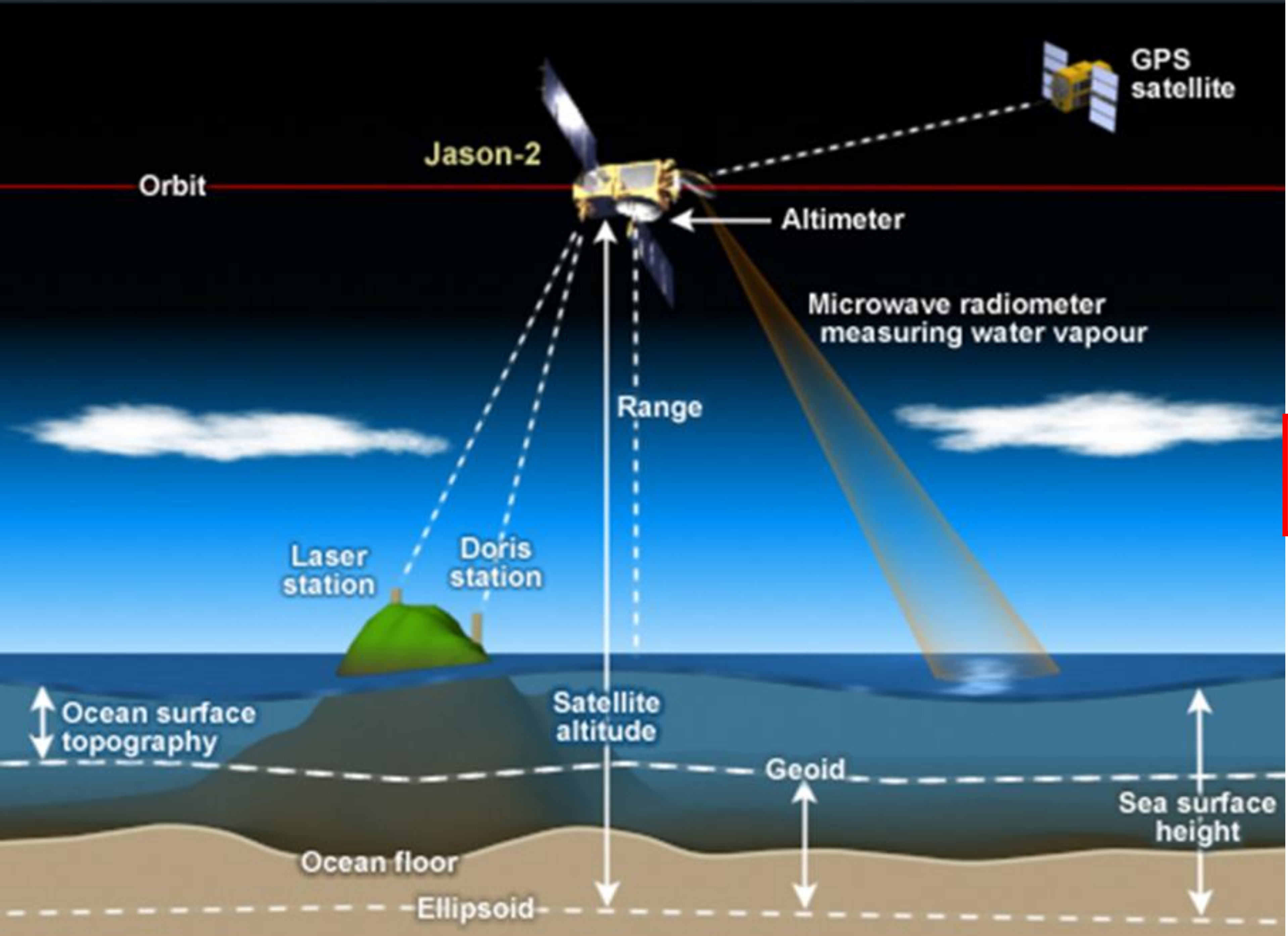
Sea Level Observations: Radar Altimetry and SWOT

Angelica Rodriguez with Contributions from the SWOT Project and Science Teams

2026 JPL Center for Climate Science Summer School



https://sealevel.jpl.nasa.gov/missions/technology/

Radar altimetry missions' primary payload is a microwave radar altimeter.

To estimate ocean height, the radar operates in a known frequency (e.g., the "Ku-band" with central frequency: 13.575 GHz, total bandwidth: 320 MHz).

Sea Surface Height (SSH) = Satellite Altitude – Range

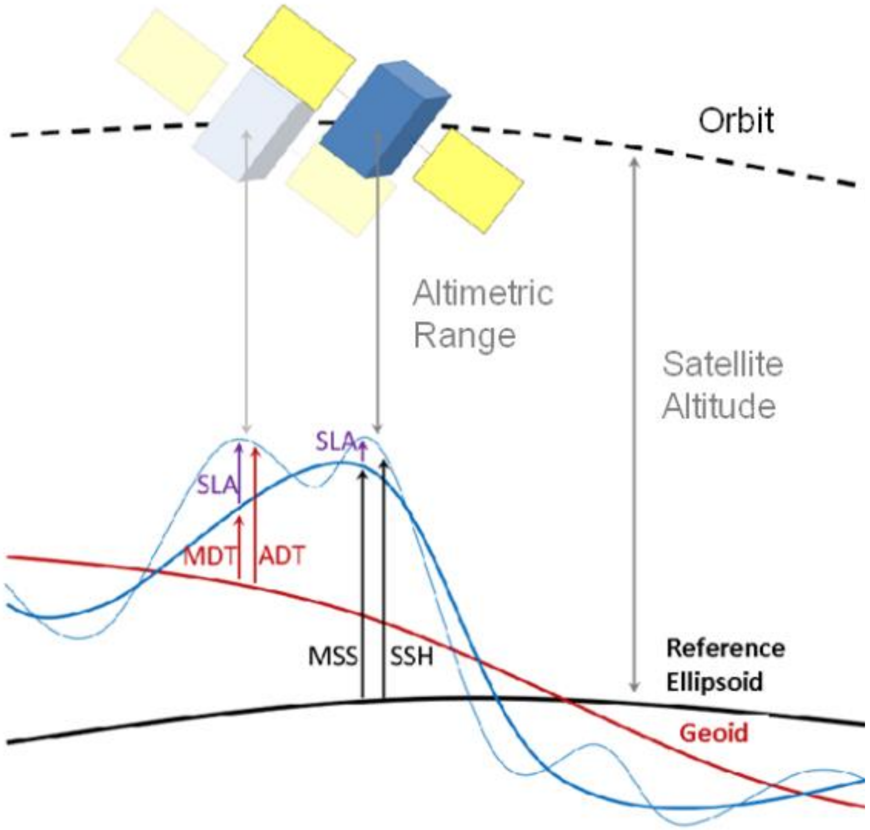
Range = the distance between satellite and the ocean surface

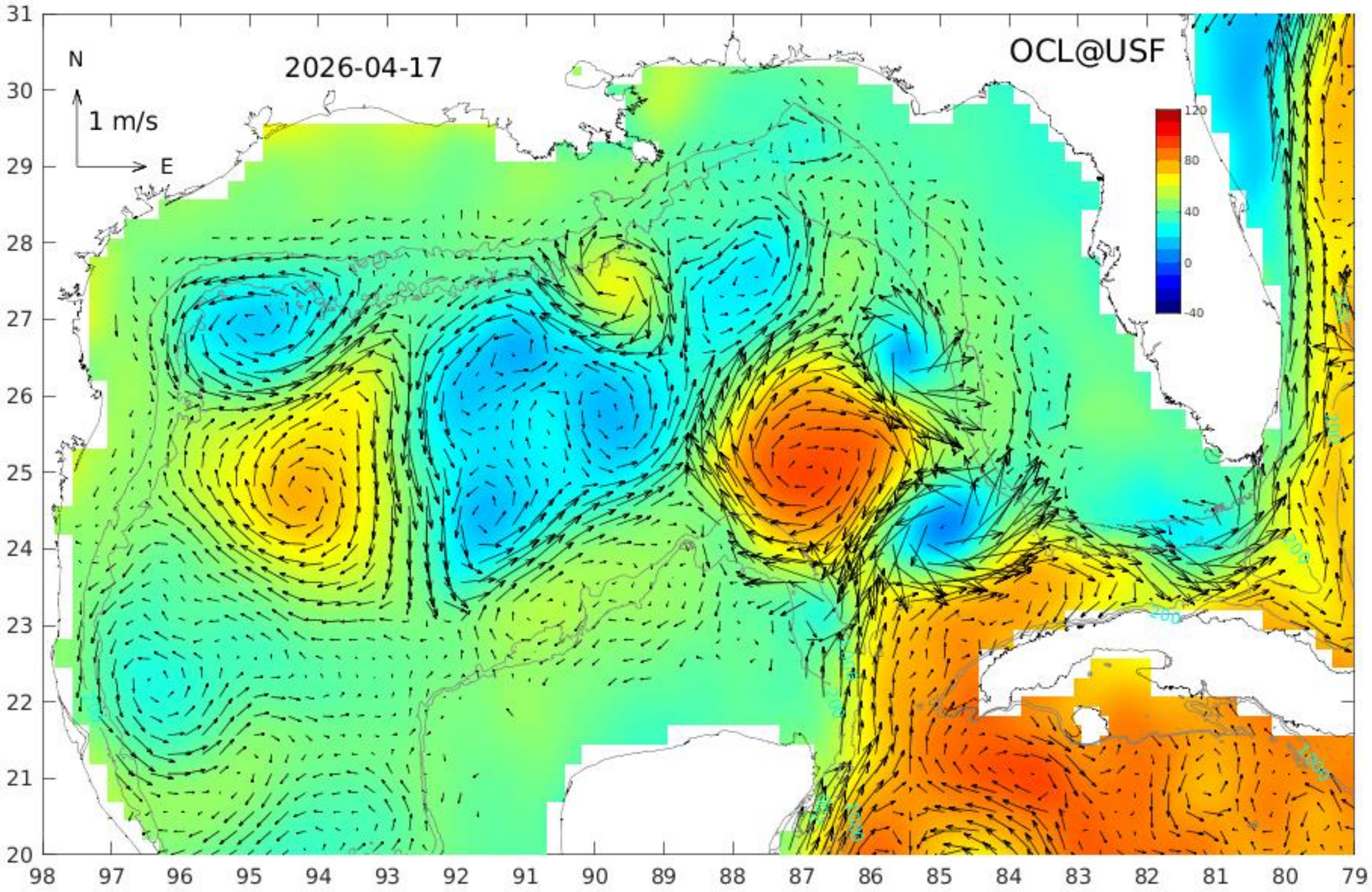
- Altitude ~ 1336 km
- Speed > 7 km/s
- Repeat period = 10 days (the time to complete a full cycle of the satellite orbit)

Radar Altimetry and Oceanography

The sea surface height (SSH) is a proxy for **surface pressure**, from which ***ocean currents*** can be retrieved using the ***geostrophic approximation***

$$u = -\frac{g}{f}\frac{\partial h}{\partial y};\ v = \frac{g}{f}\frac{\partial h}{\partial x}$$

