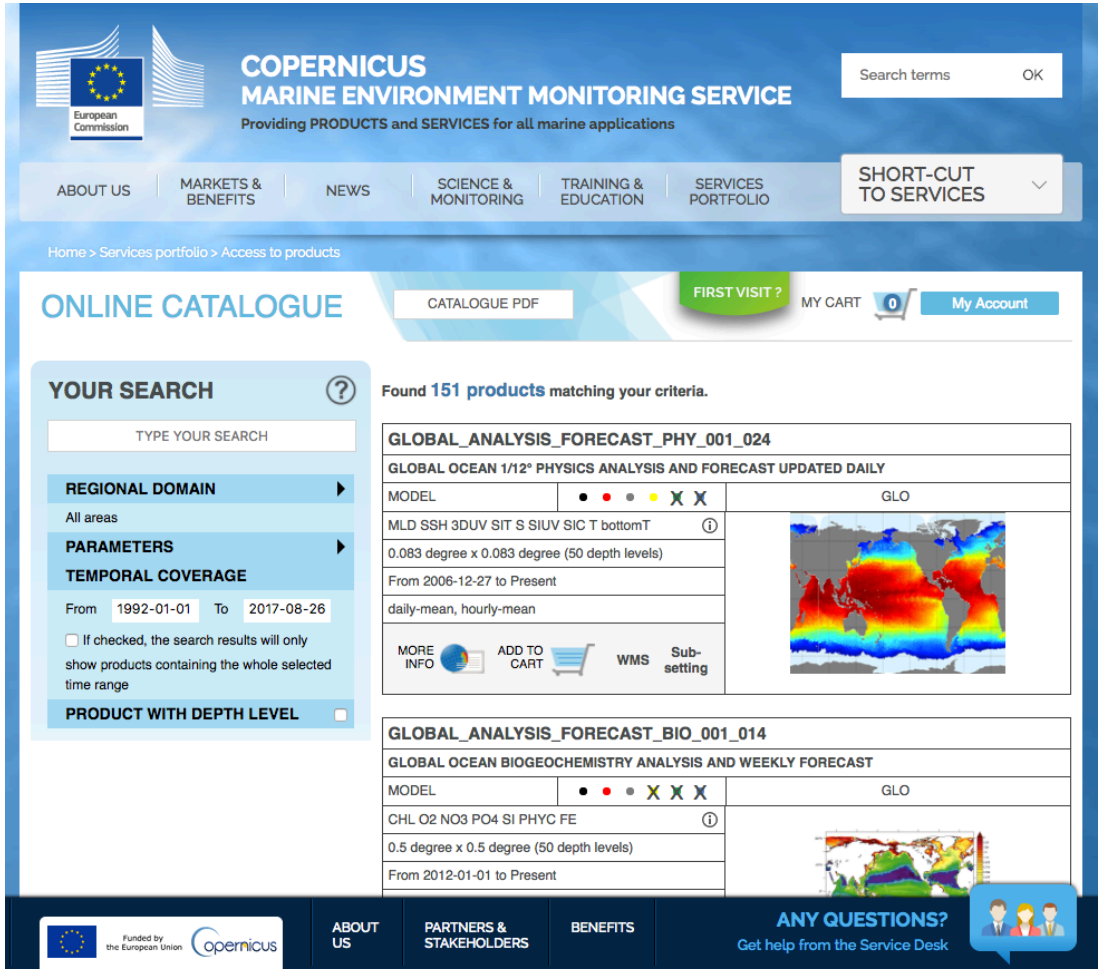


CoastWatch chlorophyll 3-day composite viewed on NOAA's HABSOS.

