L-band Satellite Salinity for Ocean/Climate Research and Synergy With Other Measurements

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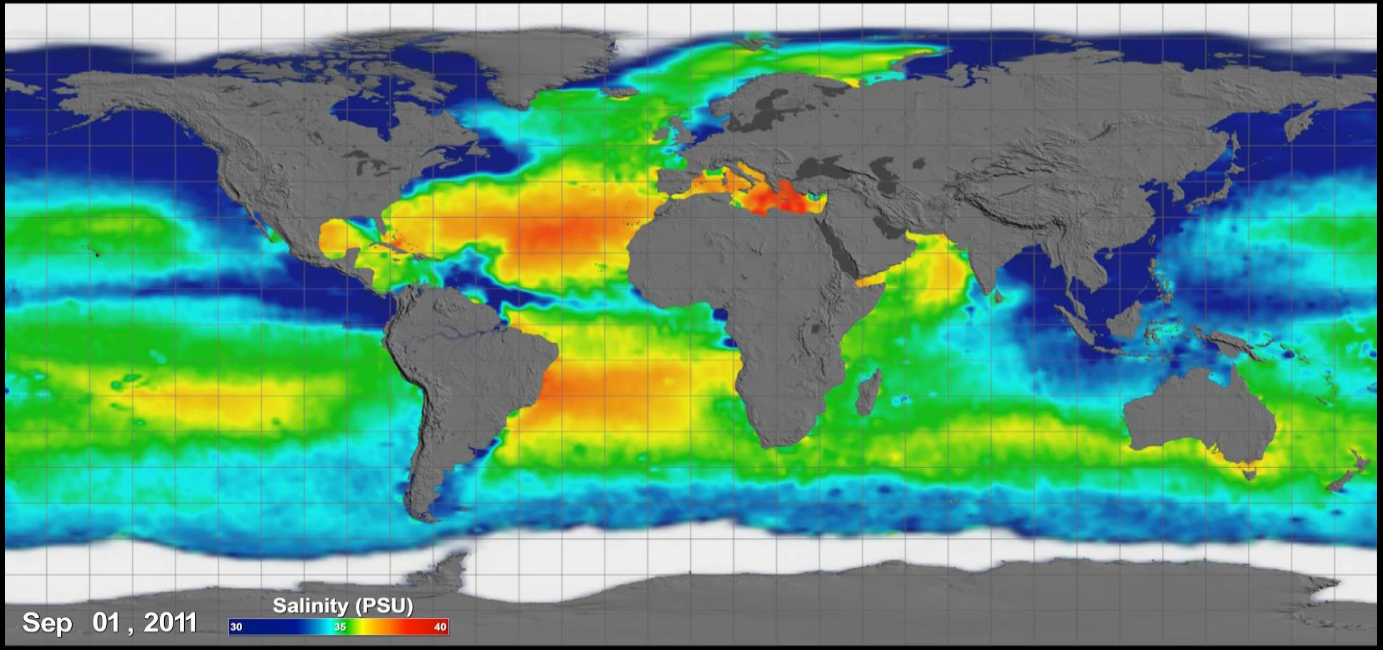
with contributions from the Aquarius, SMOS, & SMAP teams

Main Mission Objectives:
SMOS: SM & SSS
Aquarius: SSS
SMAP: SM

The three L-band (~1.4 GHz) satellite missions that have pioneered SSS measurement from space

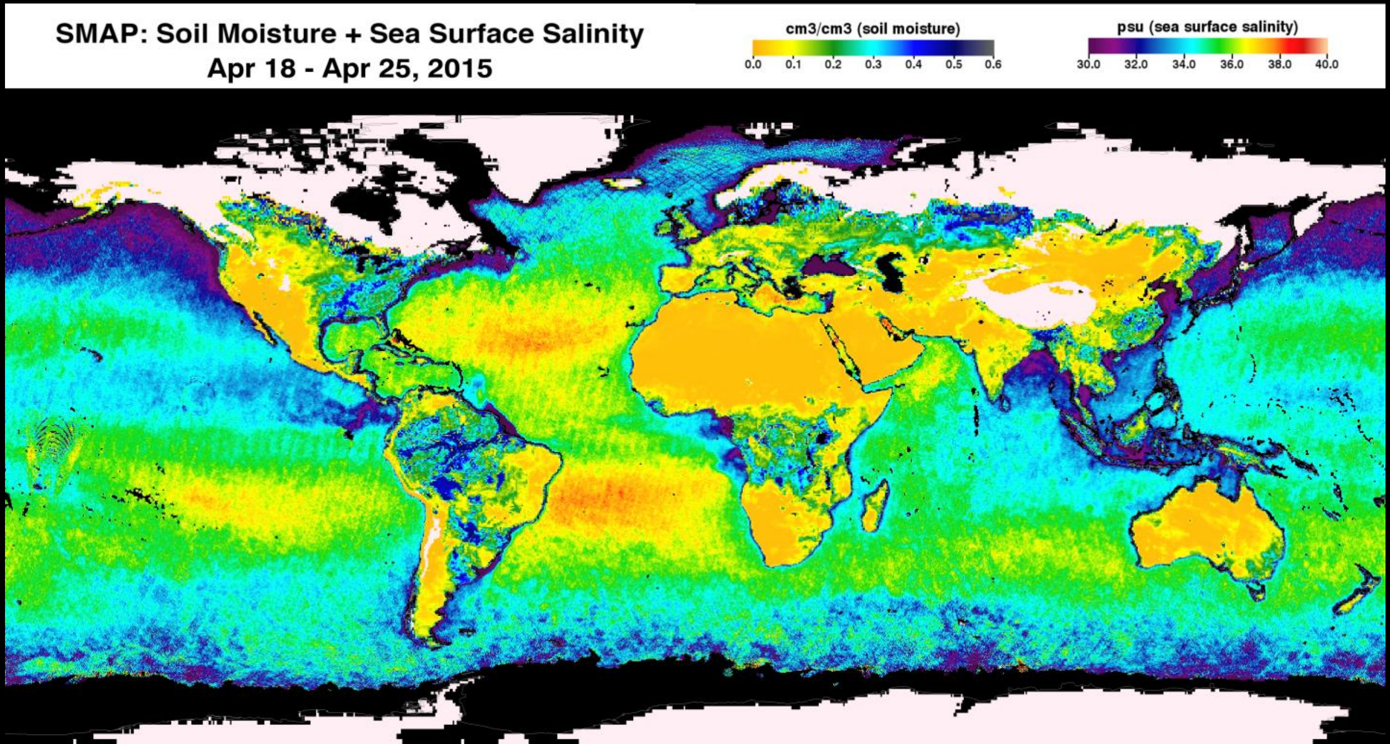
Aquarius SSS (V4.0) 09/2011-05/2015

~100 km resolution



SMAP SM & SSS 04/2015 onward

~40 km resolution (similar to SMOS)



Advantages of satellite Sea Surface Salinity (SSS) (relative to in situ)

- Systematic monitoring of features with smaller scales and shorter periods: important for cross-scale interactions

- More uniform spatiotemporal sampling improves the ability to estimate horizontal gradients: important for frontal genesis, eddy-mean flow interaction, and biogeochemistry

- Global coverage: important for studying teleconnections & land-sea linkages.

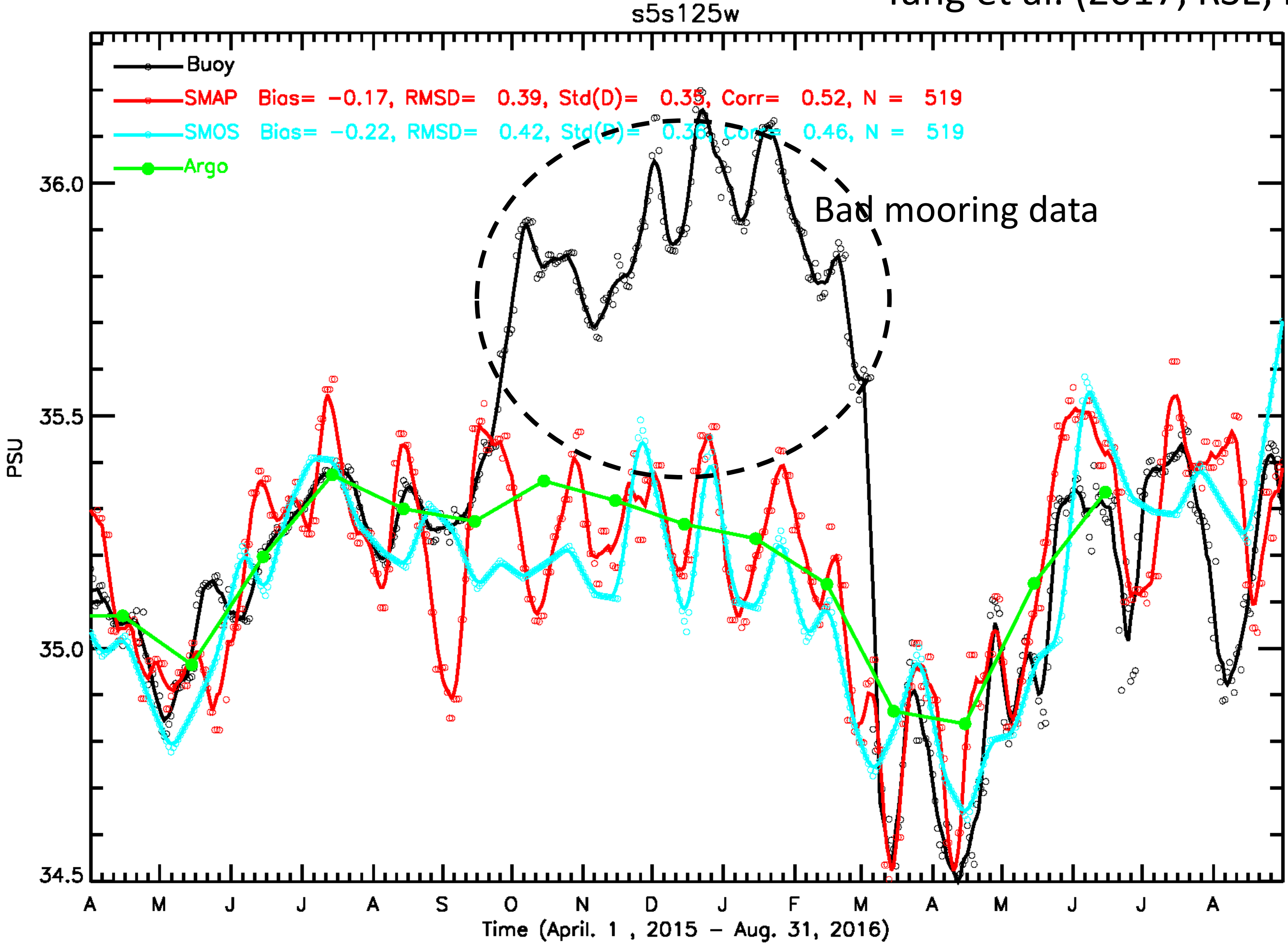
L-band radiometry is the only viable technology for systematic, synoptic monitoring of mesoscale SSS, coastal ocean & marginal sea SSS.

Complementarity with in-situ observations

- Linking surface & subsurface structure
- In-situ measurements important to cal/val of satellite SSS
- Stable L-band satellites can help identify mooring conductivity sensor drifts

Comparison of SMAP & SMOS SSS with mooring 1-m and Argo 2.5 m salinity

Tang et al. (2017, RSE, in press)



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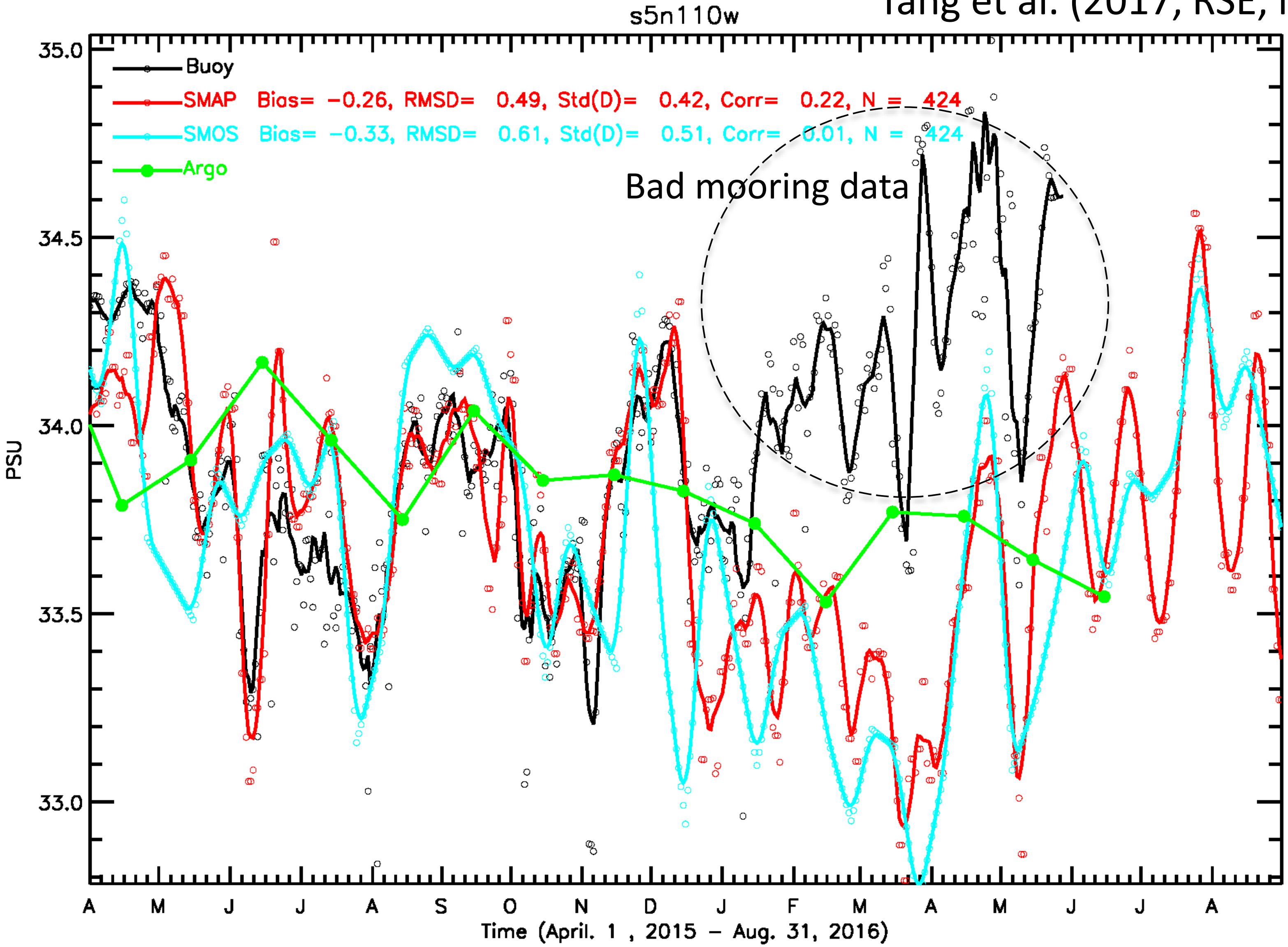


Summary of key achievements by L-band satellite SSS

- Oceanic features/processes (e.g., hurricane haline wake, TIWs, Rossby waves, river plumes, eddies, fronts, marginal sea salinity, cross-shelf exchanges, dynamics of S_{MAX} & S_{MIN} zones)
- Linkages with the water cycle (atmosphere, land).
- Relationships with climate variability (MJO, IOD, ENSO, etc.).
- Constraining ocean models & improving seasonal prediction.
- Emerging biogeochemical applications (e.g., TA, ocean acidification, fCO_2).

Filling significant SSS observing system gaps (spatiotemporal scales & regions not/inadequately sampled by in-situ platforms).

Highlights of satellite SSS applications to study ocean & climate processes

(focusing on examples showing advantages of satellite SSS,
as well as the synergy with other satellite measurements)

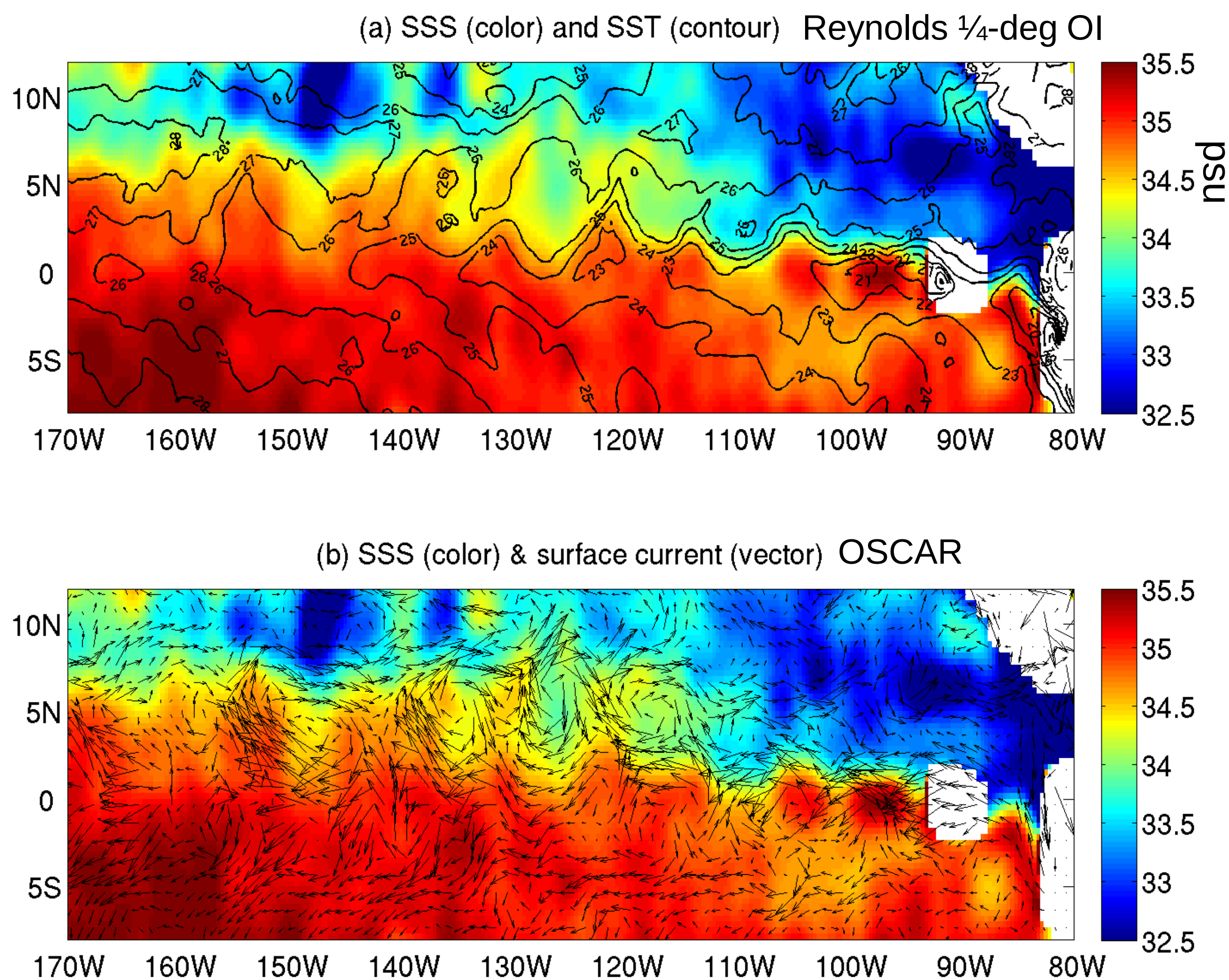
- Tropical instability waves (TIWs)
- Mesoscale eddies
- River plumes & linkages to water cycle
- Relationships to climate variability (MJO example)

Aquarius & SMOS observed new features of Pacific TIWs

Lee et al. (2012), Yin et al. (2014)

- TIWs are important to ocean, air-sea interaction, & BCG
- Satellite SSS revealed new features of Pacific TIWs

