Advances in Satellite Oceanography
(Monitoring Earth's water resources)

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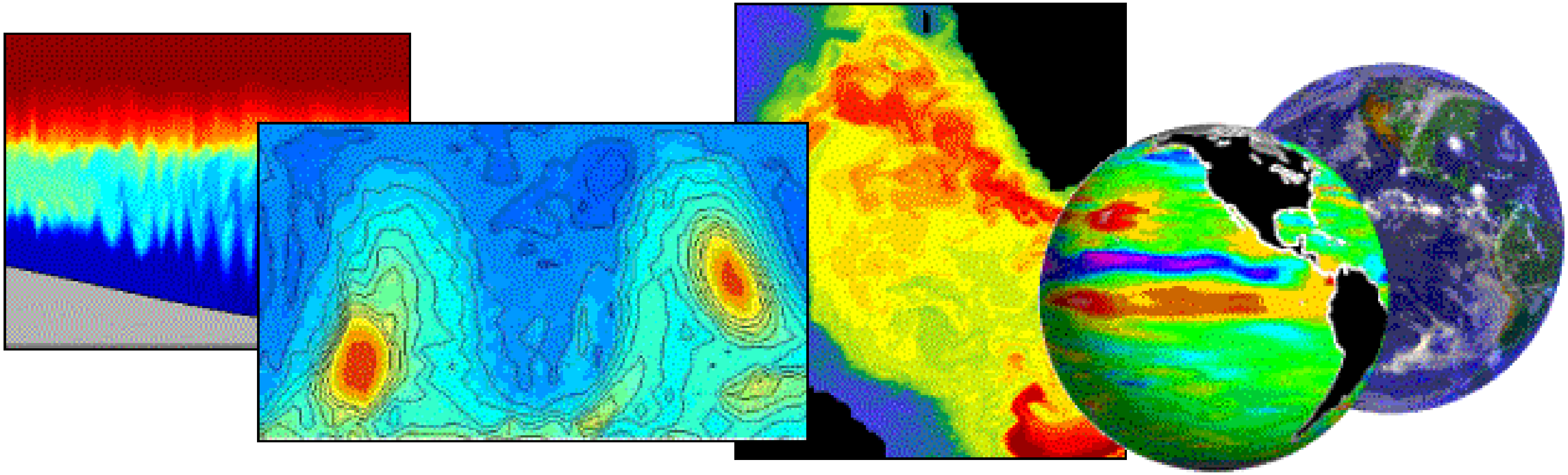
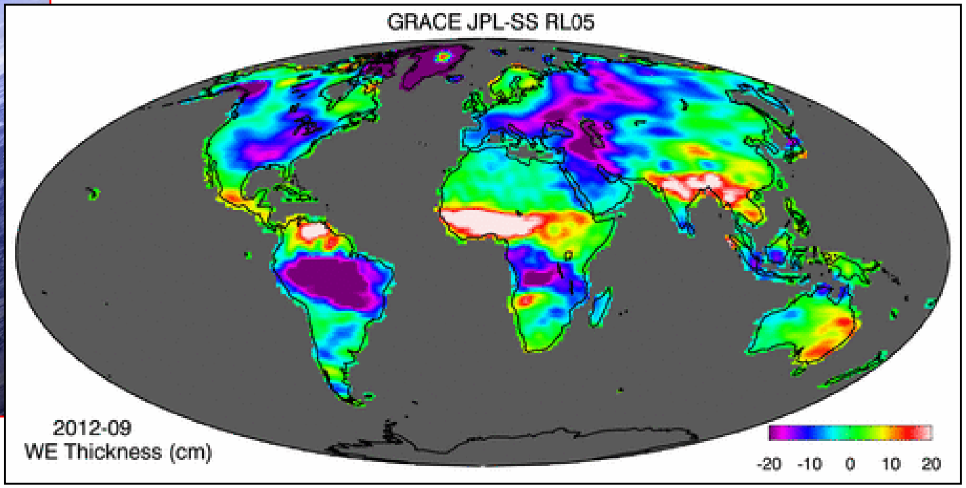


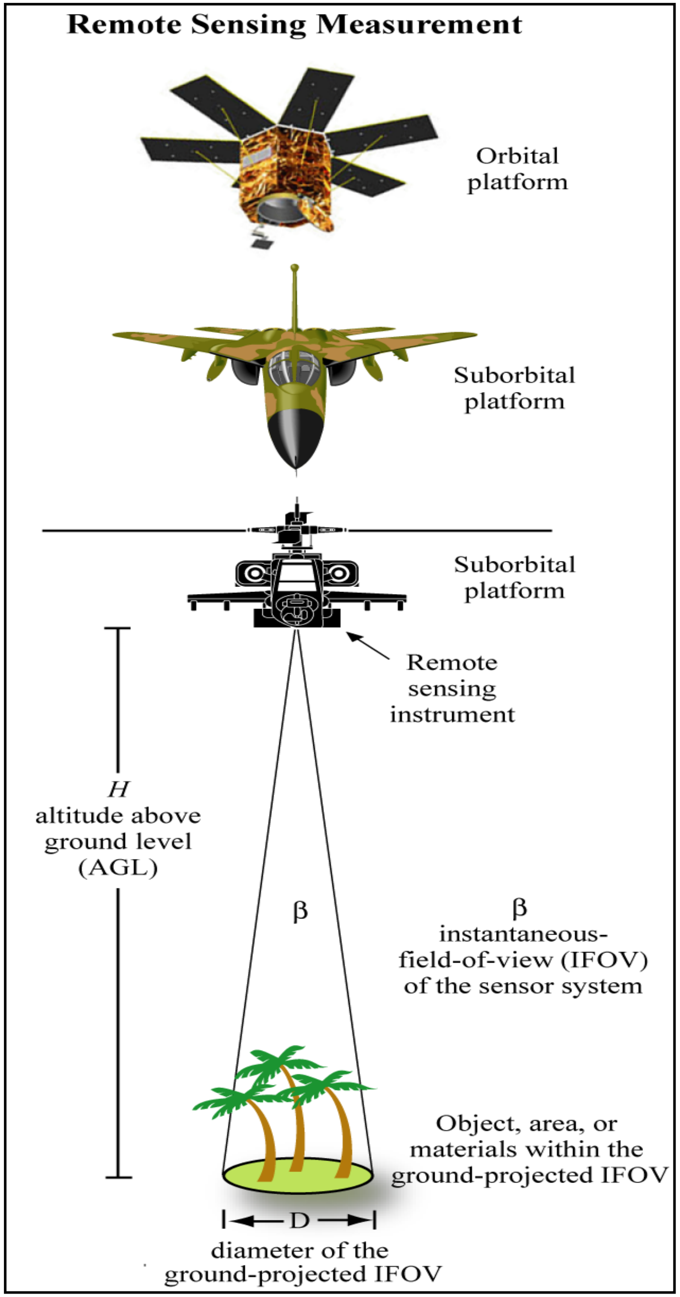
UG-DMFS Summer Program (AUGUST 1-5, 2016)

Outline:

- ➢ Remote Sensing: brief intro
- ➢ Salinity sensing
- ➢ GRACE



Introduction



ASPRS adopted a combined formal definition of *photogrammetry* and *remote sensing* as (Colwell, 1997):

> "the *art*, *science*, and *technology* of obtaining reliable information about physical objects and the environment, through the process of recording, measuring and interpreting imagery and digital representations of energy patterns derived from **noncontact sensor systems**".

Remote Sensing: A brief history

Hot-air Balloons Invented by the Montgolfier Brothers in 1783

A cartoon by the artis

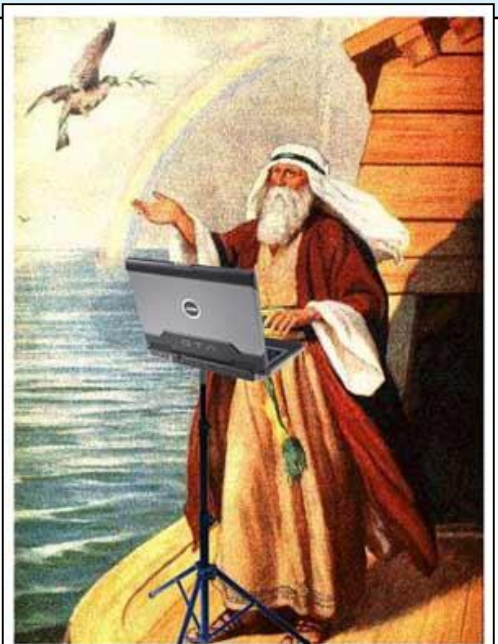
Gaspard Felix Tournachon (Nadar)

1858 Gaspard Felix Tournachon (Nadar) takes first aerial photograph near Paris, using a captive balloon and a collodion plate. Unfortunately, this first aerial photograph did not survive.

Remote Sensing: A brief history

In 1903, Julius Neubronner patented a breast-mounted camera for carrier pigeons that weighed only 70 grams.

A squadron of pigeons is equipped with light-weight 70-mm aerial cameras.



Importance of satellite oceanography

- Observes the distribution of certain ocean surface properties in exquisite spatial detail: allows the true spatial structure to be examine

- Captures a “snapshot” of the spatial distribution. “Freezes” the continually changing ocean

- Offers a repeated view: consistent measurements by a single sensor

- Observes part of the ocean other methods miss
  - Shipping routes are concentrated in certain zones
  - Ships tend to avoid poor weather hazardous regions
  - Drifting buoys tend to avoid regions of divergent currents

Limitations of satellite oceanography

- Can observe only some of the ocean's properties and variables
- Measures the ocean only at or near the surface

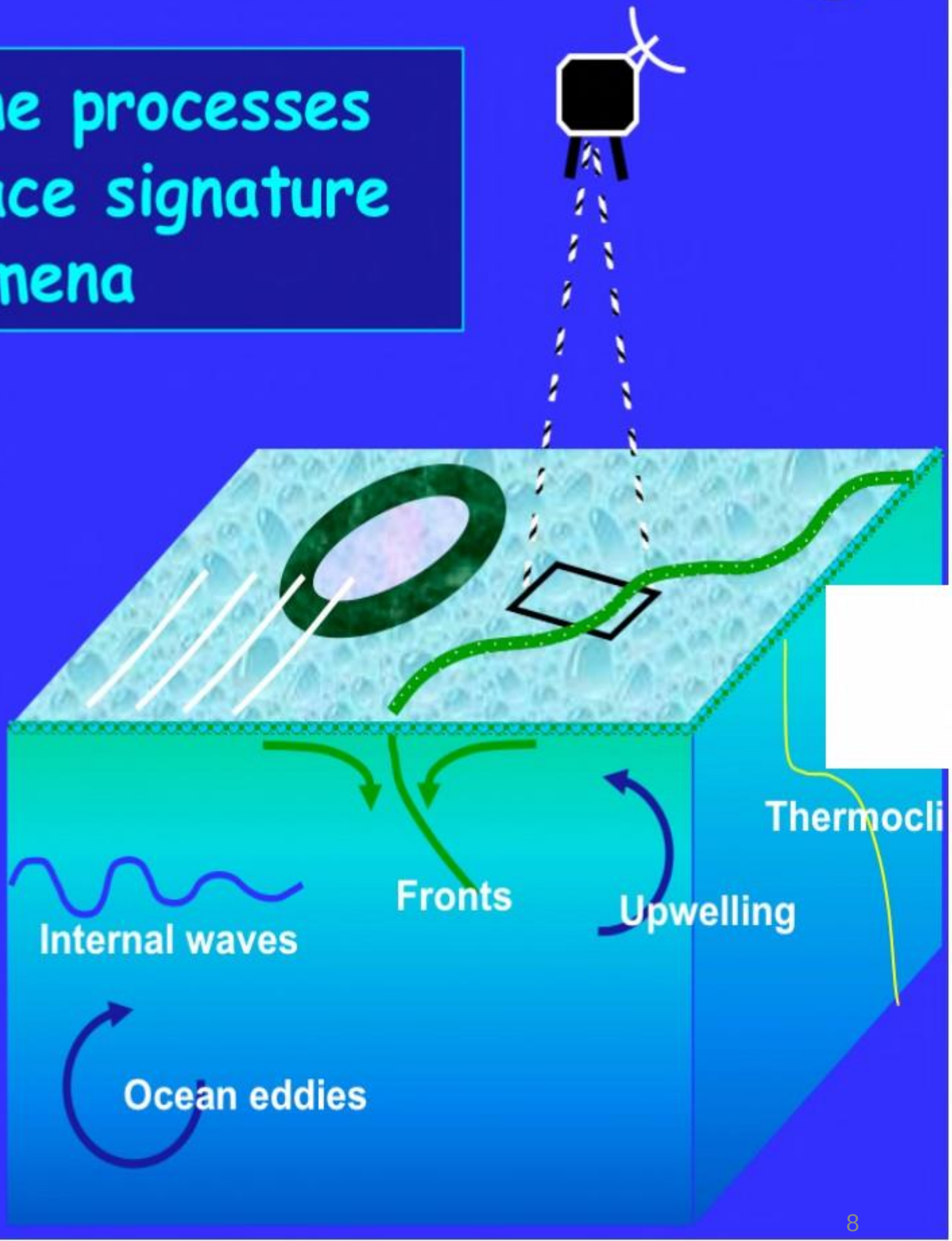
-- Although the surface is the most critical place to measure

- Ocean measurements may be corrupted by the atmosphere
- Some satellites/methods cannot see through clouds at all
- Can make measurements only when the satellite is in the right place at the right time
- All measurements require calibration and validation using in situ data

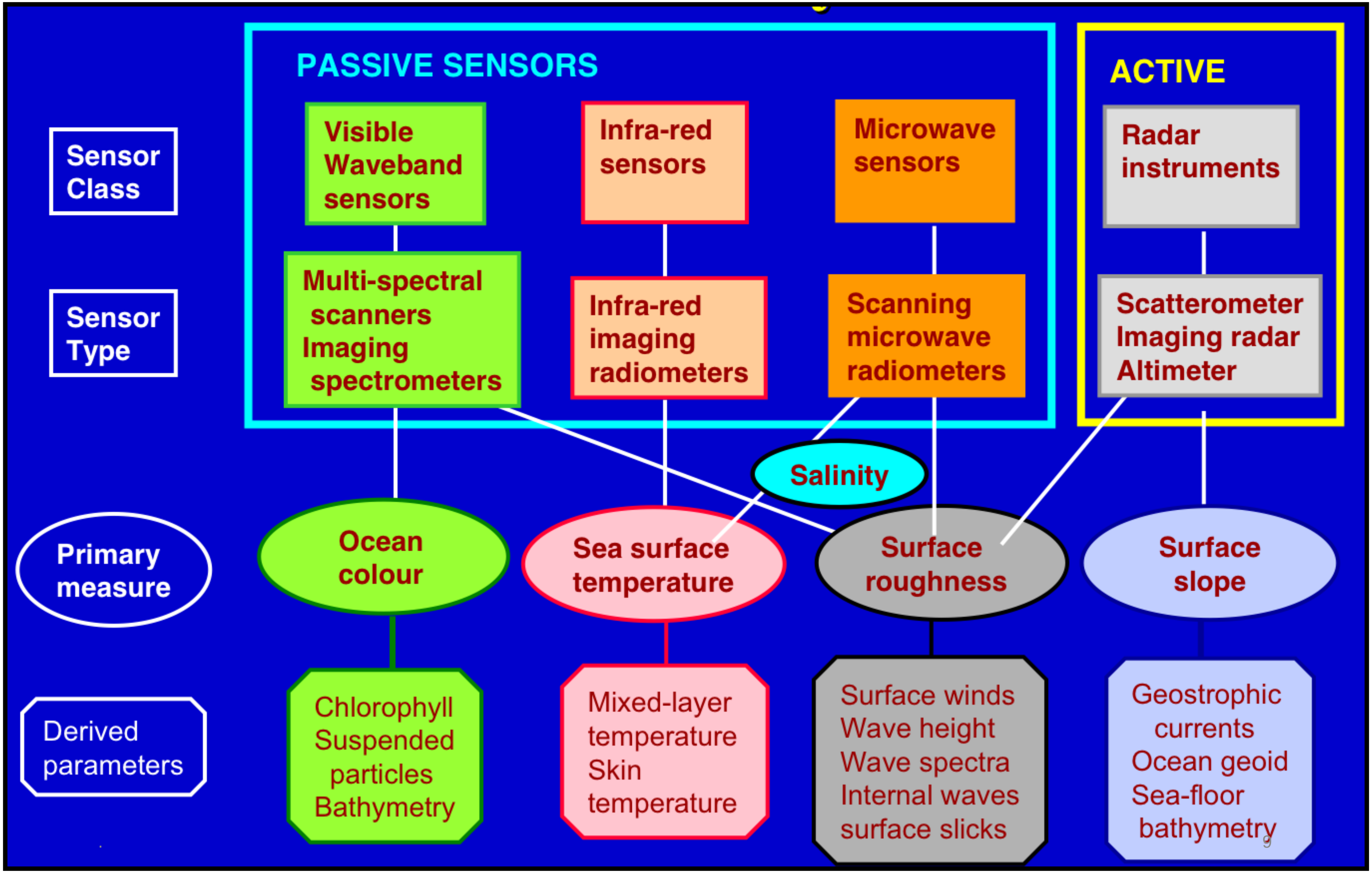
An obvious limitation of remote sensing

__Challenge__: Understand the processes which produce a surface signature for subsurface phenomena

- Remote sensors observe the sea SURFACE
- **We often want to observe processes INSIDE the sea**
- **Subsurface processes can only be detected if they have a *surface signature***



A summary of sensor types & what they measure



PASSIVE SENSORS

ACTIVE

Sensor Class

- Visible Waveband sensors
- Infra-red sensors
- Microwave sensors
- Radar instruments

Sensor Type

- Multi-spectral scanners Imaging spectrometers
- Infra-red imaging radiometers
- Scanning microwave radiometers
- Scatterometer Imaging radar Altimeter

Salinity

Primary measure

- Ocean colour
- Sea surface temperature
- Surface roughness
- Surface slope

Derived parameters

- Chlorophyll Suspended particles Bathymetry
- Mixed-layer temperature Skin temperature
- Surface winds Wave height Wave spectra Internal waves surface slicks
- Geostrophic currents Ocean geoid Sea-floor bathymetry

