Satellite SST & SSS observations and their roles to constrain ocean models
Part II
Salinity remote sensing: a new frontier in satellite oceanography

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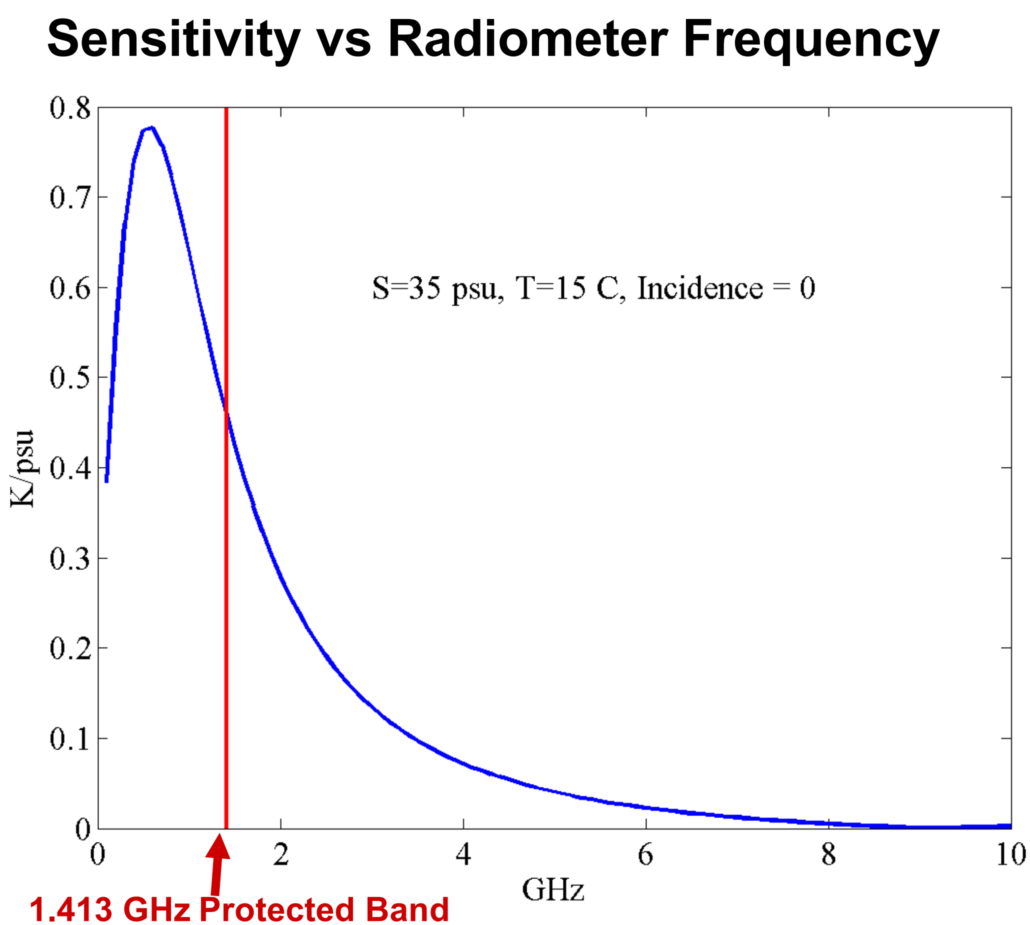
Outline

1. Overview of SSS satellite missions
2. Basic principles of measuring SSS from space
3. Calibration/validation and satellite SSS error characteristics
4. Scientific accomplishments of satellite SSS missions
5. Future challenges and ongoing development
6. Use of satellite SSS for constraining ocean models

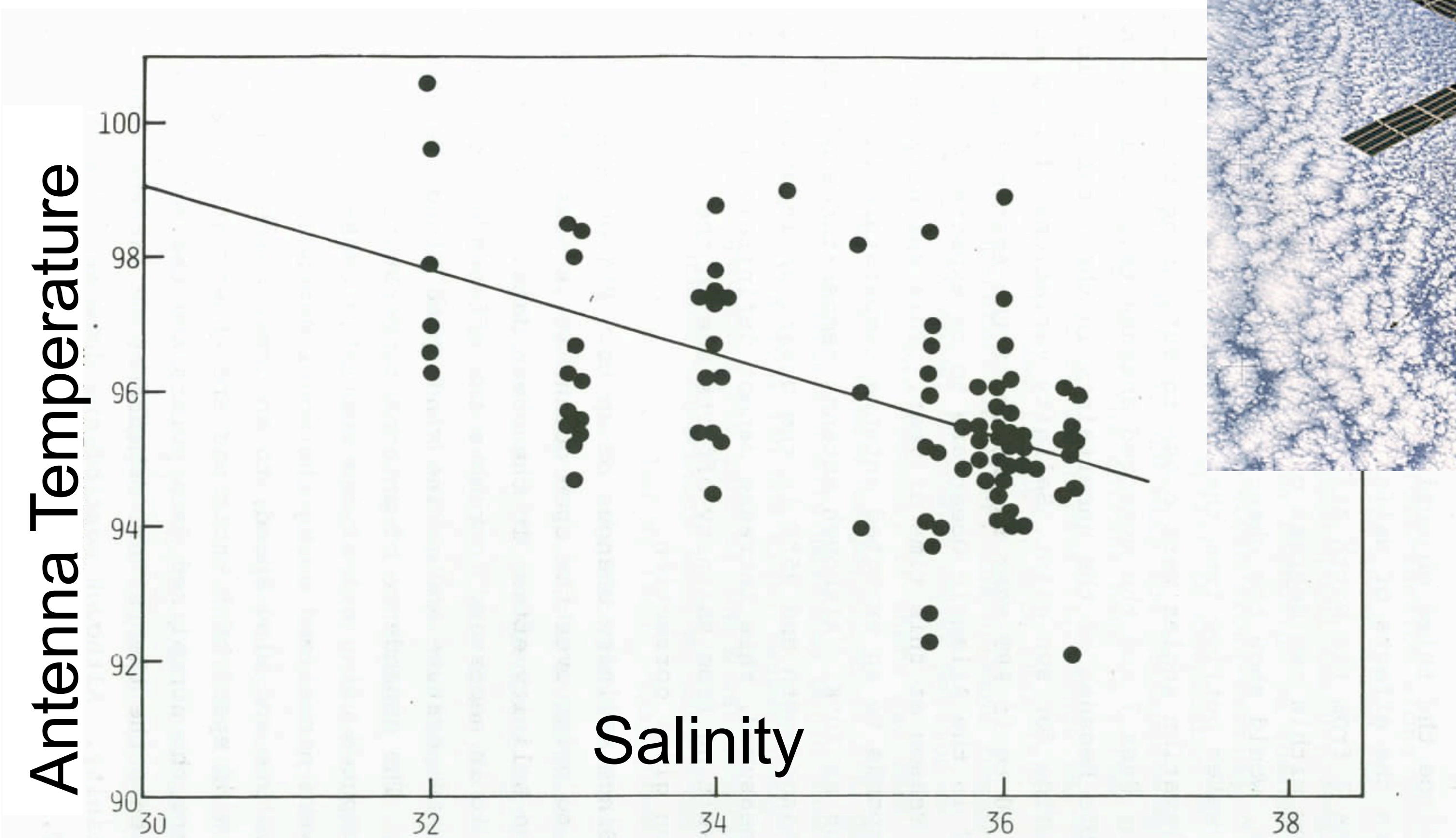
SSS Remote Sensing has been Based on L-band Radiometry (~1.4 GHz). Why?



- Protected band (used for radio astronomy)
- Relatively good sensitivity to SSS for SST > 5°C

- Other applications of L-band radiometry: **soil moisture, freeze/thaw state**, thin sea ice thickness, high winds
- SSS has the most stringent requirement for L-band radiometer precision

The first L-band SSS 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

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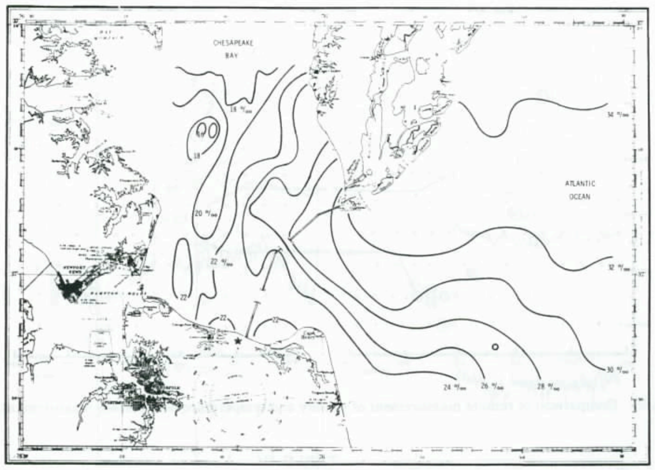
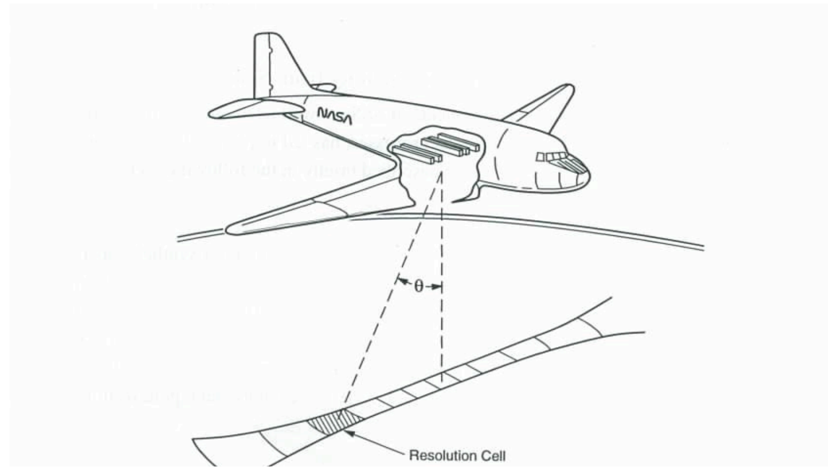


Fig. 8. Isohalines of the lower Chesapeake Bay with 2‰ increments on 24 August, 1976.



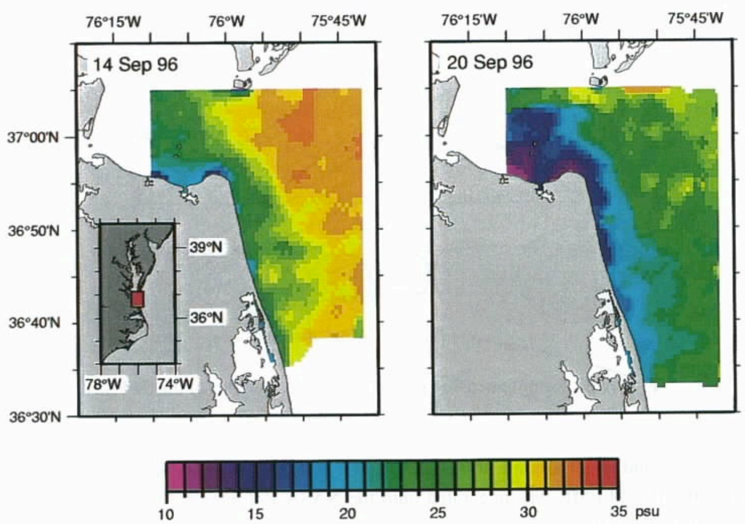
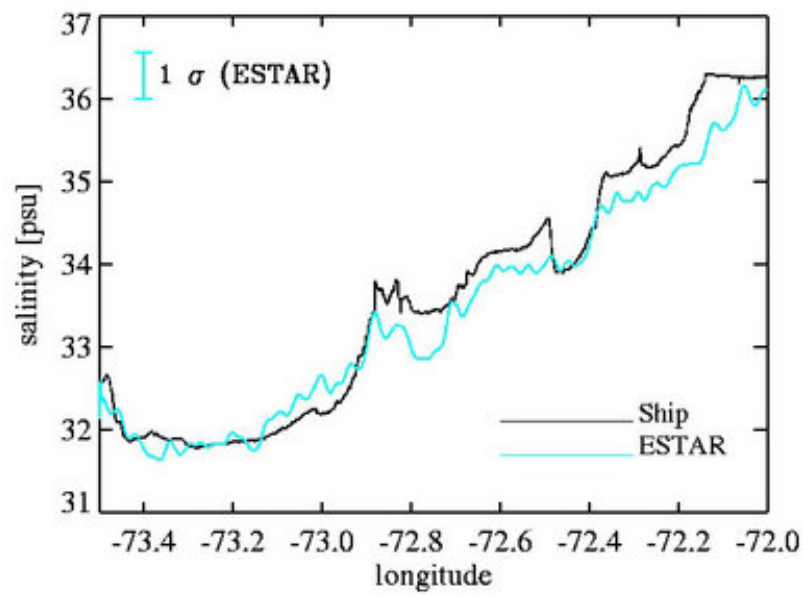


Figure 4. Airborne SLFMR measurements of sea surface salinity of the Chesapeake Bay plume on (right) 14 September 1996 and (left) 20 September 1996.