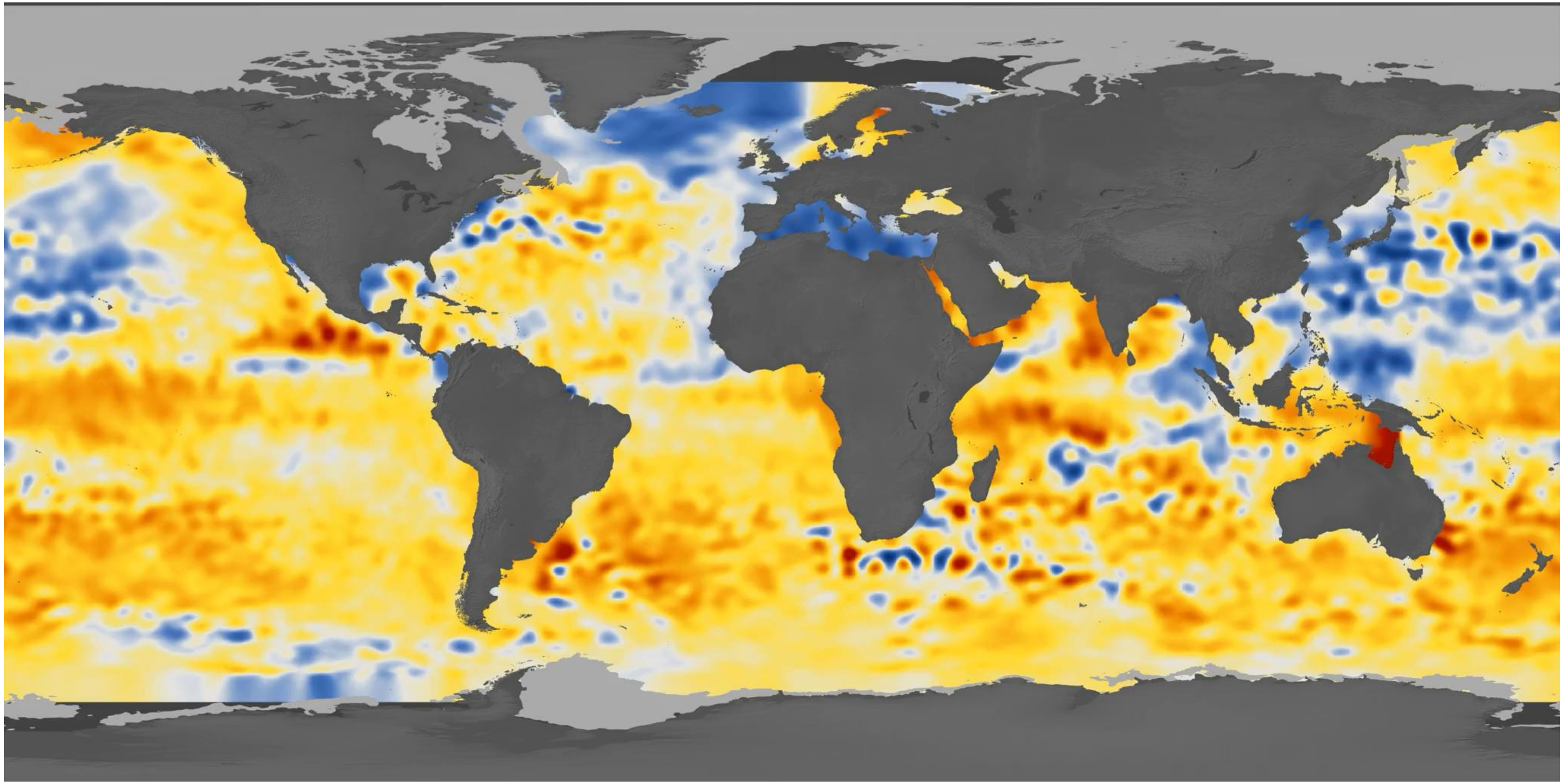




https://ocl.marine.usf.edu/Products/geov.html

Legacy of Altimetry

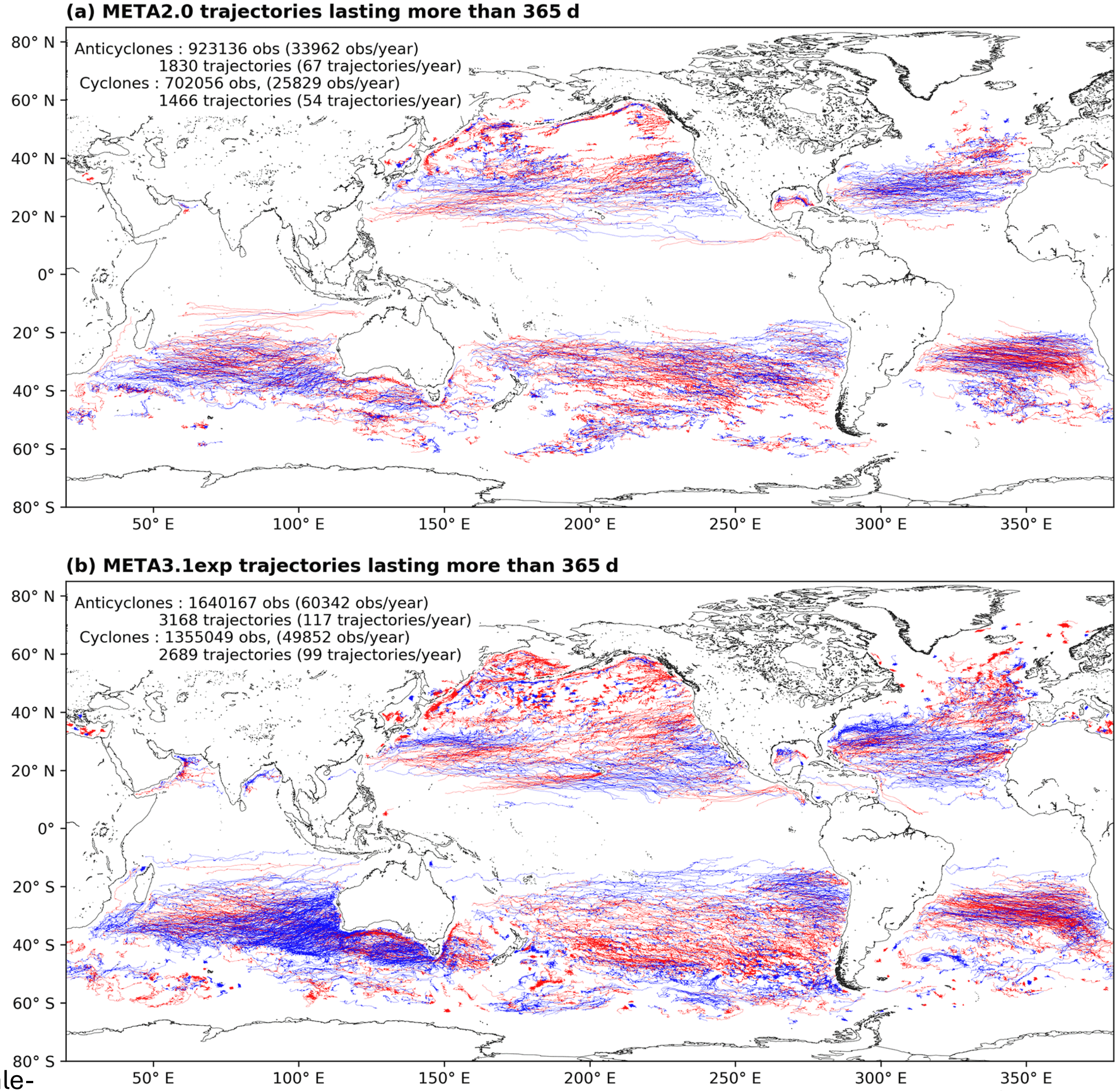
- Dispelled any lingering belief that the global ocean flow was primarily laminar, instead revealing a turbulent fluid that fluctuates over many scales in space and time



https://svs.gsfc.nasa.gov/5504/

Legacy of Altimetry

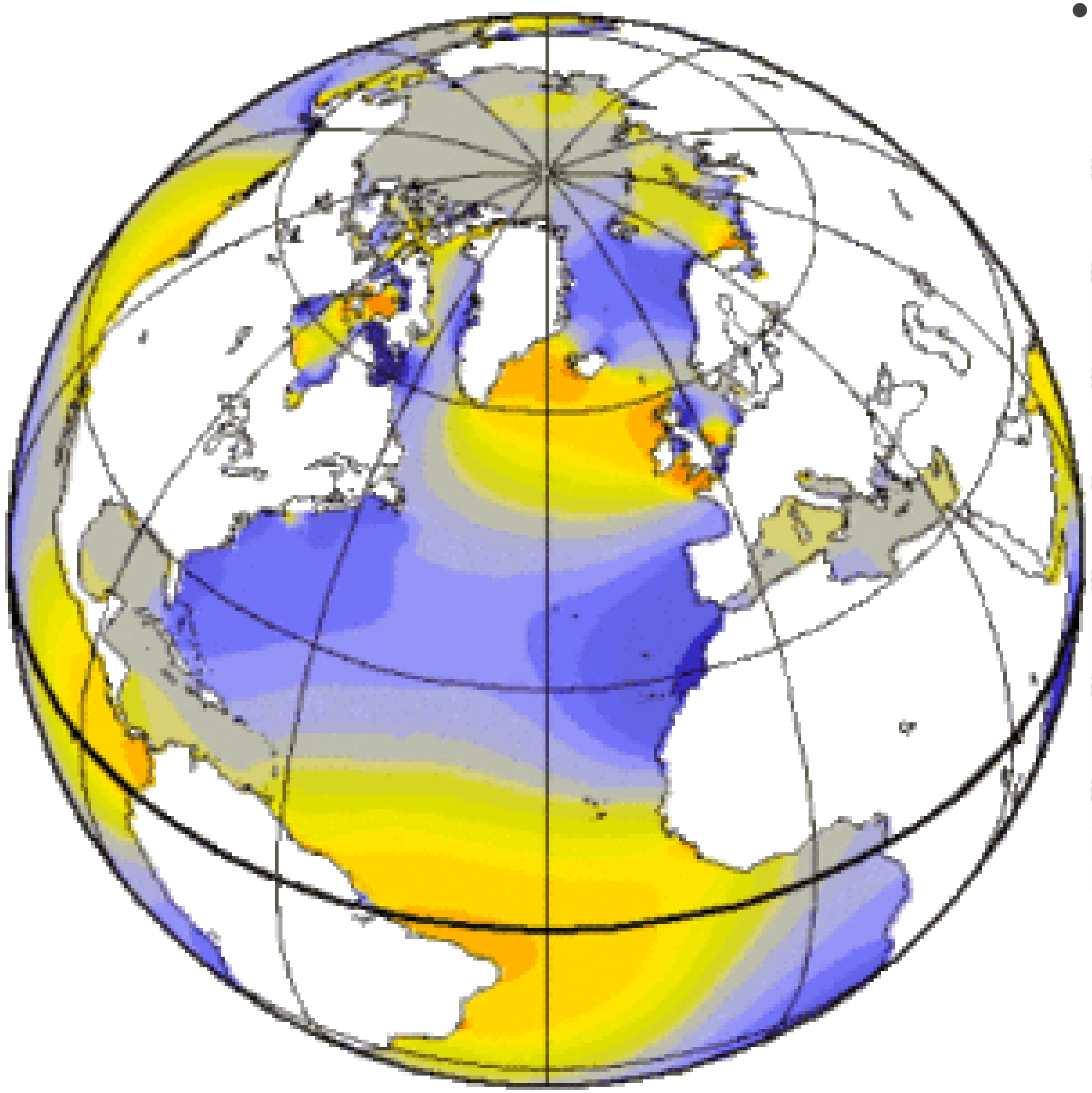
- Revealed westward propagating features that do not follow expected dispersion relation curves associated with linear Rossby waves, but rather nondispersive mesoscale eddy propagation - these eddies have since been systematically identified and tracked globally to build a large database of observed eddy characteristics.



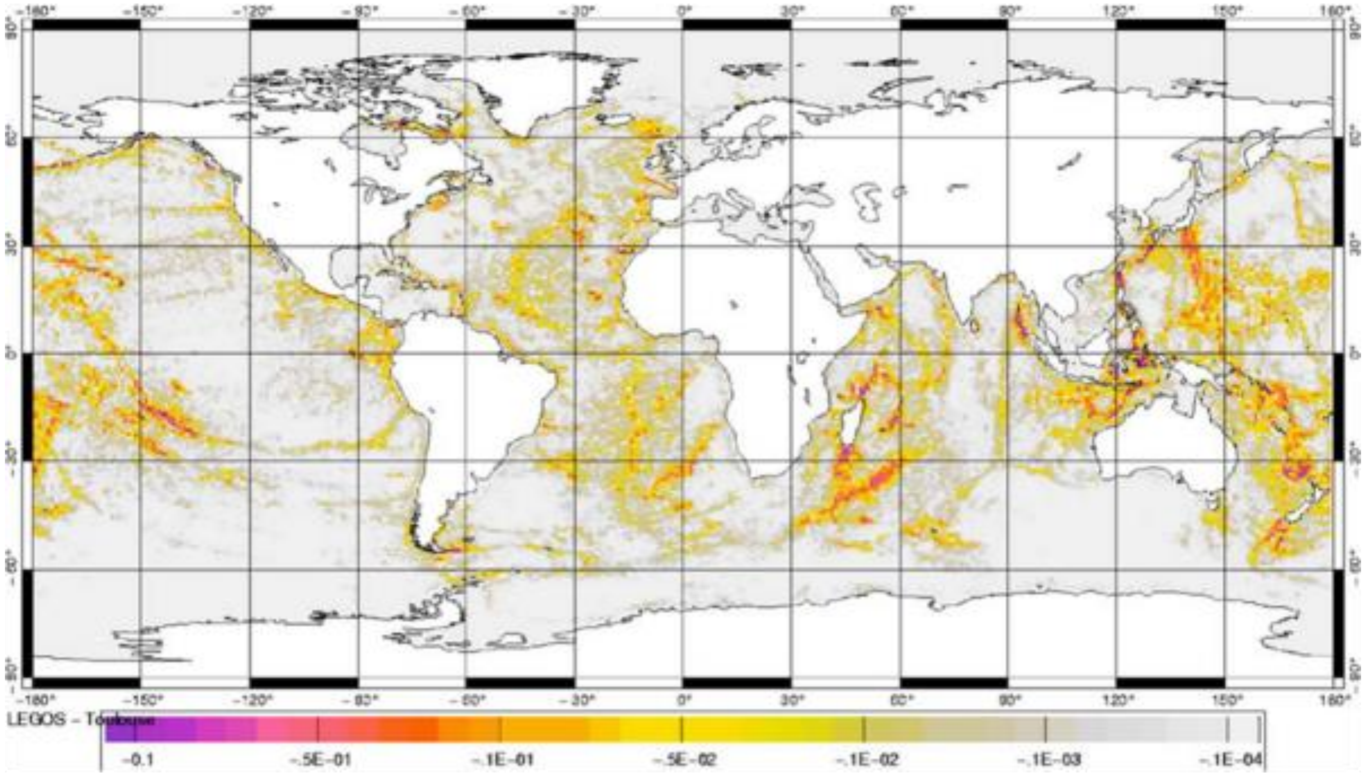
https://www.aviso.altimetry.fr/en/data/products/value-added-products/global-mesoscale-eddy-trajectory-product.html

