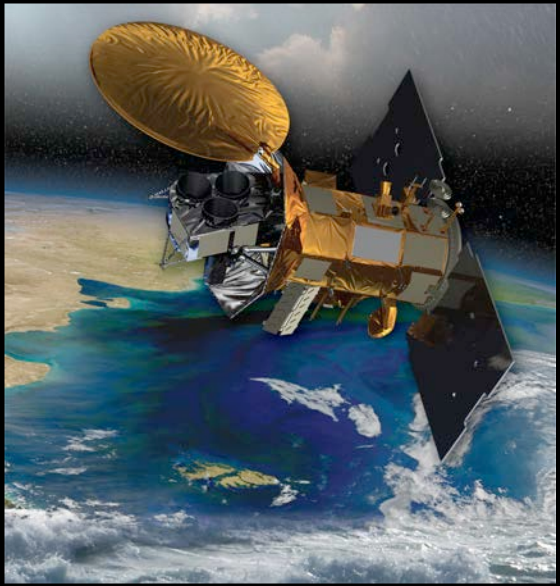
Monitoring Sea Surface Salinity From Space with Aquarius and SMOS Satellites



Nicolas Reul, SMOS Scientist (IFREMER)

Tony Lee, Aquarius Project Scientist (NASA/JPL)

With contributions from SM0S & Aquarius science team members

Outline

- **Why?**
  - Importance of ocean salinity
  - The unique vantage point from space

- **How?**
  - The basics
  - SMOS & Aquarius/SAC-D missions overview

- **What are we learning?**
  - Intraseasonal, seasonal, & interannual variability of SSS (relationships with ocean circulation, climate variability, & water cycle)
  - Improvements of ocean state estimation & climate prediction through assimilation of satellite SSS data

Why is it important to study ocean salinity?

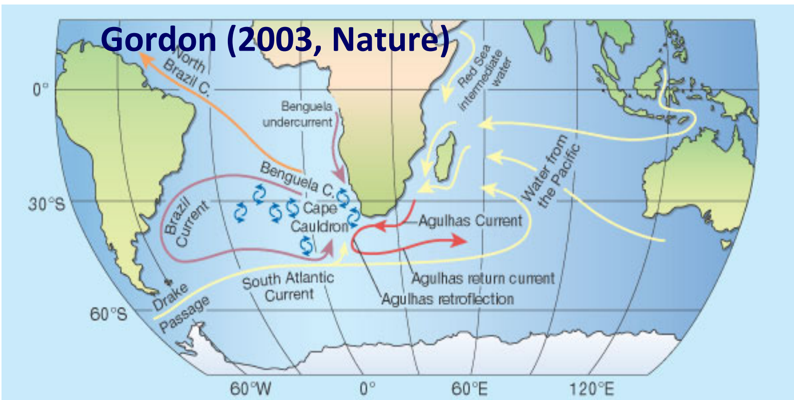
- One of the important factors that affect ocean currents & climate
  - Salinity & temperature are major factors determining seawater density.
  - Horizontal change of density creates pressure gradient, drives horizontal currents.
  - Vertical gradient of density controls static stability/instability of the water column (influences vertical mixing, convection, and air-sea interaction),
  - Ocean currents redistribute heat geographically to regulate ocean-atmosphere coupling and climate.

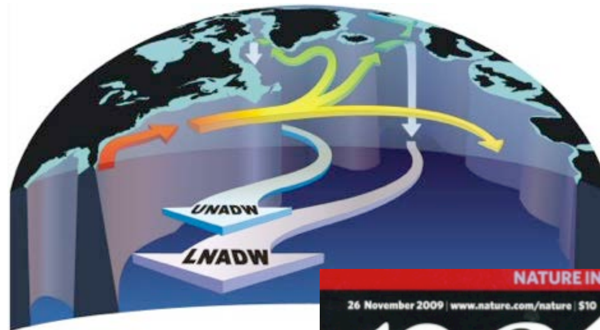
- A key indicator of the global water cycle
  - Large uncertainties in the estimates of evaporation & precipitation; lack of river runoff & ice melt measurements in some regions.
  - Ocean salinity decreases in response to precipitation, river runoff, & ice melt.
  - Ocean salinity increases in response to evaporation & sea ice formation.

- An ecological factor for many pieces of marine organisms
  - Most marine species are adapted to certain ambient salinities.
  - Change in salinity influences osmosis process for many marine organisms.

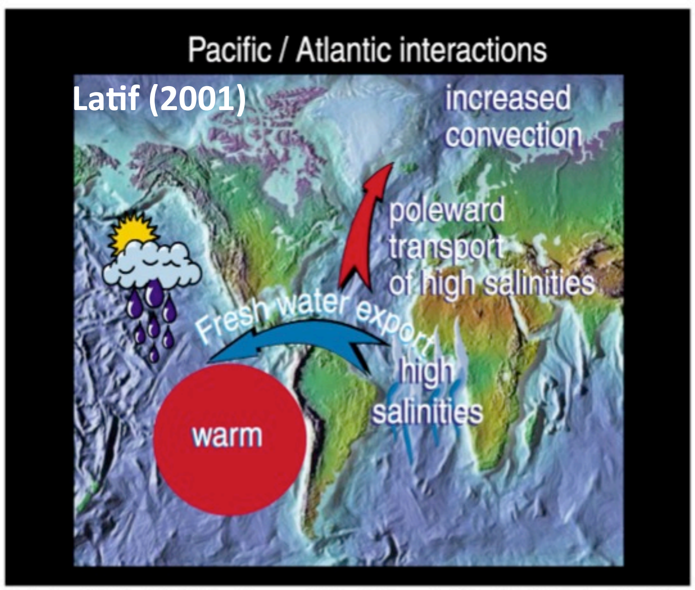
Salinity important to large-scale ocean circulation

Salinity changes, inter-basin salt exchanges, and atmospheric freshwater transport regulate thermohaline circulation





Freshening of subpolar N. Atlantic & AMOC
Curry et al. (2003),
Wu et al. (2004)



Mechanism of Pacific - Atlantic Interactions on multi-decadal time scales. From, M. Latif, Geophys. Res. Lett., 2001, 28, 538-542

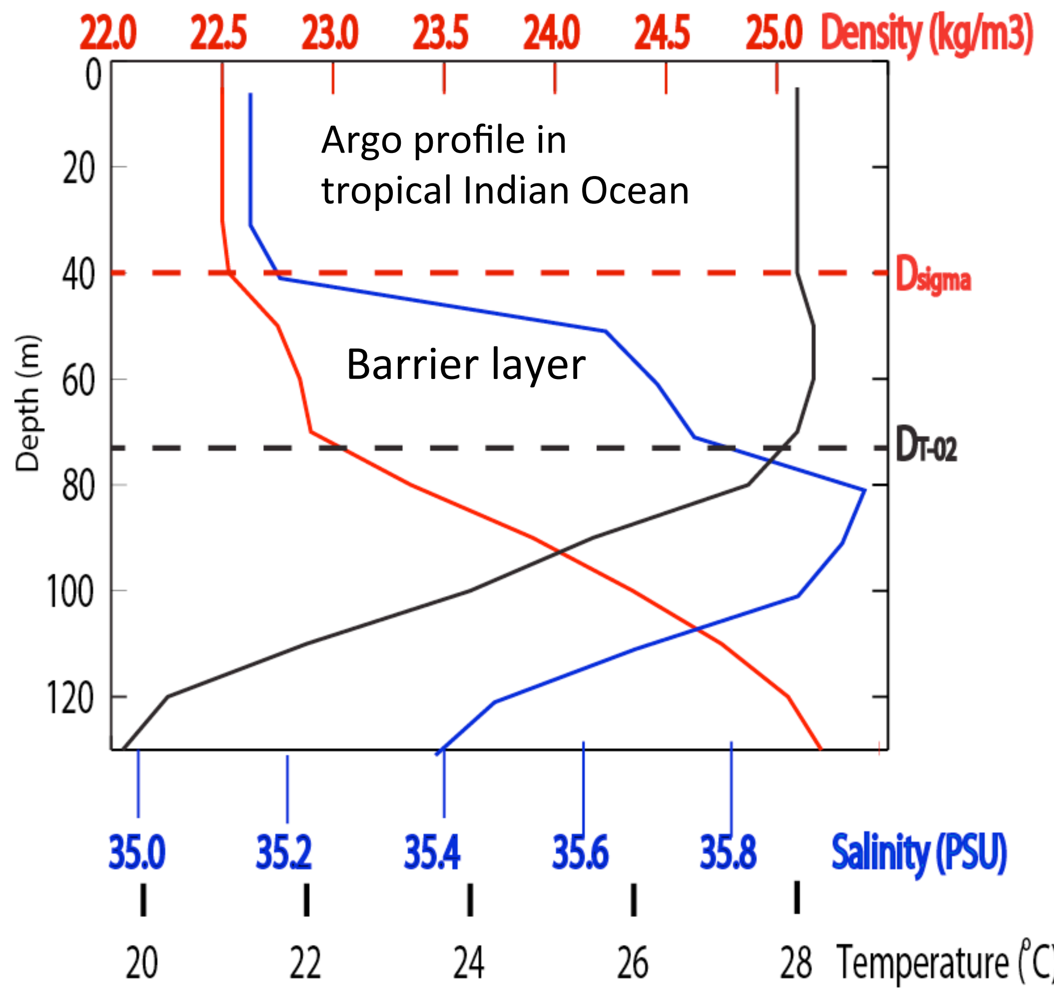
AV/D3/0101

Salinity & "barrier layer" important to air-sea interaction

(e.g., Lukas & Lindstrom 1991, Sprintall & Tomczak 1982, Maes et al. 2005)

Barrier layer: a layer between the isothermal layer & (density) mixed layer, associated with near uniform temperature but significant salinity stratification.

Barrier layer tends to inhibit the communication between the thermocline and mixed layer; amplifies SST response to surface heat flux.



Salinity trend 1950-2000: intensification of global water cycle?

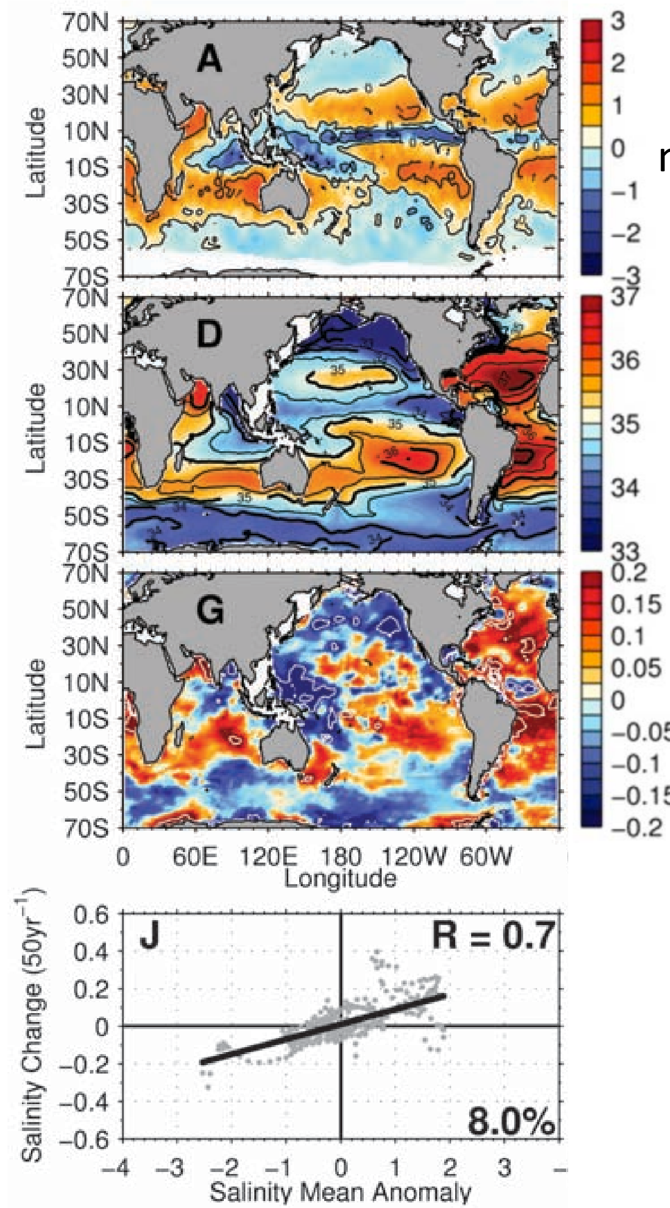
Durack et al. (2012, Science)

Net freshwater flux (evaporation – precipitation)

Mean sea surface salinity (SSS)

Observed 50-year SSS trend

Correlation of SSS change & mean SSS
(fresh gets fresher, salty gets saltier)



m^3/year

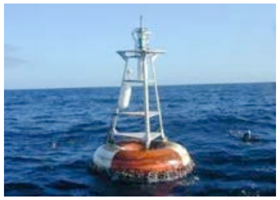
psu

psu

Primary in-situ systems that measure ocean salinity

- Argo profiling floats

- Moored buoys (mostly in the tropics)



- CTD sensors deployed from research vessels

Limitations:

- Sparse (e.g., averaged density of Argo floats is 1 float per 3^ox3^o).
- 10-day surfacing interval of Argo floats is inadequate to resolve shorter-period features such as tropical instability waves.
- Mooring data have a lot of discontinuities; do not allow estimates of spatial gradients.
- CTD data are available only at limited transects.

Measuring sea surface salinity (SSS) from space: a new frontier of ocean remote sensing

Soil Moisture & Ocean Salinity (SMOS) Mission by European Space Agency

Aquarius/SAC-D Mission by NASA & CONAE

Main scientific objectives of SMOS & Aquarius

- Monitor global ocean SSS variability
  on intraseasonal, seasonal, to interannual time scales.

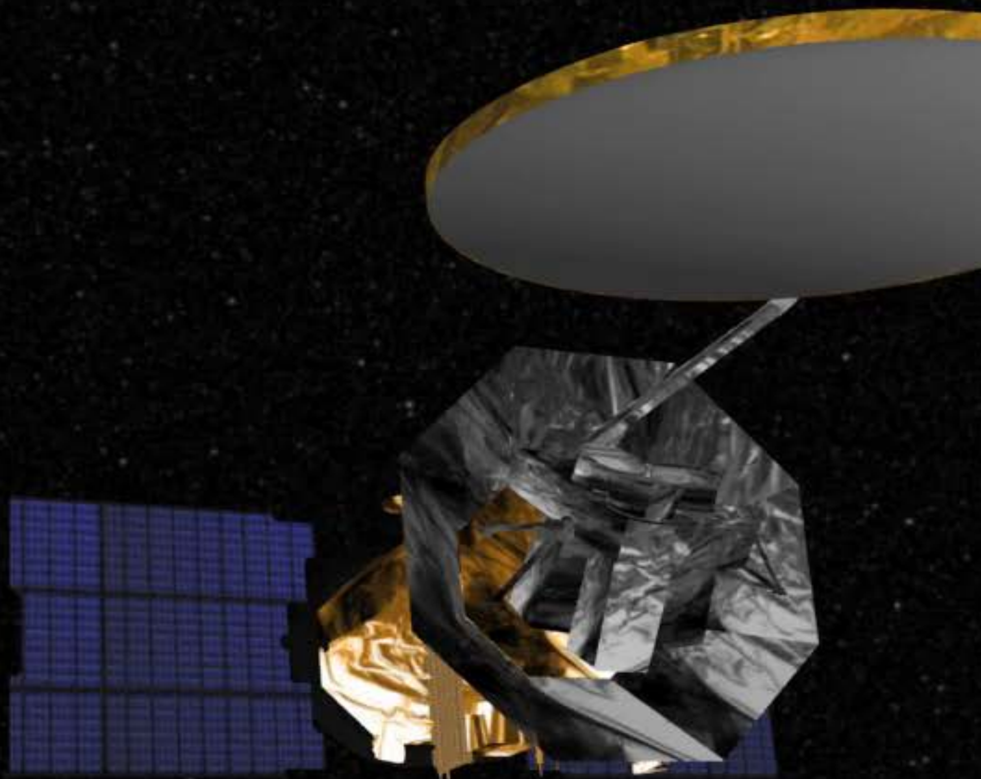
- Investigate SSS effects on ocean (thermohaline) circulation:

-Large Scale frontal dynamics
-Evolution of Large scale salinity events
-Mesoscale activity (eddies)

- Investigate the relationships between SSS and:
- climate variability (El-Niño, la Niña, IOD, MJO,..)
- global water cycle (Evaporation minus Precipitation, run offs).

- Improve ocean and climate models.

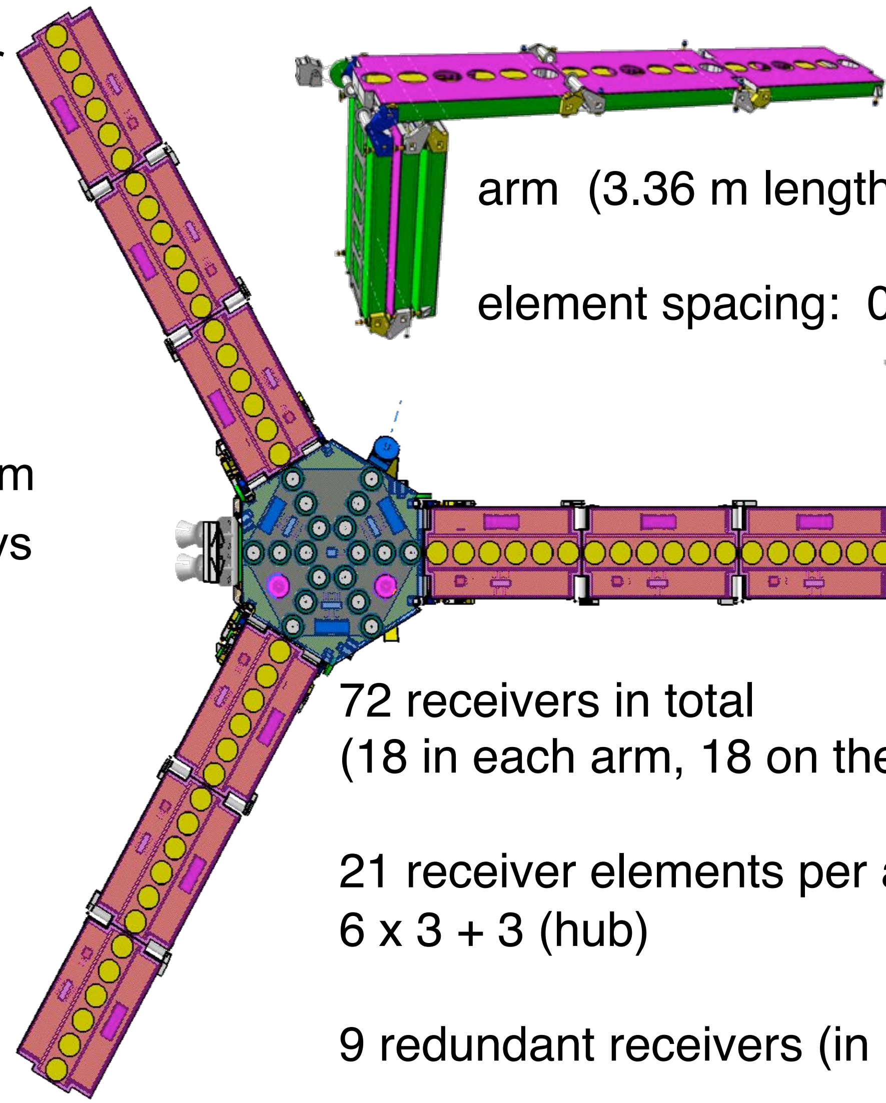
Aquarius/SAC-D - Joint venture between NASA and Comisión Nacional de Actividades Espaciales (CONAE) of Argentina



- Aquarius instrument from NASA
- SAC-D spacecraft from CONAE
- Participation from Italy, France, Brazil, and Canada.
- Launched June 10, 2011
- Science data from Aug. 2011
- Mission development: JPL
- Ground op control: CONAE
- Data processing system: GSFC
- Data distribution: PO.DAAC at JPL
- Sun-synchronous orbit
- Altitude 657 km (408 mi)
- 150-km resolution
- 7-day repeat w/ global coverage

SMOS Technical Concept

- Passive microwave radiometer (L-band - 1.4GHz)
- 2D interferometry
- multi-incident angles (0°-55º)
- ~ 1000 km swath
- Fully polarimetric observations
- spatial resolution: 20-50km
- revisit time: 1-3 days
- Launch: 2009
- Nominal 3 year mission,
- Extended to 2017



arm (3.36 m length)

element spacing: 0.88 λ

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

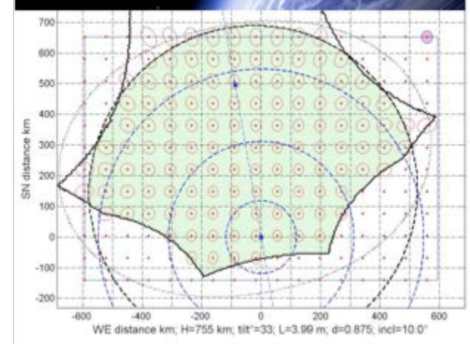
21 receiver elements per arm:
6 x 3 + 3 (hub)

9 redundant receivers (in hub)

More on missions design

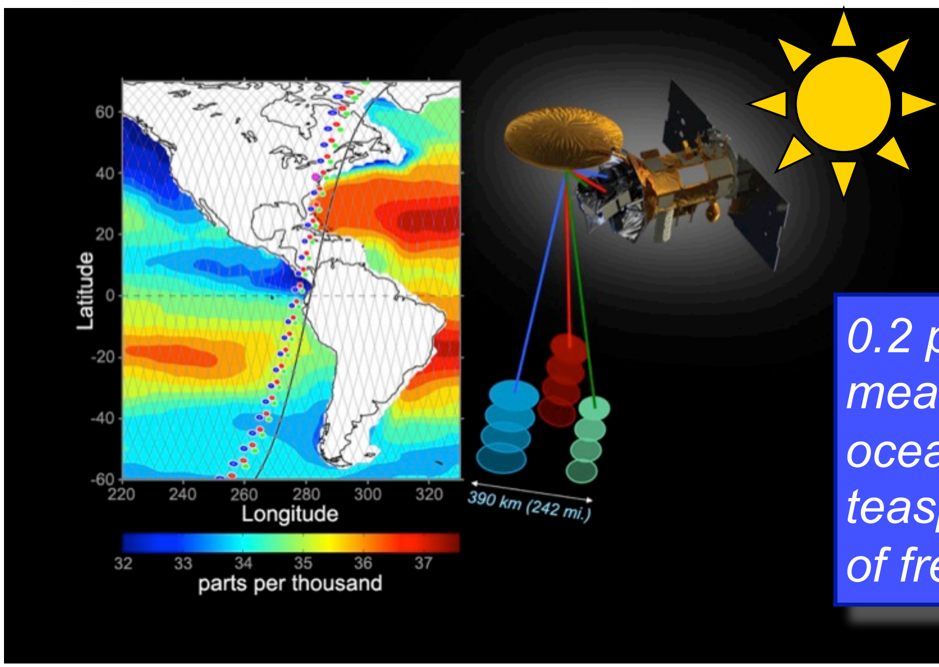
Sun-synchronous exact repeat orbits 6pm (am) ascending (descending) node for Aquarius & reversed for SMOS

1000 km Swath, 40 km Spatial resolution, multi-incidence angle views

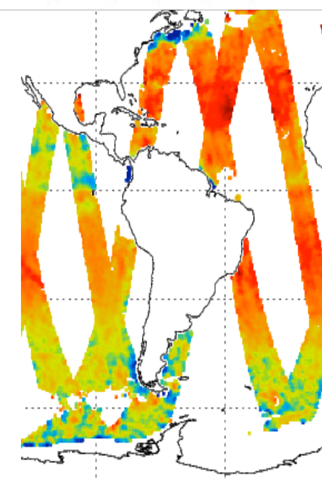


3-beam "pushbroom" forming a 390-km swath, pointing toward the night side to avoid sunglint

Target accuracy: 0.2 parts per thousand (ppt) or practical salinity unit (psu) at 150-km, monthly scales.