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



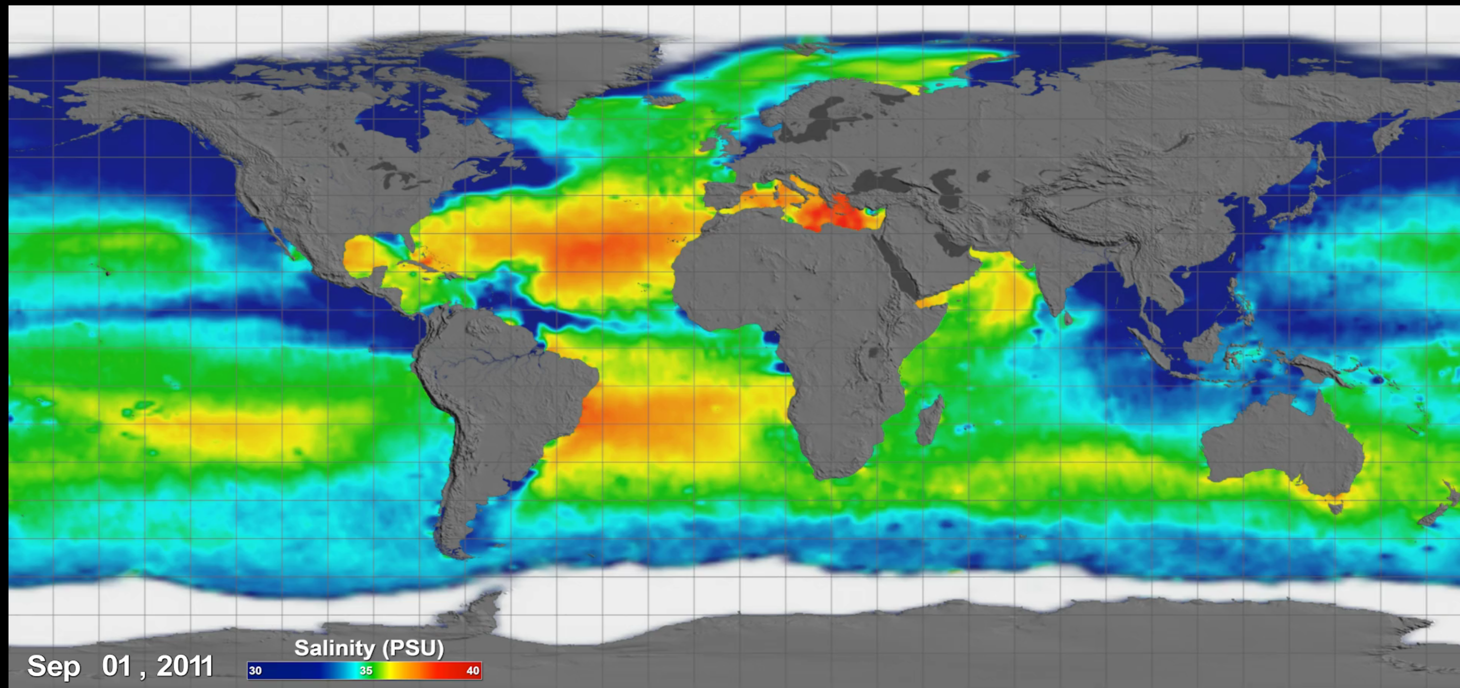
See Klemas (2011) for review of other airborne campaigns

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

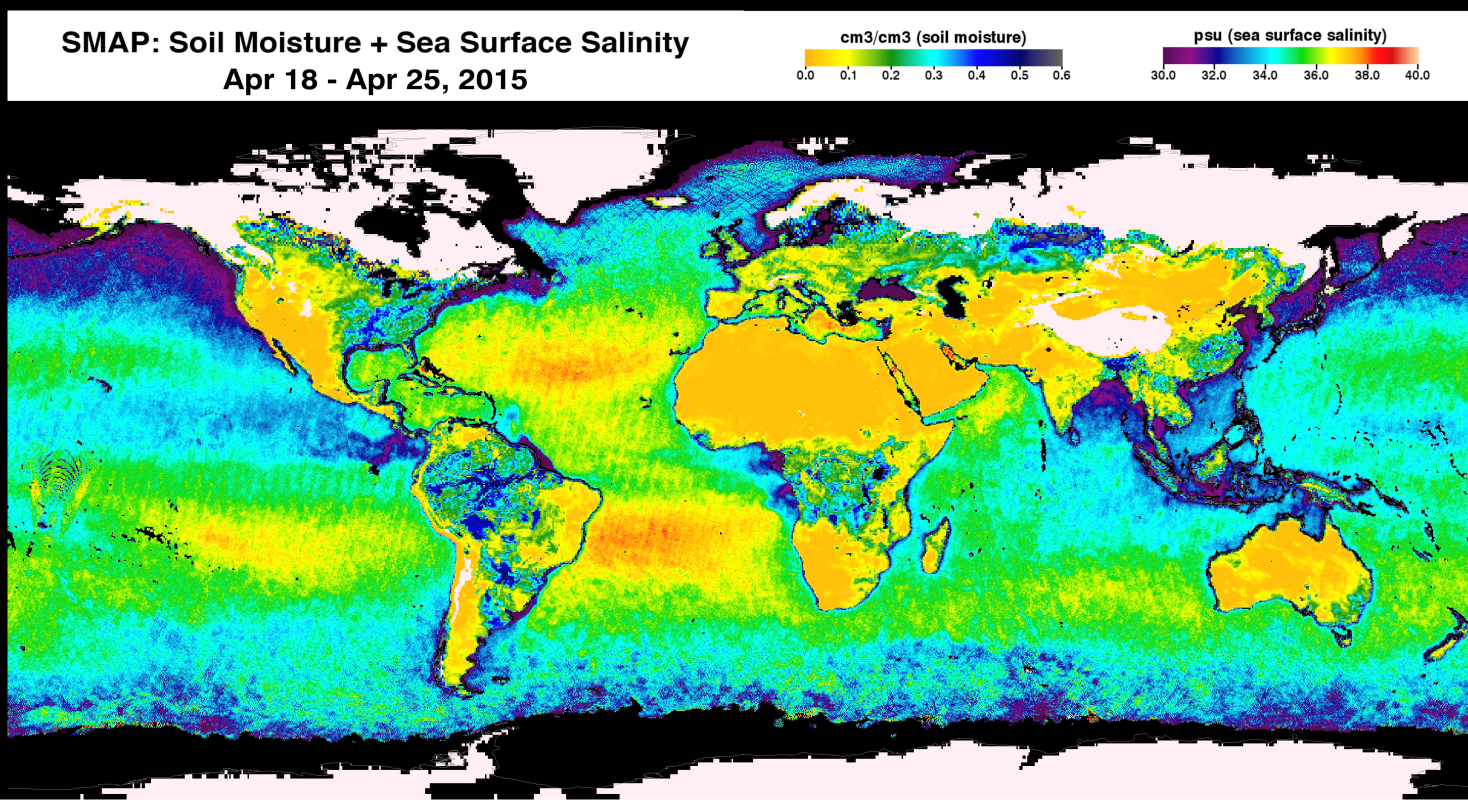
Aquarius SSS
(V4.0)
09/2011-
05/2015

~150 km
resolution

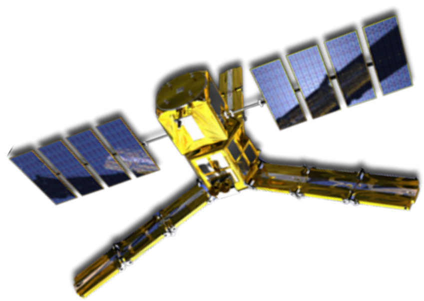


SMAP
SM & SSS
04/2015
onward

~40 km
resolution

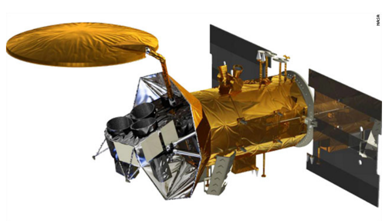


Main Instrument characteristics



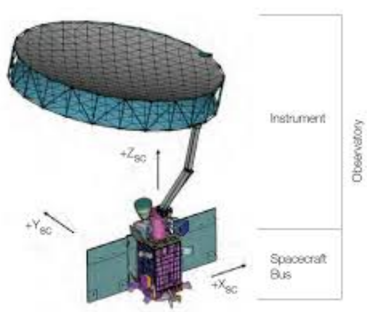
SMOS

- L-band radiometer
- synthetic aperture antenna with three 3-m arms, interferometry



Aquarius/SAC-D

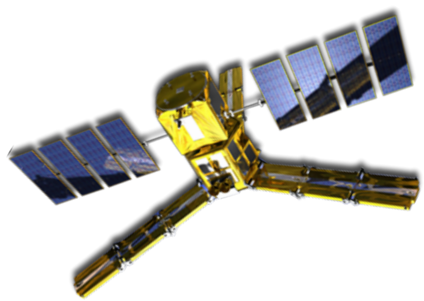
- Three L-band radiometers (0.1^{o}K precision!) + integrated L-band radar scatterometer
- Real aperture, 2.5-m antenna



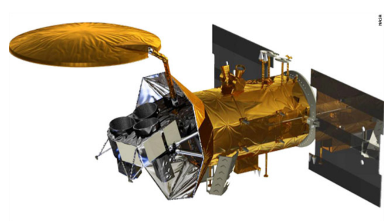
SMAP

- L-band radiometer + integrated L-band radar scatterometer
- Real aperture, 6-m spinning antenna (conical scanning)

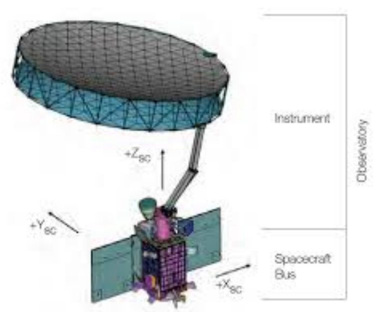
Orbit and sampling characteristics



SMOS
- ~40-km footprint
- 23-day repeat, 3-day sub-cycle
- Sun-synchronous polar orbit, 755 km
- ~1000-km swath



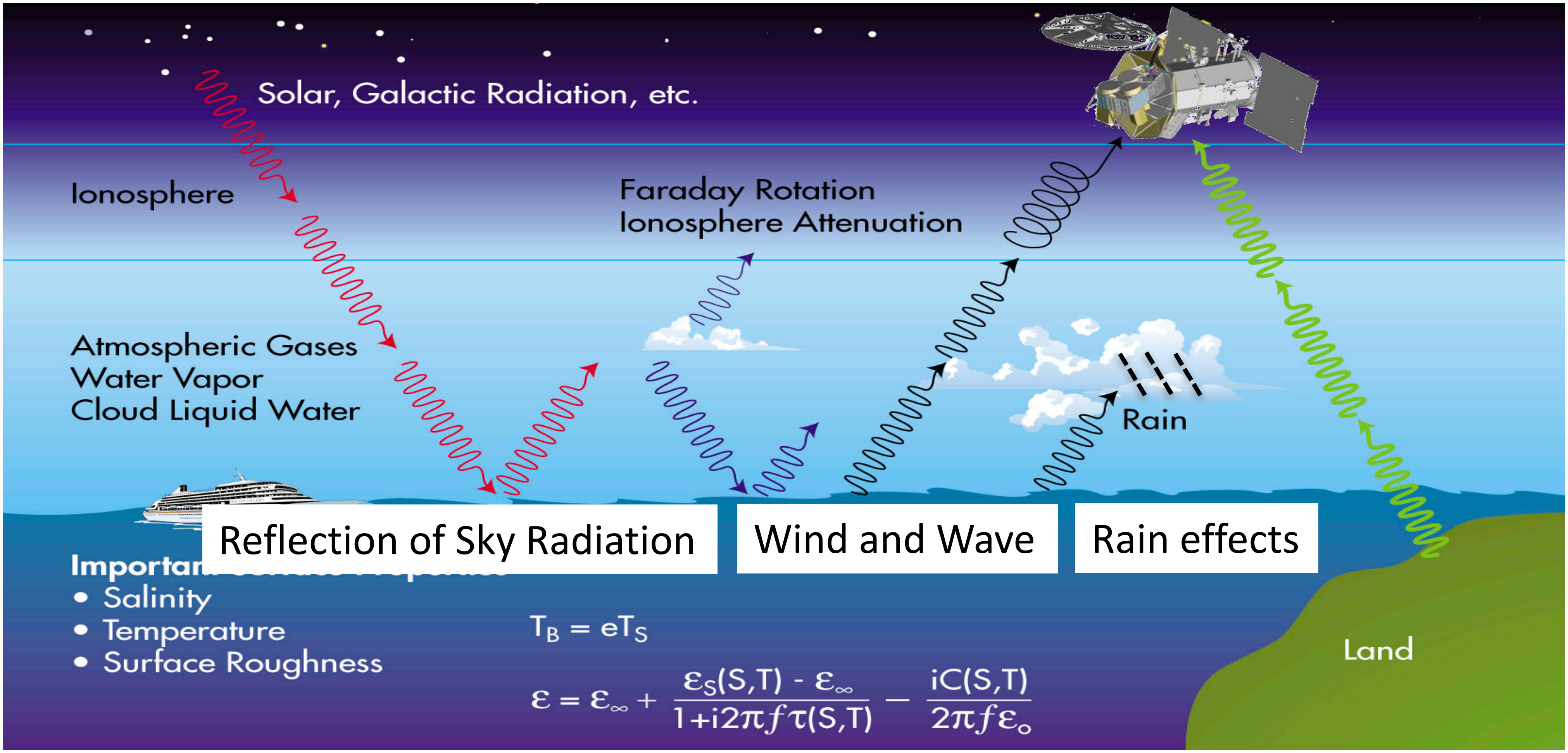
Aquarius/SAC-D
- ~100-150 km
- 7-day repeat
- Sun-synchronous polar orbit, 657 km
- 390-km swath



SMAP
- ~40-km footprint
- 8-day repeat
- Sun-synchronous polar orbit, 685 km
- 1000-km swath

The challenges of retrieving SSS from space

Need to correct for effects due to the sky (galactic) , atmosphere, ionosphere, land and ice, SST, and <u>especially surface roughness (from wind & rain)</u>.