Pegliasco et al. 2022

Legacy of Altimetry



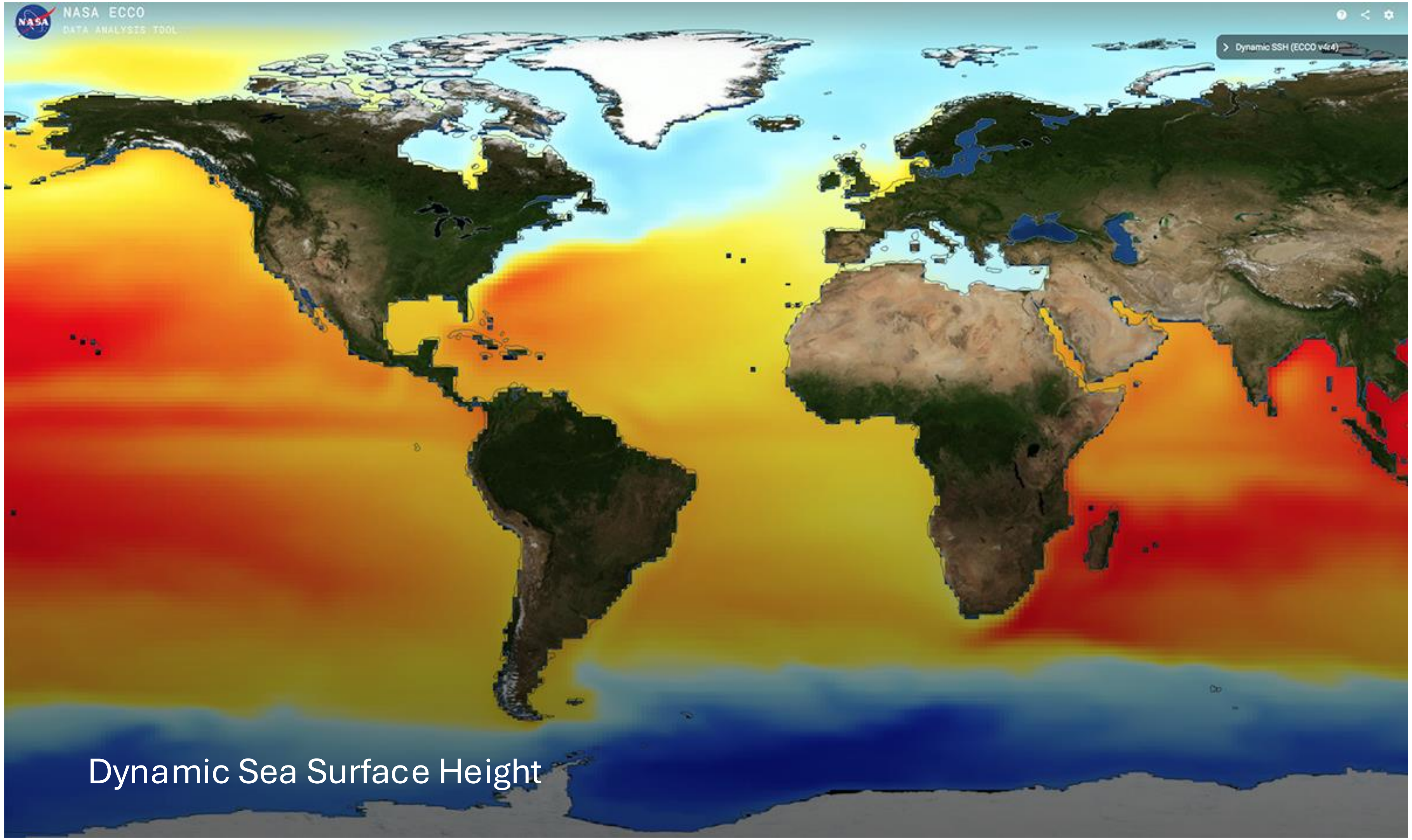
- Accurately mapped the barotropic tide and coherent internal tides



https://www.aviso.altimetry.fr/en/applications/ocean/tides.html
M2 wave drag dissipation (W/m2) (Lyard et al 2006) (Credits Legos)

Legacy of Altimetry

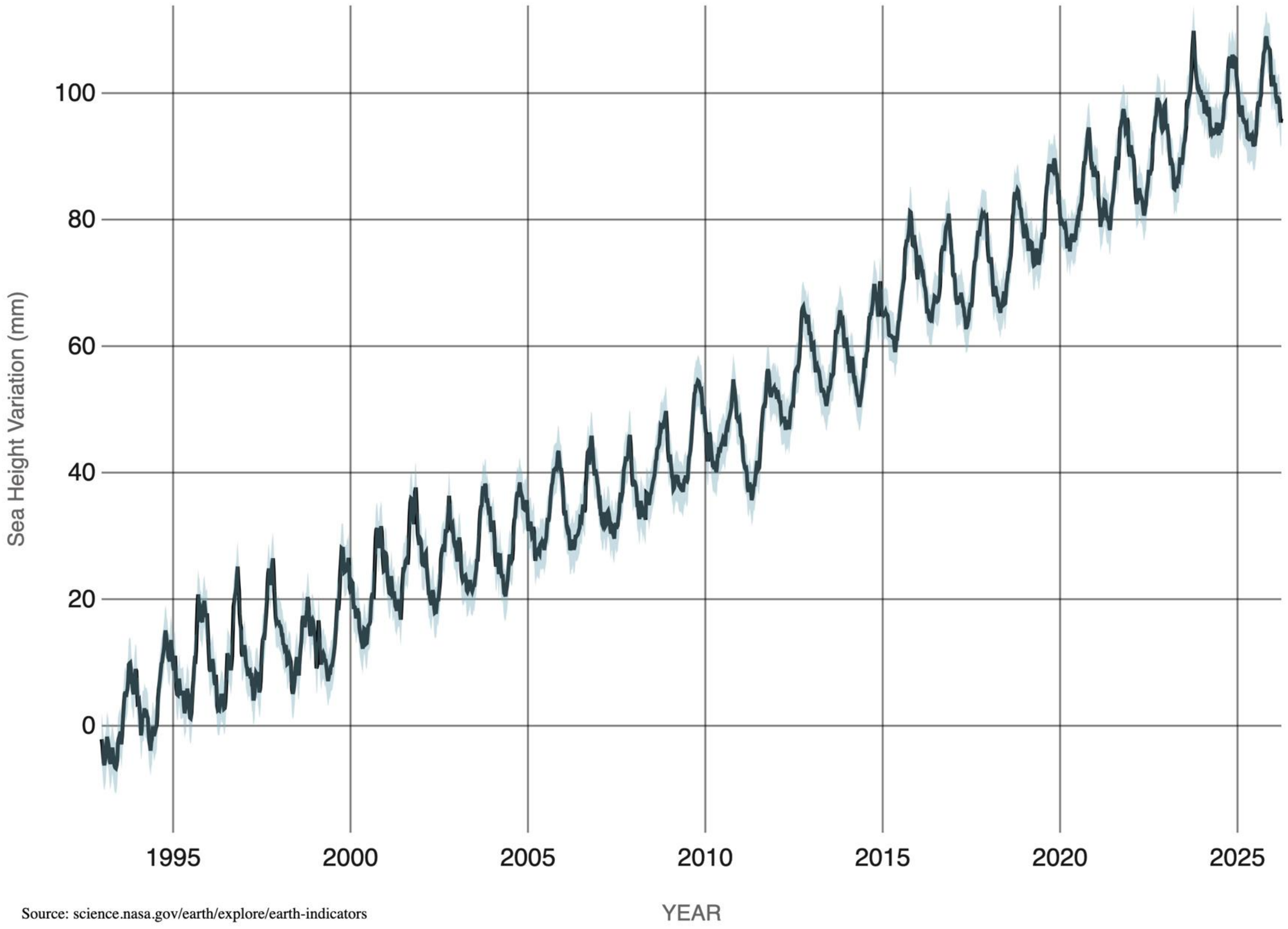
- Constrained global ocean state estimates and forecasts built from state-of-the-art numerical models



Legacy of Altimetry

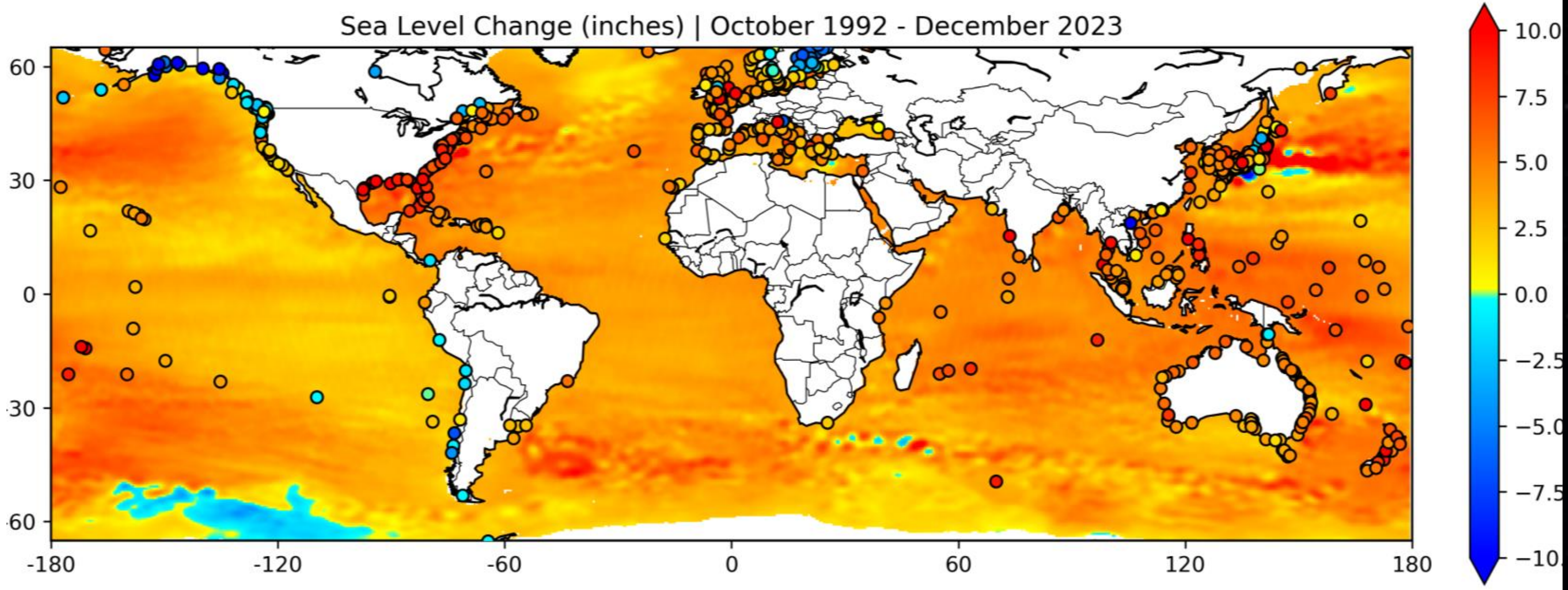
Global SSH measurements are used daily around the world by operational forecast centers, and have been fundamental to thousands of scientific studies of the ocean, atmosphere, and climate