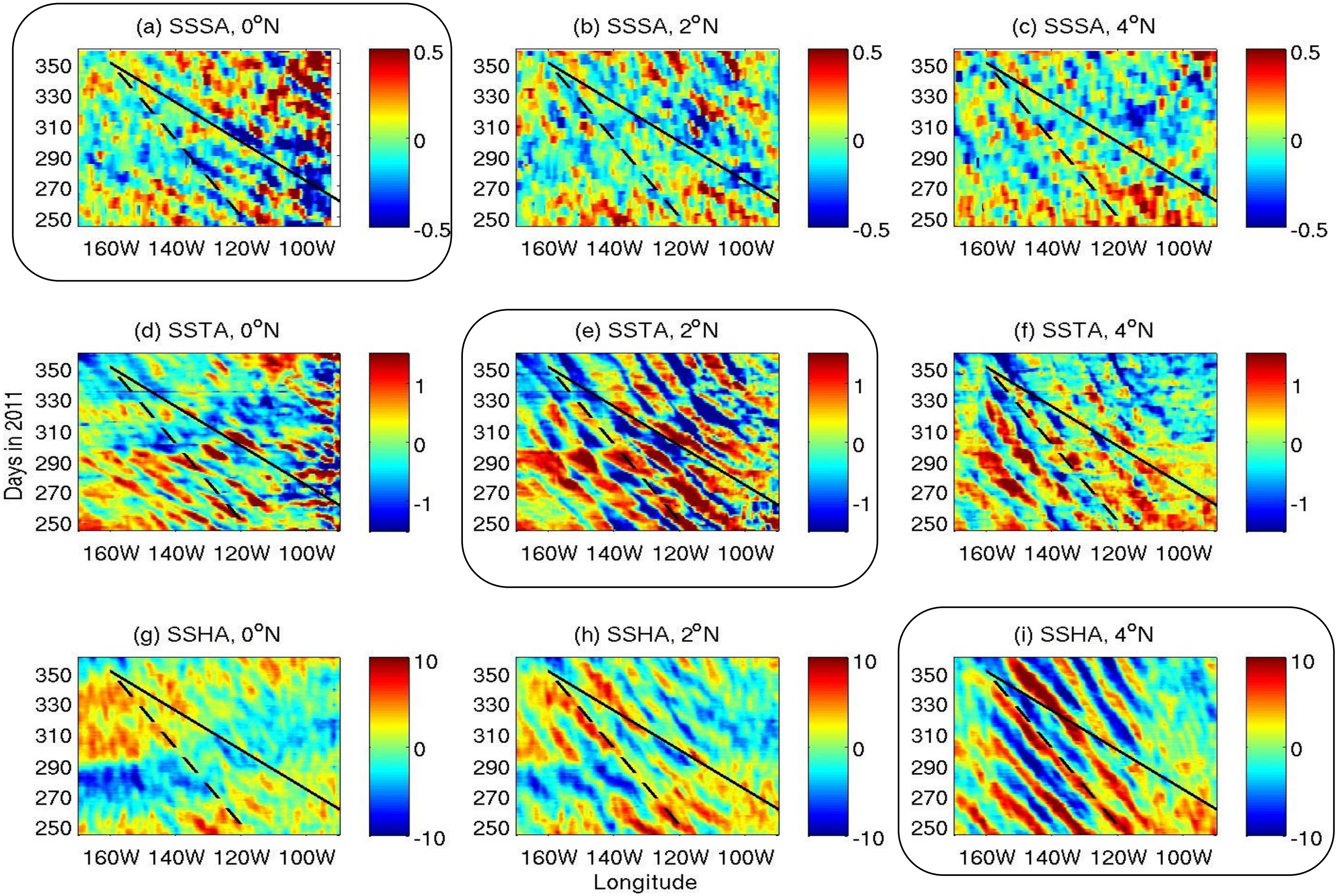
SSS from Aquarius (color shading), SST (contours in a), surface currents (arrows in b) on Dec. 11, 2011 (7-day maps)



Aquarius revealed faster TIW speed near than off equator

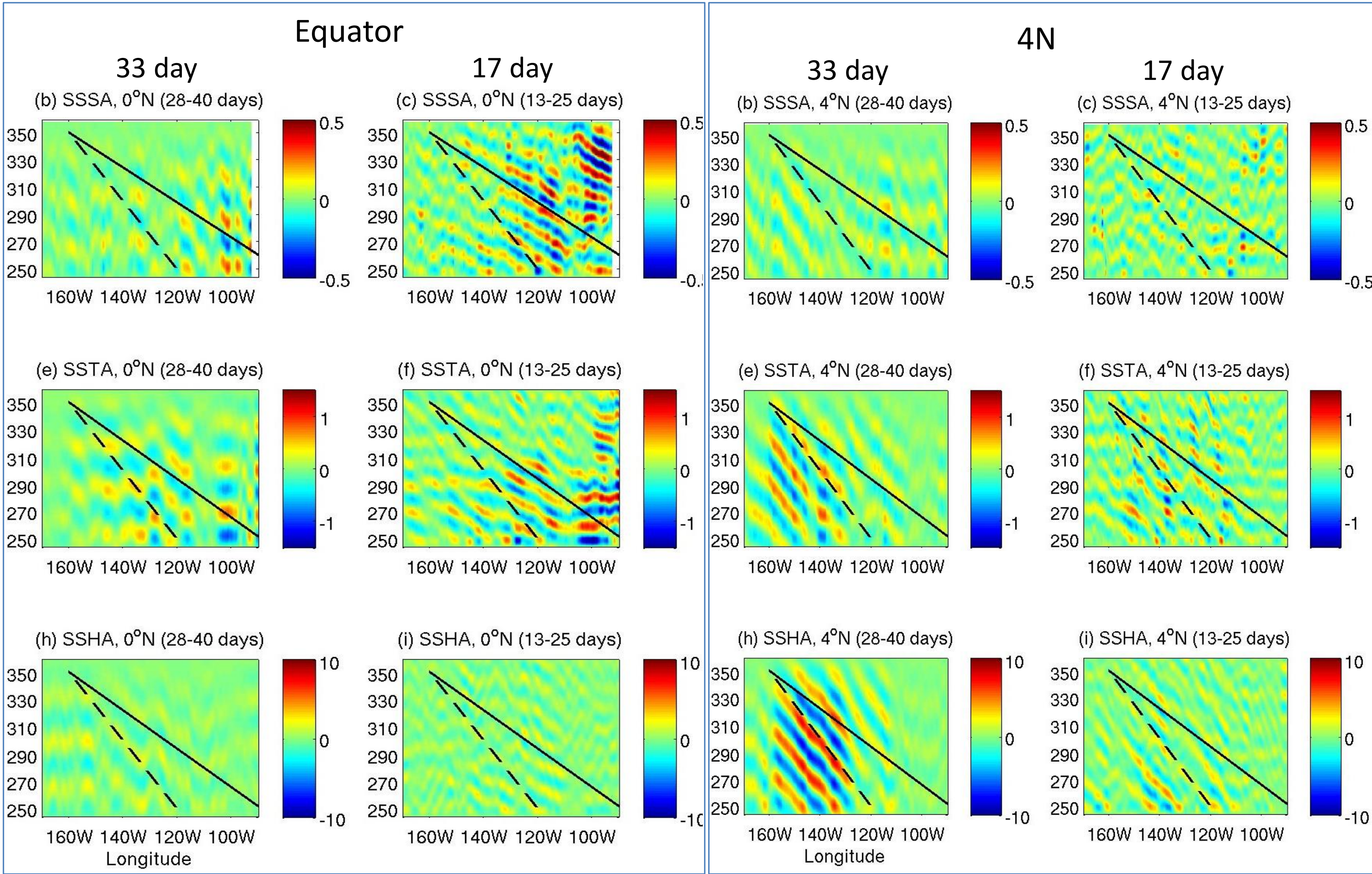
- Twice as fast as that off the equator observed by SST & SSHA (during 2011)
- Not reported in the past few decades of literature

Lee et al. (2012)

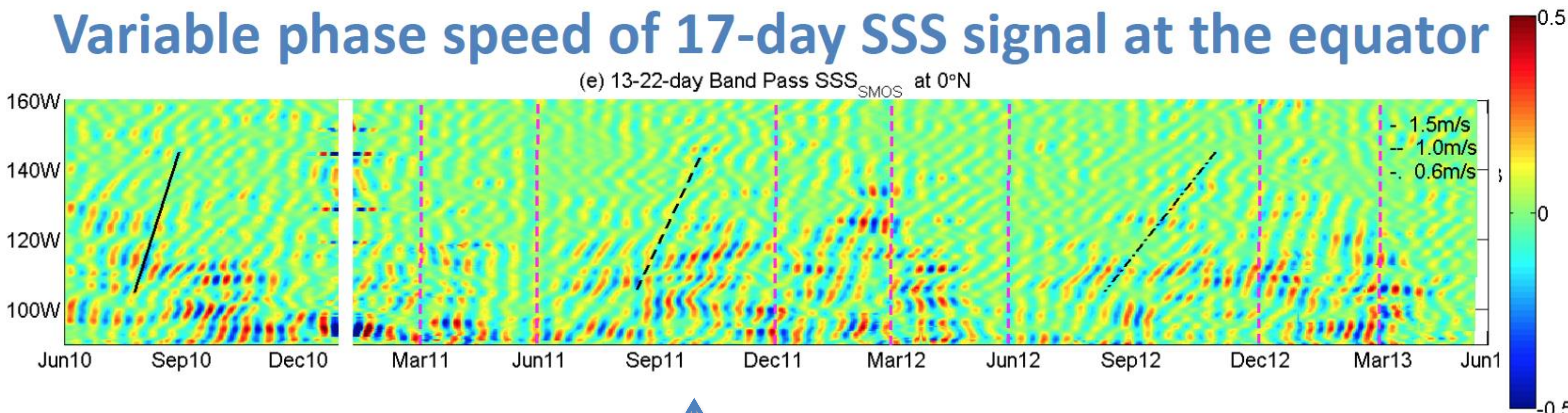


SSS, SST, SSH show strongest signals at 0, 2, 4N, complementary

TIWs near the equator: 17-day dominant period (Yanai Waves)
TIWs away from equator: 33-day dominant period (Rossby waves)



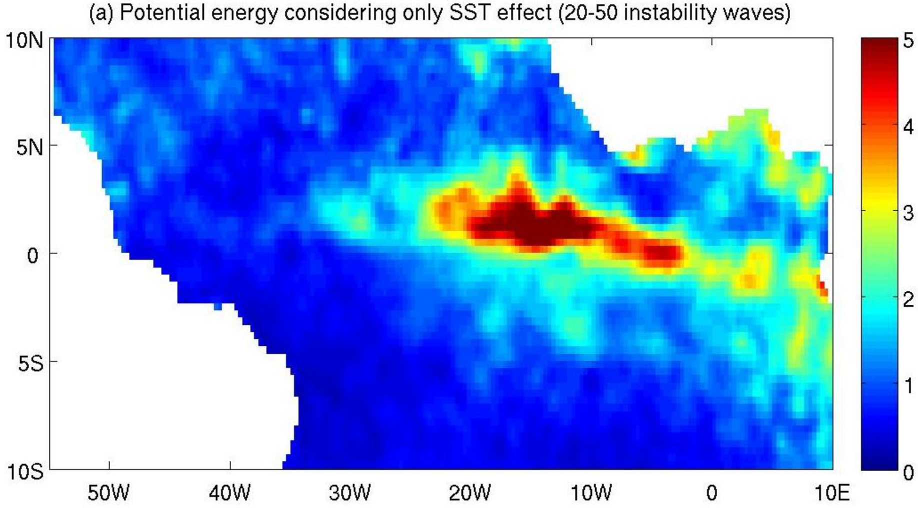
SMOS data revealed interannual variation of TIW speed at the equator, faster during La Nina



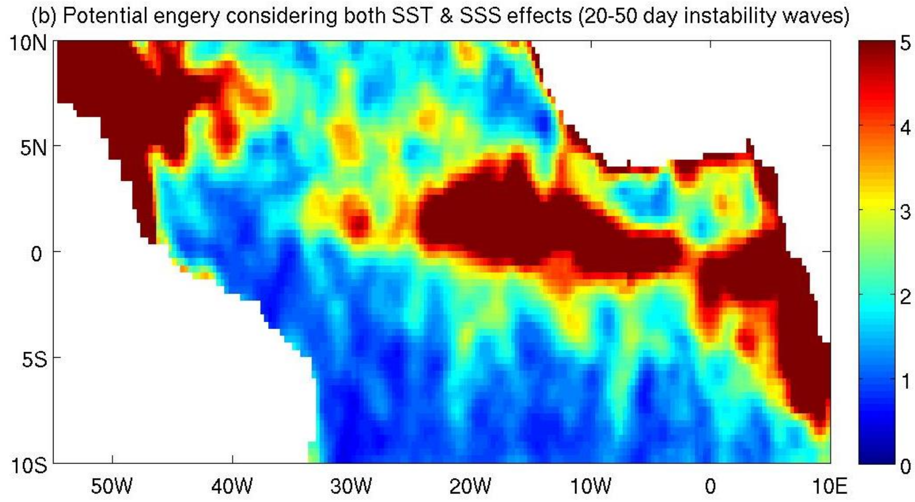
Consistent with Aquarius result (Lee et al. 2012) during this period

Aquarius reveals importance of salinity in energy budget of Tropical Atlantic instability waves *(Lee et al 2014)*

Surface EPE considering only SST effect



Surface EPE considering both SST & SSS effects



Science question: How important is salinity to Tropical Atlantic TIW energetics?

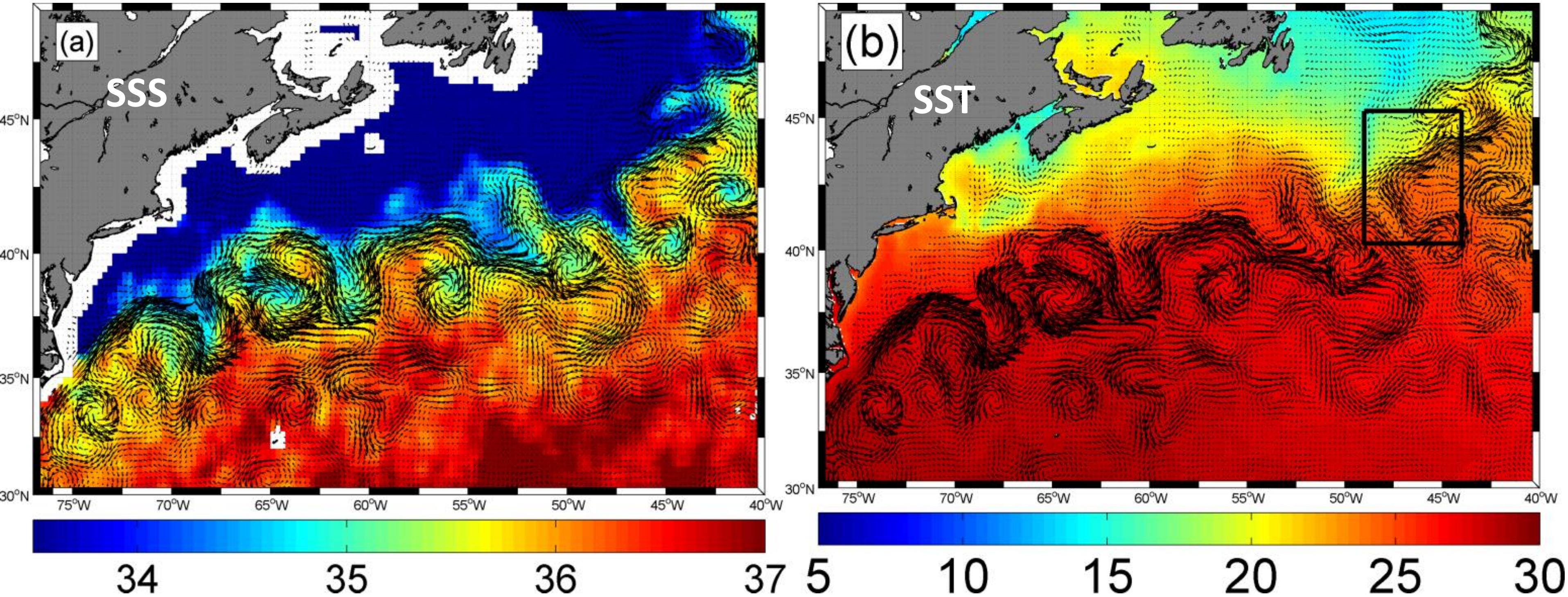
Result: ignoring SSS effect would under-estimate TIW-related Eddy Potential Energy (EPE) by 3 times

Significance/implication:

- SSS need to be considered in energy budget and studies of wave-mean flow interaction.
- Revisit the relative roles of baroclinic vs barotropic instabilites

SMOS reveal SSS structure of the Gulf Stream & cold-core eddies with unprecedented spatiotemporal resolutions

Reul et al. (2014)

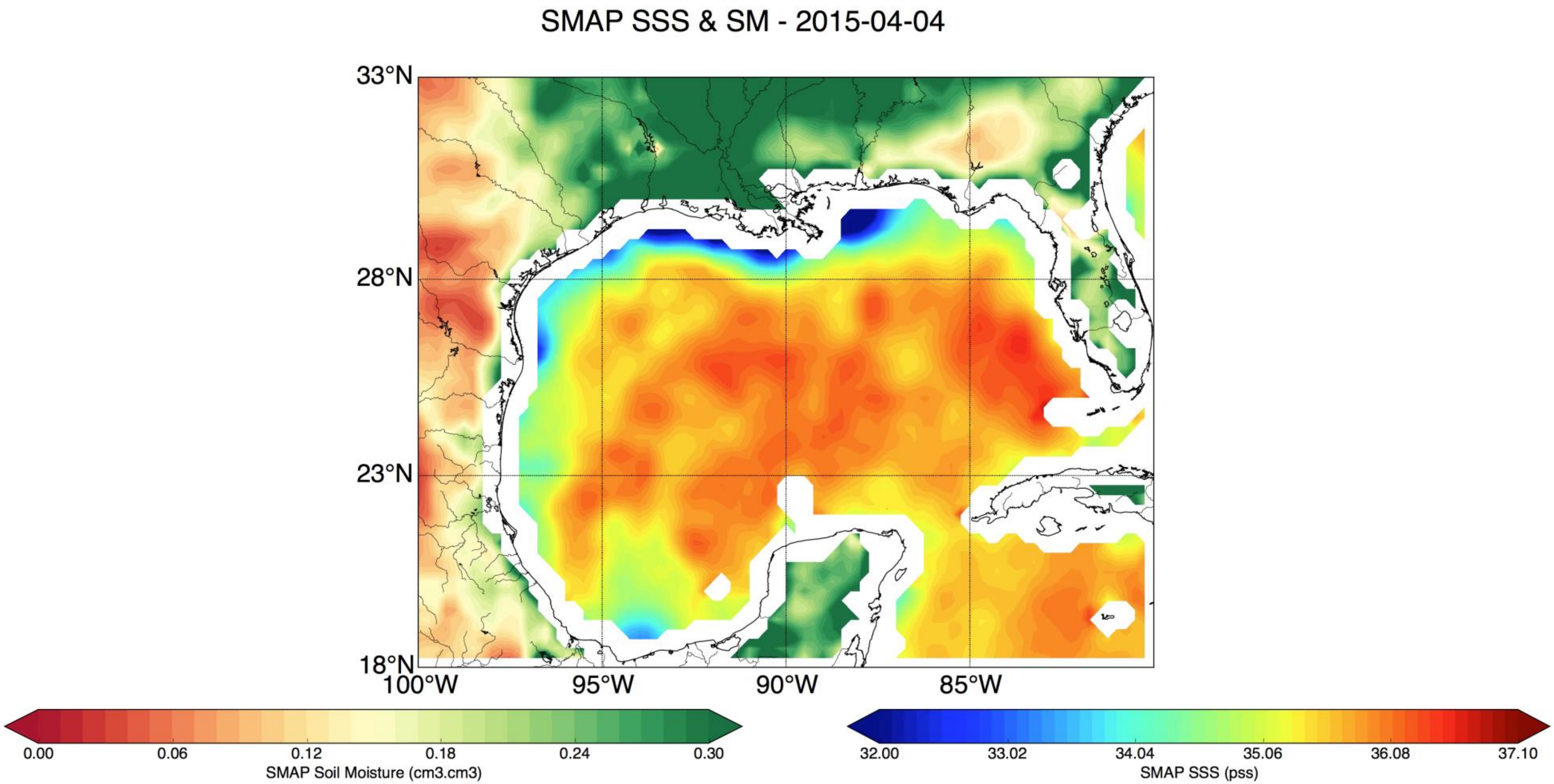


- Cold/fresh Core rings are better captured by SSS than SST during summer.
- Implication: cross-gyre salt transport by eddies

Several related studies (focusing on cross-shelf exchanges):

e.g., Grodsky, S.A., Reul, N., Chapron, et al. (2017). Interannual Surface Salinity in Northwest Atlantic Shelf, JGR, 122, 3638–3659.

