L-band radiometry from space: SMOS, SMAP, AQUARIUS

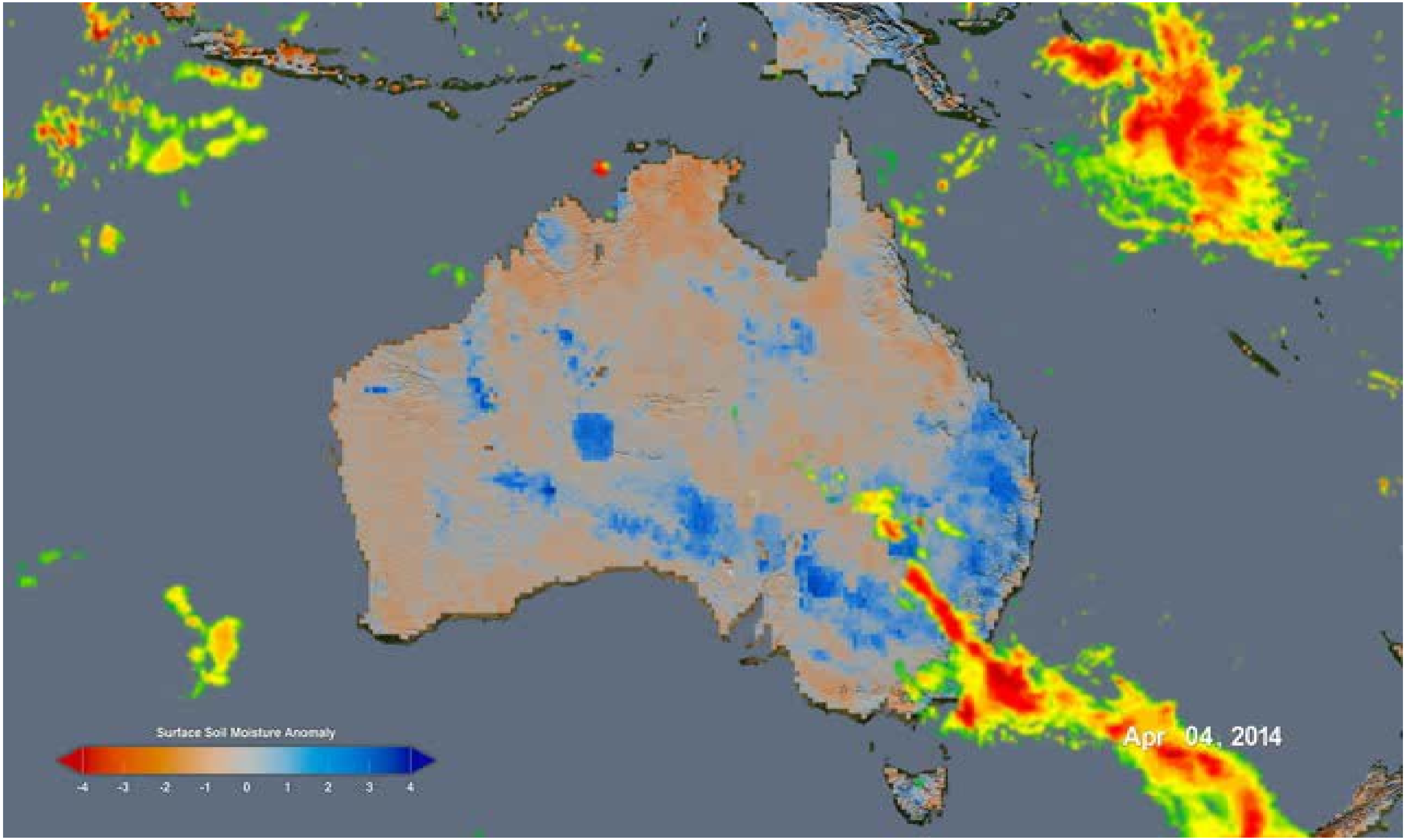
Yann Kerr

&

SMOS Aquarius and SMAP Teams

SMOS and Precipitations (IMERG)

J. Bolten



Unicity of passive L band measurements

PROS

- Passive microwaves at low frequency
  - Reduced sensitivity to atmosphere and sun irradiance (all weather)
  - reduced sensitivity to structure
    - Vegetation canopy
    - Surface roughness
- L band measurements (passive: Radiometry different from RADAR)
  - Reduced sensitivity to vegetation canopy
  - Good penetration depth
  - Sensitivity to sea salinity
  - High sensitivity to soil moisture
- Direct measurements of Soil moisture and Sea Surface salinity (no proxy, no scaling, …) hence usable in applications

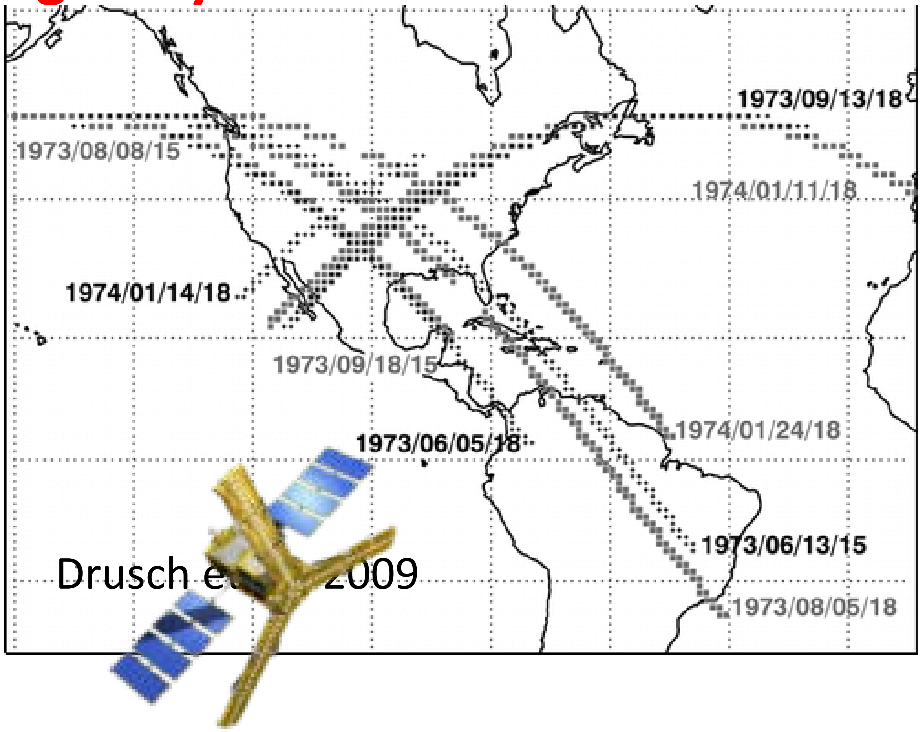
CONS

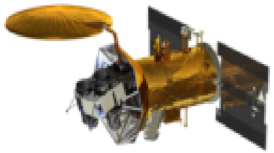
- Spatial resolution (antenna diameter)
  - Meaning different options (i.e., SMOS, Aquarius, SMAP)
  - and different price tags (€ 315 M, $400 M - instrument, $ 915 M)
  - Radio frequency interferences
    - …See ITU actions and SMAP approach

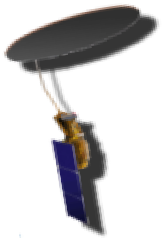
L band measurements

A Short long story

- Initiated in 1977
  - S194 on SKYLab
  - A few days of partial acquisitions
  - Very coarse resolution (125 km HPBW)
  - Interesting results but spatial resolution limited
    - ➔ waiting for new technologies
- Rekindled in the 90's
  - ESTAR and 2D interferometry
  - Large deployable antennas
- SMOS selected in 1997 (CNES) and 99 (ESA)
  - CNES TAOB programme
  - ESA Earth Explorer opportunity mission (ESA, CNES CDTI)
  - Launched in 2009
- Aquarius
  - Selected by NASA ESSP in 2001
  - Launched in June 2011
  - End of life July 2015
- SMAP
  - Heritage of HYDROS (NASA ESSP 1999) cancelled in 2005
  - Reinitiated after 2007 Decadal survey
  - Launched in 2015
  - Radar failure in 2015







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

Where are we?

- L Band in SPACE
  - SMOS 2009 - … → over 8 years
  - Aquarius 2011- 2015 → 4 years
  - SMAP 2015 - … → over 2 years
- Gigantic success
  - Unique measurements
  - Unique contribution
  - Unprecedented publication record (to my knowledge)
  - Operational application almost immediately after launch
  - Many (very) various fields of application
- And different missions give same outputs
  - Design not an issue (as long as correct!)
  - **What counts is L band radiometry**

L-Band Missions

SMOS	Aquarius	SMAP
First L-band mission in space	Real aperture radiometer	Deployable mesh Antenna
Synthetic Aperture radiometer	Combined radiometer and scatterometer	Combined radar and radiometer
First to observe the RFI environment	Very low NEDT	Advanced RFI mitigation
Soil Moisture	Ocean Salinity	Soil Moisture
Ocean Salinity	Soil Moisture	Ocean Salinity
40 km resolution	100 km resolution	40 km resolution (radiometer), active-passive (9 km)
Global coverage – 2 days	Global coverage – 7 days	Global coverage – 2 days

- SMOS and SMAP are currently both healthy (both in extended missions)
- Aquarius/SAC-D had a s/c anomaly in June 2015 after 3 years 8 months of operation
- It typically takes 5-7 years from pre-formulation to launch

R Bindlish

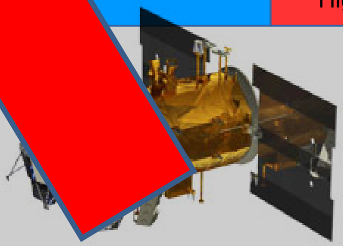
Golden period of L-band radiometry in 2015: 78 days

L-Band radiometry missions

SMOS
since November, 2nd 2009
4 Stokes, incidences [0°,65°]
Radiometric interferometer
Calibration based on internal noise diodes and sky
Absolute brightness temperature accuracy
Temporal stability short/long term
Directional stability
Within field of view, special care given to extended alias free
Processing v620

Aquari
from to June,
3 Sto 28°, 38
2.5 m r l ho
internal noise diode
consistency
Processing v

SMAP
Launch January, 31st 2016, in operation since March 31st 2016
4 Stokes, incidence 40°
6 m reflector and feed horn
Calibration based on internal noise diode and vicarious
High sensitivity



Albitar and Kerr

L-Band radiometry missions

2008 2010 2012 2014 2016 2018 2020 2022 2024 2026 2028 2030 2032

SMOS (ESA CNES) (40 km / 3days / L-band / global)

Aquarius (NASA) (100km / 8days / L-Band/ global)

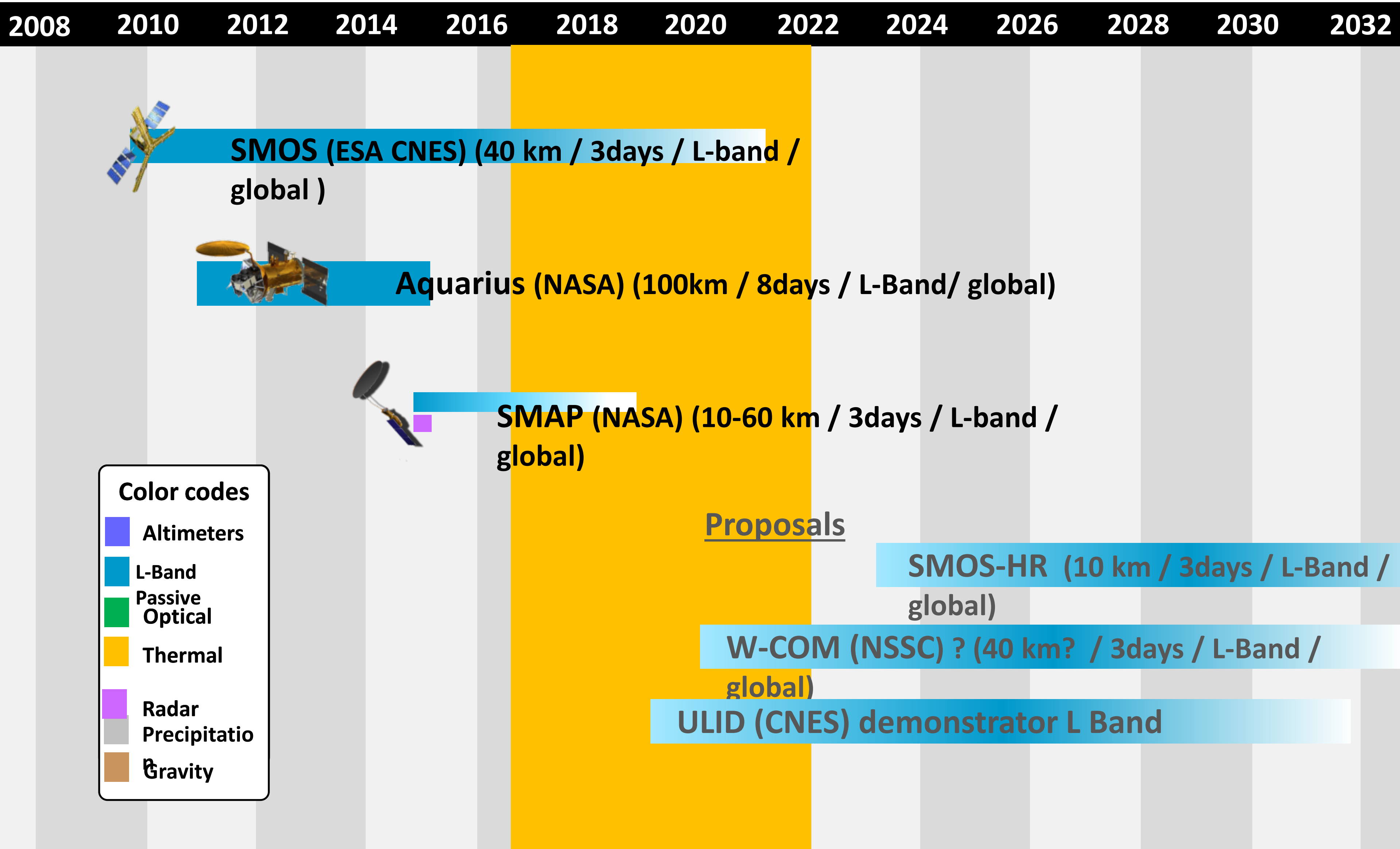
SMAP (NASA) (10-60 km / 3days / L-band / global)

Color codes

- Altimeters
- L-Band Passive
- Optical
- Thermal
- Radar
- Precipitation
- Gravity

