Salinity: from Pot to Port

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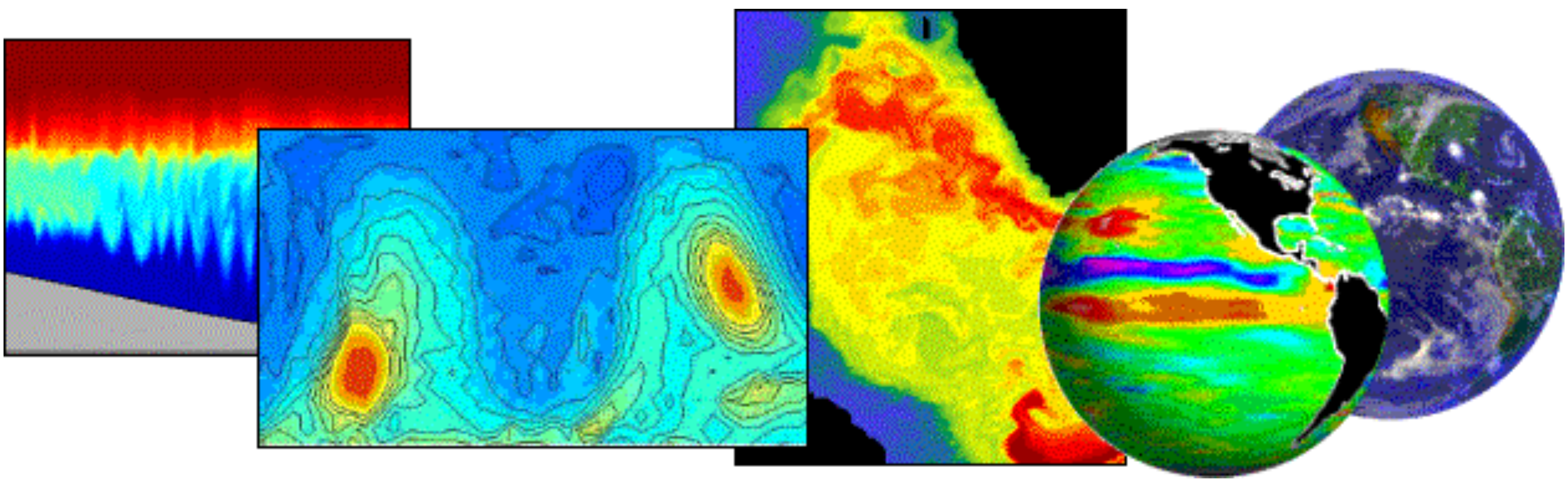
University of New Orleans



RMU Summer School (August 5-10, 2019)

Importance of salt: Food & Health

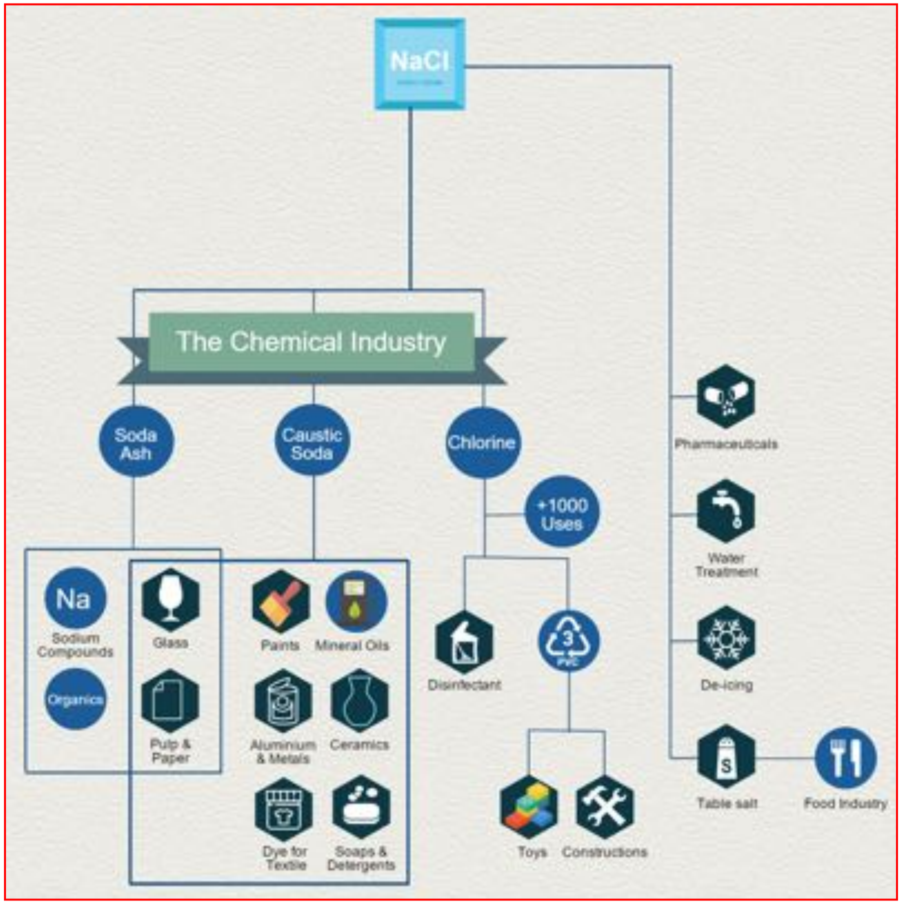
- NaCl : Sodium Chloride (table salt)

- ✓ food seasoning
- ✓ food preservation

- ✓ regulates body fluids
- ✓ controls blood pH, pressure and volume

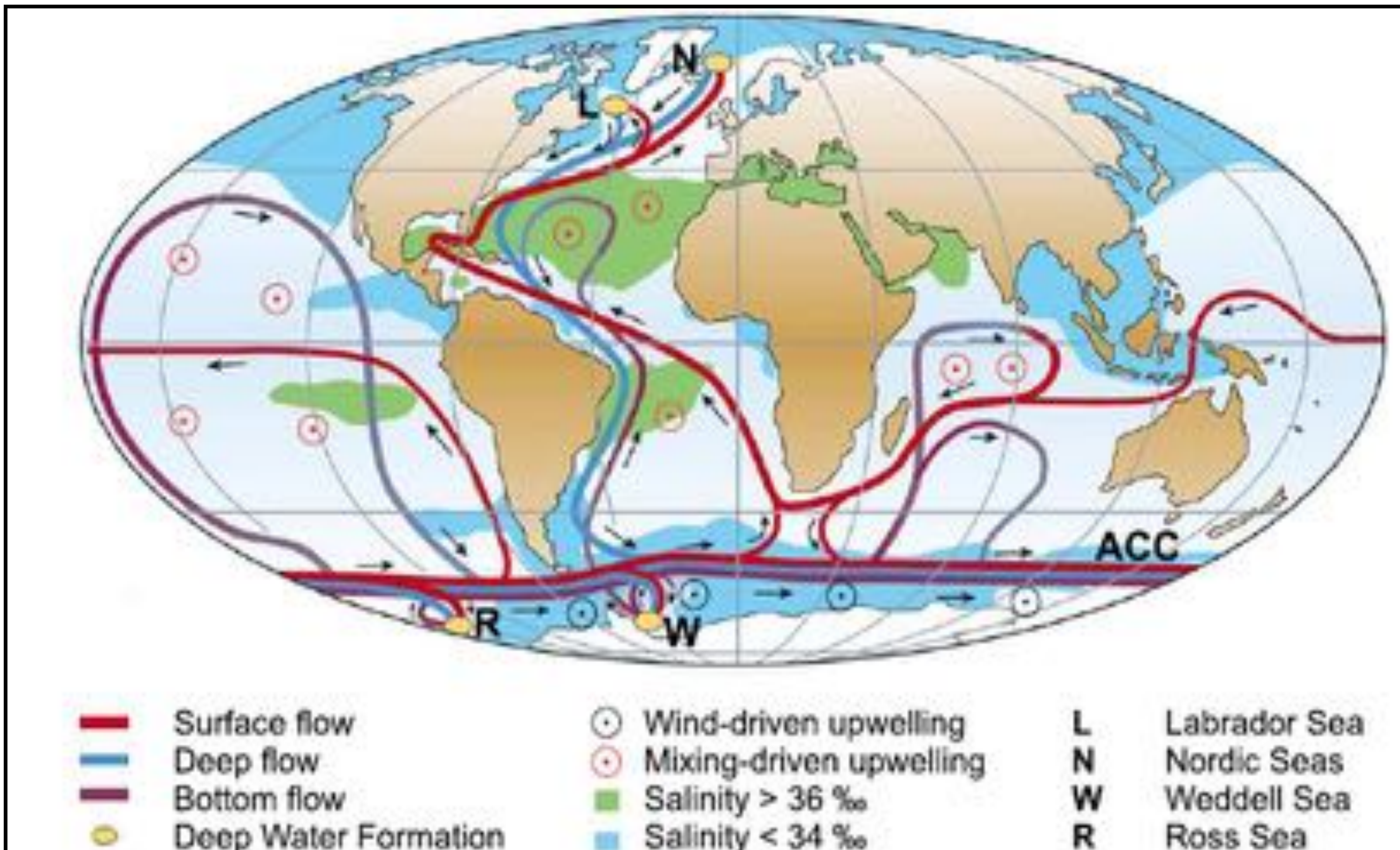
Importance of salt: Industry

- ✓ manufacturing: glass, paper, rubber, and textiles
- ✓ waste & water treatment
- ✓ de-icing
- ✓ animal feed



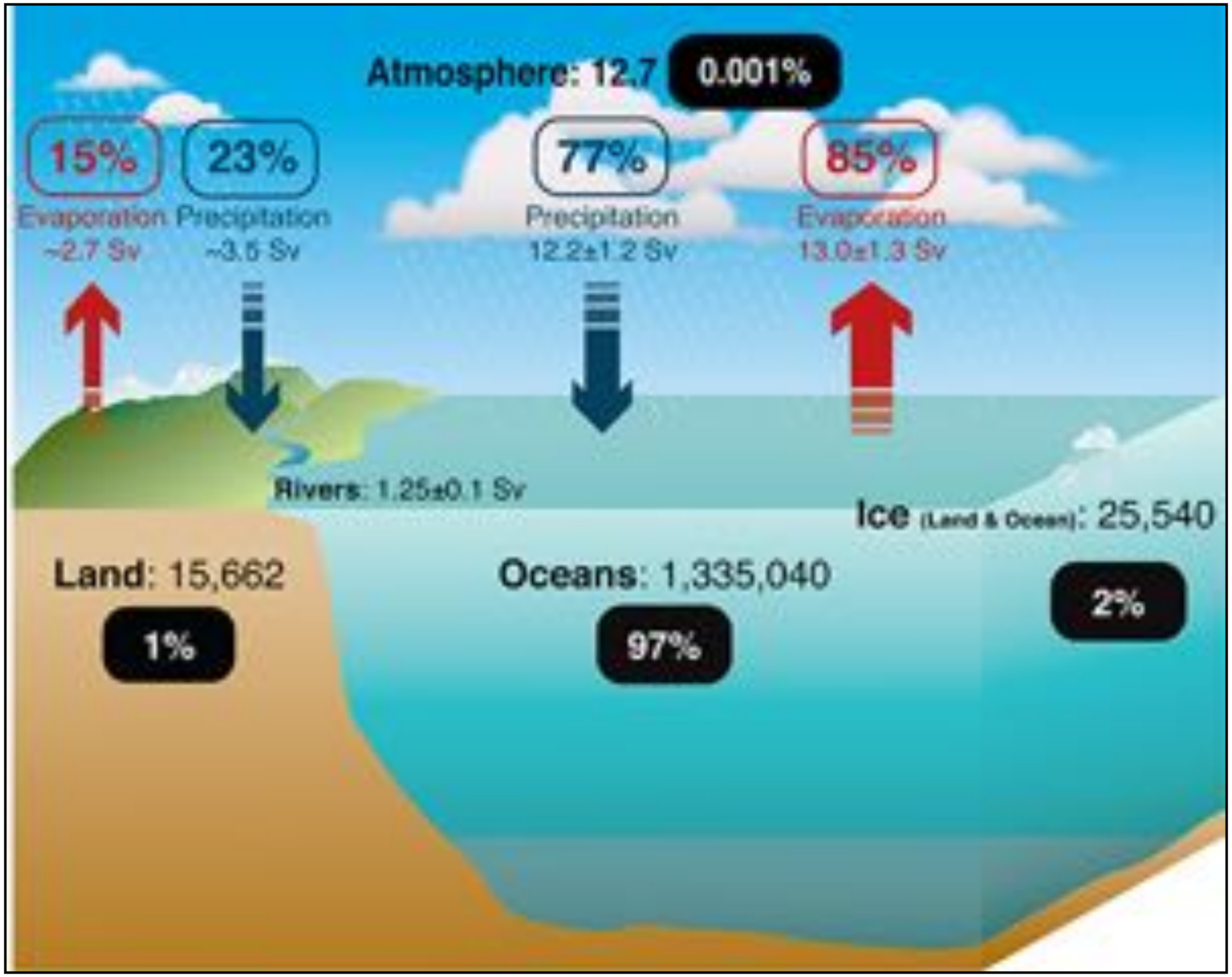
Importance of salinity

- ✓ 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)

Ocean salinity

- Salinity—the amount of dissolved salt in the water
- Salt in the ocean comes from rocks on land.
- On average, oceans salinity: 3.5%, or 35 parts per thousand.
- Thus for every 1 liter (1000 mL) of seawater there are 35 grams of salts (mostly ~ 90%, but not entirely, NaCl) dissolved in it.

Dissolved salts in sea water (atoms):
55.3 % Chlorine
30.8 % Sodium
3.7 % Magnesium
2.6 % Sulfur
1.2 % Calcium
1.1 % Potassium

Ocean salinity

- Units: practical salinity unit (psu); parts per thousand (ppt)

- Based on properties of sea water conductivity

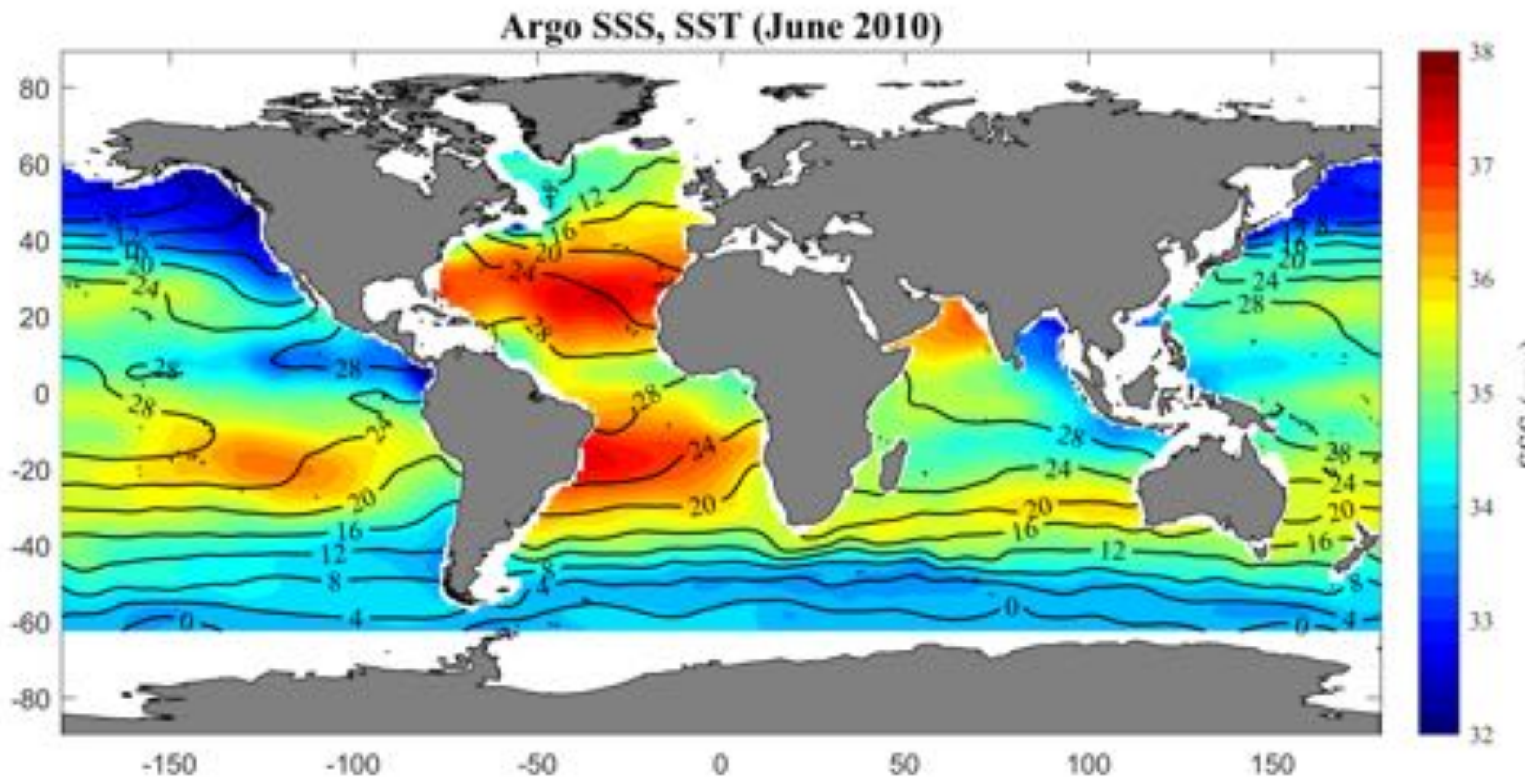
- Equivalent to per thousand ($^{o}/_{00}$) or to g/kg

