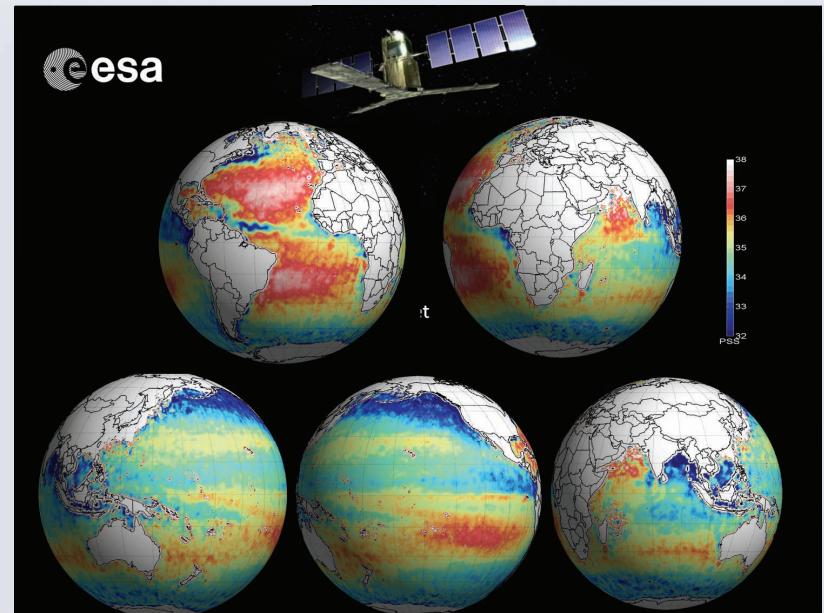


→ 4th ESA ADVANCED TRAINING  
ON OCEAN REMOTE SENSING

**Nicolas Reul, SMOS Scientist  
(IFREMER)**

**With contributions from SMOS &  
Aquarius science team members**



## Outline

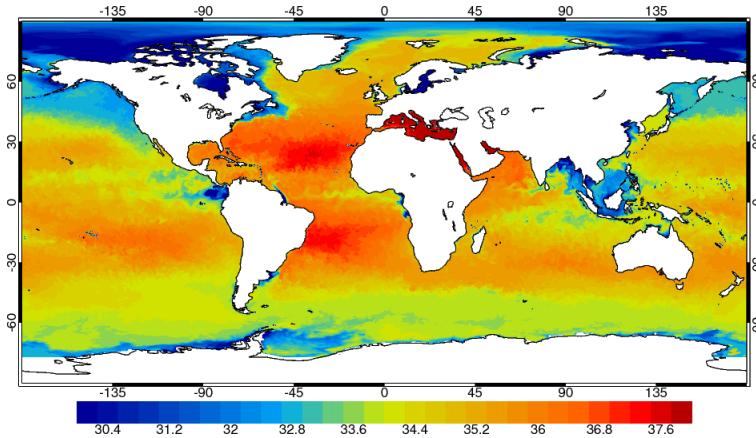
### Highlights of Science Results:

- ❑ Where are we ?
- ❑ Mesoscale variability of SSS (and density) in frontal structures, eddies
- ❑ Ocean propagative SSS signals (e.g. TIW, planetary waves)
- ❑ Large scale SSS anomalies related to climate fluctuations (e.g. ENSO, IOD)
- ❑ Freshwater flux Monitoring (precip, river run off)
- ❑ Air-Sea interactions (upwellings, Tropical cyclone wakes)
- ❑ T-S diagrams
- ❑ Bio-chemistry
- ❑ Surface Wind Remote Sensing in Tropical Cyclones

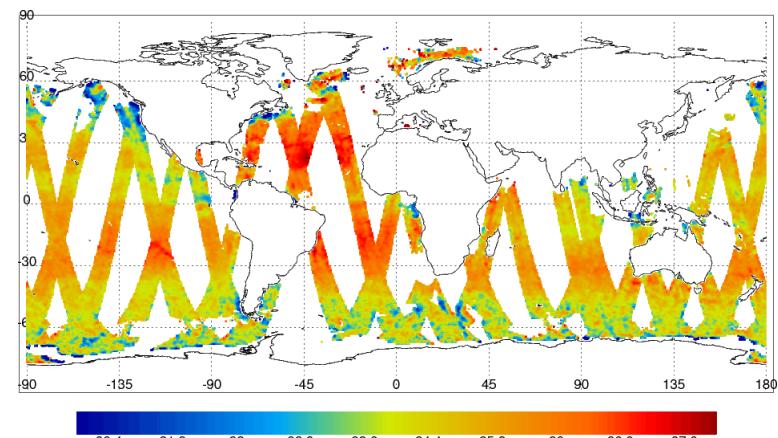


- Where are we in term of SMOS SSS data quality ?

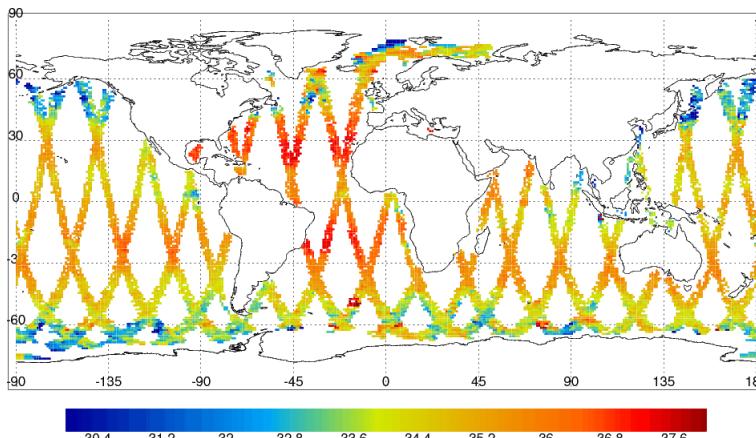
FOAM model



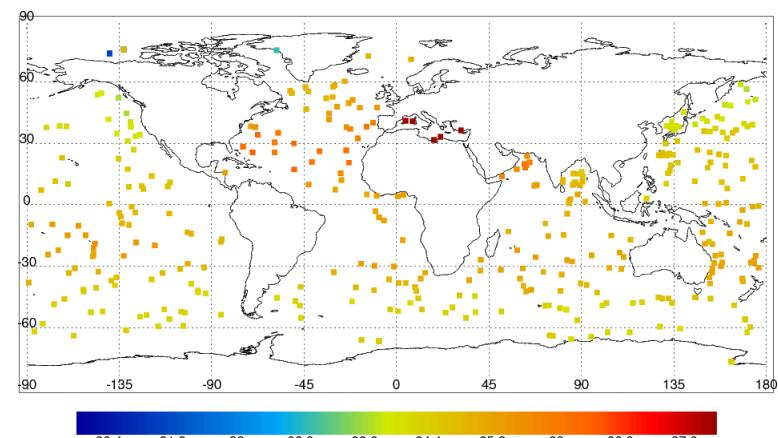
SMOS



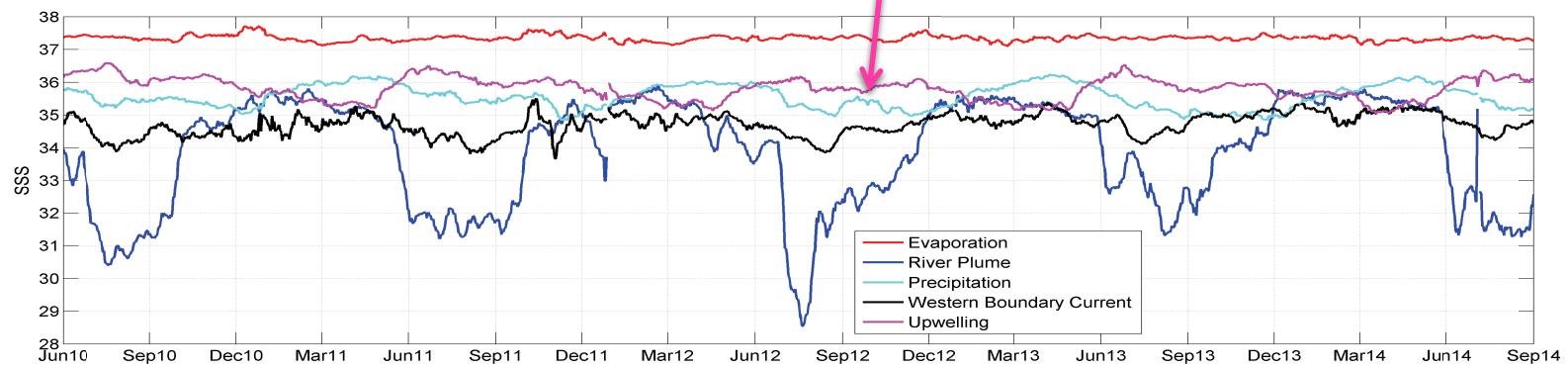
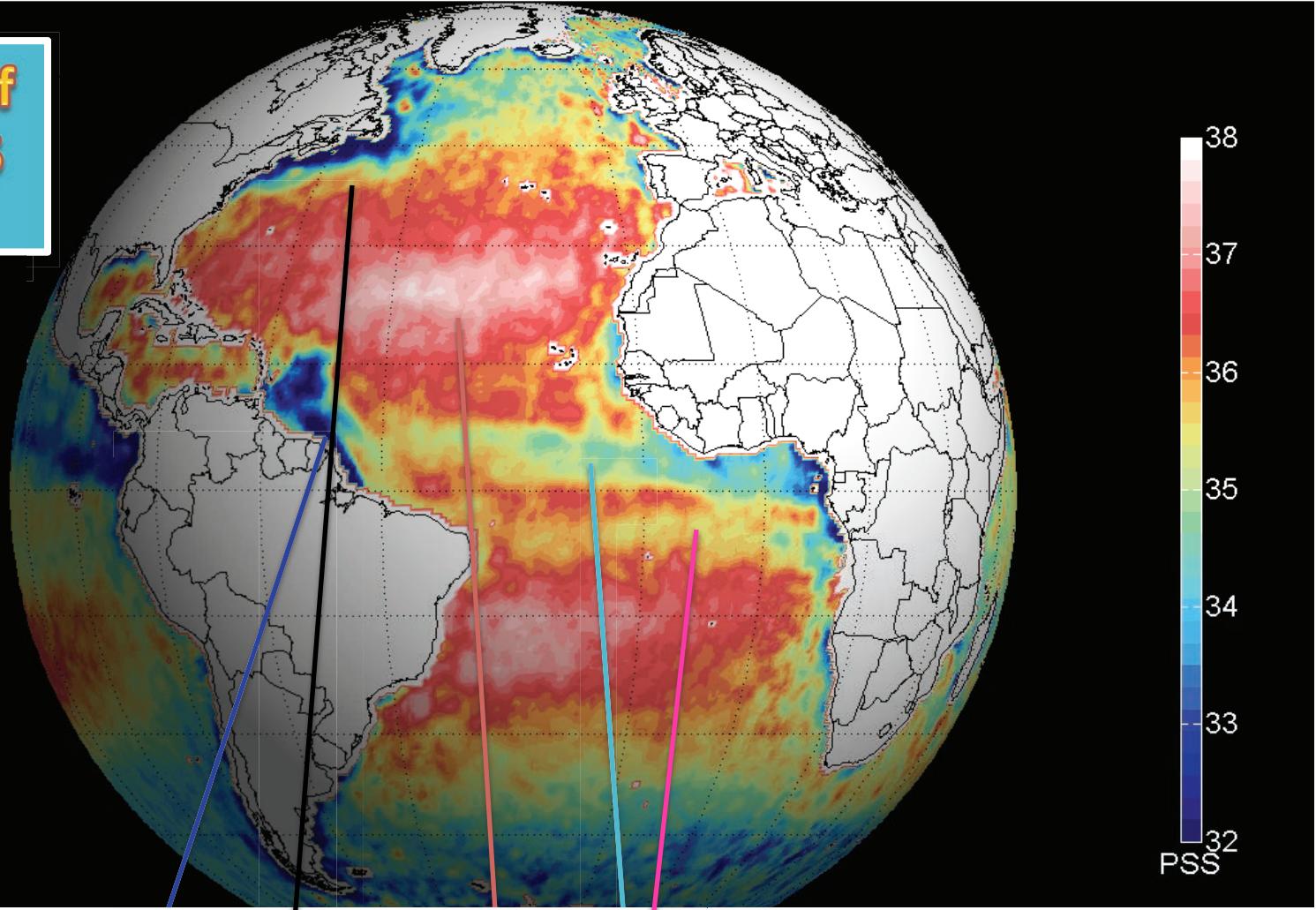
Aquarius



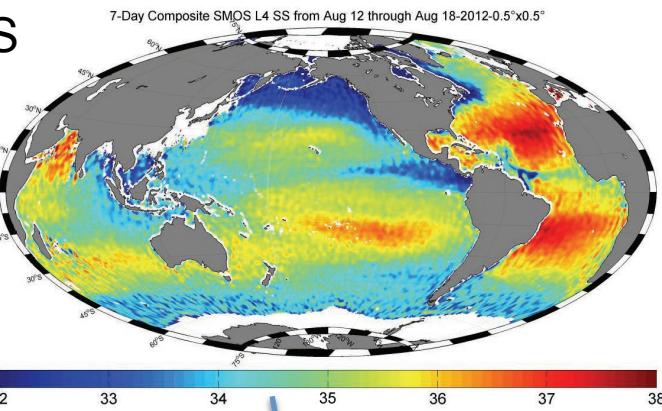
Argo



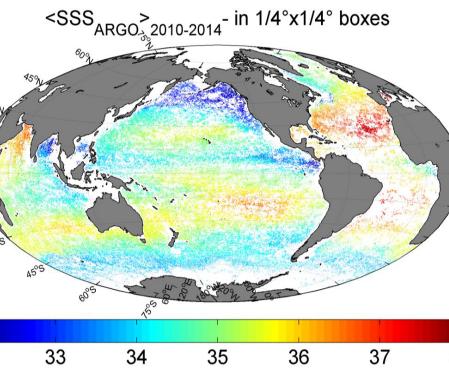
**~5 years of  
SMOS SSS  
data**



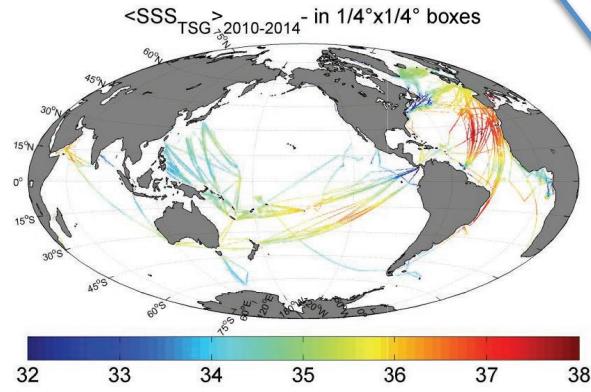
## Satellite SSS



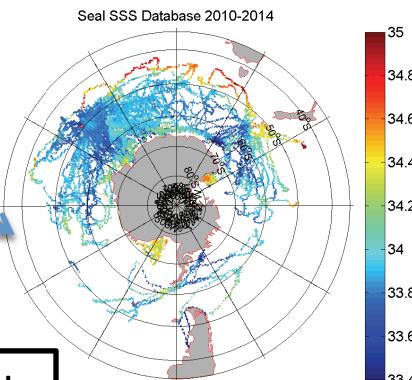
ARGO floats SSS



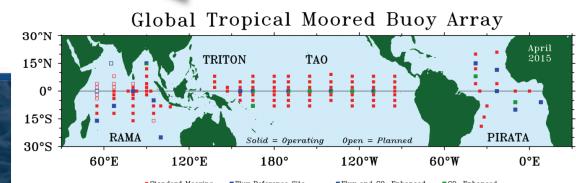
Ship TSG SSS



Equipped Mammals SSS



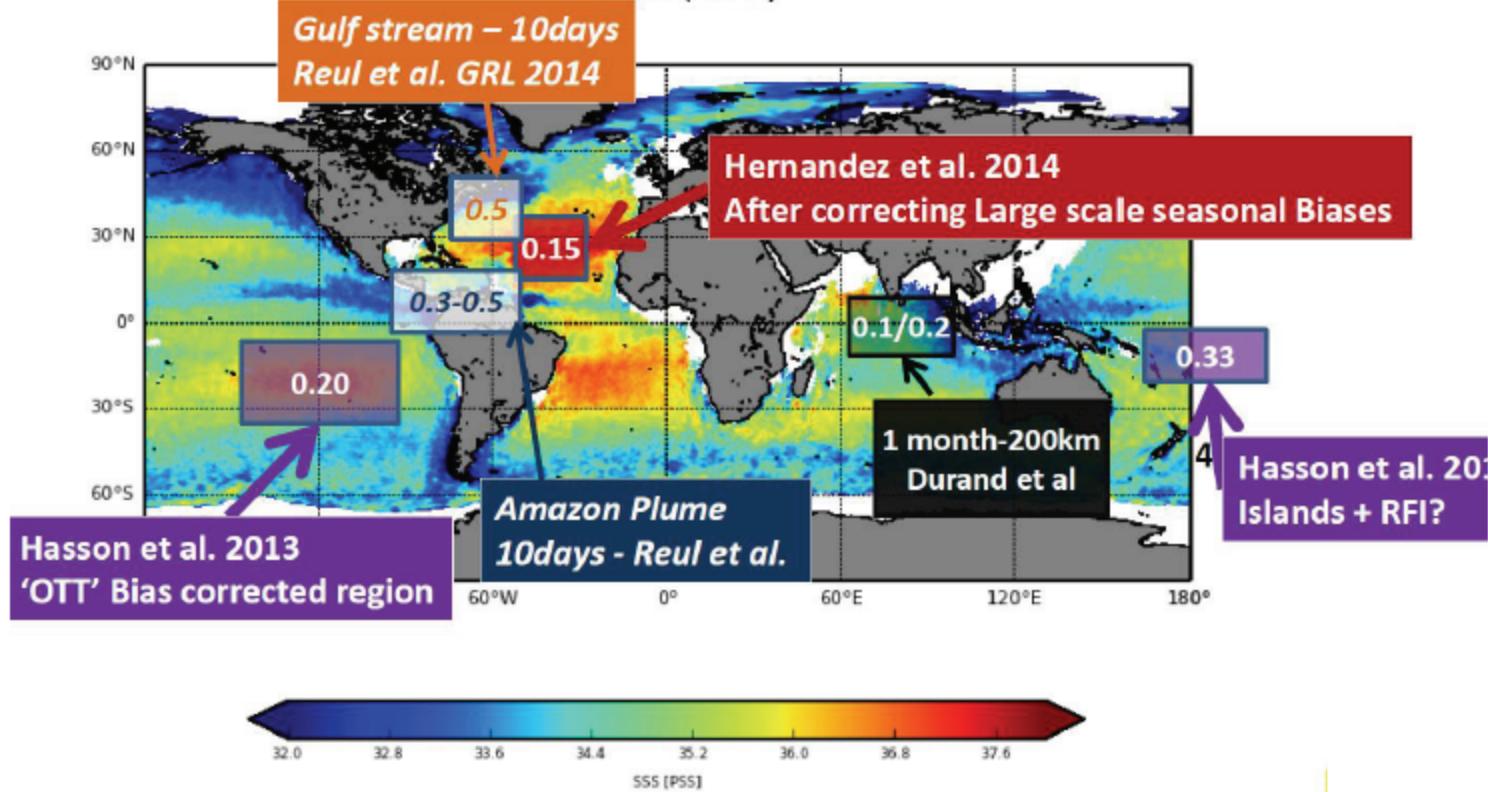
Tropical Moorings SSS



# Validation of Level 3 SMOS SSS with In Situ Observations

RMSDifference (SMOS SSS (**1 MONTH or 10 days**- $100 \times 100 \text{KM}^2$ ) – IN SITU SSS)

YEAR (2012)

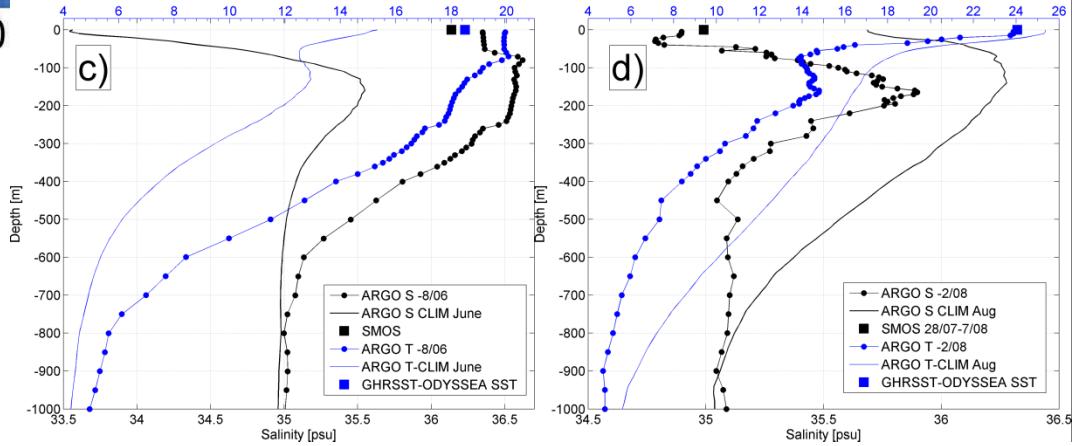
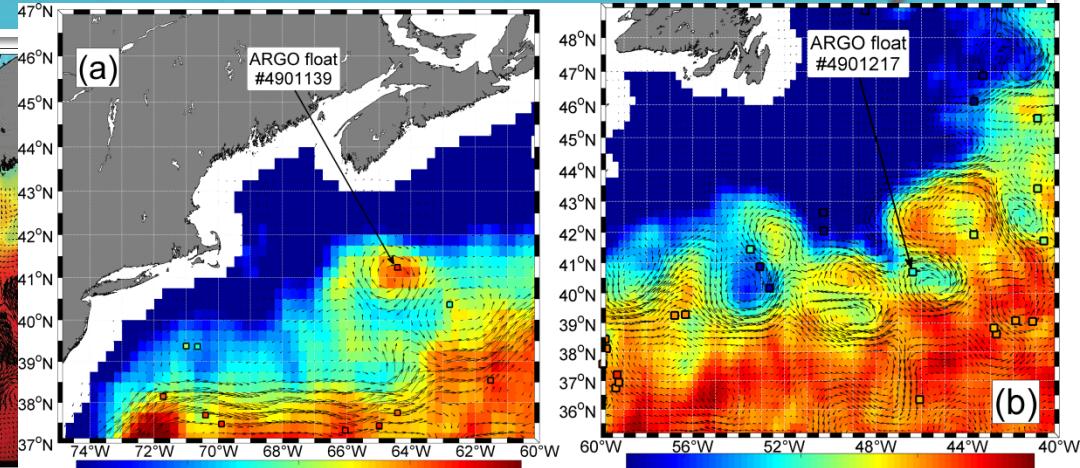
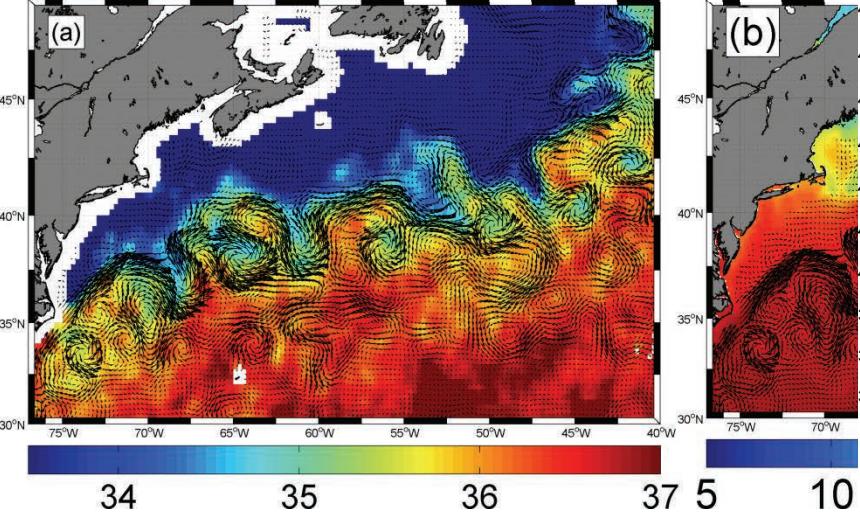


**Figure 2:** Regional Comparisons between SMOS Level 3 data (here CATDS CEC-LOCEAN, CEC-IFREMER and CATDS/OPER) and in situ data including ARGO profiler, moorings and TSGSSS data (1-10m depth). The numbers given show the rms difference between Level 3 data and in situ observations averaged over  $100\text{km} \times 1\text{month}$  (otherwise specified).