Global Mean Sea Level



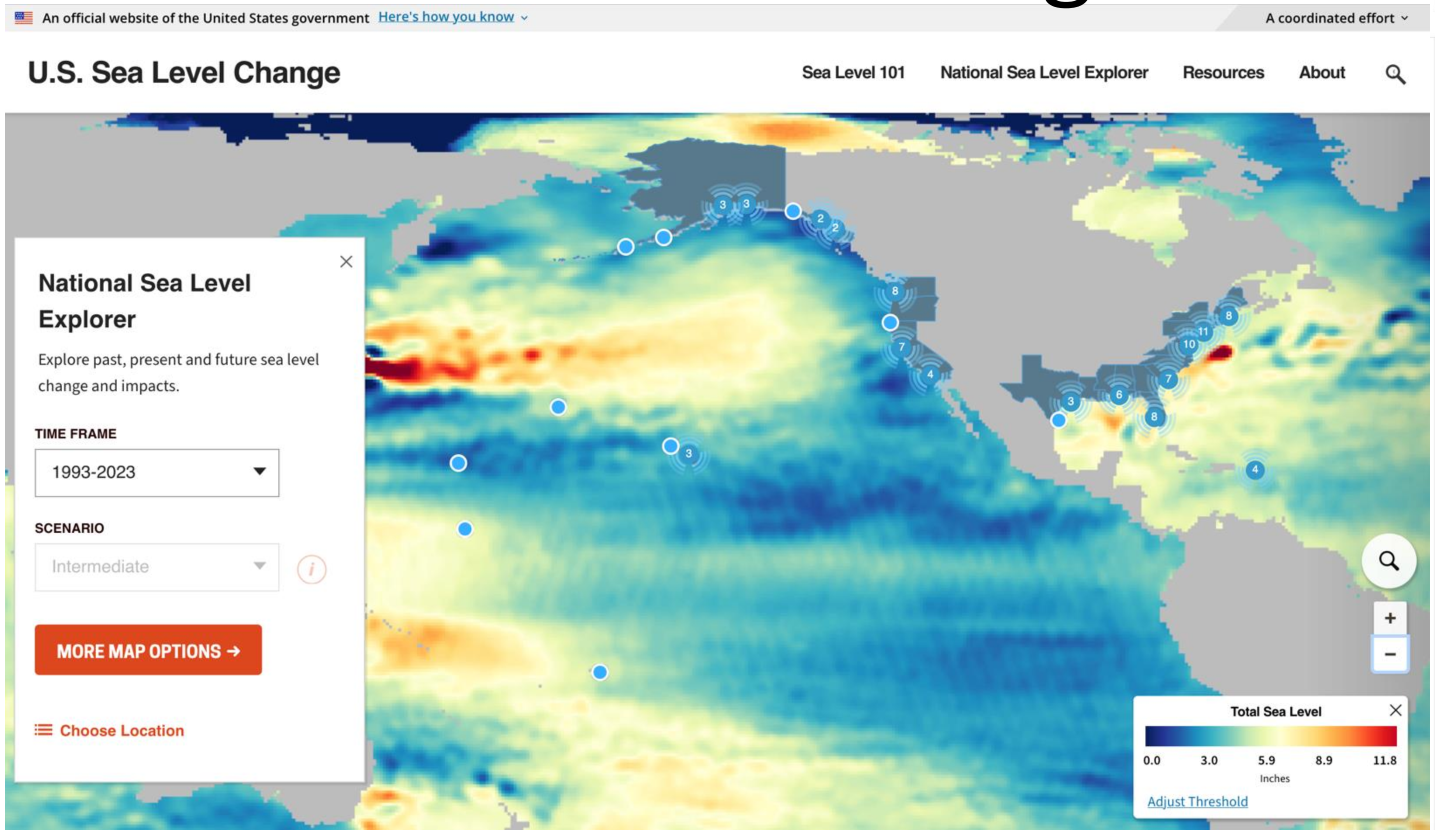
Source: science.nasa.gov/earth/explore/earth-indicators

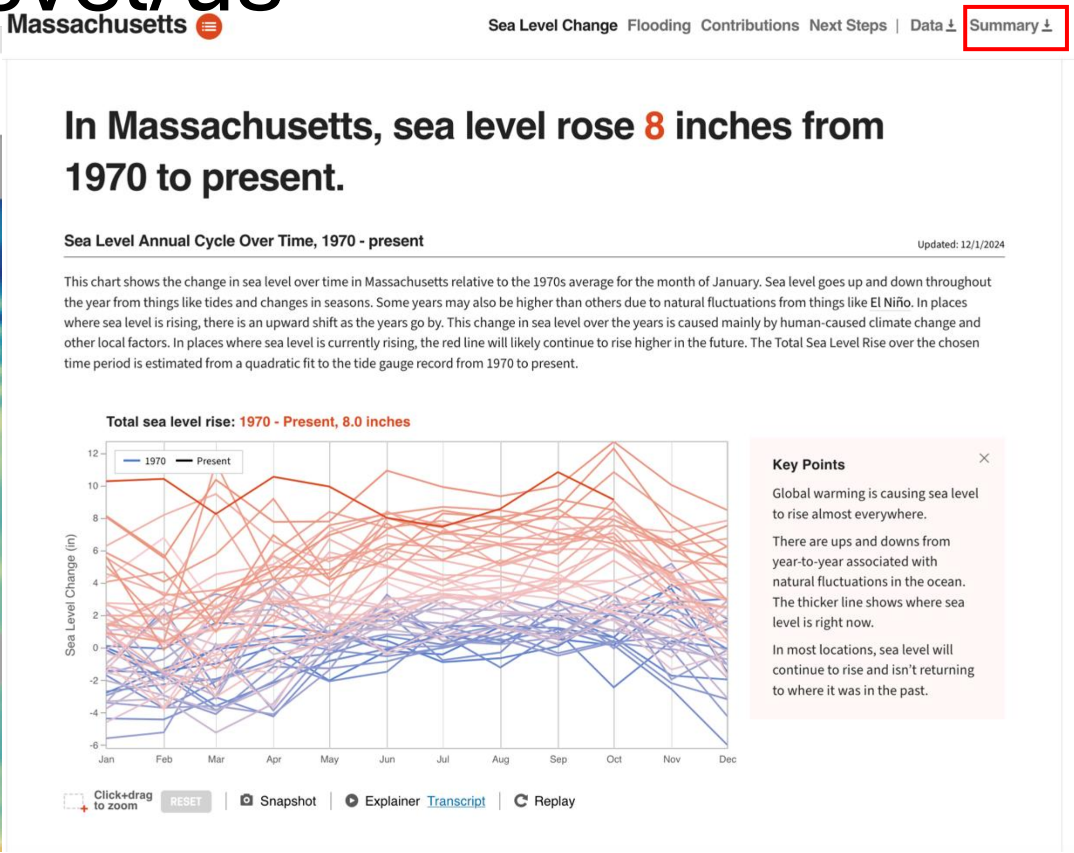
Regional Sea Level Trends



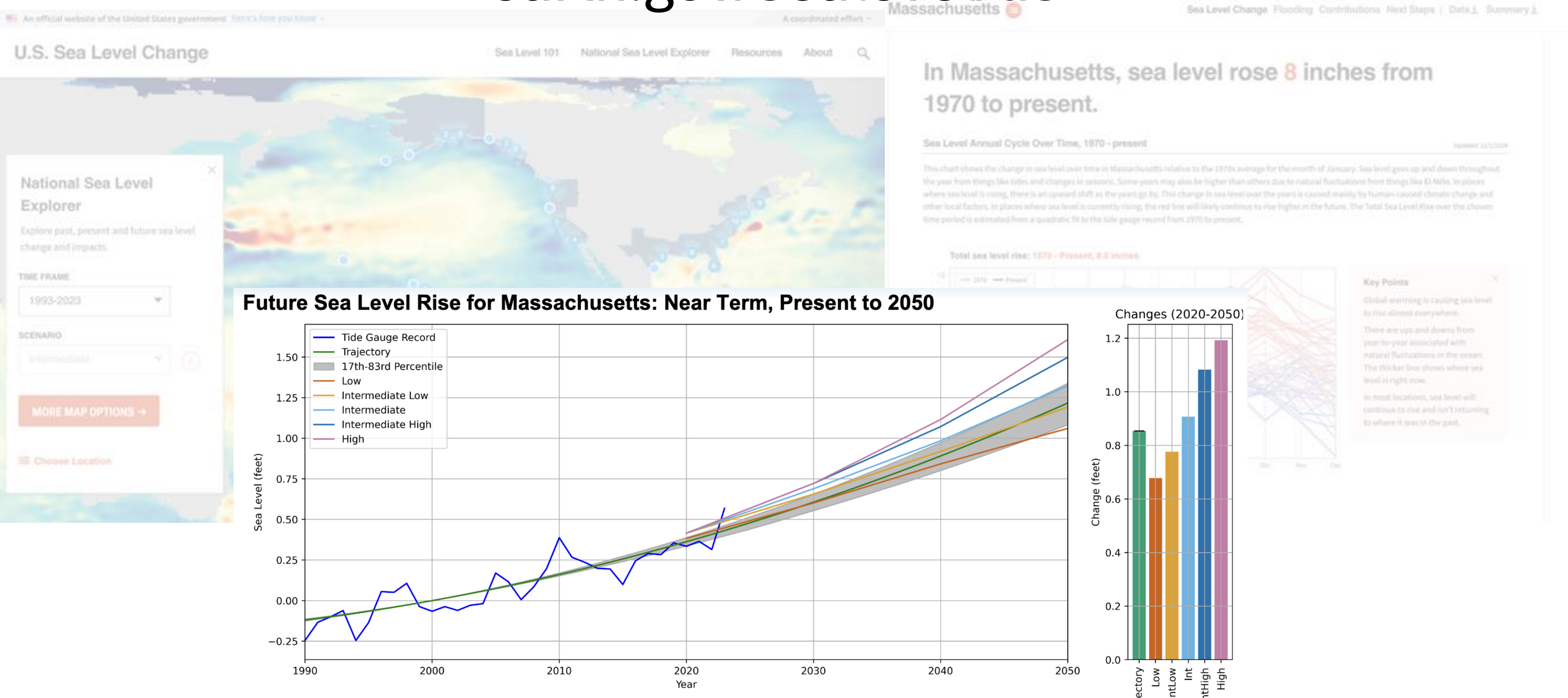
Sea Level Planning and Public Eductation

earth.gov/sealevel/us





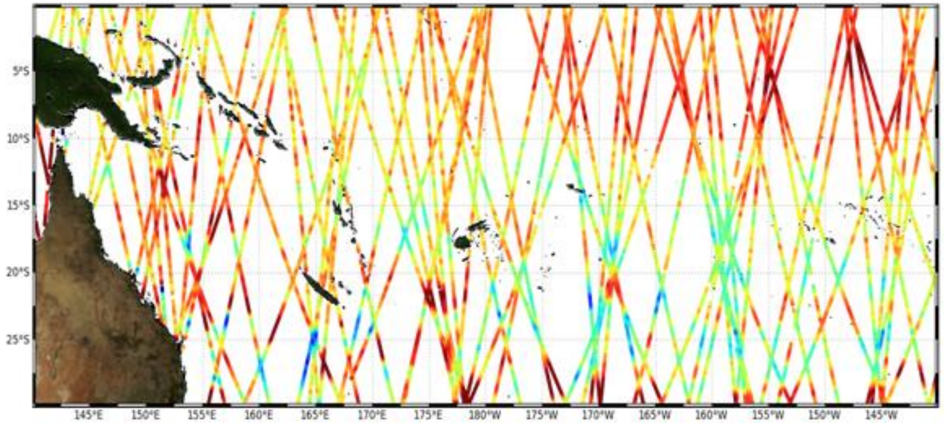
earth.gov/sealevel/us



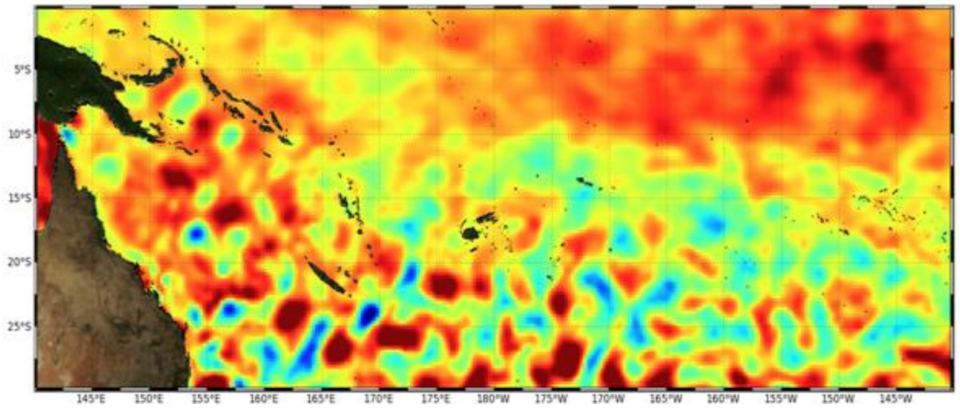
What does this show?