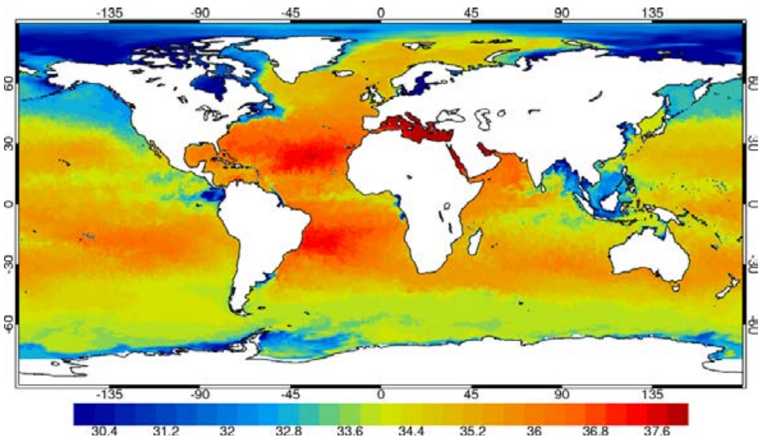


0.2 psu is about 0.6% of mean salinity of the world ocean, equivalent to 1/8th teaspoon of salt in a gallon of freshwater

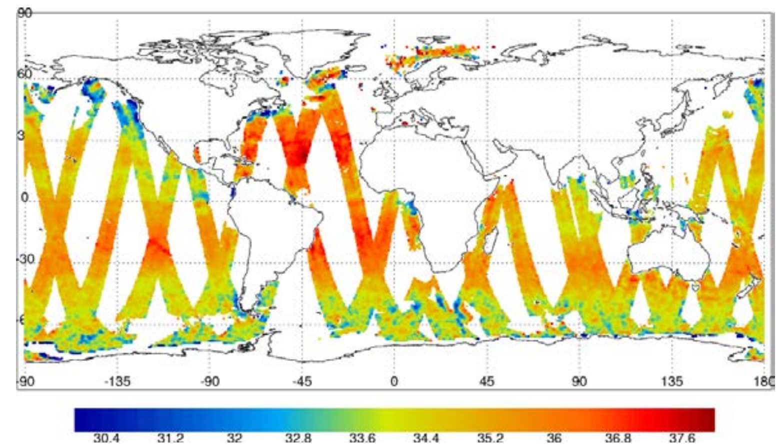


Satellite SSS daily Sampling

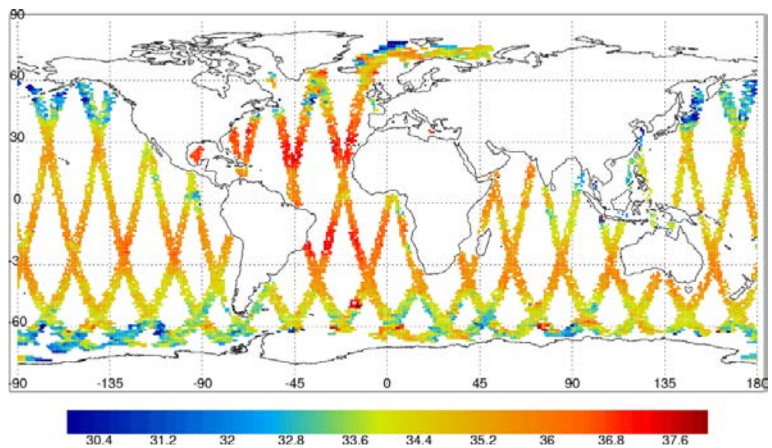
FOAM model



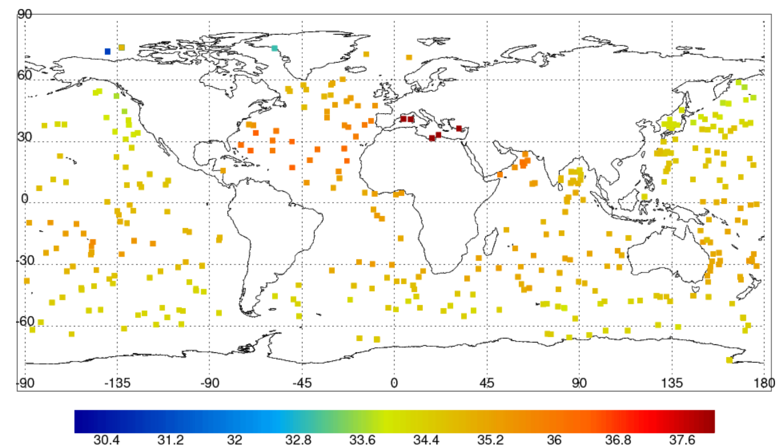
SMOS



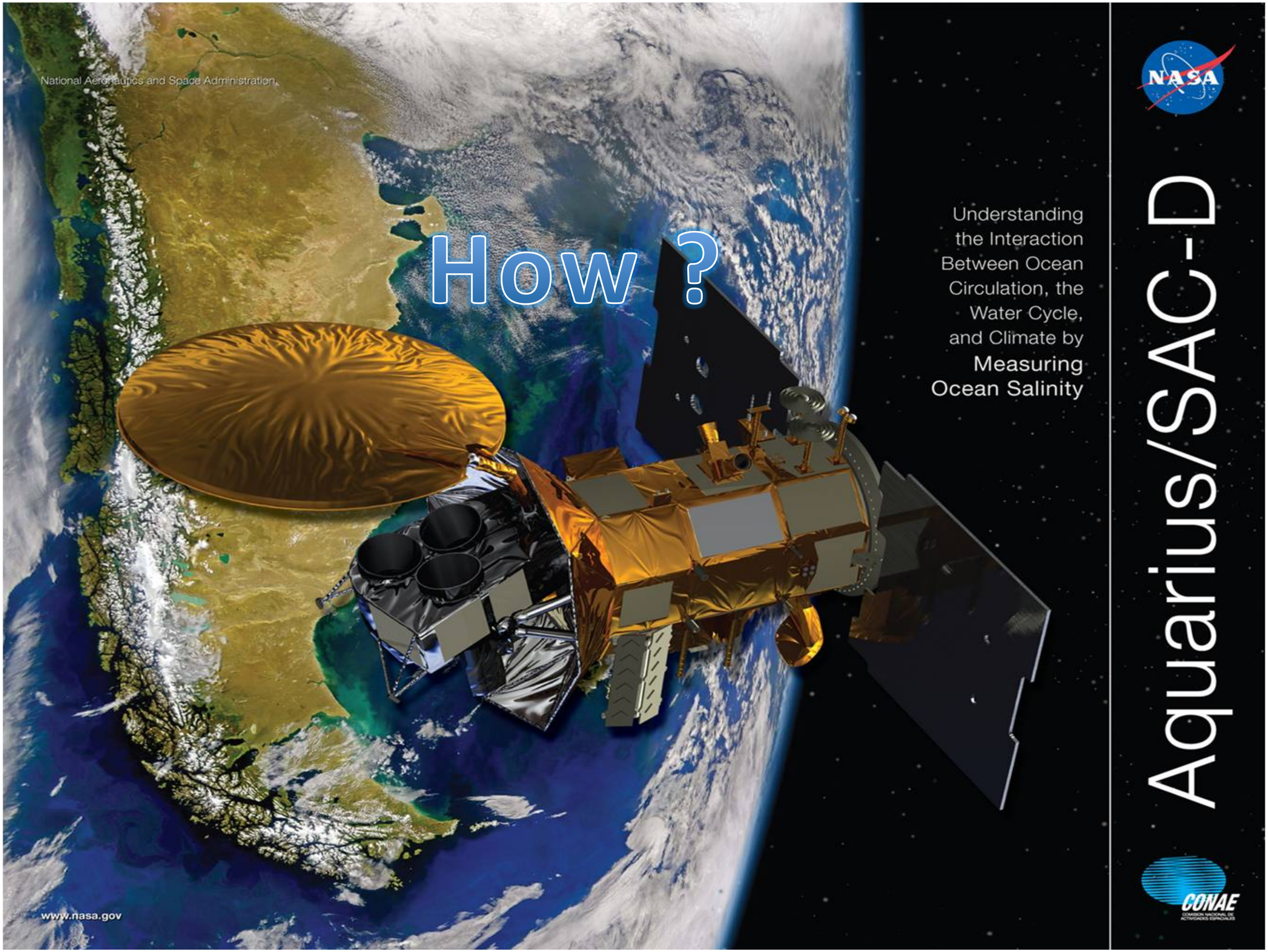
Aquarius



Argo

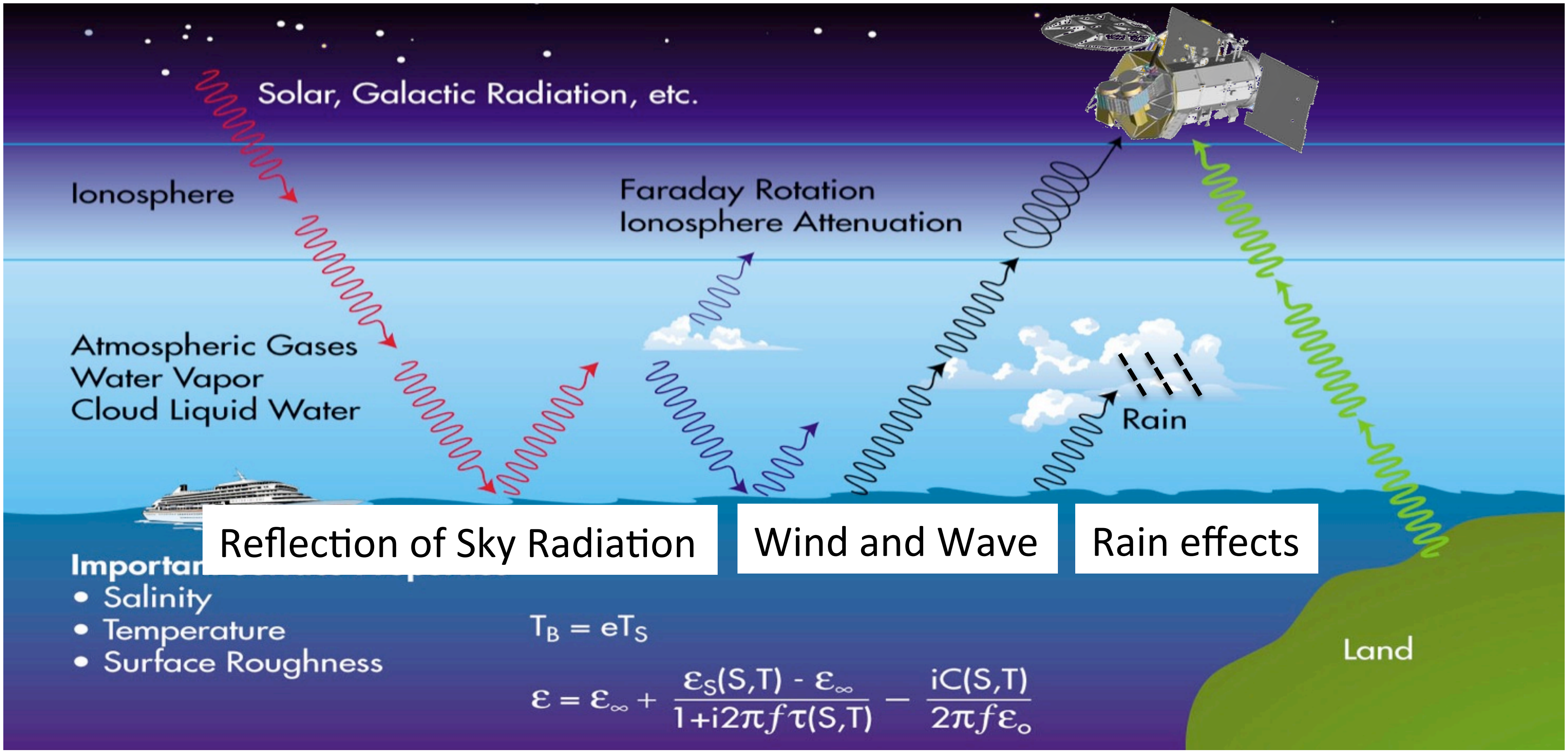


Courtesy Mattiew Martin (UK Metoffice)

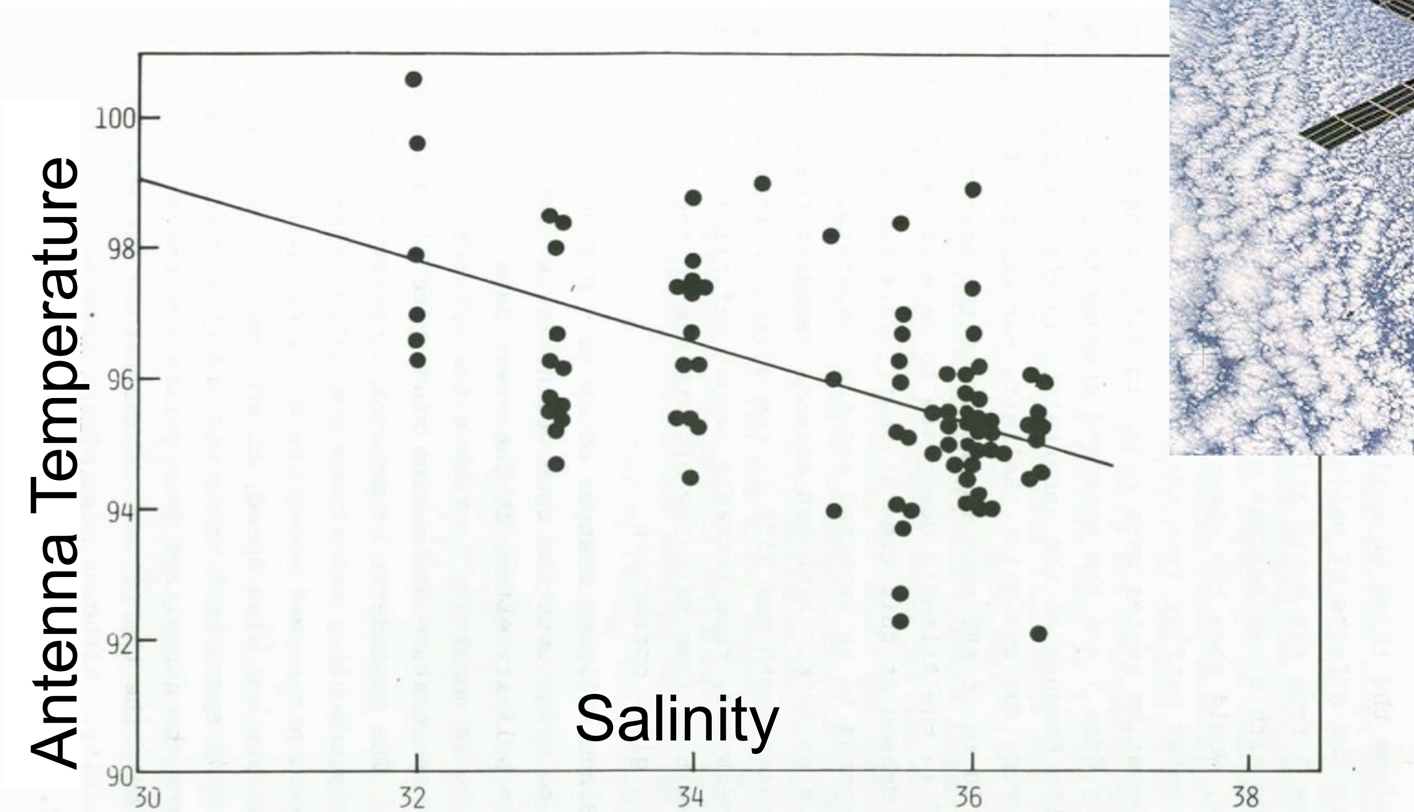

National Aeronautics and Space Administration
How ?
Understanding the Interaction Between Ocean Circulation, the Water Cycle, and Climate by Measuring Ocean Salinity
Aquarius/SAC-D
NASA
CONAE
www.nasa.gov

The challenges of retrieving SSS from space

In addition to the “flat” sea surface emission, we must correct for effects due to the sky, atmosphere, ionosphere, land and ice, and <u>especially surface roughness</u>.



The first salinity measurements from Space
Skylab Space Station (1973)



1.4 GHz radiometer with 1 m phased array antenna

Lerner & Hollinger, 1976, NRL Memo 3306

Some early airborne campaigns

306 HANS-JUERGEN C. BLUME ET AL.

Fig. 8. Isohalines of the lower Chesapeake Bay with 2‰ increments on 24 August, 1976.

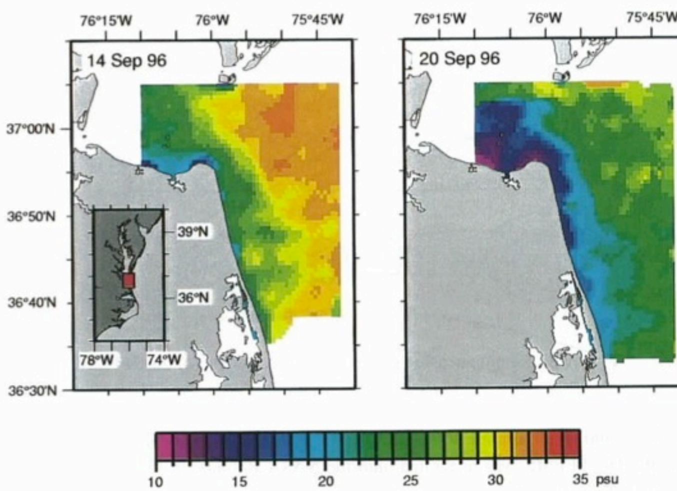
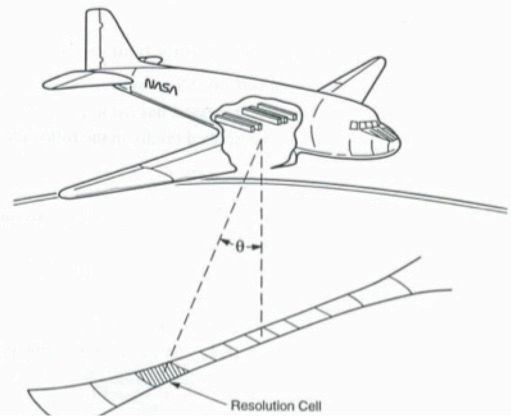
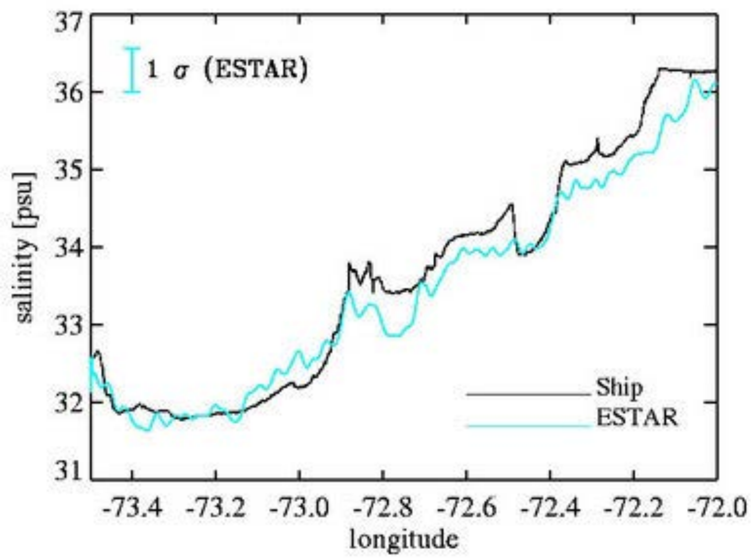


Figure 4. Airborne SLFMR measurements of sea surface salinity of the Chesapeake Bay plume on (right) 14 September 1996 and (left) 20 September 1996.



Salinity Measurements 29 Aug 1999, E-W line at lat=38.65



Aquarius/SAC-D instrument characteristics

Primary instruments

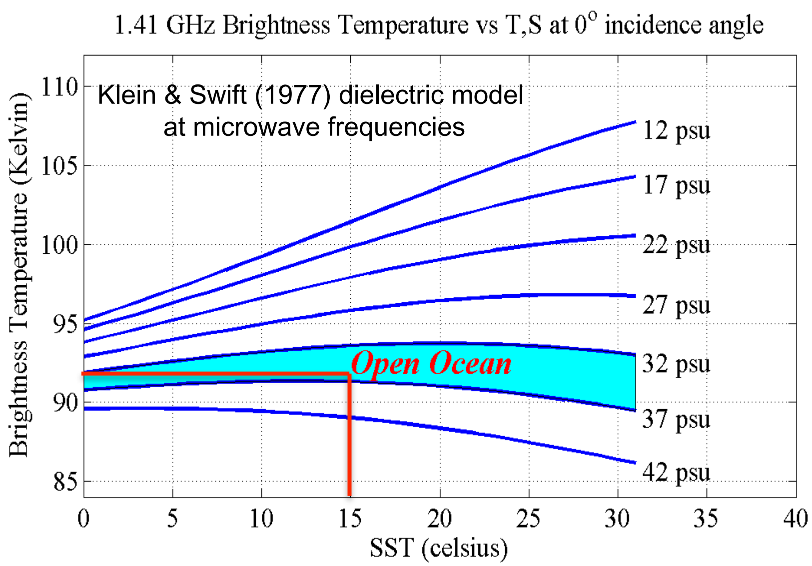
Aquarius/SAC-D Science Instruments				
Instrument	**Objective**	**Description**	**Resolution**	**Source**
Aquarius:	Sea Surface Salinity (SSS)	Integrated 1.413 GHz polarimetric radiometer, 1.26 GHz radar, 390 km swath	3 beams 76x94 km, 84x120 km, 96x156 km	NASA
MWR: Microwave Radiometer	Precipitation, wind speed, sea ice concentration, water vapor	23.8 GHz and 37 GHz; Dual polarized; 390 km swath	40 km	CONAE
NIRST: New IR Sensor Technology	Hot spots (fires); Sea Surface Temperature	Bands: 3.8, 10.7 and 11.7 µm Swath: 180 km;	350 meters	CONAE
HSC: High Sensitivity Camera	Urban lights; fires, Aurora	Bands: 450-900 nm; Swath: 700 km;	200-300 m	CONAE
DCS: Data Collection System	Environmental data collection	Band: 401.55 MHz uplink	2 contacts per day w 200 platforms	CONAE
ROSA: Radio Occultation Sounder for Atmosphere	Atmosphere temperature and humidity profiles	GPS occultation	Hor: 300 km Vert: 300 km	ASI (Italy)
CARMEN 1: (ICARE and SODAD)	ICARE: Effect of cosmic radiation on electronics; SODAD: Distribution micro-particles and space debris	ICARE: Three depleted Si and Si/Li detectors SODAD: Four SMOS sensors	I: 256 channels S: 0.5 µ at 20 km/s sensitivity	CNES (France)

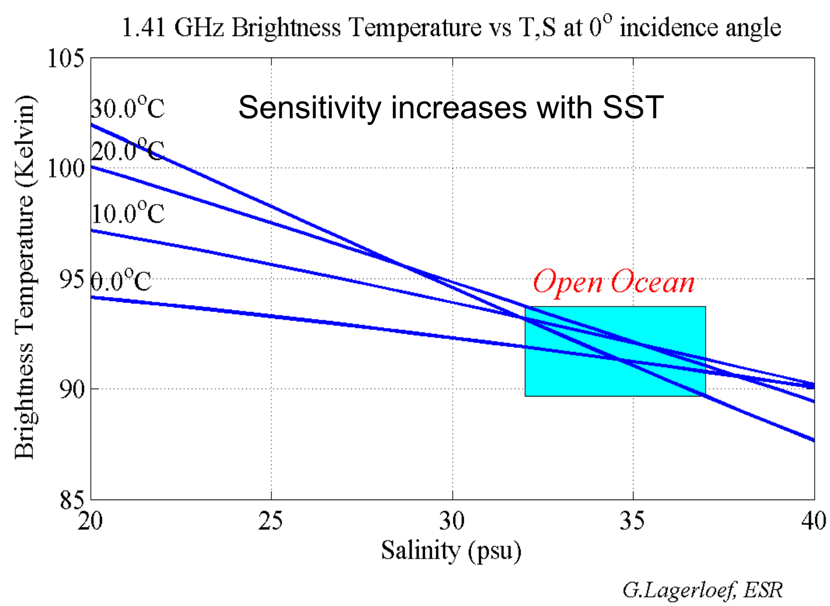
How does SMOS & Aquarius infer SSS?

