

-The SMOS Mission-

N.REUL

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



Outline

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



**Why?
Why about salinity ?
And
Why about SMOS ?**

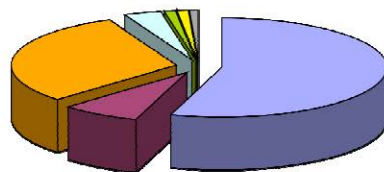
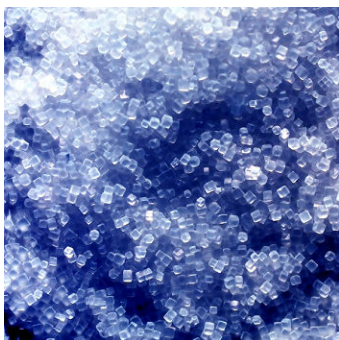
Salinity of the Ocean: What do we know about it ?



What is ocean salinity ?

Ocean salinity $S \equiv$ 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 \approx 1 g/kg.



Chloride (Cl ⁻):	19 g
Sodium (Na ⁺):	11 g
Sulphate (SO ₄ ⁻⁻):	3 g
Magnesium (Mg ⁺⁺):	1.5 g
Calcium (Ca ⁺⁺):	0,35 g
Potassium (K ⁺):	0,35 g
Others :	0,00.. g

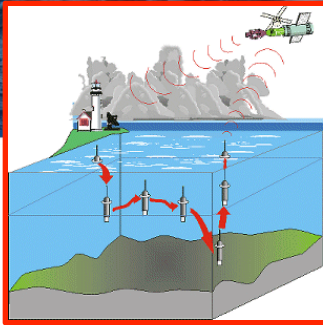
Total \approx 35 g/kg



(Mean chemical composition)

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

In Situ measurements of S



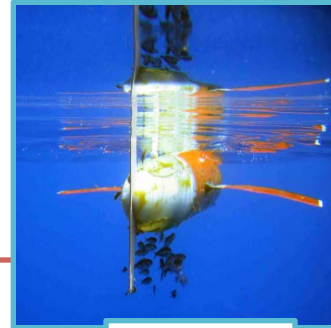
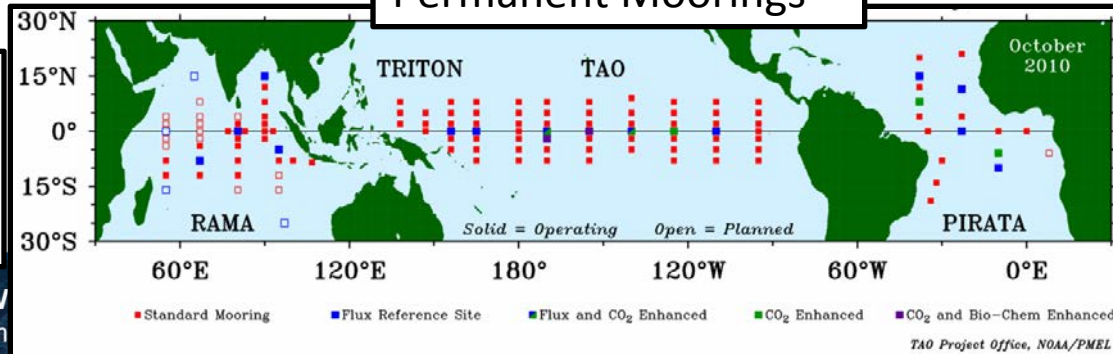
Profilers from the Argo network



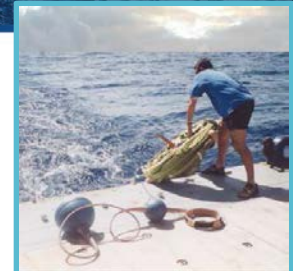
Thermo-salinographs
Installed onboard research
Vessels and ships of opportunity



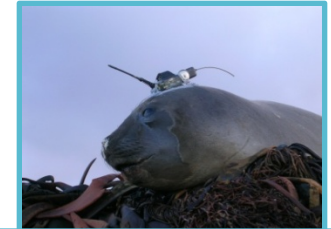
Permanent Moorings



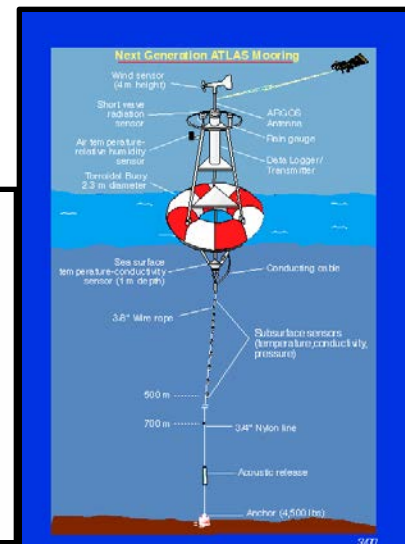
Gliders



Surface 'Drifters'

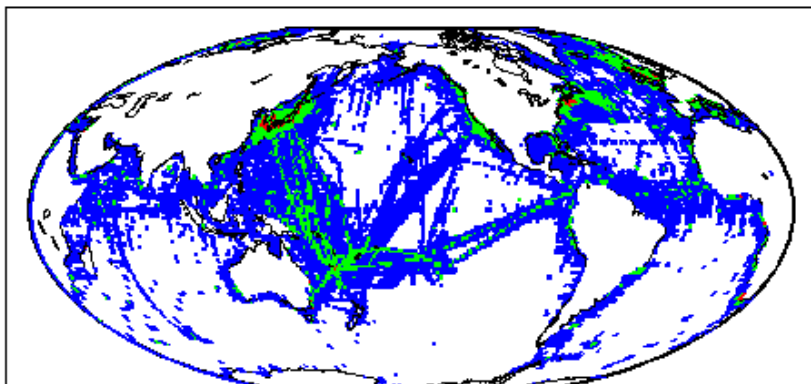


Equipped Mammals



Historical Density of surface observations 1874-2002

Number of Observations by 1° Square



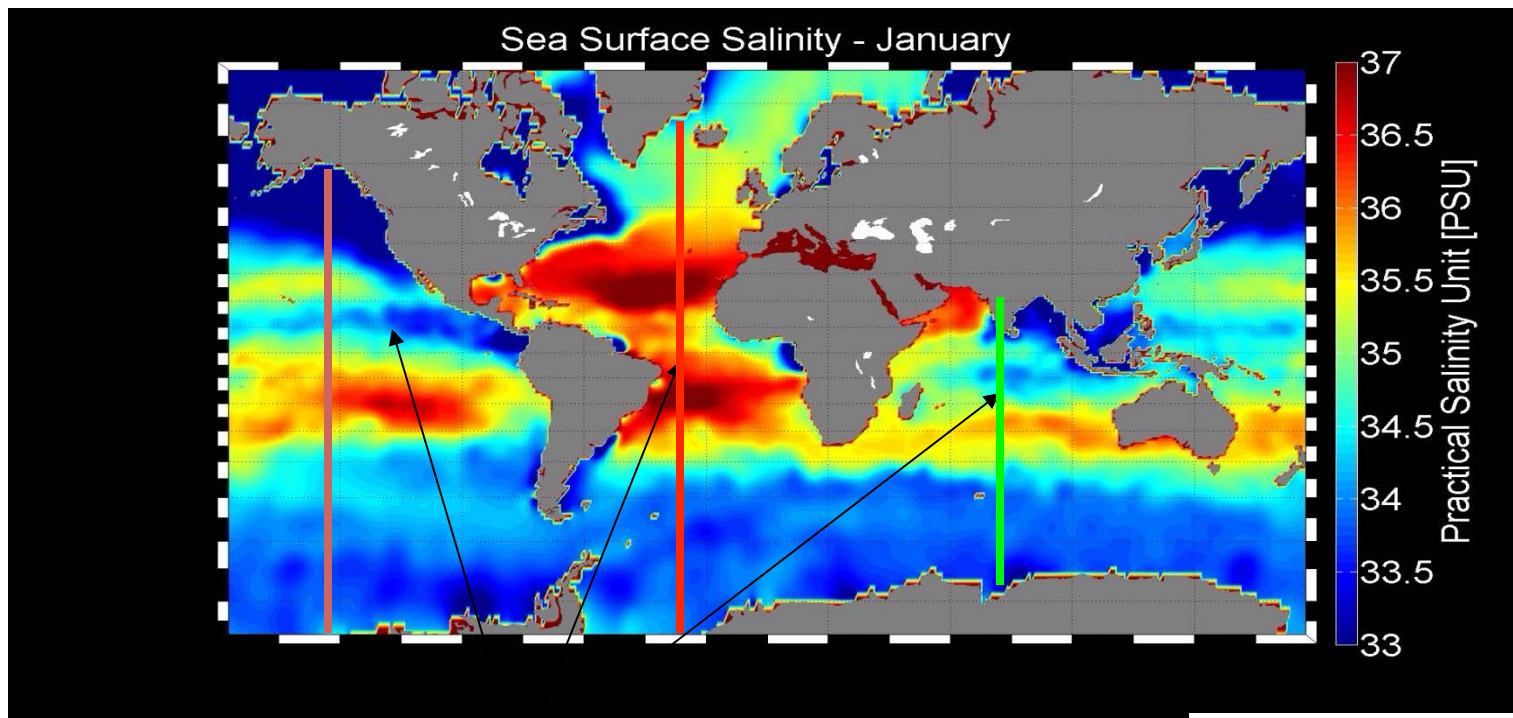
White - $N < 10$
Blue - $10 < N < 100$
Green - $100 < N < 1000$
Red - $1000 < N$

F. Bingham et al, 2002

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

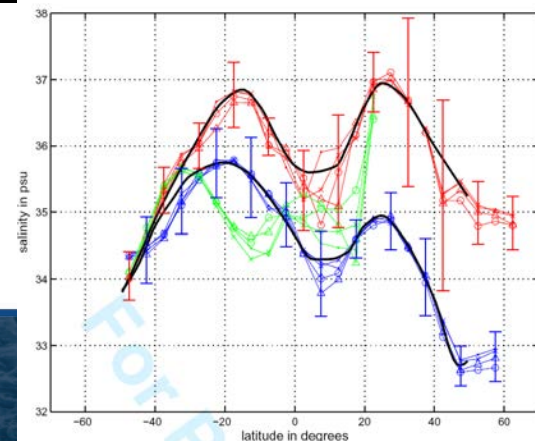
- ✓ No data in 27% elementary oceanic 1° x 1° area, not accounting for arctic zones.
- ✓ 70% of these surfaces present at most 10 historical observations
- ✓ 28% of all observations were sampled in the coastal domain
- ✓ Up to 1960, there was no more than 10,000 observations/year \Leftrightarrow 1 observation per 4°X4° cell
- ✓ Since 2002, very net increase in the density of measurements (ARGO network)

Monthly climatology of the sea surface salinity:



Atlantic Ocean saltier than Pacific and Indian oceans

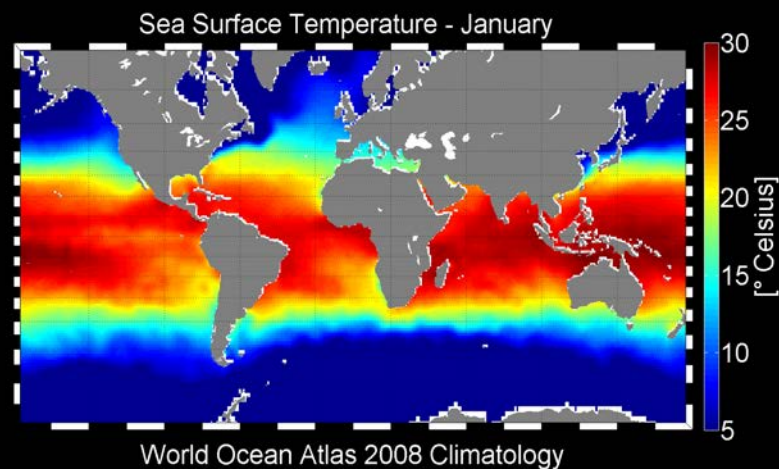
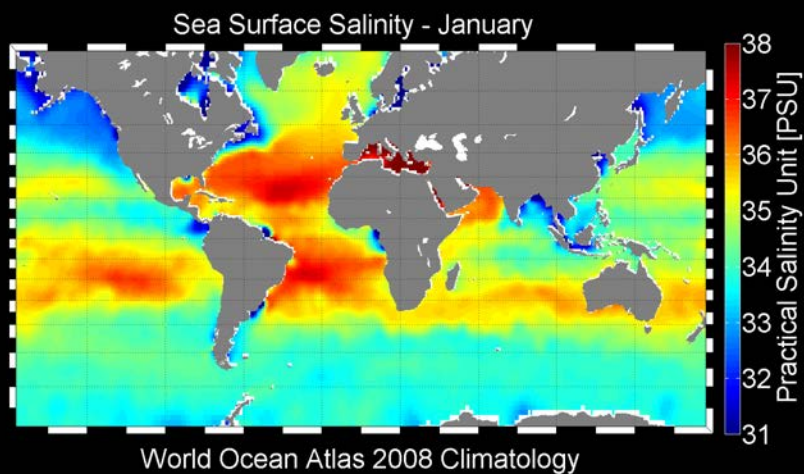
- ✓ Low variability particularly in the Southern seas and North Pacific
- ✓ But higher variability around large river run off (Amazon Congo, Yang Tse, Ganga..), largest currents (Gulf Stream, kuroshio, Agullas, ...) & in the Tropical bands



Salt versus temperature at the Ocean Surface

Salinity

Temperature



Global and seasonal 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 latitudes
- 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

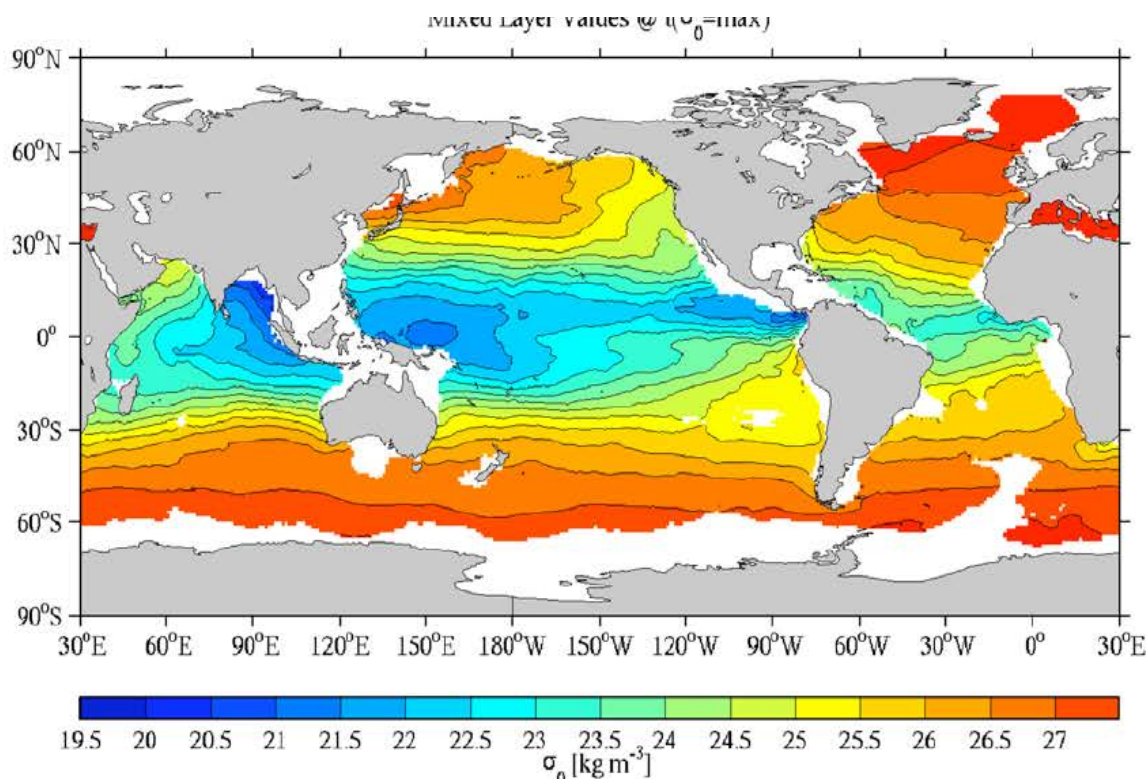


Salinity S & Temperature T are indicators of the water masses density ρ :

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

« State equation »

Similar to temperature and humidity for the atmosphere



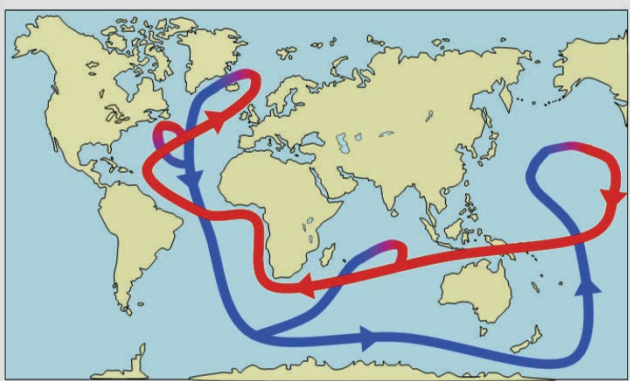
- Denser Poleward
- Equatorial Cold Tongue
- Salty (& Dense) N. Atlantic
- Warm Pool & ITCZ
- Eastern Subtropics
 - Compensating T & S
- Indian Ocean Contrast

Mixed Layer Values @ $t(\sigma_0 = \max)$



The Thermo-Haline Circulation

Idealized global thermohaline circulation (~1000 years)



- Warm surface currents
- Deep cold currents

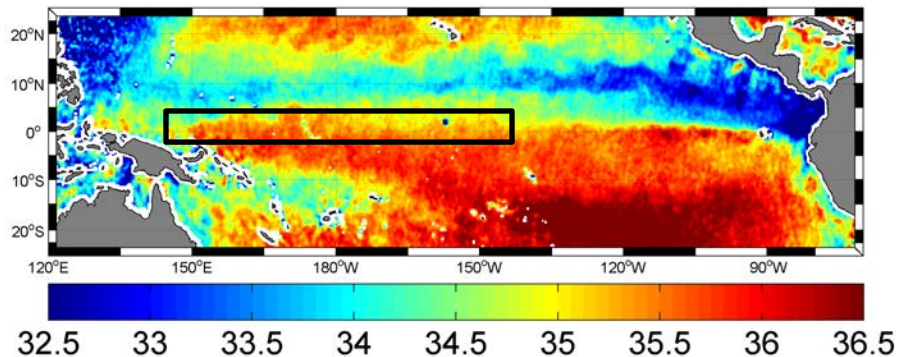
The higher salinity in the Atlantic sustains the oceanic deep overturning circulation



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

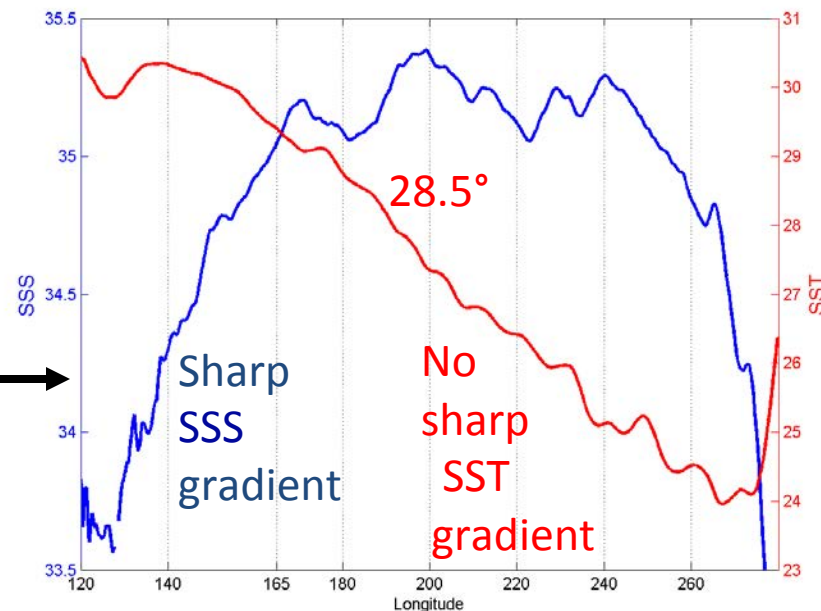
Oceanic Fronts Monitoring

SSS SMOS Nov



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

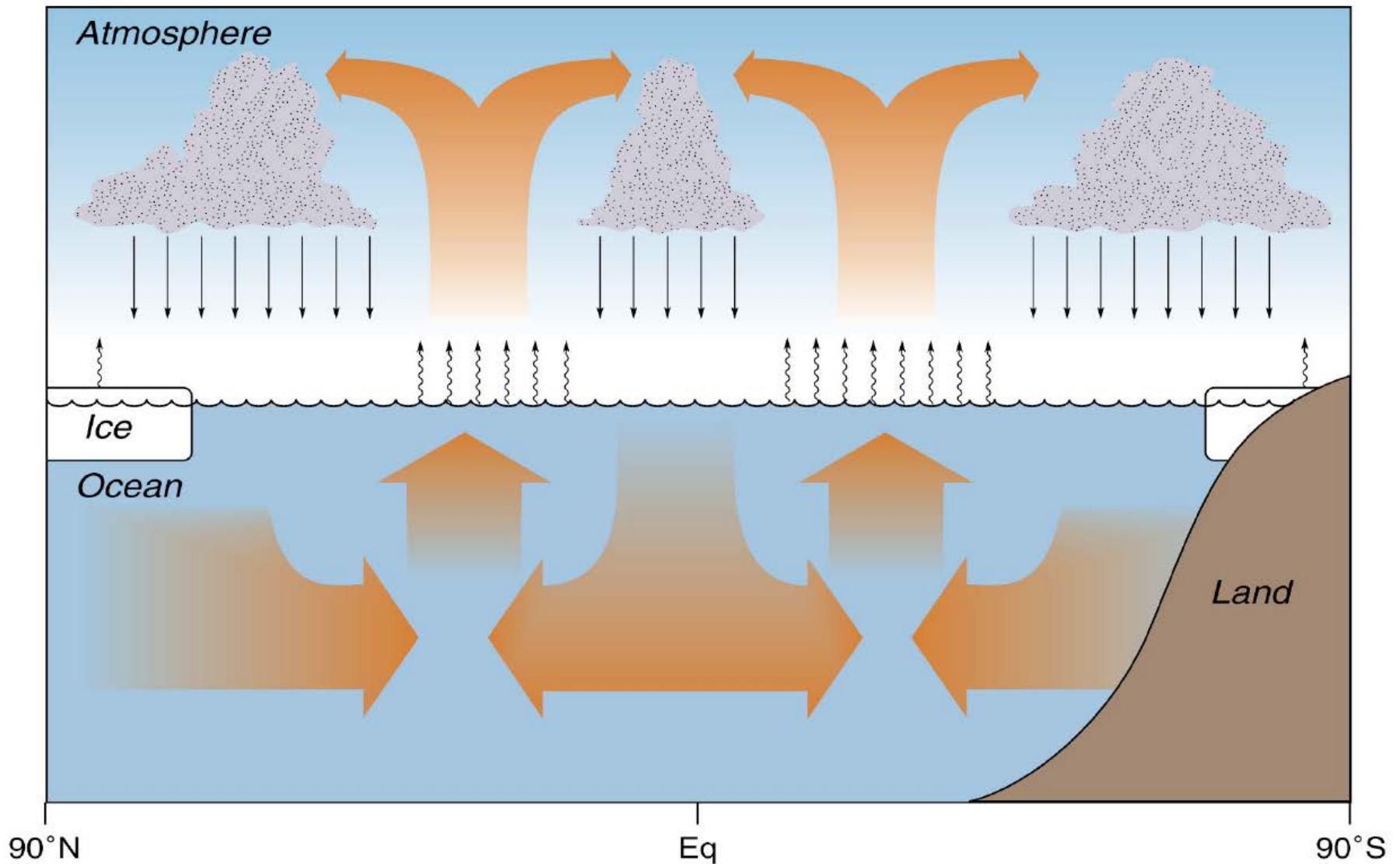
Equatorial Warm Pool Edge



Rodier et al. (JPO, 2000)