Copernicus Marine Environment Monitoring Service

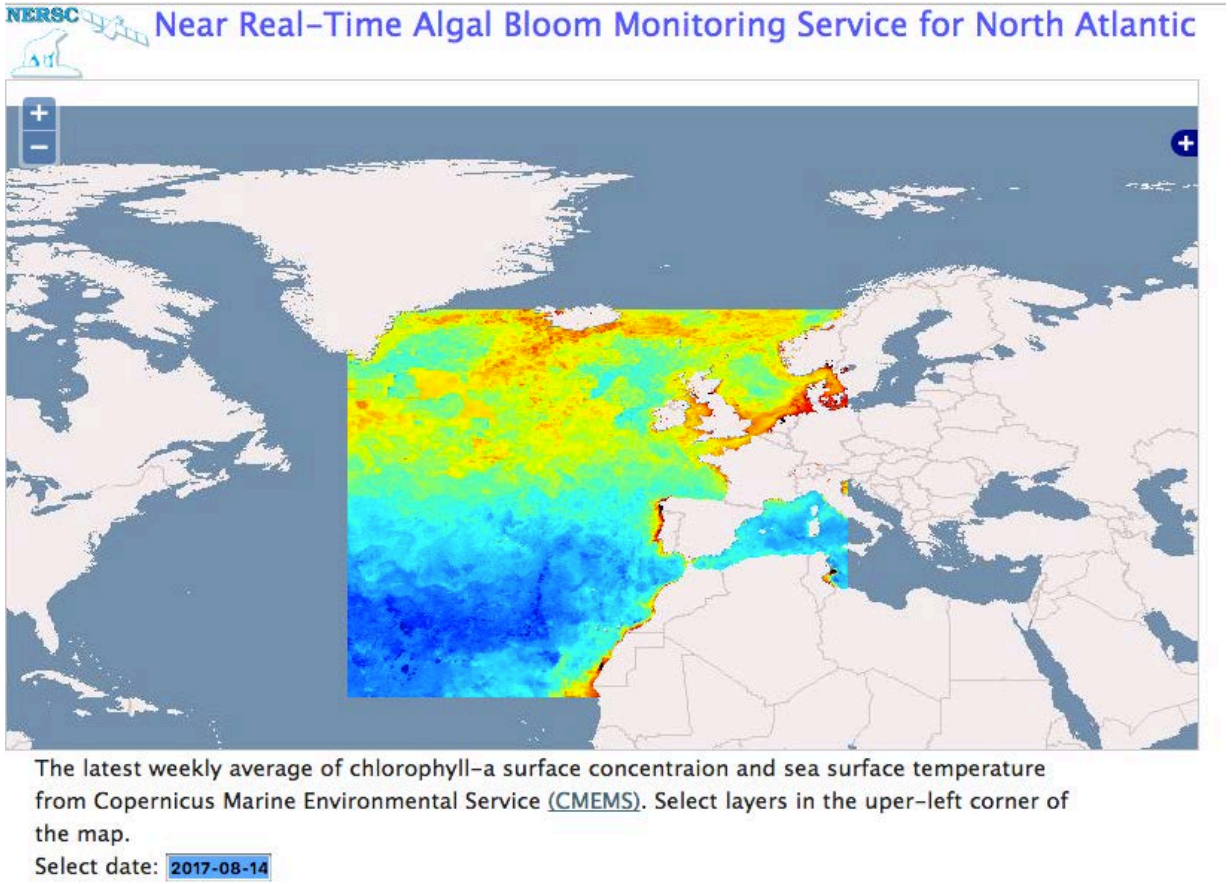
http://marine.copernicus.eu/

- Combined MODIS & VIIRS observations are used for monitoring HABs in:
  - North Atlantic
  - Arctic Ocean
  - Baltic Sea
  - Black Sea
  - Mediterranean Sea