- Aquarius & SMOS radiometers measure microwave radiation from the sea surface, expressed as “brightness temperature” T_B
- T_B is the product of emissivity (e) & sea surface temperature (T):

  $T_B = eT$, where $e \approx 0.3$ for seawater
- e is a function of incidence angle θ, polarization (H or V), sea state (surface roughness), and dielectric coefficient ε (function of SSS, SST, and radio frequency)
- Main factors controlling T_B are SSS, SST, and surface roughness.
- “Back out” SSS from measurements of T_B (from radiometer), SST, & surface roughness (from scatterometer for Aquarius)
  by constraining a theoretical/empirical “Geophysical Model Function” of T_B with various measurements
- Also need to correct for effects of galactic reflection, land signal leakage, radio frequency inference (RFI), surface roughness caused by rain, etc.

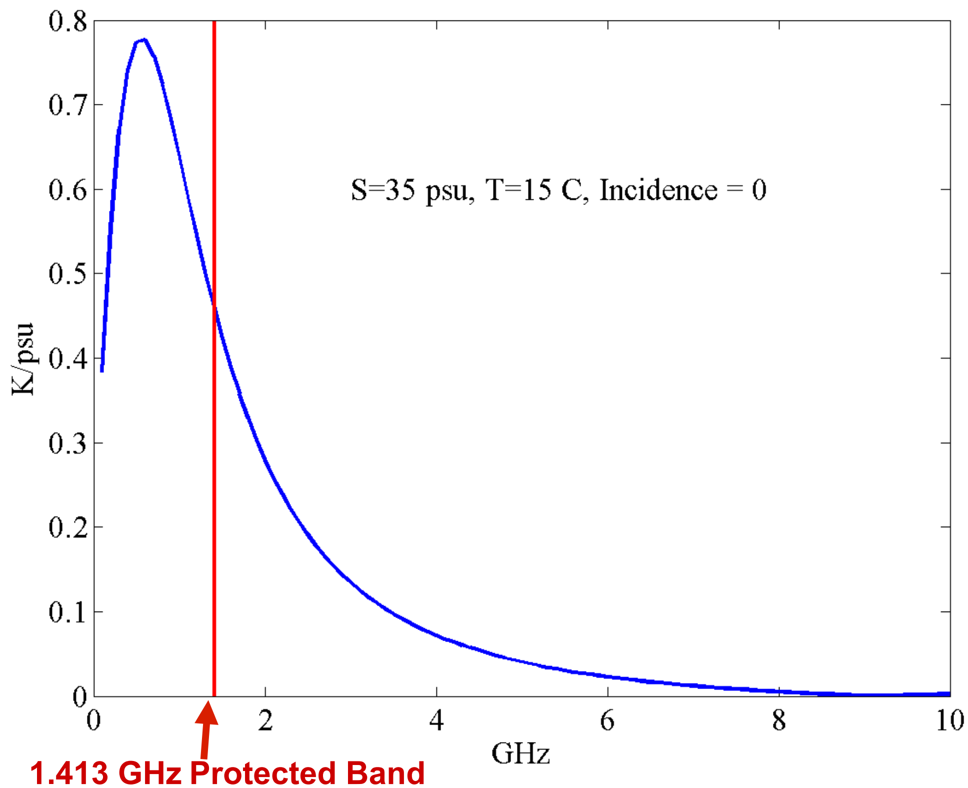
L-band T_B has better sensitivity to SST at warm waters





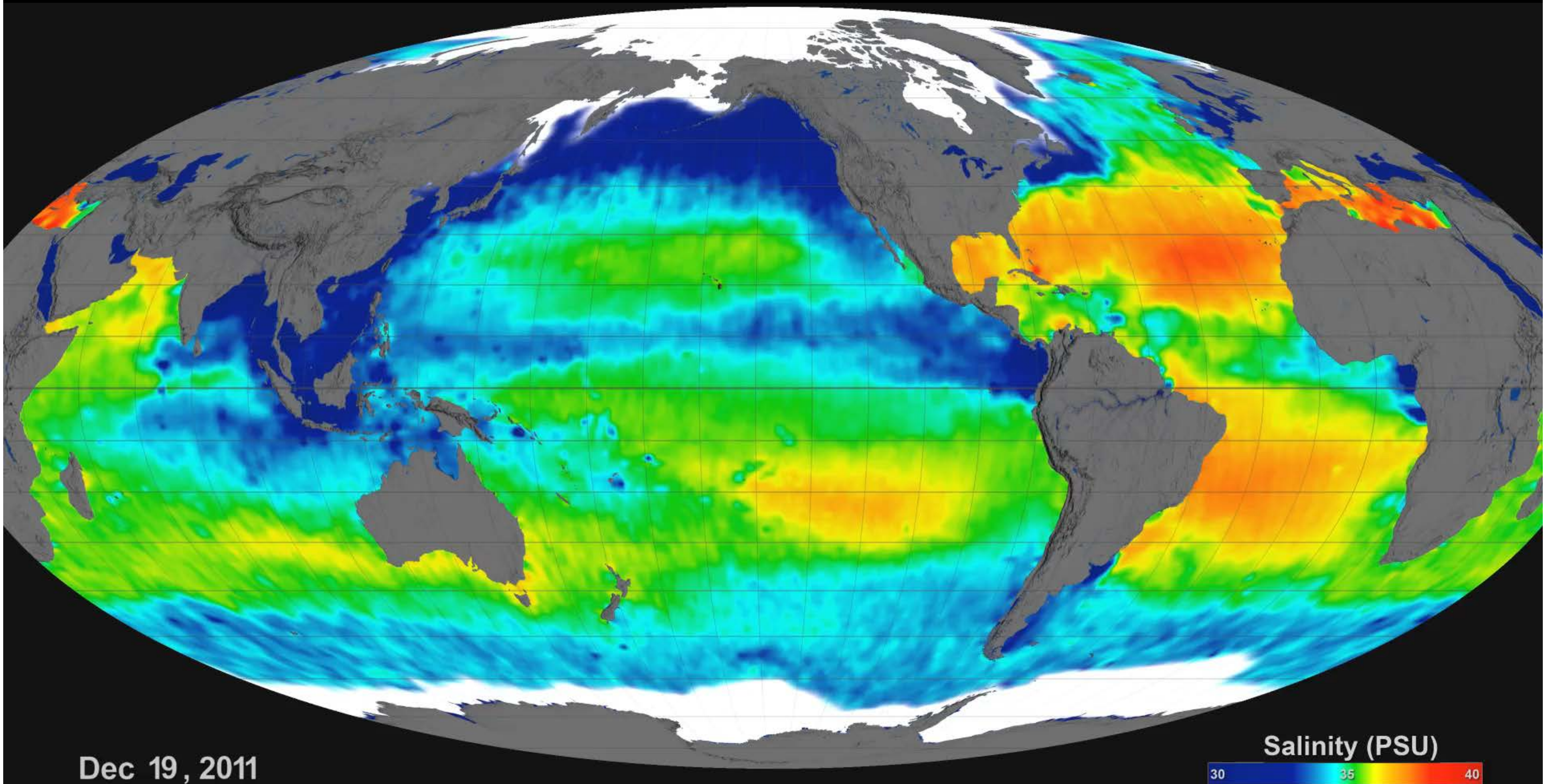
Why 1.413 GHz?

Sensitivity vs Radiometer Frequency

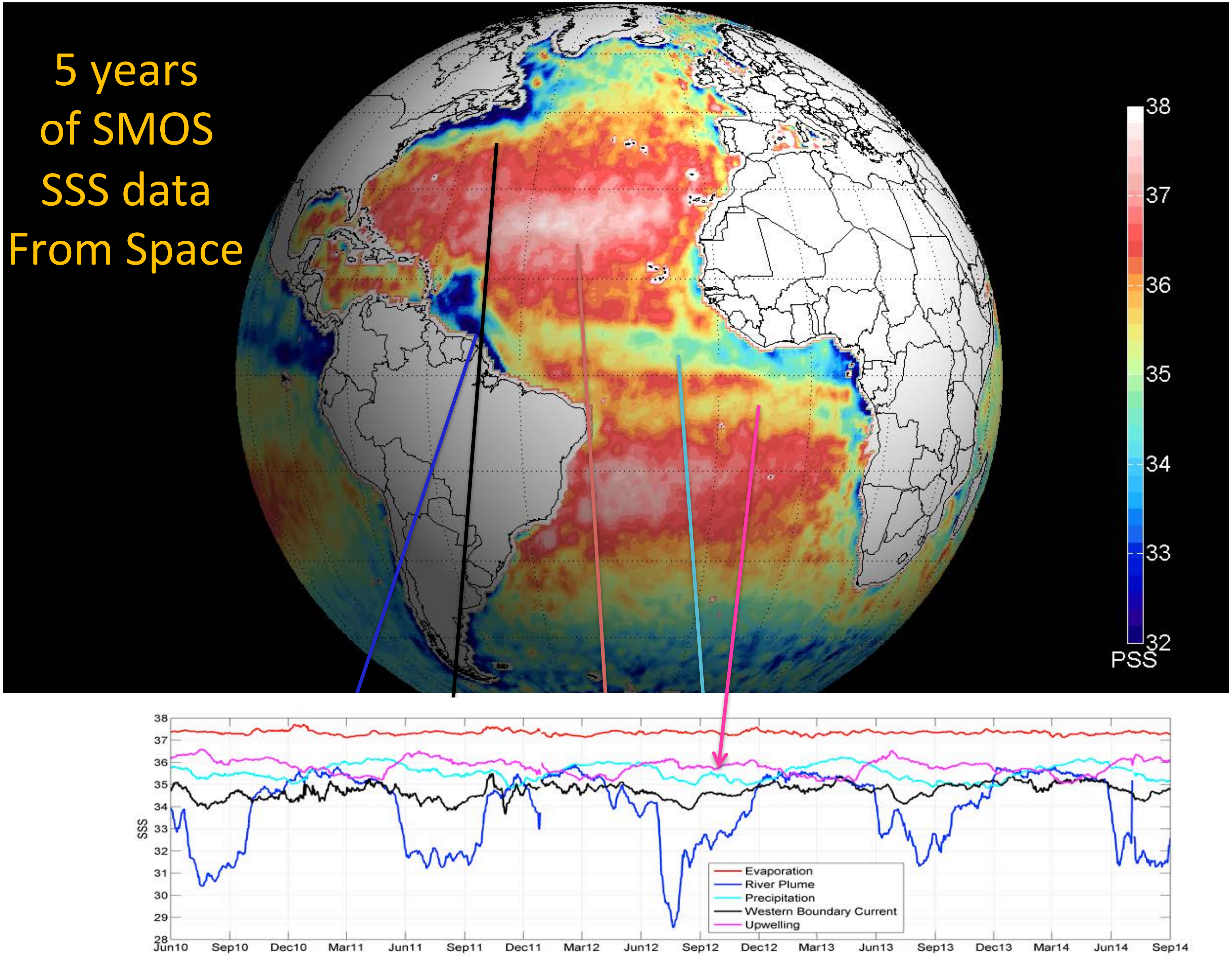


- It is a protected band (radio astronomy)
- Antenna size is manageable. Aquarius will have a 2.5 m antenna to yield a footprint ~100 -150km.
- There is enough sensitivity to detect SSS signatures (~0.1K ≈ 0.2 psu)
- To achieve the required accuracy, the Aquarius radiometers are built with unprecedented precision (0.1K)

Aquarius SSS in 2012



Target accuracy of 0.2 psu is about 0.5% of mean SSS of the global oean


5 years
of SMOS
SSS data
From Space
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PSS
SSS
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Mar11
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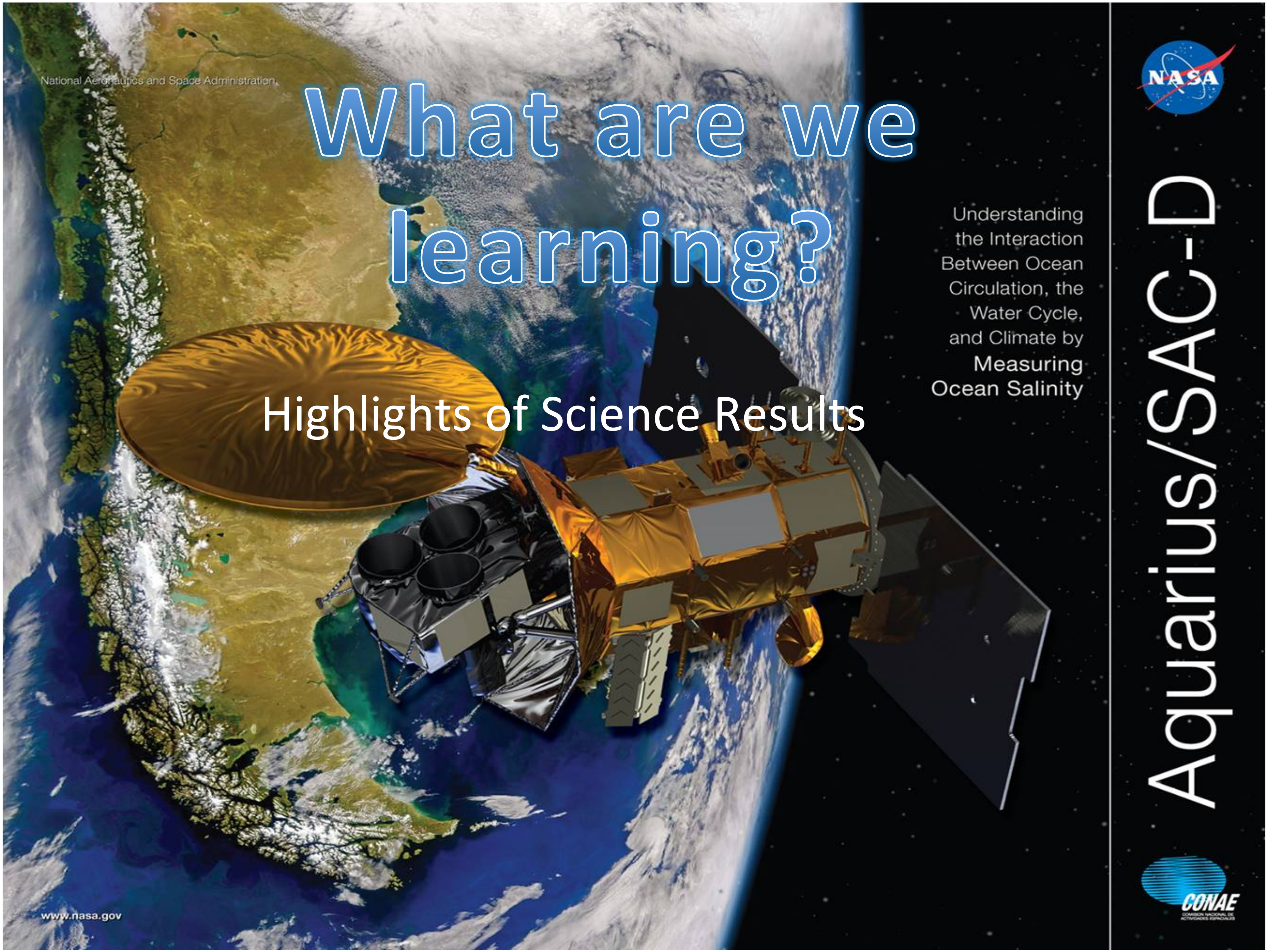
Dec12
Mar13
Jun13
Sep13
Dec13
Mar14
Jun14
Sep14
Evaporation
River Plume
Precipitation
Western Boundary Current
Upwelling

What are we learning?

Highlights of Science Results



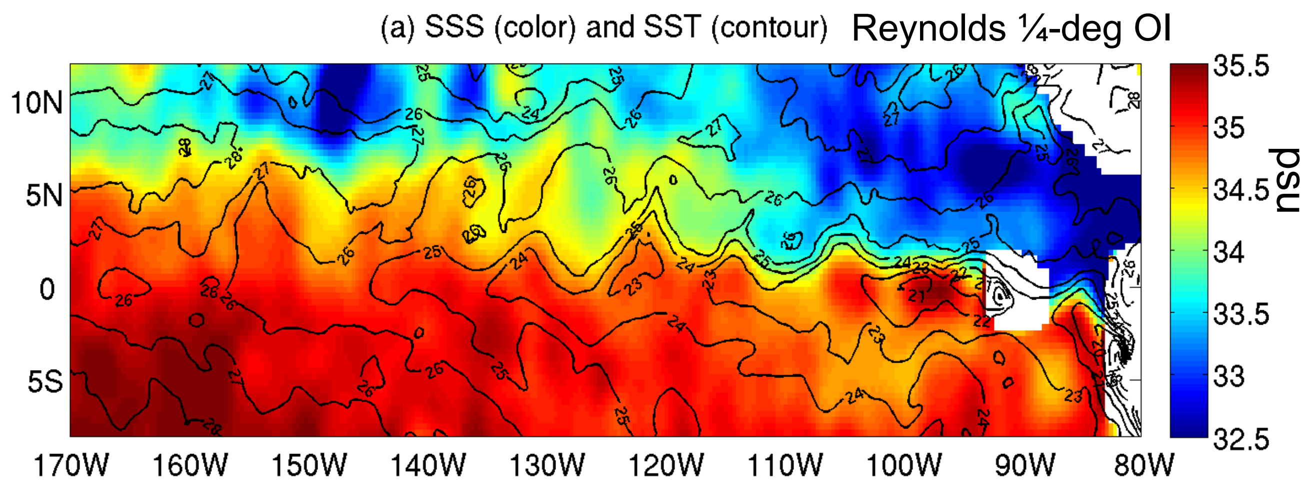
TIW, Meso-scale cicrularion features

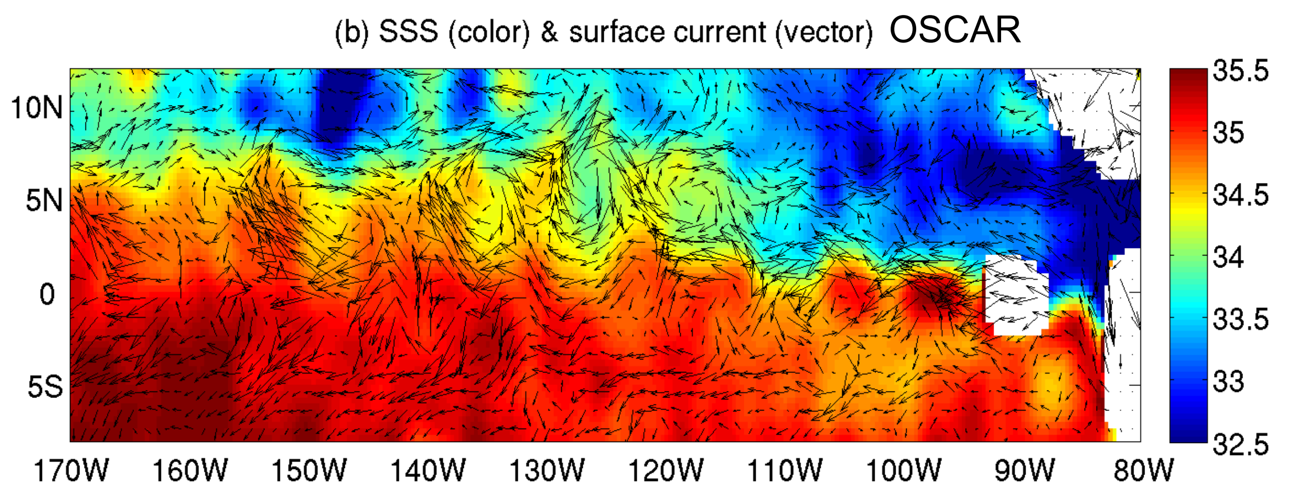
Aquarius Captures Pacific Tropical Instability Waves (TIWs)

- TIWs affect ocean, climate, biogeochemistry
- Aquarius reveals TIWs salinity structure for the 1st time from space).
- Brings new understanding to TIWs.