- varying from less than 15 psu at the mouth of the rivers to more than 40 psu in the Dead Sea

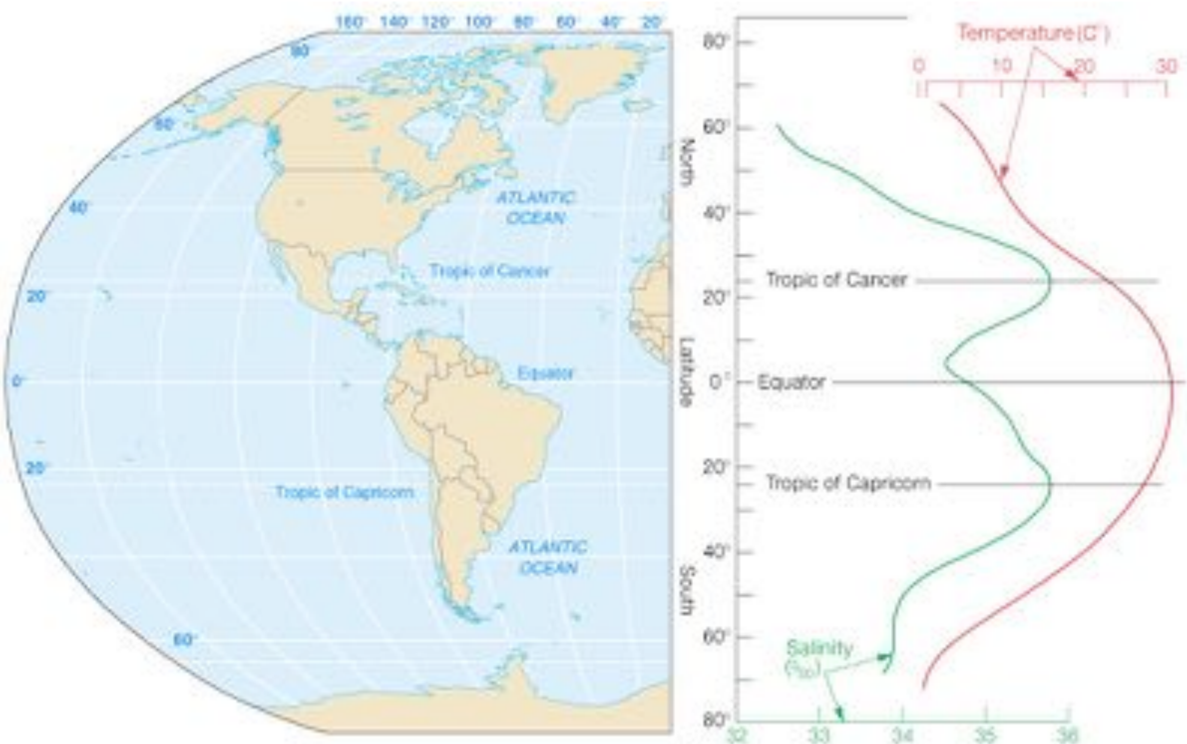
Ocean salinity

- Ocean salinity based on properties of sea water conductivity
- Conductivity: a substance/material's conductivity is the extent that it allows an electric current to flow through it.
- By measuring conductivity one can get a measurement of that water sample's salinity.
- This is because electric current passes much more easily through water with a higher salt content.
- Thus, if we know the conductivity of the water, we know how much salt is in the water.

Global salinity pattern



Surface salinity variation

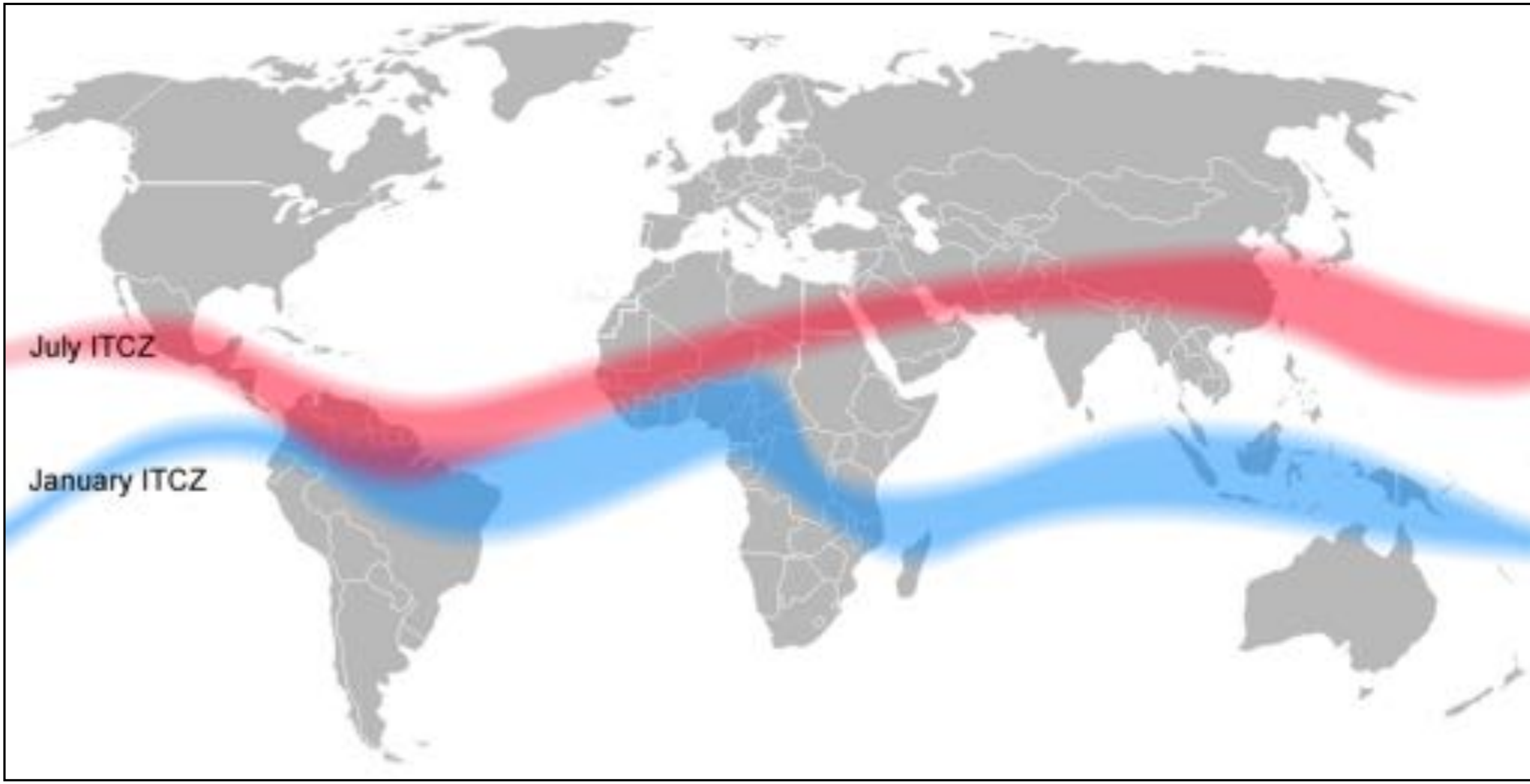


Pattern of surface salinity:

- Lowest in temperate and high latitudes
- Highest in the tropics
- Dips at the Equator

• Surface processes help explain pattern

ITCZ



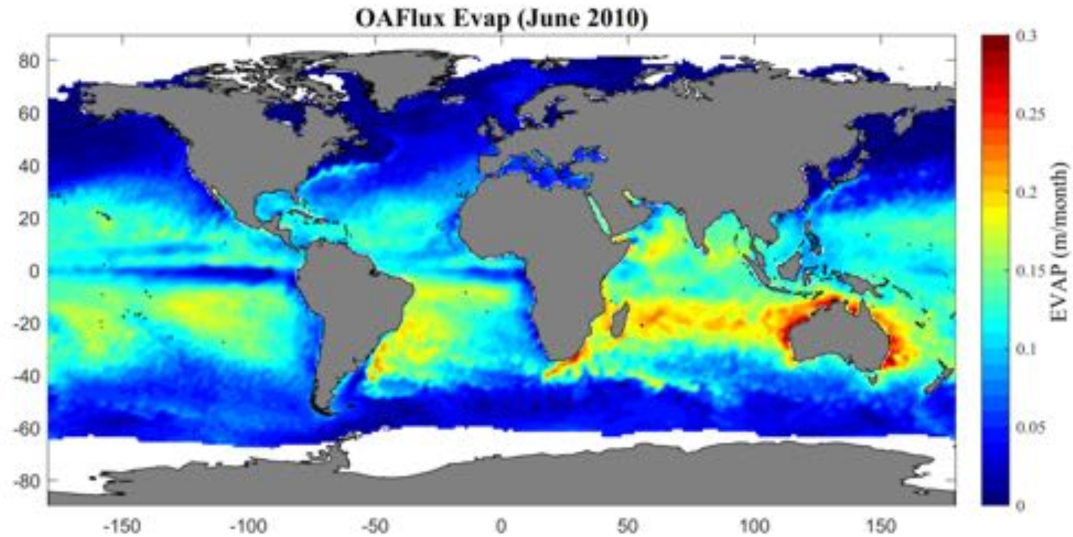
- ✓ Climate system influenced by wind variability and ITCZ migration
- ✓ ITCZ: band where the southeasterly and northeasterly wind converge

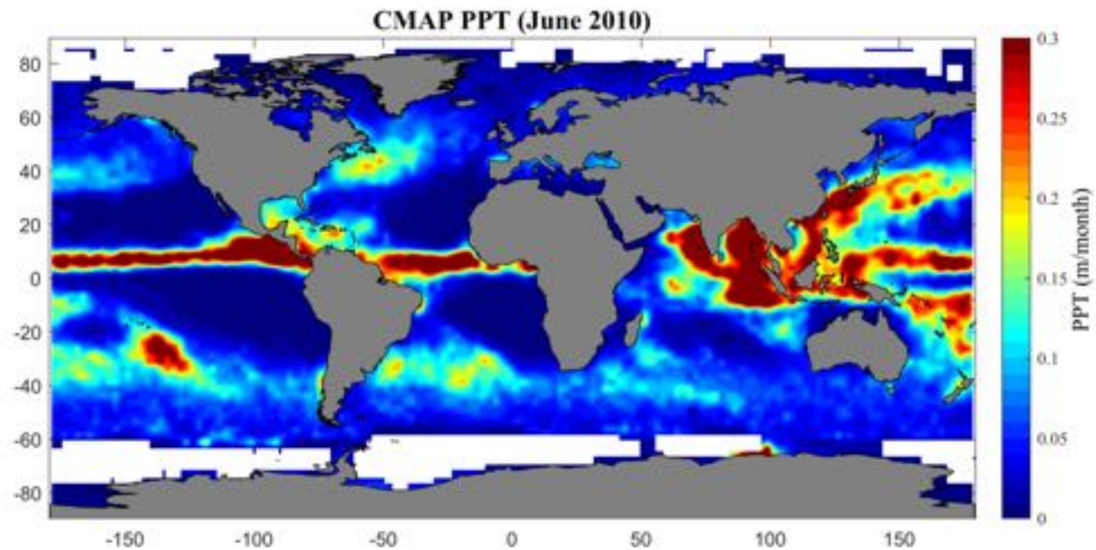
Evaporation and Precipitation

FW = E – P + R

Net E =13 Sv

1Sv = 10^6 m^3s^{-1}



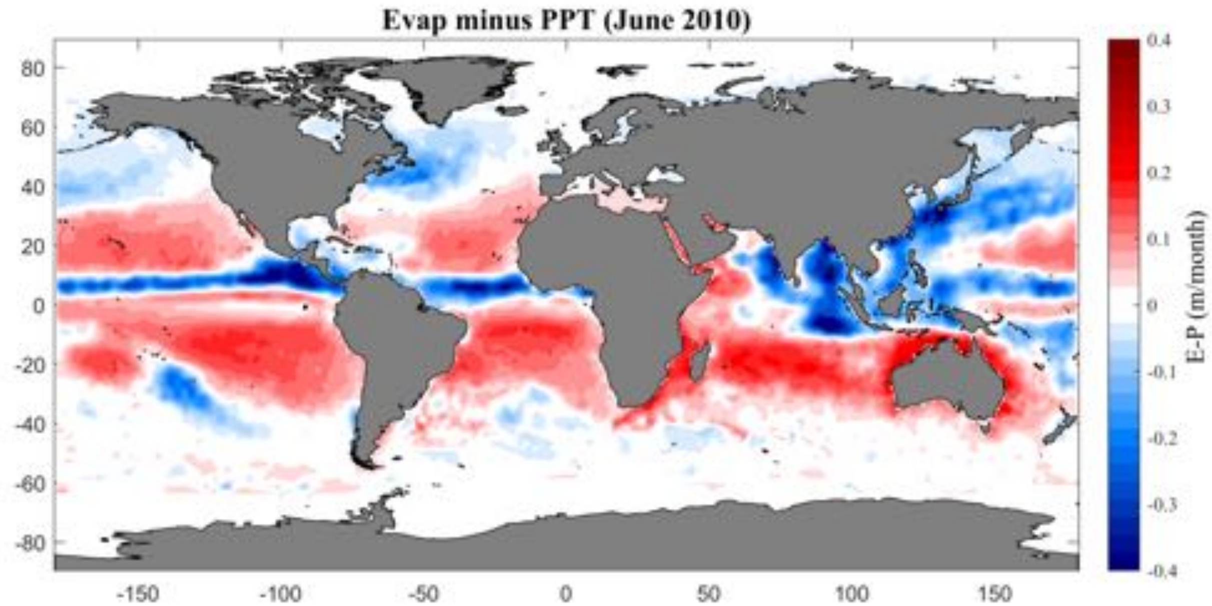


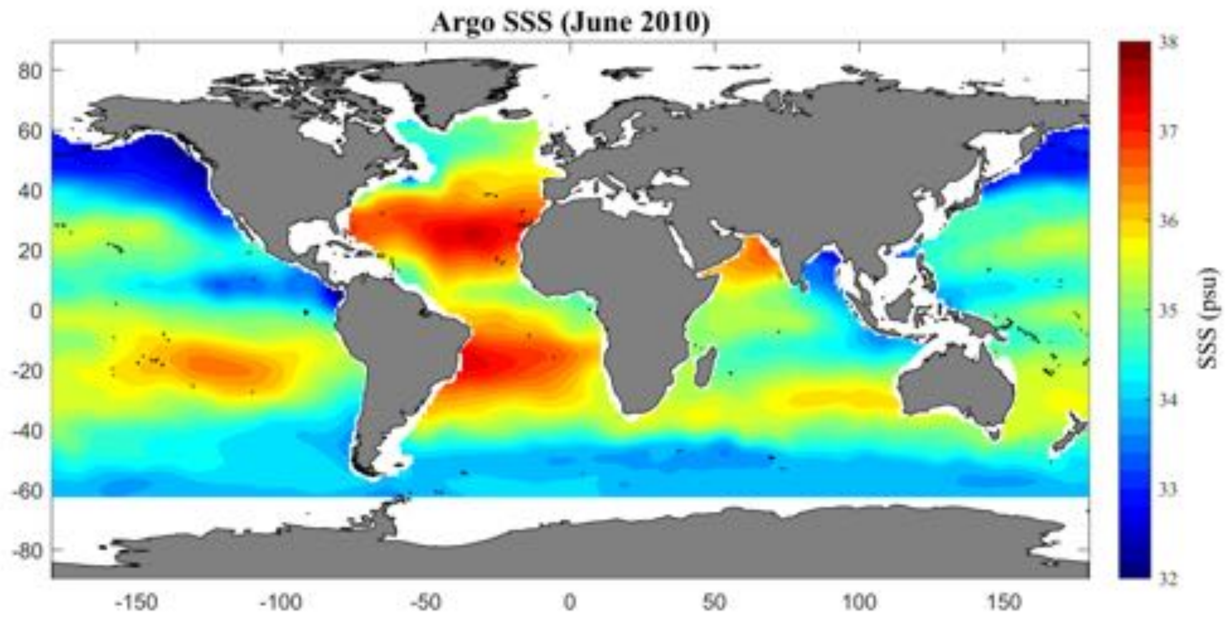
Net P = 12.2 Sv

Net River = 1.25 Sv

Diff = ~ -0.45 Sv

Evaporation Minus Precipitation and Salinity

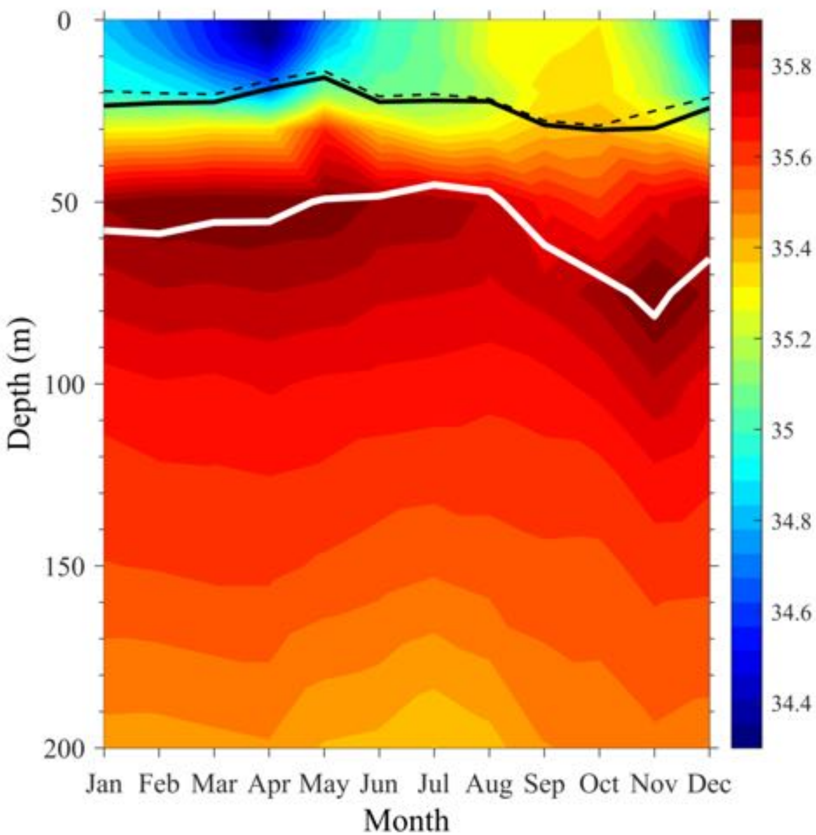




Surface salinity variation

Salt budget estimated from:

$$\frac{\partial S}{\partial t} = S\frac{(E-P)}{h} - u\frac{\partial S}{\partial x} - v\frac{\partial S}{\partial y} - w\frac{\partial S}{\partial z} + R$$



$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Ocean continuity equation

S = salinity
E = evaporation
P = precipitation
u = zonal advection
v = meridional advection
w = vertical advection
R = residual

Intensification of global water cycle !!!

