-The SMOS Mission-

N.REUL
French Research Institute for the Exploration of the Sea
Oceanography from Space Laboratory

Outline

- Why ?
- How ?
- So What ?
- Aftermath

Ifremer

esa

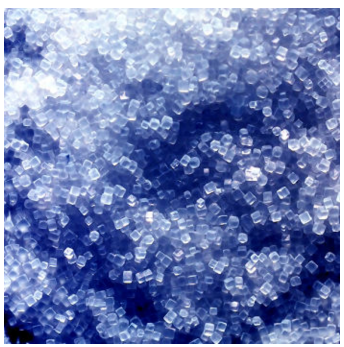
Why?
Why about salinity ?
And
Why about SMOS ?

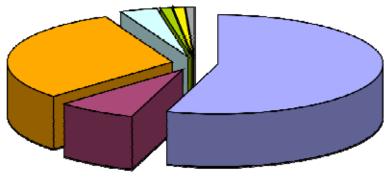
Salinity of the Ocean: What do we know about it ?

What is ocean salinity ?

Ocean salinity S≡ ionic salt concentration in sea water
At the sea surface it is referred to as “SSS” (Sea Surface Salinity)

Unity = PSU (Practical Salinity Unit)
1 PSU≈ 1 g/kg.





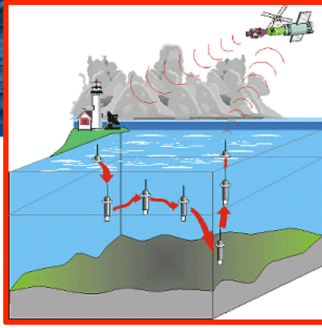
Chloride (Cl-):	**19 g**
Sodium (Na+):	**11 g**
Sulphate (SO4--):	**3 g**
Magnesium (Mg++):	**1.5 g**
Calcium (Ca++):	**0,35 g**
Potassium (K+):	**0,35 g**
Others :	**0,00.. g**

Total ≈ 35 g/kg

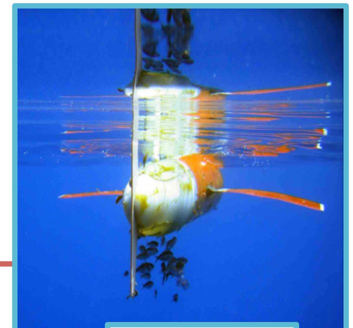
(Mean chemical composition)

99% of oceanic waters have salinity between 33.1 and 37.2:
=>a global variation in salt concentration between 3.31% and 3.72% !

In Situ measurements of S



Profilers from the Argo network



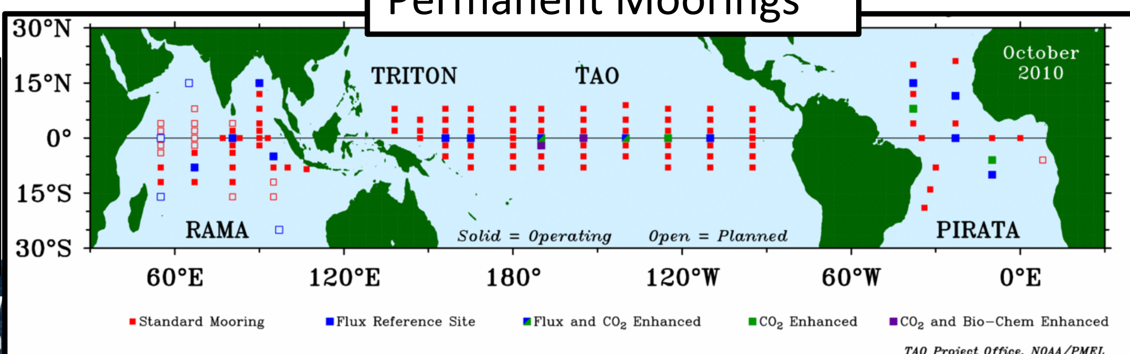
Gliders

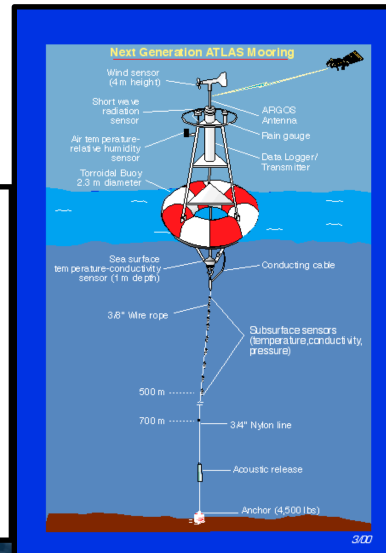
Surface 'Drifters'

Equipped Mammals

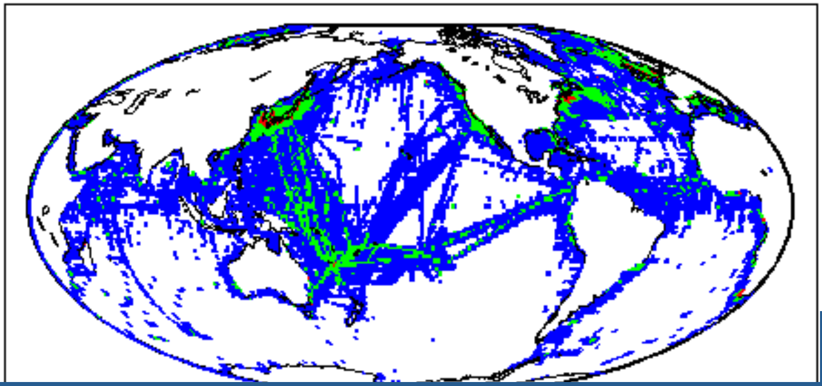
Thermo-salinographs
Installed onboard reasearch
Vessels and ships of opportunity

Permanent Moorings





Historical Density of surface observations 1874-2002



White - N < 10
Blue - 10 < N < 100
Green- 100 < N < 1000
Red - 1000 < N

F. Bingham et al, 2002

1.3 million SSS observations distributed over the global ocean since 125 years:

✓ No data in 27% elementary oceanic 1° x1° area, not accounting for arctic zones.

✓70% of these surfaces present at most 10 historical observations

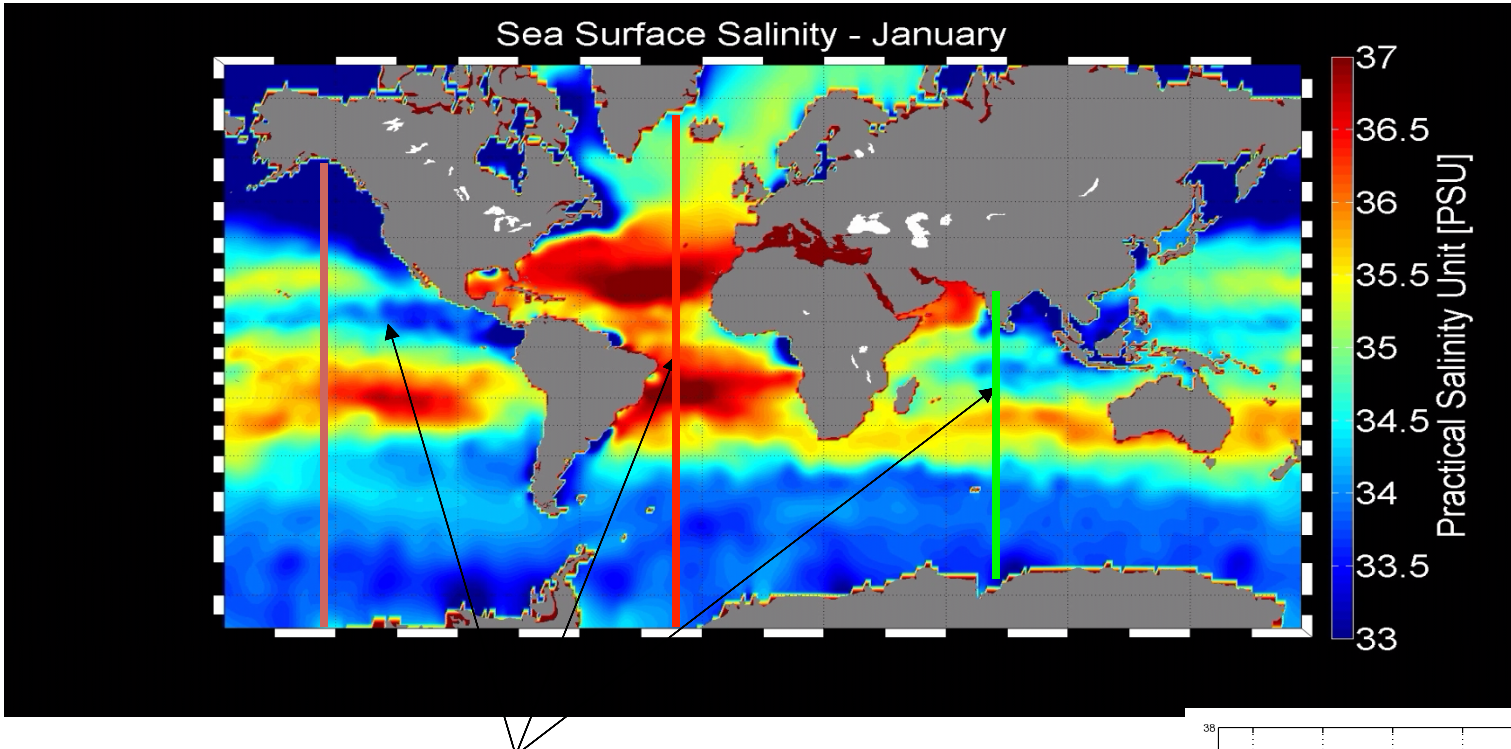
✓28% of all observations were sampled in the coastal domain

✓ Up to 1960, there was no more than 10,000 observations/year ⇔ 1 observation per 4°X4° cell

✓Since 2002, very net increase in the density of measurements (ARGO network)

Global distribution of the SSS

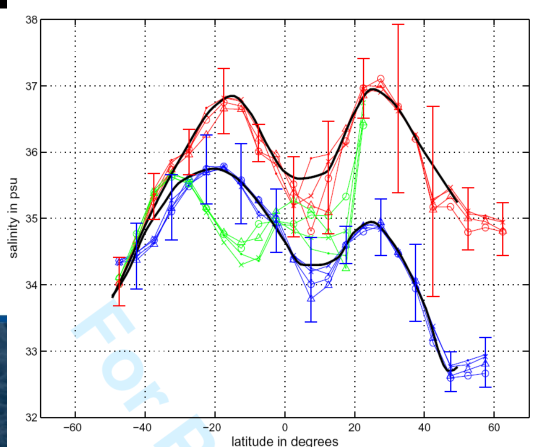
Monthly climatology of the sea surface salinity:



Atlantic Ocean saltier than Pacific and Indian oceans

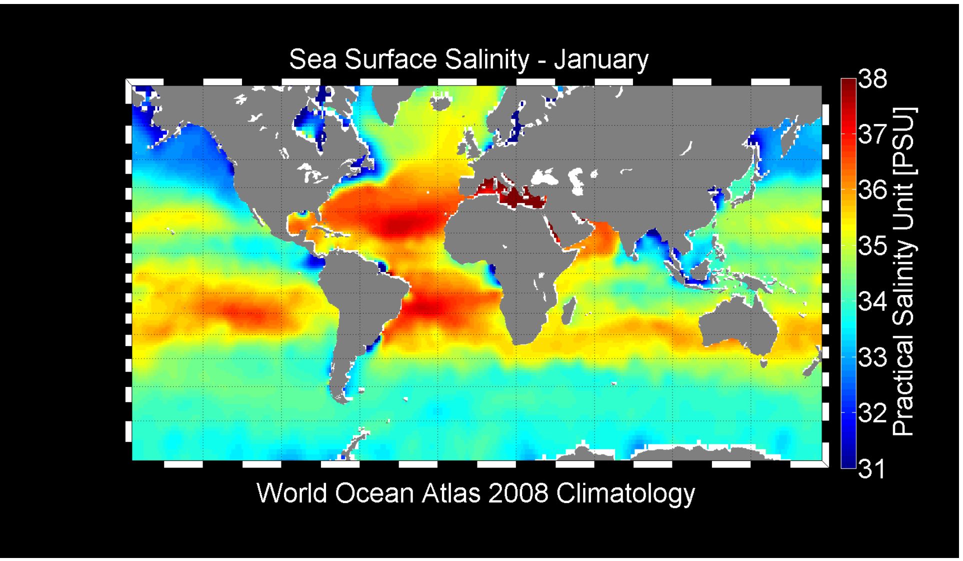
✓ Low variability particularly in the Southern seas and North Pacific

✓But higher variability around large river run off (Amazon Congo, Yang Tse, Ganga..), largest currents (Gulf Stream, kuroshio, Agullas, …) & in the Tropical bands

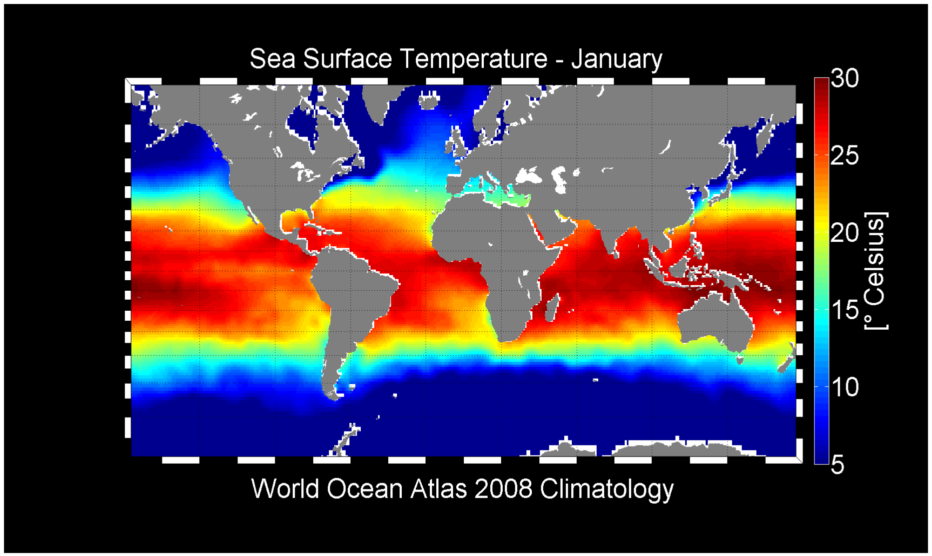


Salt versus temperature at the Ocean Surface

Salinity



Temperature



Global and seasonnal distributions of surface salinity strongly differ from the surface temperature one.
It is because the processes involved and sources responsible for their own variability are different:

➢Ocean are heated in the Tropics and lose heat at higher latitutes

➢Salinity is modified by dilution-concentration processes associated with the fresh water fluxes.
The latter result from the balance between precipitation, evaporation, ice melting/pounding and river run off.

Why Measuring Ocean Salinity From Space ?

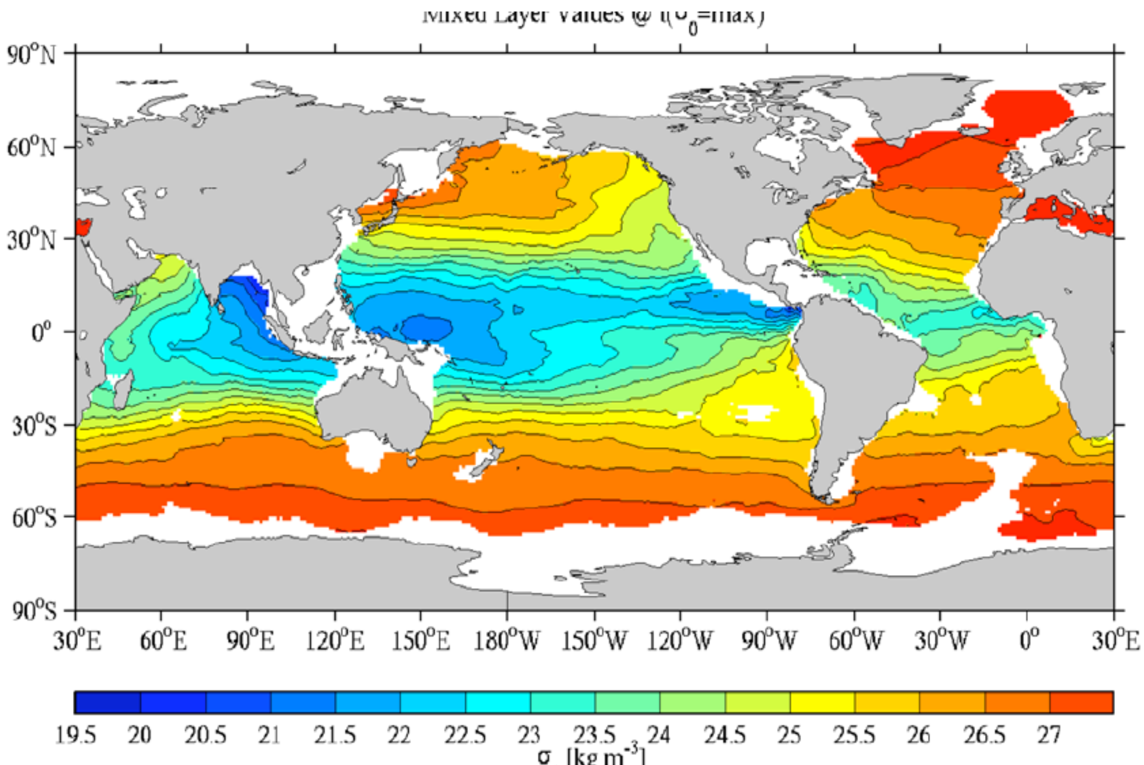
Salinity & Temperature: indicators of water masses thermo-dynamical state

Salinity S & Temperature T are indicators of the water masses density ρ:

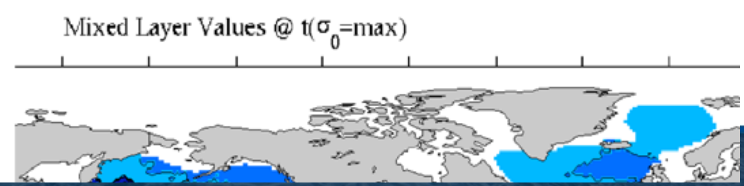
$$\rho_{sw}(S,T) = \rho_{fw}(T) + b(T)S + c(T)S^{3/2} + dS^2$$

« State equation »

Similar to temperature and humidity for the atmosphere

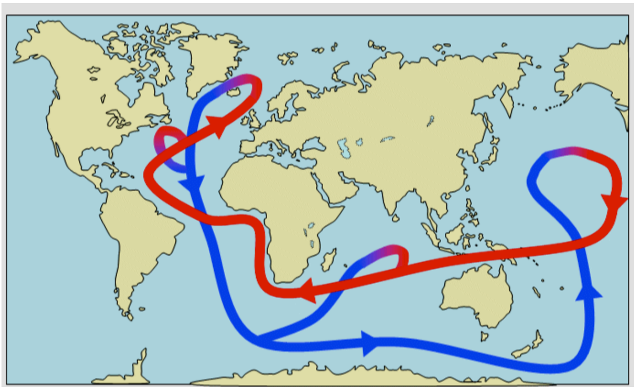


- Denser Poleward
- Equatorial Cold Tongue
- Salty (&Dense) N. Atlantic
- Warm Pool & ITCZ
- Eastern Subtropics
  - Compensating T & S
- Indian Ocean Contrast



The Thermo-Haline Circulation

Idealized global thermohaline circulation (~1000 years)



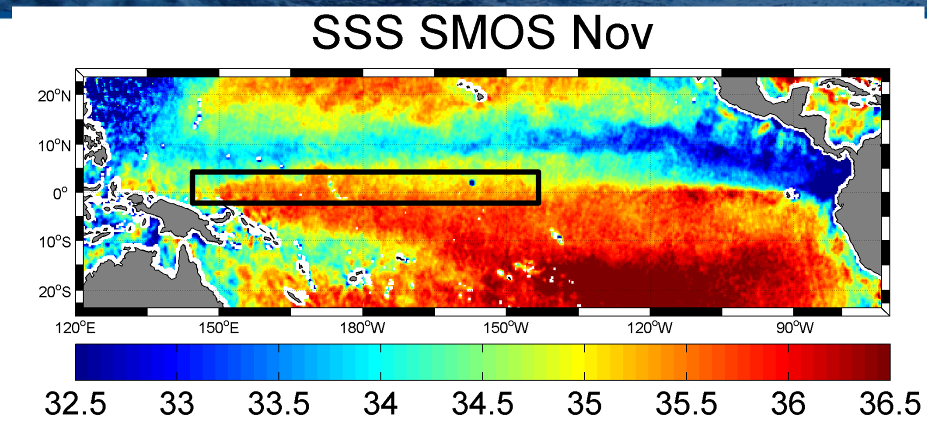
Warm surface currents

Deep cold currents

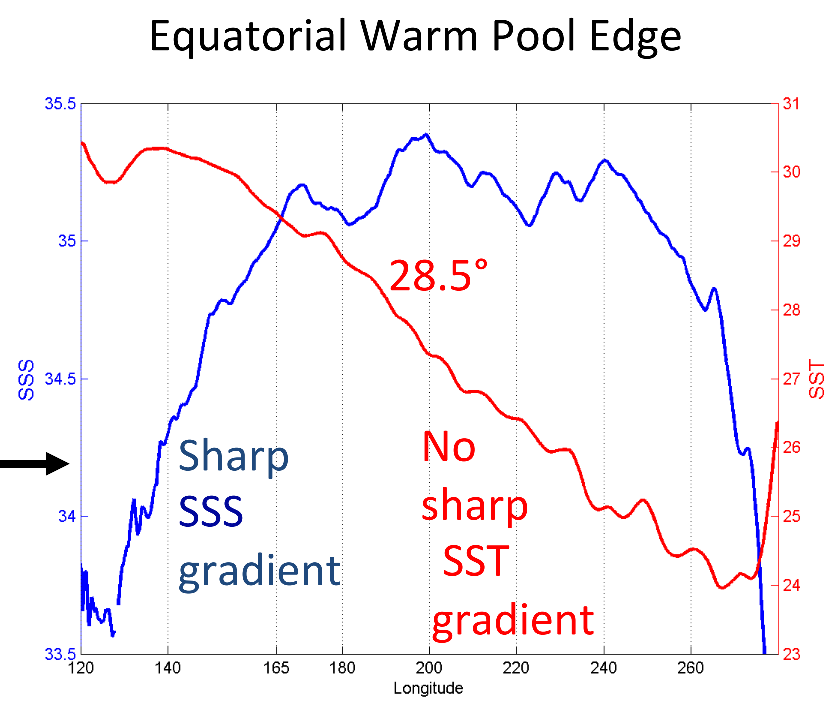
The higher salinity in the Atlantic sustains the oceanic deep overturning circulation

- Conveyor belt . Return period ~1000 years.
- Density differences
- Global scale circulation