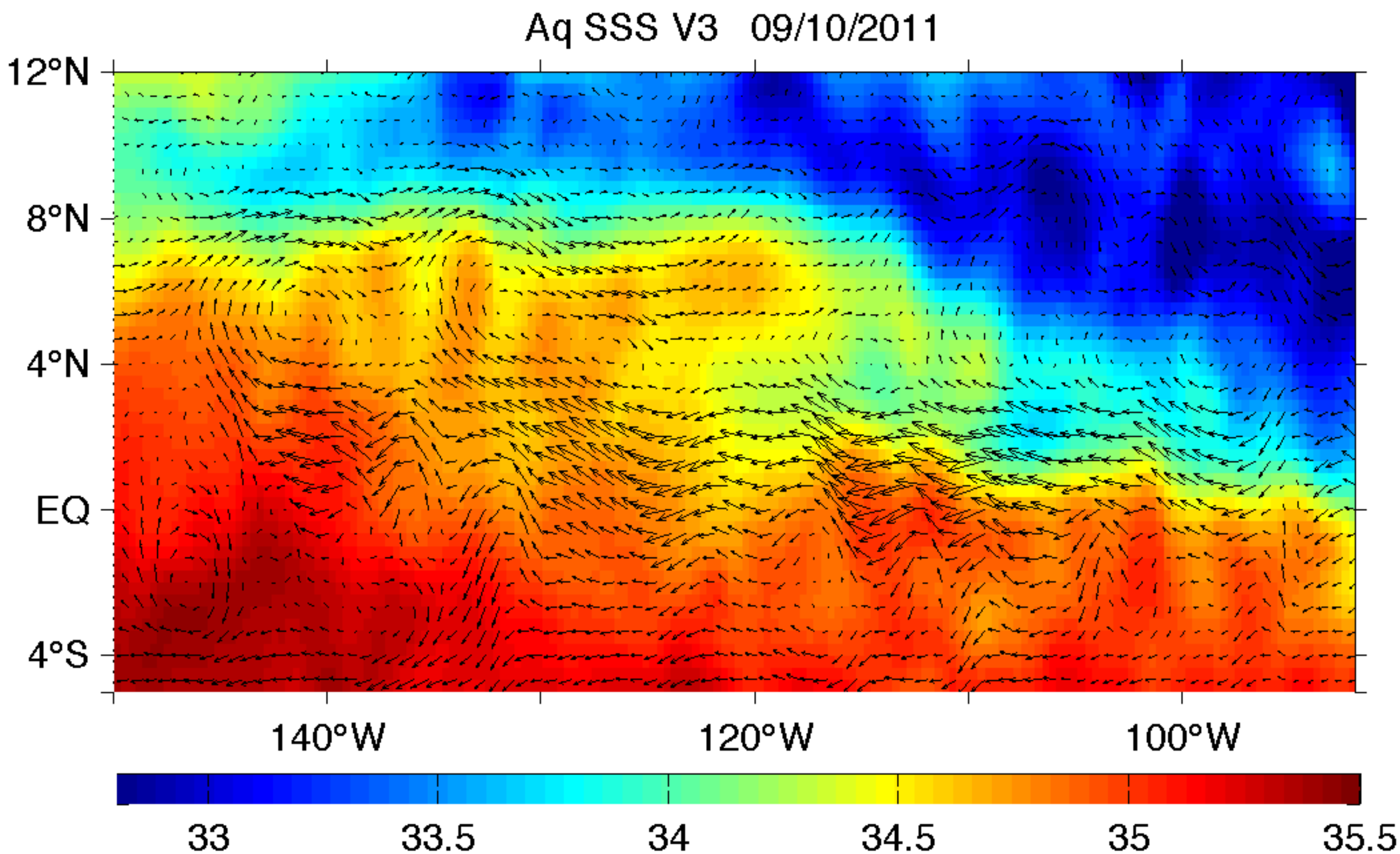
Lee, Lagerloef, Gierach, Yueh, Dohan (2012, June GRL)

SSS from Aquarius (color shading), SST (contours in a), surface currents (arrows in b) on Dec. 11, 2011 (7-day maps)





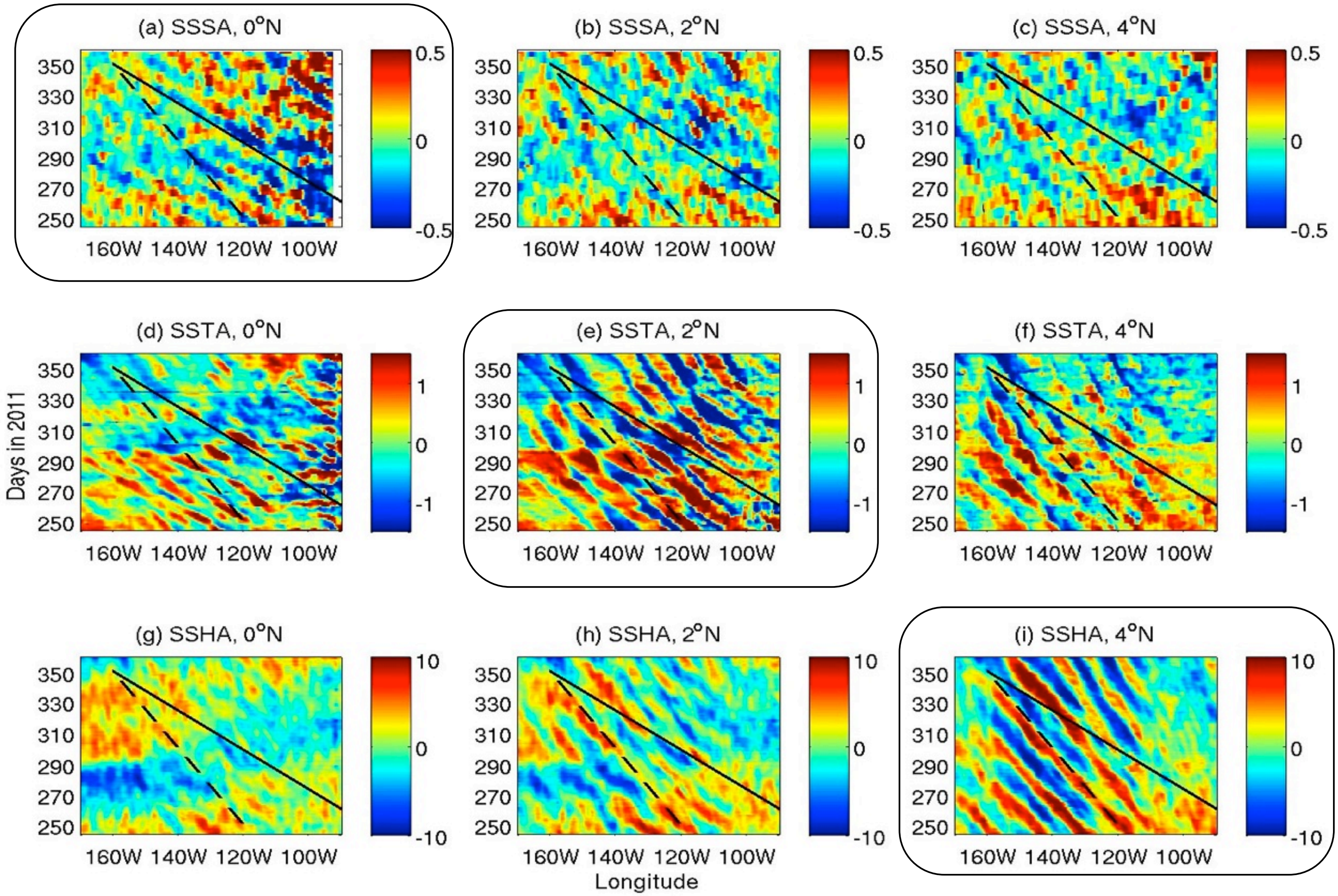
Aquarius SSS & OSCAR surface current



Animation produced by Hsun-Ying Kao, Earth & Space Research

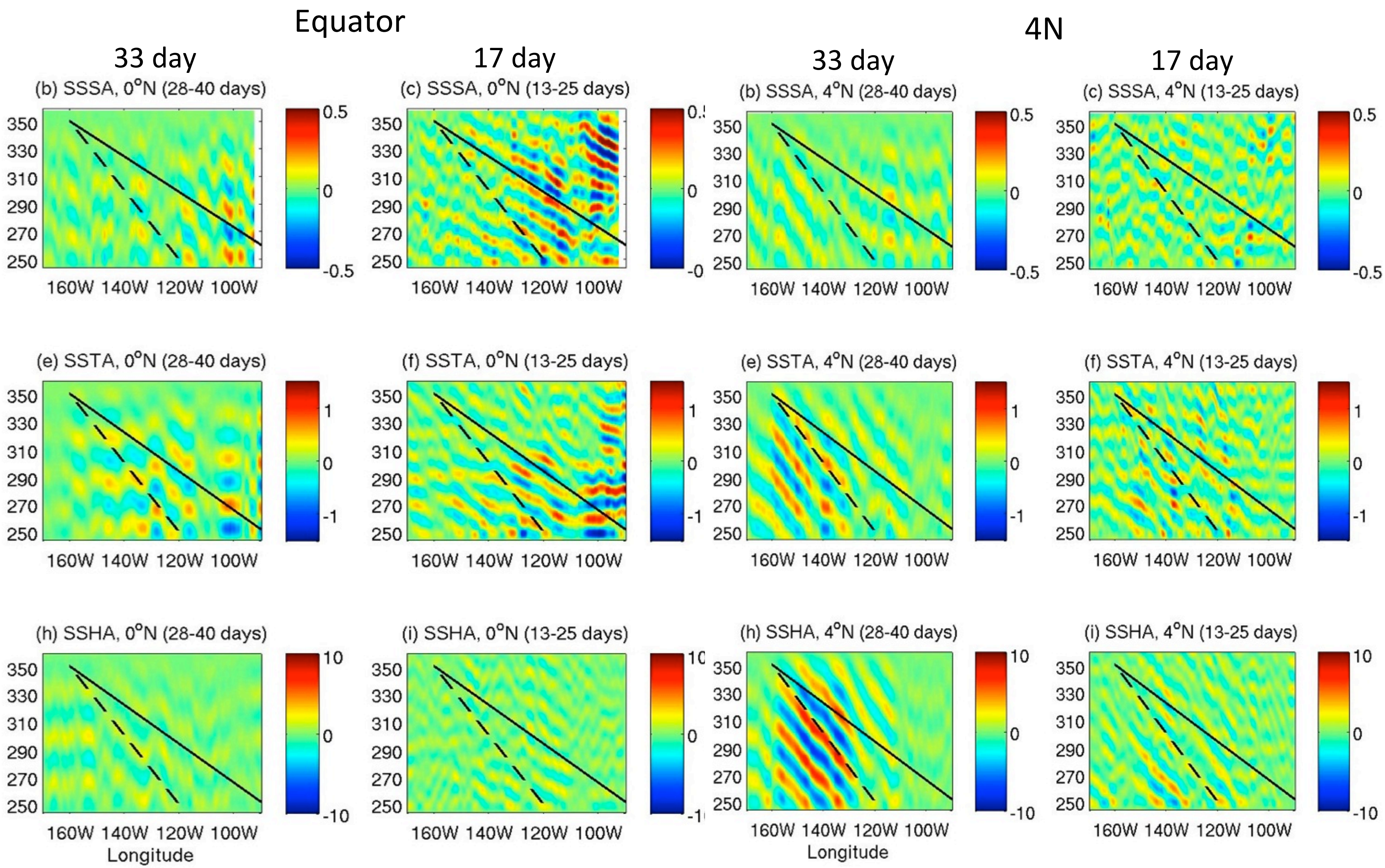
Aquarius reveals faster TIW propagation near equator than off equator

- Twice as fast as that off the equator observed by SST & SSHA (during 2011)
- Not reported in the past 3 and half decades of TIW literature



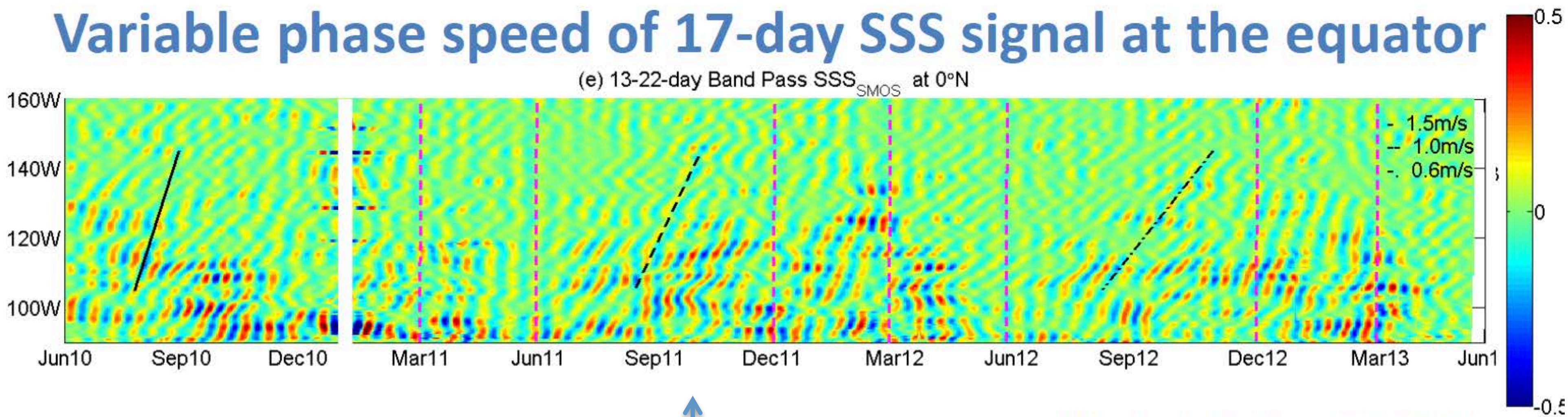
SSS, SST, SSH show strongest signals at 0, 2, 4N, complementary

TIWs near the equator have a dominant period of 17 days (characteristic of Yanai Waves). Those away from equator have dominant periods of 33 days (characteristics of Rossby waves)



SMOS data reveal interannual variation of TIW speed at equator, faster during La Nina

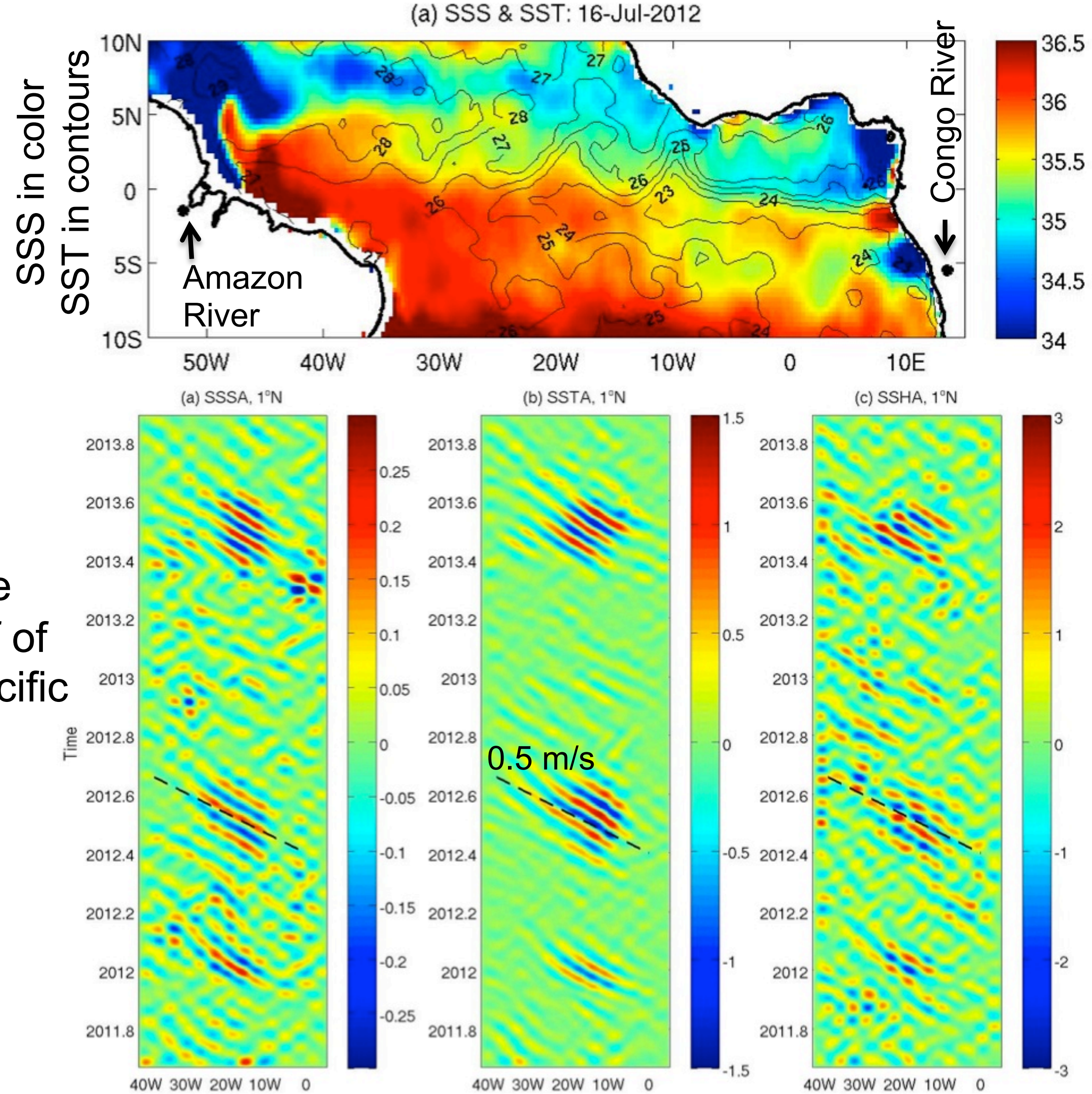
Yin, Boutin, Reverdin, Lee, Arnault, and Martin, 2014, JGR, accepted



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

Aquarius also captures the much weaker Atlantic TIWs

Lee, Lagerloef, Kao, McPhaden, Willis, and Geriach (2014, JGR accepted)



SSS' magnitude about half of that of Pacific TIWs

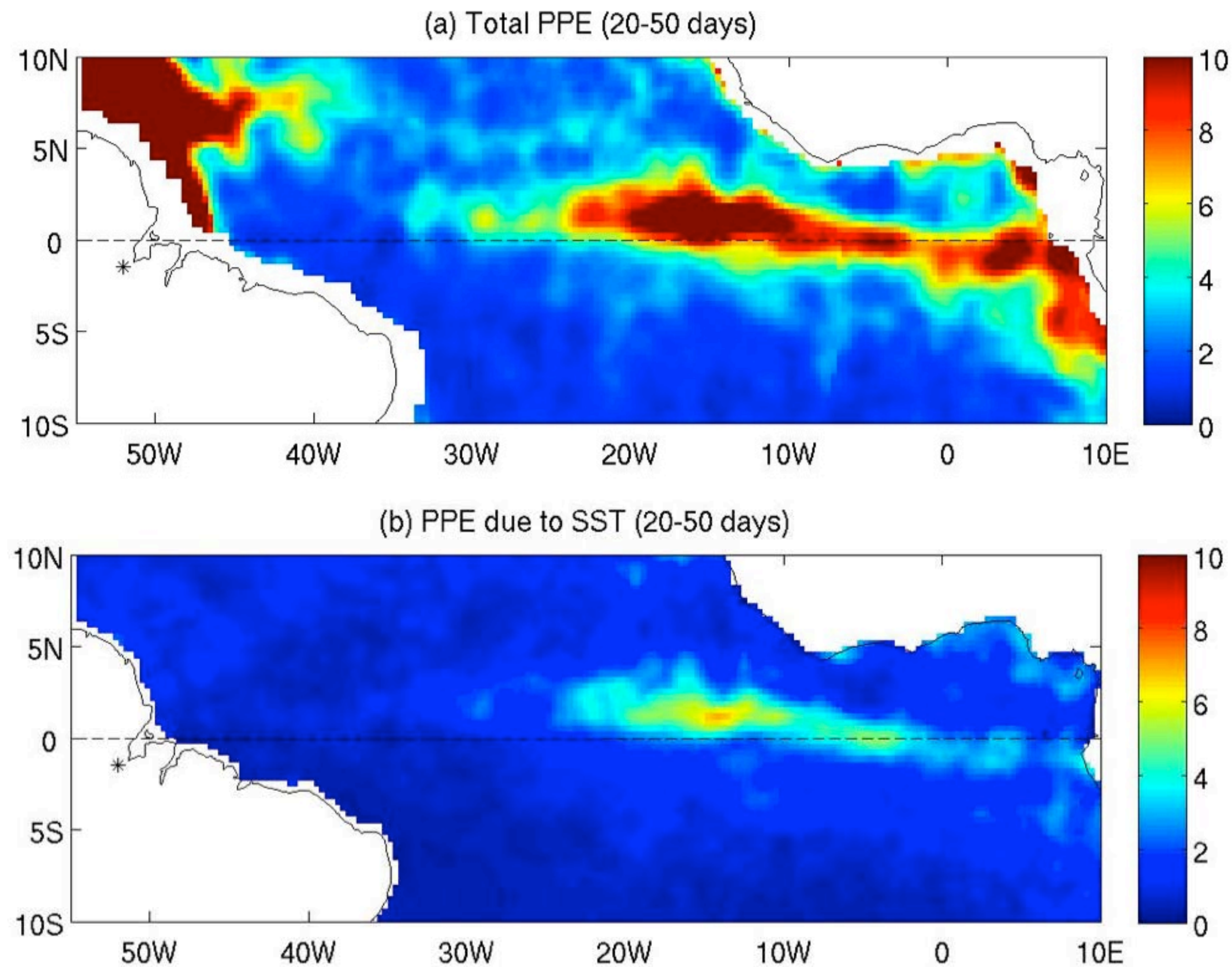
Substantial influence of salinity on energetics of tropical Atlantic TIWs

Lee, Lagerloef, Kao, McPhaden, Willis, and Gierach (2014, JGR, accepted)

20-50 day surface perturbation potential energy (PPE)

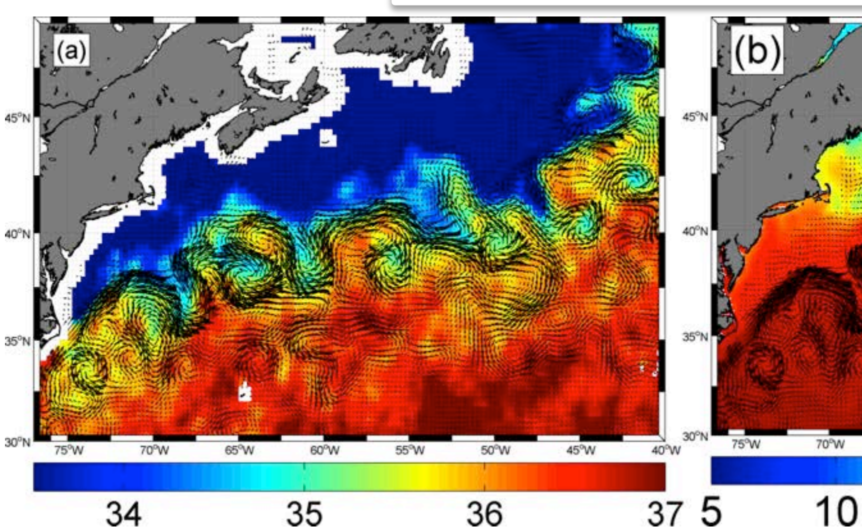
accounting for SSS & SST contributions

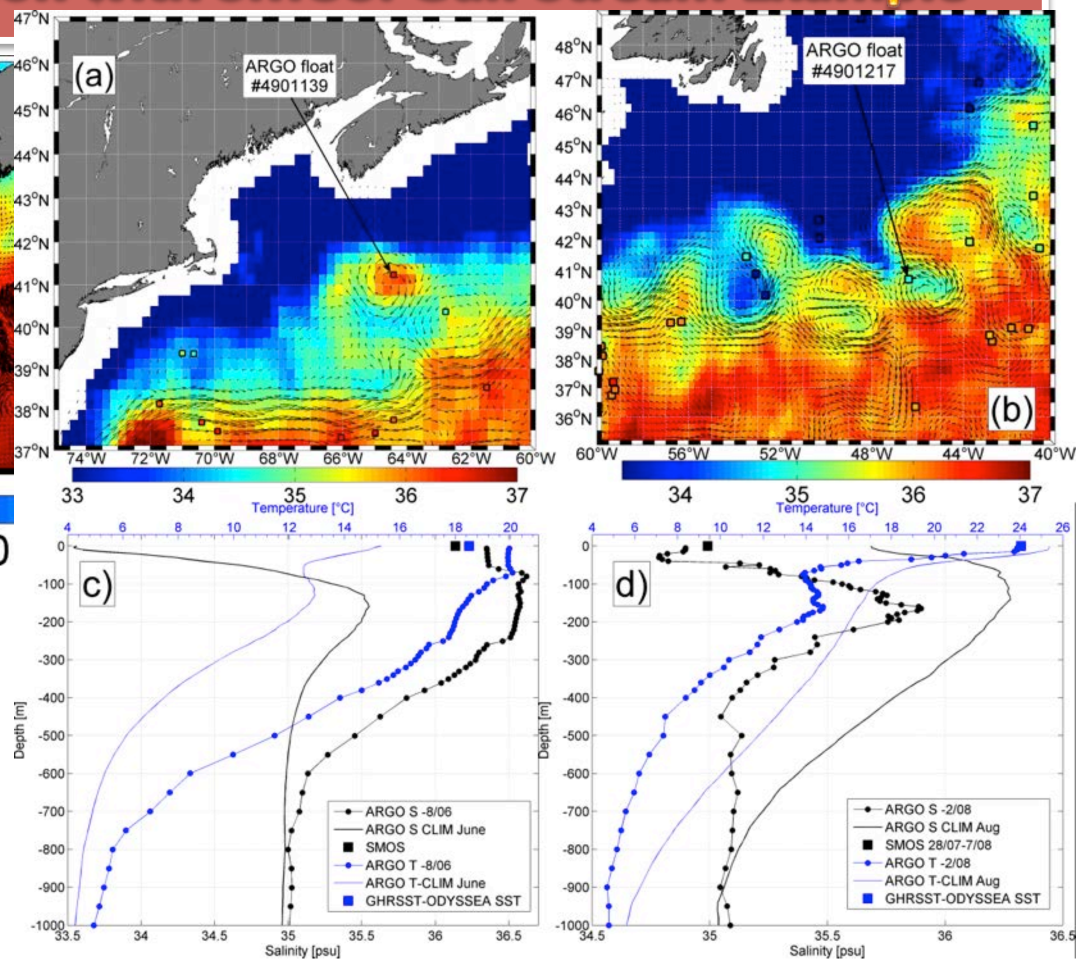
considering only SST contribution



Ignoring salinity underestimates surface PPE by 3 times in the central eq. Atl!