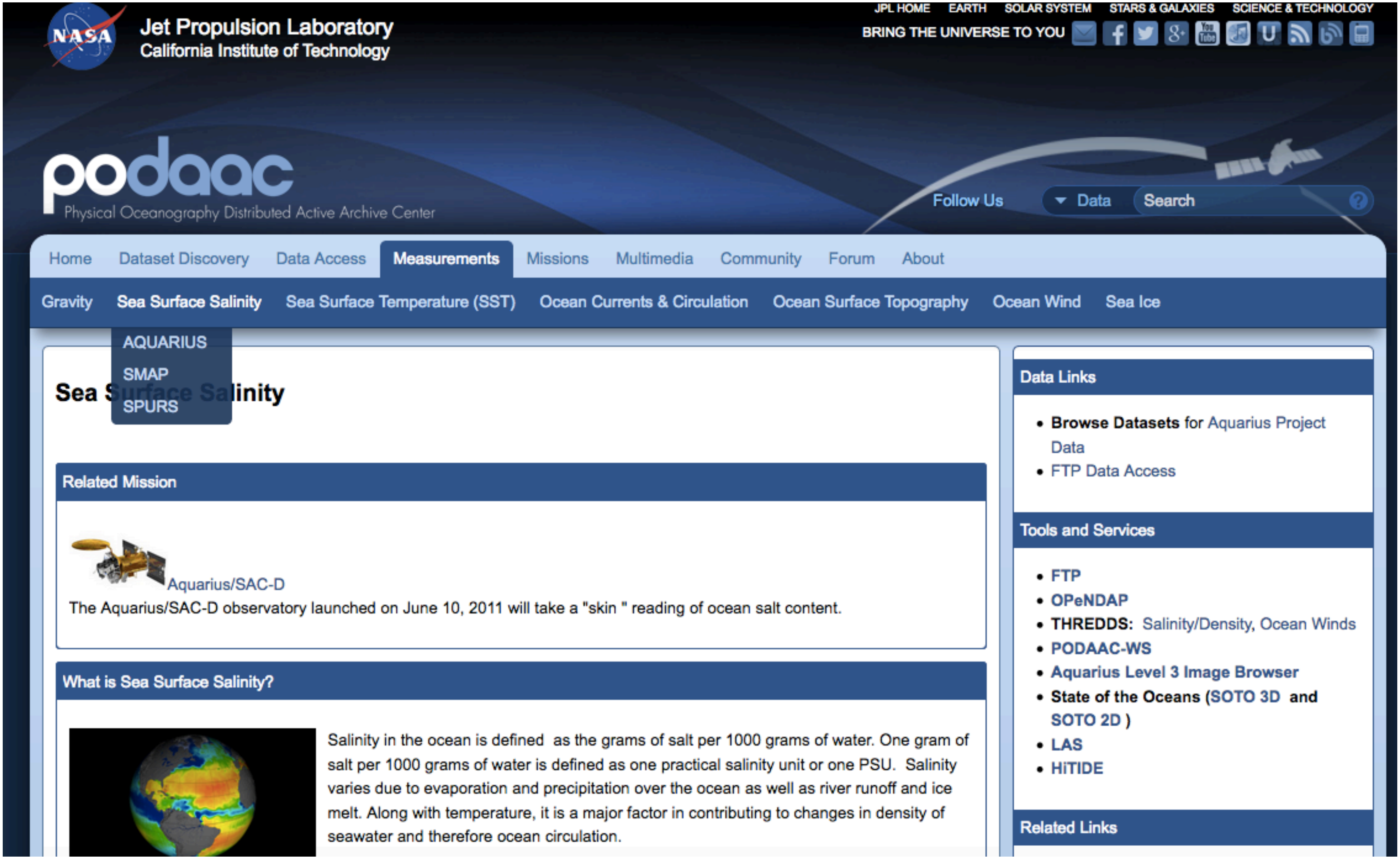


SSS retrieval from space

- L-band radiometer measures 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
- e is a function of, incidence angle θ, polarization (H or V), surface roughness, and dielectric coefficient ε (function of SSS, SST, and radio frequency)
- Main factors controlling L-band T_B are SSS, SST, and **surface roughness**
- Derive SSS (using a Geophysical Model Function) by removing effects of SST (ancillary data) & surface roughness (from onboard radar or ancillary data)
- Also need to correct for effects of galactic reflection, land/ice signal leakage, radio frequency inference (RFI).

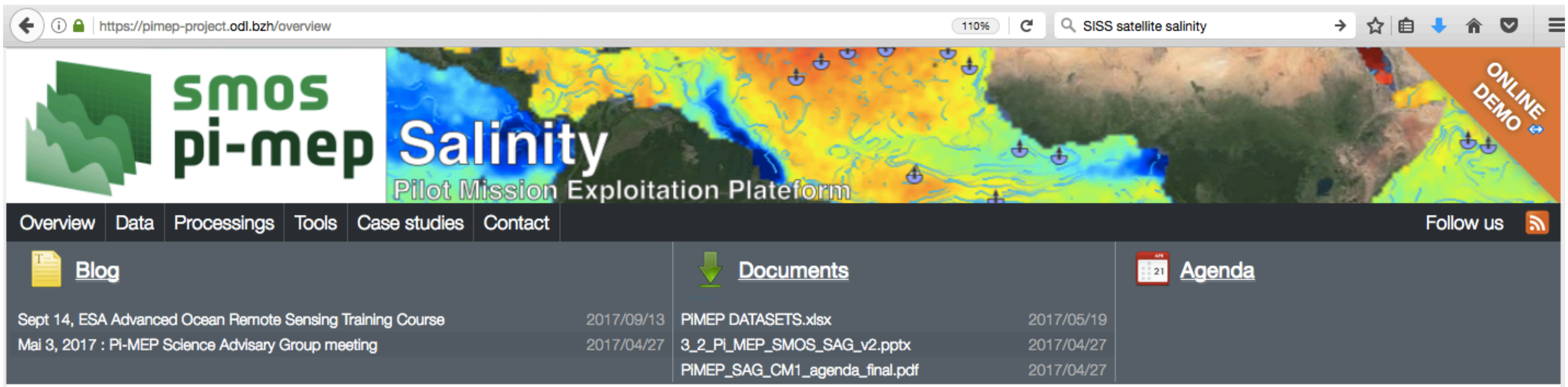
Where to get satellite SSS products?

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



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

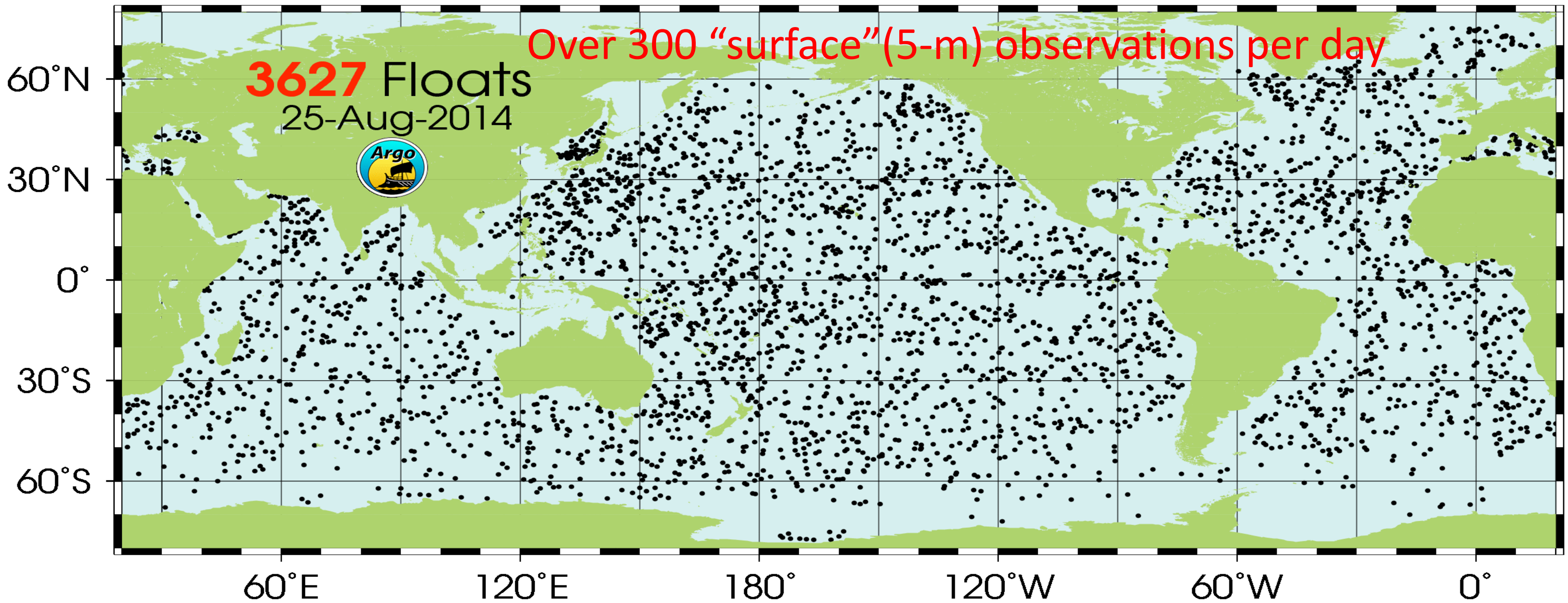
For all L-band satellite SSS:
ESA funded **SMOS Pilot Mission Exploitation Platform (SMOS Pi-MEP):**
https://pimep-project.odl.bzh/data
has http links to various level-2 to level-4 satellite SSS products

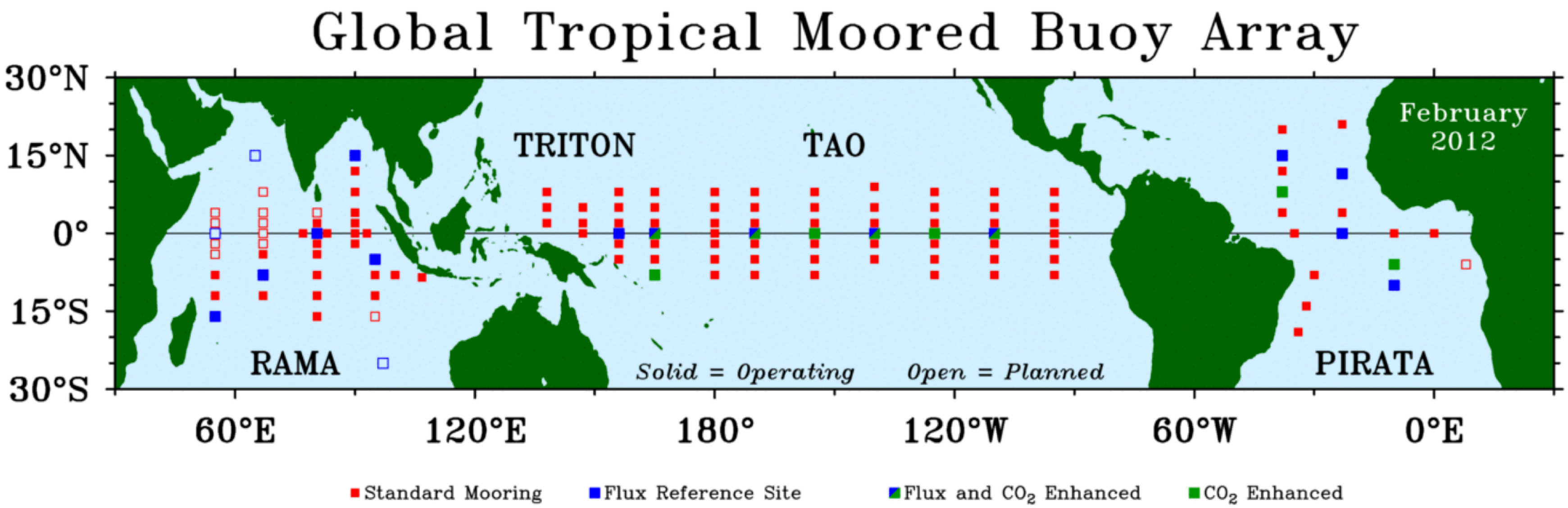


Other useful resources:
Satellite and In-situ Salinity (SISS) Working Group: http://siss.locean-ipsl.upmc.fr/
Aquarius: https://aquarius.nasa.gov

Main Sources of validation data for Satellite SSS

Distribution of Argo floats





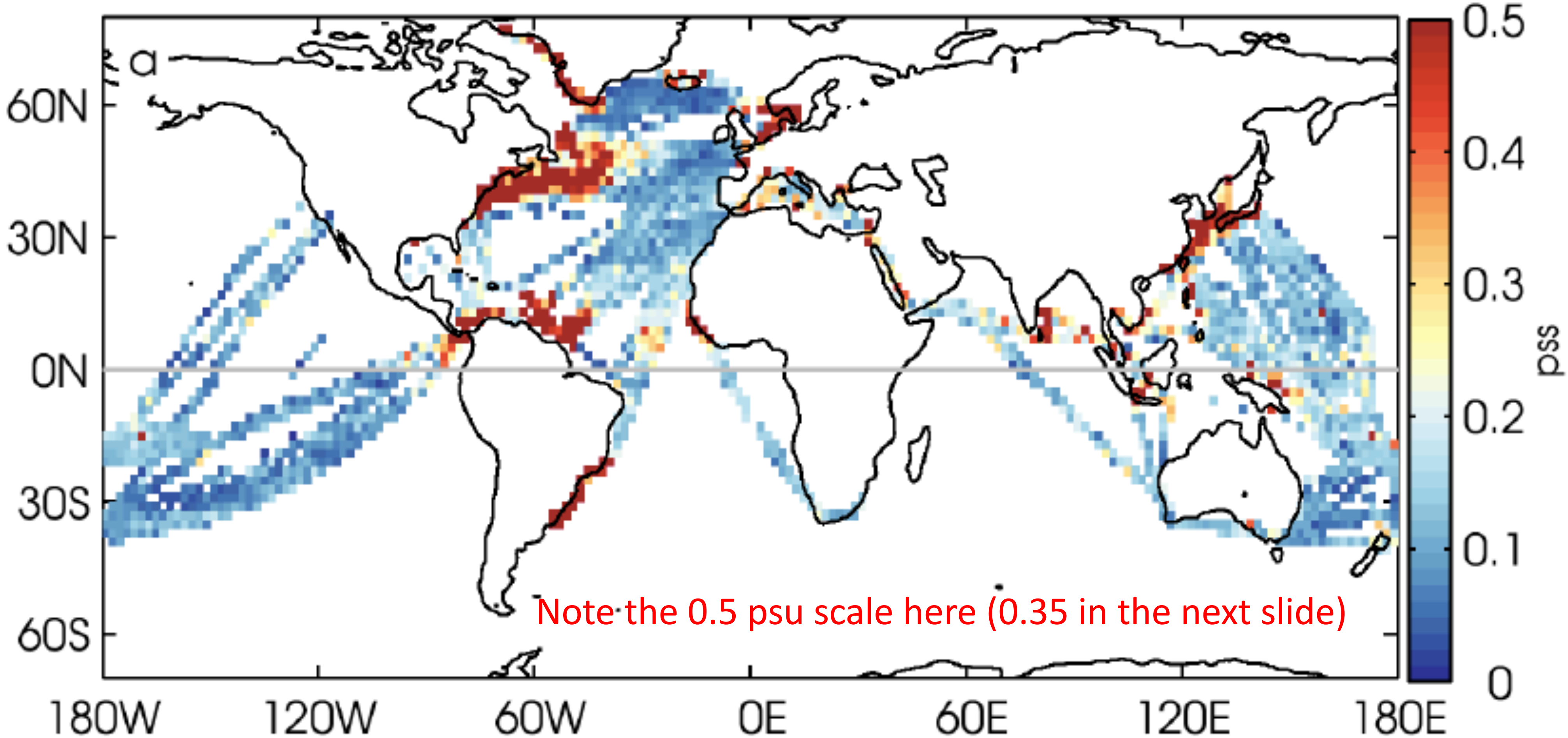
Also ship-based measurements, esp. high-resolution thermosalinograph (TSG) data

