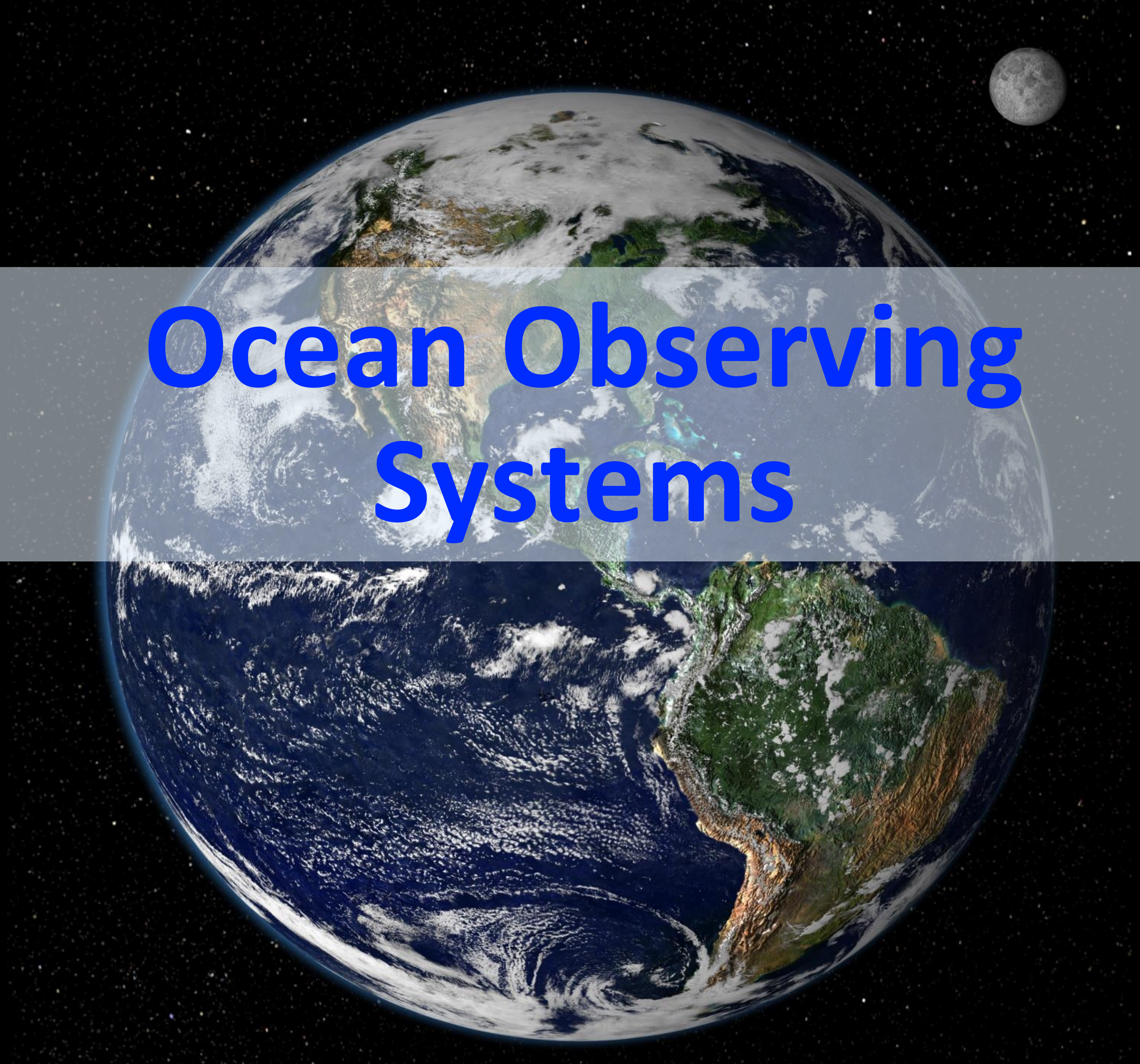
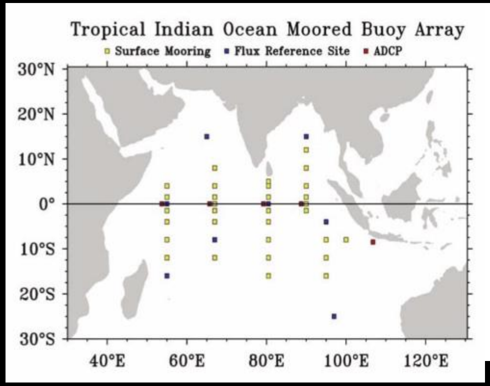
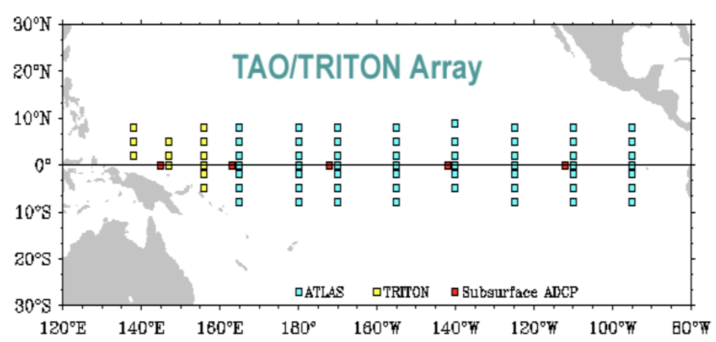
Ocean Observing Systems

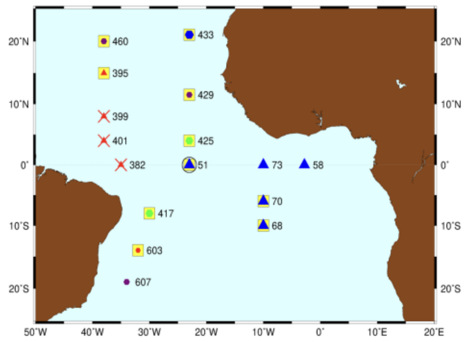


Séverine Fournier – NASA JPL/Caltech

In Situ Observations

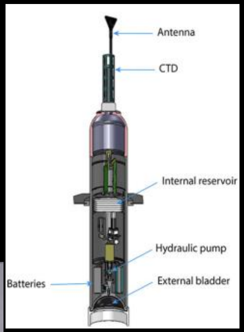


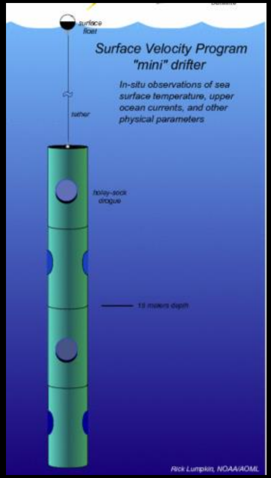


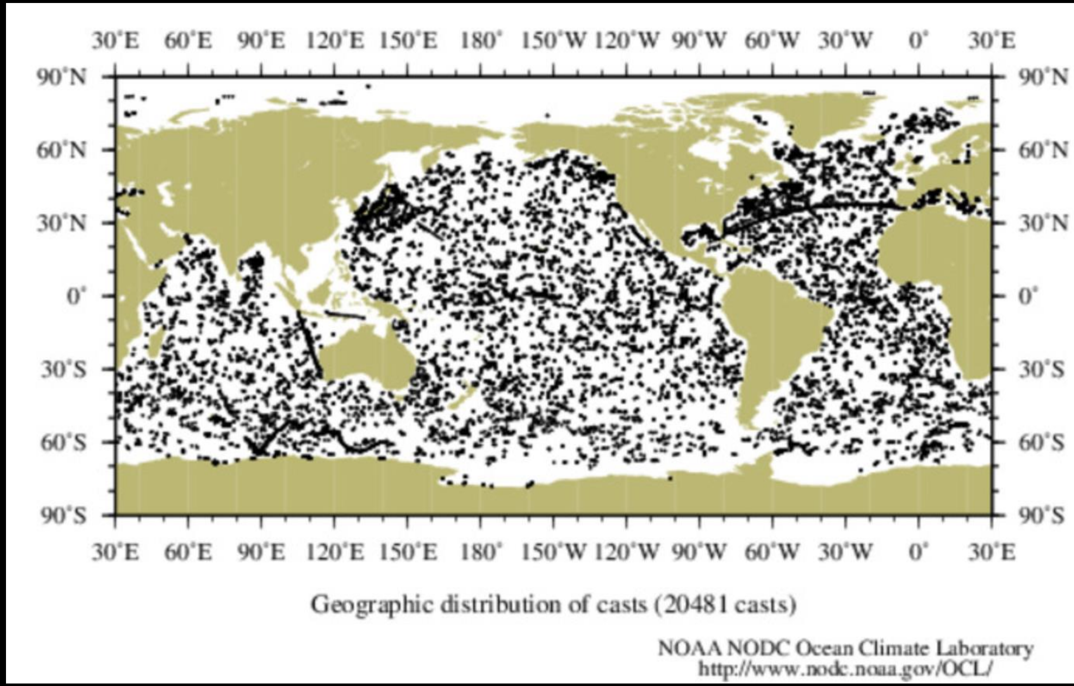


Moorings:
TAO/TRITON (Pacific)
PIRATA (Atlantic Ocean)
RAMA (Indian Ocean)

Argo, TSG, moored buoys, drifting buoys, CTD, marine mammals, XBT, drifters, etc. -> temperature, salinity but also velocities, biogeochemistry observations



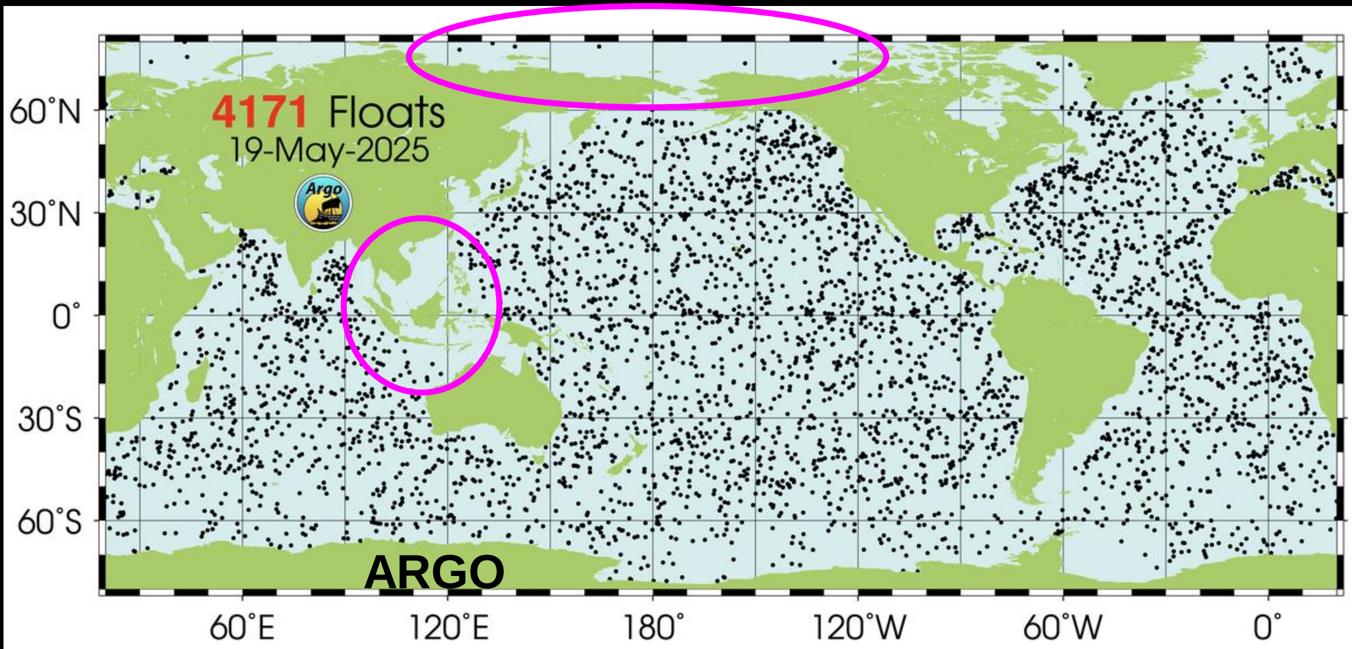


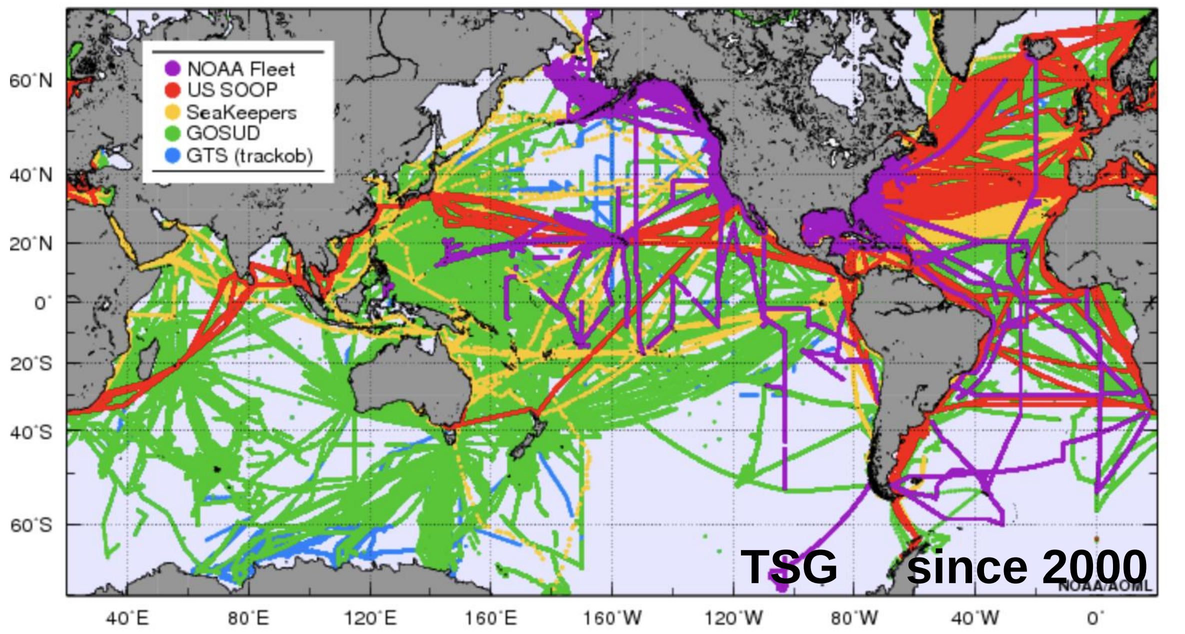


argo.ucsd.edu; www.aoml.noaa.gov/; www.pmel.noaa.gov/; www.ncei.noaa.gov/

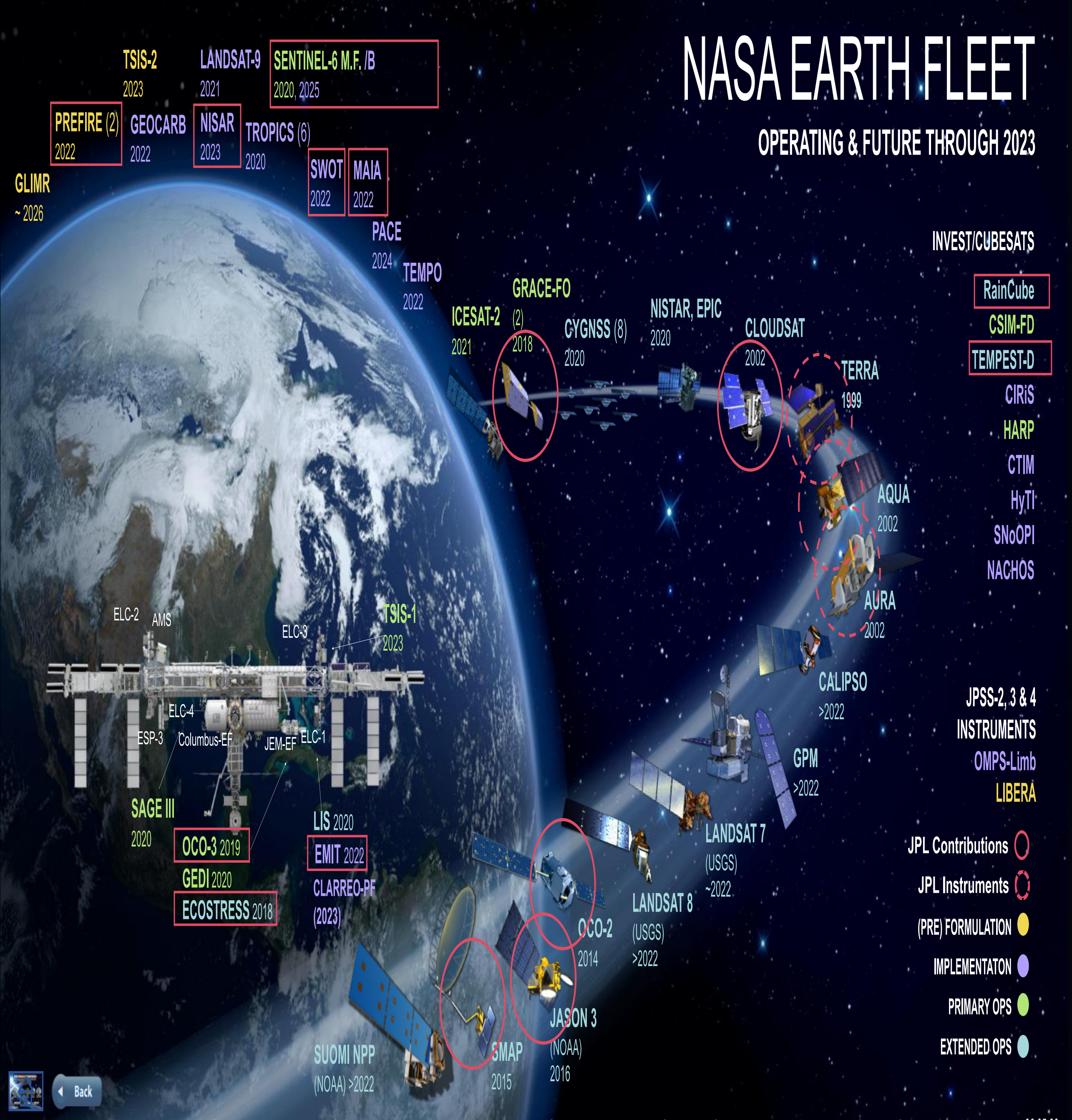
In Situ Observations

- Very accurate
- Extremely important for calibration and validation of satellite data
- Complementary of satellite data, 3D view
- Pointwise measurements
- Specific single time
- Limitations: spatial: limited coverage (especially in marginal seas and coastal regions)
  temporal: doesn't always allow to resolve all time scales





Credit: ESA (https://www.esa.int/ESA_Multimedia/Images/2019/05/ESA-developed_Earth_observation_missions)



Credit: NASA/JPL (https://earth.jpl.nasa.gov/resources/103/nasa-earth-fleet/)

Satellite Ocean Observing System – List non exhaustive

- Altimetry:
  - Sea Surface Height
  - Ocean Currents
  - Sea ice properties

- Gravimetry – Mass

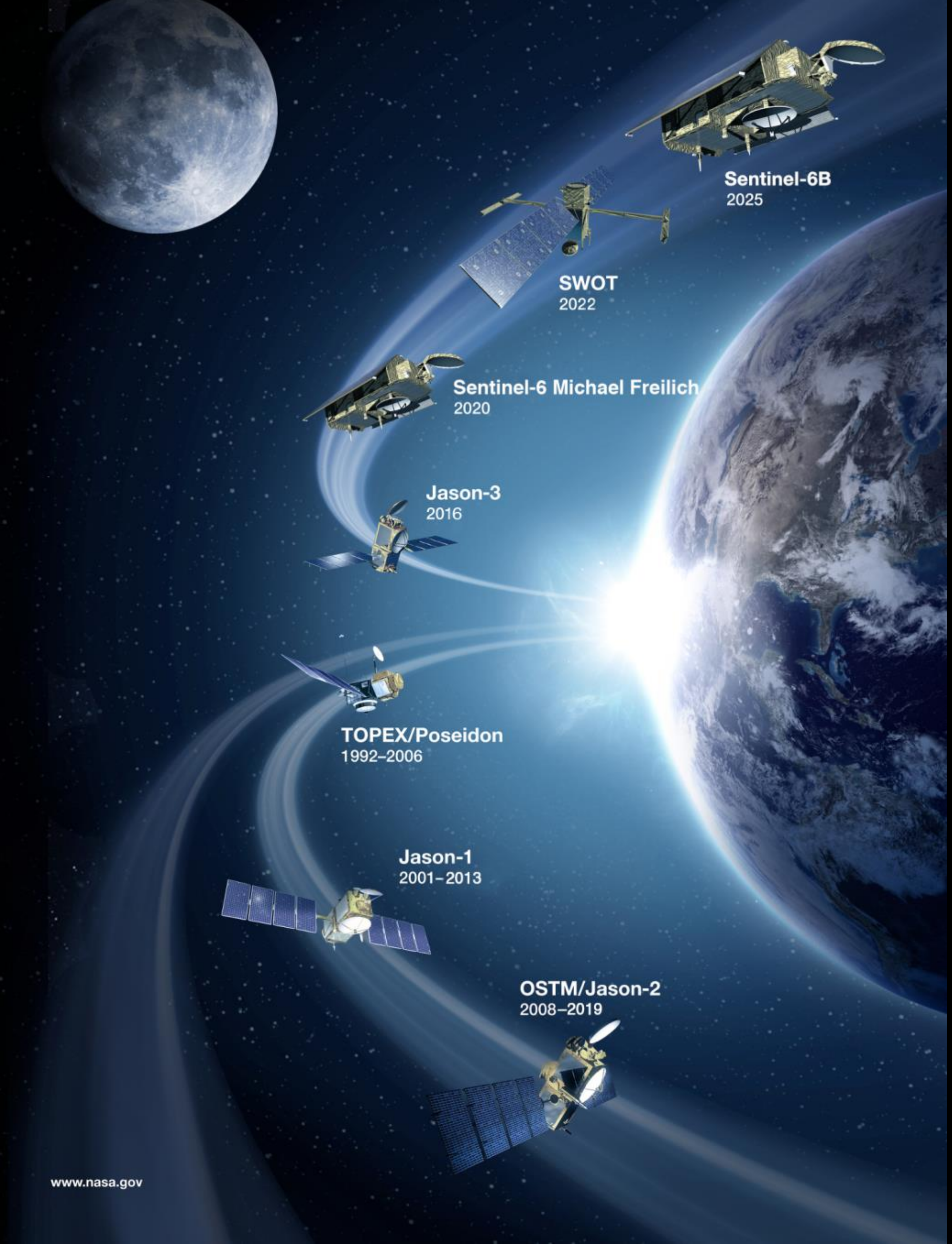
- Radiometry:
  - Sea Surface Salinity
  - Sea Surface Temperature
  - Ocean Color
  - Sea Ice properties
  - Sea Surface Winds