The figure shows sea level scenarios for Massachusetts from 2020 to 2050. The trajectory determined from the observations is shown for comparison. In 2050, the range across scenarios is relatively small. This narrow range, plus the comparison to the observation trajectory, provides additional context when choosing a scenario for planning in the near term.

Limits of conventional altimetry



https://duacs.cls.fr/



https://duacs.cls.fr/

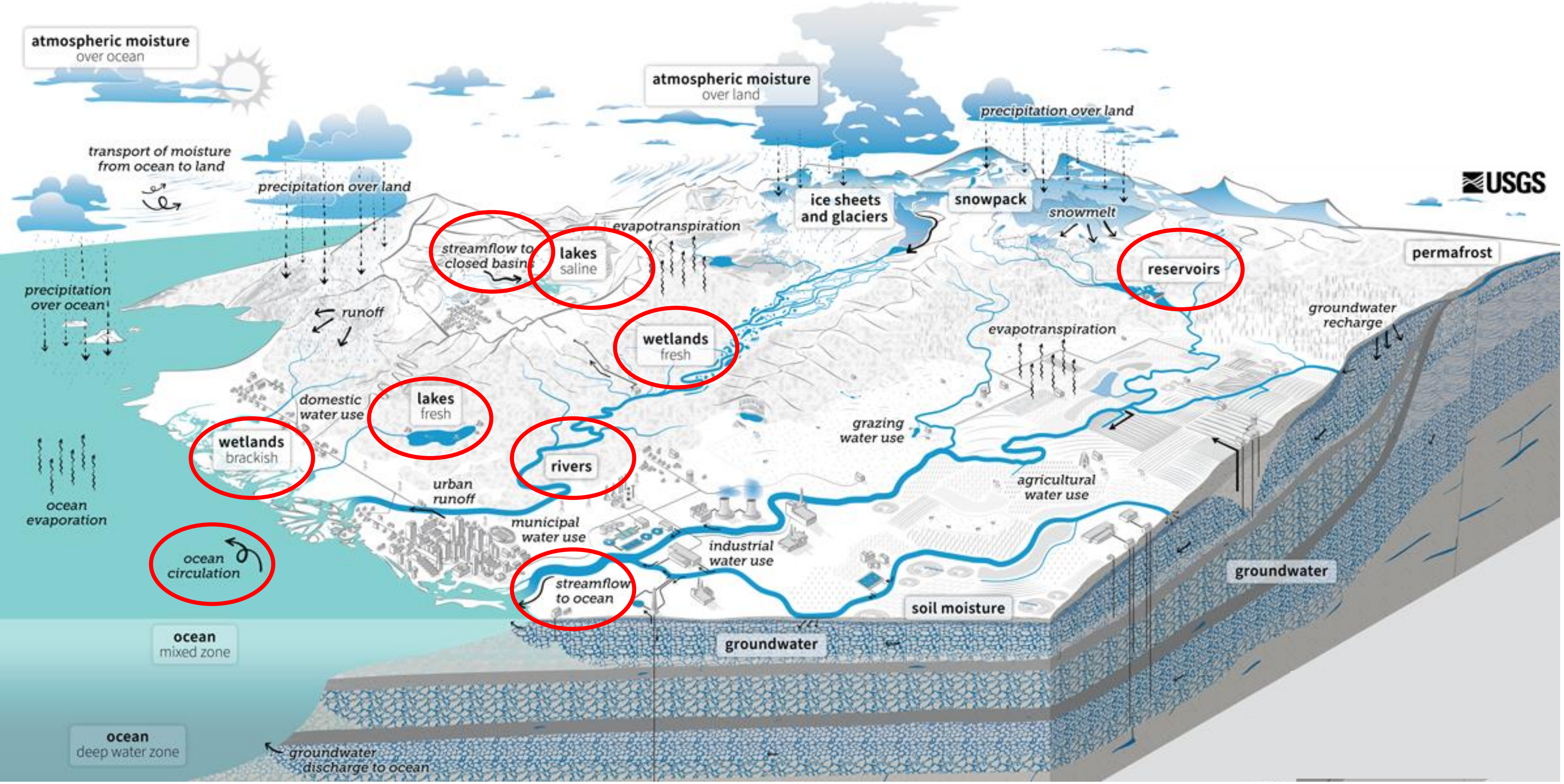
- One dimensional
- Meridionally-oriented sampling
- Instrument noise limits along-track resolution to ~50-km
- Coastal contamination leaves gaps

Requires mapping

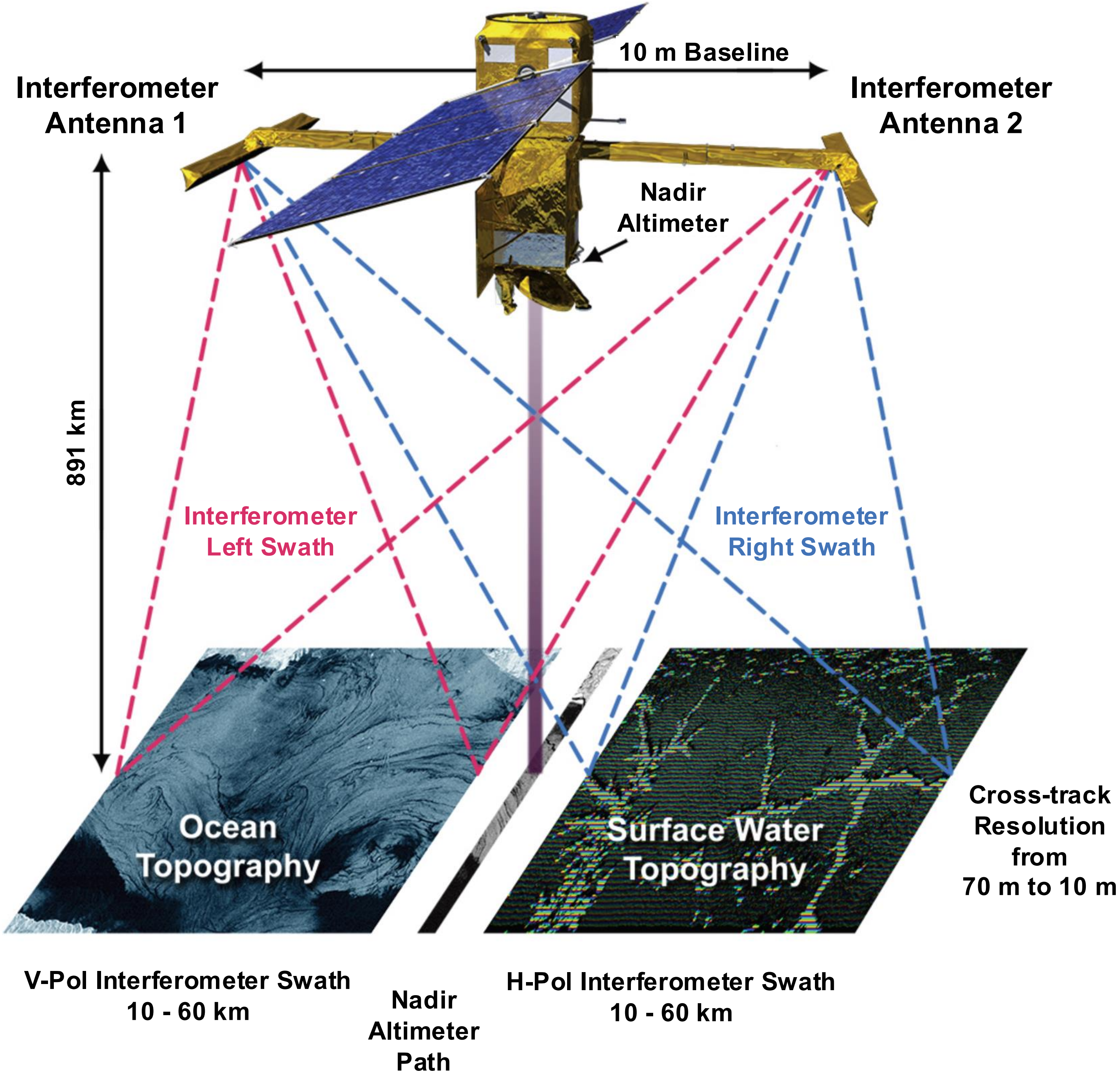
- Mapping is the important final step that allows for a wide range of scientific analyses, including:
  - 2-D geostrophic velocity
  - Eddy identification and tracking
  - Eddy fluxes

However, mapping limits resolution to > 150 km…

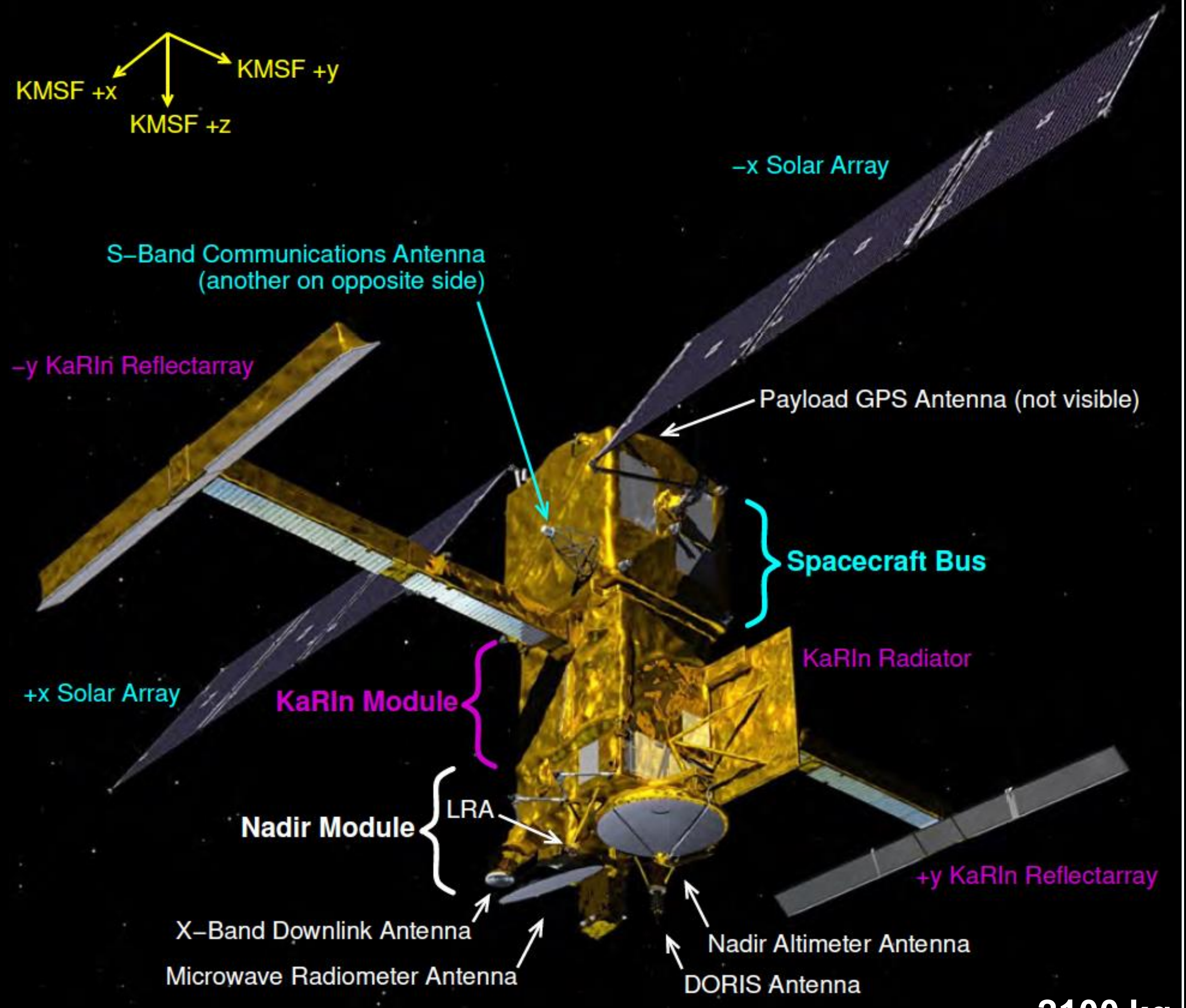
SWOT Provides Unprecedented Observations of Earth's Oceans and Surface Water



KaRIn is the **first wide swath altimeter** to observe the oceans, and SWOT is the first mission specifically designed to measure rivers and lakes