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)**

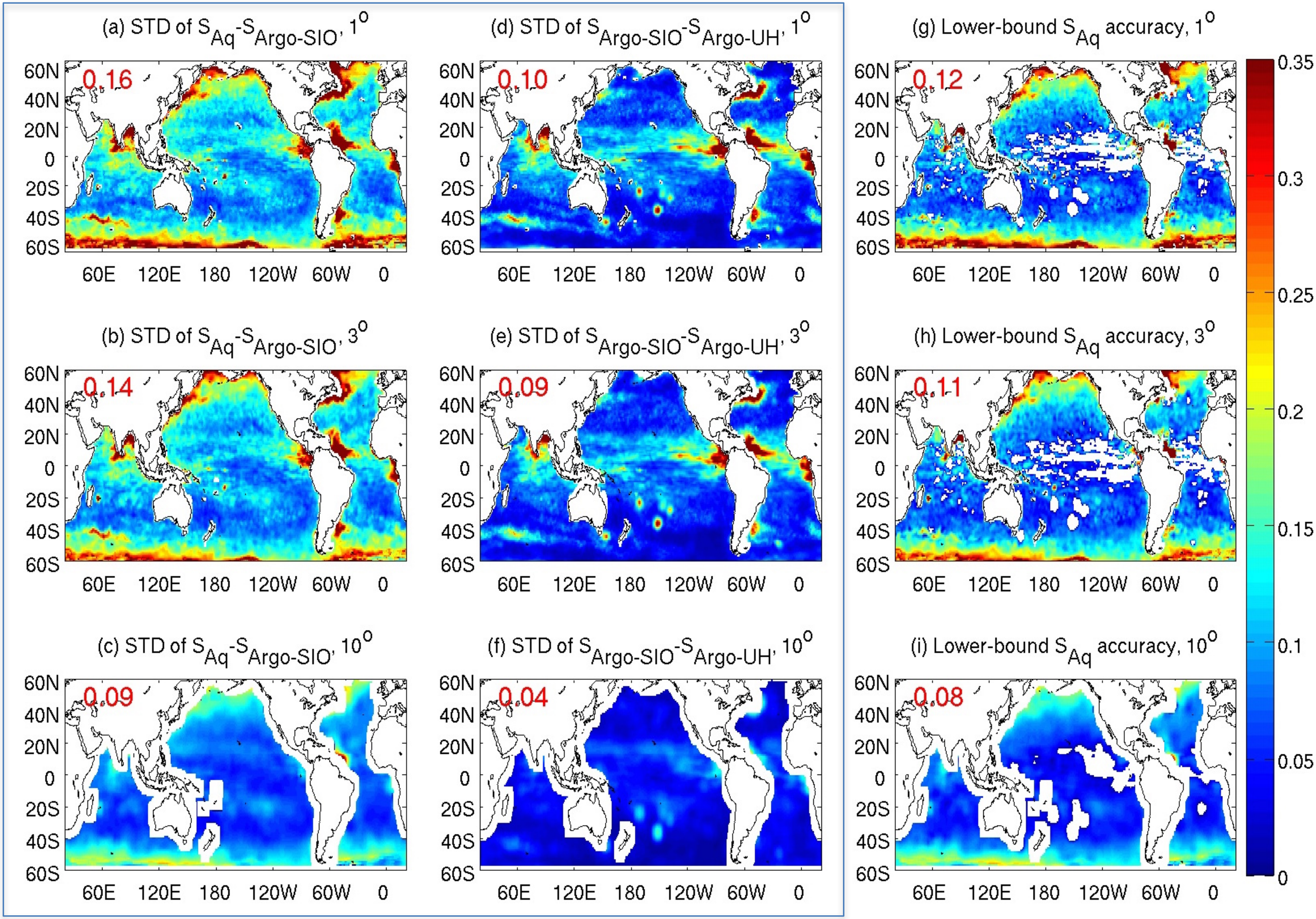
2. **Effect of near-surface salinity stratification**
   - Satellites measure salinity in the upper cm
   - Most in-situ measurements are >= 5 m (Argo) or >= 1 m (mooring)
   - Importance of salinity stratification in the upper meter under certainty conditions (e.g., during SPURS & SPURS2 field campaigns)

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)



Summary of key achievements by Satellite SSS

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

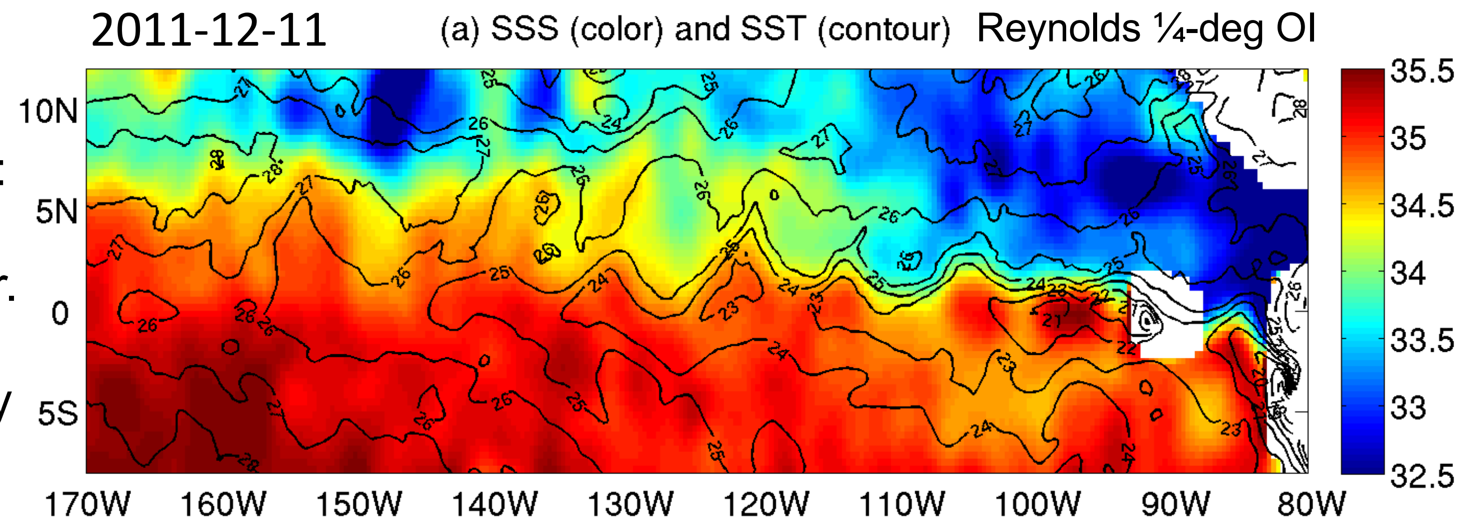
Filling gaps in SSS observations (spatiotemporal scales & regions not resolved or inadequately sampled by in-situ platforms).

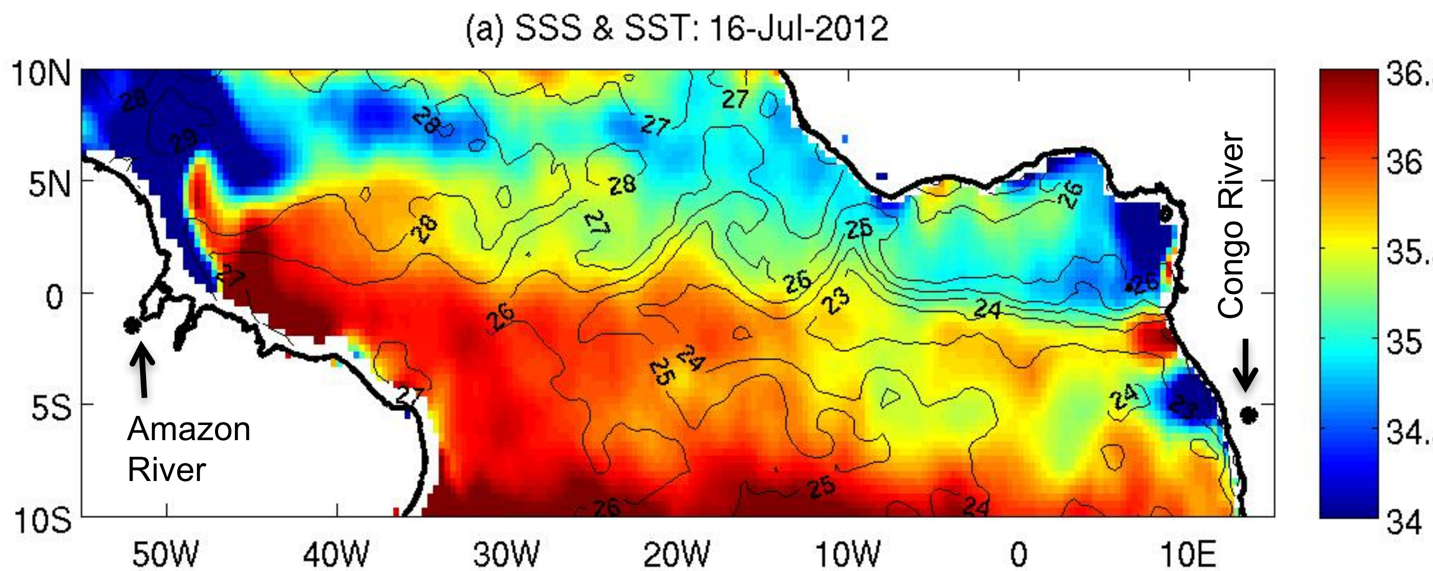
A few examples next

Improving understanding of ocean variability/processes: Tropical Instability Waves (TIWs) examples

- Revealed new features: e.g., faster speed at than away from equator.
- Important role of salinity to energetics
- Implication to eddy-mean flow interaction.

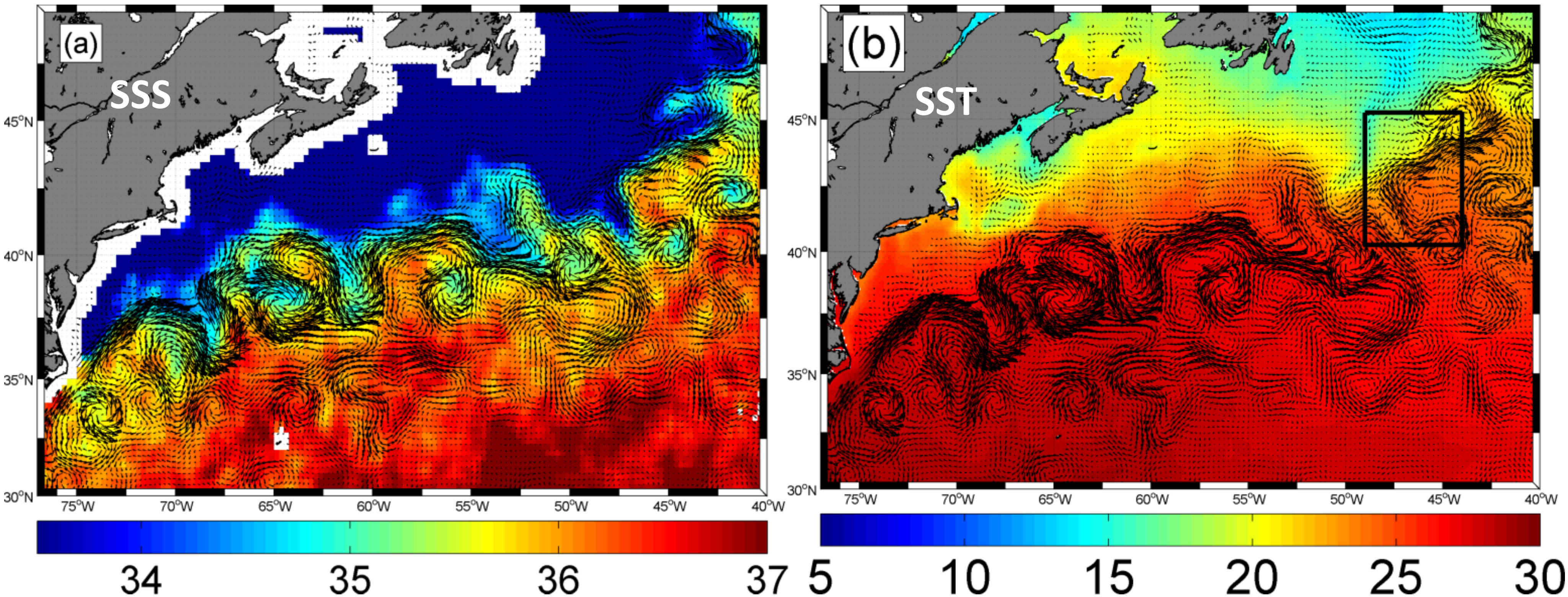
Lee et al. (2012)
Lee et al. (2014)
Yin et al. (2014)