Oceanic Fronts Monitoring

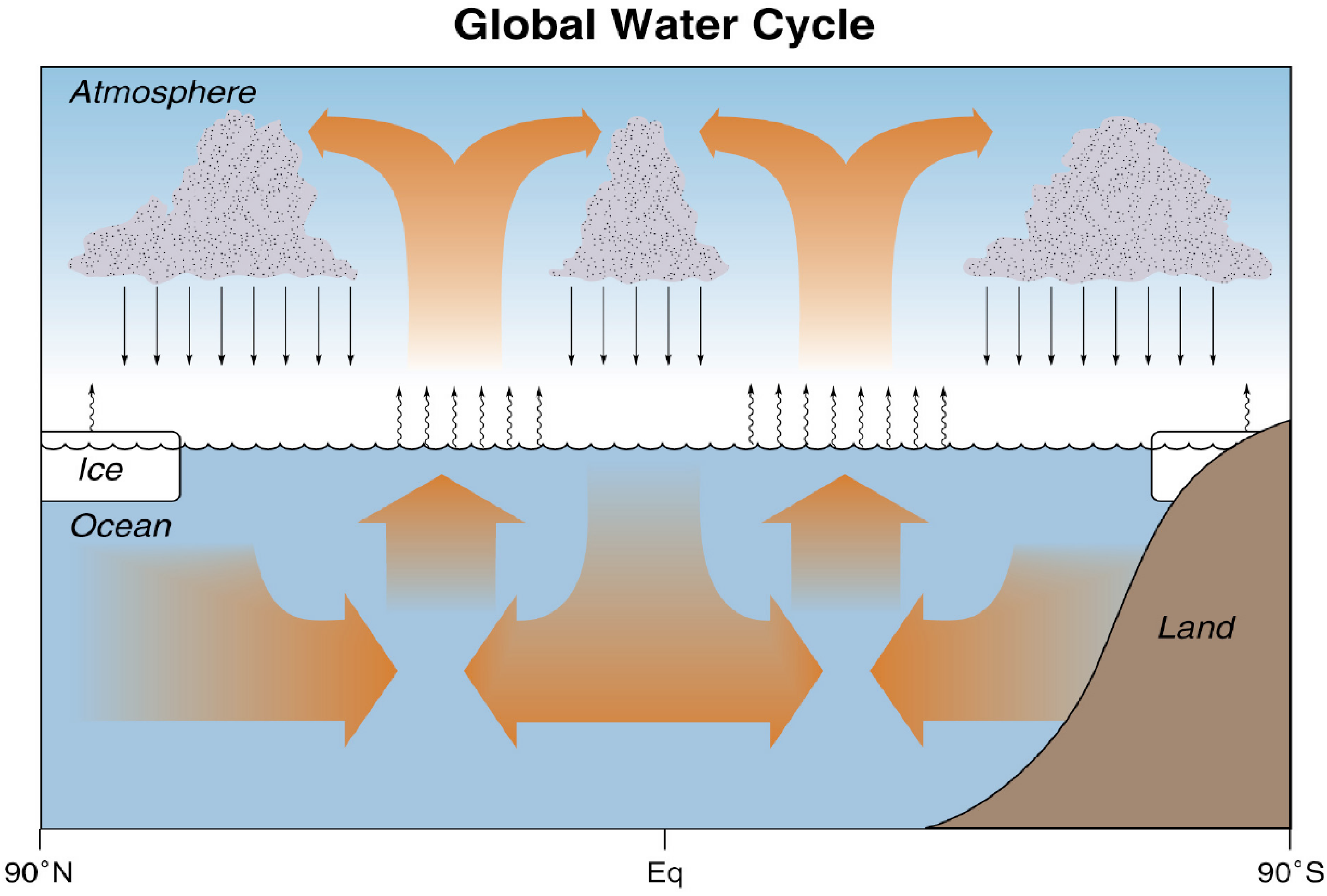


- Oceanic fronts at ocean surface often clearer on SSS than on SST (SST strongly affected by air-sea heat exchanges)



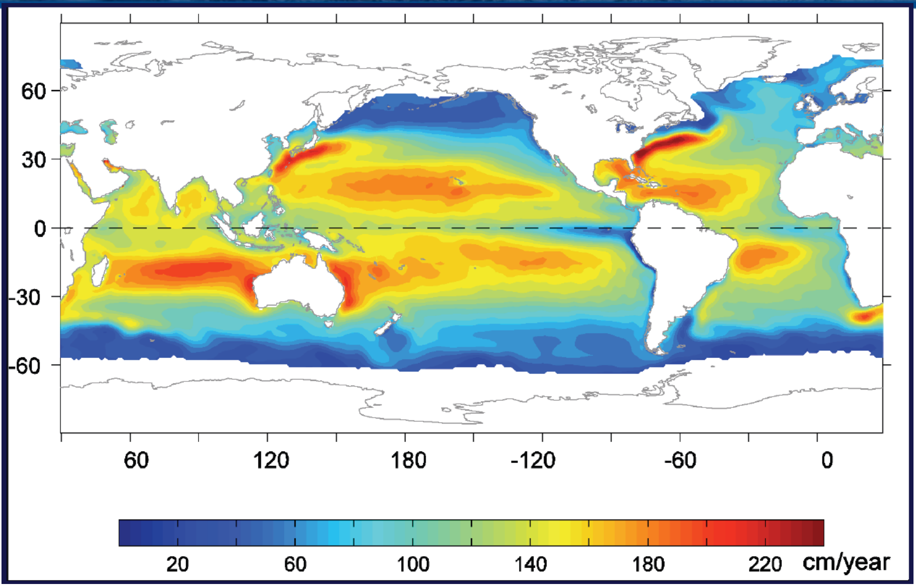
Rodier et al. (JPO, 2000)

The Oceanographer's Water Cycle

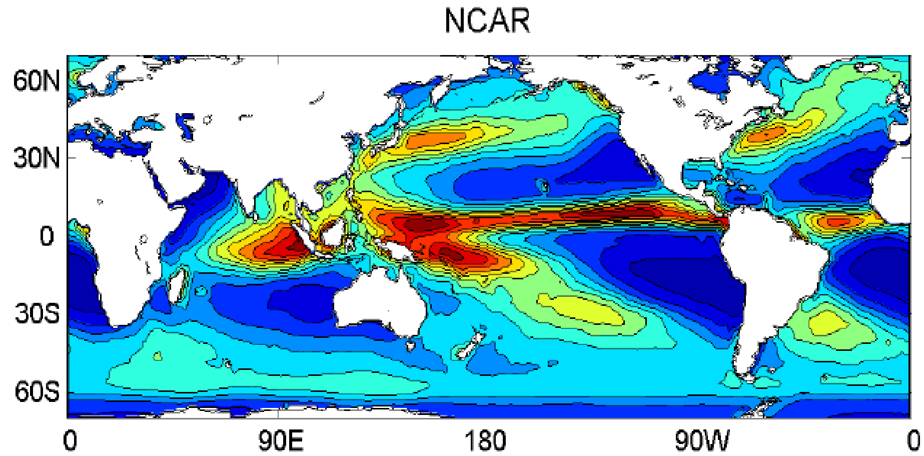


Sea Surface Salinity : an air/sea/land/ice interface proxy of The Global Freshwater Exchanges

Evaporation

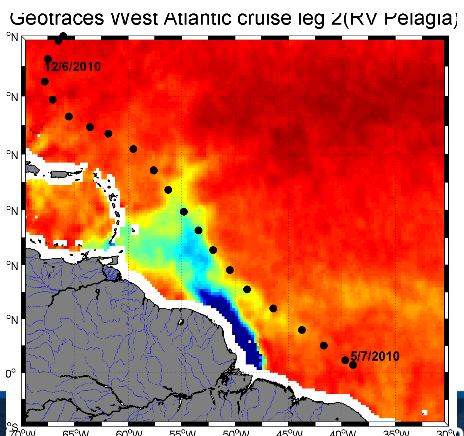


Precipitation

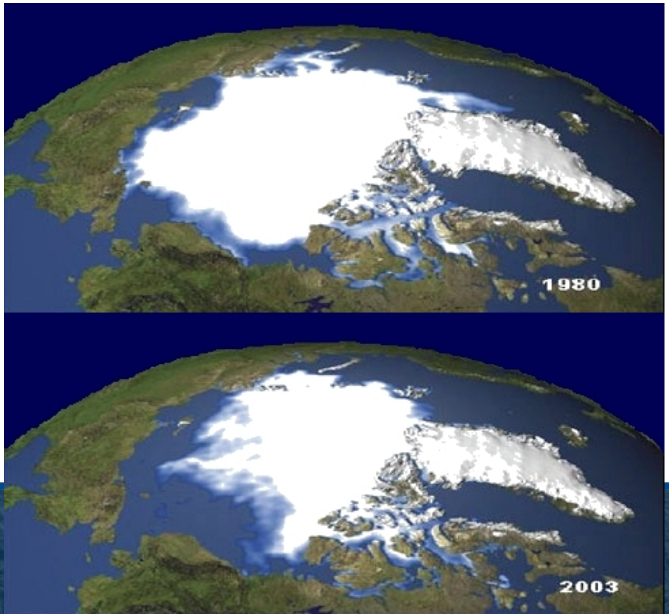


Sea ice Melting/Pounding

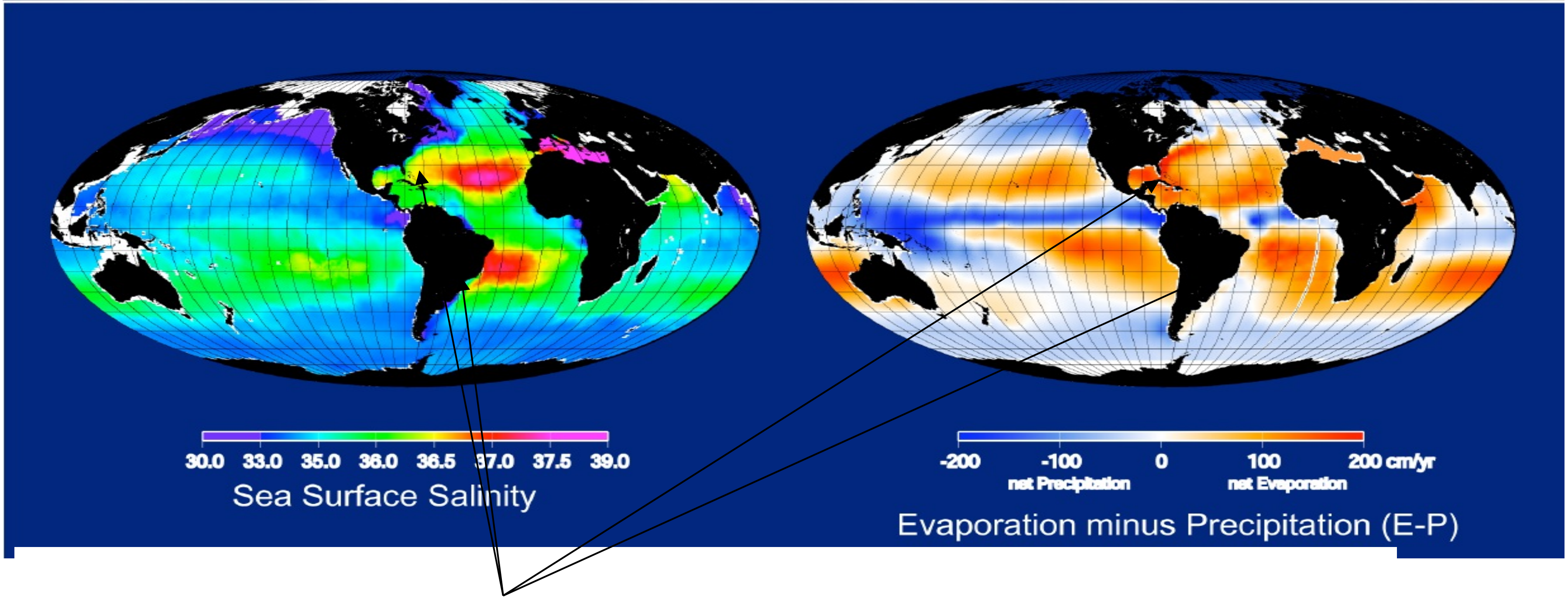
Large River run offs



- 86% of evaporation over the ocean
- 78% of precipitations over the ocean
- => Ocean is a main component of the earth water cycle
- **Sea surface salinity is a tracer of the fresh water flux:**
-



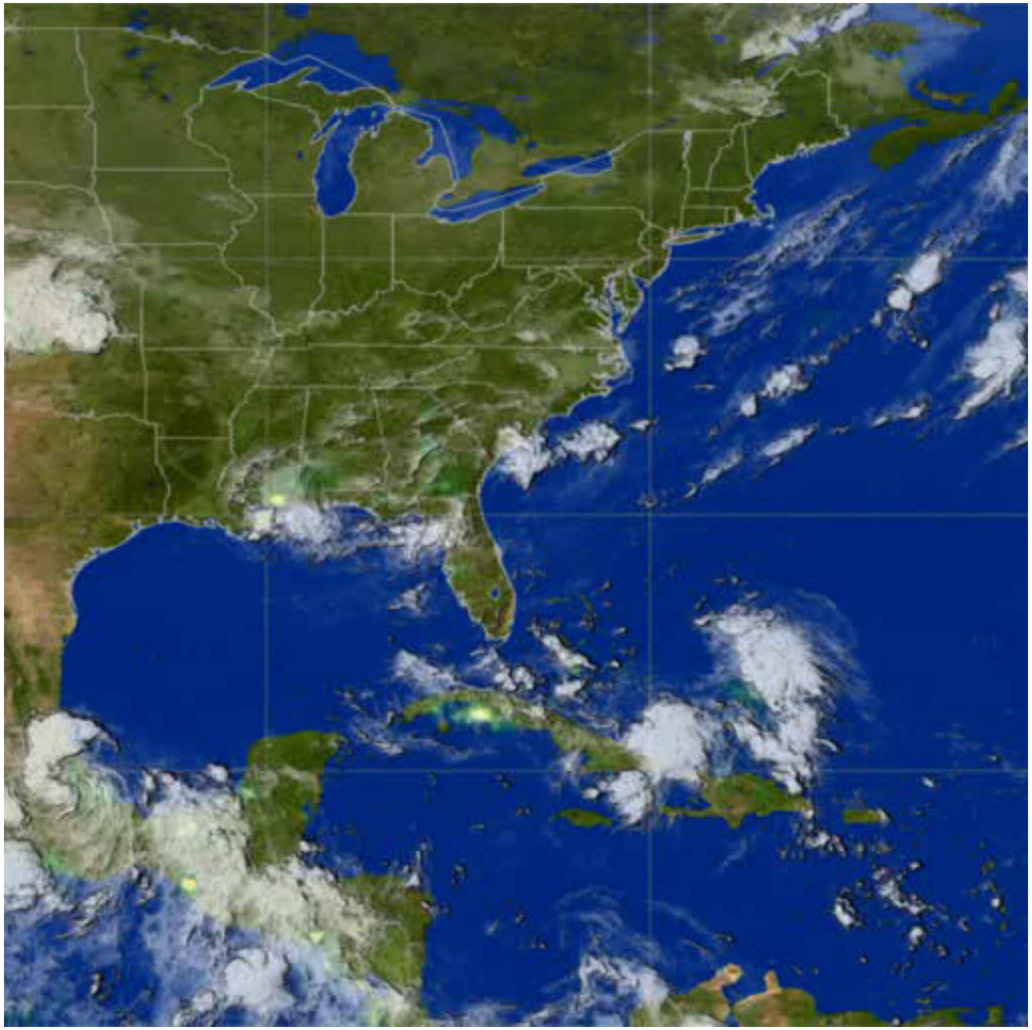
Surface salinity distributions are closely tied to E-P patterns



Evaporation increases in the Sub-tropical areas and so does the surface salinity

Where precipitation dominates, surface salinity decreases. (Equatorial convection zone & mid-latitudes

Salinity wake behind hurricanes



Heavy rainfall

=>
Fresh water lenses ?

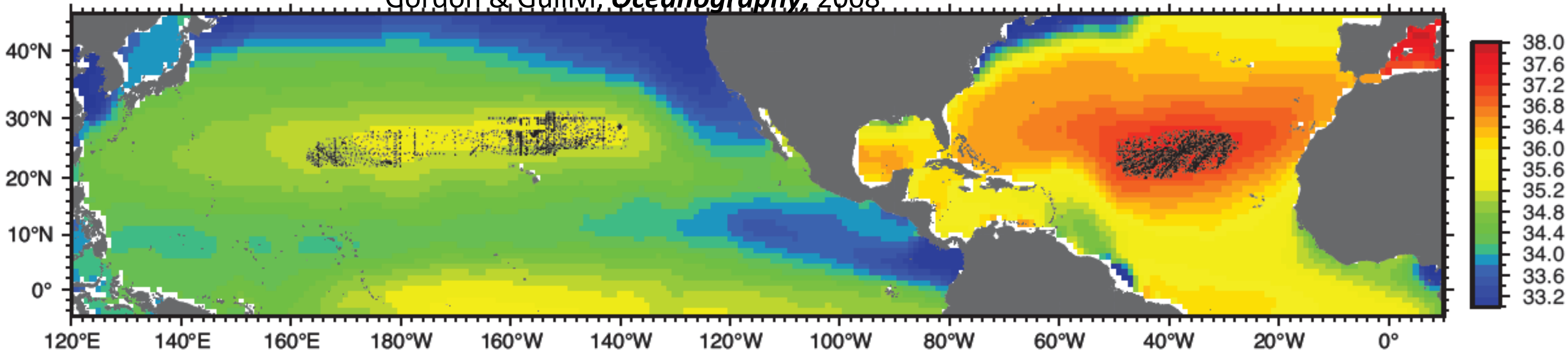
Very large winds=>mixing
And upwellings

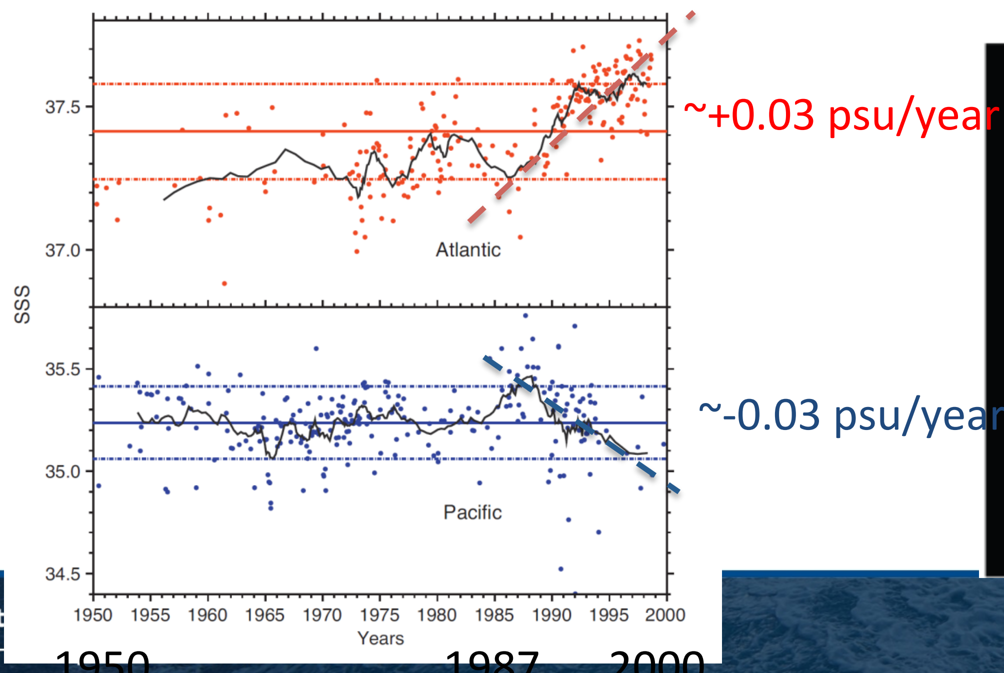
Salty or Fresh water response
Of the upper ocean in the
wakes of Tropical Cyclones?

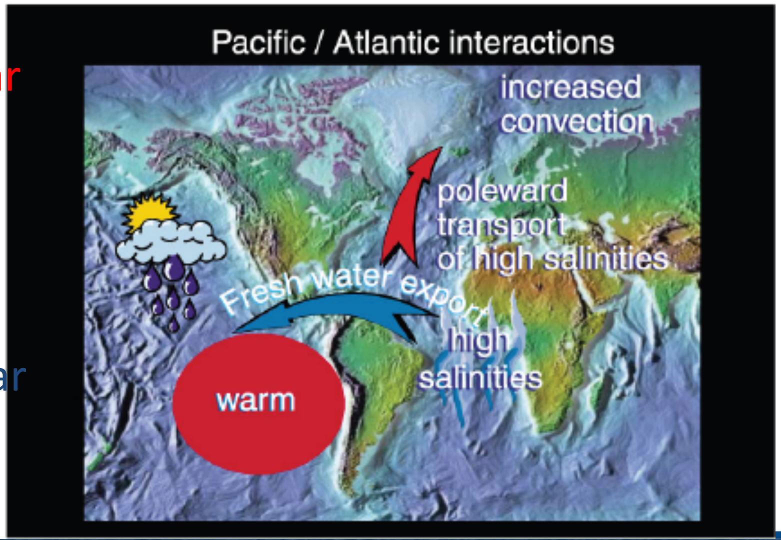
Sea Surface salinity: a climat change indicator

Trends in Sea Surface Salinity in Pacific and Atlantic Oceans

Gordon & Guilivi, ***Oceanography***, 2008

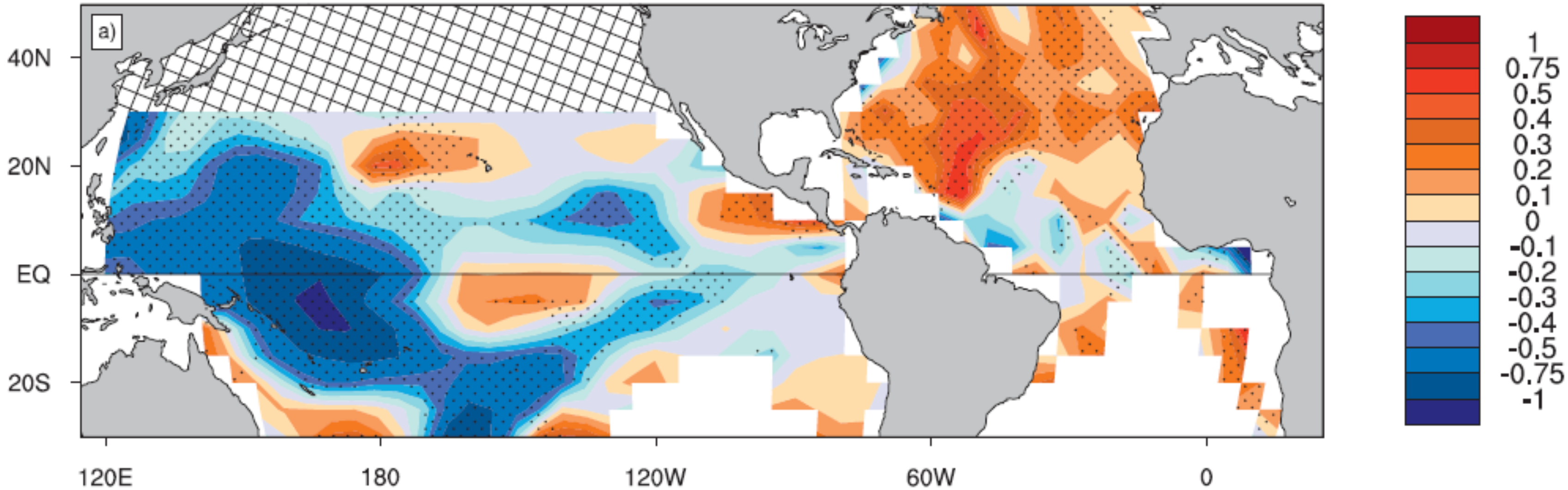






Near-Surface Salinity as Nature's Rain Gauge to Detect influence of Climate Changes on the Tropical Water Cycle

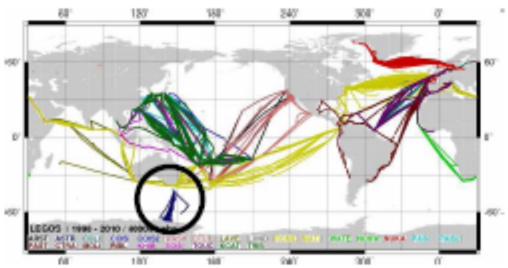
Trends in the observed SSS from *in situ* data over 1970-2002 (PSU/century)



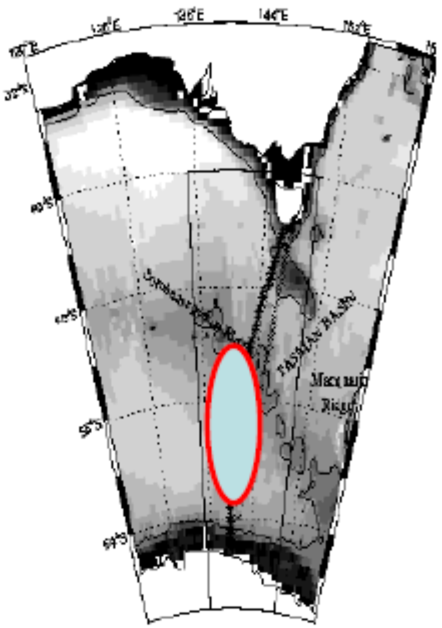
SSS changes over the past decades exhibit a strong Pacific freshening and Atlantic salinity increase leading to a strengthening of the mean SSS interbasin contrast, which reflects to a large extent the mean pattern of freshwater fluxes.