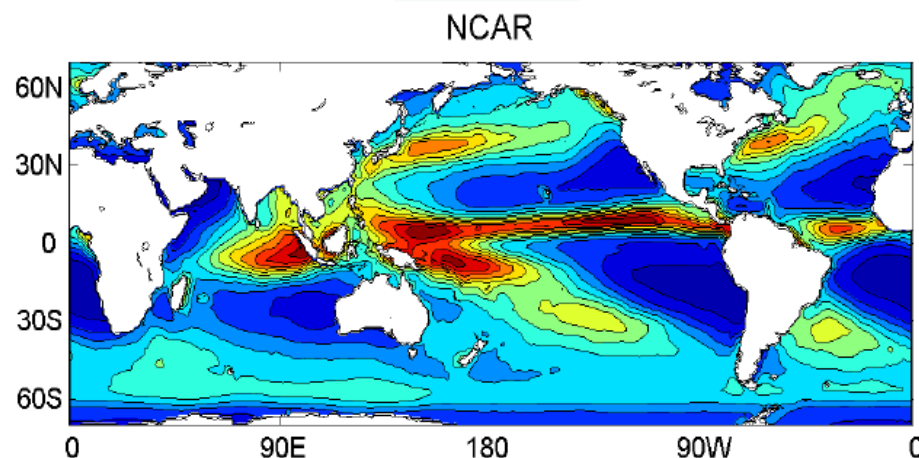
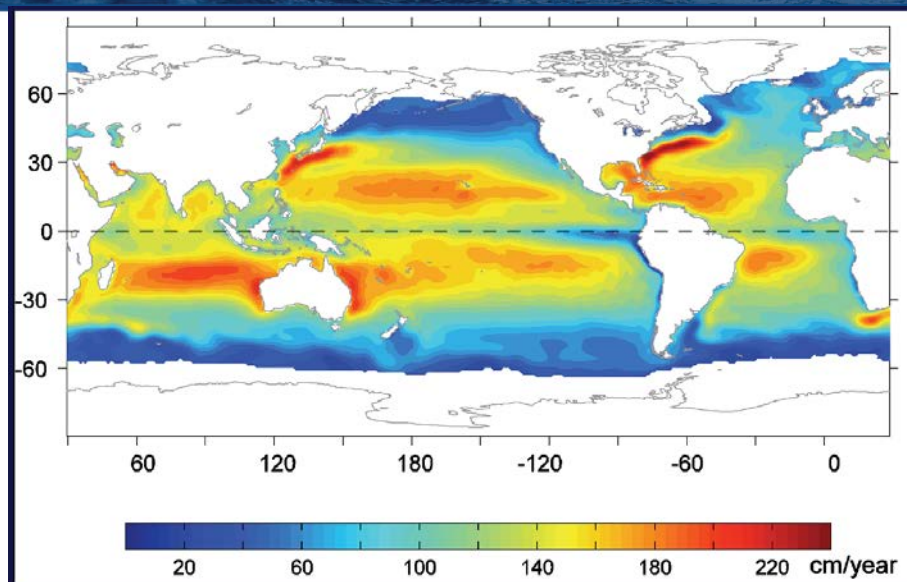
The Oceanographer's Water Cycle

Global Water Cycle



Evaporation

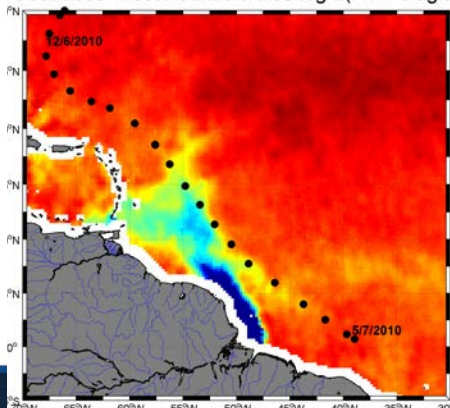
Precipitation



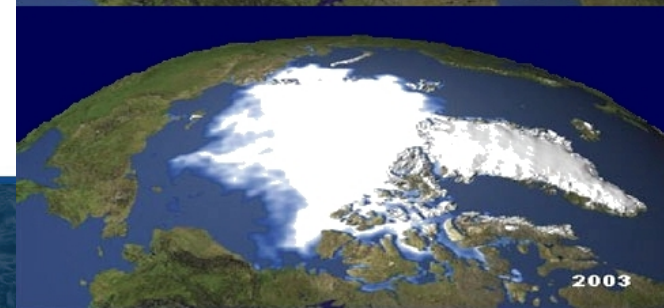
Sea ice Melting/Pounding

Large River run offs

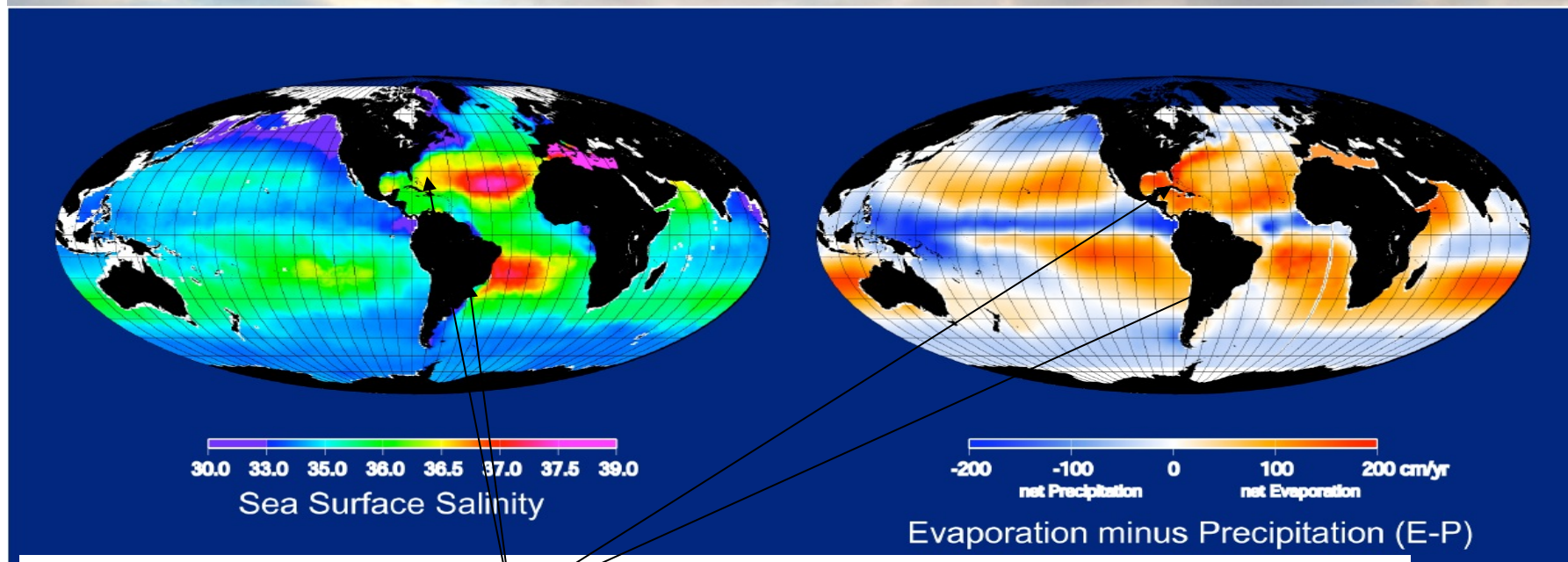
Geotraces West Atlantic cruise leg Z(RV Pelagia)



- 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:**



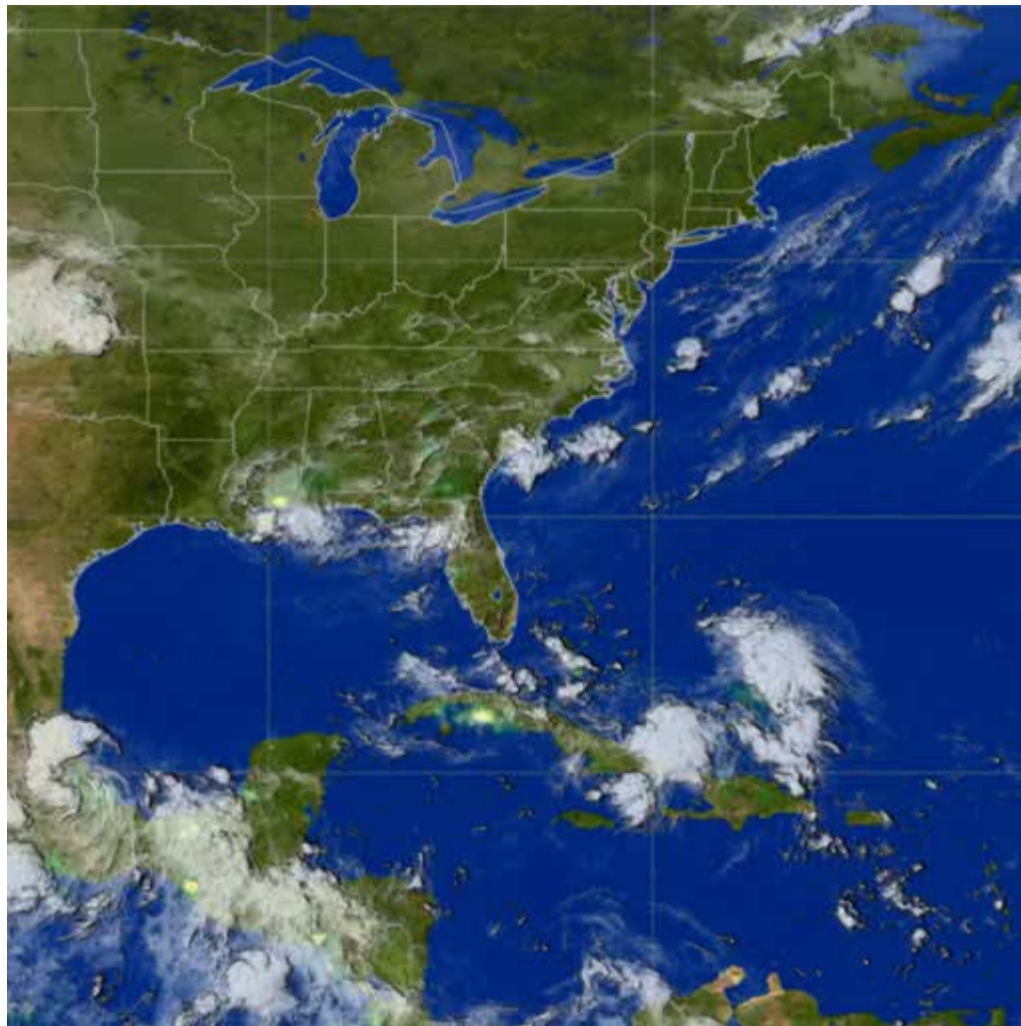
Surface salinity distributions are closely tied to E-P patterns



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 ?

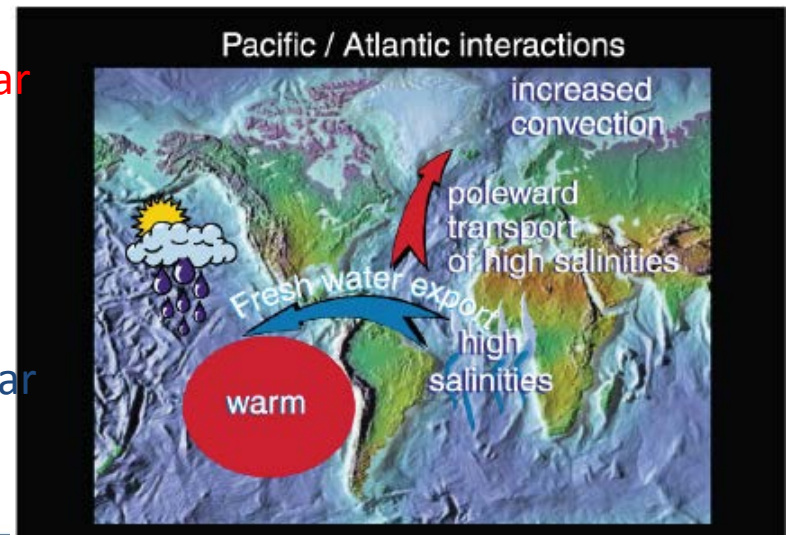
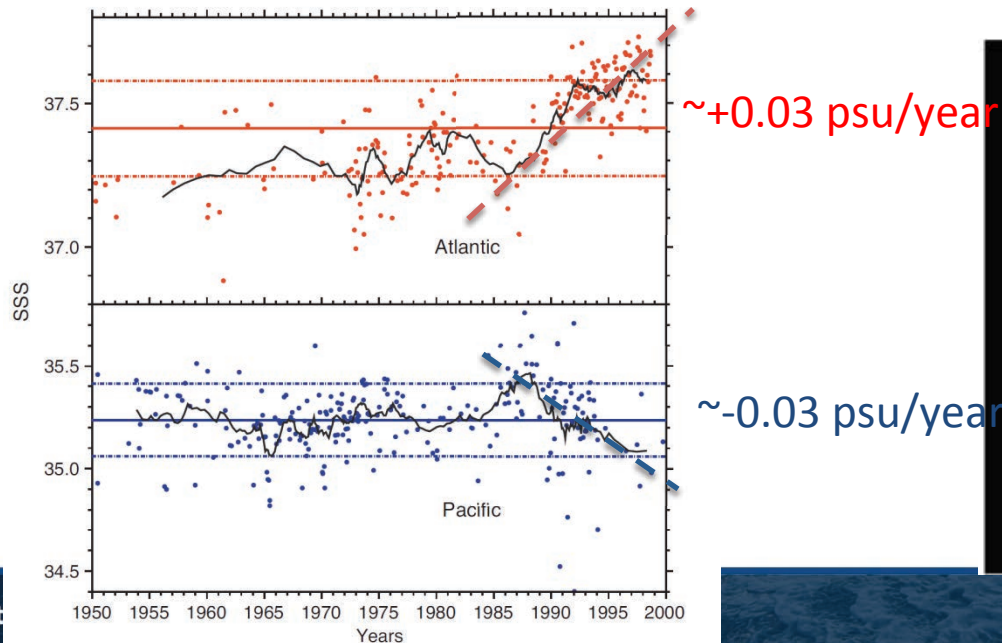
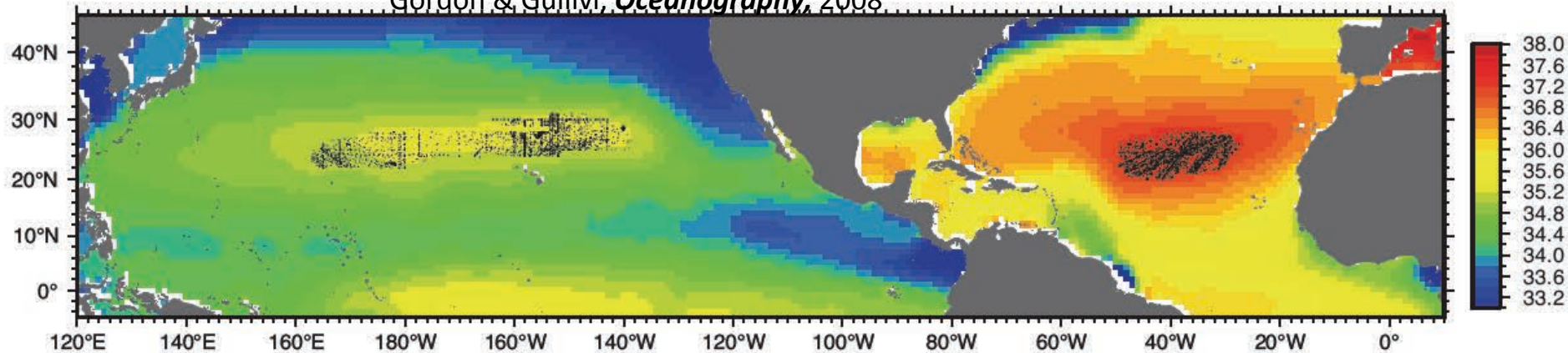
Very large winds=>mixing
And upwellings

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

Sea Surface salinity: a climate change indicator

Trends in Sea Surface Salinity in Pacific and Atlantic Oceans

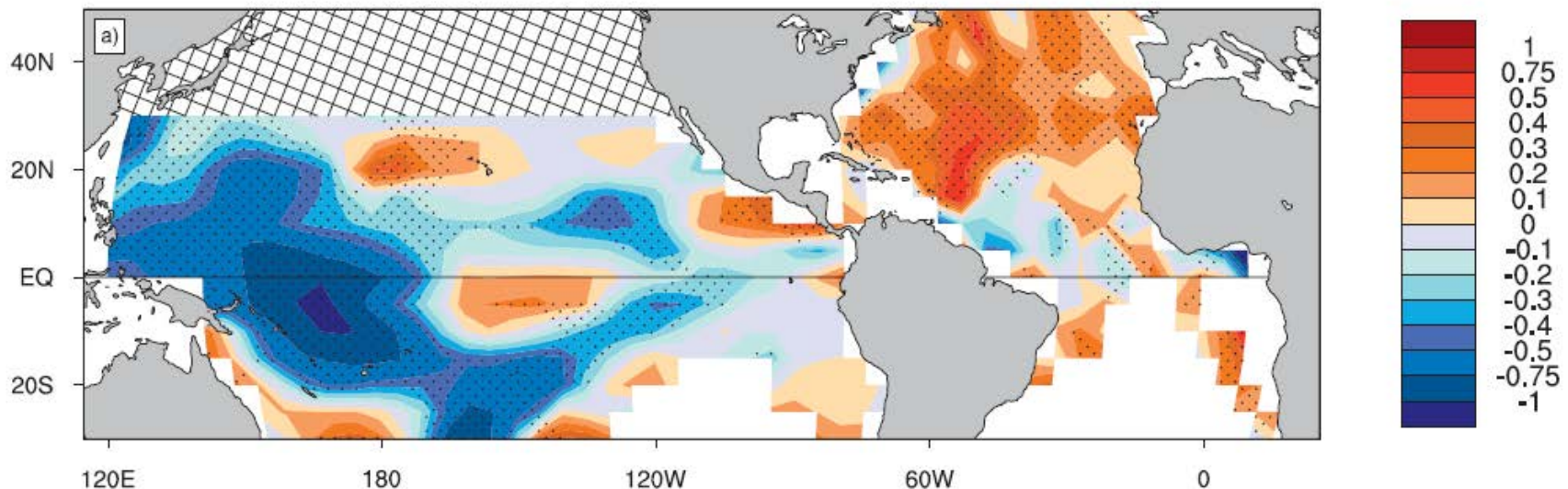
Gordon & Gillett, *Oceanography*, 2008.