□ SMOS monitoring of Mesoscale variability of SSS in frontal structures, eddies

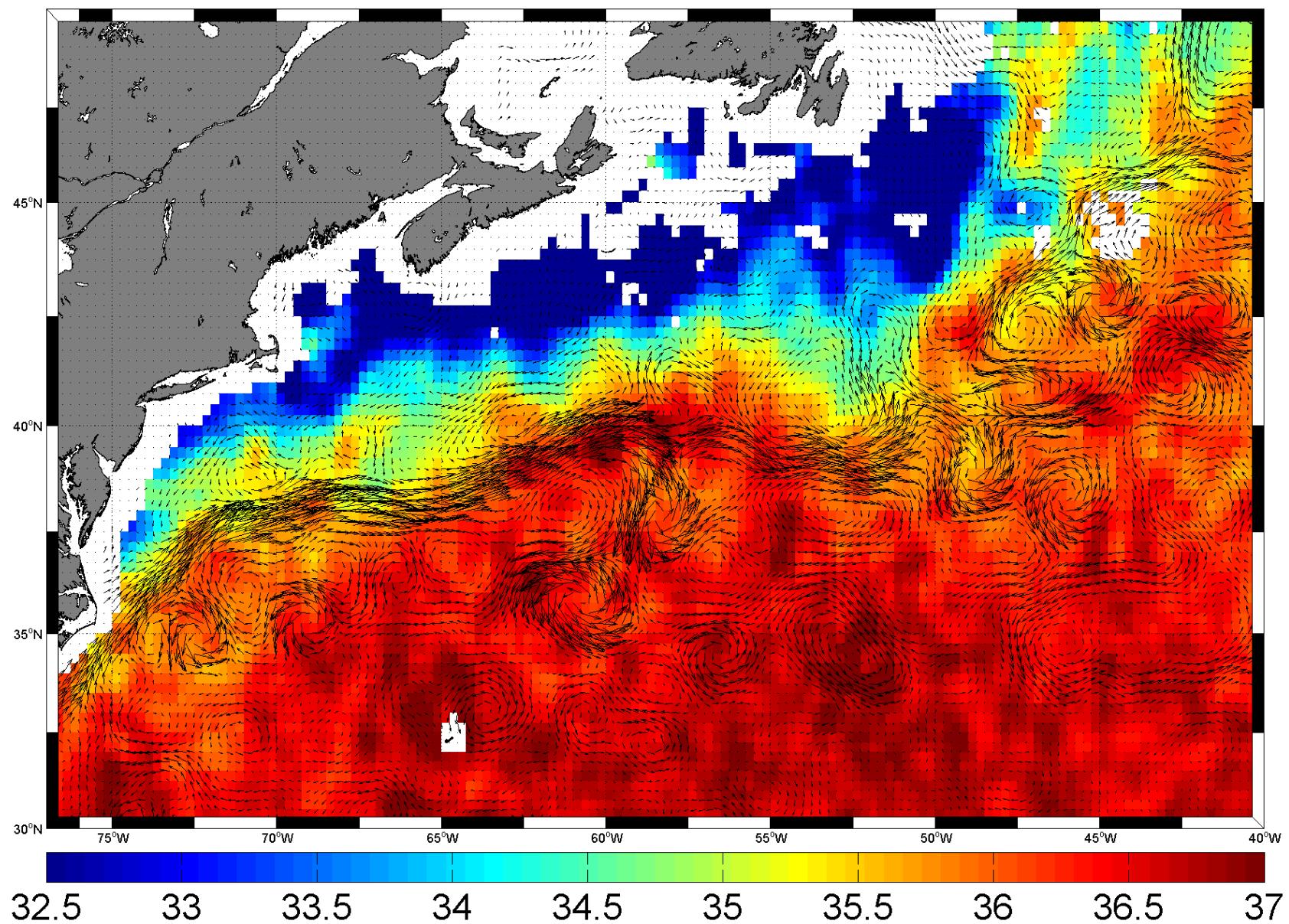
# Monitoring Salt Exchanges in Strong water mass Boundary region with SMOS: Gulf Stream Example



- SMOS reveals SSS structure of the Gulf Stream with an unprecedented Space and time resolution
- Cold/fresh Core rings are better captured by SSS observations than by SST during summer.
- Chl concentration in the separated Gulf Stream significantly correlated with SSS
- Synergistics analysis SSS-SST-SSH-Color
- Perspective : Surface salt-transport estimates By Eddies Subtropical↔Subpolar Gyres

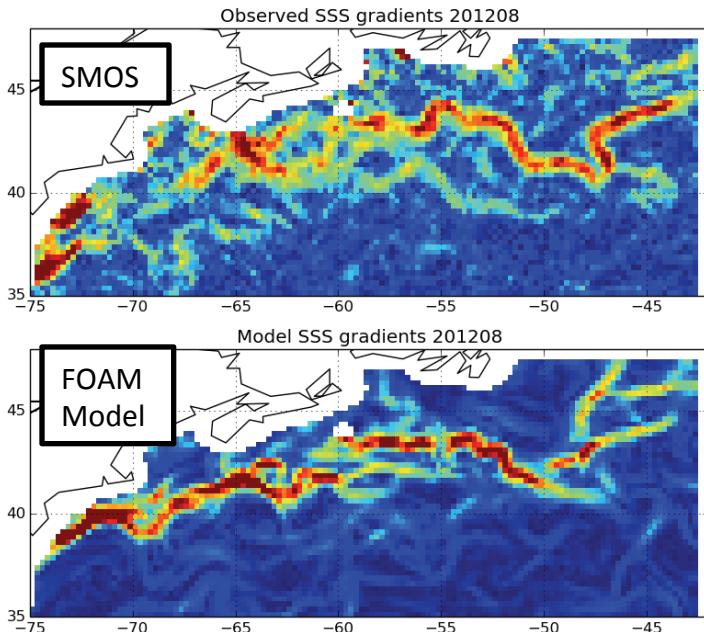
*Reul et al. GRL 2014*

SMOS SSS (color)+ currents (vector) from 03/03 to 17/03 2012

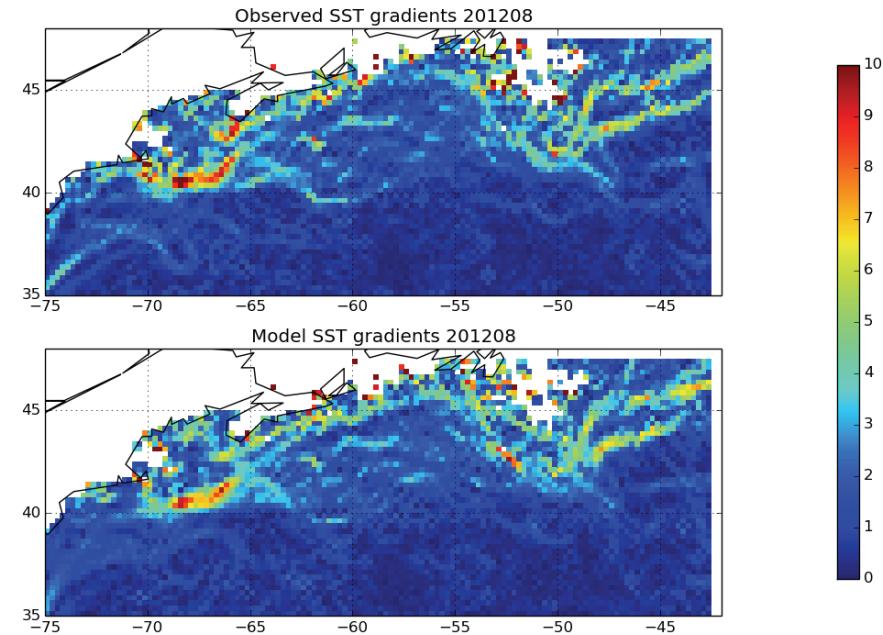


# Monitoring Fronts at Strong water mass Boundary region: Gulf Stream Example

SSS horizontal gradients

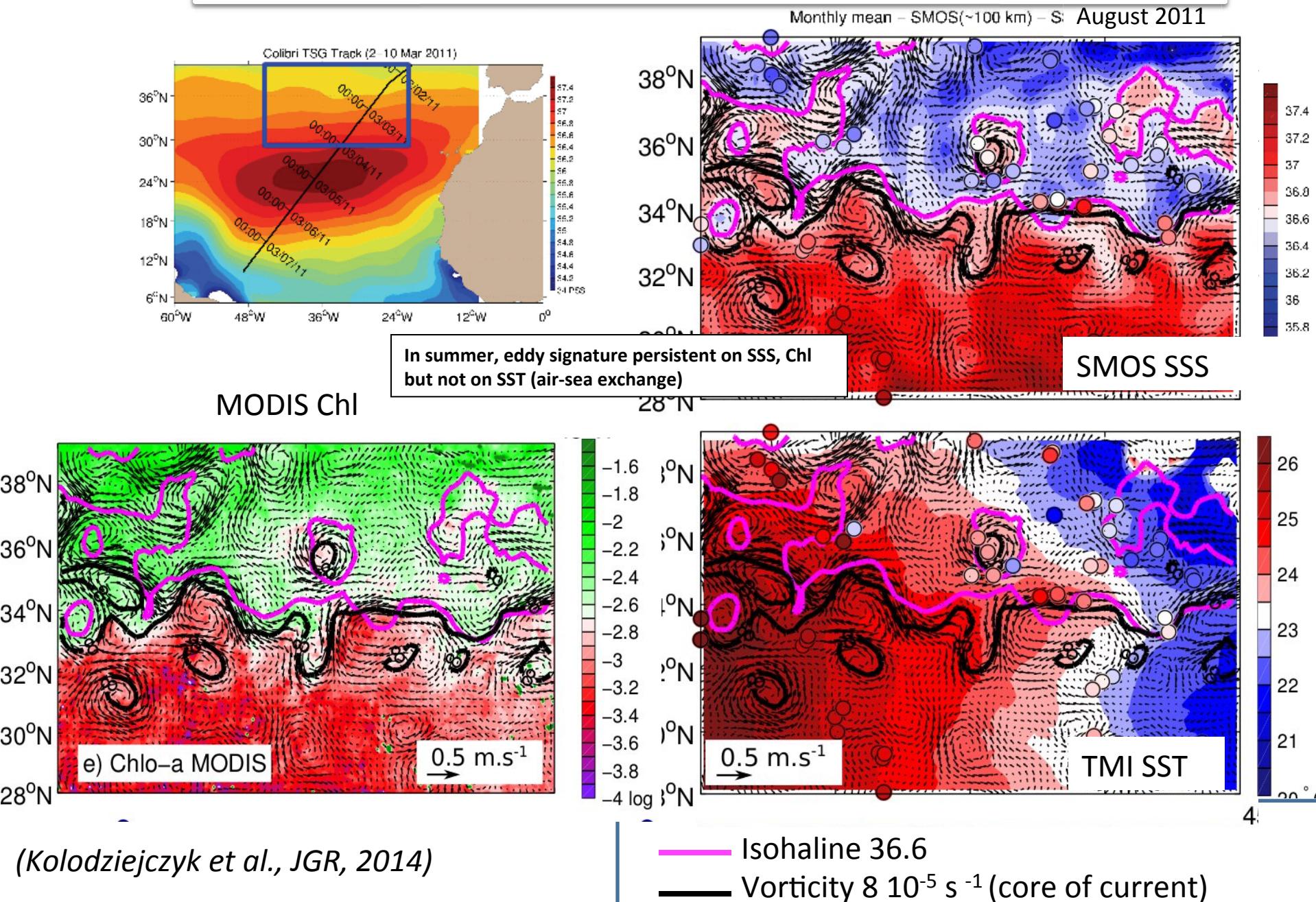


SST horizontal gradients



- SSS fronts agree well between model and SMOS observations
- However, SMOS data shows a frontal structure in the main part of the GS which the model doesn't represent. Who is right ?
- Surface warming has masked the underlying structures in SST in summer, SSS comes as a natural complement to SST & SSH observations

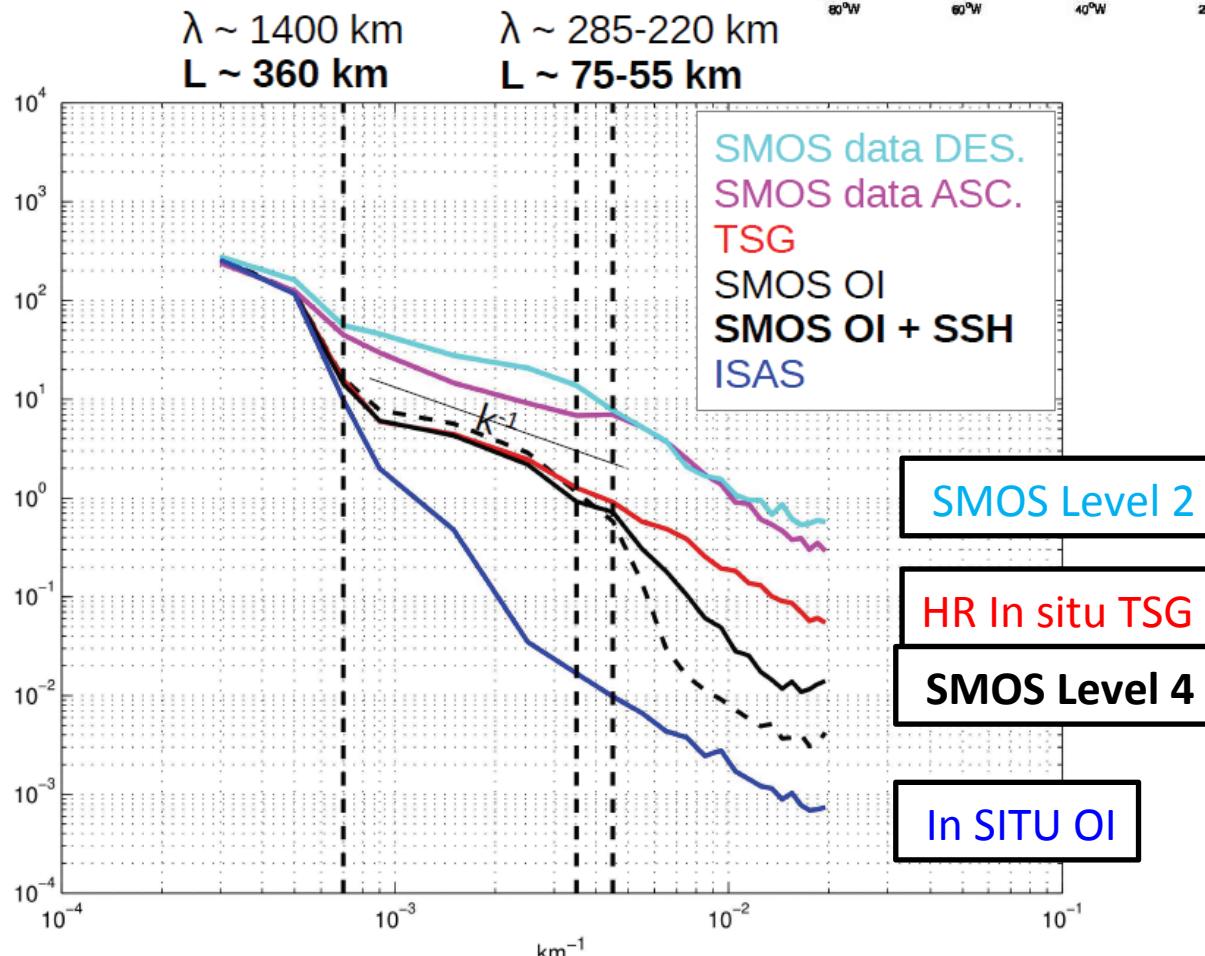
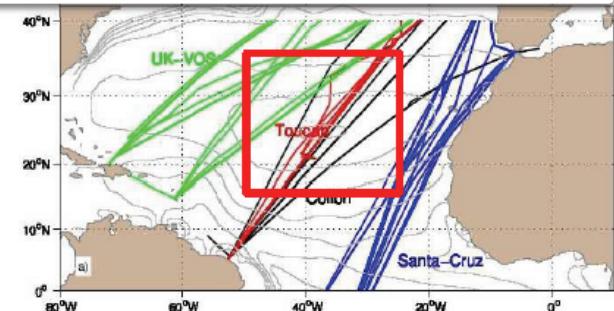
# Azores current/Front Example