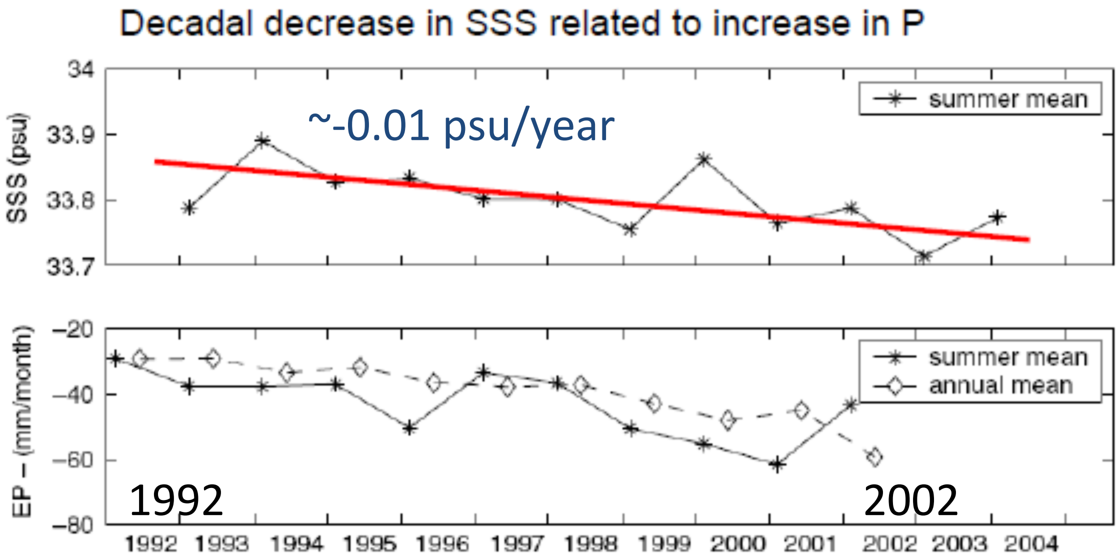
=>We observe a recent increase in the marine tropical hydrological cycle strength (*Terray et al, 2012*).

Trends in SSS in the Antarctic Ocean



10 sections /year since 1993

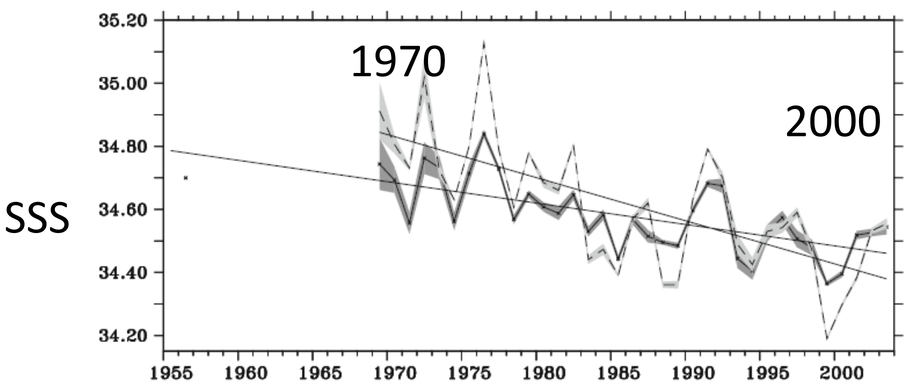




(Morrow et al., 2008)

Trends in Sea Surface Salinity in the Western Tropical Pacific Warm Pool

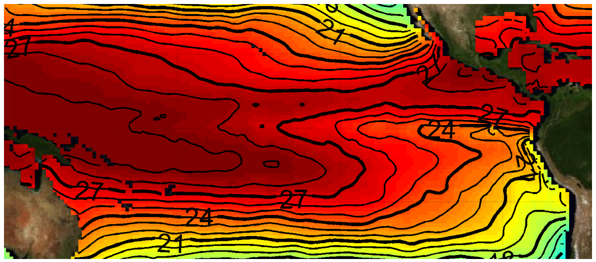
The surface extension of the Warm Pool (equivalent to Europe Area with temperatures>28°C) is associated with a surface salinity freshening



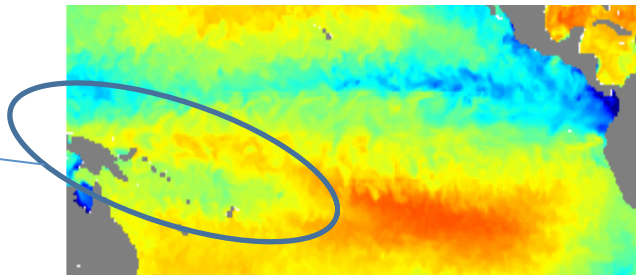
~-0.013 psu/year

Cravatte et al., 2009

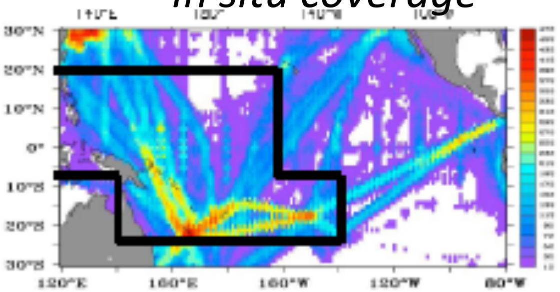
Temperature



Salinity

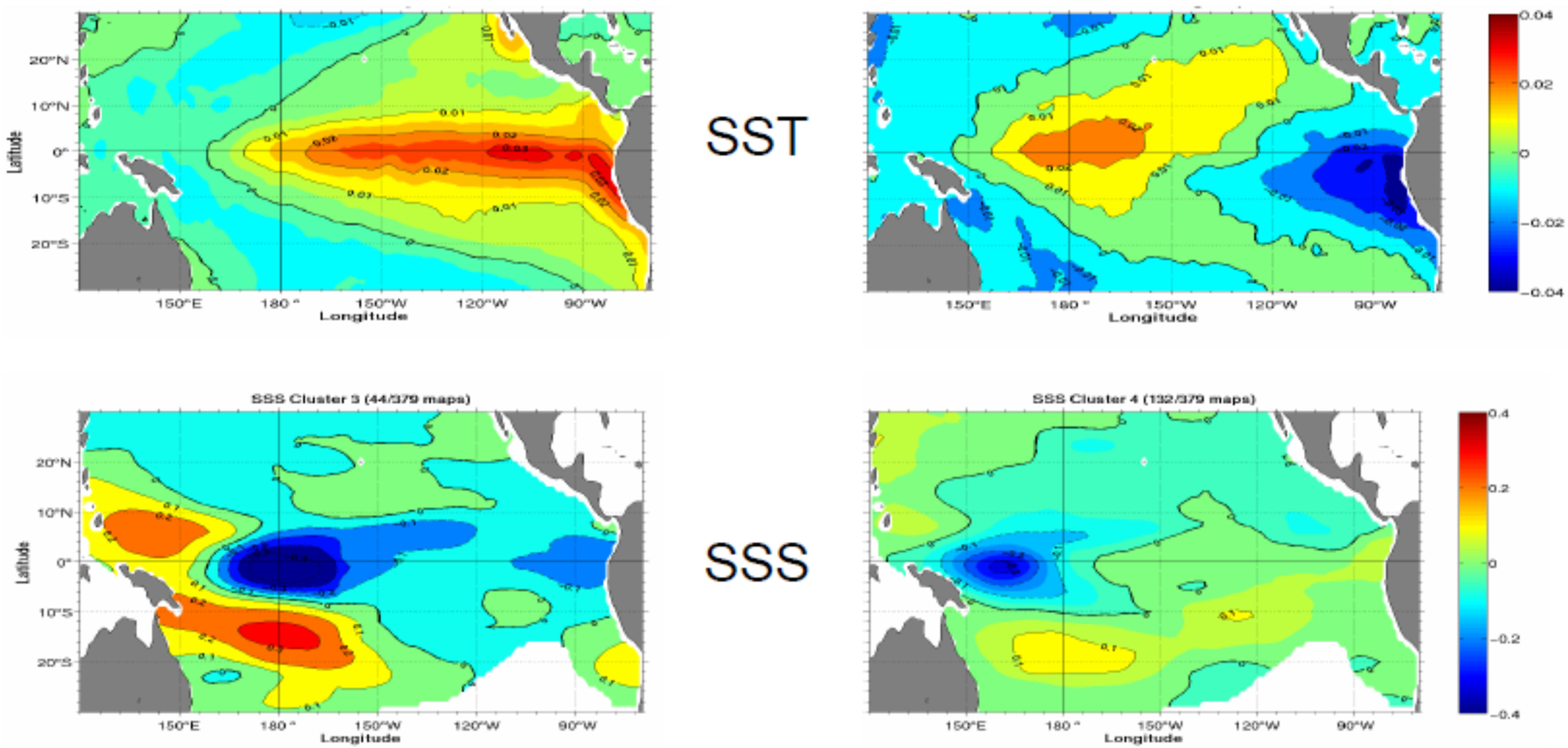


In situ coverage



The spicy waters that change El Niño

Eastern Pacific El Niño | Central Pacific El Niño



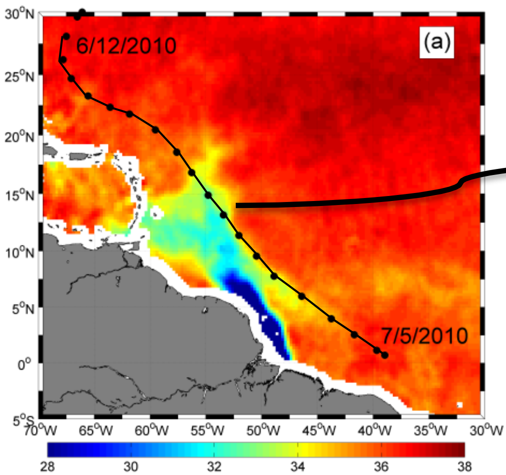
Christophe Maes, 2002
Singh et al., 2010

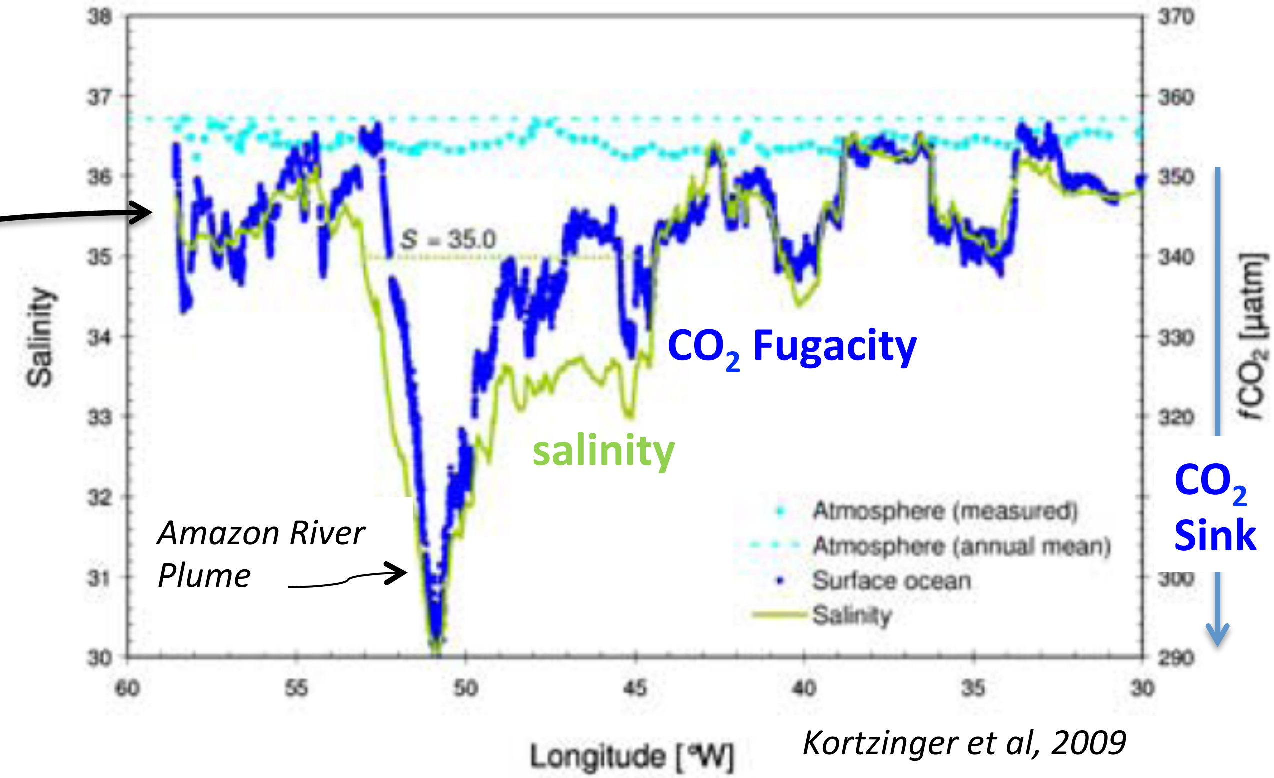
Salinity of the upper ocean play an important role (barrier-layer effects) in the on-set of the phenomenon. Monitoring this variable will help in better predicting El Niño.

Surface Salinity & Marine Bio-chemistry

Ocean is a major sink for atmospheric CO2

It absorbs ~25% of human emission in the atmosphere, however it is saturated and start acidifying





Kortzinger et al, 2009

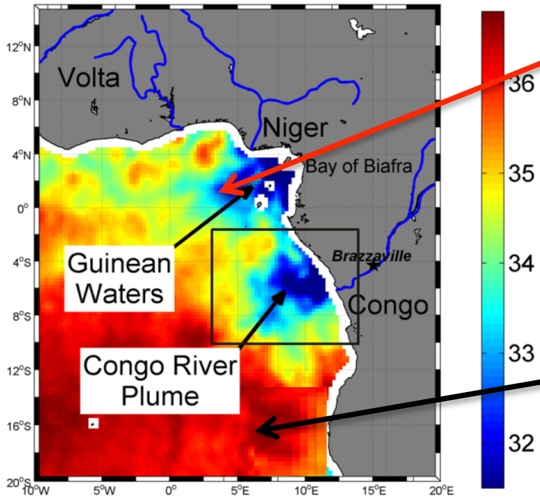
Through its links with carbonate chemistry and surface water masses monitoring, **Sea surface salinity data will improve estimates of air-sea CO_2 fluxes.**

SMOS will help in better quantifying ocean acidification (corals reefs, tropical ecosystem) & ocean-atmosphere CO_2 exchanges in some key areas

Surface Salinity and Marine Biology

Salinity is one of the key environmental factor for the living of fishes and marine biology

SSS SMOS

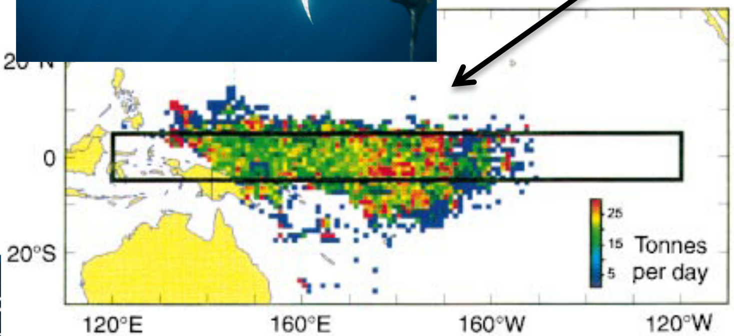


Sardinella mad

S. Maderensis is stenohaline: it lives in warm freshwaters of the Guinean Gulf (rain effects, river influence from Volga, Niger, Congo,..)

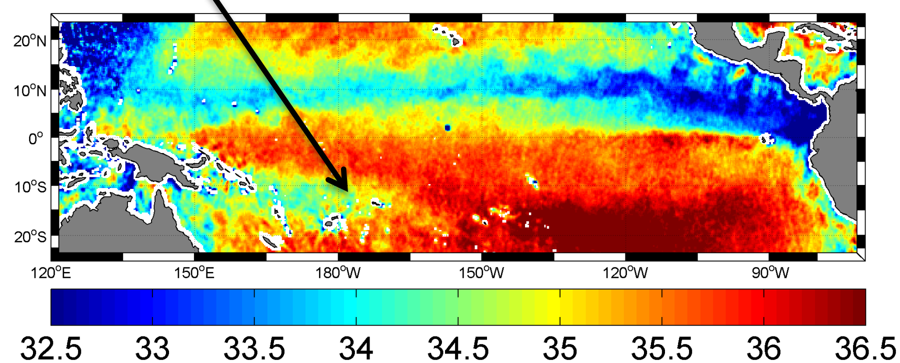
S. Aurita is stenohaline: it lives in the cold and salty waters of the benguela upwelling

Tuna takes & Haline Fronts in the western Tropical Pacific



Lehodey, 1997

SSS SMOS Nov



Why measuring SSS from Space?

•Salinity is a key parameter of ocean dynamics and Climate:

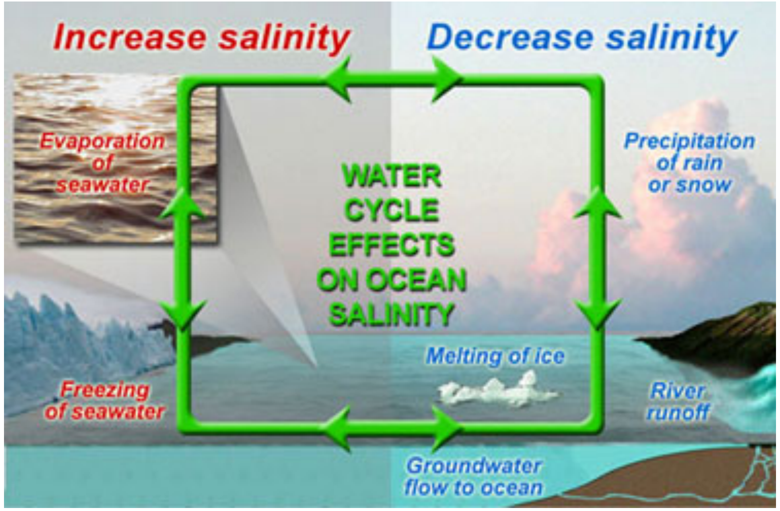
✓Thermo-haline Circulation

✓Global Water Cycle

(Fresh water flux , E-P-R)

✓Oocean-atmosphere Coupling

(e.g., ENSO, en rate of CO_2 absorbtion)



•Salinity is a key parameter for ocean Bio-chemistry and Biology

•Lack of SSS measurements

Implications on climatology

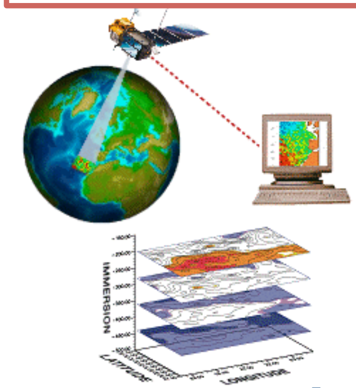
GOOS (Global Ocean Observing System) scientific plan :

Accuracy ~0.1 psu/monthly

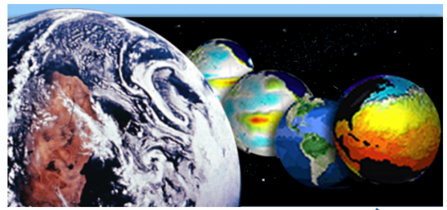
Spatial scale: 100-200 km^2

What are the main oceanic applications ?