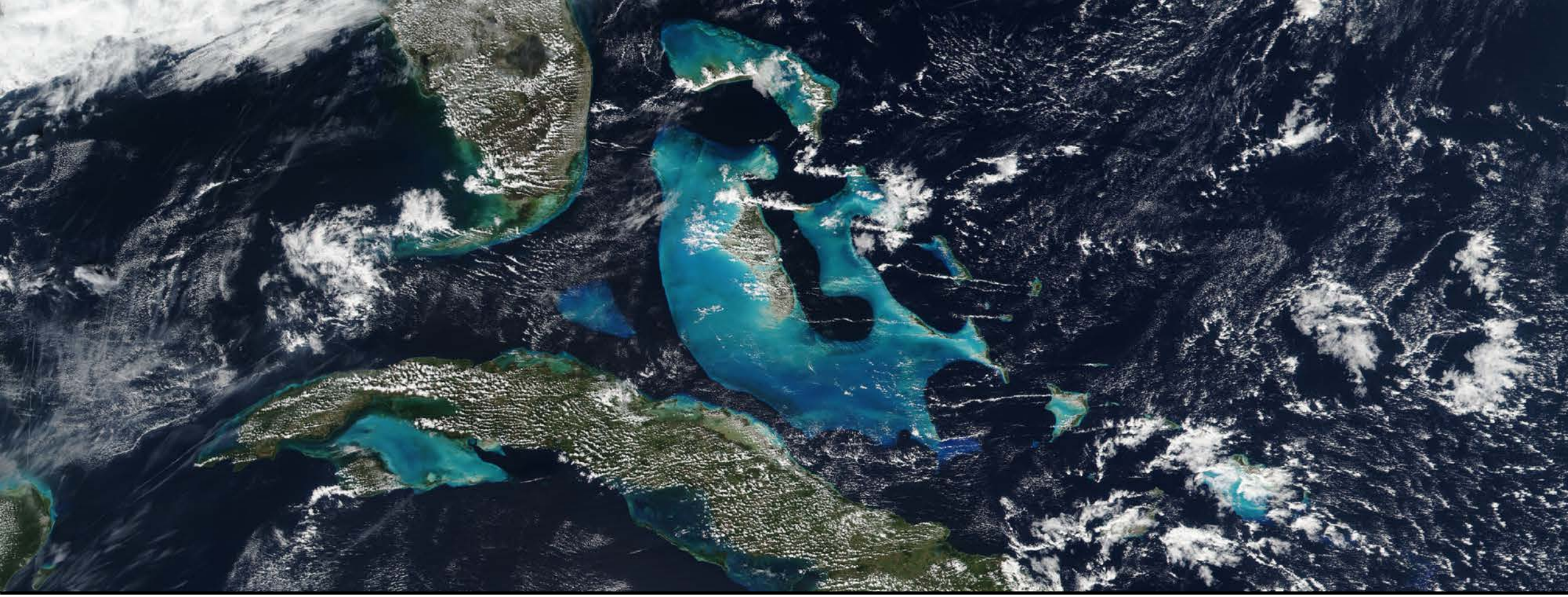


Near Real-Time Algal Bloom Monitoring Services in the North Atlantic

http://hab.nersc.no/



- Based on ocean color data from Copernicus Marine Environment Monitoring Service



Demonstration of Web-Based Tools for Water Quality Data Access
Example: Lake Titicaca