- **KaRIn provides unprecedented 2-D observations on a swath spanning 10–60 km from nadir**
  - High-accuracy interferometric surface heights
  - Synthetic aperture radar backscatter imagery
- **KaRIn has proven its capability to provide unprecedented observations:**
  - **Oceans**: Sea surface height at ~1 km resolution, versus ~50 km from traditional altimeters
  - **Inland water**: Water surface elevation and extent for rivers with > 30 m width and lakes > 1 hectare, at 10x better accuracy than traditional altimeters
- **Prior remote sensing instruments had key limitations**.
  - Imaging radars lacked elevation measurement
  - Nadir altimeters provided 1-D measurements along ground track

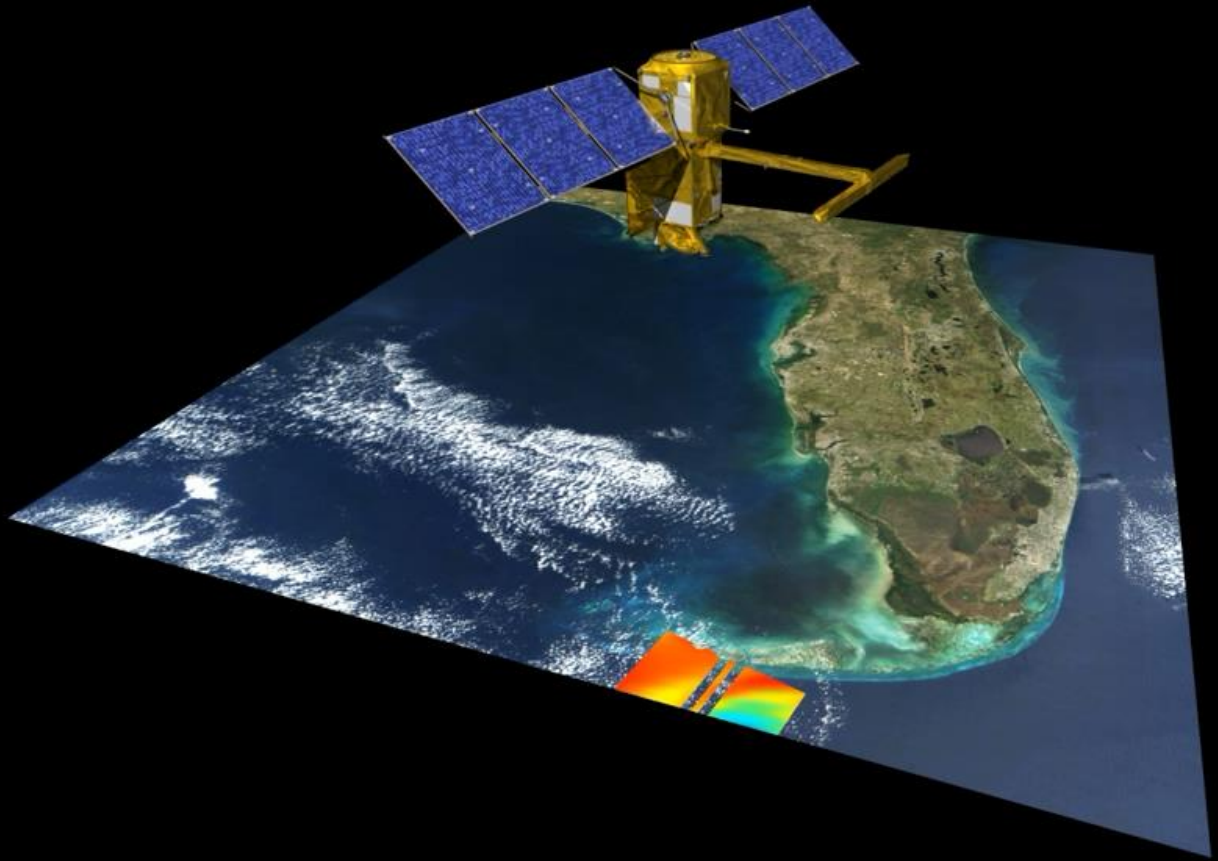


https://swot.jpl.nasa.gov/

2100 kg

- **KaRIn**
  - Ka-band radar interferometer
- **Nadir Altimeter**
  - Ku- and C-band; heritage instrument for consistency
  - Determines orbital height
- **X-Band**
  - High-rate data downlink
- **DORIS**
  - "Doppler Orbitography and Radiopositioning Integrated by Satellite"
  - Precise orbit demonstration, will pick up signals from 50-60 ground-based radio beacons
- **Microwave Radiometer**
  - Measures the amount of water vapor between SWOT and Earth's surface. More water vapor means slower signals
- **GPS**
  - More orbital determination

SWOT measures global **ocean** surface topography and **land surface water** extents & elevation with great accuracy using wide swath altimetry.

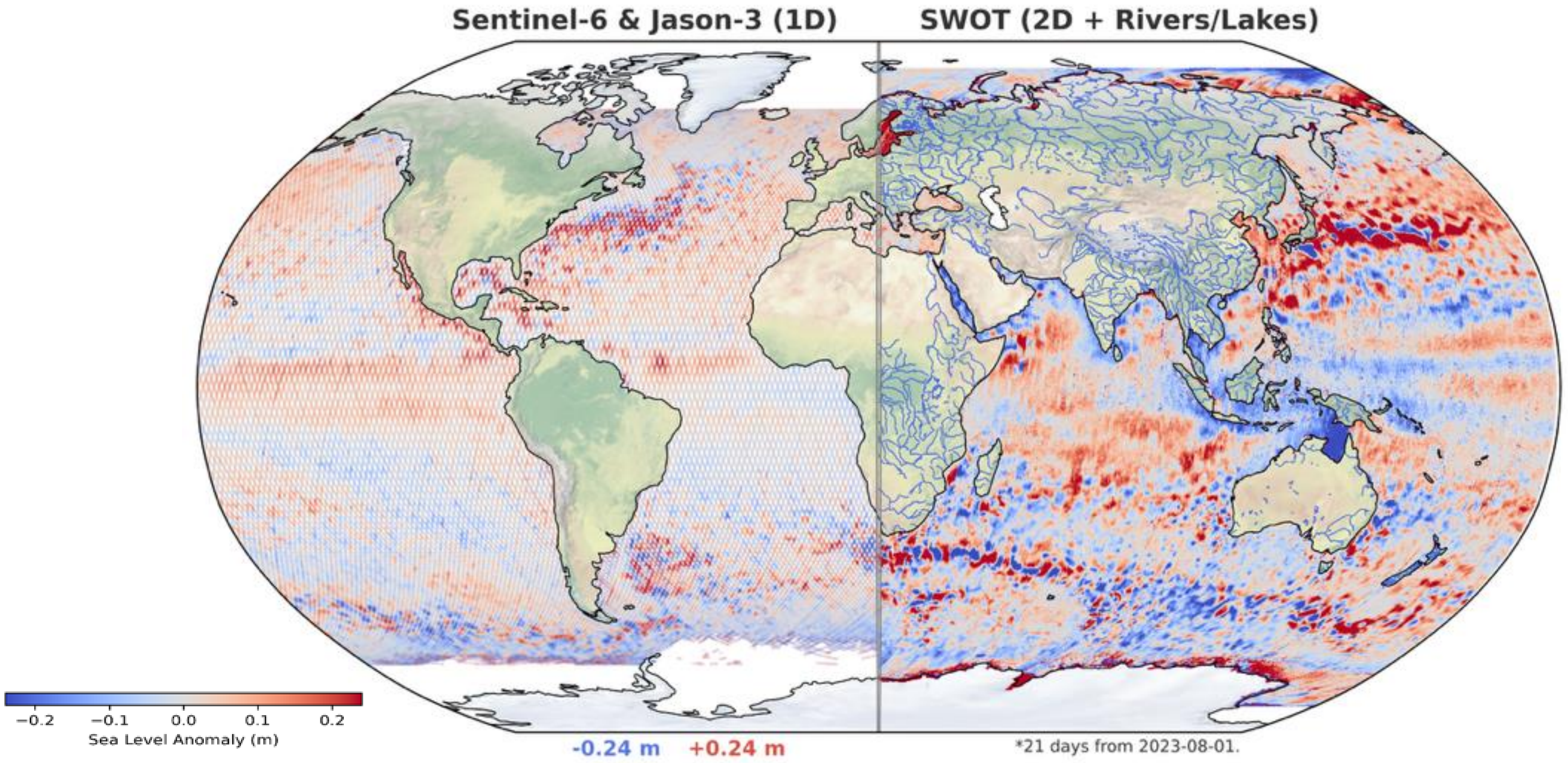


- Non-sunsynchronus orbit with coverage between 78 N/S (inclination of 77.6 deg)
- Launched: December 16, 2022
- Calibration and Validation Period: March 30 – July 10, 2023
- Prime Mission Complete: June 2026

https://swot.jpl.nasa.gov/

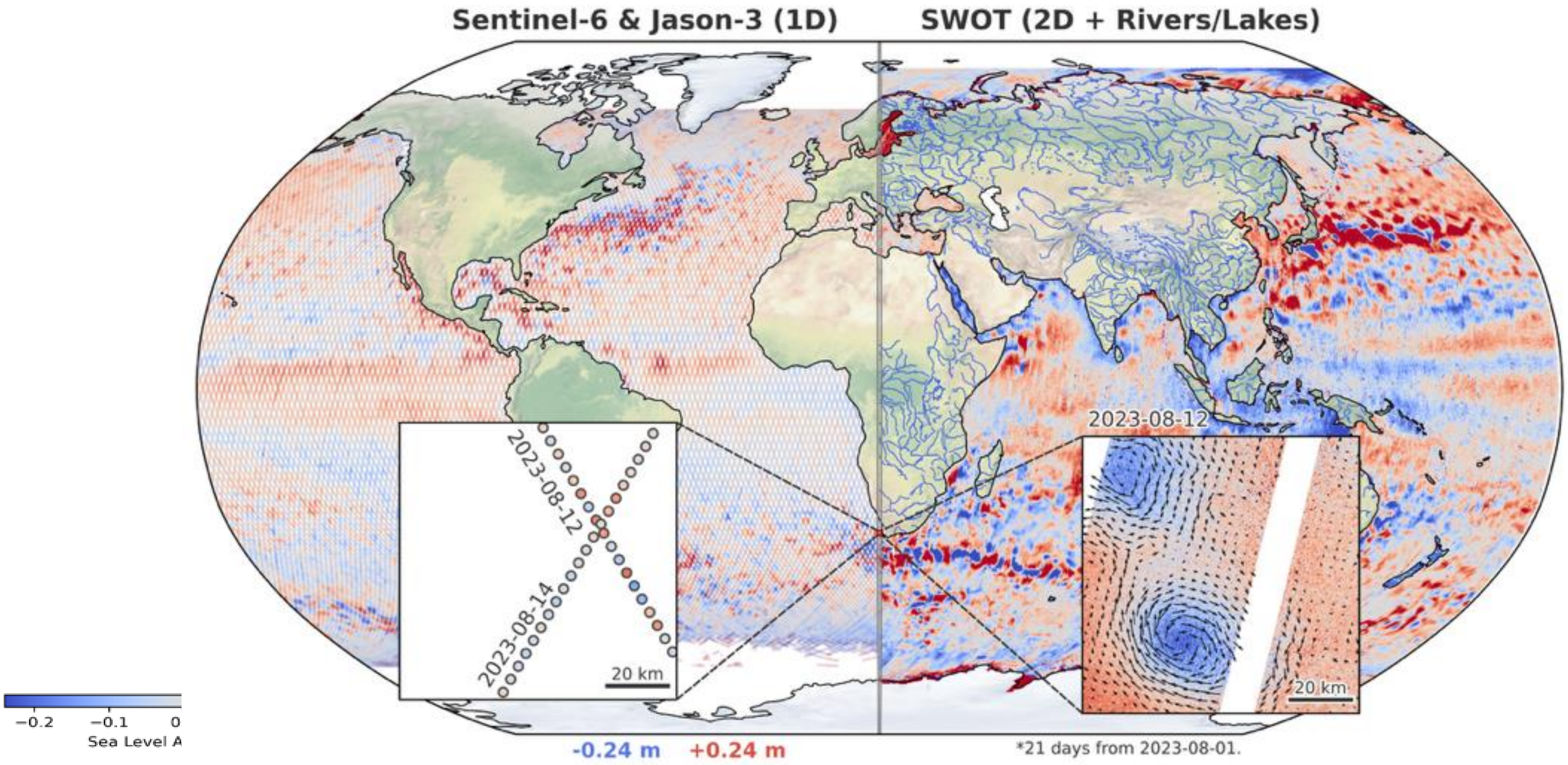
NASA/JPL-Caltech/CNES

SWOT's Two-Dimensional Observations Capture Fine Scale Structure of the Oceans and Inland Water



SWOT's 2-D measurements capture finer spatial structure than those from combination of multiple nadir altimeters