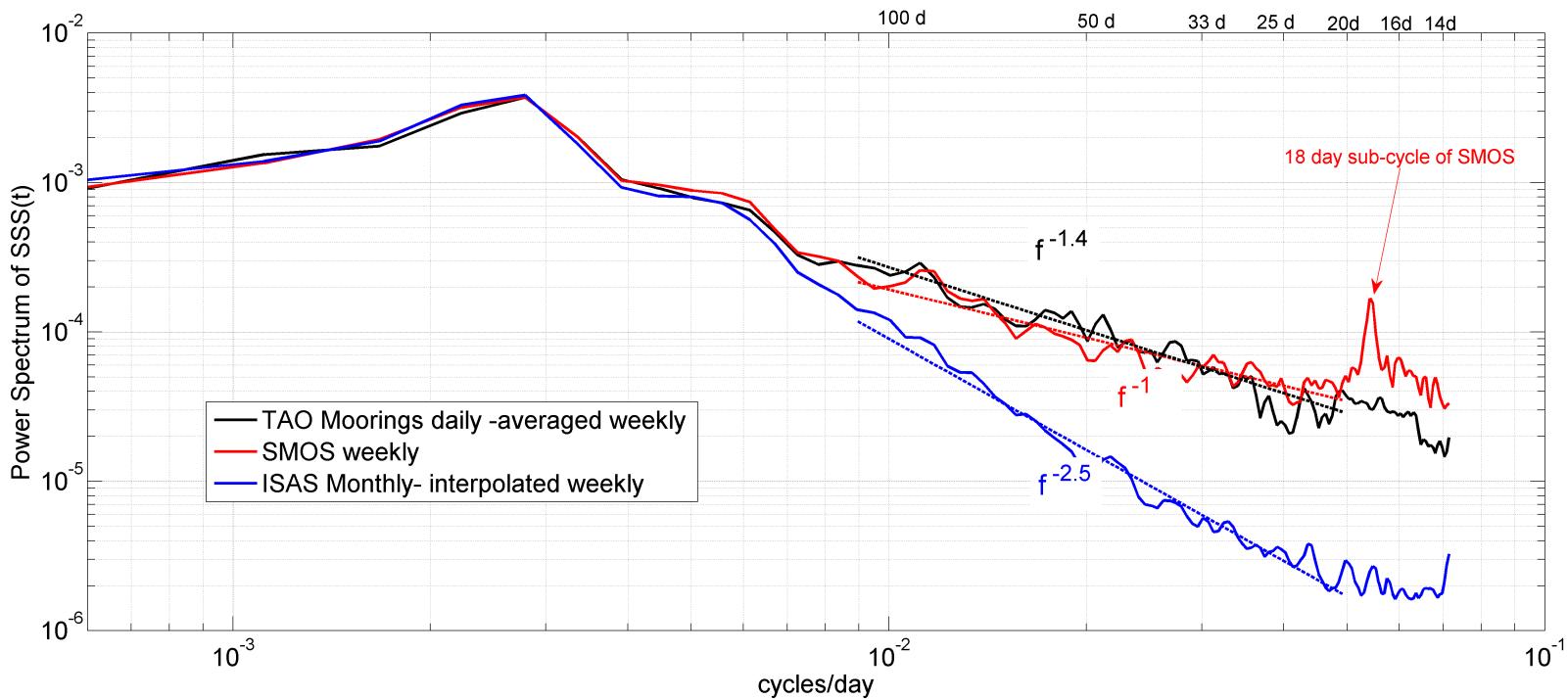
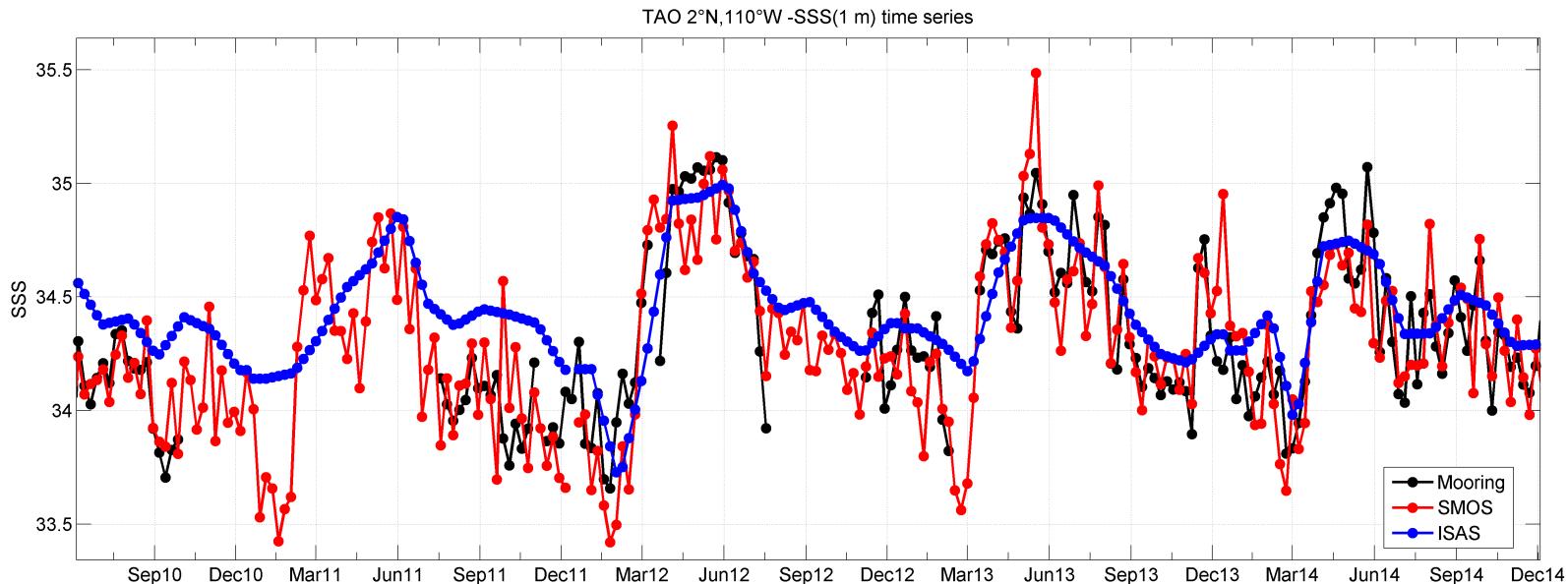
# SMOS « sees » the Meso-scale SSS variability down to ~100-50 km

## Comparison with TSG

- Power Spectra
- 32 TSG section (Colibri & Toucan)



See N. Kolodziejczyk's talk





- SMOS monitoring of Ocean propagative SSS signals (e.g. TIW, planetary waves)

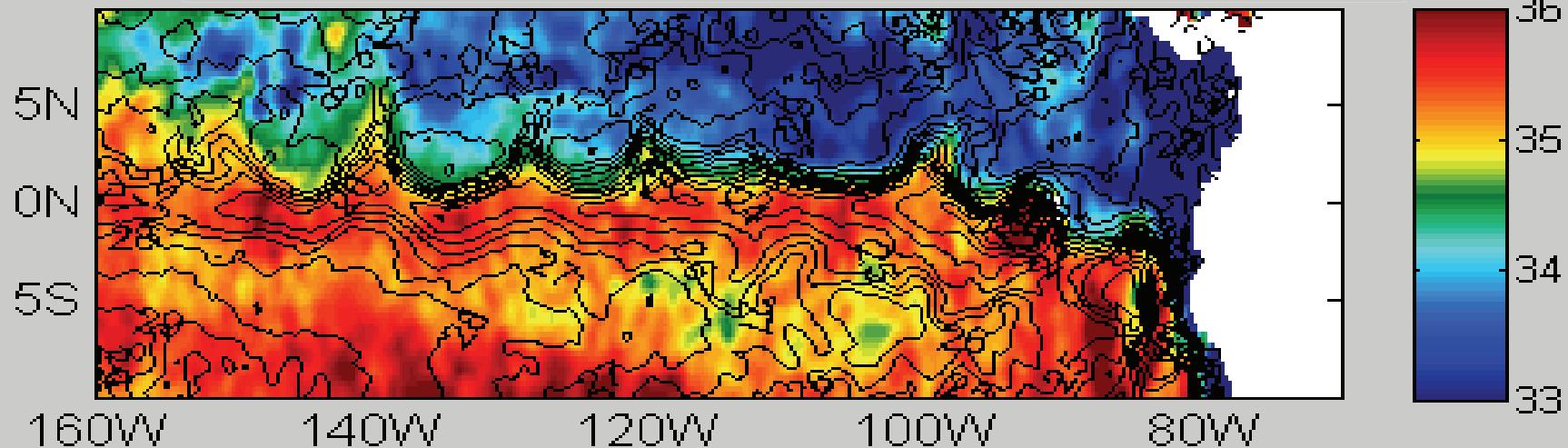
# SMOS Sea Surface Salinity signatures of tropical instability waves

Xiaobin Yin<sup>1,2</sup>, Jacqueline Boutin<sup>1</sup>, Gilles Reverdin<sup>1</sup>, Tong Lee<sup>3</sup>, Nicolas Martin<sup>1</sup> and Sabine Arnault<sup>1</sup>

1. Laboratoire d'Océanographie et du Climat-Expérimentation et Approches numériques / Institut Pierre Simon Laplace – UMR 7159 CNRS/IRD/UPMC/MNHN, Paris, France
2. ARGANS, Plymouth, UK
3. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

# SMOS SSS signal of Tropical Instability Waves

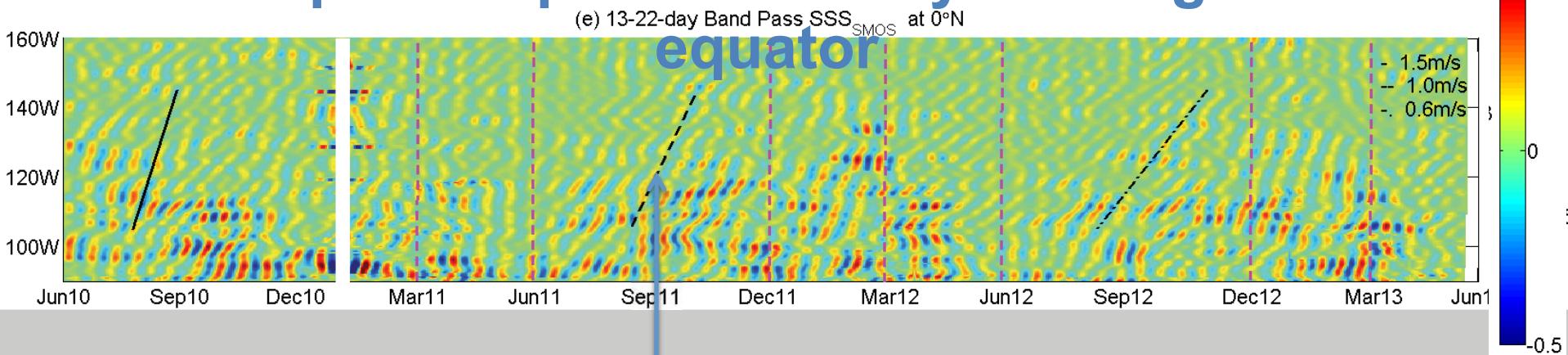
01-Jun-2010, SSS (color) and SST (isolines)



*Yin et al., JGR 2014*

Decrease in TIW speed at the equator during La Niña-> El Niño transition

## Variable phase speed of 17-day SSS signal at the equator

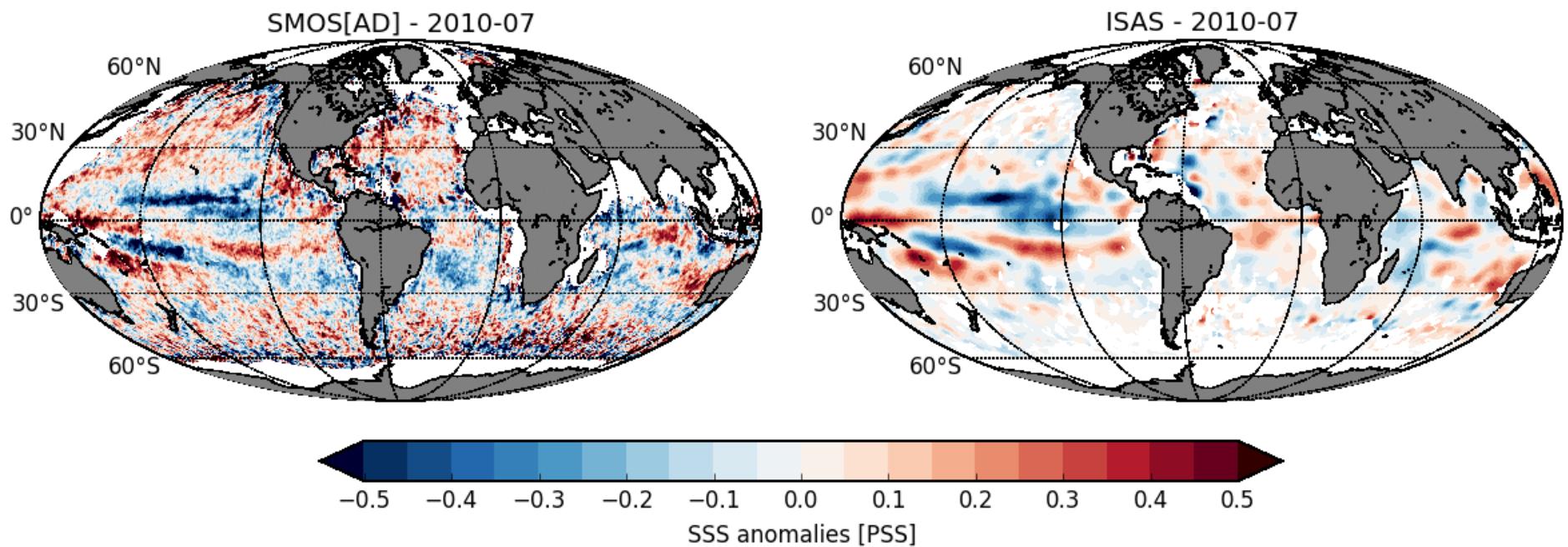
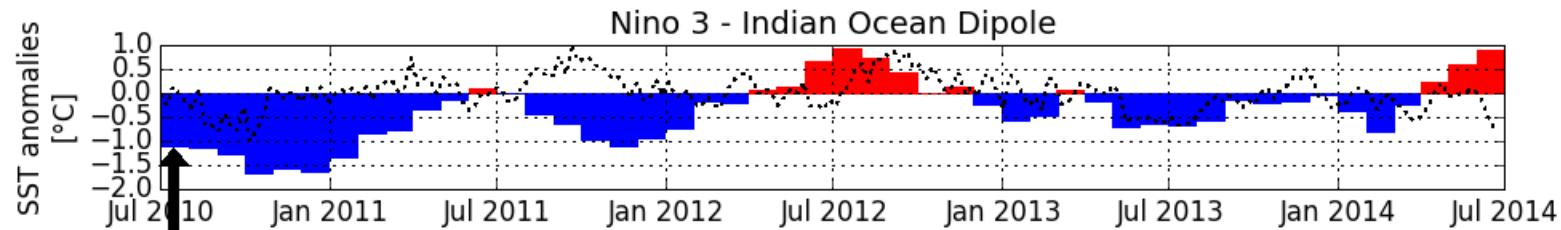


Consistent with Aquarius result (Lee et al. 2012) during this period



- Detection and monitoring of Large scale SSS anomalies related to climate fluctuations (e.g. ENSO, Indian Ocean Dipole)

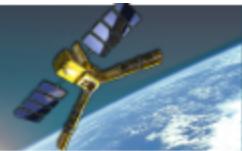
## Interannual anomalies SMOS/ ARGO OI (ISAS)



Boutin et al 2014

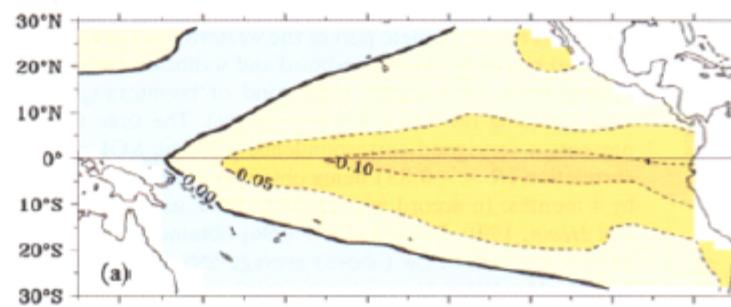


# SST and SSS ENSO Signature

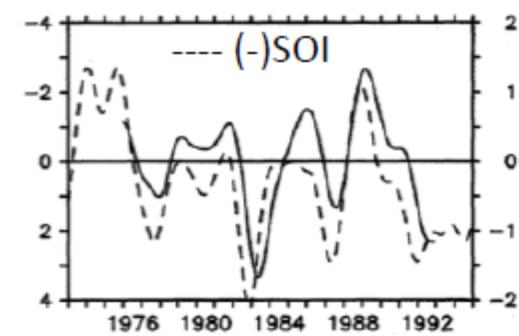
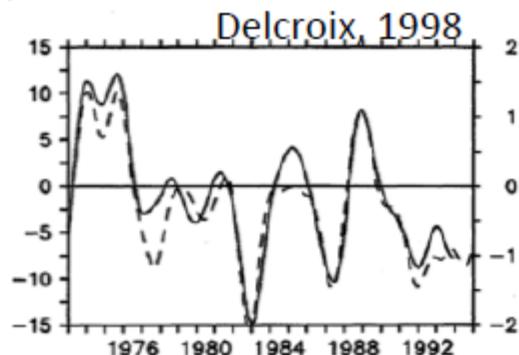
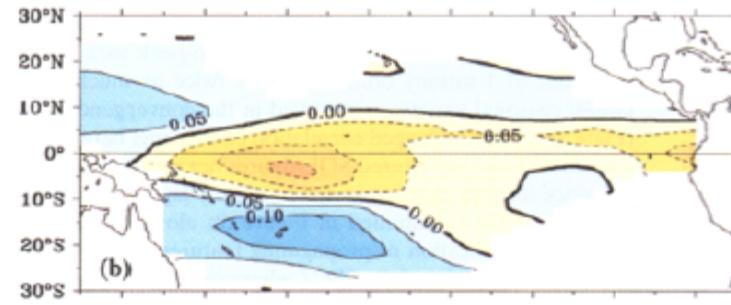


- SST ENSO signature located on the Equatorial Eastern half of the basin and in phase with SOI
- SSS ENSO signature located on the Equatorial Western half of the basin and under the SPCZ, following SOI with a few month lag

1st EOF on SST  
interannual signal



1st EOF on SSS  
interannual signal



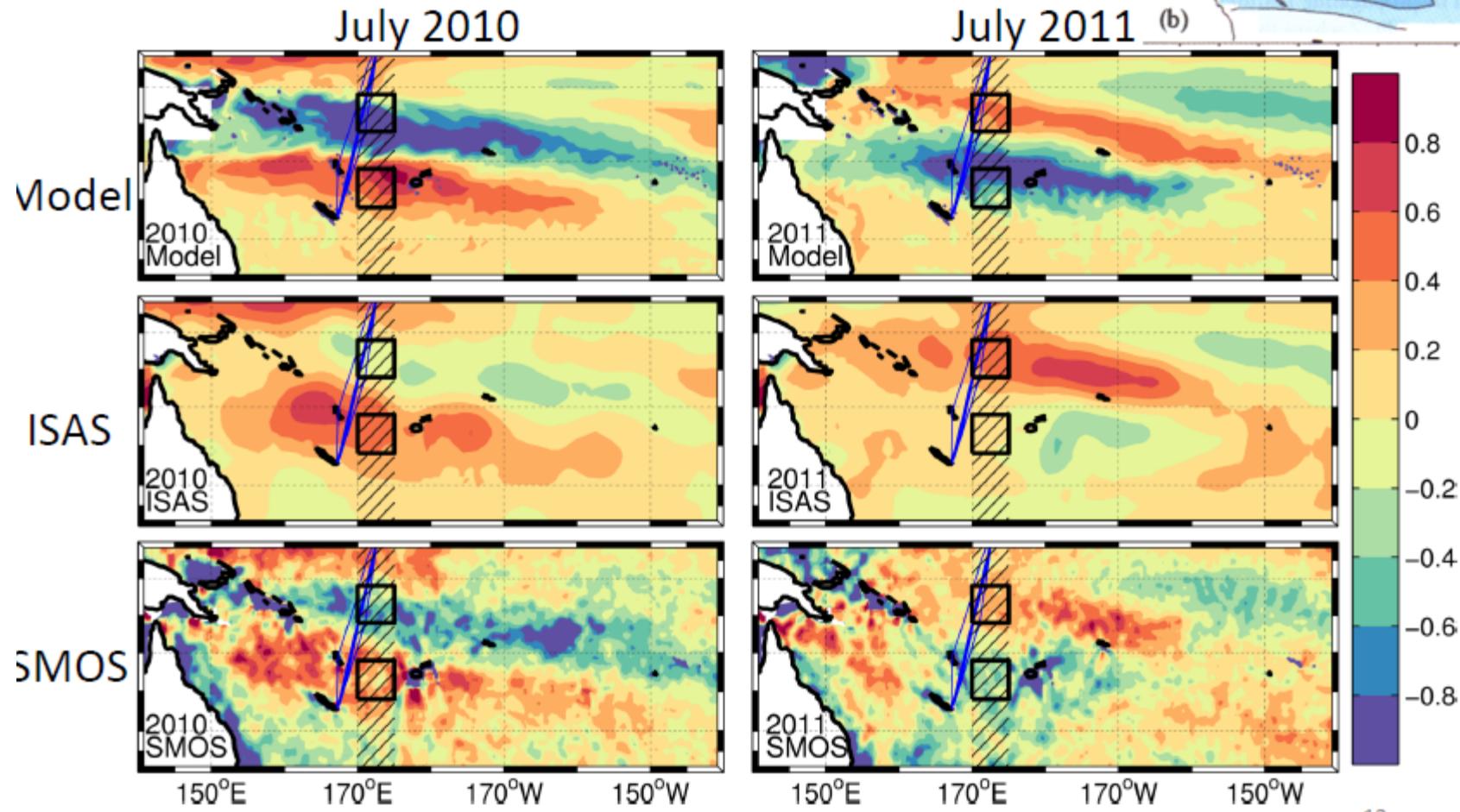
See also for similar results : Gouriou and Delcroix 2002 , Singh et al. 2011 etc... 2



# July 2010 & 2011 SSS Anomalies



Anomalies relative to mean July ISAS climatology.





# Conclusions



**The tropical Pacific Ocean has been in a La Niña phase from mid 2010 to early 2012.**

0.6 psu expected SSS variation associated with ENSO from previous studies

**Four complementary datasets** were used to describe this event.

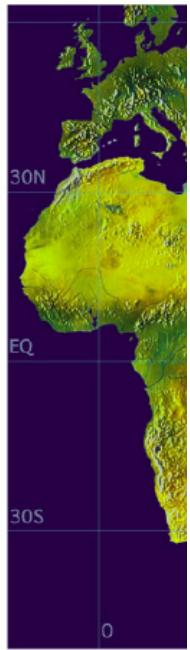
**SMOS ability to capture the unusually strong bi-polar anomaly** in the southwestern Pacific associated with La Niña has been shown.

The **responsible processes** for this anomaly are quantified with the model output only.