→ 4t
7-
1950 1987 2000

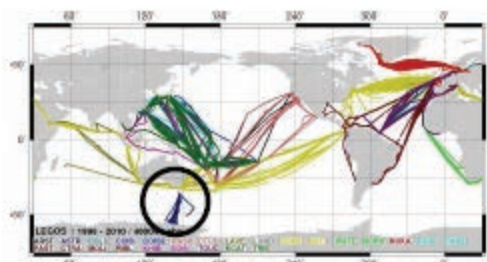
Near-Surface Salinity as Nature's Rain Gauge to Detect influence of Climate Changes on the Tropical Water Cycle

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

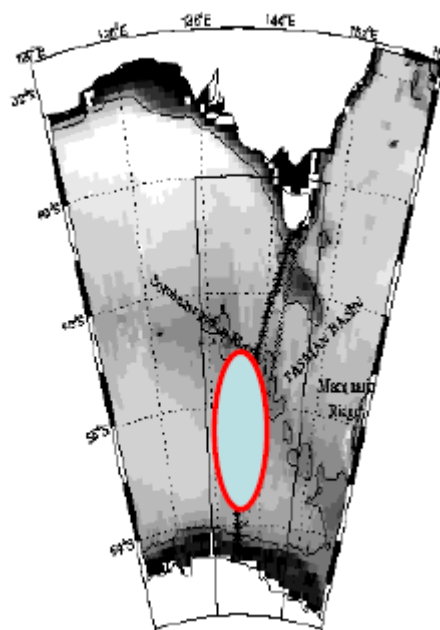


SSS changes over the past decades exhibit a strong Pacific freshening and Atlantic salinity increase leading to a strengthening of the mean SSS interbasin contrast, which reflects to a large extent the mean pattern of freshwater fluxes.

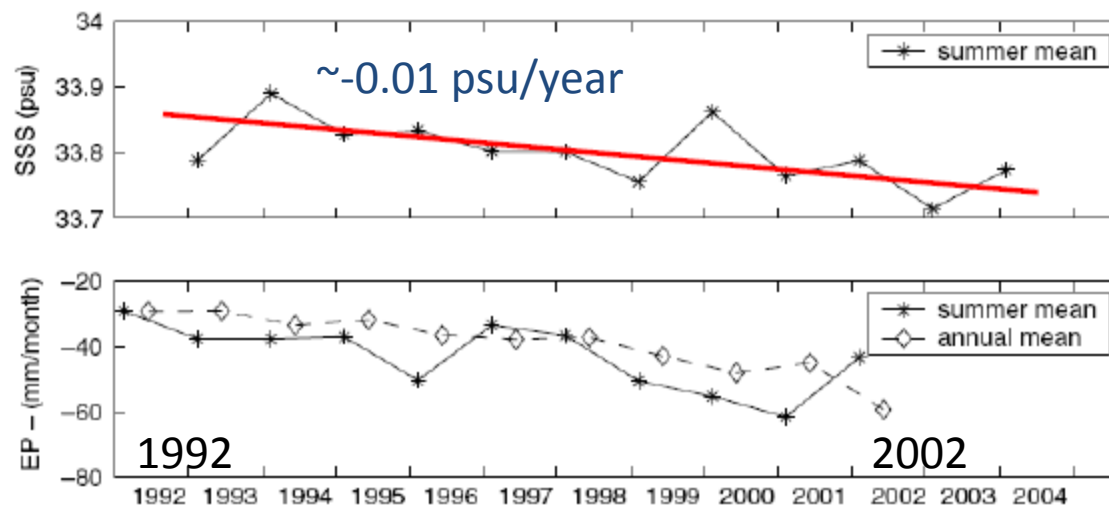
=>We observe a recent increase in the marine tropical hydrological cycle strength (Terray *et al*, 2012).



10 sections /year
since 1993



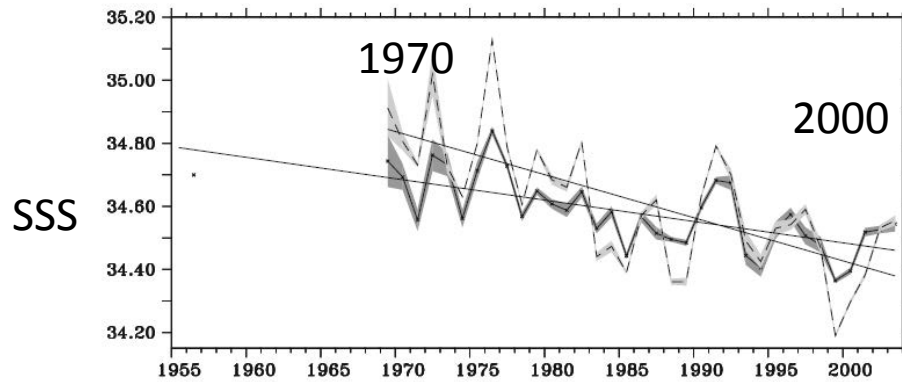
Decadal decrease in SSS related to increase in P



(Morrow et al., 2008)

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

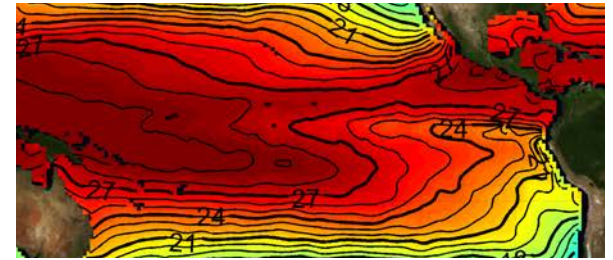
The surface extension of the Warm Pool (equivalent to Europe Area with temperatures $>28^{\circ}\text{C}$) is associated with a surface salinity freshening



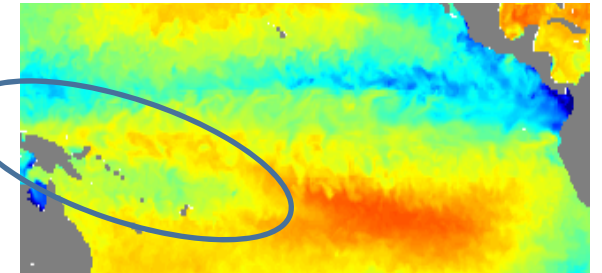
~ -0.013 psu/year

Cravatte et al., 2009

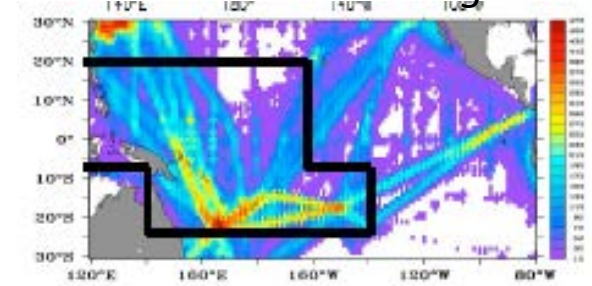
Temperature



Salinity

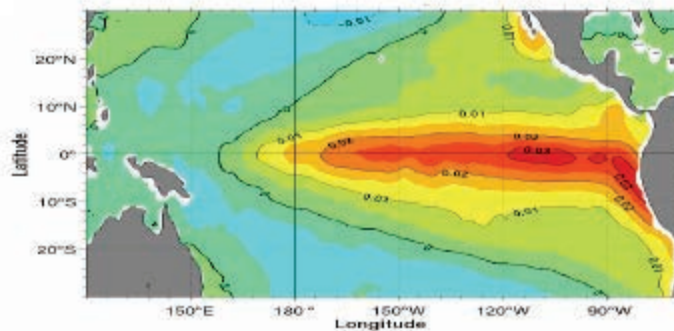


In situ coverage



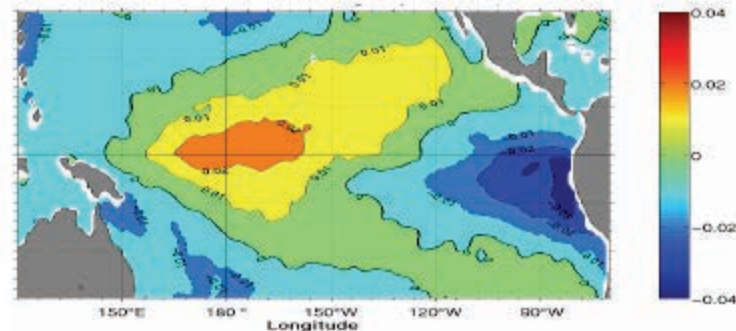
The spicy waters that change El Niño

Eastern Pacific El Niño

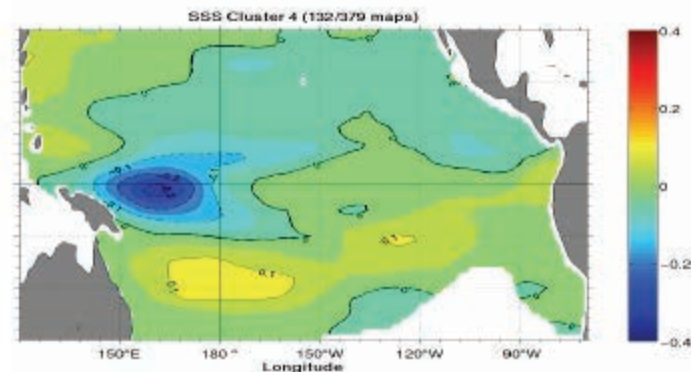
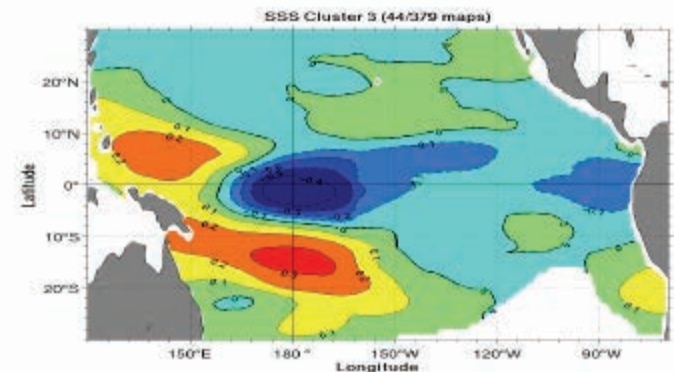


SST

Central Pacific El Niño



SSS



Christophe Maes, 2002
Singh et al., 2010

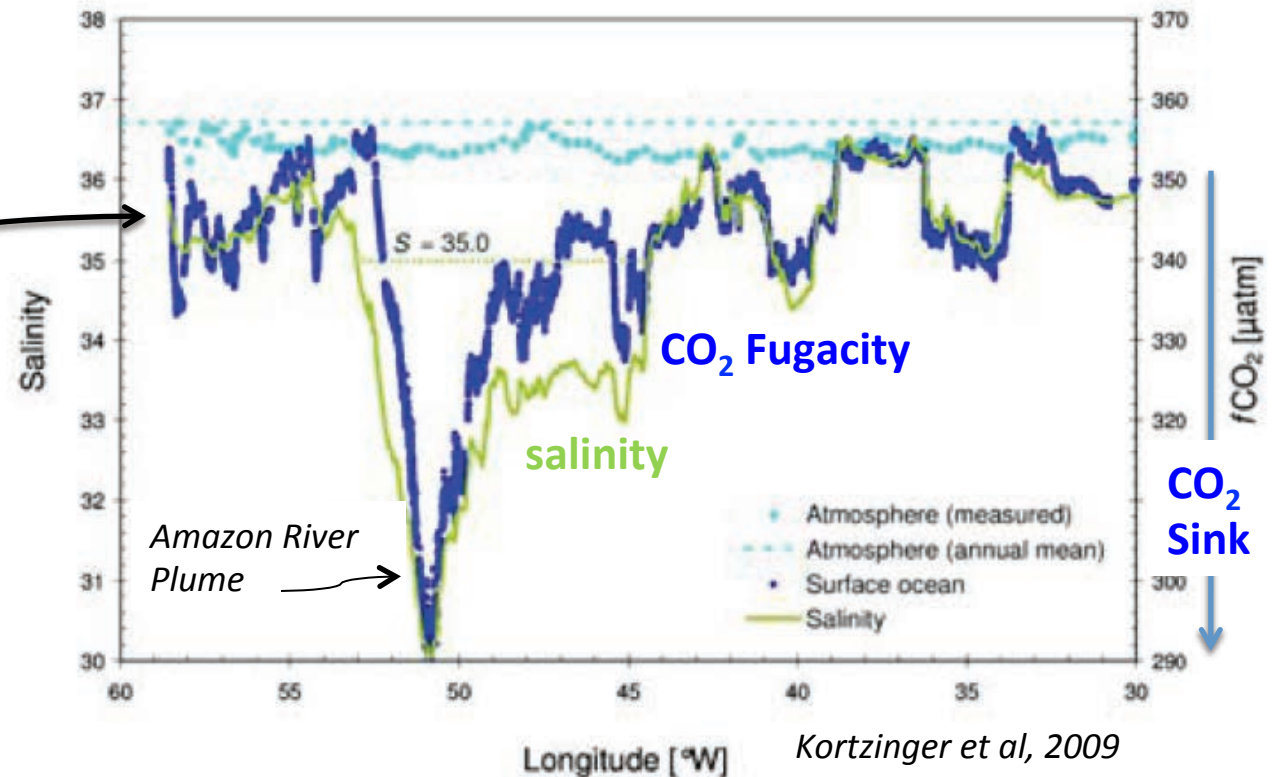
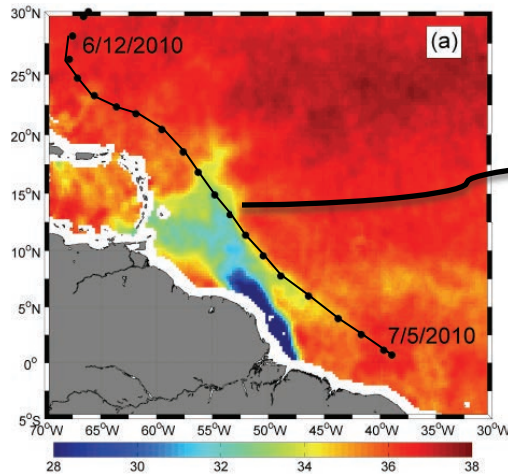
Salinity of the upper ocean play an important role (barrier-layer effects) in the on-set of the phenomenon. Monitoring this variable will help in better predicting El Niño.

Surface Salinity & Marine Bio-chemistry

sa

Ocean is a major sink for atmospheric CO₂

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



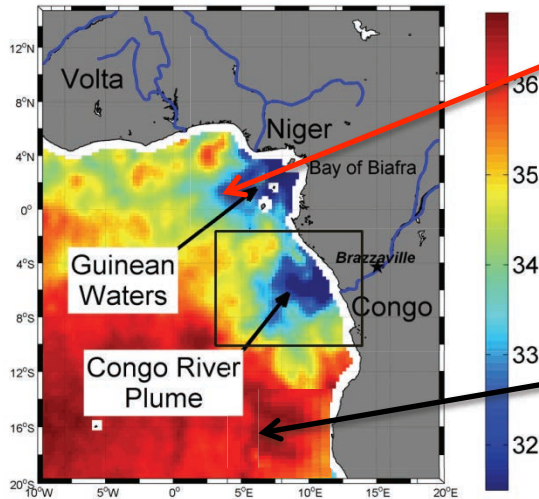
Through its links with carbonate chemistry and surface water masses monitoring, **Sea surface salinity data will improve estimates of air-sea CO₂ fluxes.**

SMOS will help in better quantifying ocean acidification (corals reefs, tropical ecosystem) & ocean-atmosphere CO₂ 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 maderensis

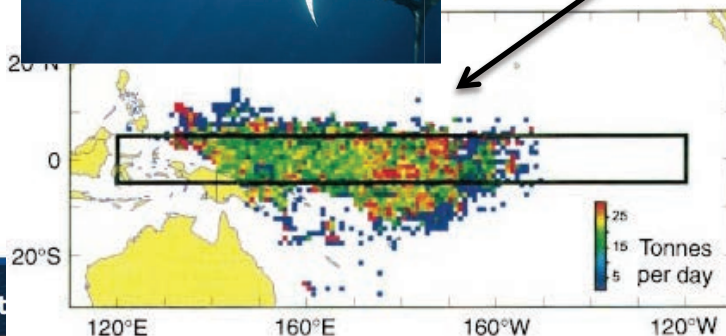
S. Maderensis is stenohaline: it lives in warm freshwaters of the Guinean Gulf (rain effects, river influence from Volga, Niger, Congo,..)



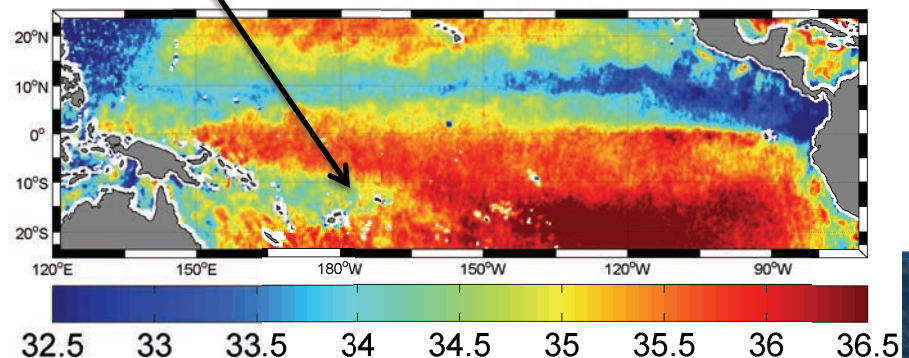
S. Aurita is stenohaline: it lives in the cold and salty waters of the benguela upwelling



Tuna takes & Haline Fronts in the western Tropical Pacific

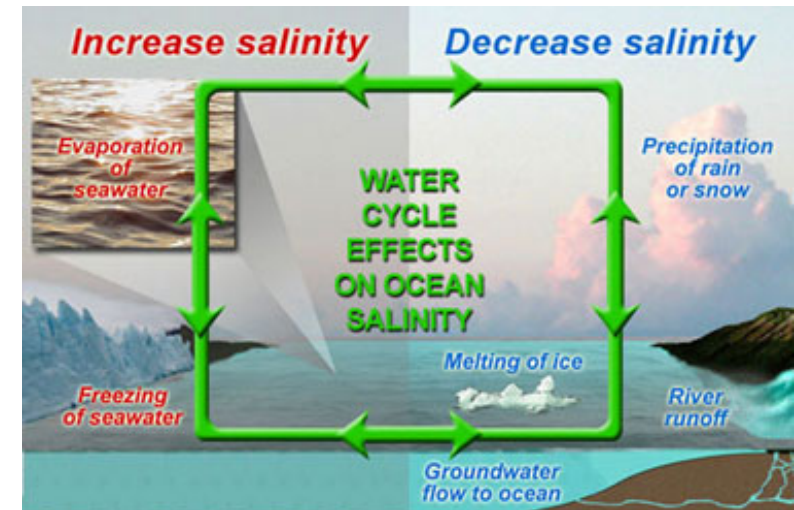


SSS SMOS Nov



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

- ✓ Thermo-haline Circulation
- ✓ Global Water Cycle
(Fresh water flux , E-P-R)
- ✓ Ocean-atmosphere Coupling
(e.g., ENSO, en rate of CO2 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 km²

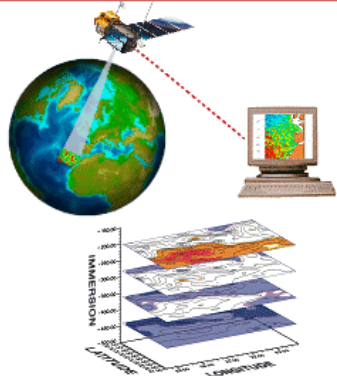
What are the main oceanic applications ?