Chl-a and SST Data Access for HAB Monitoring

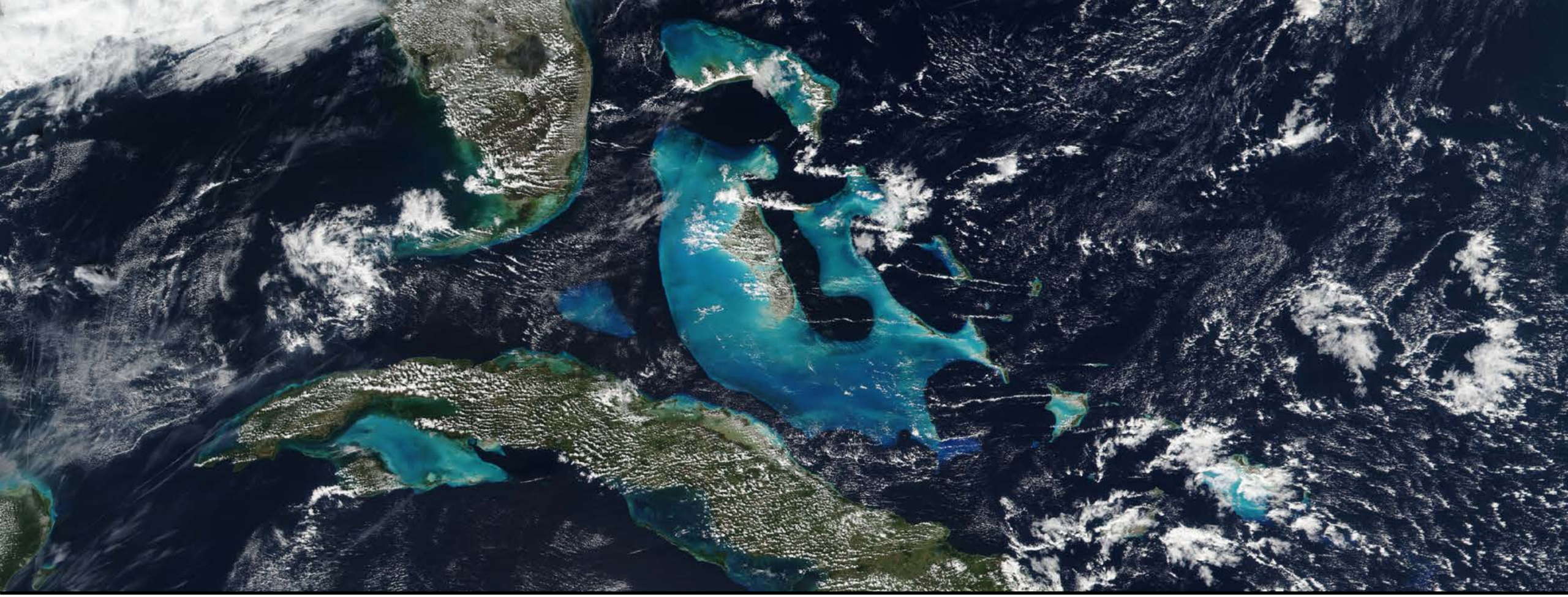
- These tools enable data search, spatial and temporal subsetting, analysis, and visualization:
  - OceanColor Web: https://oceancolor.gsfc.nasa.gov/
  - Giovanni: http://giovanni.gsfc.nasa.gov/giovanni/
- Image Processing and Visualization Software:
  - SeaDAS: http://seadas.gsfc.nasa.gov/


APPLIED REMOTE SENSING TRAINING PROGRAM
TRAIN - EMPOWER - ADVANCE

Thank You

Questions

1. Are you using any remote sensing information?
2. Are you focusing more on coastal or inland estuaries?
3. In addition to HABs, what other parameters are you looking for? What water parameter are you most concerned about?
   a) e.g. turbidity, sediments, salinity, SST
4. What kind of decisions do you have to make?
   a) e.g. water intake, changing agricultural practices.
5. What time frame (weekly, daily) are you making decisions on?
6. Do you have access to in situ data that you can combine with remote sensing? (Is that something you would like to learn?)



Extra Slides

Landsat Bands

Landsat 7 ETM+

Band	Band Range (µm)	Spatial Resolution (m)
1	0.45 – 0.515	30
2	0.525 – 0.605	
3	0.63 – 0.69	
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