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

Reul, Chapron, Lee, et al. (2014)



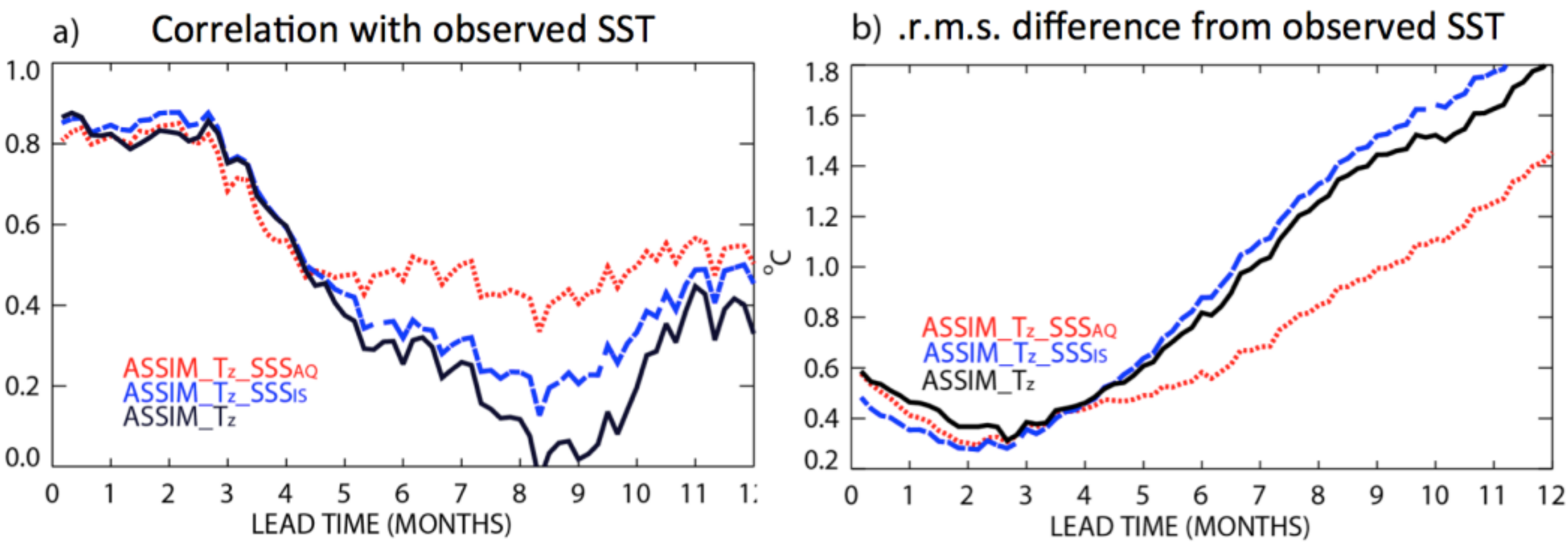
- Cold/fresh Core rings are better captured by SSS than SST during summer.
- Implication: cross-gyre salt transport by eddies

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 seasonal-interannual prediction

Hackert et al. (2014) Will discuss later



ASSIM_T_Z: baseline experiment, assimilation of all subsurface temperature data.

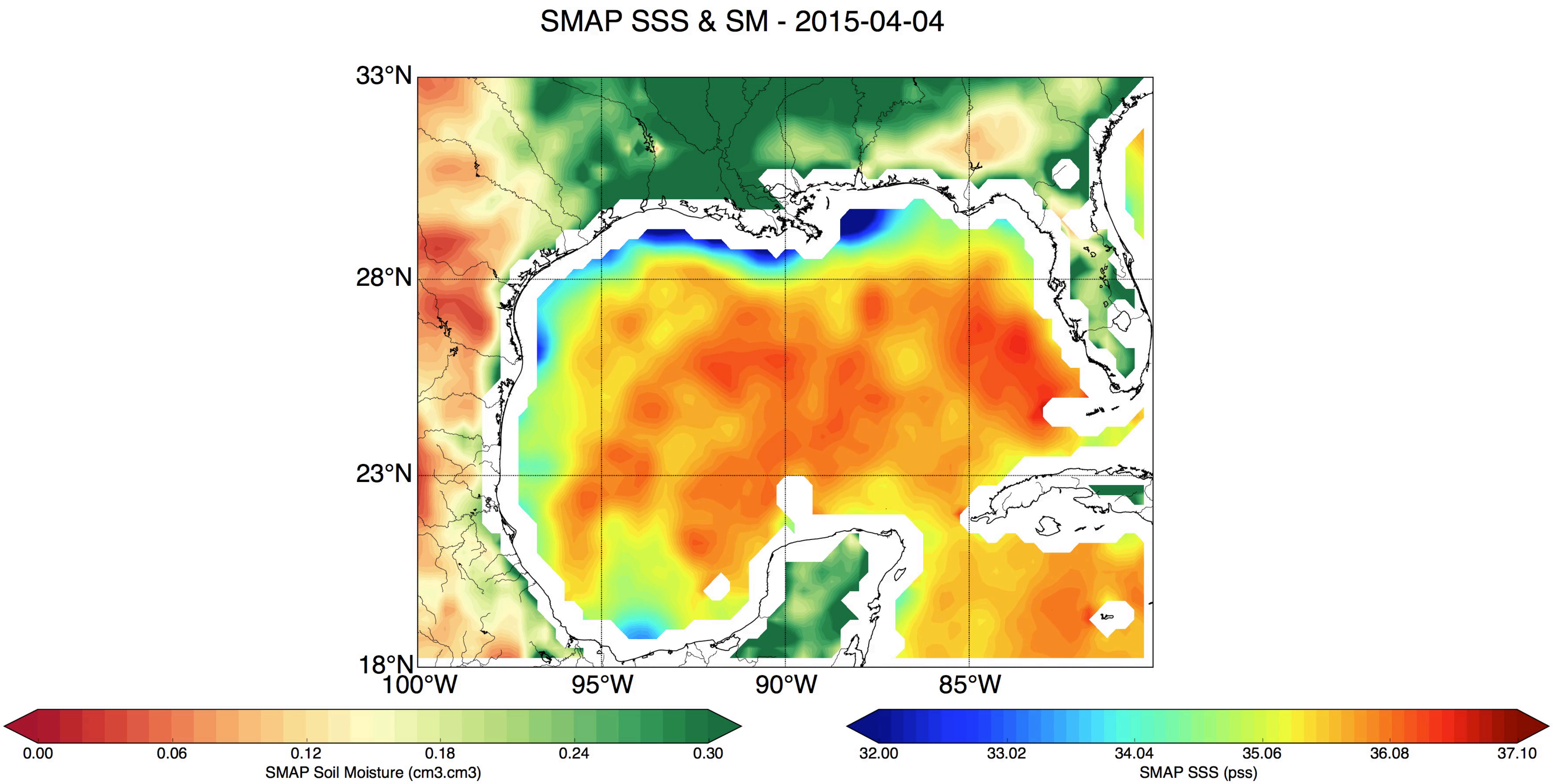
ASSIM_T_Z_SSS_{IS}: assimilation of all subsurface temperature and in-situ salinity data.

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.

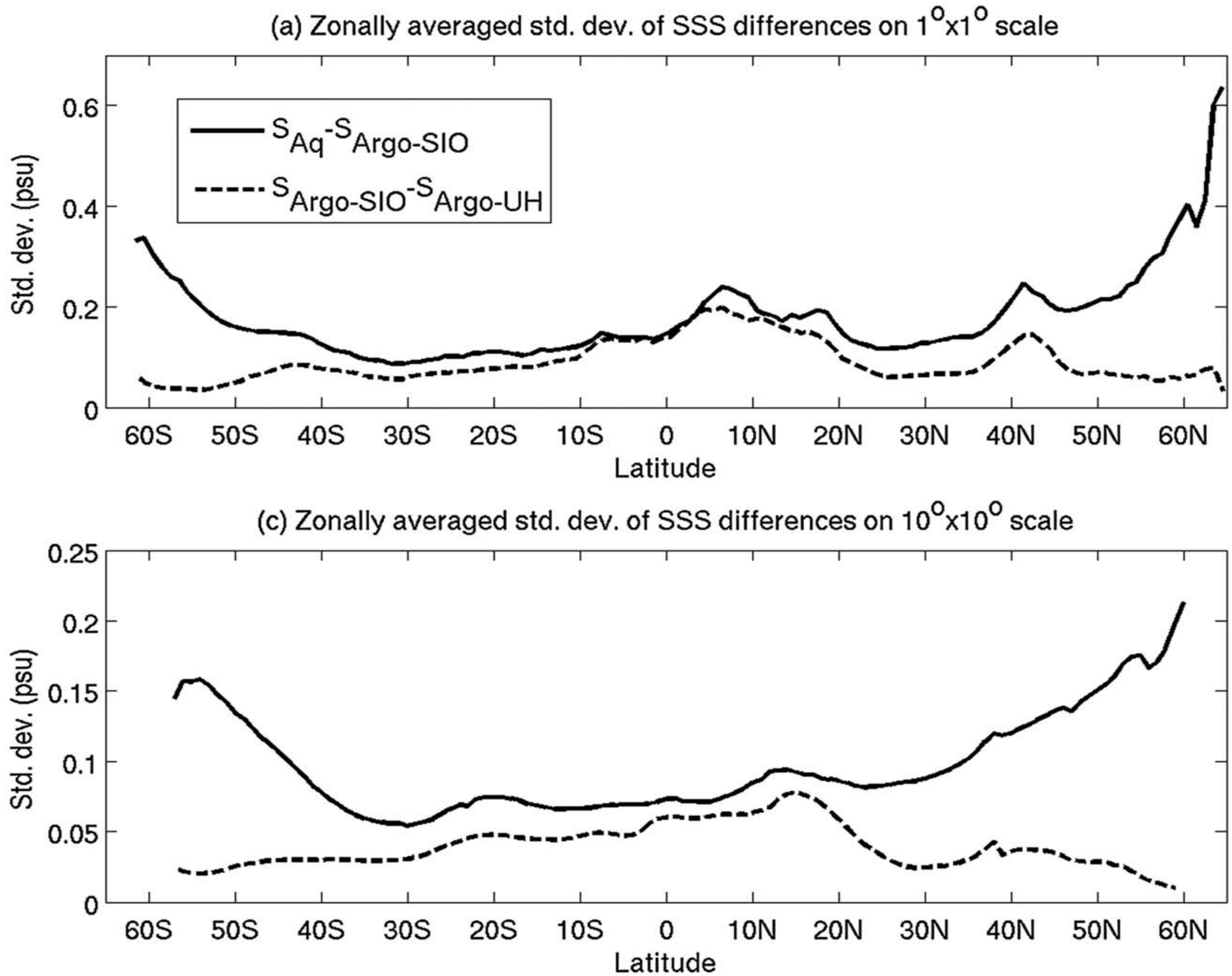
Improving environmental assessment:
SMAP sea surface salinity & soil moisture during & after the May'15 extreme flooding event in Texas



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

Uncertainty characteristics of Aquarius SSS:
Tropics & subtropics ✓ high-latitudes ✘

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

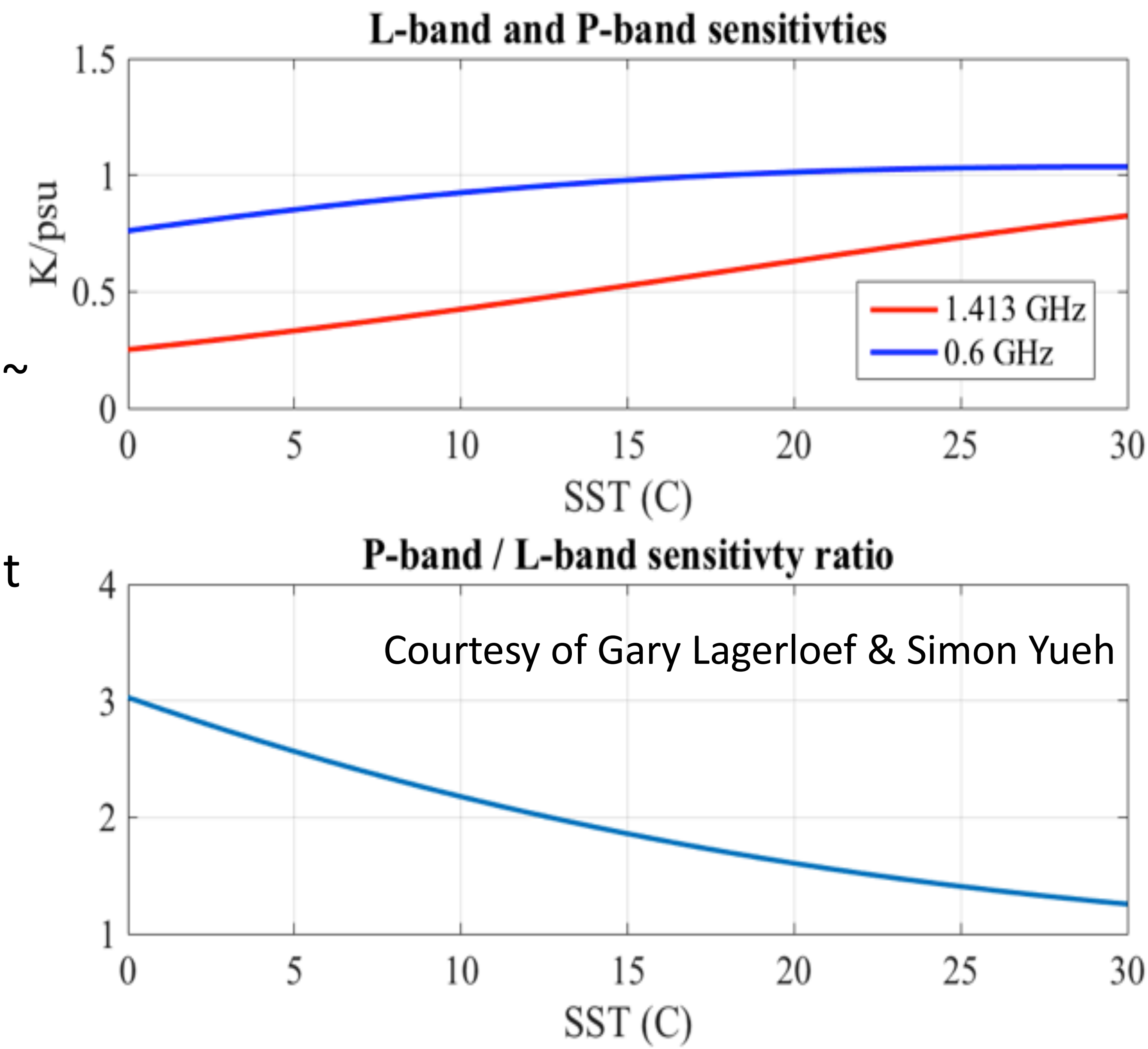


Community input to US Decadal Survey: adding P-band to L-band to improve high-latitude SSS & sea ice thickness measurements