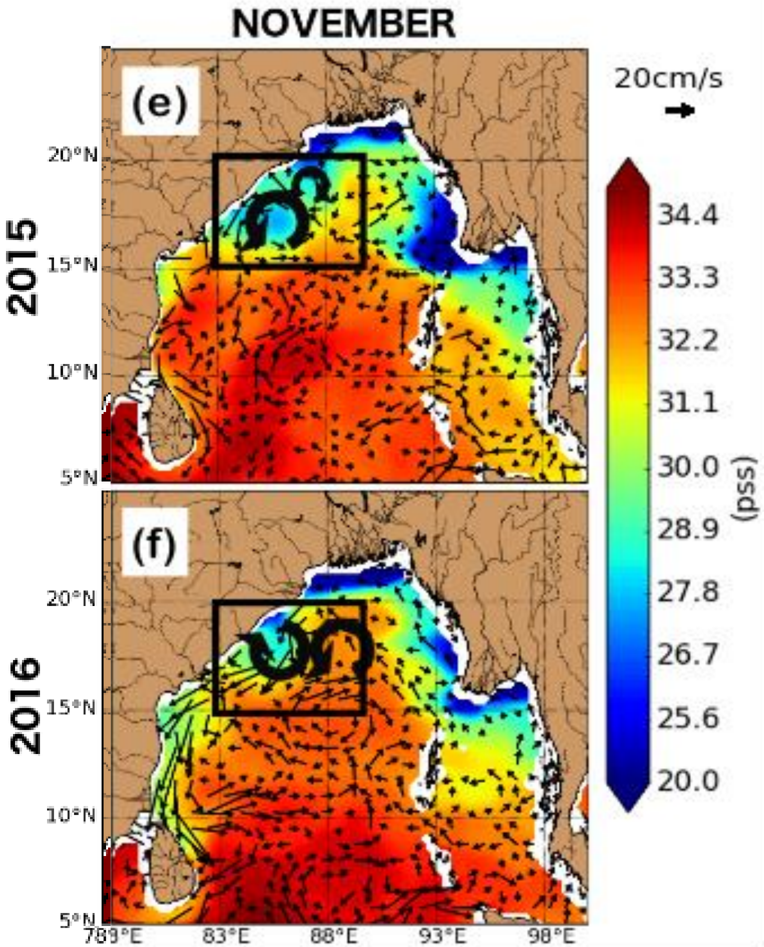
Improving environmental assessment:
SMAP sea surface salinity & soil moisture during & after the May'15 extreme flooding event in Texas



Unusually large freshwater plume in the central Gulf of Mexico was caused by runoff to Texas shelf (*Fournier et al. 2016a*)

Modulation of the Bay of Bengal river plume by the Indian Ocean Dipole (IOD) and ocean eddies inferred from satellite data

(Fournier et al. 2017a)



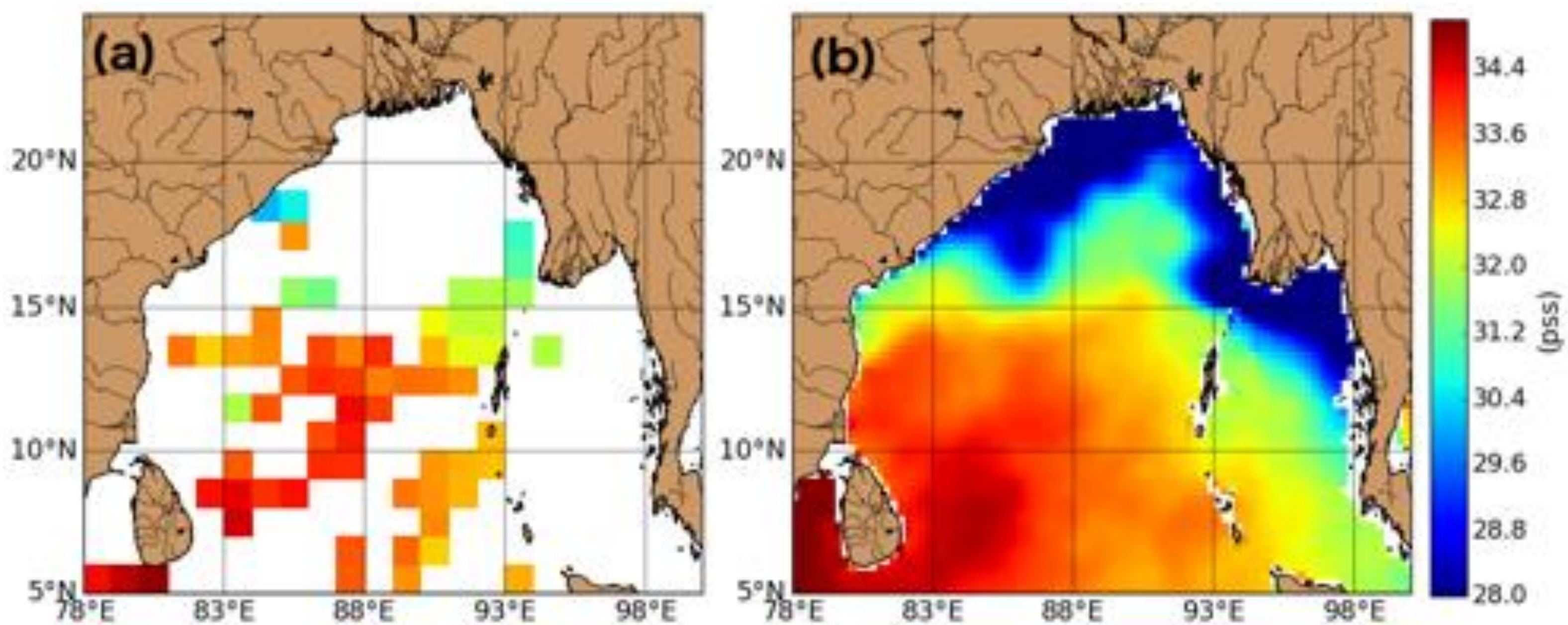
SMAP SSS for November 2015 & 2016 with ocean surface currents superimposed. Thick arrows highlight eddies.

Science question: What processes influence the variability of the climatically and biologically important Ganges-Brahmaputra (GB) River plume in the Bay of Bengal (BoB)?

Finding: (1) Negative IOD in 2016 caused a stronger East India Coastal Current (EEIC) that carried the GB river plume ~600 km further south. (2) Ocean mesoscale eddies help transport river freshwater plume offshore.

Significance/implication: Satellite SSS provide new resources to monitor intraseasonal to interannual variability of the GB river plume & study its impacts on monsoon, cyclones, and biological productivity.

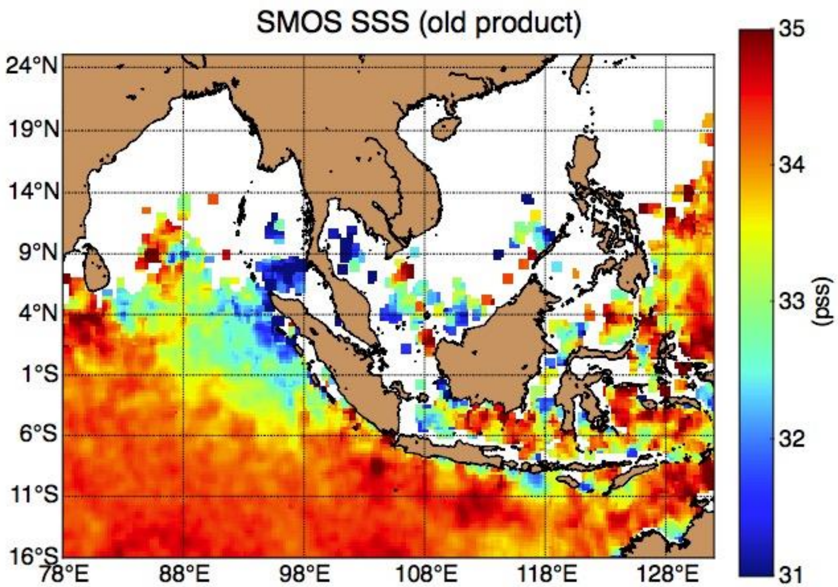
Satellite SSS provide much better spatiotemporal coverage

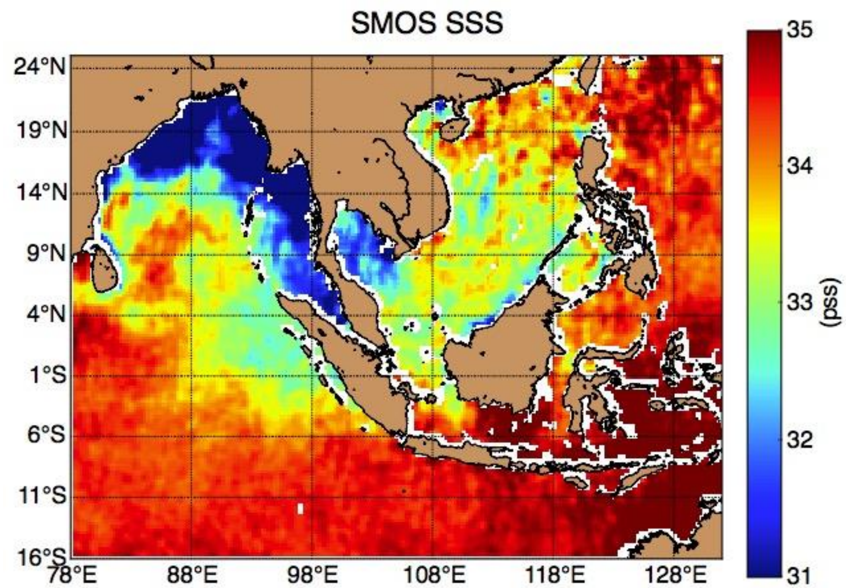


(a) September-November 2015 Argo 5-m SSS measurements averaged within 1 degree pixels and **(b)** September-November 2015 average map of SMAP SSS (complete coverage was actually achieved in 8 days)

Fournier et al. (2017a)

Improvement of new SMOS SSS product & consistency with SMAP SSS





New SMOS SSS product (CATDS, Boutin et al. 2017) brought significant improvements in marginal seas & coastal oceans.

New SMOS SSS very consistent with SMAP SSS

SMOS & SMAP SSS further enhanced sampling

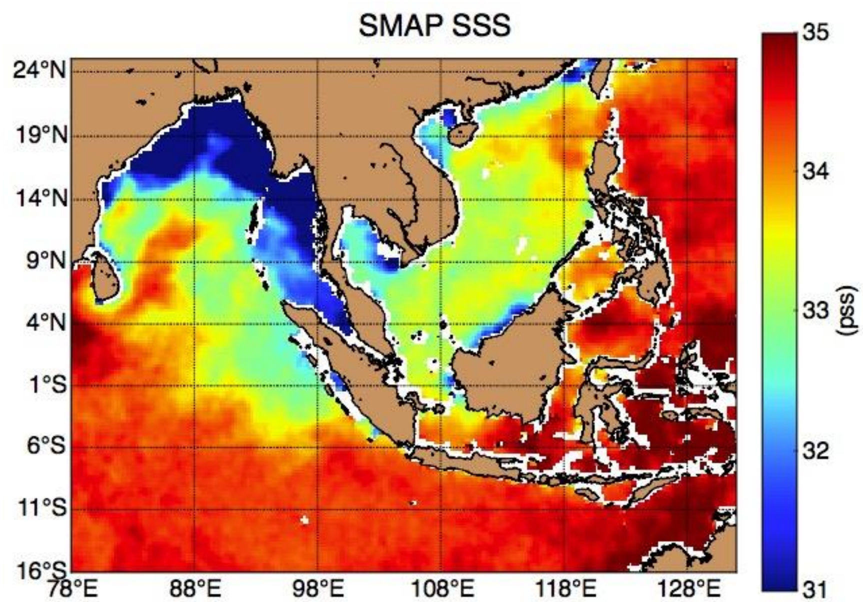
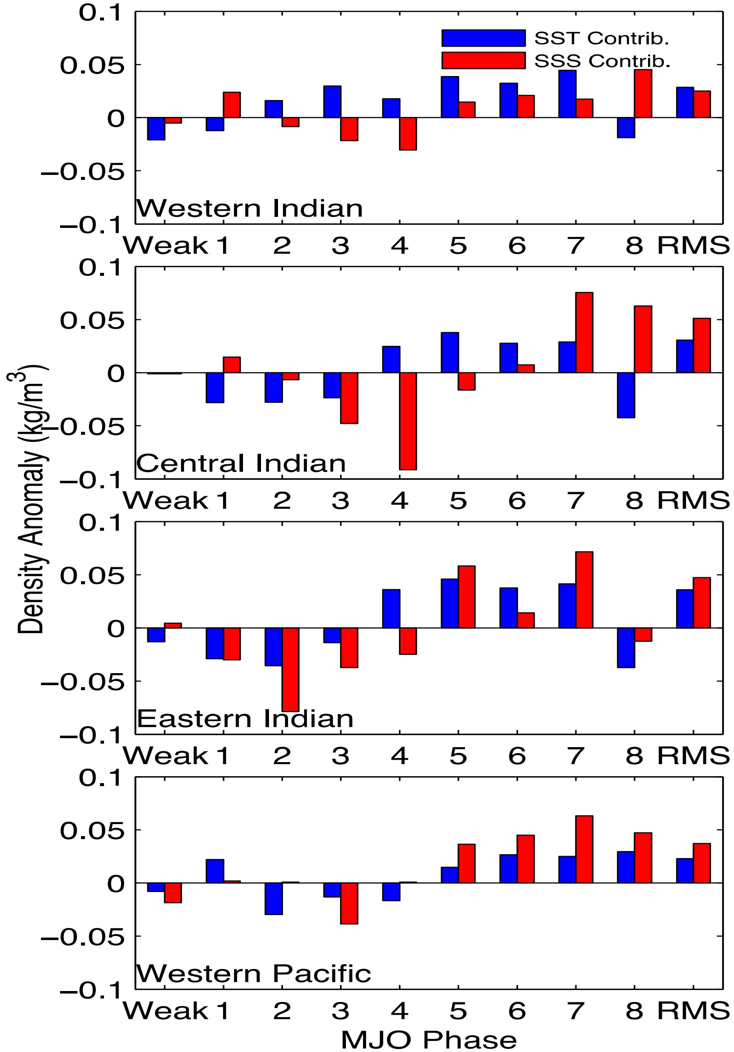


Image credit: Severine Fournier

Sea surface salinity (SSS) & the Madden-Julian Oscillation (MJO)

(Guan et al. 2014)

Contribution of SST & SSS to surface density anomalies during a composite MJO life cycle (Phases 1-8, in different regions)



Problem: Relative contributions of SSS & SST to MJO-related changes in ocean surface density are poorly known.

Finding: Aquarius SSS together with satellite SST suggest that SSS has a similar or larger contribution as SST to MJO-related variation in surface density.

Significance/Implication: Modeling and assimilation products need to properly account for SSS effects in order to correctly represent mixed layer variability associated with the MJO and the related ocean-atmosphere coupling.

Need PMW SST as well as SSS for convective systems like MJO!

Use of satellite SSS for constraining E-P forcing & ocean models

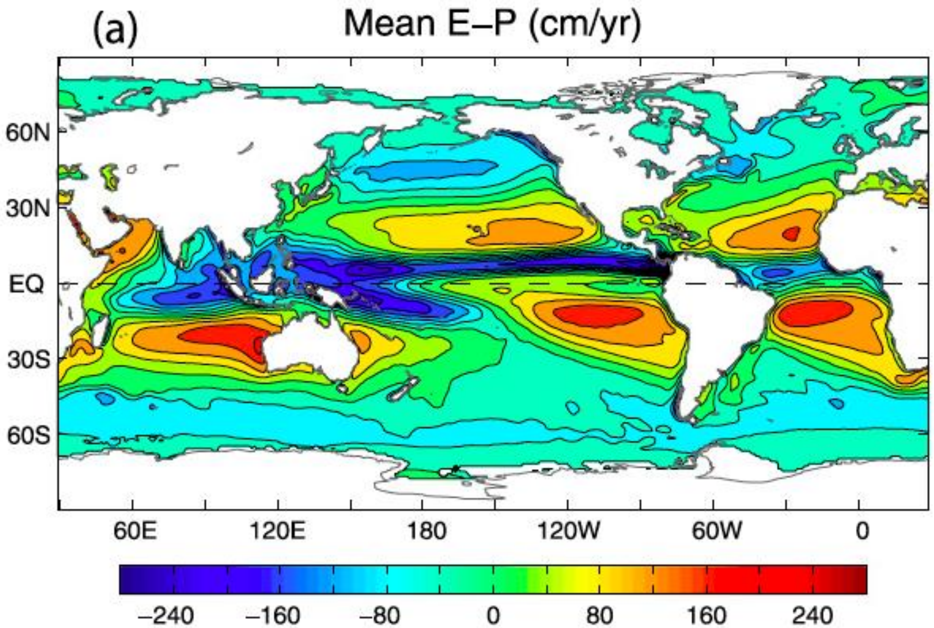
Ocean model salinity are affected by:

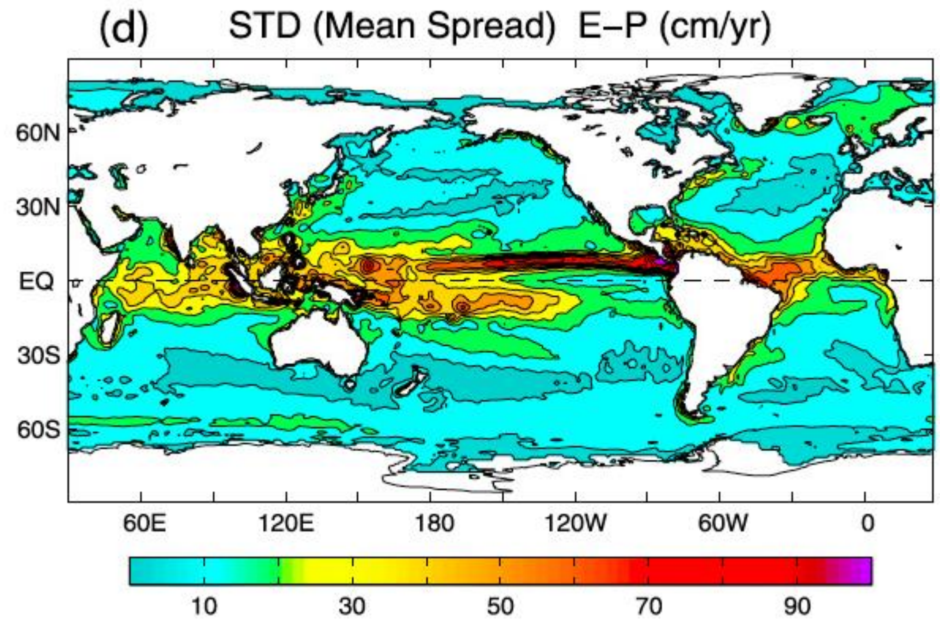
- significant E-P forcing error;
- use of river discharge climatology;
- relaxation to SSS climatology;
- errors in model physics (e.g., advection & mixing) & numerics