Ocean circulation Modeling

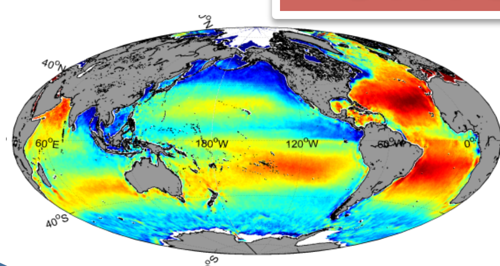


Climate change Studies

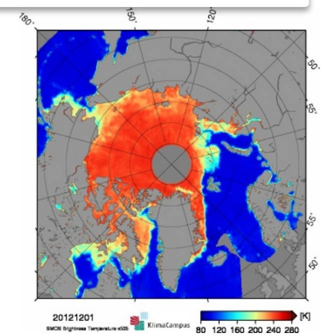


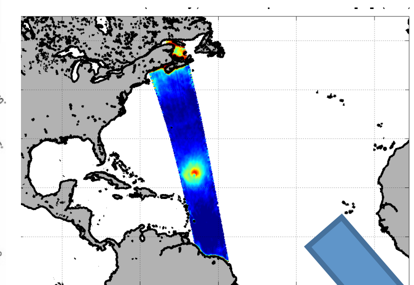
Marine Biology & Biochemistry

SMOS data



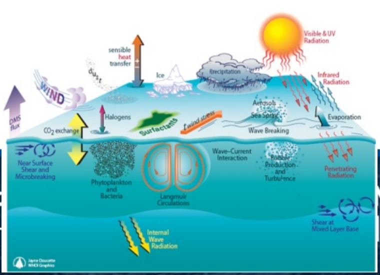
Salinity



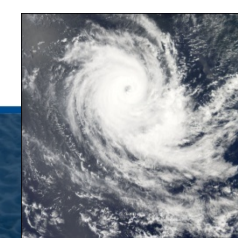


brightnesses

Ocean-atmosphere interactions



Weather Predictions

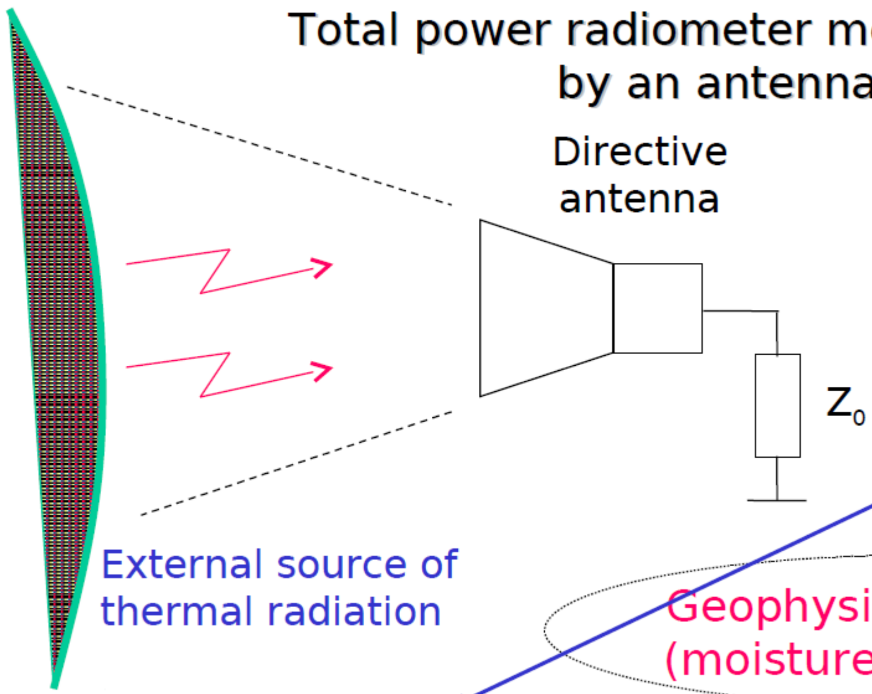


How can we measure sea surface salinity From Space?

Physics principle Of SSS measurements From Low Microwave frequency radiometry

Radiometry

Total power radiometer measures the signal power captured by an antenna (Rayleigh-Jeans Law)



Black body: $P = k\,T\,B$

T: physical temperature

Grey body: $P = k\,T_B\,B$

T_B: brightness temperature

Geophysics parameters (moisture, salinity, etc.)

Wind speed over the sea

T_B depends on:

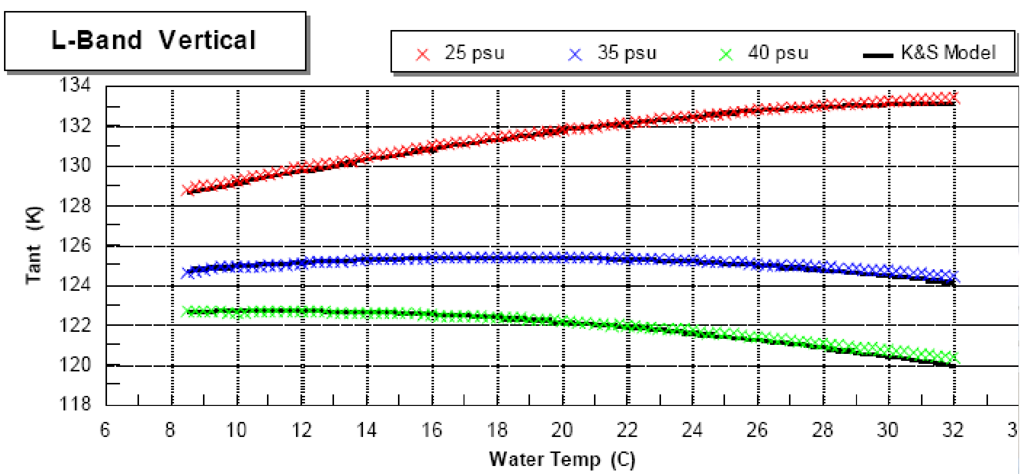
- Physical temperature
- Electrical and geometrical parameters
- Antenna orientation and polarization
- Frecuency

Basics of SSS measurements from Space

- At electromagnetic frequency f < 20 GHz, sea water dielectric constant ε is a function of SSS and sea surface temperature SST. $\varepsilon = \varepsilon(SSS, SST)$.

$\varepsilon = f(S, T, Freq, Incidence)$ $\quad T_b = \varepsilon T$

- The sea surface brightness temperature T_{ant} as measured by a radiometer is thus related to salinity

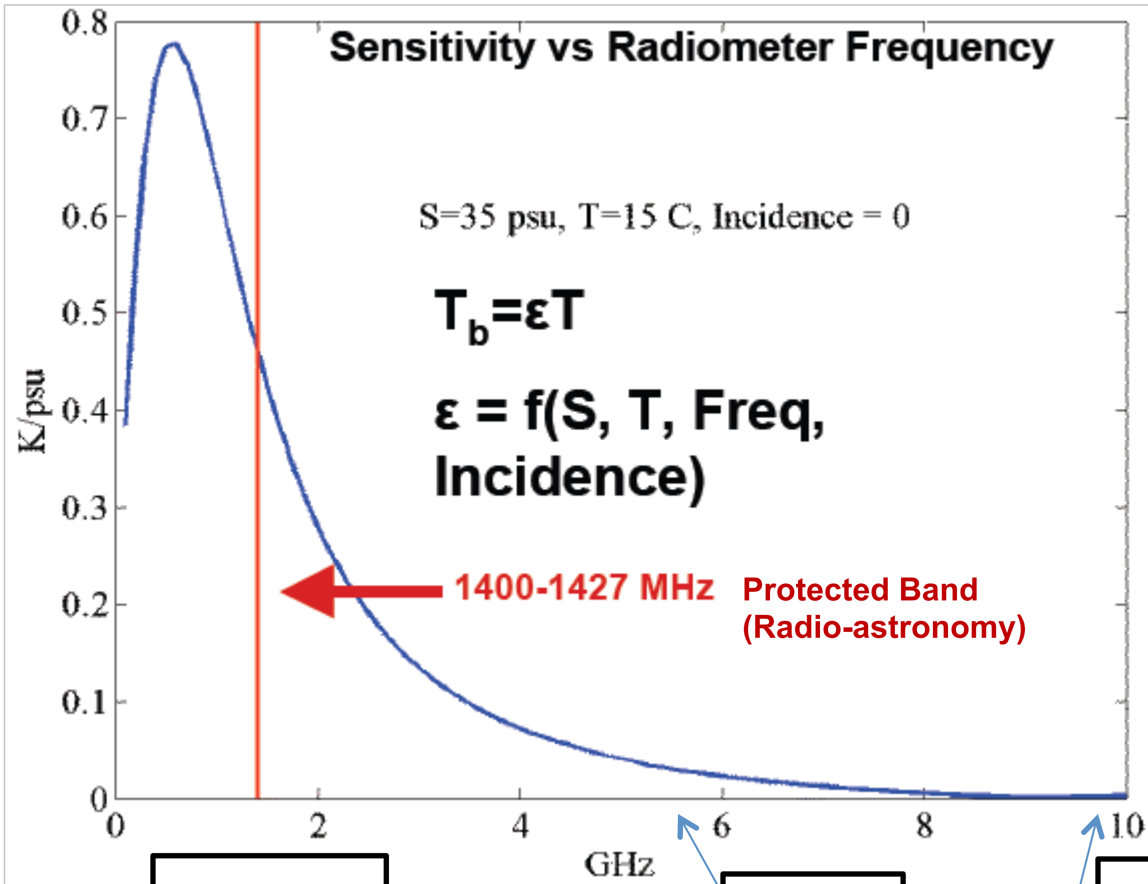


Given SST(T) & Tb data=> one can deduce SSS (S) in theory

Tb sensitivity to SSS as function of Electromagnetic Frequency

Brightness temperature Sensitivity to Salinity as function of **Electromagnetic Frequency**

$$\frac{\partial T_B}{\partial SSS}$$



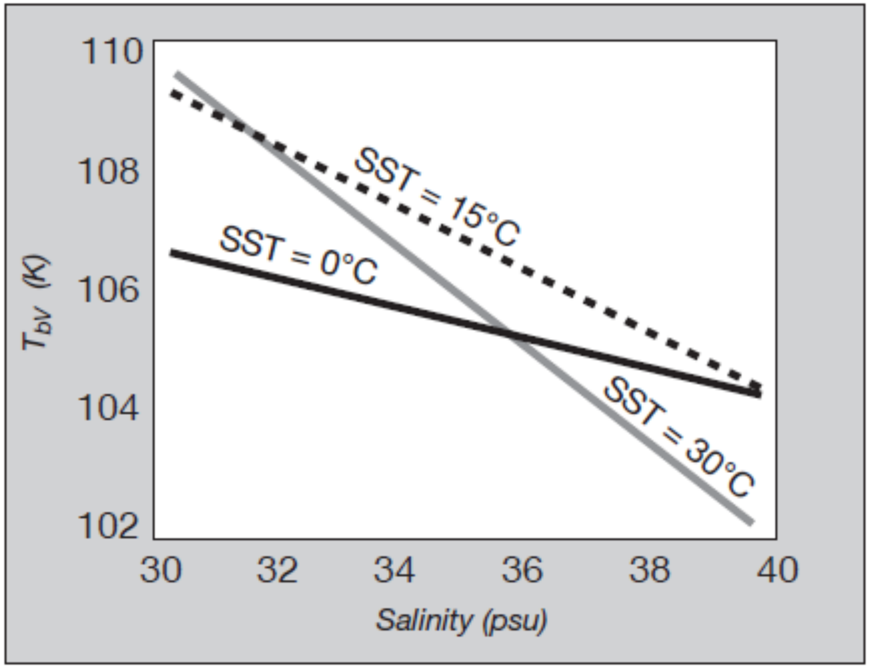
SMOS
Aquarius
(L-Band)

C-Band

X-Band

AMSR-E, WindSat, TMI

A weakly sensitive principle



The sensitivity of the brightness temperature at L-band to SSS remains small. It depends on the sea surface temperature (SST):

-0.3 K/psu in cold waters (~0°C)
à
-0.7 K/psu in warm seas (~30°C)

An istantaneous accuracy on SSS of 0.1 psu would require a radiometer TB measurement accurate to within:
~0.03 K for an SST=0°C !
~0.07 K for an SST=30°C !

The one from **AMSR-E & WindSat at 6 GHz: 0.5-0.6 K** => technological challenge !

First attempts during NASA Mission SkyLab in 1973

First trial 1973 SkyLab S-194:

L-band radiometer data

Low accuracy & Spatial resolution

Not enough data

Technical limitations due to the size of antennas at L band

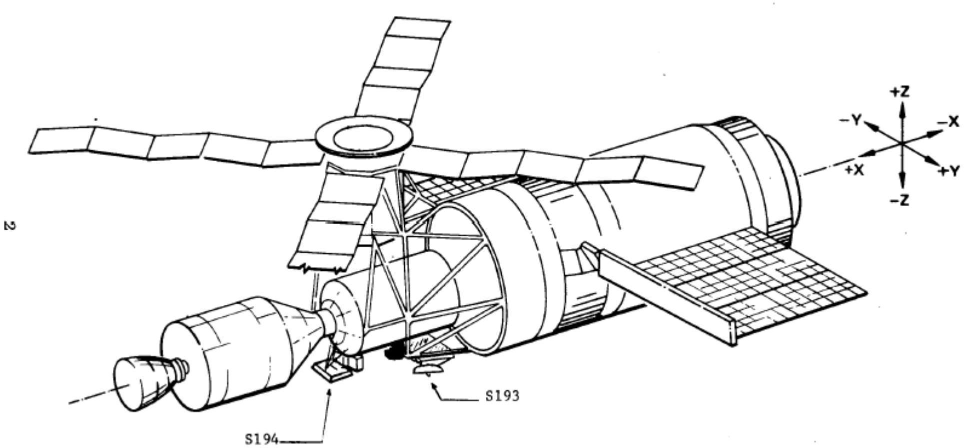
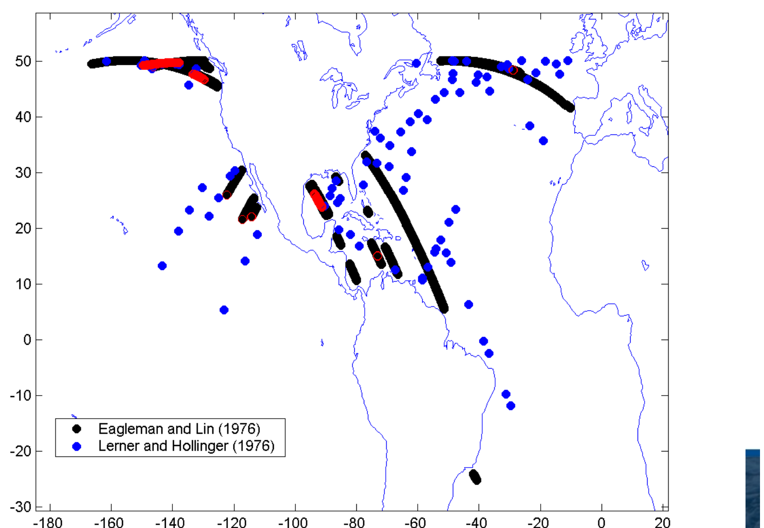


Fig. 1 — Location of radiometers on Skylab



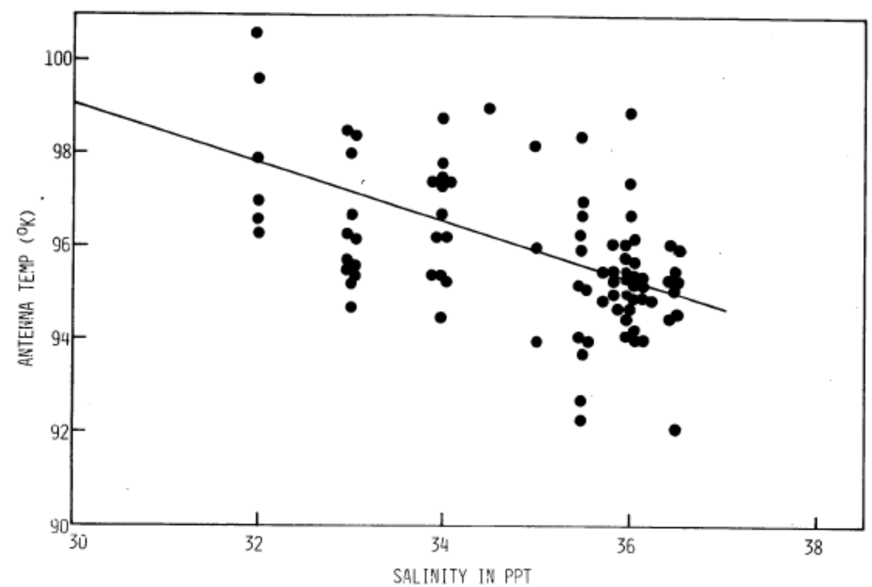
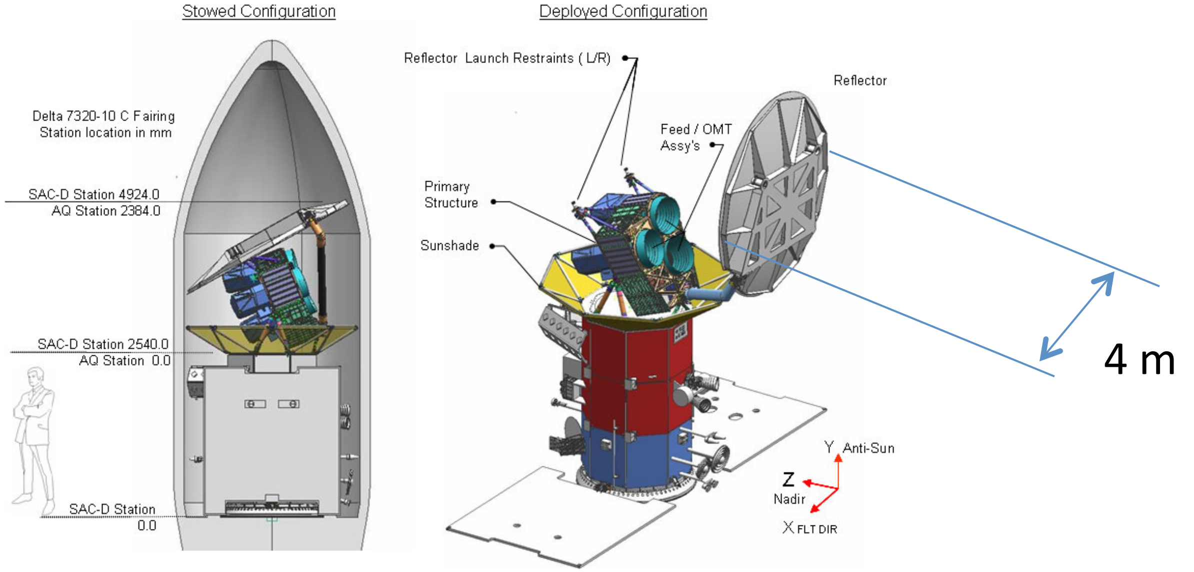


Fig. 17 — Antenna temperature dependence on salinity

Antenna size: the limiting technological factor for SSS remote sensing developement until the 1990s

To obtain a spatial resolution on ground of 50 km (at nadir), from an altitude of 750 km and for an electromagntic wavelength of 20 cm (f=1.4 GHz), a real aperture radiometer must have a characteristic antenna size of ~4 m



Technological Evolution associated with Antenna

➢ SMOS (Soil Moisture & Ocean Salinity)

Launch date: November 2[sd], 2009

L band radiometer required: No existing device

How to by-pass the antenna size technical difficulty ?:
Antenna deployed in space and Interferometry

ESTAR ir … selec

➢ AQUARIUS/SAC-D (NASA/CONAE): launch date: july 2010

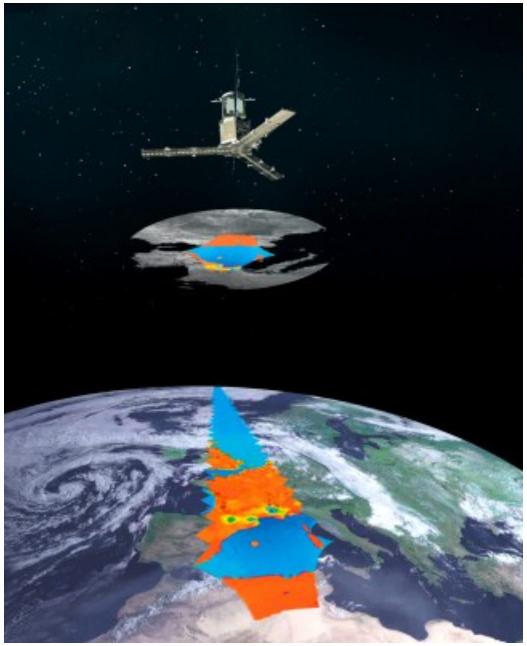
Goal of both missions:

- SSS measurments with an accuracy of 0.1-0.2 psu and a spatial resolution of 100x100 km every 10 days (GODAE requirements).