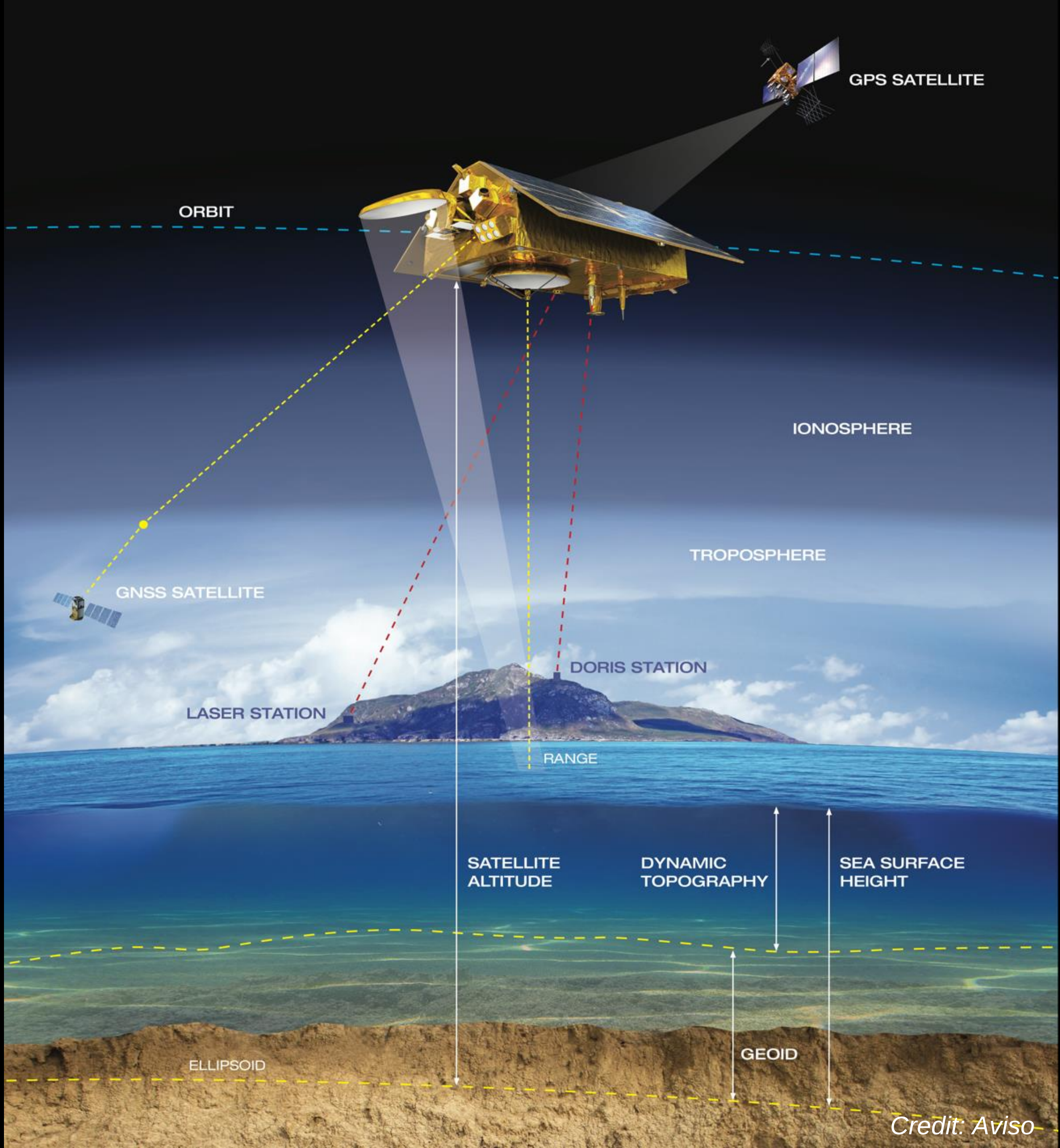
- Scatterometry – Sea Surface Winds

Altimetry

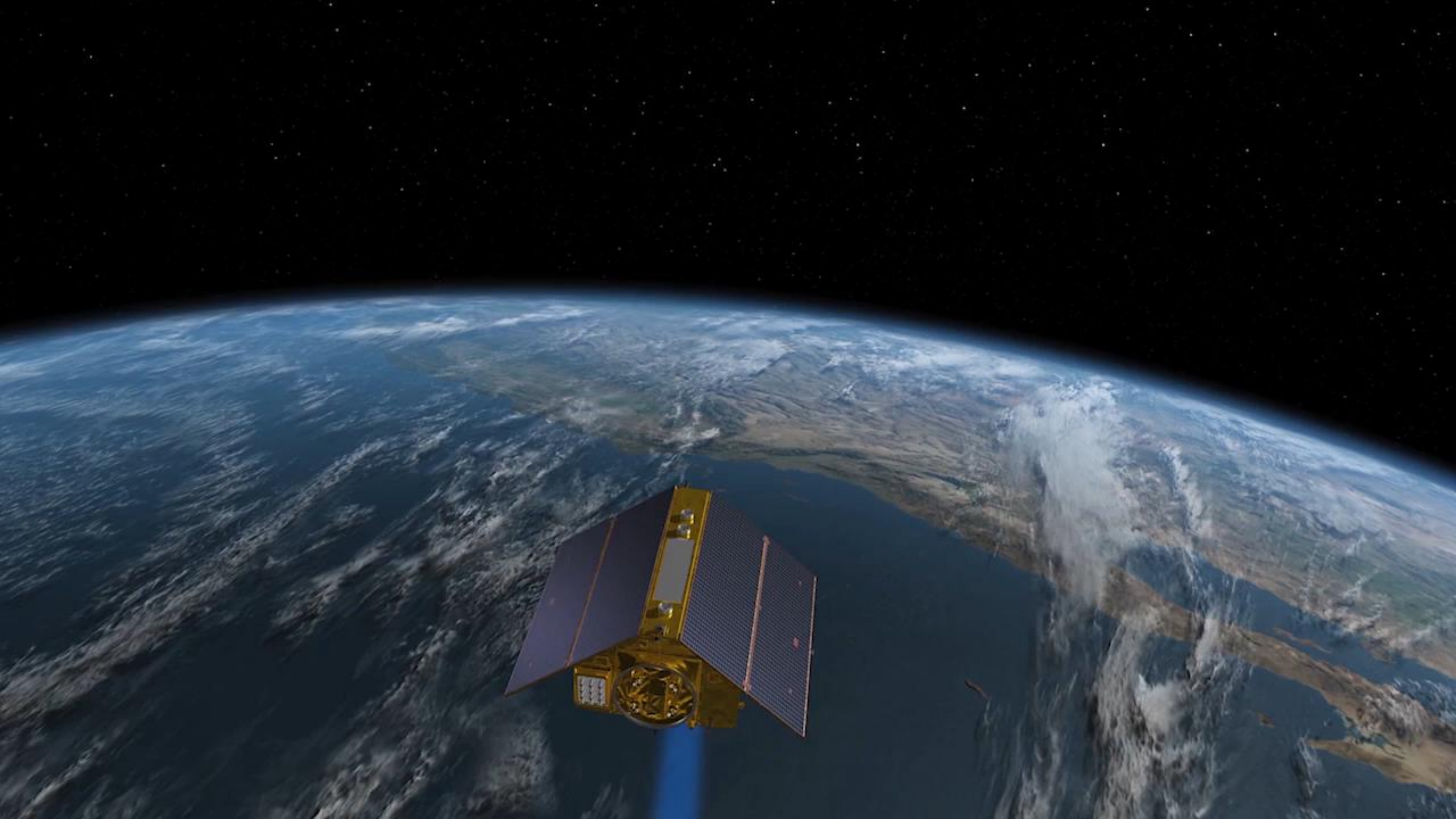
Reference Mission: T/P, J1, J2, J3, S6MF, S6B

How altimeters work

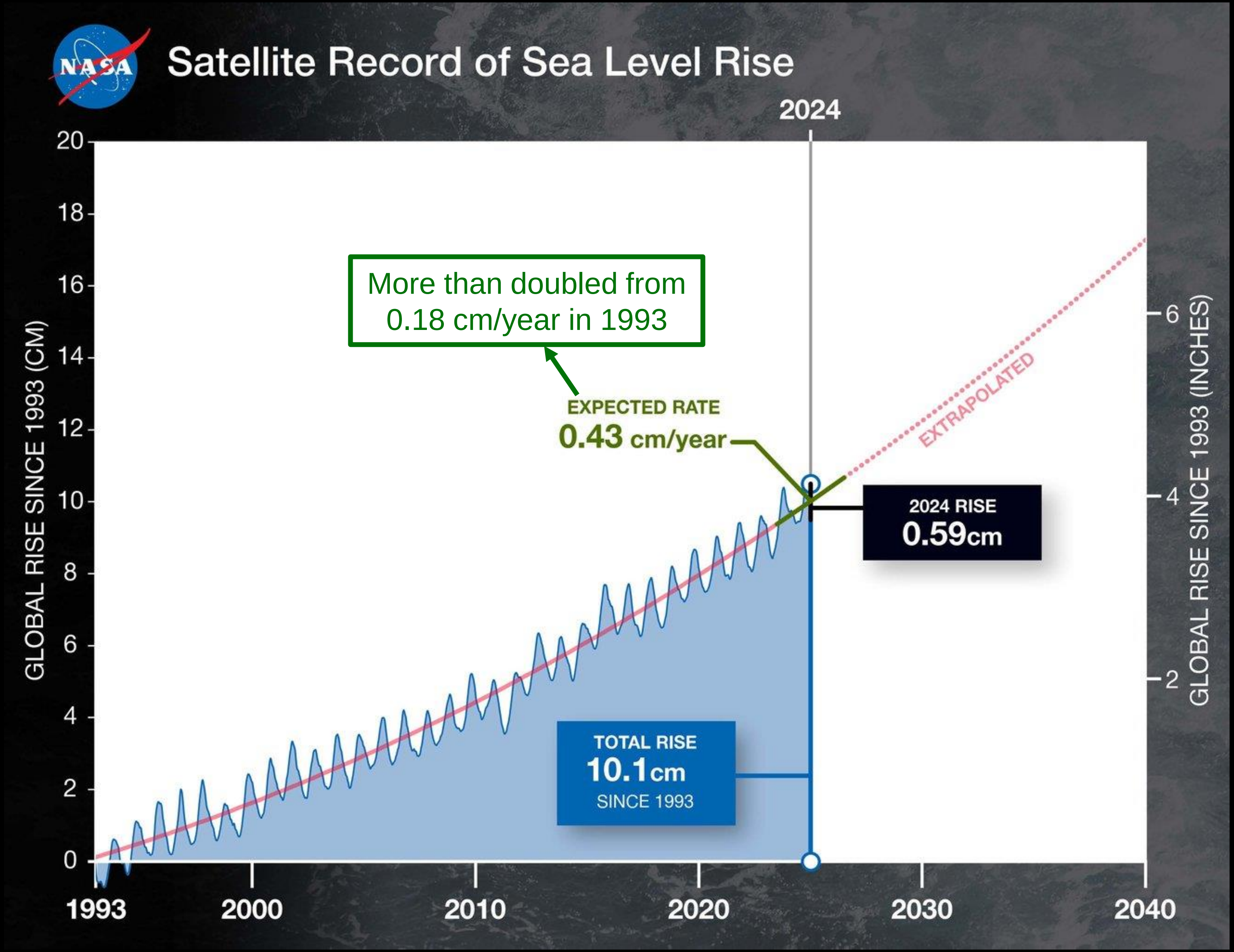




Credit: Aviso

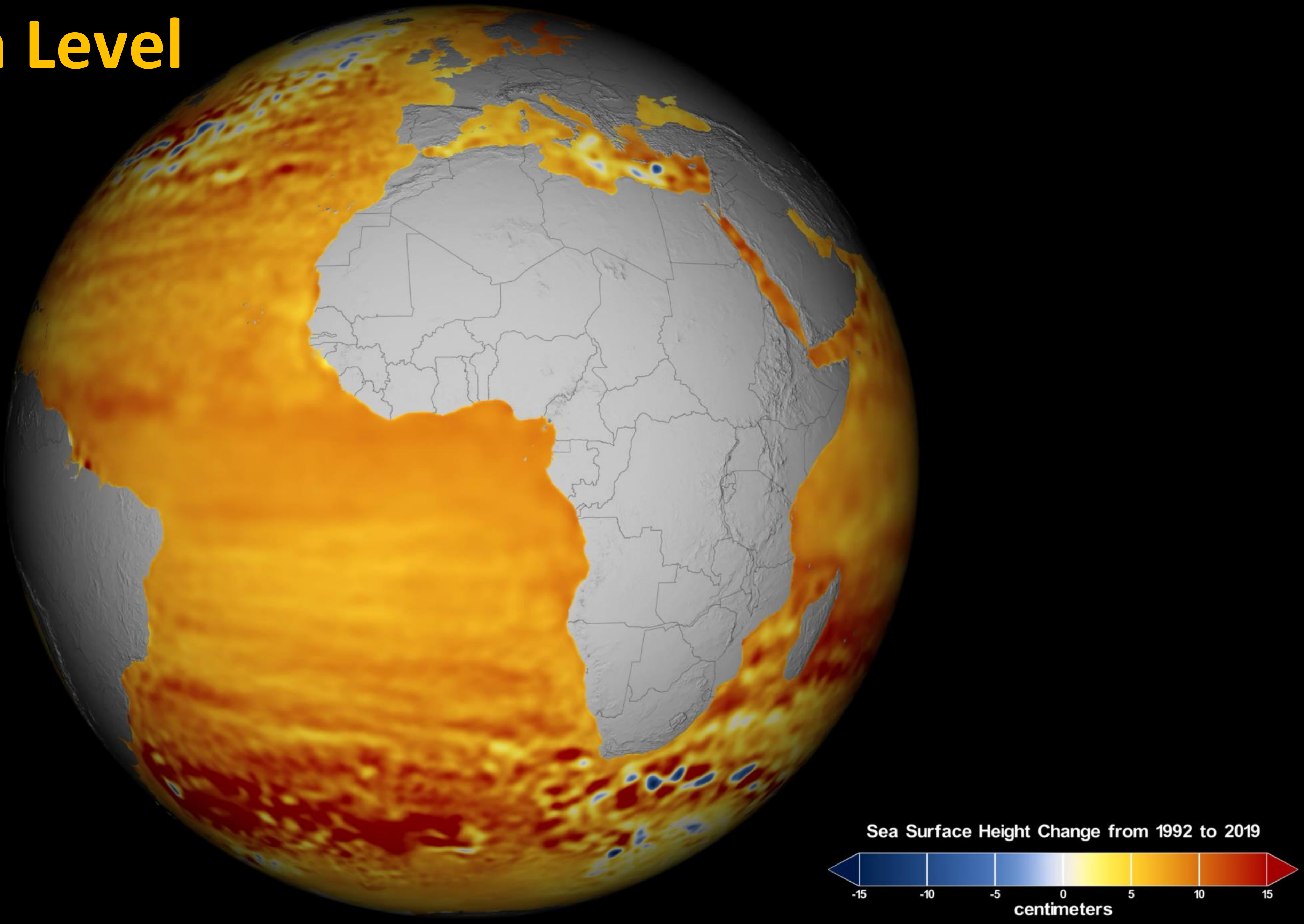


Altimeters measure the rising ocean



Worldwide, 200 million people live on land that will be regularly flooded or below sea level by 2100

Regional Sea Level



Credit: NASA's Scientific Visualization Studio

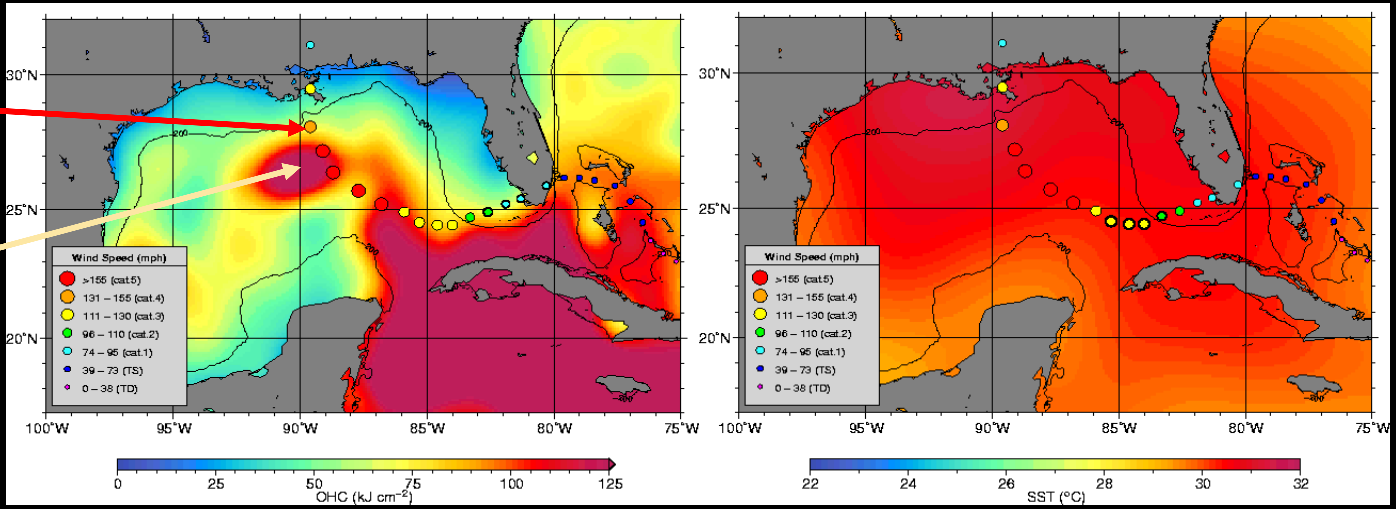
Sea level and ocean warming to predict tropical storms intensity

Ocean Heat Content derived from Altimetry

Sea Surface Temperature

Hurricane Katrina intensifying

Blob of warm water below the surface = high sea level

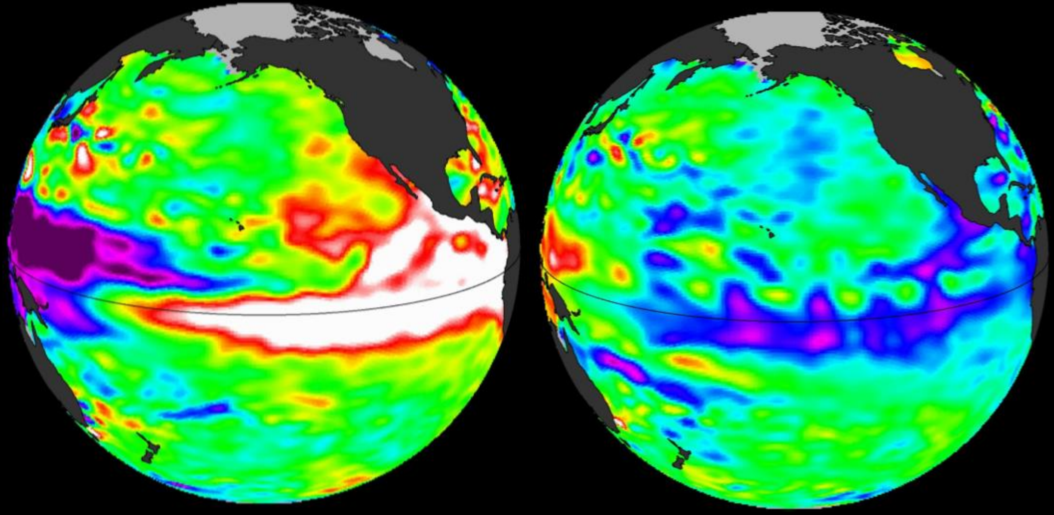


No particular warm surface waters

Monitoring El Niño/La Niña from Space

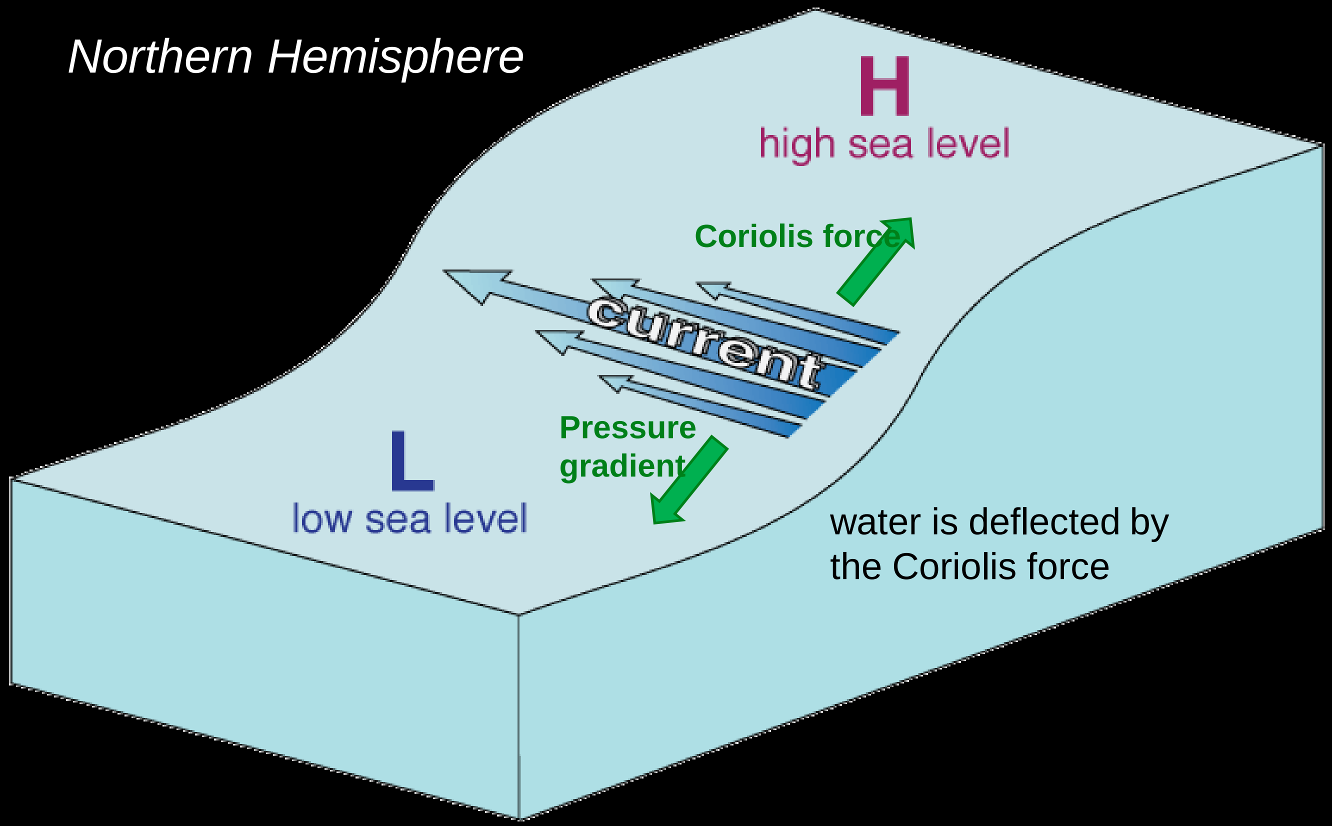
6 December 2015 – El Niño

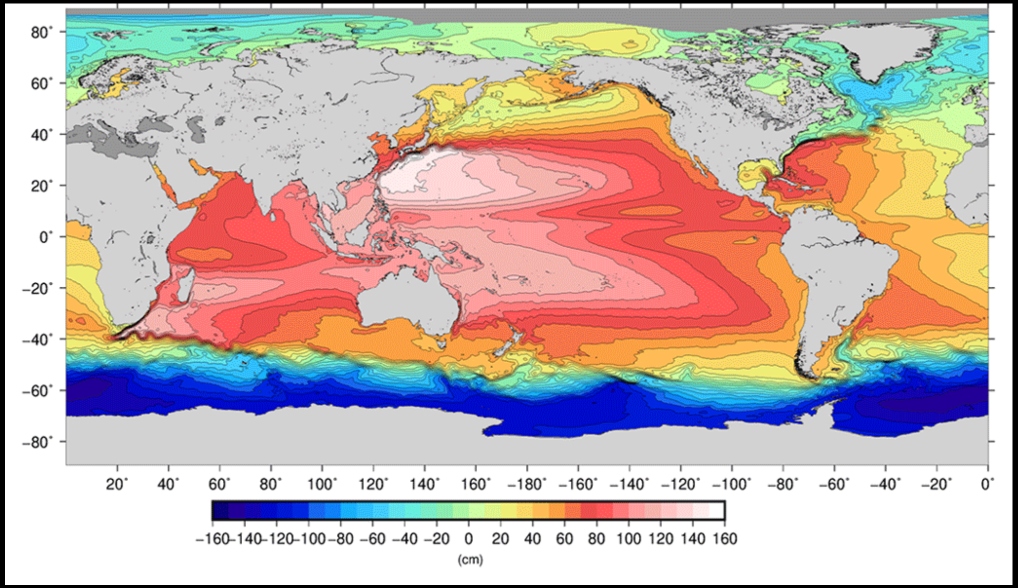
2 December 2010 – La Niña



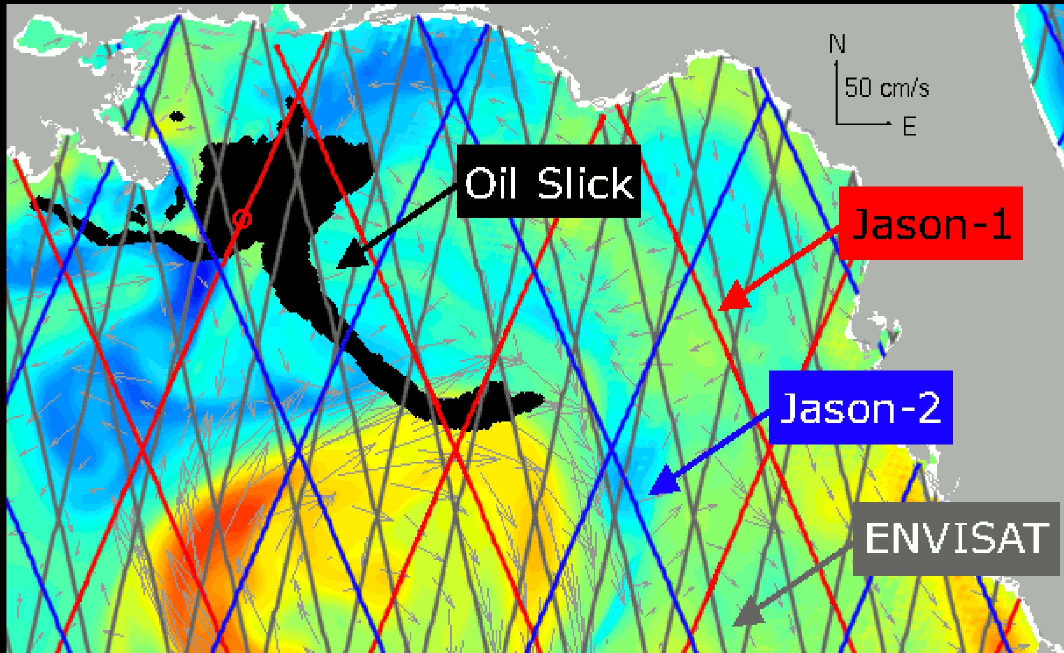
Source: https://sealevel.jpl.nasa.gov/data/el-nino-la-nina-watch-and-pdo/overview/

The slope of the ocean tells us the surface currents





Credit: CLS 2018



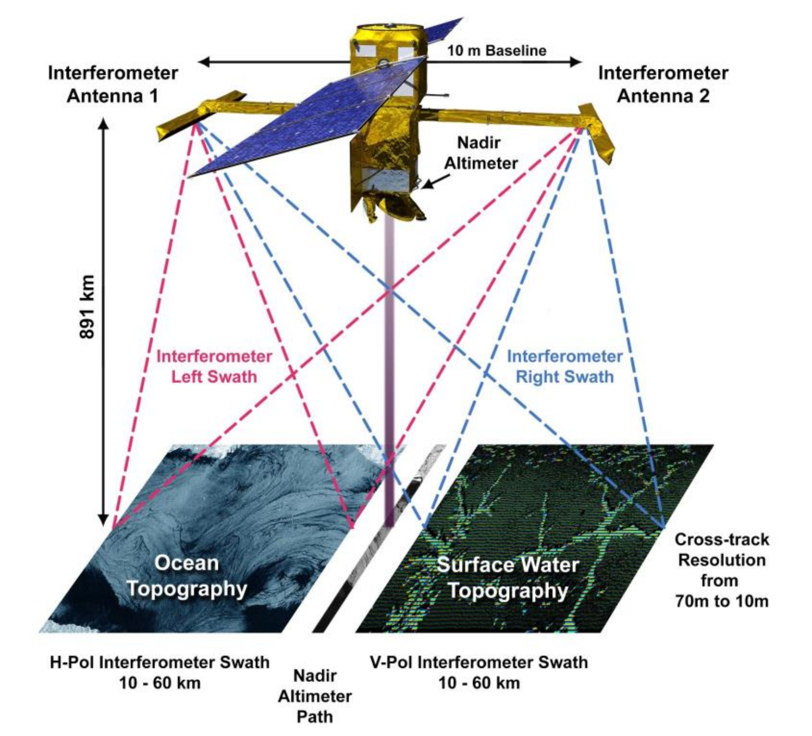
- Pressure gradient depends on the slope (measured by altimetry)
- Coriolis force depends on the speed of the current