Basic physics and principles

Sources of energy for remote sensing

❑ The Sun

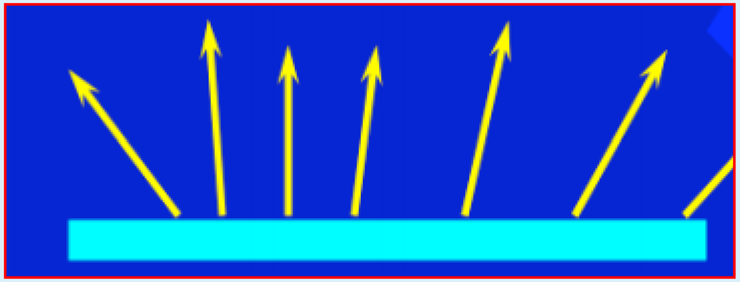
--- Visible waveband

--- Near Infra red waveband

❑ Thermal emission by the ocean surface

--- Thermal infra red

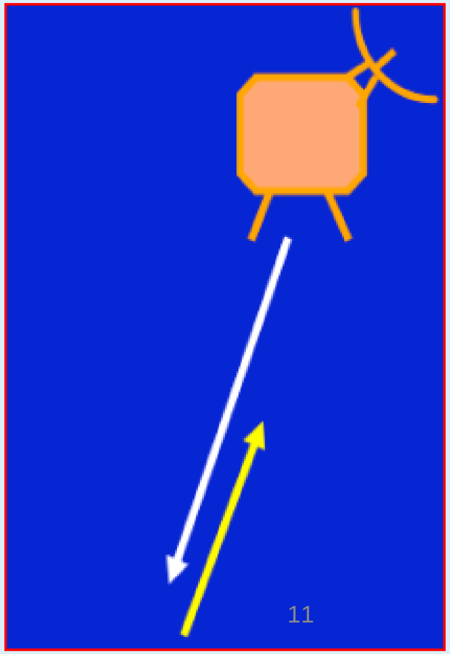
--- Microwaves



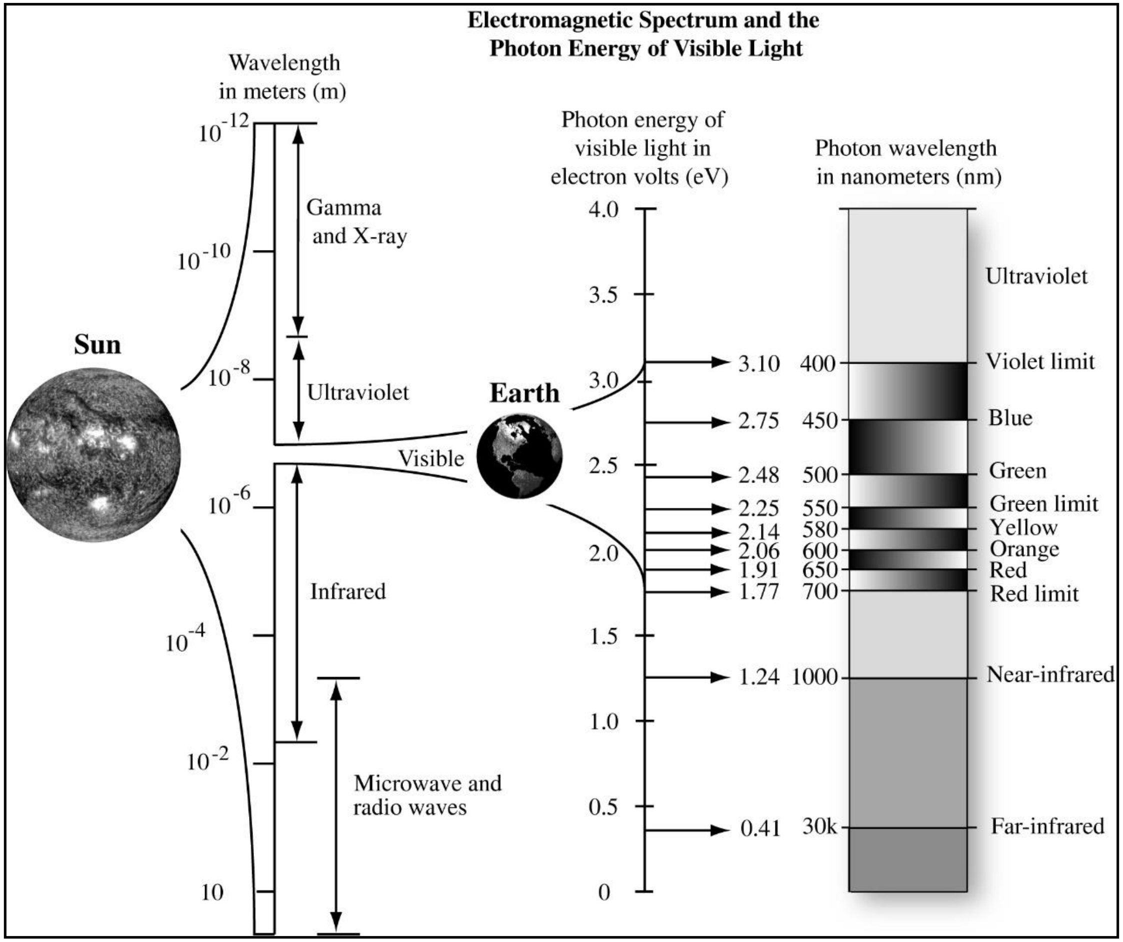
❑ Energy source on the satellite

--- Microwaves (Radar)

--- Visible (Lidar)



Electromagnetic Spectrum

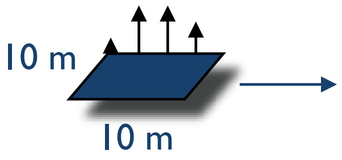


The Sun produces a *continuous spectrum* of energy from gamma rays to radio waves that continually bathe the Earth in energy.

The visible portion of the spectrum may be measured using wavelength (micrometers or nanometers) or electron volts (eV).

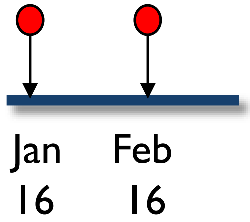
All units are interchangeable.

Remote Sensor Resolution Considerations

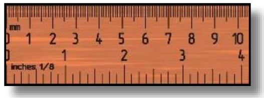


- **Spatial** - the size of the field-of-view, e.g. 10 × 10 m.

- **Spectral** - the *number* and *size* of spectral regions (or frequencies) the sensor records data in, e.g. blue, green, red, near-infrared, thermal infrared.



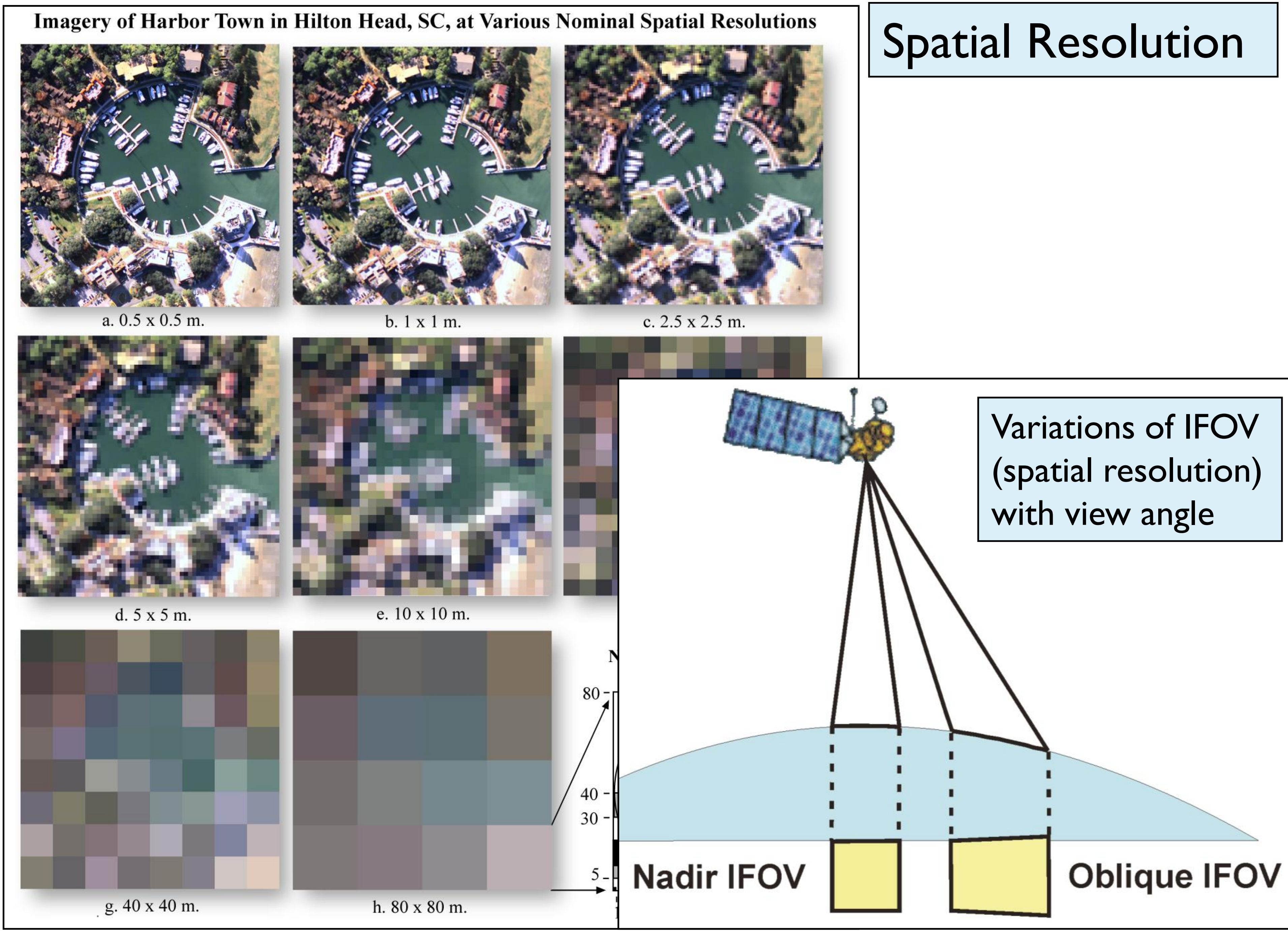
- **Temporal** - how often the sensor acquires data, e.g., every 30 days.



8-bit
(0 - 255)
10-bit
(0 - 1023)

- **Radiometric** - sensitivity of detectors to small difference in electromagnetic energy.

Spatial Resolution



Imagery of Harbor Town in Hilton Head, SC, at Various Nominal Spatial Resolutions

a. 0.5 x 0.5 m.

b. 1 x 1 m.

c. 2.5 x 2.5 m.

d. 5 x 5 m.

e. 10 x 10 m.

g. 40 x 40 m.

h. 80 x 80 m.

Variations of IFOV (spatial resolution) with view angle

RECAP: Satellite data sources

- **Radiometers:** sea surface temperature

-- Envisat (AATSR) -- NOAA (AVHRR)

- **Spectral sensors:** ocean color and water quality

-- Envisat (MERIS) -- Aqua (MODIS) -- Quickbird

- **Altimeters:** SSH, SWH, surface wind speed, ocean currents

-- Envisat -- Jason-1 -- Jason-2 -- GFO-- ERS-2

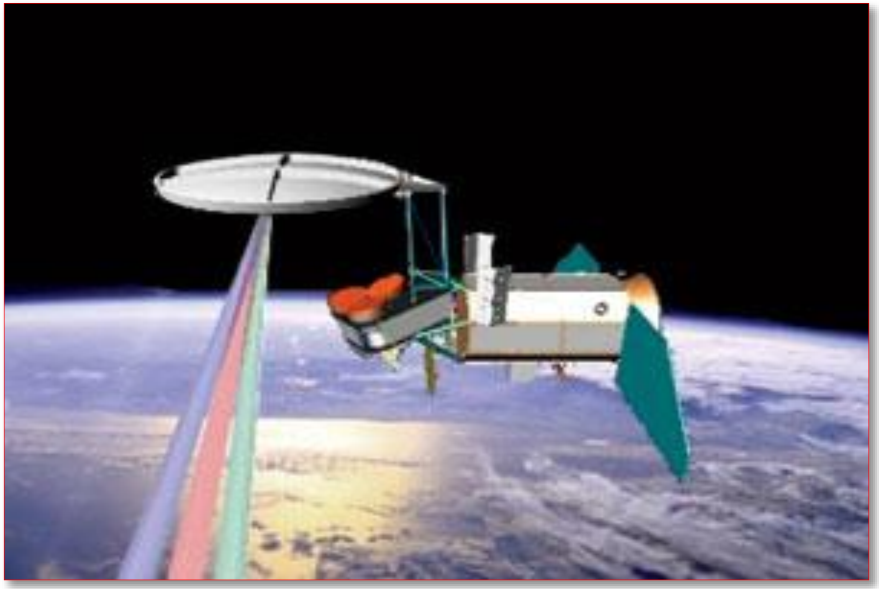
- **Scatterometers:** surface wind speed and direction.

-- QuikSCAT -- ASCAT -- ERS-2

- **Synthetic Aperture Radars** (SAR): winds, waves, currents, oil slicks and ship detection.

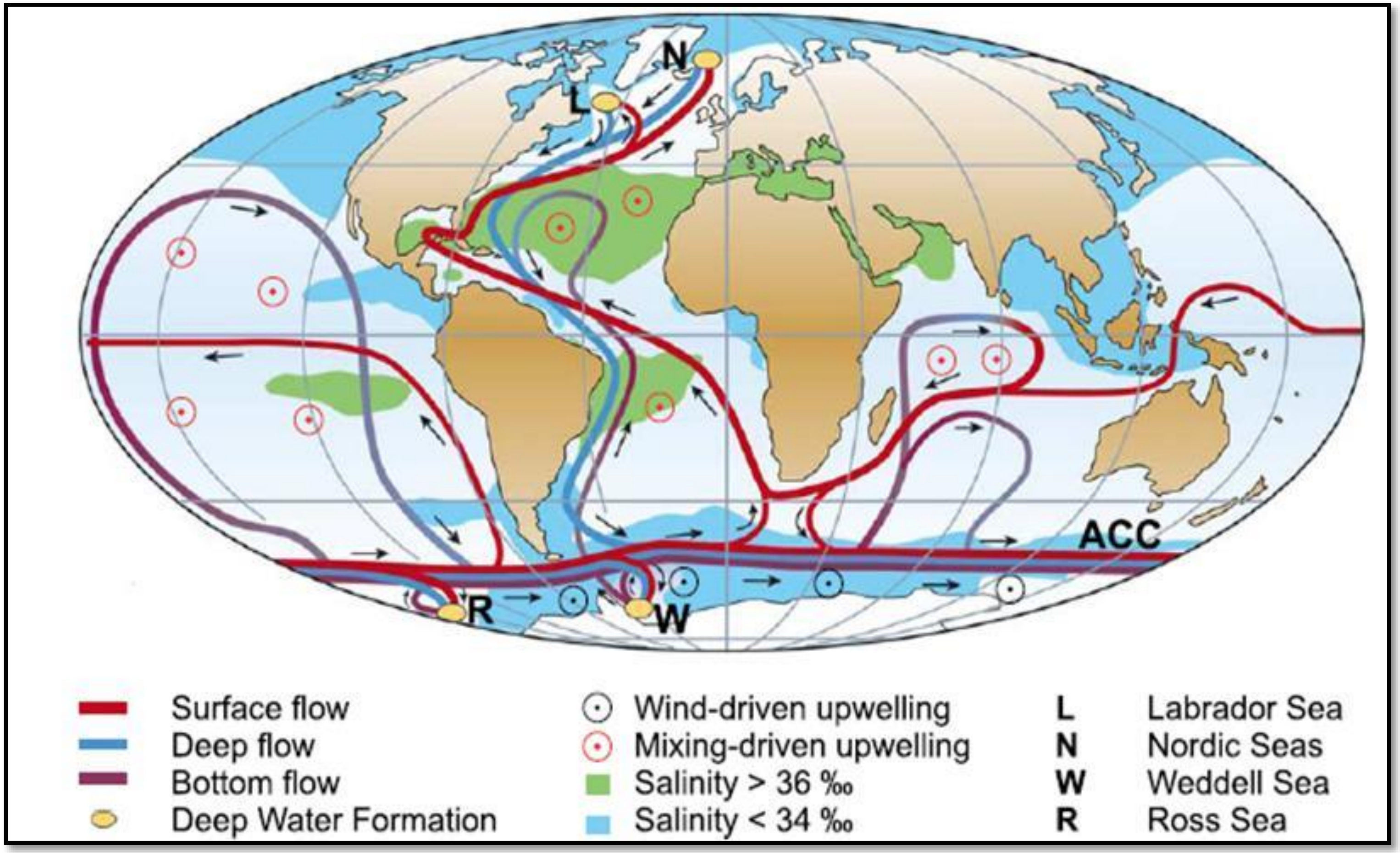
-- Envisat (ASAR) -- Radarsat -- TerraSAR-X

Salinity



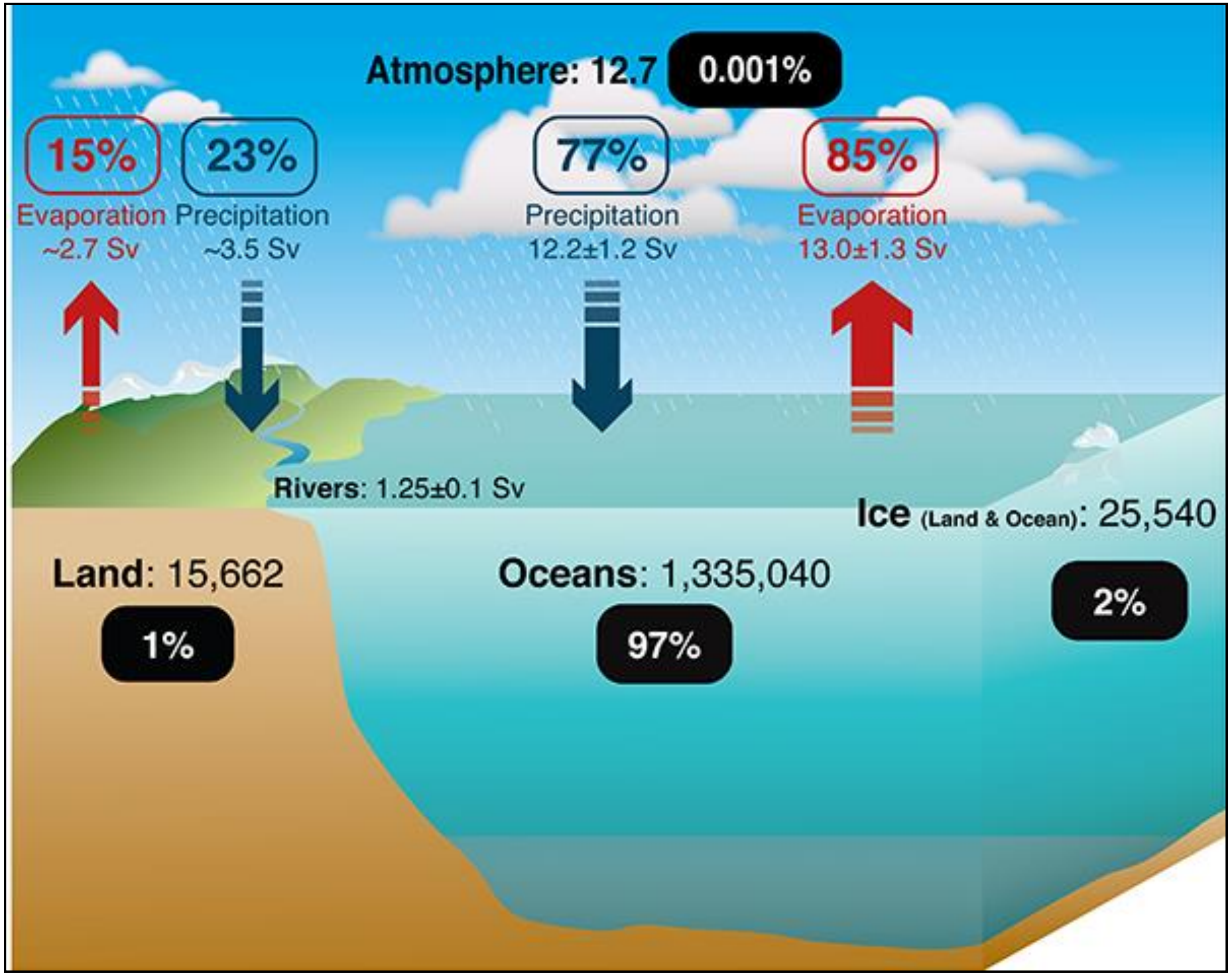
Importance of salinity

- ✓ density/water mass
- ✓ ocean circulation
- ✓ hydrological cycle
- ✓ air-sea interaction