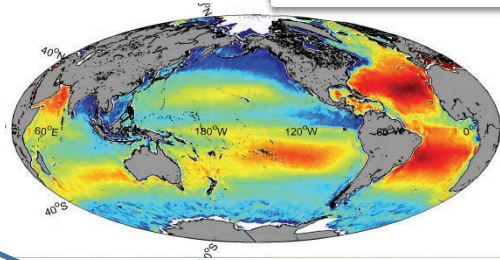
Climate change Studies

Ocean circulation
Modeling

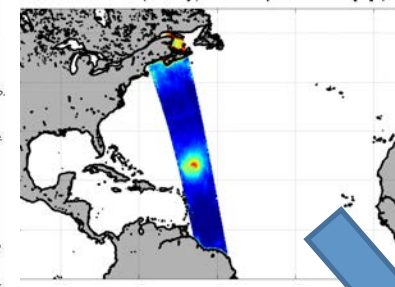
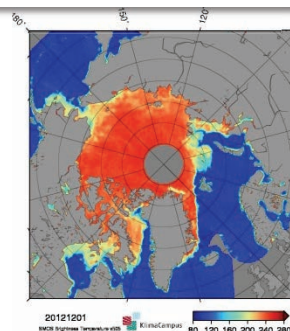
Marine Biology & Biochemistry



SMOS data



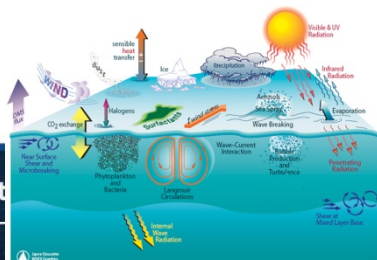
Salinity



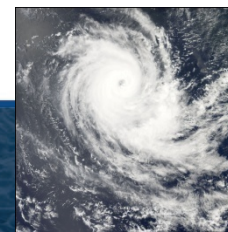
brightnesses

Ocean-atmosphere
interactions

Weather Predictions



OCEAN REMOTE SENSING
Brest, France

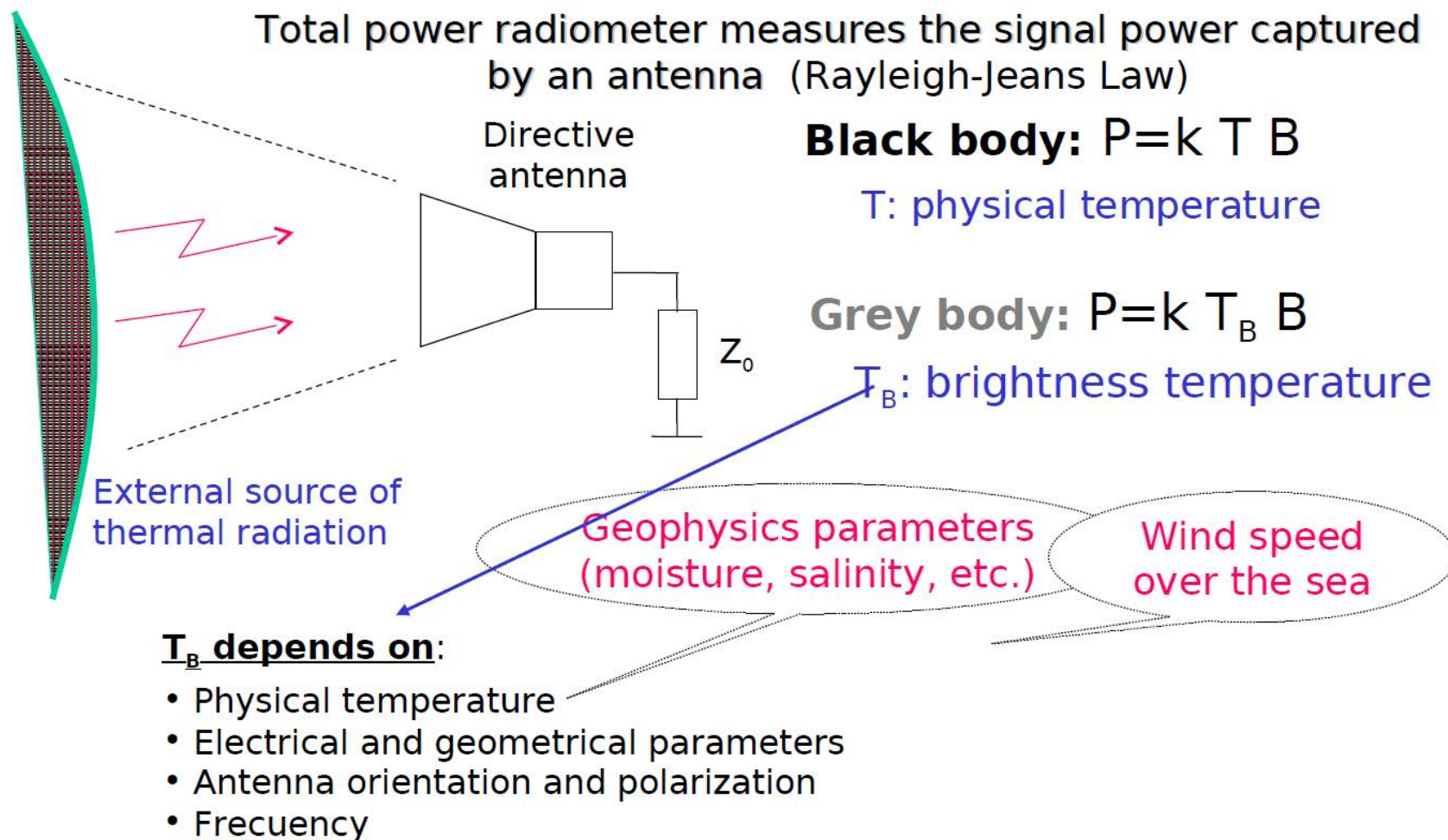




How can we measure sea surface salinity From Space?

**Physics principle
Of SSS measurements
From Low Microwave
frequency radiometry**





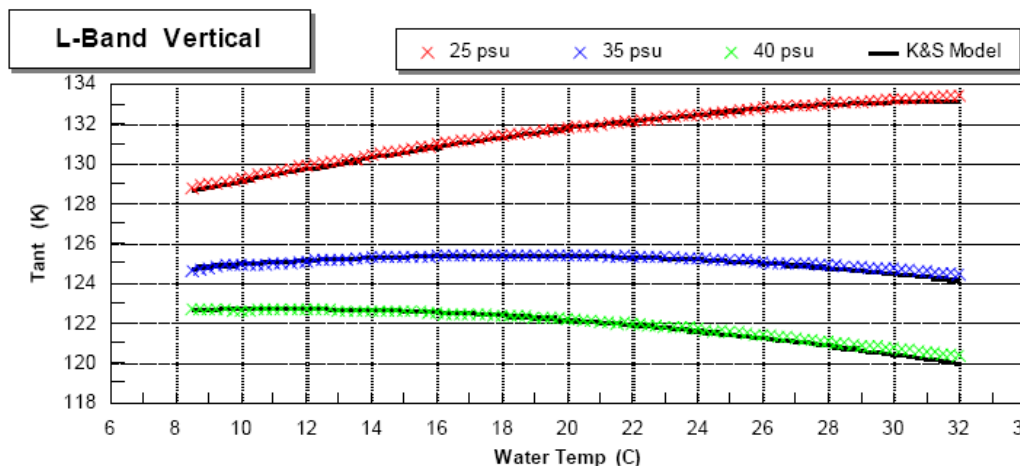
Basics of SSS measurements from Space

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

$$\epsilon = f(\text{S}, \text{T}, \text{Freq}, \text{Incidence})$$

$$T_b = \epsilon T$$

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

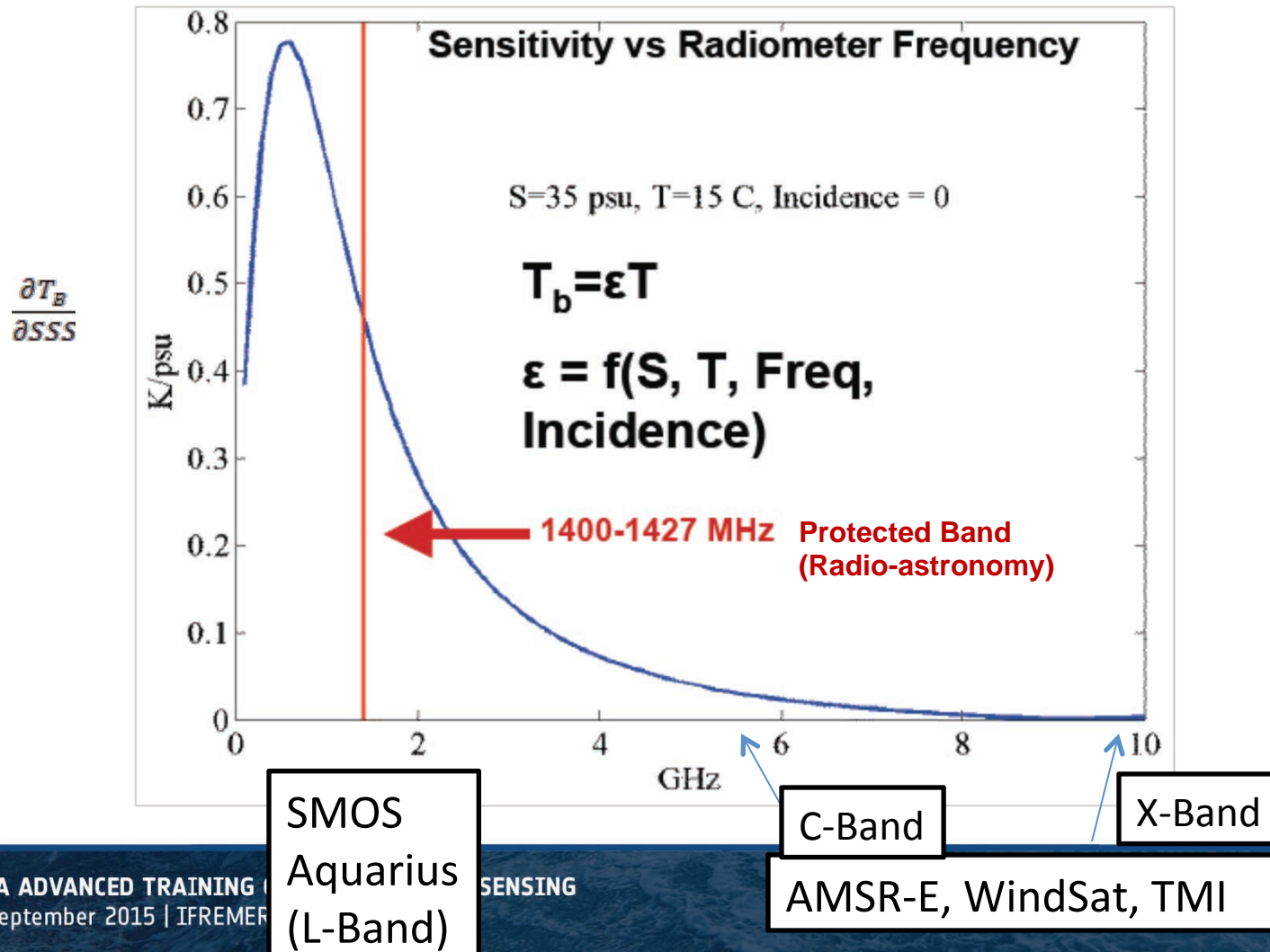


Given SST(T) & T_b data \Rightarrow one can deduce SSS (S) in theory

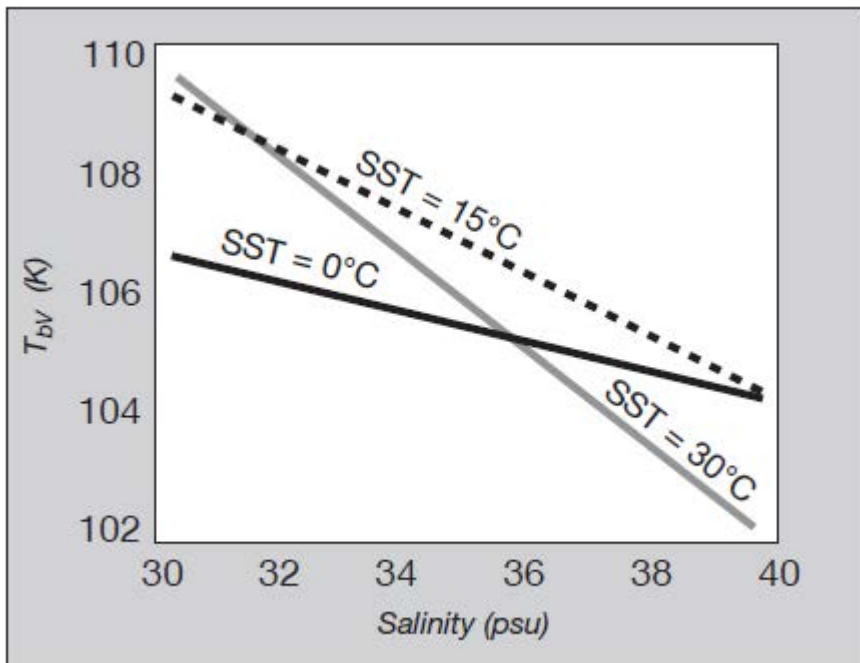


Tb sensitivity to SSS as function of Electromagnetic Frequency

Brightness temperature Sensitivity to Salinity as function of Electromagnetic Frequency



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 ($\sim 0^\circ\text{C}$)
- à
- 0.7 K/psu in warm seas ($\sim 30^\circ\text{C}$)

An instantaneous 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

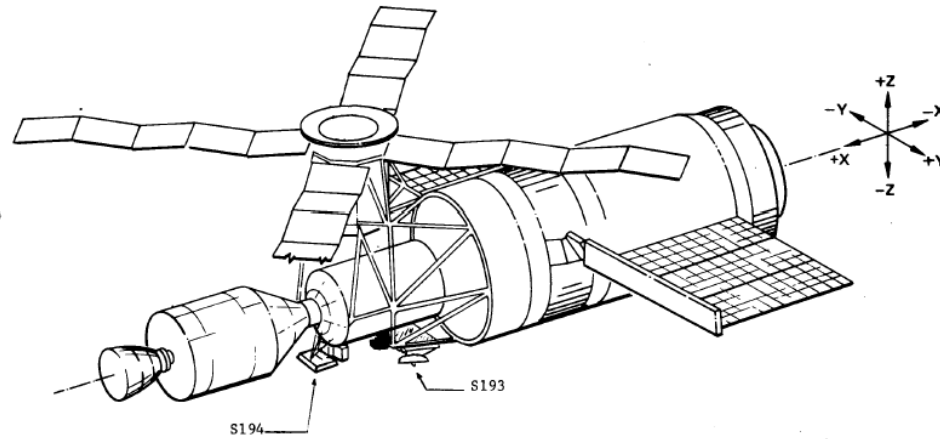


Fig. 1 — Location of radiometers on Skylab

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

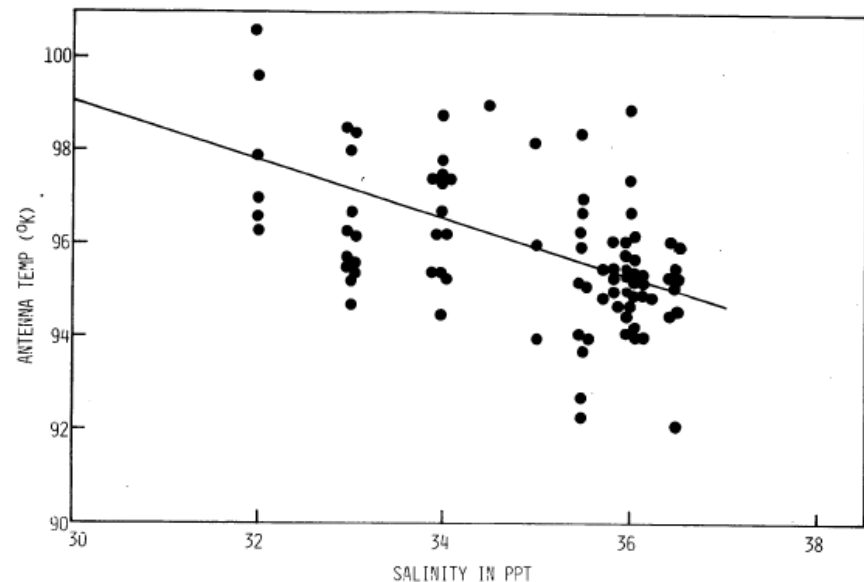
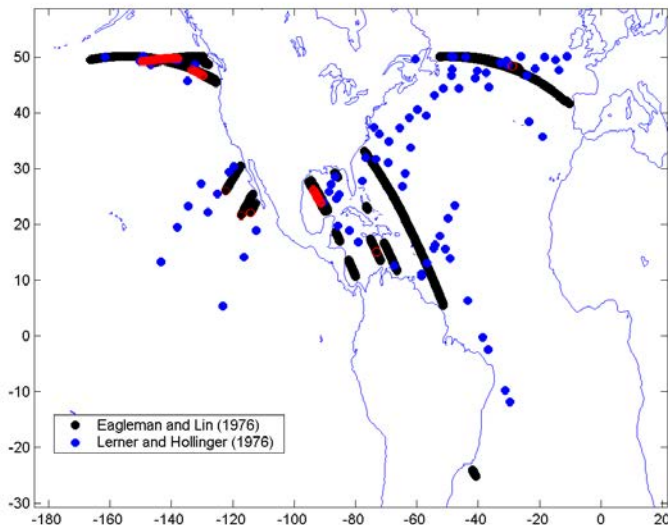
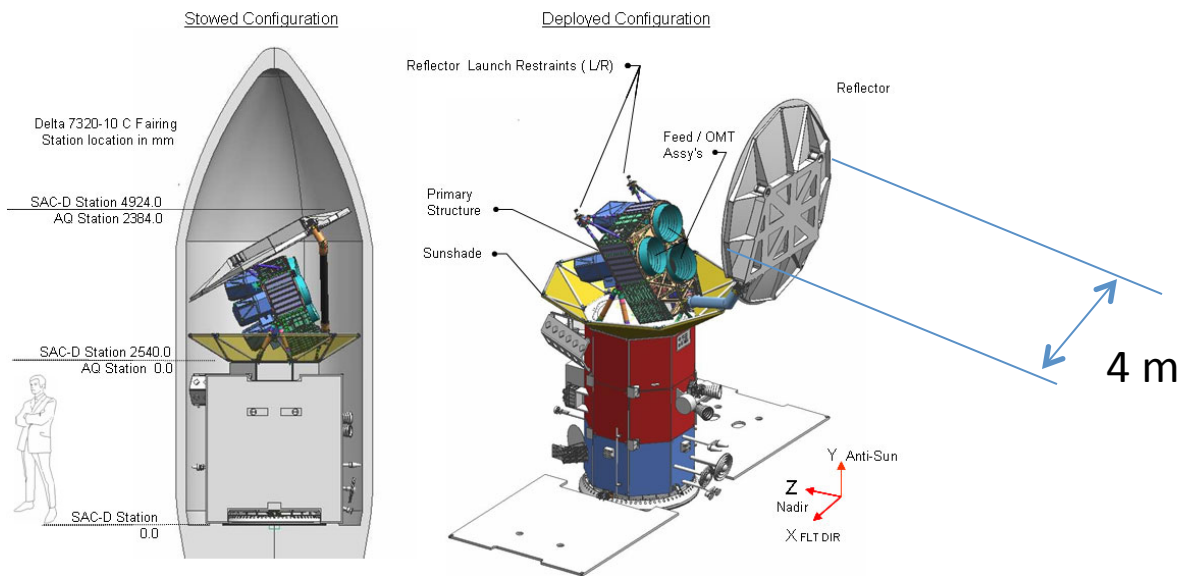


Fig. 17 — Antenna temperature dependence on salinity

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

To obtain a spatial resolution on ground of 50 km (at nadir), from an altitude of 750 km and for an electromagnetic 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

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selec



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

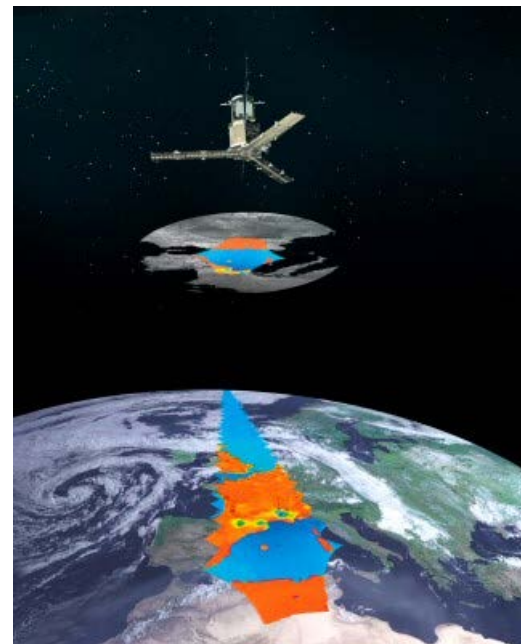
Goal of both missions:

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

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



a) SMOS artist view



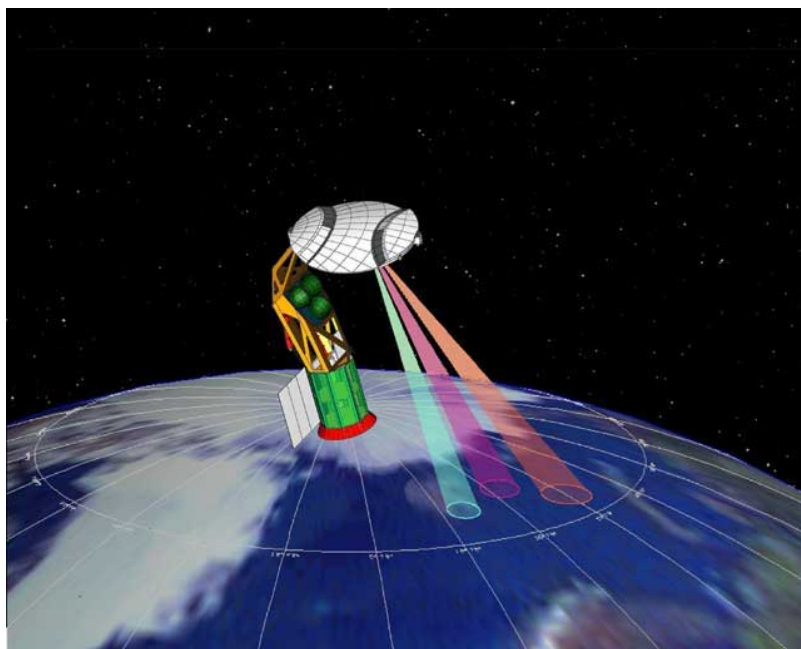
b) SMOS swath

Brightness temperature measurements at different incidence angles ($0^\circ - 60^\circ$)

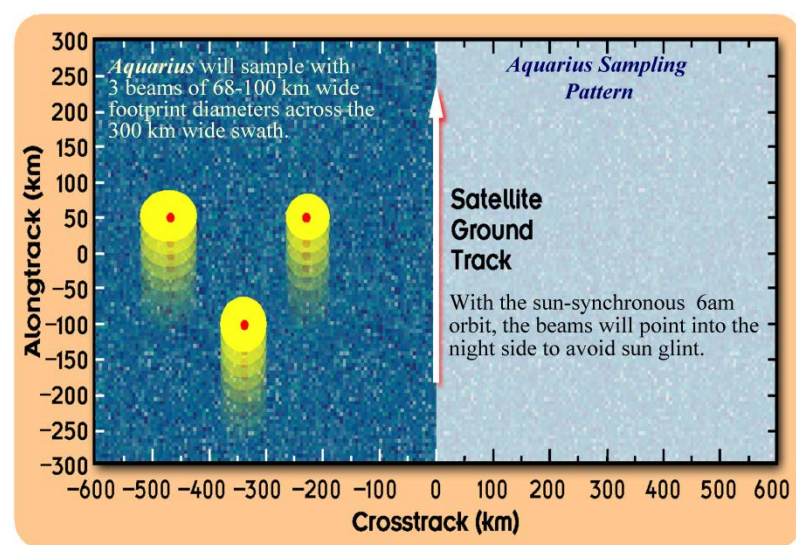
Ground resolution: 35-80 km Global coverage every 3 days