Science AAAS

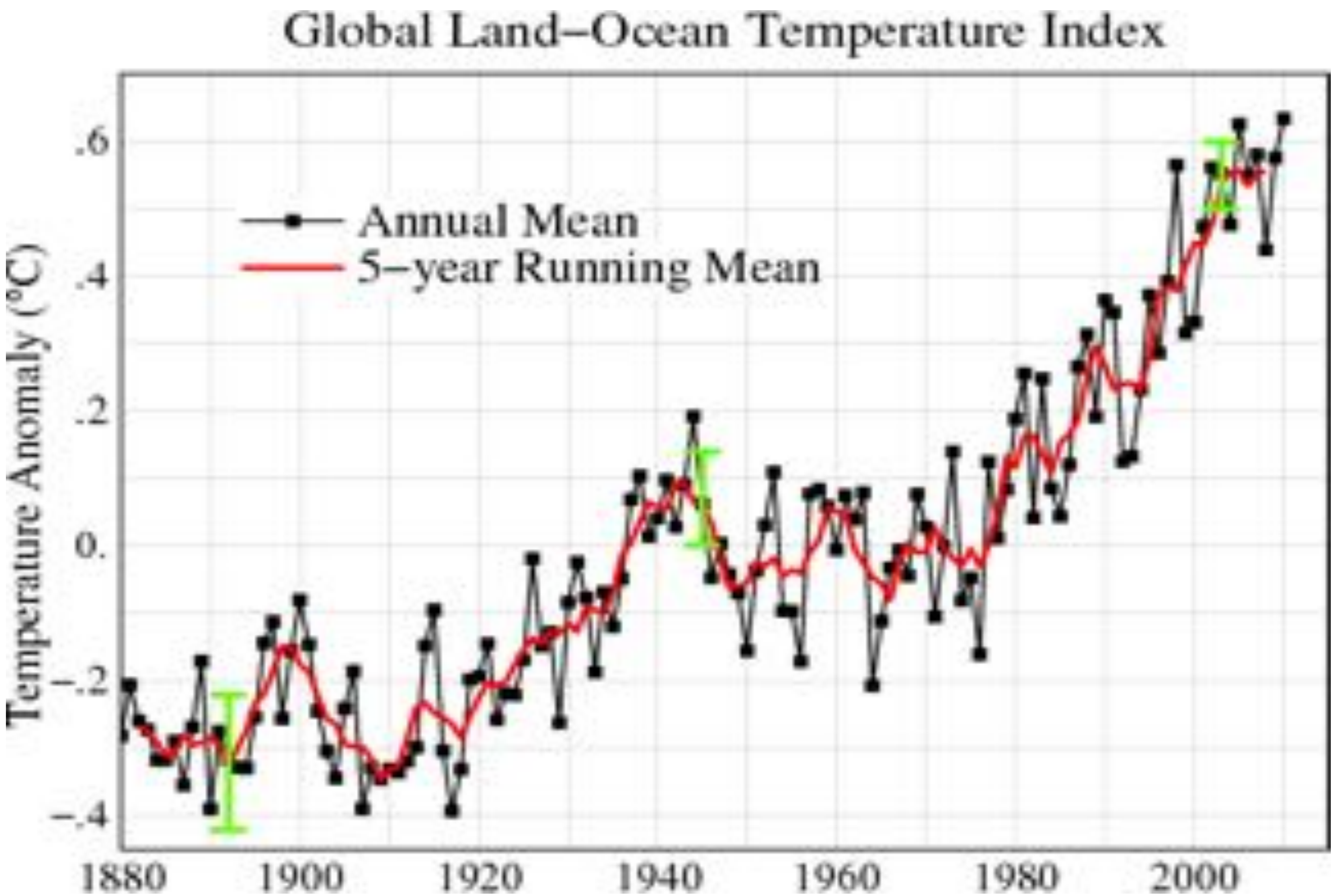
Ocean Salinities Reveal Strong Global Water Cycle Intensification During 1950 to 2000
Paul J. Durack *et al.*
Science **336**, 455 (2012);
DOI: 10.1126/science.1212222

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.

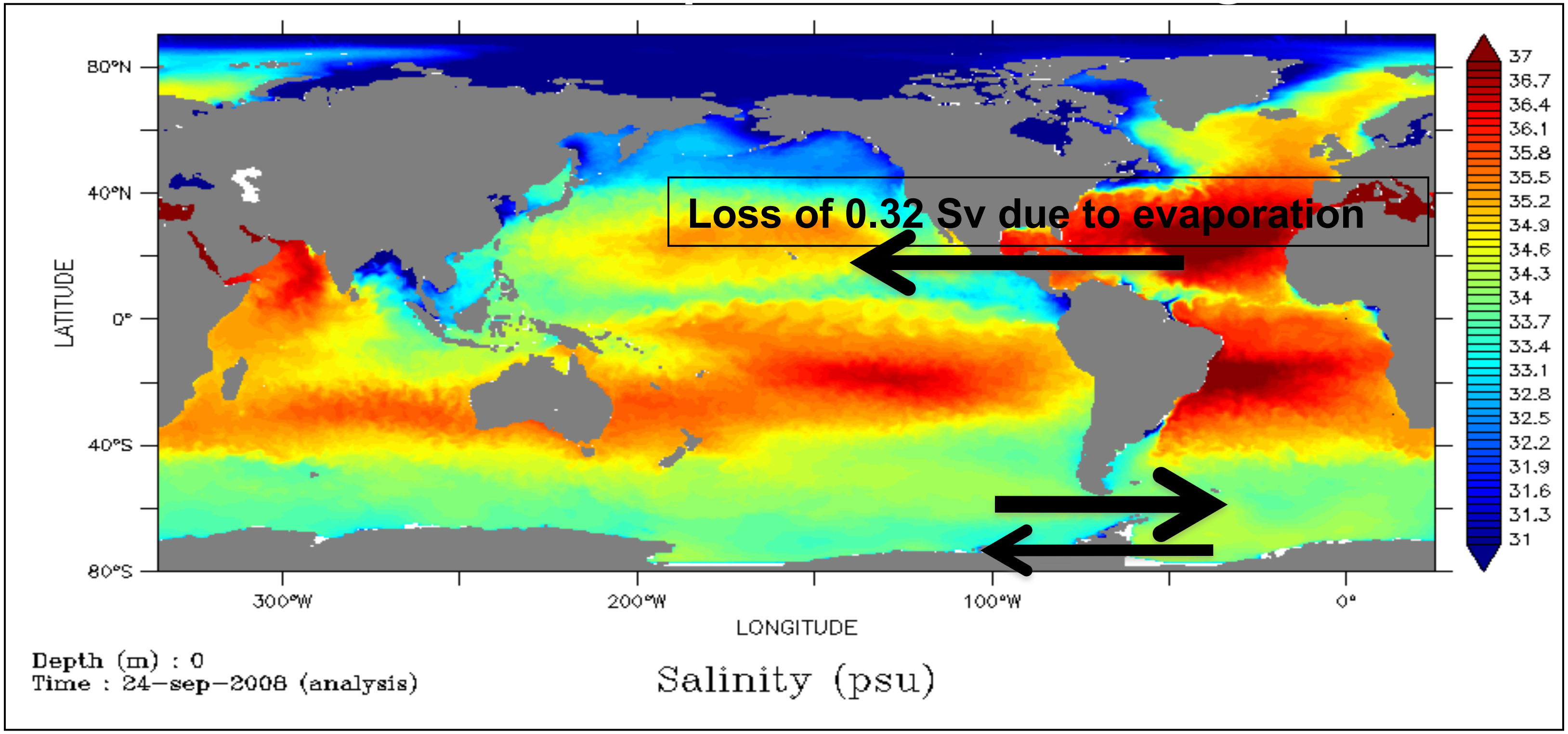
16 to 24% intensification of the global water cycle will occur in a future **2° to 3°** warmer world.

Temperatures are rising !!!



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

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

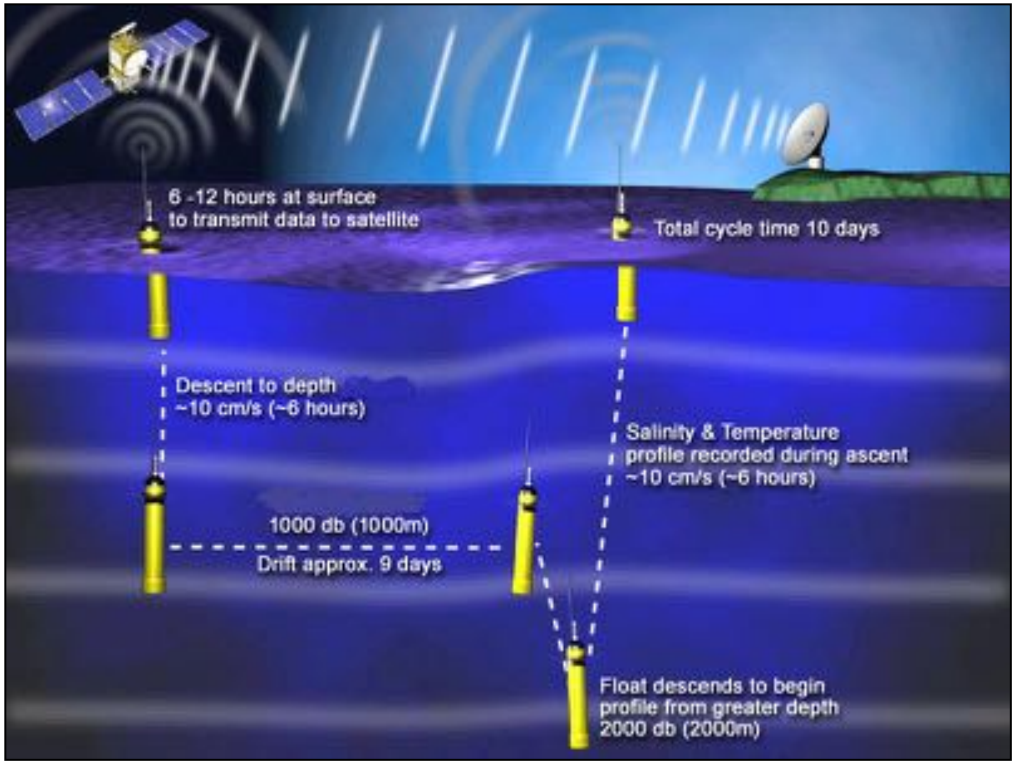


- Evaporative loss of water from the Atlantic; compensated by a net import of water from the Pacific.
- Increase in Atlantic salinity compensated by less salty Pacific waters
- In warming climate, inter-basin contrasts increase (saltier Atl, fresher Pacific)
- Warming-driven amplification of the Earth's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

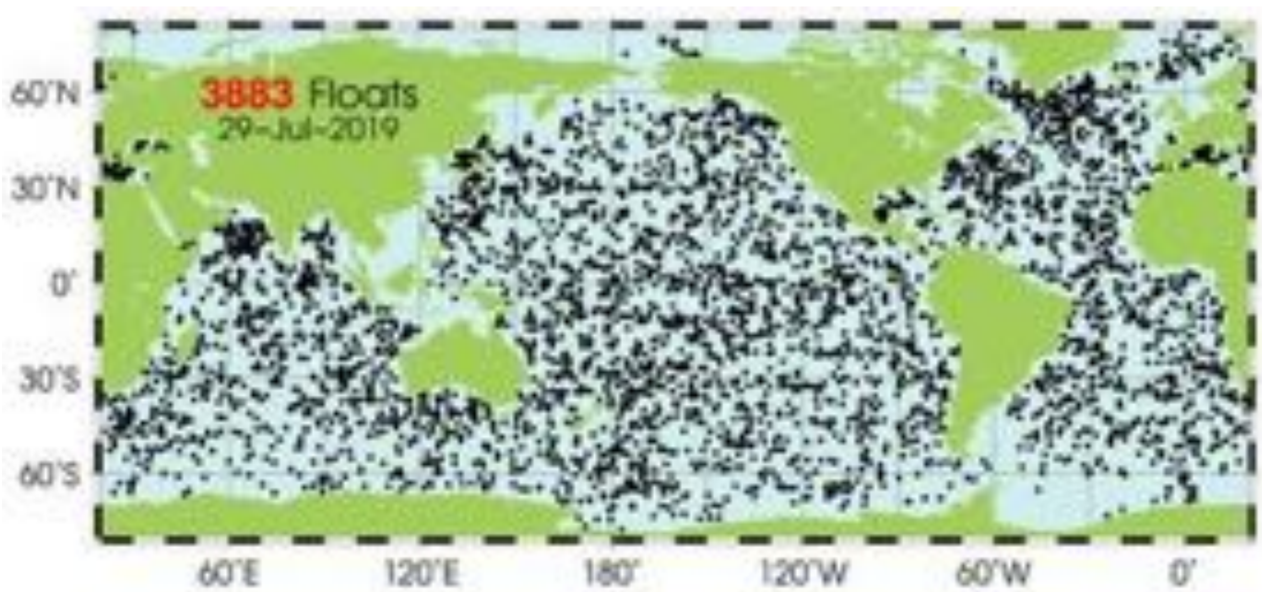
Measuring salinity

In-situ: CTD – Conductivity-Temperature-Depth

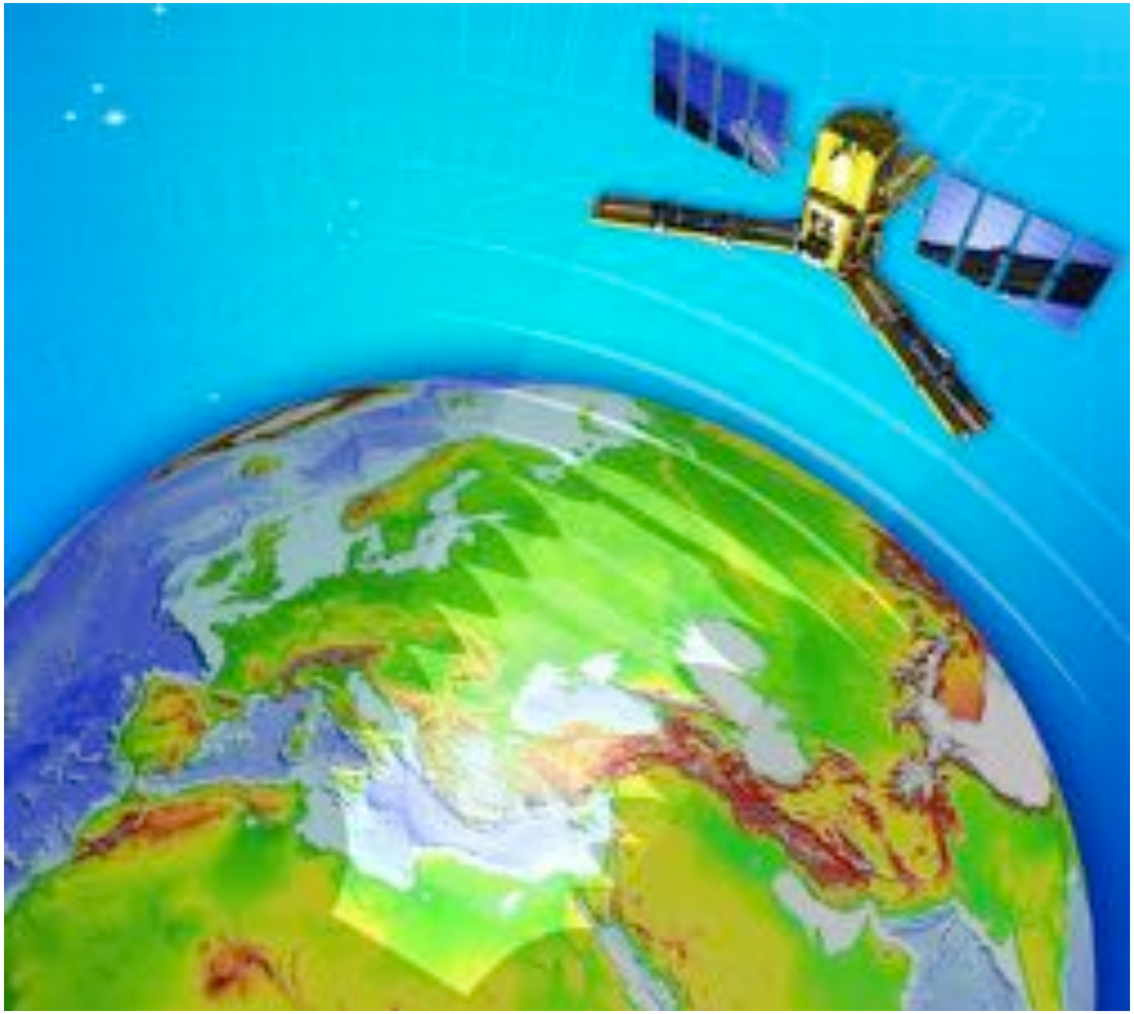
Argo float



Argo is a global array of more than 3,900 free-drifting profiling floats that measures the temperature and salinity of the upper 2000 m of the ocean.