Albitar and Kerr

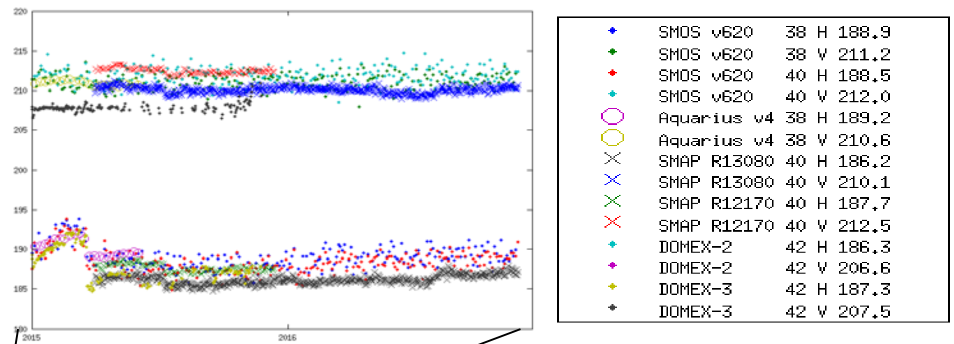
L-Band radiometry missions

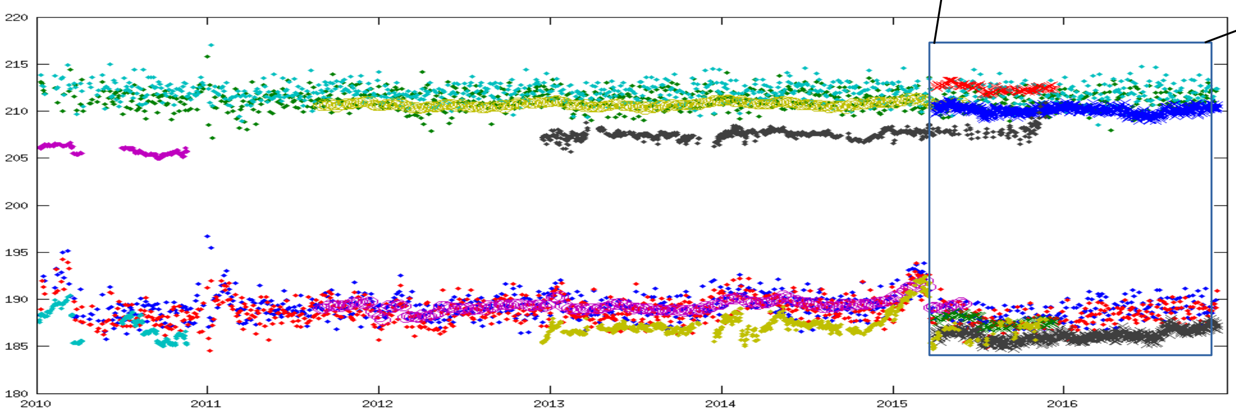


SMOS and DomeX

Long term stability
Overall good agreement
Incidence induced bias
between SMAP and Aquarius

F. Cabot

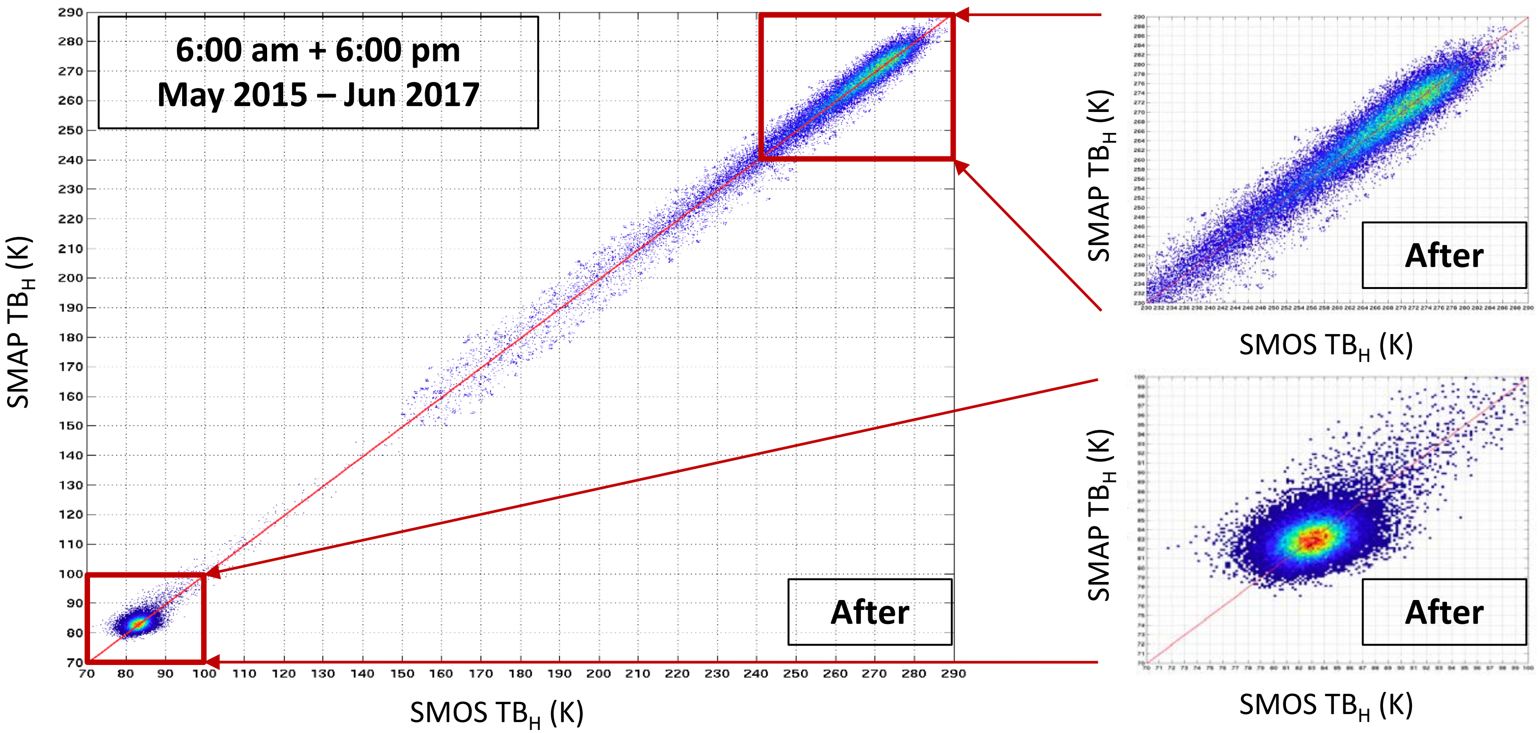




Sensor	Version	Inc	TBH	TBV	DTBH	DTBV
Aquarius	v4	28	192.90	206.19	0.59	1.16
Aquarius	v4	38	189.23	210.61	0.33	-0.62
Aquarius	v4	45	185.03	213.40	1.01	-0.98
SMAP	R12170	40	187.67	212.46	-0.88	0.41
SMAP	R13080	40	186.17	210.08	-2.38	-1.97
SMOS	v620	38	188.90	211.23		
SMOS	v620	40	188.55	212.05		
SMOS	v620	28	192.31	205.03		
SMOS	v620	45	184.02	214.38		
DOMEX-2		42	186.27	206.57	-0.015	-6.645
DOMEX-3		42	187.34	207.54	1.055	-5.675

Part 1: SMAP TB vs. SMOS TB

Chen et al (2017)



- After adjustments, SMOS and SMAP exhibit minimal bias over the entire TB range
- Separate adjustments needed for 6:00 am TB$_H$, 6:00 am TB$_V$, 6:00 pm TB$_H$, and 6:00 pm TB$_V$

32nd URSI General Assembly and Scientific Symposium | Montreal, Canada | Aug 19-26, 2017 | Steven Chan et al.

Part 1: SMAP TB vs. SMOS TB

Chen et al (2017)

	Bias (SMAP minus SMOS) (K)		RMSE (K)	
	Before Adjustments	After Adjustments	Before Adjustments	After Adjustments
6:00 am ocean TB_H	1.18	0.04	2.36	2.02
6:00 am land TB_H	-1.66	-0.07	3.59	3.14
6:00 am TB_H	**0.59**	**0.03**	**2.66**	**2.30**
6:00 pm ocean TB_H	0.57	0.01	2.20	2.10
6:00 pm land TB_H	-2.10	-0.02	3.91	3.27
6:00 pm TB_H	**-0.04**	**0.00**	**2.69**	**2.42**
6:00 am ocean TB_V	0.72	-0.02	2.04	1.88
6:00 am land TB_V	-2.51	-0.05	3.81	2.81
6:00 am TB_V	**0.06**	**-0.03**	**2.50**	**2.11**
6:00 pm ocean TB_V	0.57	-0.03	2.12	2.01
6:00 pm land TB_V	-2.67	0.00	4.00	2.92
6:00 pm TB_V	**-0.16**	**-0.03**	**2.66**	**2.25**

- After adjustments, SMOS and SMAP exhibit minimal bias over the entire TB range
- Customized adjustments necessary for 6:00 am TB_H, 6:00 am TB_V, 6:00 pm TB_H, and 6:00 pm TB_V

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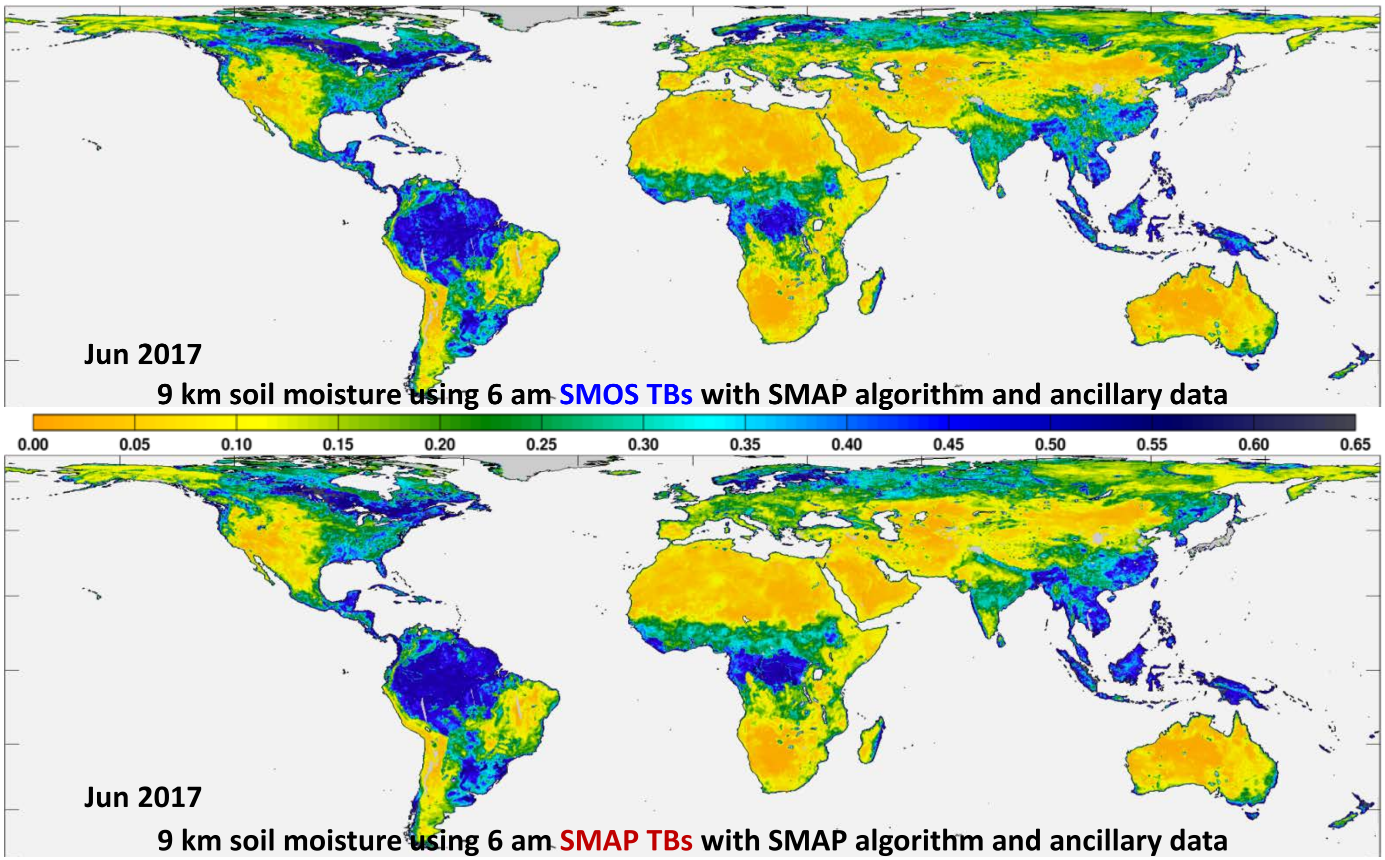
Part 2: Soil Moisture Retrieval

Chen et al (2017)

- Good agreement between SMOS and SMAP
- Slight code differences from current SMAP operational setup (further work needed)
- Consistent TBs, algorithm, and ancillary data lead to consistent SMOS/SMAP soil



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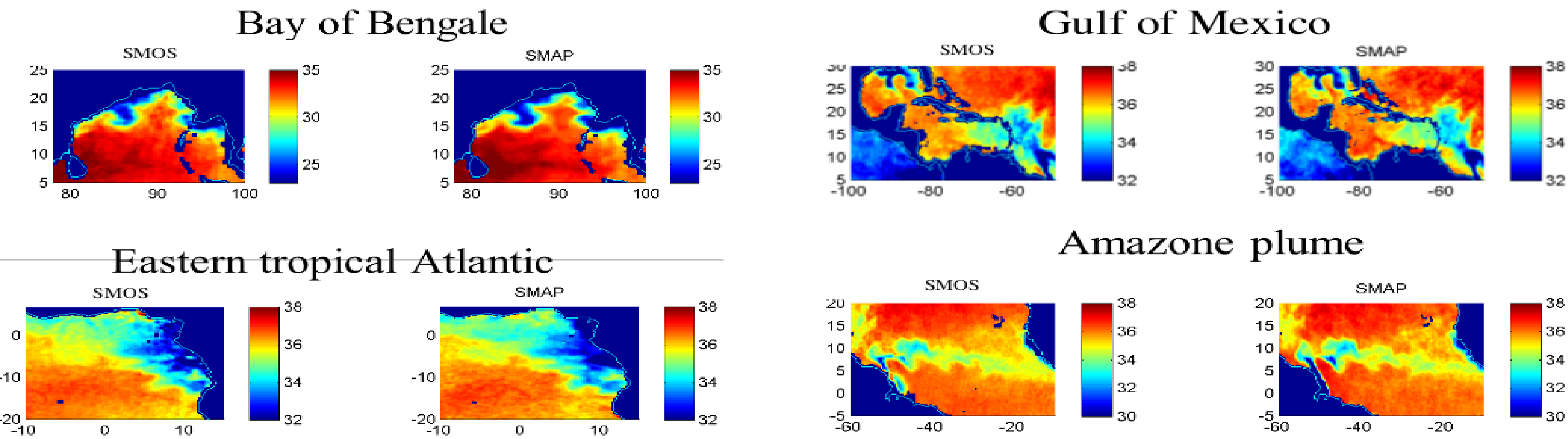
Freshwater river plumes from SMOS (CATDS) and SMAP(CAP) => monitoring at ~50km resolution