Soil Moisture and Ocean Salinity

The sensor: L band interferometric synthetic aperture Radiometer (1.4 GHz)

a) SMOS artist view

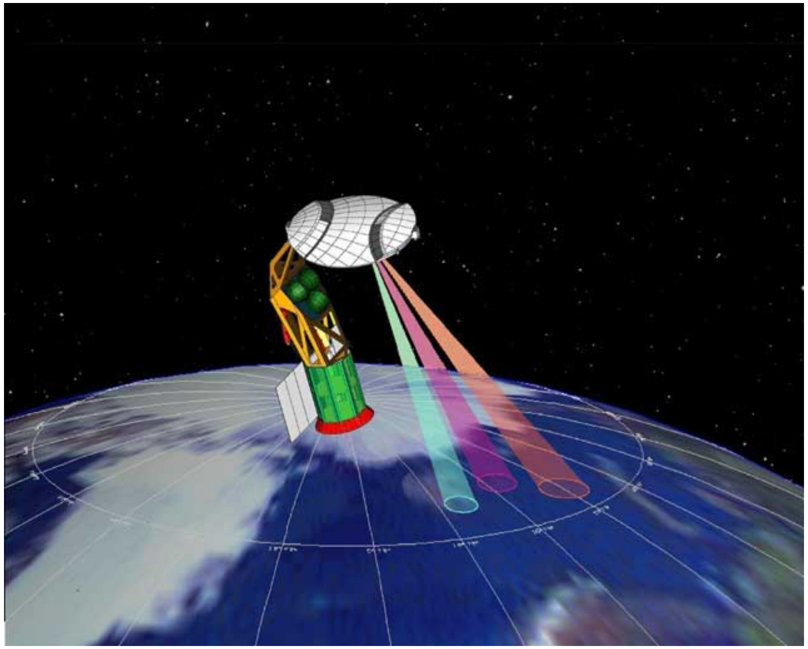


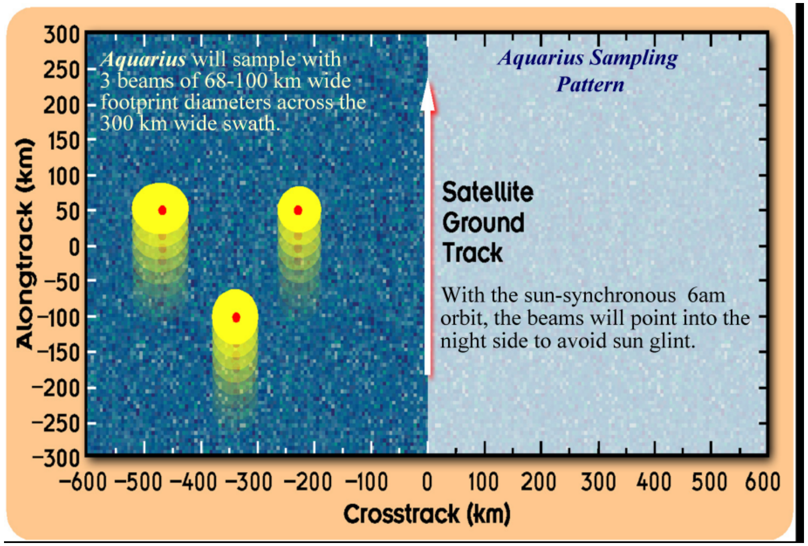
b) SMOS swath

Brightness temperature measurements at different incidence angles (0° – 60°)
Ground resolution: 35-80 km Global coverage every 3 days
Spot accuracy (instantaneous) ~1 psu

Aquarius/SAC-D

L band (1.4 GHz) radiometer with 3 incidence angles + L band scatterometer



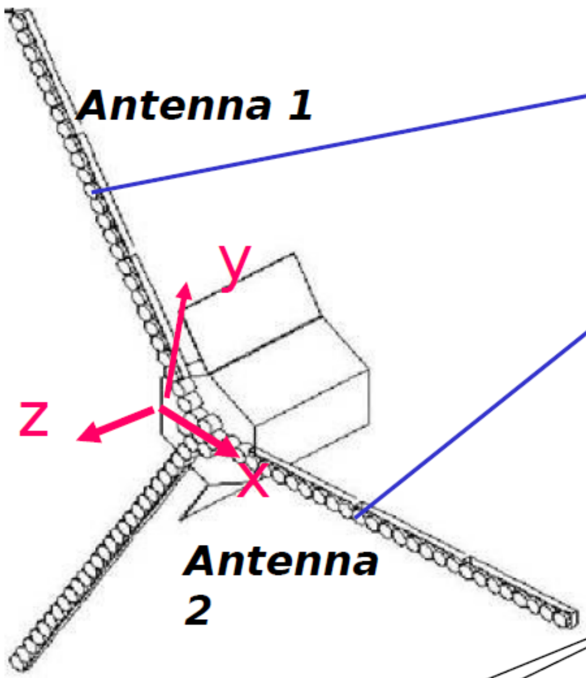


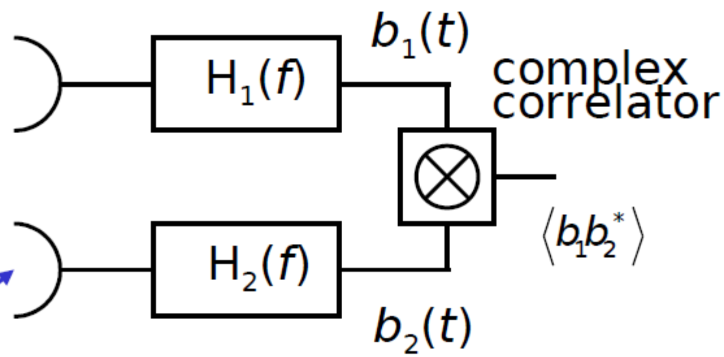
a) Aquarius artist view

b) Swath

Spatial resolution: 100 km every 10 days. Accuracy ~0.5 psu

The interferometry in SMOS





Complex Correlation

$$V(u,v) = \frac{1}{k_B \sqrt{B_1 B_2} \sqrt{G_1 G_2}} \frac{1}{2} \langle b_1(t)\, b_2^*(t) \rangle$$

Spatial coordinates

Boltzmann Constant

Noise bandwidths

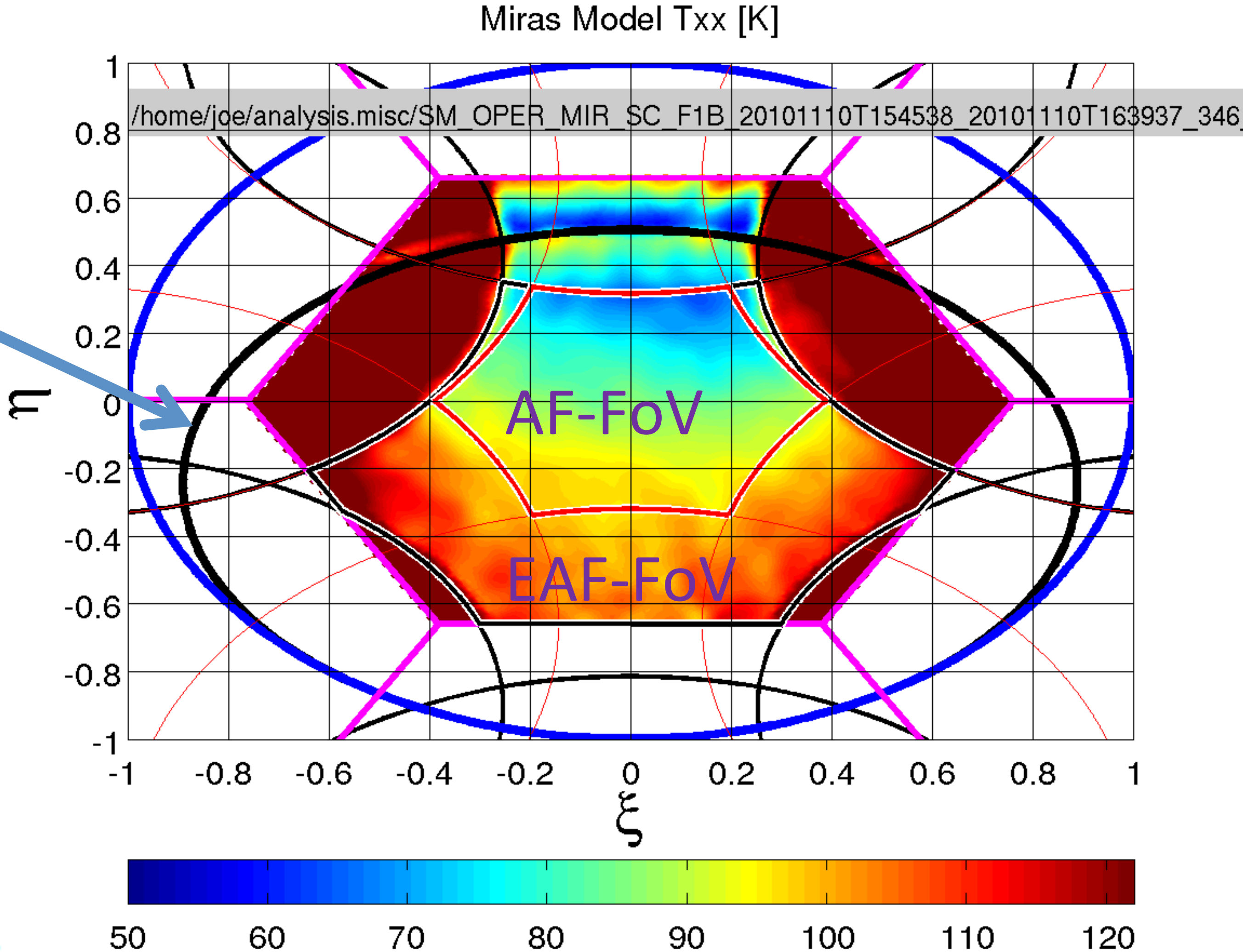
Available power gains

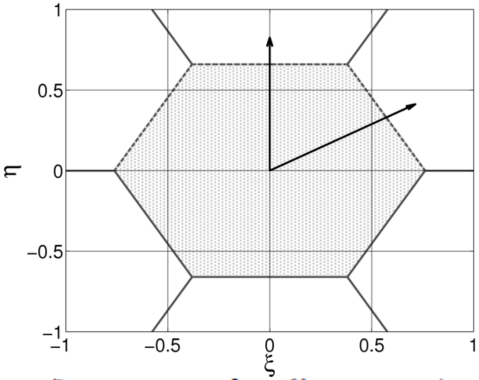
$$(u,v) = (\Delta x, \Delta y)/\lambda_0$$

THE FIELD OF VIEW AT ANTENNA LEVEL

Ifremer

The earth boundary passes outside fundamental hexagon (magenta) and thus earth aliases appear inside the fundamental hexagon.





$$\xi = \sin\theta_s \cos\phi_s,$$
$$\eta = -\sin\theta_s \sin\phi_s,$$
$$\zeta = -\cos\theta_s.$$

AF-FoV = alias-free field of view

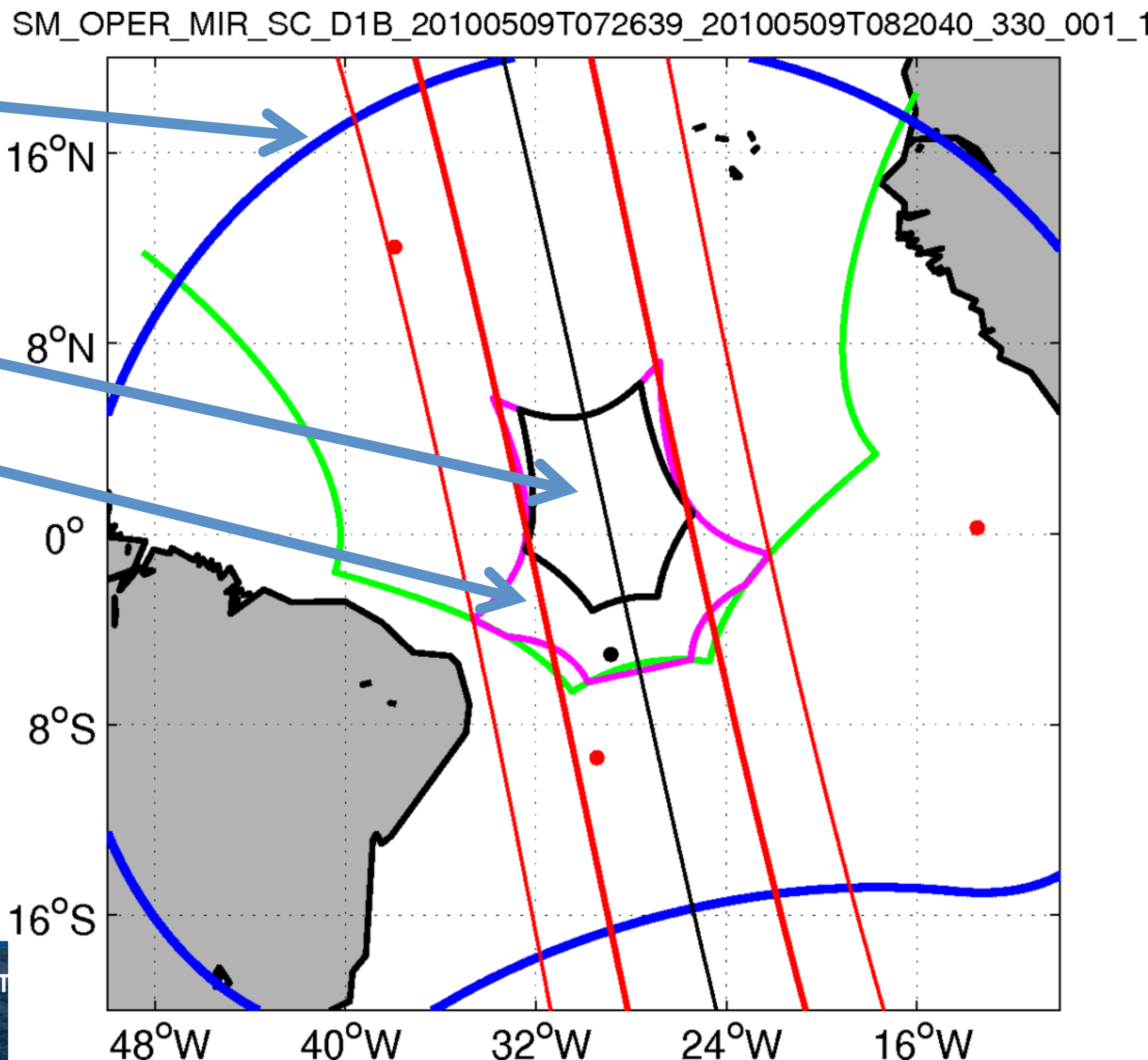
EAF-FoV = extended alias-free field of view

THE FIELD OF VIEW PROJECTED ONTO THE EARTH

Boundary of visible portion of earth

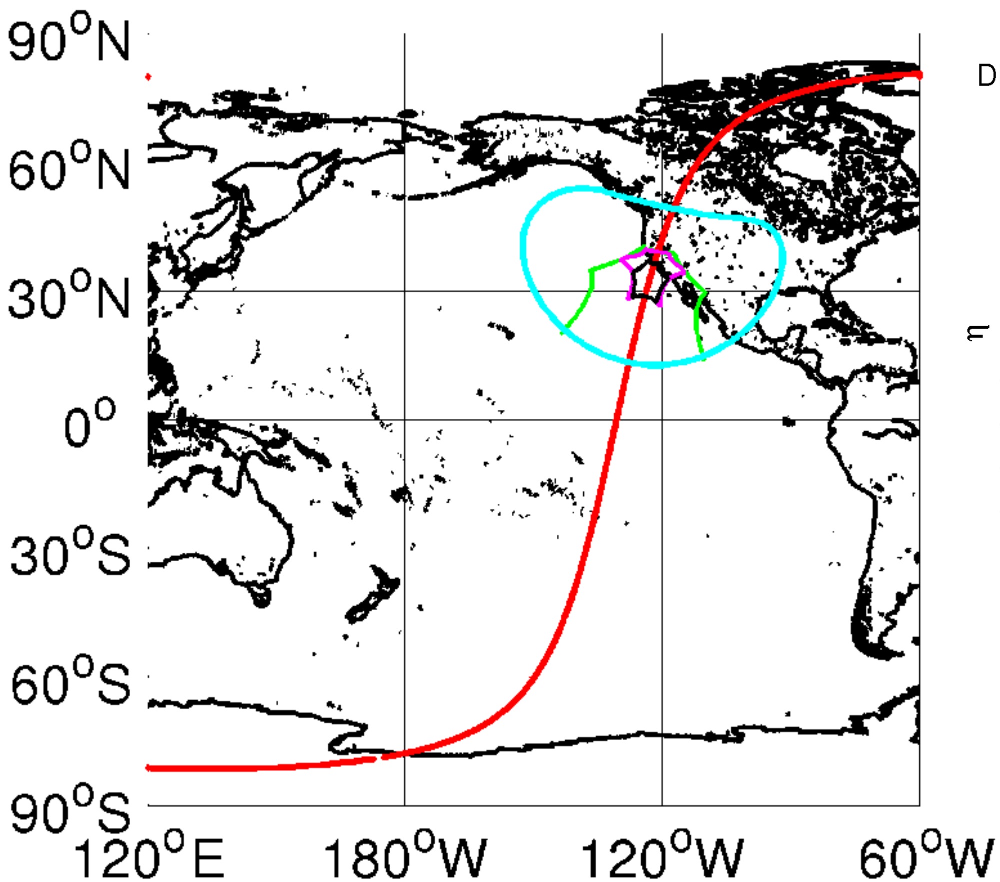
AF-FoV

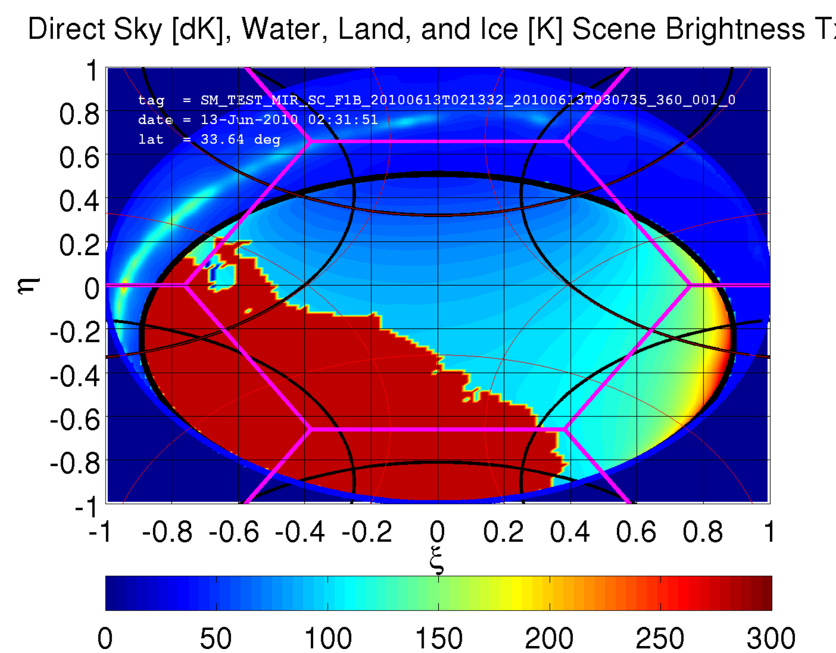
EAF-FoV



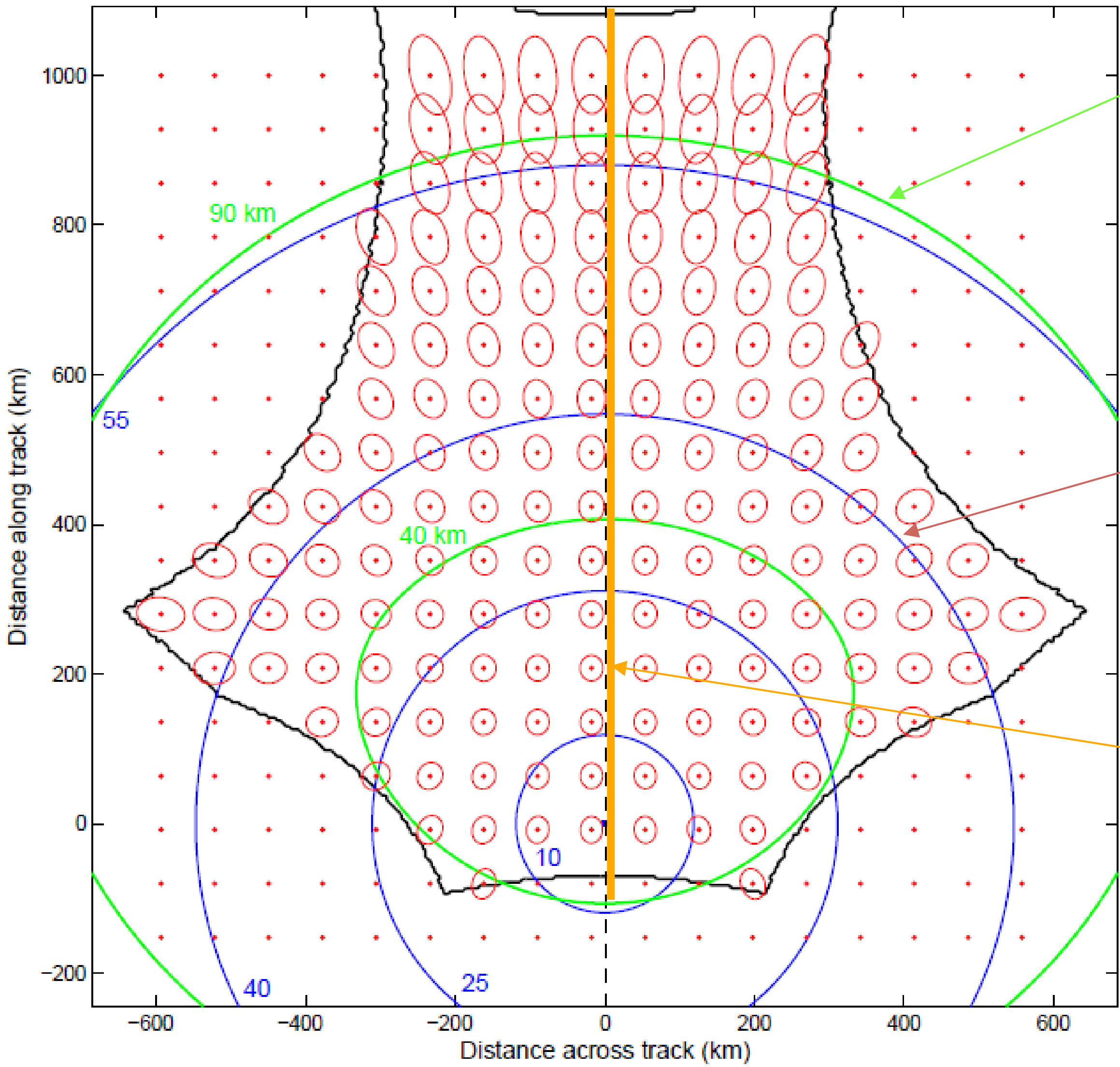
EXAMPLE of SMOS BRIGHTNESS TEMPERATURE MAPS at antenna Level

Here is an example of the scene brightness model for one coastal snapshot. Direct celestial sky brightness has been multiplied by ten in the plot to show it more clearly, and land brightness temperature has been set to 280 K arbitrarily.





SMOS Field of View (Blackman)



Major axis *in L2OS, equivalent resolution up to 100km*

Incidence angle

Dwell line:
Tb measured during successive snapshots along a dwell line fall into the same grid point => set of Tb used for retrieving SSS

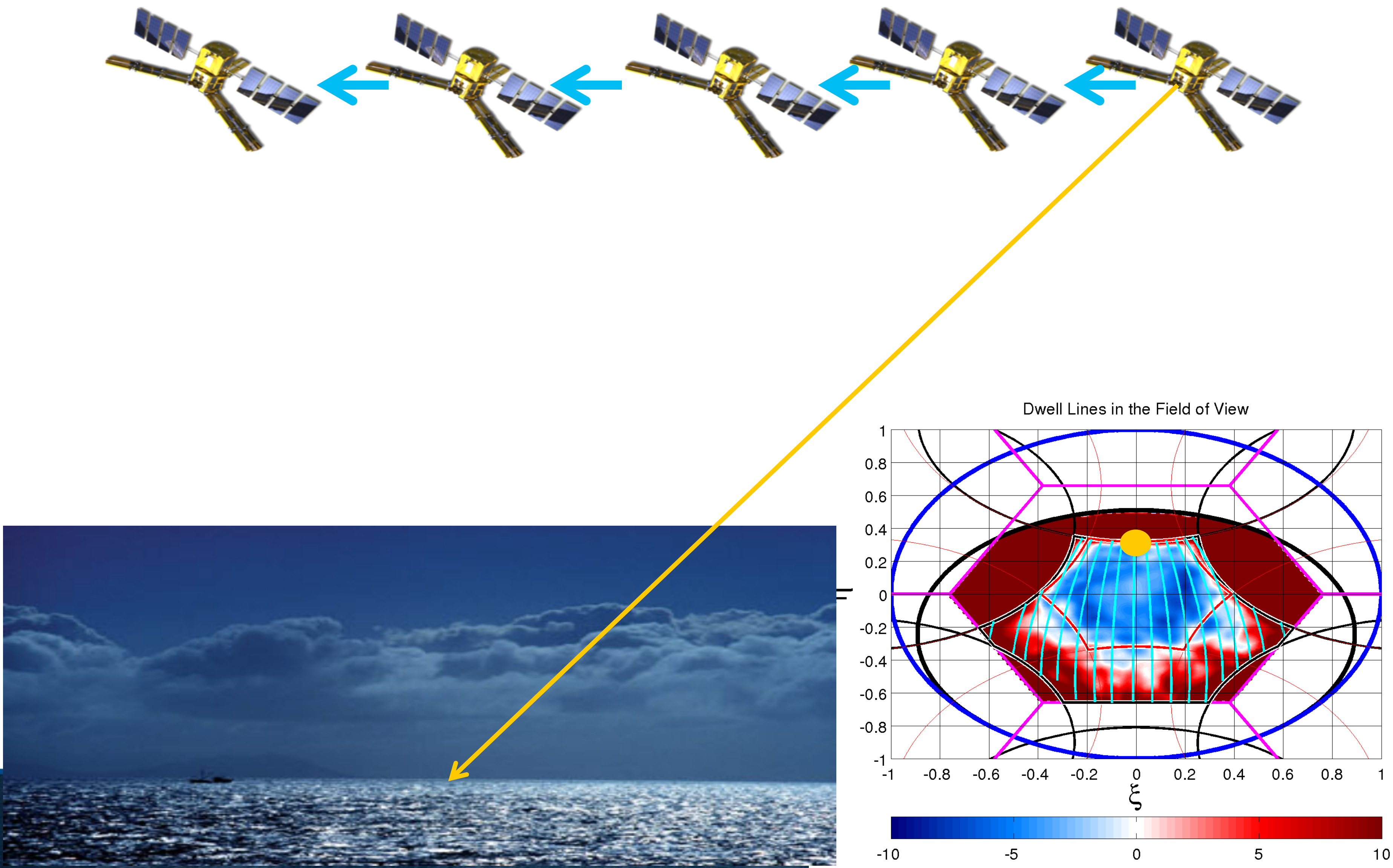
Fig. 1 – SMOS field of view (solid line). The red ellipses represent 3 dB synthetic antenna pattern contours (Blackman exact apodization window). The 40-km and 90-km major axis limits appear in green. The blue circles represent the locations of the incidence angles 10°, 25°, 40° and 55°. One dwell line is also shown (dashed line).