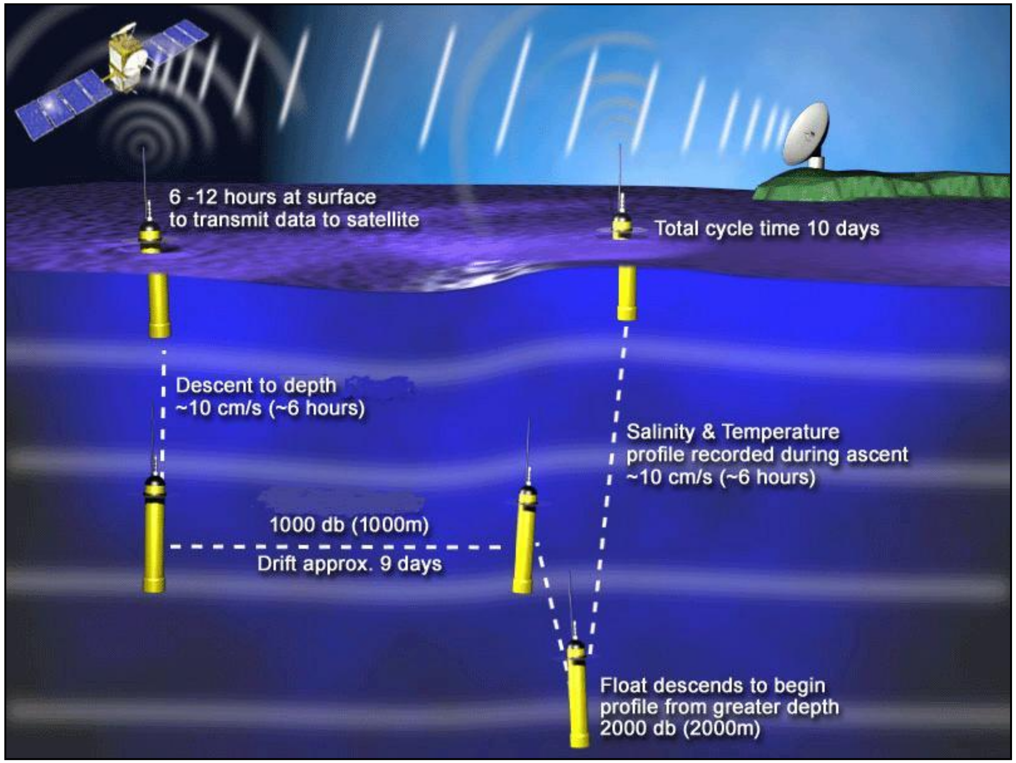
Schmitz, 2005

Ocean salinity and the global water cycle

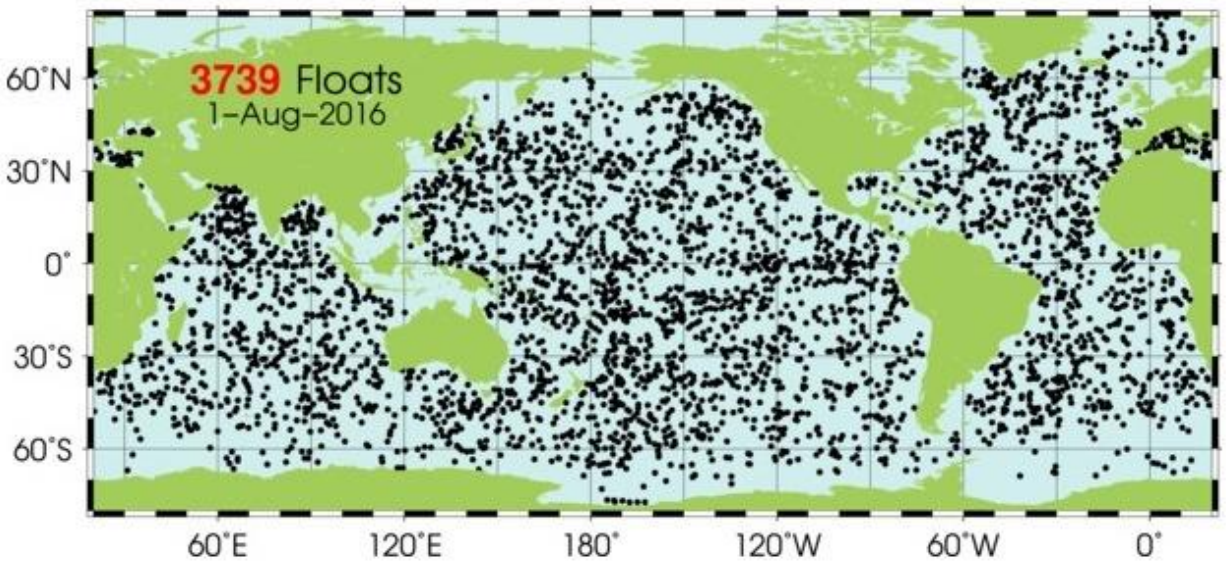


The ocean contains the vast majority of Earth's water reservoirs, and ~80% of surface water fluxes occur over the ocean. Reservoirs represented by solid boxes: 10^3 km^3, fluxes represented by arrows. Source: Durack (2015-Oceanography)

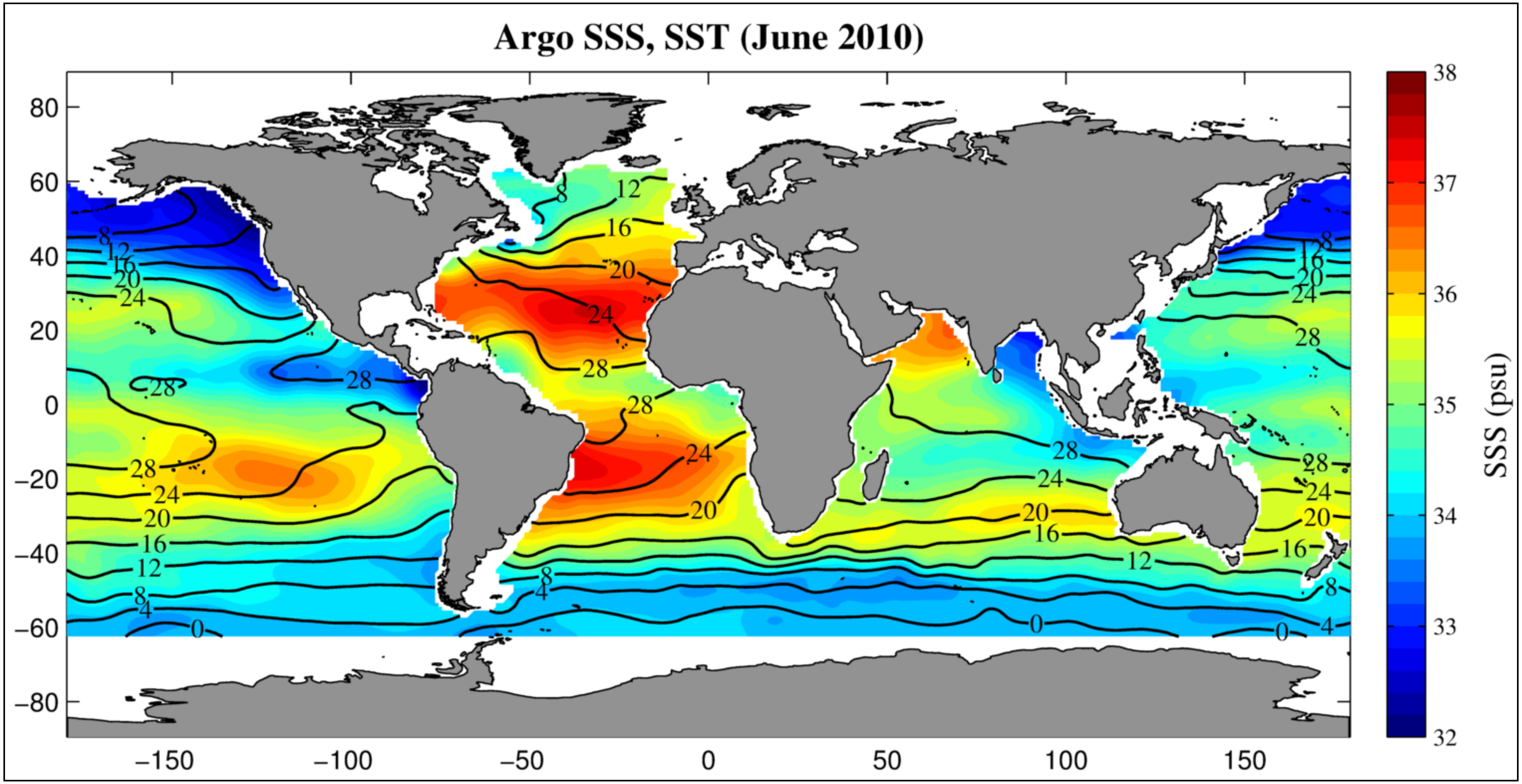
Argo float data



Argo is a global array of more than 3,700 free-drifting profiling floats that measures the temperature and salinity of the upper 2000 m of the ocean.



Global salinity pattern


Argo SSS, SST (June 2010)

Evaporation and Precipitation

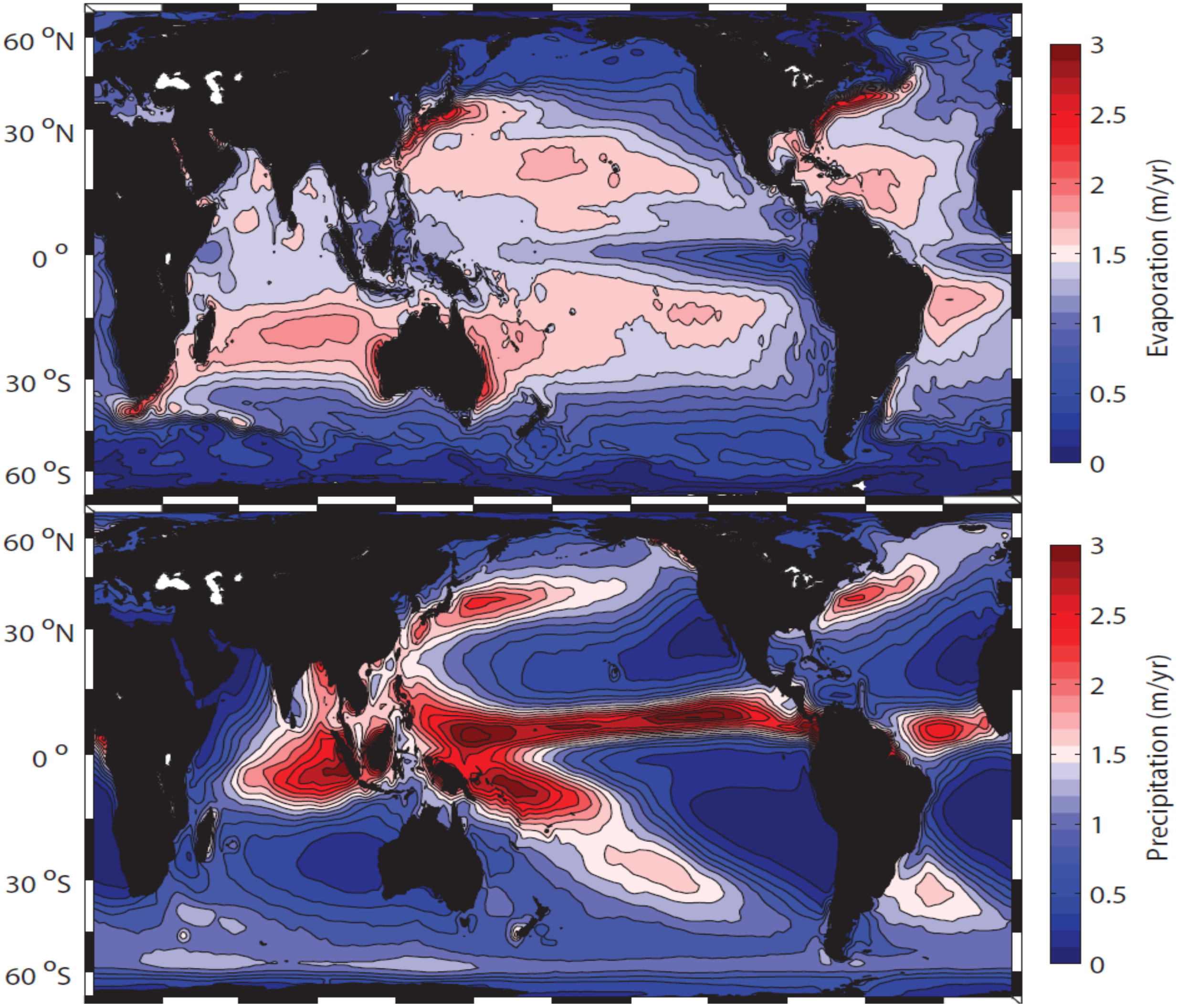
FW = E – P + R

Net E =13 Sv

Net P = 12.2 Sv

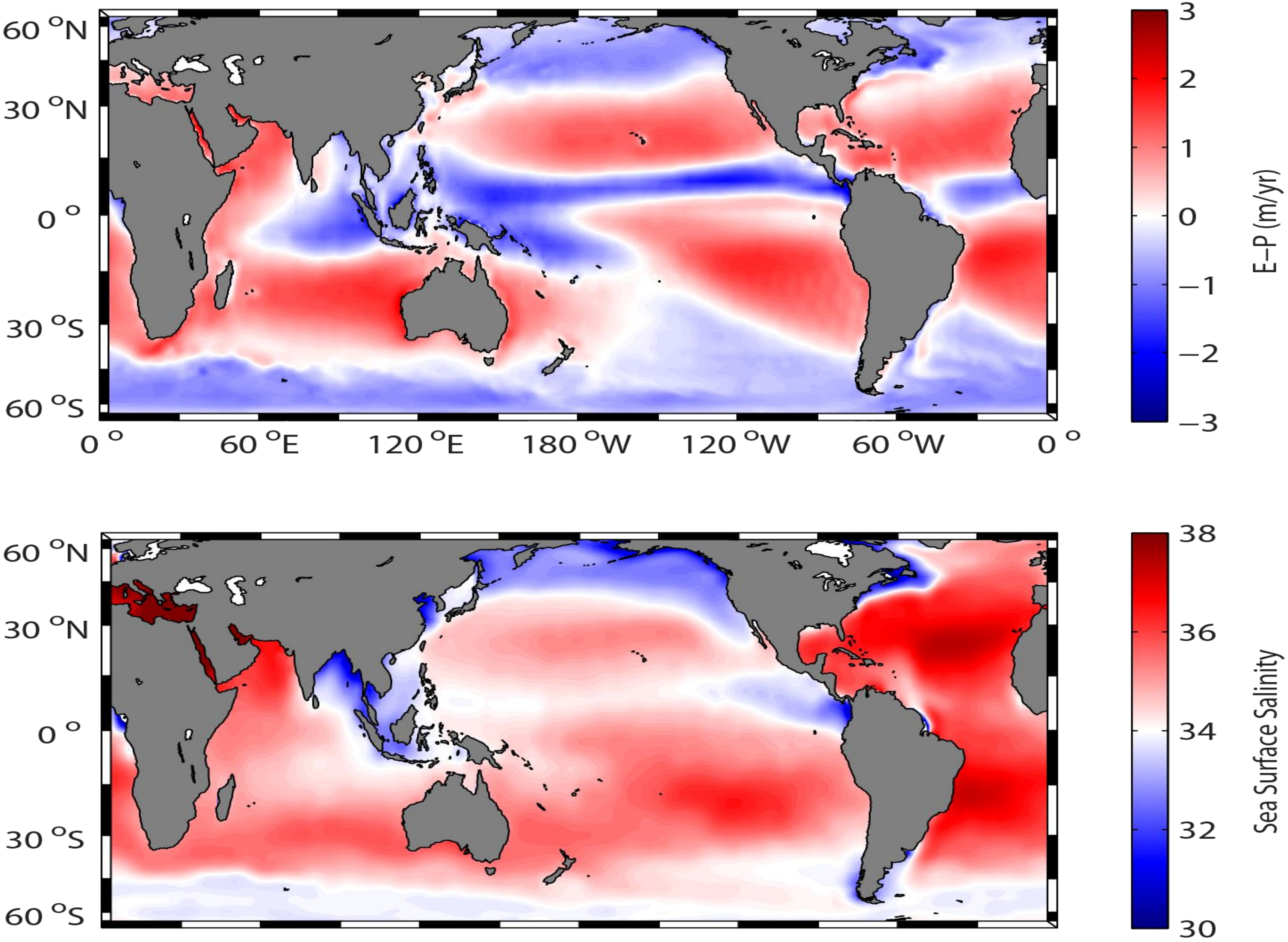
Net River = 1.25 Sv

Diff = ~0.45 Sv

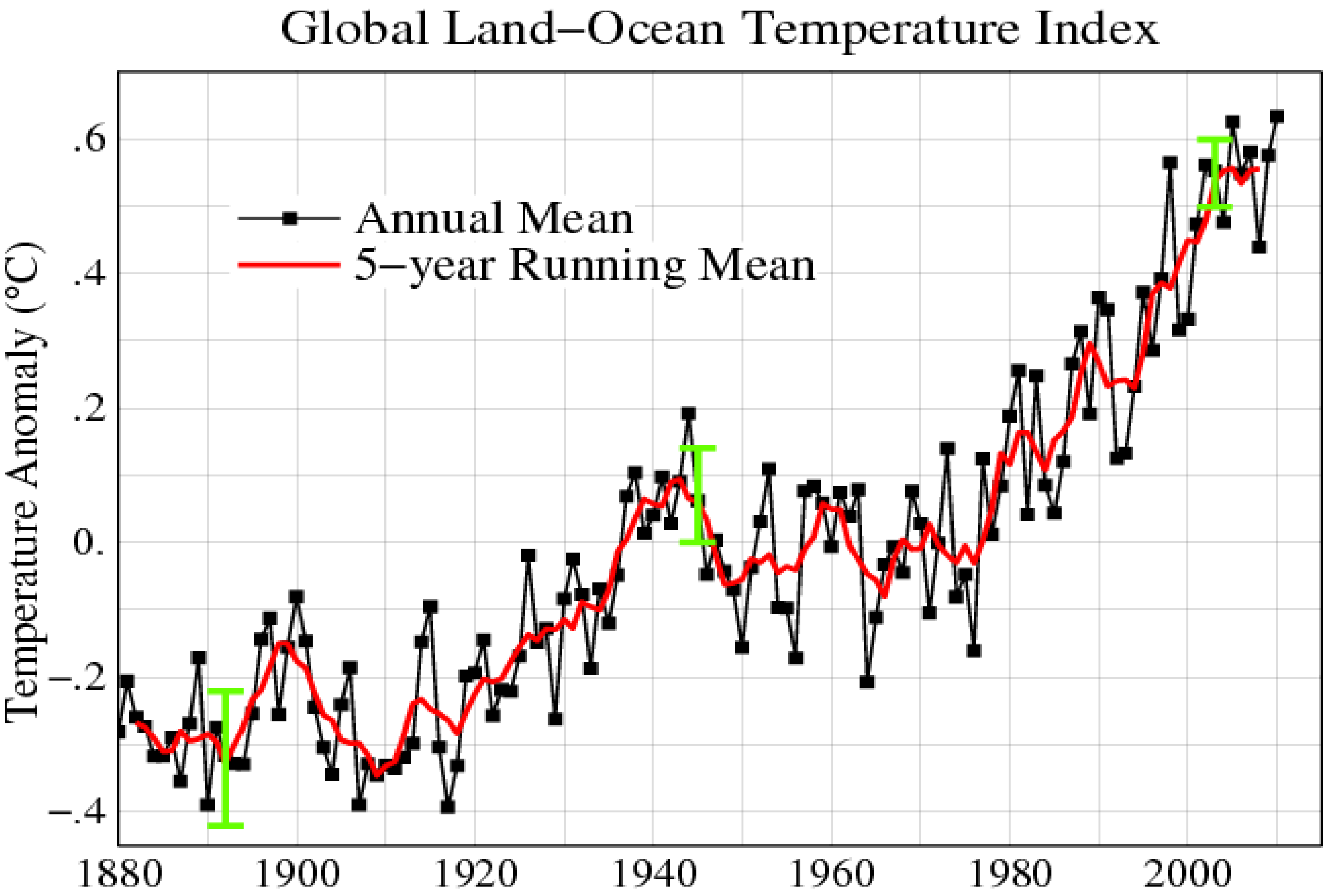


Schanze, Schmitt & Yu, 2010 J. Mar. Res.

Evaporation Minus Precipitation and Salinity

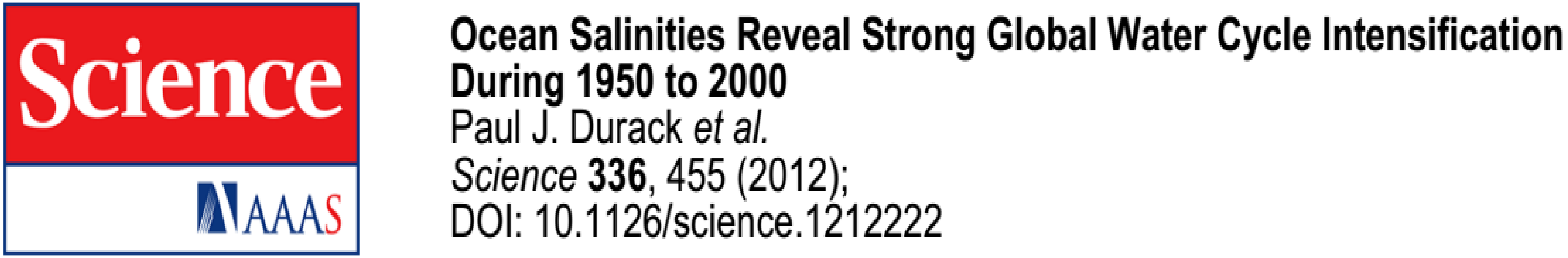


Temperatures are rising !!!