(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



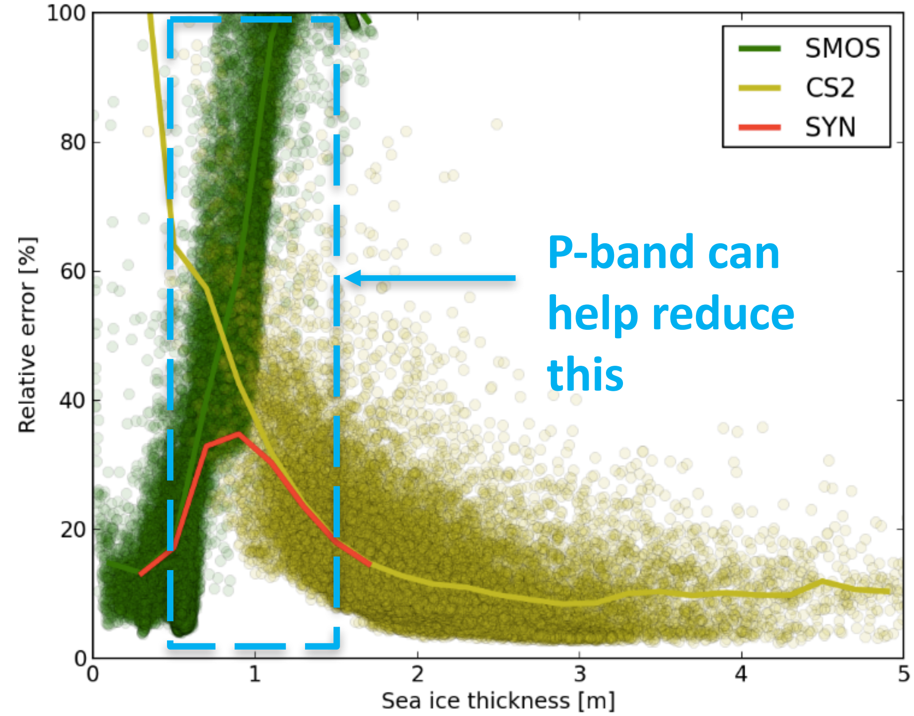
Additional values of P-band radiometry

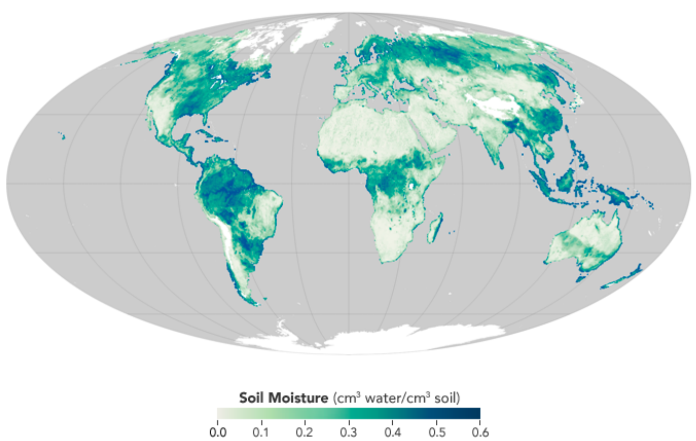
- Improving sea ice thickness measurements by complementing radar and L-band radiometry measurements

- Better thickness measurements for 1st-year ice in turn help improve SSS retrievals near sea ice.

- Other values: measurements of ice shelf thickness, land applications (e.g., soil moisture, evapotranspiration).

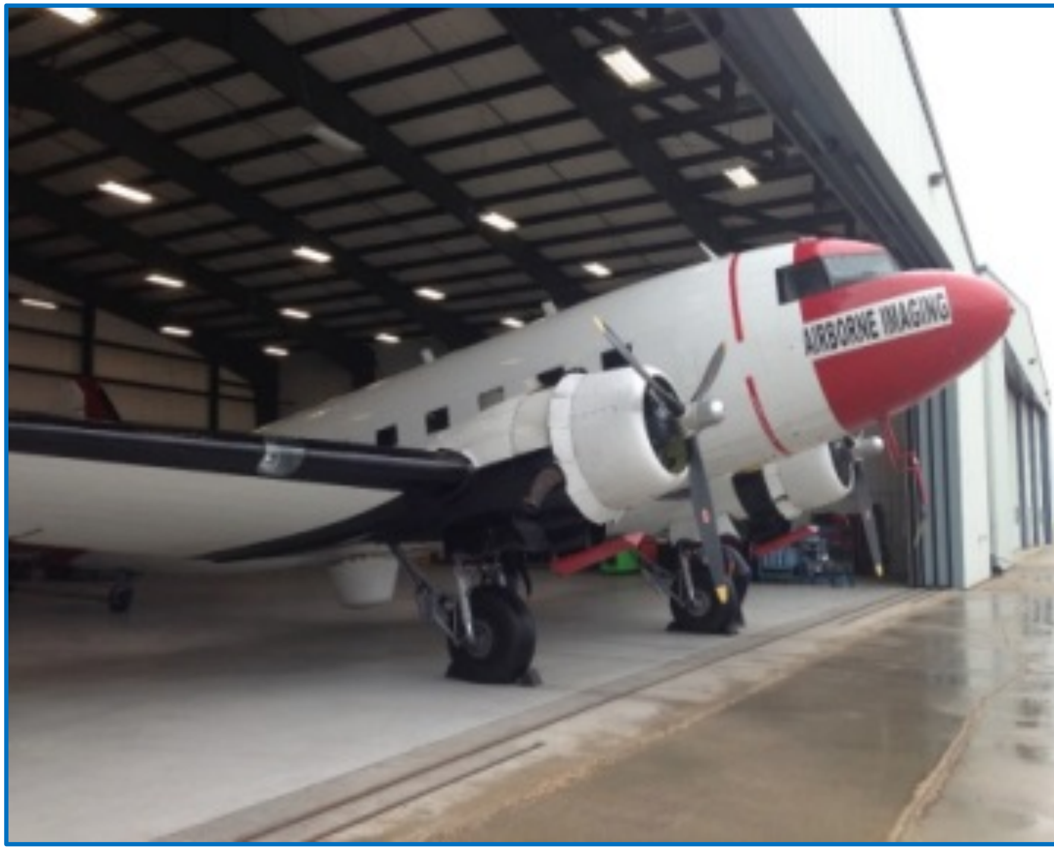
Sea-ice thickness measurement error (Kaleschke et al. 2015)

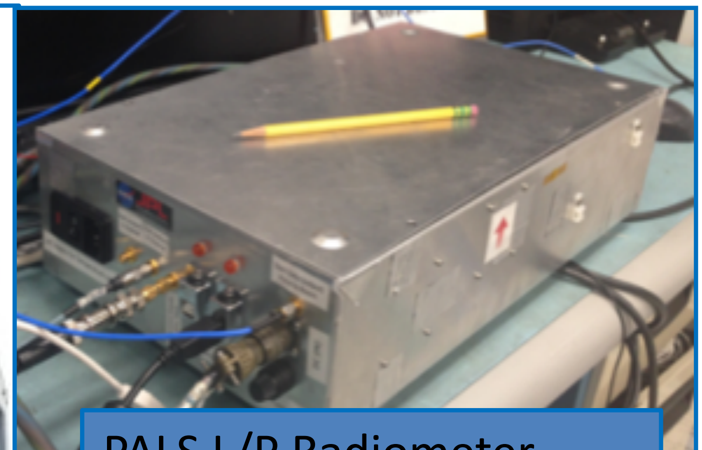




Ongoing technology development

- JPL's Passive-Active L/P-band radiometry + L-band radar.
- Land controlled & field tests (2017); flight test (2018 onward).