Zine et al. 2007

CONCEPT OF A DWELL LINE

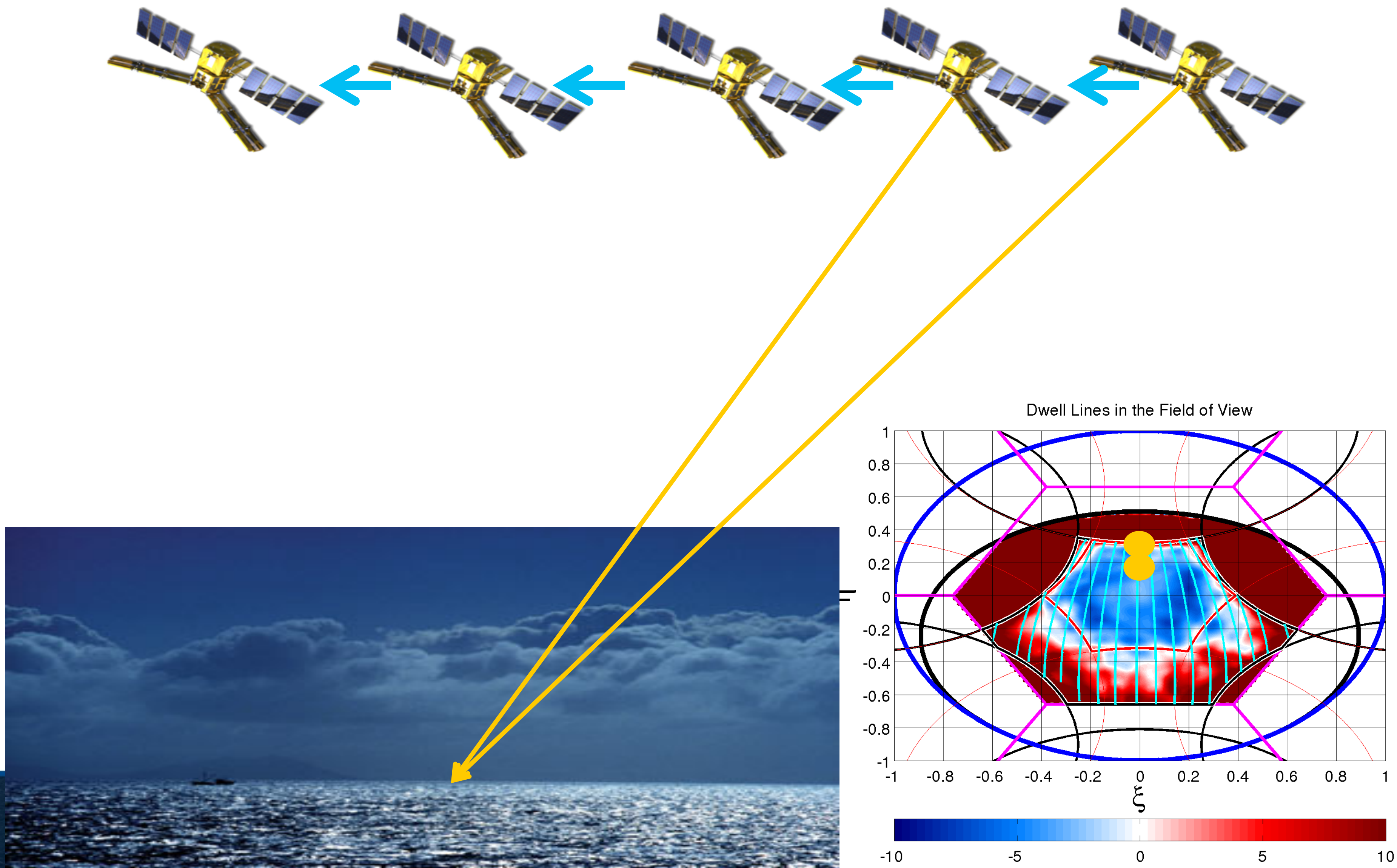
THE CONCEPT OF A DWELL LINE

As the SMOS satellite propagates along its orbit, a given point on earth appears in many snapshots at a large range of incidence angles…



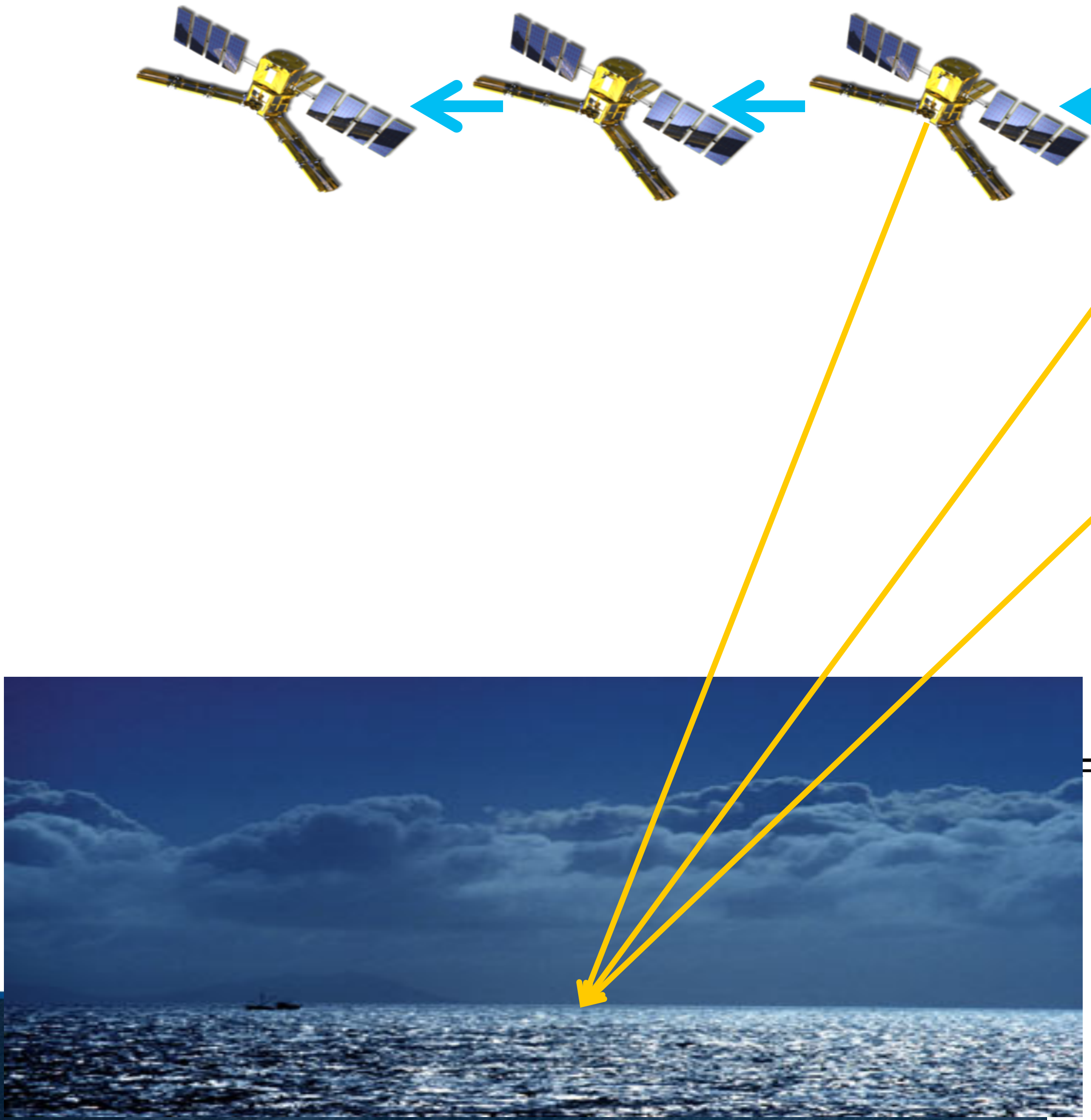
THE CONCEPT OF A DWELL LINE

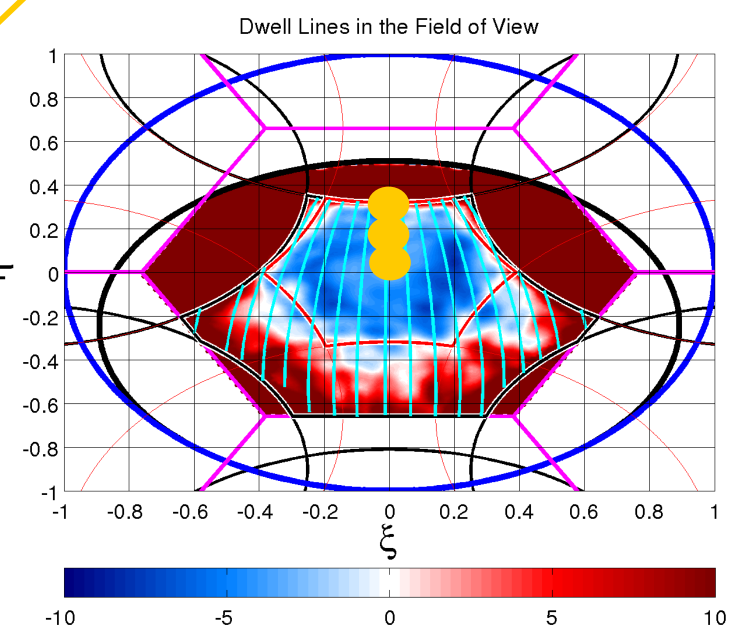
As the SMOS satellite propagates along its orbit, a given point on earth appears in many snapshots at a large range of incidence angles…



THE CONCEPT OF A DWELL LINE

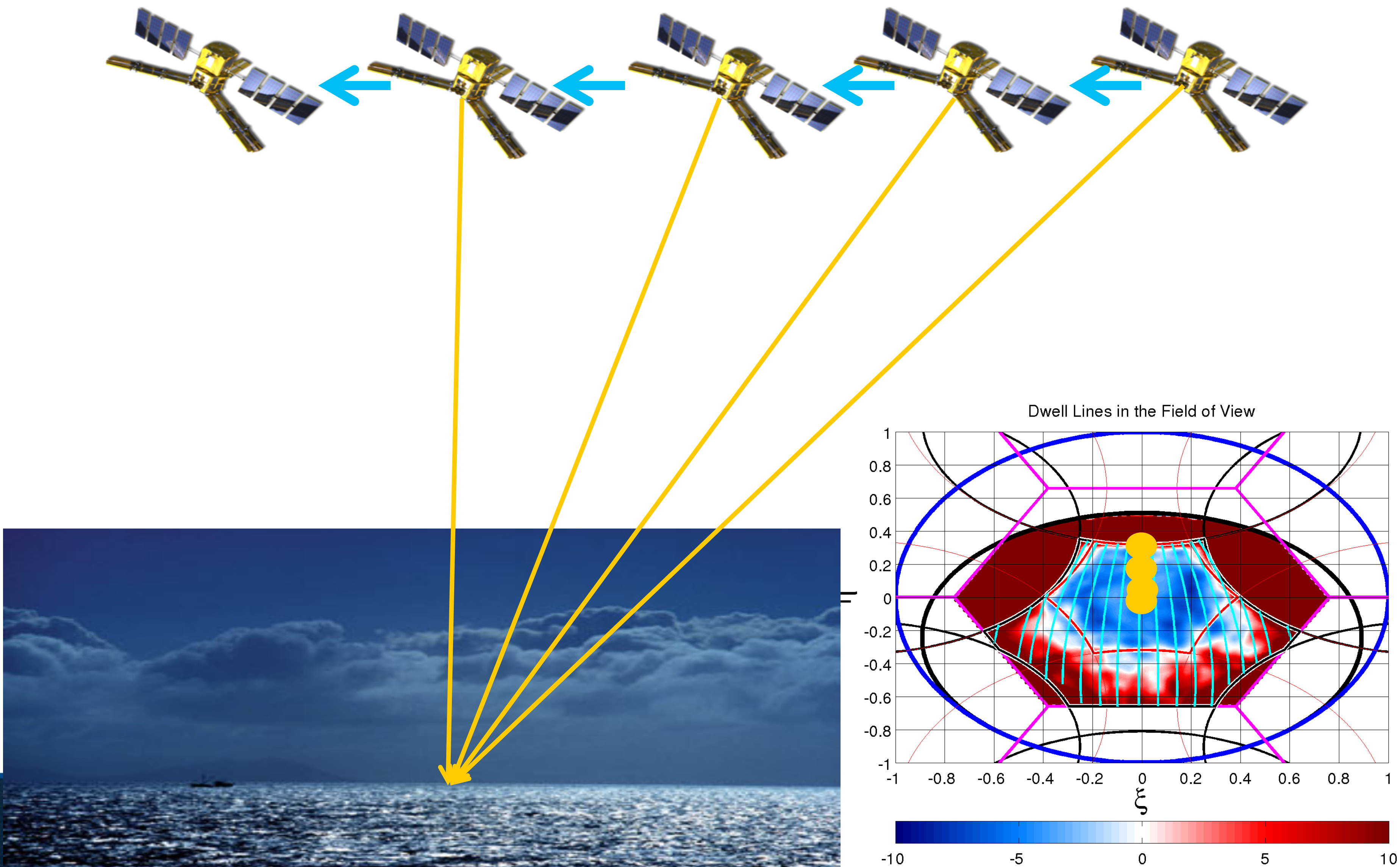
As the SMOS satellite propagates along its orbit, a given point on earth appears in many snapshots at a large range of incidence angles…





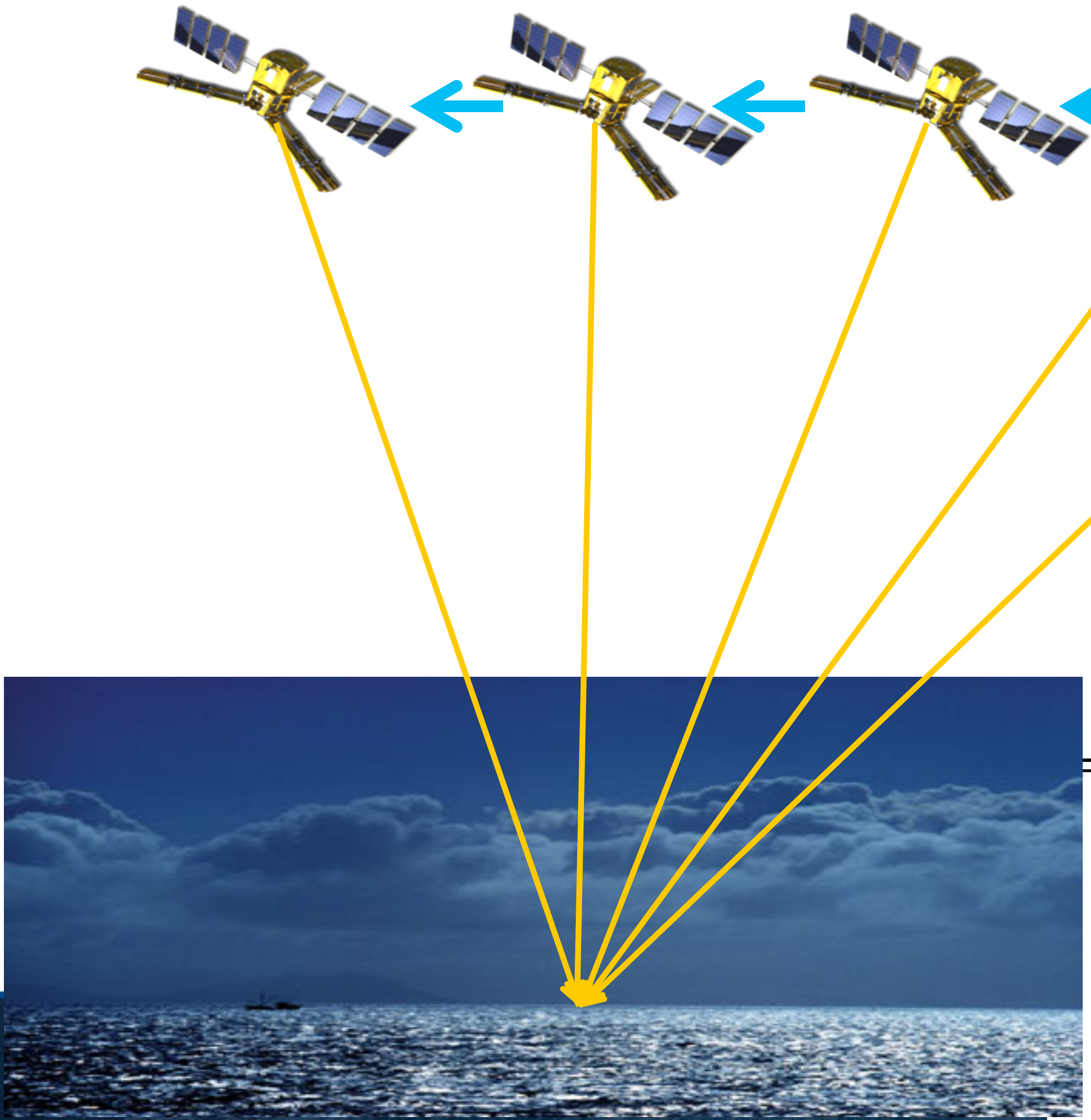
THE CONCEPT OF A DWELL LINE

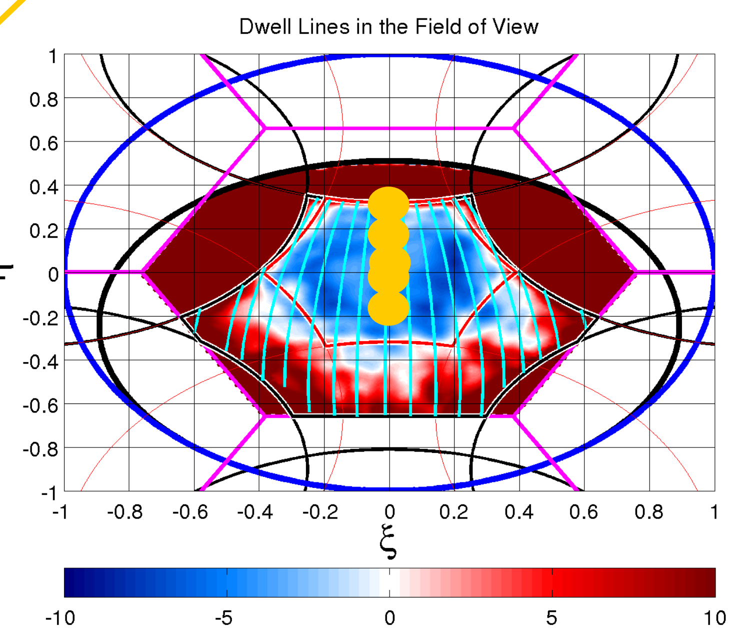
As the SMOS satellite propagates along its orbit, a given point on earth appears in many snapshots at a large range of incidence angles…



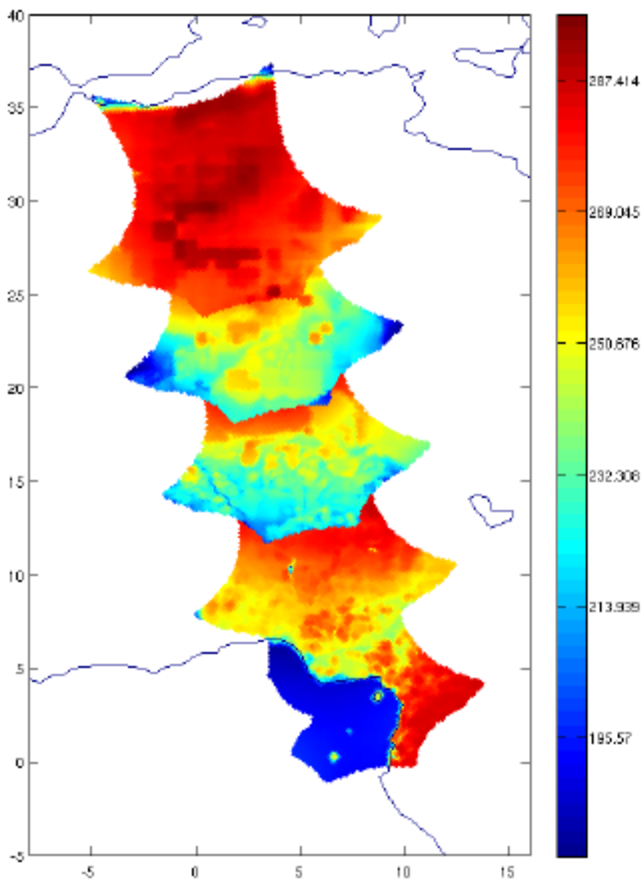
THE CONCEPT OF A DWELL LINE

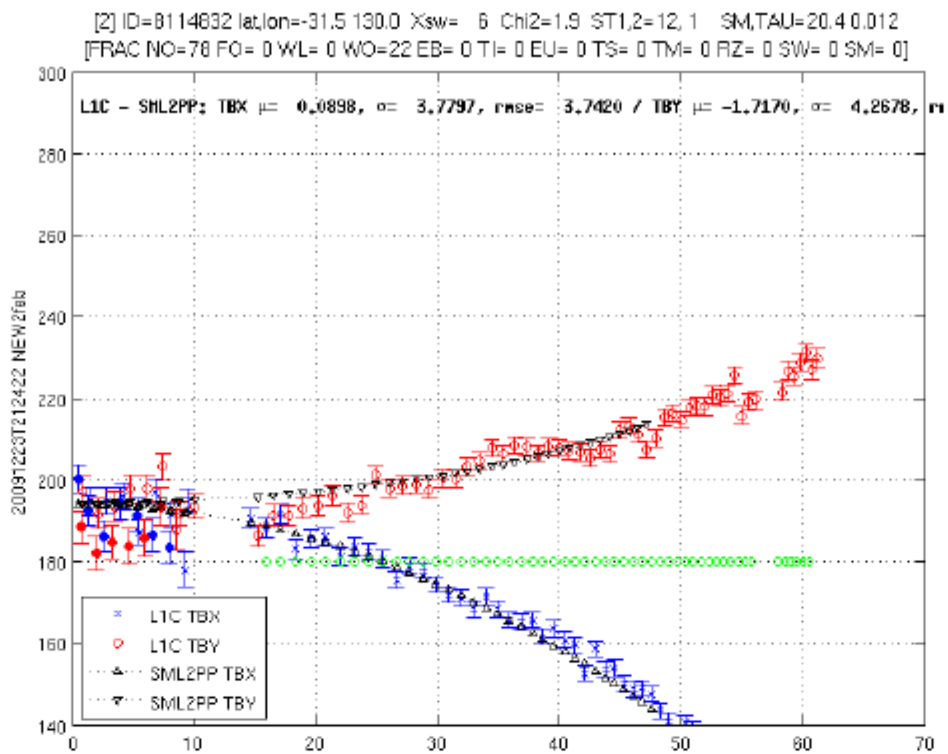
As the SMOS satellite propagates along its orbit, a given point on earth appears in many snapshots at a large range of incidence angles…