Boutin et al., subm RSE, 2017

New CATDS SMOS SSS in very good agreement with SMAP data in river plumes

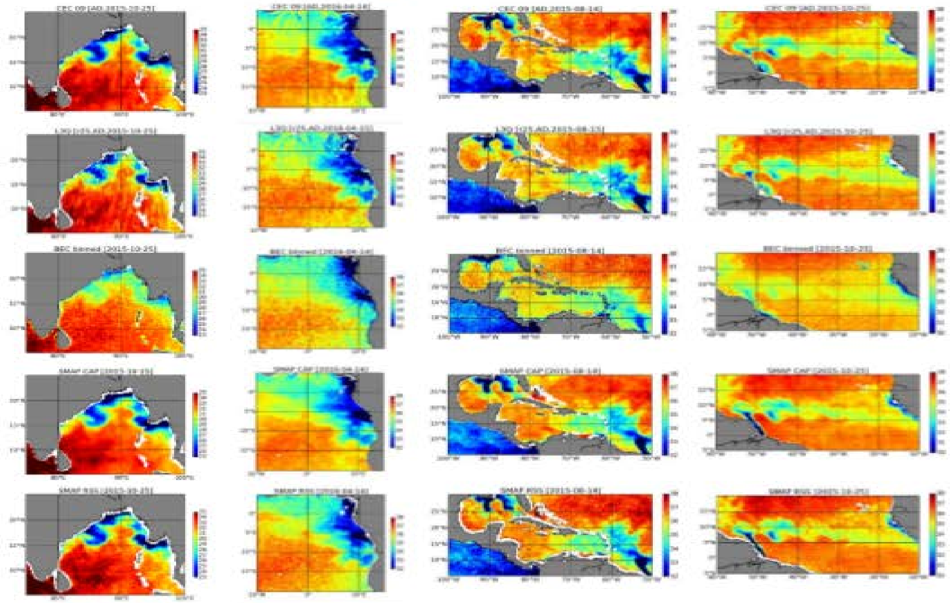
SMOS CATDS CEC LOCEAN Debias_v2

SMOS CATDS CPDC L3Q Binned - near-real time

SMOS BEC non bayesian binned

SMAP CAP/JPL

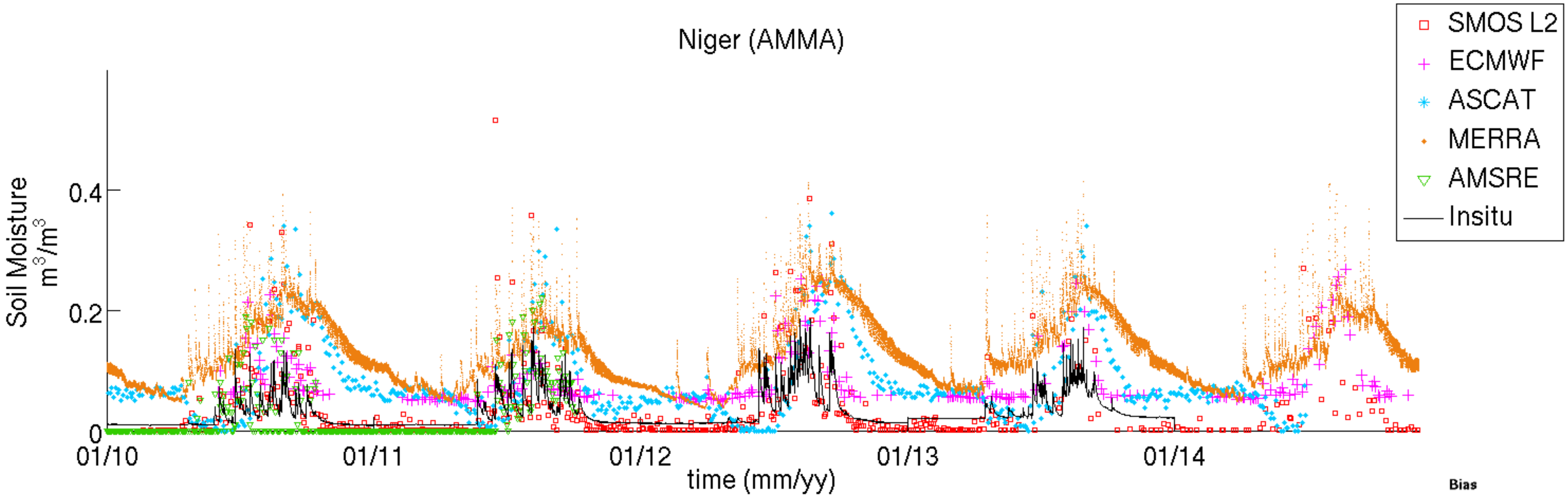
SMAP RemSS (binned)

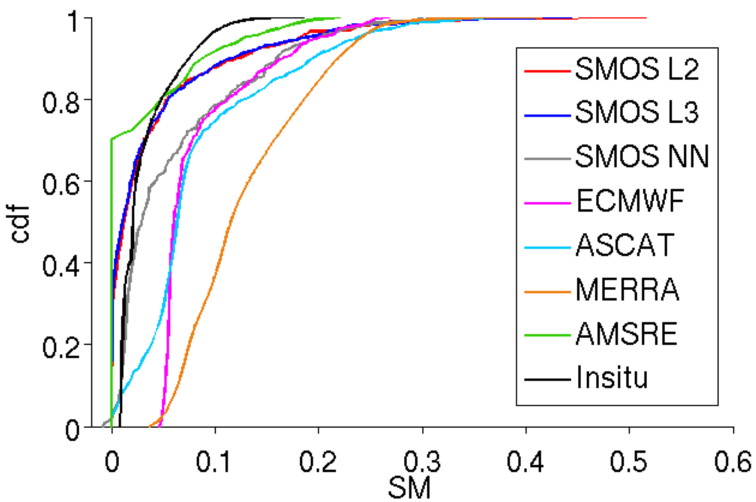


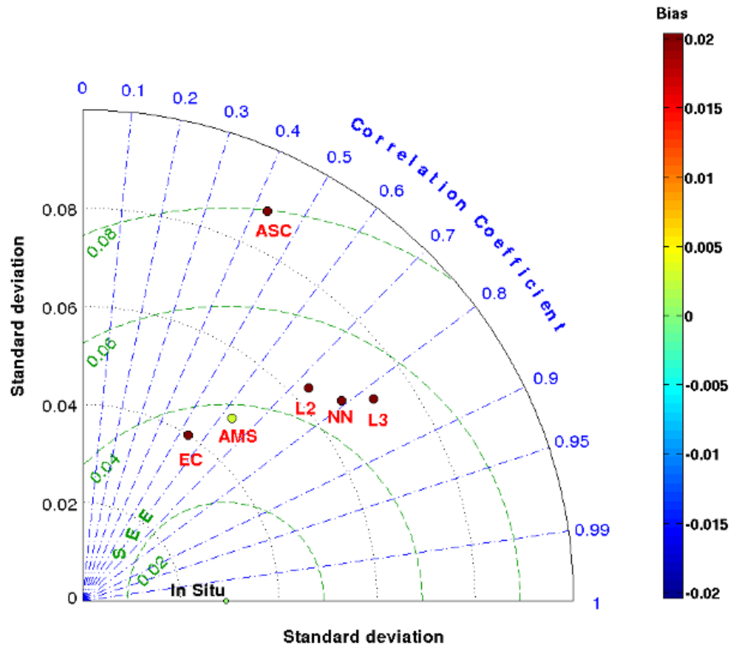
Boutin et al., subm. RSE, 2017

Message

- If
  - Instruments are good
  - of similar characteristics
- Results are similar
- Hence
  - Algorithm more important than instruments in terms of performances for similar measurements
- But validation and comparisons are tricky
  - Representativity of sites
  - Ecosystems sampled
  - Understanding of the physics of measurements
  - Analysis techniques


Niger (AMMA)
SMOS L2
ECMWF
ASCAT
MERRA
AMSRE
Insitu
Soil Moisture
m3/m3
0.4
0.2
0
01/10
01/11
01/12
01/13
01/14
time (mm/yy)


cdf
SM
SMOS L2
SMOS L3
SMOS NN
ECMWF
ASCAT
MERRA
AMSRE
Insitu


Correlation Coefficient
Standard deviation
Standard deviation
RMSE
ASC
L2
NN
L3
AMS
EC
In Situ
Bias

Detrending and triple collocation (TC)

- The application of any filter comes at the risk of <u>information loss</u>
- Detrending prior to TC:
  - can help to reduce non-linearities
  - BUT removes a part of the signal that is important
- Detrending may benefit sensors with “wrong” seasonality
- Moreover, the detrending window length is arbitrary !

Experiment

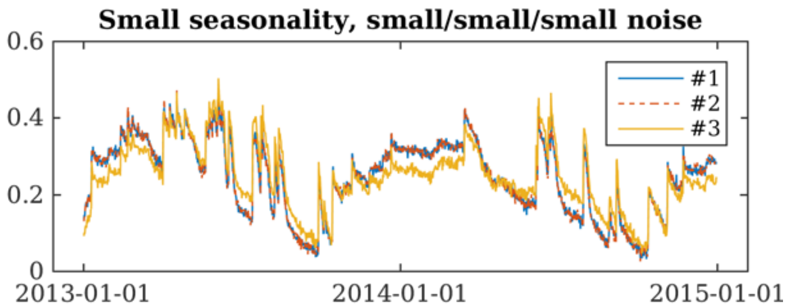
- ❑3 datasets (#1, #2, #3) built from a common SM series
  - ❖In situ series recorded at one Little Washita station during 2 years, no gaps
- ❑Each dataset: X = SM_insitu + noise + seasonality
- ❑Evaluation of TC correlation (correlation between the observation and the unknown true signal)
- ❑The #3 dataset exhibits a seasonality shift (1.5 months): does detrending benefits its TC score?
  - ❖Try different amplitudes of seasonality and noise

Example 1

Same small noise (nanstd(sm)./10)

Seasonality of #3 shifted 1.5 months

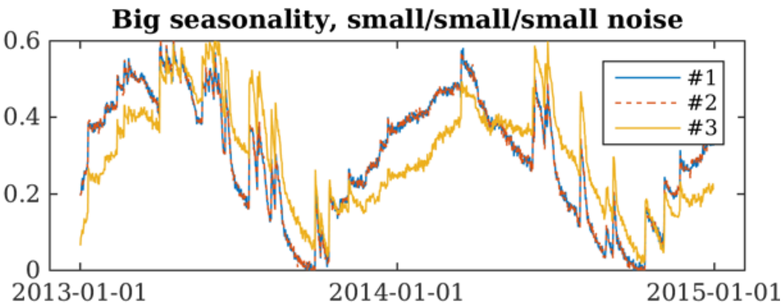
a) Small seasonality (nanstd(sm))



	#1	#2	#3
R:	1	1	0.92
R (detrend):	0.98	0.98	0.98

The #3 dataset benefits from the detrending

b) Big seasonality (2.5*nanstd(sm))



	#1	#2	#3
R:	1	1	0.81
R (detrend):	0.98	0.98	0.98

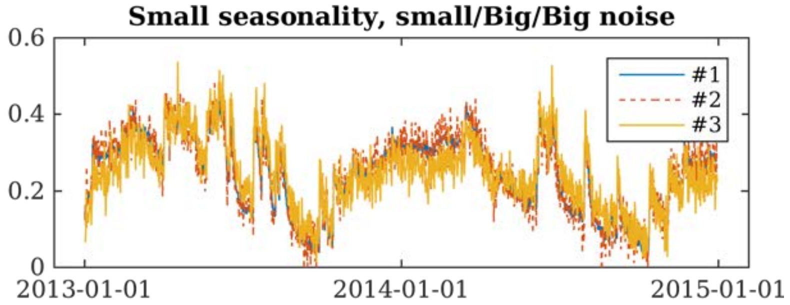
The #3 dataset benefits from the detrending

B. Molero

Example 2

#1 small noise, #2 & #3 big noise (nanstd(sm)./2)
Seasonality of #3 shifted 1.5 months

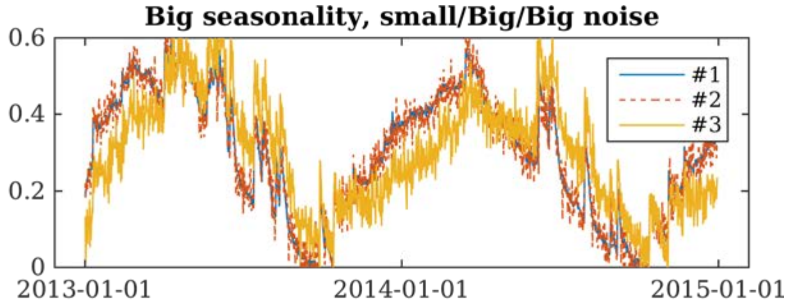
a) Small seasonality
(nanstd(sm))



	#1	#2	#3
R:	1	0.94	0.86
R (detrend):	0.97	0.68	0.67

The #3 dataset benefits from the detrending

b) Big seasonality
(2.5*nanstd(sm))



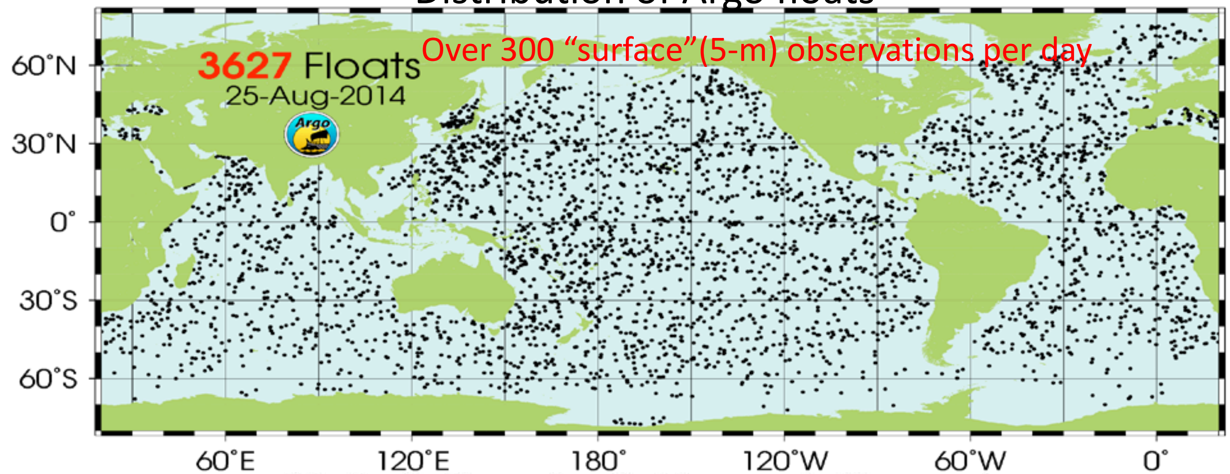
	#1	#2	#3
R:	1	0.98	0.79
R (detrend):	0.96	0.67	0.66