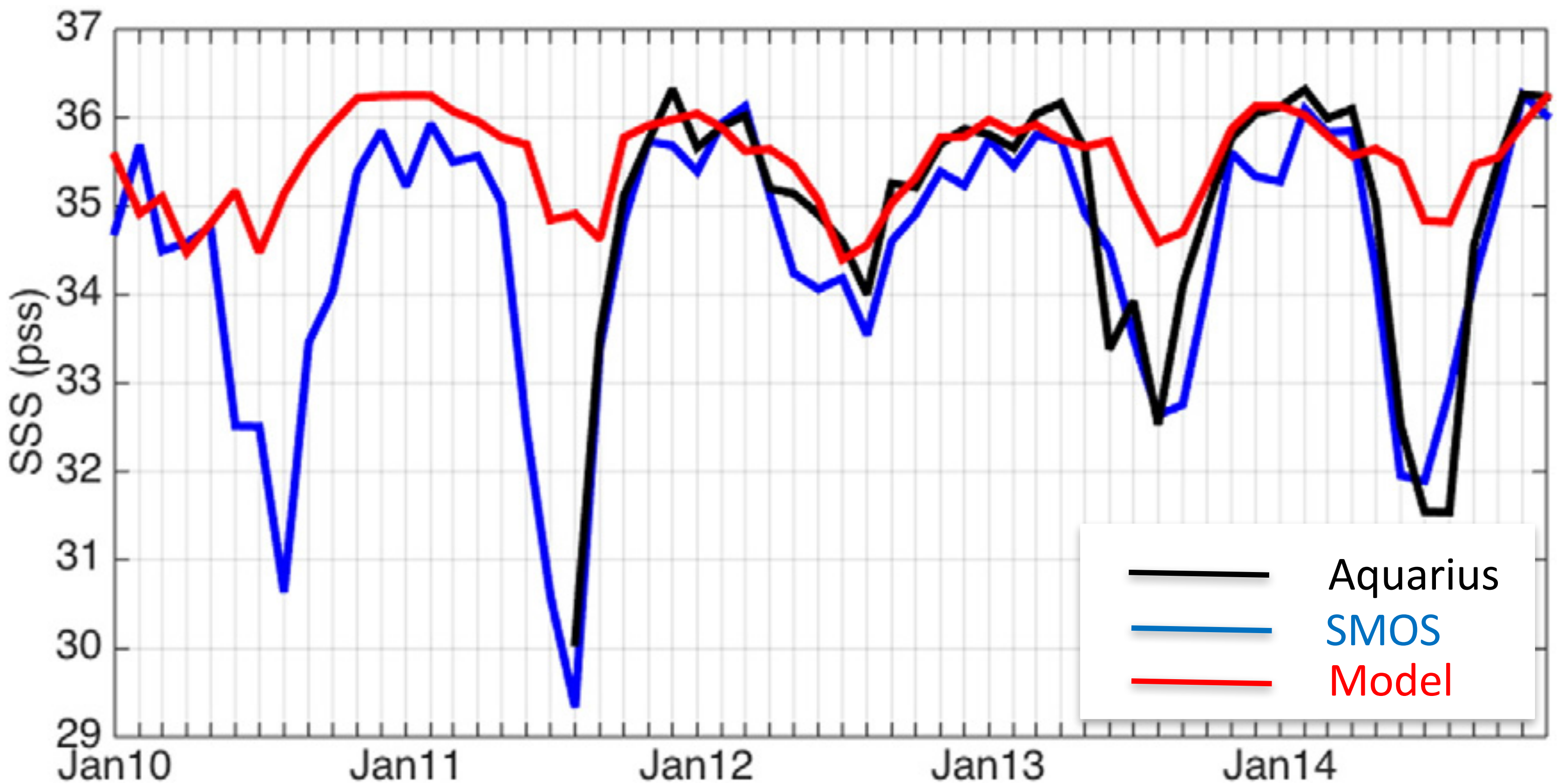


PALS L/P Radiometer

Use of satellite SSS for constraining ocean models

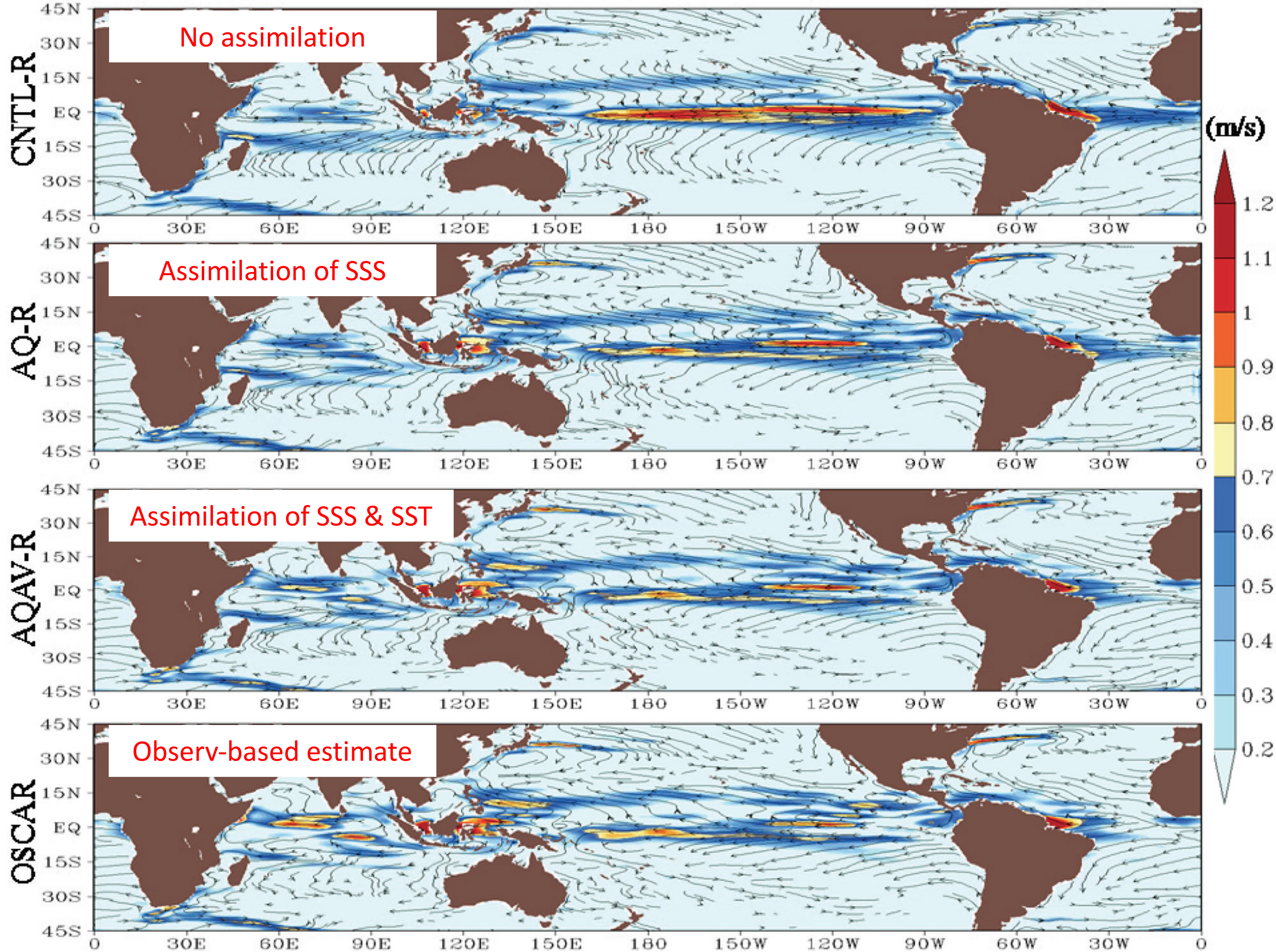
- Significant E-P forcing error
- Relaxation to SSS climatology (to prevent model drift) suppresses non-seasonal variability
- Common use of seasonal river discharge climatology in global ocean models

SSS near the Mississippi River mouth:
global model/assimilation products typically show little non-seasonal variations



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



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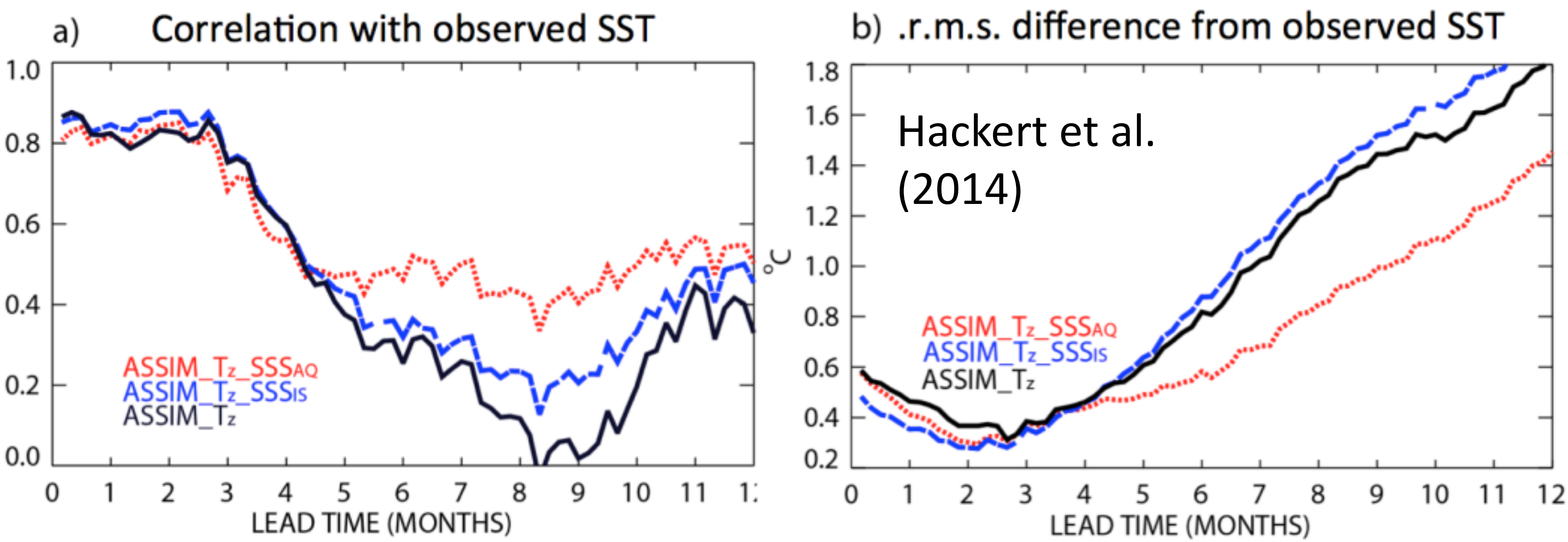
Statistics of estimated surface currents w.r.t. observ-based estimate for the three dominant modes of EOFs

Table 2. Statistics of Comparison of the First Three Dominant Modes of Observed and Simulated Surface Currents in the Spatial and Temporal Domains

Modes	Variables	Spatial Correlation	Temporal Correlation	Spatial RMSE (m/s)	Temporal RMSE (m/s)
1	CNTL-R/OSCAR	0.73	0.70	0.42	0.41
	AQ-R/OSCAR	0.81	0.76	0.33	0.31
	AQAV-R/OSCAR	0.85	0.78	0.30	0.28
2	CNTL-R/OSCAR	0.79	0.65	0.36	0.39
	AQ-R/OSCAR	0.82	0.74	0.28	0.29
	AQAV-R/OSCAR	0.86	0.79	0.25	0.27
3	CNTL-R/OSCAR	0.69	0.51	0.28	0.35
	AQ-R/OSCAR	0.71	0.62	0.24	0.25
	AQAV-R/OSCAR	0.73	0.64	0.19	0.22

CNTL-R: Control Run (no assimilation)
AQ-R: Assimilation of Aquarius SSS
AQAV-R: Assimilation of Aquarius SSS and AVHRR SST
OSCAR: Observation-based estimate of surface currents

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



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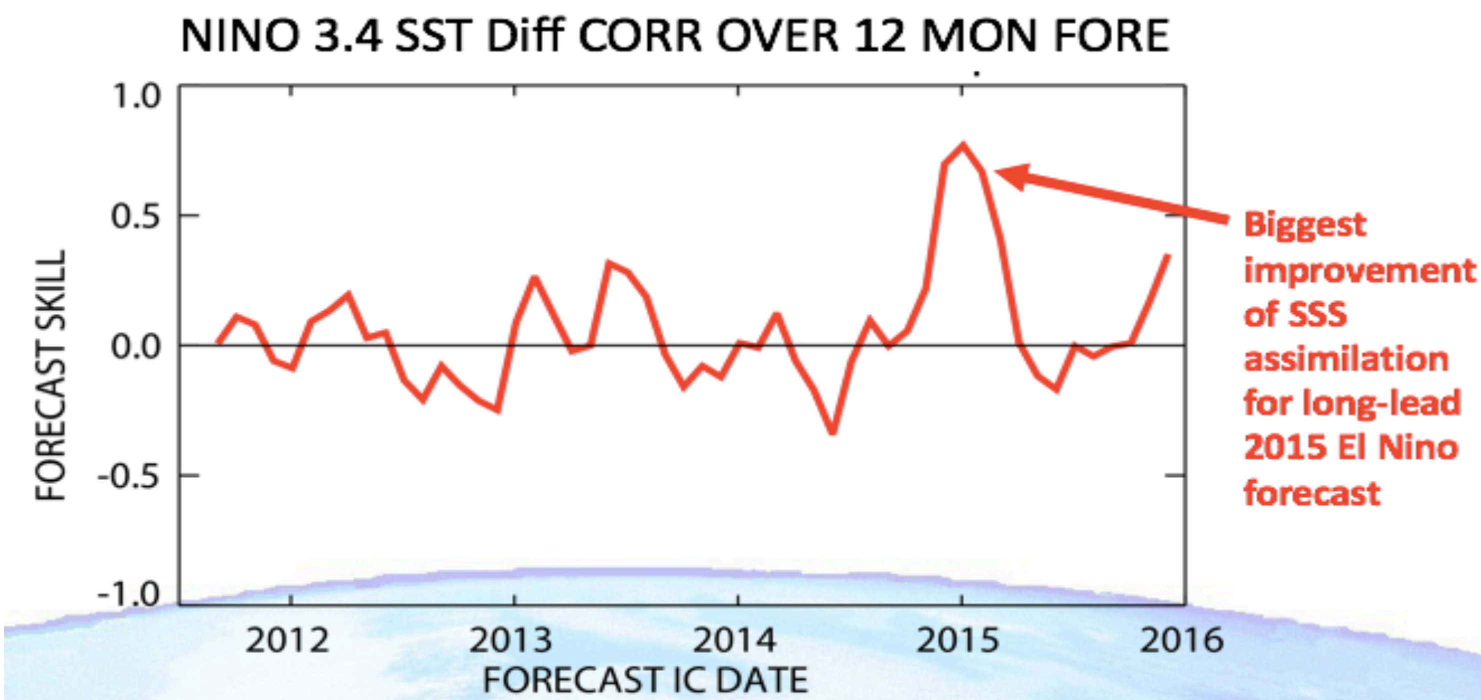
The latter has higher correlation & lower RMSE wrt observed SST for lead times > 4 months.

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

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



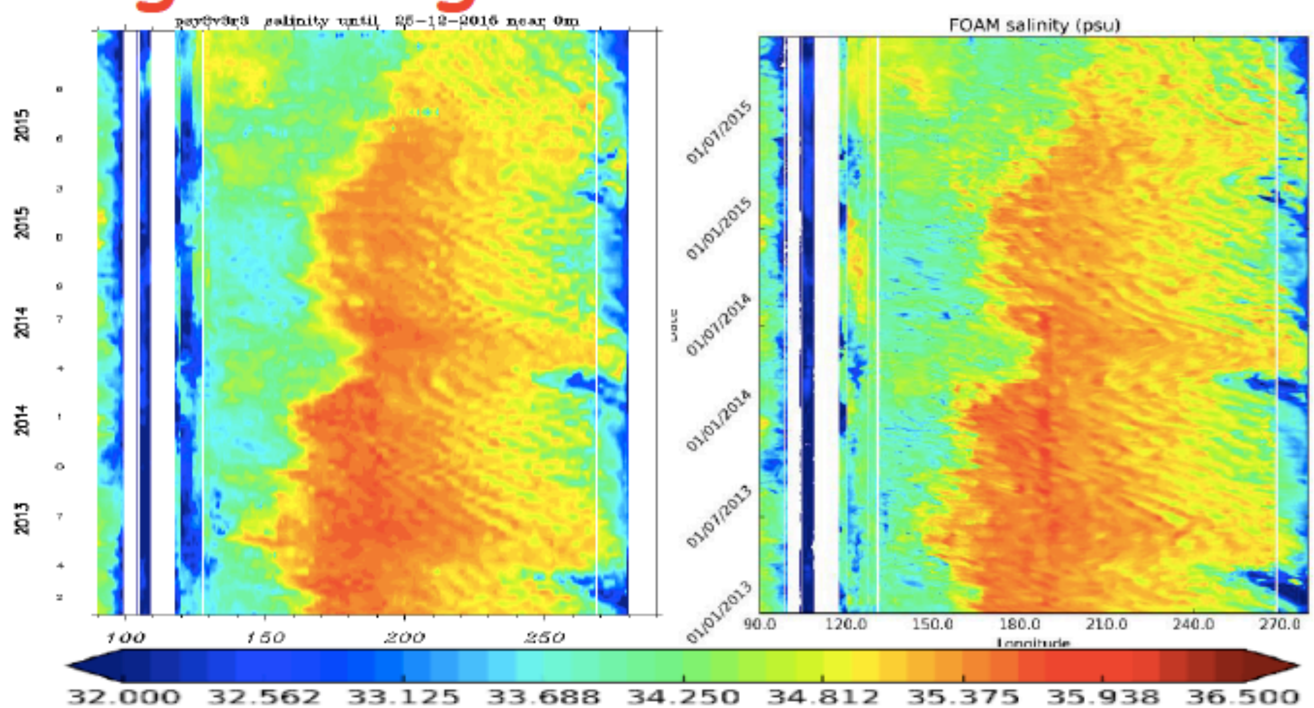
Courtesy of Eric Hackert NASA/GMAO

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.