Spot accuracy (instantaneous) ~ 1 psu

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



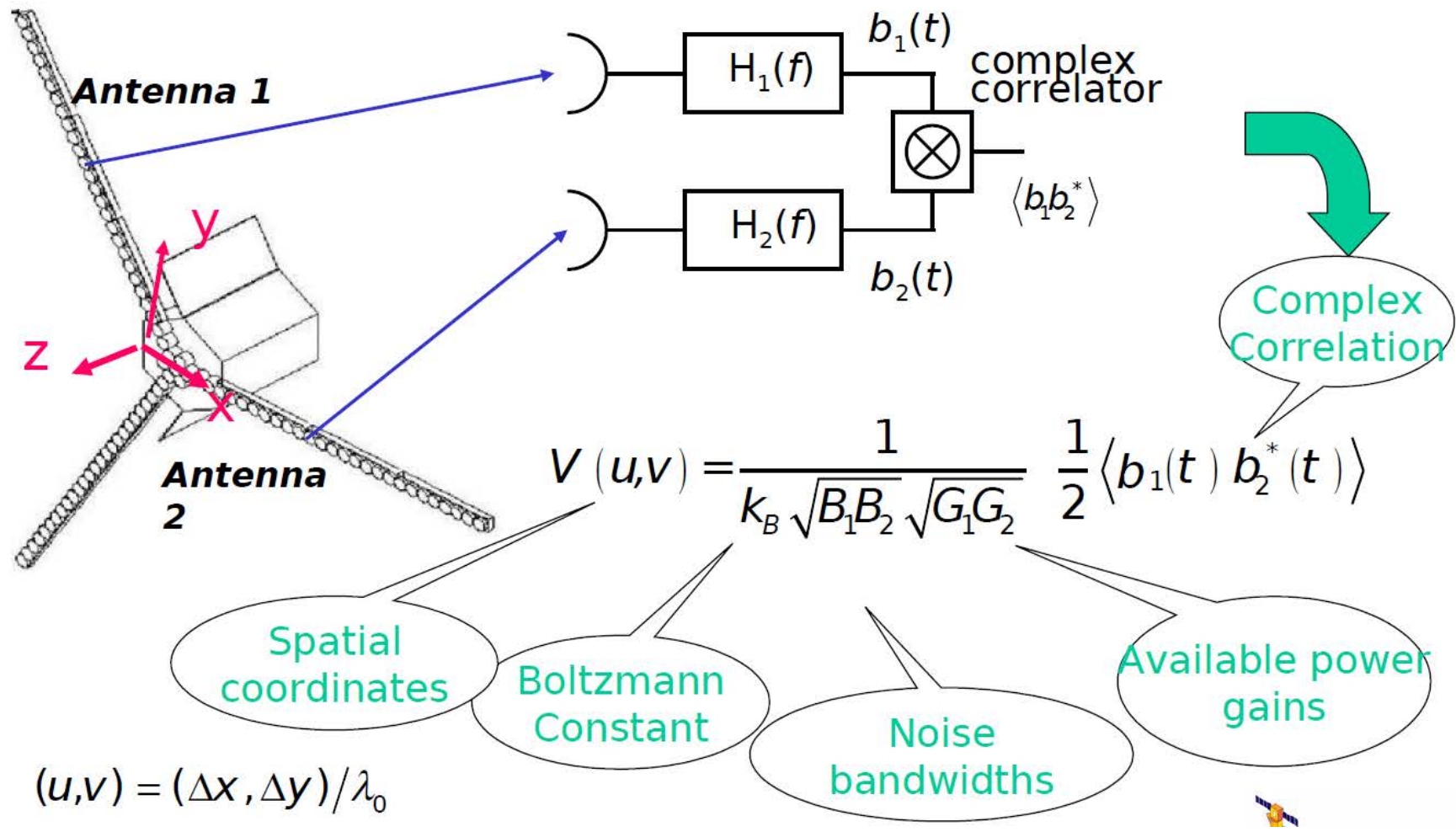
a) Aquarius artist view



b) Swath

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

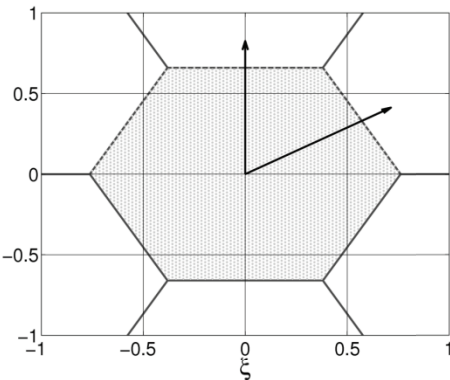
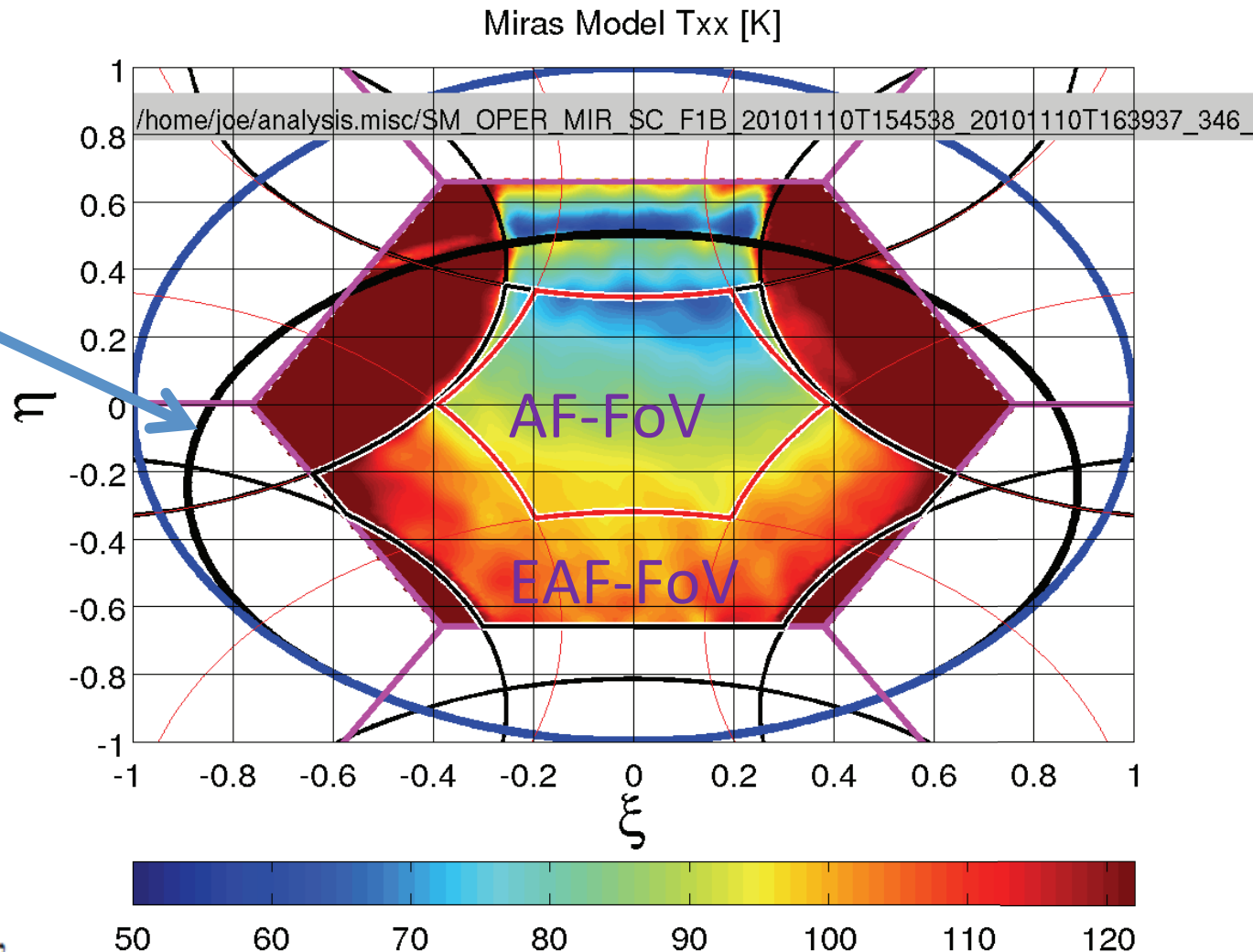
The interferometry in SMOS



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.



$$\begin{aligned}\xi &= \sin \theta_s \cos \phi_s, \\ \eta &= -\sin \theta_s \sin \phi_s, \\ \zeta &= -\cos \theta_s.\end{aligned}$$

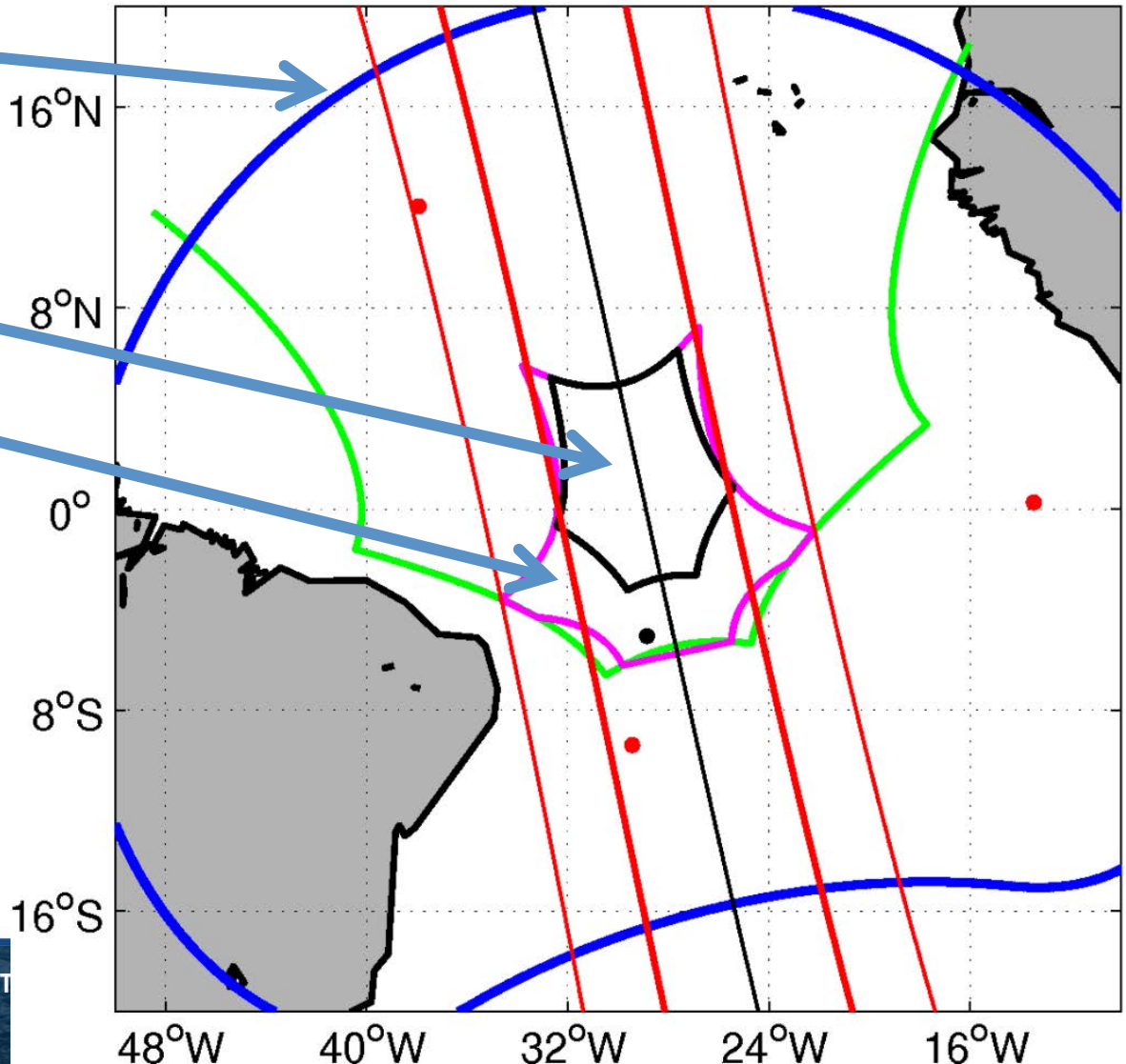
AF-FoV = alias-free field of view
EAF-FoV = extended alias-free field of view

THE FIELD OF VIEW PROJECTED ONTO THE EARTH

Ifremer



SM_OPER_MIR_SC_D1B_20100509T072639_20100509T082040_330_001_1



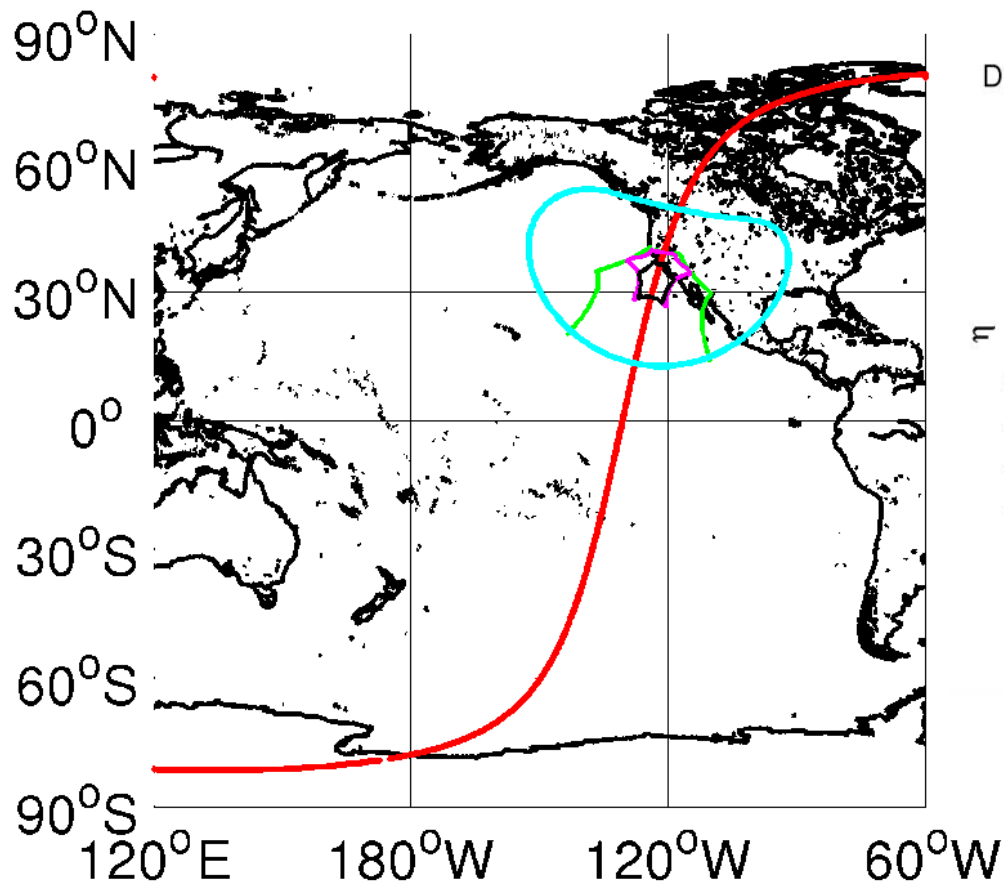
Boundary of
visible portion
of earth

AF-FoV

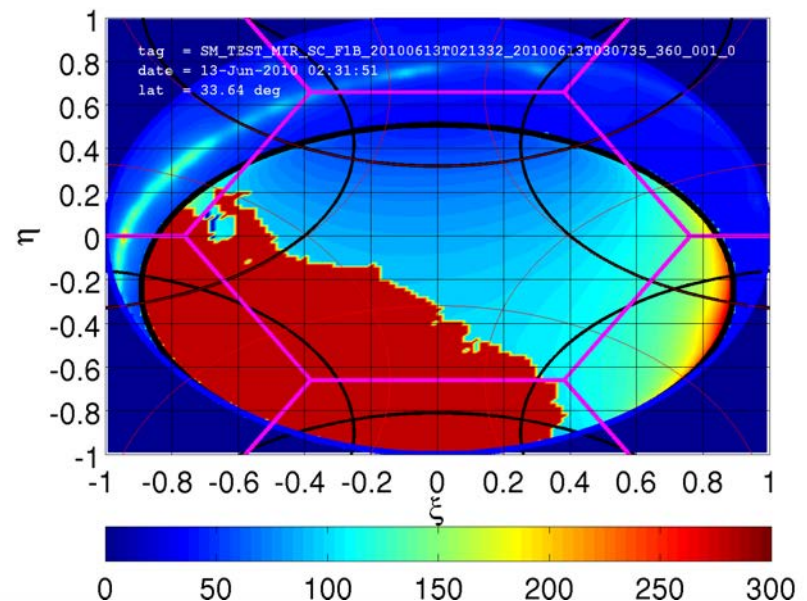
EAF-FoV

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.



Direct Sky [dK], Water, Land, and Ice [K] Scene Brightness Tx



SMOS Field of View (Blackman)

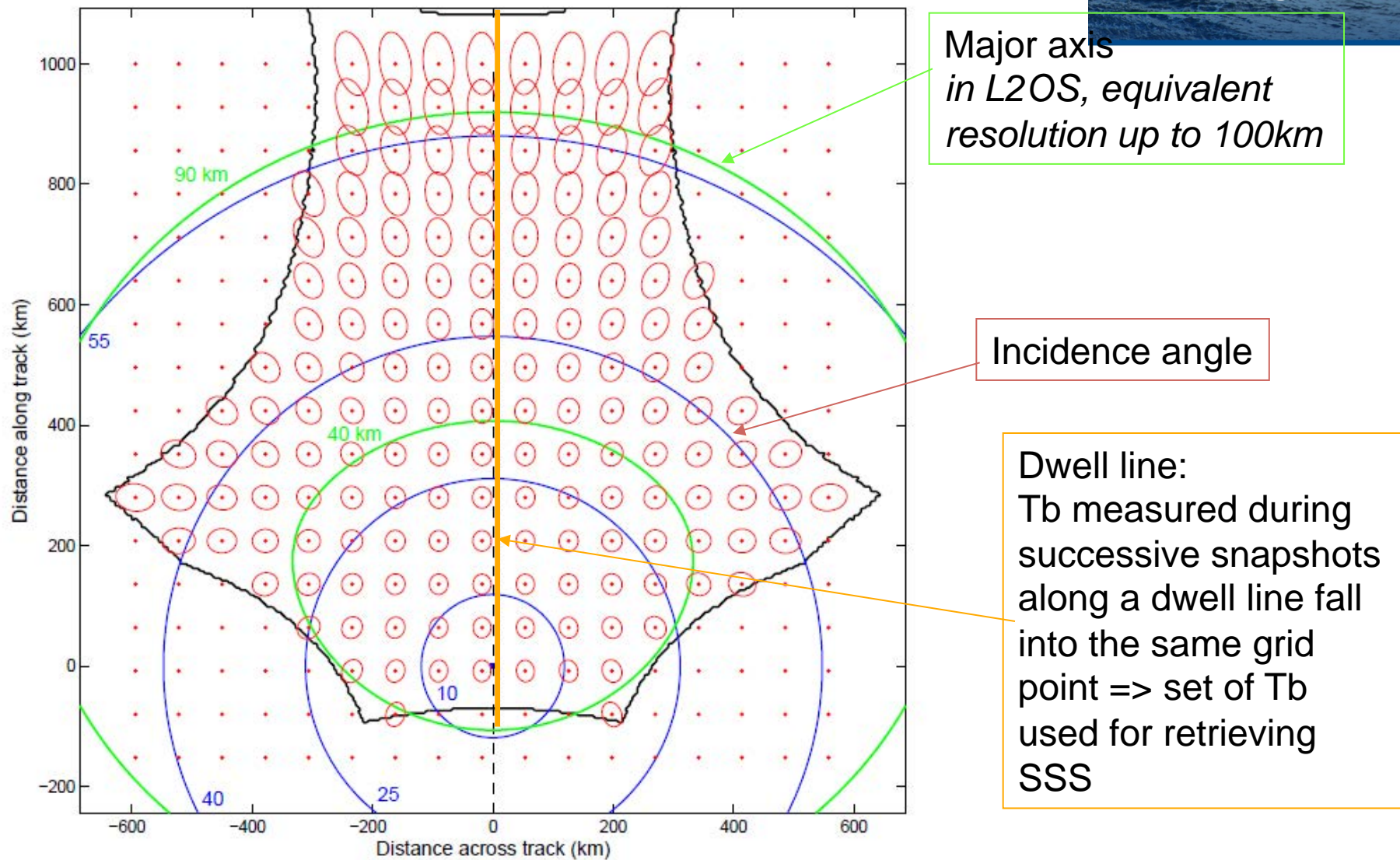


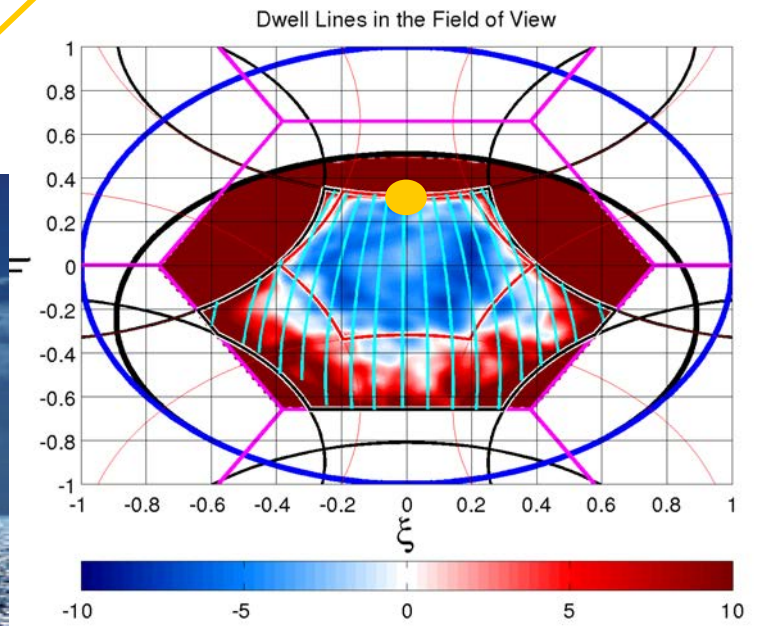
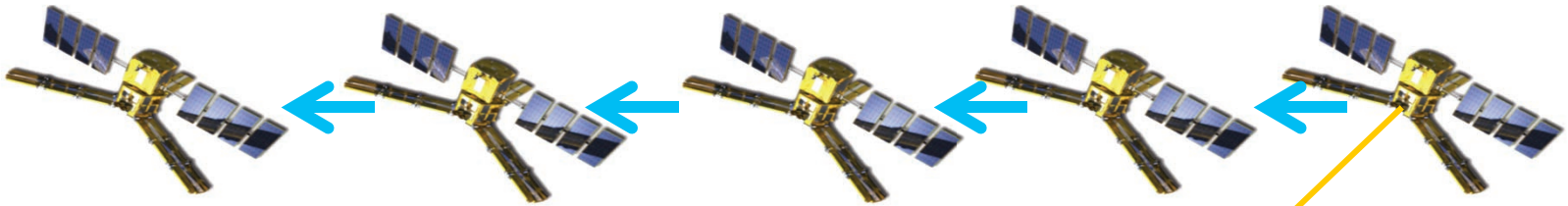
Fig. 1 – SMOS field of view (solid line). The red ellipses represent 3 dB synthetic antenna pattern contours (Blackman exact apodization window). The 40-km and 90-km major axis limits appear in green. The blue circles represent the locations of the incidence angles 10°, 25°, 40° and 55°. One dwell line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