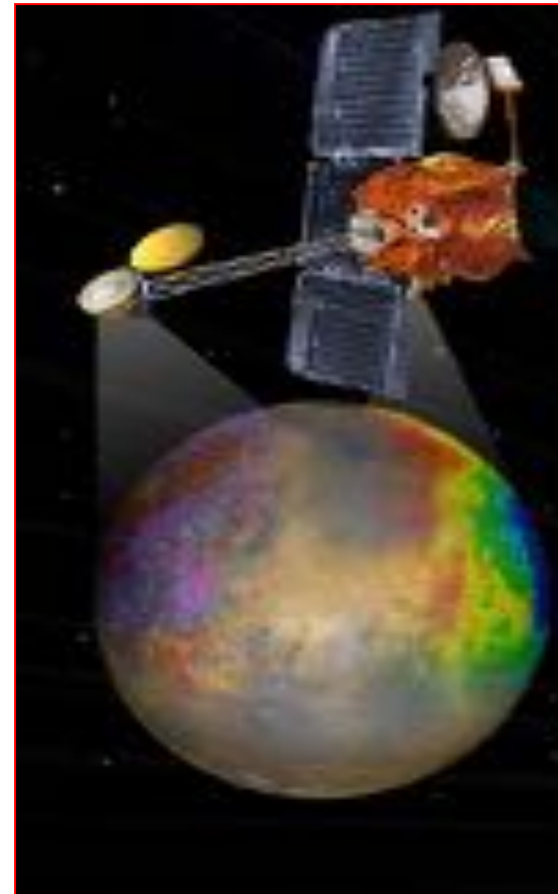
Salinity from Space



Remote sensing platforms

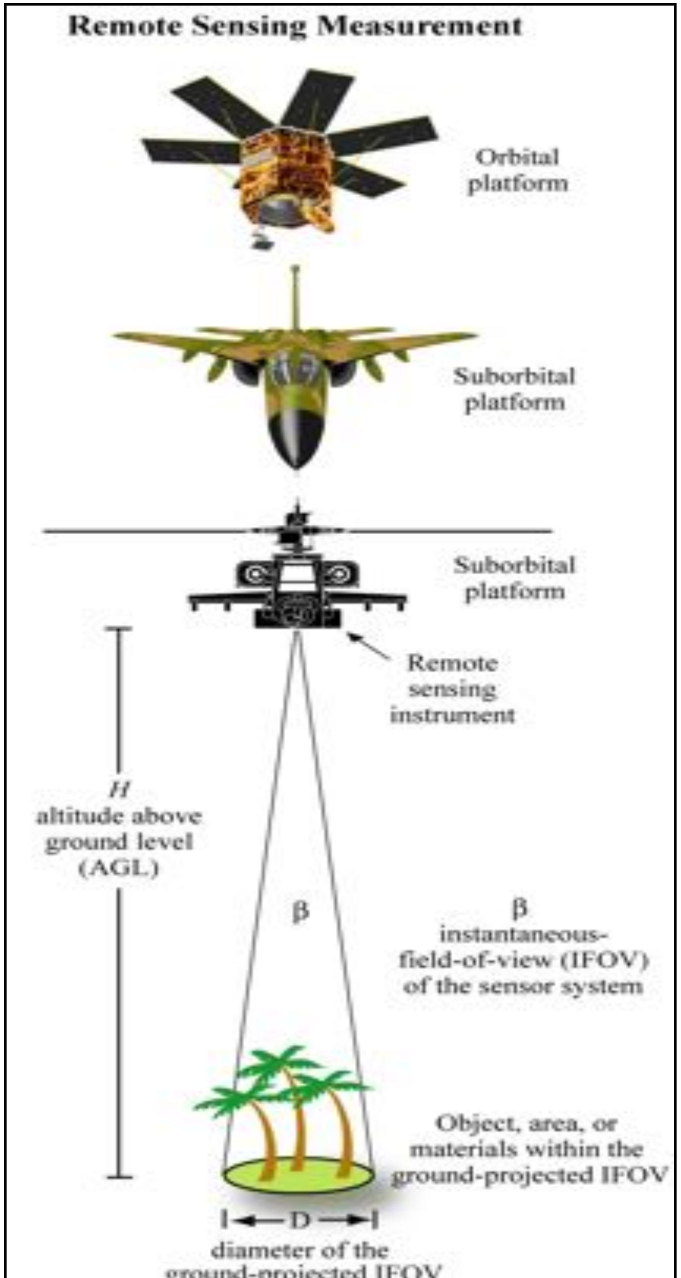
Ground-based

Airplane-based



Satellite-based

Introduction



What is remote sensing:

the art, science and technology of

- acquiring,
- processing, and
- interpreting

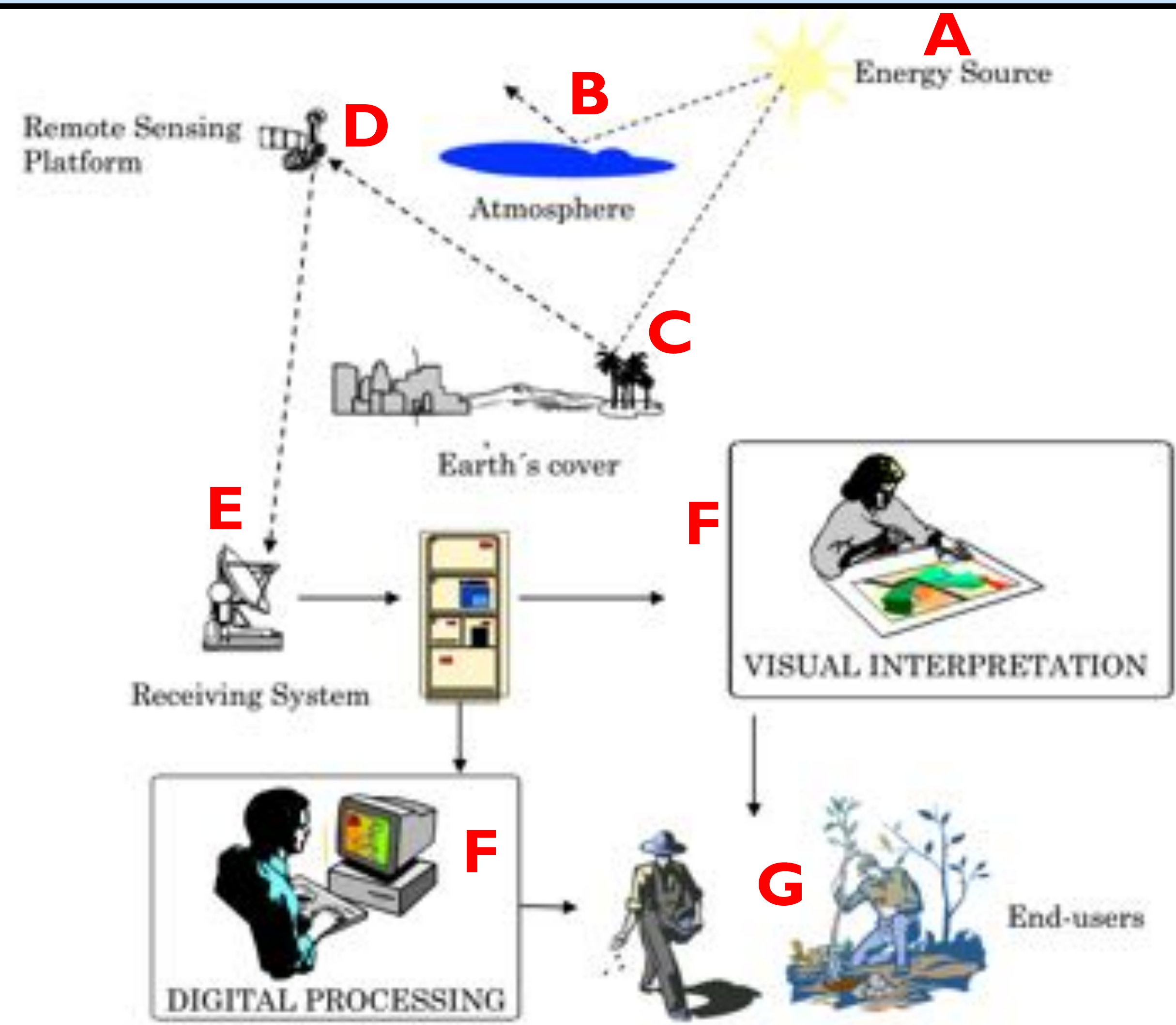
images and related data that are obtained from **ground-based, air-or space-borne instruments** that record the interaction between matter (target) and electromagnetic radiation

Energy patterns derived from **noncontact sensor systems**

Remote Sensing: using electromagnetic spectrum to image the **land, ocean,** and **atmosphere**.

Remote Sensing: Primary components

- Energy- radiation
- Sensor
- Object



A. Energy Source

B. Radiation and Atmosphere

C. Interaction with target

D. Energy recorded by sensor

E. Transmission, reception, processing

F. Interpretation and analysis

G. Application of information

Remote Sensing: A brief history

Hot-air Balloons Invented by the Montgolfier Brothers in 1783

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

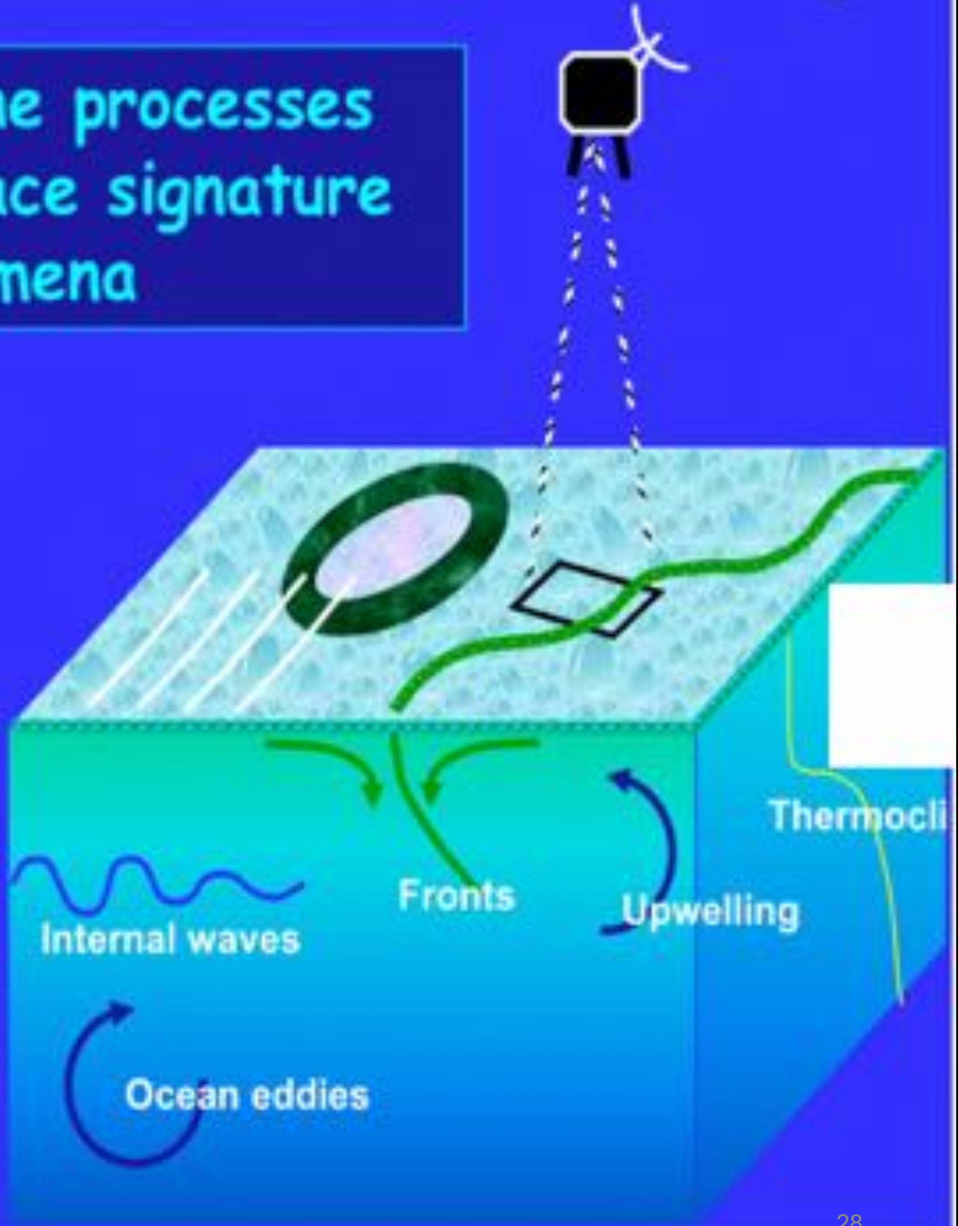
Limitations of satellite oceanography

- 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***

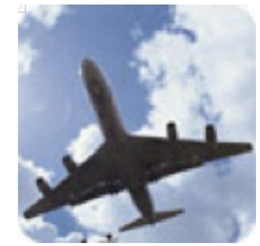


Applications of Remote Sensing

Carbon Management

Public Health

Energy Management



Aviation

Water Management

Homeland Security

Coastal Management

Disaster Management

Agricultural Efficiency

Invasive Species

Ecological Forecasting

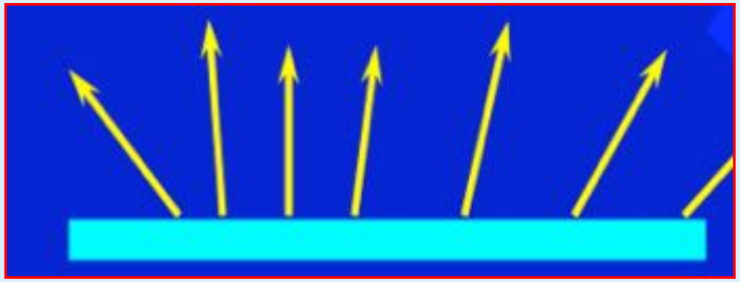
Air Quality

Basic physics and principles

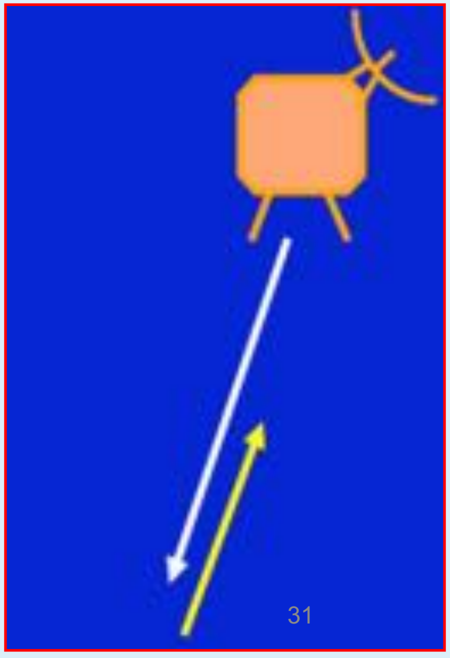
Sources of energy for remote sensing

- ❑ The Sun
  - --- Visible waveband
  - --- Near Infra red waveband

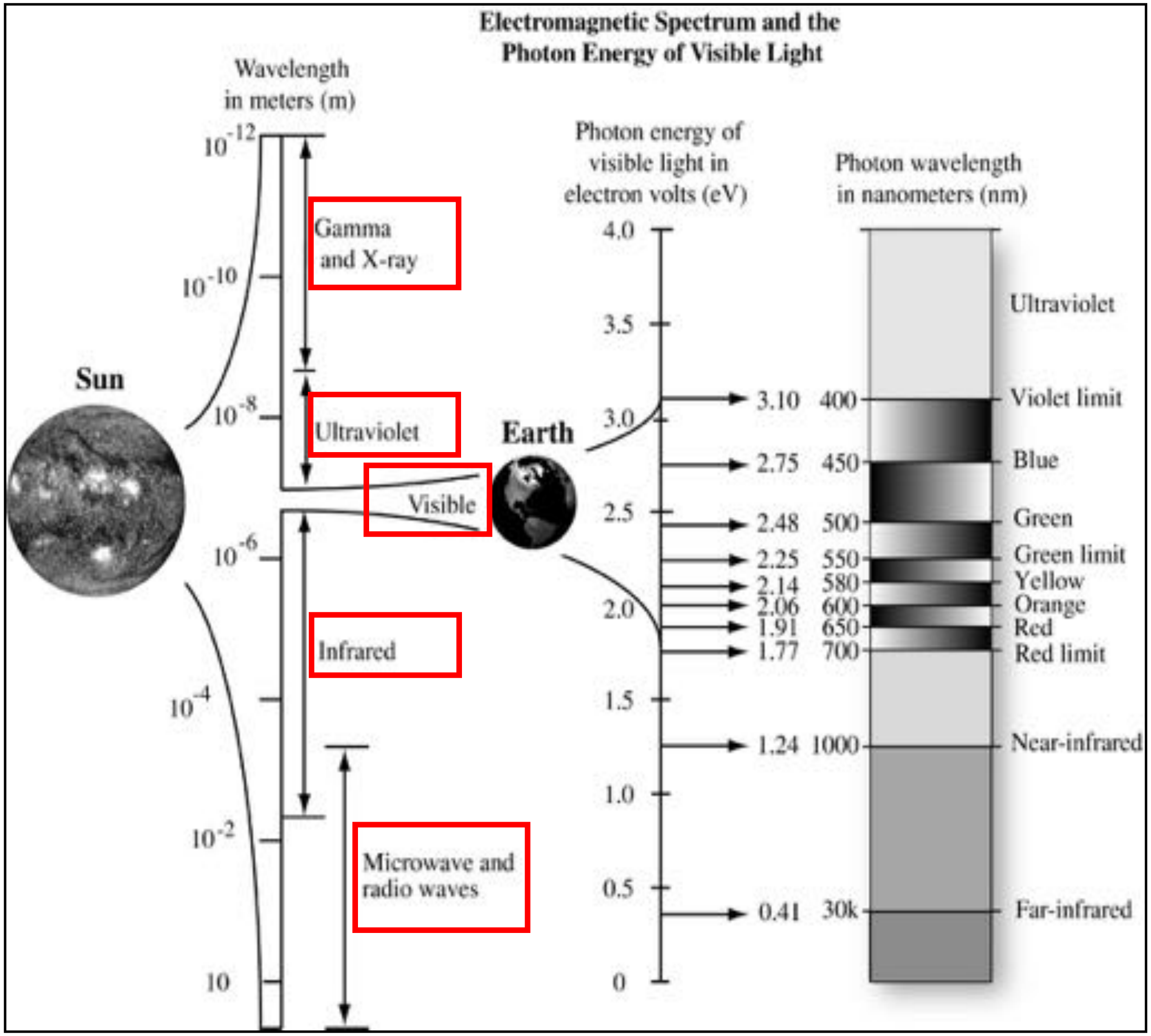
- ❑ Thermal emission by the ocean surface
  - --- Thermal infra red
  - --- Microwaves