SWOT's Two-Dimensional Observations Capture Fine Scale Structure of the Oceans and Inland Water



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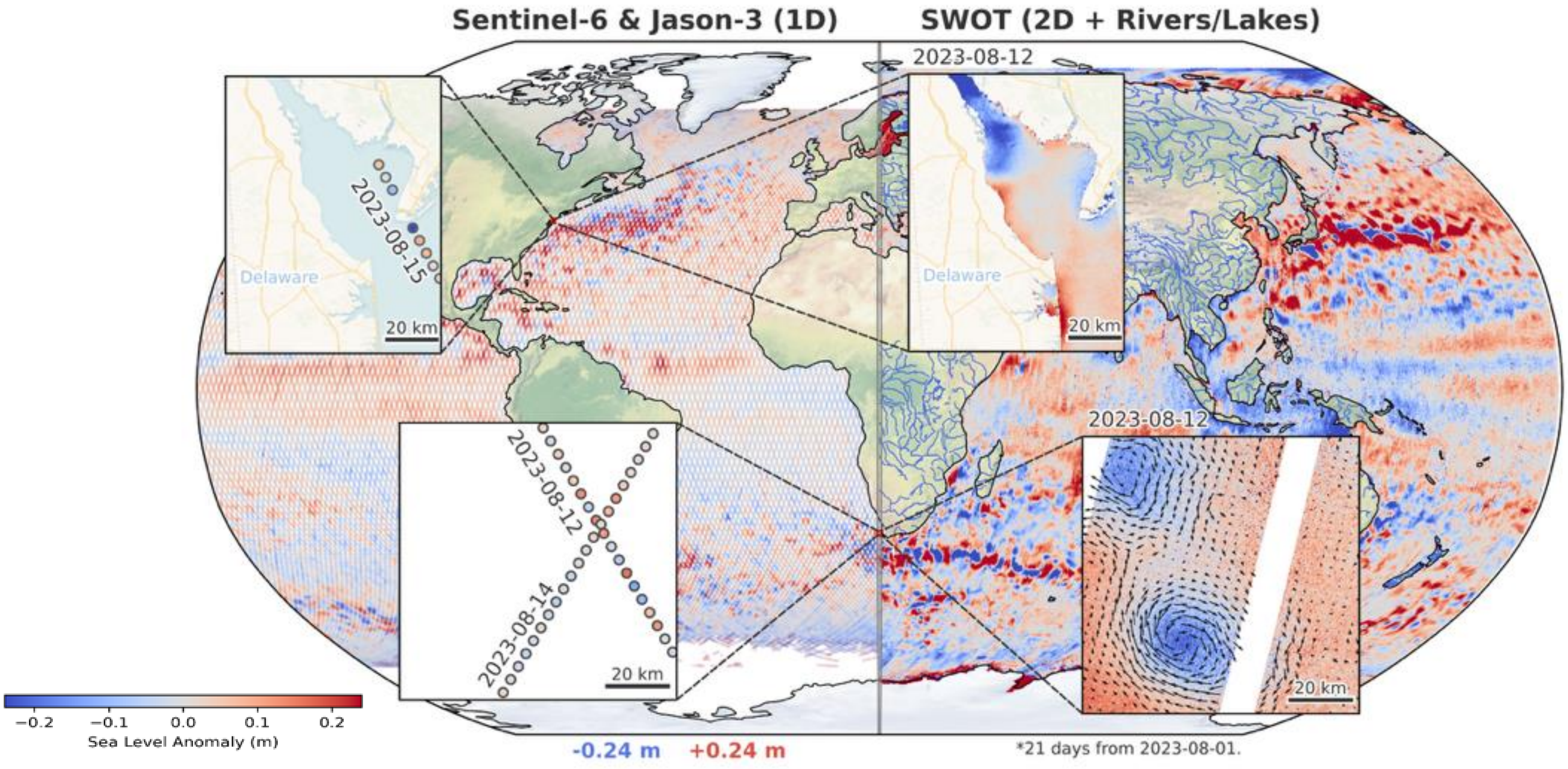
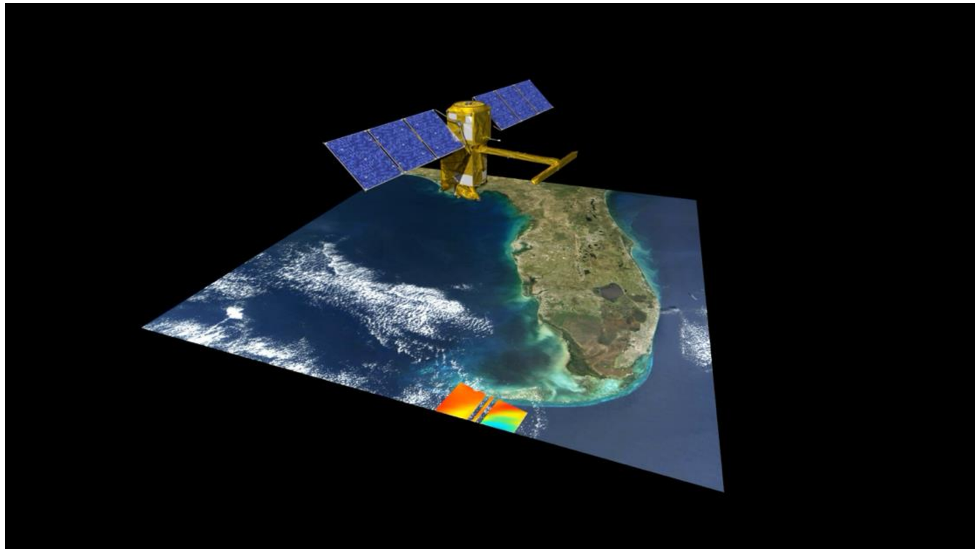
SWOT's Two-Dimensional Observations Capture Fine Scale Structure of the Oceans and Inland Water



Extended mission will provide observations of interannual variations in coastal dynamics and enable new coastal applications

CCS Summer School Project: SWOT Oceanography

Topic: SWOT Oceanography
Goal: Explore oceanographic data from the Surface Water and Ocean Topography mission – including calibration and geophysical corrections, ocean heights, and derived velocities - and validate against coastal tide gauge water level observations for applications to sea level rise coastal impacts.
Introduction: Global mean total sea level variations measured by satellite radar altimeters from 1993 to 2026 show an increase of 91.2 mm in global mean sea level since 1993. Coastal communities are now grappling with the regional expression of this mean height increase and preparing for flooding on a range of time scales. Historically, coastal sea level has been difficult to measure from space due to the large footprint of radar altimeters. The SWOT mission has opened a new door to both small scale ocean height features and coastal sea level which may be used to explore the range of dynamics impacting coastal sea level rise impacts.
Datasets:
NASA/CNES SWOT Level 3 Low Rate Data
NOAA Tide Gauge Data
NOAA VDatum API