The #3 dataset benefits from the detrending

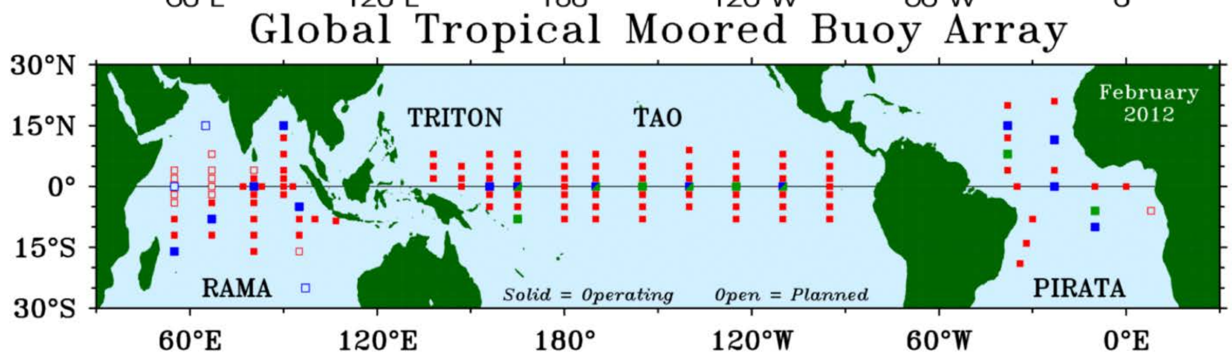
B. Molero

Lesson learned from Aquarius SSS validation using in-situ data

Distribution of Argo floats



Main sources of validation data for Satellite SSS



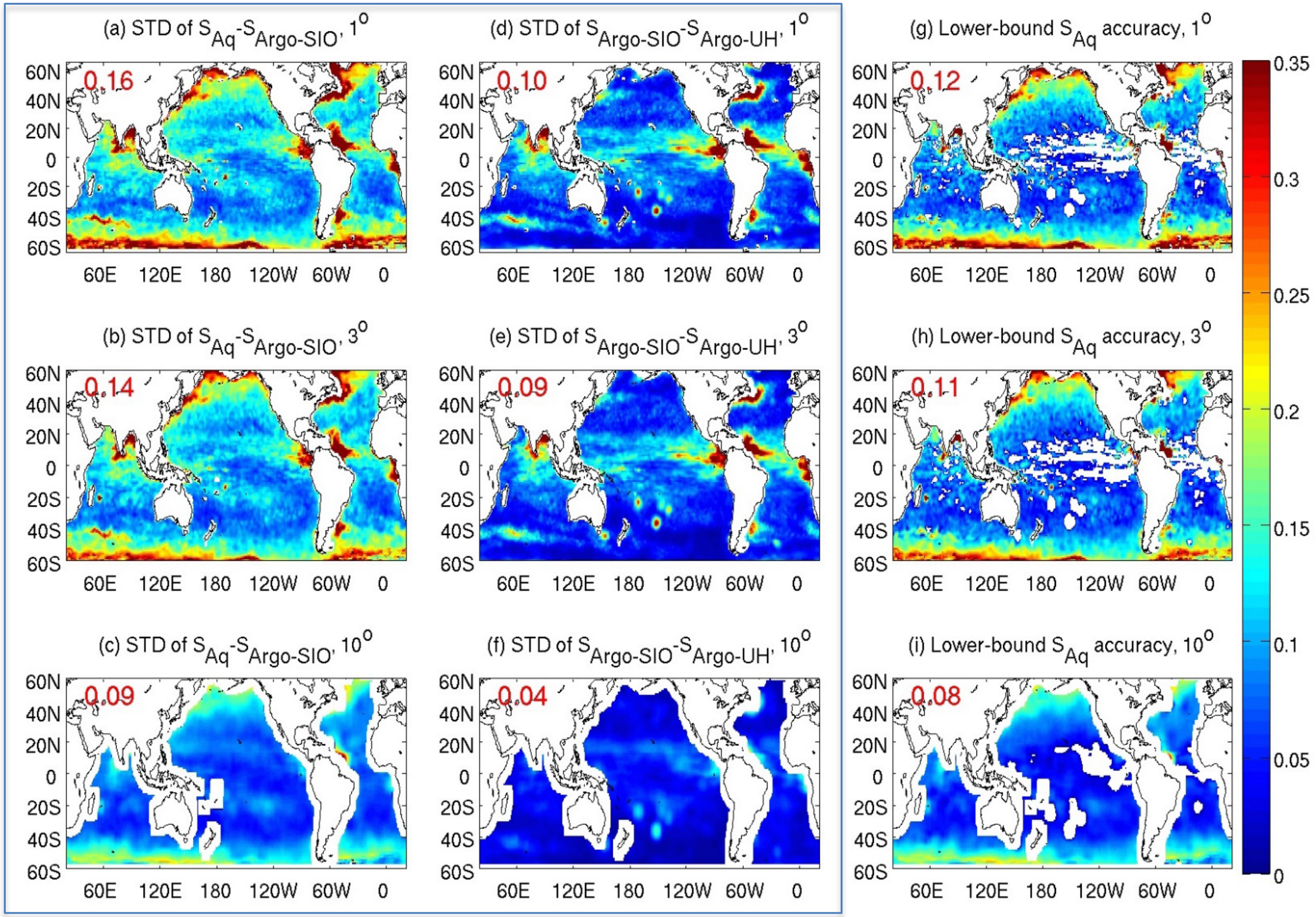
- Aquarius mission requirement for SSS accuracy is 0.2 psu for 150-km, monthly scales.
- But there is no exactly equivalent ground truth for this.

T Lee

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

Red numbers represent aerial average

In regions of strong variability, the difference between the two Argo OI products can be as large as or larger than the difference between Aquarius and the Argo OI products.