- ❑ Energy source on the satellite
  - --- Microwaves (Radar)
  - --- Visible (Lidar)

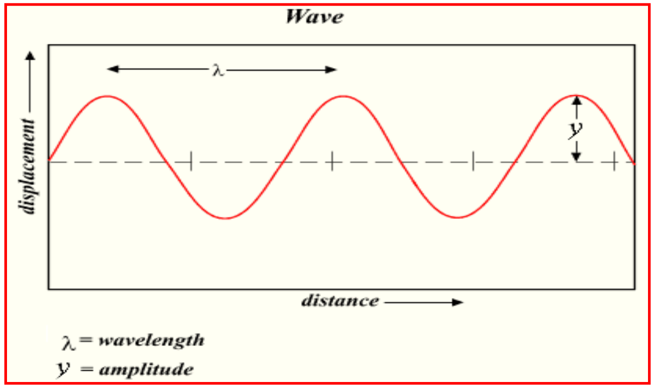


Electromagnetic Spectrum



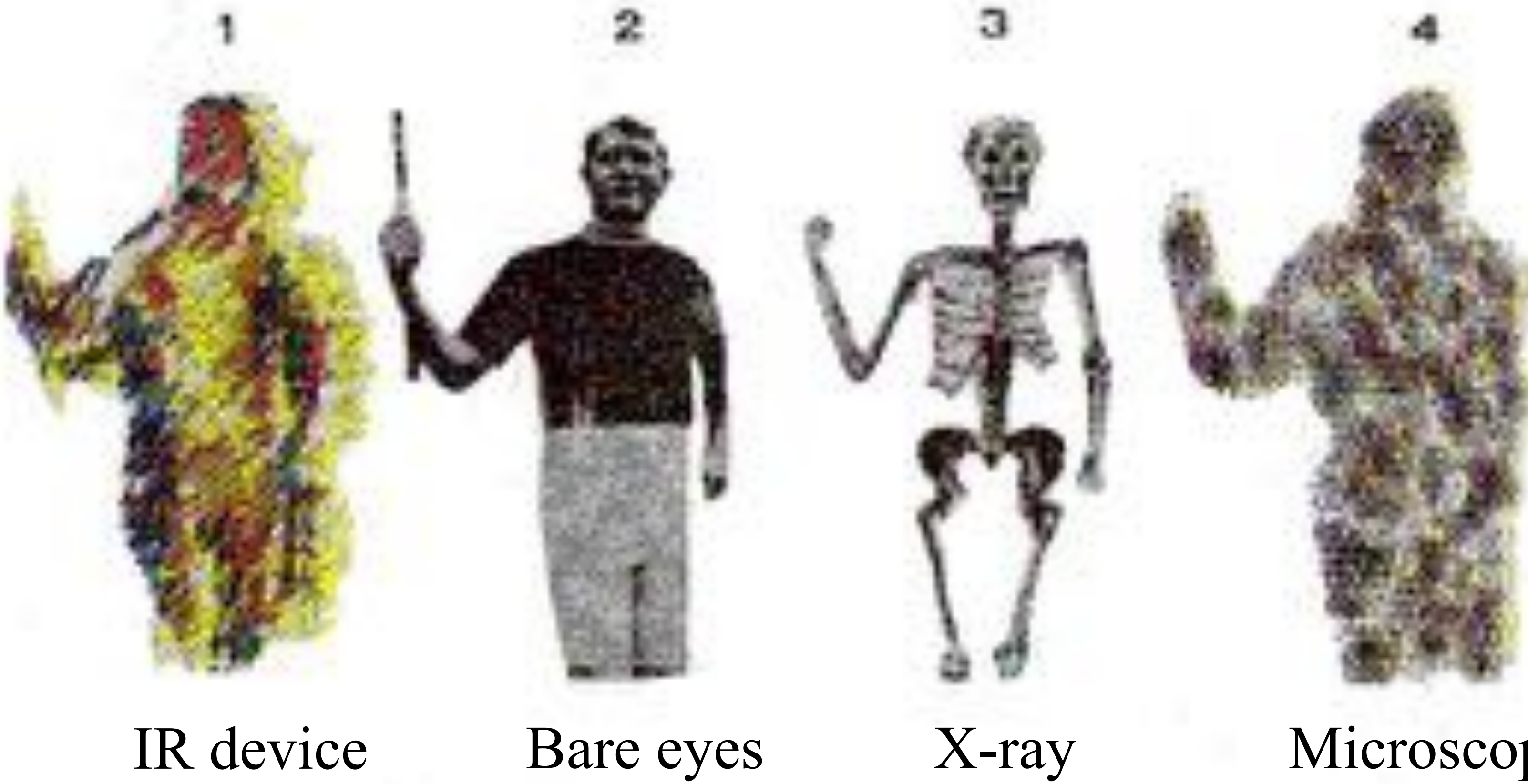
The Sun produces a *continuous spectrum* of energy that continually bathe the Earth in energy.

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



Electromagnetic radiation behaves in most circumstances as waves and can thus be characterized as waves.

Electromagnetic Spectrum

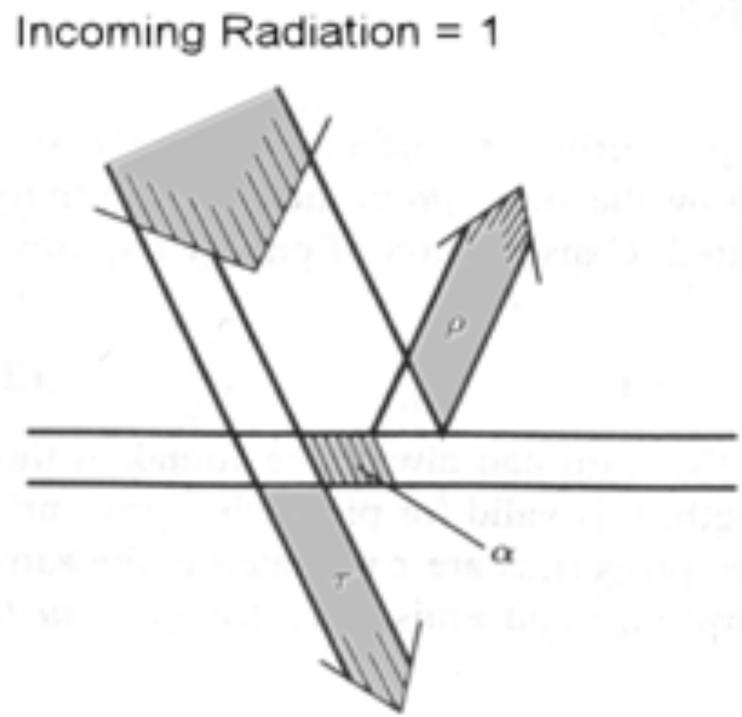


A human detected by different instruments

Thermal radiation

- All matter above absolute zero (0 Kelvin = -273°C = -459.4°F) emits radiant energy in form of electromagnetic waves.

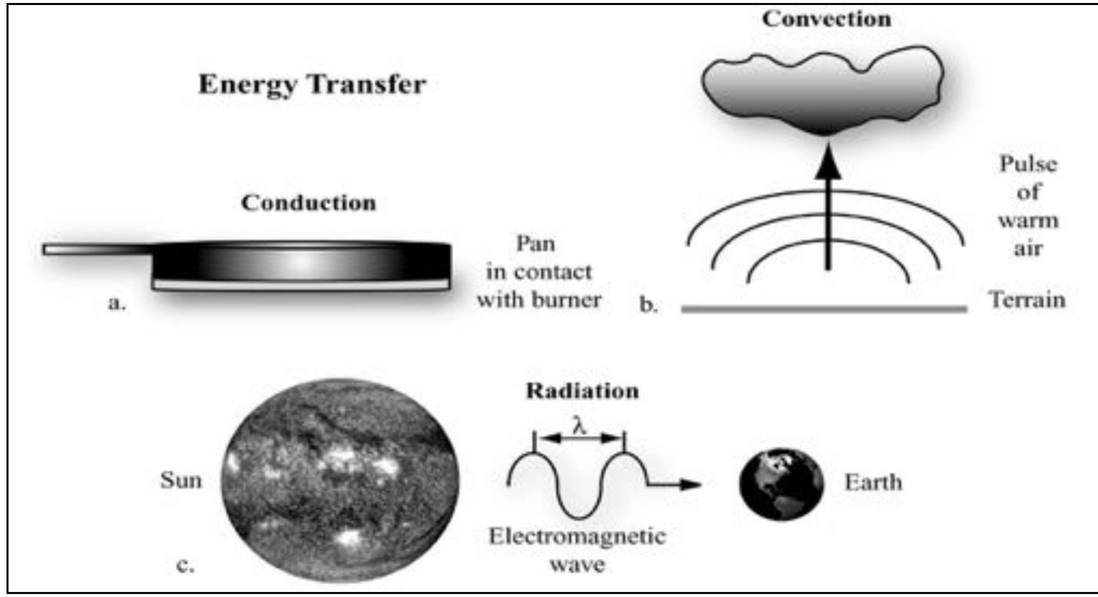
$$\alpha + \tau + \rho = 1$$



3 key additional properties of surfaces which control the radiation heat transfer of a surface:

- absorptivity α,
- transmissivity *T* and
- reflectivity ρ.

How is Energy Transferred?



Energy may be transferred 3 ways: *conduction*, *convection*, and *radiation*:

(a) conduction: one body (molecule or atom) transfers its kinetic energy to another by colliding with it (direct contact).

(b) ***convection****:* the KE of a body is transferred from one place to another by physically moving the bodies. E.g. the convectional heating of air in the atmosphere in the early afternoon

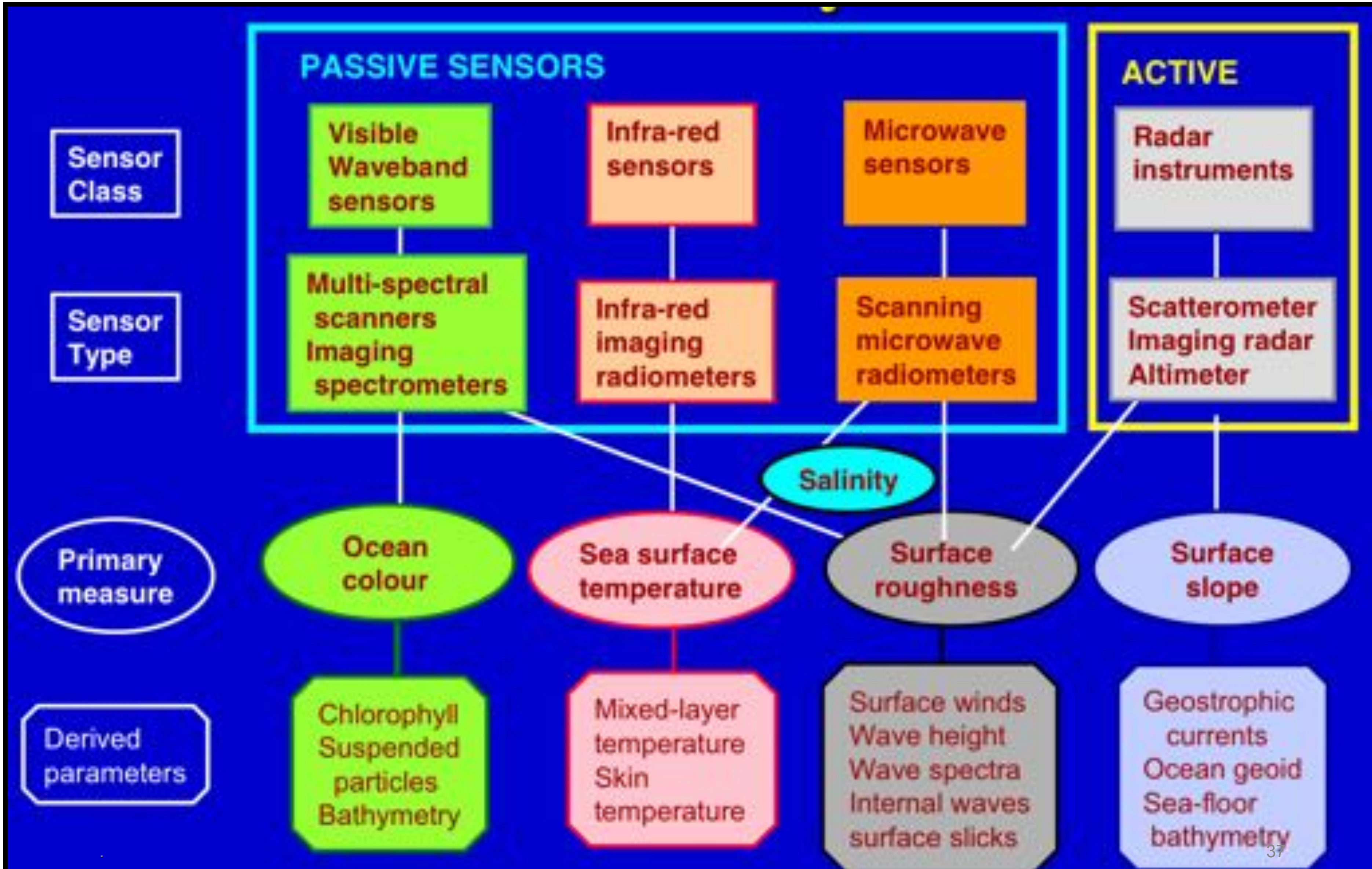
(c) Electromagnetic energy in the form of *electromagnetic* waves (***radiation***) transmitted through the vacuum of space from the Sun to the Earth.

Active and passive sensors

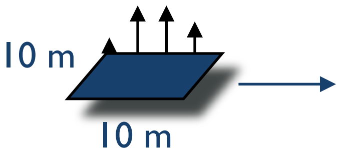
Active sensors (microwave) create their own radiation with which to illuminate the target, and then observe the nature of the reflected signal, in contrast to **passive** (sun, IR and visible wavelength) sensors which rely on naturally occurring radiation.

Passive sensors	**Wavelength**	**Information**
Visible wavelength radiometers	400 nm - 1 μm	Solar radiation reflected by Earth surface
Infrared (IR) radiometers	about 10 μm	Thermal emission of the Earth
Microwave radiometers	1.5 - 300 mm	Thermal emission of the Earth in the microwave
Active devices		
Altimeters	3 - 30 GHz	Earth surface topography
Scatterometers	3 - 30 GHz	Sea surface roughness
Synthetic aperture radars	3 - 30 GHz	Sea surface roughness and movement

A summary of sensor types & what they measure

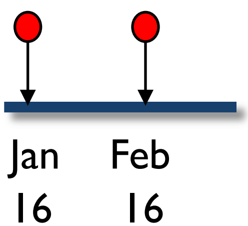


Remote Sensor Resolution Considerations

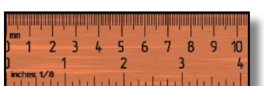


- Spatial - the size of the field-of-view, e.g. 10 × 10 m.