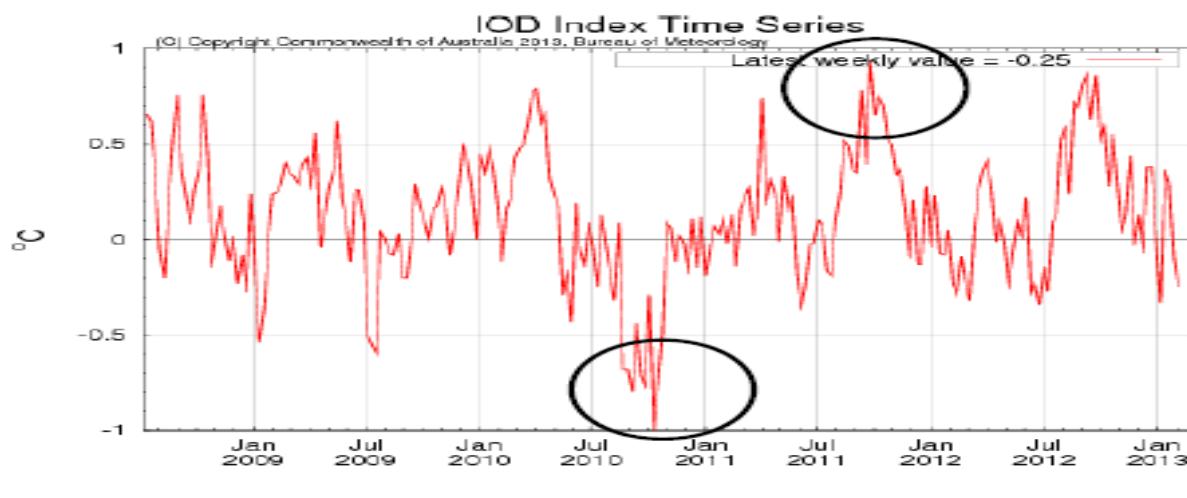
- The salinity tendency in the SPCZ region is in phase with NINO3.4
- The decrease is mainly driven by **Meridional Advection** caused by a steep change in the Meridional SSS gradient
- **Surface Forcing** strongly freshens the surface by the end of 2010 but is damped by **Subsurface Forcing**

## Indian Ocean Dipole

Negative Dip



IOD events in 2010-2011



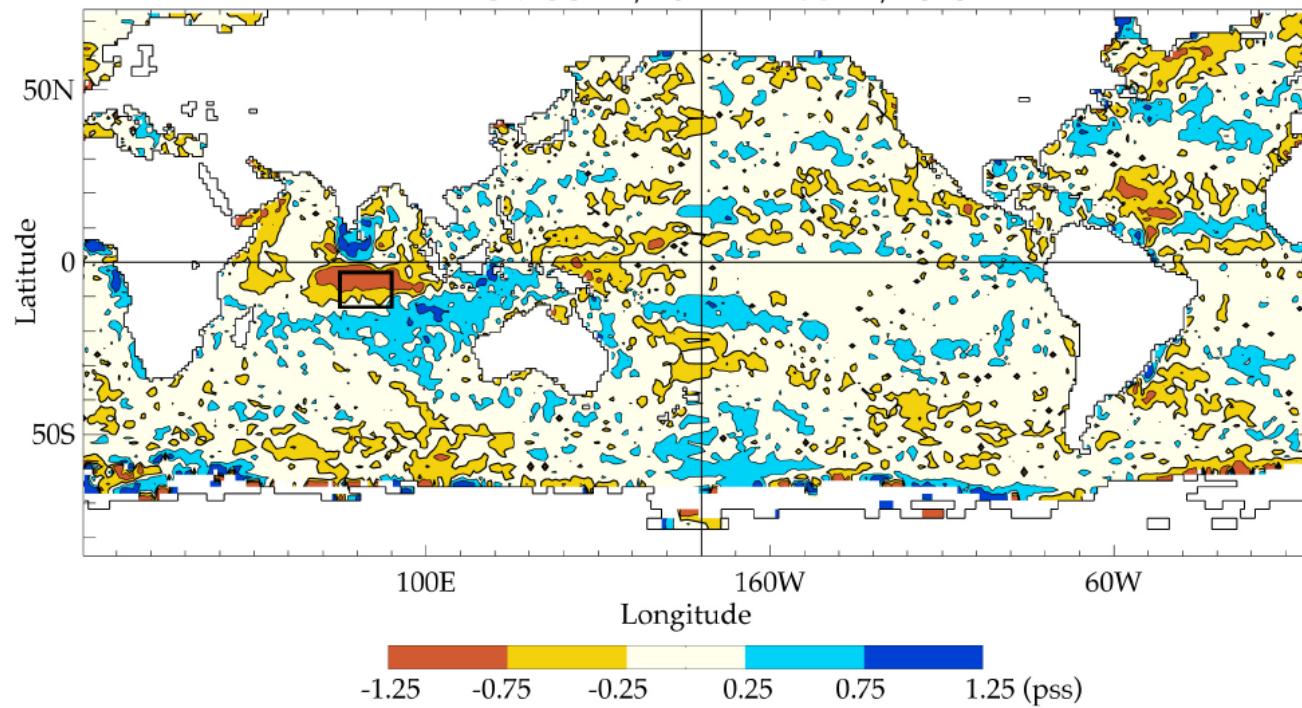
Reverdin et al., 1986; Webster et al., 1999; Saji et al., 1999

IOD: the dominant mode of climatic variability in the Indian Ocean

## SMOS SSS variability in 2010-2011

Product: Level3,  $1^\circ \times 1^\circ \times 1\text{month}$  from CATDS-CPDC

SMOS 12/2011 minus 12/2010



SMOS SSS difference between 12/2011 and 12/2010 in the Indian Ocean : the largest, longest-lasting year-to-year observed signal over SMOS period

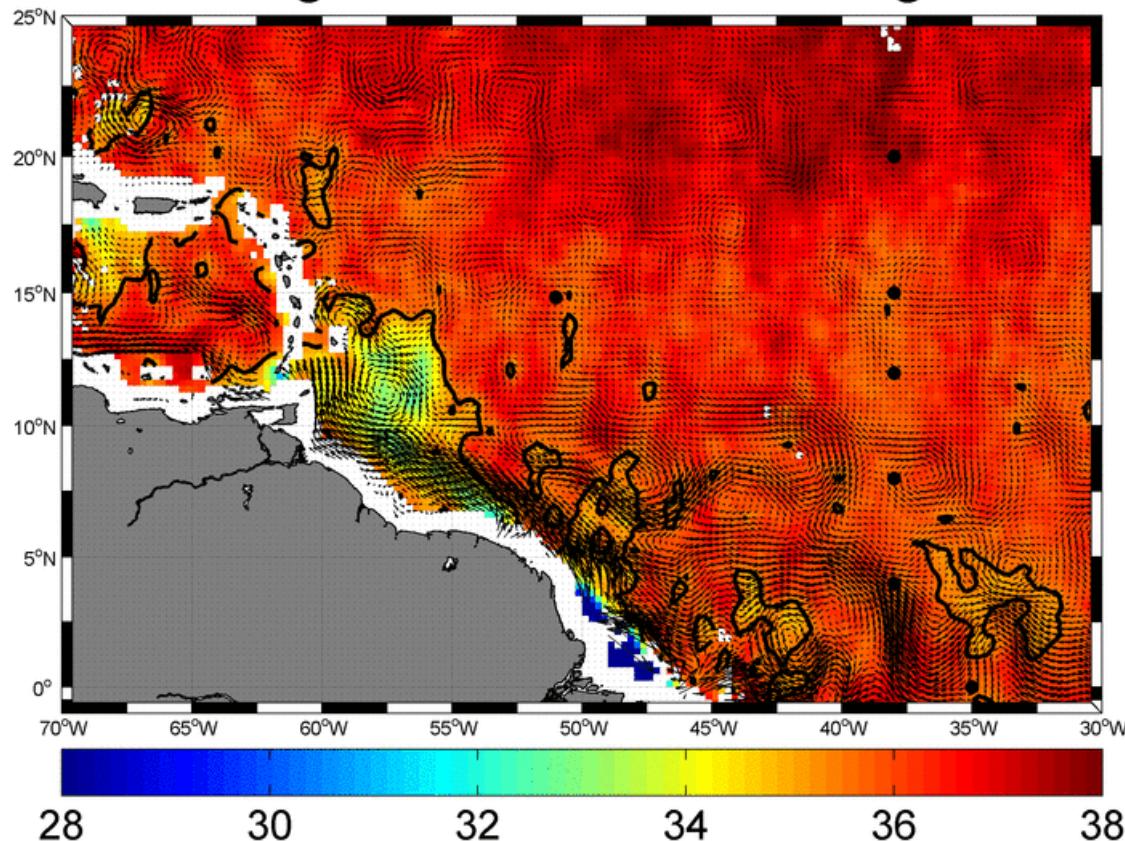
IOD-/IOD+ peaks in november 2010/2011



## ❑ Freshwater flux Monitoring (precipitation induced signals, river run off)

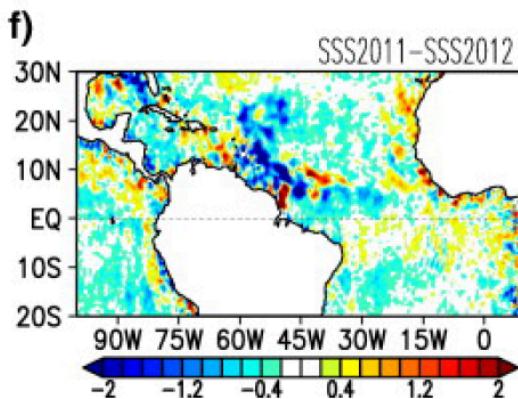
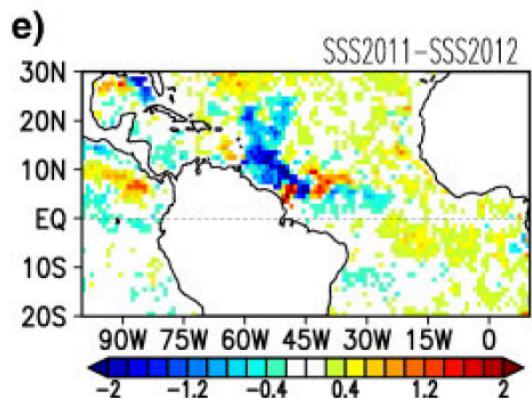
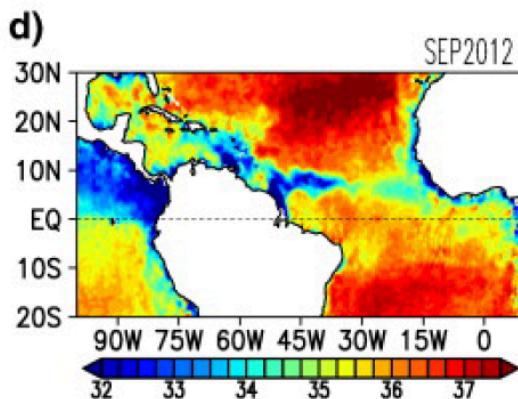
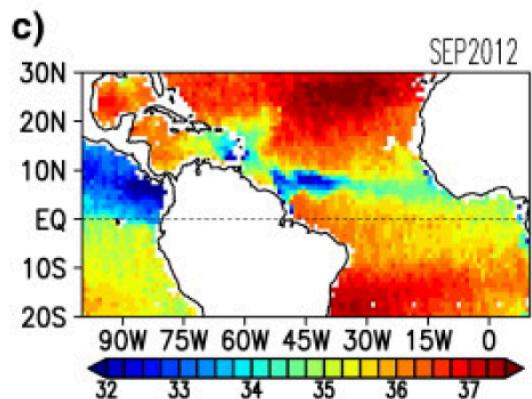
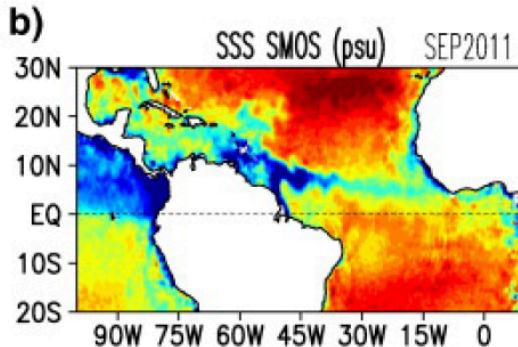
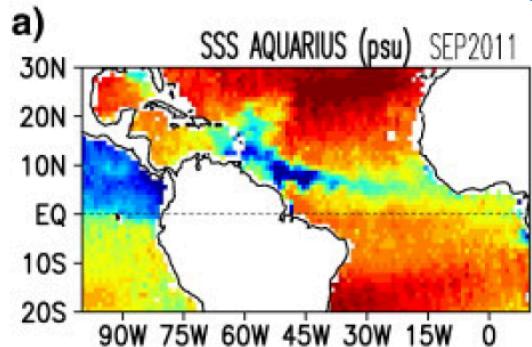
# Satellite SSS monitors variability of river discharges: Amazone and Orinoco River Plumes

SSS Averaged from Feb 26 through Mar 08



*Reul et al., Surv. Geophys., 2014*

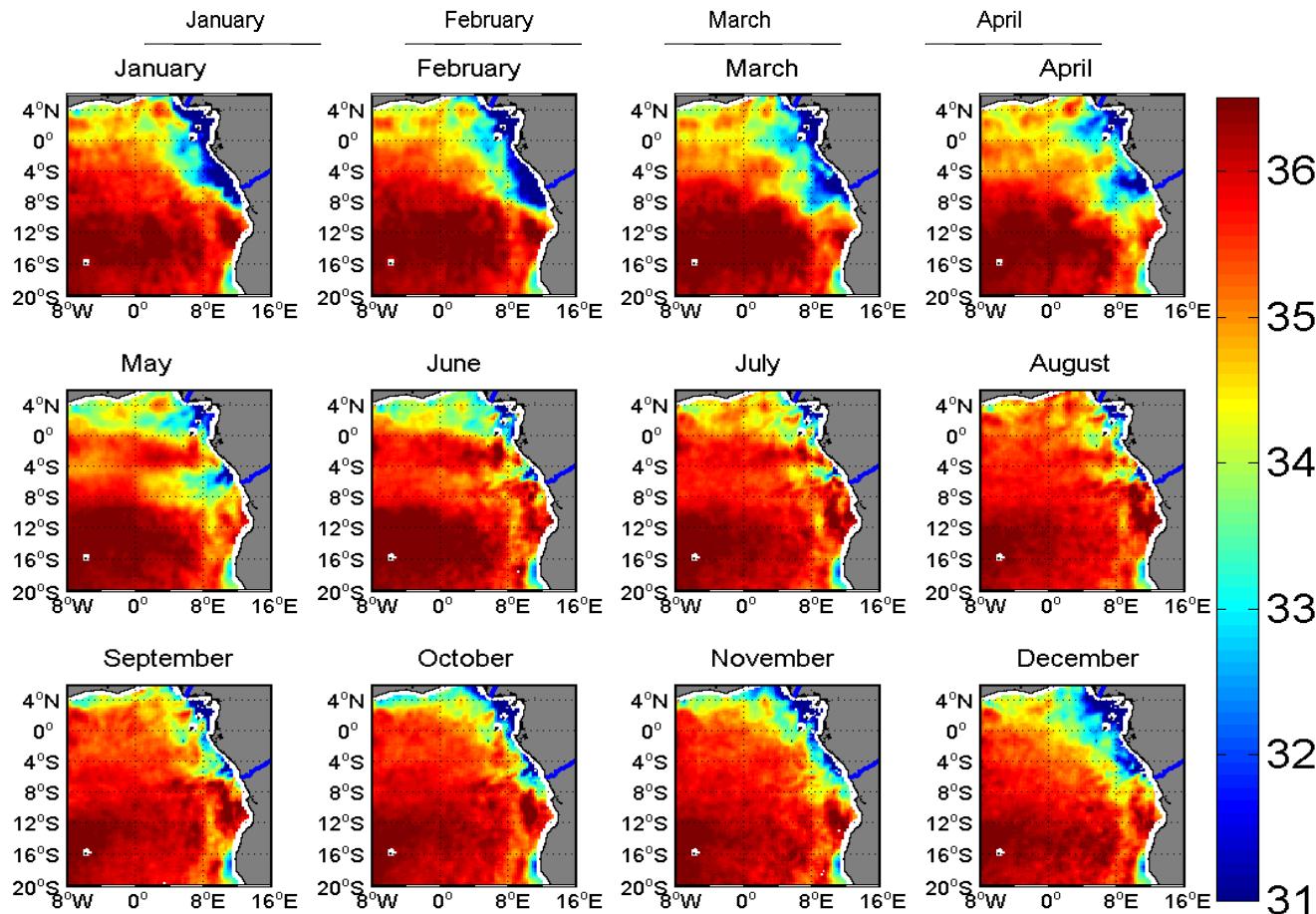
# Variability of the Amazon plume: not only an effect of river discharge



The plume was 1 psu saltier in early fall 2012 than in the previous fall (despite a stronger Amazon discharge in 2012) - The most likely causes of the 2012 salinification are a **relative deficit of rainfall** over the inflow to the plume region well southeast of the plume in spring and a weaker North Brazil current in spring–summer.

Grodsky et al. RSE 2014

# Monitoring the Congo river Plume Mean Seasonal Cycle



SMOS data collected during the period 2010-2012

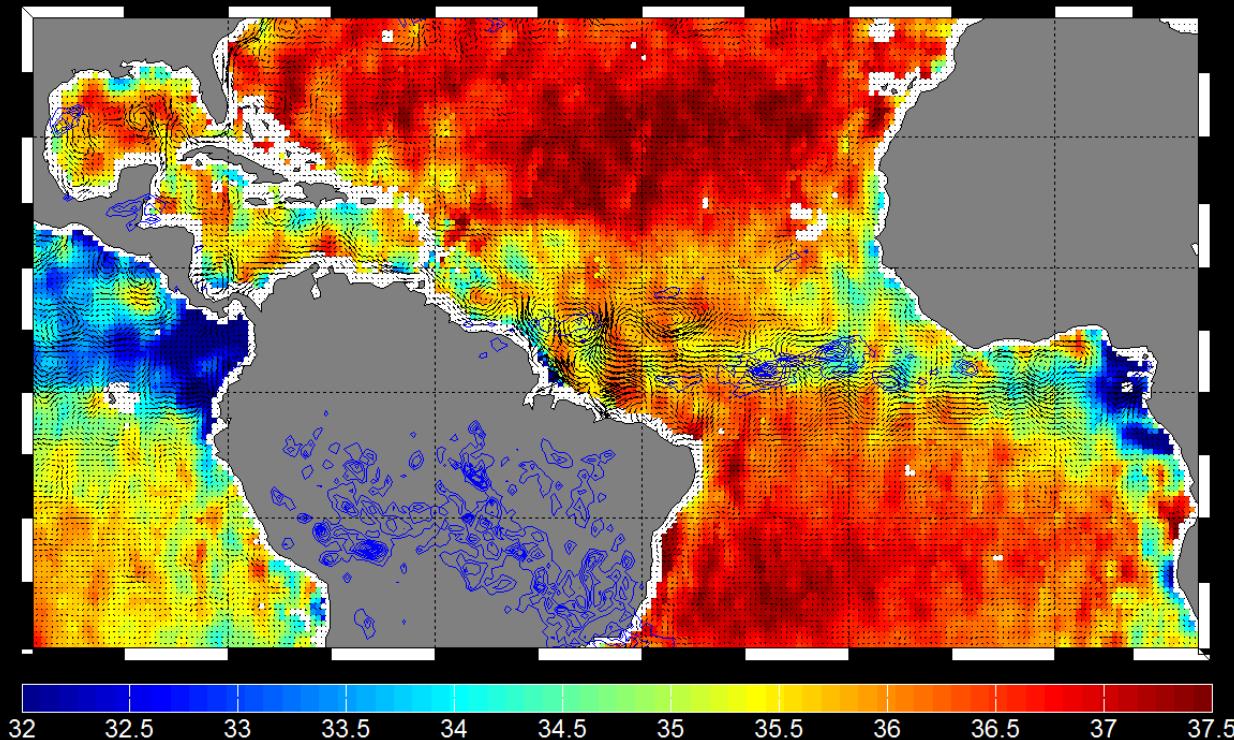
Hopkins et al., RSE, 2013

Reul et al.,  
Rev Geophys 2014

SMOS data now allow the regular monitoring of the seasonal & interannual variability in the discharge & advection of freshwater river plumes into the ocean