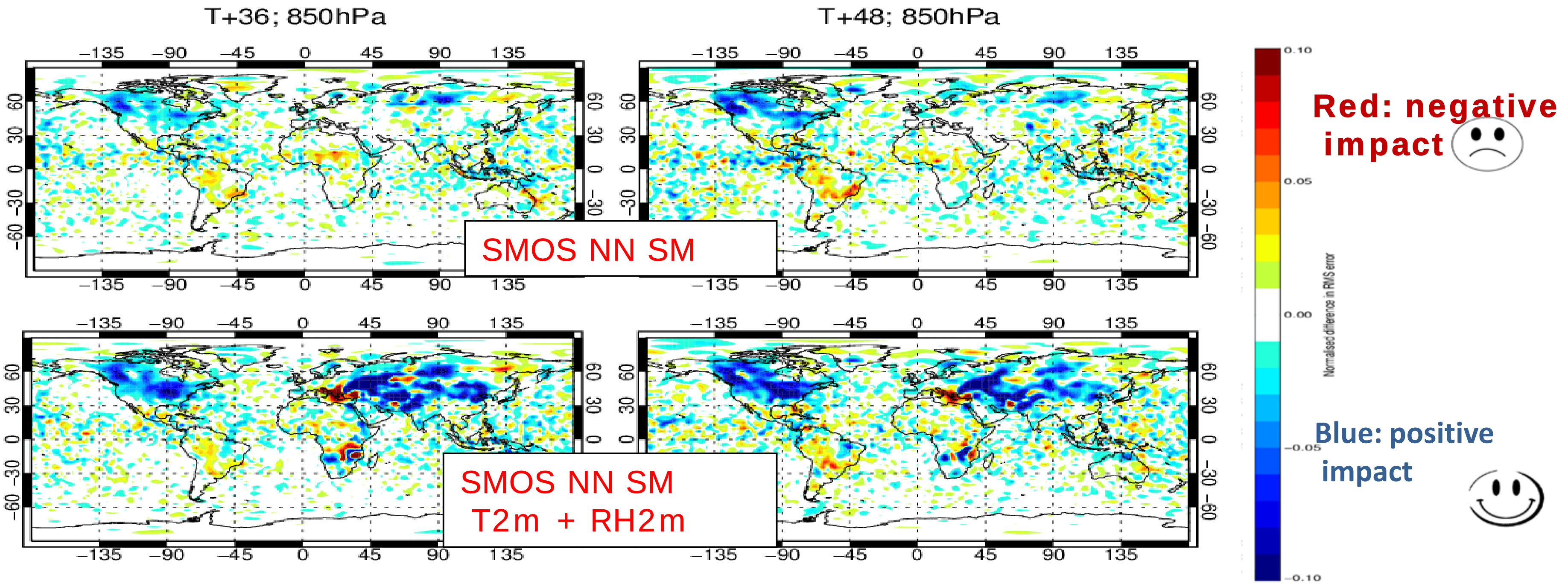


T Lee

Some examples

SMOS neural network soil moisture for ECMWF data assimilation

Rodriguez-Fernandez, de Rosnay et al

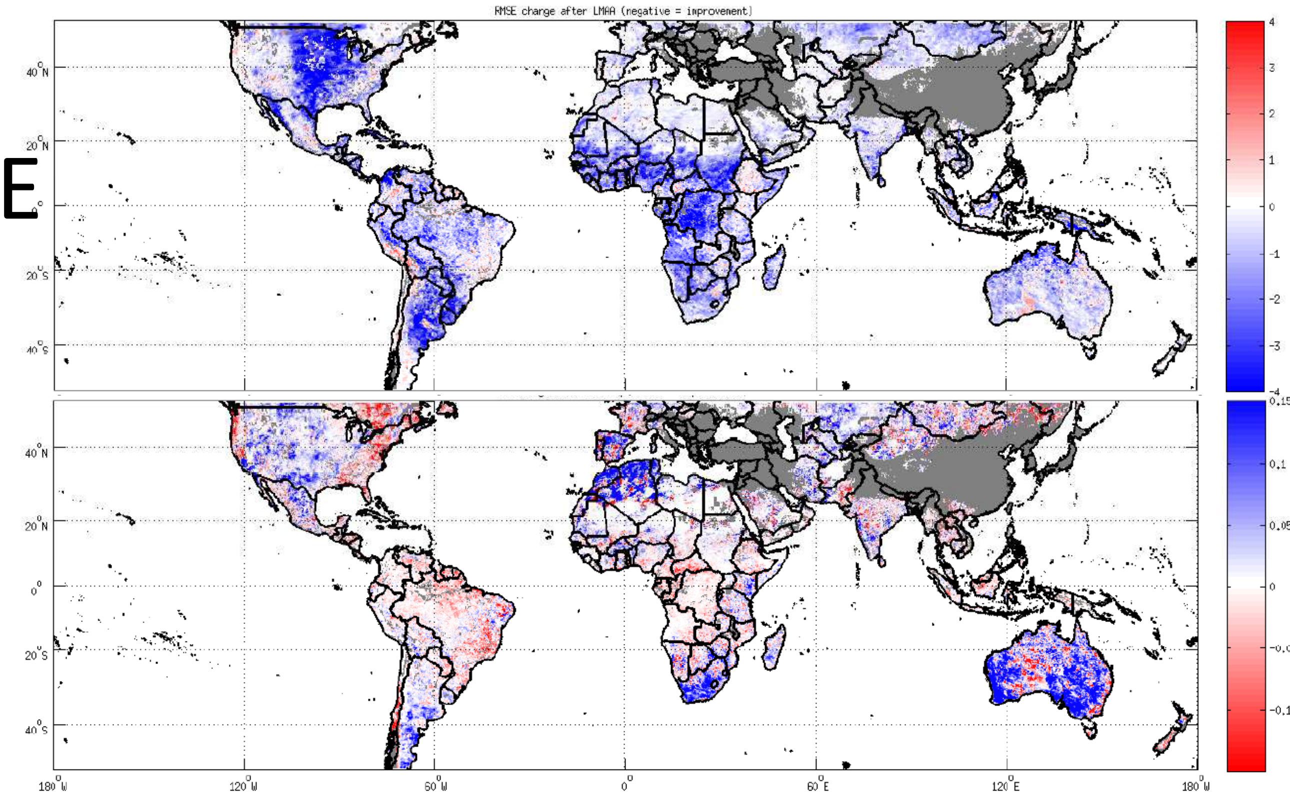


GPM Rainfall estimates improved with SMOS

T. Pellarin, C. Roman, F. Gibon, Y. Kerr

ΔRMSE

ΔR²

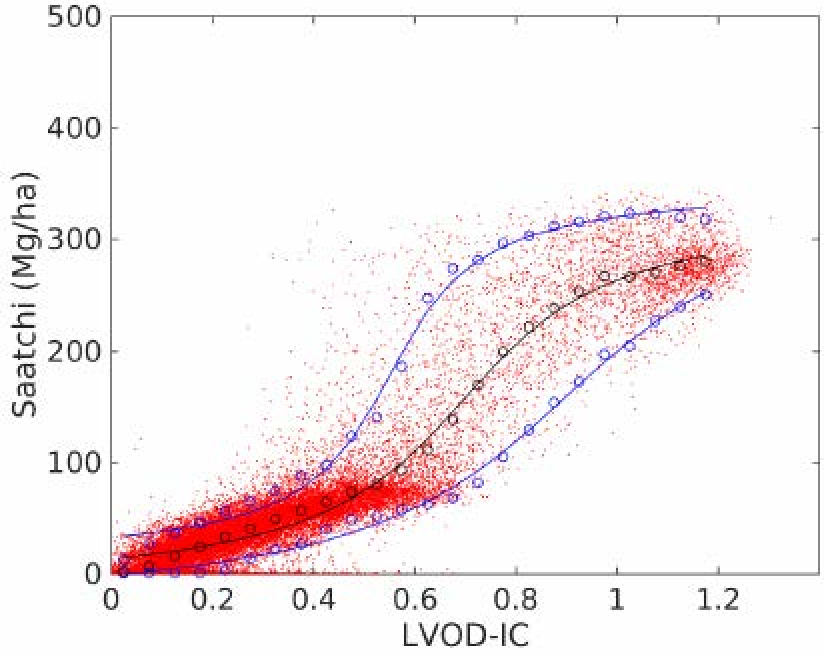


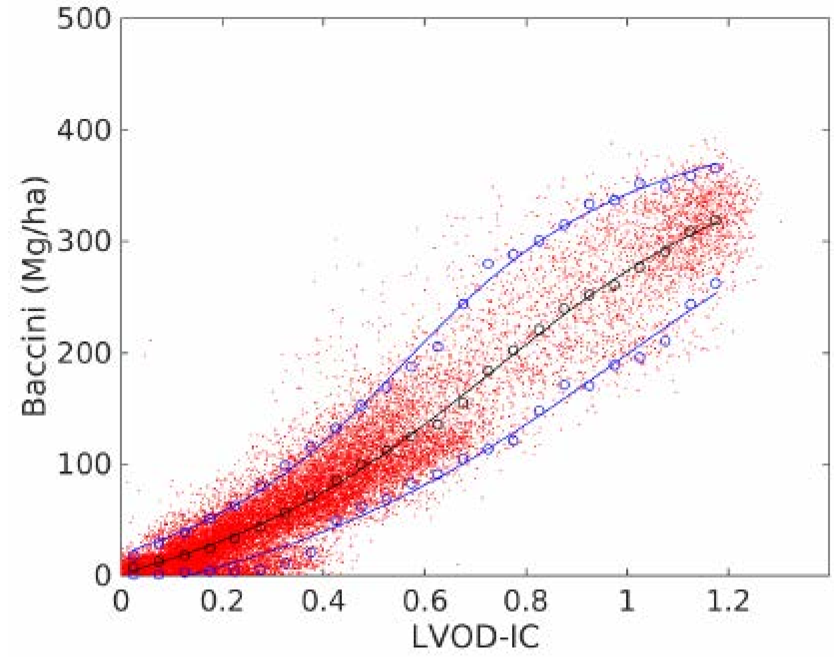
worsening

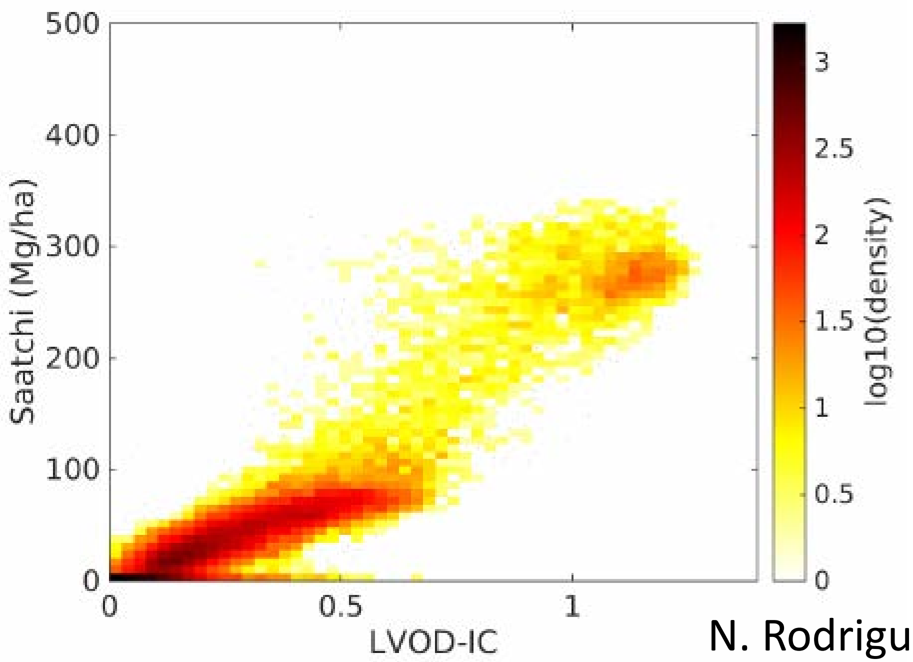
Improvement

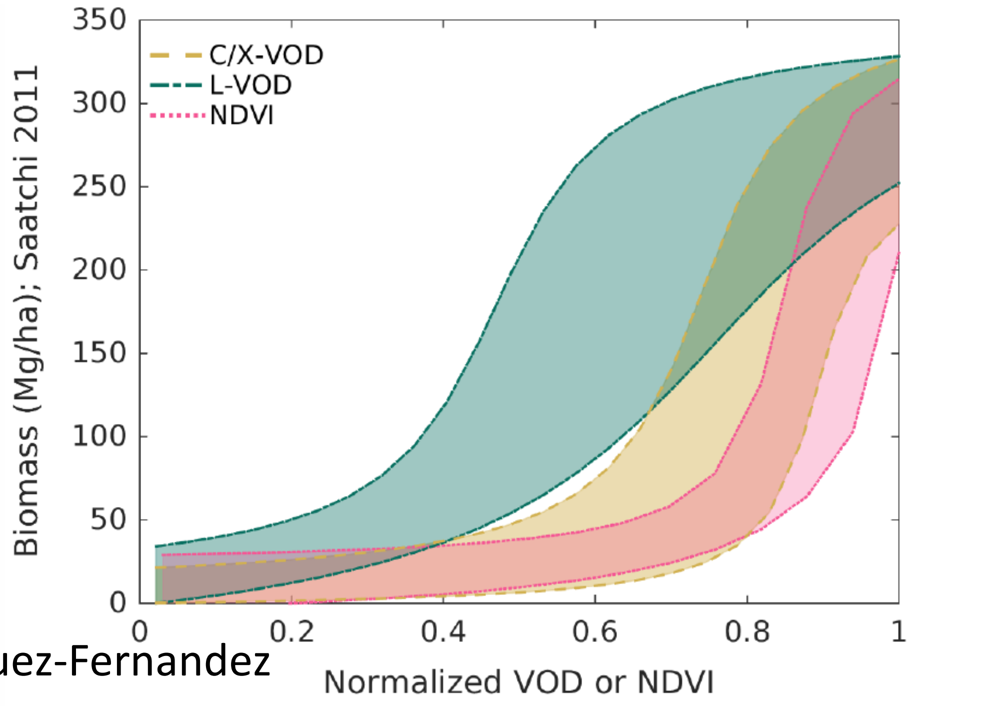
Improvement

worsening









N. Rodriguez-Fernandez

Snow Wetness Retrieved from L-band TB's:

"Indications for a potential novel SMOS data-product"

Reza Naderpour & Mike Schwank (WSL-Birmensdorf, GAMMA Remote Sensing)

Forward-emission model used to retrieve snow liquid-water:

- *L-band specific (no volume scattering), single-layer version of MEMLS*

Snow liquid-water column WC_S estimated from $T_{B,R}{}^{p}(\theta)$ measured over areas with the metal Reflector placed below the snow ("gridded areas"):

- *Expected to work due to the very high sensitivity of $T_{B,R}{}^{p}(\theta)$ with respect to snow wetness.*
- *Retrievals are seen as "references"; no better in-situ method exists for snow wetness.*

Snow liquid-water column WC_S estimated from $T_{B,N}{}^{p}(\theta)$ measured over "natural snow-covered areas":

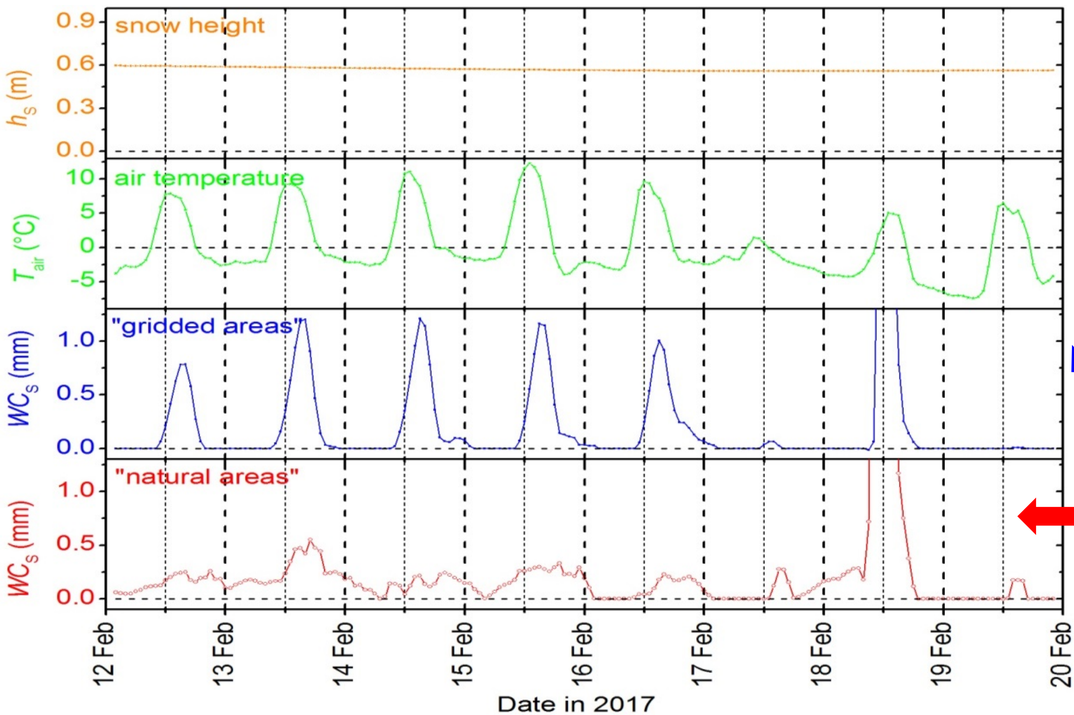
- WC_S is retrieved simultaneously with snow density ρ_S and ground permittivity ε_G
- Expected to be challenging because: interfering effects of ρ_S and ε_G
- However, if successful is a new useful data-product based on passive L-band

Snow Wetness Retrieved from L-band TB's:

"Indications for a potential novel SMOS data-product"

Reza Naderpour & Mike Schwank (WSL-Birmensdorf, GAMMA Remote Sensing)

HERE IS THE RESULT FROM ELBARA MEASUREMENTS OVER EARLY SPRING SNOW:

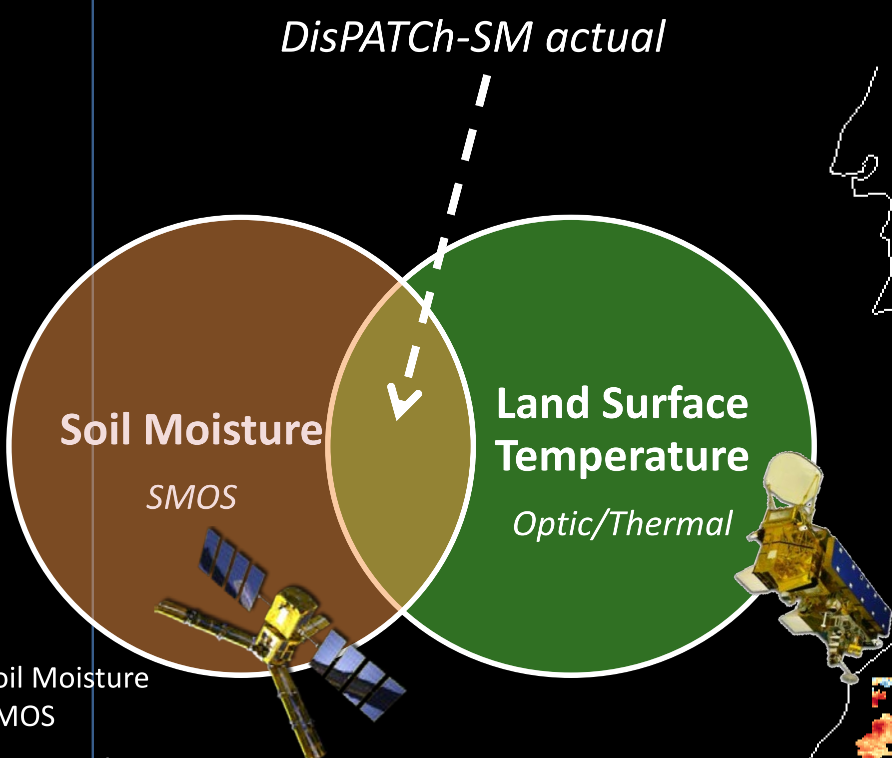


- Increased snow liquid-water WC_S diurnally during afternoons when air temperature T_{air} rises above 0°C.
- Temporal pattern of retrieved WC_S is consistent with T_{air}.

- High synchronicity between WC_S retrieved from $T_{B,N}^p$ and $T_{B,R}^p$ (considered as "references").
- For $T_{air} << °0 \Rightarrow WC_S \cong 0$ mm $\Rightarrow$ retrievals are not a "direct" side-effect of temperature.
- Evidence that WC_S can be estimated from L-band TB's measured over natural snow-covered grounds!

J. Malbeteau

Soil Moisture 1 km Morocco

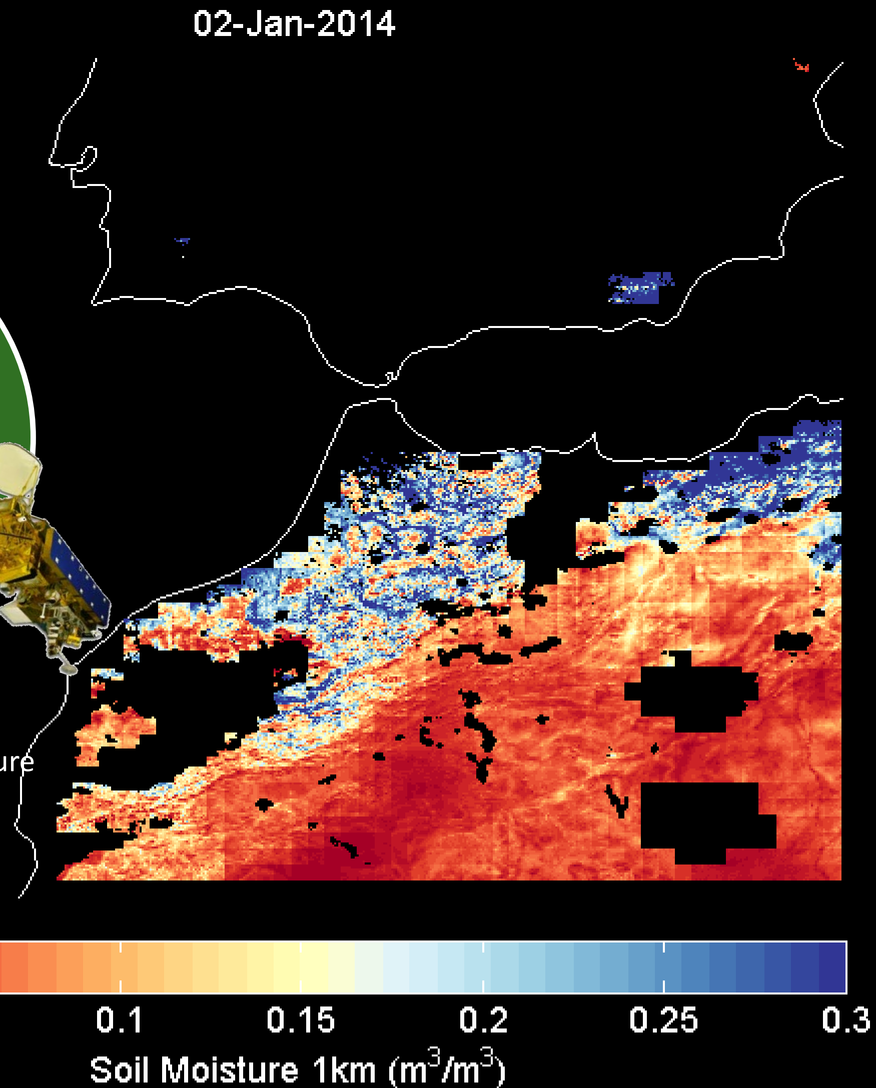


Soil Moisture
SMOS

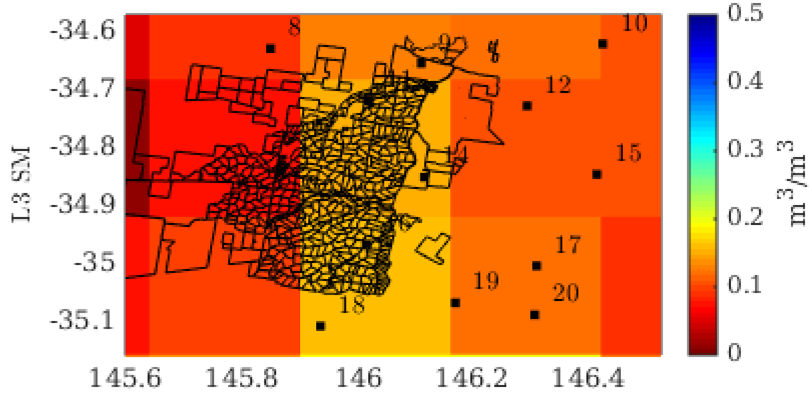
40 km / 3 days

Land Surface Temperature
MODIS (Aqua/Terra)