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



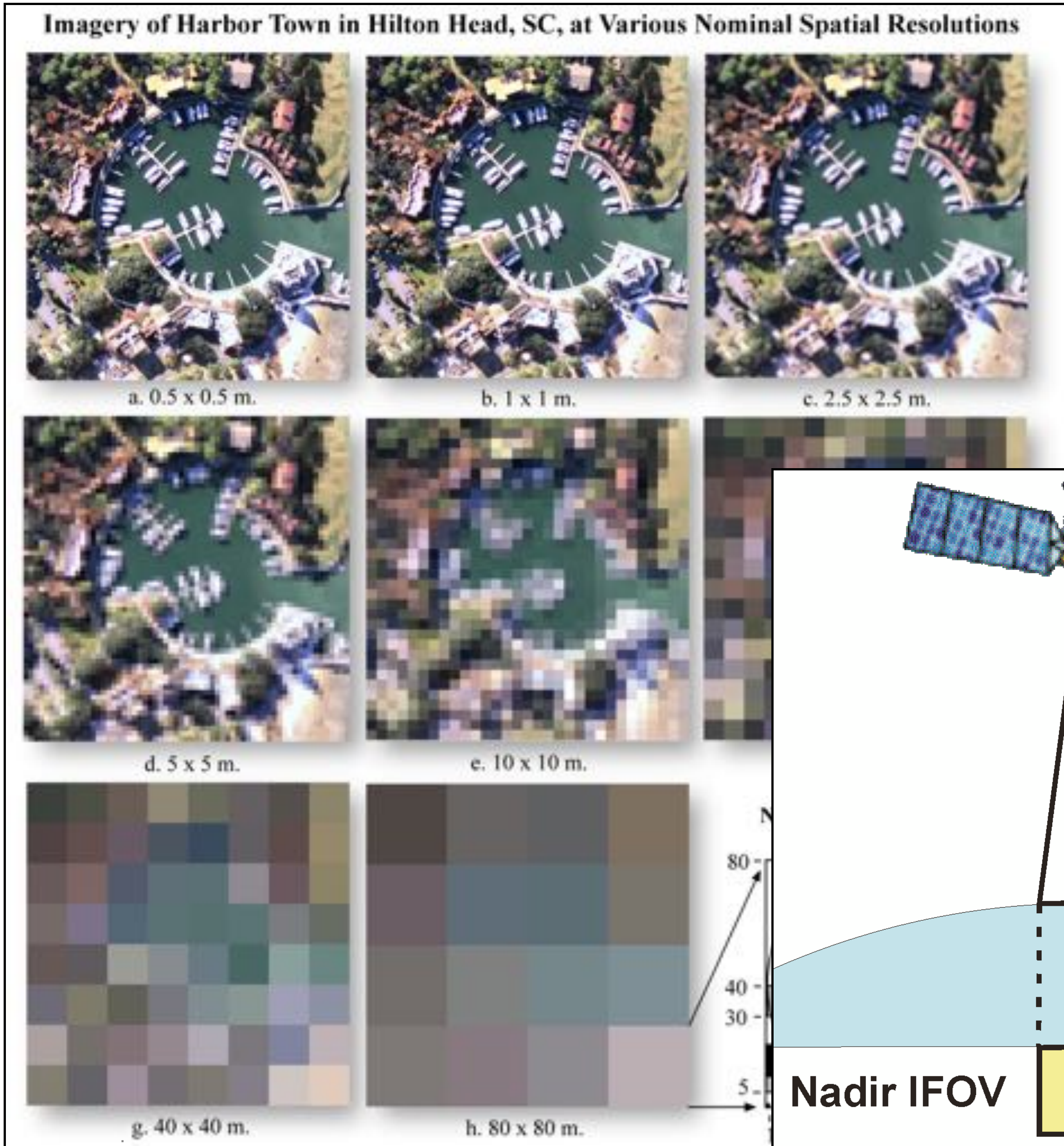
- Temporal - how often the sensor acquires data, e.g., every 30 days.

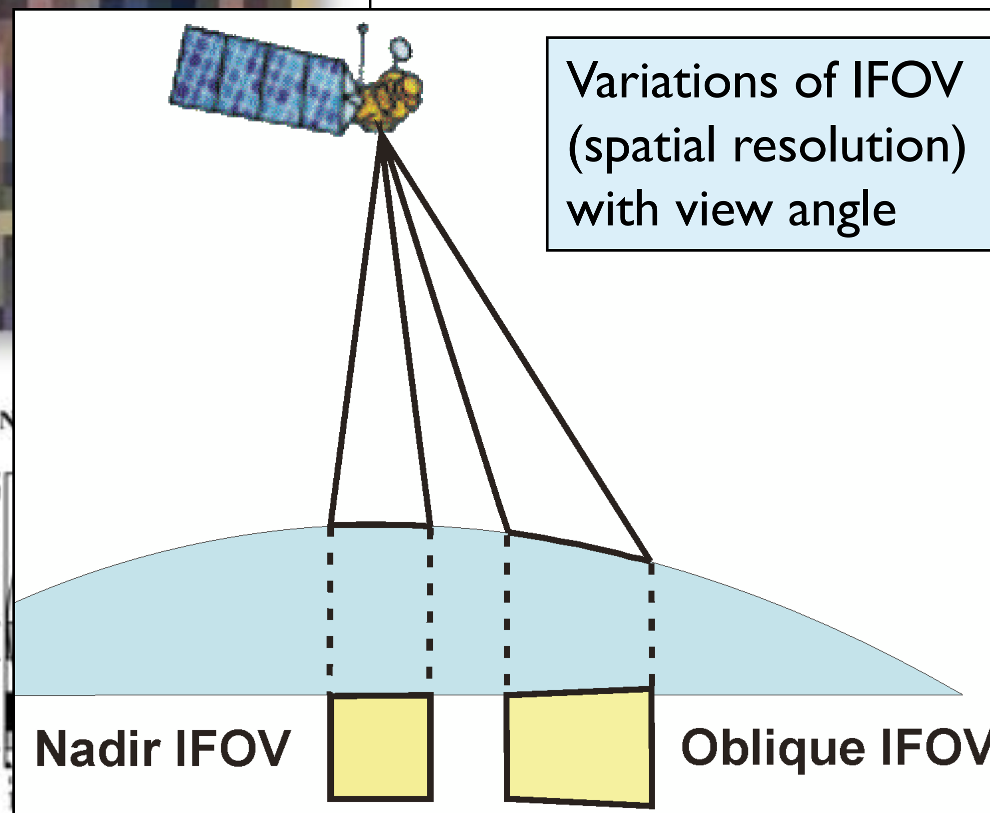


8-bit
(0 - 255)
10-bit
(0 - 1023)

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

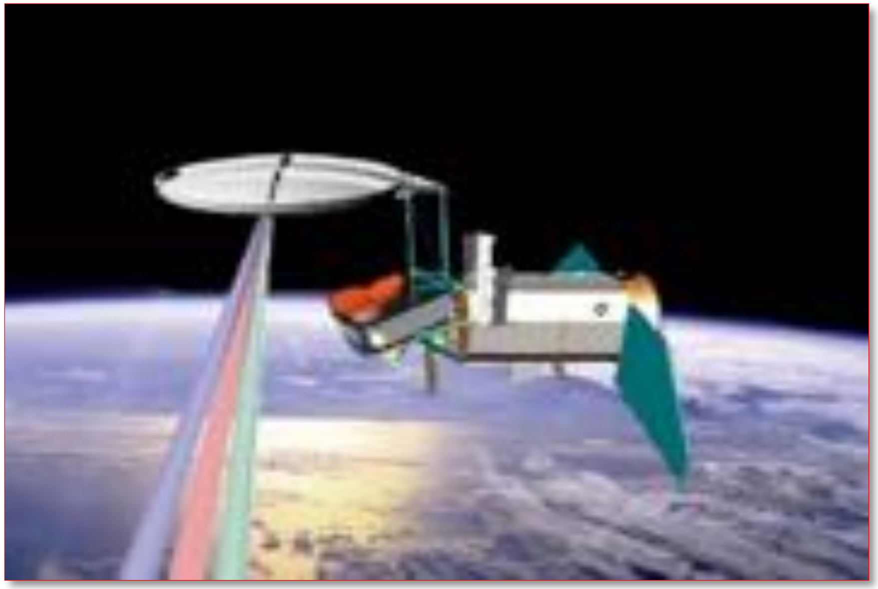
Spatial Resolution



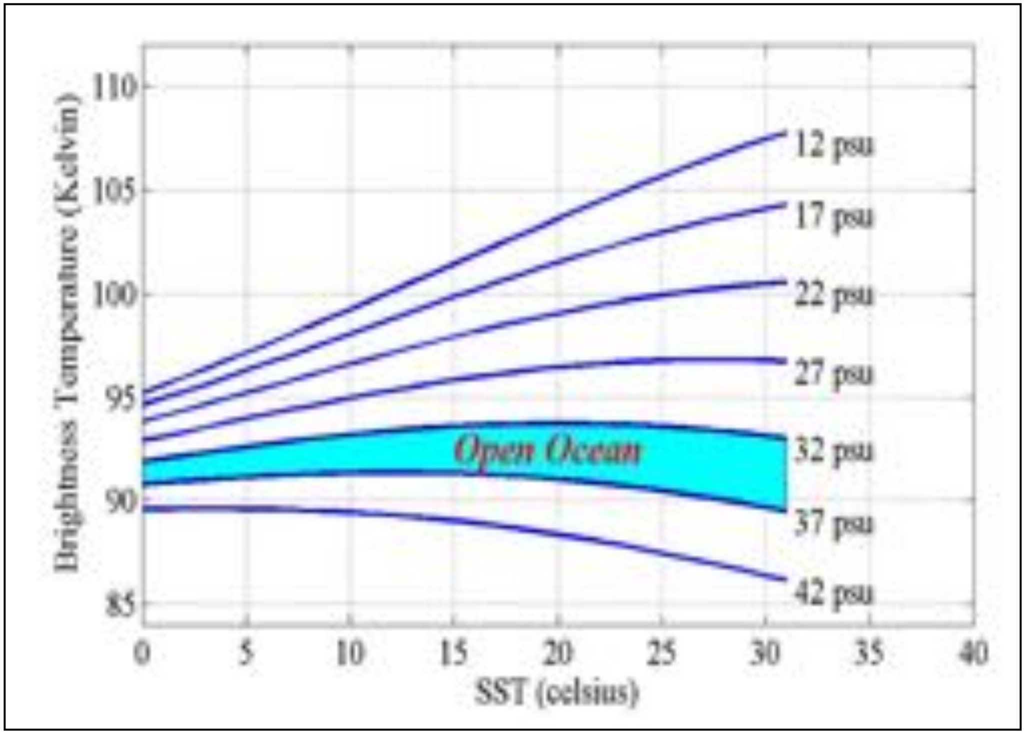


Variations of IFOV (spatial resolution) with view angle

Salinity sensing



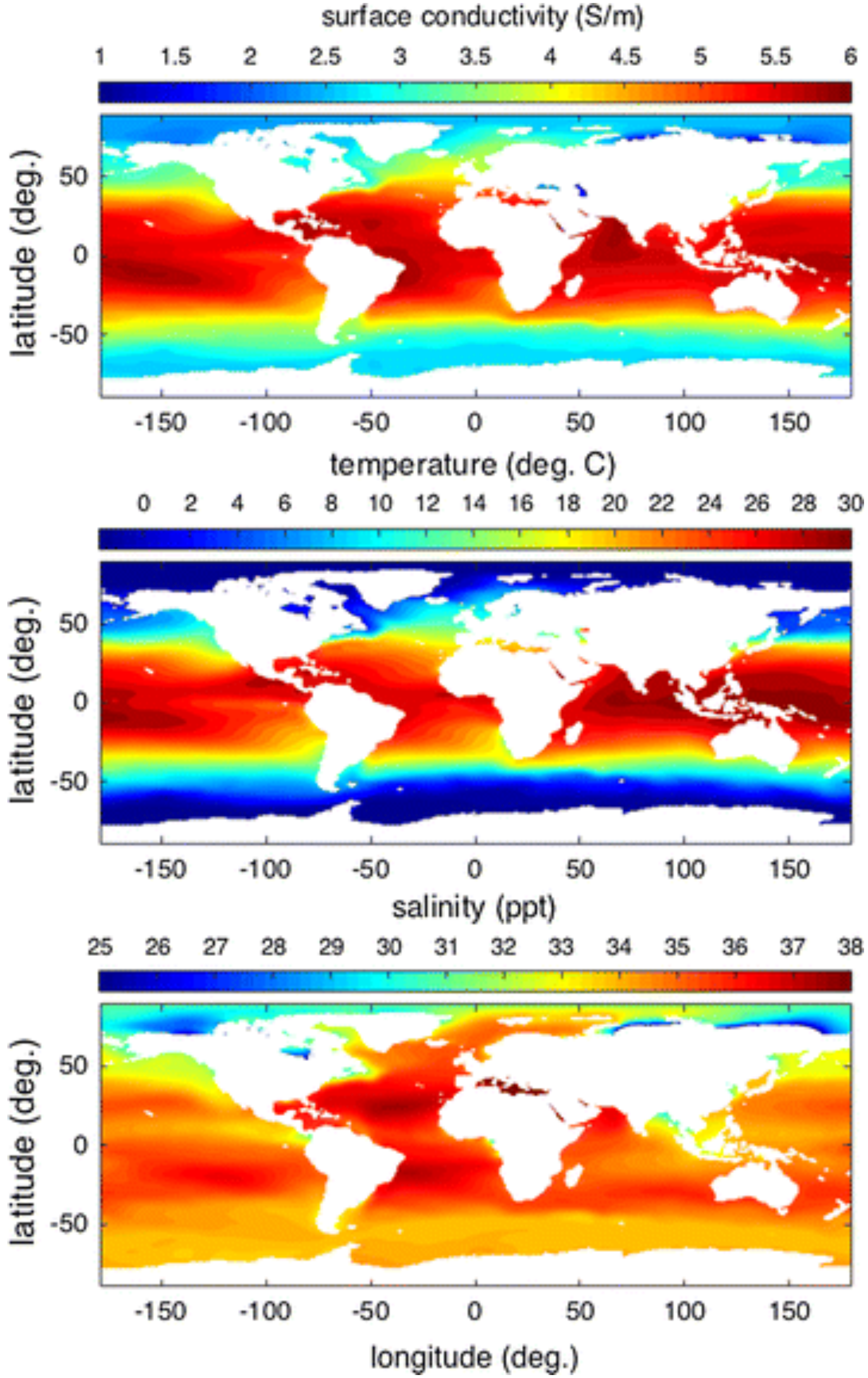
The Technology



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

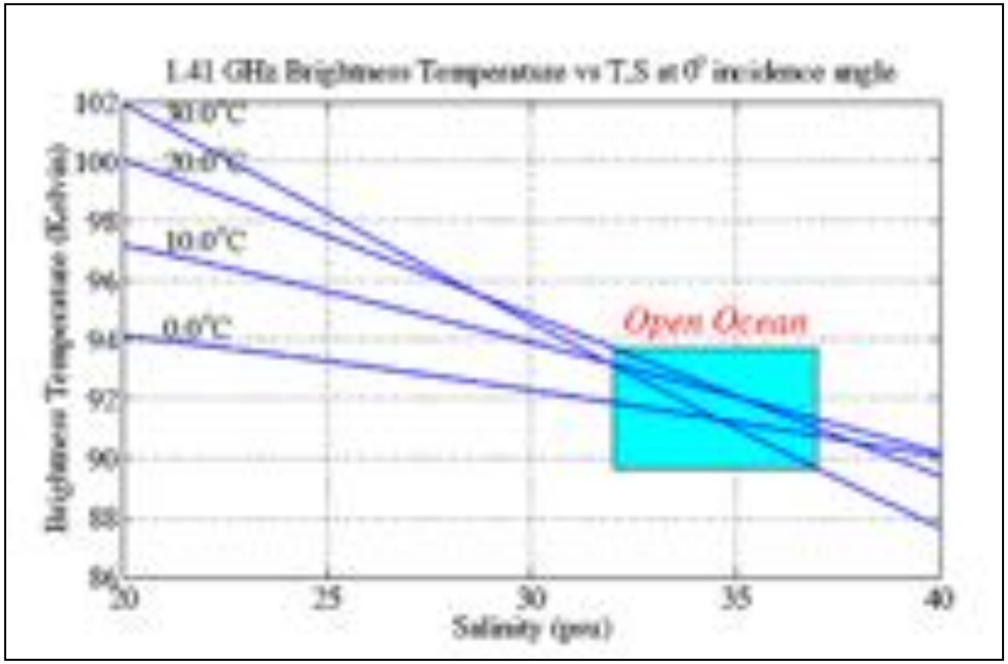
- L-Band microwave (passive) radiometer
- 1.413 GHz
- Radiometer measures the brightness temperature (T_b)

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



surface conductivity (S/m)
1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6
latitude (deg.)
50
0
-50
-150 -100 -50 0 50 100 150
temperature (deg. C)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
latitude (deg.)
50
0
-50
-150 -100 -50 0 50 100 150
salinity (ppt)
25 26 27 28 29 30 31 32 33 34 35 36 37 38
latitude (deg.)
50
0
-50
-150 -100 -50 0 50 100 150
longitude (deg.)

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)

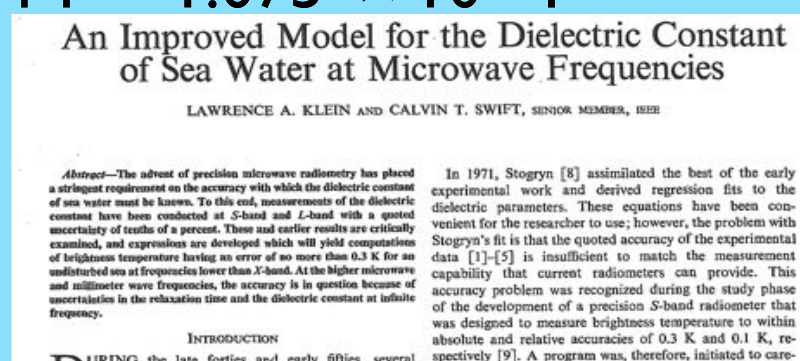
ε = Relative Dielectric Constant

= ε(freq, S, T)

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

ε_r = 88.045 - 0.4147 T + 6.295 × 10-4 T^2 +1.075 × 10^{-5} T^3

(Klein and Swift, 1977)



An Improved Model for the Dielectric Constant of Sea Water at Microwave Frequencies

LAWRENCE A. KLEIN AND CALVIN T. SWIFT, SENIOR MEMBER, IEEE

Abstract—The advent of precision microwave radiometry has placed a stringent requirement on the accuracy with which the dielectric constant of sea water must be known. To this end, measurements of the dielectric constant have been conducted at *S*-band and *L*-band with a quoted uncertainty of tenths of a percent. These and earlier results are critically examined, and expressions are developed which will yield computations of brightness temperature having an error of no more than 0.3 K for an undisturbed sea at frequencies lower than *X*-band. At the higher microwave and millimeter wave frequencies, the accuracy is in question because of uncertainties in the relaxation time and the dielectric constant at infinite frequency.