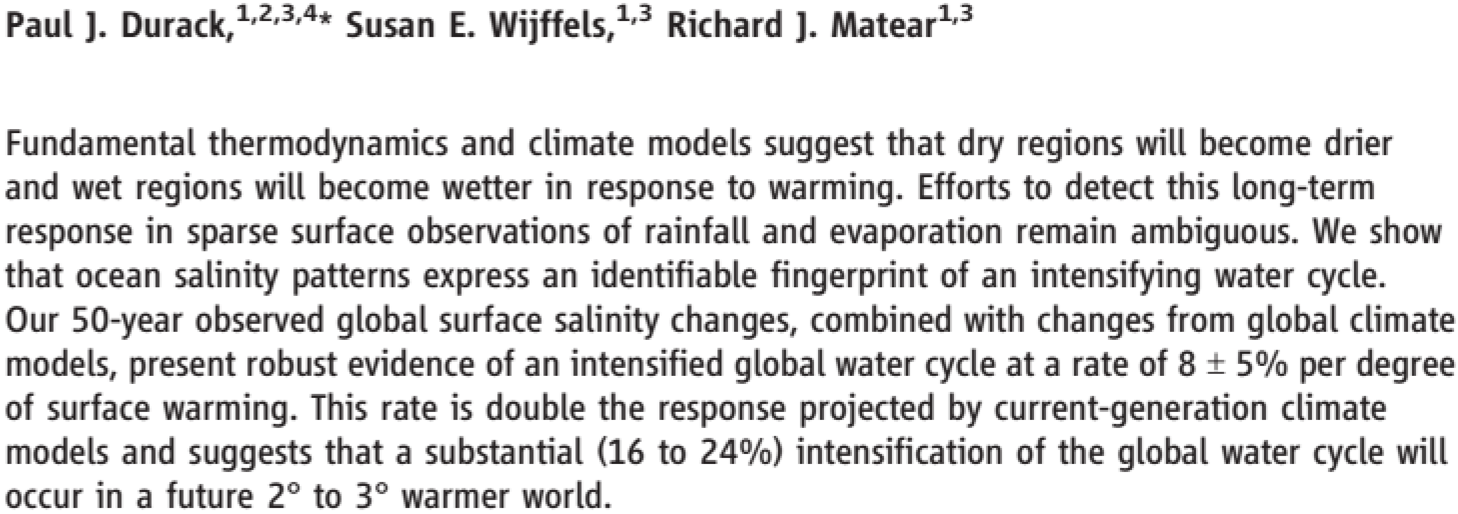


1.4 °F (0.8°C) around the world since 1880, mostly recent decades

Intensification of global water cycle !!!



Ocean Salinities Reveal Strong Global Water Cycle Intensification During 1950 to 2000
Paul J. Durack *et al.*
Science **336**, 455 (2012);
DOI: 10.1126/science.1212222

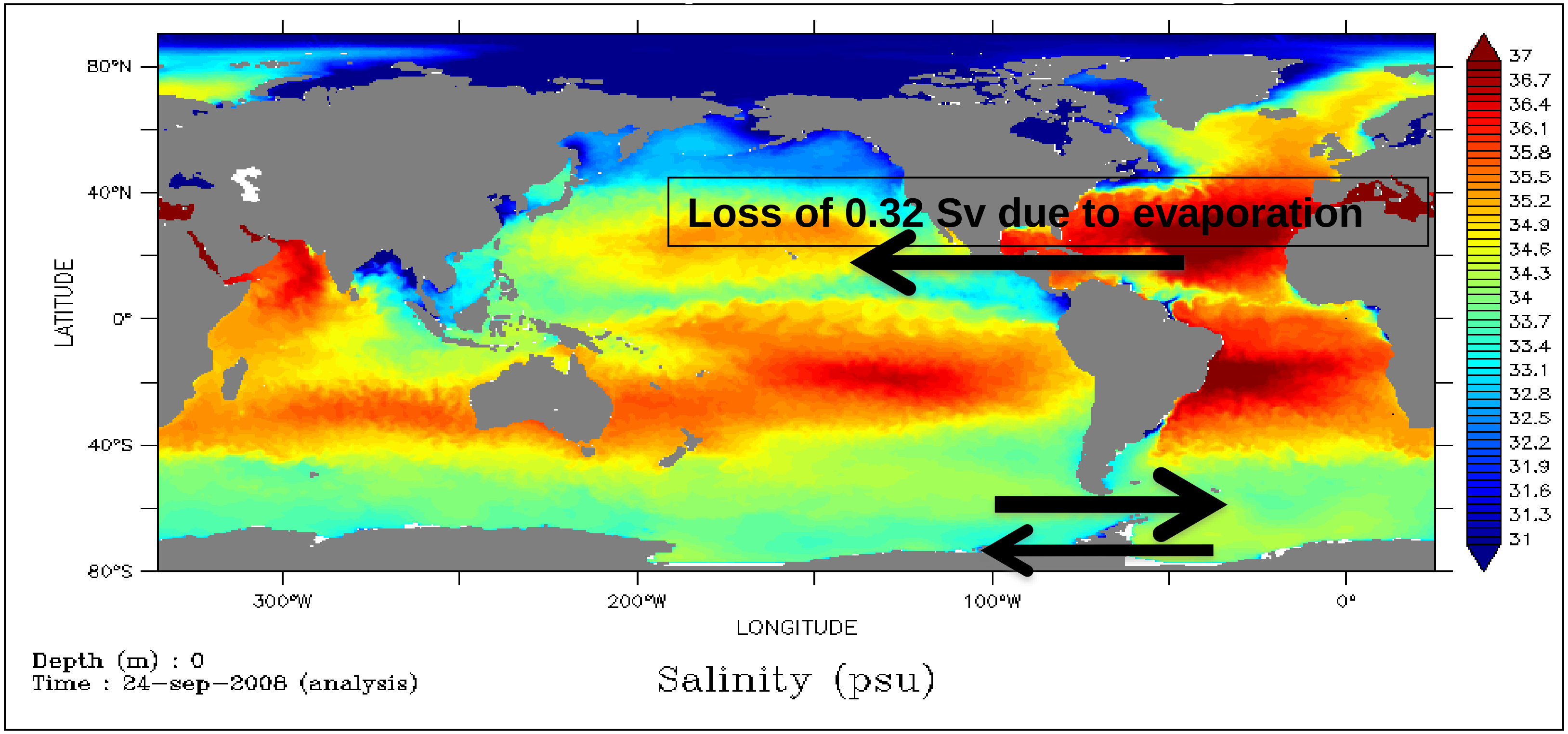


Paul J. Durack,[1,2,3,4]* Susan E. Wijffels,[1,3] Richard J. Matear[1,3]

Fundamental thermodynamics and climate models suggest that dry regions will become drier and wet regions will become wetter in response to warming. Efforts to detect this long-term response in sparse surface observations of rainfall and evaporation remain ambiguous. We show that ocean salinity patterns express an identifiable fingerprint of an intensifying water cycle. Our 50-year observed global surface salinity changes, combined with changes from global climate models, present robust evidence of an intensified global water cycle at a rate of 8 ± 5% per degree of surface warming. This rate is double the response projected by current-generation climate models and suggests that a substantial (16 to 24%) intensification of the global water cycle will occur in a future 2° to 3° warmer world.

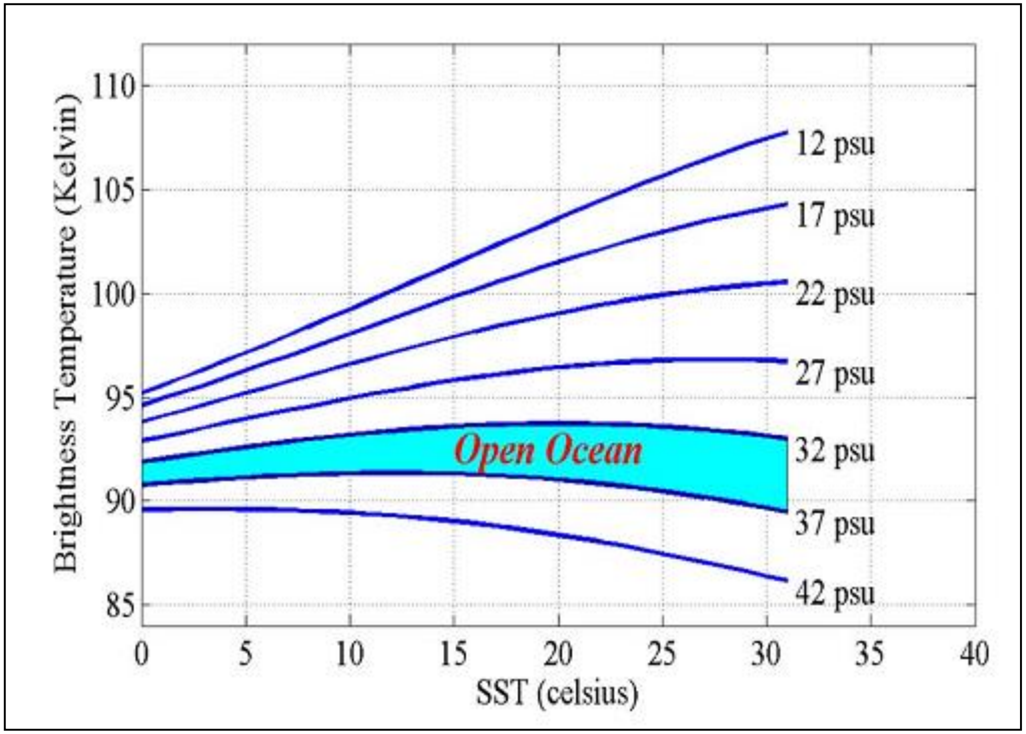
16 to 24% intensification of the global water cycle will occur in a future **2° to 3°** warmer world.

Dry regions will become drier; wet regions will become wetter in response to warming



- Evaporative loss of water from the Atlantic; compensated by a net import of water from the Pacific.
- Increase in Atl salinity compensated by less salty Pacific waters
- In warming climate, inter-basin contrasts increase (saltier Atl, fresher Pacific)
- Warming-driven amplification of the Earth's hydrological cycle
- Due to simple physics - warm air carries more water vapor

The Technology

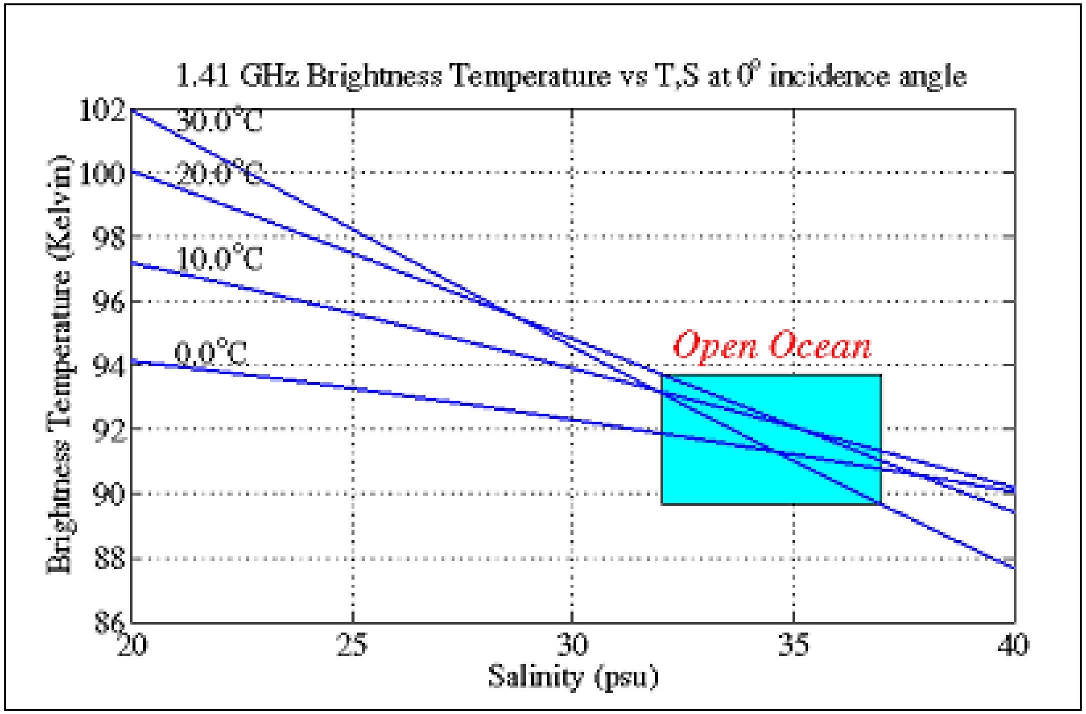


Dependence of T_B at nadir with SST and SSS [*Camps et al.*, 2003]

- L-Band microwave (passive) radiometer
- 1.4 GHz
- Radiometer measures the brightness temperature (T_b)

- T_b is linked to salinity through the dielectric constant of the sea water via its emissivity, e:
- $$\boxed{\mathbf{T_b = eT}}$$
- This is then linked to the Klein-Swift model (1977) & retrieval algorithms to obtain SSS

The Technology



T_b = e T

e = Emissivity

T = Physical Temperature

e = function (freq, S, T)

= 1 - R^2

= 1 - $[(1-\sqrt{\varepsilon})/(1+\sqrt{\varepsilon})]^2$

(normal incidence)

ε = Relative Dielectric Constant

= ε(freq, S, T)

- T_b depends on salinity through the dielectric constant (ε_r)

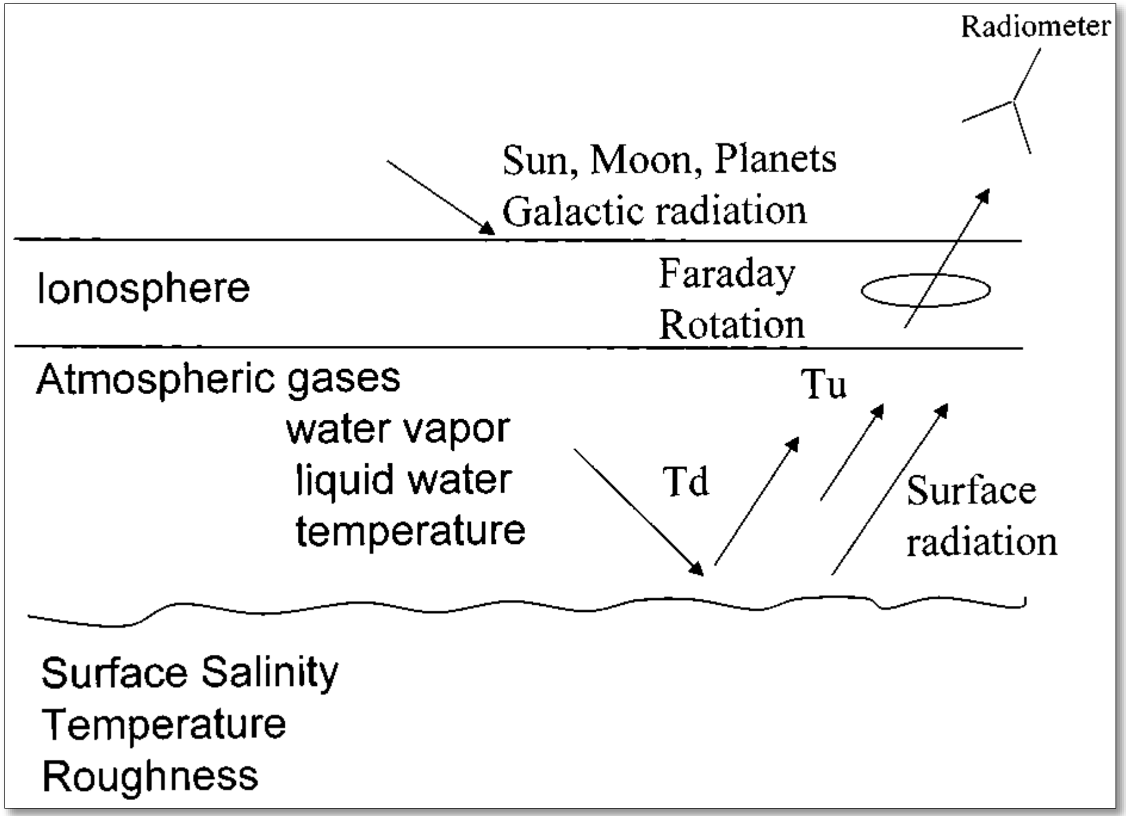
$\varepsilon_r = 88.045 - 0.4147\,T + 6.295 \times 10\text{-}4\,T^2 + 1.075 \times 10^{-5}\,T^3$

(Klein and Swift, 1977)

The Technology

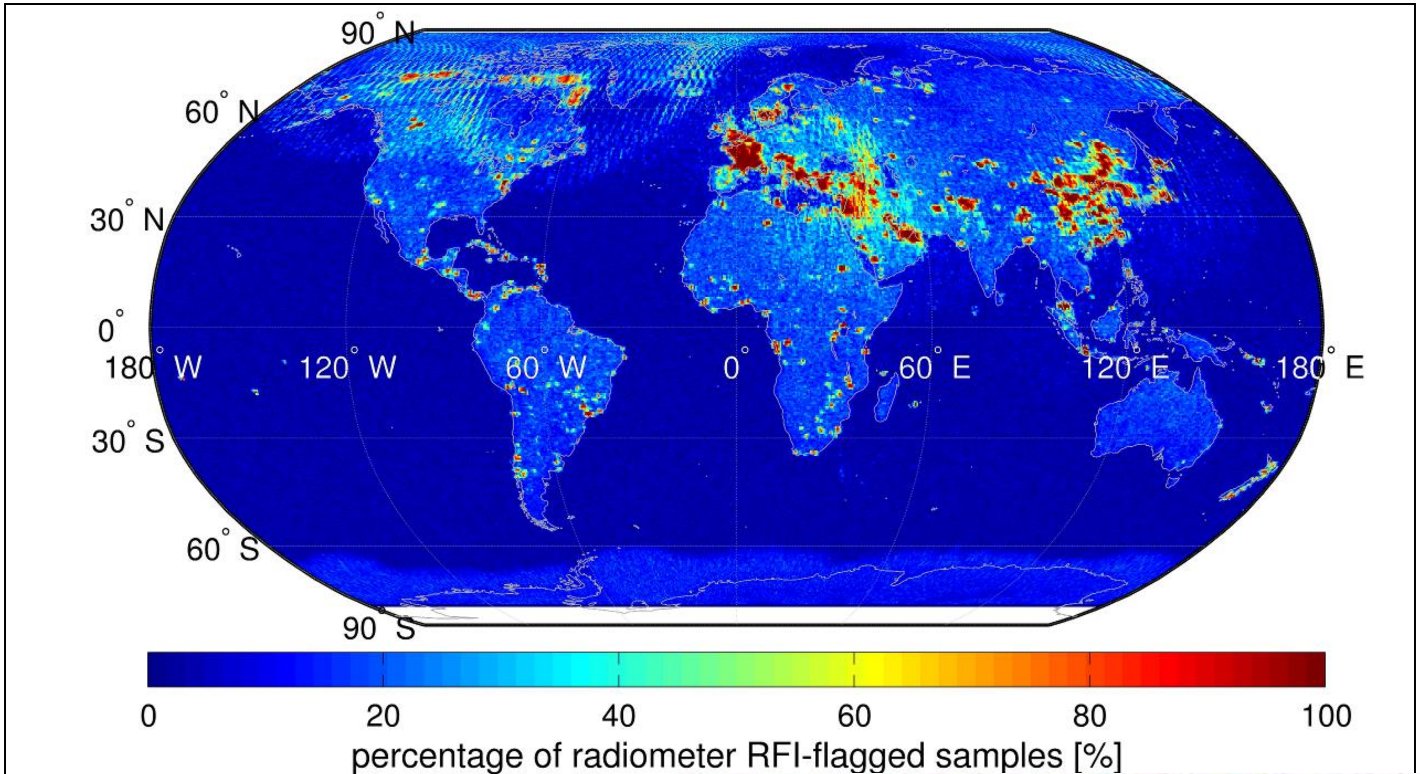
Error sources:

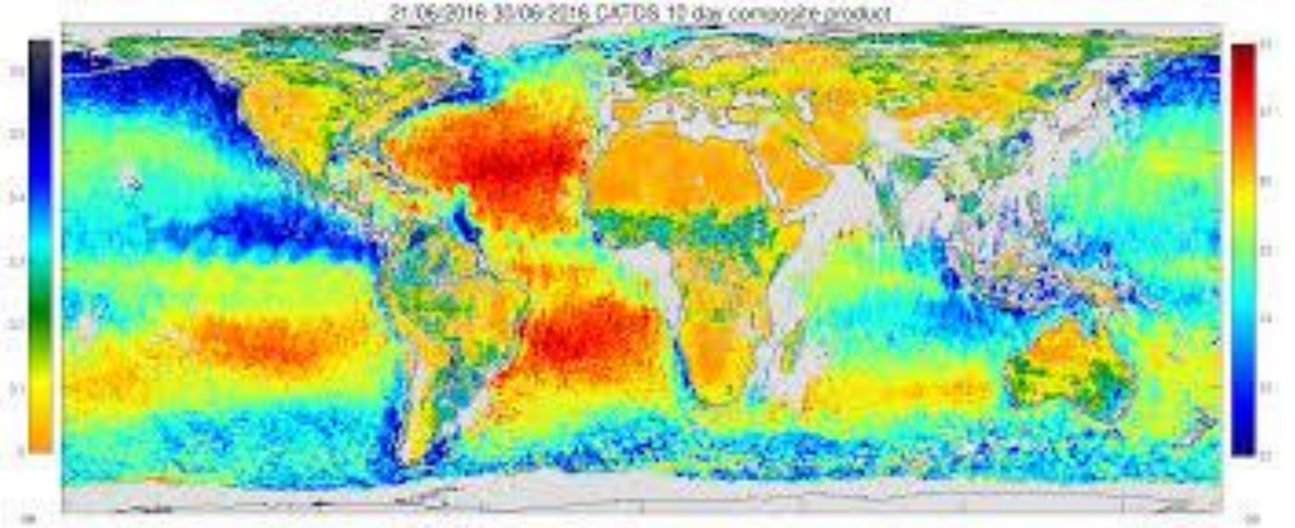
- solar reflection
- atmospheric oxygen
- galactic noises
- SST
- wind speed (sea surface roughness)