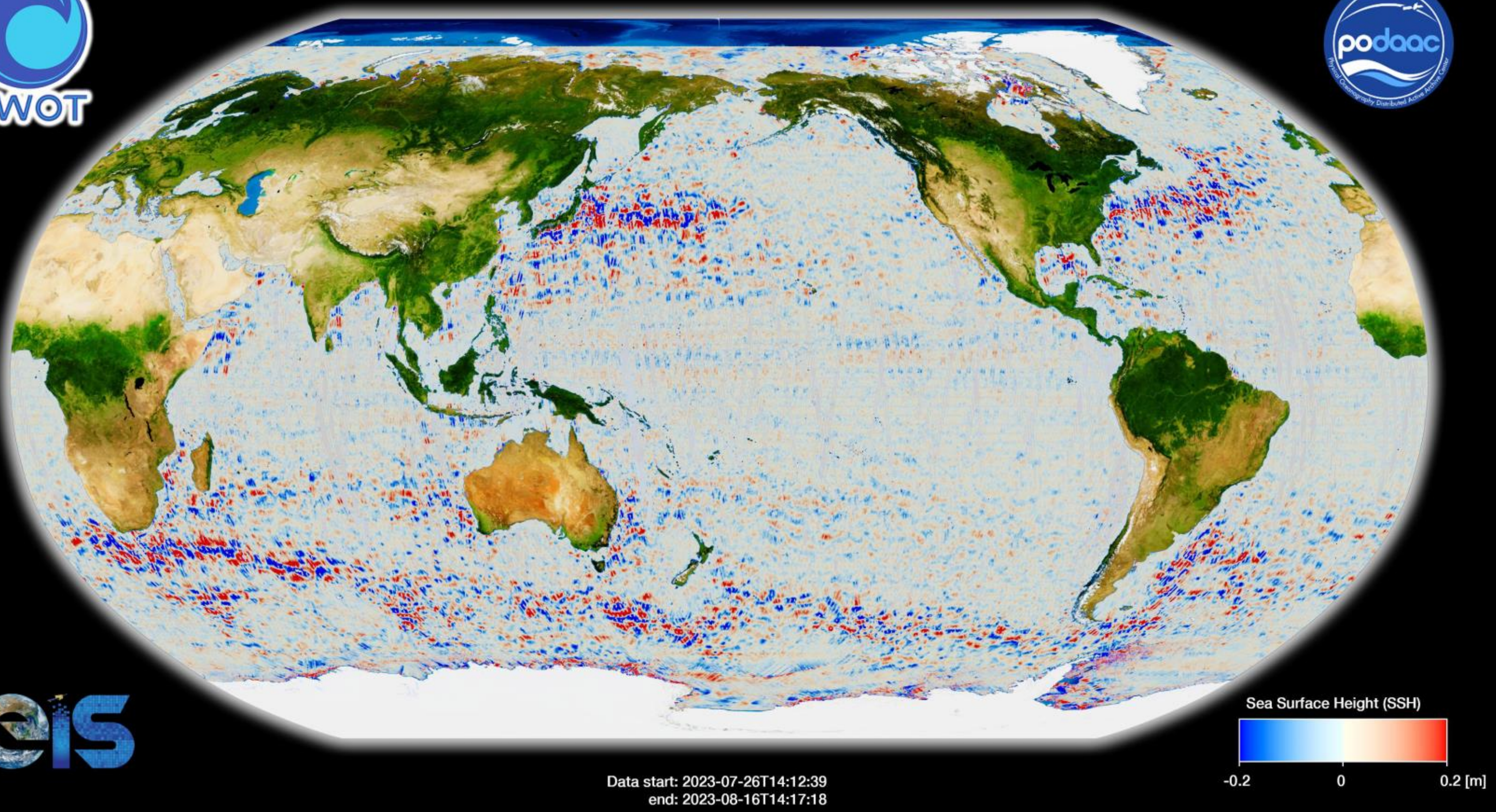
geostrophic balance → geostrophic current speed

Altimetry

SWOT

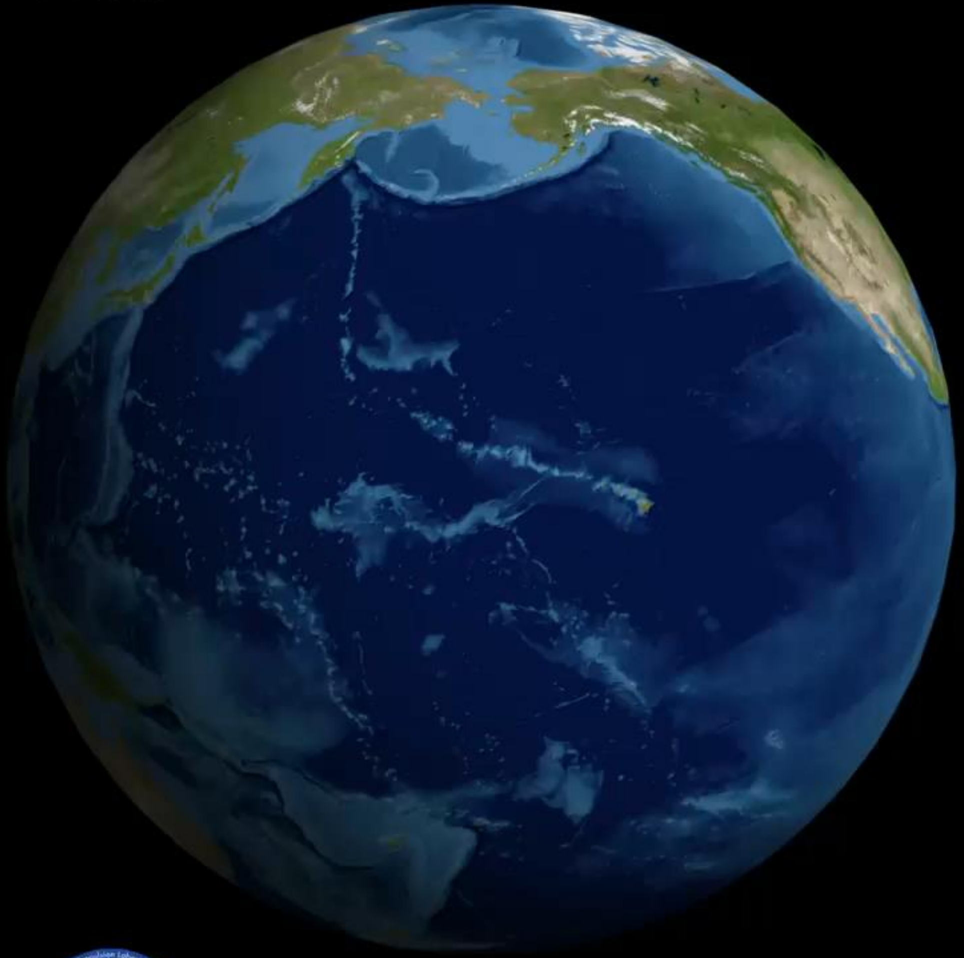
SWOT observes oceanic features that have never been seen before

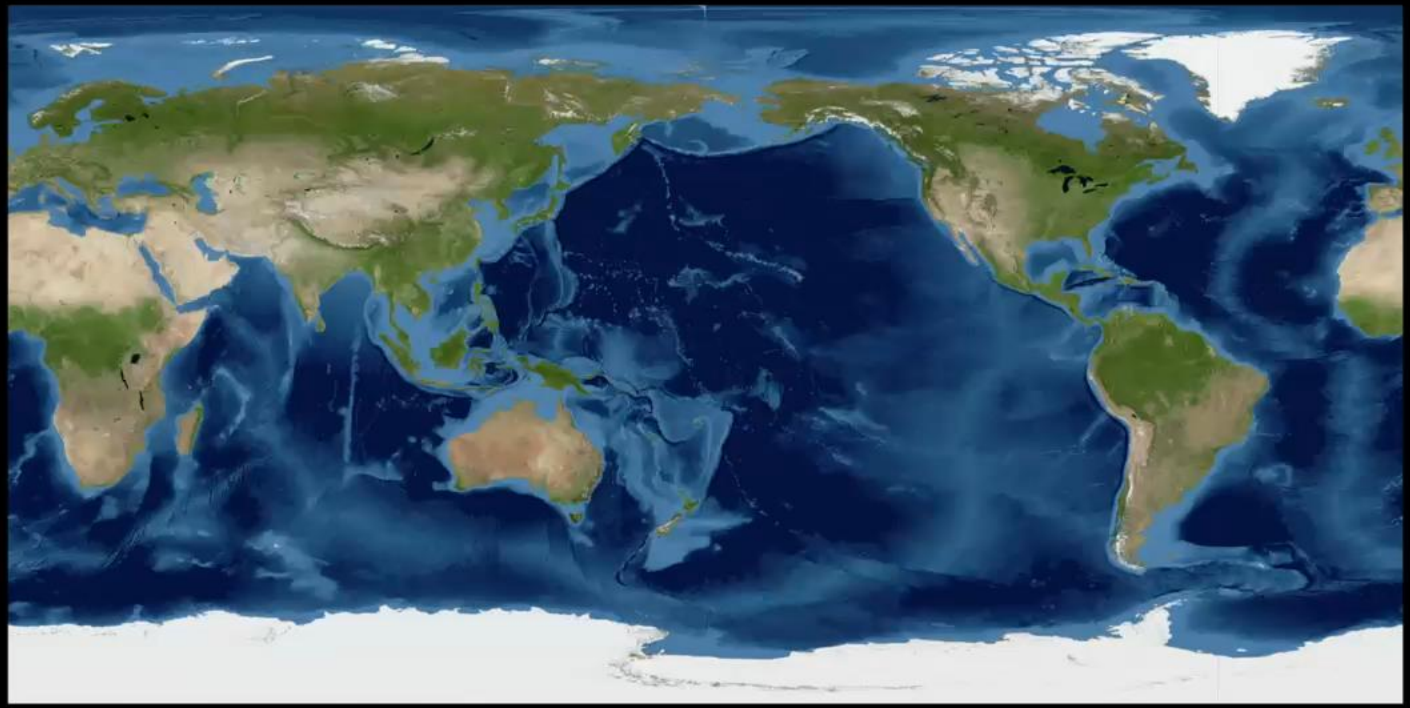




- 21-day cycle
- resolution below 10-km (~100 km for conventional altimetry) – SAR interferometry
- monitor small scale dynamics that contribute to vertical transport of heat and carbon and coastal sea level

Sea surface height anomaly (SSHA) from SWOT Ka-band Radar Interferometer (KaRIn) over one full 21-day cycle
Same field, difference perspectives

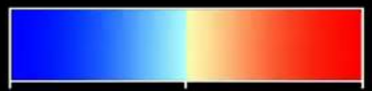




2023-08-11 02:19

Pass:

Sea Surface Height Anomaly (SSHA)

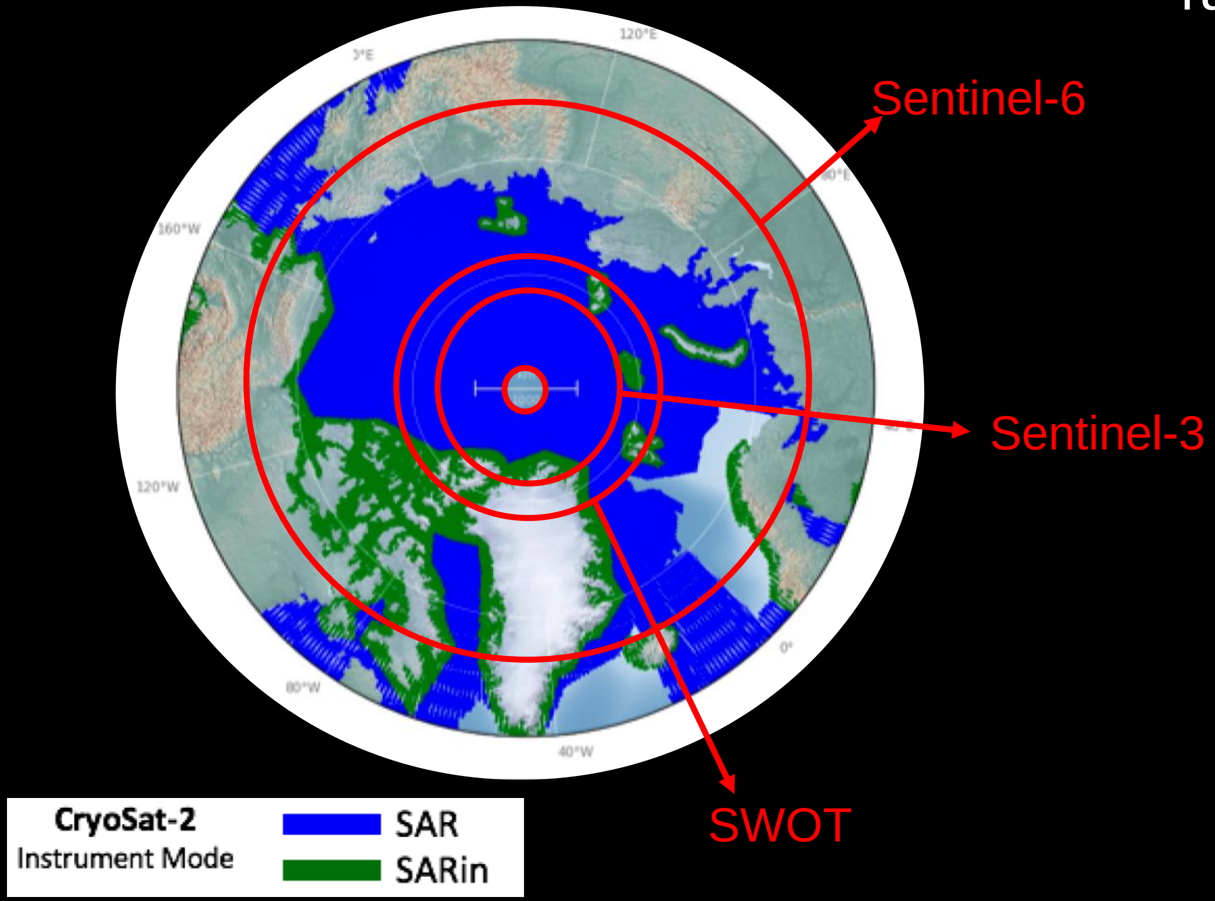


Credit: Jinbo Wang – PO.DAAC Data in Action

Altimetry

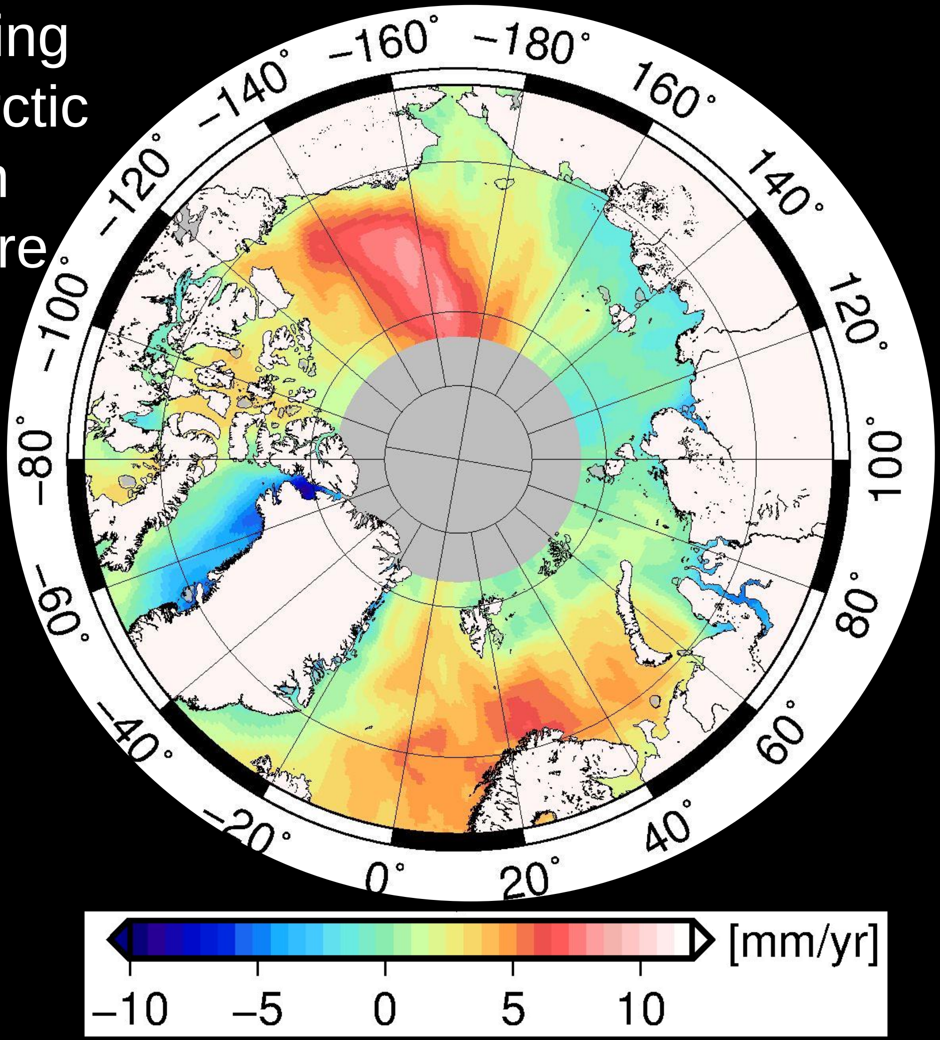
CRISTAL, CryoSat, IceSat

High Latitude Altimeters



Quartly et al., 2020

Sea level is rising rapidly in the Arctic as the ocean circulation there changes

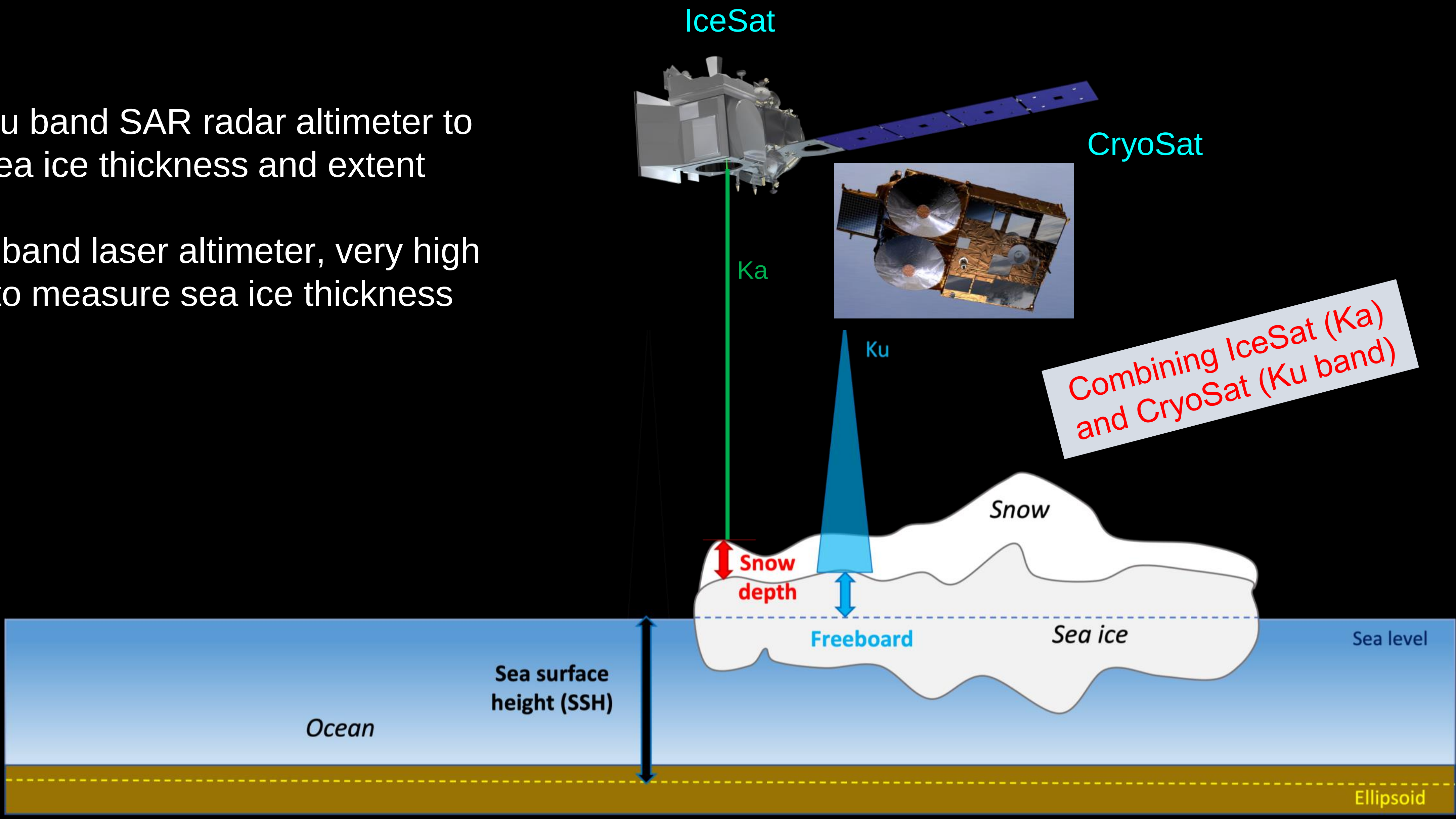


Rose et al., 2019

Altimeters to monitor Sea Ice – IceSat / CryoSat

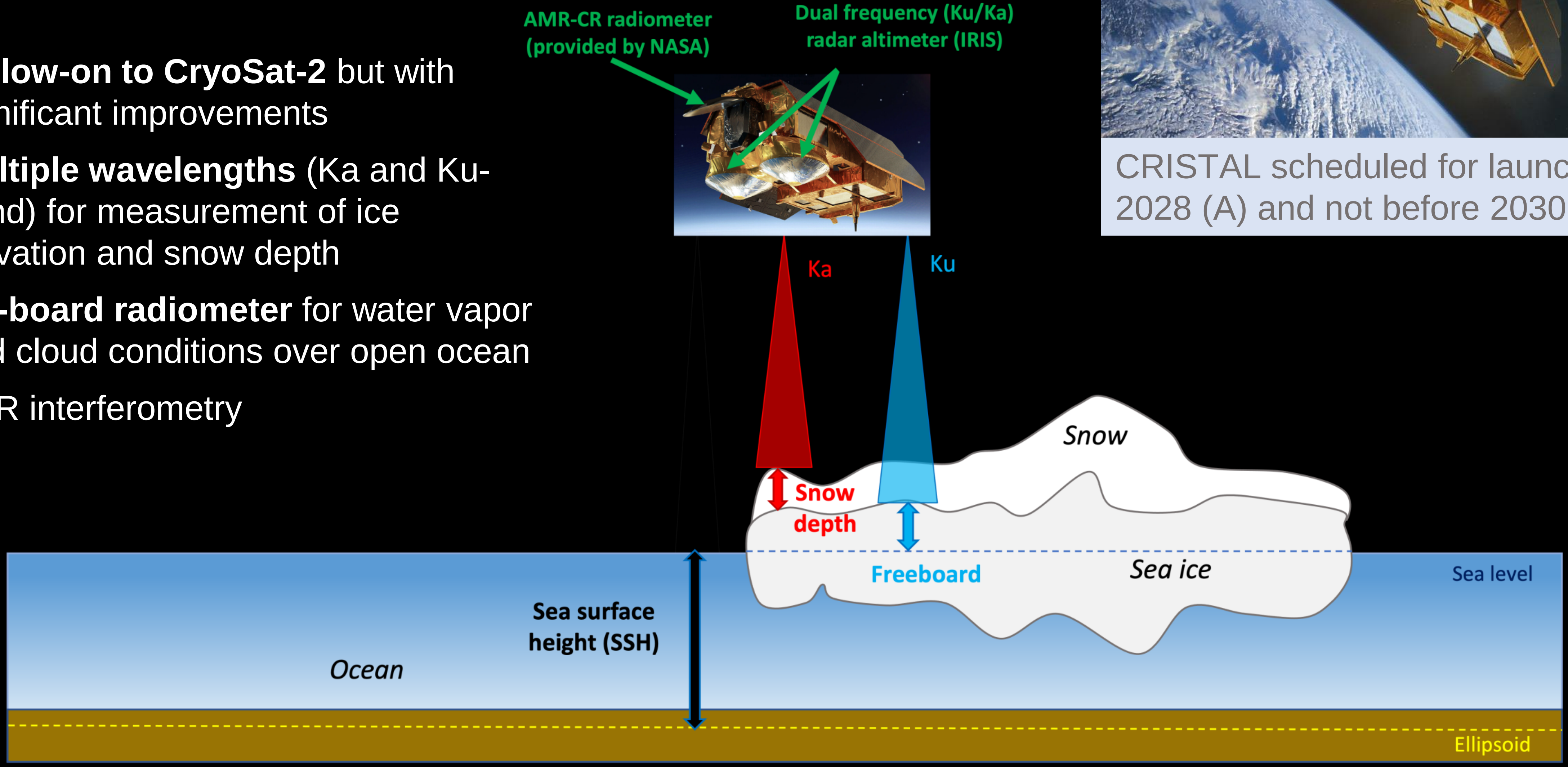
- CryoSat: Ku band SAR radar altimeter to measure sea ice thickness and extent