INTRODUCTION

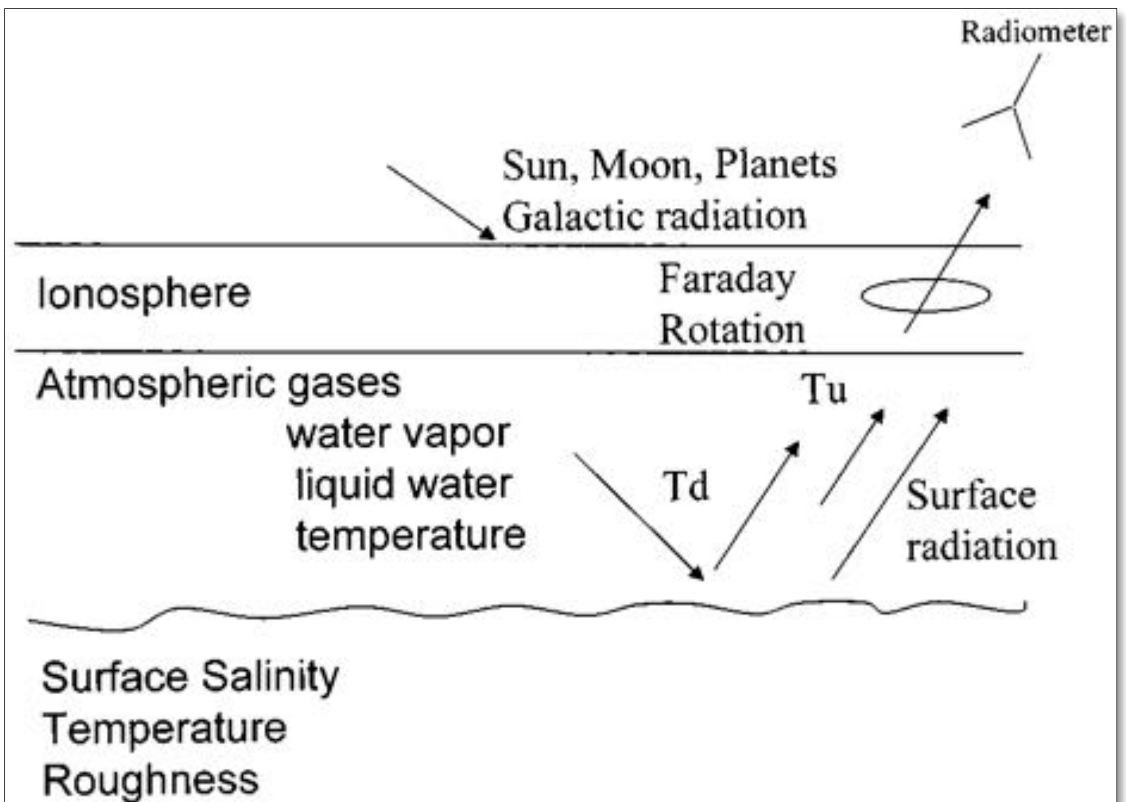
DURING the late forties and early fifties, several

In 1971, Stogryn [8] assimilated the best of the early experimental work and derived regression fits to the dielectric parameters. These equations have been convenient for the researcher to use; however, the problem with Stogryn's fit is that the quoted accuracy of the experimental data [1]–[5] is insufficient to match the measurement capability that current radiometers can provide. This accuracy problem was recognized during the study phase of the development of a precision *S*-band radiometer that was designed to measure brightness temperature to within absolute and relative accuracies of 0.3 K and 0.1 K, respectively [9]. A program was, therefore, initiated to carefully measure the dielectric constant of sea water at 2.65

The Technology

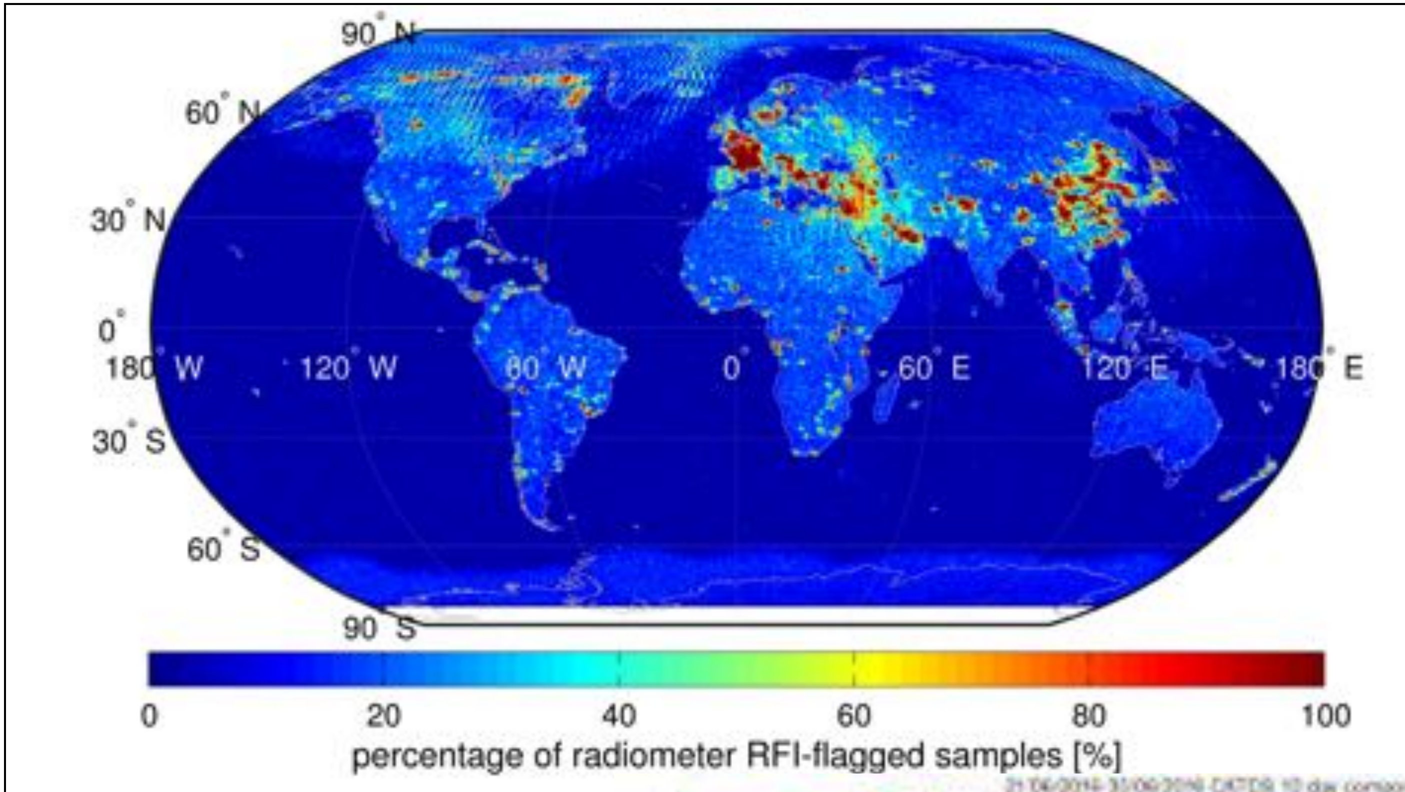
Error sources:

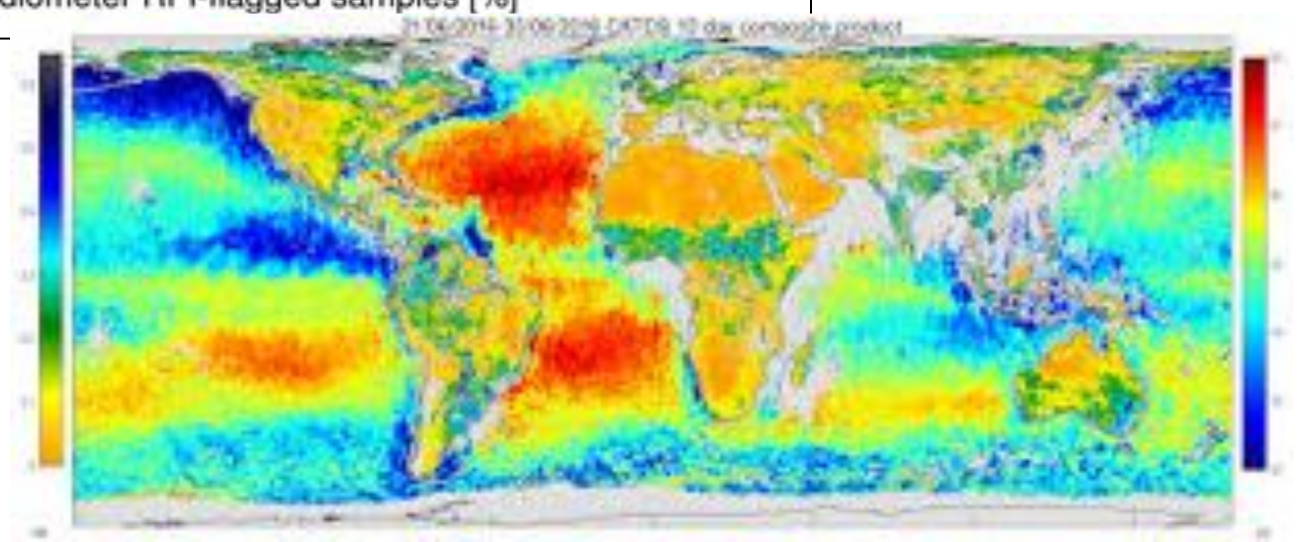
- solar reflection
- atmospheric oxygen
- galactic noises
- SST
- wind speed (sea surface roughness)



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

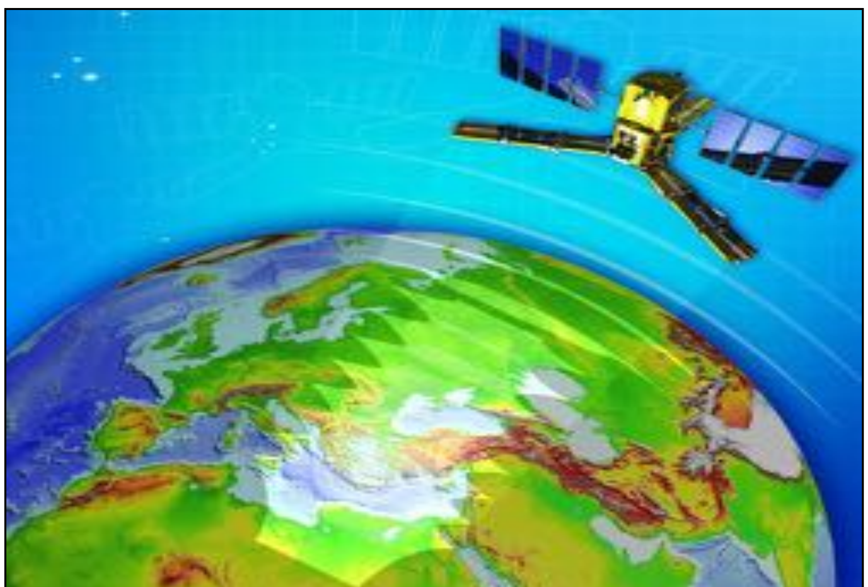
Radio Frequency Interference (RFI)



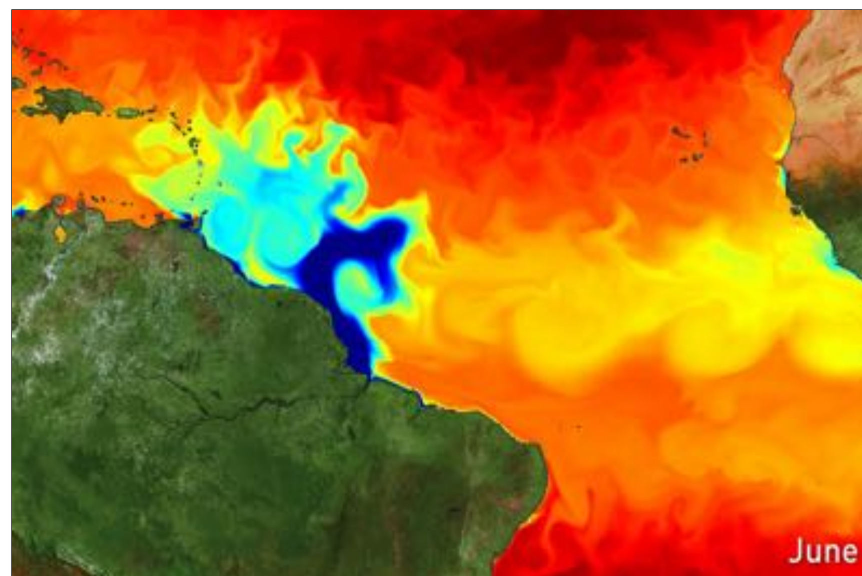


Soil Moisture and Ocean Salinity (SMOS)

- 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



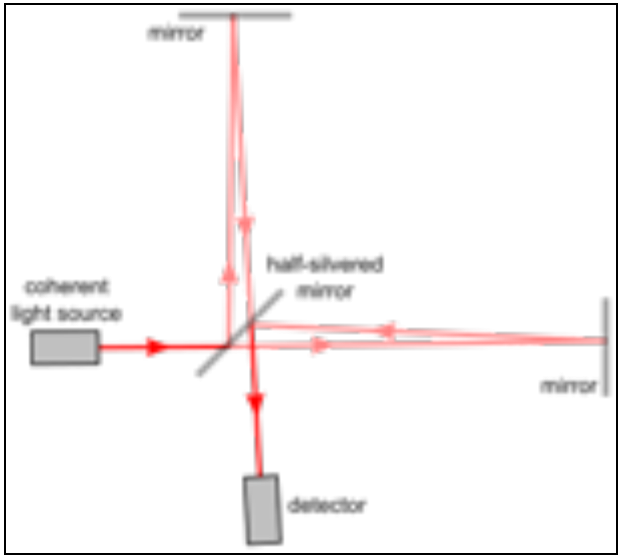
The SMOS satellite

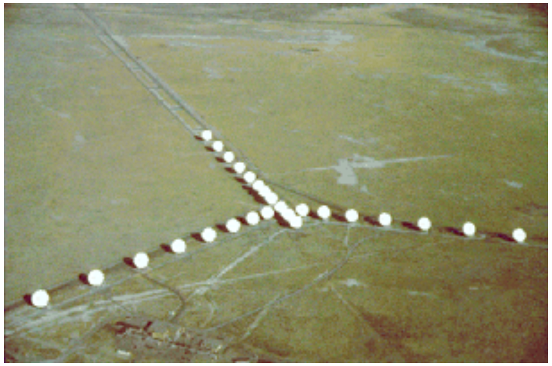


Amazon freshwater plume

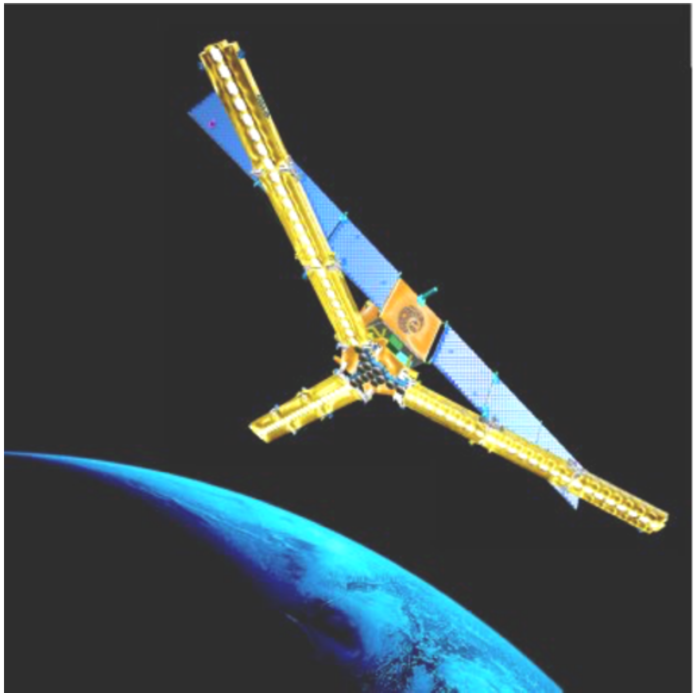
Technical Concept

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)