THE MultiAngular SMOS Aquisition



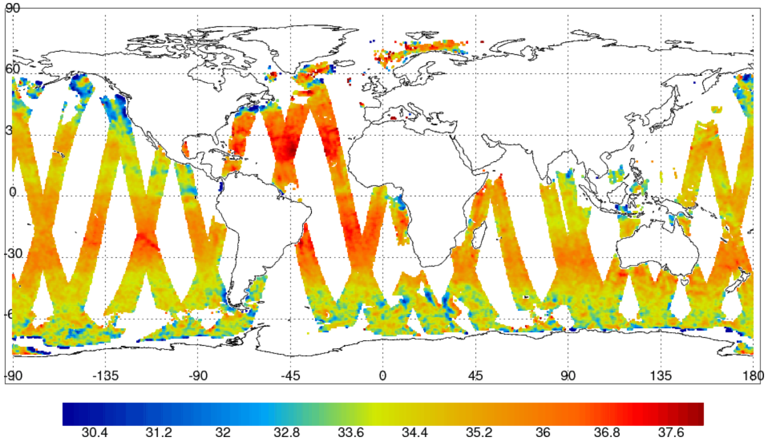


SMOS orbital characteristics

Morning ascending passes

Over terminator to minimise sun contamination

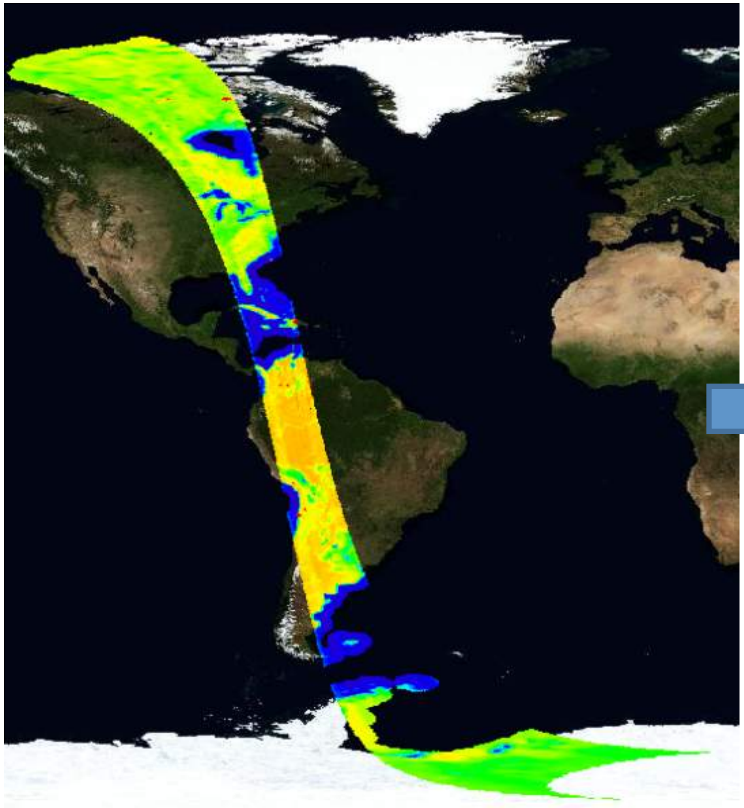
Parameter	Mean Value
Semi-major axis	a = 7134.552 km
Eccentricity	e = 0.00116
Inclination (sun-synchronous)	i = 98.445°
Argument of perigee	ω = 90°
Mean Local Solar Time	Ω = 06:00 AM
Repeat cycle / cycle length	149 days, 2144 orbits
Orbital duration	6004.478 s



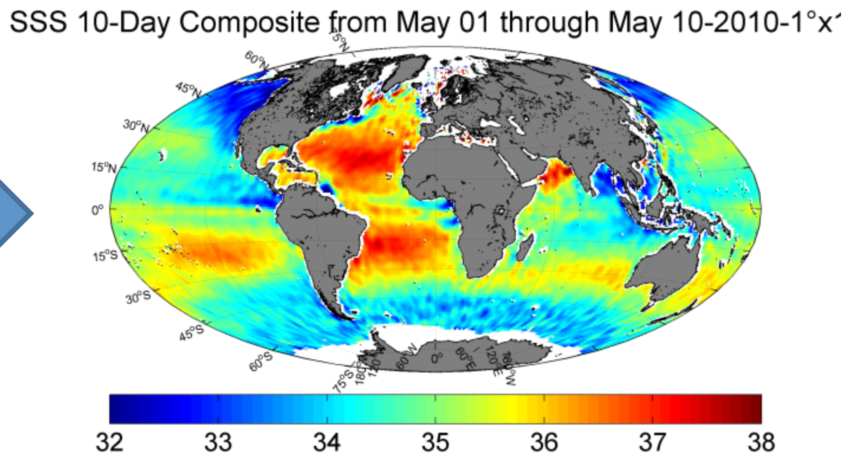
1 day of SMOS data over the ocean

How in Practice ?

Brightness Temperature



Salinity maps



SMOS L2 OS retrieval method

SMOS SSS is retrieved through a least square minimisation of the difference between SMOS and modeled Tb along a dwell line:

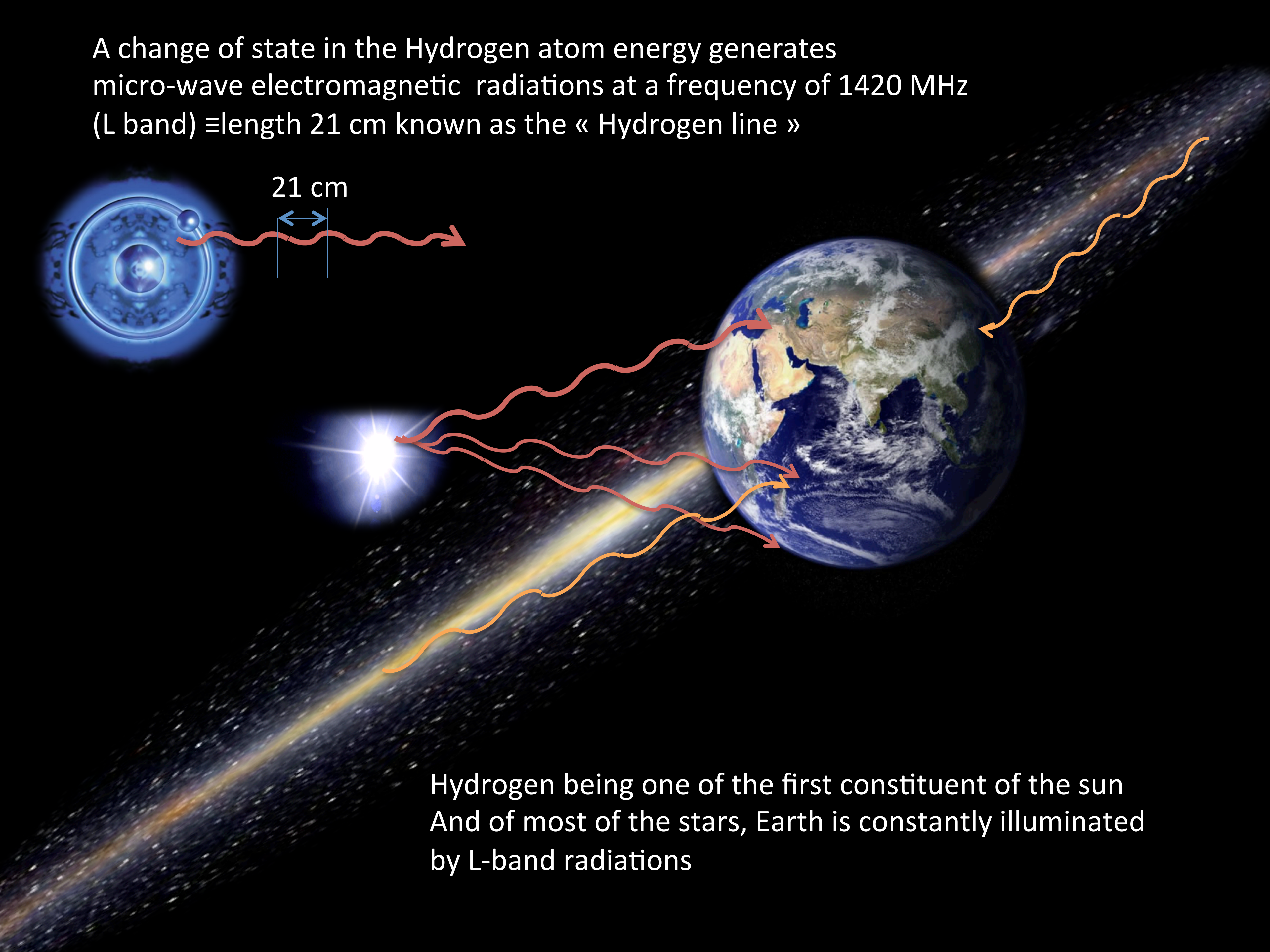
Retrieval of SSS (σ=100pss), SST (σ=1°C), WS(σ=2m/s on wind components (model 1), σ=2m/s on wind modulus (model 2 & 3)), TEC (σ=5TecU) through the minimisation of:

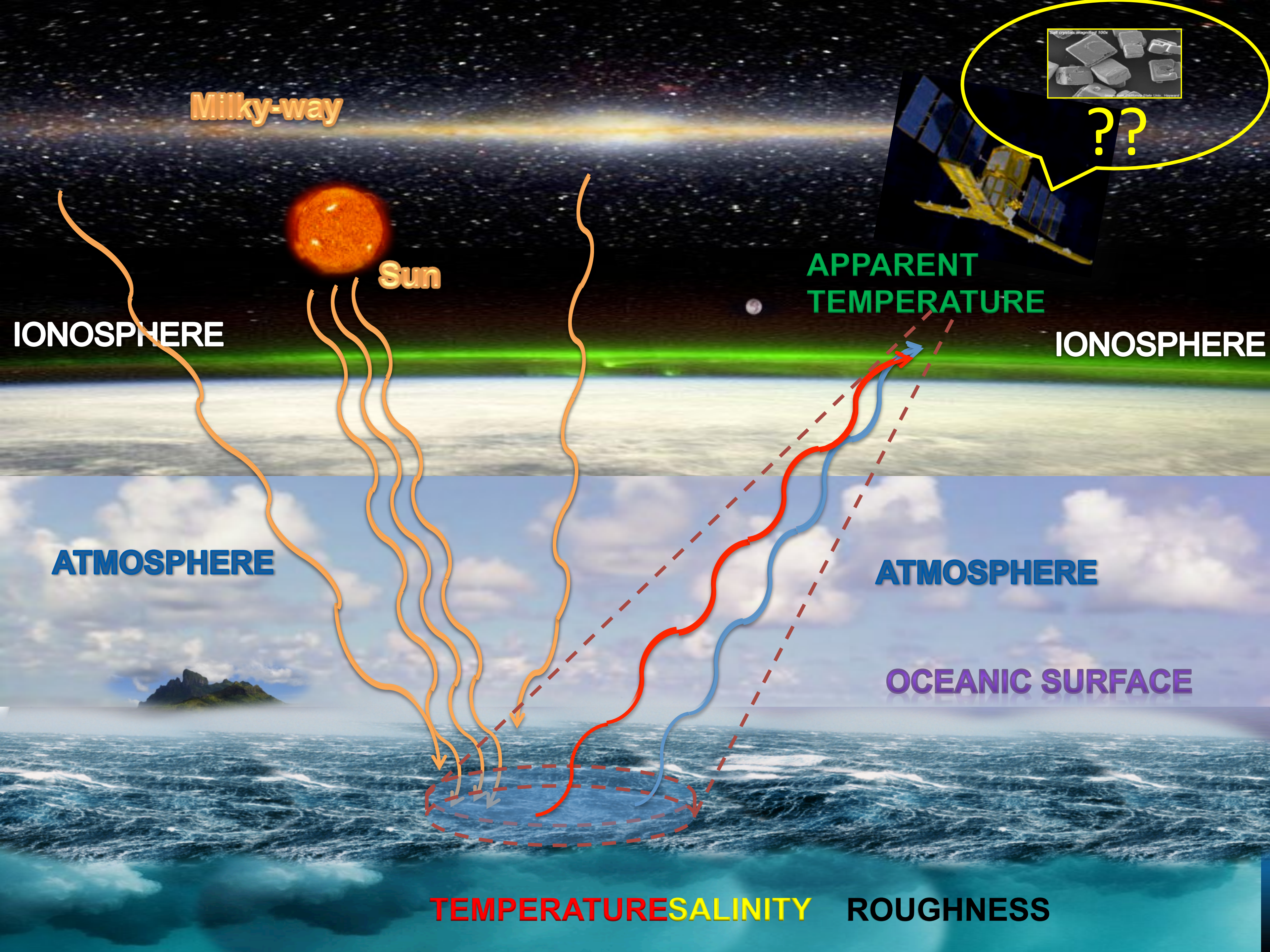
$$\chi^2 = \sum_{i=0}^{Nm-1} \frac{\left[T_{b\,i}^{\,meas} - T_{bi}^{\,\mathrm{mod}}(\theta, P)\right]^2}{\sigma_{T_{bi}}^{\;2}} + \sum_{j=0}^{Np-1} \frac{\left[P_j - P_{j,\,prior}\right]^2}{\sigma_{P_j}^{\;2}}$$

(iterative Levenberg & Marquard algorithm)

Tb^{meas} corrected for OTT

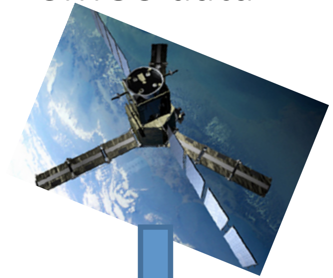
Tb^{mod} is computed at antenna level (Tx, Ty) in order to avoid interpolation for getting same incidence angle.


A change of state in the Hydrogen atom energy generates
micro-wave electromagnetic radiations at a frequency of 1420 MHz
(L band) ≡length 21 cm known as the « Hydrogen line »
21 cm
Hydrogen being one of the first constituent of the sun
And of most of the stars, Earth is constantly illuminated
by L-band radiations

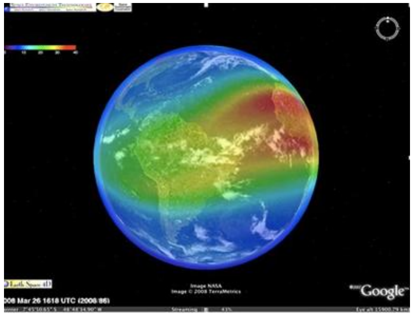

Milky-way
Sun
??
APPARENT
TEMPERATURE
IONOSPHERE
IONOSPHERE
ATMOSPHERE
ATMOSPHERE
OCEANIC SURFACE
TEMPERATURE
SALINITY
ROUGHNESS

Retrieving SSS from Space: a challenge !

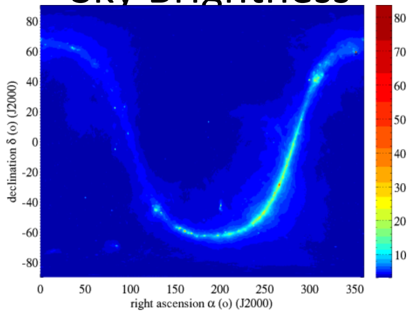
SMOS data



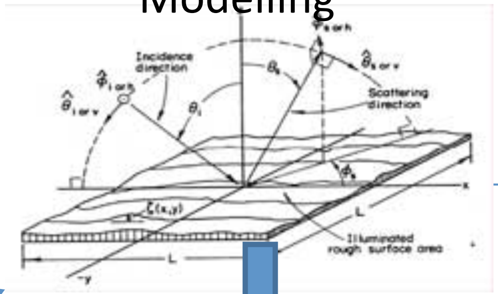
Ionosphere



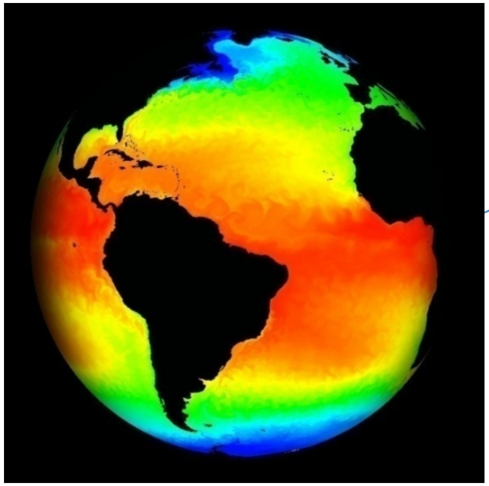
Sky Brightness



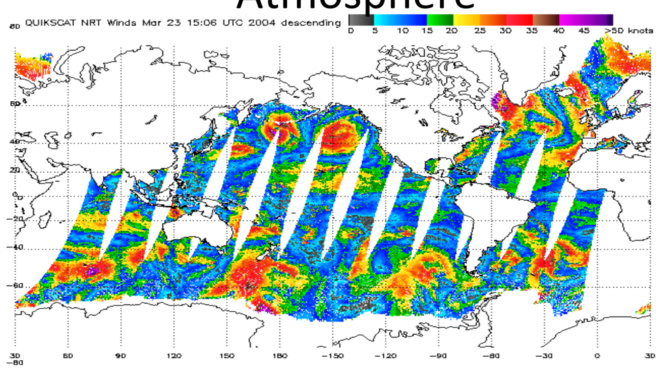
Electromagnetic Modelling



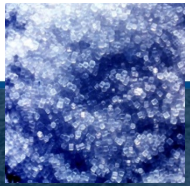
Sea Surface Temperature



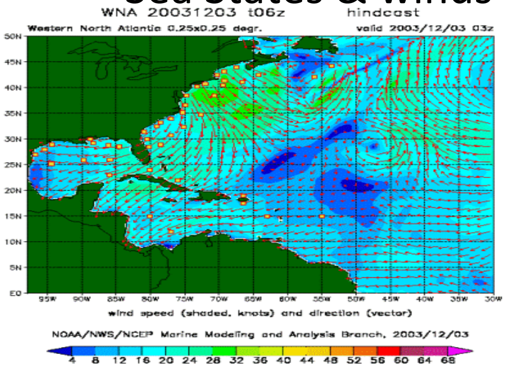
Atmosphere



Salts



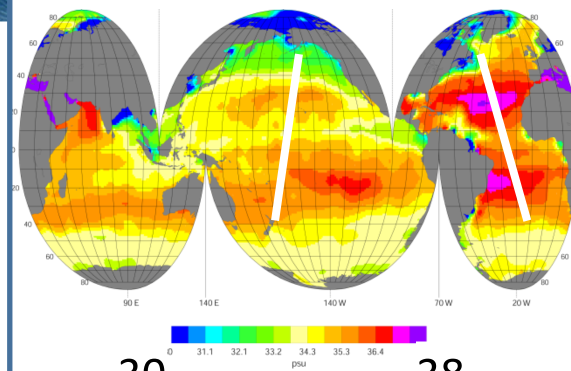
Sea States & winds

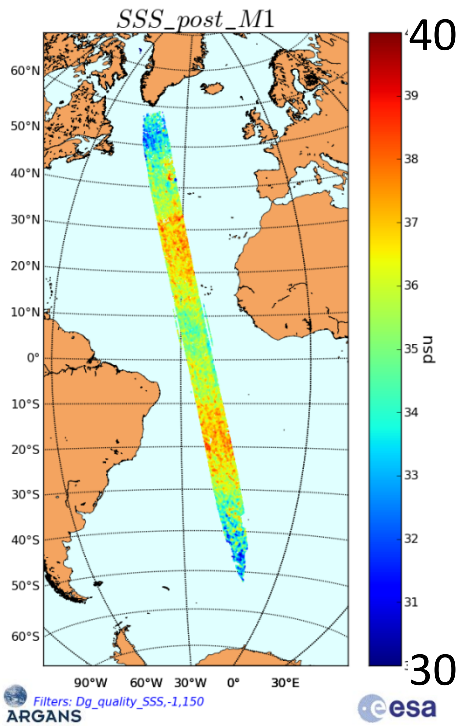


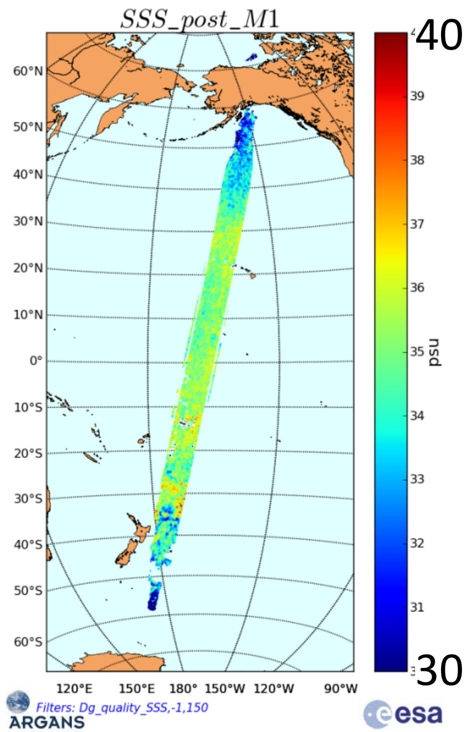
What can SMOS achieve in salinity observations?