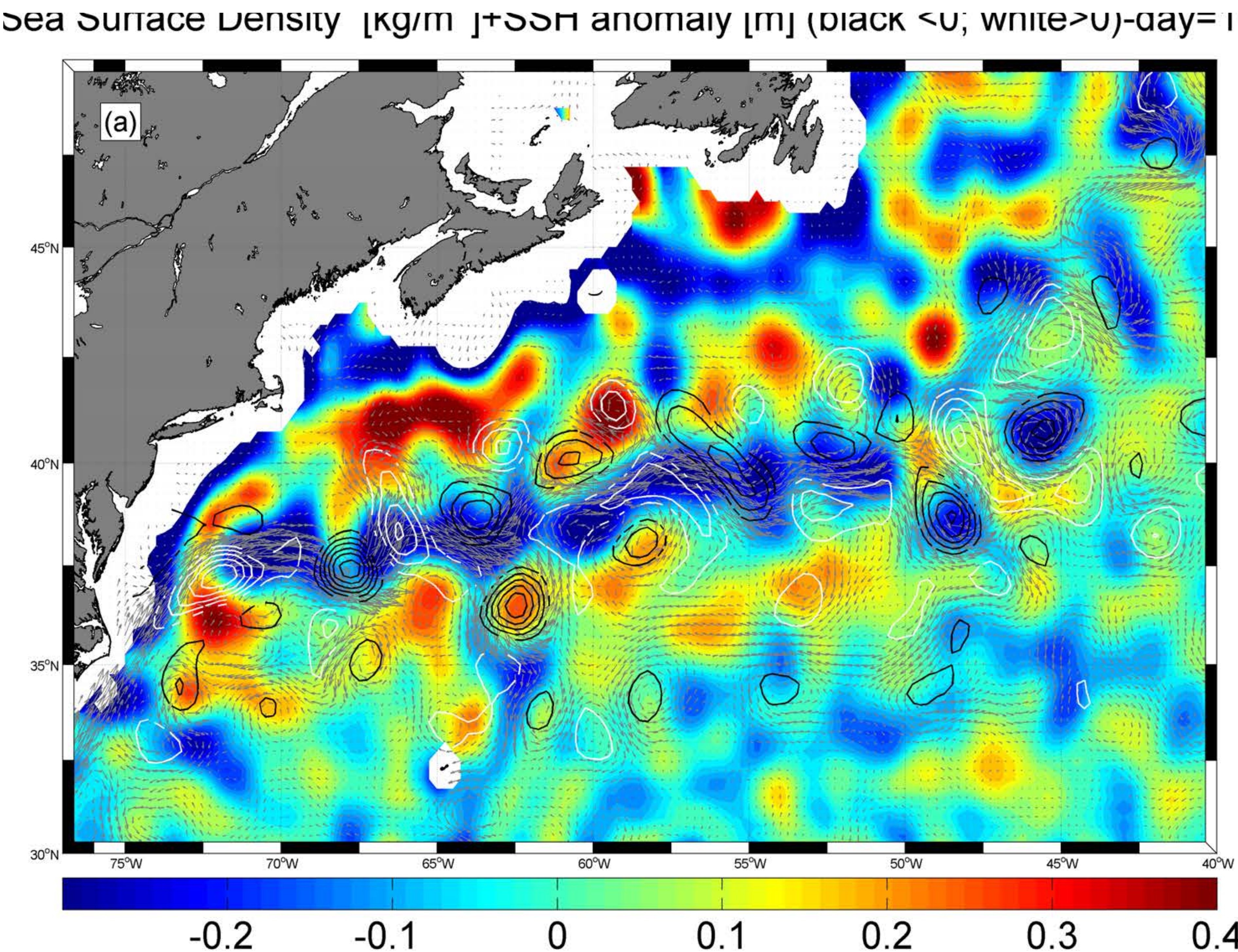
Monitoring Salt Exchanges in Strong water mass Boundary region with SMOS: Gulf Stream Example



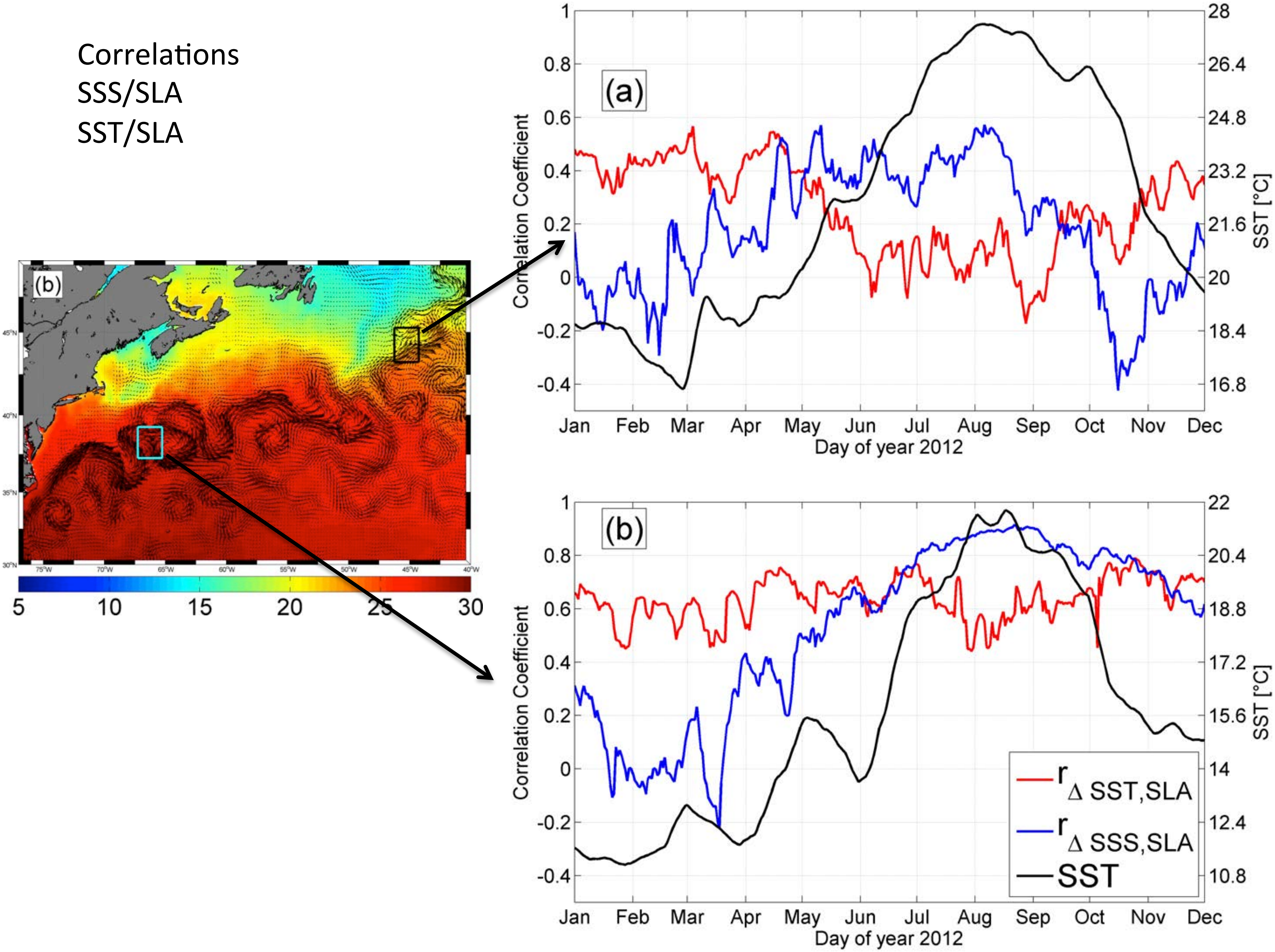


- SMOS reveals SSS structure of the Gulf Stream with an unprecedented Space and time resolution
- Cold/fresh Core rings are better captured by SSS observations than by SST during summer.
- Chl concentration in the separated Gulf Stream significantly depend on SSS
- Synergistics analysis SSS-SST-SSH-Color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

N. Reul et al. GRL 2014


Sea Surface Density [kg/m]+SSH anomaly [m] (black <0; white>0)-day=19
(a)
45°N
40°N
35°N
30°N
75°W
70°W
65°W
60°W
55°W
50°W
45°W
40°W
-0.2
-0.1
0
0.1
0.2
0.3
0.4

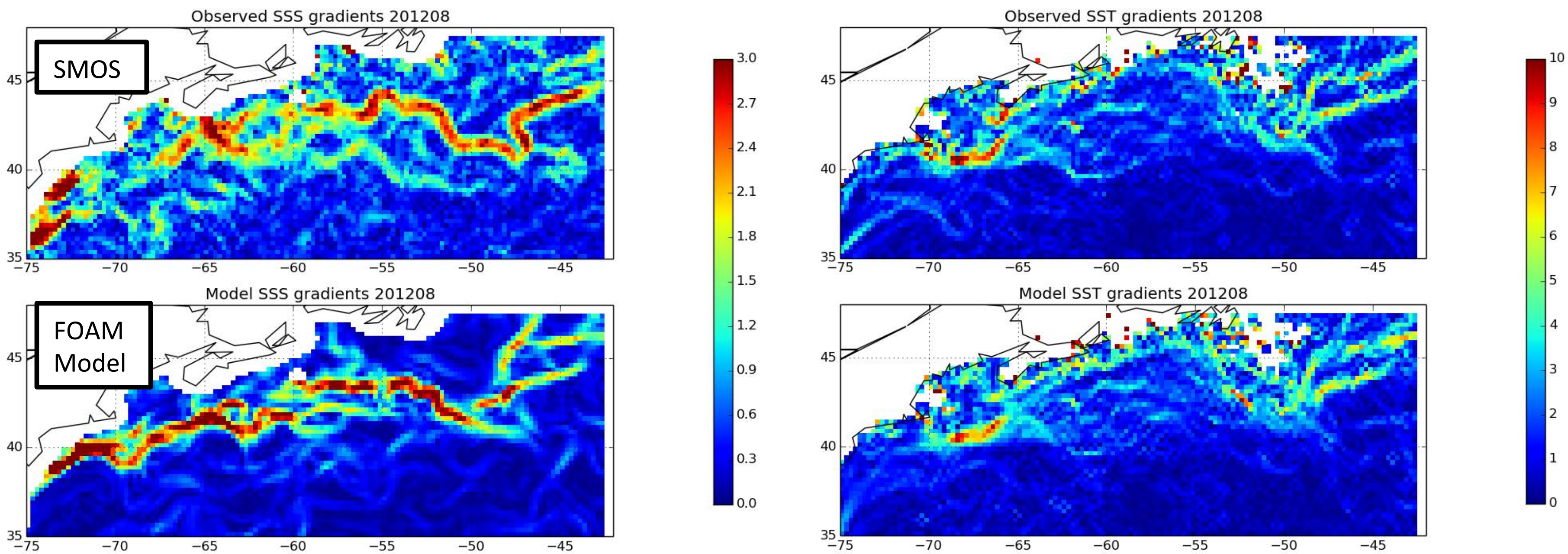
Correlations
SSS/SLA
SST/SLA



Monitoring Strong water mass Boundary region: Gulf Stream Example

SSS horizontal gradients

SST horizontal gradients

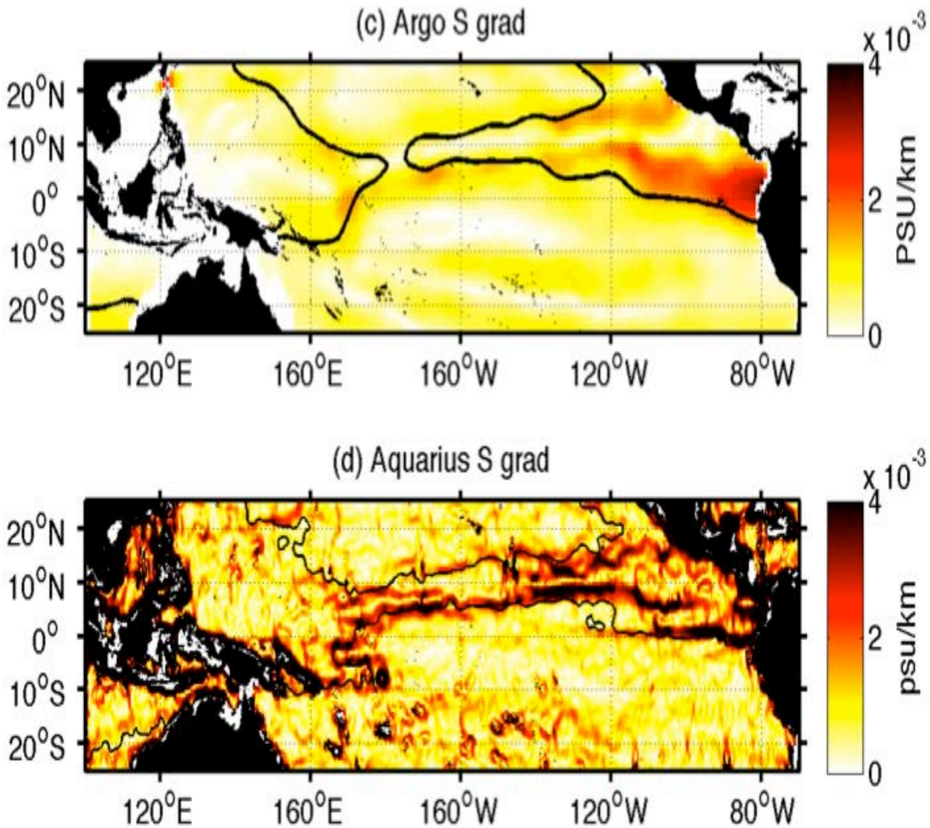


- SSS fronts agree well between model and SMOS observations
- However, SMOS data shows a frontal structure in the main part of the GS which the model doesn't represent. Who is right ?
- Surface warming has masked the underlying structures in SST in summer, SSS comes as a natural complement to SST & SSH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

M. Martin (UK Metoffice)

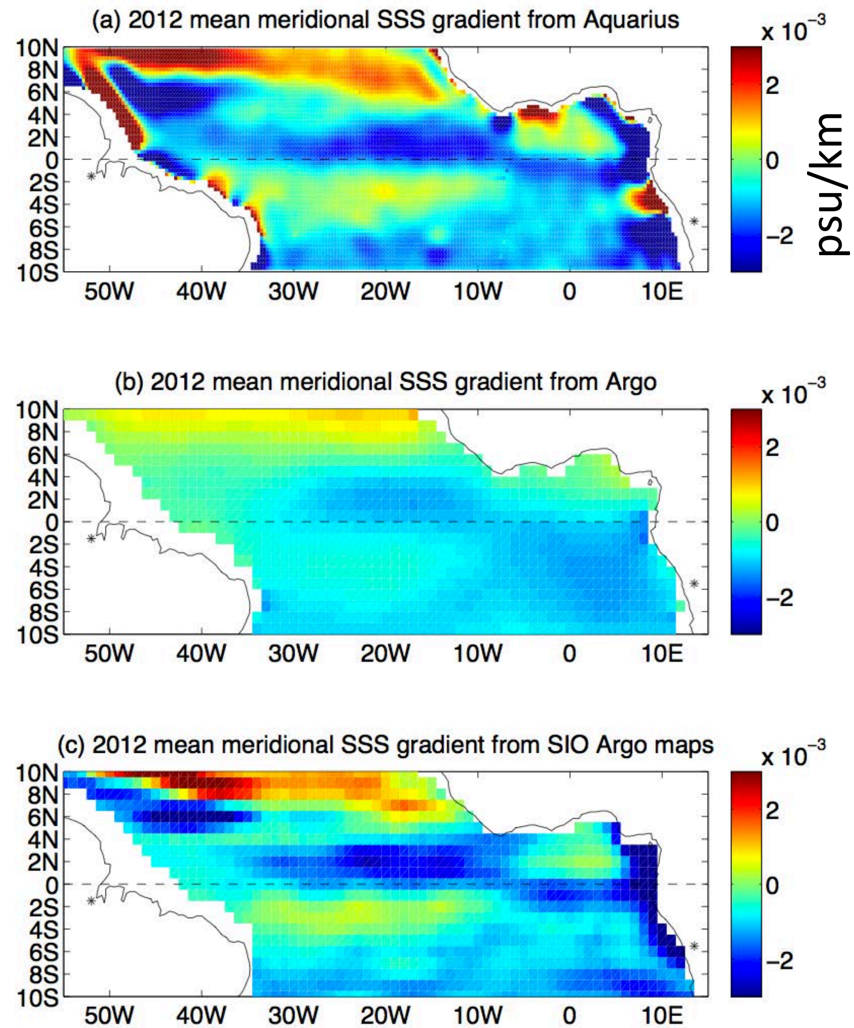
Aquarius resolves much sharper SSS gradients than Argo

Magnitude of SSS gradient
in the tropical Pacific
(Kao & Lagerloef 2014, JGR)

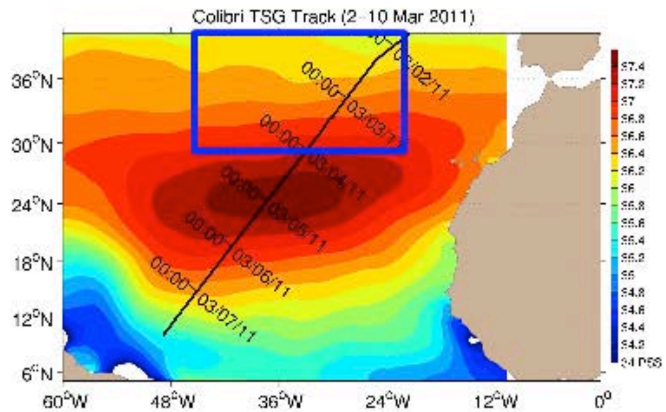


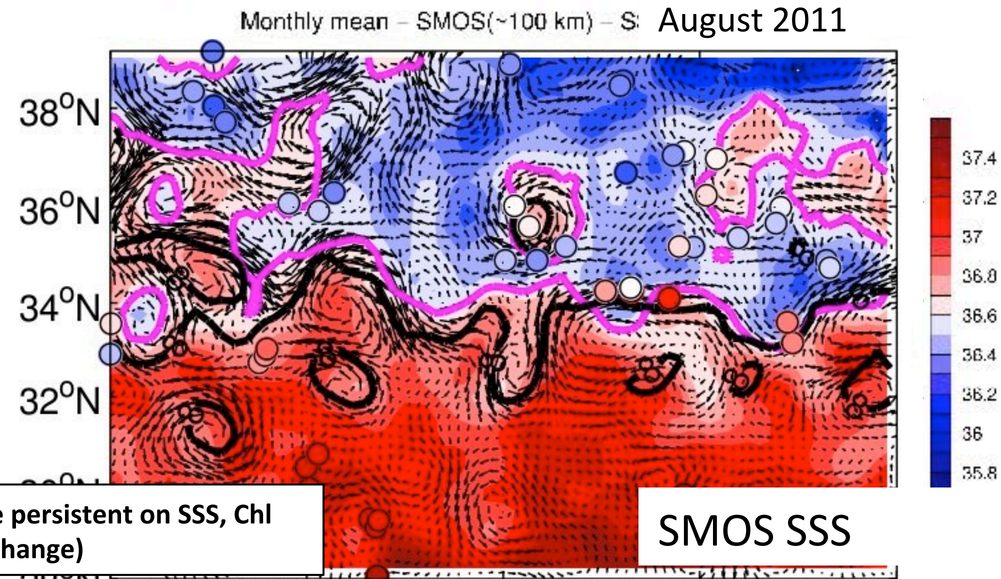
October 2012 monthly average
Dark contour is 34.6 isohaline

SSS gradient in the tropical Atlantic
(Lee et al. 2014, JGR)



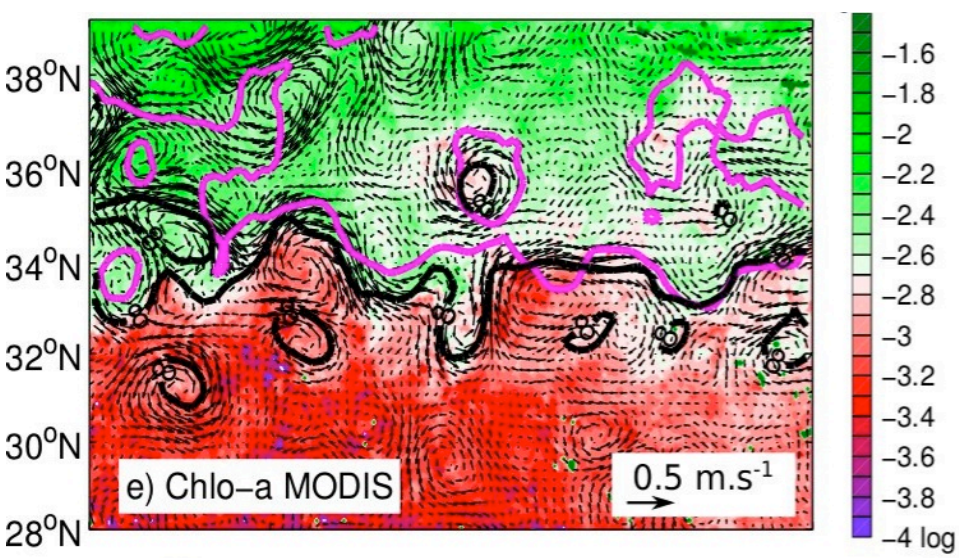
Case study : Azores Front/current

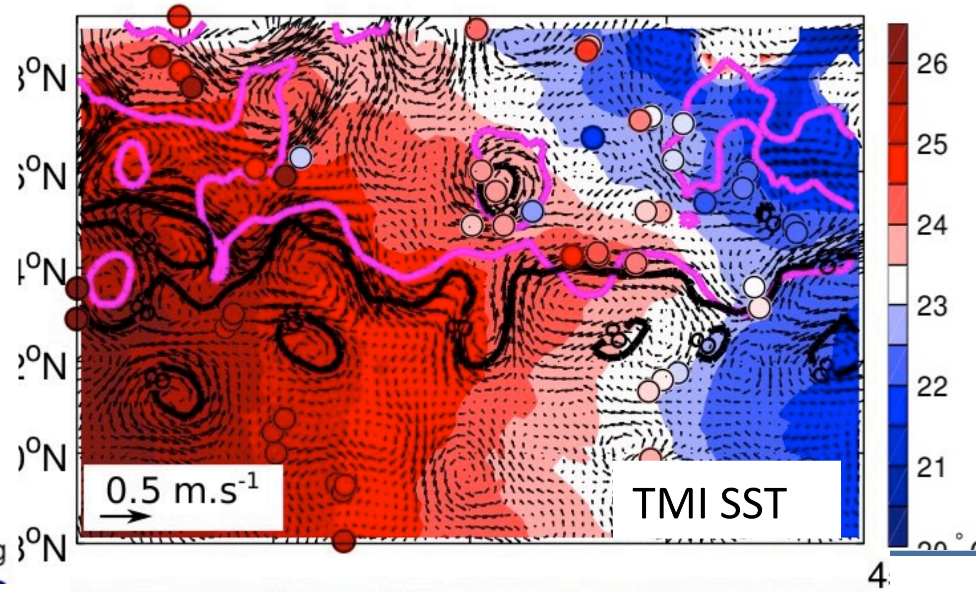




In summer, eddy signature persistent on SSS, Chl but not on SST (air-sea exchange)