- IceSat: Ka band laser altimeter, very high resolution to measure sea ice thickness



Altimeters to monitor Sea Ice - CRISTAL

- **Follow-on to CryoSat-2** but with significant improvements
- **Multiple wavelengths** (Ka and Ku-band) for measurement of ice elevation and snow depth
- **On-board radiometer** for water vapor and cloud conditions over open ocean
- SAR interferometry



CRISTAL scheduled for launch in 2028 (A) and not before 2030 (B)

Credit: Sahra Kacimi, JPL

Gravimetry

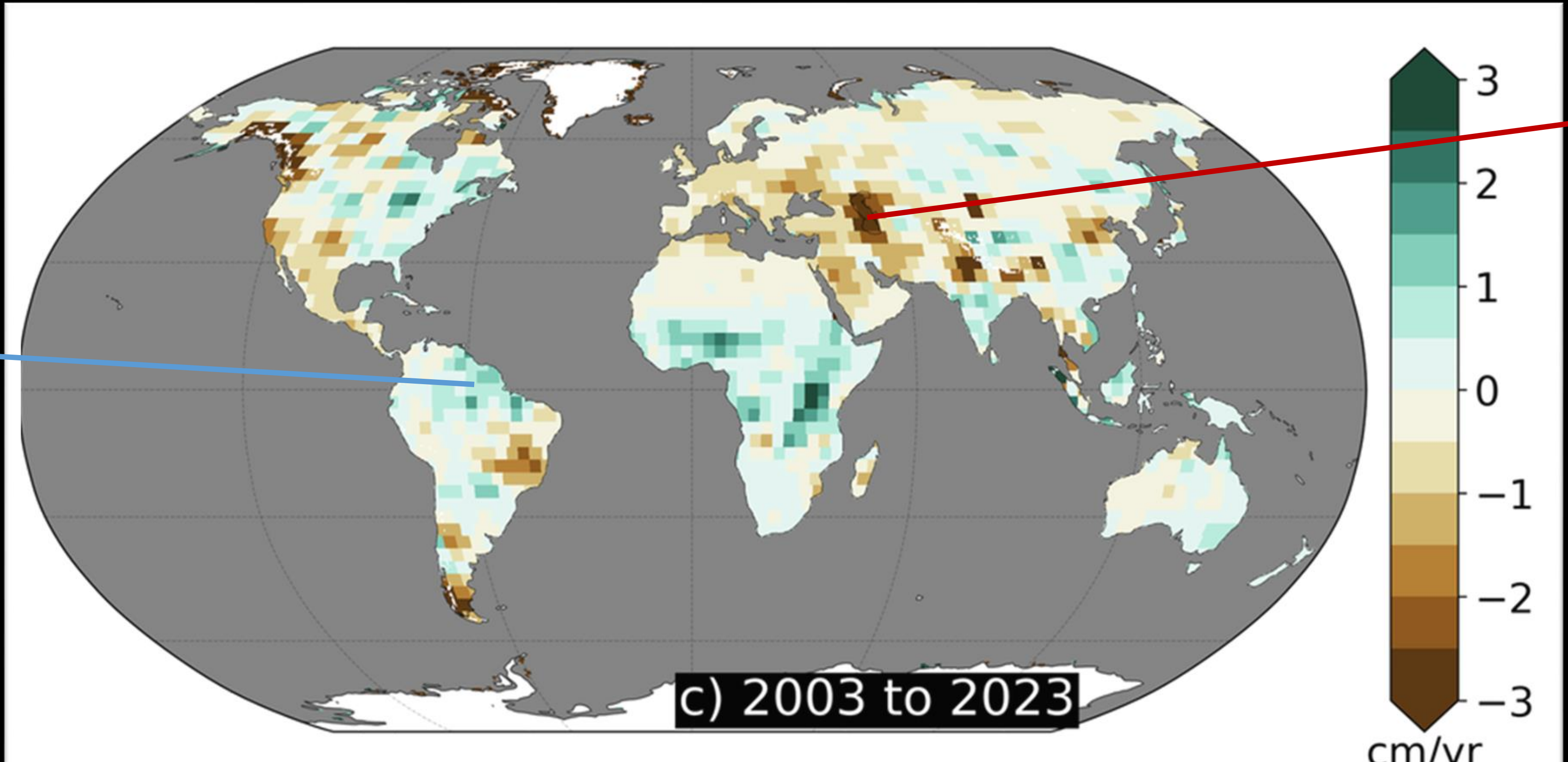
GRACE, GRACE-FO

How does GRACE work?

https://grace.jpl.nasa.gov/resources/40/grace-fo-from-range-observations-to-global-mass-change/

Land Water Storage Changes

Trends in land water storage from GRACE observations, 2003-2023



Water mass gain

Water mass loss

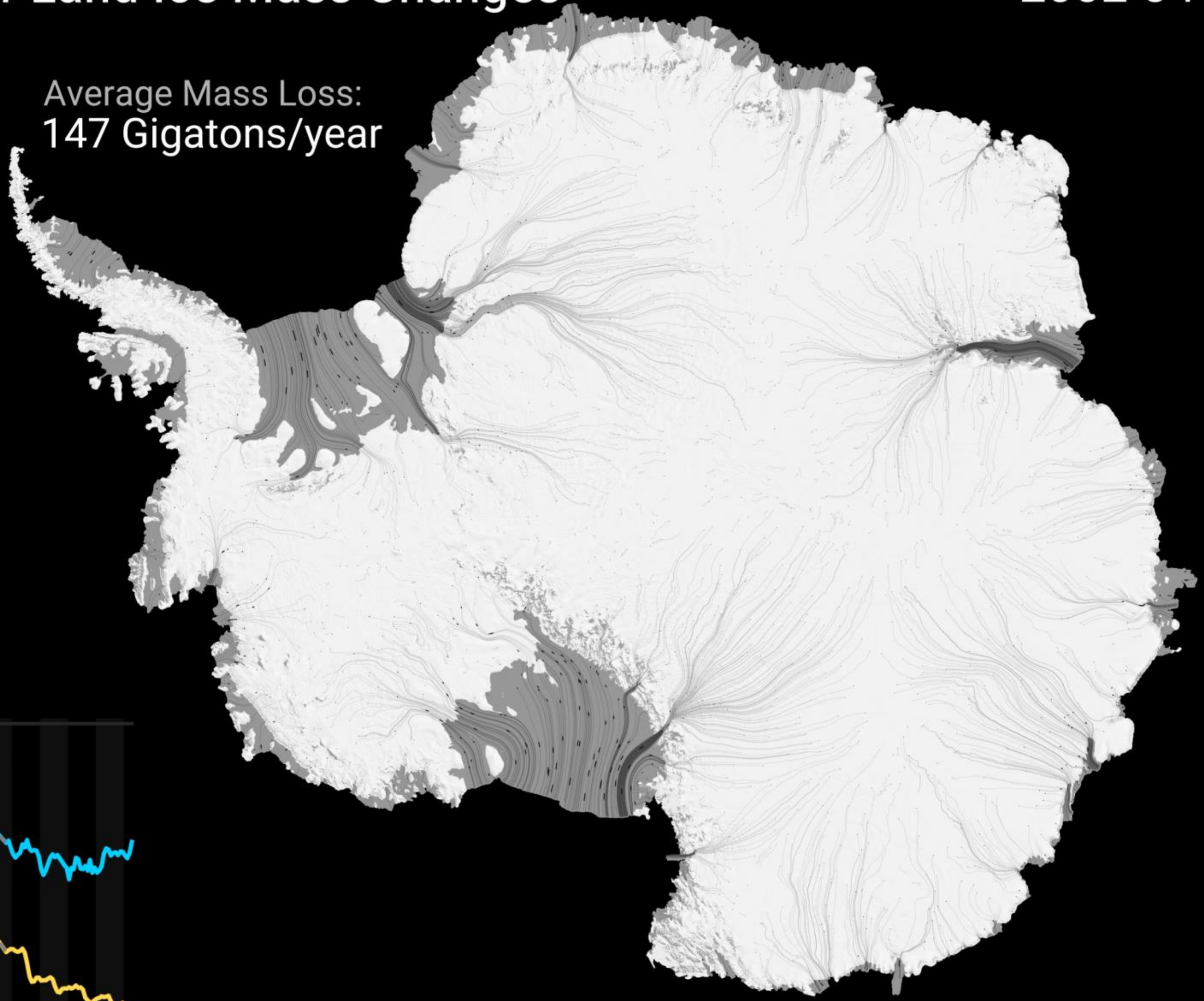
Buzzanga et al., 2024

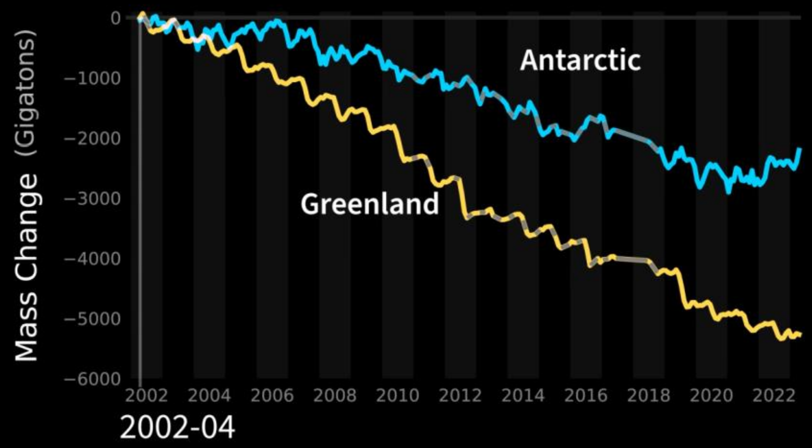
GRACE and GRACE-FO Observations of Polar Land Ice Mass Changes

2002-04

Average Mass Loss:
271 Gigatons/year

Average Mass Loss:
147 Gigatons/year



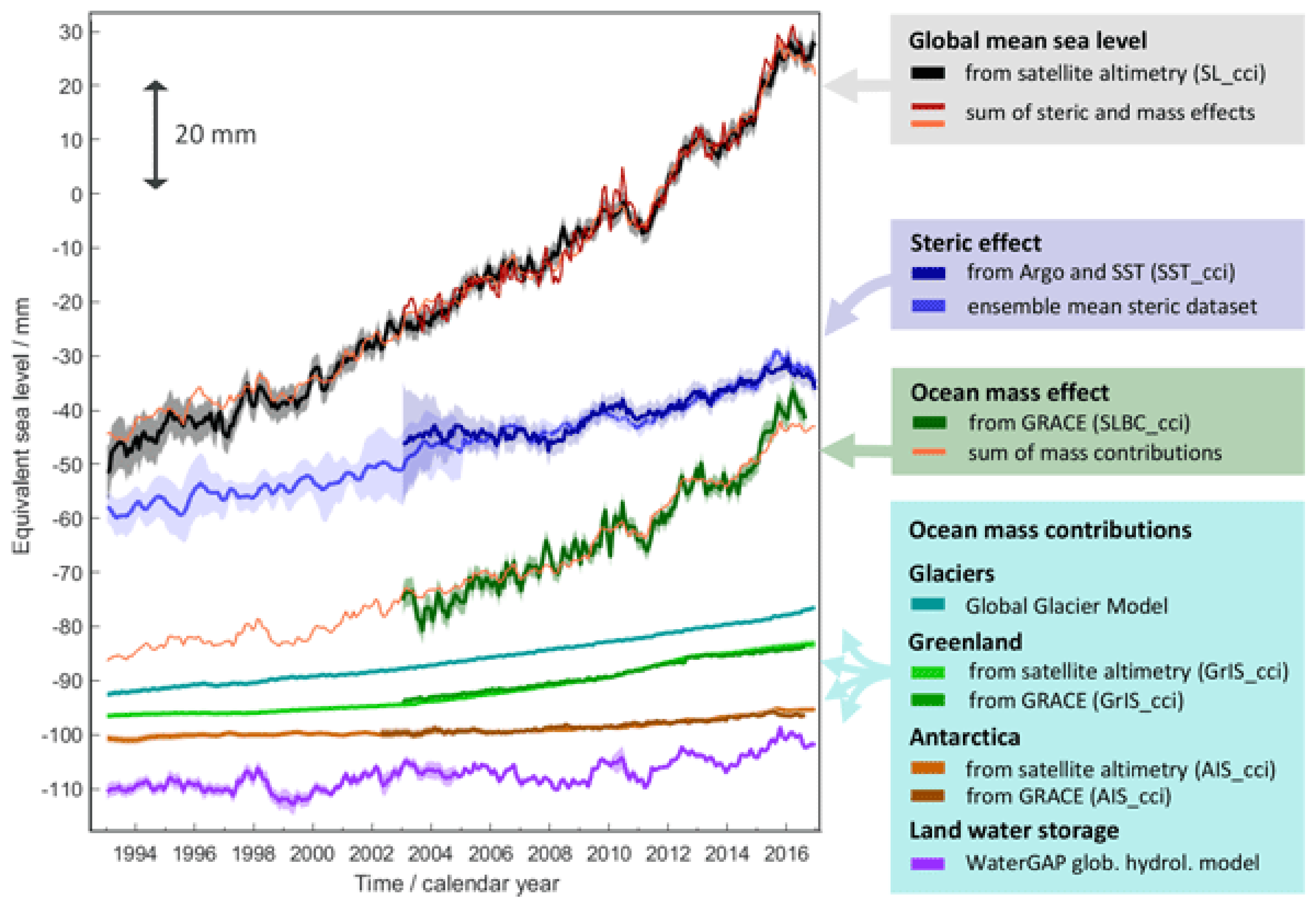


Ice Mass Change
(meters water equivalent relative to 2002)
-6 -4 -2 0 2

Credit: NASA and JPL/Caltech (https://svs.gsfc.nasa.gov/31166/)

Sea Level – Ocean mass contribution

Argo (steric) and GRACE (mass) help to estimate the contributions to the sea level

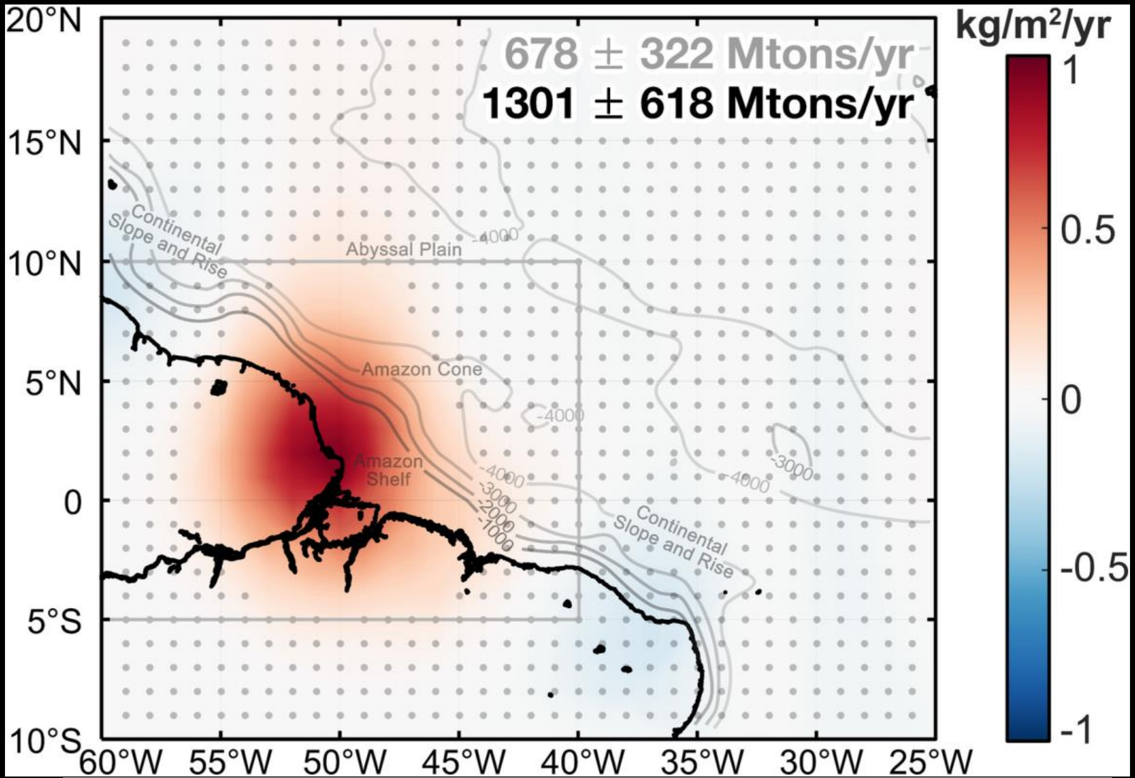


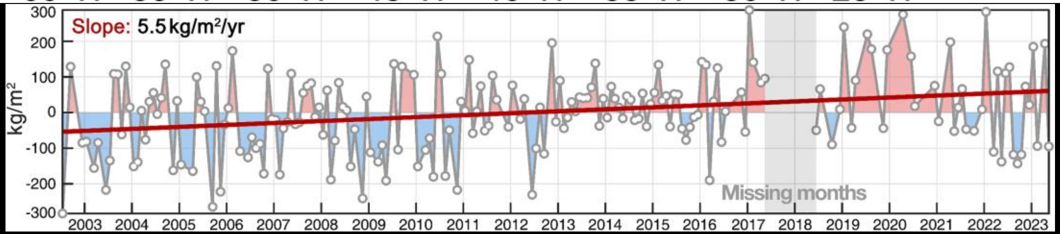
Horwath et al., 2022

Sediments Accumulation

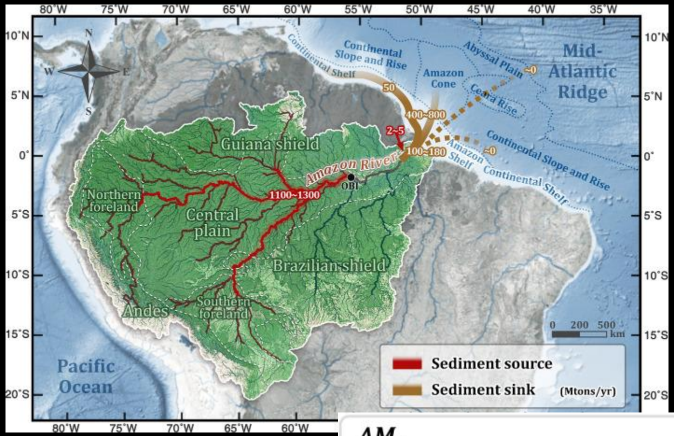
- First use of **GRACE-FO** data in geomorphology study
- Measured ocean sediment deposition
- Requires a long-record to distinguish subtle mass changes
- Implications for tides, coastal zone

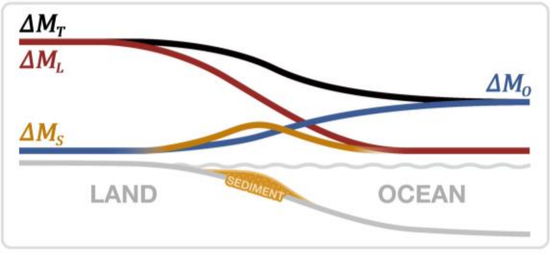
Measured mass accumulation





Sediment source map

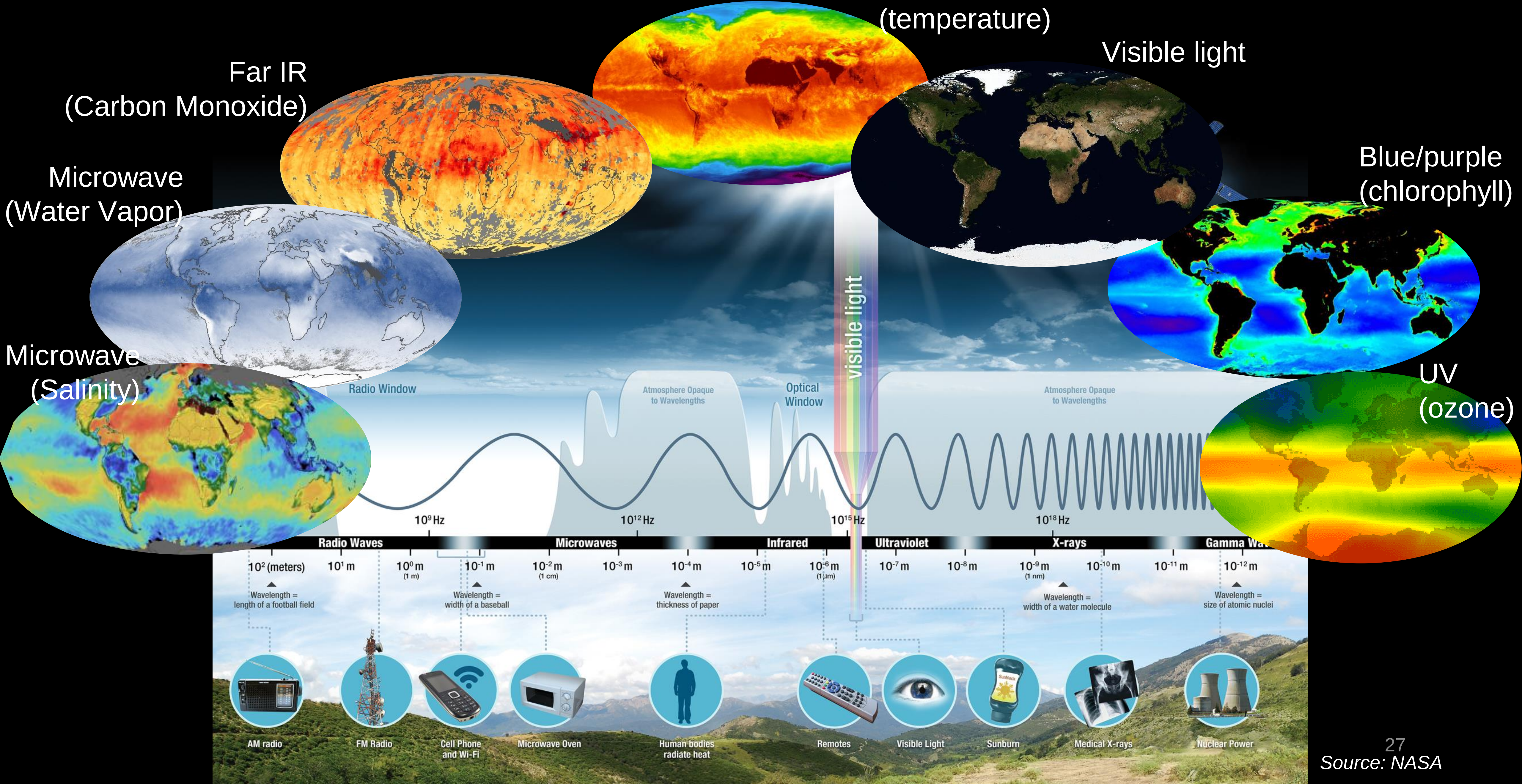




Credit: JT Reager; Source: Earthu et al. (2025) – Remote Sensing of Environment

Radiometry

Radiometry from Space



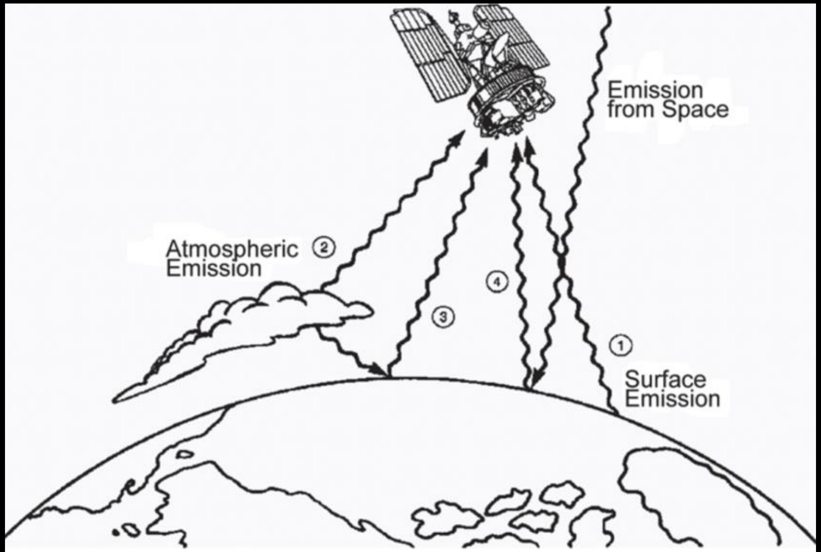
Source: NASA

Microwave Radiometry
Sea Surface Salinity

SMOS, Aquarius, SMAP

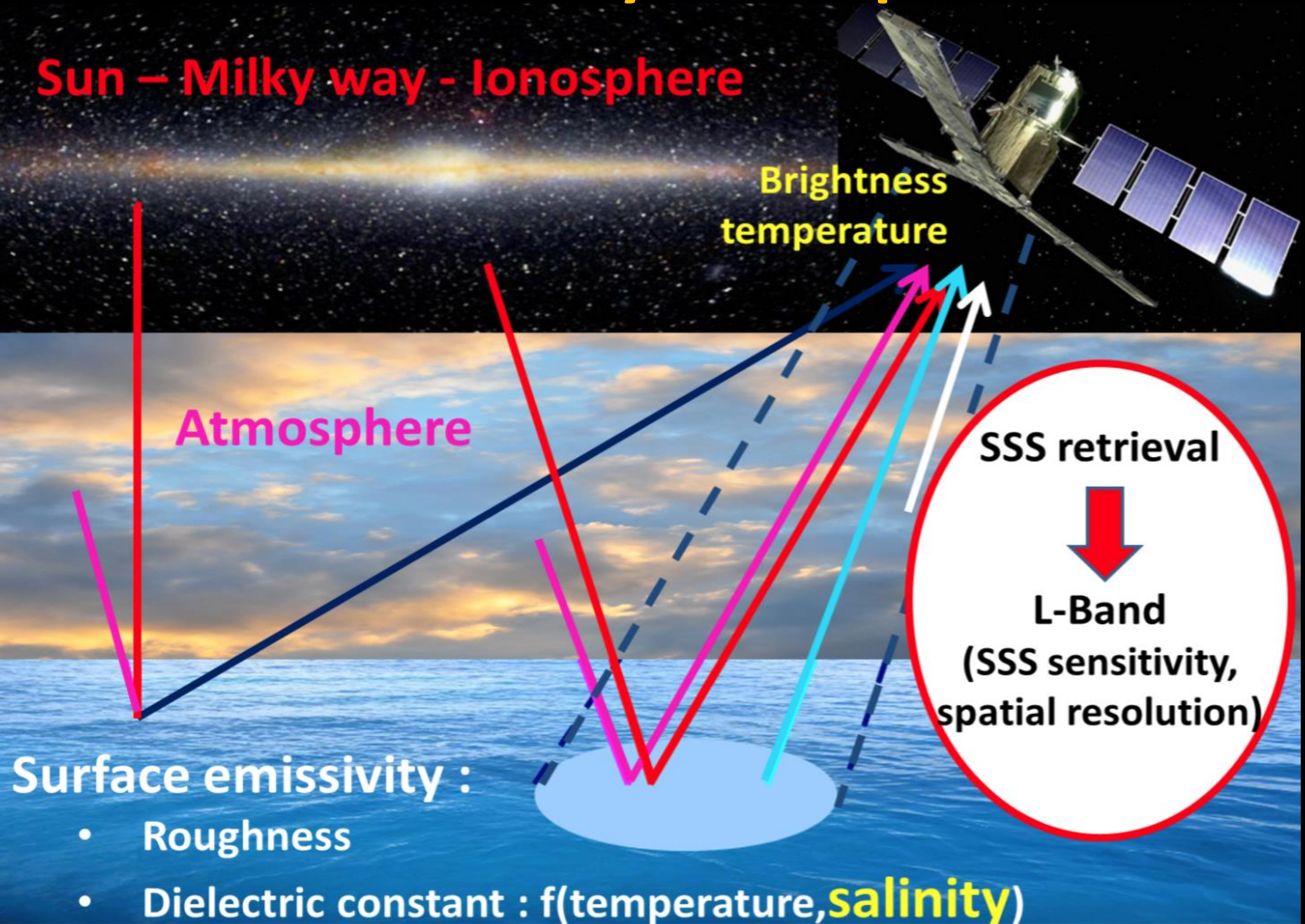
Microwave Radiometry

- Passive Microwave Radiometers measure the emissivity of a body (ocean) in the microwave region (~1-300 GHz)
- Emissivity of the surface is its effectiveness in emitting energy (1-reflectivity)
- Low reflectivity -> high emissivity -> high brightness temperature (black body)
- Emissivity of the ocean depends on:
  - Wavelength
  - Salinity
  - Temperature
  - Roughness (wind speed)