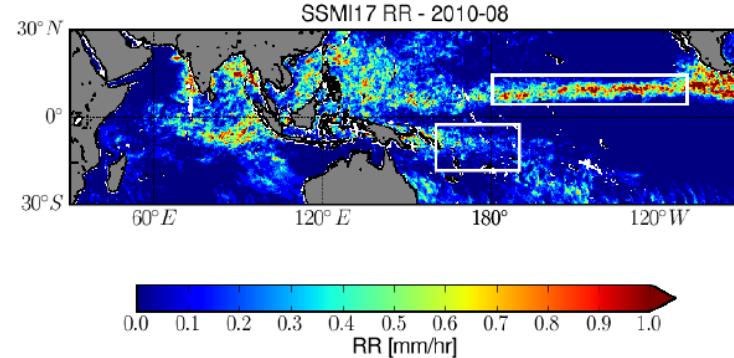
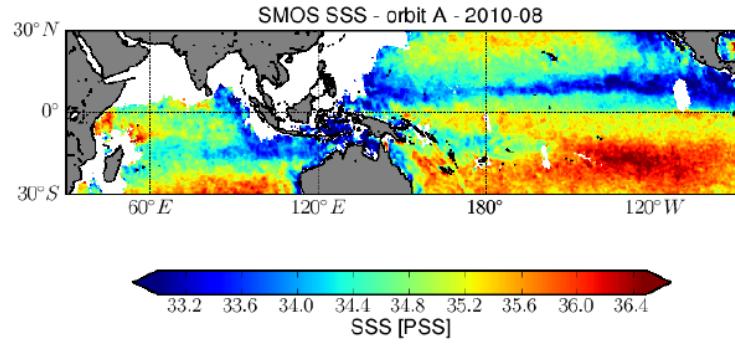
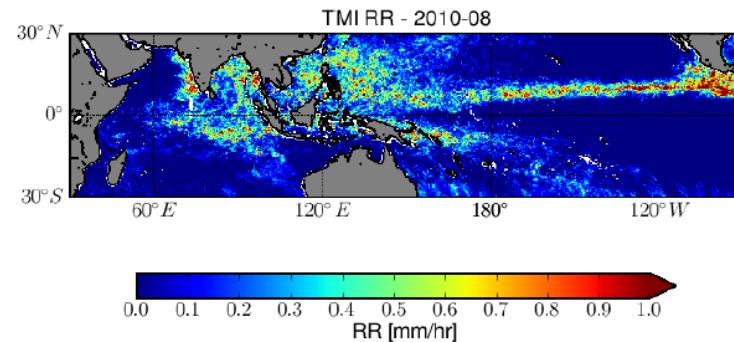
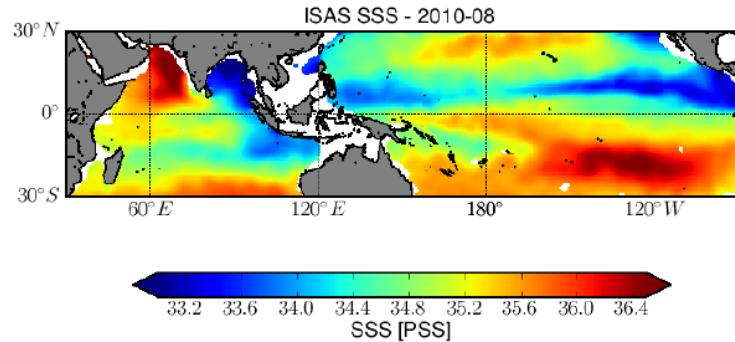
## Precipitation Signatures in Satellite SSS

SMOS 10 days SSS centered on Jan 01-2012



SMOS SSS= color background fields  
Oscar currents= arrows  
Blue contours=TRMM 3B42 rain rate

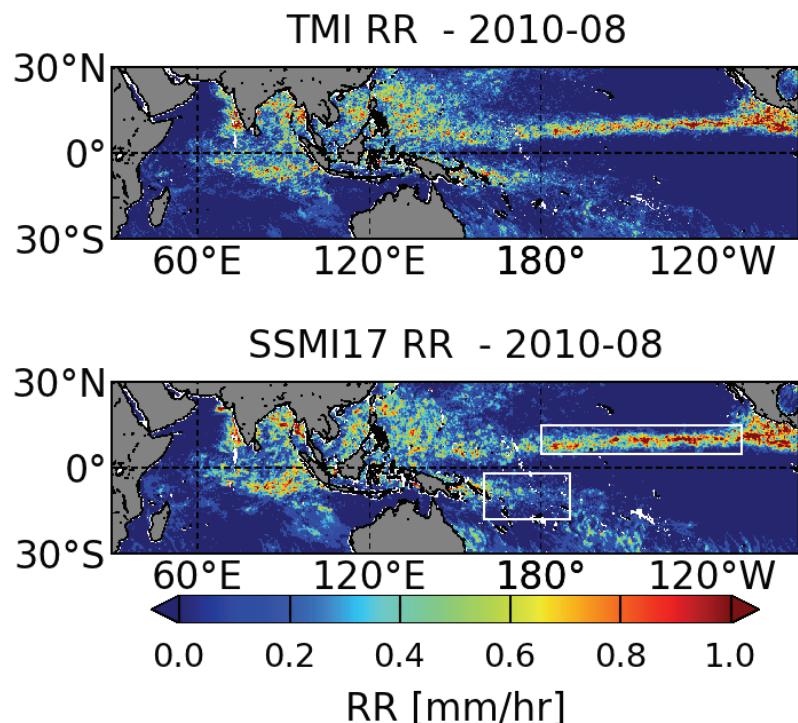
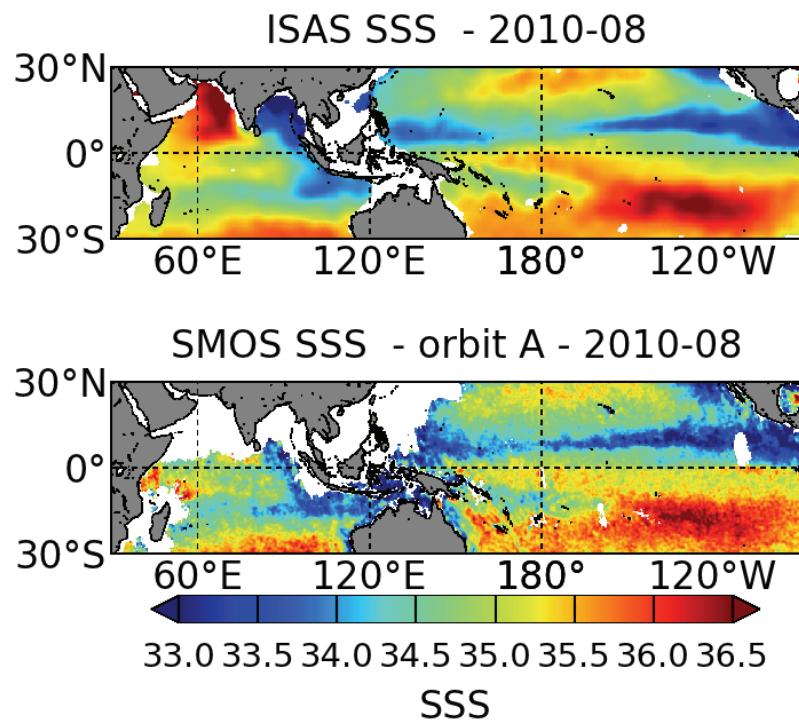
## Impact of Rain on SMOS SSS



*Boutin et al. (2014), JGR Oceans*

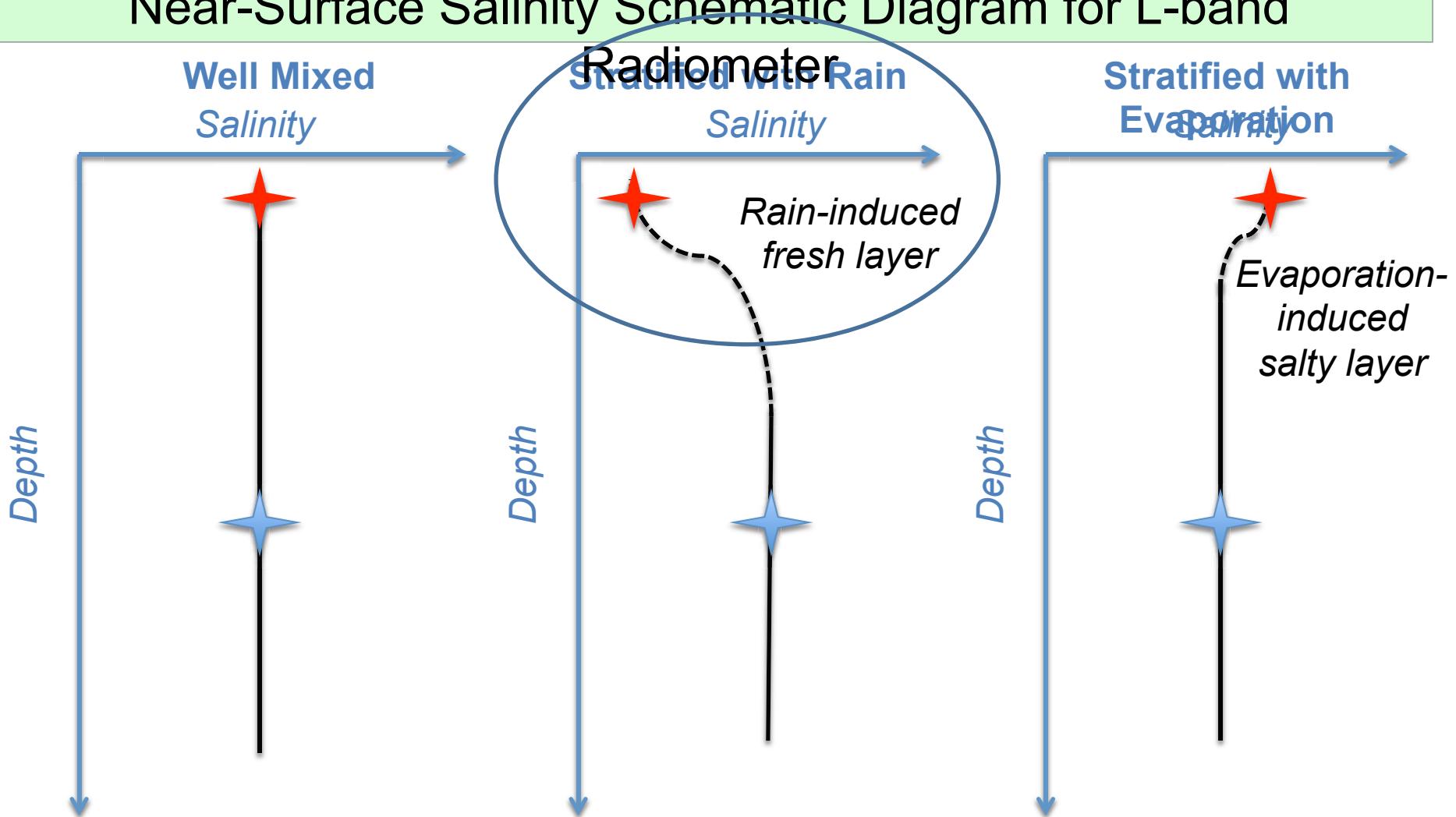
Through its links with Precipitations, SMOS salinity data provide a new tool to better characterize the increase in the marine tropical hydrological cycle strength

## Impact of Rain on SMOS SSS



SMOS SSS lower than ARGO optimal Interpolated SSS maps in rainy regions (e.g. ITCZ, SPCZ..) : what part of this difference explainable by rain stratification/intermittency?

# Near-Surface Salinity Schematic Diagram for L-band Radiometer



Satellite L-band radiometric salinity at depth range from 1 to 10 cm

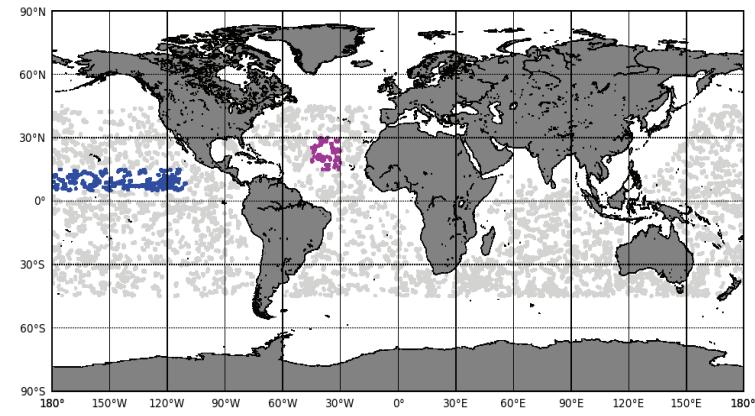
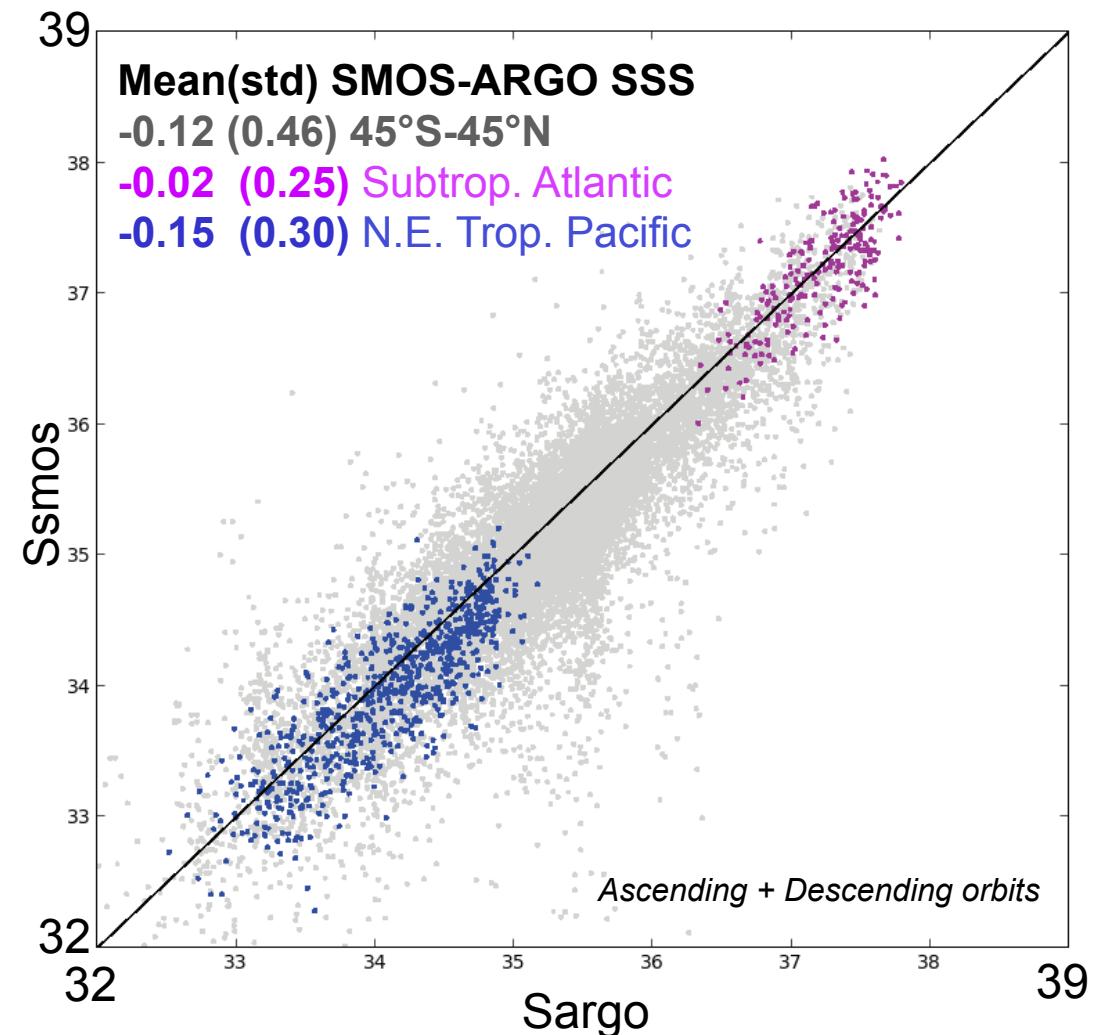


Salinity measured by in situ sensors/platforms at depth below 1 m

*Schematic Diagram made by the SISS working group*

# SMOS - ARGO (Jul-Sep 2010)

SMOS SSS averaged within +/-50km & +/- 5days around ARGO SSS

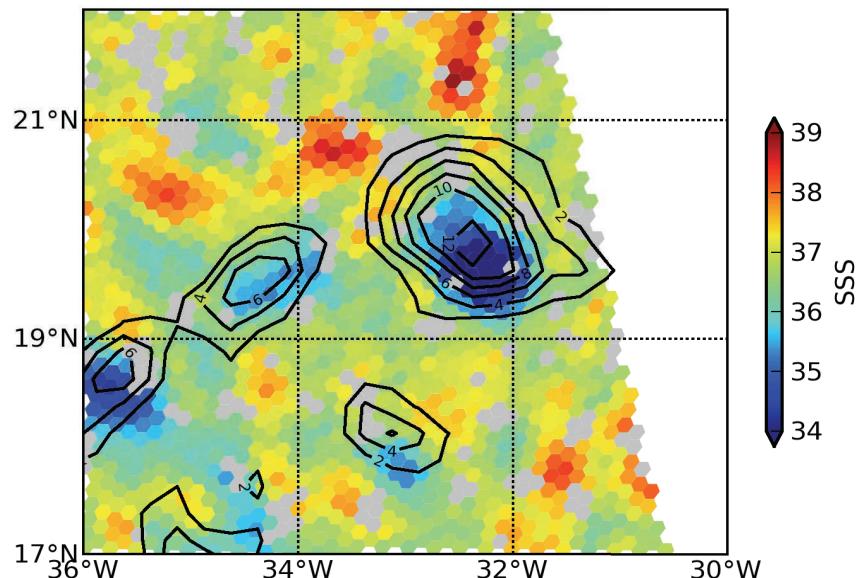


**SMOS – ARGO SSS in tropical Pacific 0.1 fresher and more variable than in subtrop Atlantic; if SMOS rainy measurements are removed, std\_diff in ITCZ and SPURS becomes the same => rain effect in ITCZ**

# Question

How reliable is the rain induced SSS variability measured by SMOS?

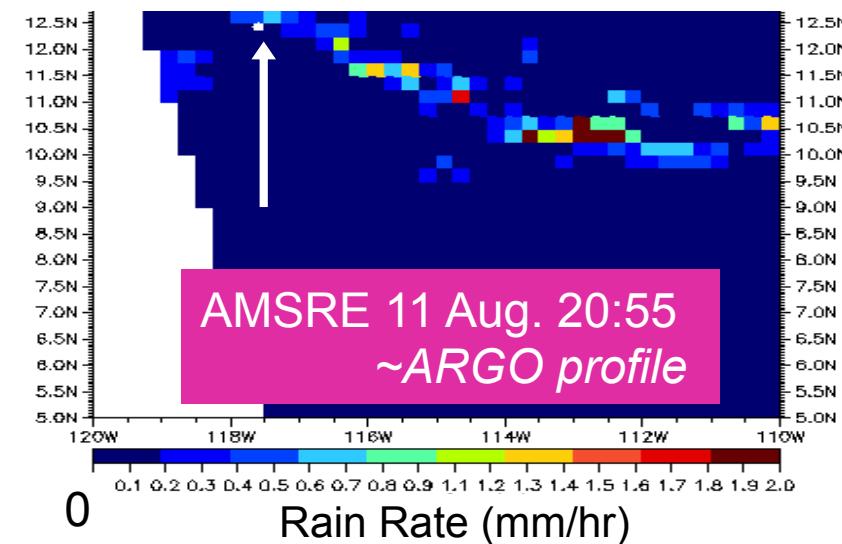
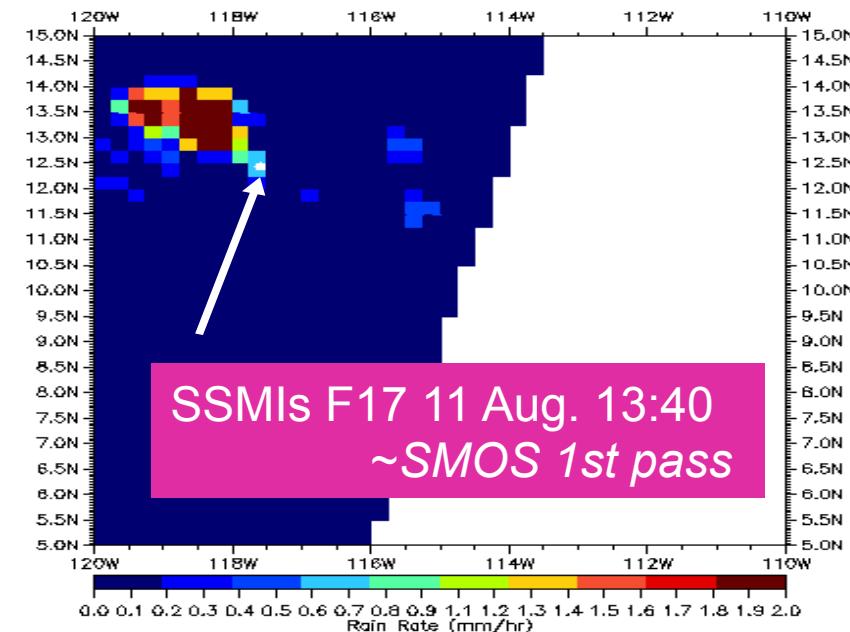
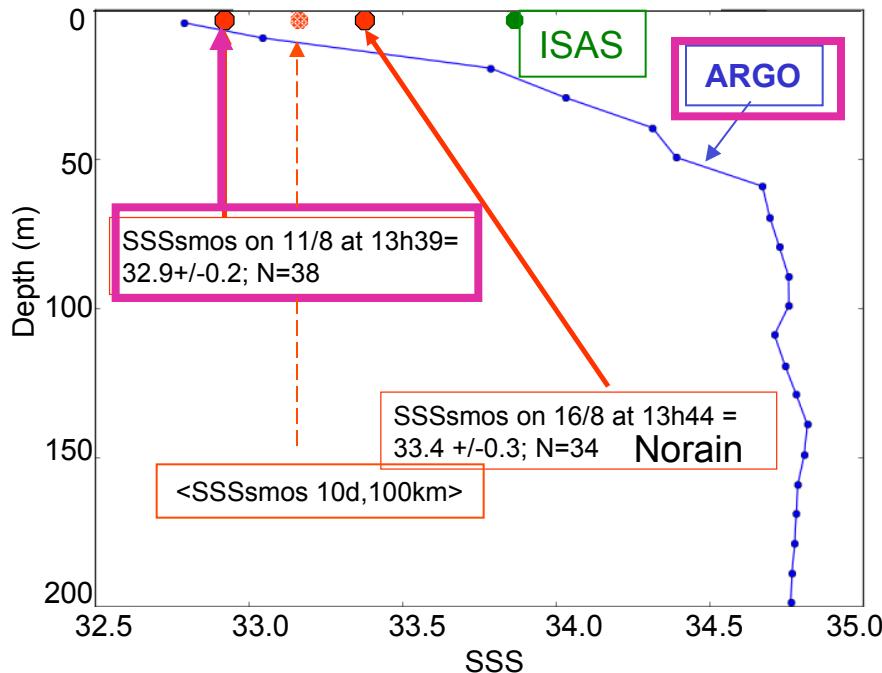
Can we confidently use satellite SSS for studying the influence of rain on sea surface (~1cm) salinity?