MODIS Chl





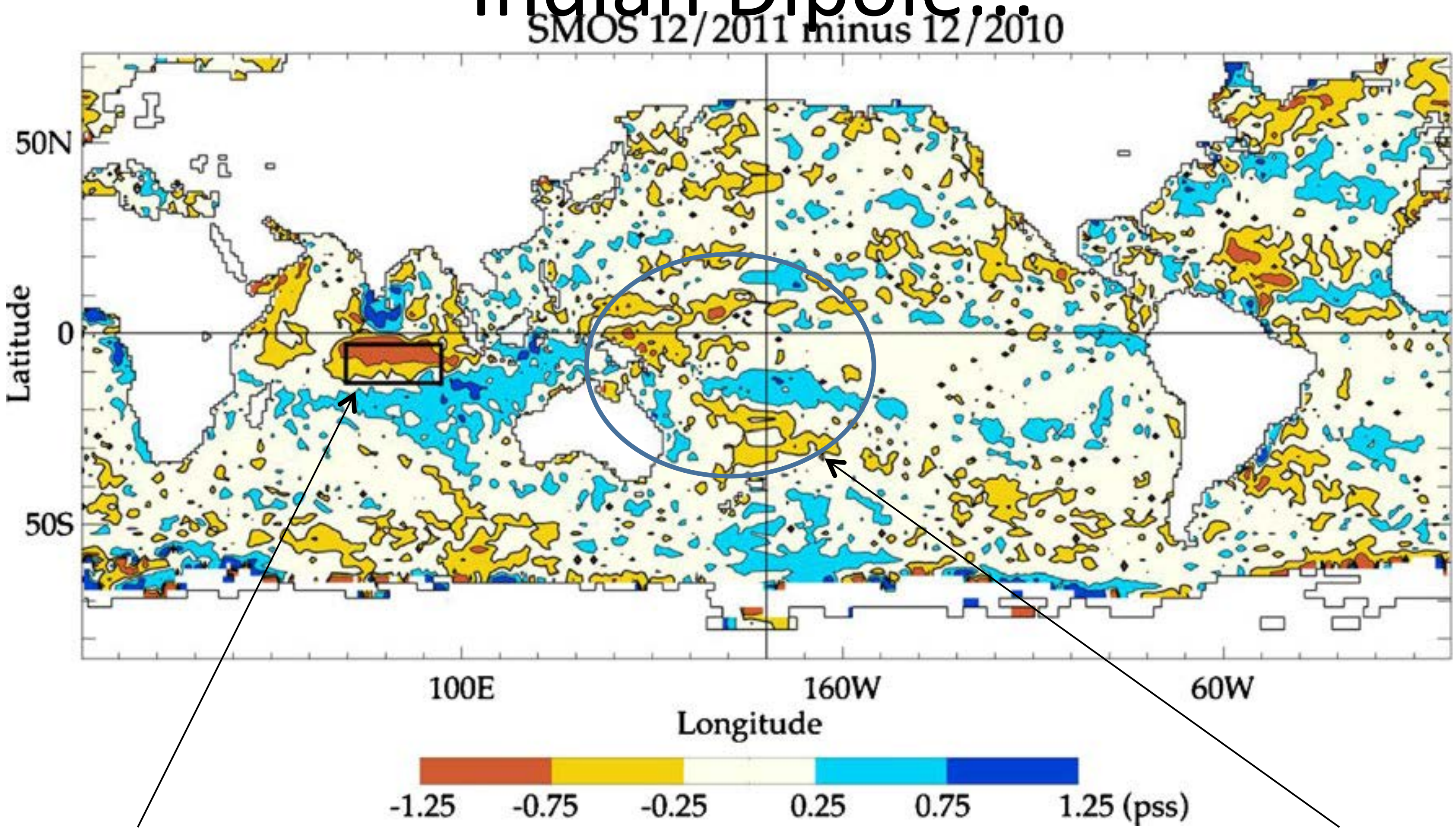
(Kolodziejczyk et al., JGR, 2014)

Isohaline 36.6

Vorticity 8 10^{-5} s $^{-1}$ (core of current)

Large Scale salinity Events & Climat indexes

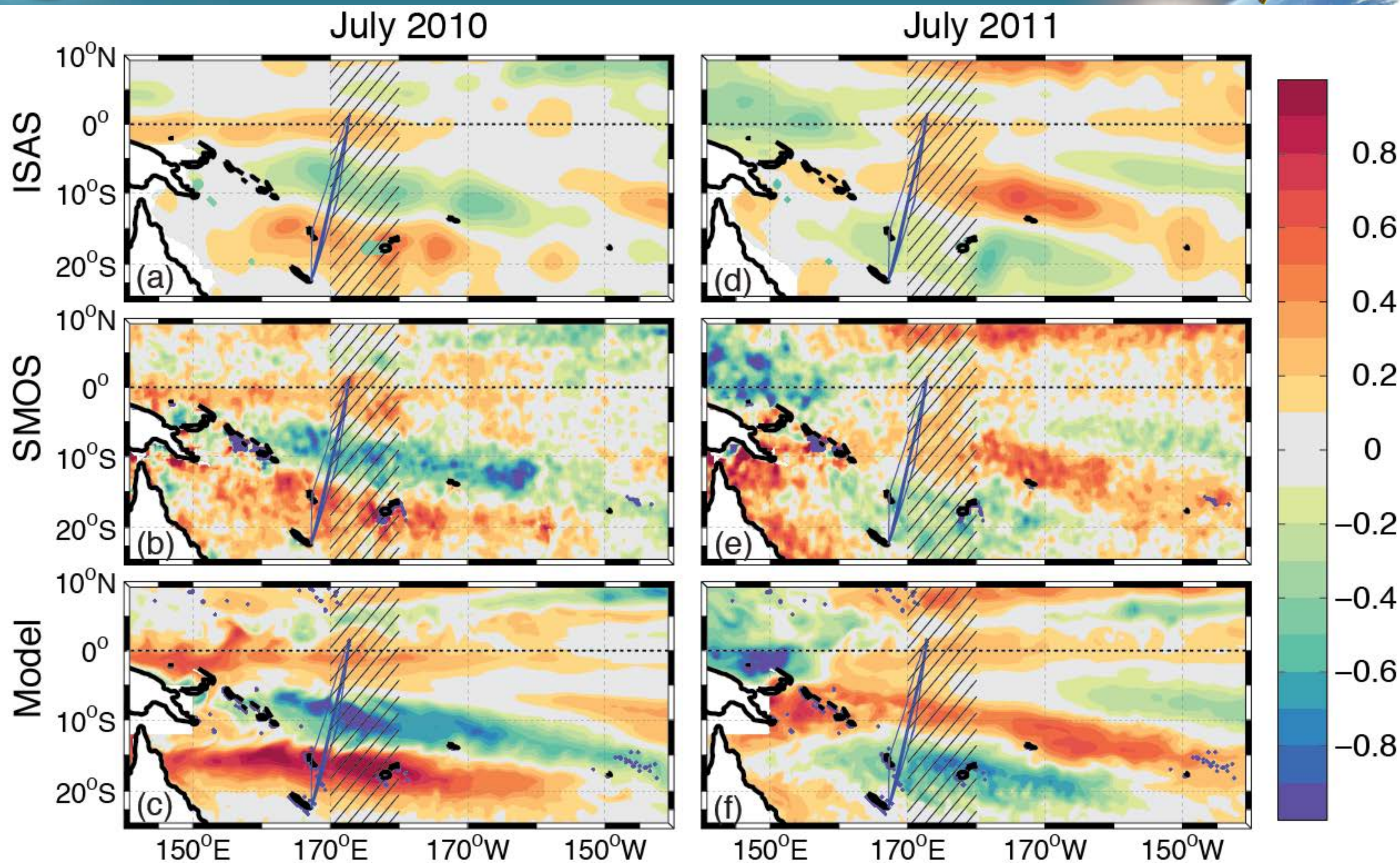
Satellite SSS reveals large scale anomalies related to ENSO, Ocean Indian Dipole…



Durand et al., Ocean Dynamics, 2013

Hasson et al, JGR-Ocean, 2014

The Western Pacific SSS Anomaly



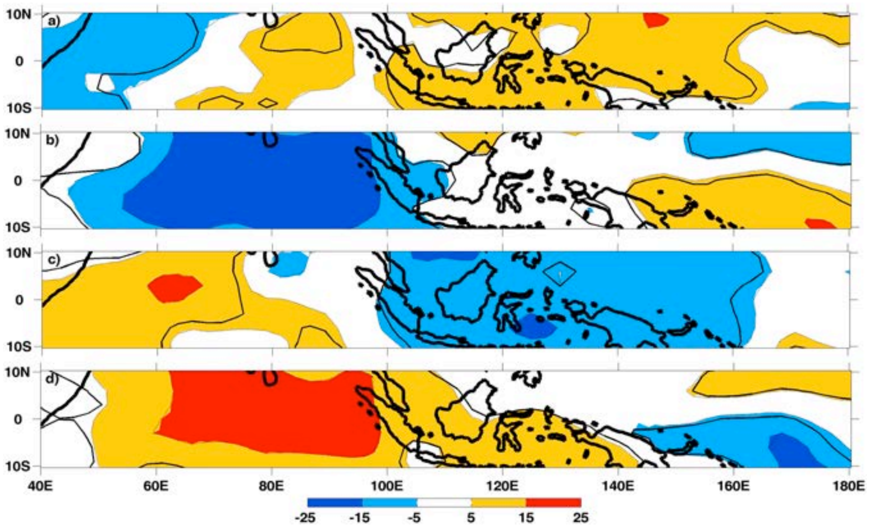
"Analyzing the 2010-2011 La Niña signature in the tropical Pacific sea surface salinity using in situ data, SMOS observations and a numerical simulation" by A. Hasson, T. Delcroix, J. Boutin, R. Dussin, and J. Ballabrera-Poy. In revision , JGR- SMOS/ Aquarius Special Issue

Aquarius reveals MJO-related SSS signature & importance of SSS

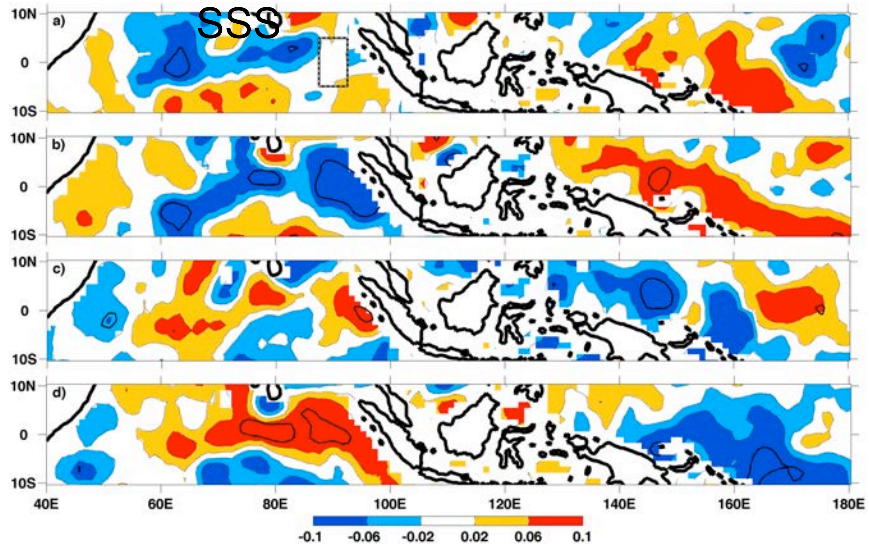
Grunseich, Subrahmanyam, & Wang (2013, GRL)

Guan, Lee, Halkides, & Waliser (2014, GRL)

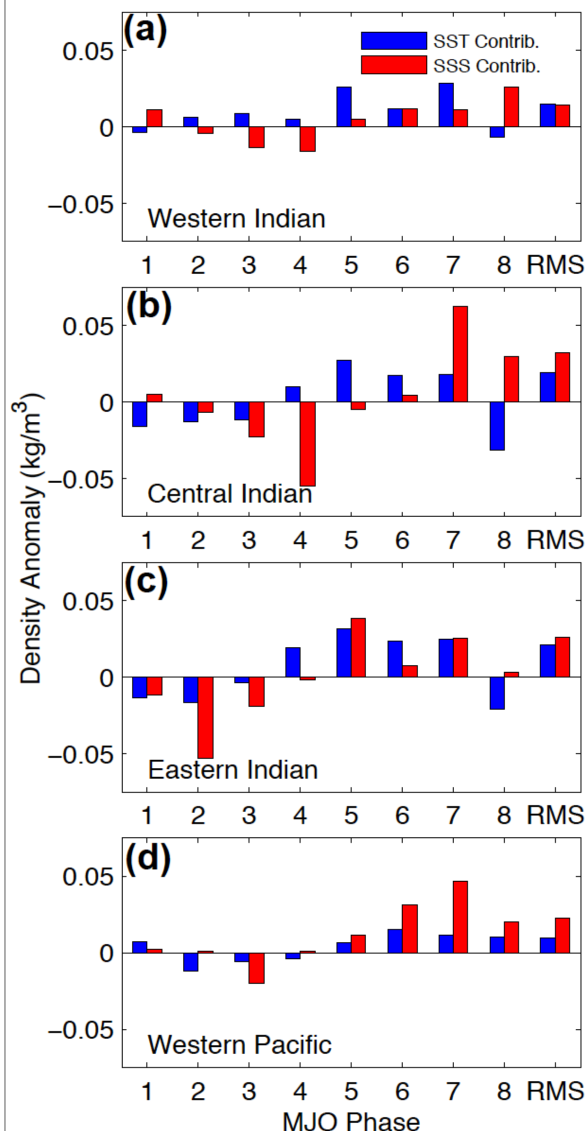
MJO composite pattern of outgoing longwave radiation



MJO composite pattern of SSS



Density

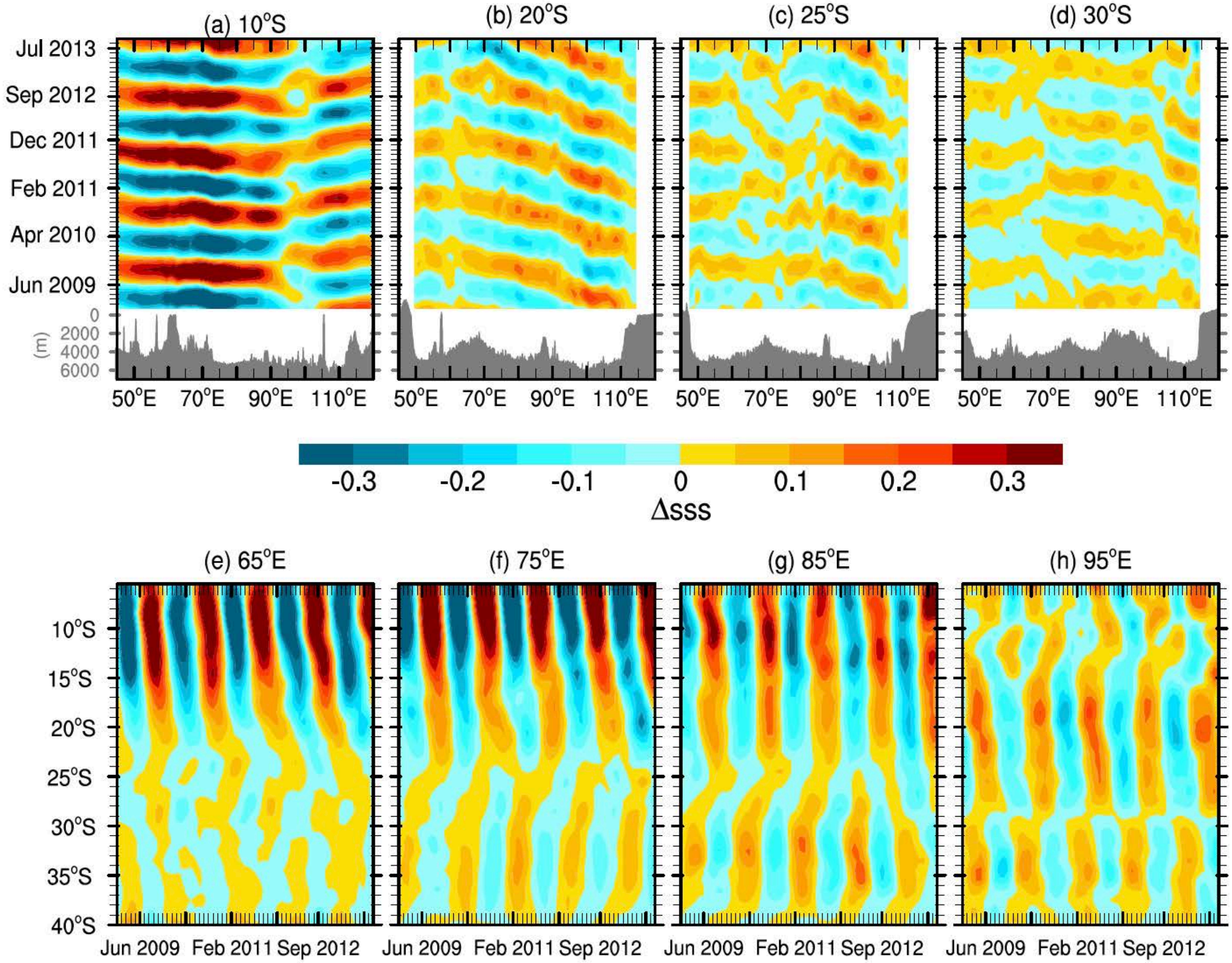


Based on 8-phase WH Index

Aquarius SSS reveal annual-period Rossby Waves in the S. Indian Ocean

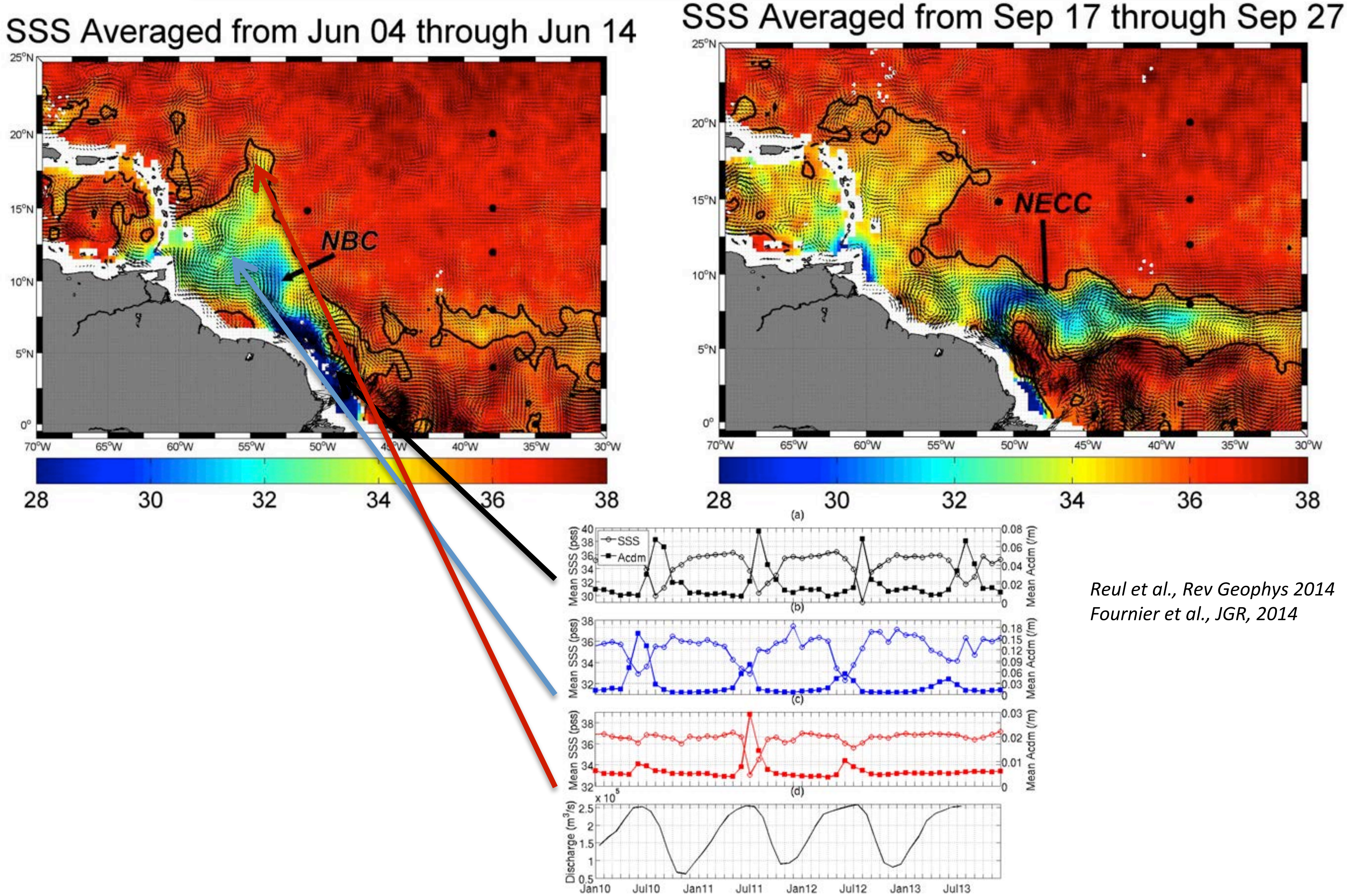
Menezes, Vianna, and Phillipes (2014, JGR)