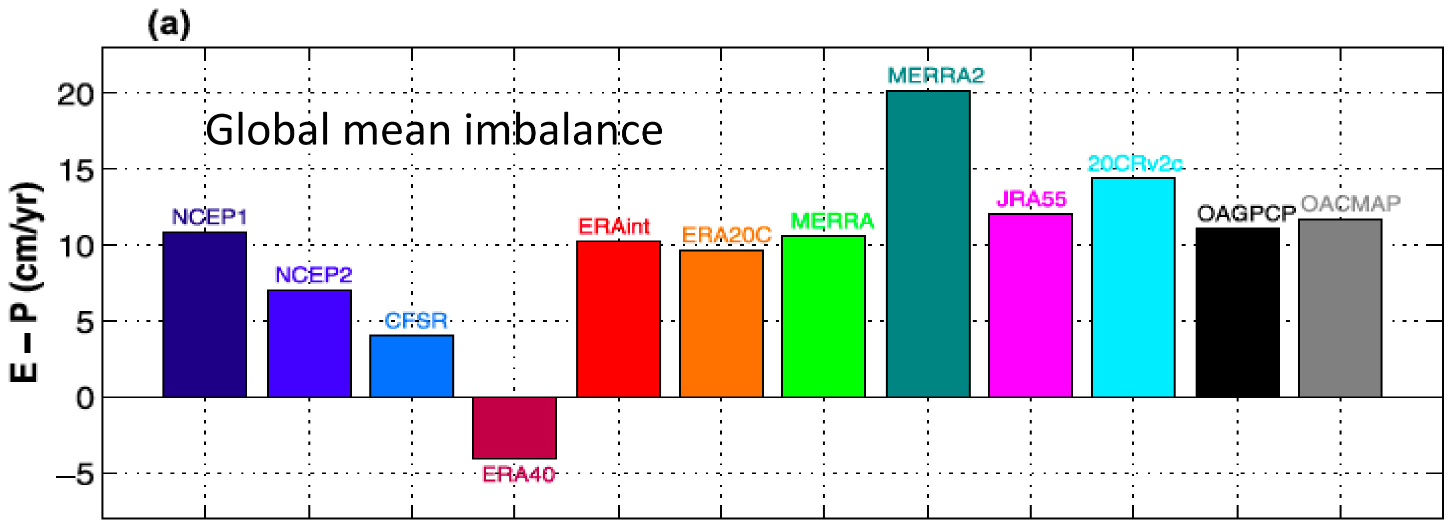
Satellite SSS have the potential alleviate these limitations

Large spread among 12 E-P products

(Yu et al. 2017)

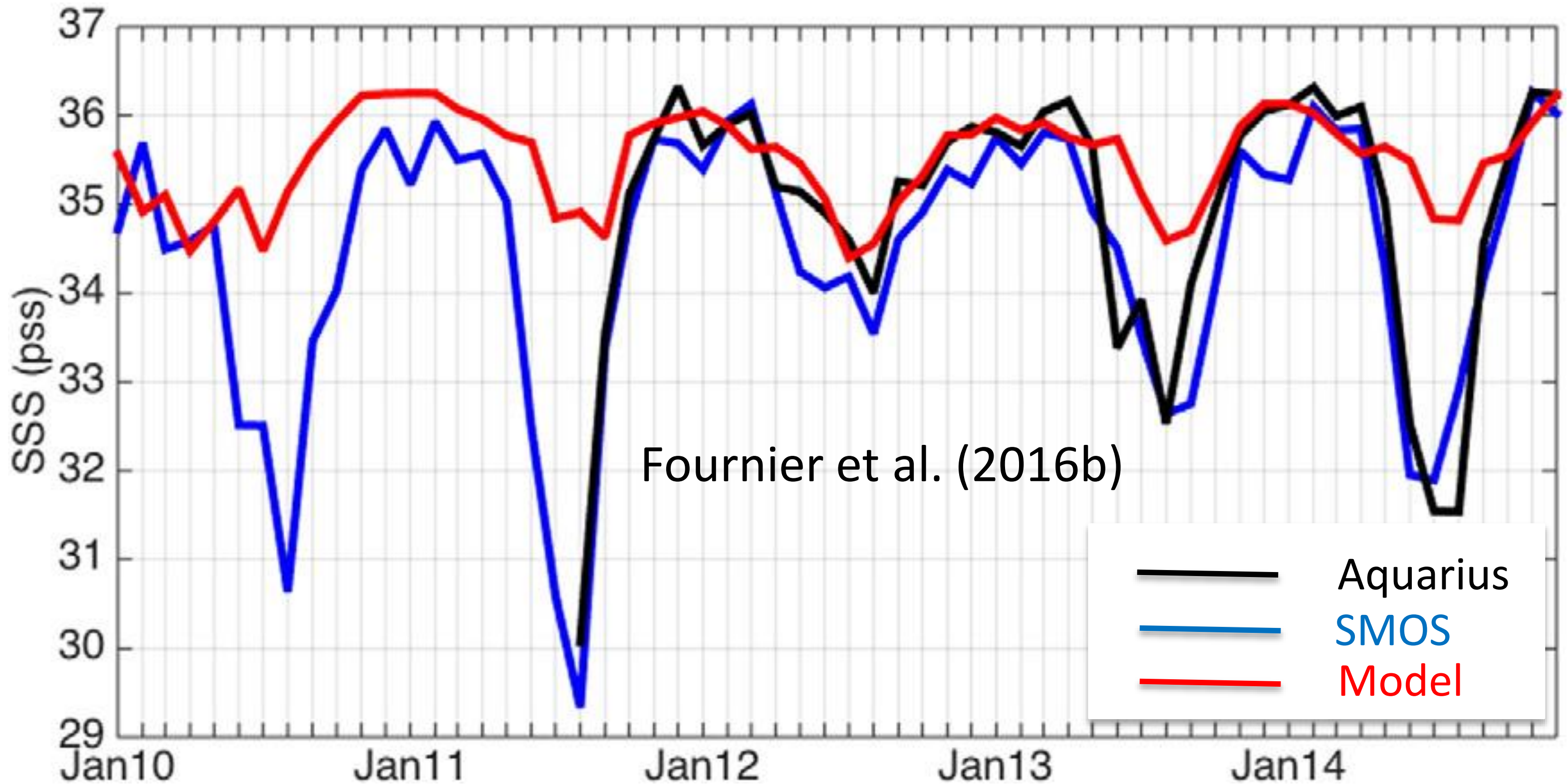






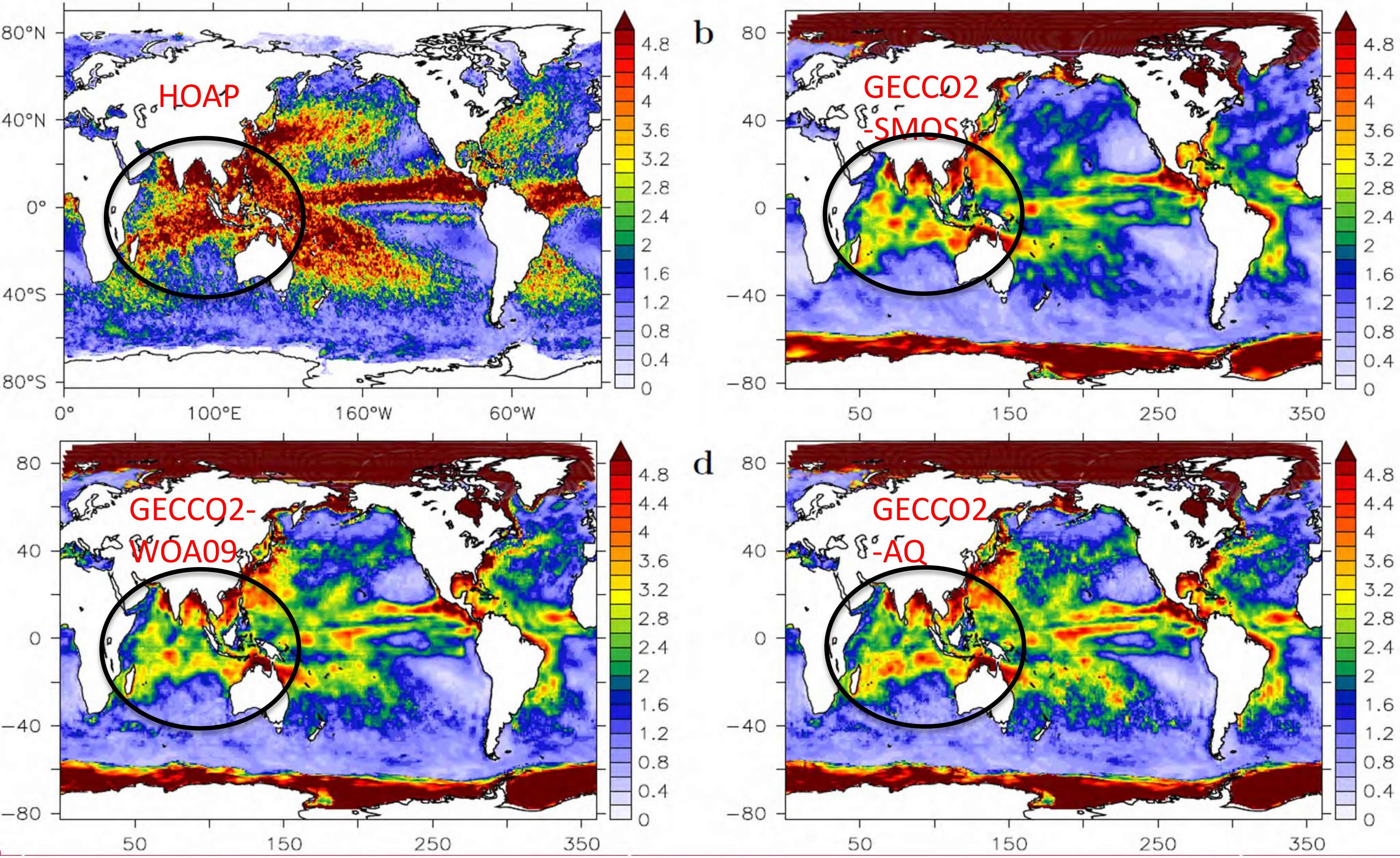
Lack of interannual variations of SSS near river mouths in ocean models

SSS near the Mississippi River mouth from Aquarius, SMOS, and an operational global ocean assimilation product



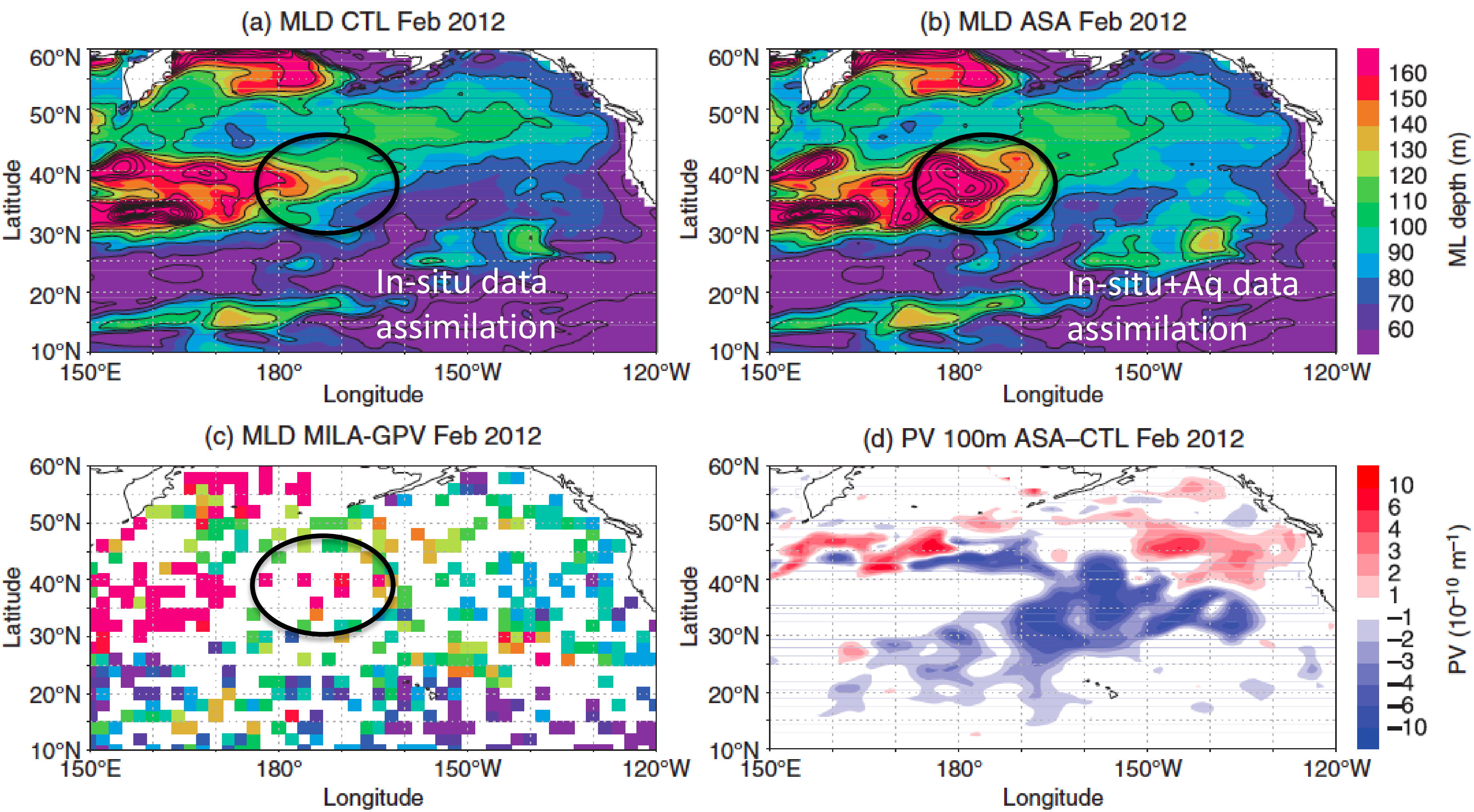
Significant implications to marine biogeochemistry

Impact of satellite SSS assimilation on inverse estimate of E-P variability in GECCO2 *(Köhl et al. 2014)*



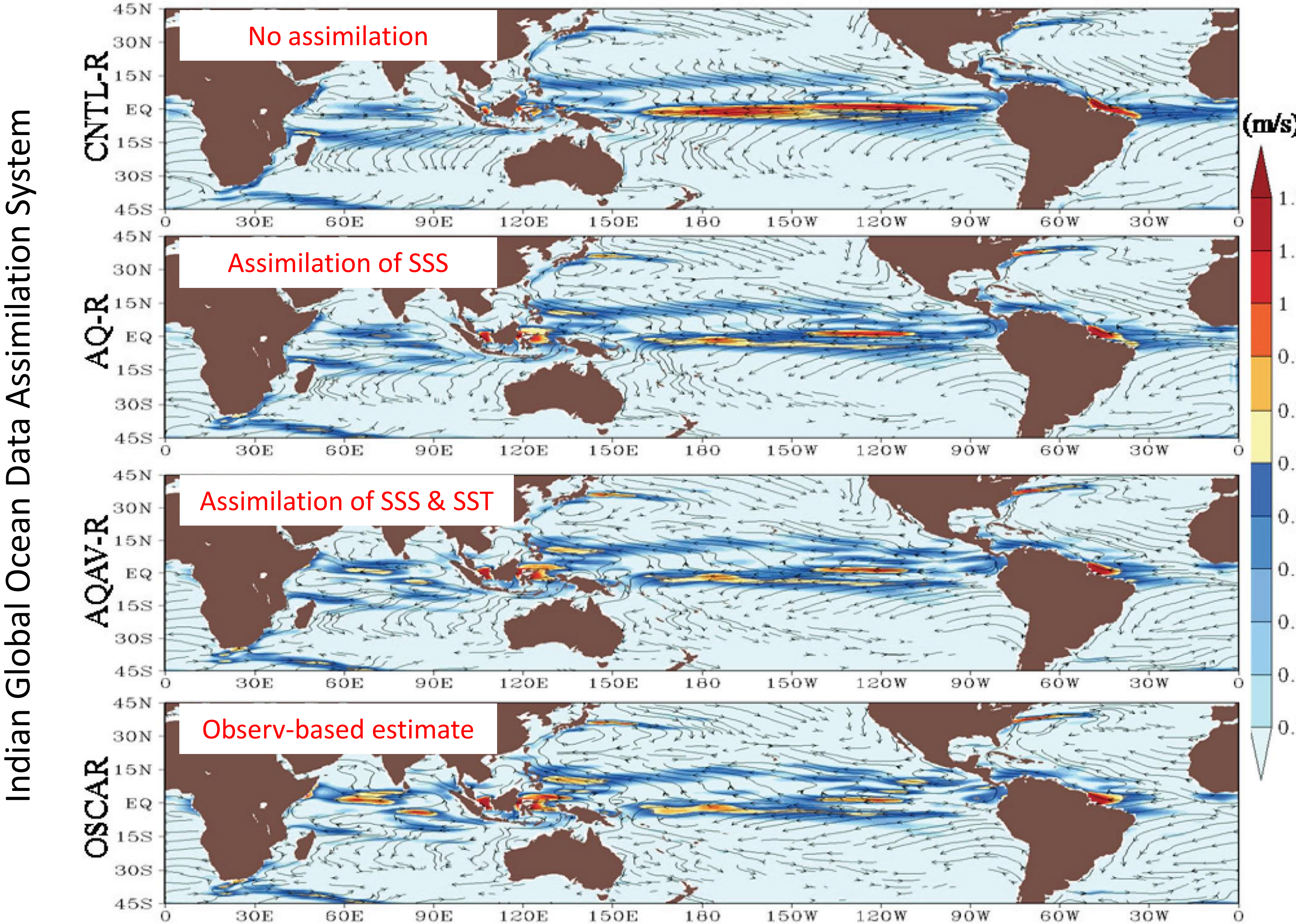
Improvements of JMA/MRI global ocean data assimilation system by assimilating Aquarius SSS *(Toyoda et al. 2014)*

Example for North Pacific Mode Water distribution in winter of 2012

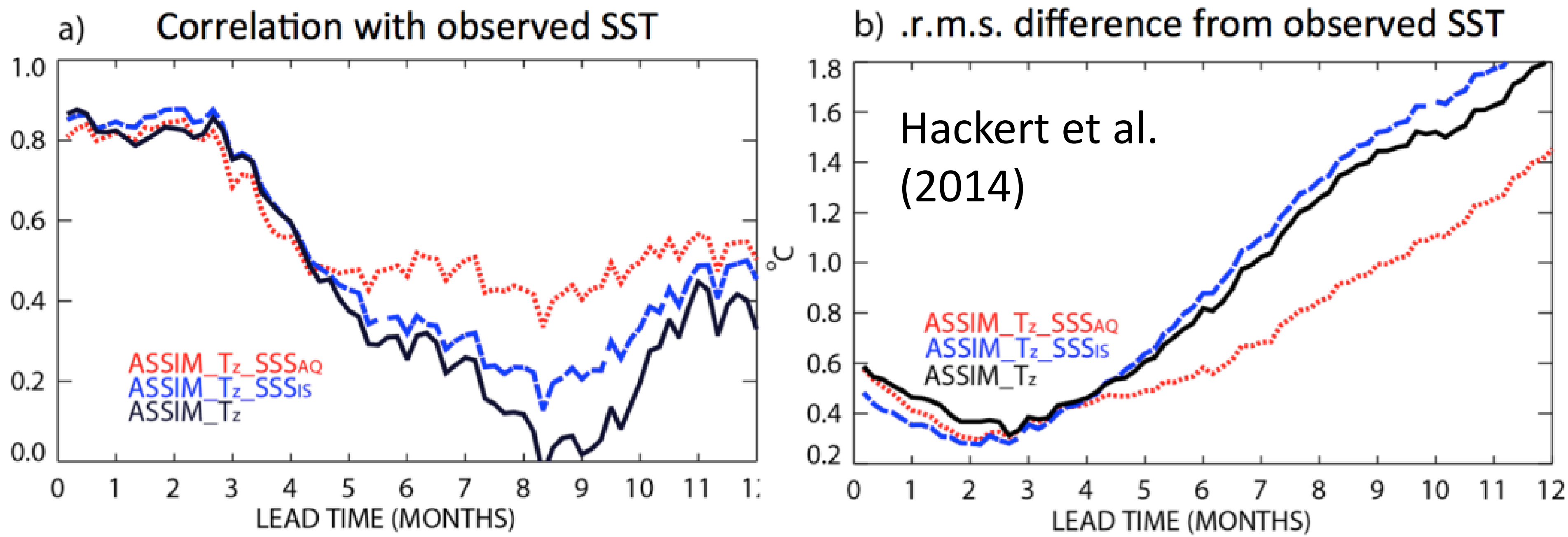


Assimilation of Aquarius SSS & AVHRR SST improves representation of ocean surface currents *(Chakraborty et al. 2014)*

Spatial amplitude of the 1st EOF mode of surface currents



Impact of satellite SSS assimilation on seasonal-to-interannual prediction for 2011-2014



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 RMSE wrt observed SST for lead times > 4 months.