Geophysical sources that influence the microwave radiation from sea surface [*Yueh et al.*, 2001]

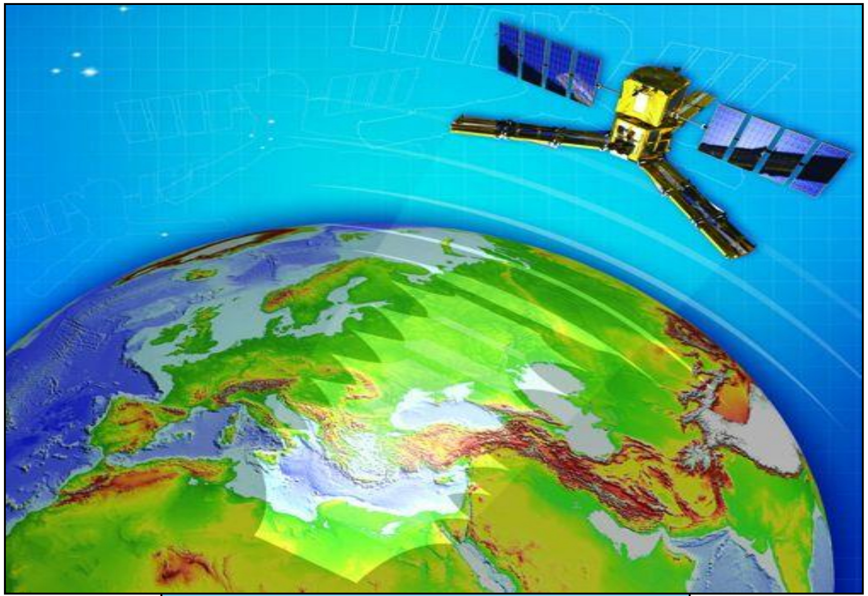
Radio Frequency Interference (RFI)



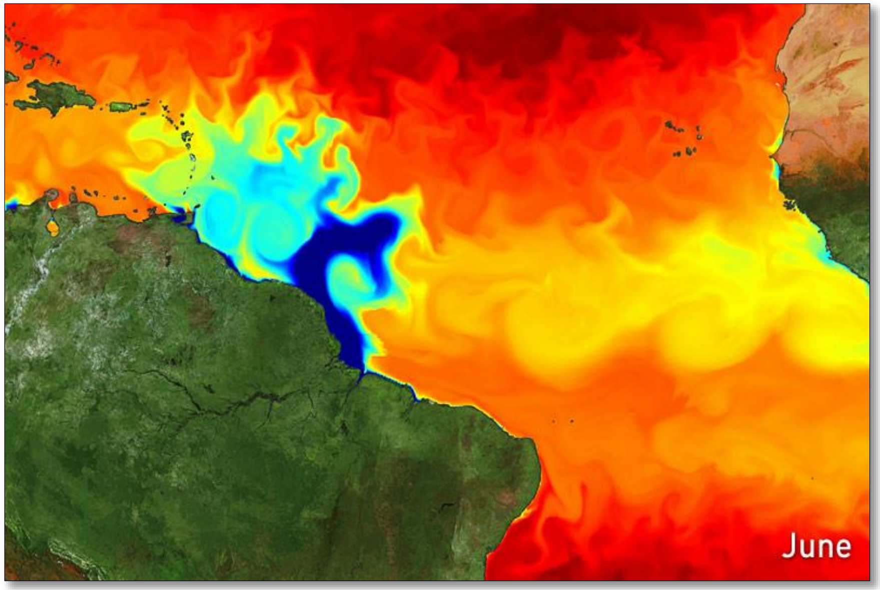


Soil Moisture and Ocean Salinity (SMOS)

- European Space Agency (ESA)
- Launched on 2 November 2009
- Soil moisture (SM) and ocean salinity (OS)
- Resolution : 1-3 days & 45 km
- Accuracy of 0.1 psu/ 30 days/200 km



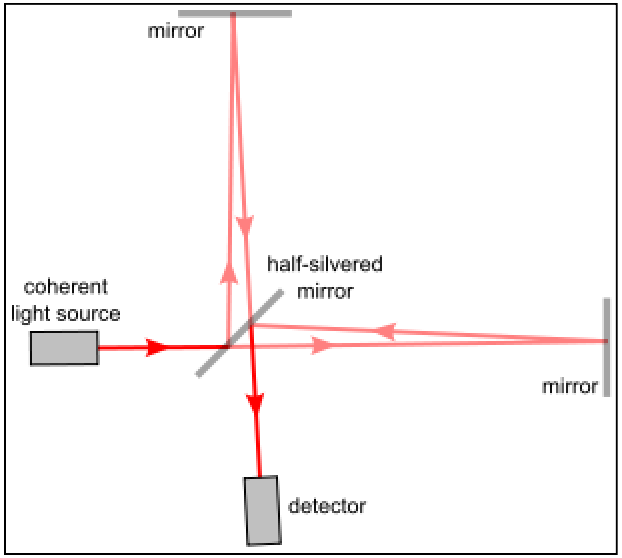
The SMOS satellite

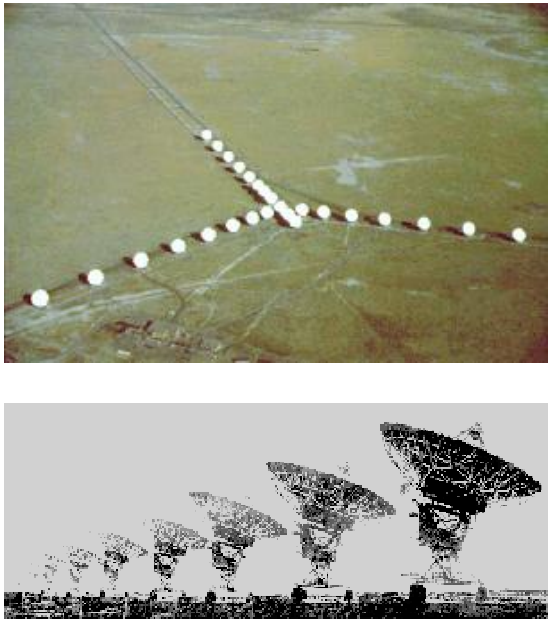


Amazon freshwater plume

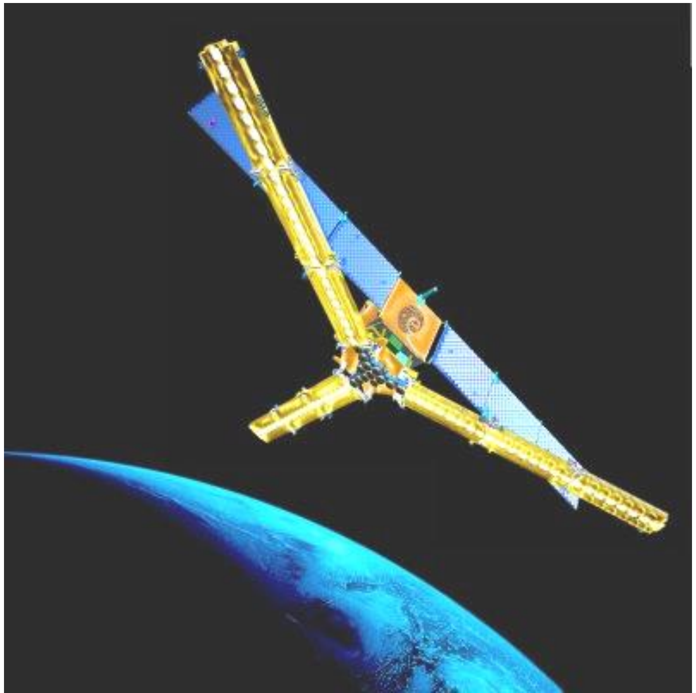
Technical Concept

Antenna aperture synthesis, as used in radio-astronomy: an array of receivers constitute a **V**ery **L**arge baseline **A**ntenna and generate an image by interferometry





VLA (*Socorro*, NM)



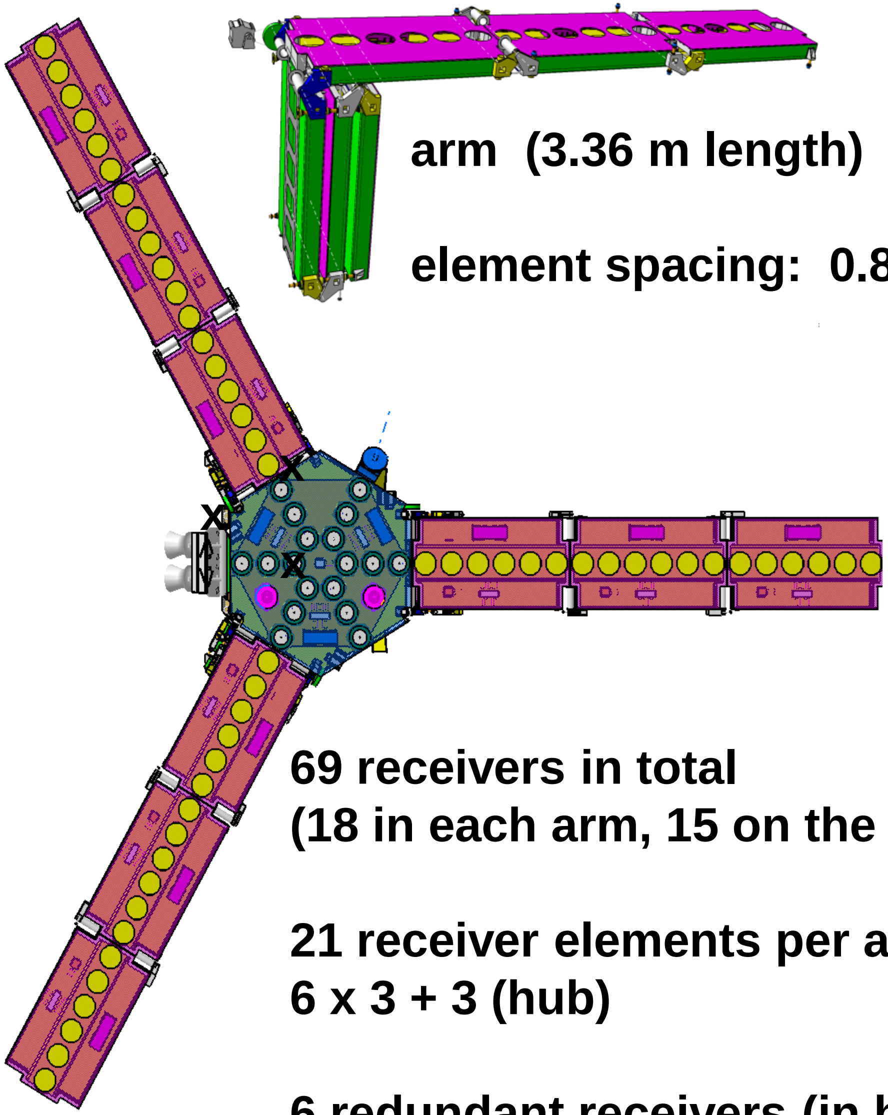
Technical Concept

MIRAS: MIcrowave Radiometer with Aperture Synthesis

- Passive microwave radiometer (L-band - 1.4GHz)
- 2D interferometry
- multi-incident angles (0-55°)

- 755.5 km altitude
- ~ 1000 km swath
- polarimetric observations

- 30° steer angle
- 32.5° tilt angle



arm (3.36 m length)

element spacing: 0.875 λ

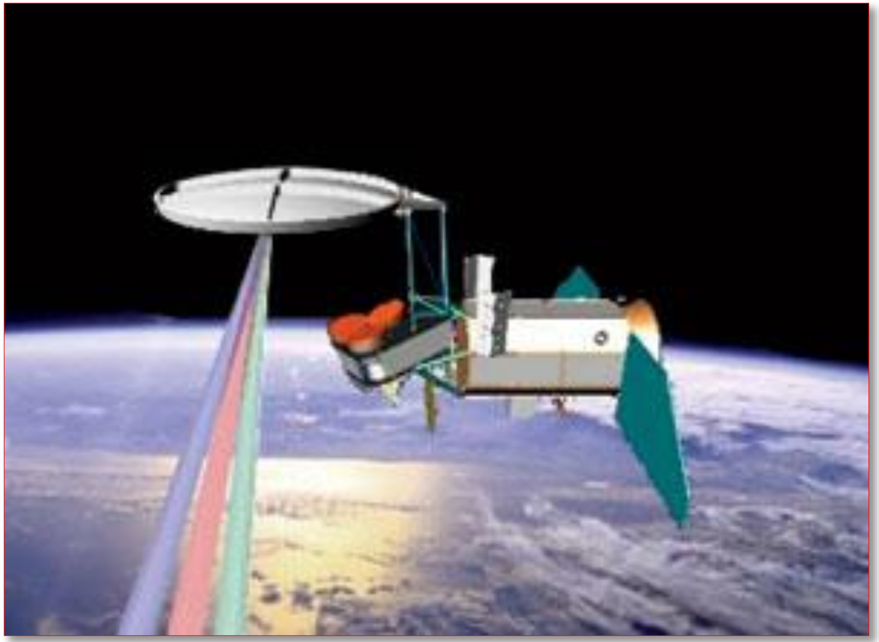
69 receivers in total
(18 in each arm, 15 on the hub)

21 receiver elements per arm:
6 x 3 + 3 (hub)

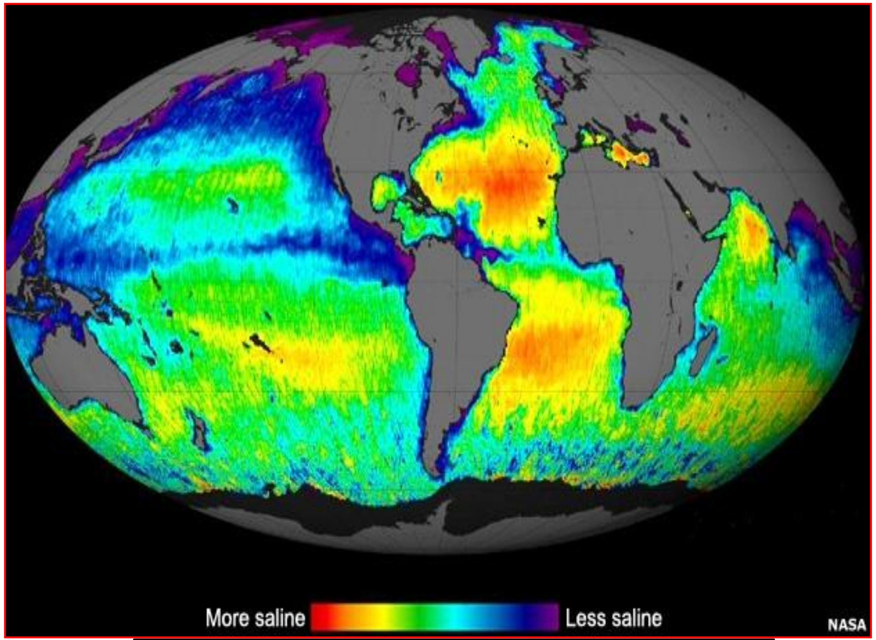
6 redundant receivers (in hub)

Aquarius

- NASA & CONAE; launched10 June 2011; died June 2015
- MWR-ocean wind & direction, rain, sea ice
- NIRST – SST; 3 bands
- Resolution: 7 days & 150 km
- Accuracy: 0.2 psu/30 days/150 km