Freshening during El-Niño 2015

Mercator Ocean



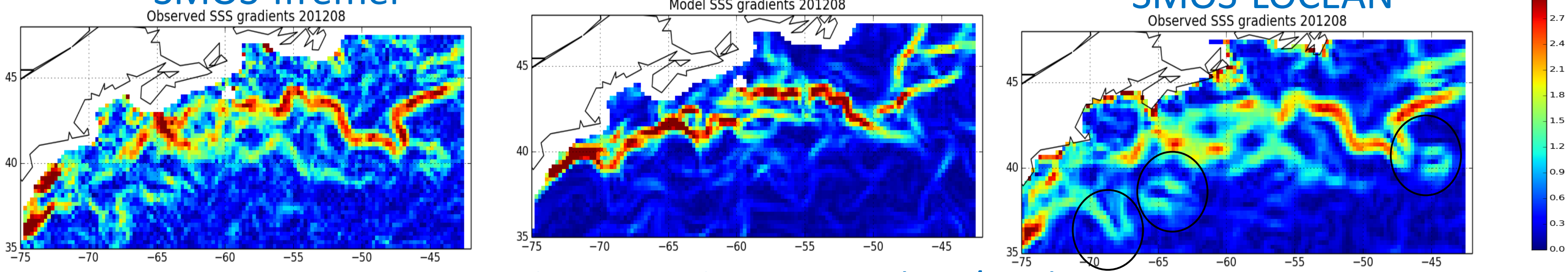
MetOffice

Courtesy of Matt Martin and Benoit Tranchant (Mercator Ocean)

Ongoing effort for satellite SSS assimilation at UKMO

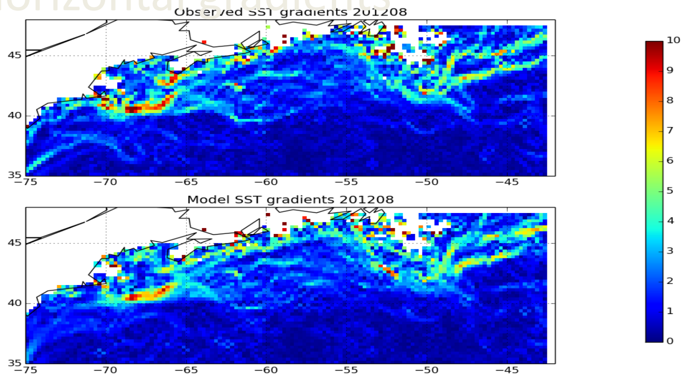
Spatial information in satellite SSS data

[Martin, M.J., 2016, doi:10.1016/j.rse.2016.02.004.](https://doi.org/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.

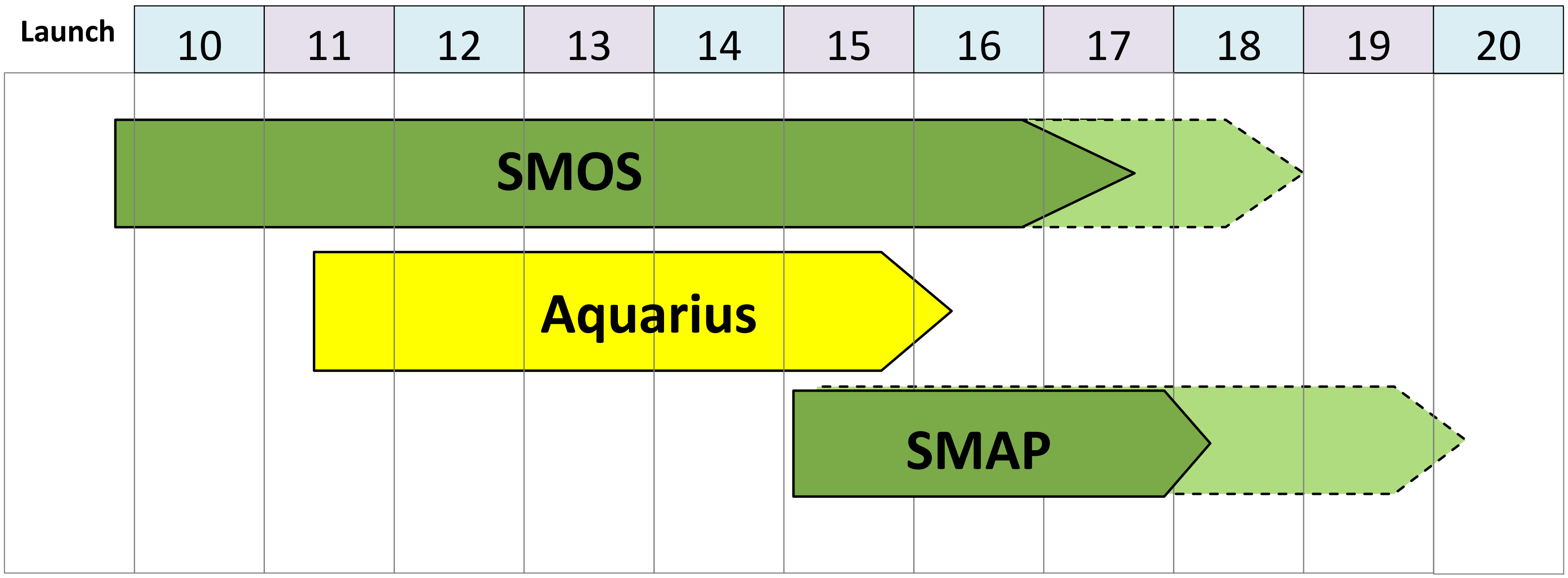
Courtesy of Matt Martin, UK Met Office

Other ongoing efforts for satellite SSS assimilation

- Japan Meteorology Agency/MRI Aquarius SSS assimilation improved salinity representation in marginal sea & mode water formation etc. (Toyoda et al. 2014)
- Indian Global Ocean Data Assimilation System (e.g., Chakraborty et al. 2014)
- ECCO and G-ECCO 4D-VAR systems: impacts on inverse estimation of E-P variability (Koehl et al. 2014)
- NOAA Real-time Ocean Forecasting System (RTOFS)
- Chinese National Marine Environmental Forecasting Center

Important to engage satellite SSS product developers to understand error characteristics for different SSS products (including versions)

Continuity of satellite SSS missions not ensured beyond 2020; need community advocacy



Summary

- Satellite SSS have demonstrate the values added to existing observations to improve understanding of ocean processes (physical & biogeochemical), linkages with the water cycle, environmental monitoring, and seasonal-to-interannual prediction

- Satellite SSS have encouraging quality in tropics & subtropics, but at least 3 times larger uncertainties in polar oceans

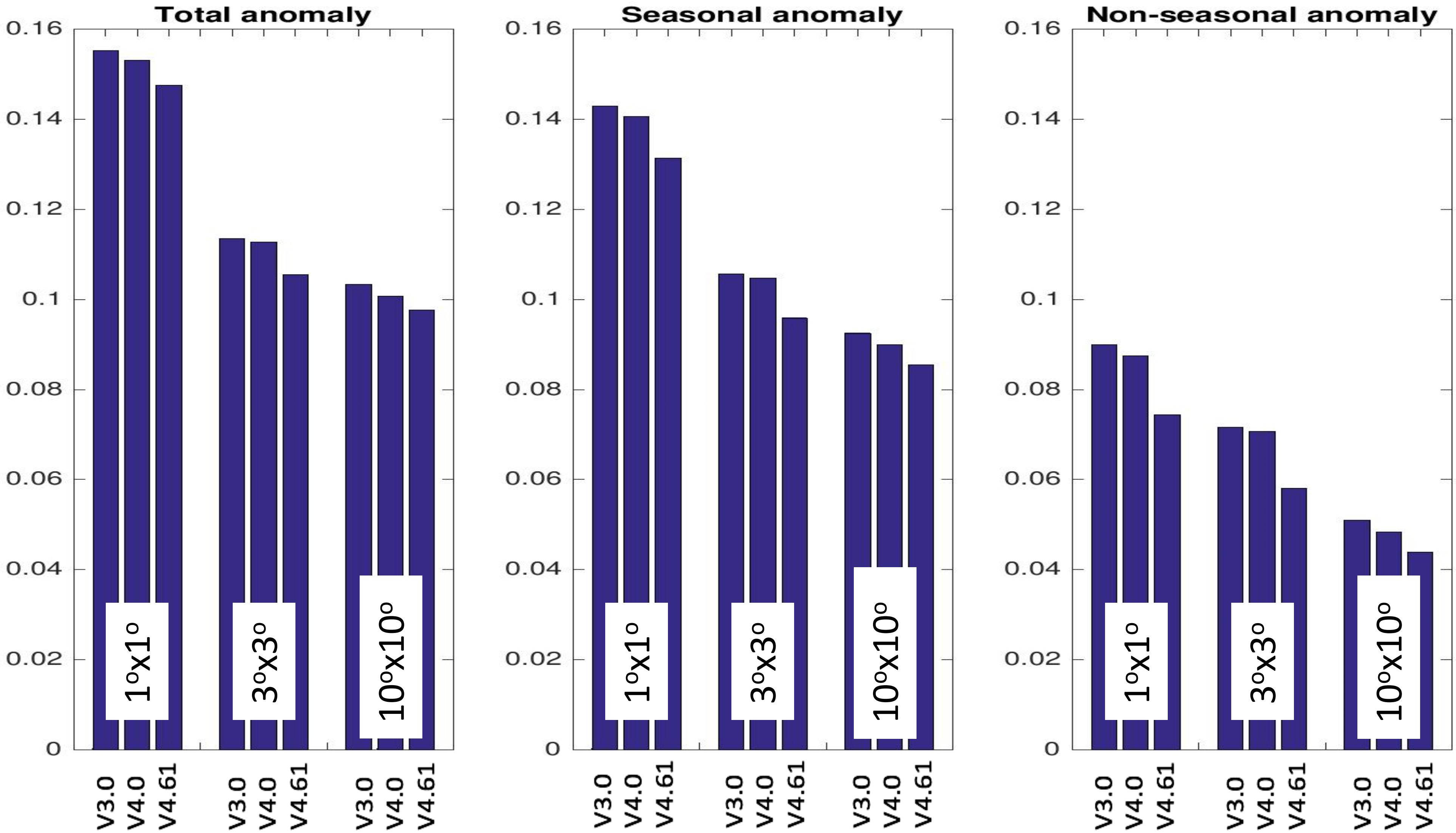
- Ongoing improvements of retrieval algorithms and technology to improve polar-ocean SSS (as well as seasonal sea ice thickness) measurement

- Important to understanding satellite SSS error characteristics by taking into account sampling differences from in-situ measurements

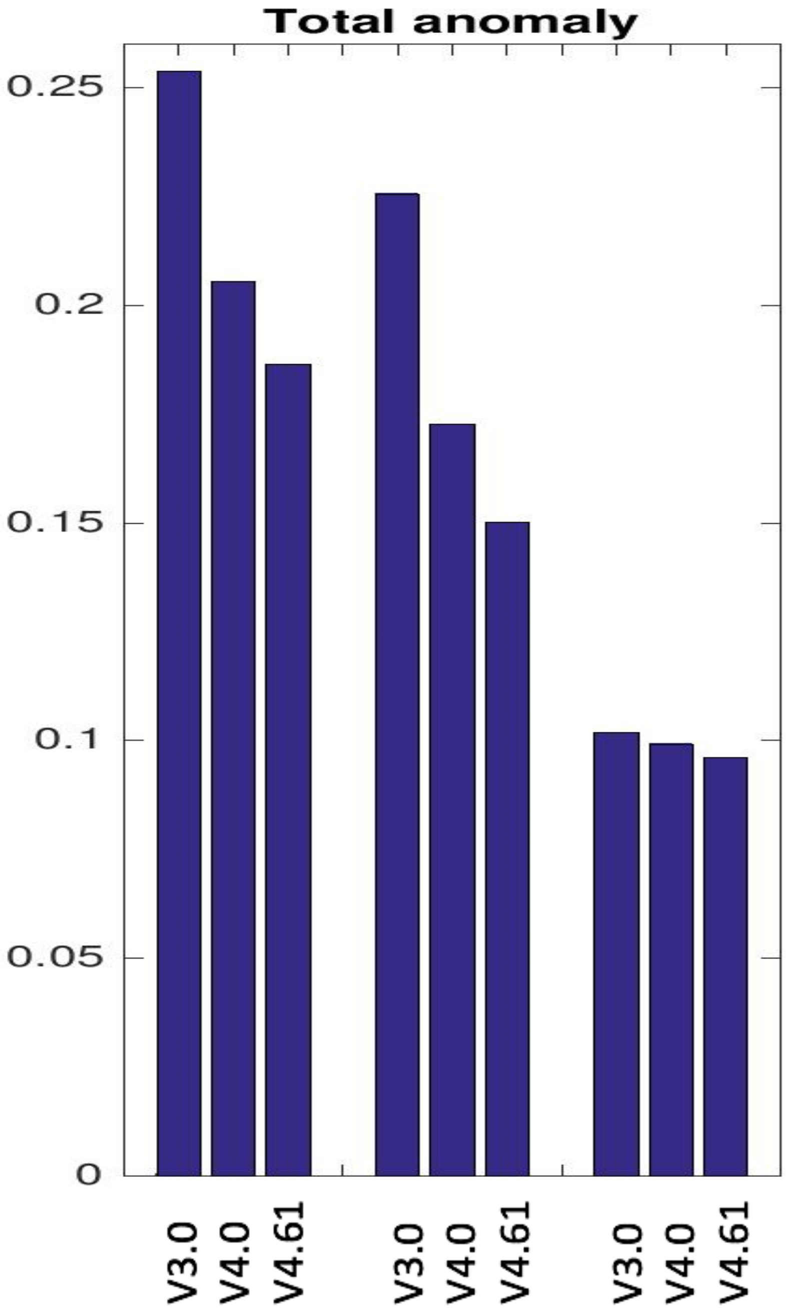
- Need community advocacy for continuing satellite SSS

Backup

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)