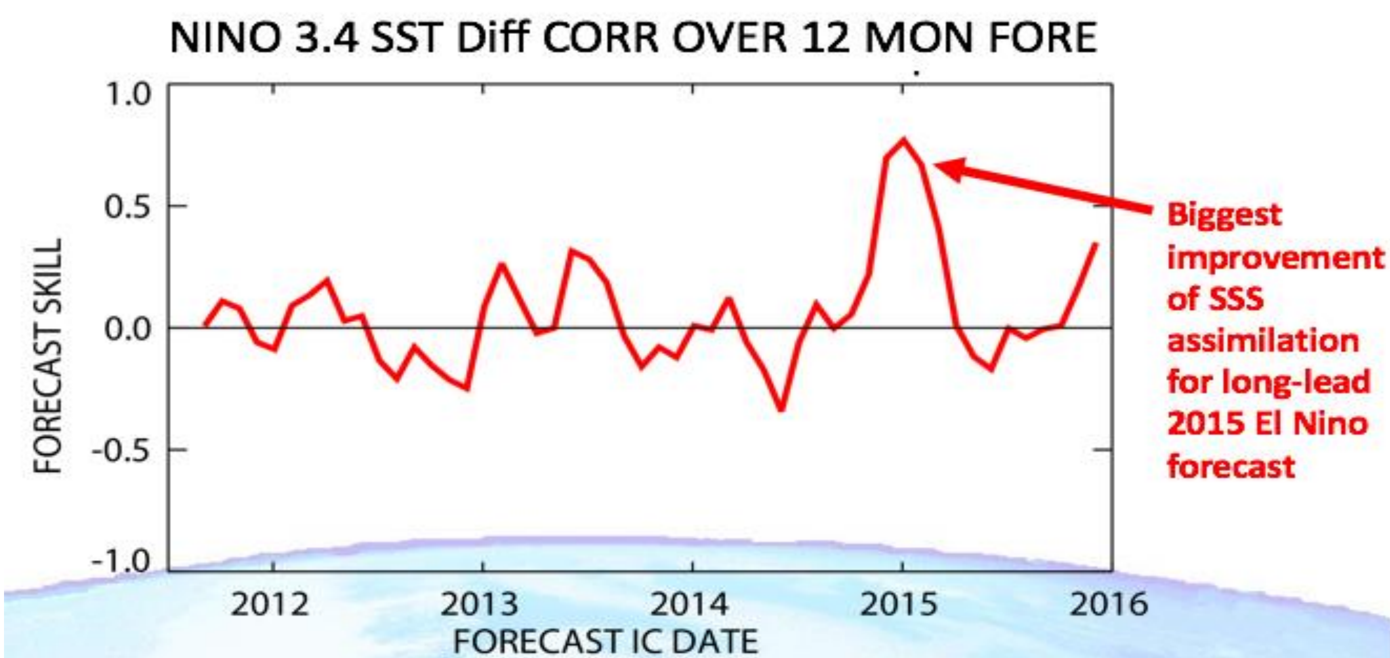
Need long data record (covering many ENSO events) to establish the robustness of impacts on prediction

-> continuity of L-band mission important

Ongoing work based on NASA/GMAO ocean data assimilation & coupled model hindcasts

Experiment Design

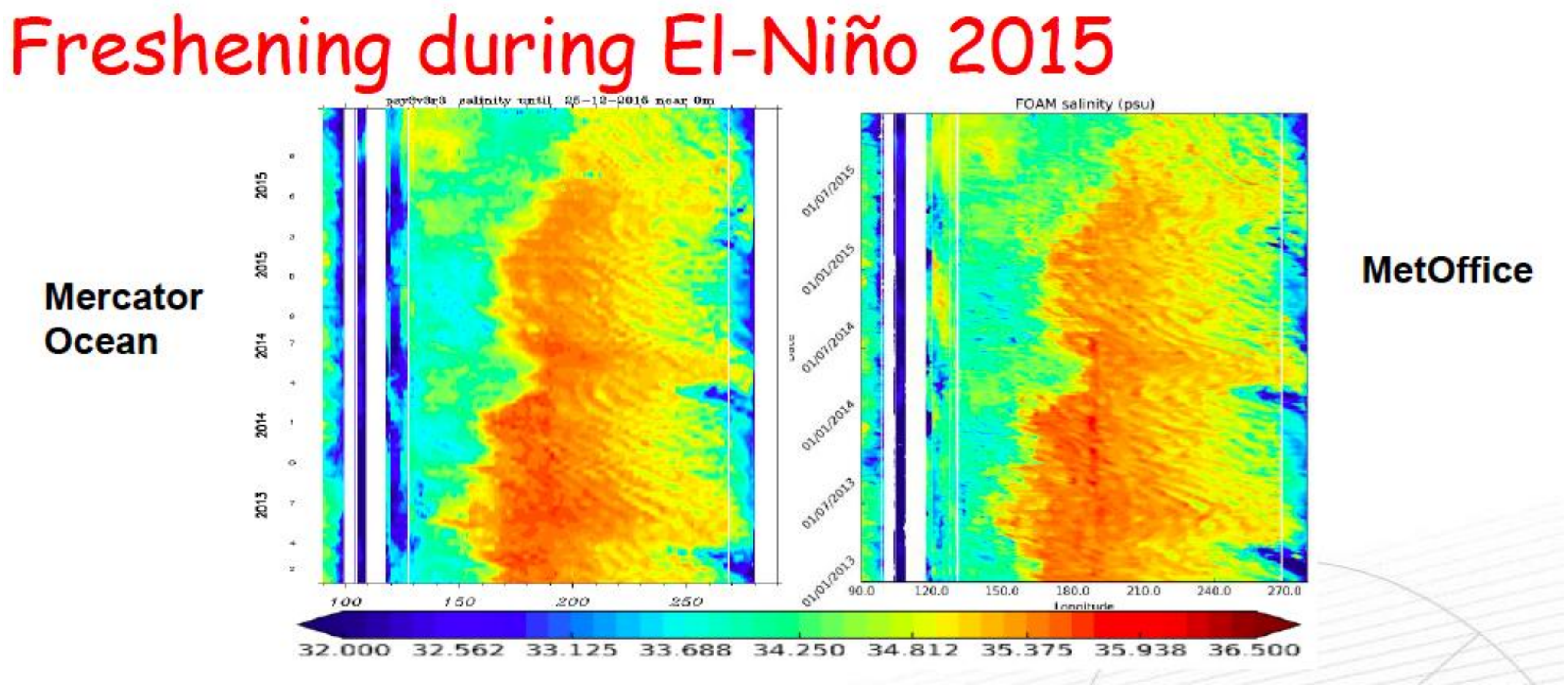
Experiment Name	Period	Assimilation Variables
ASSIM_SL_SST_T_z_S_z "Control"	Jan 1993 – Dec 2016	SL, SST, T_z and S_z
ASSIM_SL_SST_SSS_T_z_S_z Known as "SSS Assimilation"	Sep 2011 – Dec 2016*	SSS from Aquarius Version 4.0 combined with SMAP Version 2.0 Level 3 data and SL, SST, T_z, and S_z



Courtesy of Eric Hackert NASA/GMAO

SMOS-NINO15 Project funded by ESA

Coordinated experiments between **UK Met Office & Mercator Ocean** to investigate the impacts of assimilating satellite SSS from SMOS, Aquarius and SMAP on simulating the 2015/16 El Nino period.

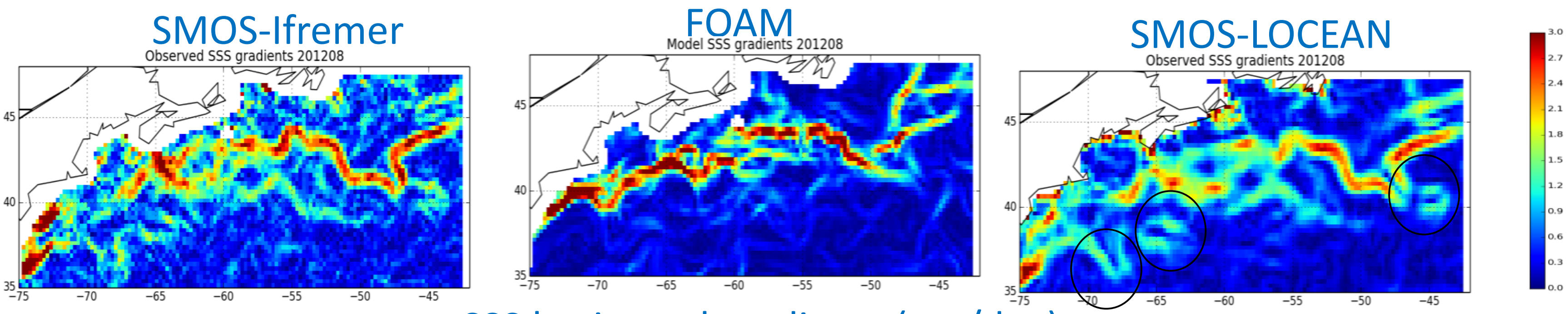


Courtesy of Matt Martin and Benoit Tranchant (Mercator Ocean)

Ongoing effort for satellite SSS assimilation at UKMO

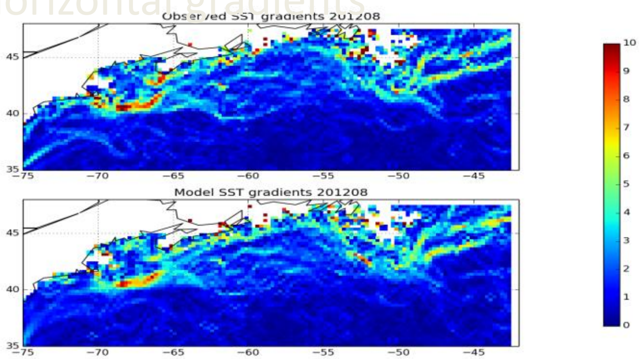
Spatial information in satellite SSS data

Martin, M.J., 2016, doi:10.1016/j.rse.2016.02.004.



SSS horizontal gradients (pss/deg)

SST horizontal gradients

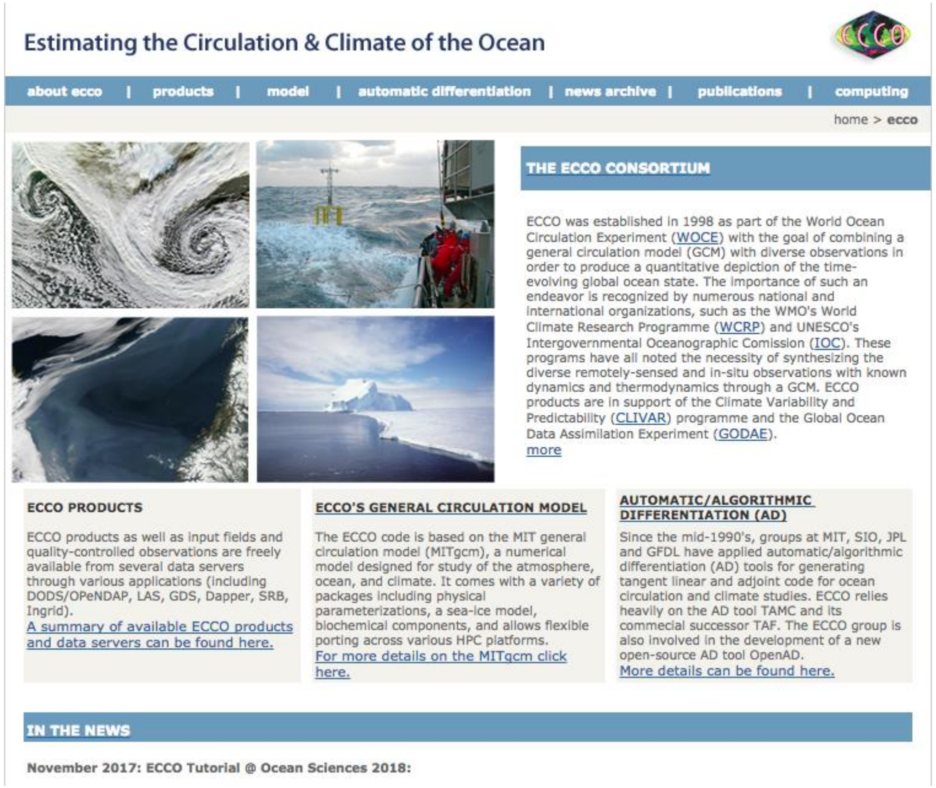


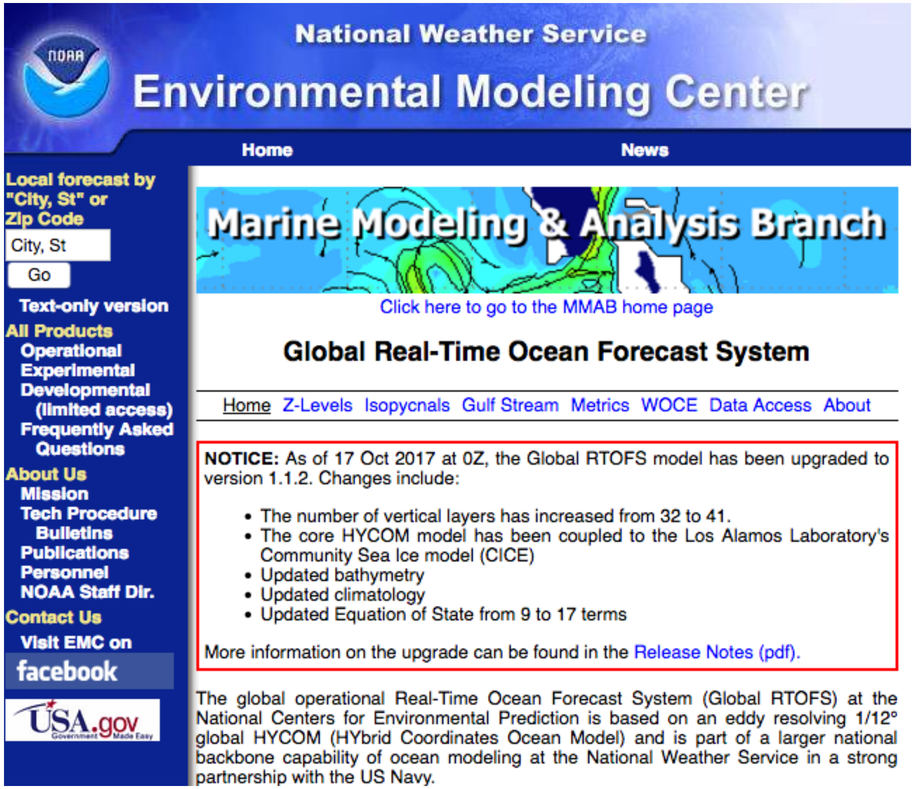
- SSS fronts agree reasonably well between model and obs.
- SMOS data shows some frontal structures in the main part of the Gulf Stream which the model doesn't represent.
- Surface warming has masked the underlying structures in SST in August.

Courtesy of Matt Martin, UK Met Office

Other ongoing efforts for satellite SSS assimilation

- Estimating the Circulation & Climate of the Ocean (ECCO) 4D-VAR
- NOAA: Global Real-time Ocean Forecasting System (RTOFS); West Coast Ocean Forecasting System (WCOFS)
- Chinese National Marine Environmental Forecasting Center





Future challenges & requirements for satellite SSS

(based on community inputs to US Decadal Survey 2017-2027)

- Continuity to extend data record
- Enhancing spatial resolution and getting closer to the coasts.
- Improving accuracy, esp. at high-latitude oceans

Community white papers in response to US Decadal Survey advocating for future requirements of satellite SSS

Response to Decadal Survey RFI: Linkage of the Water Cycle, Ocean Circulation, and Climate

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Response to NRC 2017-2027 Decadal Survey Request for Information #2:

"Linkages of salinity with ocean circulation, water cycle, and climate variability"

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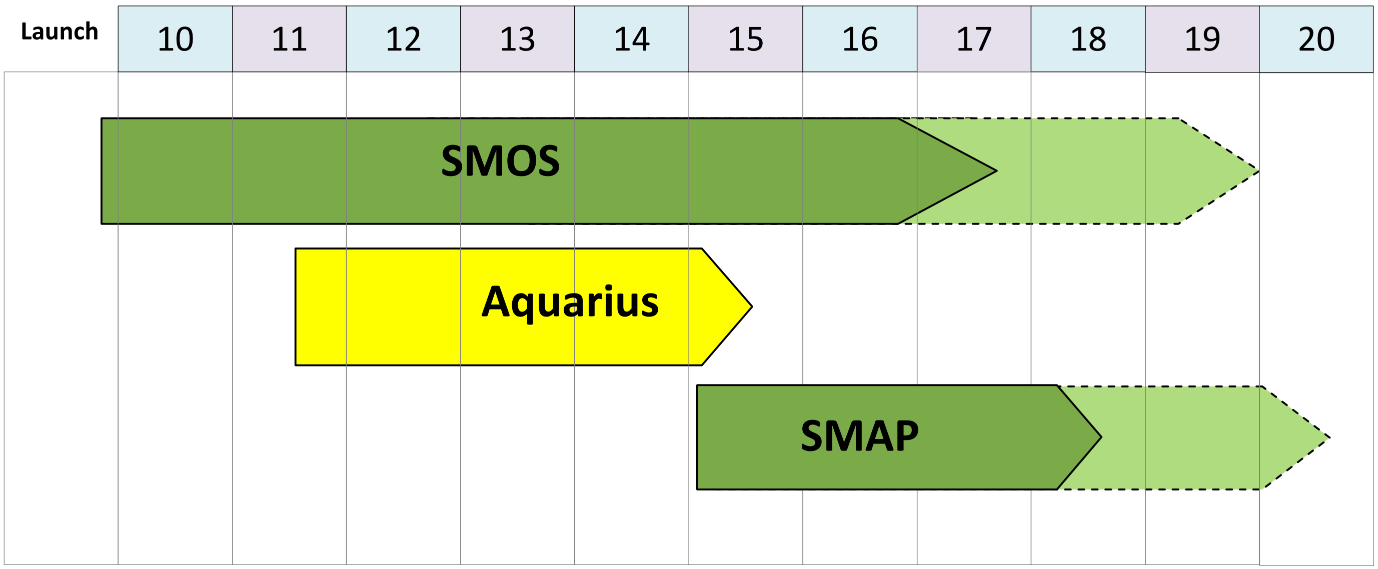
Continuity to extend data record

- Important for monitoring changes in the water cycle
- Necessary for studying and predicting seasonal, interannual, and decadal climate variability.