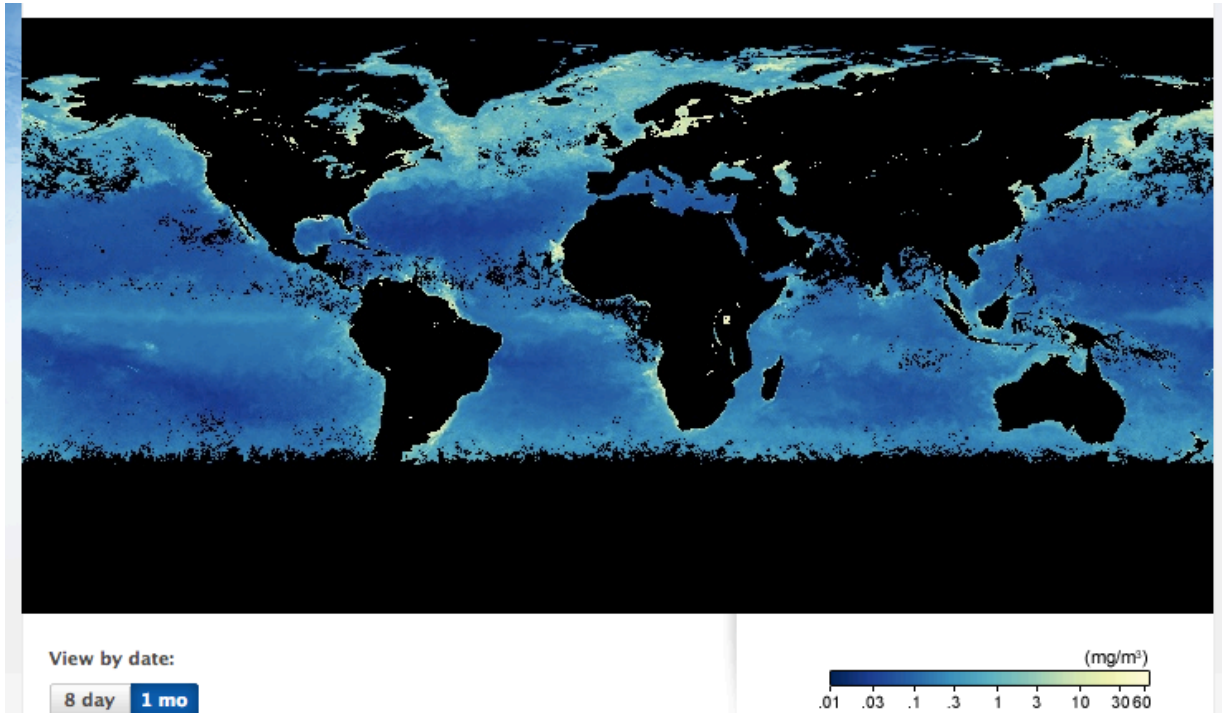
Band	Band Range (µm)	Spatial Resolution (m)
1	0.433 – 0.453	30
2	0.450 – 0.515	
3	0.525 – 0.60	
4	0.630 – 0.680	
5	0.845 – 0.885	
6	2.10 – 2.30	
7	0.500 – 0.680	
8	2.08 – 2.35	15
9	1.36 – 1.39	30