1 km / 1 day

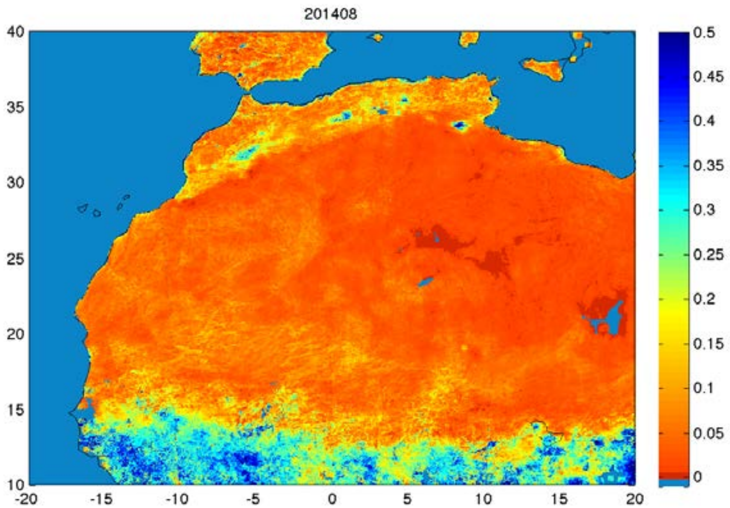


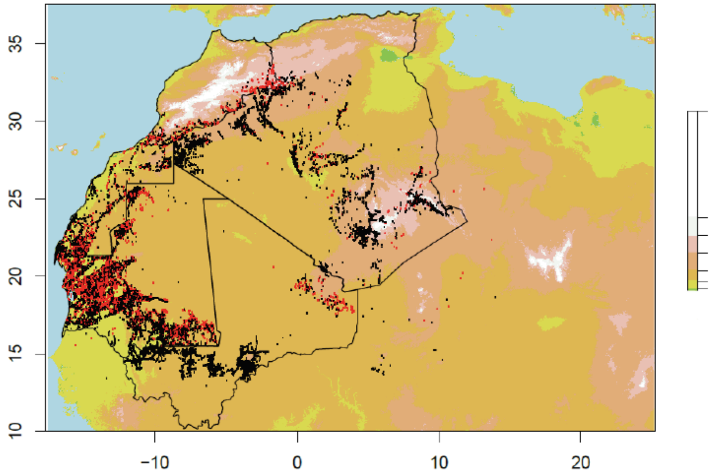
Example of SMOS High Resolution data fo irrigation monitoring

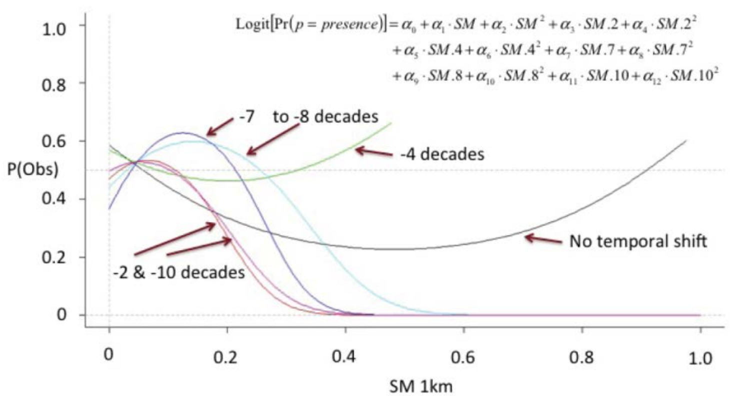


Molero et al

SMELLS 1 km v2





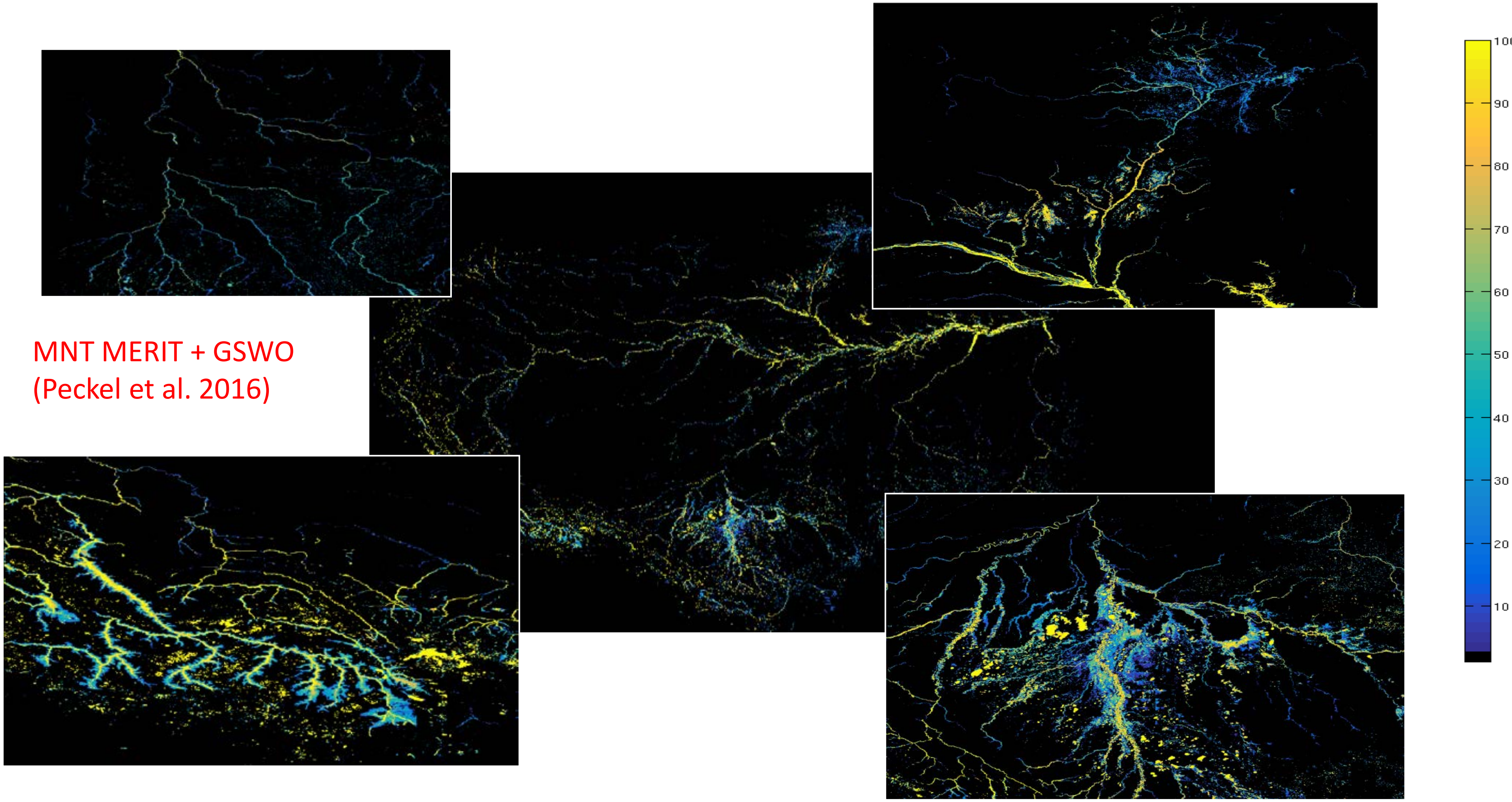


- SMOS soil moisture downscaled at 1km (DisPATCh) produced over the entire region (2010 -2015)
- SMELLS 1km can explain Desert Locust (DL) presence
- Current approaches rely on NDVI at 3km
- Introduction of SM increases resolution (1km)

SM precedes vegetation by 2 months -> high impact on DL management

M.J. Escorihuela

L4 Water Surfaces at High resolution (M Parrens A AlBitar)

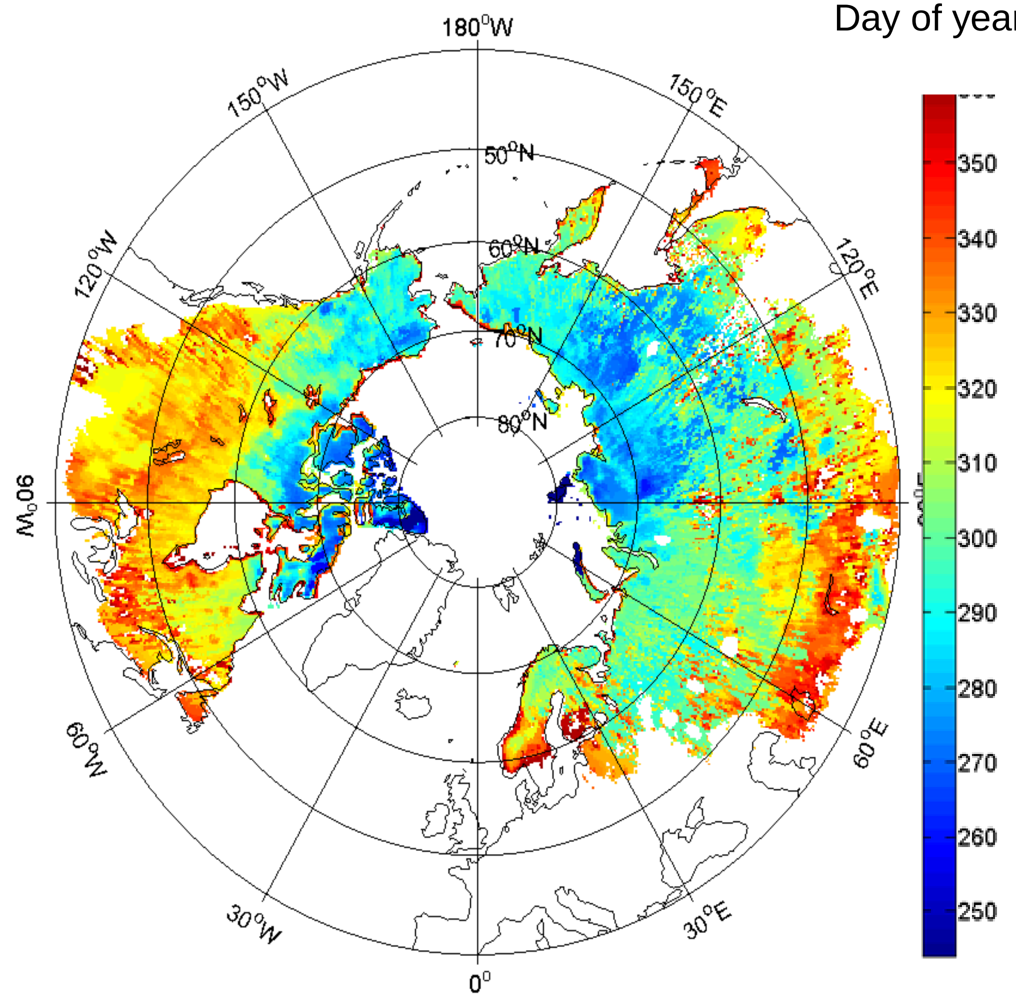


MNT MERIT + GSWO
(Peckel et al. 2016)

Cryosphere

Freeze onset 2014

- Example for final soil freezing date on 2014 calculated from SMOS freeze/thaw data

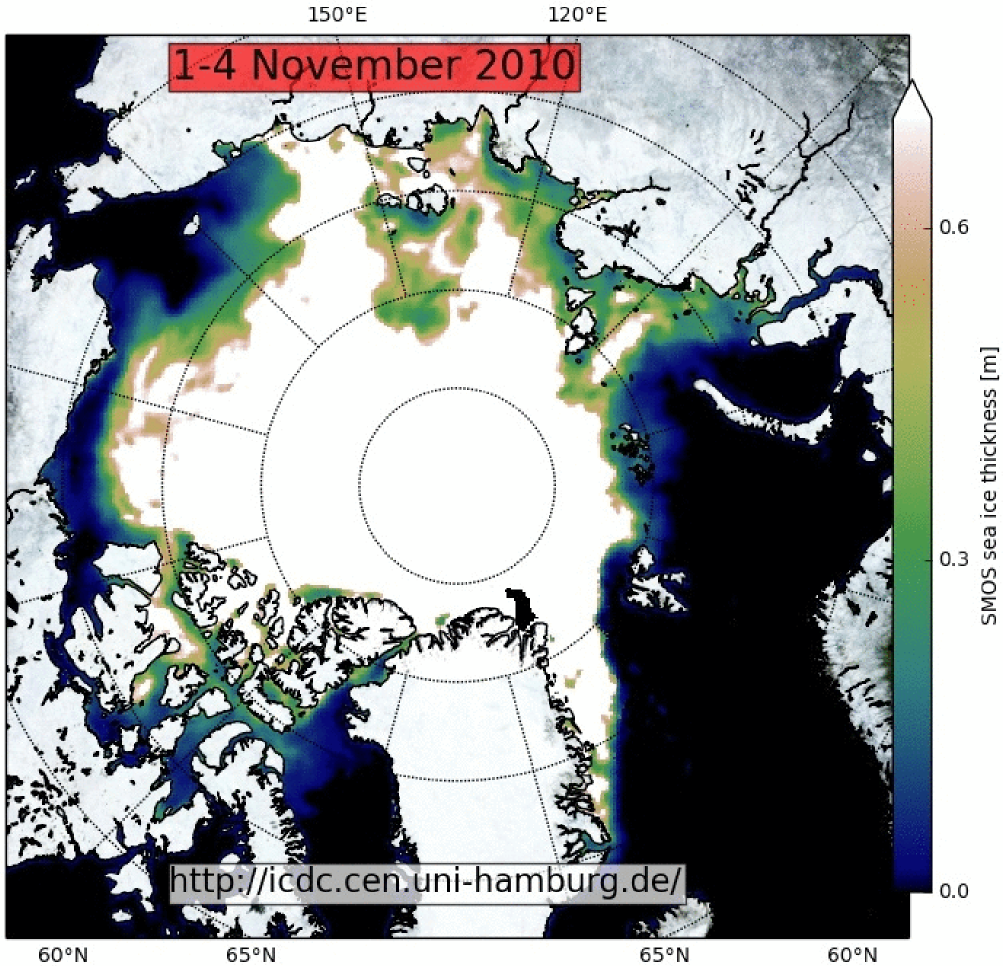


Rautiainen, K., Lemmetyinen, J., Schwank, M., Kontu, A., Ménard, C.B., Mätzler, C., Drusch, M., Wiesmann, A., Ikonen, J., & Pulliainen, J. 2014. Detection of soil freezing from L-band passive microwave observations. *Remote Sensing of Environment.* 147, pp. 206-218.