CONCEPT OF A DWELL LINE

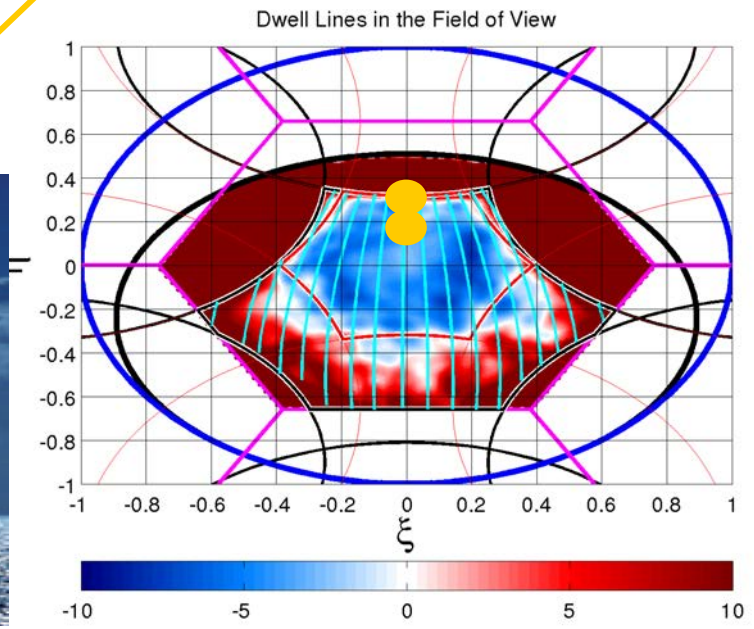
THE CONCEPT OF A DWELL LINE

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



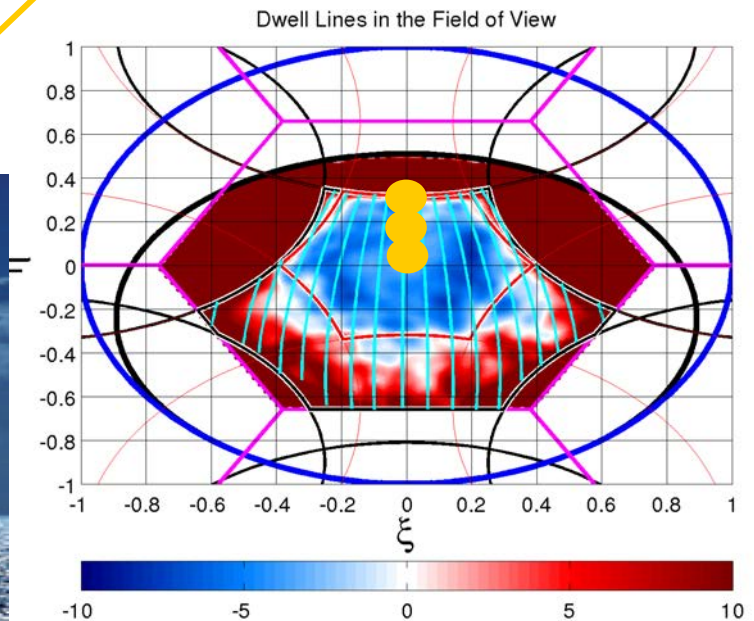
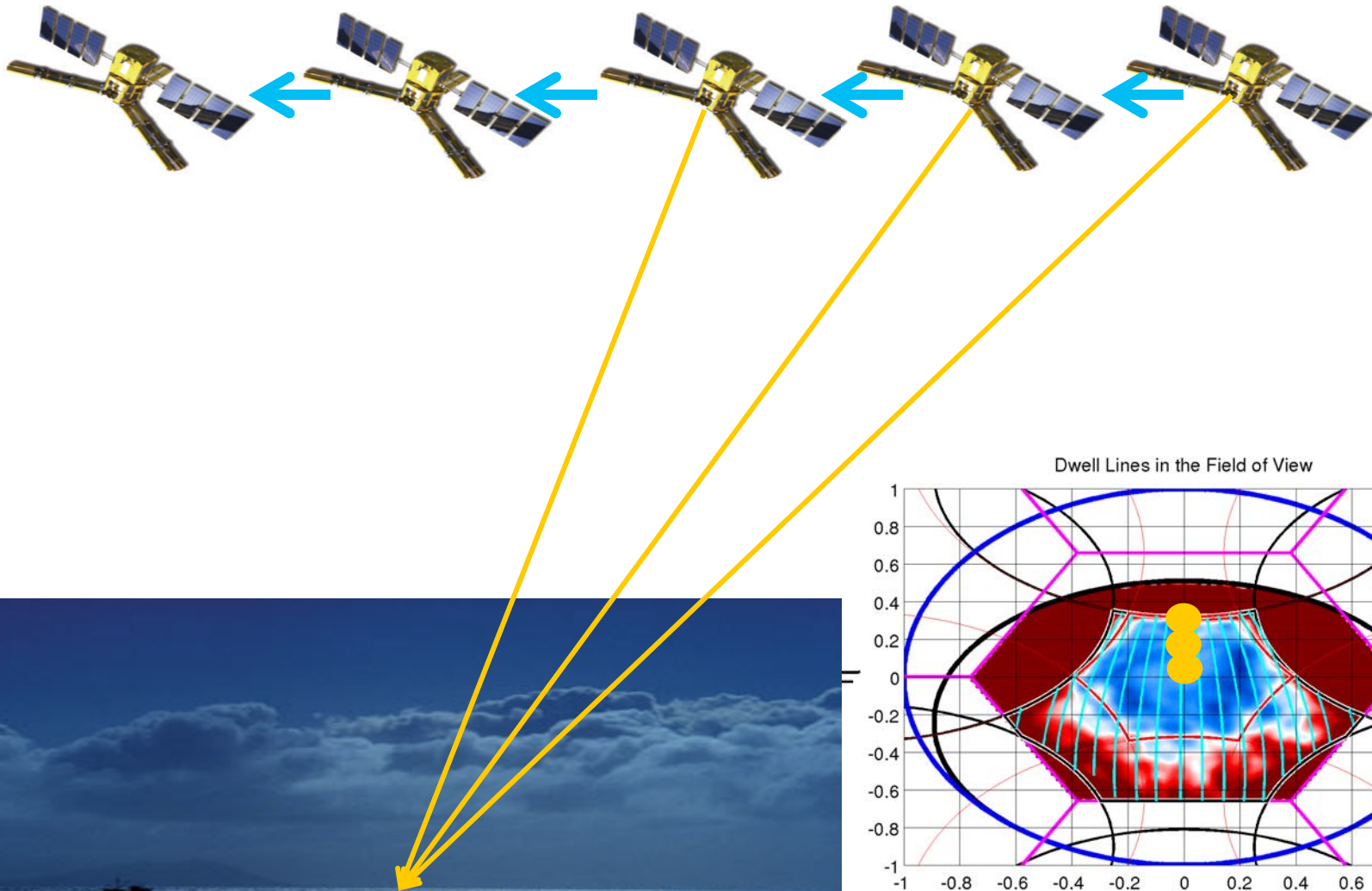
THE CONCEPT OF A DWELL LINE

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



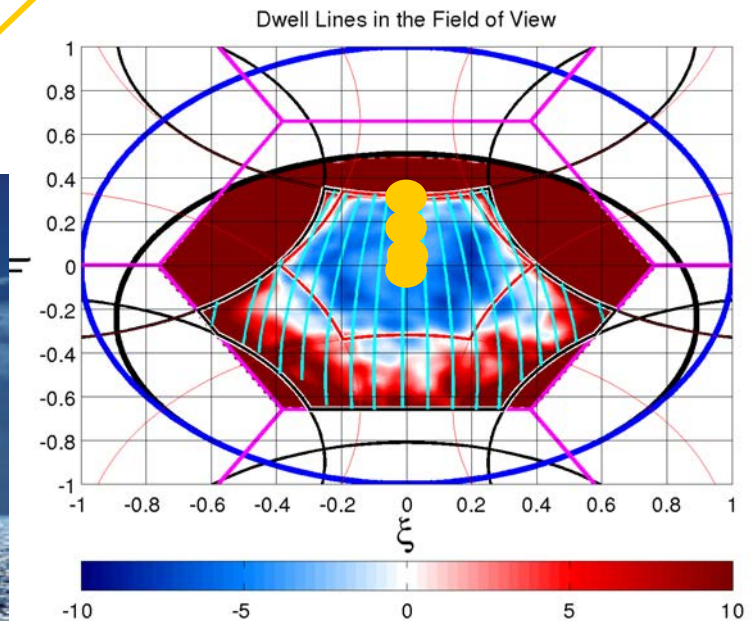
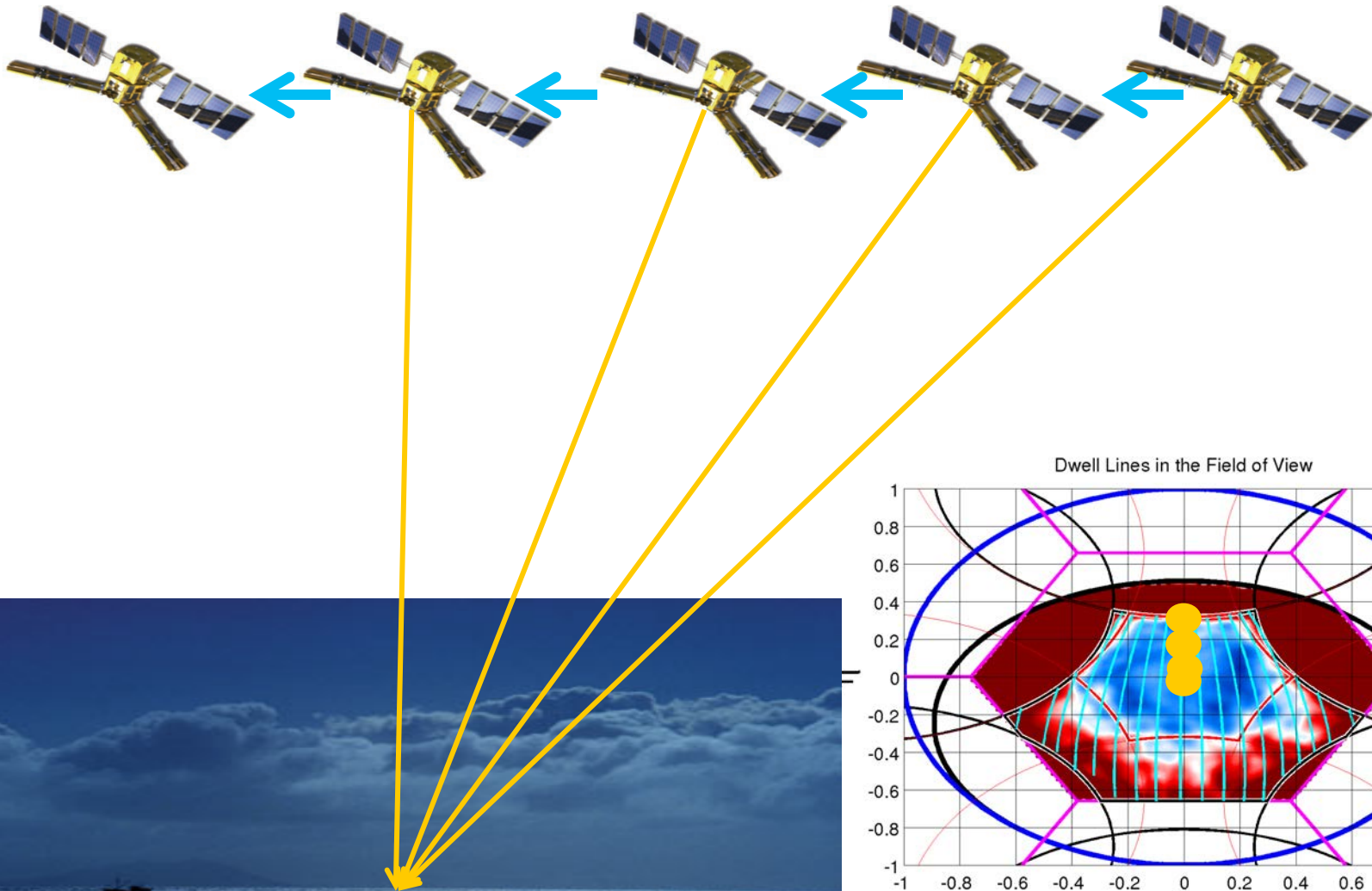
THE CONCEPT OF A DWELL LINE

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



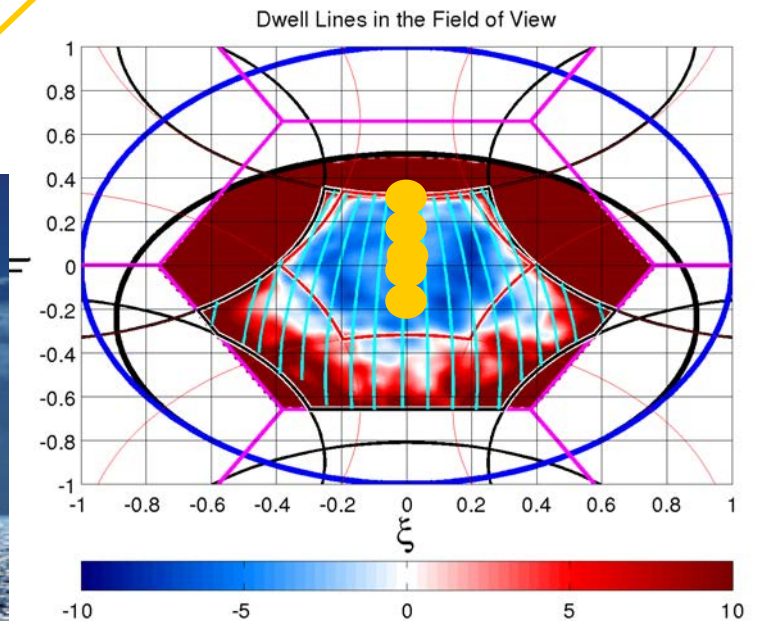
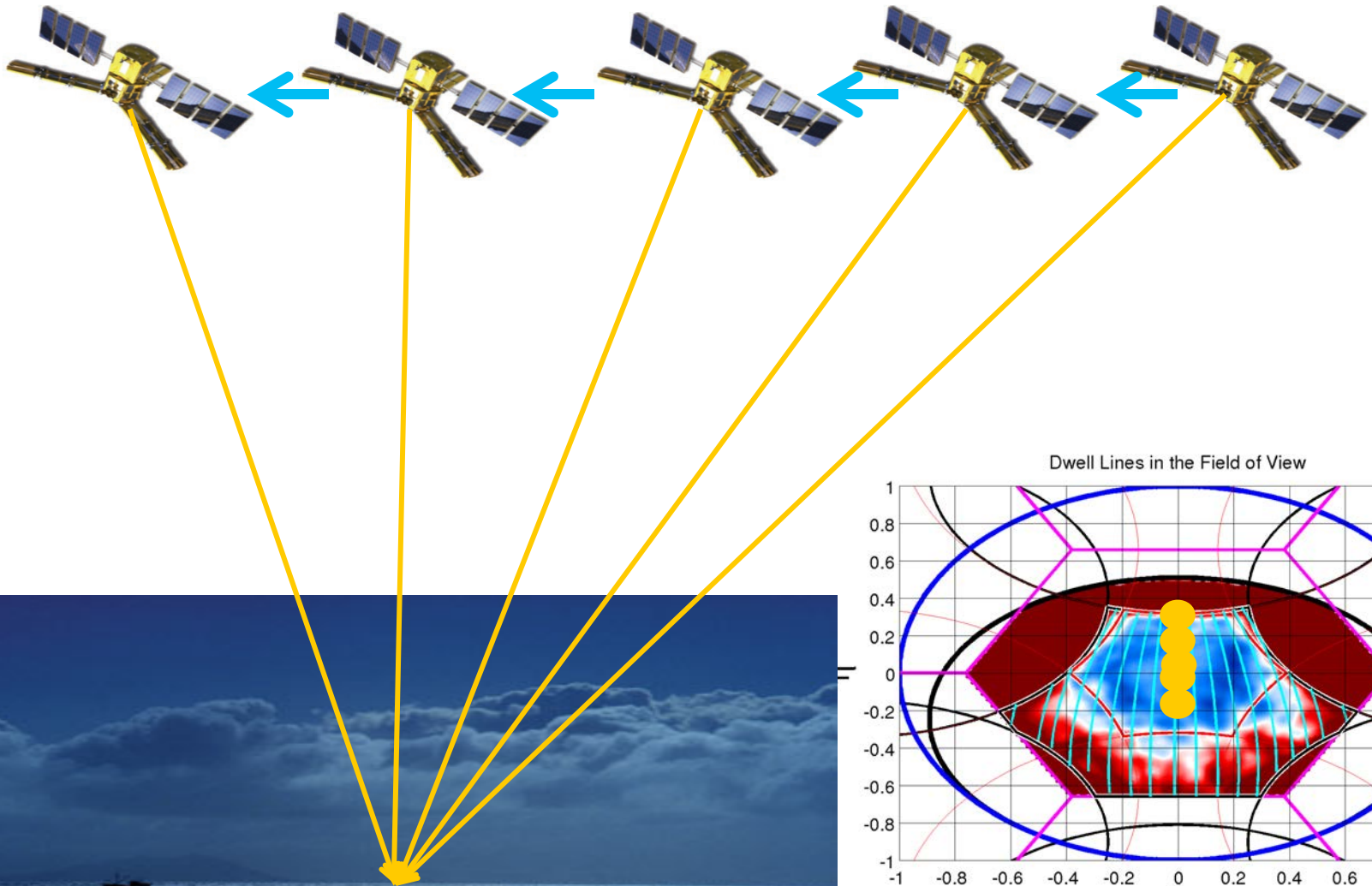
THE CONCEPT OF A DWELL LINE

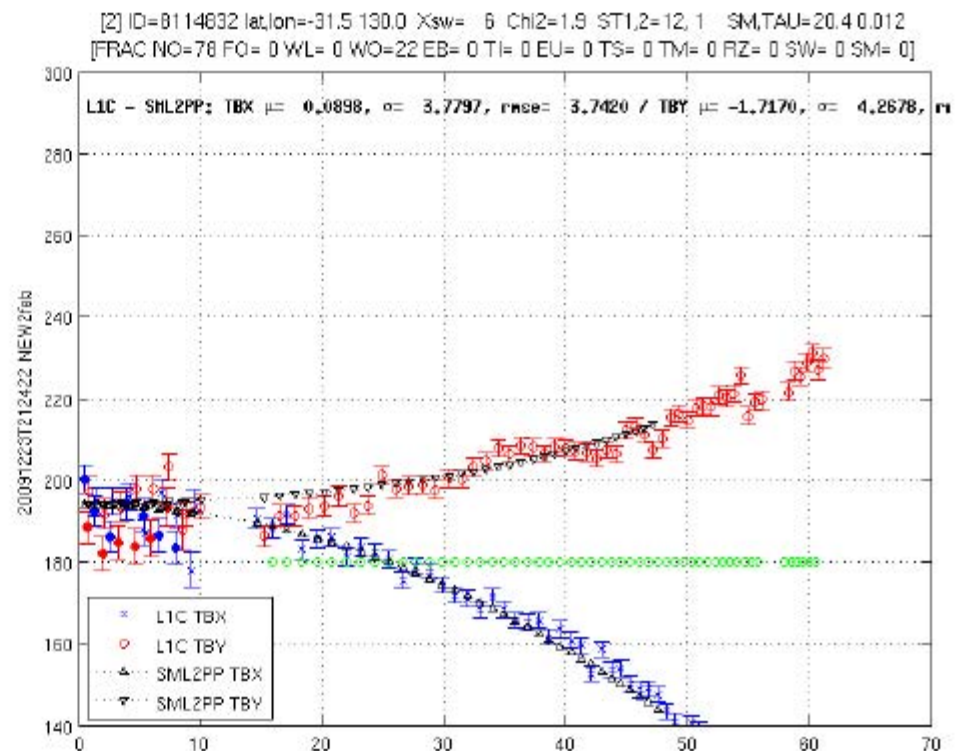
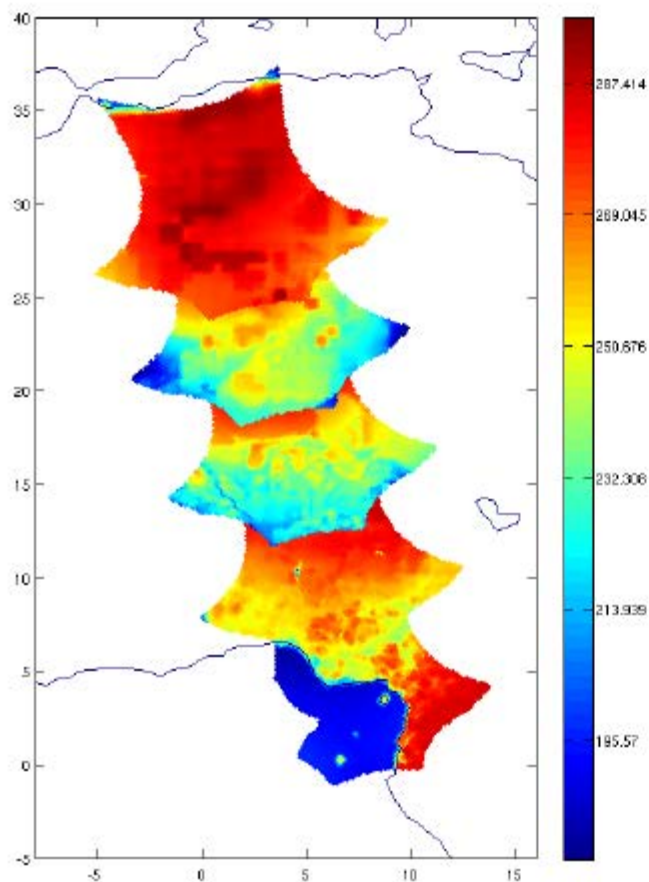
As the SMOS satellite propagates along its orbit, a given point on earth appears in many snapshots at a large range of incidence angles...