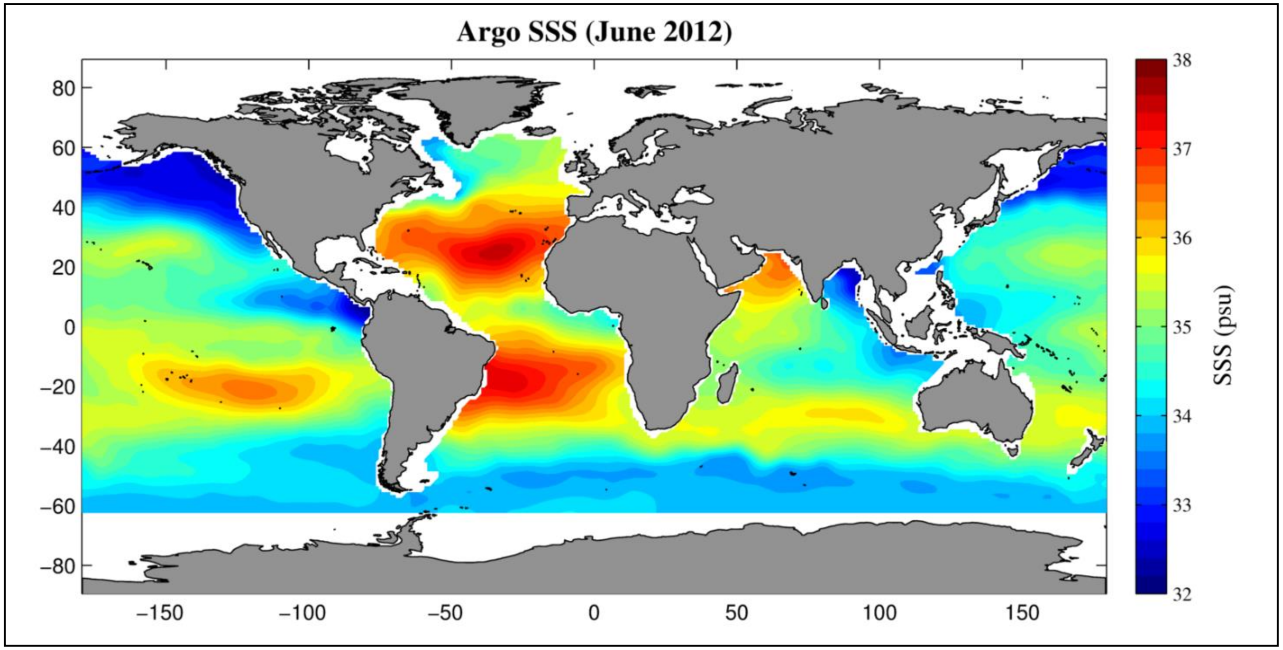


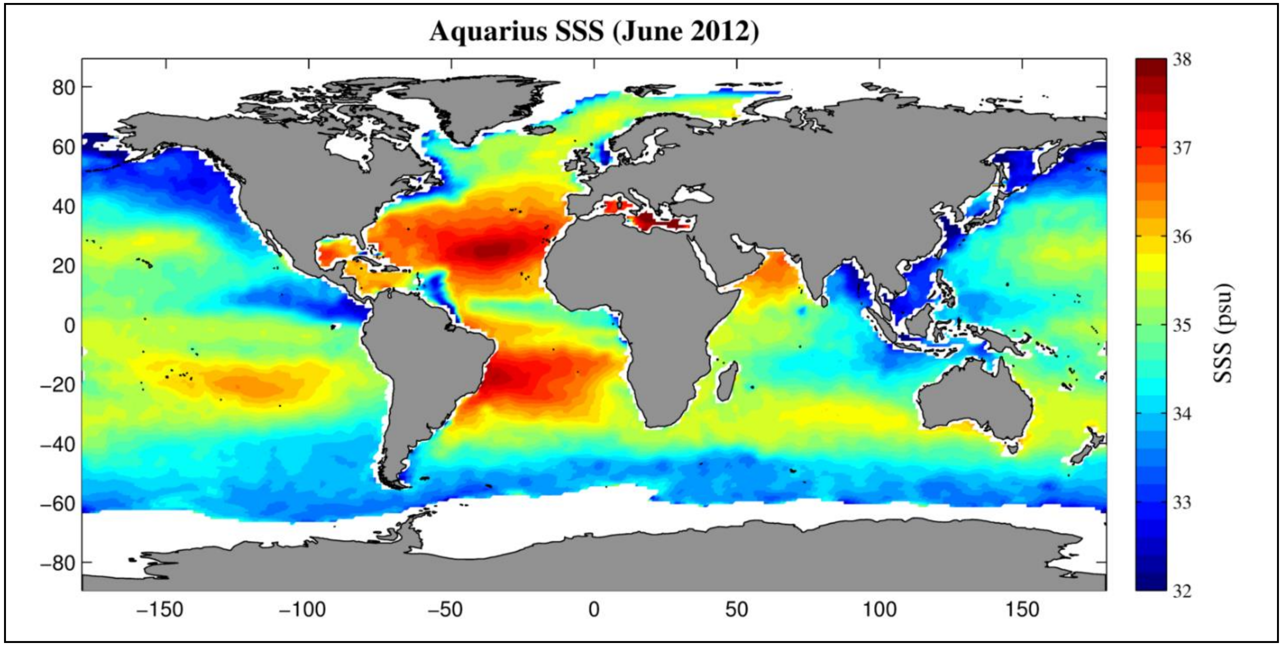
Aquarius satellite in orbit



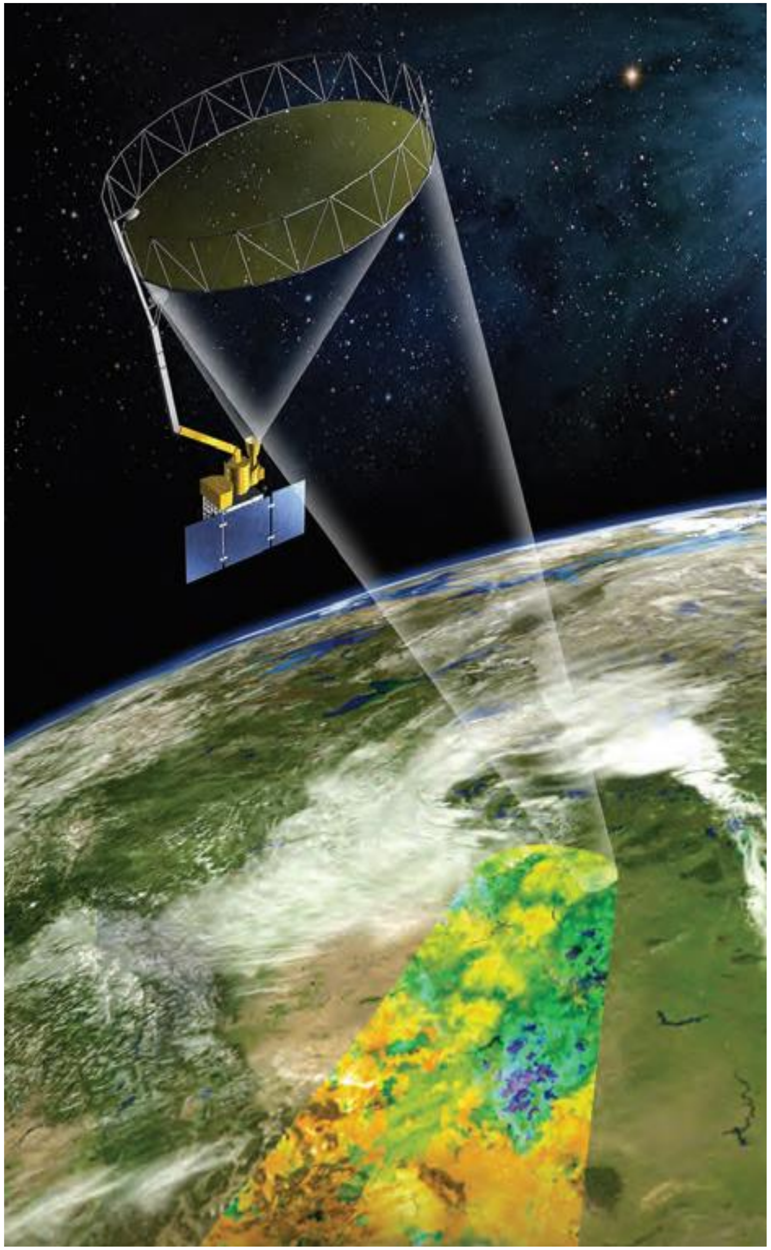
Aquarius global mean SSS

Global salinity pattern





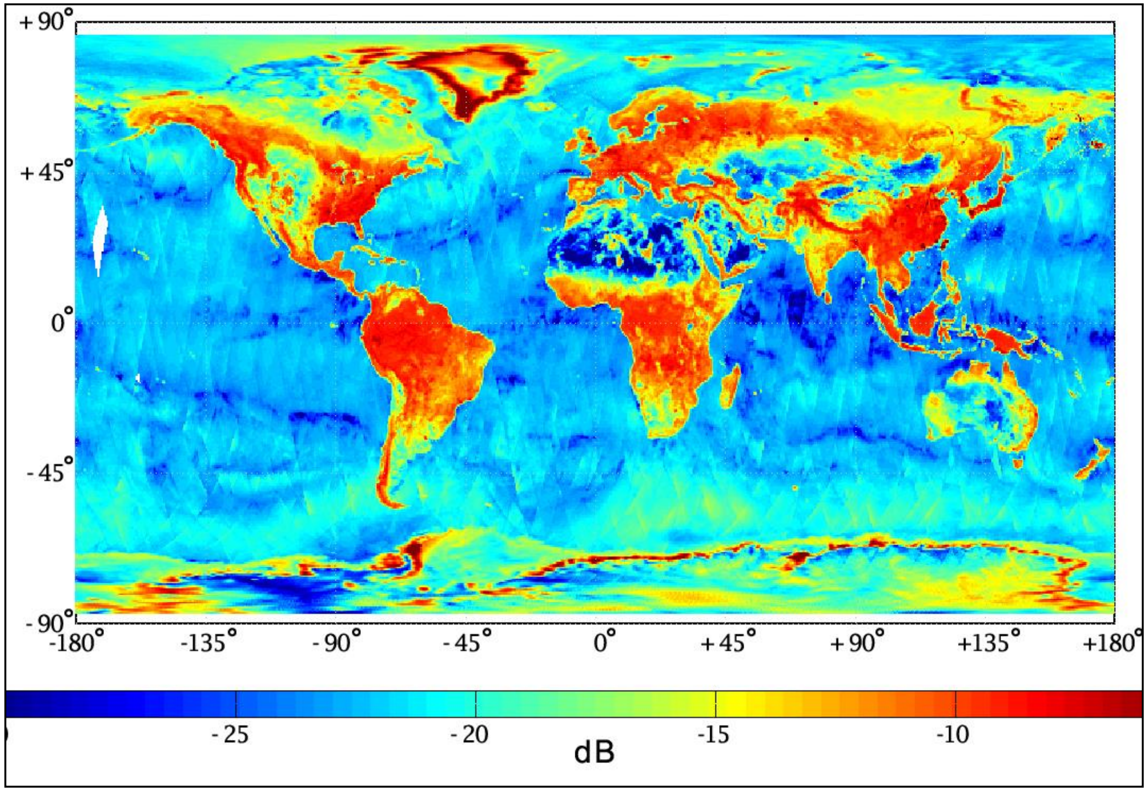
SMAP (Soil Moisture Active Passive)



- NASA; launched 31 Jan 2015
- Resolution : 2-3 days; Footprint of ~9 km.
- uses both an L-band **radar** and an L-band **radiometer**
- takes advantage of the relative strengths of active (radar-SAR) and passive (radiometer) microwave remote sensing;
- advantage of the spatial resolution of radar and sensing accuracy of radiometer

SMAP

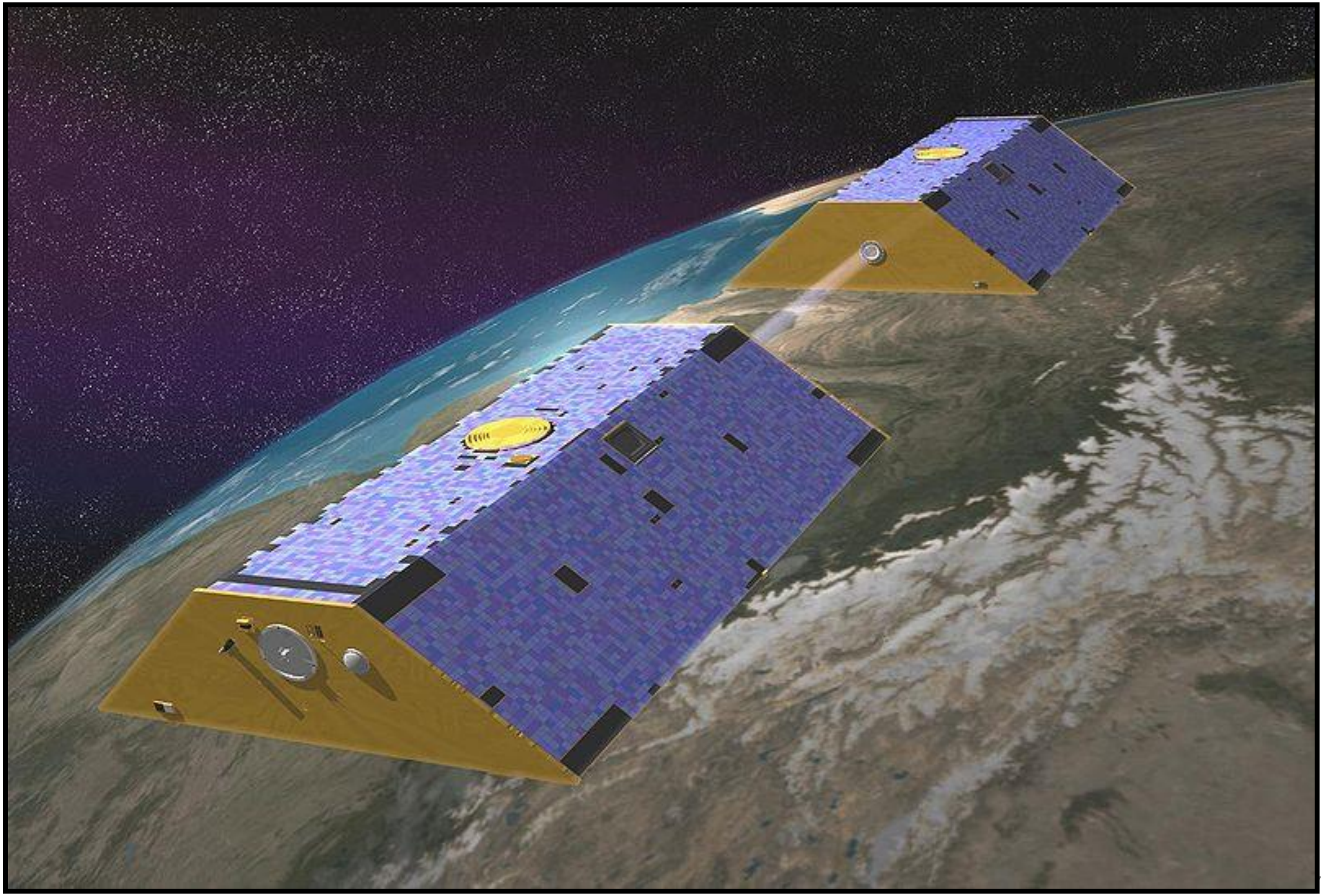
- measures the amount of water in the top 5 cm (2 in) of soil
- help study Earth's water, energy and carbon cycles
- soil moisture is a primary state variable of hydrology and the water cycle over land.



SMAP radar image. Weaker radar signals (blues) reflect low soil moisture or lack of vegetation, such as in deserts.

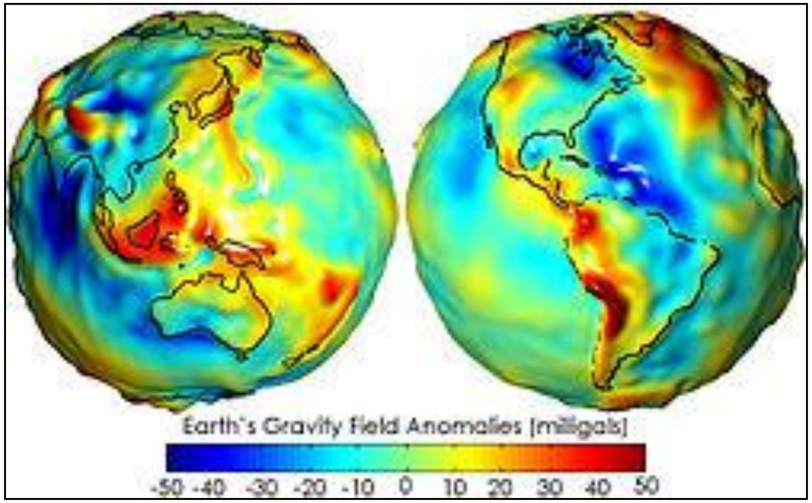
Strong radar signals (reds) are seen in forests. SMAP's radar also takes data over the ocean and sea ice.

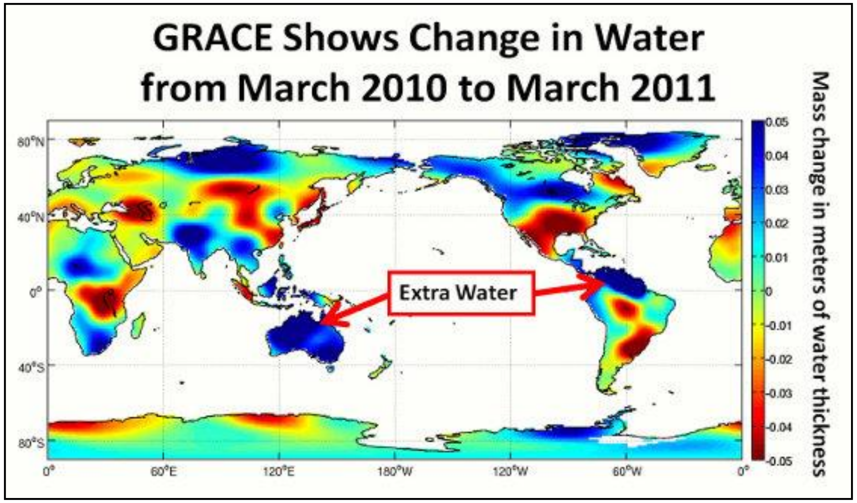
GRACE



GRACE

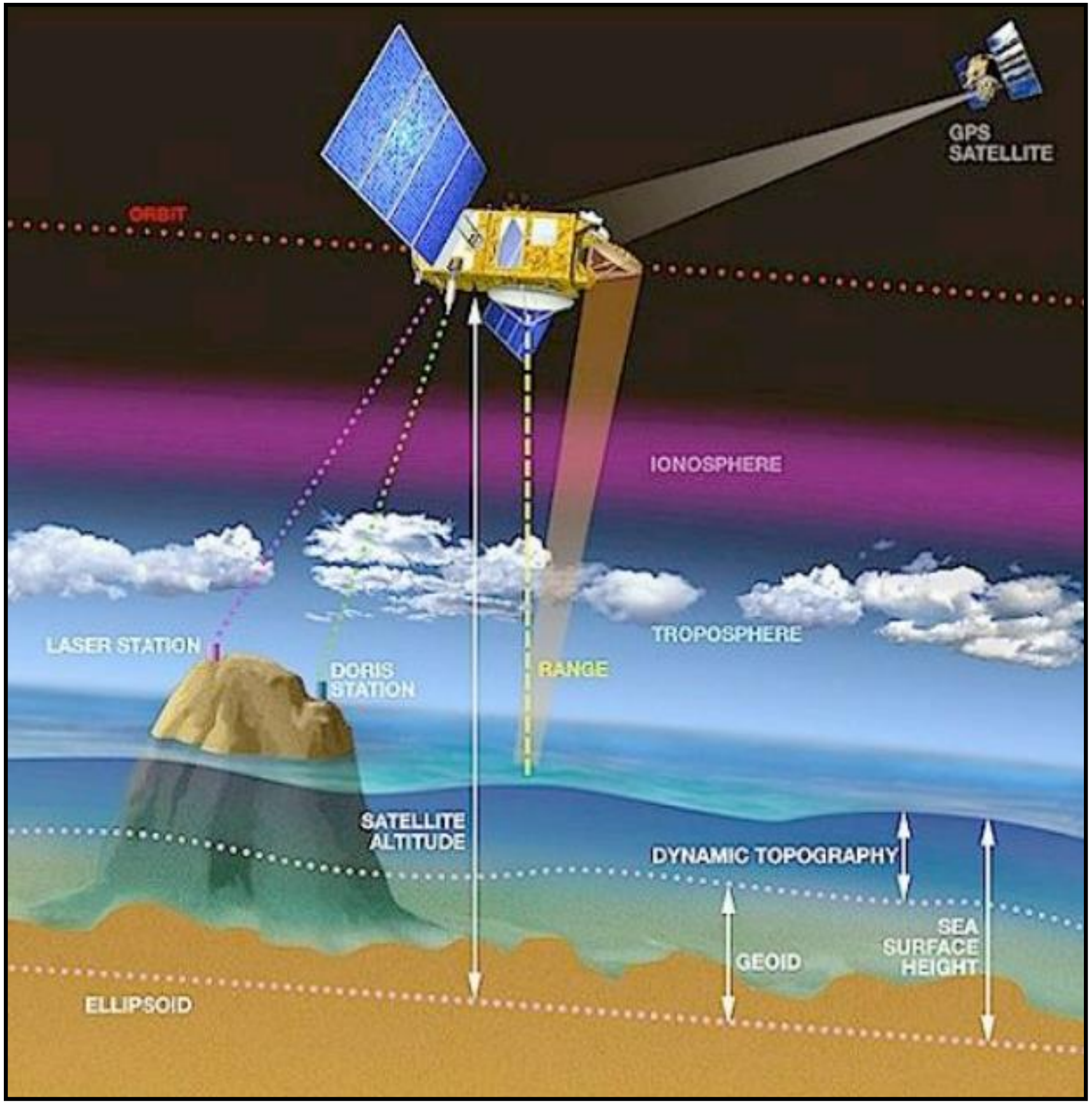
- **GRACE:** Gravity Recovery And Climate Experiment
- NASA & German Aerospace Center. Launched March 17, 2002
- GRACE makes detailed measurements of Earth's gravity field anomalies
- Measure time variable gravity field to detect changes in the water storage and movement from reservoir to another (e.g., from ice sheets to ocean)





SSH measurement

SSH (relative to an earth ellipsoid) = Orbit height – Range – Σ Corr



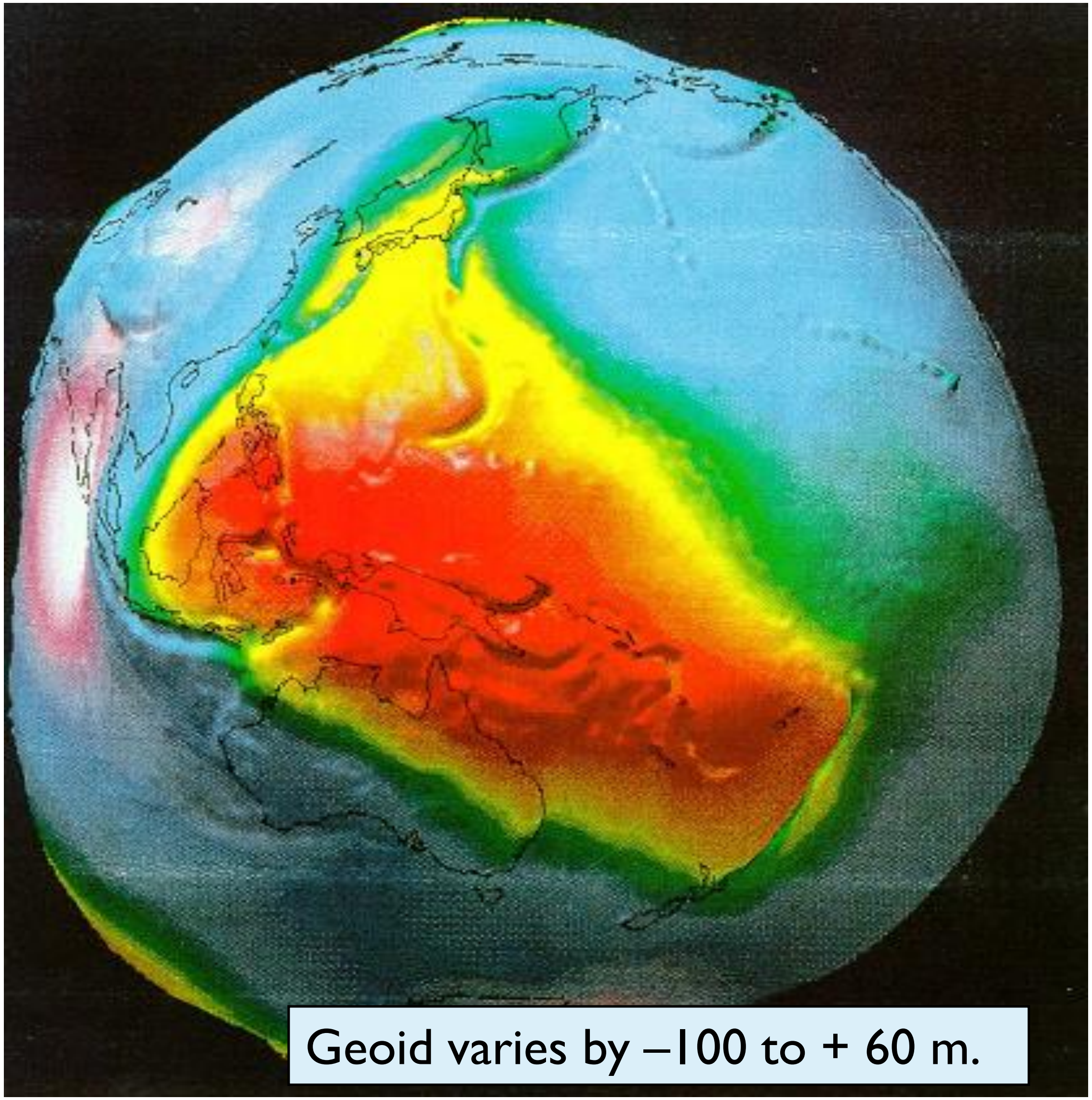
SSH = Geiod + Dynamic topography (η)

Geoid: is that equipotential surface of the Earth gravity field, that most closely approximates the mean sea surface height.