Rautiainen, K., Parkkinen, T., Lemmetyinen, J., Schwank, M., Wiesmann, A., Ikonen, J., Derksen, C., Davydove, S., Davydova, A., Boike, J., Langer, M., Drusch, M., & Pulliainen, J. SMOS prototype algorithm for detecting autumn soil freezing. *Remote Sensing of Environment.* submitted in July 2015

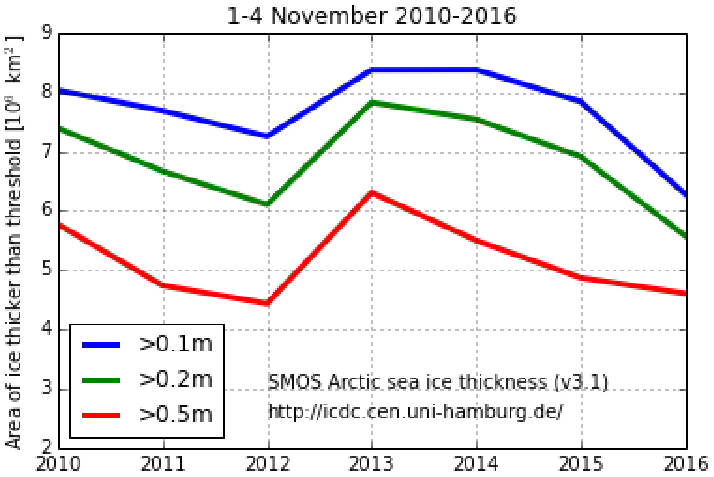
K. Rautiainen

Towards a climate data record:
7 years of Arctic freeze-up observed with SMOS

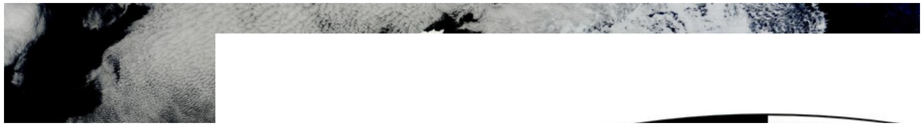


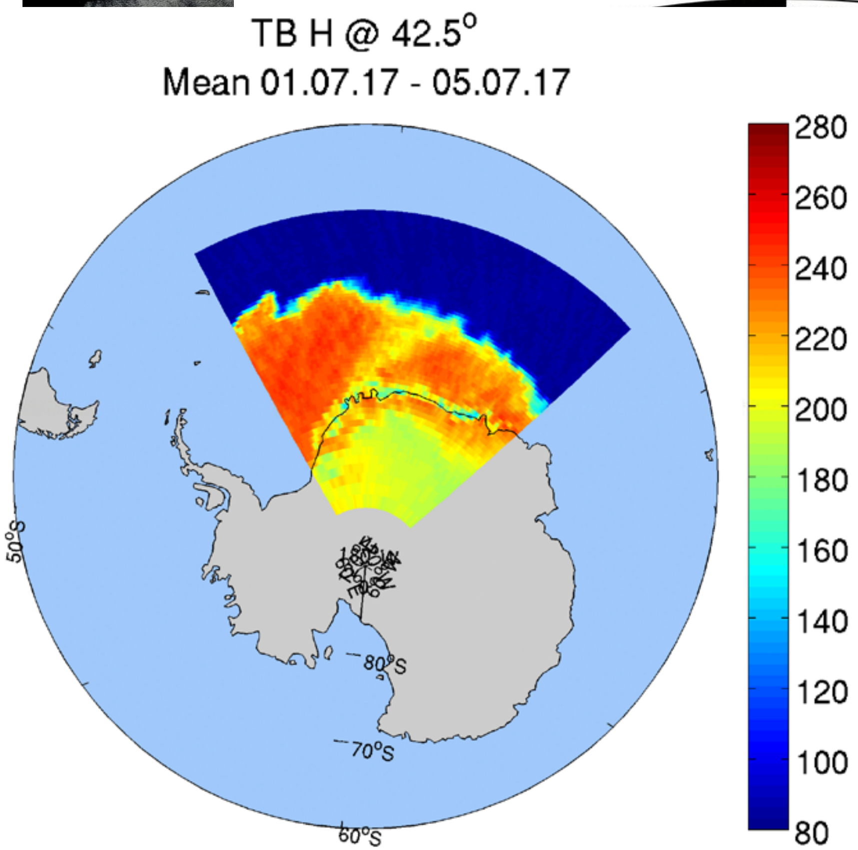
2016 slowest sea ice growth since 2010

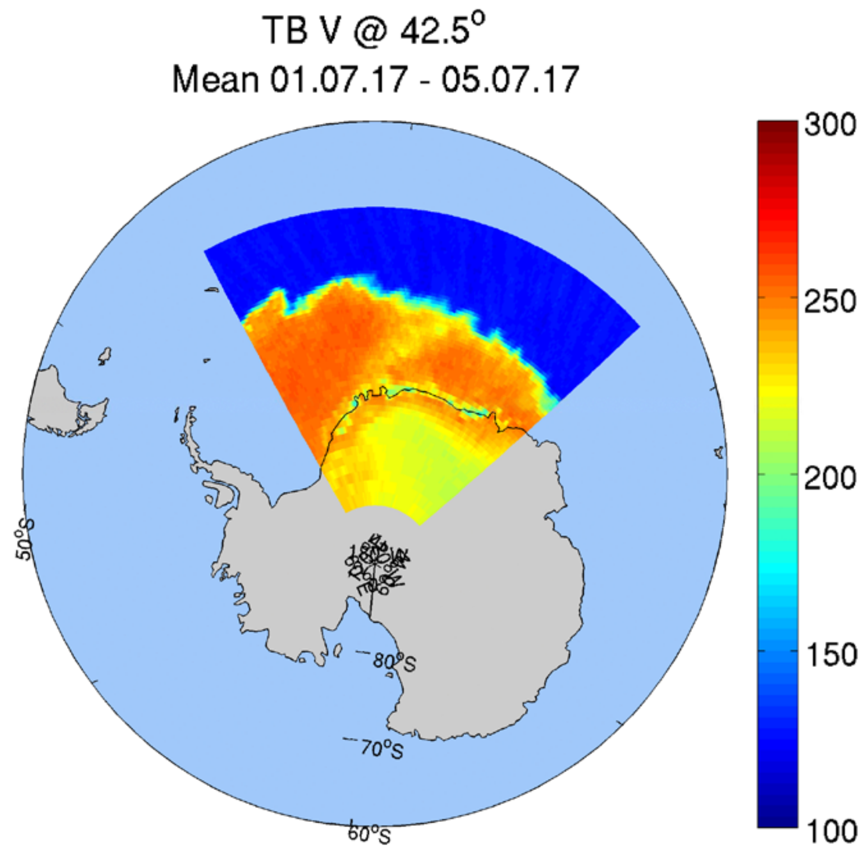
Kaleschke, L

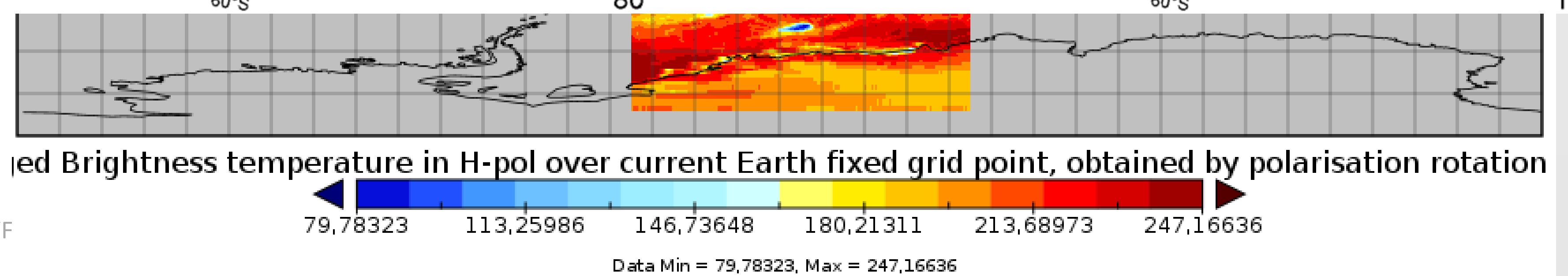


Hole in Antarctica (A. Mialon)



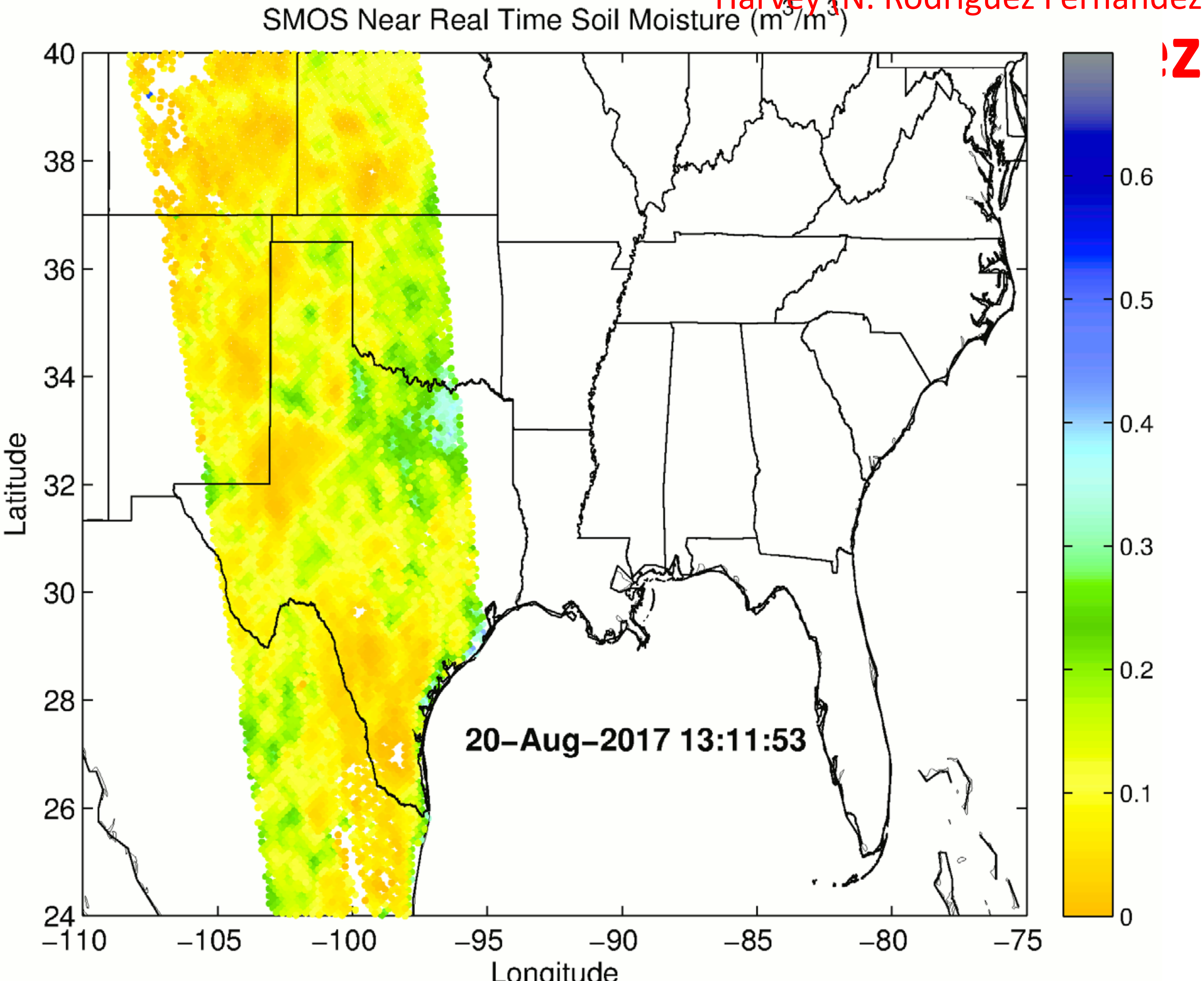




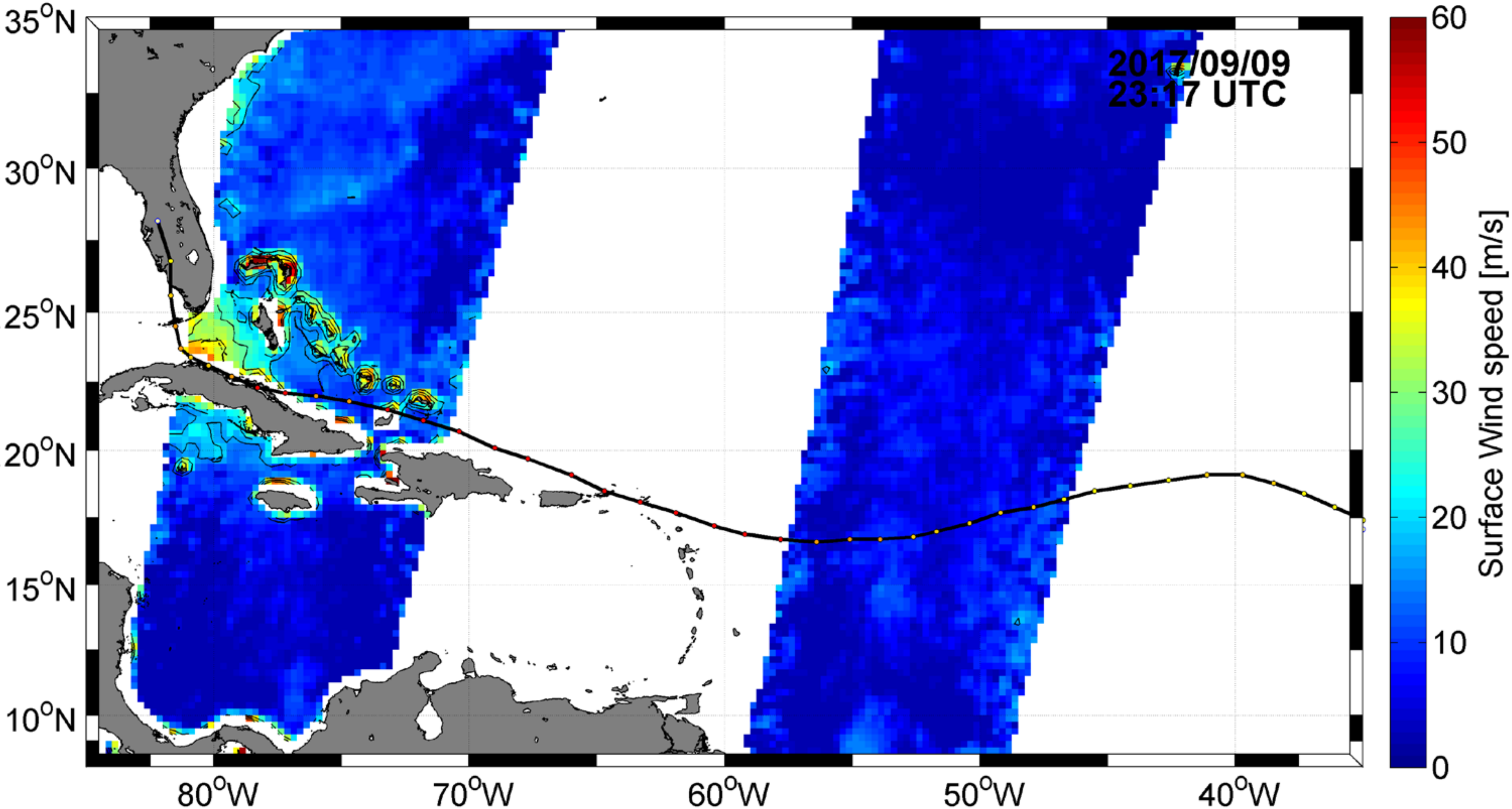


ECMWF

Harvey (N. Rodriguez Fernandez)