Spatial amplitude of the 1st EOF mode of surface currents



Water cycle: rain & River Runoffs

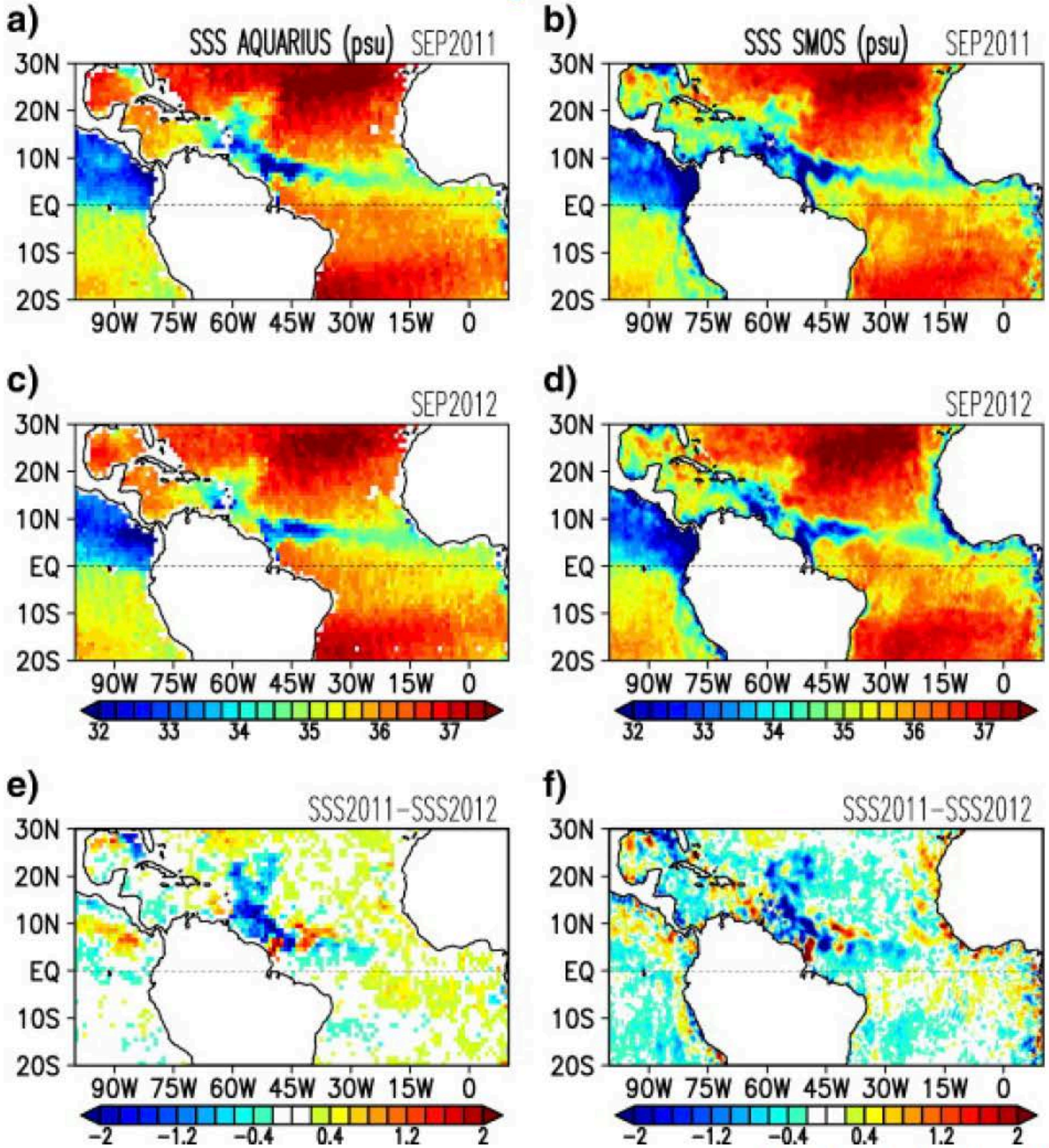
Monitoring Large Tropical River Discharges into the Ocean



Reul et al., Rev Geophys 2014
Fournier et al., JGR, 2014

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

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

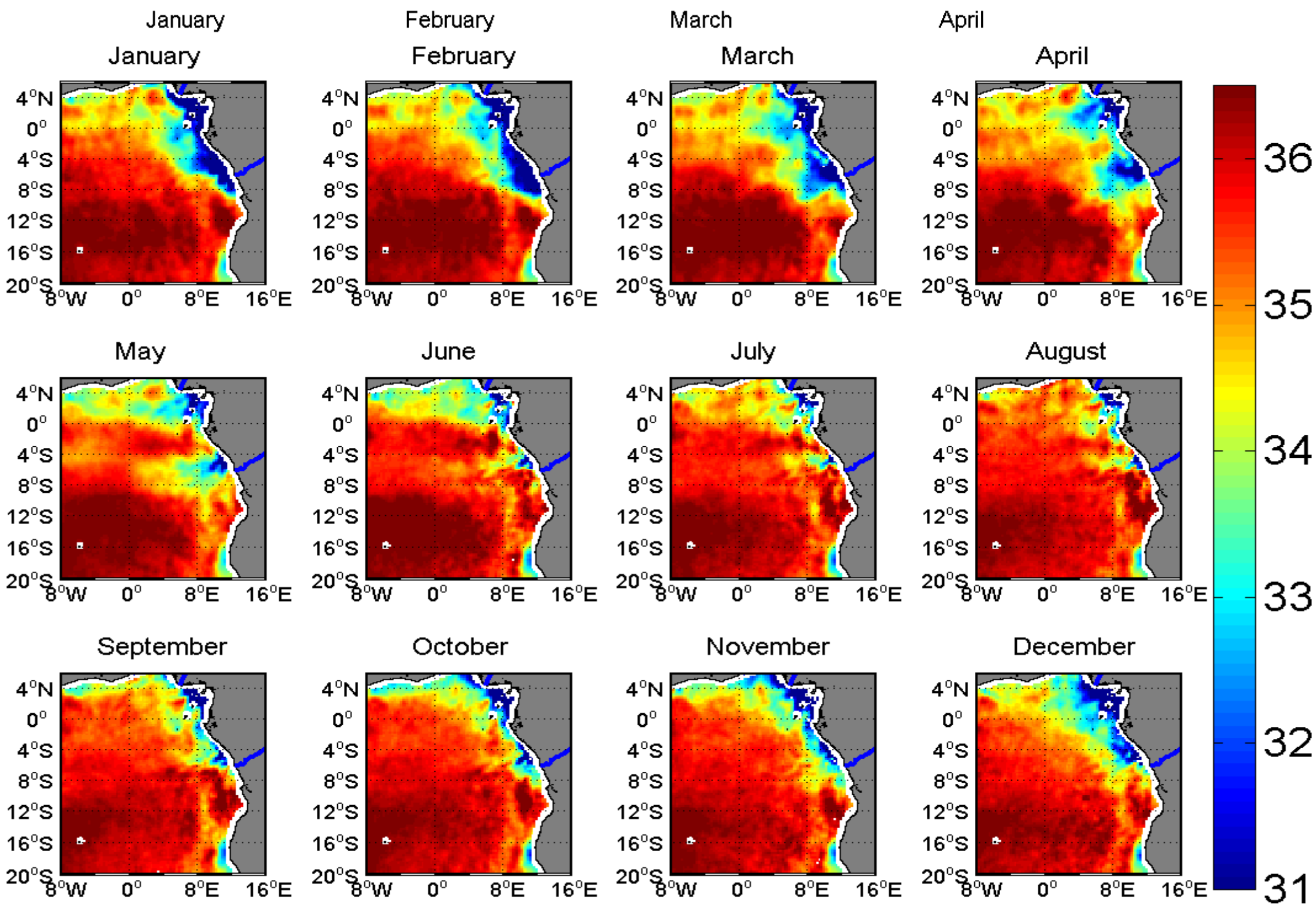


The plume was 1 psu saltier in early fall 2012 than in the previous fall (despite a stronger Amazon discharge in 2012) - The most likely causes of the 2012 salinification are **a relative deficit of rainfall** over the inflow to the plume region well southeast of the plume in spring and a weaker North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

Grodsky et al. RSE 2014

Boutin et al., The Climate Symposium 2014

Monitoring the Congo river Plume Mean Seasonal Cycle

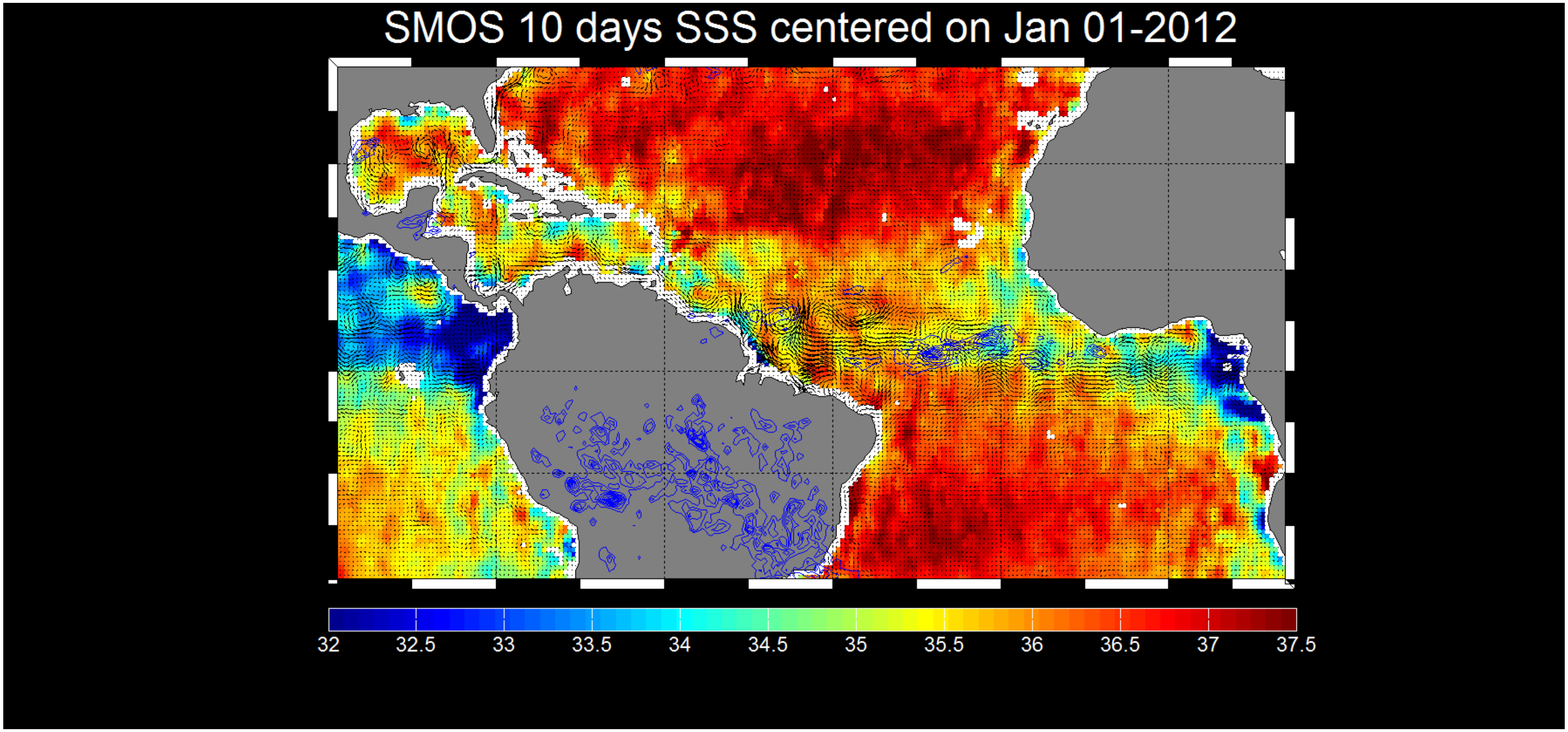


Reul et al., Rev Geophys 2014

SMOS data collected during the period 2010-2012

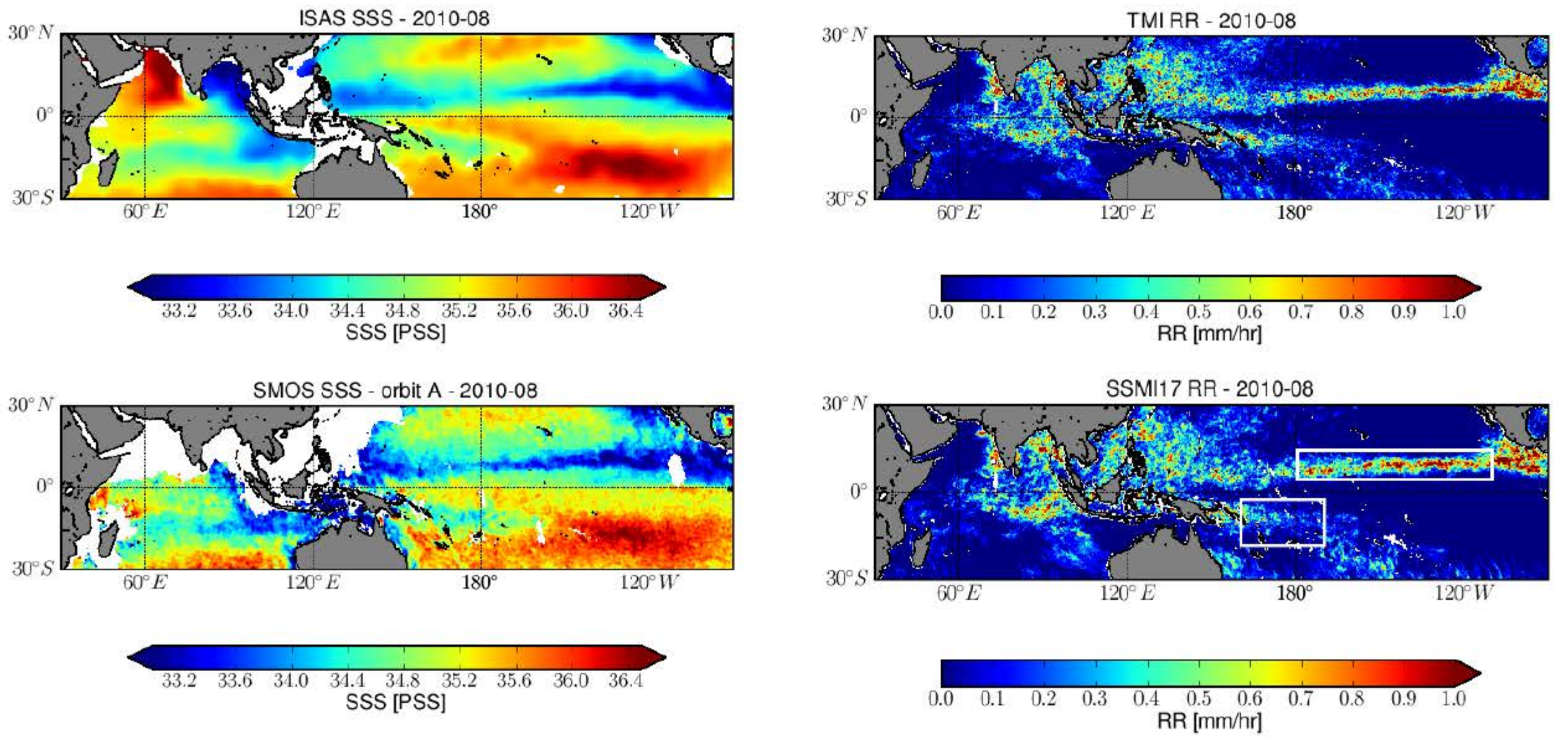
SMOS data now allow the regular monitoring of the seasonal & interannual variability in the discharge & advection of freshwater river plumes into the ocean

Precipitation Signatures in Satellite SSS



Impact of Rain on SMOS SSS

Boutin et al. (2014), Sea surface salinity under rain cells: SMOS satellite and in situ drifters observations, JGR Oceans



Courtesy J. Boutin (LOCEAN)

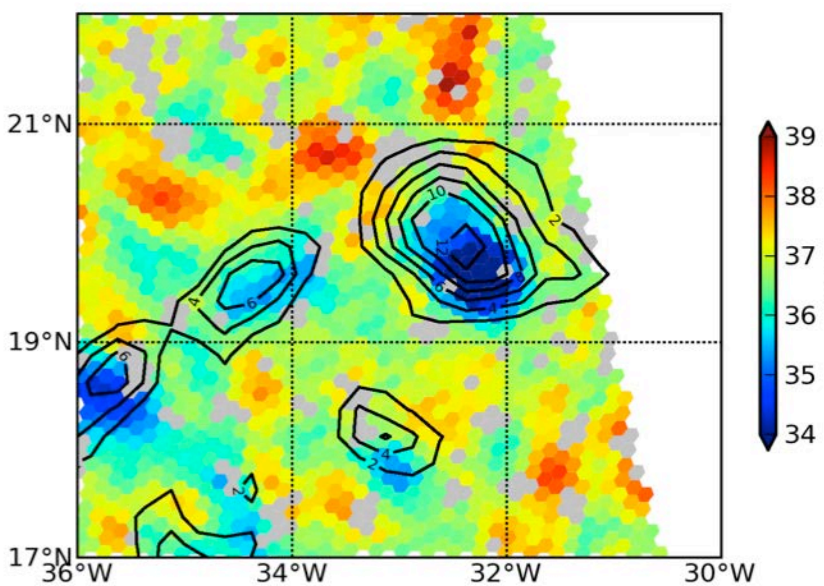
Through its links with Precipitations, SMOS salinity data provide a new tool to **better characterize the increase in the marine tropical hydrological cycle strength**

The impact of rain on SMOS SSS
1-SMOS SSS spatial variations

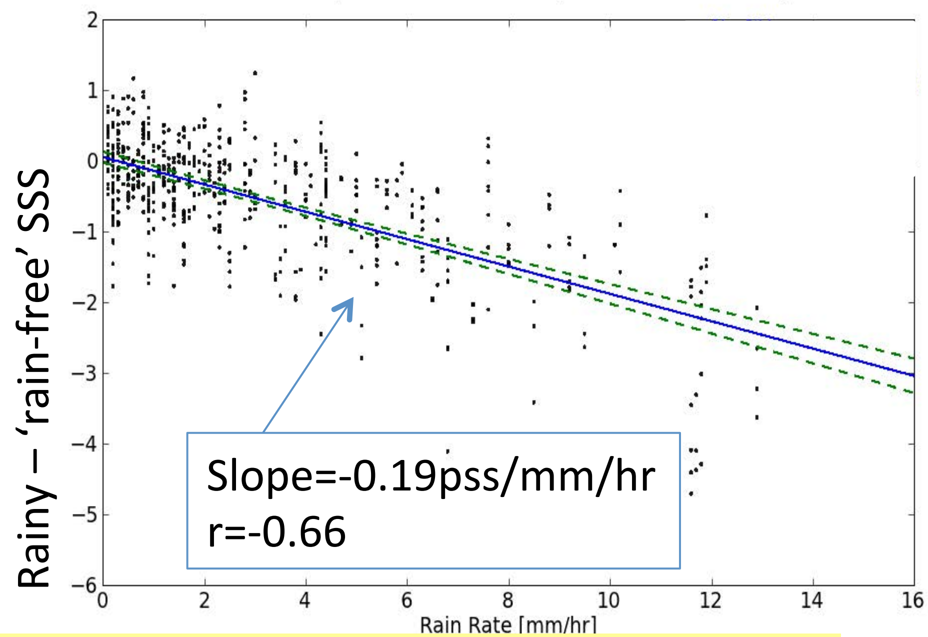
Rainy SSS – 'Rain-free' SSS ~ -0.19 RR

SMOS SSS (color) &
SSM/I rain rate (isolines)

Train-Tsmos =0.5h



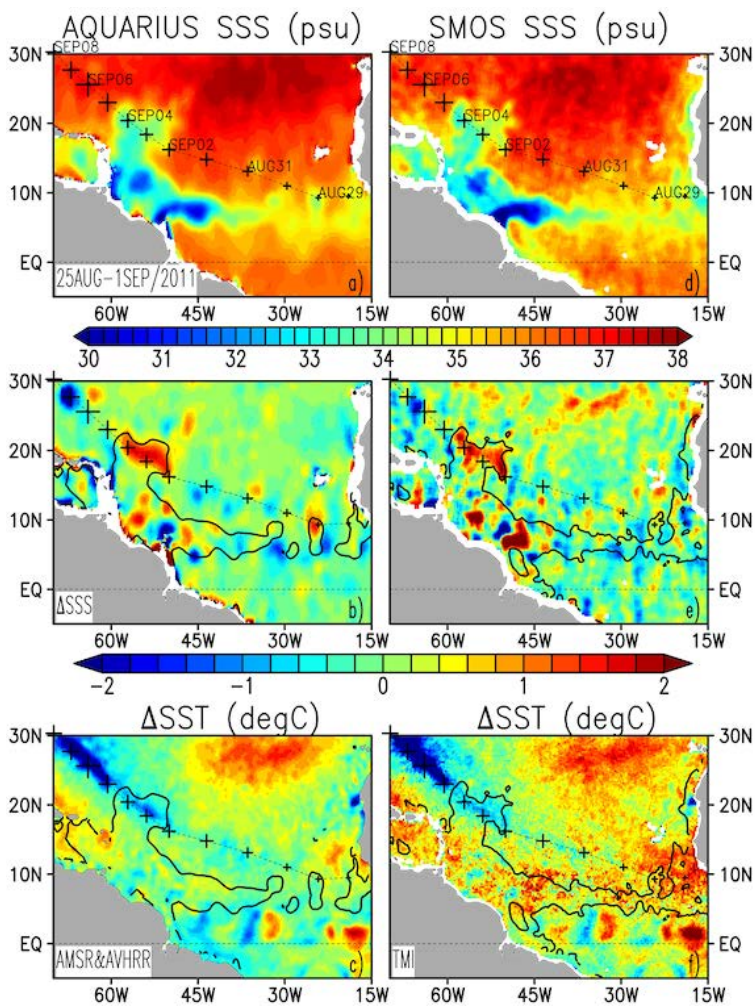
'Rain-free' SSS: average of SSS colocated with RR=0 in a radius of 150km around rainy pixels



Satellite radiometer records salinity in the first top cm: an information not accessible by ARGO measurement => surface salinity stratification and rain events

Satellite SSS and Air-Sea interactions

Haline wake of Hurricanes in the Amazon plume & Impact on Intensification *Grodsky et al. (2012, GRL); Reul et al. (2014, JGR)*

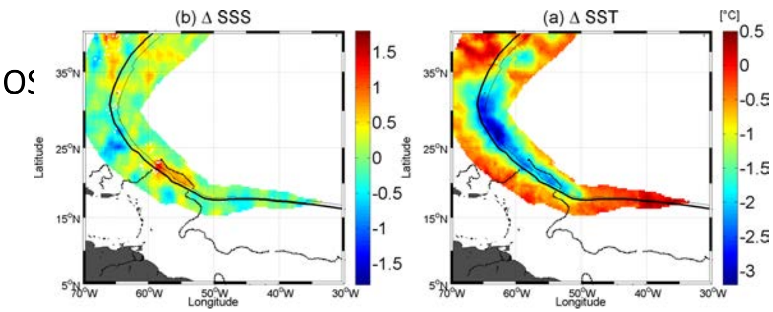


AQUARIUS and SMOS SSS before hurricane Katia (2011). Crosses are the hurricane daily position.