The earth is not a perfect ellipsoid due to uneven distribution of mass

SSH measurement

SSH (relative to an earth ellipsoid) = Orbit height – Range – Σ Corr



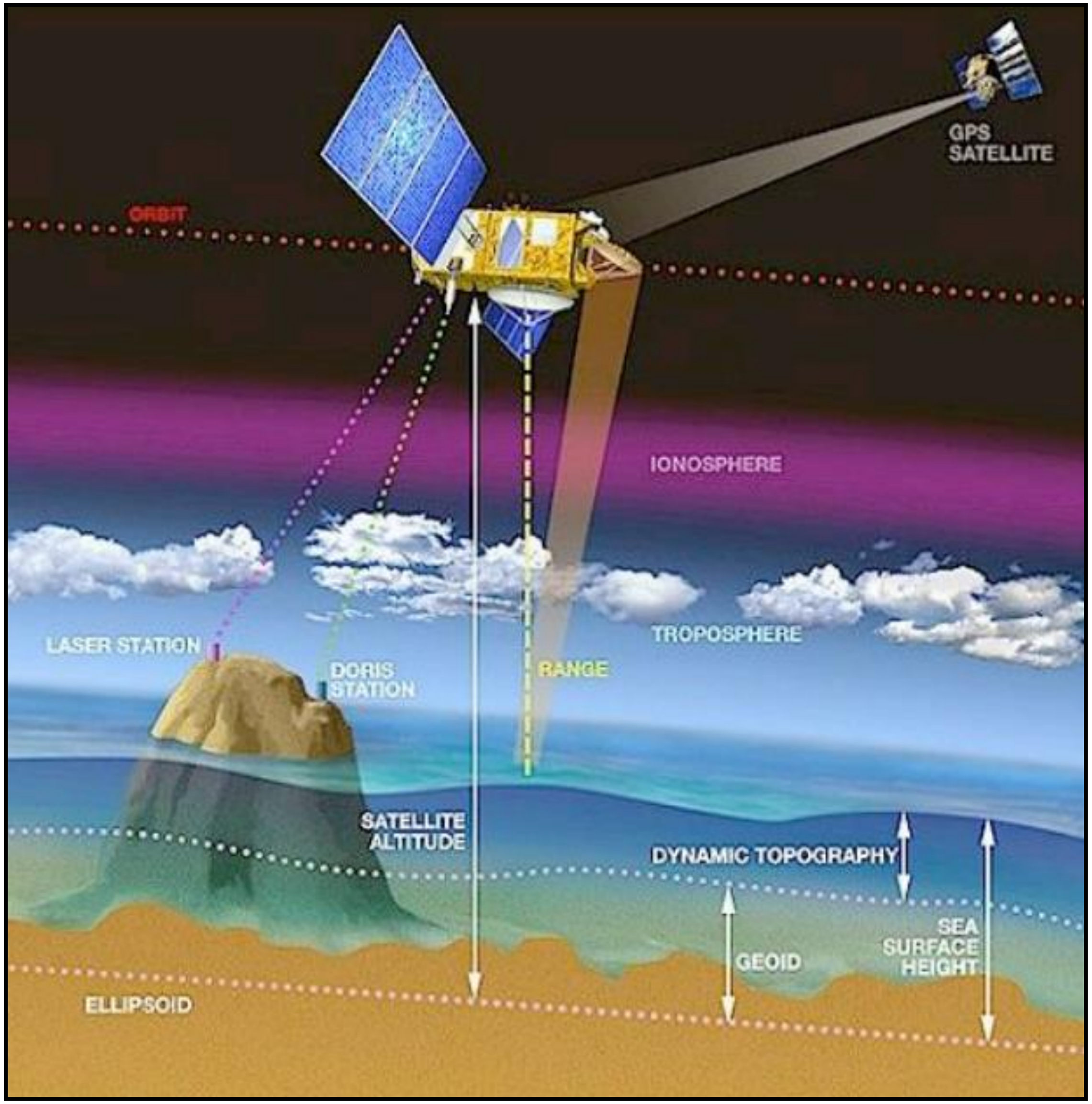
Geoid varies by –100 to + 60 m.

The earth has large bumps and troughs due to variations in the ocean bottom topography and inhomogeneous density distributions in the earth's interior.

These density variations create a **bumpy geoid**. If the ocean were at rest, the sea surface would exactly follow the geoid.

SSH measurement

SSH (relative to an earth ellipsoid) = Orbit height – Range – Σ Corr

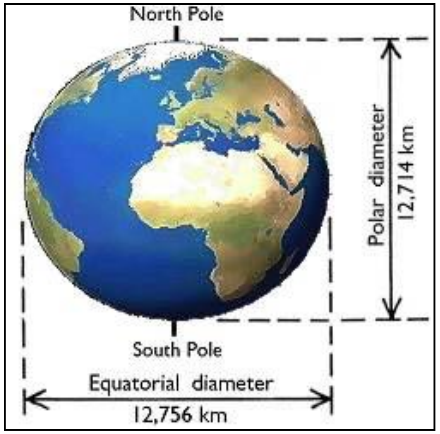


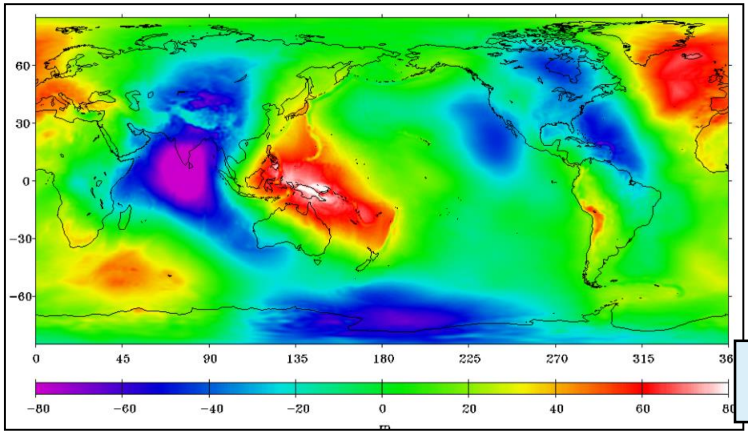
Precision of the SSH:

- Orbit error
- Errors on the range
  - - instrumental noise
  - - various instrument errors
  - - various geophysical errors (e.g., atmospheric attenuation, tides, inverse barometer effects, …)

Shape of the Earth

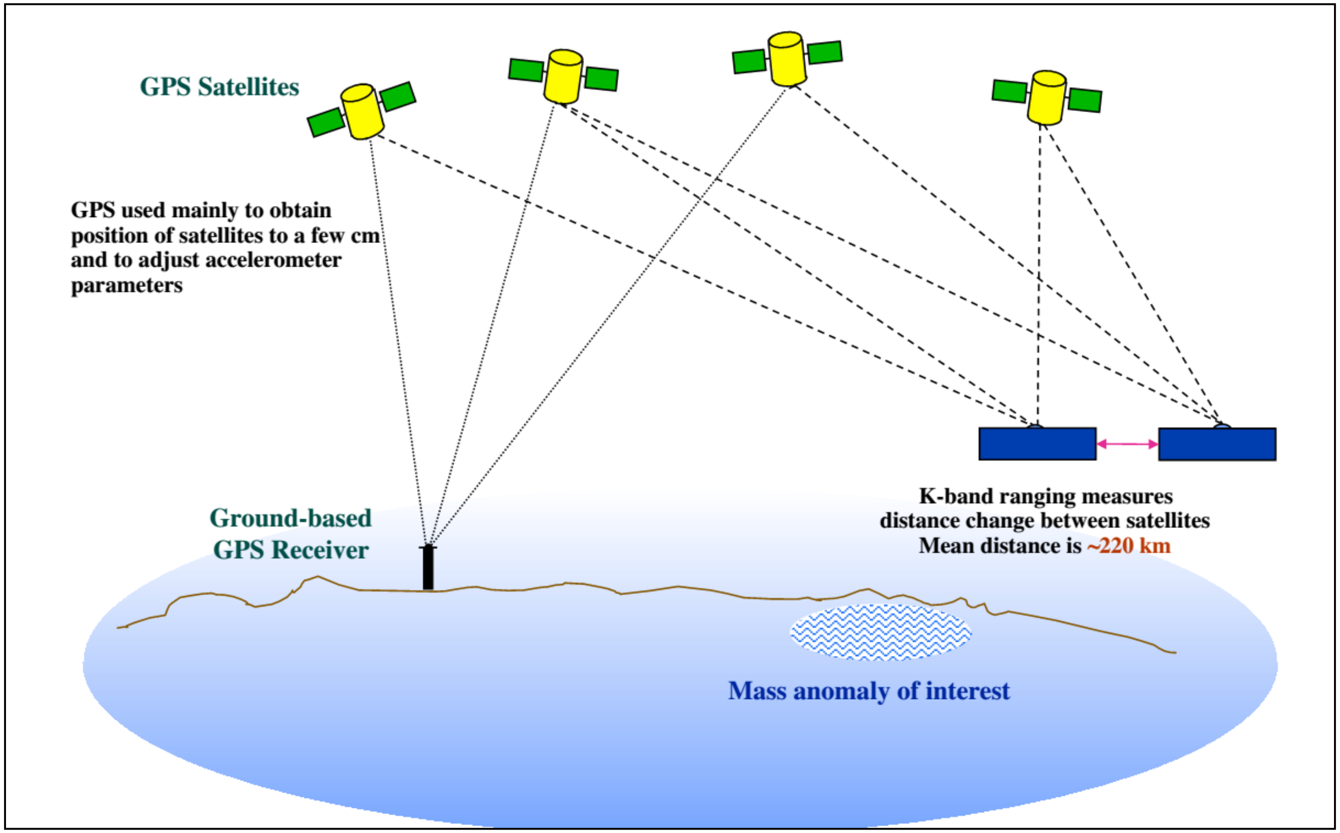
- Earth is not a perfect sphere
- Poles are ~ 21 km (13 mi) closer to the center of the Earth than the Equator (shape of an ellipsoid)
  -- Only a 0.3% difference
- 99.99% of the sea surface height measured by an altimeter is due to this gravitational shape of the Earth (or geoid)
- If we remove the ellipsoid shape, there are still ± 100 m deviations in the SSH or geoid





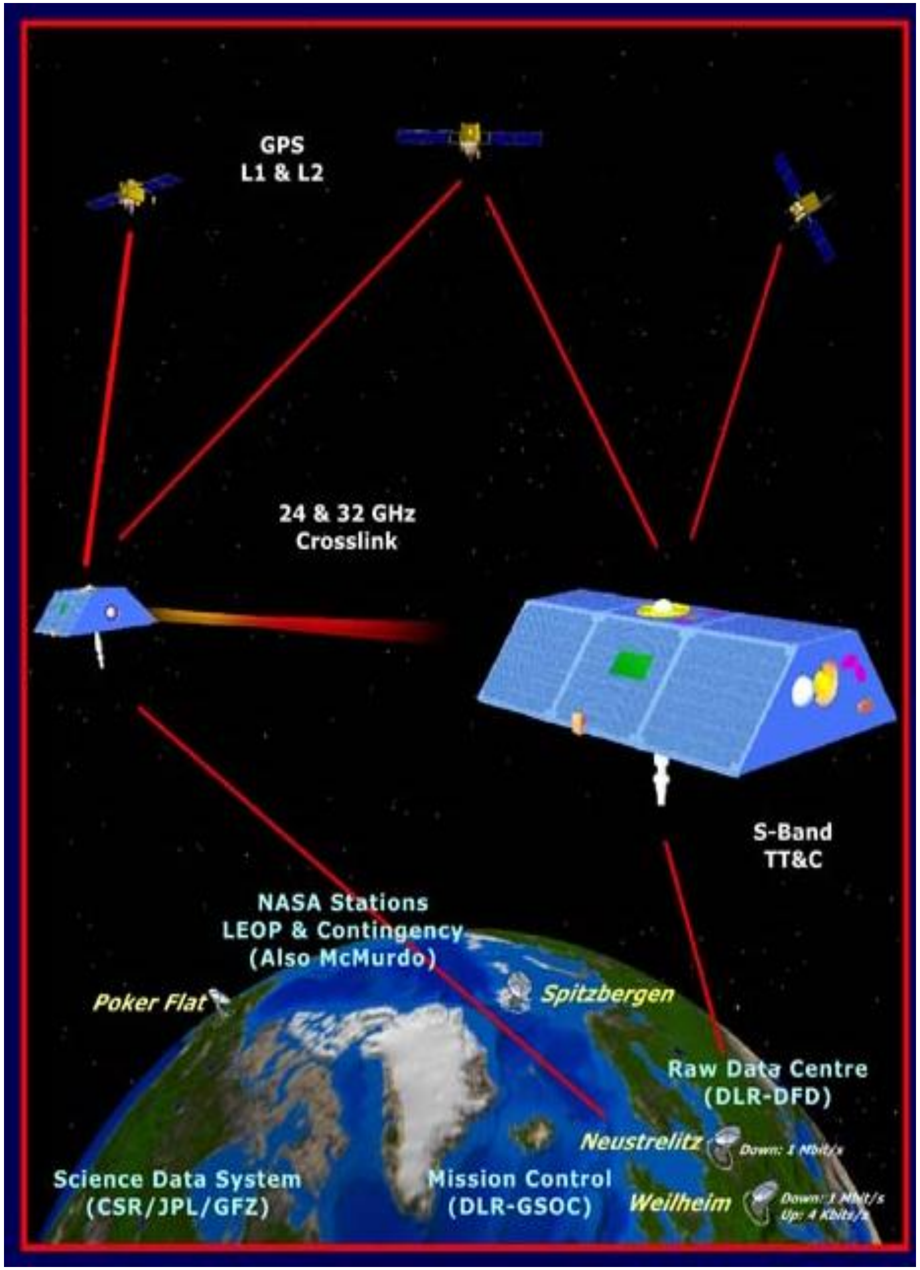
Earth mean sea surface/geiod

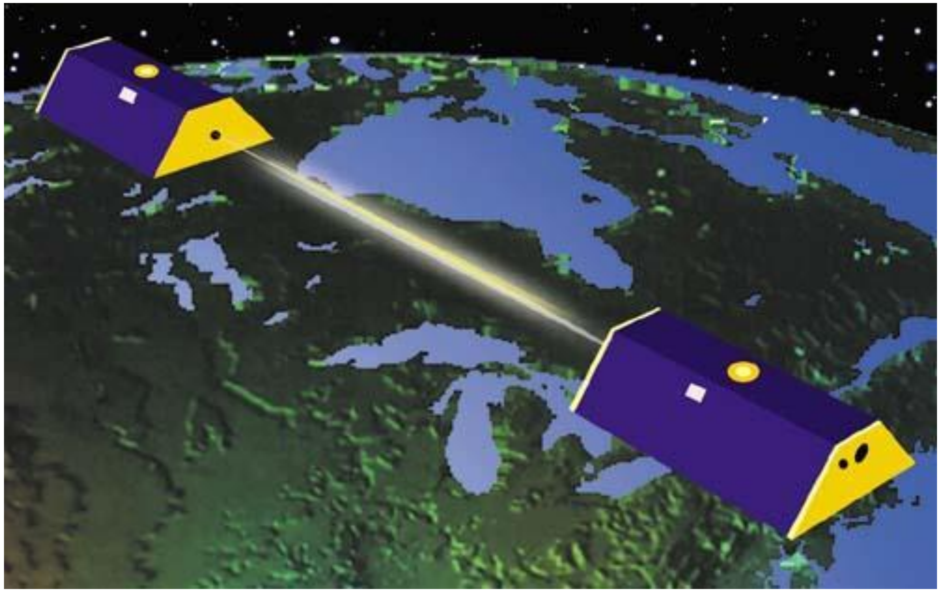
GRACE: Measurement principle



- uses a microwave ranging system to accurately measure changes in the speed and distance between ***two identical spacecraft*** flying in a polar orbit about 220 kilometers (140 mi) apart, 500 kilometers (310 mi) above Earth.

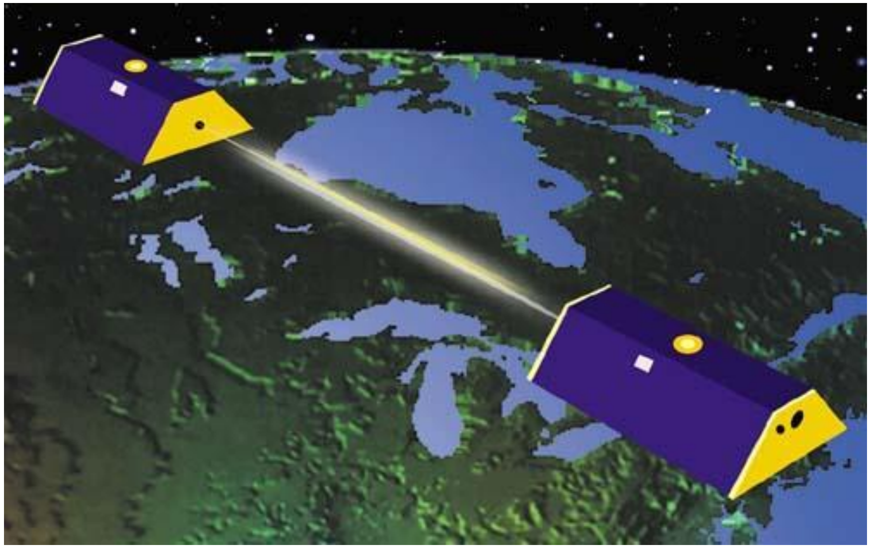
GRACE: Measurement principle





- The ranging system is sensitive enough to detect separation changes as small as 10 micrometers
- (approximately one-tenth the width of a human hair) over a distance of 220 kilometers

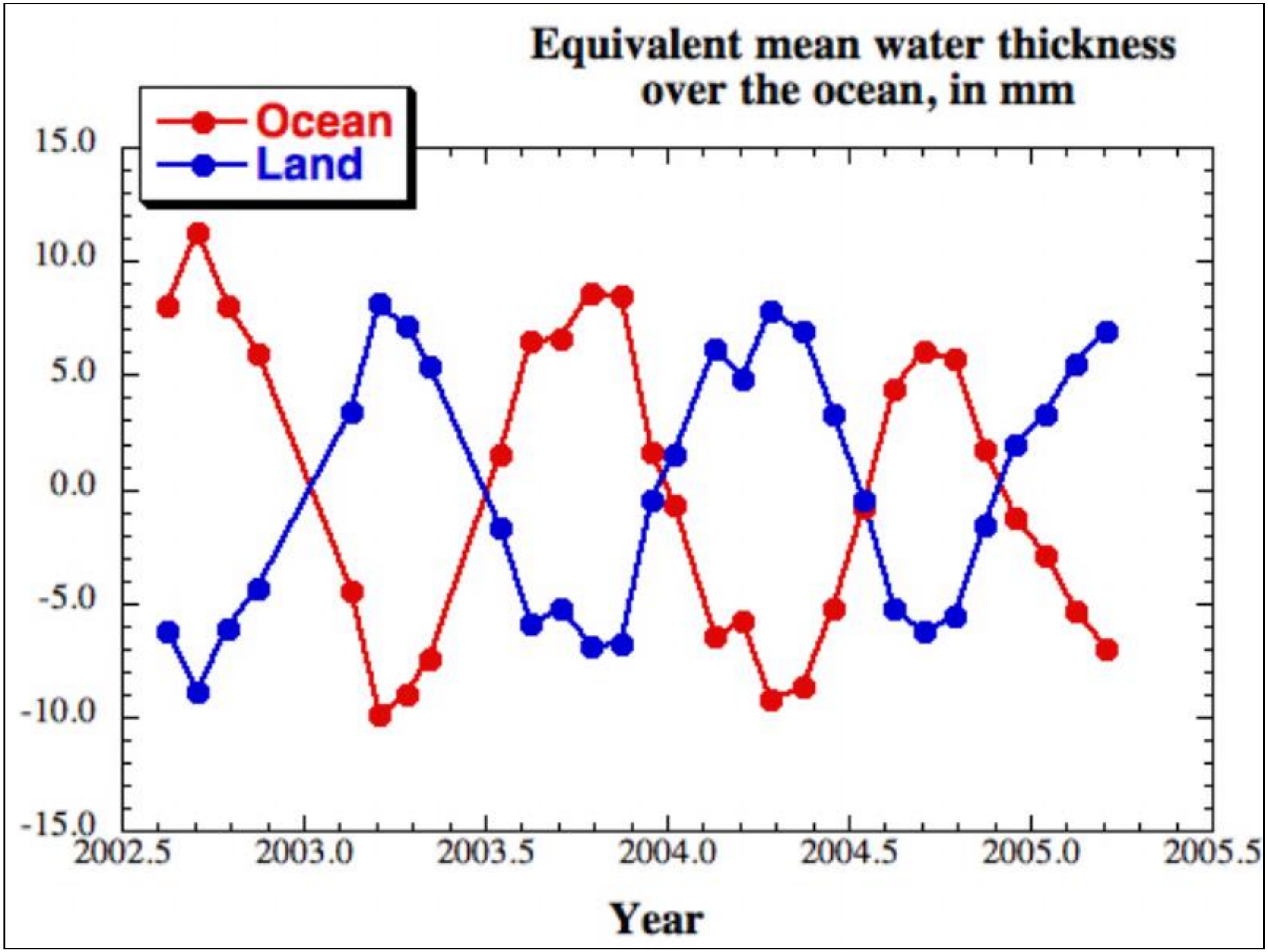
GRACE: Measurement principle



- As the twin GRACE satellites circle the globe 15 times a day, they sense minute variations in Earth's gravitational pull
- When the first satellite passes over a region of slightly stronger gravity, a gravity anomaly, it is pulled slightly ahead of the trailing satellite.