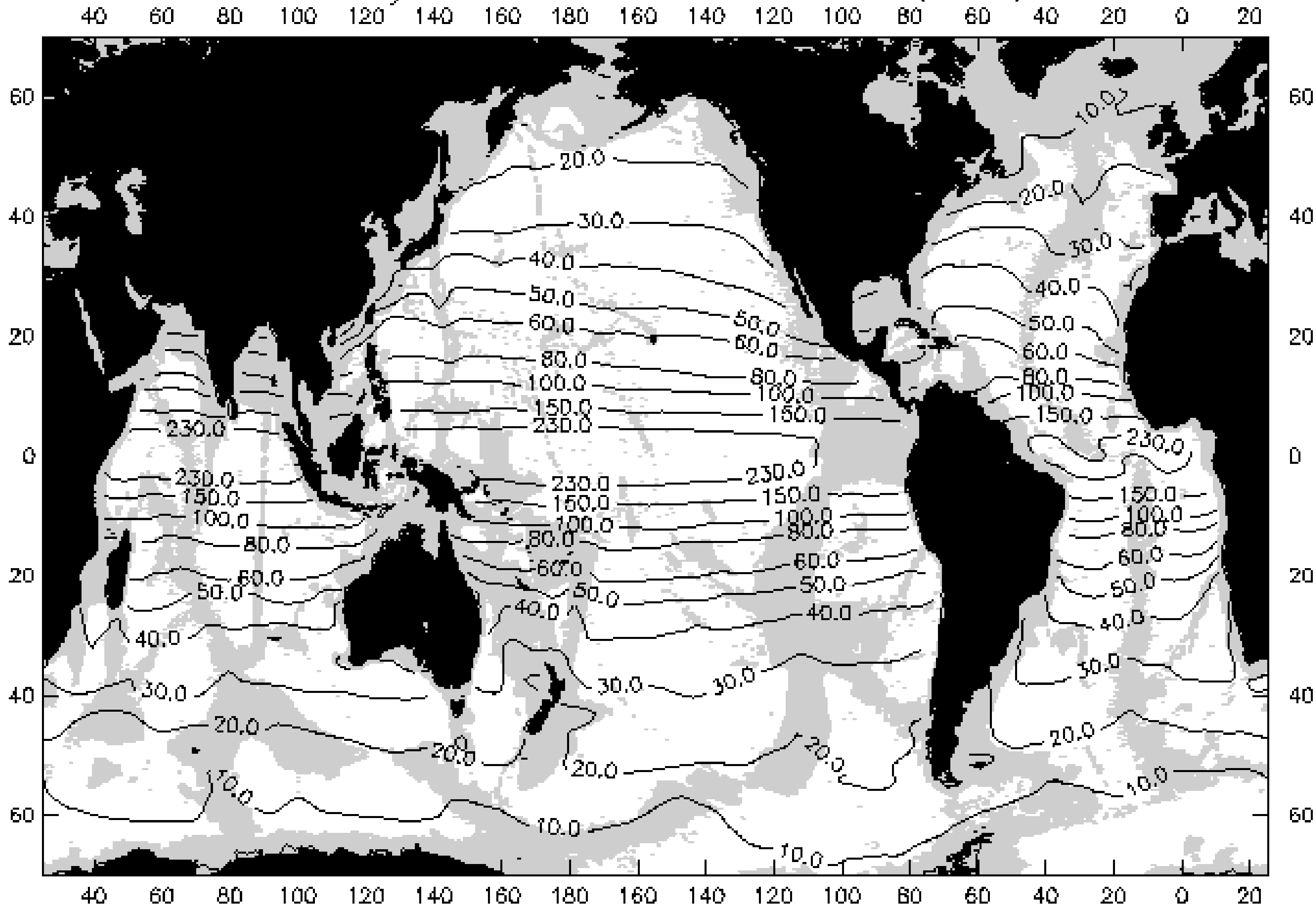


Enhancing spatial resolution and getting closer to the coasts

- Meso- & sub-mesoscale ocean dynamics
- Shelf-open ocean interactions
- Linkage of ocean and terrestrial element of the water cycle.
- Importance to biogeochemistry.

Spatial scales to resolve: the Rossby radius

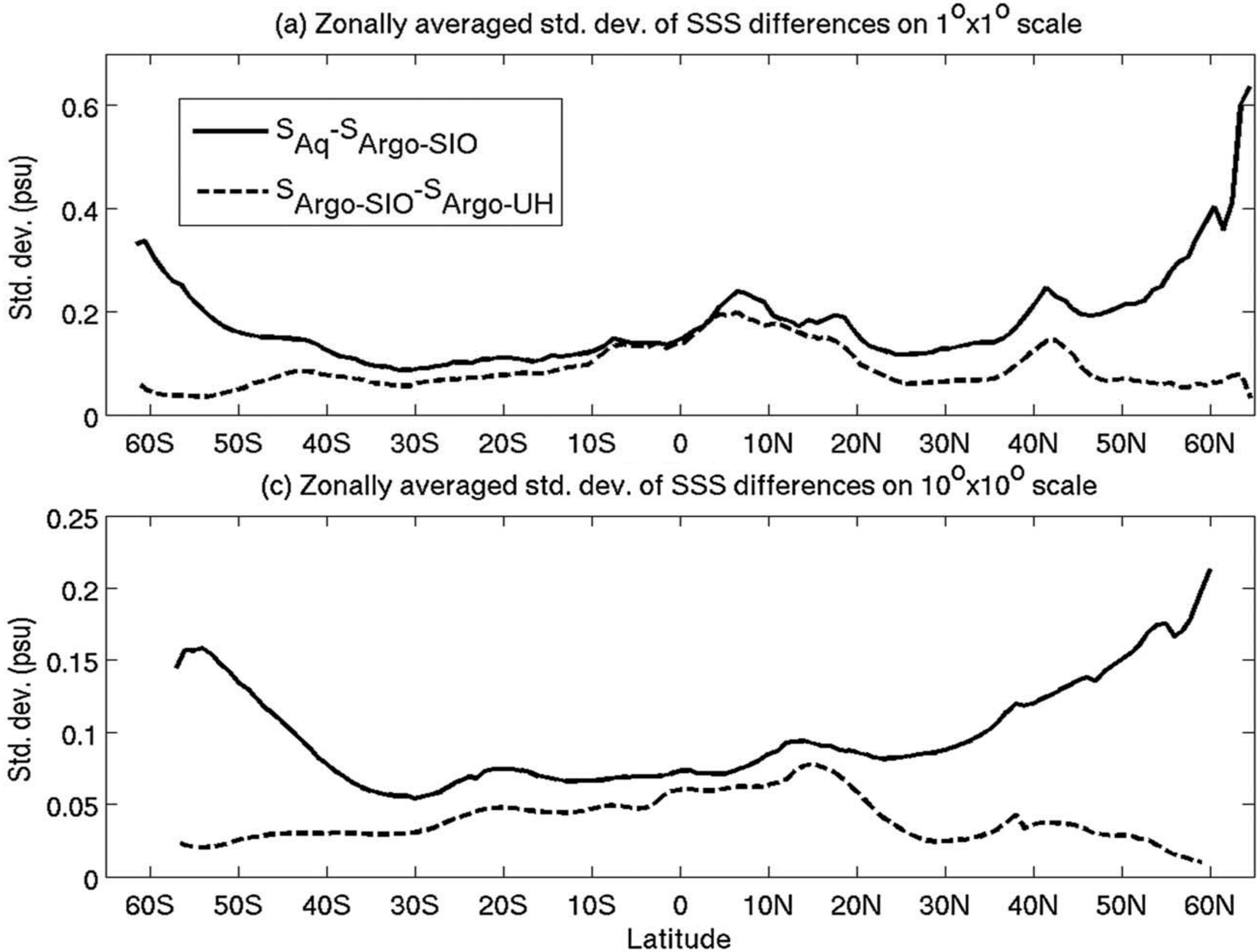
Baroclinic Rossby radius of deformation (in km)



Improving high-latitude SSS accuracies

L-band SSS accuracies: Tropics & subtropics ✓ high-latitudes ✗

Zonally averaged STD of ΔSSS for (Aquarius - Argo-SIO) & (Argo-SIO - Argo-UH)

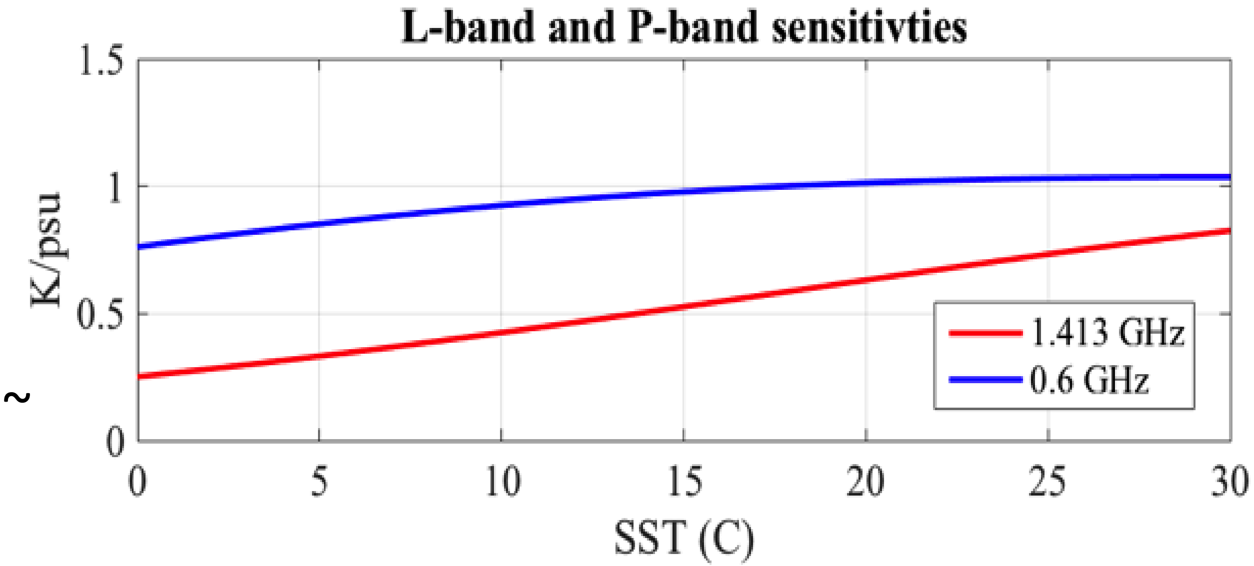


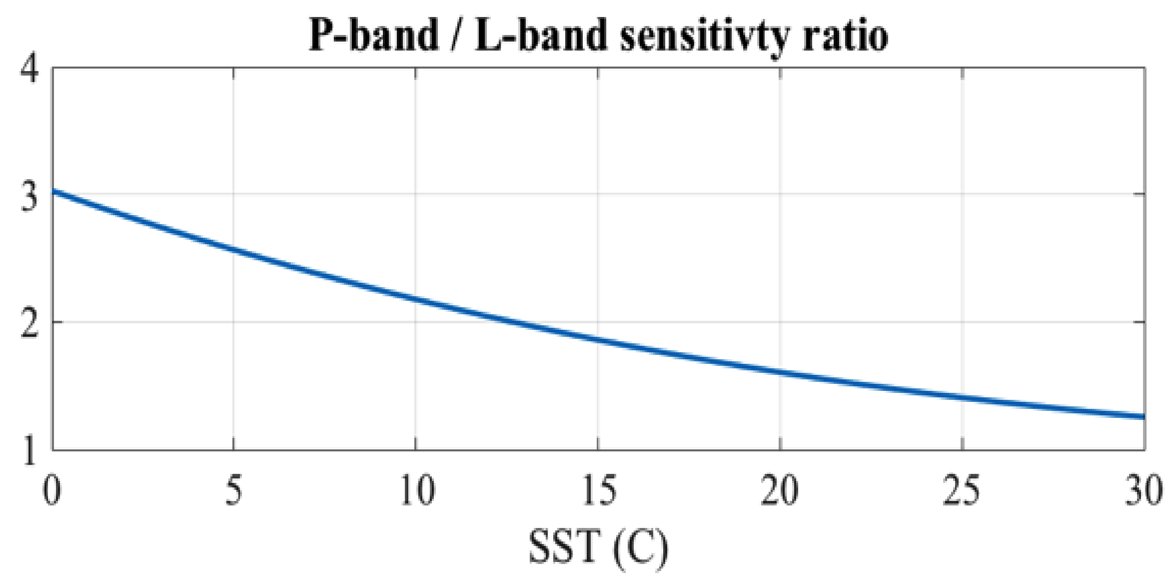
Community input to US Decadal Survey: adding P-band to L-band to improve high-latitude SSS & sea ice thickness measurements

(Lee et al. 2016, NRC)

Rationale:

T_B at P-band has ~ 3 times better sensitivity to SSS than at L-band at high-latitude oceans

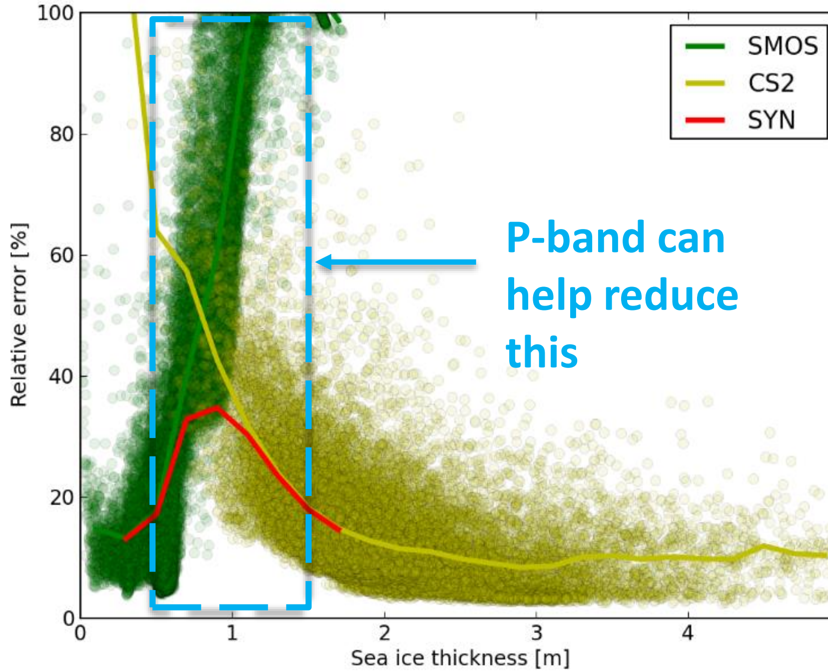


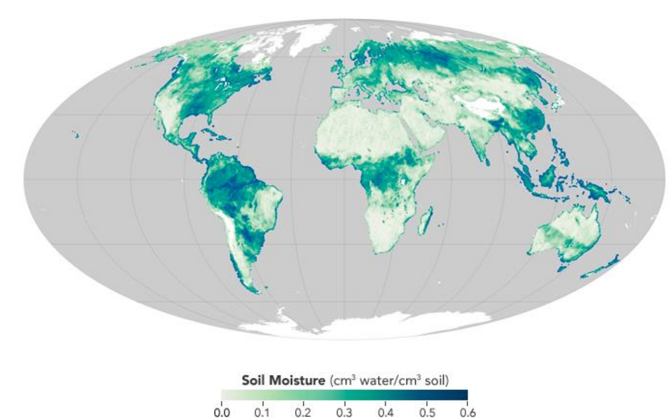


Additional values of P-band radiometry

- Improving sea ice thickness measurements by complementing radar and L-band radiometry measurements
- Better thickness measurements for 1st-year ice in turn help improve SSS retrievals near sea ice.
- Other applications: ice shelf, land (e.g., soil moisture, evapotranspiration).

Sea-ice thickness measurement error (Kaleschke et al. 2015)





Summary

- L-band satellite SSS have demonstrated the values to improve
  - the understanding of ocean processes and their linkages with the water cycle & climate variability;
  - environmental monitoring/assessment;
  - ocean state estimation & seasonal prediction
    - Important to understanding satellite SSS error characteristics, and take into account sampling differences from in-situ data

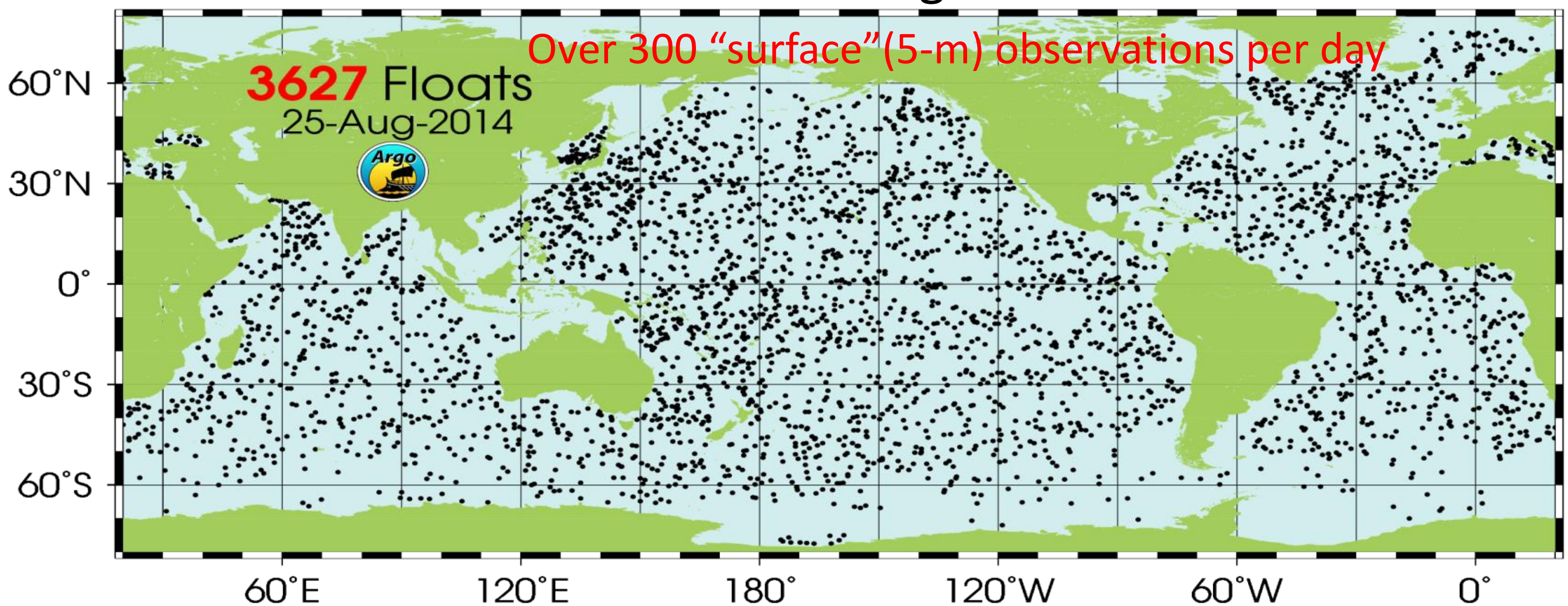
- L-band SSS have unique advantages while being synergistic to other observations to study Earth System Science.