SMOS SSS (color) &  
SSM/I rain rate (isolines)  
 $Train-T_{smos} = 0.5h$

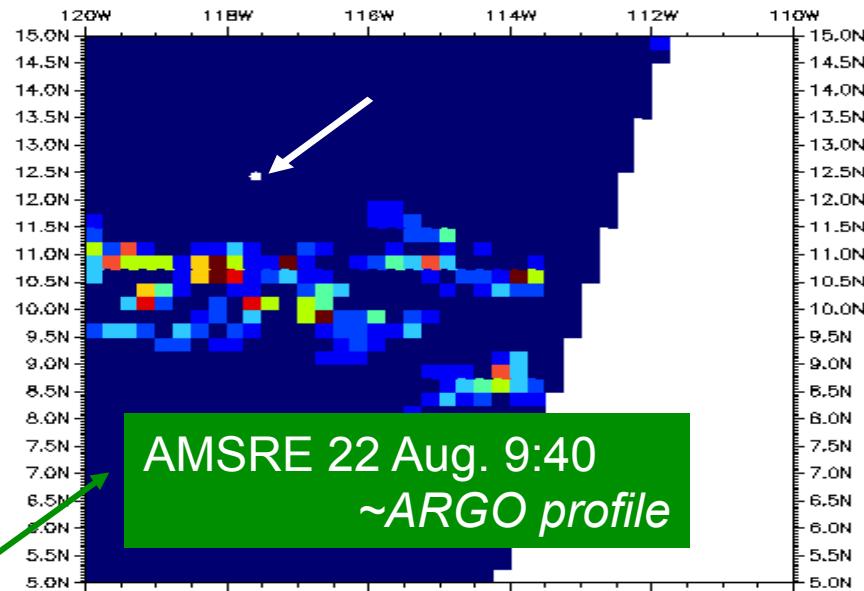
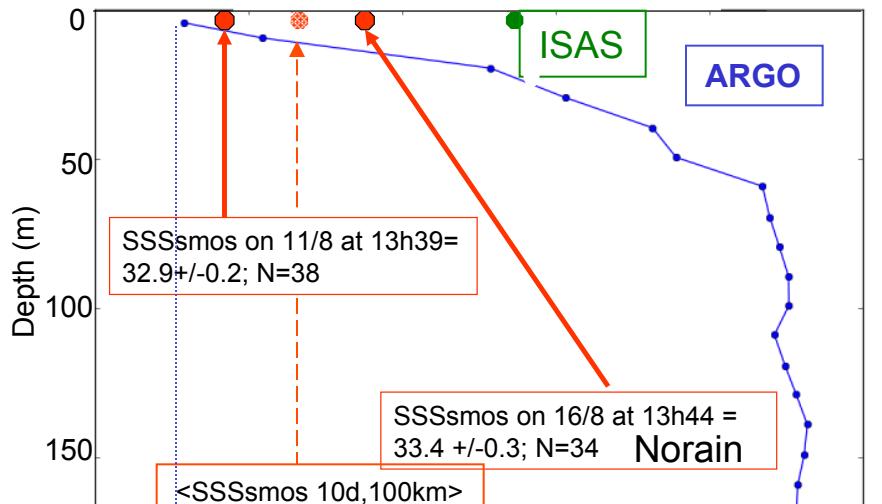
# Effect of rain on ARGO & SMOS (The closest colocated case)

a) ARGO profile on 11/8 20:00 UTC

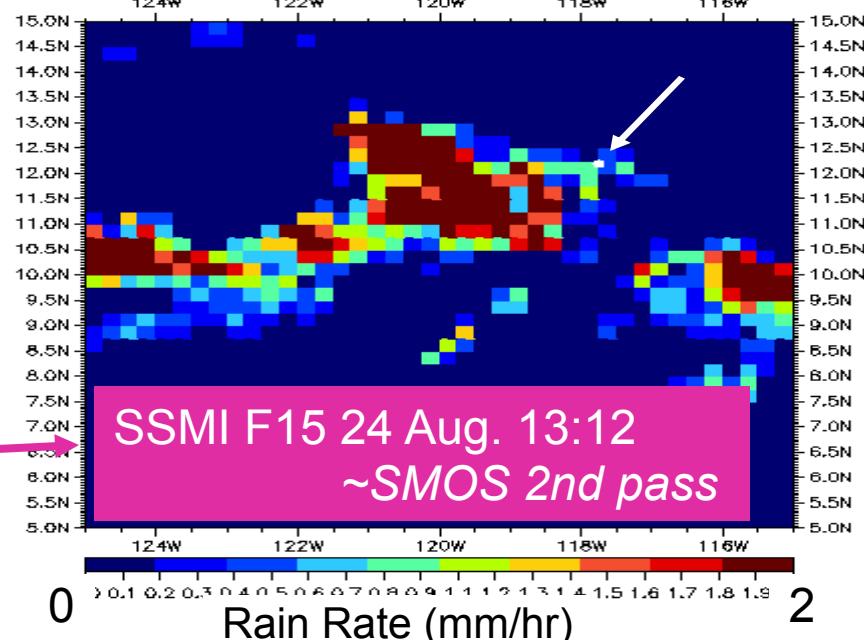
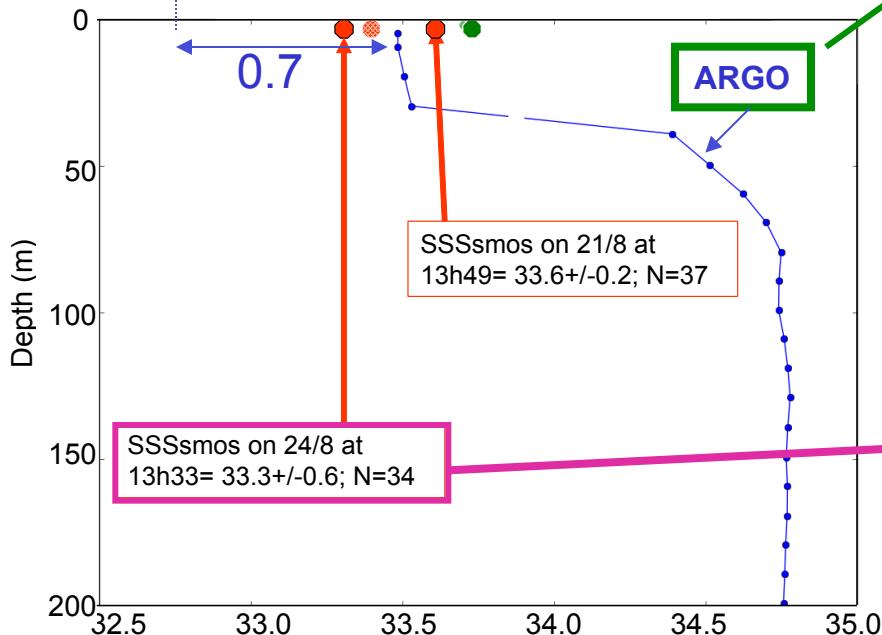


# 10 days after...

a) ARGO profile on 11/8 20:00 UTC



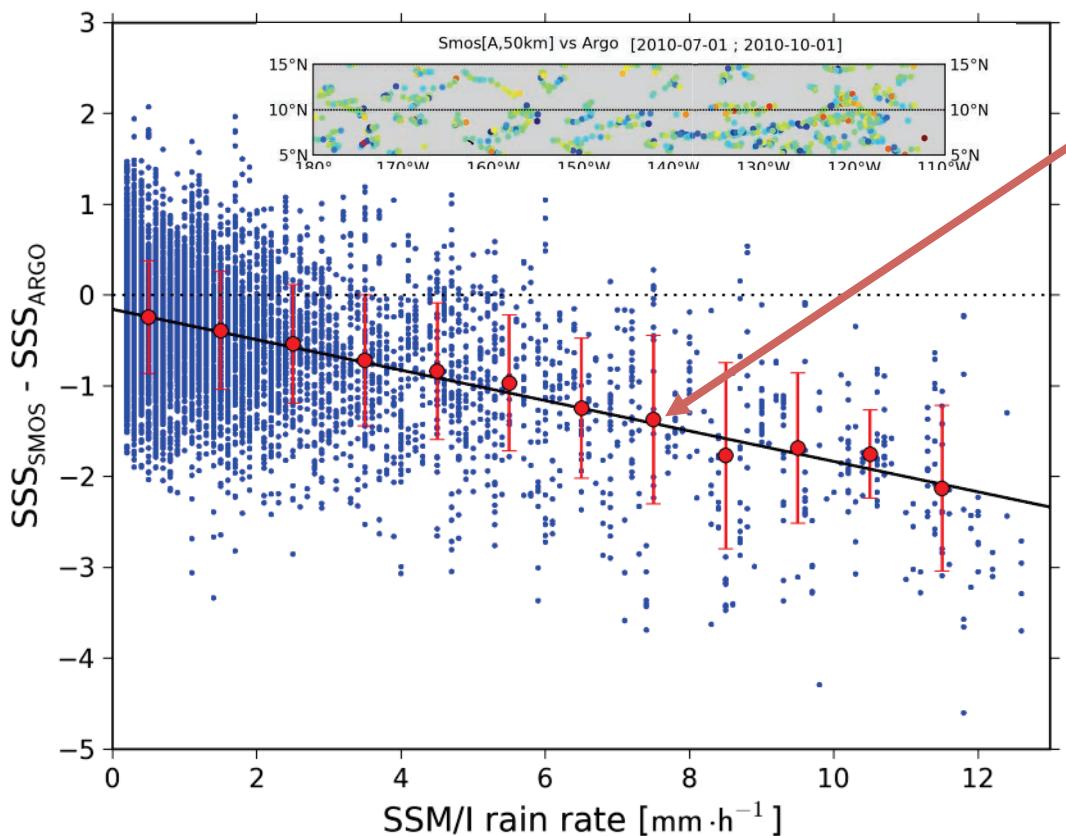
b) ARGO profile on 22/08 6:52 UTC



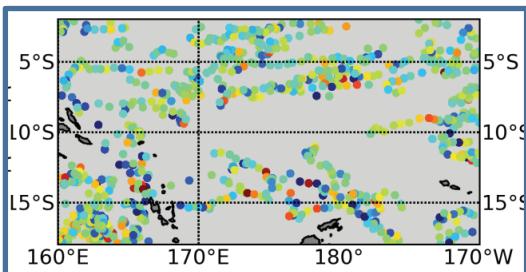
# The impact of rain on SMOS SSS

## SMOS SSS - ARGO\_rainfree[-2hr;+1hr] SSS

SMOS SSS- ARGO SSS versus satellite RR  
(-Sept 2010)

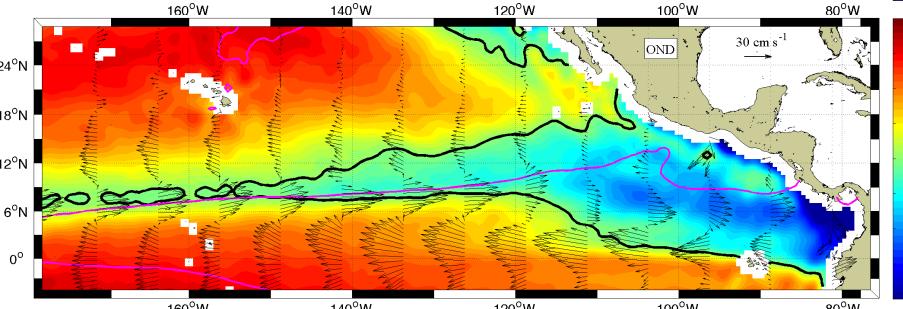
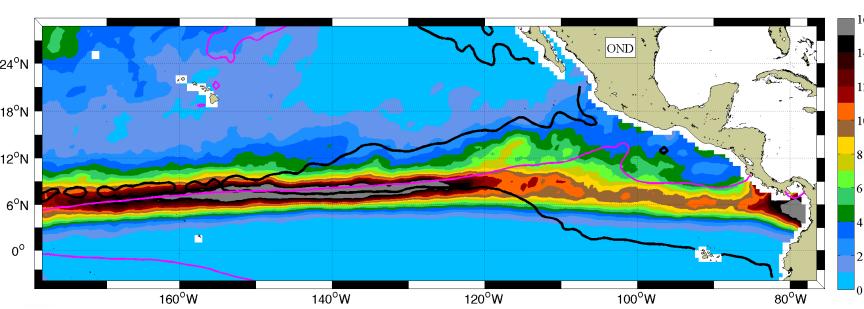
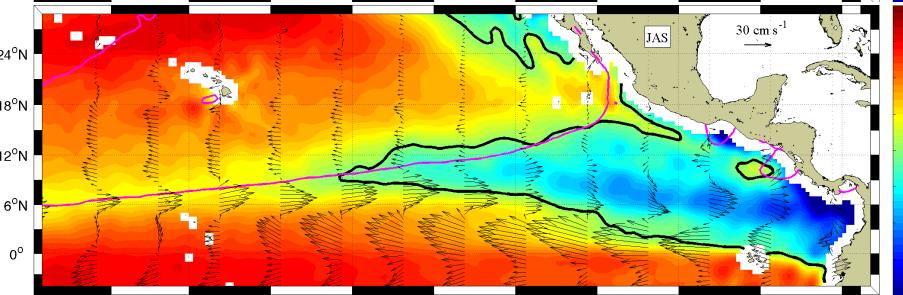
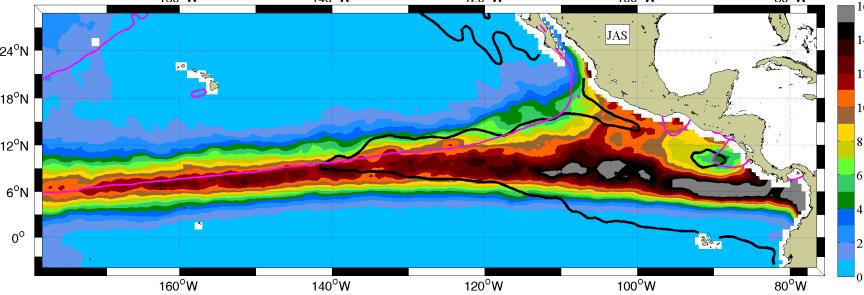
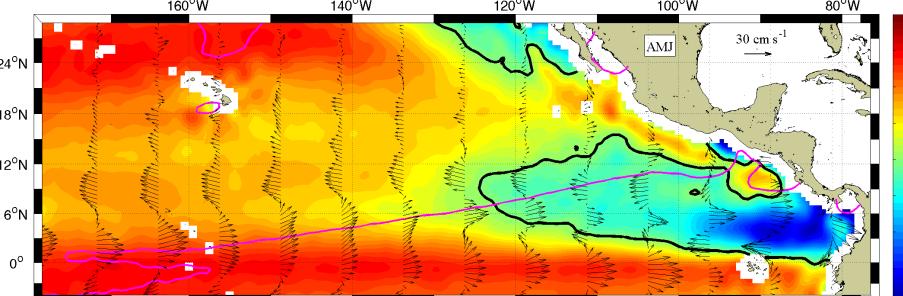
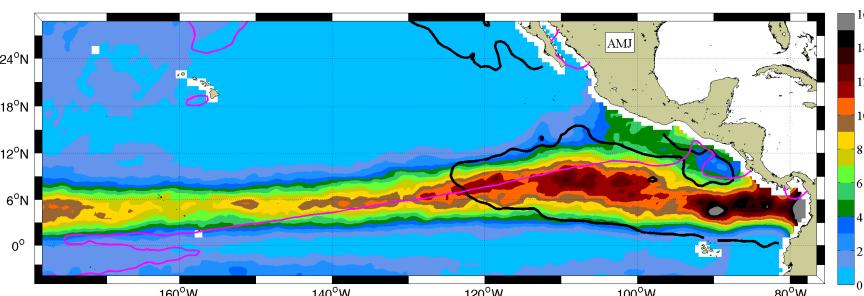
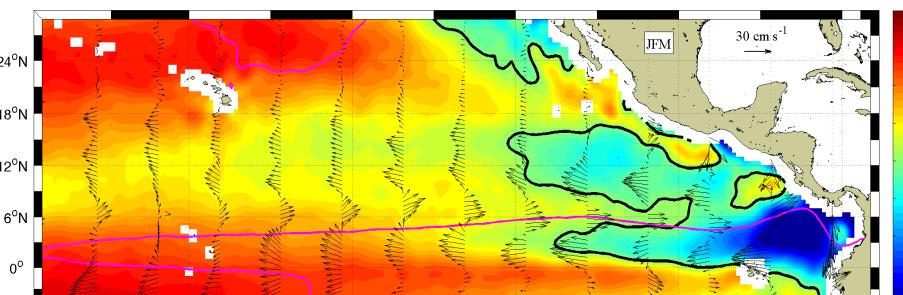
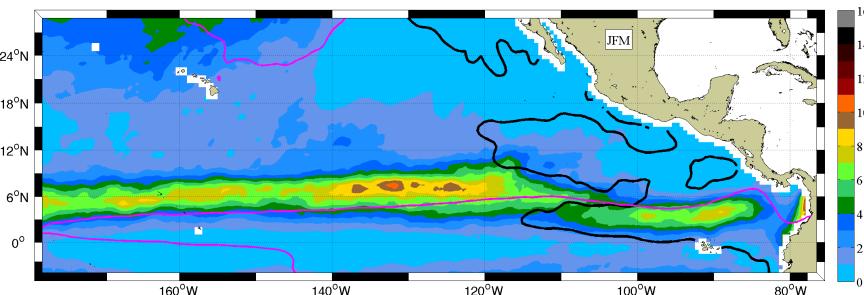


$-0.18 \text{ pss/ mm/hr}$   
 $r = -0.5$

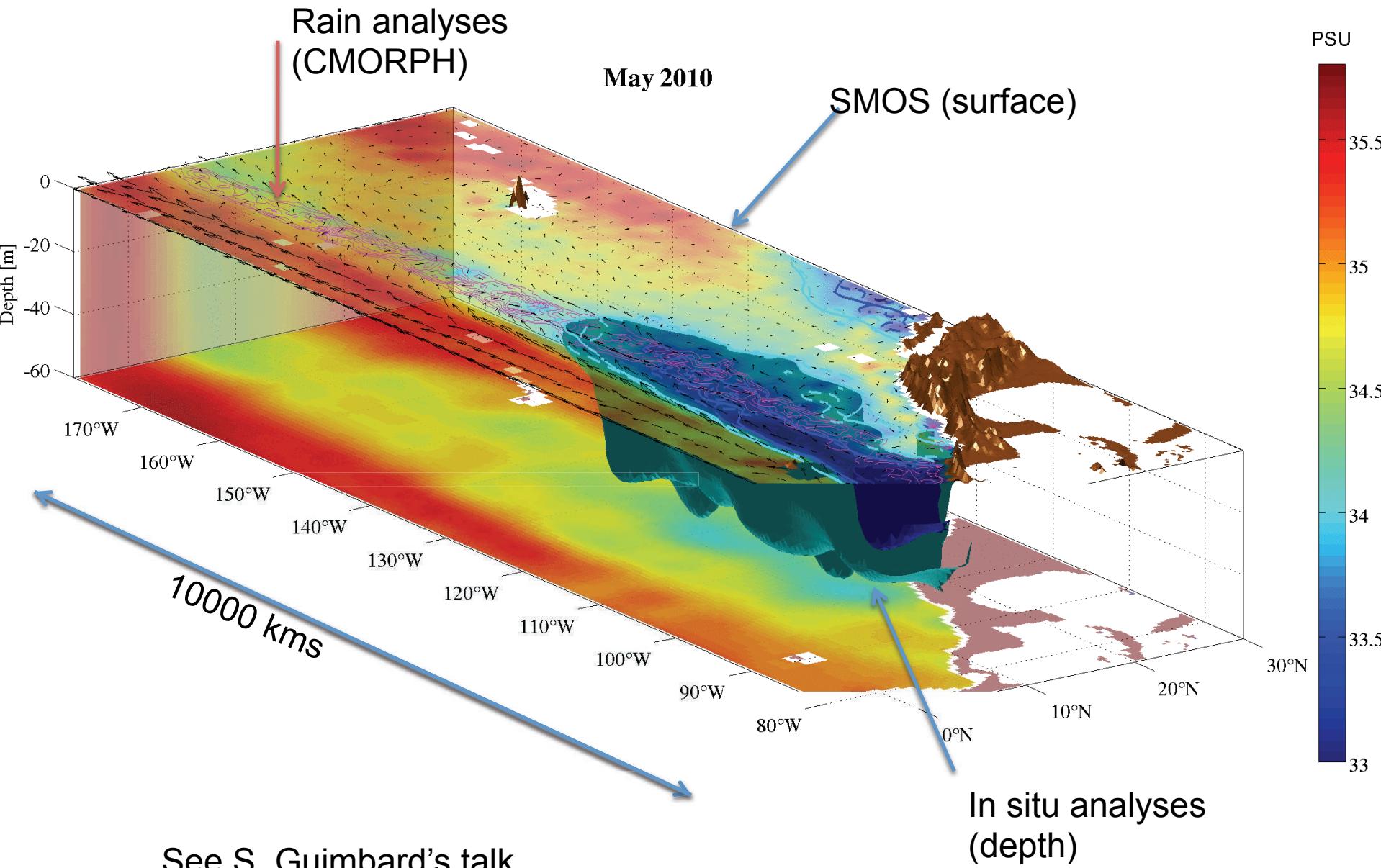


In SW Pac :  
 $-0.22 \text{ pss/mm/hr}$   
 $r = -0.5$

# Eastern Pacific Freshpool & 3D monitoring of the pool



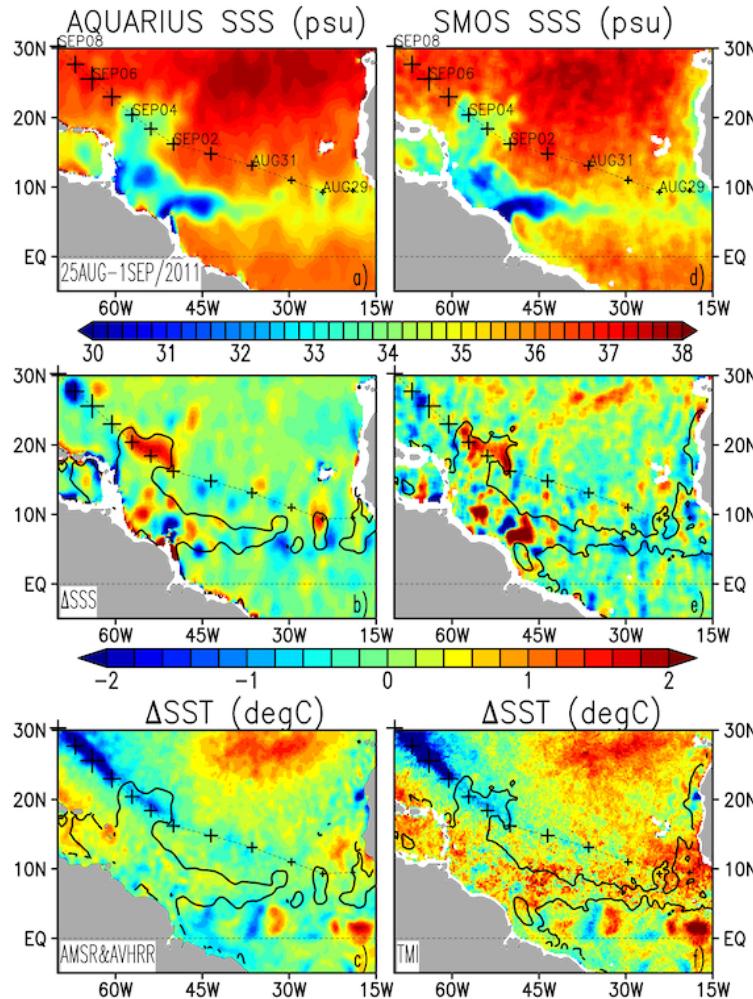
# Eastern Pacific Freshpool & 3D monitoring of the pool