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...





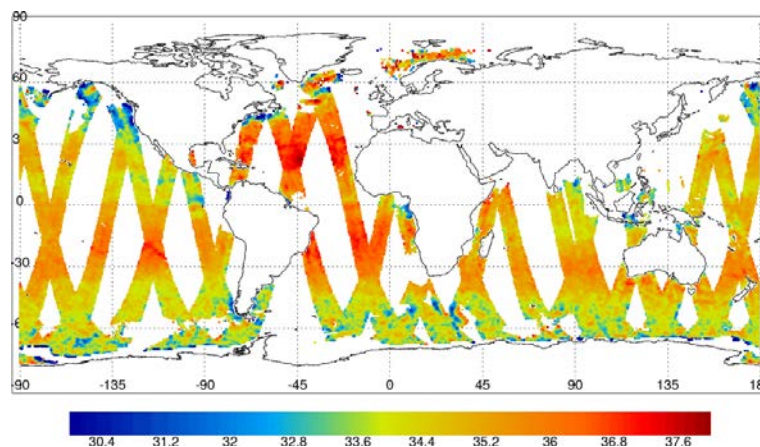


SMOS orbital characteristics



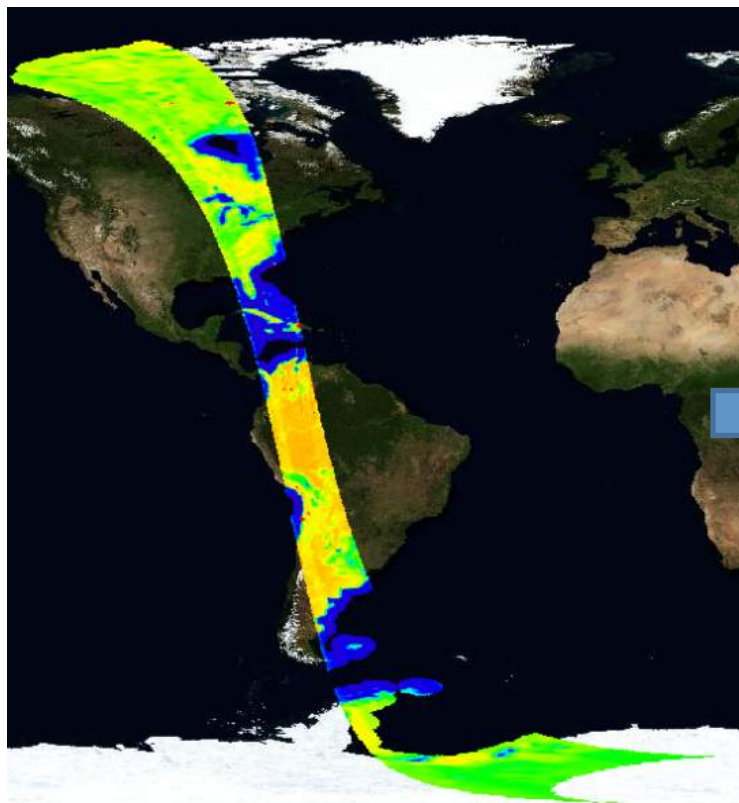
Morning ascending passes
Over terminator to minimise
sun contamination

Parameter	Mean Value
Semi-major axis	$a = 7134.552 \text{ km}$
Eccentricity	$e = 0.00116$
Inclination (sun-synchronous)	$i = 98.445^\circ$
Argument of perigee	$\omega = 90^\circ$
Mean Local Solar Time	$\Omega = 06:00 \text{ AM}$
Repeat cycle / cycle length	149 days, 2144 orbits
Orbital duration	6004.478 s



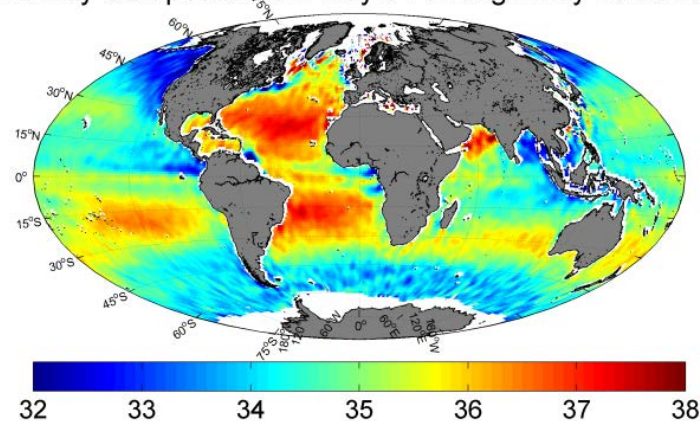
1 day of SMOS data over the
ocean

Brightness Temperature



Salinity maps

SSS 10-Day Composite from May 01 through May 10-2010-1°x'



SMOS L2 OS retrieval method

Ifremer

esa

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

Retrieval of SSS ($\sigma=100\text{pss}$), SST ($\sigma=1^\circ\text{C}$), WS ($\sigma=2\text{m/s}$ on wind components (model 1), $\sigma=2\text{m/s}$ on wind modulus (model 2 & 3)), TEC ($\sigma=5\text{TecU}$) through the minimisation of:

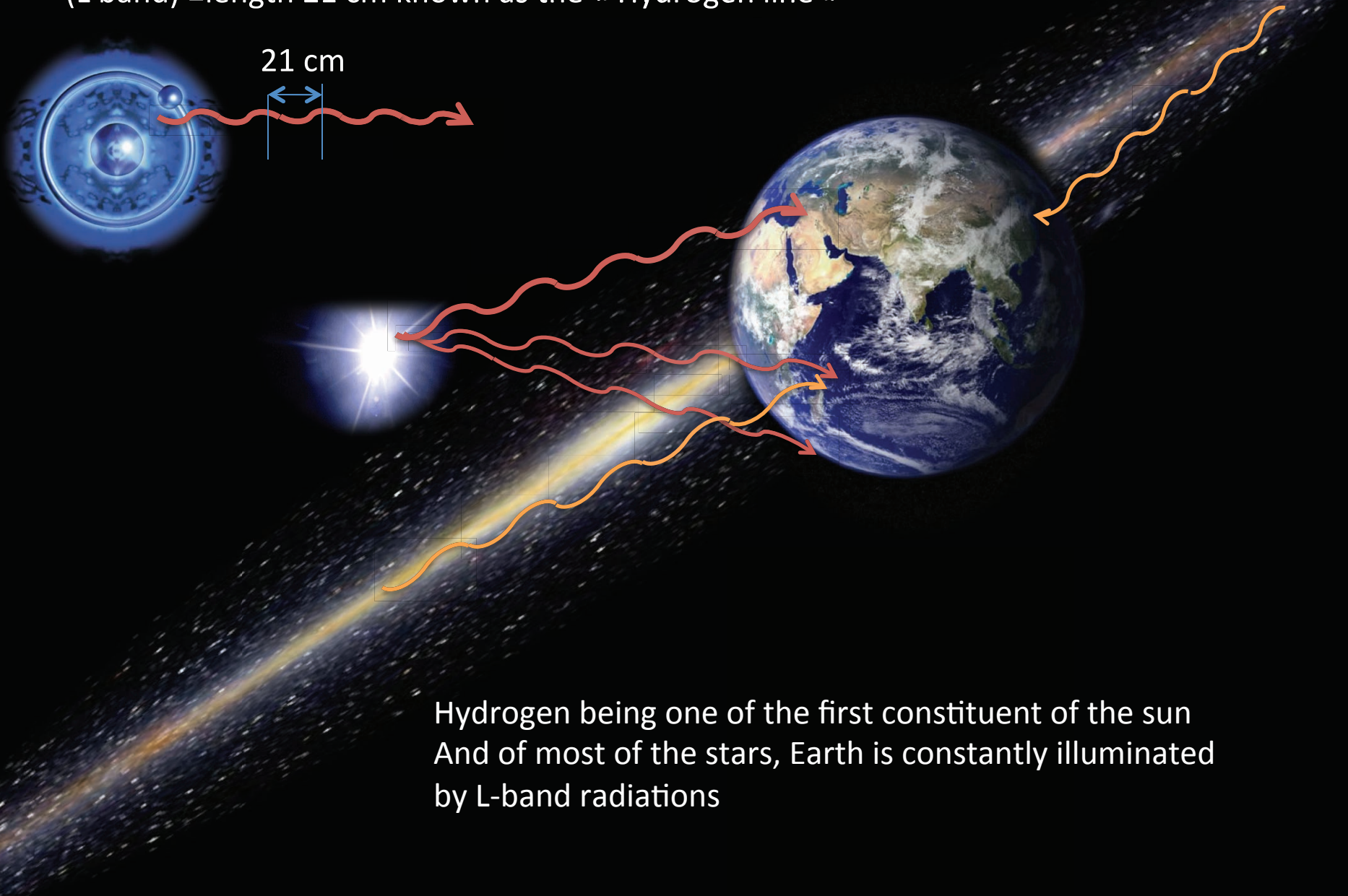
$$\chi^2 = \sum_{i=0}^{N_m-1} \frac{\left[T_{bi}^{meas} - T_{bi}^{mod}(\theta, P) \right]^2}{\sigma_{T_{bi}}^2} + \sum_{j=0}^{N_p-1} \frac{\left[P_j - P_{j, prior} \right]^2}{\sigma_{P_j}^2}$$

(iterative Levenberg & Marquard algorithm)

Tb^{meas} corrected for OTT

Tb^{mod} is computed at antenna level (T_x, T_y) 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) \equiv length 21 cm known as the « Hydrogen line »



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

IONOSPHERE

ATMOSPHERE

APPARENT
TEMPERATURE

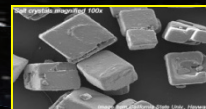
IONOSPHERE

ATMOSPHERE

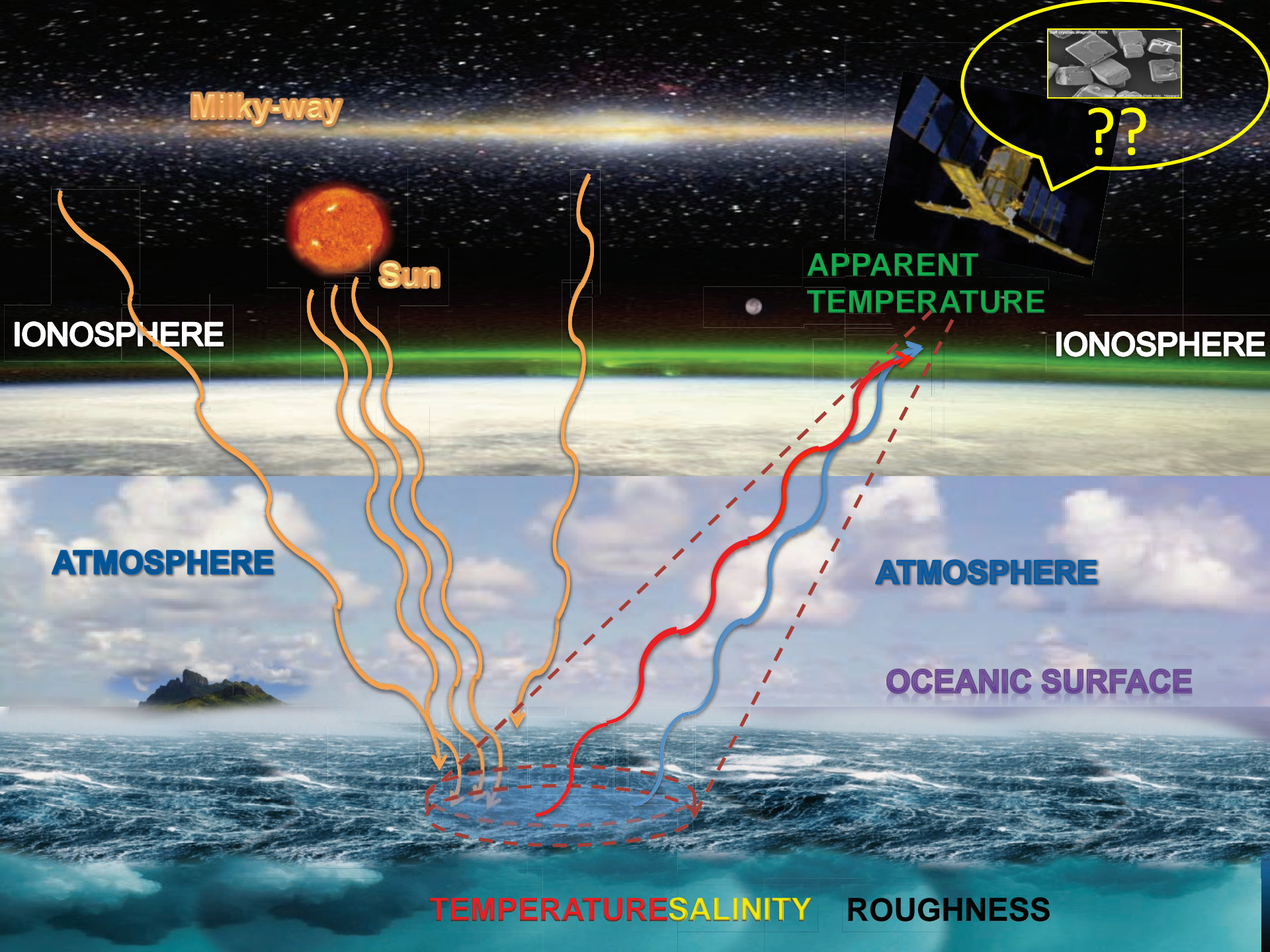
OCEANIC SURFACE

TEMPERATURESALINITY

ROUGHNESS

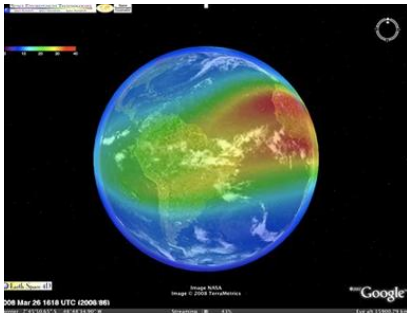


??

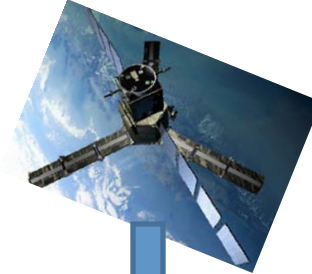


Retrieving SSS from Space: a challenge !

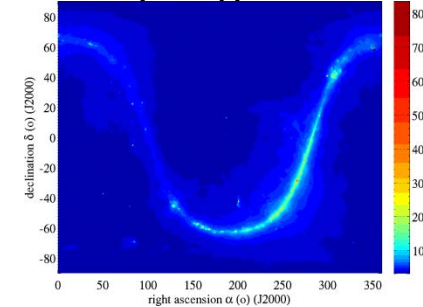
Ionosphere



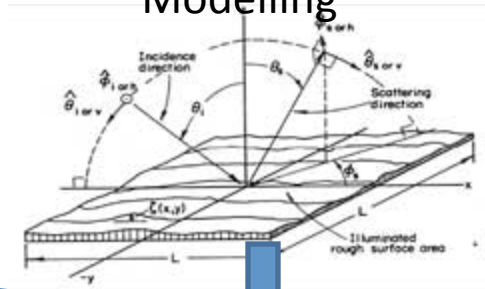
SMOS data



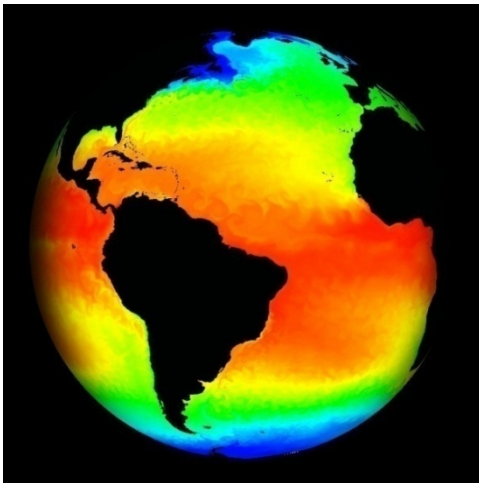
Sky Brightness



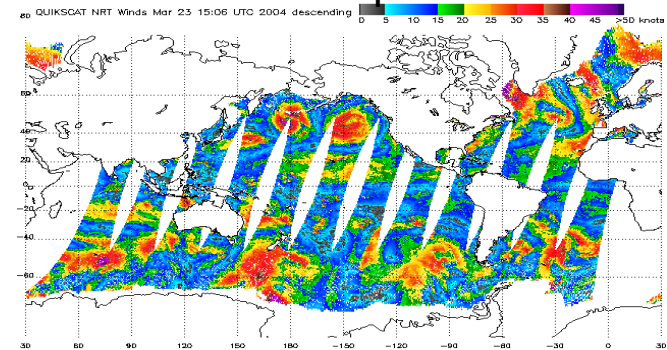
Electromagnetic Modelling



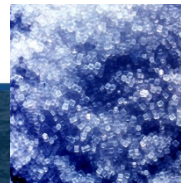
Sea Surface Temperature



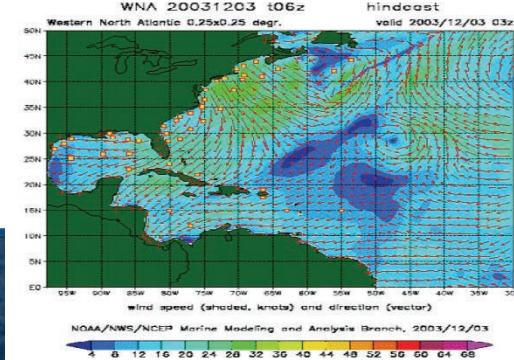
Atmosphere



Salts

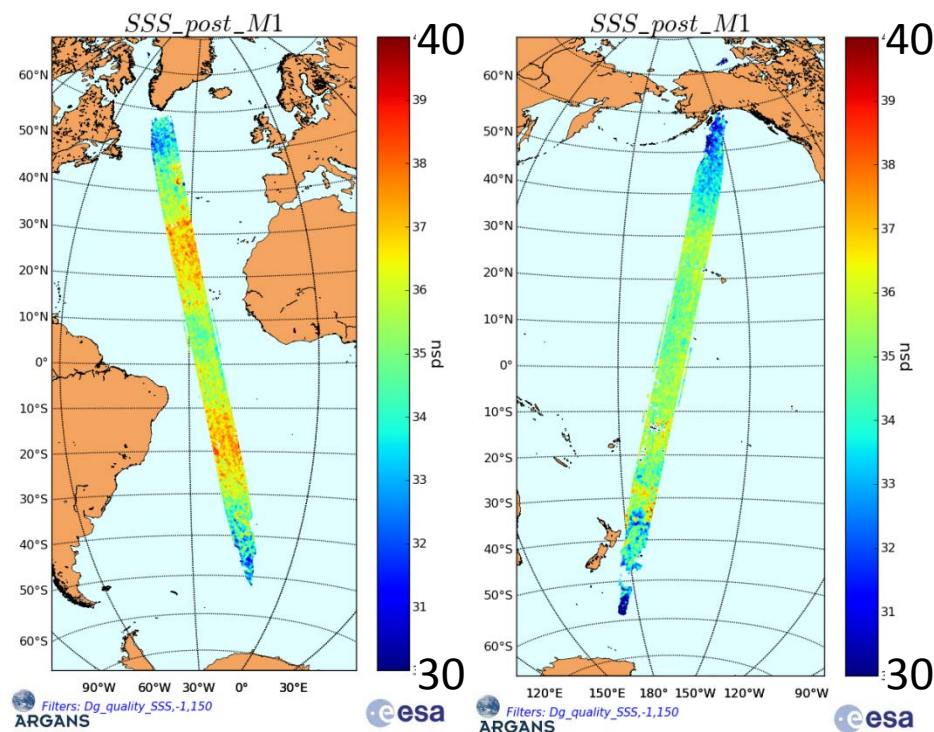
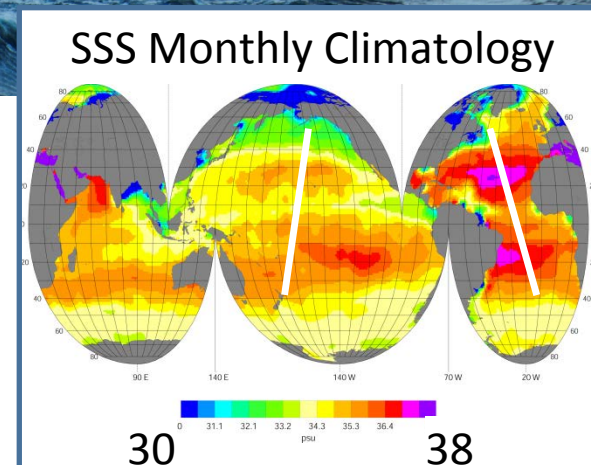


Sea States & winds



What can SMOS achieve in salinity observations?