- Requirements for future satellite SSS:
  - Continuity
  - Enhancing resolution
  - Improving accuracy, esp. in high-latitude oceans
    - Technology; retrievals

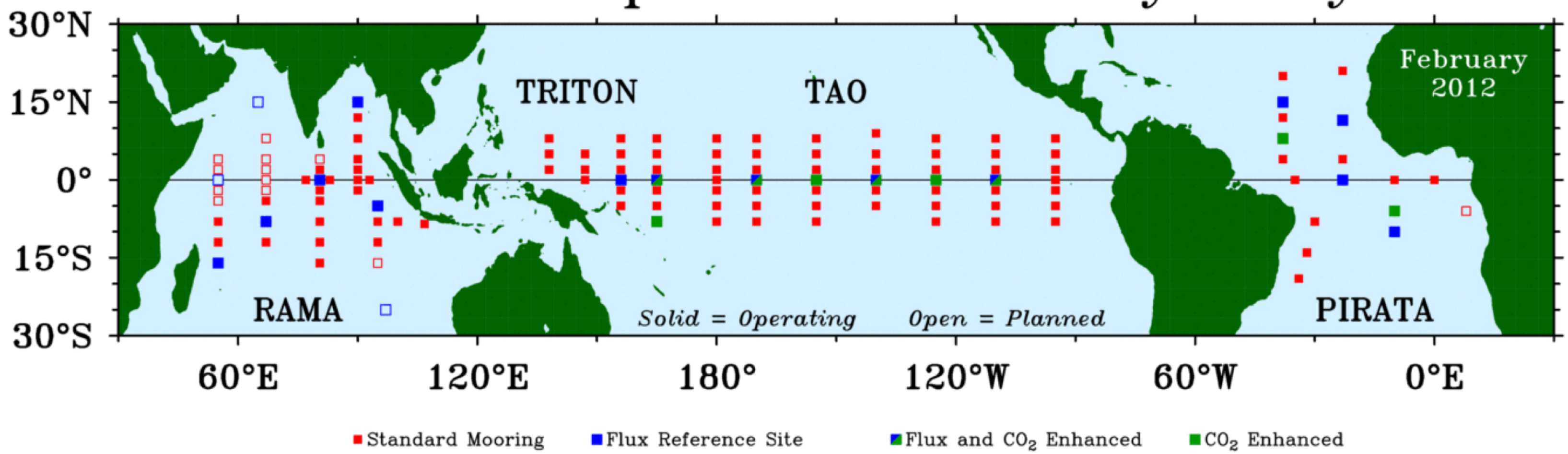
Backup

Main Sources of validation data for Satellite SSS

Distribution of Argo floats



Global Tropical Moored Buoy Array



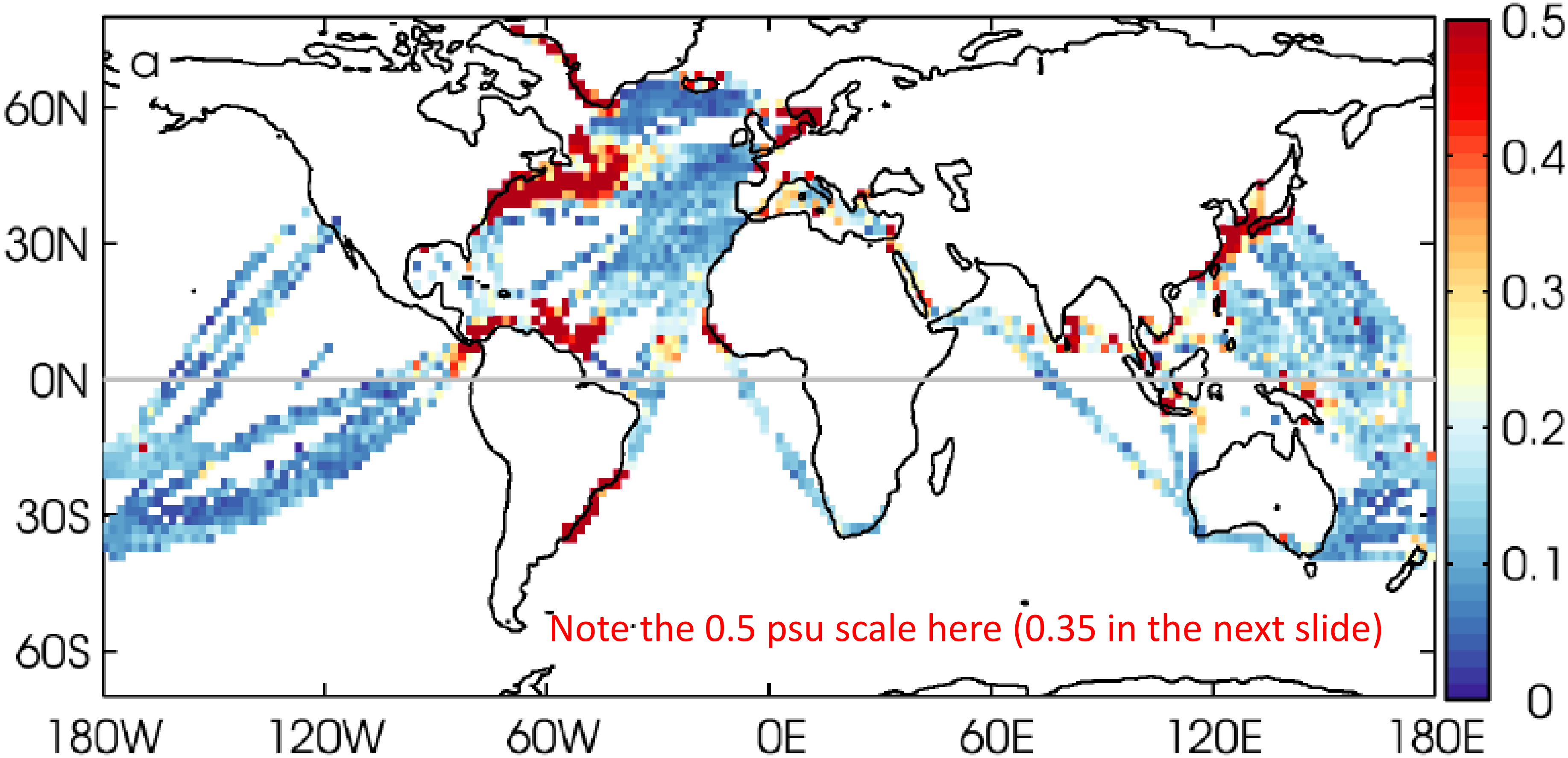
Also ship-based measurements, esp. high-resolution thermosalinograph (TSG) data

Two important issues in assessing the accuracies of satellite SSS

1. **Sampling differences between satellite & in-situ measurements**
   - Satellite SSS: averages within footprints (& time windows for L-3 data)
   - In-situ measurements: point-wise, instantaneous
   - Significant differences between the two in regions of strong spatiotemporal variability (e.g., rain bands, river plumes, strong eddying currents)
   - **Caution needed for interpreting differences between satellite & in situ salinity differences (esp. for level-2 SSS & "co-located" individual in-situ data)**

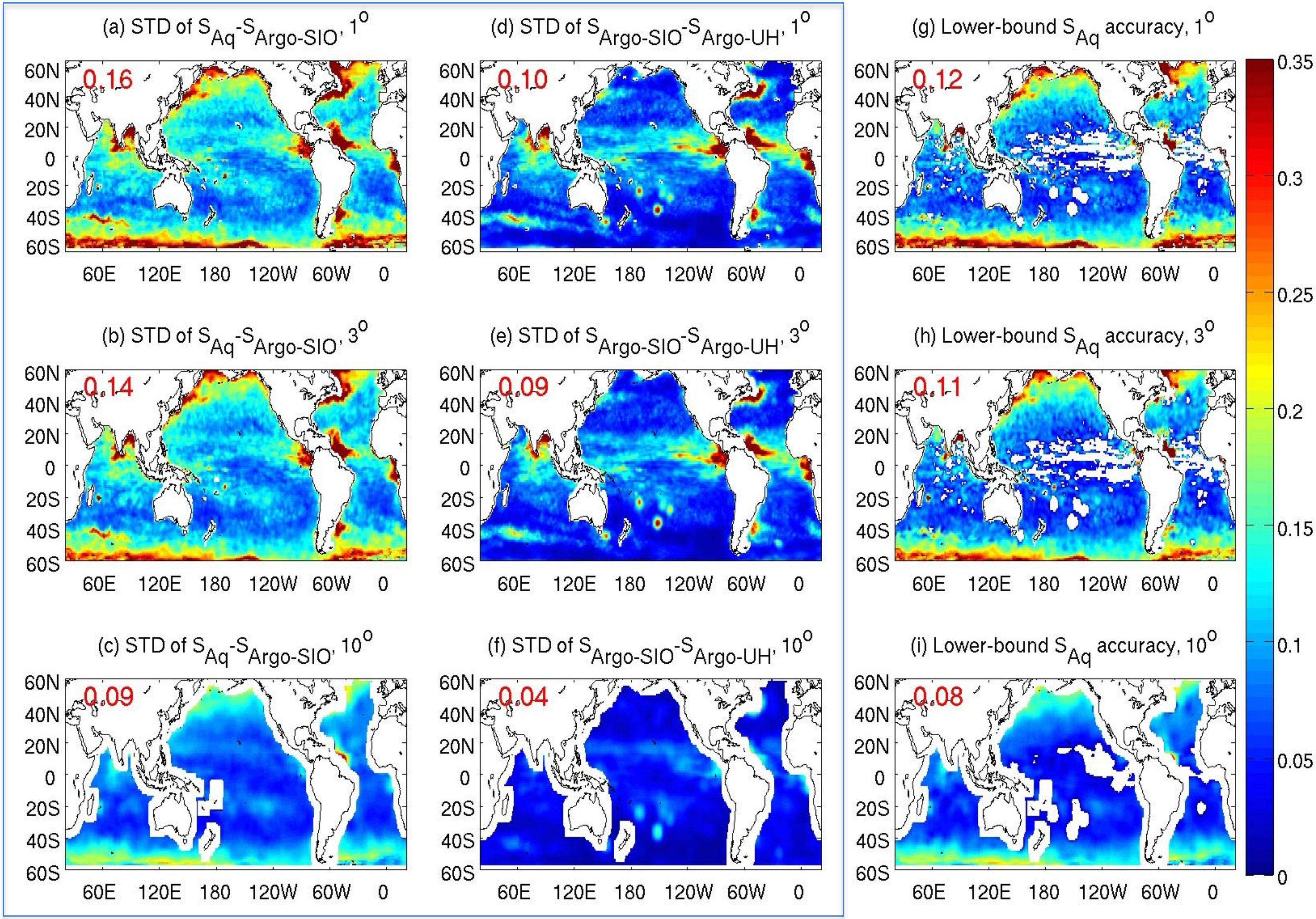
2. **Effect of near-surface salinity stratification**
   - Satellites measure salinity in the upper cm
   - Most in-situ measurements are >= 5 m (Argo) or >= 1 m (mooring)
   - Importance of salinity stratification in the upper meter under certainty conditions (e.g., during SPURS & SPURS2 field campaigns)

High-res TSG observations show large std. dev. of SSS within 100-km intervals in regions with strong variability



Boutin et al. (2016, BAMS)

STD of SSS Difference for Aquarius - Argo-SIO & Argo-SIO vs. Argo-UH for different spatial scales (Lee 2016)



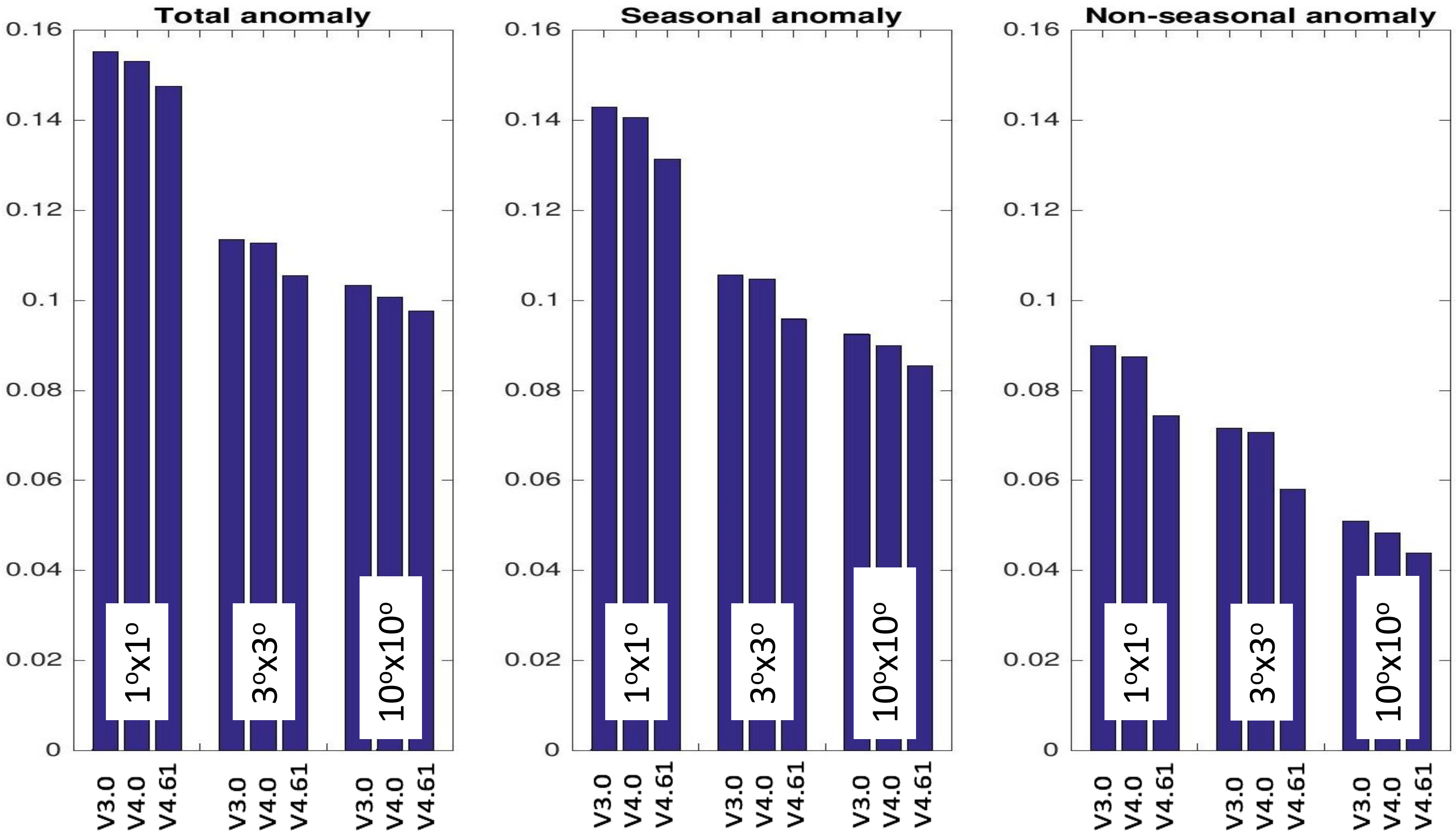
“Global” (65N-65S) area-weighted averages STD of SSS differences for Aquarius vs. Argo-SIO & Argo-SIO vs. Argo-UH for different spatial scales: seasonal time scales

Table 1. Globally averaged standard deviation values (in psu) between Aquarius and Argo-SIO and between Argo-SIO and Argo-UH.

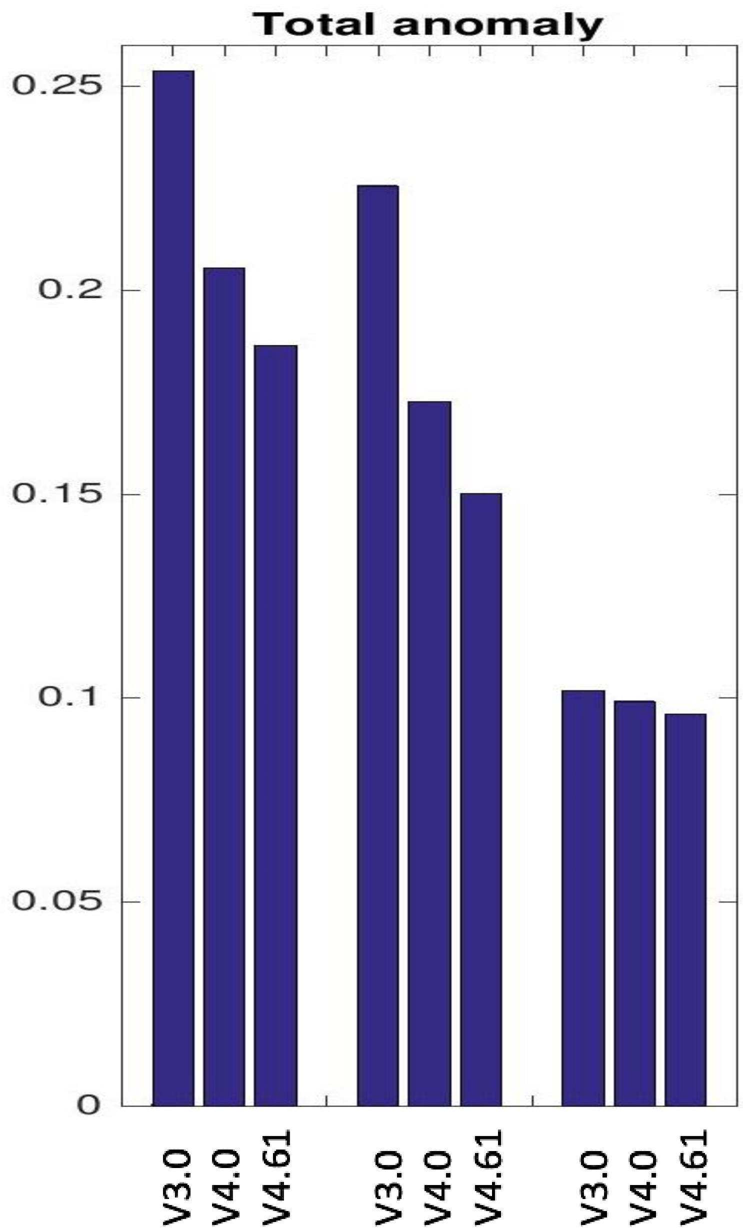
	1°x1°	3°x3°	10°x10°
Aquarius vs. Argo-SIO (total)	0.16	0.14	0.09
Argo-SIO vs. Argo-UH (total)	0.10	0.09	0.04
Aquarius vs. Argo-SIO (seasonal)	0.11	0.11	0.07
Argo-SIO vs. Argo-UH (seasonal)	0.06	0.05	0.02
Aquarius vs. Argo-SIO (non-seasonal)	0.10	0.09	0.05
Argo-SIO vs. Argo-UH (non-seasonal)	0.07	0.06	0.03

- Uncertainty of Aquarius SSS in estimating large-scale SSS changes is < 0.05 psu on monthly & longer time scales.
- Time averaging could further reduce the uncertainty.

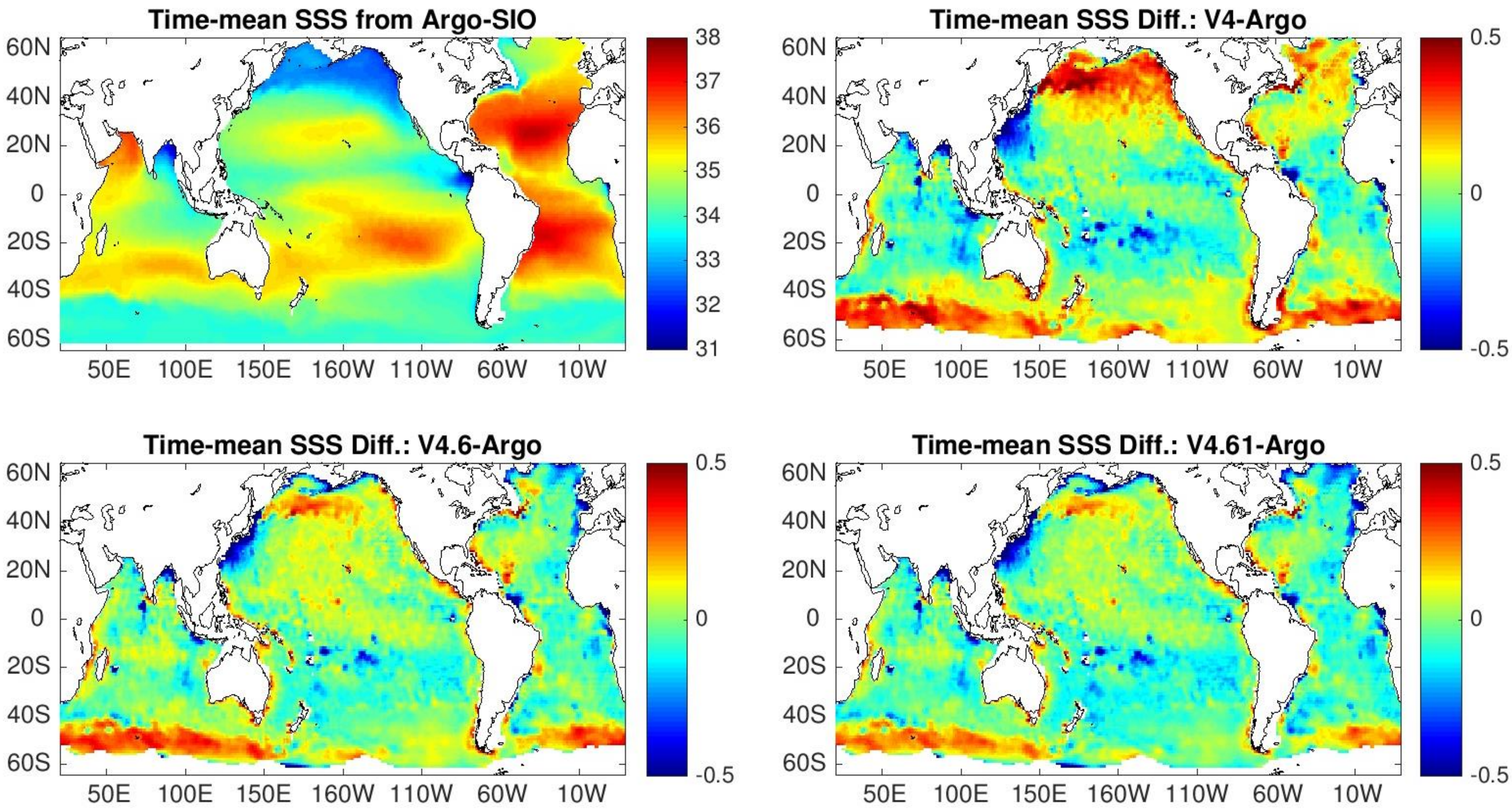
Global STD of Aquarius-Argo SSS for various spatial & temporal scales