Johannessen et al., 2006

Sea Surface Salinity from Space



Need to correct for effects due to:

- the sky (galactic)
- atmosphere
- ionosphere
- land
- ice
- SST
- surface roughness (from wind and rain)
- Radio Frequency Interference

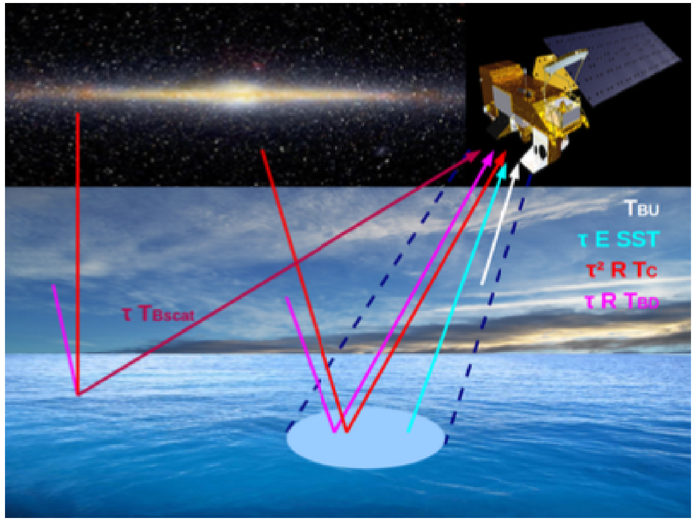
More salt
➔ conductivity increases
➔ surface more reflective
➔ lower emissivity
➔ colder Tb

Sea Surface Salinity from Space

Radiative transfer theory : the Earth's brightness temperature related to geophysical parameters

$$T_B = T_{BU} + \tau\ E\ SST + \tau\ R\ [T_{BD} + \tau\ T_C] + \tau\ T_{Bscat}\ (Wentz\ \&\ Meissner,\ 2000)$$

- E & R : the sea surface emissivity & reflectivity
- τ : the atmosphere transmittance
- T_{BU} : the upwelling atmosphere emission
- T_{BD} : the downwelling atmosphere emission reflected at the surface
- T_C : the effective cold space temperature



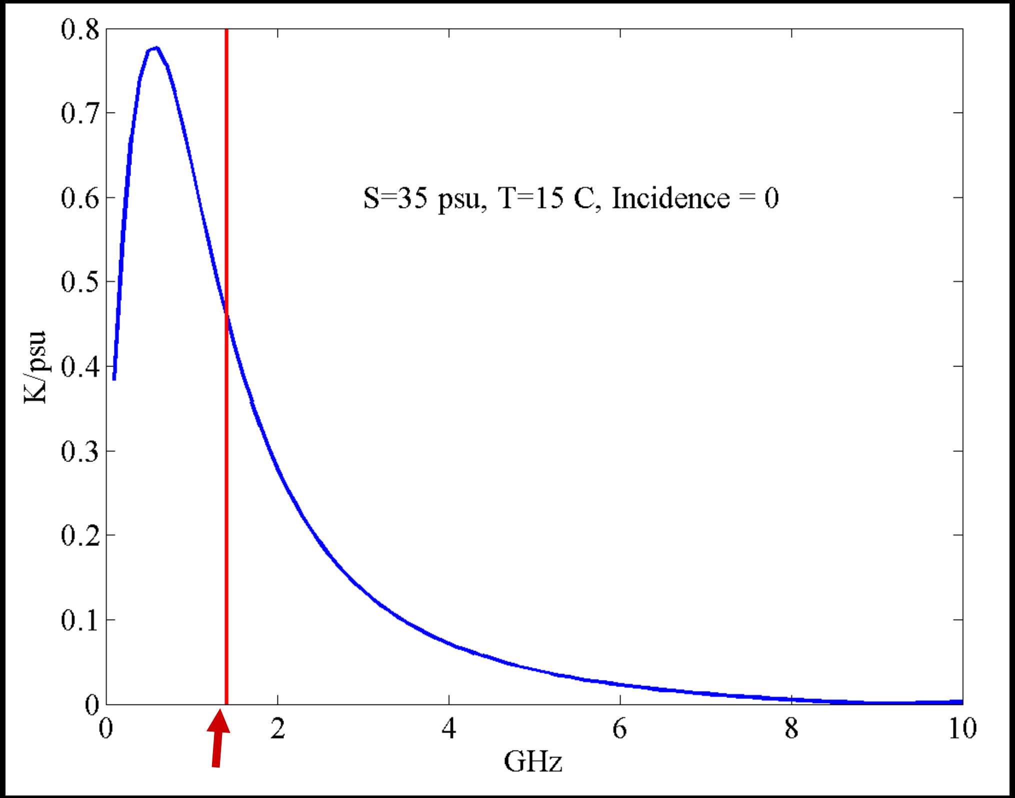
- E depends on the sea water dielectric constant & the roughness state of the sea surface
- Dielectric constant depends on electromagnetic frequency, temperature and salinity

$\Rightarrow$ **SSS retrieval from radiative transfer of microwave radiation emitted by the ocean surface**

- L-band radiometers (1.4 GHz) : a trade-off between good sensitivity to SSS & reasonable spatial resolution from Space

Why SSS is retrieved based on L-band Radiometry?

Sensitivity vs Radiometric Frequency

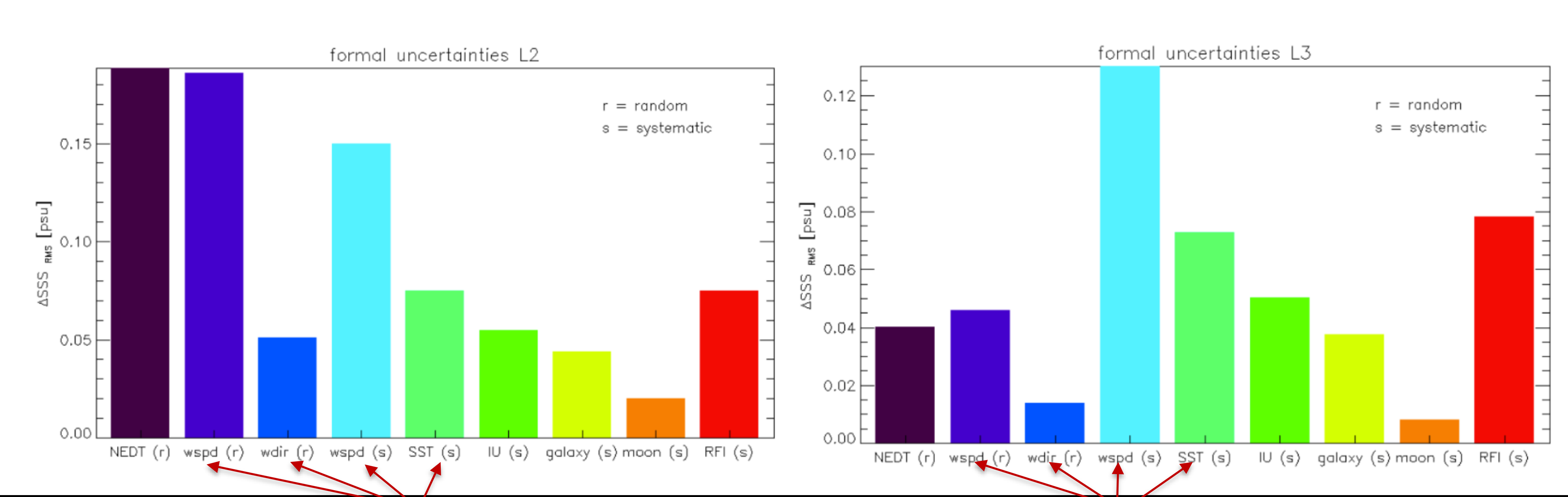


- Protected band (used for radio astronomy)
- Relatively good sensitivity to SSS for SST > 5^{o}C

- Other applications of L-band radiometry: **soil moisture, freeze/thaw state**, thin sea ice thickness, high winds
- SSS has the most stringent requirement for L-band radiometer precision

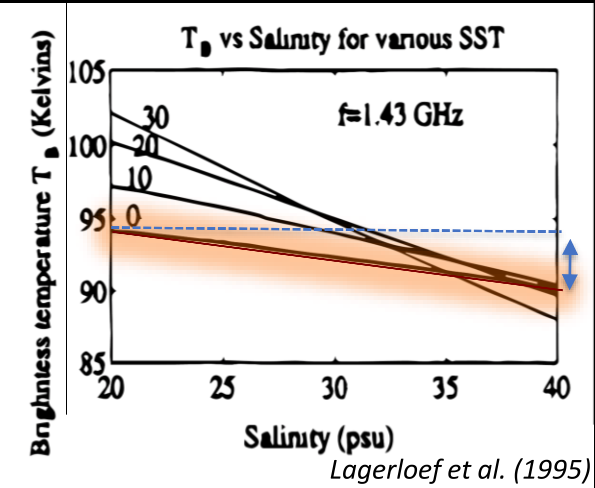
Credit: Tony Lee, JPL

Limitations current SSS sensors: ancillary data and sensitivity in cold waters



Akins et al., 2023

Wind and sea surface temperature measurements are needed to retrieve SSS – significant uncertainty



Lagerloef et al. (1995)

Tb/psu variability is very small in cold waters

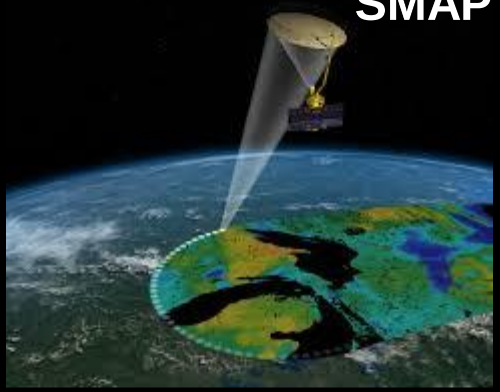
Need for **concurrent measurements of sea surface temperature, winds** and SSS (L/C/X/K Band), and **wide band** measurements in L-band

Sea Surface Salinity Measured from Space

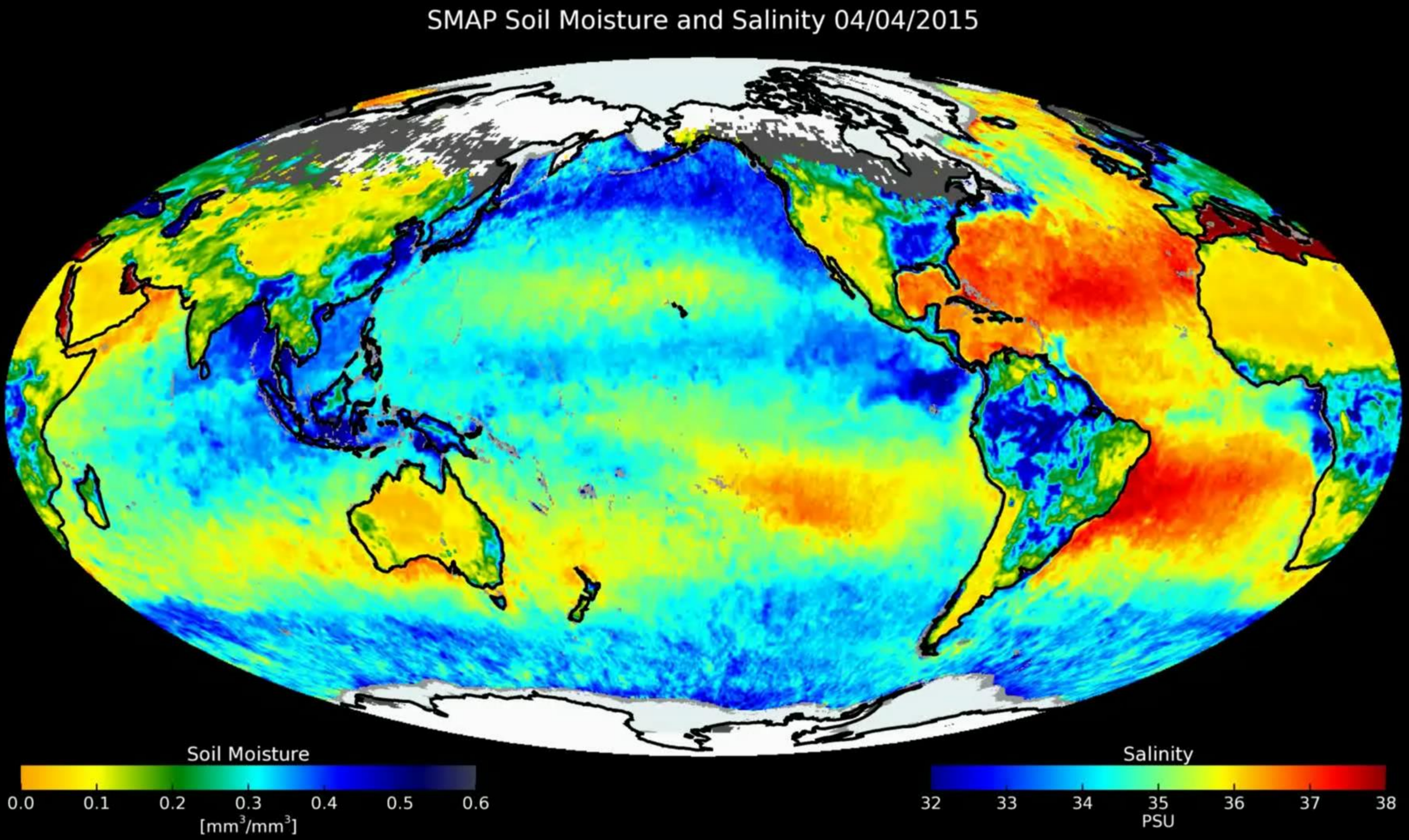
	ESA SMOS	NASA/SAC-D Aquarius	NASA SMAP
Spatial resolution	60 km	150 km	60 km
Temporal repeat	23 days (subcycle 3 days)	7 days	8 days
Data period	01/2010 onward	08/2011-05/2015	04/2015 onward
Distance from the coast	100 km	150 km	40-70 km

SMOS

Aquarius



SMAP

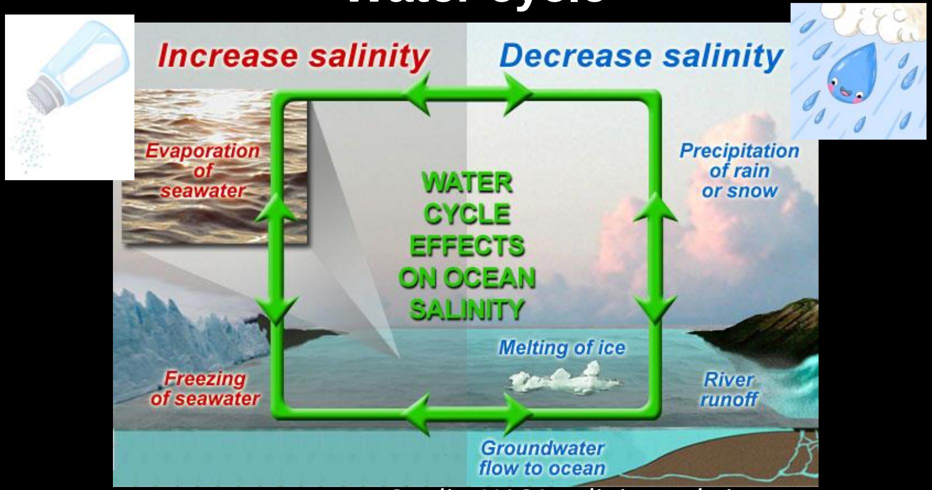

SMAP Soil Moisture and Salinity 04/04/2015
Soil Moisture
0.0 0.1 0.2 0.3 0.4 0.5 0.6
[mm3/mm3]
Salinity
32 33 34 35 36 37 38
PSU

Why observing sea surface salinity?

$$\underbrace{\frac{dS}{dt} = S\frac{E-P+R}{H}}_{\text{freshwater fluxes}} + \underbrace{u\frac{dS}{dx} + v\frac{dS}{dy} + \text{mixing processes}}_{\text{ocean processes (advection, mixing)}}$$

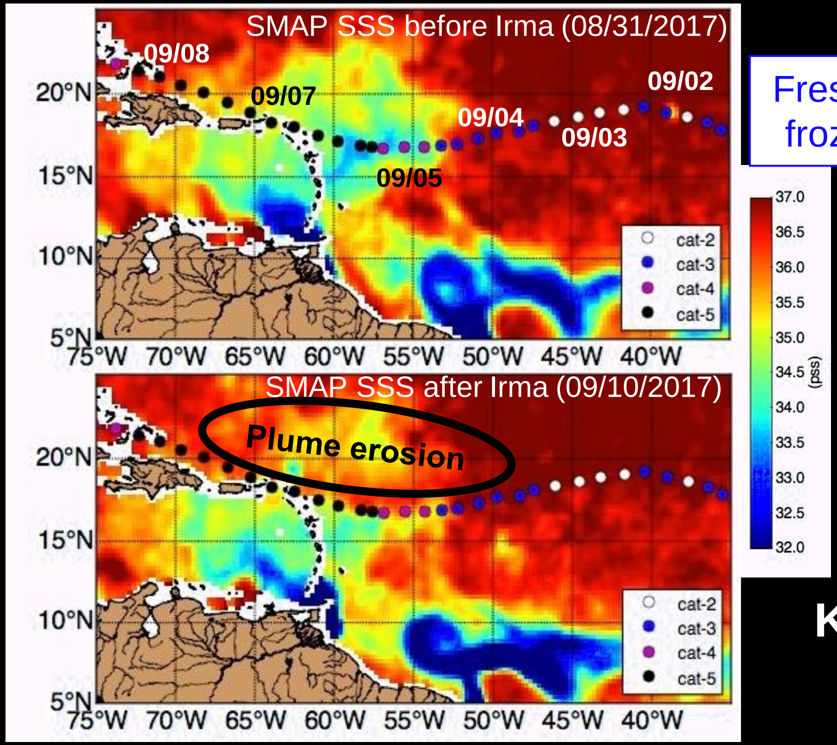
freshwater fluxes ocean processes (advection, mixing)

Water cycle

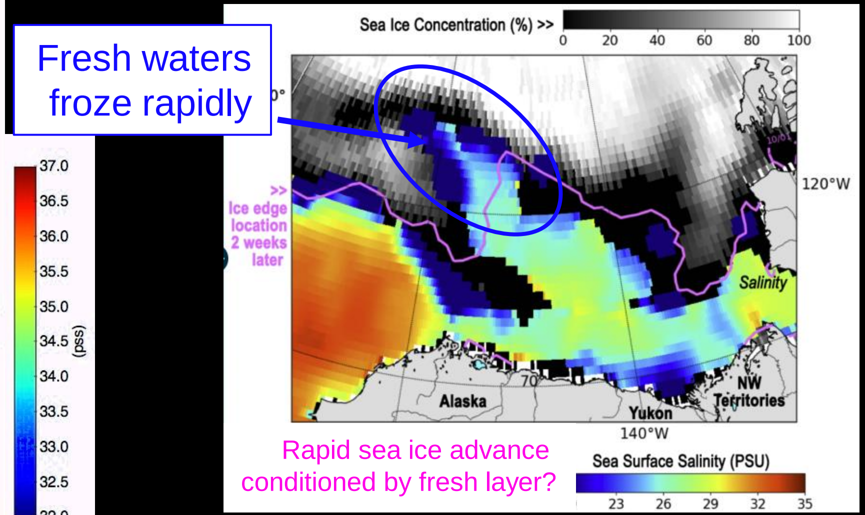


Credit: NASA salinity website (https://salinity.oceansciences.org)