A technological and scientific challenge



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>)

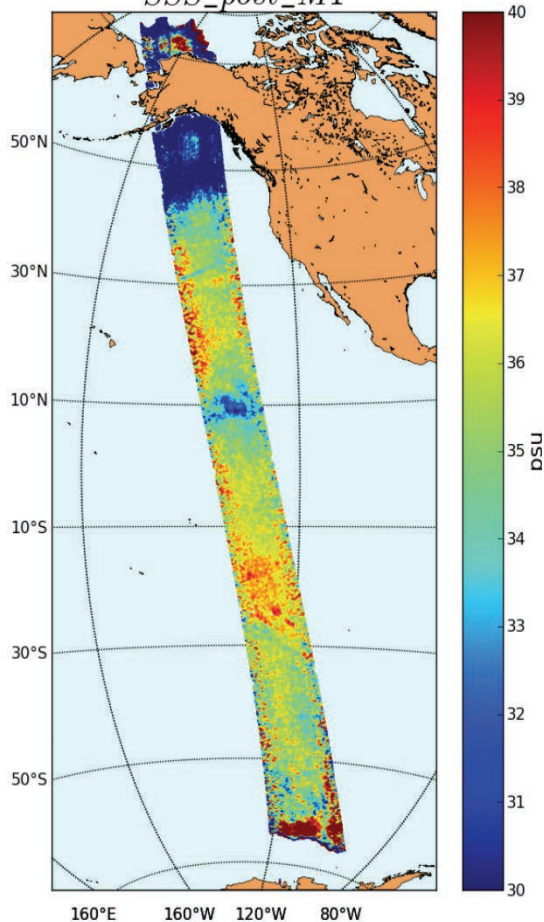
Along track Level 2 SSS qualitatively OK but very noisy.

Average needed to check mission requirements (Level 3)

SMOS Level 2 SSS products

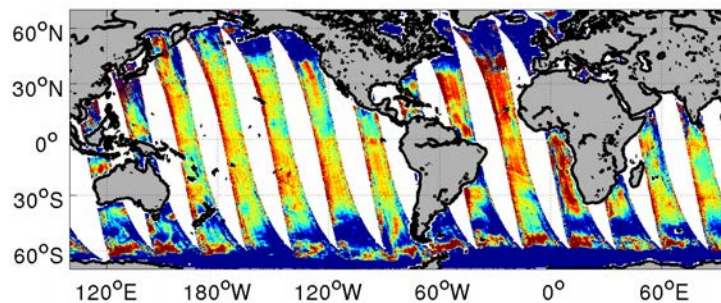
½ orbit

SSS_post_M1

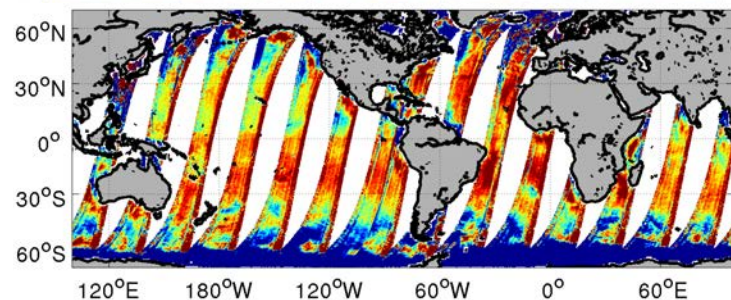


1 day

Passes ascendantes

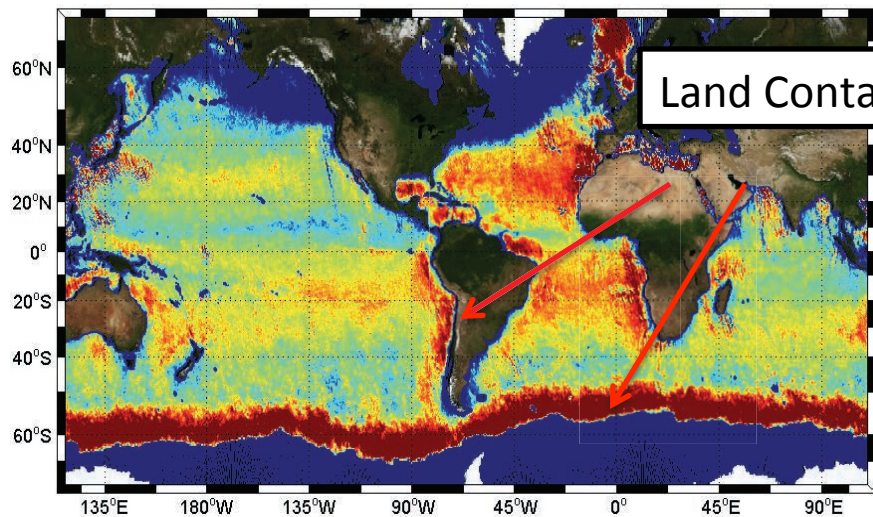


Passes descendantes

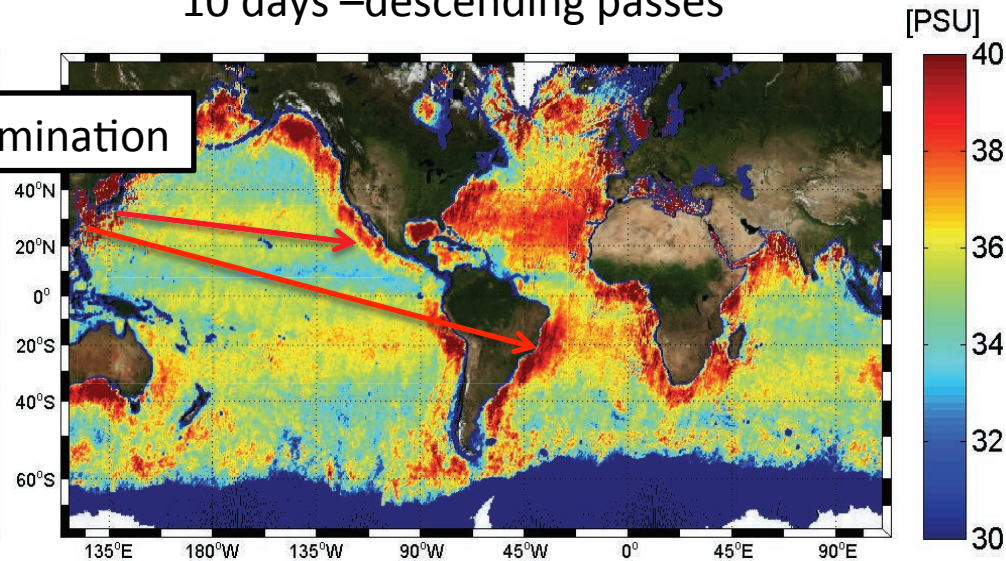


SMOS simple averaging L3 products

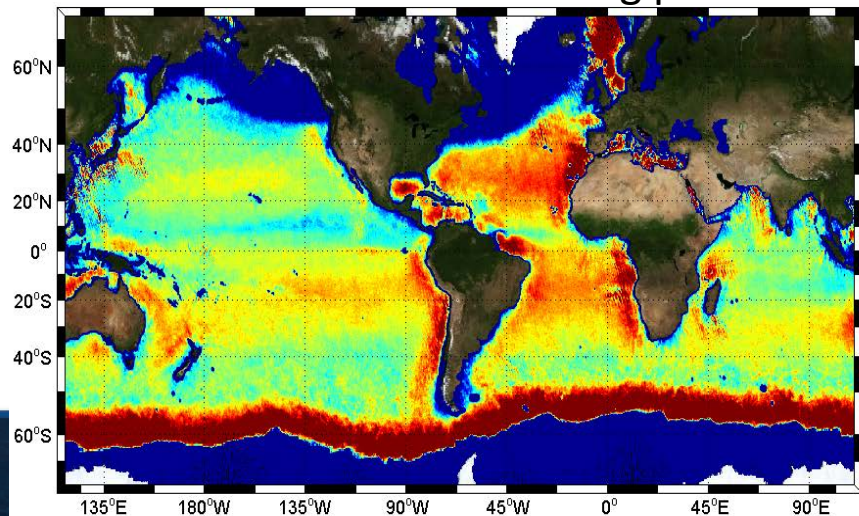
10 days –ascending passes



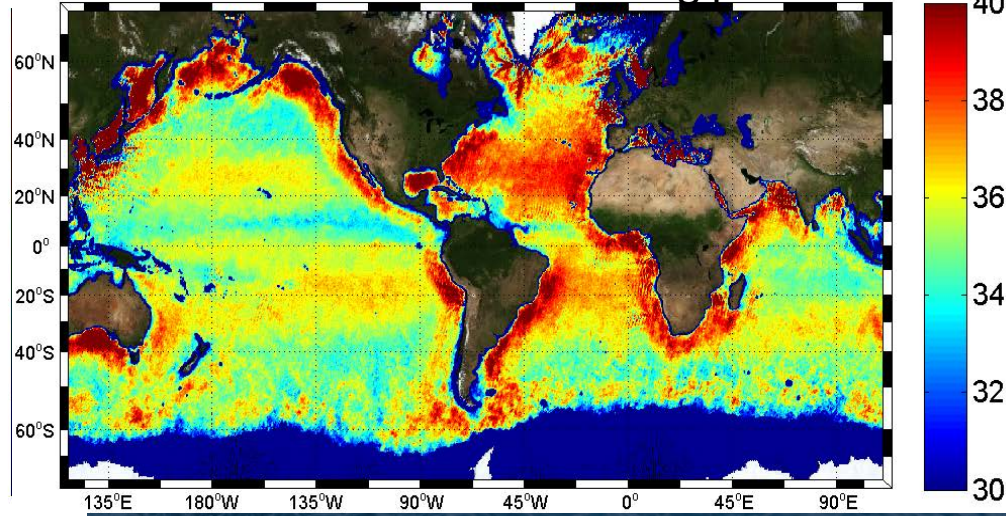
10 days –descending passes



1 month –ascending passes

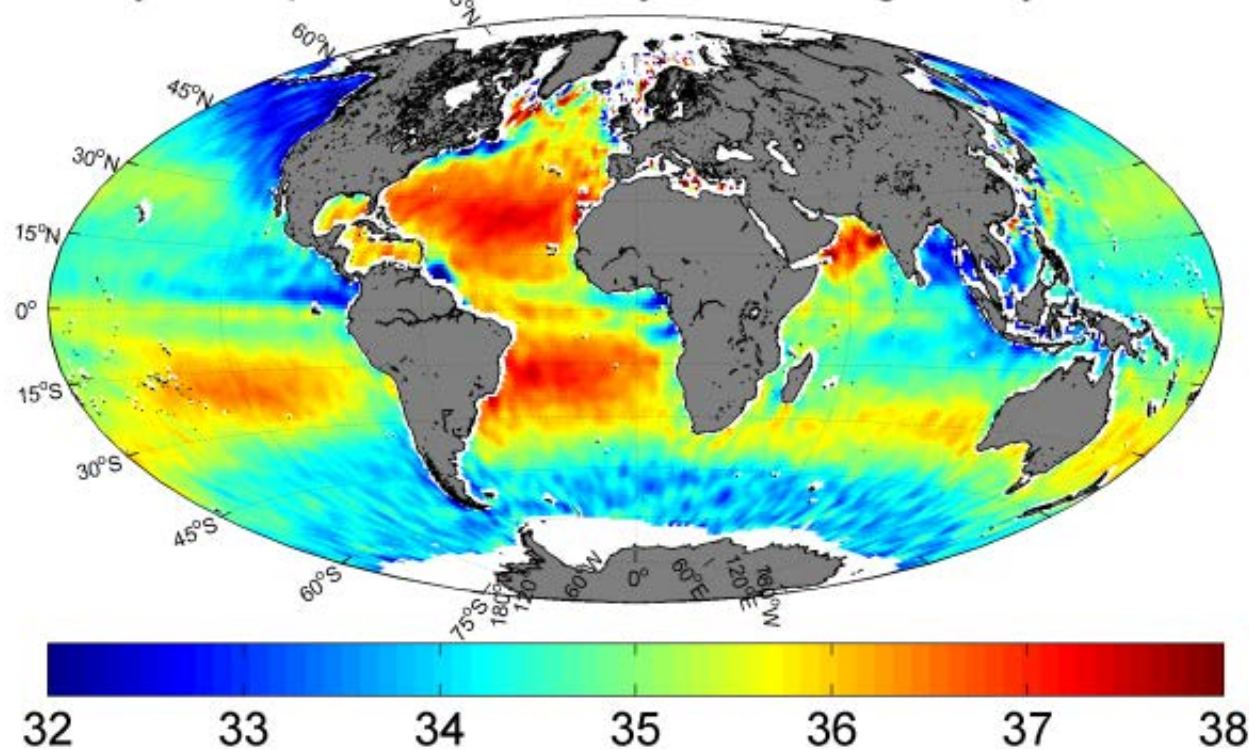


1 month –descending passes



SMOS refined Level 3 SSS products

SSS 10-Day Composite from May 01 through May 10-2010-1°x1°



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

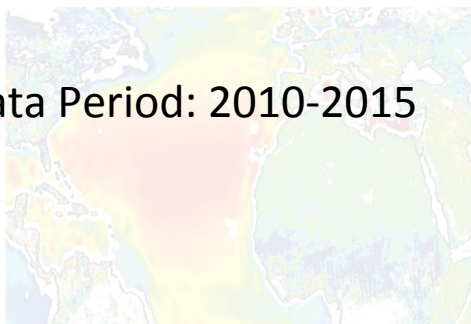


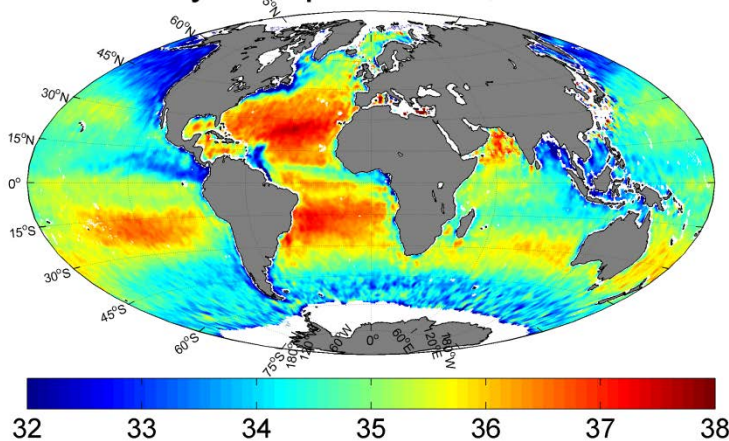
Table 1 Summary of characteristics of CATDS-CEC SSS level 3 products

	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 ($\sim \pm 300$ 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 $5^\circ \times 5^\circ$ 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

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



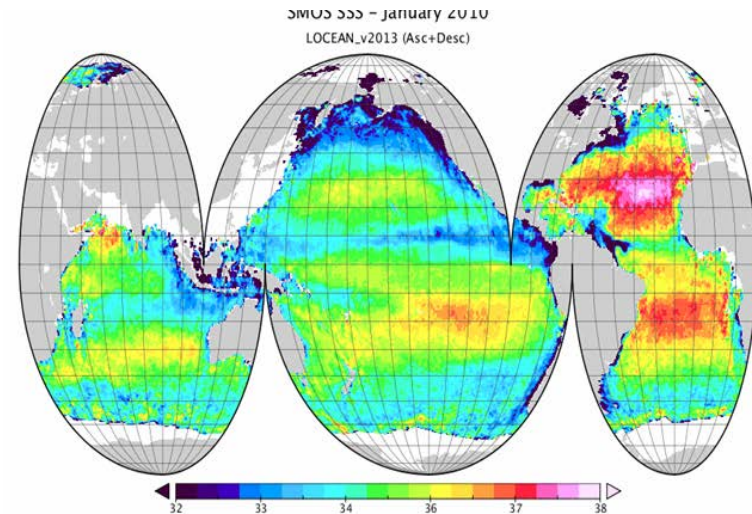
SSS Monthly Composite Jun, 2012-0.5°x0.5°



IFREMER-CEC

Stronger RFI filtering than ESA L2

Strong constraints wrt SSS climatology



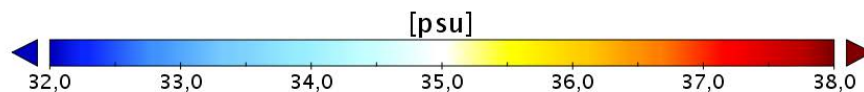
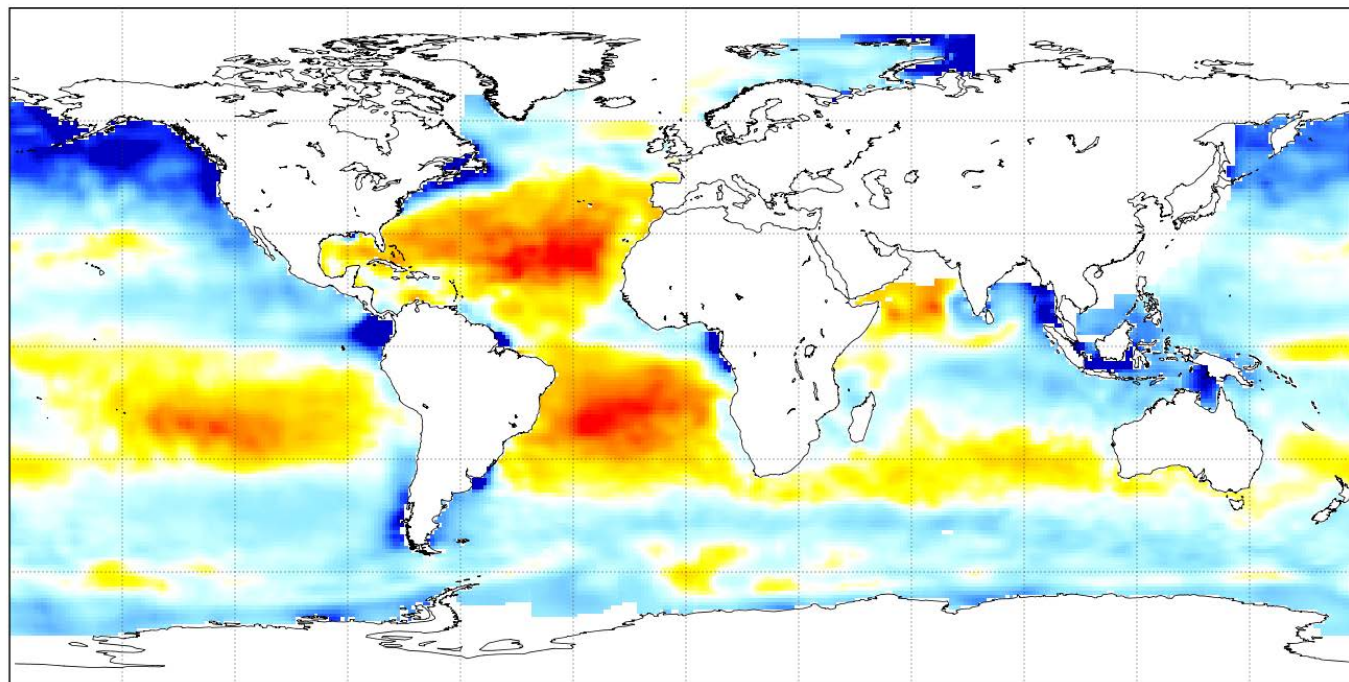
LOCEAN (ESA L2 binned SMOS SSS)

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

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

Sea Surface Salinity

1° × 1° Optimal interpolated map - 15/24 January, 2012 - BEC product



Data Min = 19,8, Max = 37,3

SMOS Barcelona Expert Centre

- **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