Global RMSD of Aquarius-Argo SSS for various spatial & temporal scales

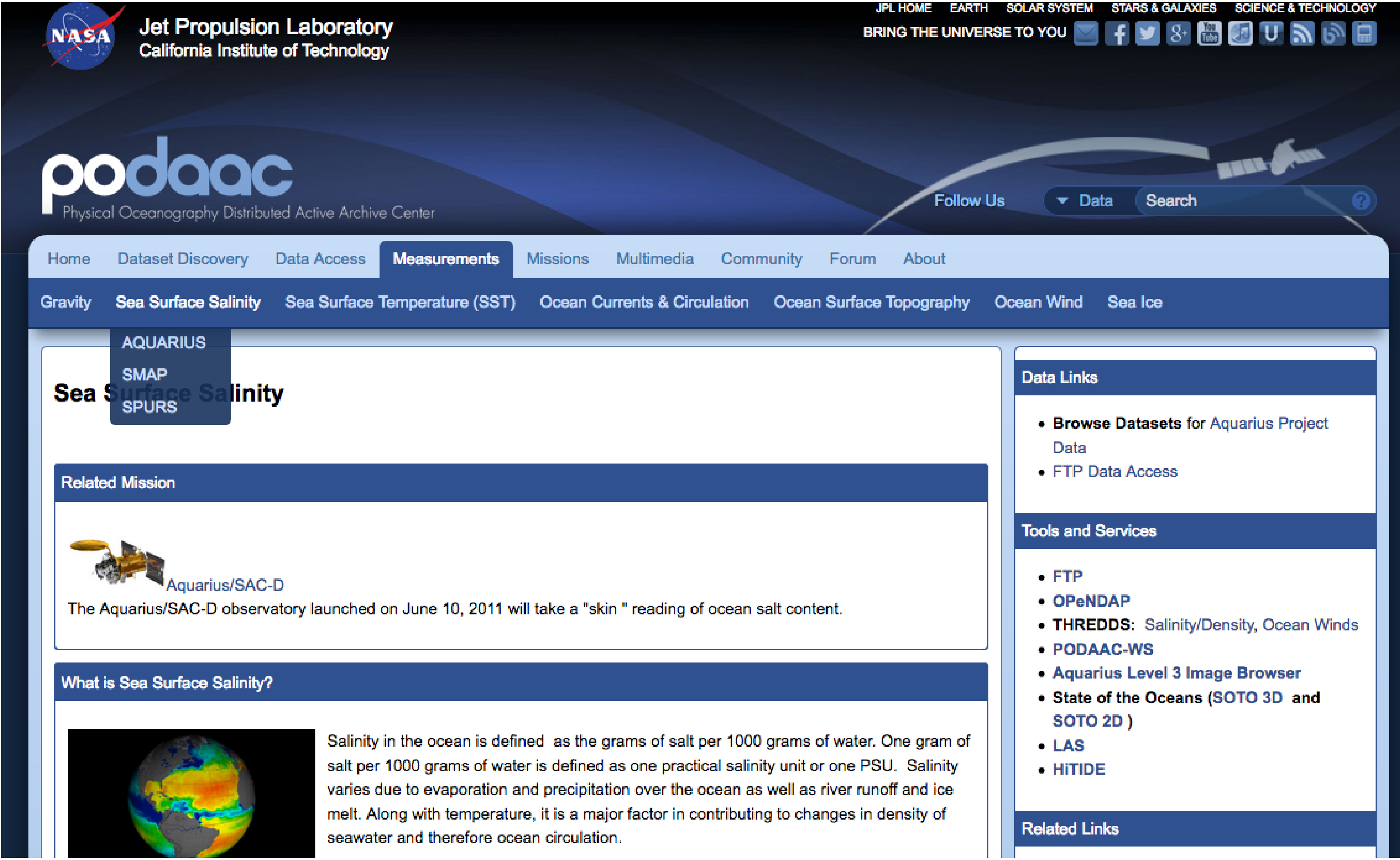


Time-mean SSS (09/2011-05/2015)



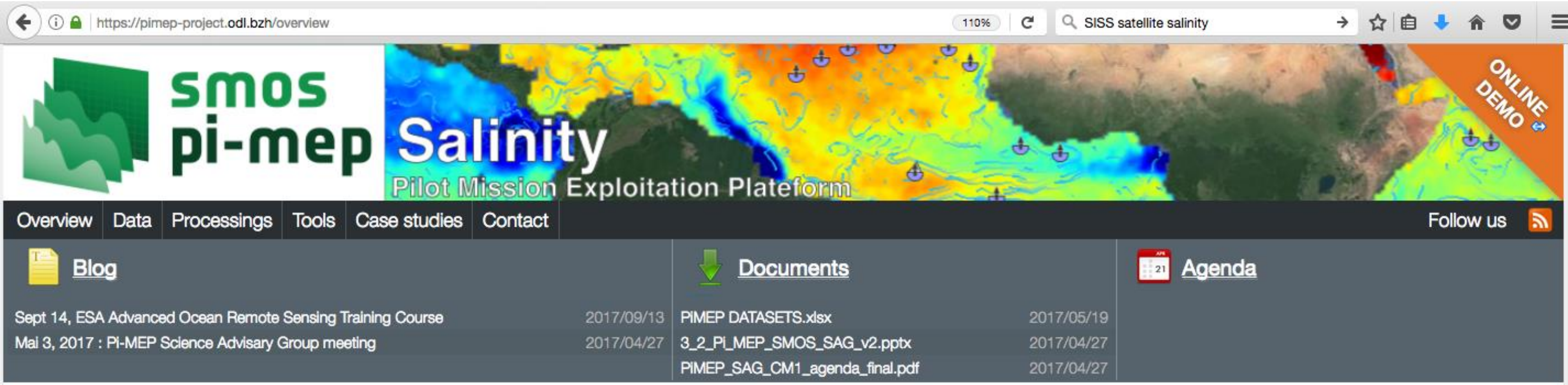
Where to get satellite SSS products?

For all Aquarius & SMAP SSS: https://podaac.jpl.nasa.gov/



Where to get satellite SSS products? (cont'd)

For all L-band satellite SSS:
ESA funded **SMOS Pilot Mission Exploitation Platform (SMOS Pi-MEP):**
https://pimep-project.odl.bzh/data
has http links to various level-2 to level-4 satellite SSS products

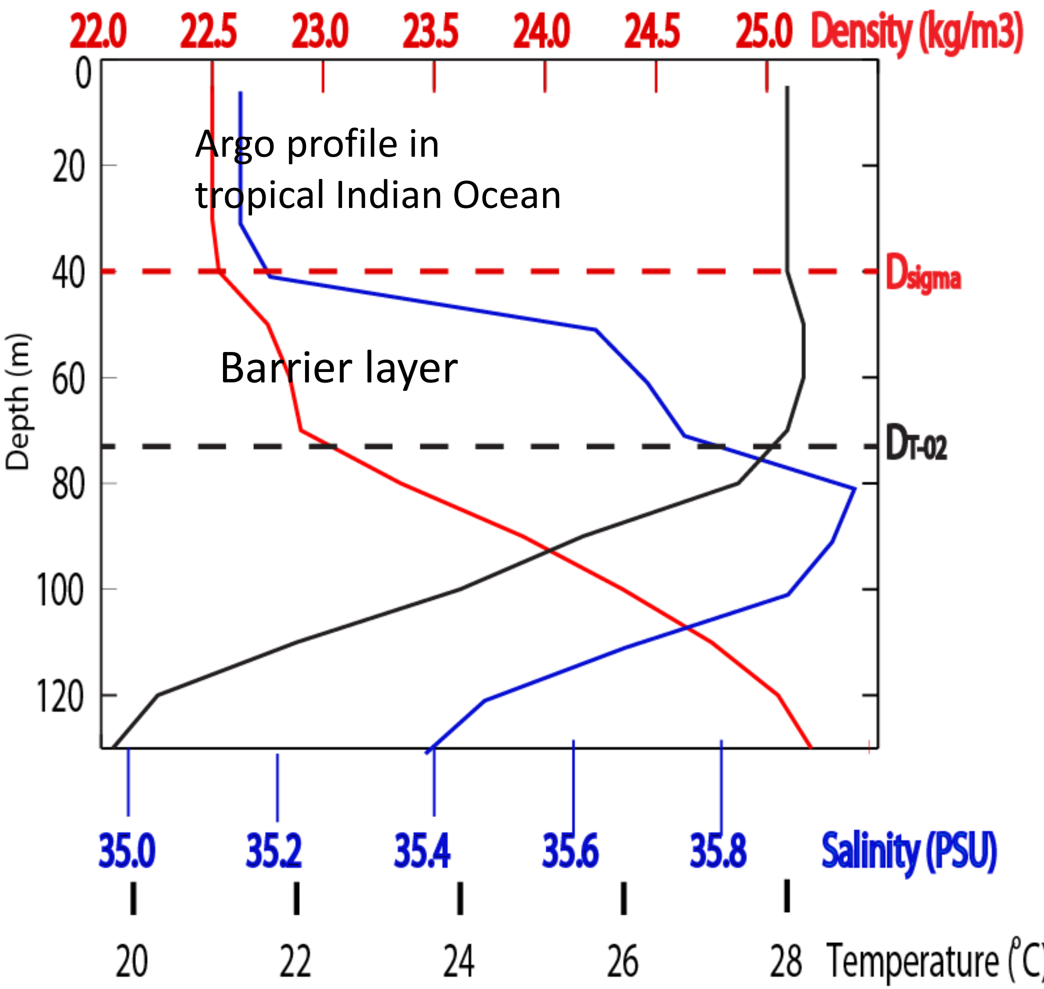


Other useful resources:
Satellite and In-situ Salinity (SISS) Working Group: http://siss.locean-ipsl.upmc.fr/
Aquarius: https://aquarius.nasa.gov

Indirect effect of salinity on SST (thus air-sea interaction): example – effects of the barrier layer

Barrier layer: a S stratified, T uniform layer below the mixed layer but within the isothermal layer

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



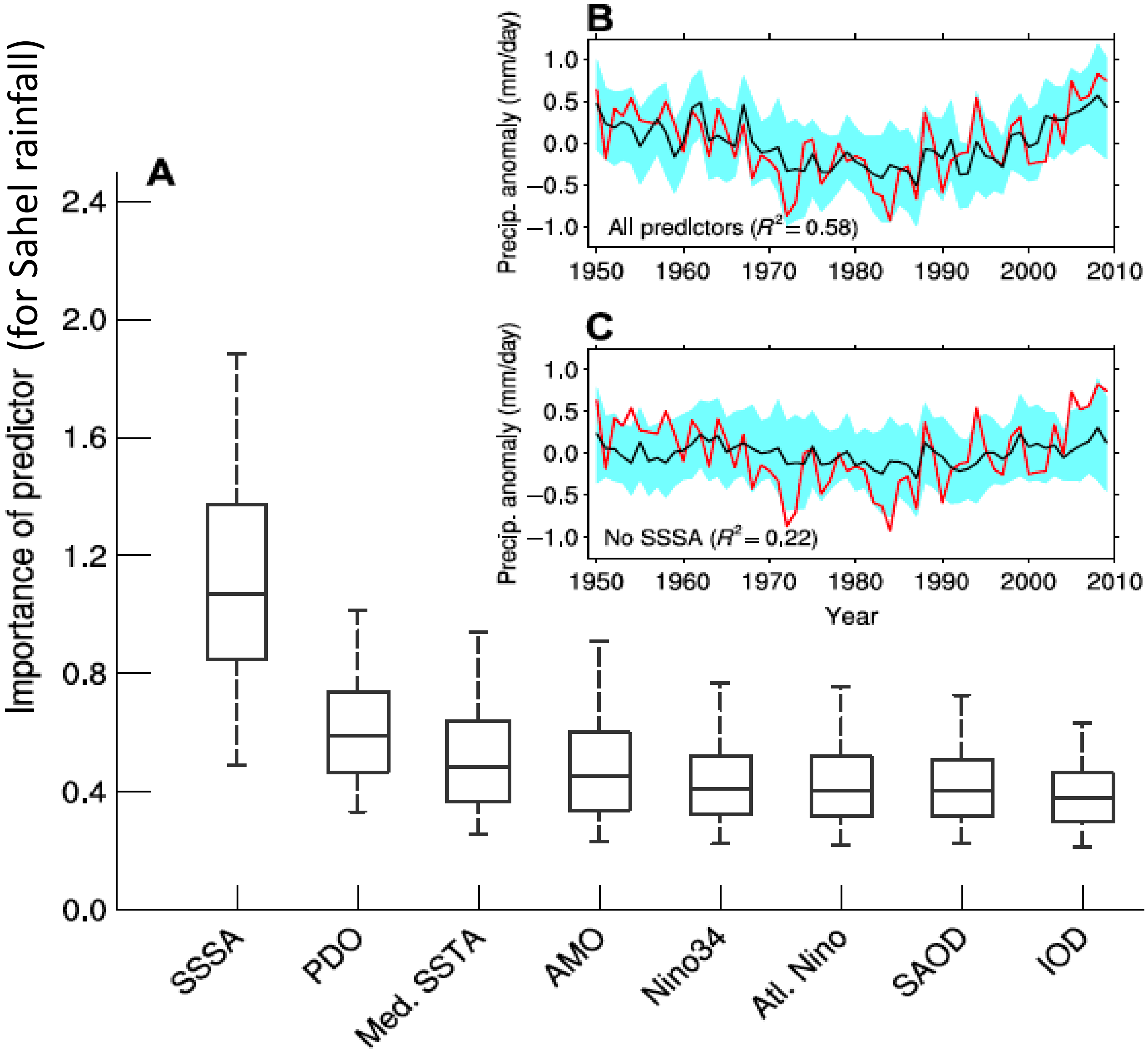
(e.g., Lukas & Lindstrom 1991, Sprintall & Tomczak 1982, Maes et al. 2005)

"Take a grain of salt when studying SST"

SSS as an indicator of global water cycle changes

- Large uncertainties in E-P estimates
- Difficulty to measure global river discharges
- SSS directly respond to E-P, river discharge, and sea ice formation/melt

Subtropical N.Atl. SSS as a predictor of Terrestrial Rainfall



Li et al. (2016a, Science Advance): for Sahel rainfall

Li et al. (2016b, J. Clim): for US Midwest rainfall

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

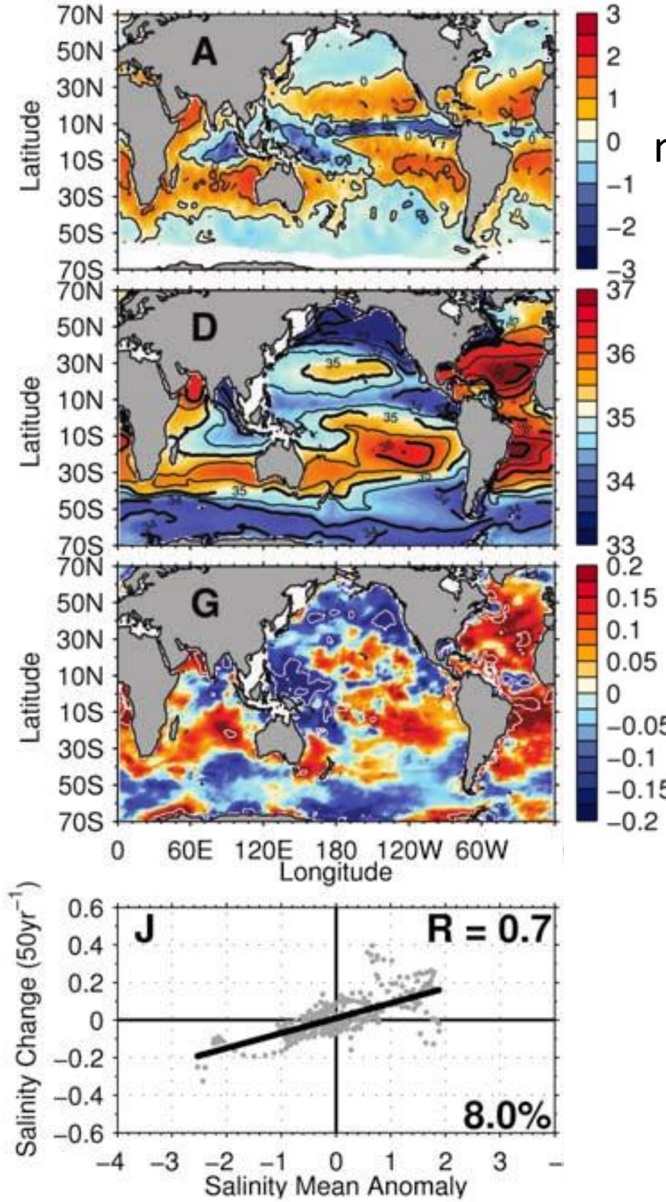
Durack et al. (2012, Science)

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)

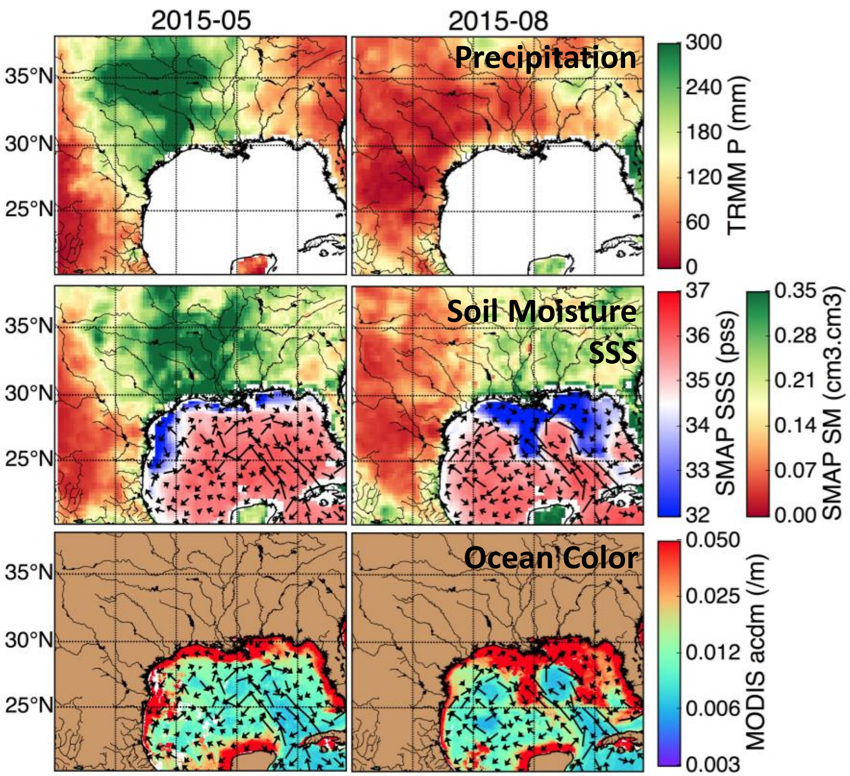


m^3/year

psu

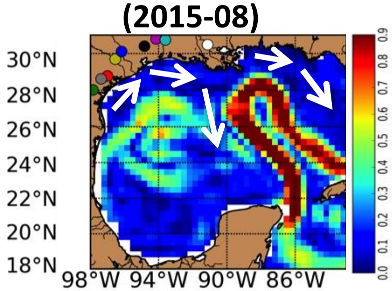
psu

A combined land/sea assessment of the impacts of the May 2015 severe Texas flooding event



May and August 2015 GPM precipitation, SMAP soil moisture and sea surface salinity (SSS) and MODIS Ocean Color.. Vectors: JASON-2 surface currents.

Current Speed & schematics (2015-08)



August 2015 surface current speed (JASON-2) showing the Loop Current, its eddy, and schematics of the flow pattern that shaped the "horseshoe" freshwater plume

Problem: How does the May'15 severe flooding in Texas affect terrestrial hydrologic conditions, marine environment, and their linkage?

Finding: Intense rainfall in May'15 over Texas caused saturated soil & record river discharges into the Gulf of Mexico (GoM). The unusually strong Loop Current & its eddy shaped the freshwater into a "horseshoe" pattern, affecting regions not normally influenced by river plume.

Significance: Implications to the extent of the GoM hypoxic zone and the Flower Garden Bank coral reef ecosystem. Multi-variate satellite observations (e.g., SMAP, GPM/TRMM, MODIS, JASON-2, GRACE, and SMOS) are essential to provide integrated assessment of land/sea impacts associated with flooding.

Fournier S., J.T. Reager, T. Lee, J. Vasquez, C. David, & M. Gierach (Aug. 2016, GRL).

Improving ancillary data (e.g., SST) for SSS retrievals at high-latitude oceans also important

- L-band brightness temperature has weak sensitivity to SSS at high latitudes
- accuracy of ancillary SST becomes more important
- but high-latitude satellite SST also have significant errors

Comparison of GHRSST blended SST products an Arctic buoy SST