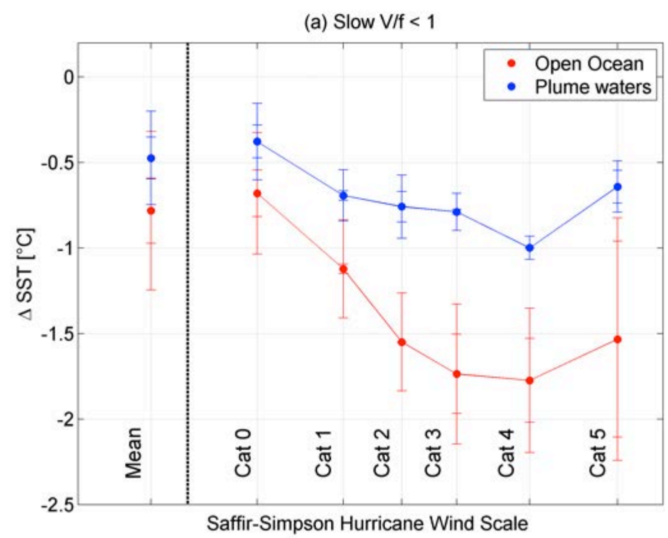
SSS differences after minus before the hurricane passage. 35 psu contour before the passage of Katia is overlain.

SST differences after minus before the hurricane passage.

Grodsky et al., GRL, 2012



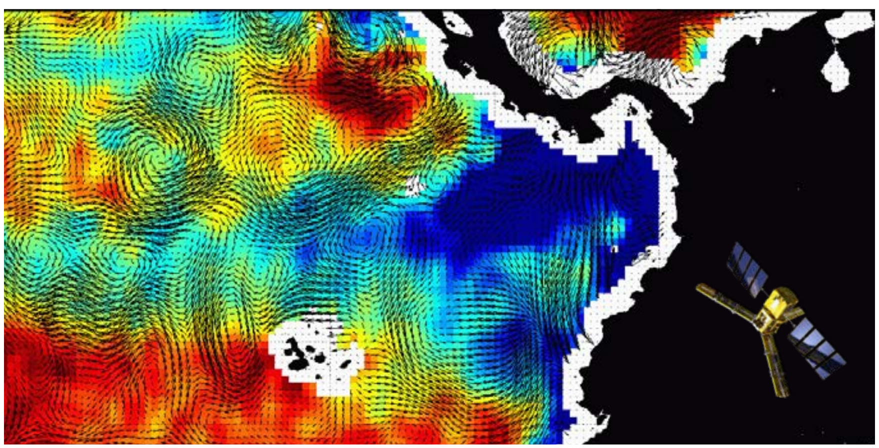
SSS & SST differences after minus before hurricane Igor passage (2010).

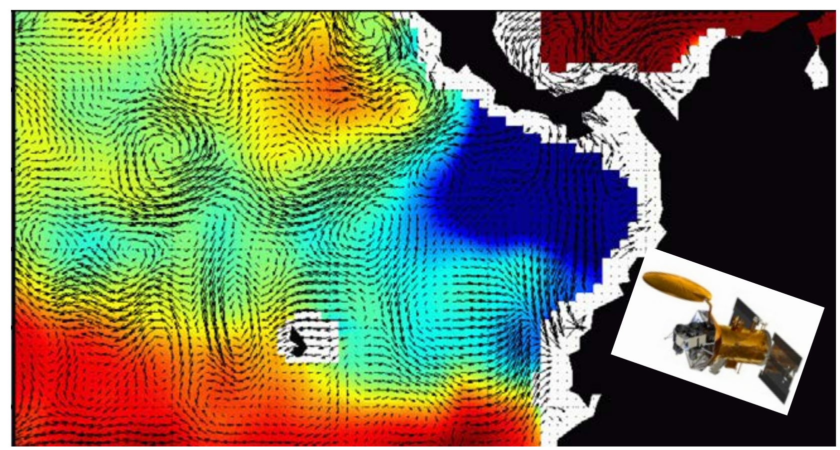


Reduced SST cooling over halocline driven stratification

Far Eastern Pacific Fresh Pool surface salinity variability observed by SMOS and Aquarius sensors over the period 2010-2012

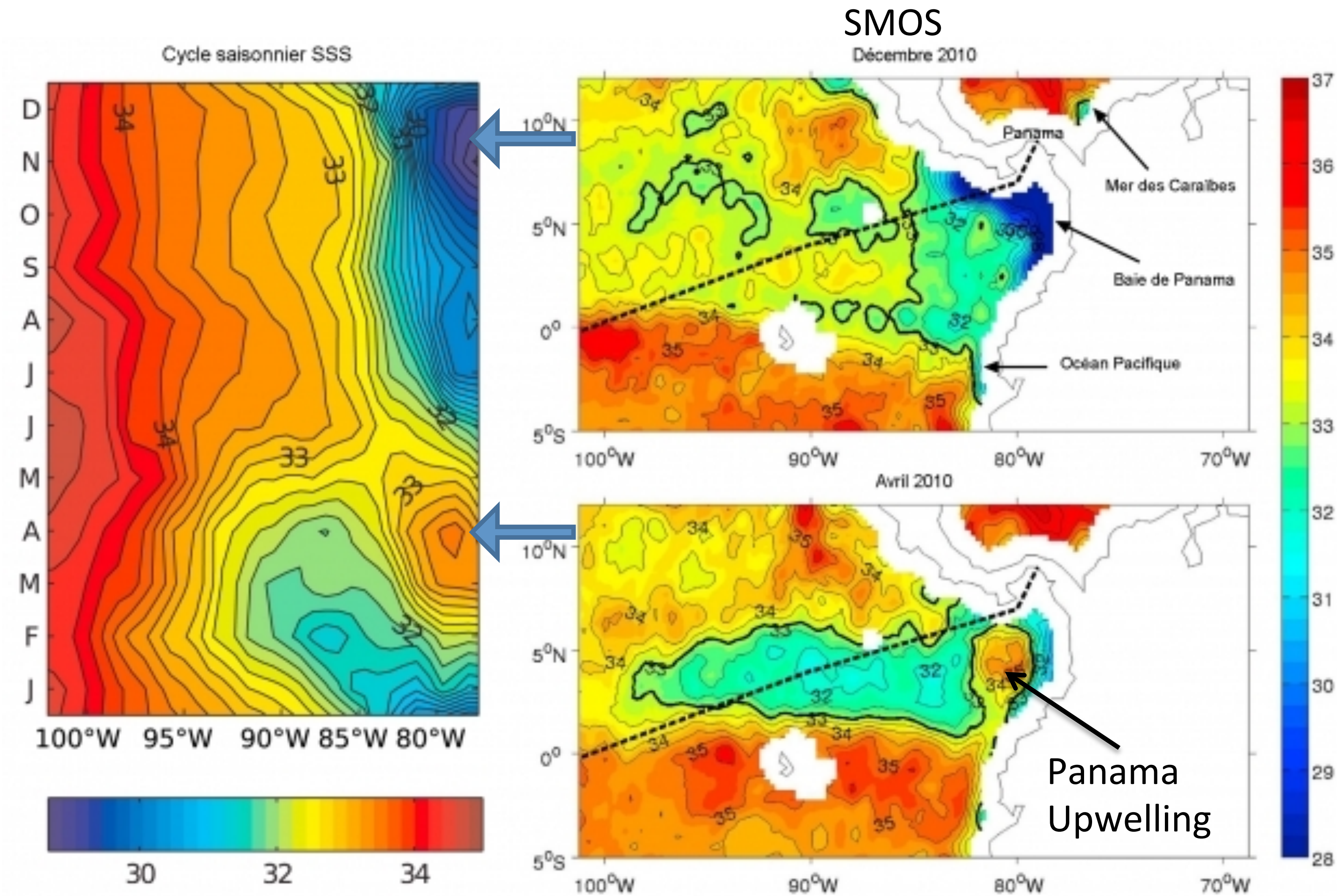
Nicolas Reul[1], *Gael Alory*[2], *Christophe Maes*[3], *Serena Illig*[3] *and Bertrand Chapron*[1]
[1]IFREMER,[2]LEGOS/CNAP,[3]LEGOS/IRD, FRANCE
Gary Lagerloef[4] *and Hsun-Ying Kao*[4]
Earth & Space Research, USA





EGU-2013, Session OS4.9

SMOS detection of the Upwelling in April 2010

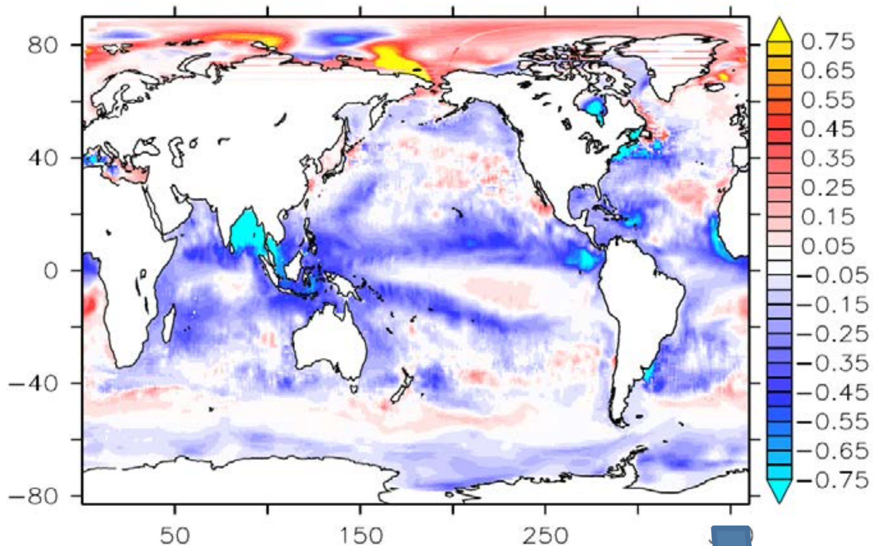


Alory et al, JGR, 2012

Satellite SSS to improve Ocean Models

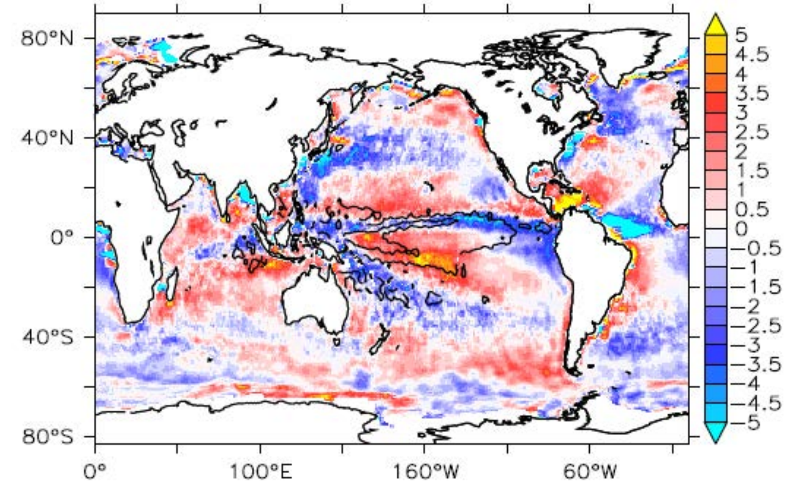
Testing the impact of assimilating satellite SSS

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



PSU

Change in E-P (mm/
d)



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

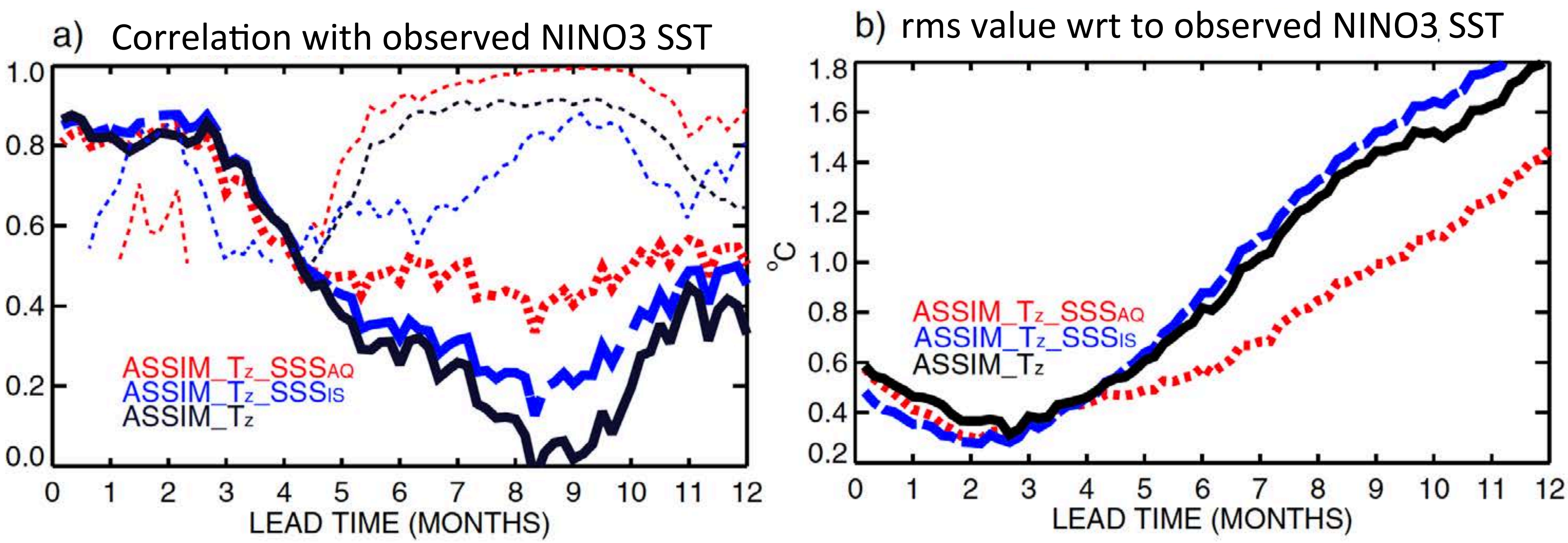
Major impact in high precipitation & river runoff zones

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

Köhl et al., (2014) **Impact of assimilating surface salinity from SMOS on ocean circulation estimates, JGR. Oceans**

Assimilation of Aquarius SSS improved coupled model hindcasts of NINO3 SST for lead time > 5 months

Hackert, Busalacchi, and Ballabrera-Poy (2014, JGR)



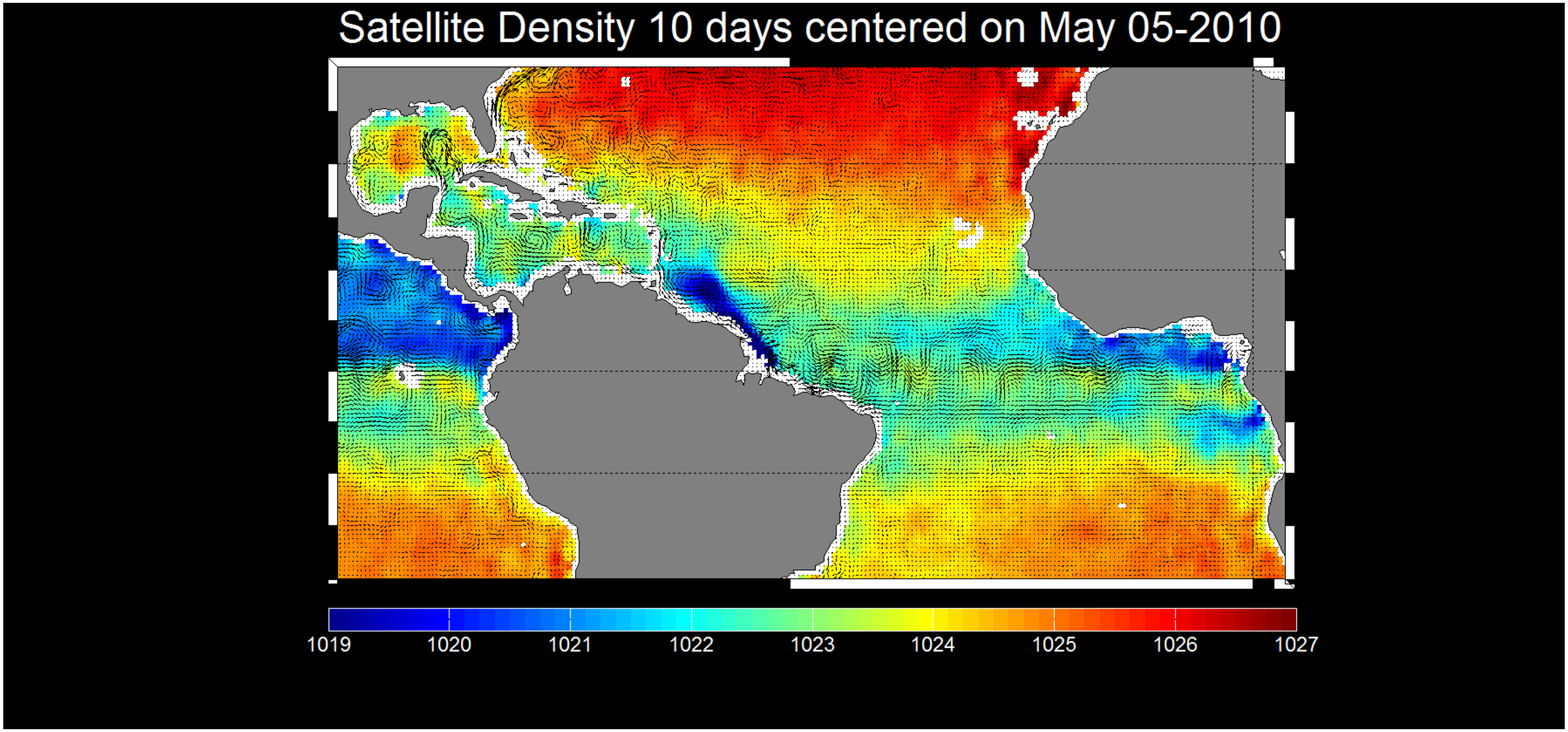
$ASSIM\_T_Z$: baseline experiment, assimilation of all subsurface temperature data

$ASSIM\_T_Z\_SSS_{IS}$: assimilation of all subsurface temperature and in-situ salinity data

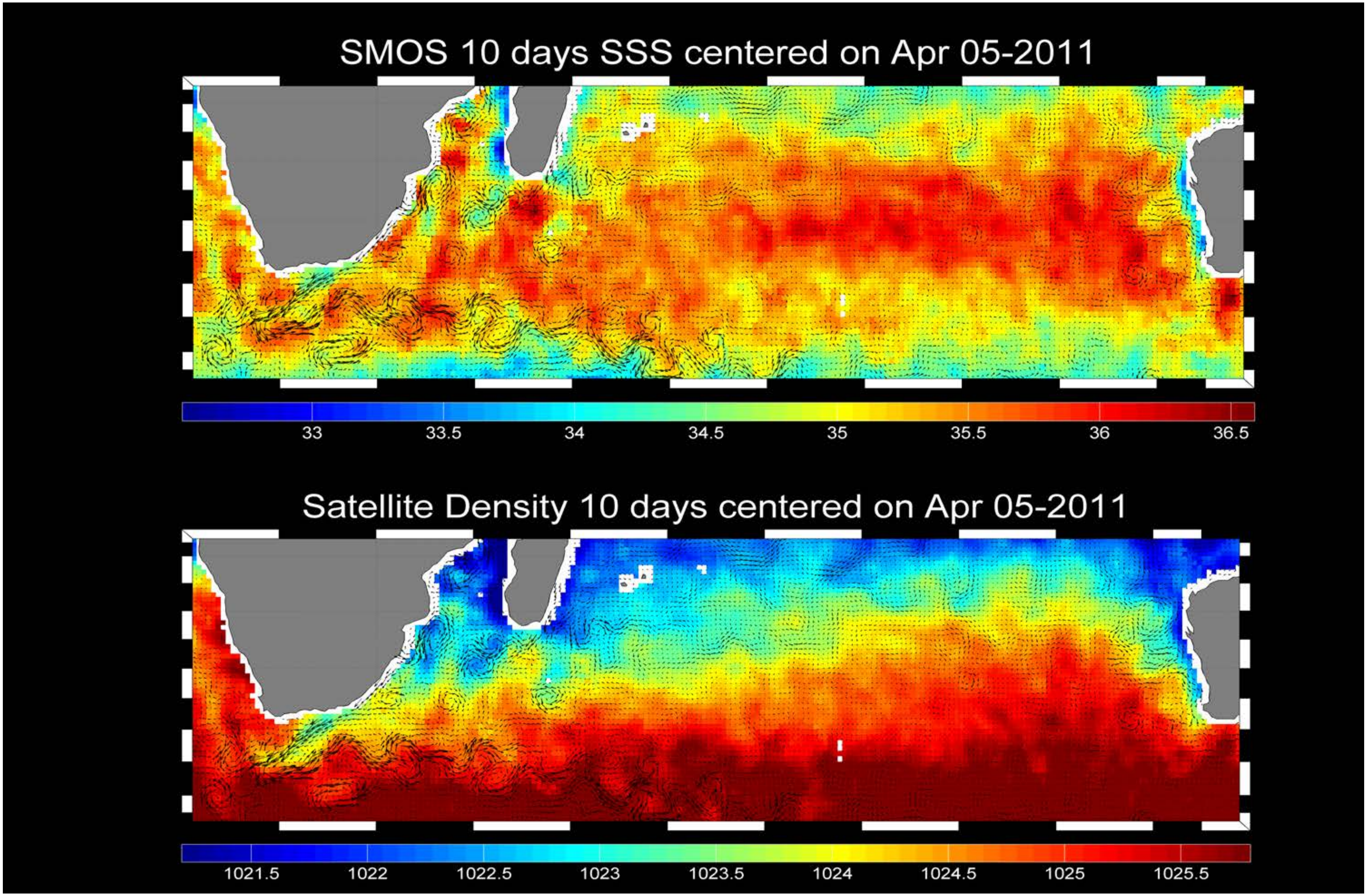
$ASSIM\_T_Z\_SSS_{AQ}$: assimilation of all subsurface temperature and Aquarius SSS data

The latter has higher correlation & lower rms values with respect to observed NINO3 SST for lead times > 5 months. (Better sampling of Eq. Kelvin wave impact on SSS by Aquarius)

Mapping and monitoring Surface Density variability from Satellite SSS & SST



Next Challenges: reaching an accurate SSS from Space in
Colder and high Latitude oceans



Summary

- SMOS and Aquarius have brought significant new understanding to intraseasonal variability in the ocean associated with mesoscale eddies, TIWs and MJO that are important to ocean dynamics, climate variability, and biogeochemistry.
- Resolving these features (esp. TIWs) went beyond the original expectation of science return (seasonal-interannual time scales).
- Demonstrates complementarity with other observing systems (e.g., SST & SSH do not show TIW propagation as well at the equator; Argo floats do not resolve TIWs, SSS & SSH better correlated in summer than SST & SSH in the Gulf Stream).
- Demonstrate the ability to monitor the path of large tropical river waters

  In the ocean
- 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)

SMOS S-MODE

SMOS-Mission Oceanographic Data Exploitation

SMOS-MODE

www.smos-mode.eu
info@smos-mode.eu

SMOS-MODE supports the **network** of SMOS ocean-related R&D

Last meeting during 2nd SMOS Science Conference (May 2015)

SMOS-MODE

(SMOS-Mission Oceanographic Data Exploitation)

www.smos-mode.eu
info@smos-mode.eu

- SMOS-MODE supports the **network** of SMOS ocean-related R&D
  - Meetings
  - Workshops
  - Training school
  - Short Term Scientific Missions
- **Overall Aim**:
  - To coordinate pan-European teams to define common protocols to produce **high-level salinity maps and related products**, and broaden expertise in their use for **operational applications**.
  - To **bridge** remote sensing and applications communities
- 21 countries represented. **Co-chairs**:
  - Antonio Turiel, SMOS Barcelona Expert Centre (SMOS-BEC), Barcelona, Spain
  - Nicolas Reul, IFREMER, Brest, France
- Last meeting during 2nd SMOS Science Conference