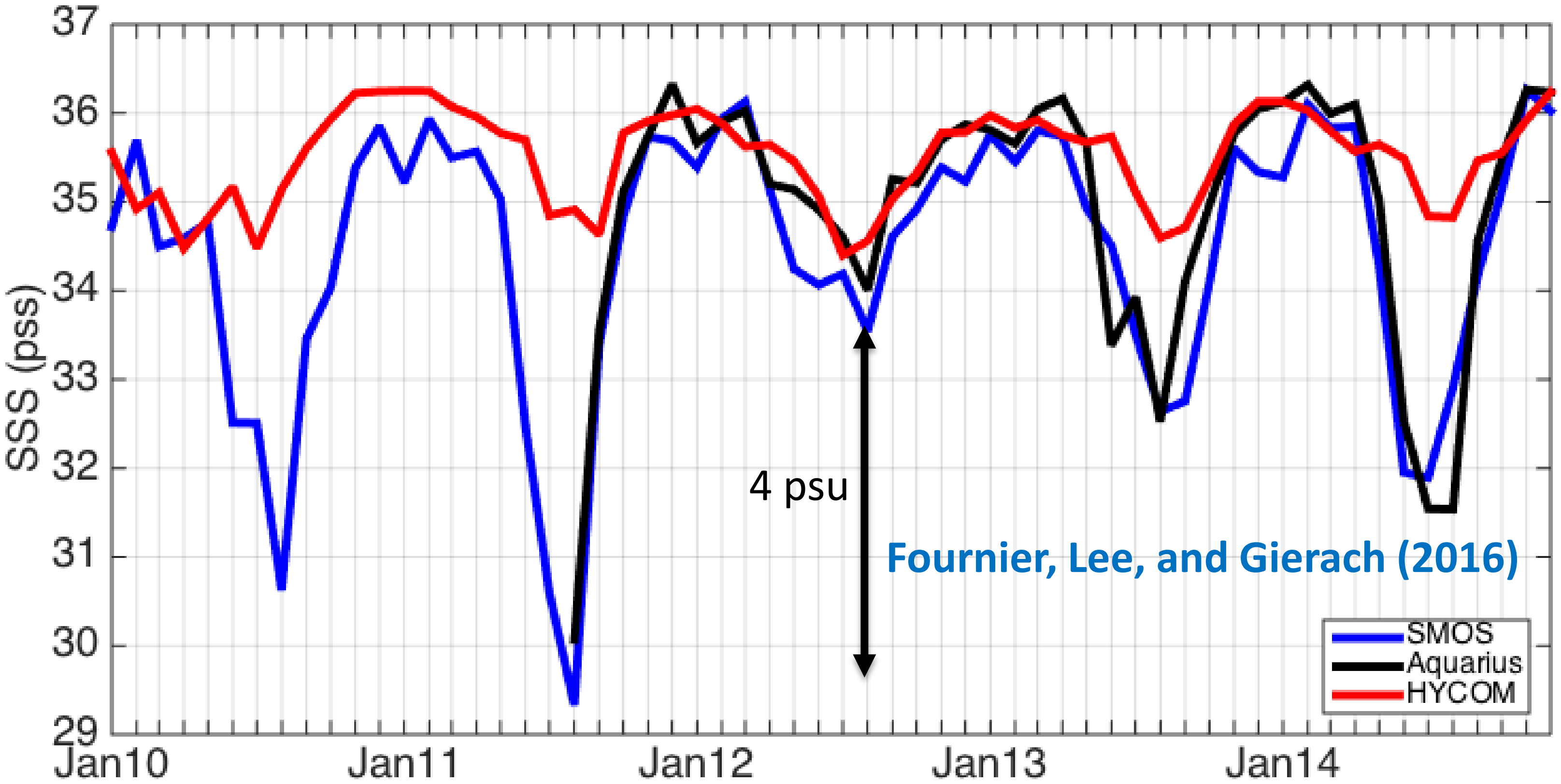


IRMA (N. Reul)



2017/09/09
23:17 UTC
35°N
30°N
25°N
20°N
15°N
10°N
80°W
70°W
60°W
50°W
40°W
60
50
40
30
20
10
0
Surface Wind speed [m/s]

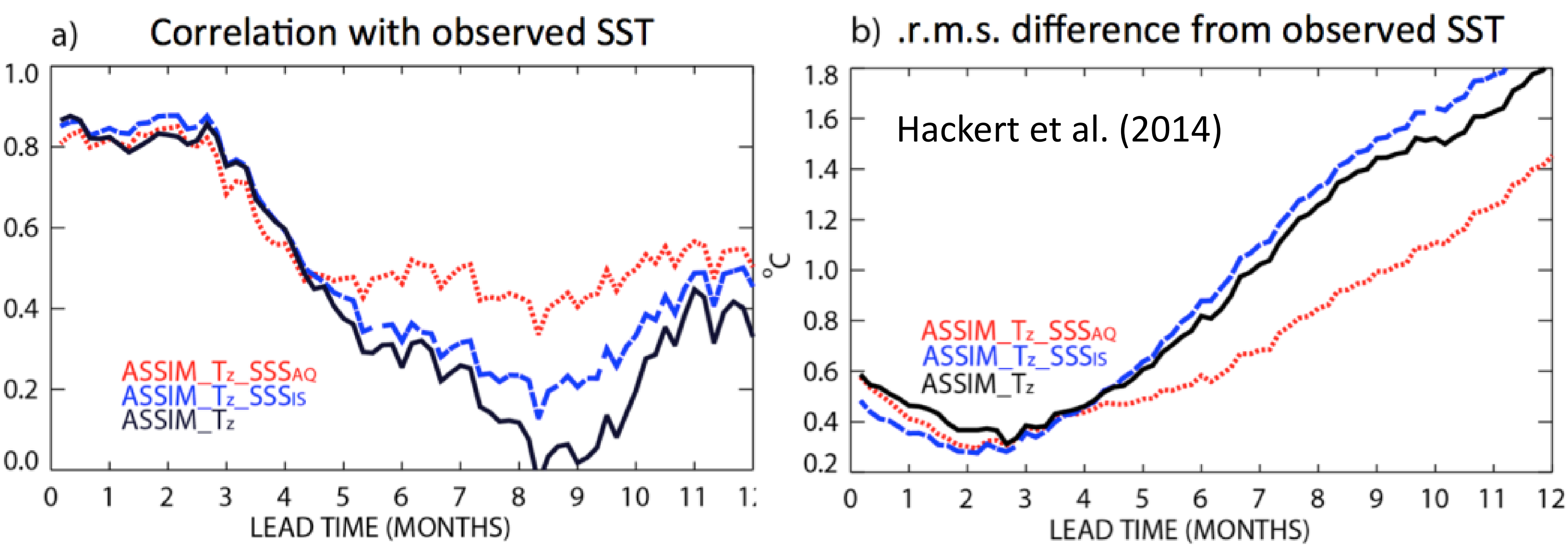
Global ocean data assimilation products failed to capture large interannual variations of SSS near river mouths



- Aquarius & SMOS revealed large interannual variations of SSS (up to 4 psu) near the Mississippi River mouth.
- Operational data assimilation products (e.g., HYCOM) failed to capture these changes.
  - Caused by climatological river discharge forcing & SSS relaxation to climatology
  - Underlines the importance of satellite SSS to constraint ocean state estimation

Impact of assimilating satellite SSS on seasonal-interannual prediction

T; Lee



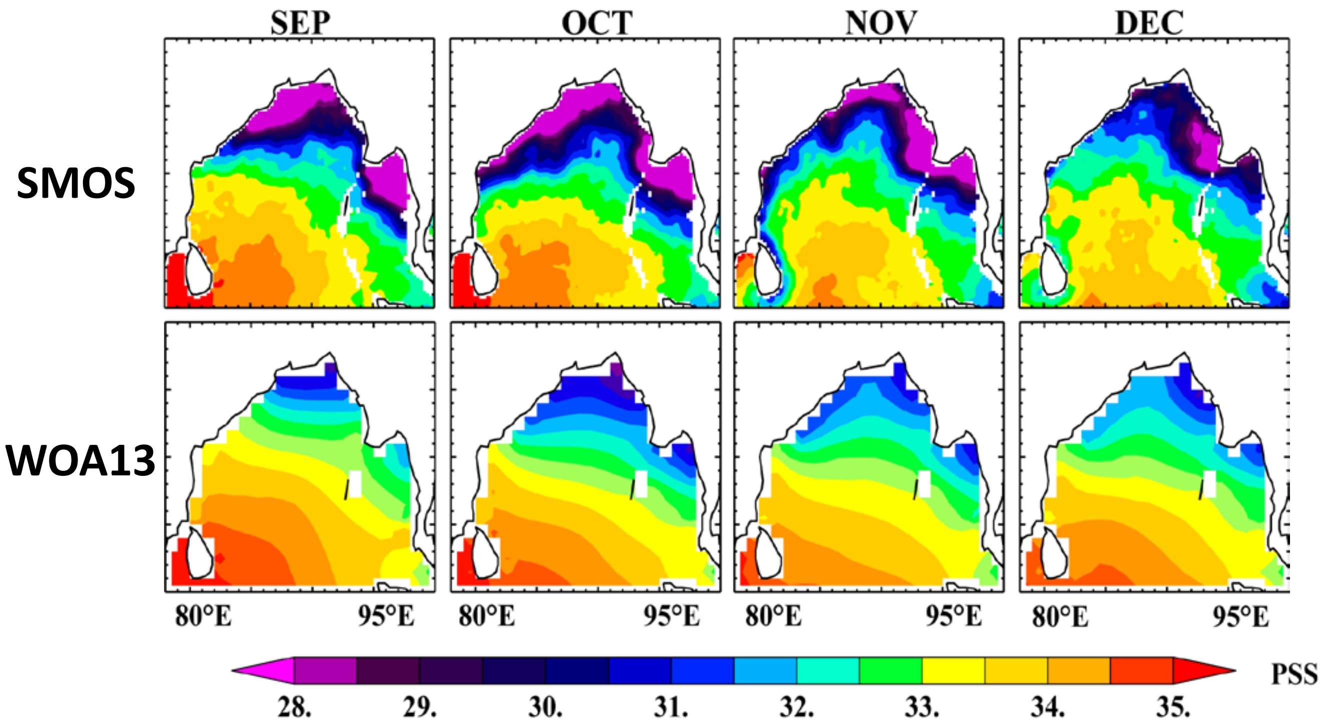
ASSIM_T_Z: baseline experiment, assimilation of all subsurface temperature data.

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

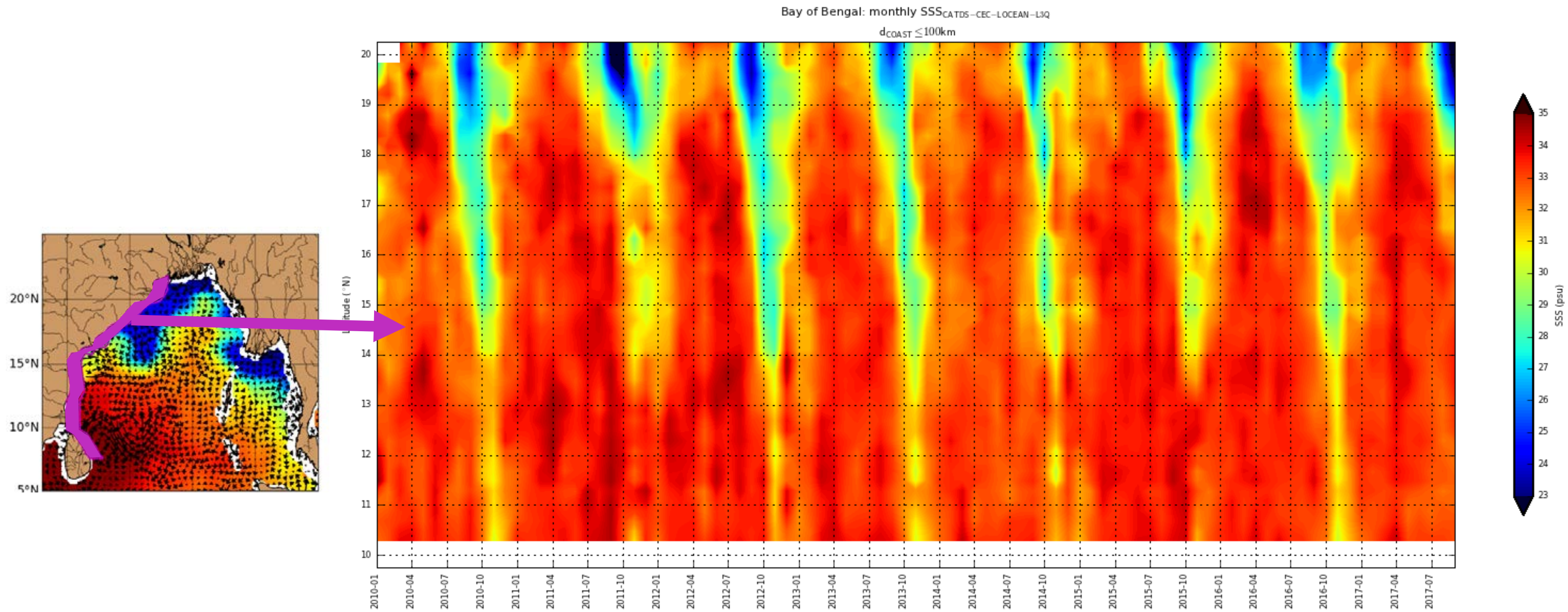
ASSIM_T_Z_SSS_{AQ}: assimilation of all subsurface temperature and Aquarius SSS data.

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

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



J. Vialard etal



J. Vialard etal

Lessons learned

- L band has demonstrated
  - Sm, SSS, thin sea ice, yield, rainfall, hurricanes etc capability of L band from Space
- SMOS has demonstrated
  - Interferometry efficiency
  - Usefulness of angular measurements
  - RFI impact
- Aquarius has demonstrated
  - push broom efficiency
  - Interest of very high sensitivity
  - spatial resolution limitations
  - Need for thinner bandwidth
  - Usefulness of Scatterometer
- SMAP has demonstrated
  - Efficiency of rotating large antenna
  - Potential usefulness of radar
  - Efficiency of RFI filtering
- Next steps
  - Continuation
  - Higher spatial resolution
  - Higher sensibility

Summary

- Need for soil moisture, sea surface salinity and thin sea ice (and …) measurements continuity
- Why L band?
  - Because of its characteristics and inherent qualities
  - The most appropriate tool as shown by all the products stemming from it
  - Temporal stability and robustness
- L band radiometry proof of concept demonstrated
  - Uniqueness of the measurements hence
    - Many science outstanding results
    - A very large number of operational or pre operational demonstration products (only a few were presented)
  - Very efficient means to reach user's requirements
- BUT …
  - No follow on mission currently → **Data gap**
  - While many possibilities are available
- New user's requirements
  - Basically 10 km SM, better SSS sensitivity
  - High enough TRL

SMOS soil moisture monthly averages (2011-2016)

Time: 1 of 72