A technological and scientific challenge

SSS Monthly Climatology





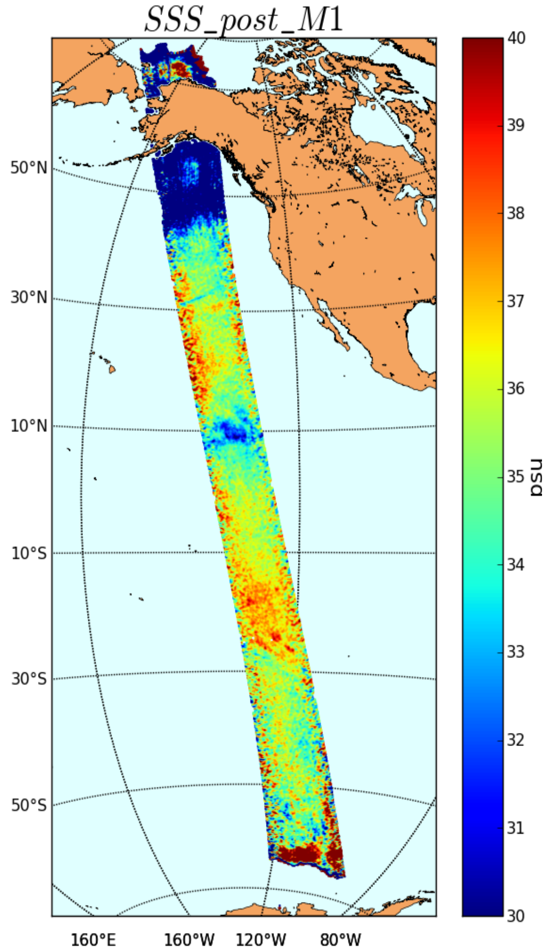


SMOS SSS from one ascending and one descending semi-orbit on 24 Jul 2012 after removing flagged data (http://www.argans.co.uk/smos/pages/products.php)

Along track Level 2 SSS qualitatively OK but very noisy.
Average needed to check mission requirements (Level 3)

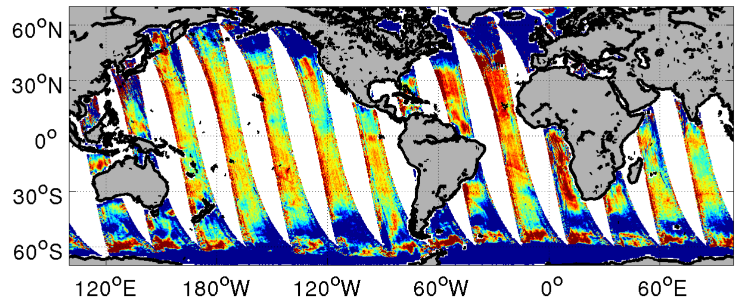
SMOS Level 2 SSS products

½ orbit

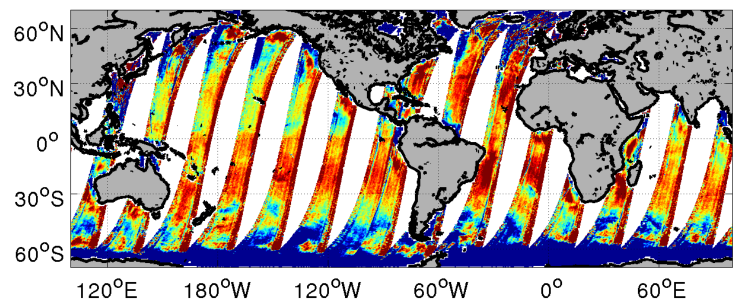


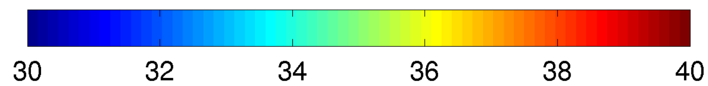
1 day

Passes ascendantes



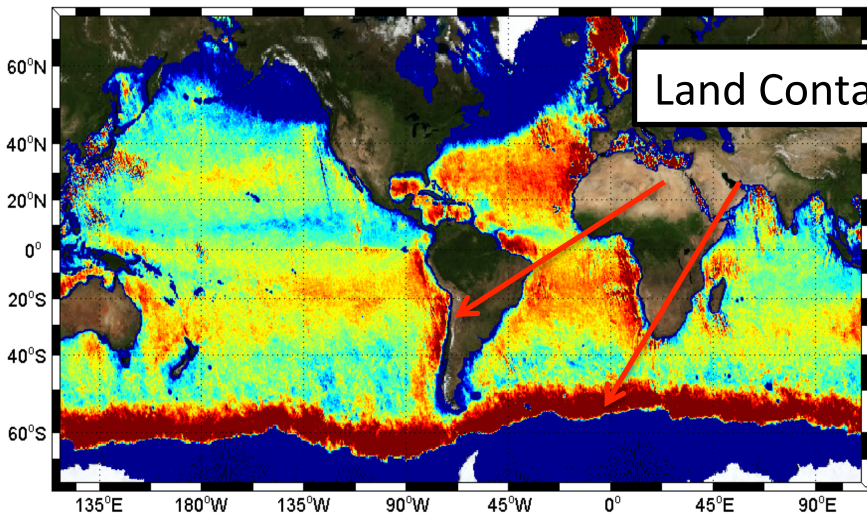
Passes descendantes



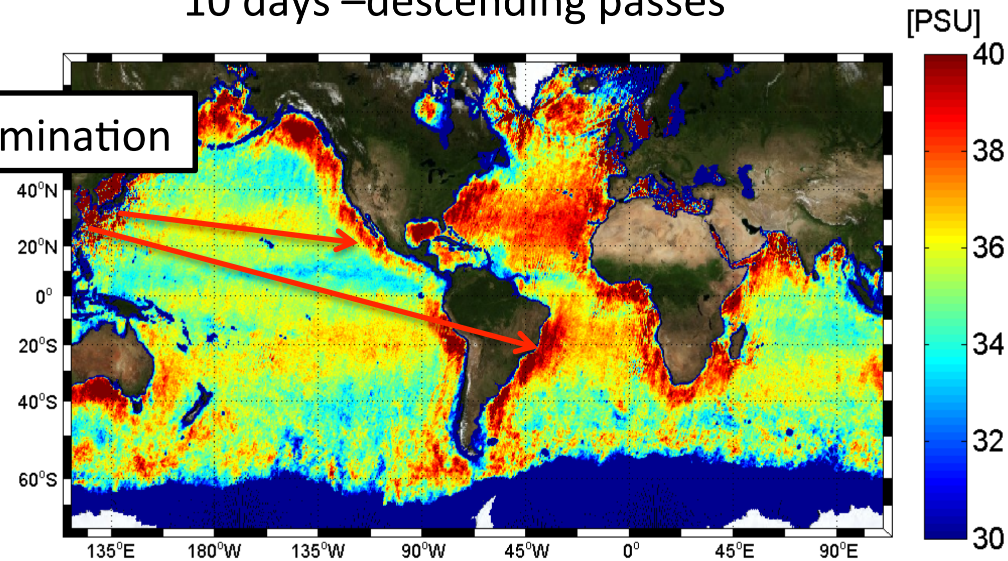


SMOS simple averaging L3 products

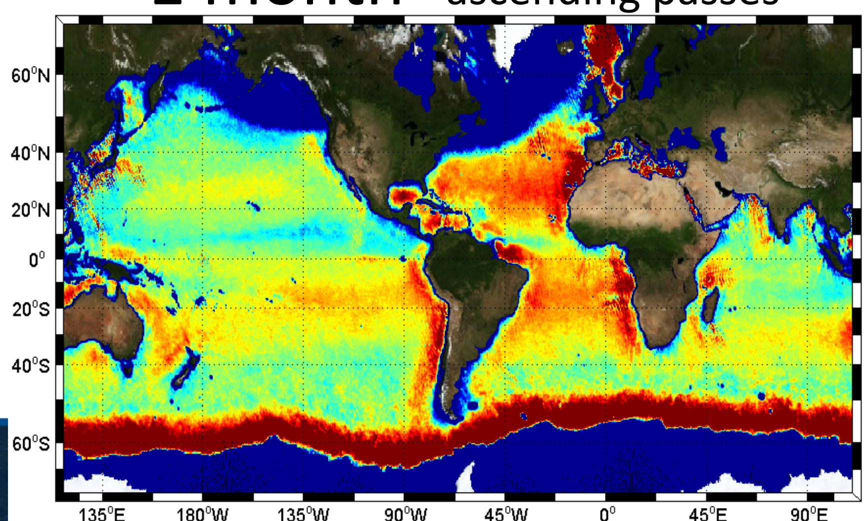
10 days –ascending passes



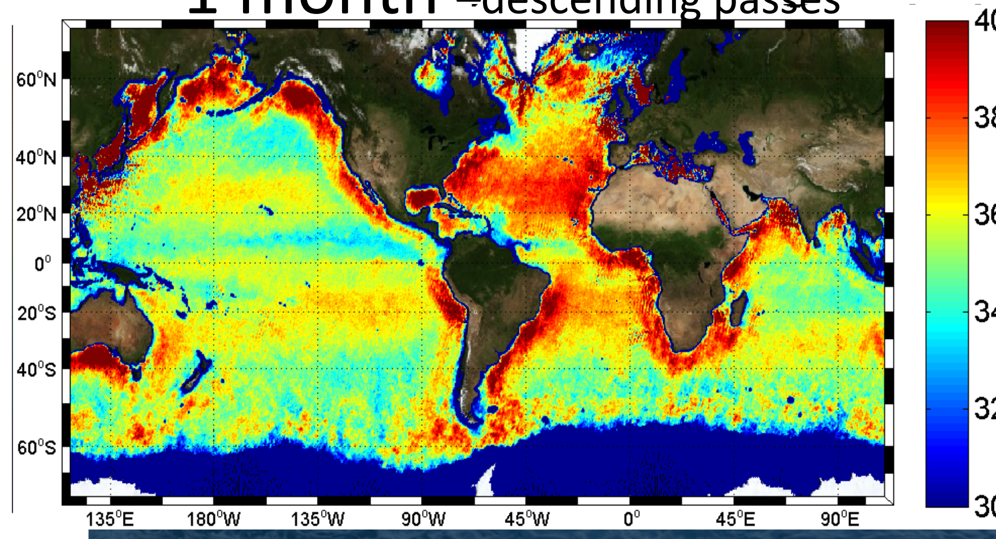
10 days –descending passes



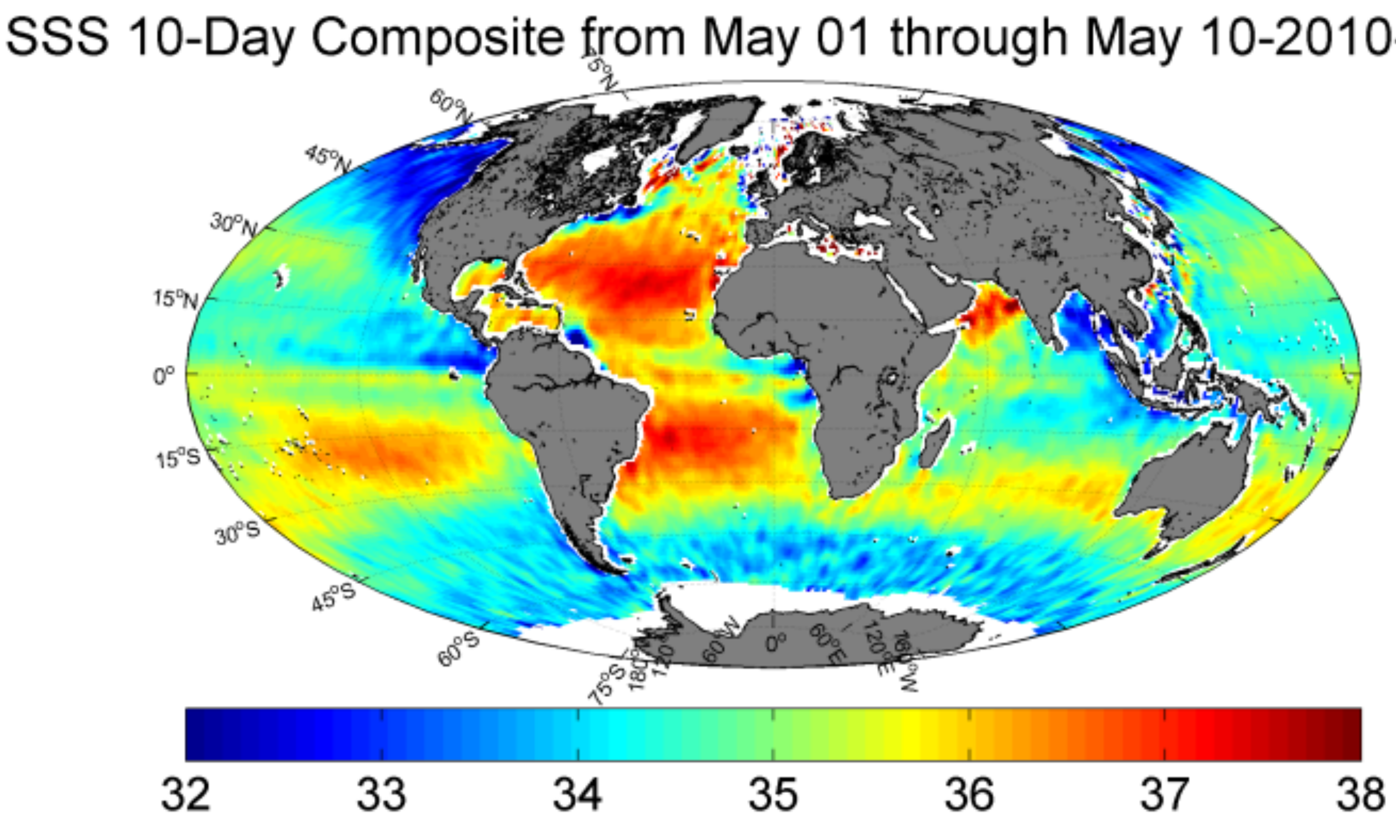
1 month –ascending passes



1 month –descending passes



SMOS refined Level 3 SSS products



CATDS research CEC products

The SMOS products used:
Centre Aval de Traitement des Données SMOS (Level 3)

CNES/CESBIO/IFREMER
French ground segment
For SMOS L3 & L4

http://www.catds.ifremer.fr/

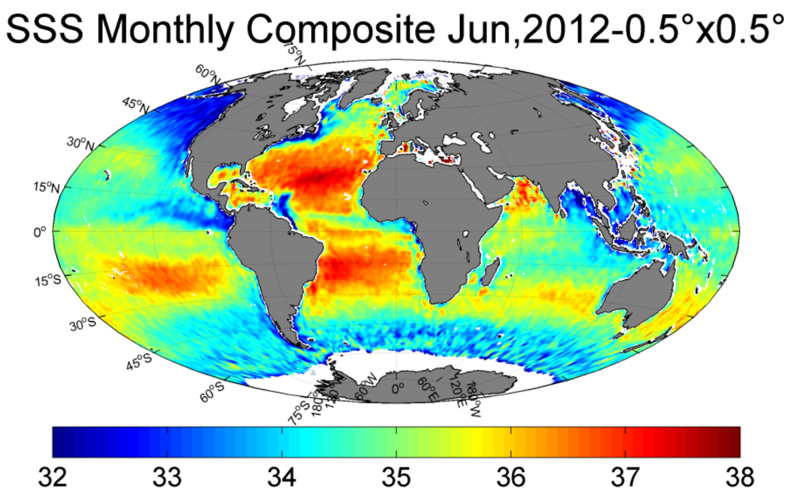
Data Period: 2010-2015

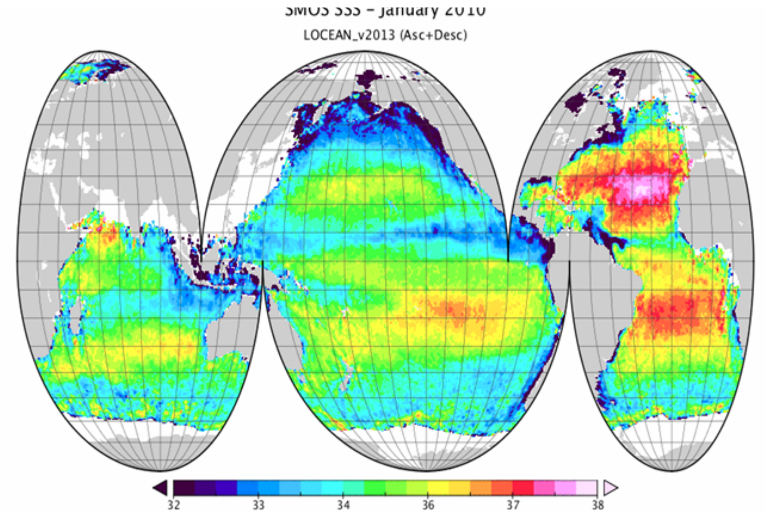
Table 1 Summary of characteristics of CATDS-CEC SSS level 3 products

	CEC-IFREMER	CEC-LOCEAN
SSS retrieval method	SSS retrieved from first Stokes parameter (Reul and Tenerelli 2011)	SSS retrieved from polarized Tbs along dwell lines using an iterative retrieval (see ESA L2OS ATBD)
Region of the instrument field of view (FOV) considered for SSS retrieval	Alias free field of view only	Alias free field of view (AFFOV) and extended AFFOV along dwell lines with at least 130 Tb data samples in AFFOV ($\sim\pm300$ km from the swath center)
Tb filtering method	Determined from interorbit consistency in incidence angles classes and thresholding	Determined from consistency along dwell lines as reported in ESA level 2 products
Galactic model	Geometrical optics model	Kirchoff's approx. scattering at 3 m/s
Roughness/foam models	Empirical adjustment of Tb dependencies to wind speed	Empirical adjustment of parameters in roughness model and foam coverage models (Yin et al. 2012)
Calibration	Single ocean target transformation (OTT) + daily $5° \times 5°$ adjustment wrt World Ocean 2001 SSS climatology	Variable OTT (every 2 weeks synchronized with noise injection radiometer as defined in ESA reprocessing)
Average	Simple average	Average weighted by theoretical error on retrieved SSS and spatial resolution

Global SMOS salinity maps: CATDS products

SMOS-CATDS-CEC Level 3 product (see http://www.catds.fr/): Monthly Composite





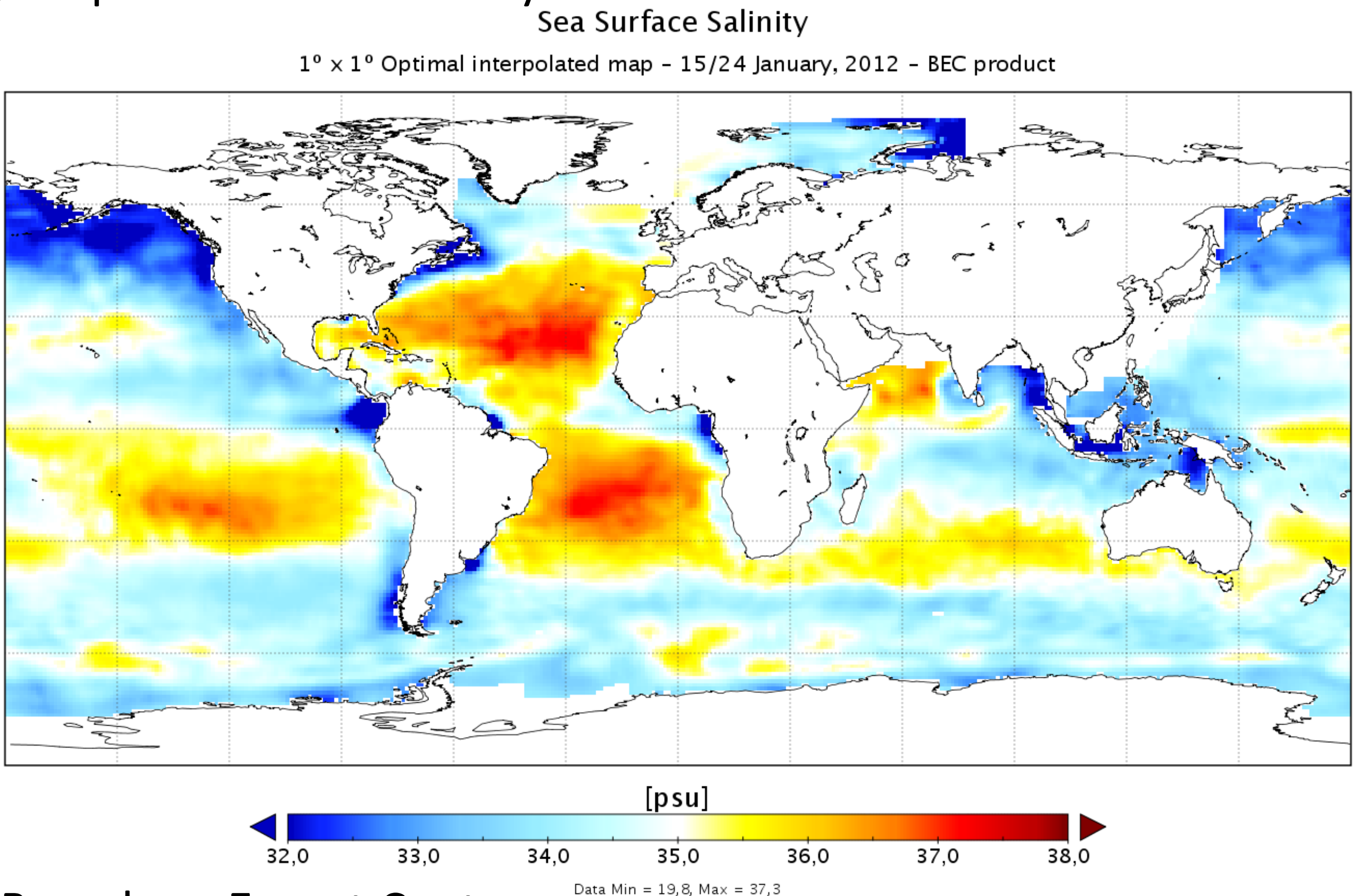
IFREMER-CEC
Stronger RFI filtering than ESA L2
Strong constraints wrt SSS climatology

LOCEAN (ESA L2 binned SMOS SSS)

So, several SSS products exists but needed because none of them is perfect and parallel efforts & progresses are required

Global SMOS salinity maps: BEC products

SMOS Level 3 product: 10 days / 1º optimally interpolated ocean salinity map for 15 – 24 January 2012



SMOS Barcelona Expert Centre

SMOS-ESA Documentation

- Newsletter (every ~2months)
- Available on *https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/smos/newsletter*
- =>Highlights (RFIs, new results etc…)
- =>Data availability (anomalies + calibration**)**
  (see also: https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/smos/available-data-processing)
- =>Upcoming meetings
- =>Data access

- L2OS release note (when new processed data delivered)
- => Recommendations about the use of released data (quality/defaults)
- Release note for v62x salinity data available on:
- *https://earth.esa.int/documents/10174/1854503/SMOS_L2OSv622_release_note*

- Access to SMOS data
- See https://earth.esa.int/web/guest/-/how-to-obtain-data-7329

Other Informations:

http://www.salinityremotesensing.ifremer.fr/

http//www.cesbio.ups-tlse.fr/us/indexsmos.html

http://www.argans.co.uk/smos

http://www.locean-ipsl.upmc.fr/smos

Special SMOS issue in IEEE TGRS, 2012

Special SMOS-AQUARIUS issue JGR 2014