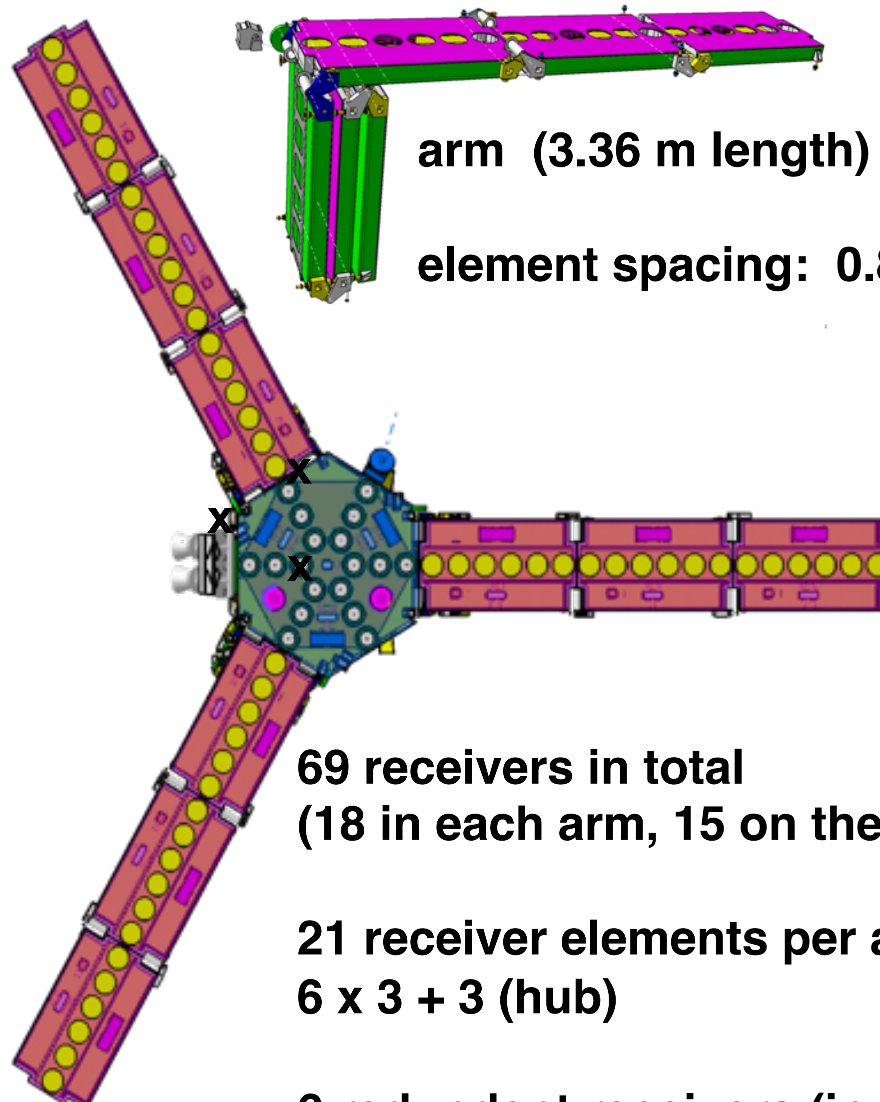
Technical Concept

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

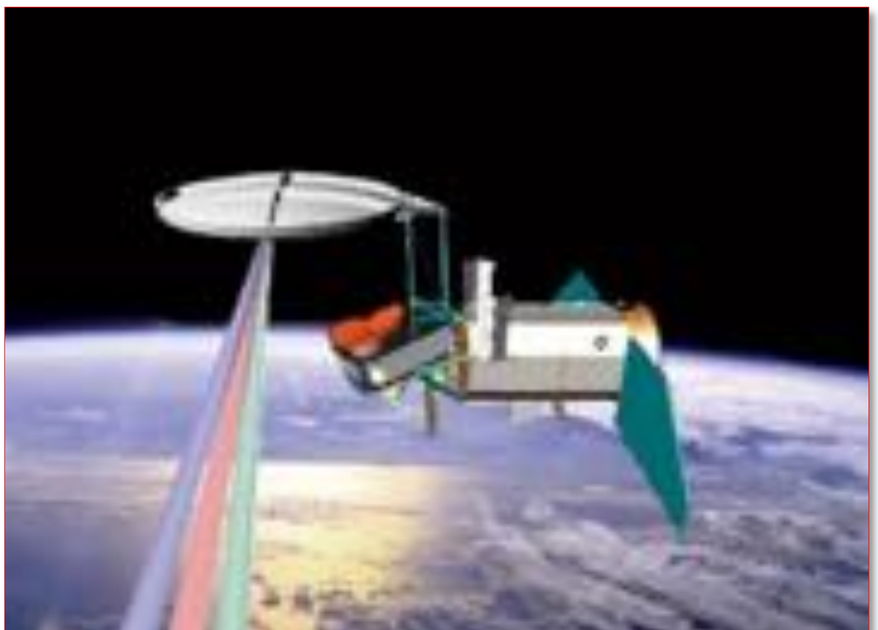
69 receivers in total
(18 in each arm, 15 on the hub)

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

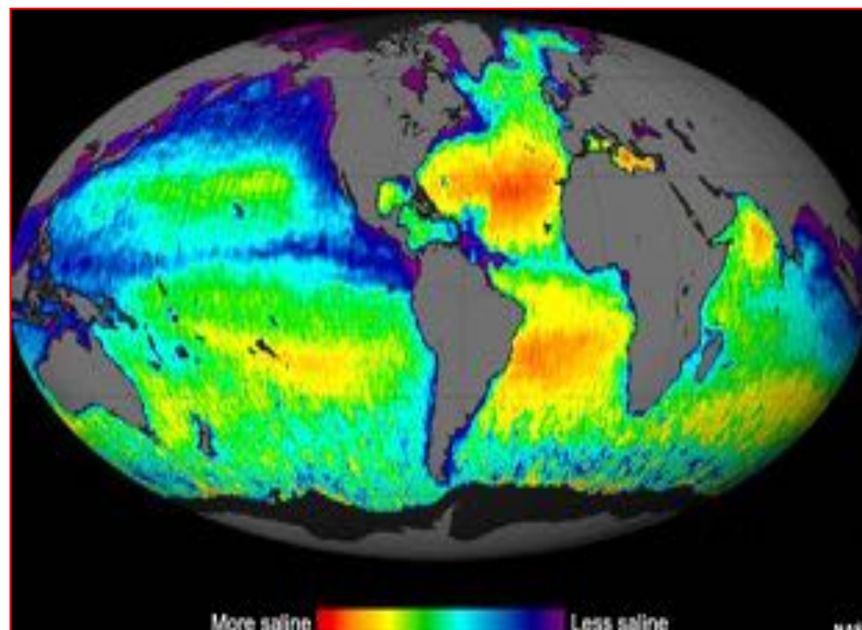
6 redundant receivers (in hub)

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

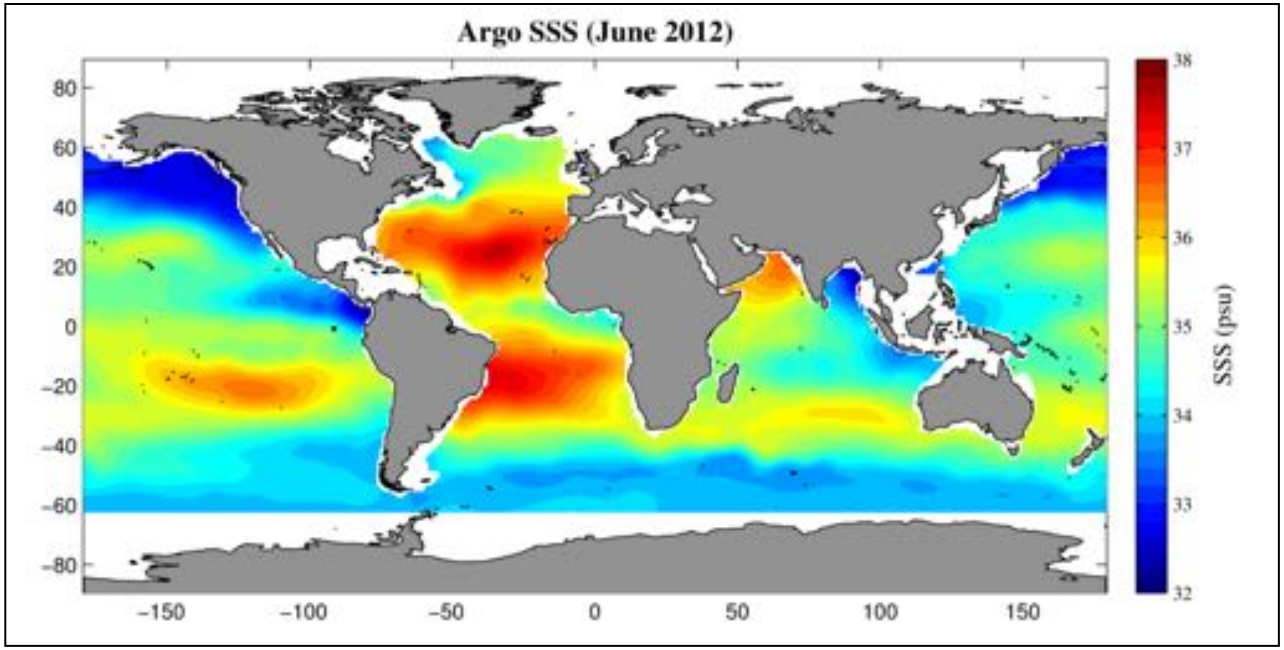


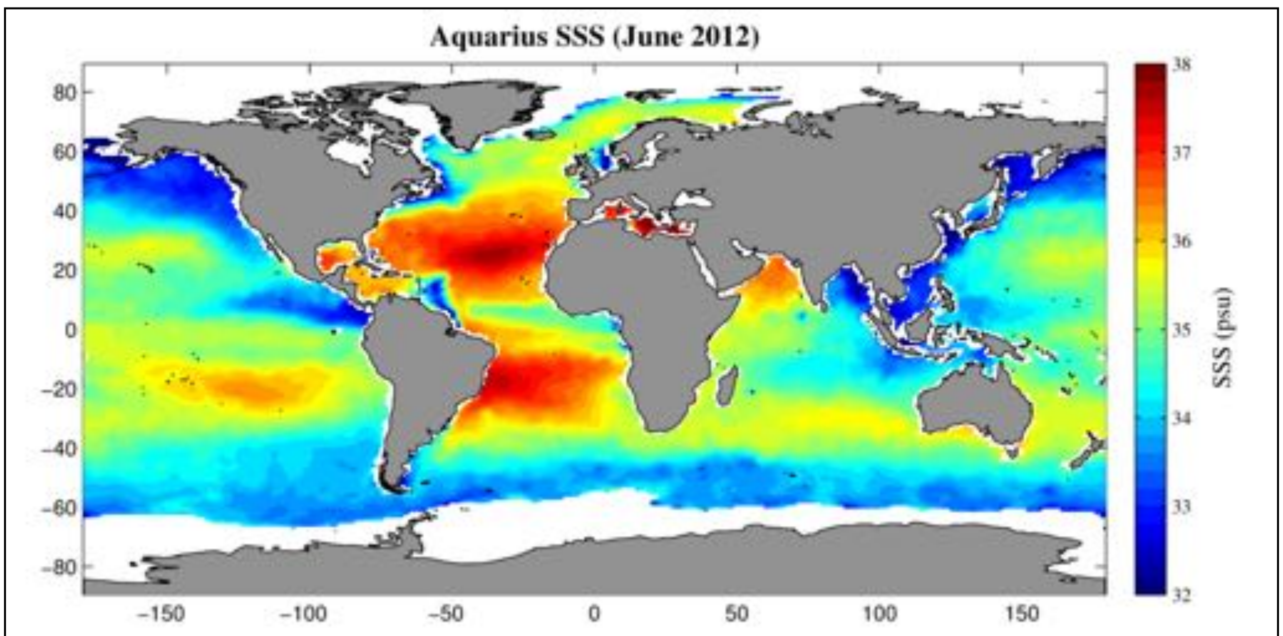
Aquarius satellite in orbit



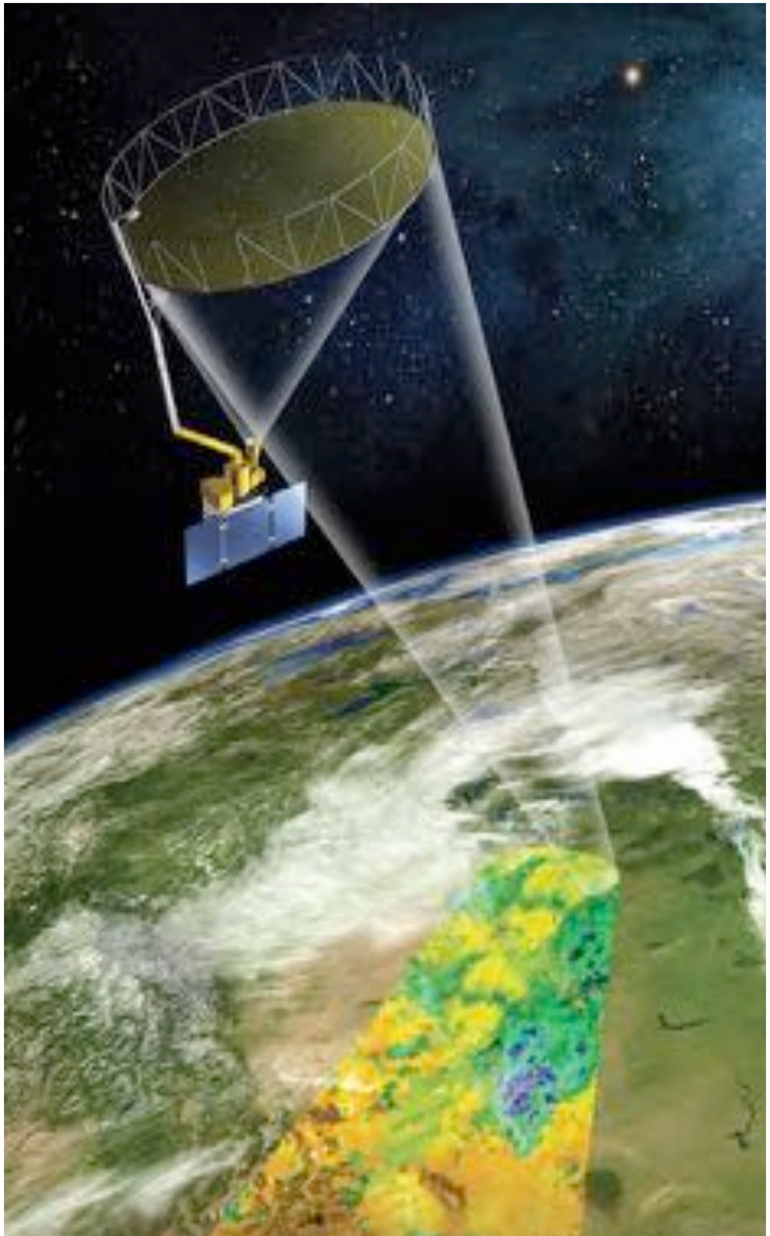
Aquarius global mean SSS

Global salinity pattern





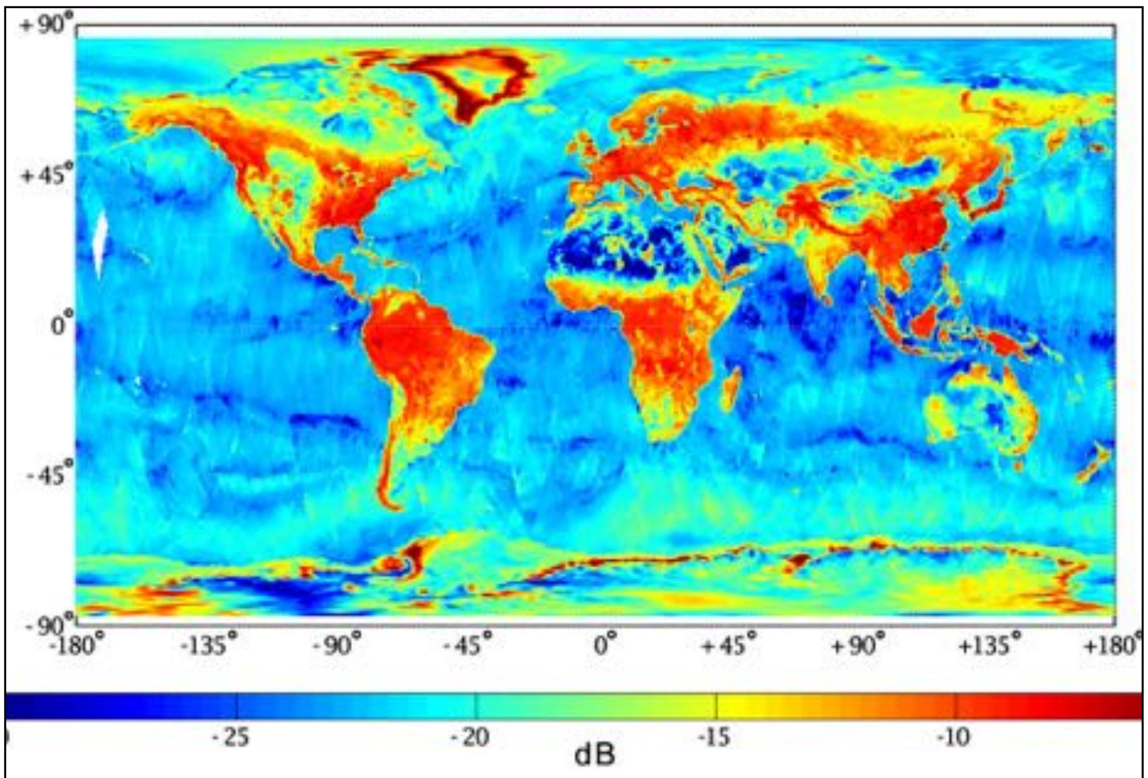
SMAP (Soil Moisture Active Passive)



- 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.