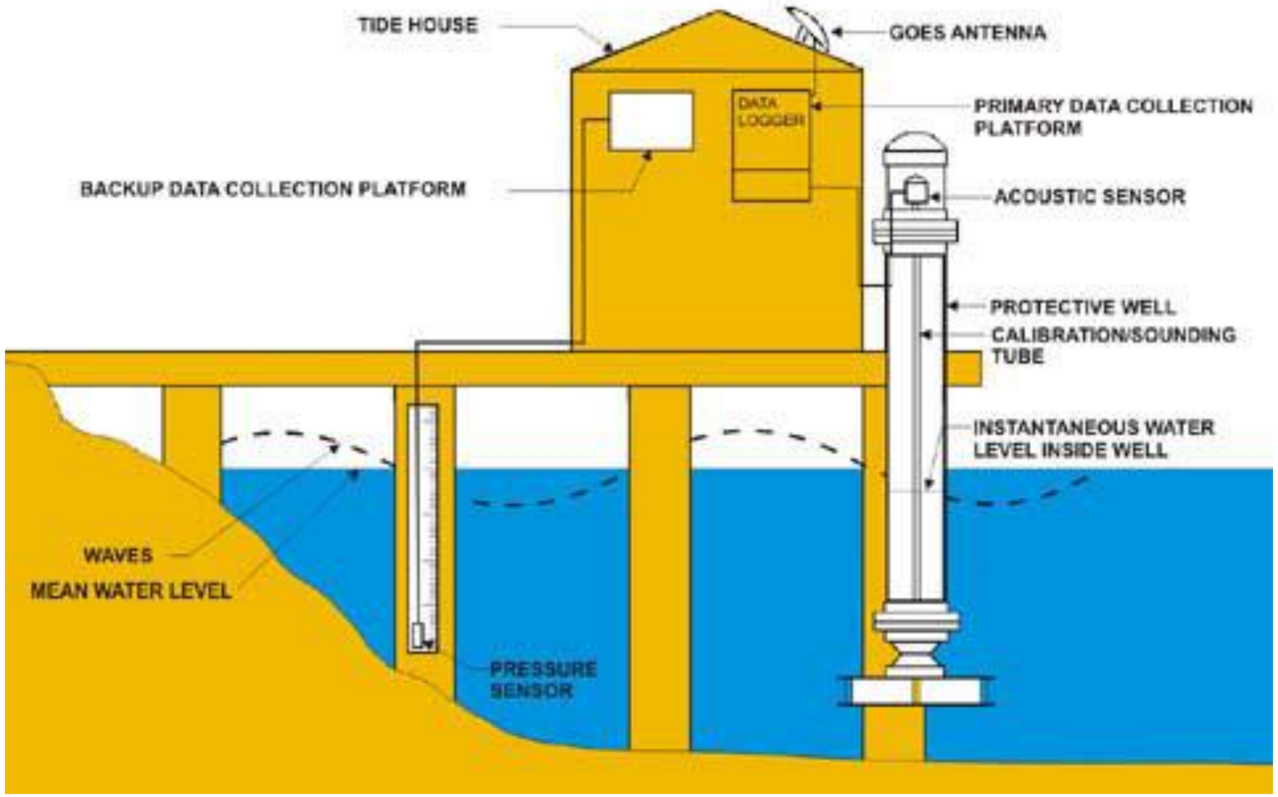
Level 3 Ocean (LR) Products

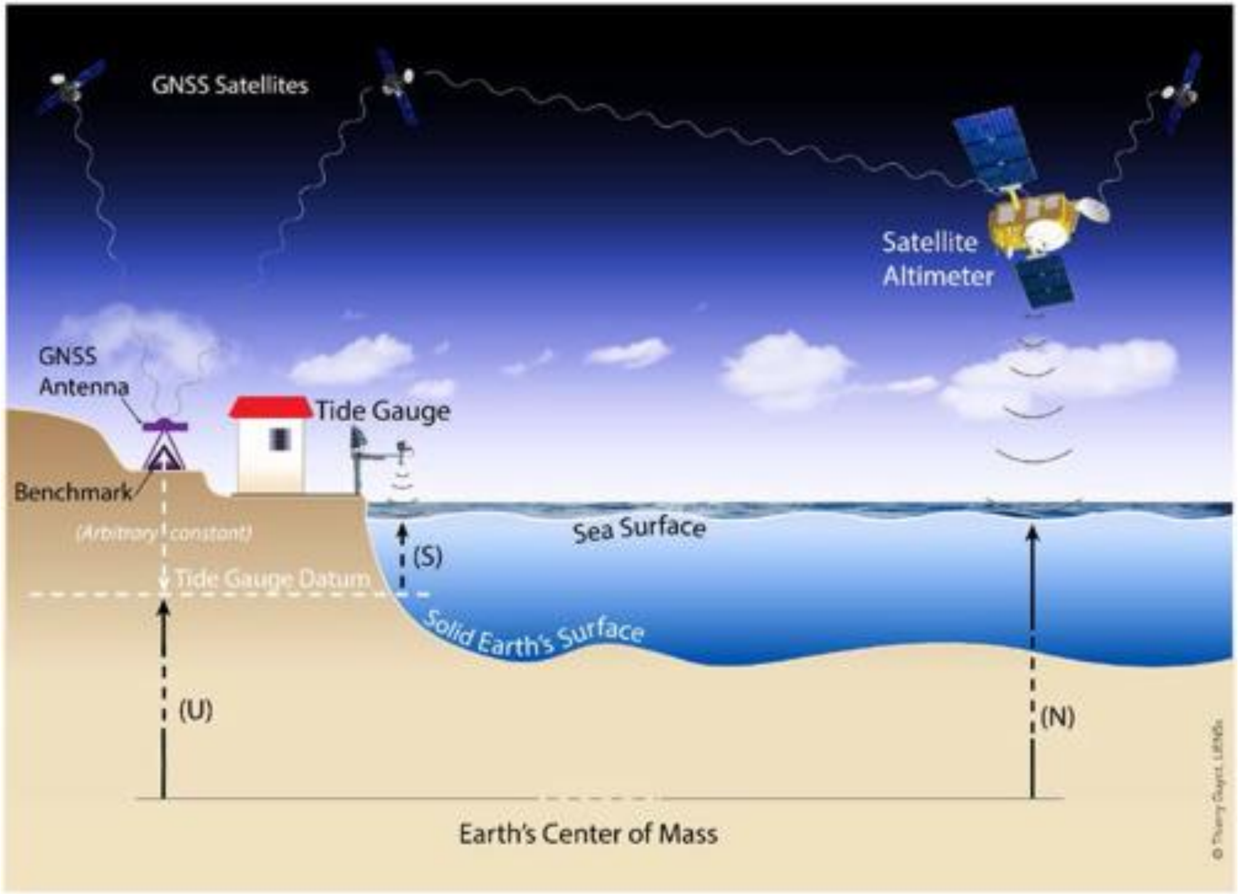
SWOT_L3_LR_SSH product

Product files	Version	AVISO Distribution services	Delivery delay	Grid	File size	Handbook
SWOT_L3_LR_SSH ['Basic']	v2.0.1	CNES AVISO FTP/SFTP access (with AVISO+ credentials): • ftp://ftp-access.aviso.altimetry.fr:21 • ftp://ftp-access.aviso.altimetry.fr:2122 • /swot_products/l3_karin/l3_lr_ssh CNES AVISO THREDDS Data Server access (with AVISO+ credentials): https://tds-odatis.aviso.altimetry.fr/thredds/catalog/dataset-l3-swot-karin-nadir-validated/l3_lr_ssh/catalog.html	-	2 km	<4MB	SWOT_L3_LR_SSH User Handbbok
	v2.0					
	v1.0					
	v0.3					
SWOT_L3_LR_SSH ['Expert']	v2.0.1		-	2 km	<12MB	
	v2.0					
	v1.0					
	v0.3					
SWOT_L3_LR_SSH ['Unsmoothed']	v2.0.1		-	250 m	<120MB	
	v1.0.2					
	v1.0.1					
	v1.0					

https://www.aviso.altimetry.fr/en/missions/current-missions/swot/swot-ocean-data-access.html

Tide Gauge Coastal Sea Level Observations





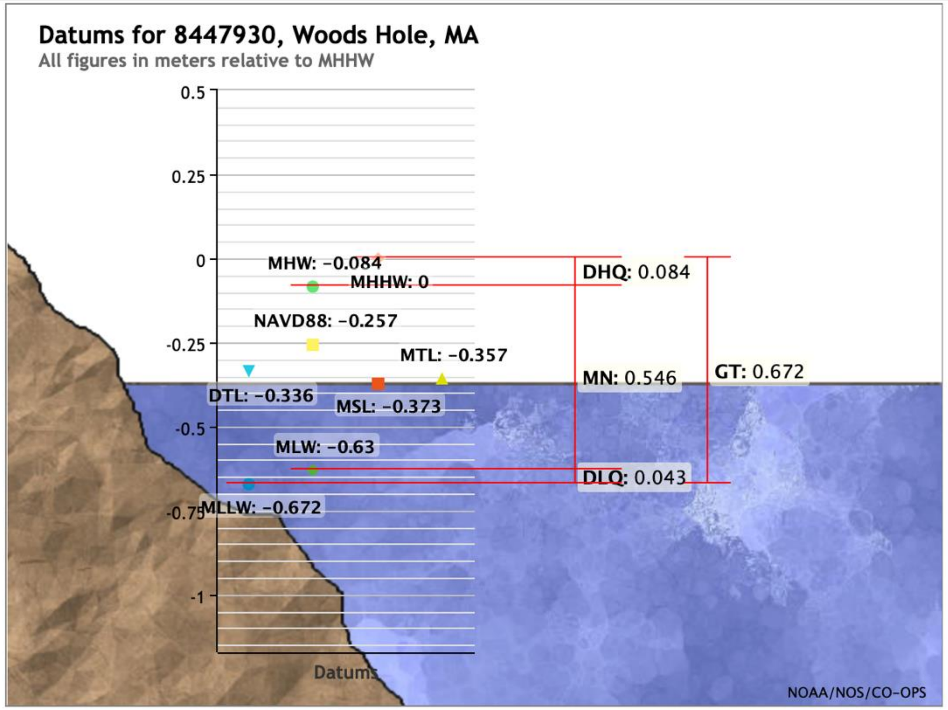
Datums

- **National Tidal Datum Epoch**The specific 19-year period (~the period of the nodal cycle) adopted by the National Ocean Service as the official time segment over which tide observations are taken and reduced to obtain mean values (e.g., mean lower low water, etc.) for tidal datums. It is necessary for standardization because of periodic and apparent secular trends in sea level.
- **MHHW** = The average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch.
- This height typically delineates perennial inundation.

Elevations on Mean Higher High Water

Station: 8447930, Woods Hole, MA **T.M.:** 75
Status: Accepted (Apr 17 2003) **Epoch:** 1983-2001
Units: Meters **Datum:** MHHW
Control Station:

Datum	Value	Description
MHHW	0.000	Mean Higher-High Water
MHW	-0.084	Mean High Water
MTL	-0.357	Mean Tide Level
MSL	-0.373	Mean Sea Level
DTL	-0.336	Mean Diurnal Tide Level
MLW	-0.630	Mean Low Water
MLLW	-0.672	Mean Lower-Low Water
NAVD88	-0.257	North American Vertical Datum of 1988
STND	-1.469	Station Datum
GT	0.672	Great Diurnal Range
MN	0.546	Mean Range of Tide
DHQ	0.084	Mean Diurnal High Water Inequality
DLQ	0.043	Mean Diurnal Low Water Inequality
HWI	0.675	Greenwich High Water Interval (in hours)
LWI	7.866	Greenwich Low Water Interval (in hours)
Max Tide	2.615	Highest Observed Tide
Max Tide Date & Time	09/21/1938 00:00	Highest Observed Tide Date & Time
Min Tide	-1.667	Lowest Observed Tide
Min Tide Date & Time	02/02/1976 17:24	Lowest Observed Tide Date & Time



Showing datums for
8447930 Woods Hole, MA

Datum
MHHW

Data Units ○ Feet
◉ Meters

Epoch ◉ Present (1983-2001)
○ Superseded (1960-1978)

https://tidesandcurrents.noaa.gov/stationhome.html?id=8447930

Vdatum

NOAA NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
UNITED STATES DEPARTMENT OF COMMERCE

VERTICAL DATUM TRANSFORMATION
INTEGRATING AMERICA'S ELEVATION DATA

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Welcome to VDatum!

VDatum is a free software tool being developed jointly by NOAA's National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic Products and Services (CO-OPS). VDatum is designed to vertically transform geospatial data among a variety of tidal, orthometric and ellipsoidal vertical datums - allowing users to convert their data from different horizontal/vertical references into a common system and enabling the fusion of diverse geospatial data in desired reference levels.

Important:

- Understanding how the Western Gulf Coast Roadmap differs from the normal Roadmap
- Understanding how the Puerto Rico and US Virgin Island Roadmap differs from the normal Roadmap
- We retired the Raster Formats (GeoTIFF and ERDAS IMG) in the File Conversion.
- Understanding how the Columbia River Roadmap differs from the normal Roadmap
- Understanding how the West Coast Roadmap differs from the normal Roadmap
- Understanding how Chesapeake/Delaware Bay Transformation Roadmap differs from the normal roadmap

View more

Download v4.8

Download the latest VDatum **(v4.8)** and its datasets.

Revision Log

Click to Subscribe

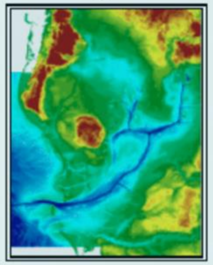
One-Pager

Features

VDatum software is written in Java, so it runs on Mac OS X, Unix, VMP, and Windows. **About Java Home**

Where available and uncertainties are established, VDatum supports the conversions among following:

- **Coordinate Systems:** Geographic, UTM, State Plane Coordinates (SPC), and geocentric (ECEF)
- **Horizontal Datums:** NAD27, NAD83_2011, NAD83_1986, NAD83_FBN, and NAD83_HARN; and ellipsoidal datums such as of ITRF, WGS84, and NAD83 serializations
- **Vertical Datums:**
  - **Ellipsoidal Datums:** NAD83_2011, WGS84, ITRF88, ITRF89, ITRF90, NEOS 90, PNEOS 90, ITRF91, ITRF92, SIO/MIT 92, ITRF93, ITRF94, ITRF96, ITRF97, IGS97, ITRF2000, ITRF2020, IGS00, IGb00, ITRF2005, IGS05, ITRF2008, IGS08, ITRF2014, IGS14, WGS84(transit), WGS84(G730), WGS84(G873), WGS84(G1150), WGS84(G1674), NAD83(PACP00), NAD83(MARP00)
  - **Orthometric Datums:** NAVD88, NGVD29, PRVD02, VIVD09, ASVD02, GUVD04, NMVD03, HAWAII, EGM2008, EGM1996, and EGM1984
  - **Tidal Datums:** MLLW, MLW, LMSL, DTL, MTL, MHW, LWD, MHHW and Local Tidal(LT)
  - IGLD85, LWD IGLD 1985, OHWM IGLD 1985
- **GEOID models:** **GEOID18**, GEOID12B, GEOID12A, GEOID09, GEOID06 (Alaska only), GEOID03, GEOID99, and GEOID96
- **EGM models:** EGM2008, EGM1996, and EGM1984
- **xGEOID models:** xGEOID16b, xGEOID17b, xGEOID18b, xGEOID19b, and xGEOID20b
- **Supported file format:** text(ASCII), LiDAR(.LAS, *.LAZ) version 1.0, 1.1, 1.2 and 1.4 with Classification, ESRI ASCII Raster(.ASC), ESRI 3D shapefile
- **NOAA VDatum APIs:** **Full API**



Integrated Bathy/Topo DEM

https://vdatum.noaa.gov/

Vdatum

- Use the API to convert TG data to be relative to ellipsoidal height in order to compare with SWOT SSH

```python
station = 8447930  ## station id of woodhole tg
t0 = 2023
tf = 2025
#datum_corr = 30.212


import requests

params = {
    "s_x": "-70.40", # input longitude
    "s_y": "41.31",  # input latitude
    "region" : "contiguous",
    "s_h_frame" : "NAD83_2011", # Input Source Horizontal Reference Frame.
    "s_v_frame" : "NAVD88",  # Input Source Vertical Reference Frame.
    "t_h_frame": "WGS84_G2296", # Target Source Horizontal Reference Frame.
    "t_v_frame": "WGS84_G2296" # Target Source Vertical Reference Frame.
}

response = requests.get(
    "https://vdatum.noaa.gov/vdatumweb/api/convert",params=params)

data = response.json()
datum_corr = pd.to_numeric(data["t_z"])
print("Converted height:", datum_corr)

sl, time = noaa_sealevel(station, t0, tf)
sl = sl + datum_corr


df_tg = pd.DataFrame({'time': pd.to_datetime(time),'sea_level': sl})#, #index=pd.to_datetime(time))
```

Resources

1. Agency Websites, SWOT General Handbook, SWOT L3 Handbook, and SWOT L2 Product Descriptions
2. Hamlington, B. D., Willis, J. K., & Vinogradova, N. (2023). The emerging golden age of satellite altimetry to prepare humanity for rising seas. Earth's Future, 11, e2023EF003673. https://doi.org/10.1029/2023EF003673
3. Pegliasco, C., Delepoulle, A., Mason, E., Morrow, R., Faugère, Y., and Dibarboure, G.: (2022). META3.1exp: a new global mesoscale eddy trajectory atlas derived from altimetry, Earth Syst. Sci. Data, **14**, 1087–1107, https://doi.org/10.5194/essd-14-1087-2022
4. Stammer, D., & Cazenave, A. (Eds.). (2017). *Satellite altimetry over oceans and land surfaces*. CRC press.
5. Tranchant, Y.-T., Legresy, B., Foppert, A., Pena-Molino, B., & Phillips, H. (2025). SWOT reveals fine-scale balanced motions driving near-surface currents and dispersion in the Antarctic Circumpolar Current. Earth and Space Science, **12**, e2025EA004248. https://doi.org/10.1029/2025EA004248
6. Vignudelli, S., Kostianoy, A. G., Cipollini, P., & Benveniste, J. (Eds.). (2011). *Coastal altimetry*. Springer Science & Business Media.
7. Vignudelli, S., Birol, F., Benveniste, J. *et al*. Satellite Altimetry Measurements of Sea Level in the Coastal Zone. *Surv Geophys* **40**, 1319–1349 (2019). https://doi.org/10.1007/s10712-019-09569-1