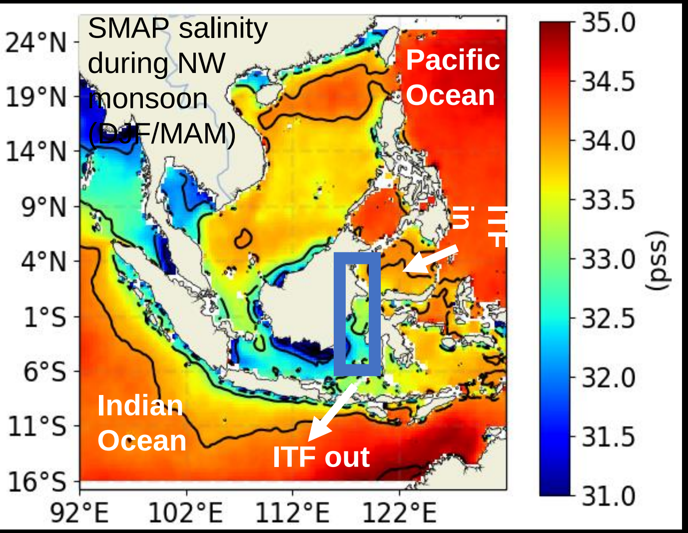
Hurricane Intensification



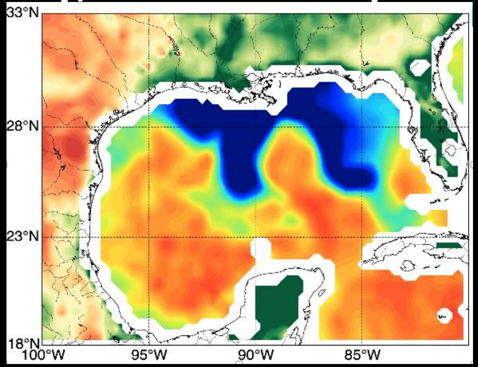
Key parameter in Arctic Ocean

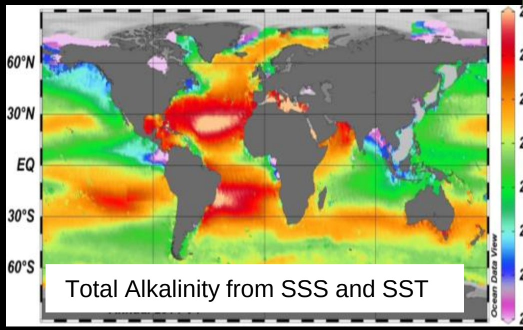


Salinity impacts on global circulation

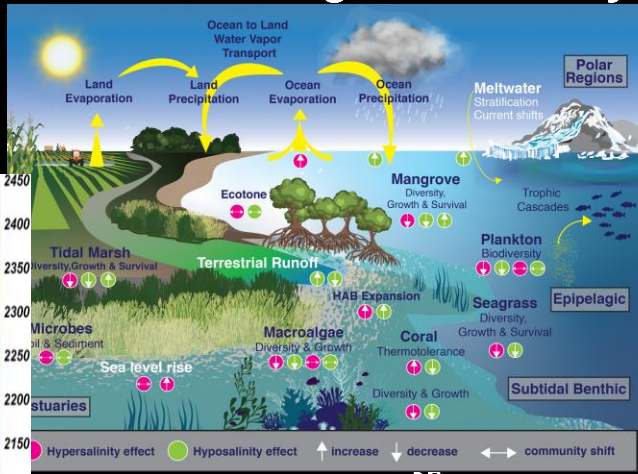


Salinity, to trace river plumes





Key parameter in biogeochemistry

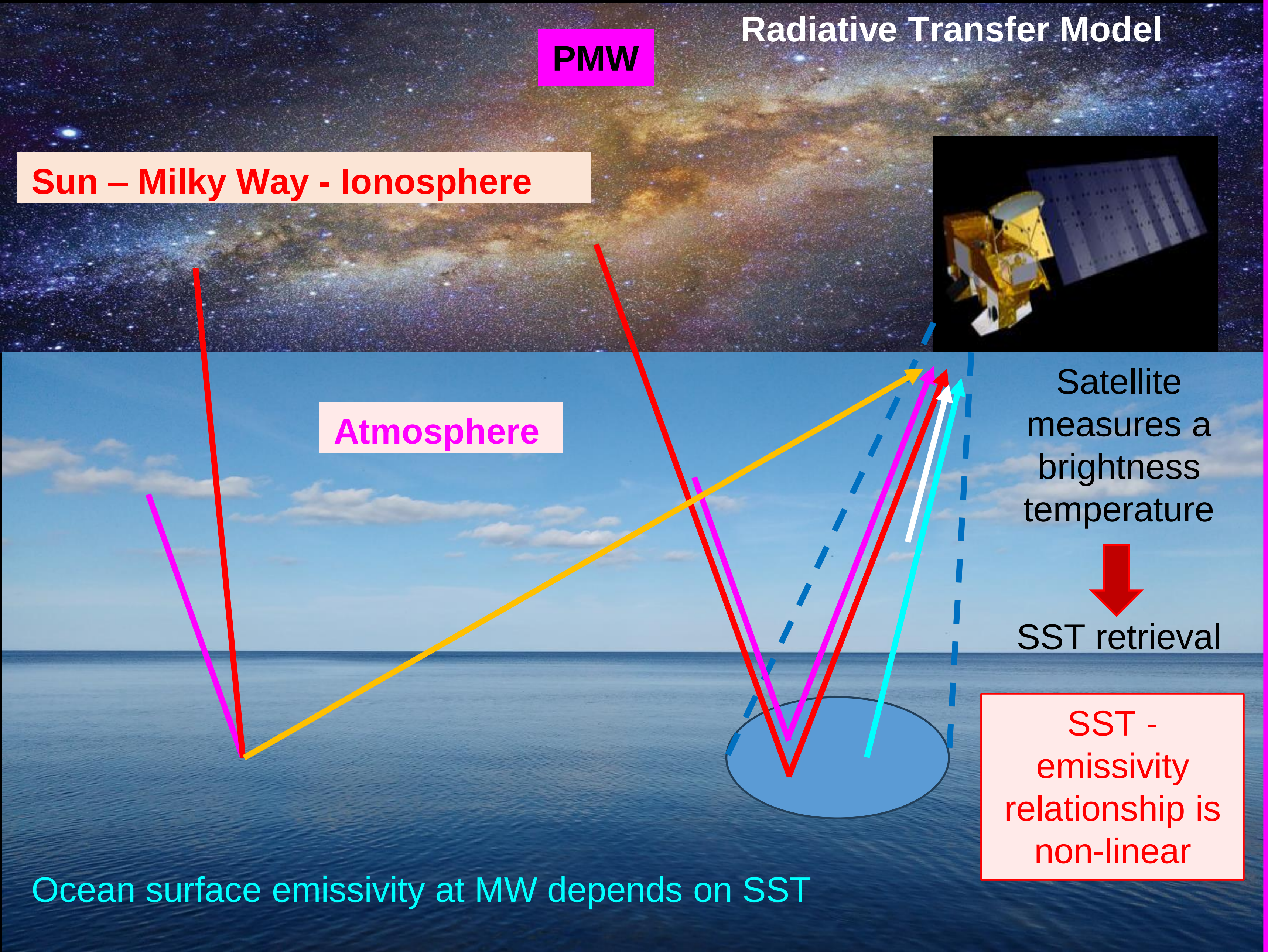


Fine et al., 2016

MW and IR Radiometry
Sea Surface Temperature

AMSR, TMI, AVHRR, VIIRS, MODIS,…

Sea Surface Temperature from Space

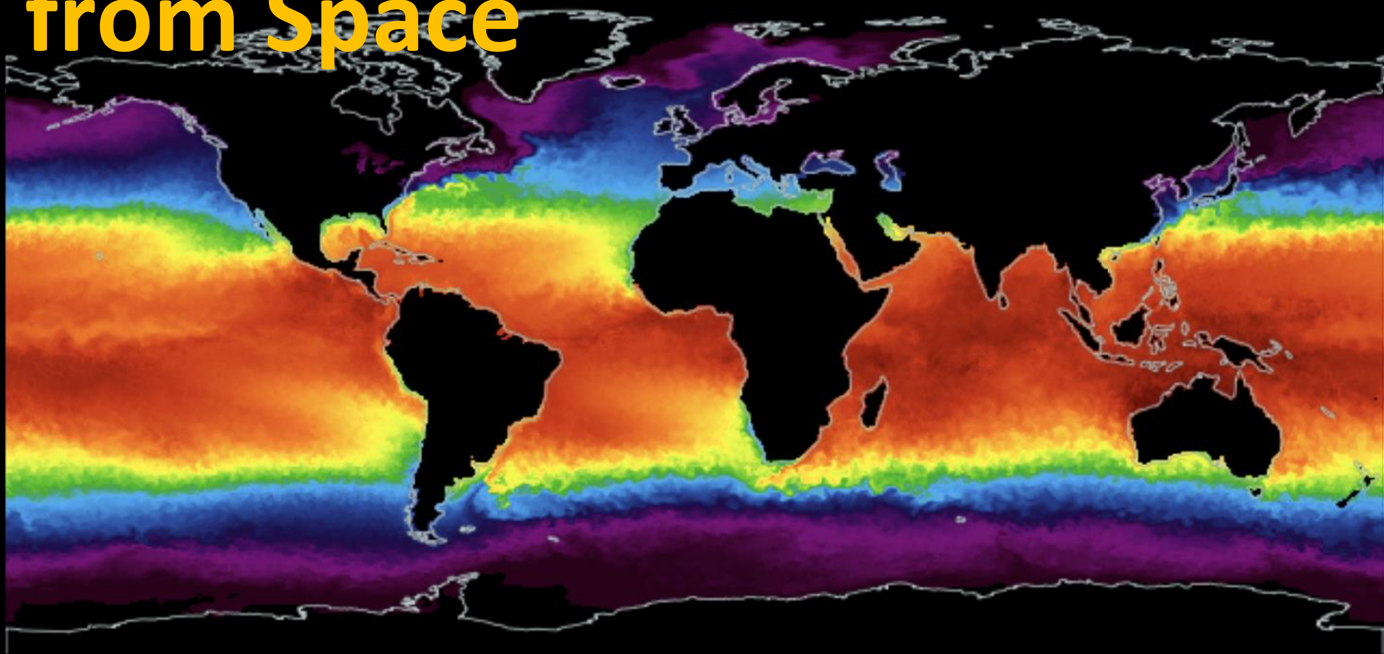


IR

Empirical retrievals:

Based on nonlinear regression by determining the regression coefficients of signals from different IR channels with respect to in-situ SST

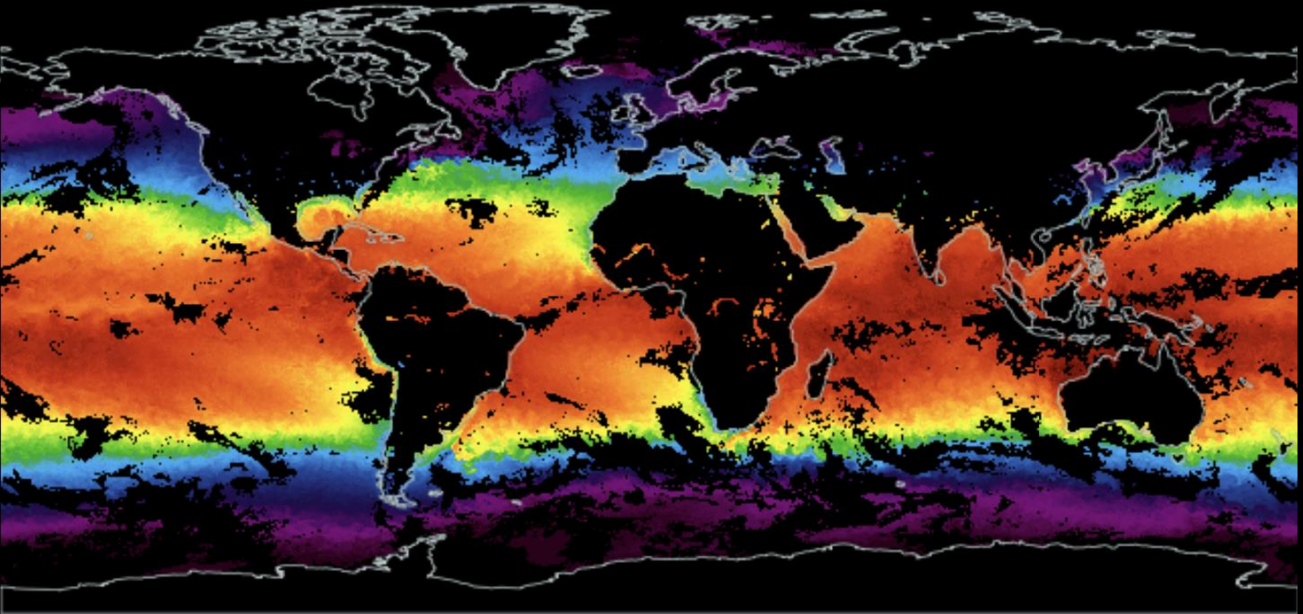
Sea Surface Temperature from Space



Infrared:

- top 10 microns of the surface
- higher spatial resolution, more accurate
- susceptible to cloud contamination, atmospheric effects

- Advanced Very High Resolution Radiometer (AVHRR) on NOAA satellites
- Along Track Scanning Radiometer (ATSR) on ESA's ERS-1 & -2
- Advanced ATSR (AATSR) on ESA's Envisat (also has near IR & visible channels)
- Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua
- Visible Infrared Imaging Radiometer (VIIRS) on NASA/NOAA Joint Polar Satellite System
- Sea and Land Surface Temperature Radiometer (SLSTR) on ESA's Sentinel-3



Microwave+Infrared (MUR):

- topmost 1-millimeter layer
- Lower spatial resolution
- Not impacted by cloud cover and atmospheric effects
- Affected by rain, surface roughness, and RFI

- NASA's TRMM Microwave Imager (TMI)
- Polarimetric Microwave Radiometer on US Navy's WindSat
- Advanced Microwave Scanning Radiometer (AMSR) on JAXA's ADOES-II
- AMSR-E on NASA's EOS Aqua
- AMSR-2 on JAXA's GCOM-W1
- Microwave Imager on NASA's GPM

Source: NASA worldview

IR SST generally more accurate than PMW SST

Overall uncertainties: IR SST ~ 0.3ºC, PMW SST ~ 0.5ºC

Example for JJA 2000 comparison with in-situ

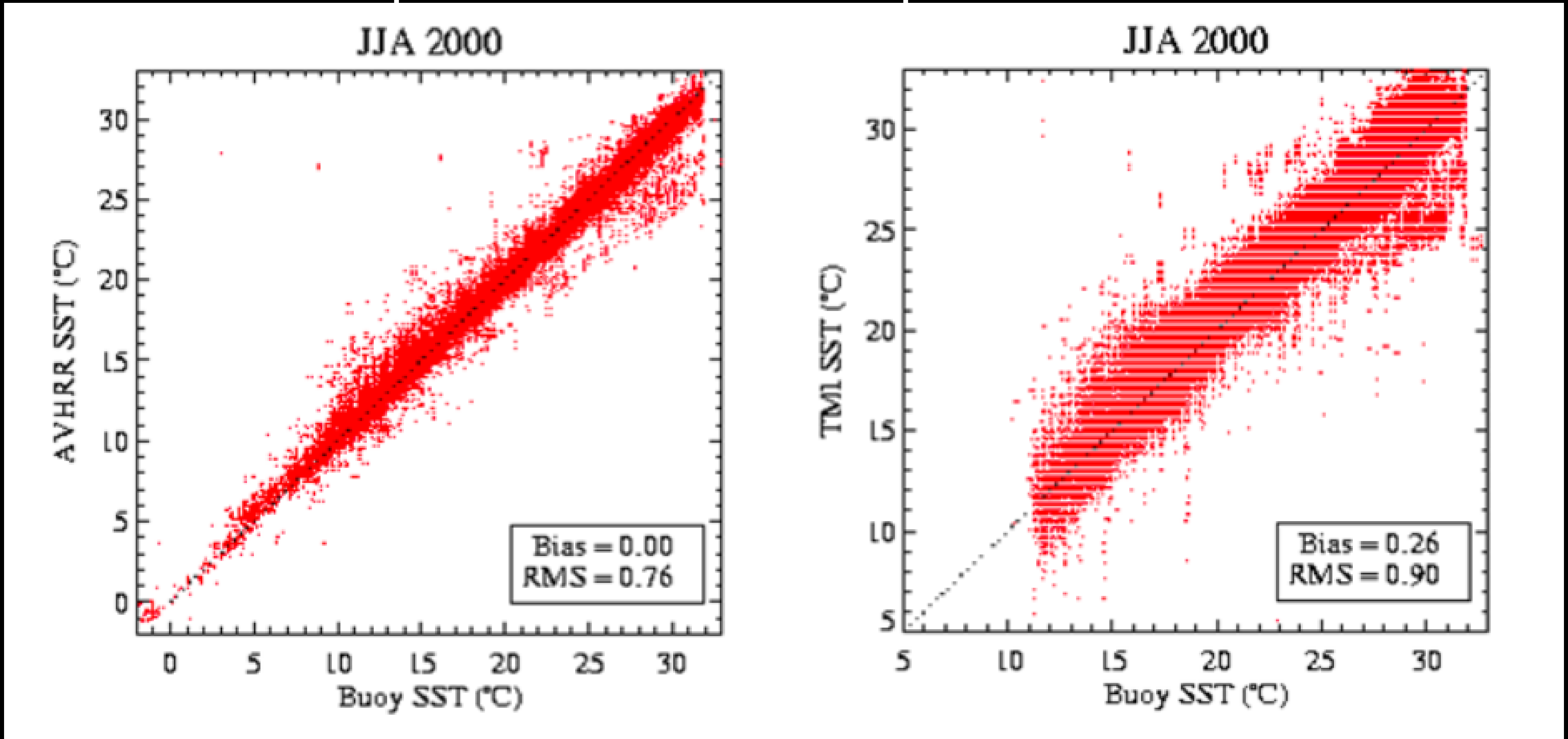
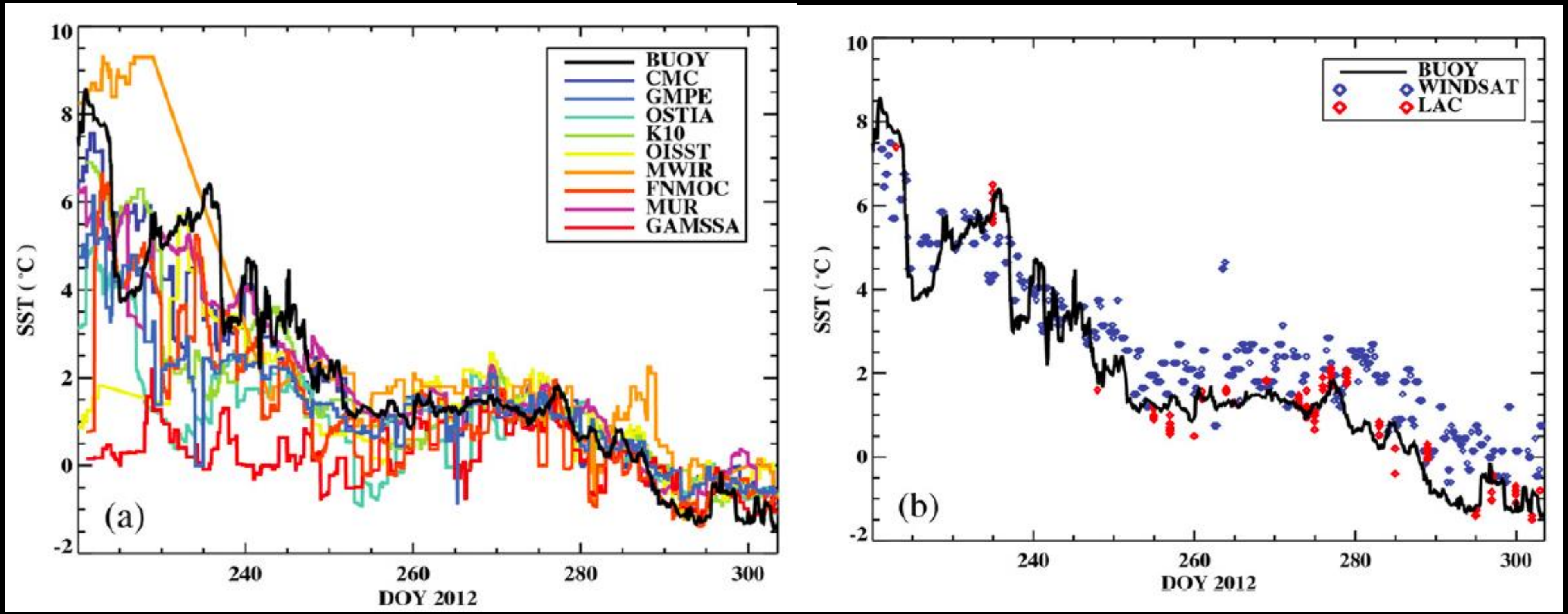


Image credit: Gary Wick

An Important Issue for Satellite SST products: consistency and accuracies in polar oceans

Comparison of GHRSST blended SST (left) and single-senor SST retrievals (right) with in-situ SST from an Arctic buoy



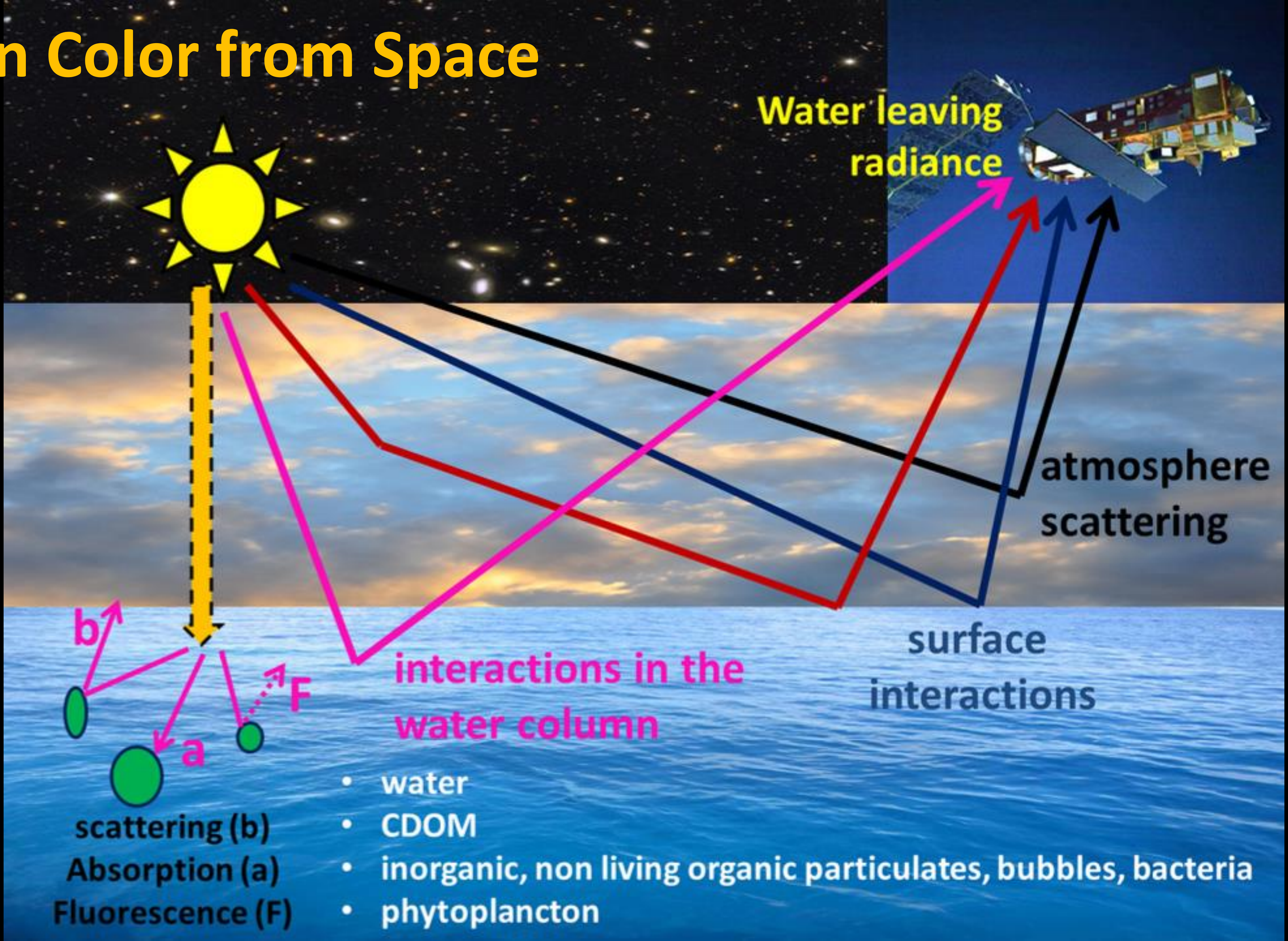
Castro, Wick, and Steele (2016)

Credit: Tony Lee, JPL

UV-Visible-IR Radiometry
Ocean Color

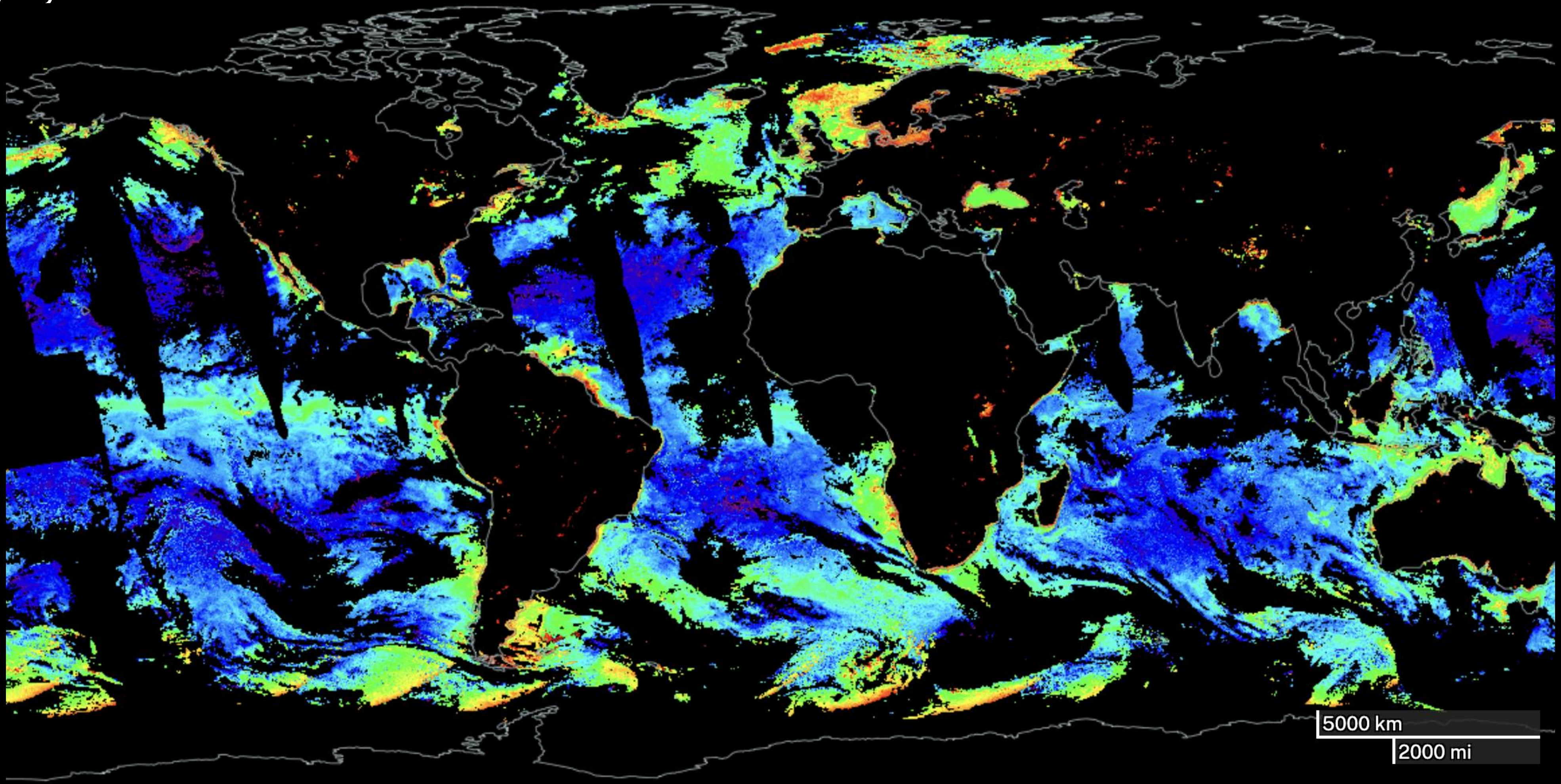
VIIRS, MODIS,…

Ocean Color from Space



Chlorophyll-a (VIIRS, 443, 486, and 551 nm – blue/green**):**

- Chlorophyll-a = concentration of the phytoplankton pigment, used as a proxy for the amount of phytoplankton in the surface water (absorbs more in blue/red, not in green)
- High spatial resolution but susceptible to cloud contamination due to the absorption of the ocean emitted infrared energy by clouds