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

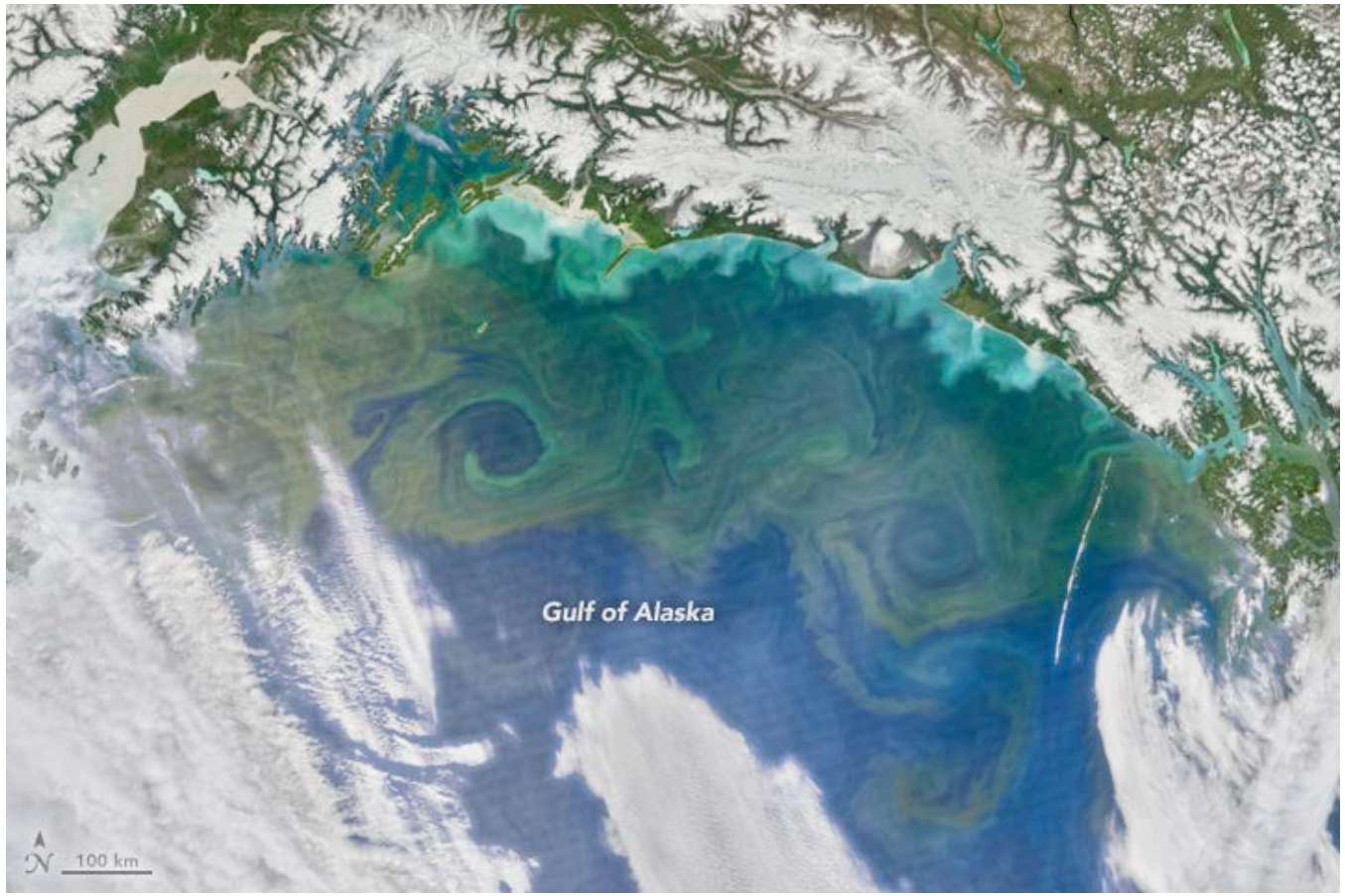


VIIRS Bands Relevant for HAB Monitoring

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

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