## □ Air-Sea Interactions (hurricanes & Barrier Layers, upwellings)

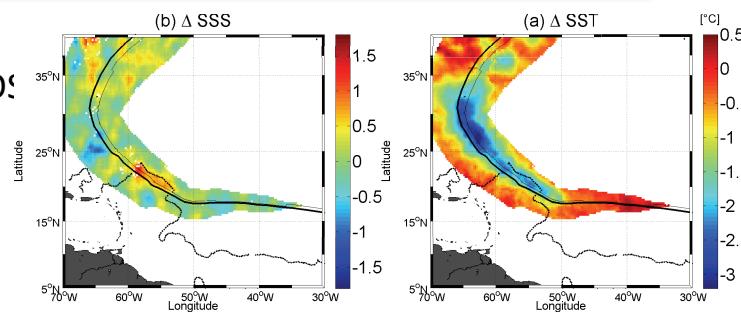
# Haline wake of Hurricanes in the Amazon plume & Impact on Intensification



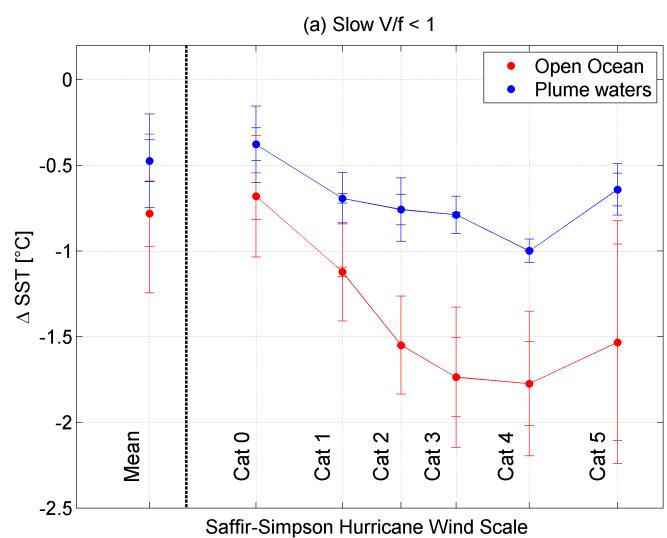
AQUARIUS and SMOS SSS before hurricane Katia (2011). Crosses are the hurricane daily position.

SSS differences after minus before the hurricane passage.  
35 psu contour before the passage of Katia is overlaid.

SST differences after minus before the hurricane passage.

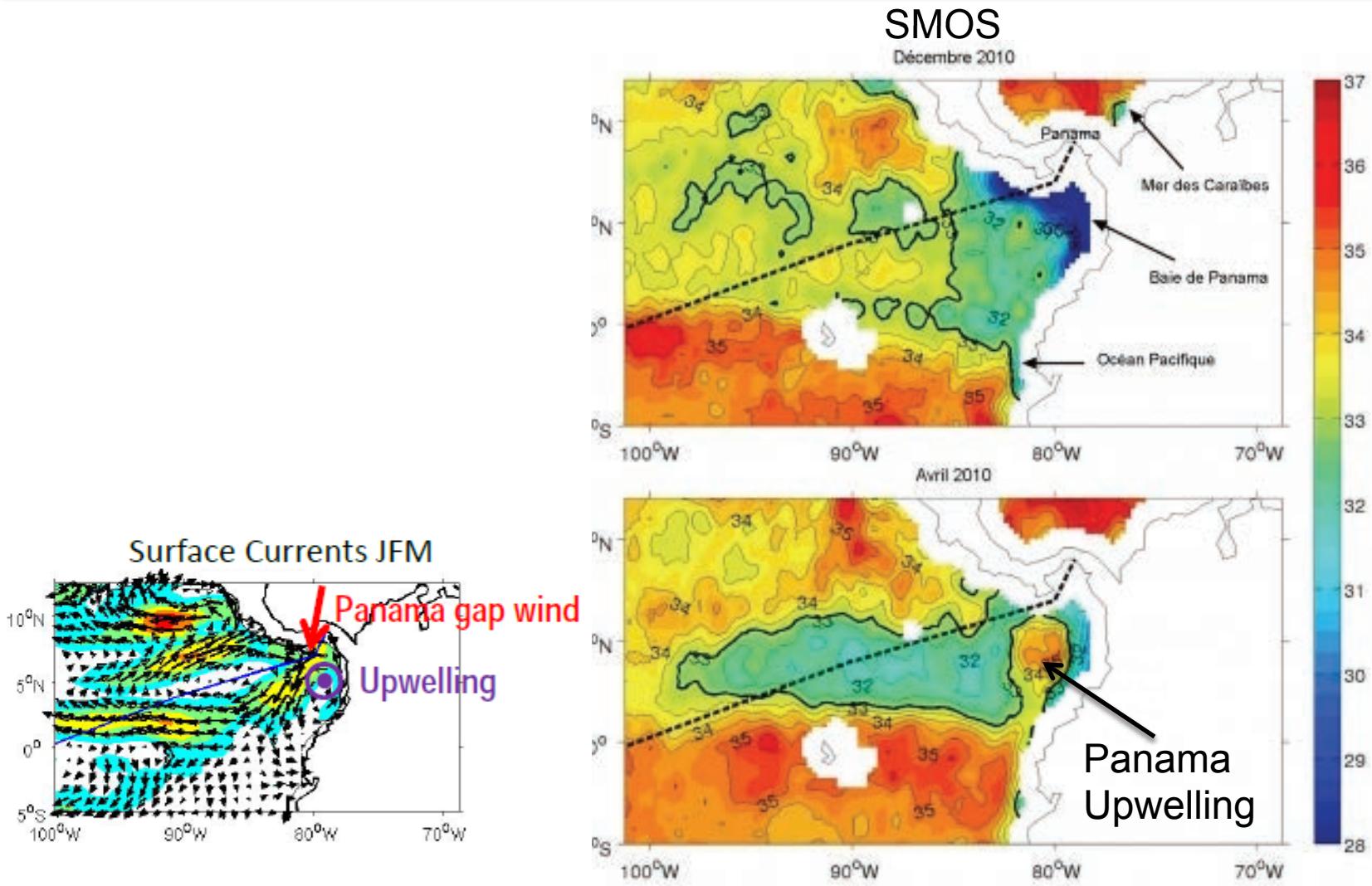


SSS & SST differences after minus before hurricane Igor passage (2010).



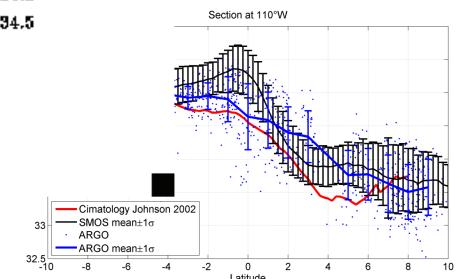
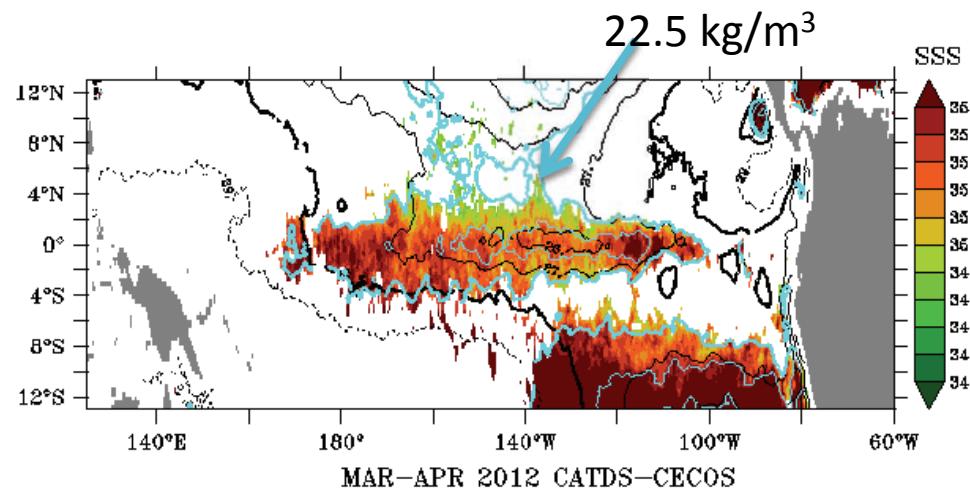
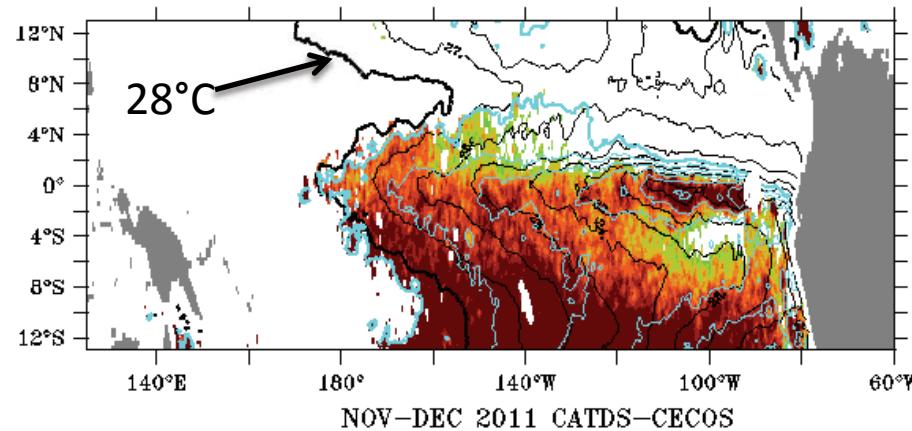
**Reduced SST cooling over halocline driven stratification**

# SSS signal of the Panama Upwelling



# The SSS signature of the Pacific Equatorial Cold Tongue as revealed by SMOS

New use of a water density criterion to characterize the cold tongue seasonal cycle

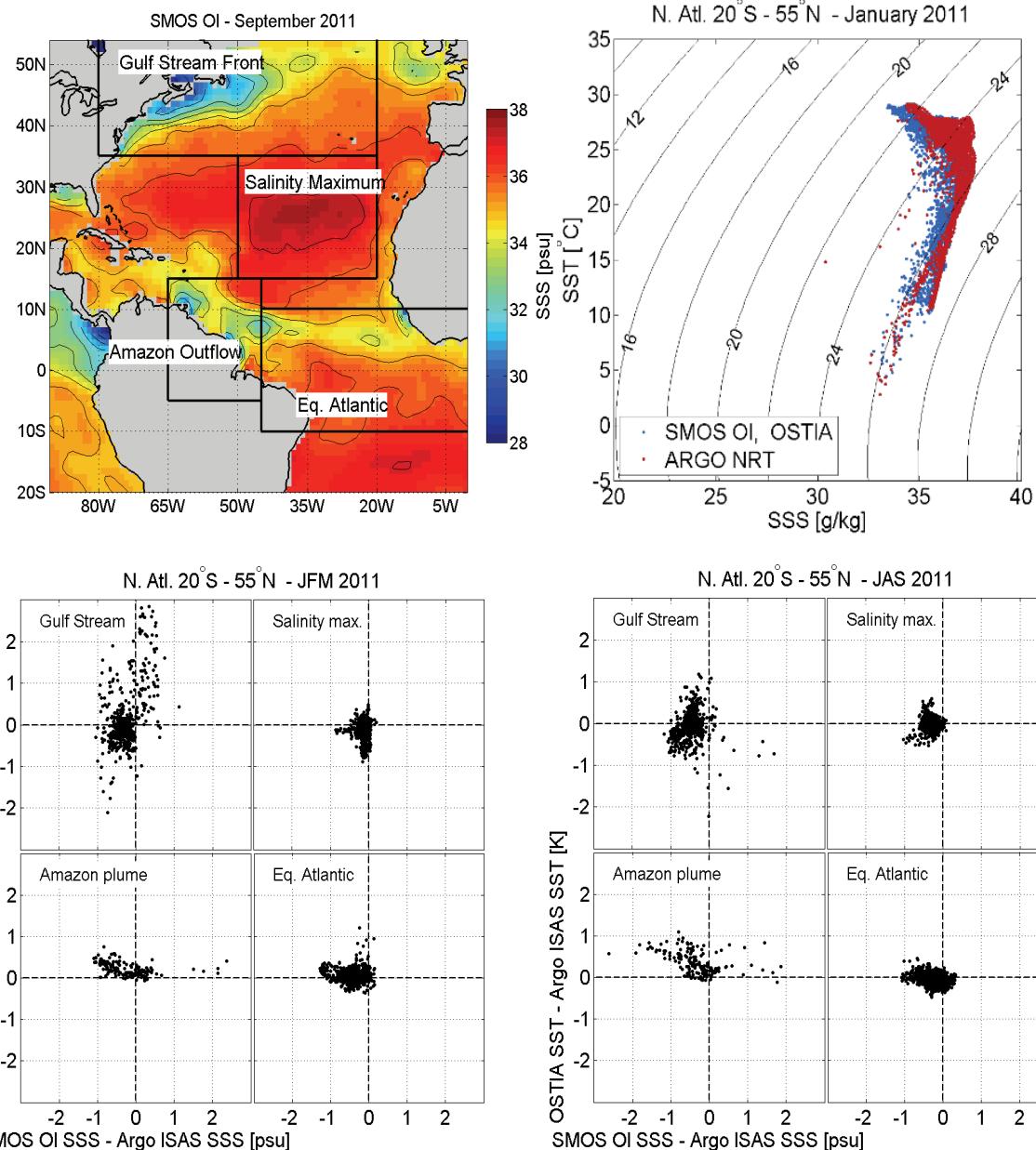




- Temperature-Salinity diagrams
- Thermo-haline circulation/surface density

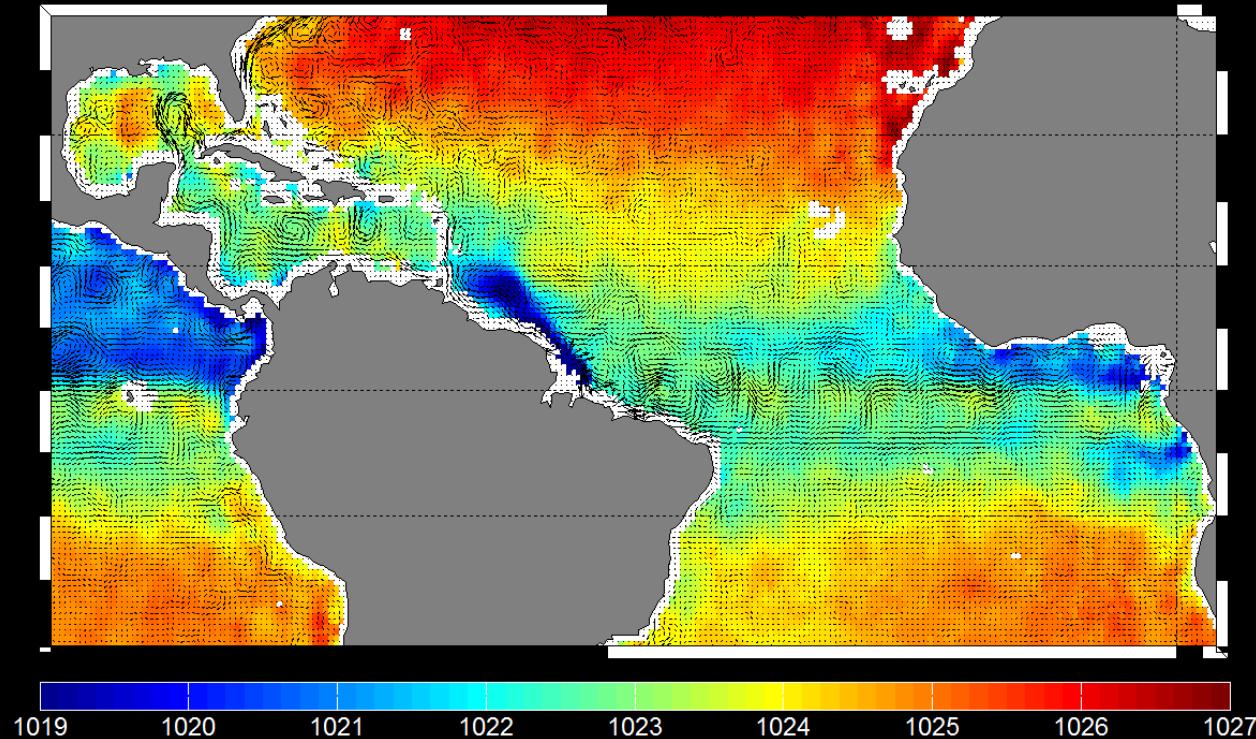
## Routinely monitoring SSS-SST diagrams

1. Generating routinely **satellite-derived surface T-S diagrams**, obviating the lack of extensive sampling of the surface open ocean
2. Displaying the T-S diagrams variability and the **distribution/dynamics of SSS**, altogether with **SST** and the relative **density** with respect to in-situ measurements



**Monitoring surface density variability (50 km/10 days)  
from satellite SSS & SST**

Satellite Density 10 days centered on May 05-2010

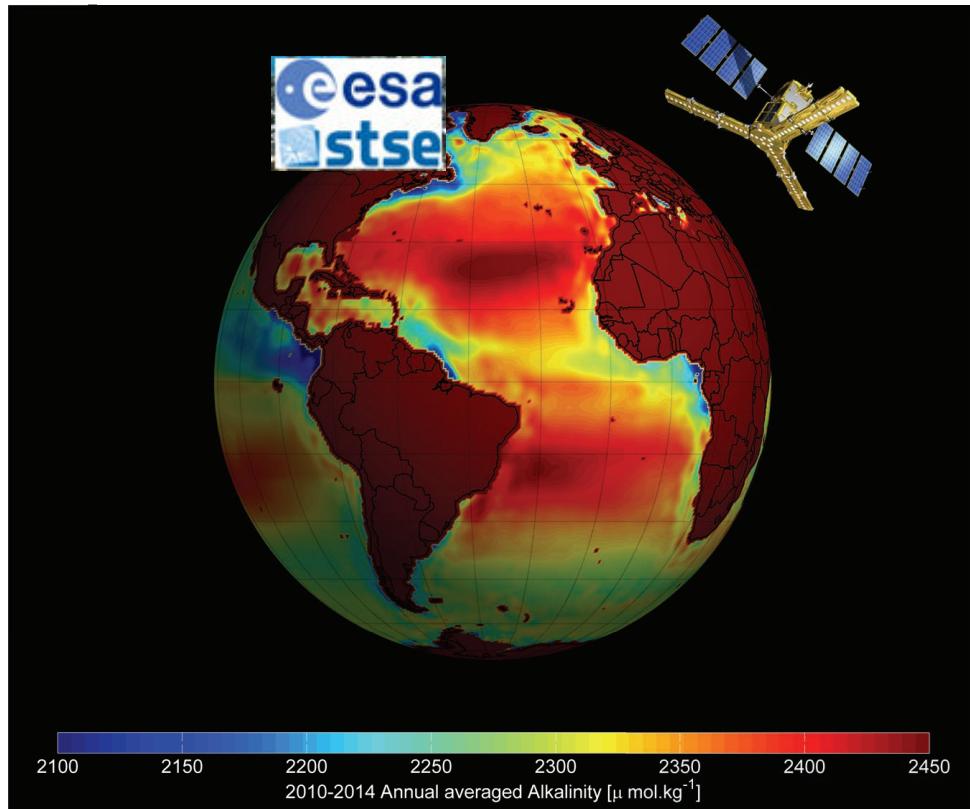


**First time mapping of Satellite Sea surface Density variability  
made possible thanks to SMOS SSS=> key for thermo-haline circulation**