Source: NASA worldview

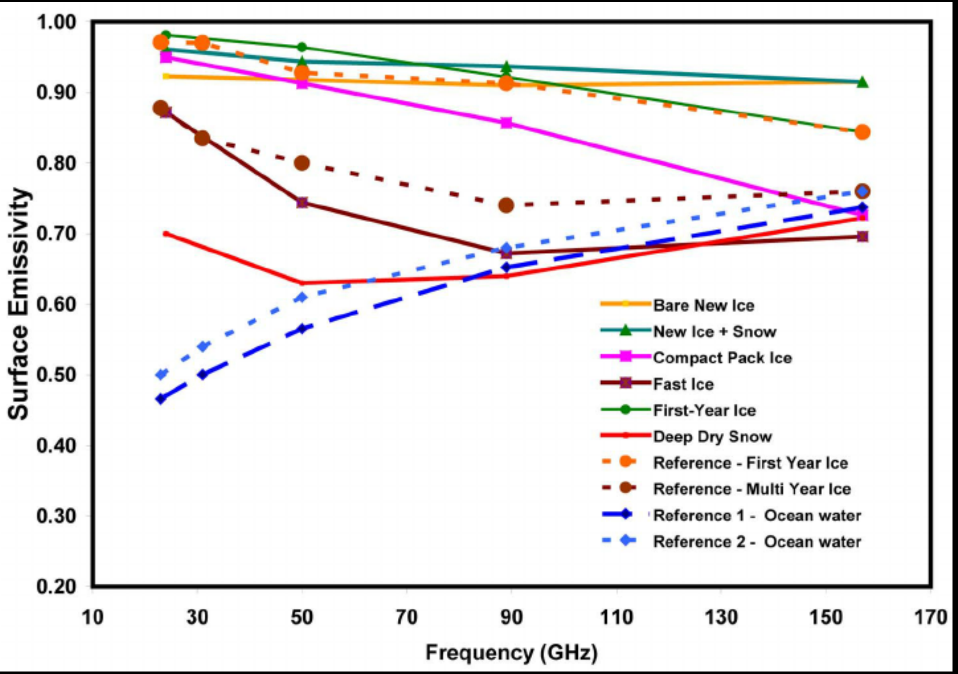
MW Radiometry
Sea Ice

AMSR, AMSR2, SMOS, SMAP,…

Sea Ice properties from Radiometry

- Passive microwave radiometer measures brightness temperature that depends on the emissivity of the surface (ocean, ice, sea ice, land)

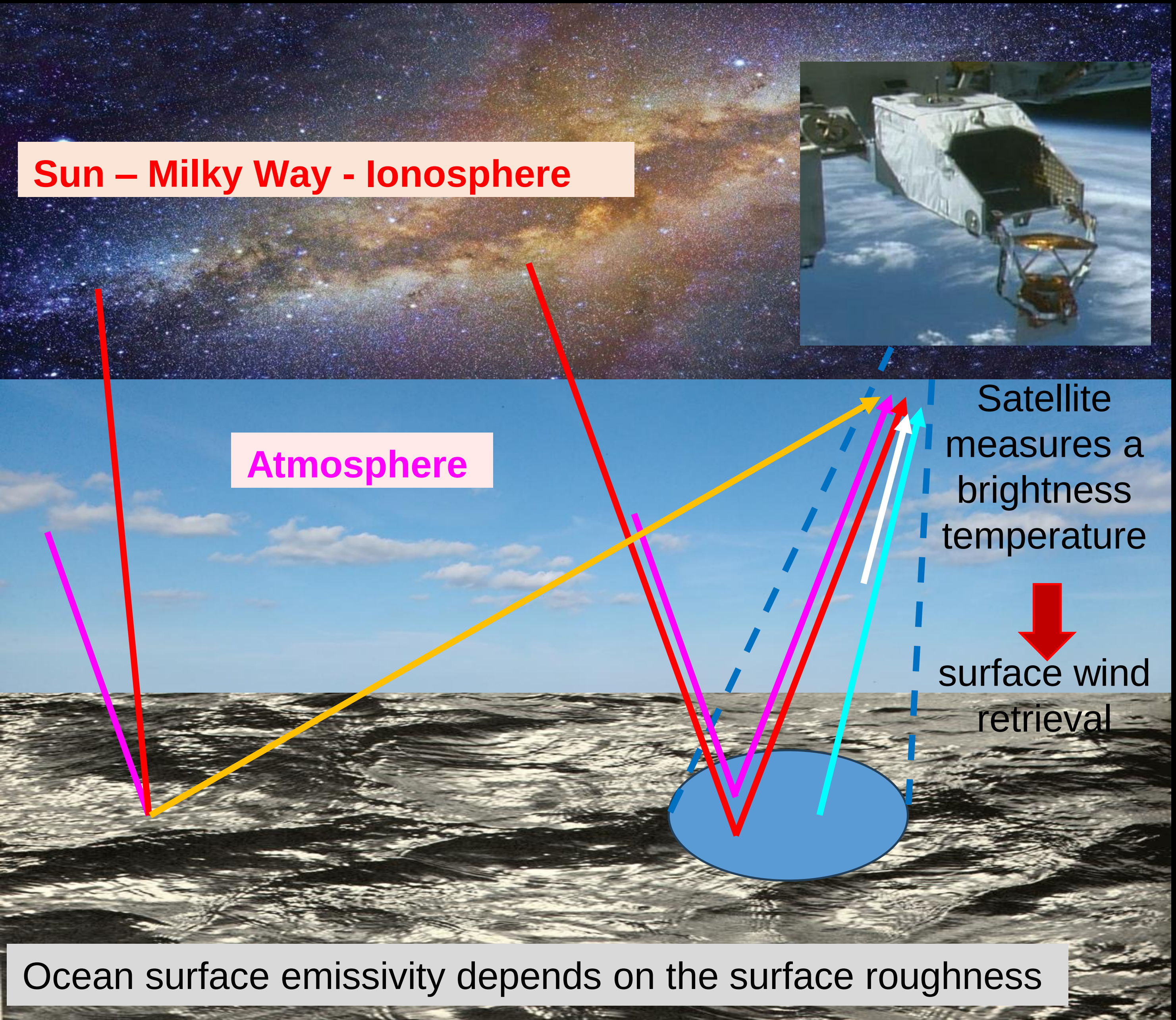
- The emissivity of sea ice:
  - depends on its physical characteristics (type of ice, age, etc.), frequency
  - is the contribution from the open water emissivity and the ice emissivity weighted by the sea-ice concentration
  - higher than ocean water emissivity at microwave frequencies



MW Radiometry
Sea Surface Winds

AMSR, COWVR, SSMI, WindSat, SMAP,…

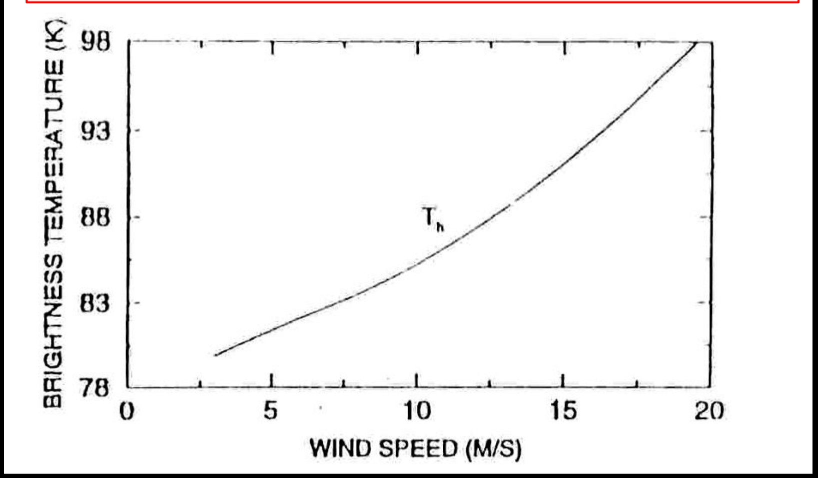
Sea Surface Wind from Radiometry



Wind Passive Microwave Radiometers:
Sensors operating from 10-40 GHz are ideal for measuring ocean wind speed

Ocean: - very reflective from 10-40 GHz
- appears cold from reflected sky (sky is cold from 10-40 GHz)

More wind (rougher):
- ➔ capillary waves and sea foam (which is absorptive)
- ➔ surface less reflective
- ➔ higher emissivity
- ➔ higher Tb

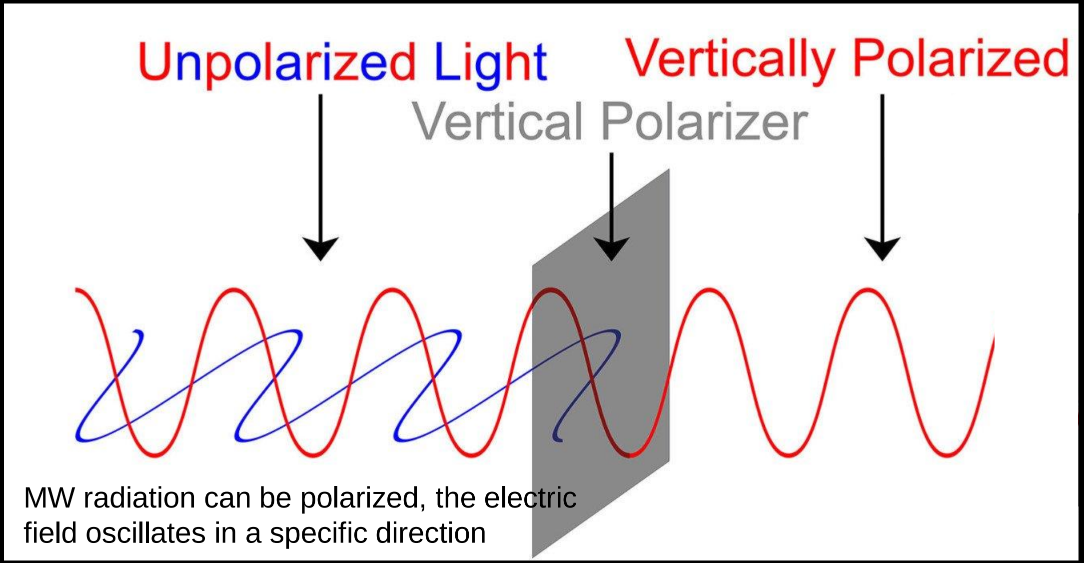


Sea Surface Wind from Radiometry

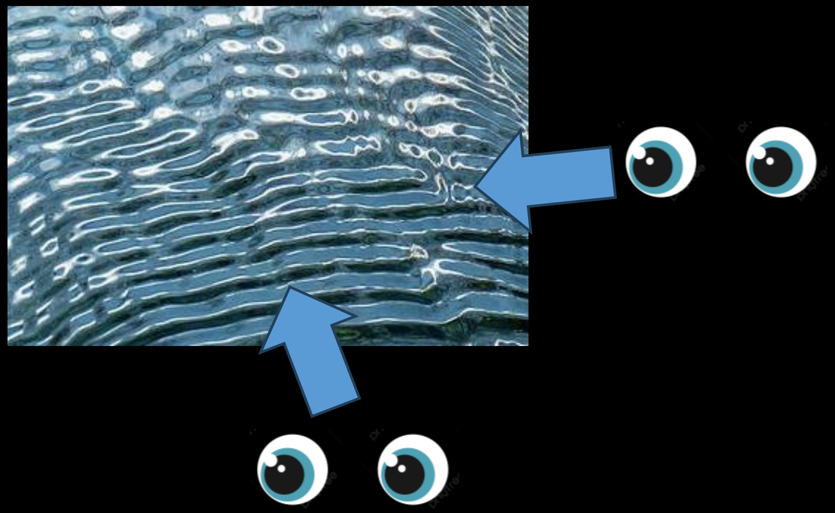
Wind Passive Microwave Radiometers:

- SMAP, AMSR, SSMI, TMI, GMI → Wind speed
- WindSat. WSF-M, COWVR → Wind speed **and direction** (because fully or cross polarized)

Capillary waves and foam align with the wind direction introducing a polarization dependence
-> Microwave radiation can be polarized, meaning the electric field oscillates in a specific direction

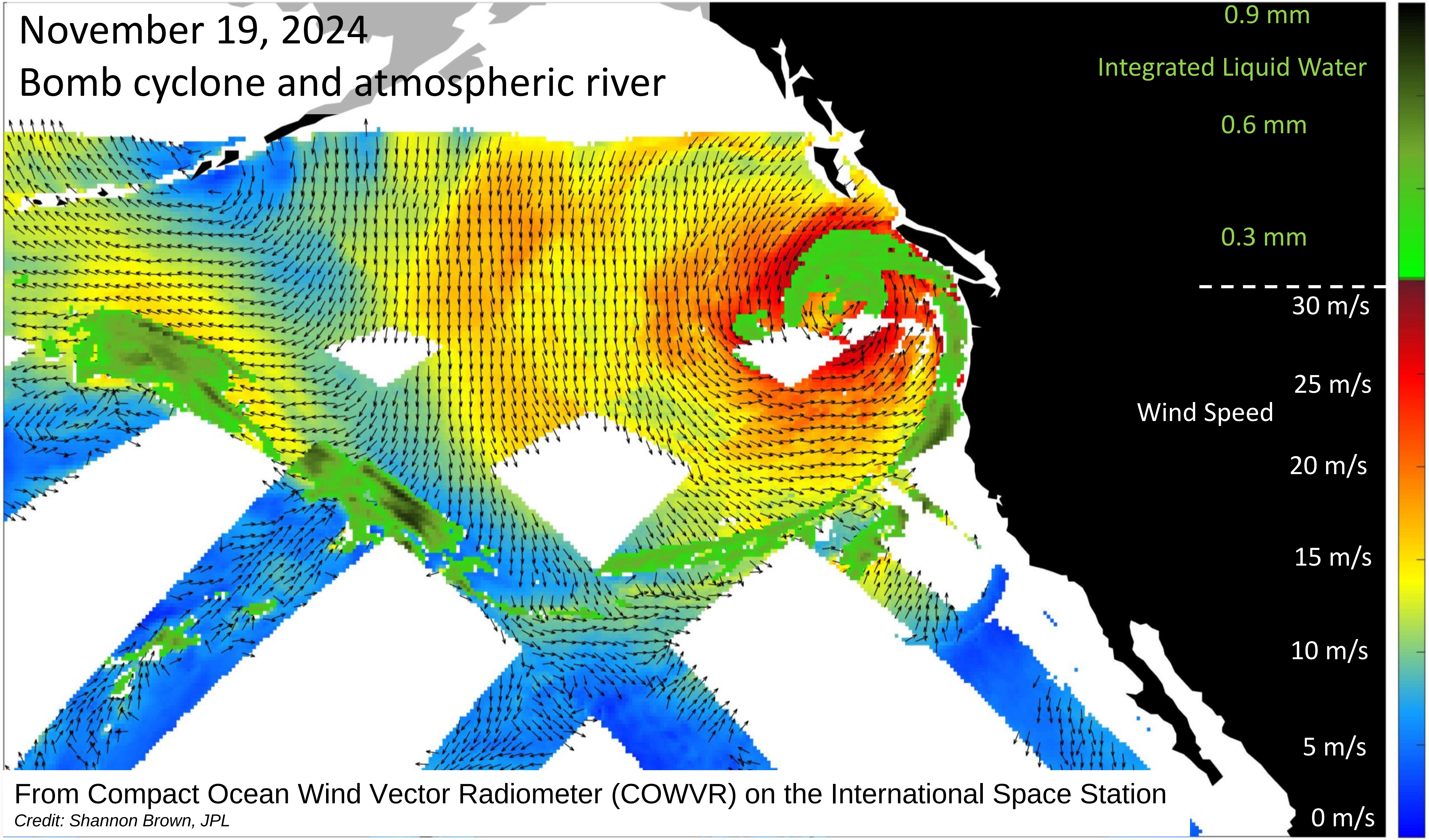


MW radiation can be polarized, the electric field oscillates in a specific direction



A fully or cross polarized radiometer gets “the full picture”: measures the complete polarization state of the surface. The relative change between polarizations give the wind direction once the speed is retrieved

November 19, 2024
Bomb cyclone and atmospheric river



From Compact Ocean Wind Vector Radiometer (COWVR) on the International Space Station

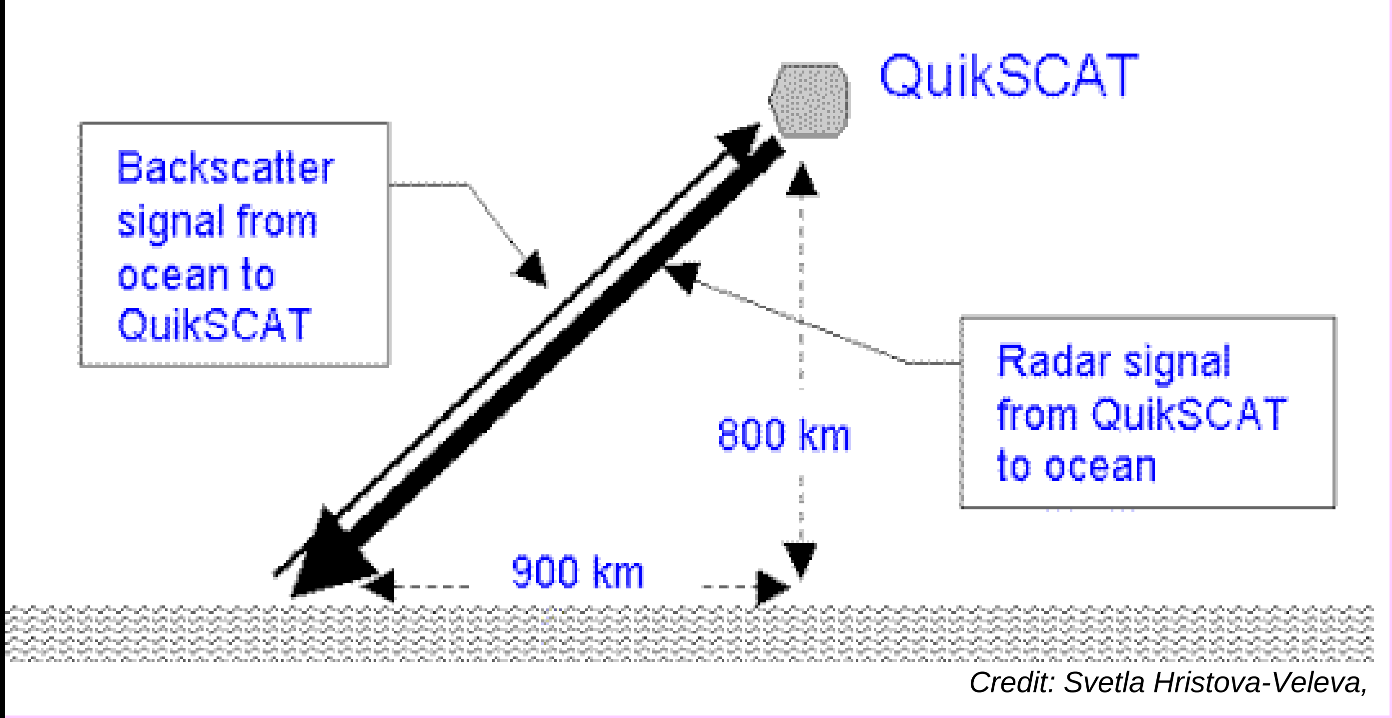
Credit: Shannon Brown, JPL

Scatterometry
Sea Surface Winds

ASCAT, QuickScat,…

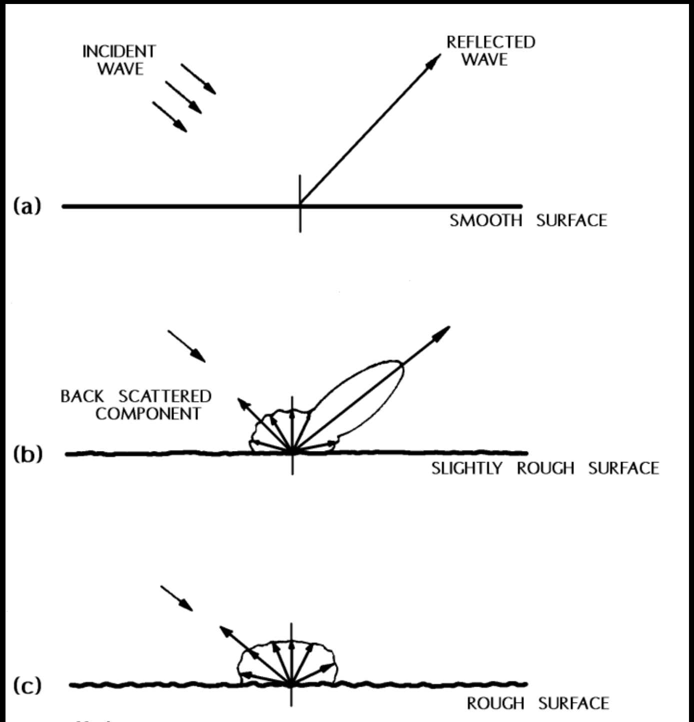
Wind Scatterometry Basic Principle

- The scatterometer:
  - a microwave radar
  - transmits a pulse towards the Earths surface and measures the reflected energy - the backscattered power from the surface roughness
  - measures ocean near-surface wind speed and direction

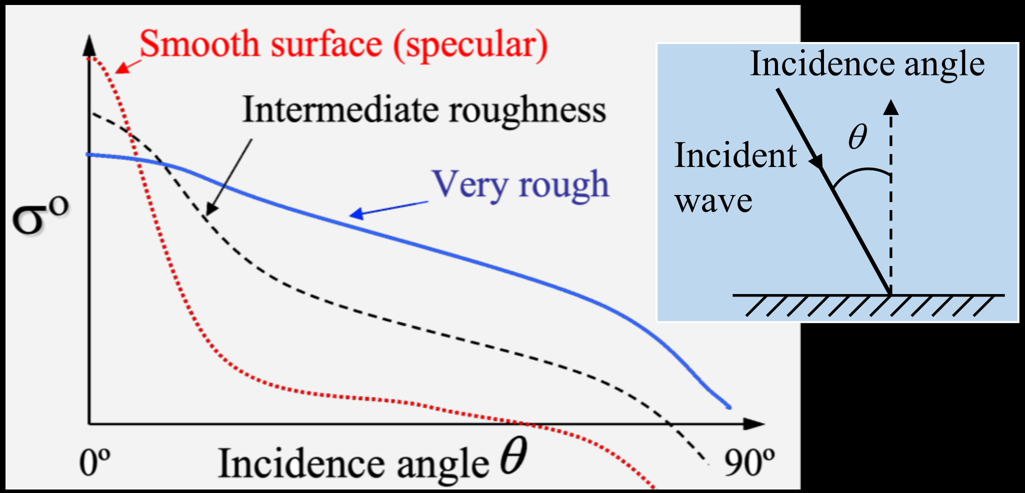


Wind Scatterometry Theory

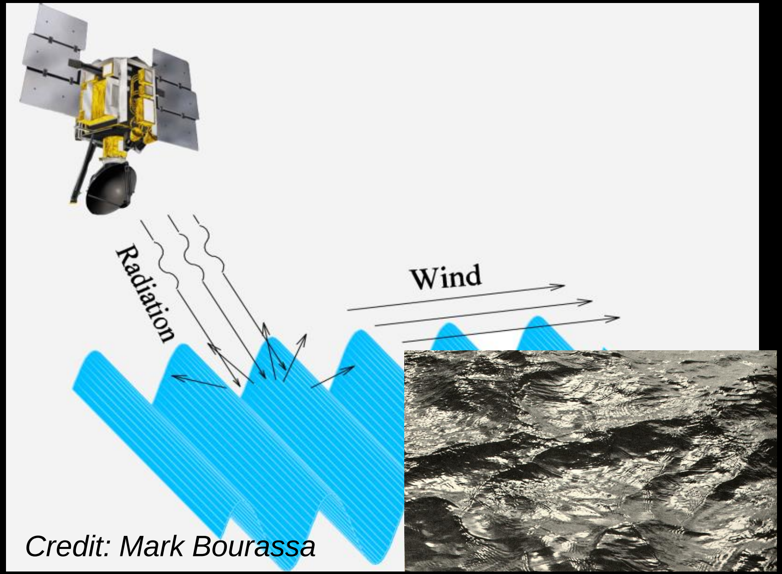
- “Backscatter” = return back toward the source
- Bragg scattering occurs for periodic surfaces, from the waves that are in resonance with the microwaves
- **σ**° is the normalized backscatter (backscatter/target area). It depends on:
  - roughness of the surface (related to wind speed and direction: winds create small capillary-gravity waves which roughen surface)
  - incidence angle: when it increases, specular reflection gets less important, and backscattering dominates
  - angle of view relative to the wind direction
  - …