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

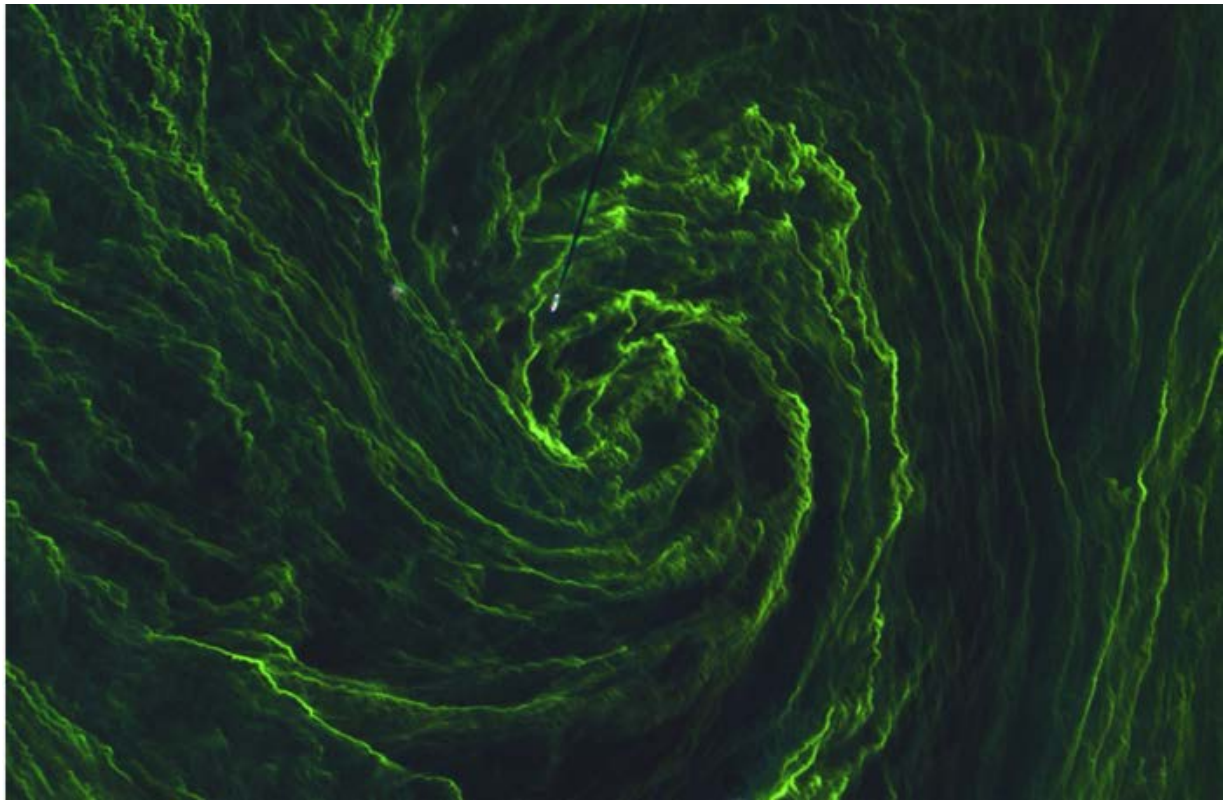


Image: Copernicus Sentinel data (2015)/ESA, CC BY-SA 3.0 IGO

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

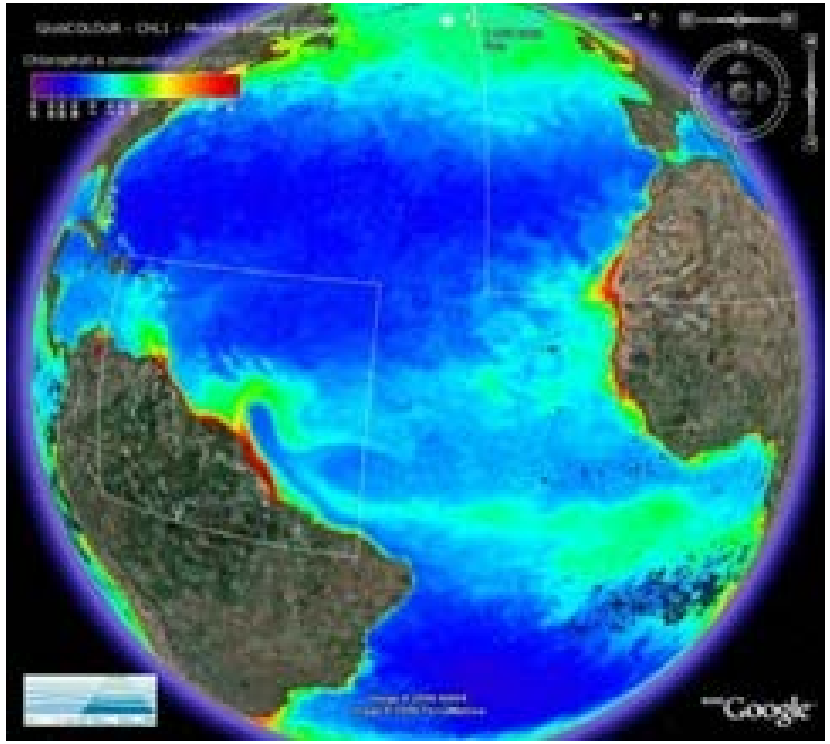
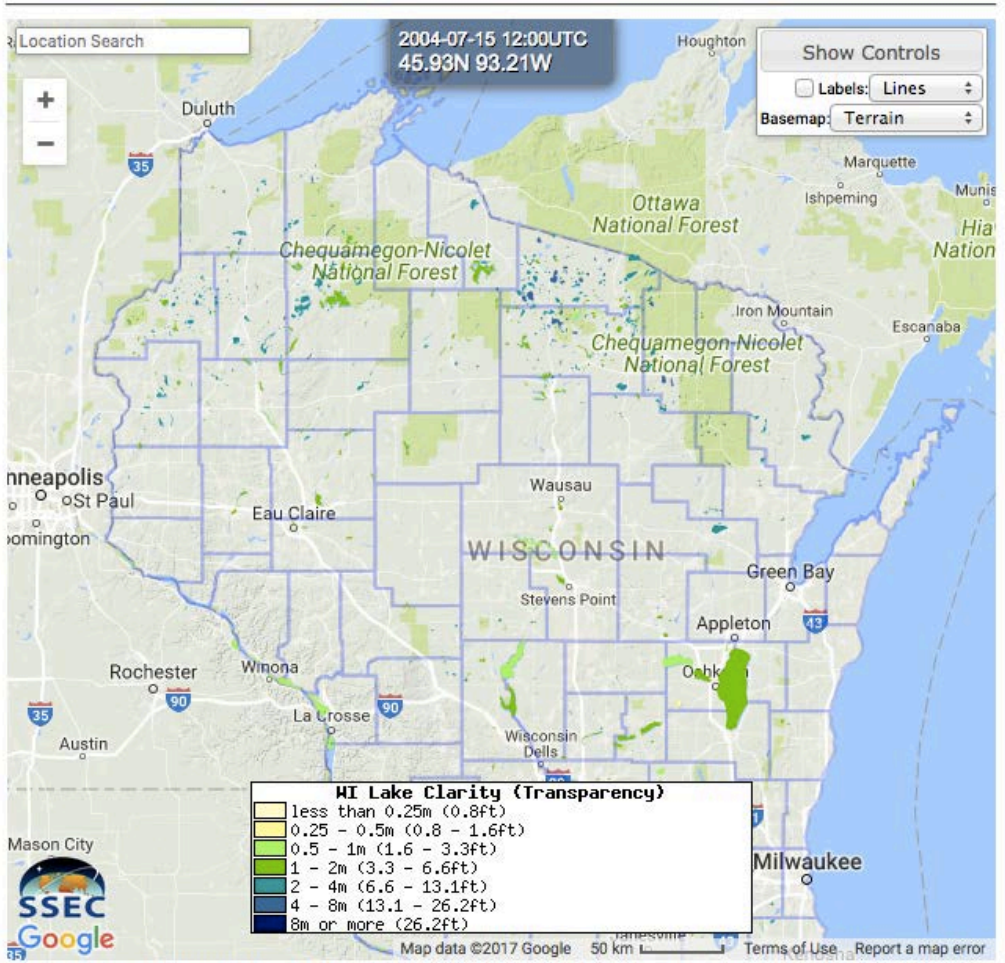


Image Credit: ESA/ACRI-ST

Lake Clarity from Landsat in Wisconsin

https://www.lakesat.org/



Two dates are available: 2000, and 2004. Use your keyboard's left and right arrow keys to move between them.

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