# □ Bio-Chemistry

## SSS used in synergy to monitor ocean Alkalinity



Land et al.,  
*Environmental Science & Technology*, 2015

Alkalinity=function(SSS,SST)  
(Lee et al, 2006)

*Lee et al. (2006) Algorithms:*

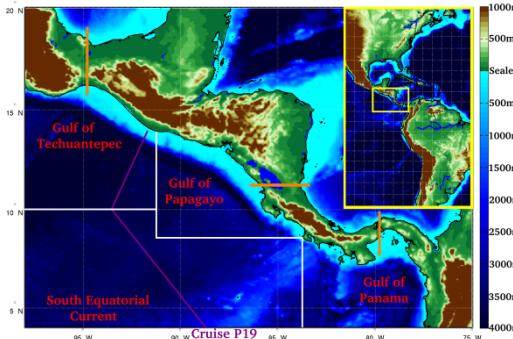
Regionally variable slope and intercept parameters (see Lee et al. [2006] for details) for the following algorithm:

$$A_T = a + b(SSS - S) + c(SSS - S)^2 - d(SST - T) + e(SST - T)^2$$

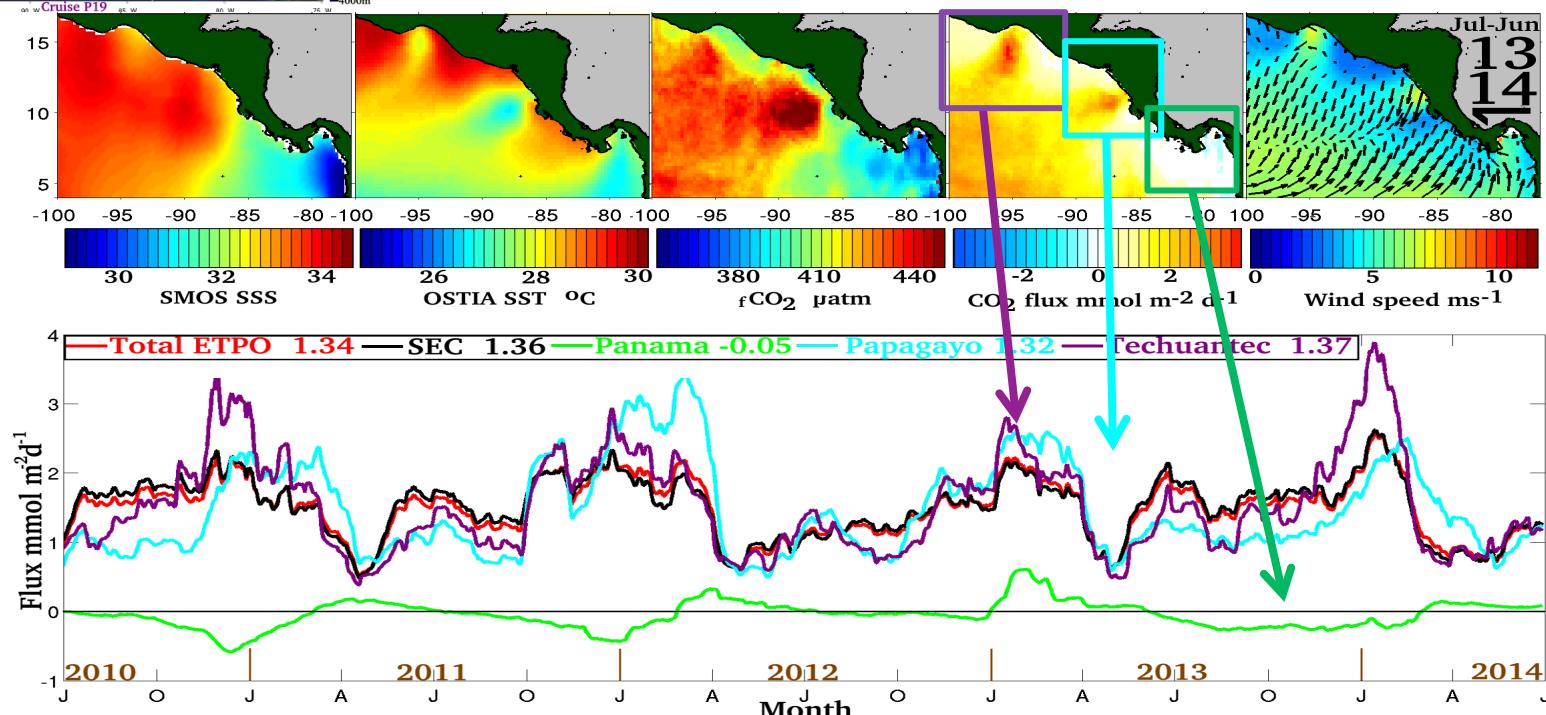
Salinity data are key for assessing the marine carbonate system, and new space-based salinity measurements will enable the development of novel space-based ocean acidification assessment. As the carbon cycle is dominantly controlled by the balance between the biological and solubility carbon pumps, innovative methods to exploit existing satellite sea surface temperature and ocean color, and new satellite sea surface salinity measurements, are needed and will enable frequent assessment of ocean acidification parameters over large spatial scales.

# New insights of pCO<sub>2</sub> variability in the tropical eastern Pacific Ocean using SMOS Salinity

C W Brown, J Boutin, L Merlivat, LOCEAN Paris



A quantitative analysis of the opposite effects of local upwellings and rainfall on the variability of surface ocean CO<sub>2</sub> partial pressure and of the air-sea CO<sub>2</sub> flux.



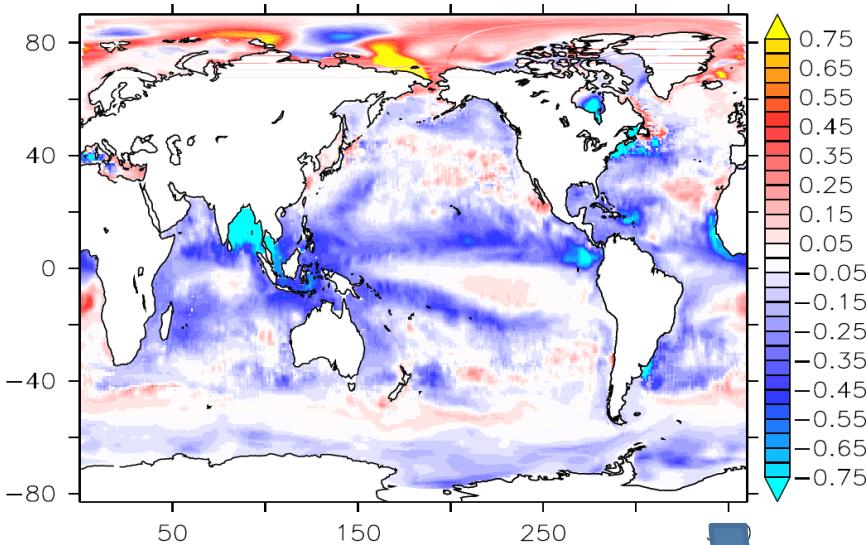
Brown et al. 2015, New insights of pCO<sub>2</sub> variability in the tropical eastern Pacific Ocean using SMOS SSS, Biogeoscience Discussion.



# □ Ocean Circulation Modeling

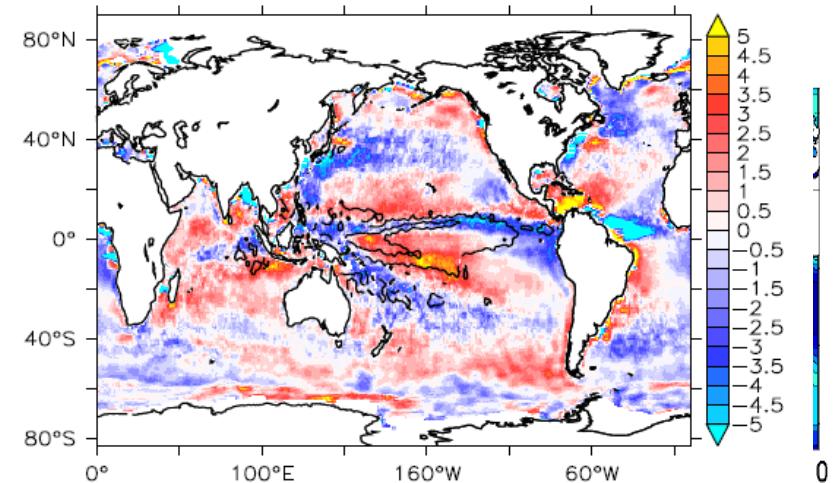
# Testing the impact of assimilating satellite SSS data

Surface salinity difference  
(SMOS assimilated minus not assimilated)  
(2010–2011 mean)



GECCO2/MIT ocean circulation Model  
A. Köhl, University of Hamburg, 2014

Change in E-P (mm/  
d)



Major impact in high precipitation & river runoff zones

*First tests => importance of careful characterization of errors and mixed layer physics*



## □ High-Surface wind remote sensing

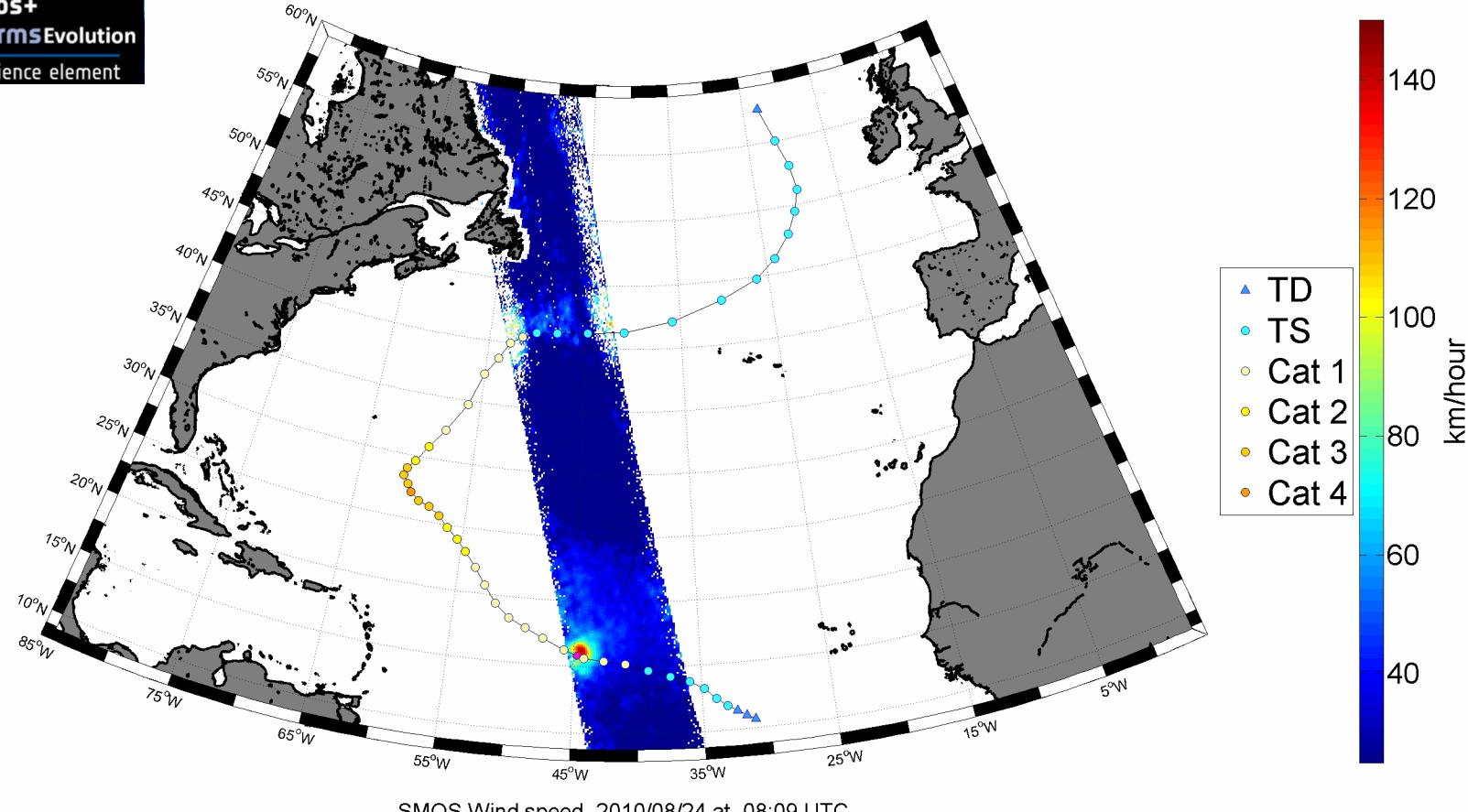
# Surface Wind Speed Monitoring in Tropical Cyclones

Atmosphere is almost transparent to L-band radiation

SMOS offer a unique opportunity to **monitor ocean surface properties in extreme wind conditions** for which scatterometry & passive microwave at higher frequencies are inadequate



Hurricane Danielle-2010/08



- SMOS have brought significant new understanding to intraseasonal variability in the ocean associated with mesoscale eddies & TIWs that are important to ocean dynamics, climate variability, and biogeochemistry.
- SMOS SSS demonstrates complementarity with other observing systems (e.g., SST & SSH, CHL, in situ).
- Demonstrate the ability to monitor the path of large tropical river waters in the ocean & the links with ocean color
- Clearly detected freshening signals associated with high precipitation zones (rain gauge ?)
- New views on air-sea interactions processes such as upwellings and hurricane interactions with fresh-pool barrier layers
- New views on the short space & time scales of the bio-chemistry of the carbonate system (pCO<sub>2</sub>, alkalinity..)
- New capability to monitor surface wind speed in extreme conditions of Tropical cyclones
- A major strength of satellite SSS relative to in-situ SSS is the ability
  - to estimate spatial gradient, which is critical to the studies of eddy-mean flow interaction and related air-sea interaction.
  - To estimate and “interfacial SSS”, proxy of ocean-atmosphere water fluxes
  - To provide in synergy with SST a first view of the surface density variability (thermo-haline circulation)

#### Future Challenges

- Data quality homogenization (Land sea contamination, RFI & drift, cold Seas)
- Multi-sensor synergies (SMOS-Aquarius-SMAP)
- Ocean Modelling Impact

# Some SMOS publications 2014-2015

- Brown, C. W., J. Boutin, and L. Merlivat (2015), New insights of pCO<sub>2</sub> variability in the tropical eastern Pacific Ocean using SMOS SSS, *Biogeosciences Discuss.*, 12(6), 4595-4625, doi:10.5194/bgd-12-4595-2015.
- Fournier Severine, Chapron Bertrand, Salisbury Joseph, Vandemark Douglas, Reul Nicolas Comparison of spaceborne measurements of sea surface salinity and colored detrital matter in the Amazon plume. *Journal of Geophysical Research - Oceans* IN PRESS. <http://dx.doi.org/10.1002/2014JC010109>.
- Kolodziejczyk, N., O. Hernandez, J. Boutin, and G. Reverdin (2015), SMOS salinity in the subtropical north Atlantic salinity maximum. Part II: Horizontal thermohaline variability, *J. Geophys. Res. Oceans*, 120, 972–987, doi: 10.1002/2014JC010103.
- Land P., Shutler J. Findlay H., Girard-Ardhuin F., Sabia R., Reul N., Piolle J.F., Chapron B., Quilfen Y., Salisbury J., Vandemark D., Bellerby R., Bhadury P. (2015). Salinity from space unlocks satellite-based assessment of ocean acidification. *Environmental Science & Technology*, 49(4), 1987-1994. <http://dx.doi.org/10.1021/es504849s>
- Boutin, J., N. Martin, G. Reverdin, S. Morisset, X. Yin, L. Centurioni, and N. Reul (2014), Sea surface salinity under rain cells: SMOS satellite and in situ drifters observations, *Journal of Geophysical Research: Oceans*, 119(8), 5533–5545, [doi: 10.1002/2014JC010070](http://dx.doi.org/10.1002/2014JC010070).
- Grodsky S., G. Reverdin, J. Carton and V. Coles, 2014. Year-to-year salinity changes in the Amazon Plume: contrasting 2011 and 2012 Aquarius/SACD and SMOS satellite data. *Remote Sensing of Environment*, 140 (2014) 14–22, doi: 10.1016/j.rse.2013.08.033.
- Hasson, A., T. Delcroix, J. Boutin, R. Dussin, and J. Ballabrera-Poy (2014), Analyzing the 2010–2011 La Niña signature in the tropical Pacific sea surface salinity using in situ data, SMOS observations, and a numerical simulation, *Journal of Geophysical Research: Oceans*, 119(6), 3855-3867, doi:10.1002/2013JC009388.
- Maes C., N. Reul, D. Behringer, and T. O’Kane (2014), The salinity signature of the equatorial Pacific cold tongue as revealed by the satellite SMOS mission, *Geoscience Letters*, 1:17 [doi: 10.1186/s40562-014-0017-5](http://dx.doi.org/10.1186/s40562-014-0017-5).
- Reul N., S. Fournier, J. Boutin, O. Hernandez, C. Maes, B. Chapron, G. Alory, Y. Quilfen, J. Tenerelli, S. Morisset, Y. Kerr, S. Mecklenburg and S. Delwart (2014a), Sea Surface Salinity Observations from Space with SMOS satellite: a new tool to better monitor the marine branch of the water cycle, *Surv in Geophys*, 35:681–722, doi:10.1007/s10712-013-9244-0.

# Some SMOS publications 2012-2014

- Reul, N., B. Chapron, T. Lee, C. Donlon, J. Boutin, and G. Alory (2014b), Sea surface salinity structure of the meandering Gulf Stream revealed by SMOS sensor, *Geophys. Res. Lett.*, 41, doi:10.1002/2014GL059215
- Reul, N., Y. Quilfen, B. Chapron, S. Fournier, V. Kudryavtsev, and R. Sabia (2014c), Multisensor observations of the Amazon-Orinoco river plume interactions with hurricanes, *Journal of Geophysical Research: Oceans*, 119(12), 8271-8295, doi: 10.1002/2014JC010107.
- Yin, X., J. Boutin, G. Reverdin, T. Lee, S. Arnault, and N. Martin (2014), SMOS Sea Surface Salinity signals of tropical instability waves, *Journal of Geophysical Research: Oceans*, 119(11), 7811-7826, doi:10.1002/2014JC009960.
- Boutin, J., N. Martin, G. Reverdin, X. Yin and F. Gaillard (2013), Sea surface freshening inferred from SMOS and ARGO salinity: Impact of rain, *Ocean Science*, 9, 183-192, [doi: 10.5194/os-9-183-2013](https://doi.org/10.5194/os-9-183-2013).
- Durand Fabien, Alory G., Dussin R., Reul N. SMOS reveals the signature of Indian Ocean Dipole events. *Ocean Dynamics*, 2013.
- Hasson, A., T. Delcroix, and J. Boutin (2013), Formation and variability of the South Pacific Sea Surface Salinity maximum in recent decades, *Journal of Geophysical Research: Oceans*, 118(10), 5109-5116, doi:10.1002/jgrc.20367.
- Hopkins, Jo; Lucas, Marc; Dufau, Claire; Sutton, Marion; Stum, Jacques; Lauret, Olivier; Channelliere, Claire. 2013  
[Detection and variability of the Congo River plume from satellite derived sea surface temperature, salinity, ocean colour and sea level.](#) *Remote Sensing of Environment*, 139. 365-385. [10.1016/j.rse.2013.08.015](https://doi.org/10.1016/j.rse.2013.08.015)
- Maes C., B. Dewitte, J. Sudre, V. Garçon, and D. Varillon (2013) : Small-scale features of temperature and salinity surface fields in the Coral Sea, *Journal of Geophysical Research: Oceans*, 118, 5426–5438, [doi: 10.1002/jgrc.20344](https://doi.org/10.1002/jgrc.20344).
- Grodsky, S. A., N. Reul, G. Lagerloef, G. Reverdin, J. A. Carton, B. Chapron, Y. Quilfen, V. N. Kudryavtsev, and H.-Y. Kao (2012), Haline hurricane wake in the Amazon/Orinoco plume: AQUARIUS/SACD and SMOS observations, *Geophysical Research Letters*, 39(20), L20603, doi:10.1029/2012GL053335.
- Alory, G., C. Maes, T. Delcroix, N. Reul, and S. Illig (2012), Seasonal dynamics of sea surface salinity off Panama: The Far Eastern Pacific fresh pool, *J. Geophys. Res.*, 117, C4, doi:10.1029/2011JC007802.