Stoffelen, 1998



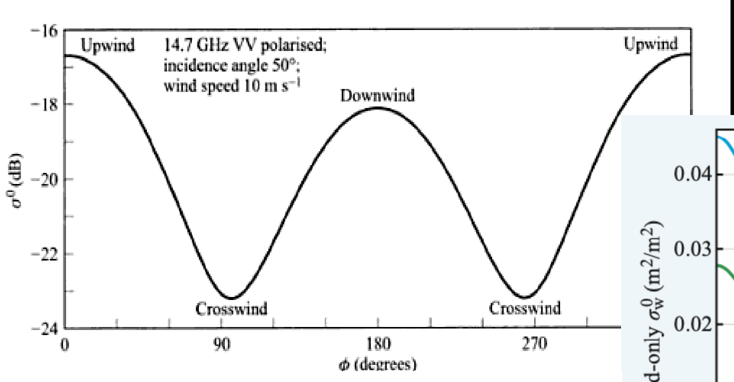
Credit: Mark Bourassa

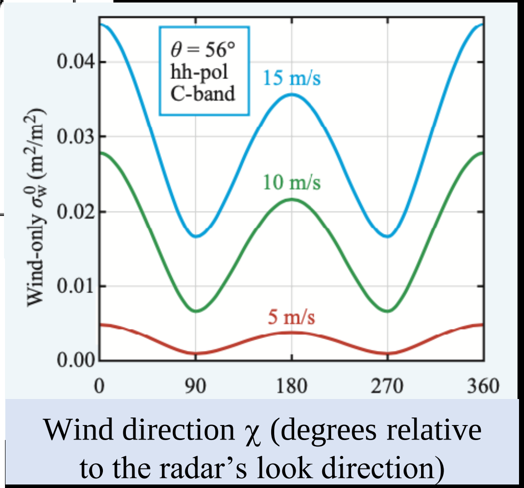


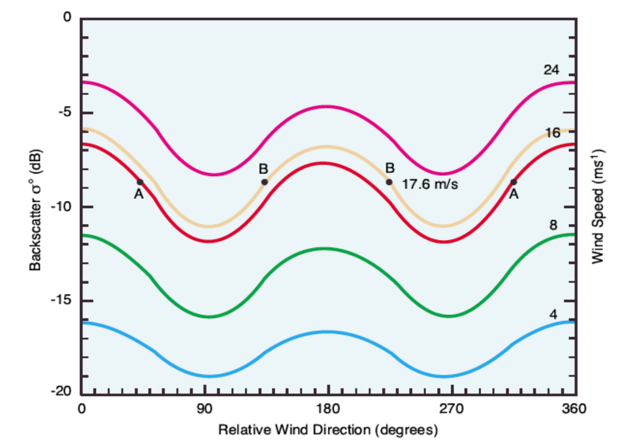
Credit: Mark Bourassa

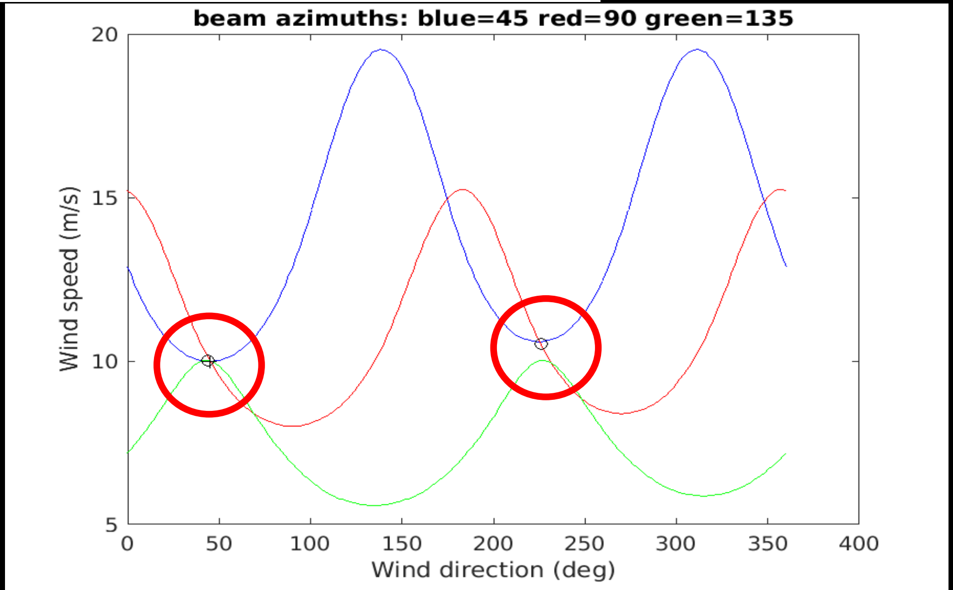
Wind Scatterometry Theory

- Geophysical Model Function (GMF): empirical relation between the backscatter and the wind speed and direction (relative to the direction of the radar beam)
- Solution with objective function (MLE, least square…)
- Multiple solutions for direction called “ambiguities”:
  - Mitigated with measurements at different azimuthal angles
  - Choice using nearby estimates (ex median filter)

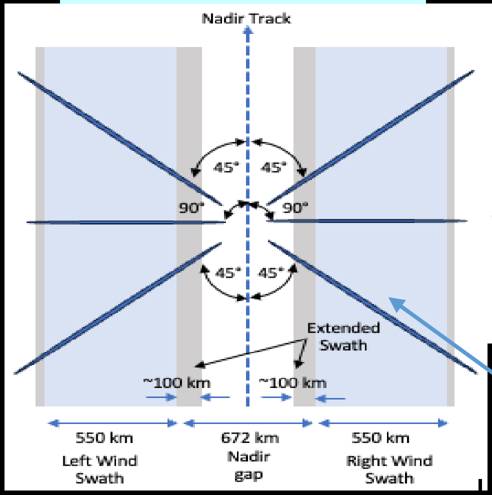




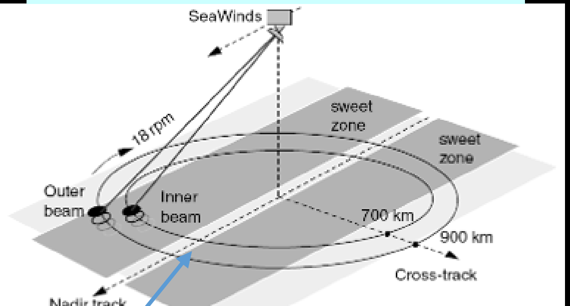




Fan-beam
(NSCAT/ASCAT…)

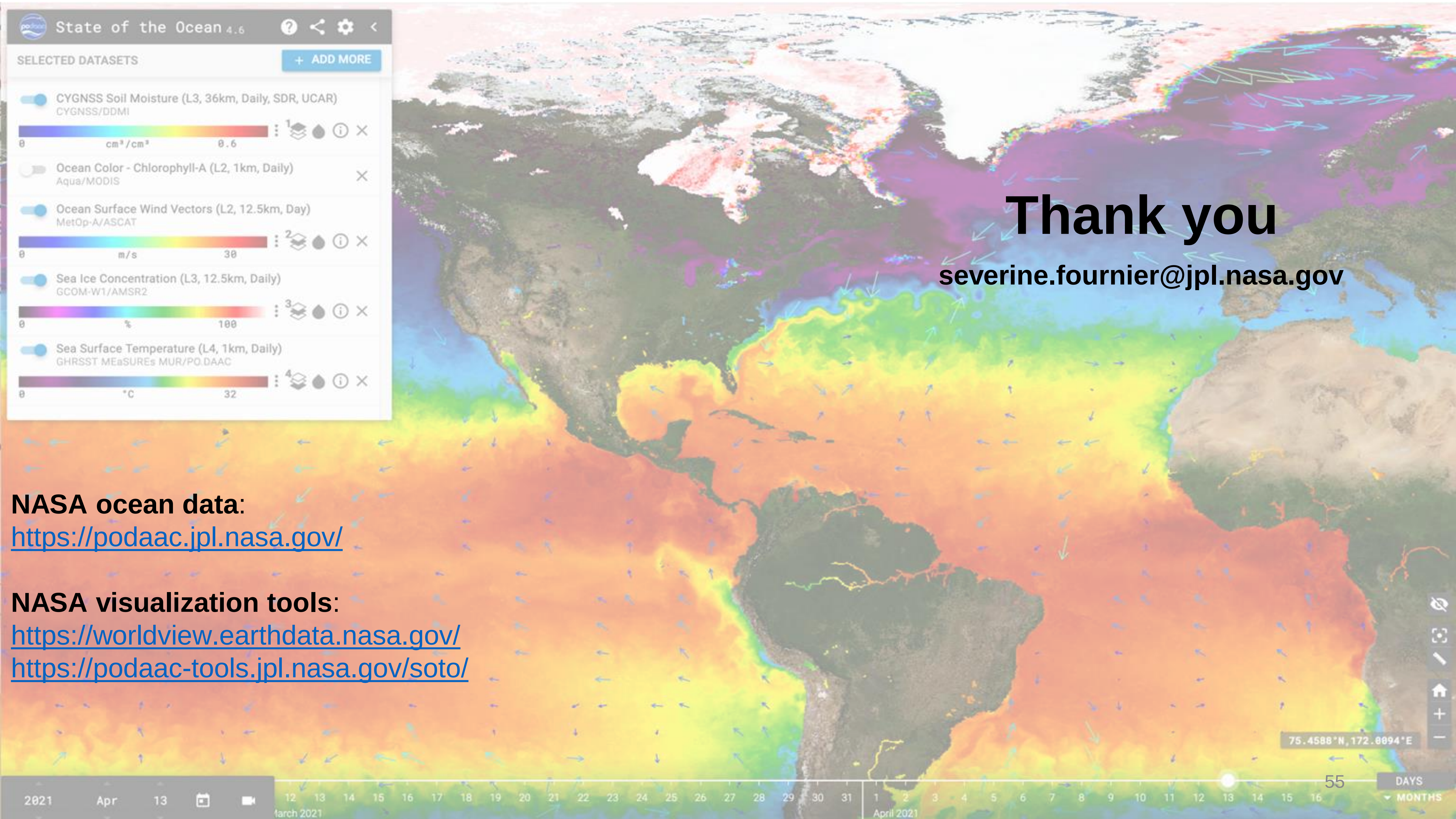


Conically Scanning
(SeaWinds/QuickSCAT…)



Credit: Mark Bourassa

Collects σ° at different azimuth angles



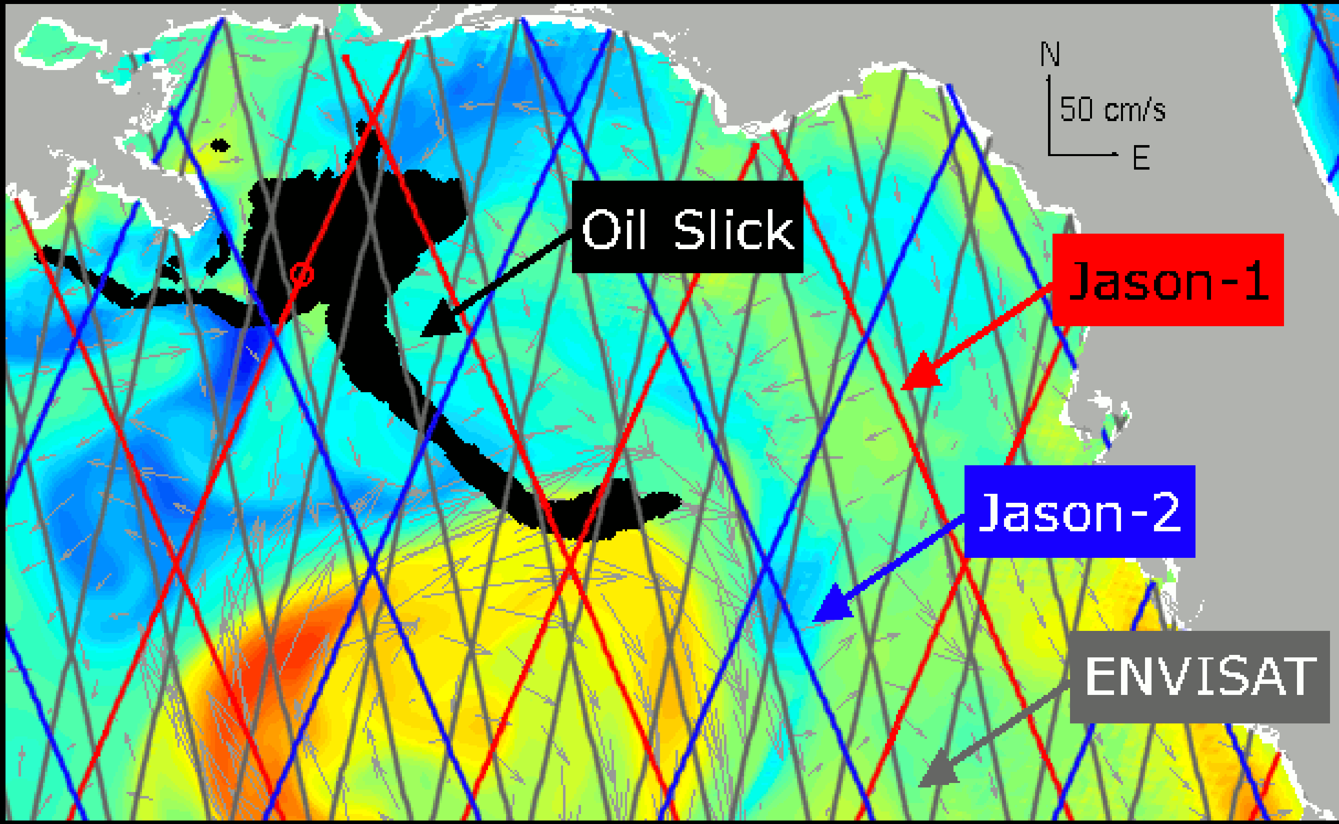
Thank you

severine.fournier@jpl.nasa.gov

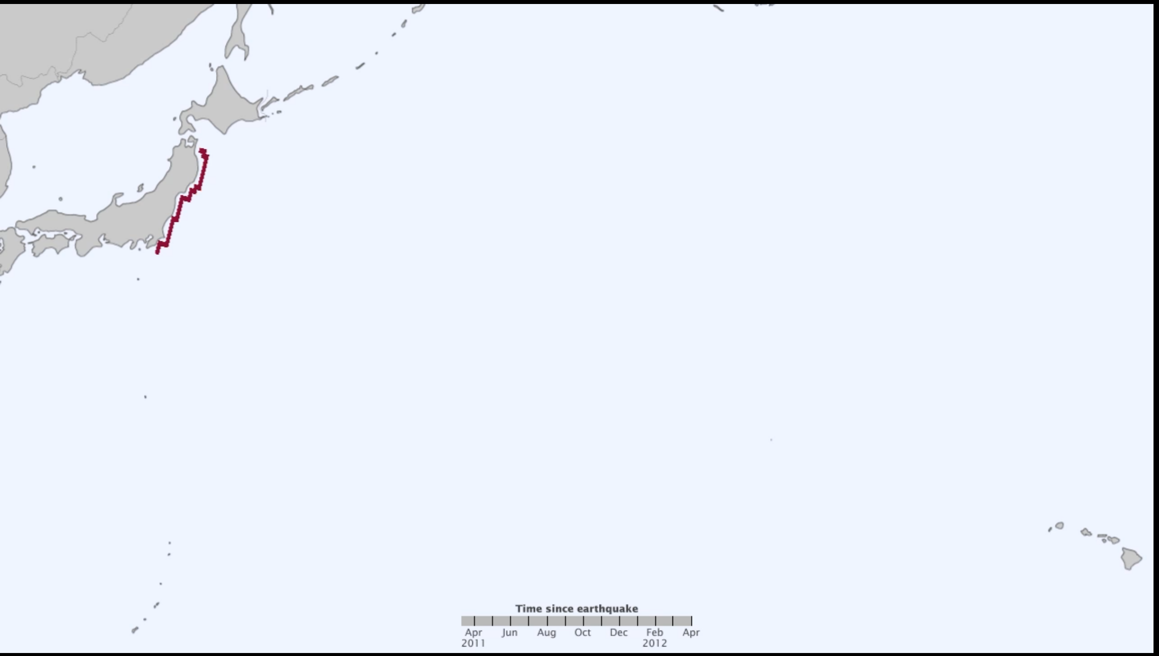
NASA ocean data:
https://podaac.jpl.nasa.gov/

NASA visualization tools:
https://worldview.earthdata.nasa.gov/
https://podaac-tools.jpl.nasa.gov/soto/

Importance of altimeters telling us about currents in real time



Deep Water Horizon Oil Spill - April 2010

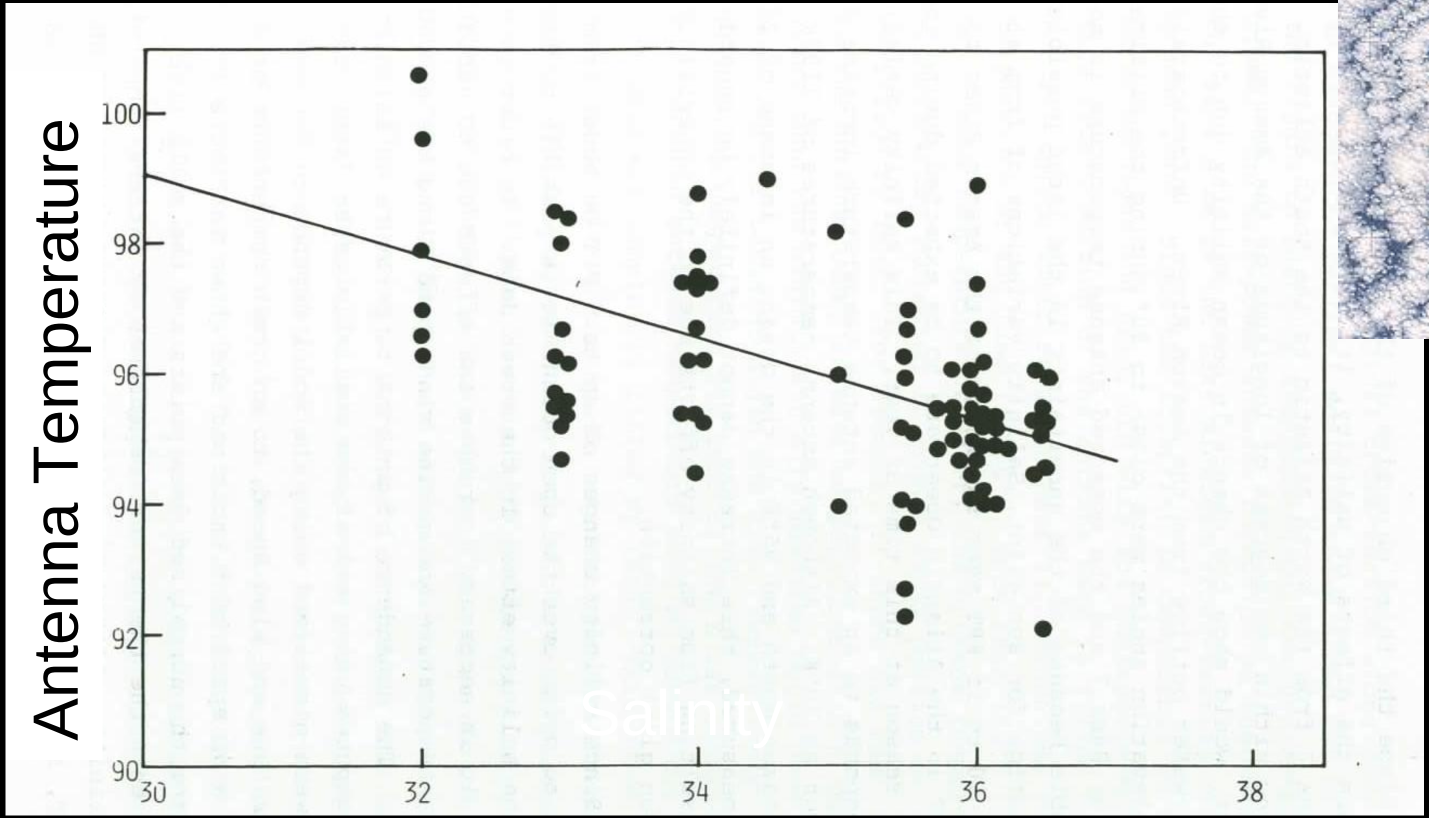


Tracking debris after Tohoku earthquake and tsunami – March 2011

https://earthobservatory.nasa.gov

The first L-band SSS measurements from Space

Skylab Space Station (1973)



Lerner & Hollinger, 1976, NRL Memo 3306

Credit: Tony Lee, JPL

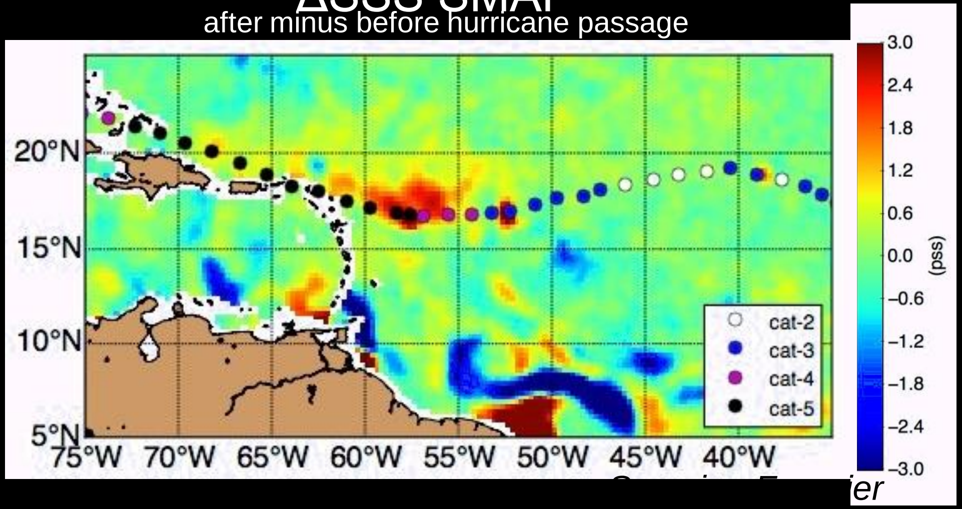
Implications to air-sea interactions (hurricane intensification)

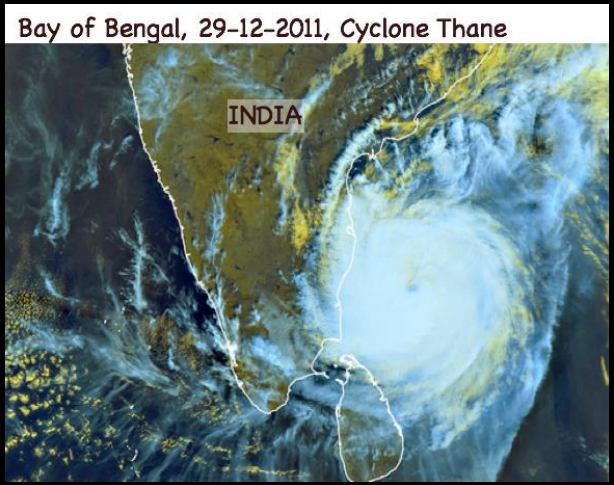
- Fresh, warm riverine waters: Formation and maintenance of a thin mixed layer and a barrier layer *[Pailler et al., 1999]*
    - Trapping of solar radiation in the surface layer enhanced leading to elevated sea surface temperatures (>1°C) *[Foltz and Mc Phaden, 2008; Ffield, 2007; Vizy and Cook, 2010; Grodsky et al., 2012]*
    - Wind-induced mixing and entrainment of cool thermocline water into the mixed layer limited *[Balaguru et al., 2012; Grodsky et al., 2012; Reul et al., 2014]*

Hurricane Irma, September 2017

ΔSSS SMAP

after minus before hurricane passage





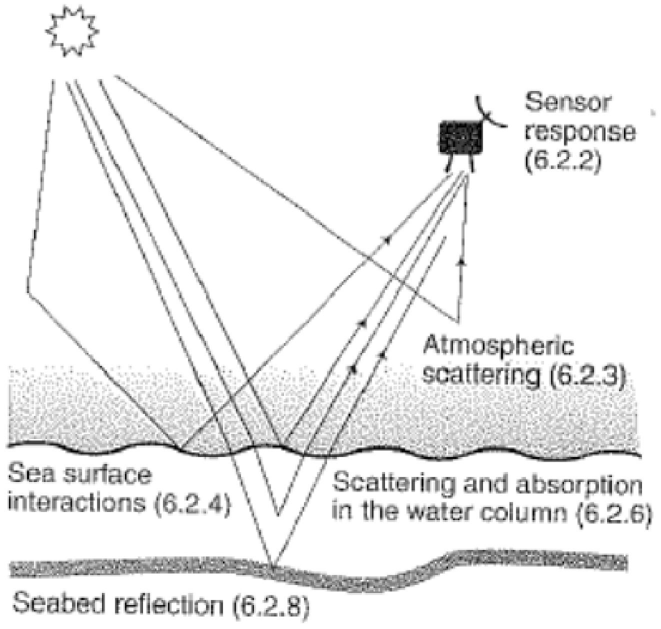
- 1.5 pss haline wake after hurricane passage due to the mixing of the fresh river plume water with subsurface saltier water (equivalent 3.5°C cooling in its impact on density)

Also seen in the Bay of Bengal *[Neetu et al., 2012; Sengupta et al., 2008]*

Ocean Color from Space

Sunlight interacts with pigments in living plant cells, dissolved organic matter and particulates in the upper ocean :

absorption / **scattering** / **fluorescence** (IOPs)



Radiometer (visible & near-IR) **measures the water-leaving radiance** in $mW/cm^2/\mu$ m/sr at different wavelengths :

- the reflected downwelling sunlight leaving the ocean surface to the sensor not absorbed or scattered
- depends on the IOPs

Absorption : water, CDOM, inorganic particulates, non living organic particulates, bubbles and bacteria, and phytoplankton

$$a(\lambda) = a_w(\lambda) + a_g(\lambda) + a_d(\lambda) + a_{ph}(\lambda) \quad \& \quad a_g(\lambda) + a_d(\lambda) = a_{cdm}(\lambda)$$

IOPs derived from radiances measured by sensors :

- GSM (Garver, Siegel and Maritorena) model (*Maritorena et al., 2002*)
- corrections for atmosphere absorption and scattering
- $a_{cdm} = a_{cdm}(443nm)\ exp(-S(\lambda - 443))$

How does scatterometer wind retrieval work?

(a simplified illustration for ASCAT)

- ASCAT collects 3 sigma-0 measurements at different azimuth angles
- GMF gives wind/speed curve for each radar look direction, <u>now relative to North</u>
- Wind estimate is where curves intersect
  - Determine by minimizing an "objective function"
- Multiple solutions called "ambiguities"
  - Typically, 1-4 ambiguities
  - Rank by "closeness" (1st, etc.)
  - First two about 180° deg apart, similar speeds
- Selection of unique wind uses nearby estimates ("Ambiguity selection")