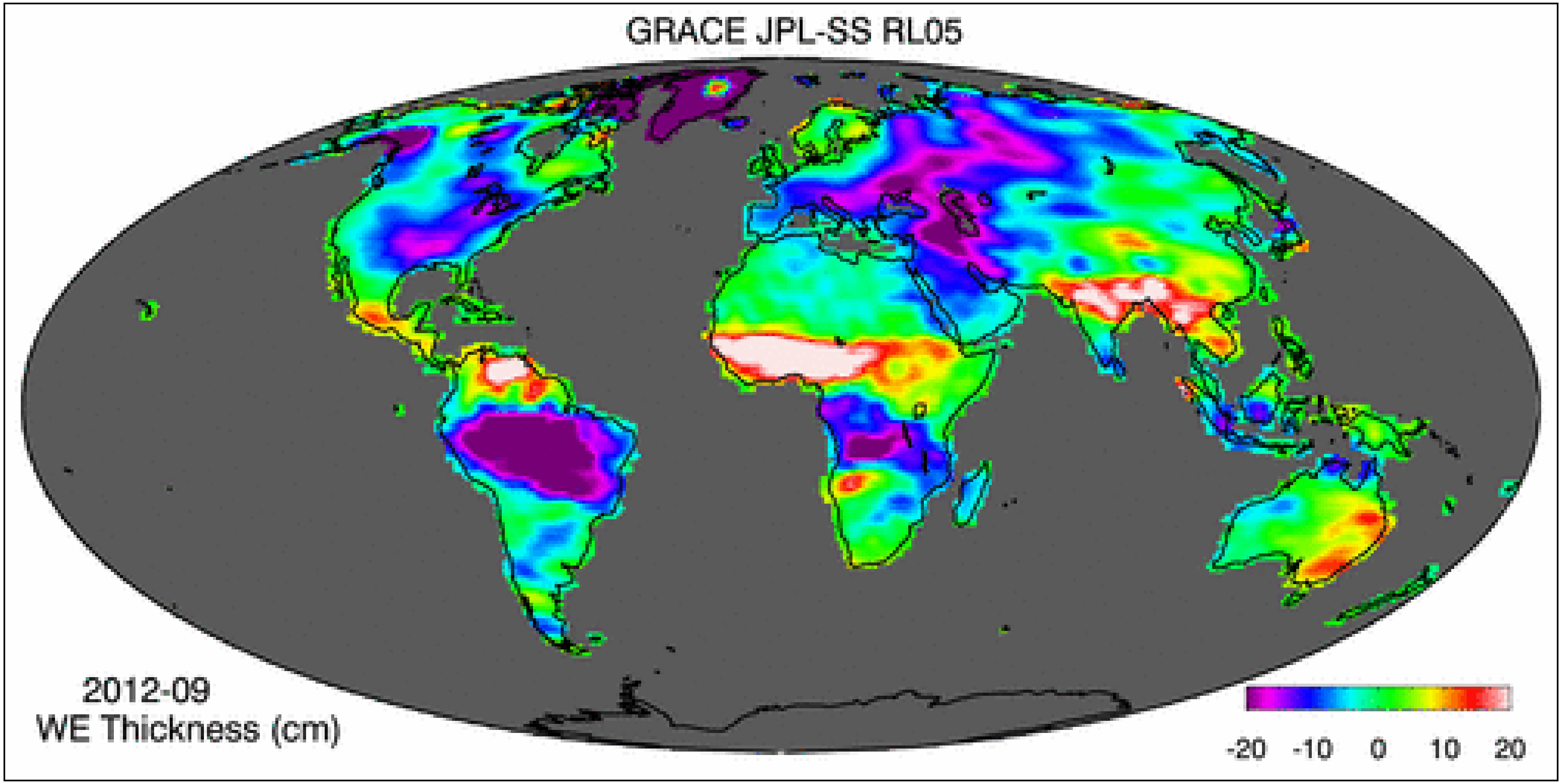
- This causes the distance between the satellites to increase.
- The first spacecraft then passes the anomaly, and slows down again; meanwhile the following spacecraft accelerates, then decelerates over the same point.

GRACE: Water Thickness



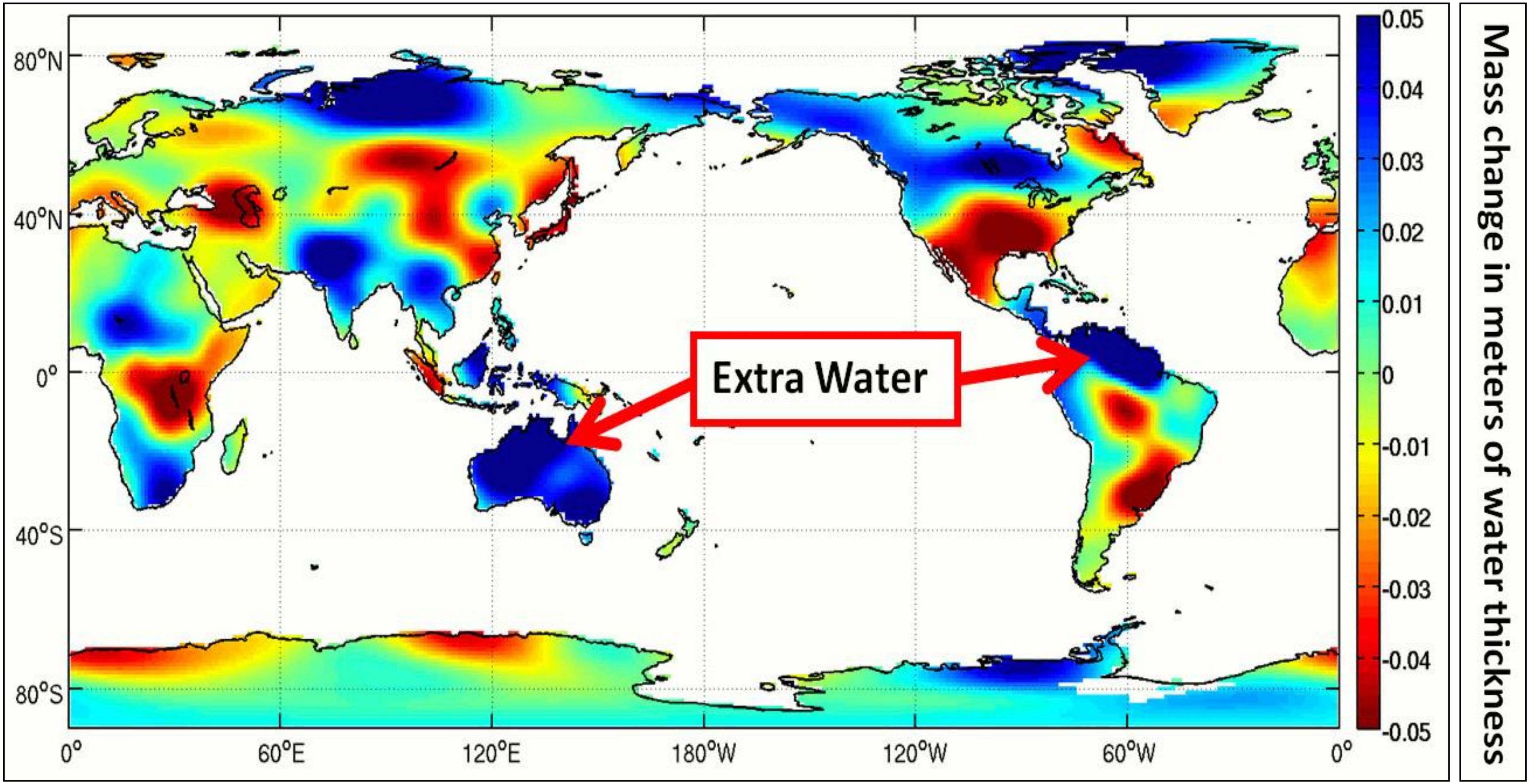
- GRACE measures the mass flux over both the ocean and land; these are out of phase

GRACE: Water Thickness



- GRACE measures the mass flux over both the ocean and land; these are out of phase

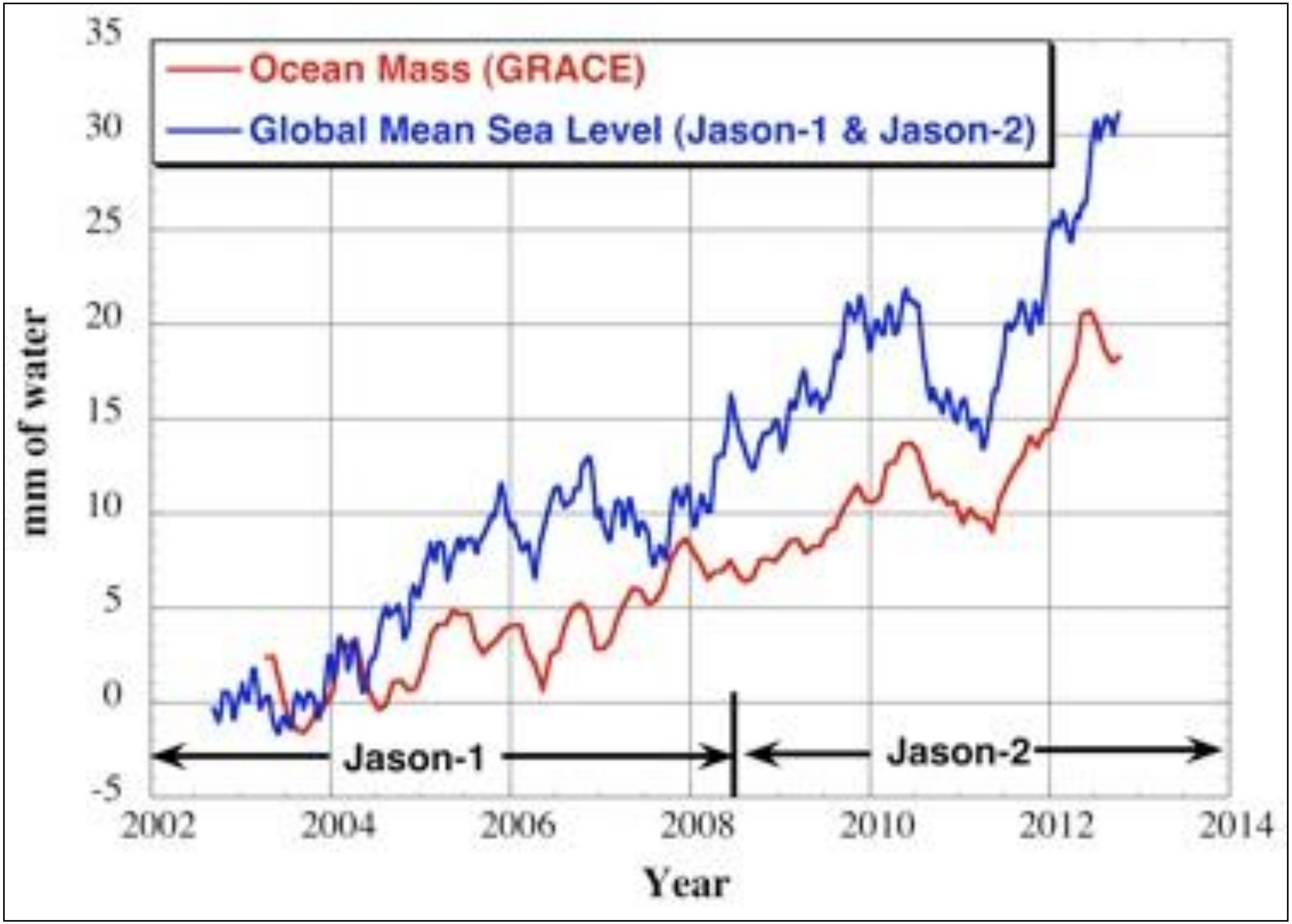
Application: Global change - Monitor changes in Earth's water



Extra Water

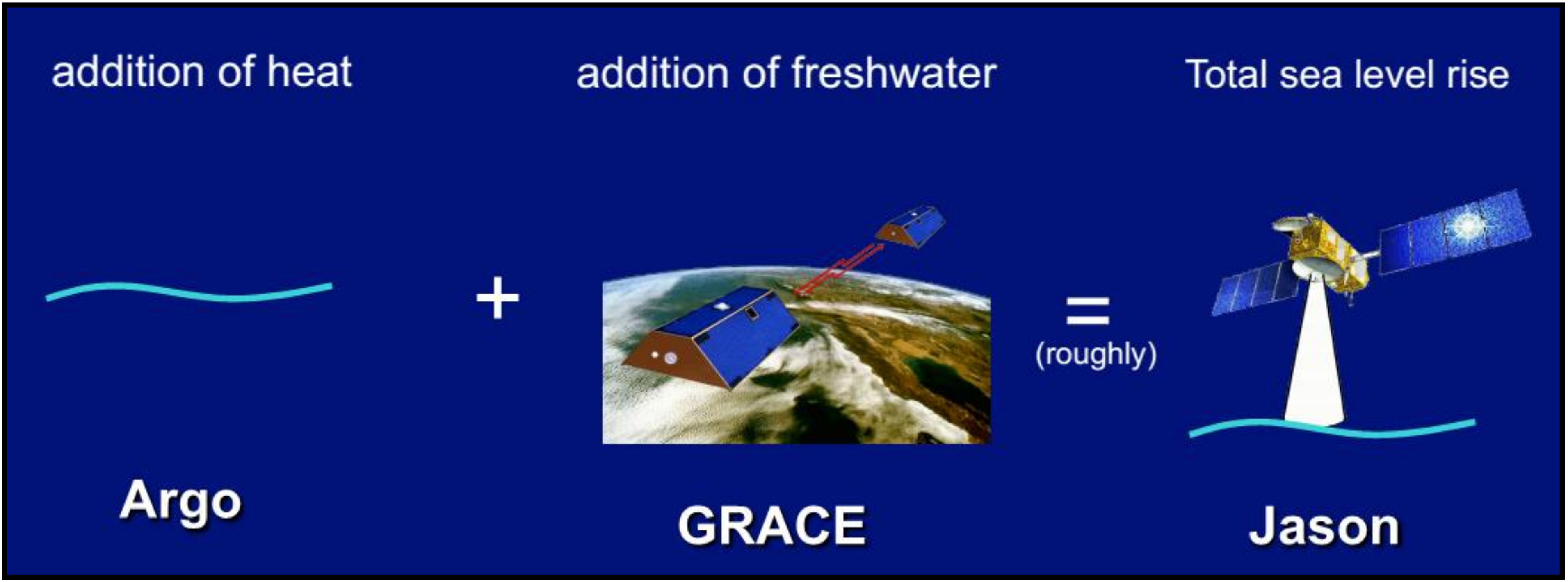
GRACE shows change in water from March 2010 to March 2011

Application: Global change - Monitor changes in Earth's water



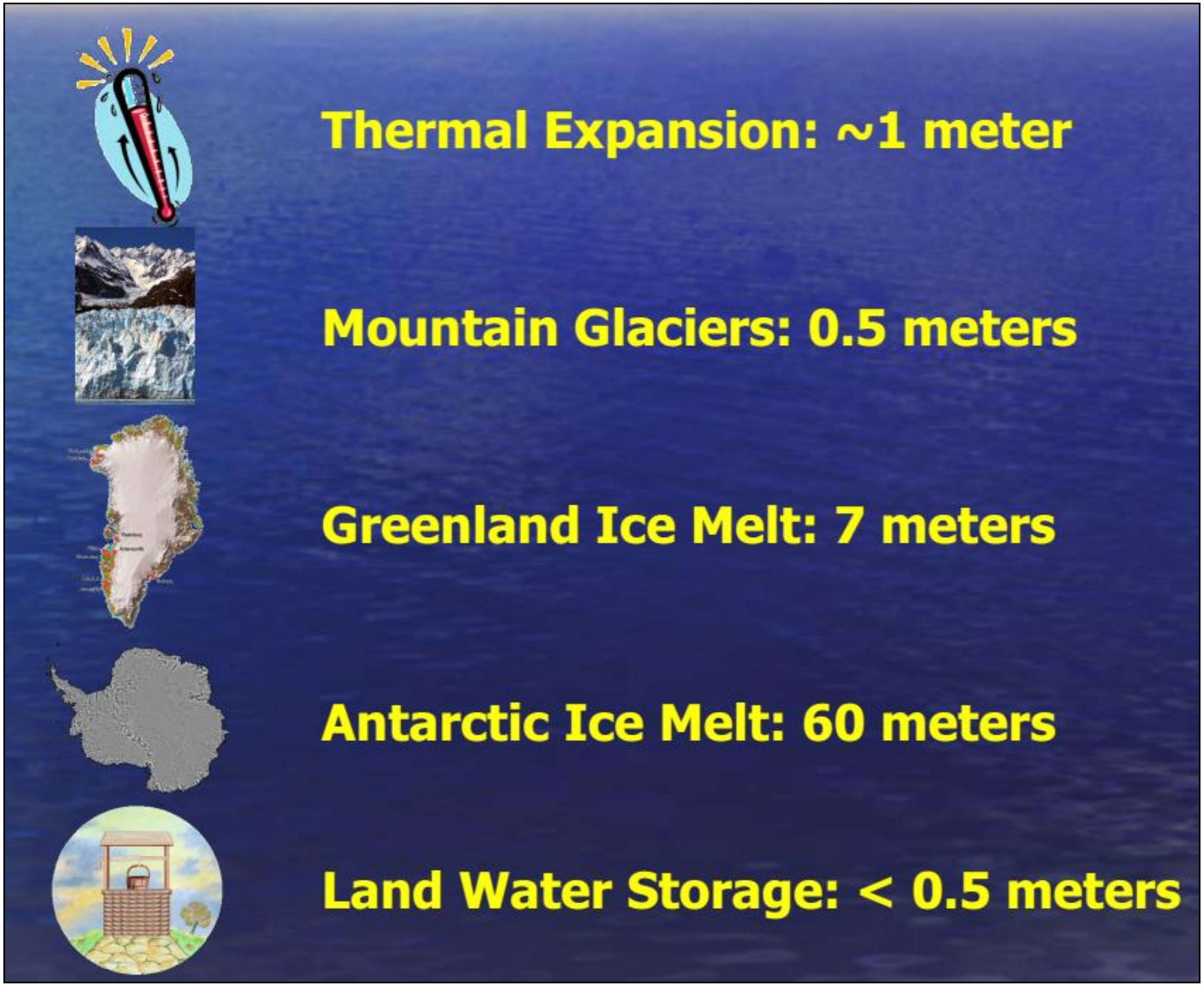
Global mean sea level (GMSL) derived from GRACE and from altimetry.

GRACE: Sea level changes



- Globally averaged sea level rise

GRACE: Sea level changes- potential contributions



Thermal Expansion: ~1 meter

Mountain Glaciers: 0.5 meters

Greenland Ice Melt: 7 meters

Antarctic Ice Melt: 60 meters

Land Water Storage: < 0.5 meters