Assessment of SMOS measurements of Arctic Sea Ice Concentration

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7th Data Assimilation and PPP Ice Verification Workshop / ESRIN, Rome 5-7 April 2016

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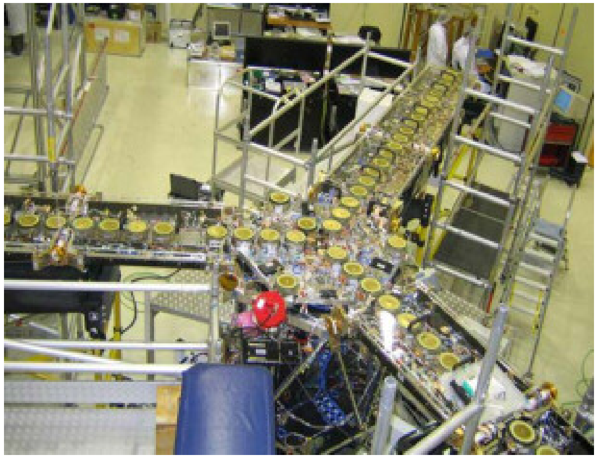
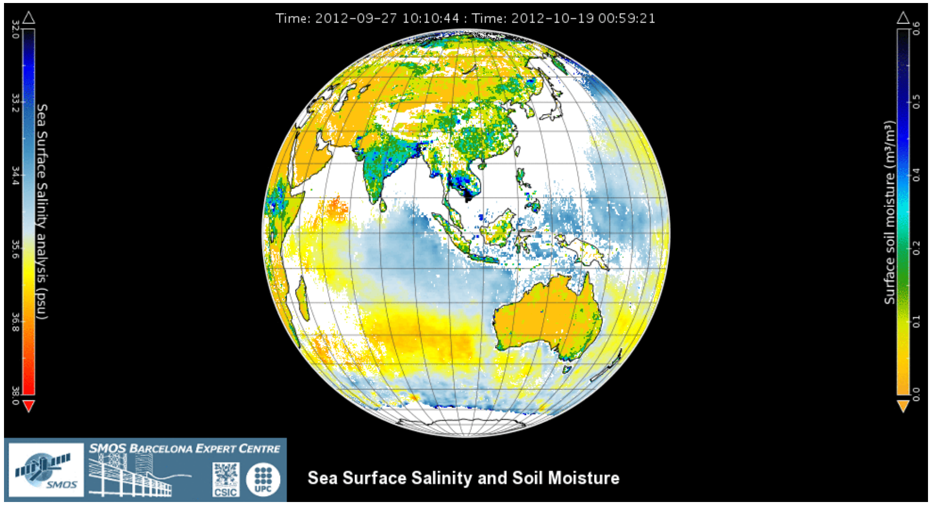
Measuring salinity from space: SMOS



ESA SMOS mission:

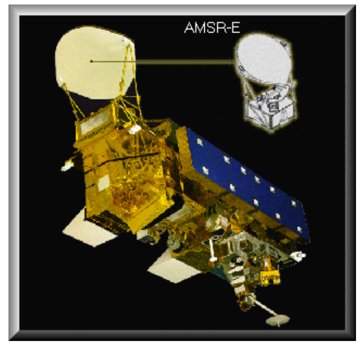
- Earth Explorer launched on Nov. 2009
- L-band (1.4 GHz) synthetic aperture radiometer, with many incidence angles (0 to 68^o), large swath and full-pol.
- Polar orbit: 6am/6pm, 3-day repeat
- Measures:
    - SSS on the ocean
    - SM on land
    - Cryospheric applications : Ice thickness, sea ice concentration, Sea Surface salinity in Arctic Ocean



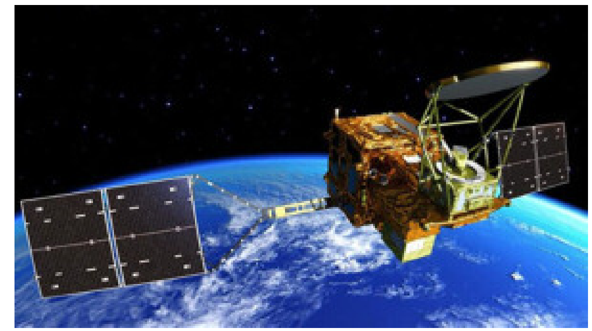
Basic Concepts on Sea Ice

- Obtained from 80s by radiometers (SSMIs, AMRS-E, AMSR-2, etc..)

SSMI



AMSR-E on Nasa AQUA



AMSR-2 on JAXA GCOM-W1

- Using combination of TB at frequencies: 6, 19, 37, 89 GHz, H/V pol.
- More than 10 different algorithms : Bootstraap, Bristol, Nasa Team, ASI, OSISAF, etc. -> each one has PROS/CONS

➡ Paper from Ivanova et al., 2015 -> good resume comparison of algorithms.

Ice concentration measurement

Sea Ice Emissivity & Ice Concentration Algorithms

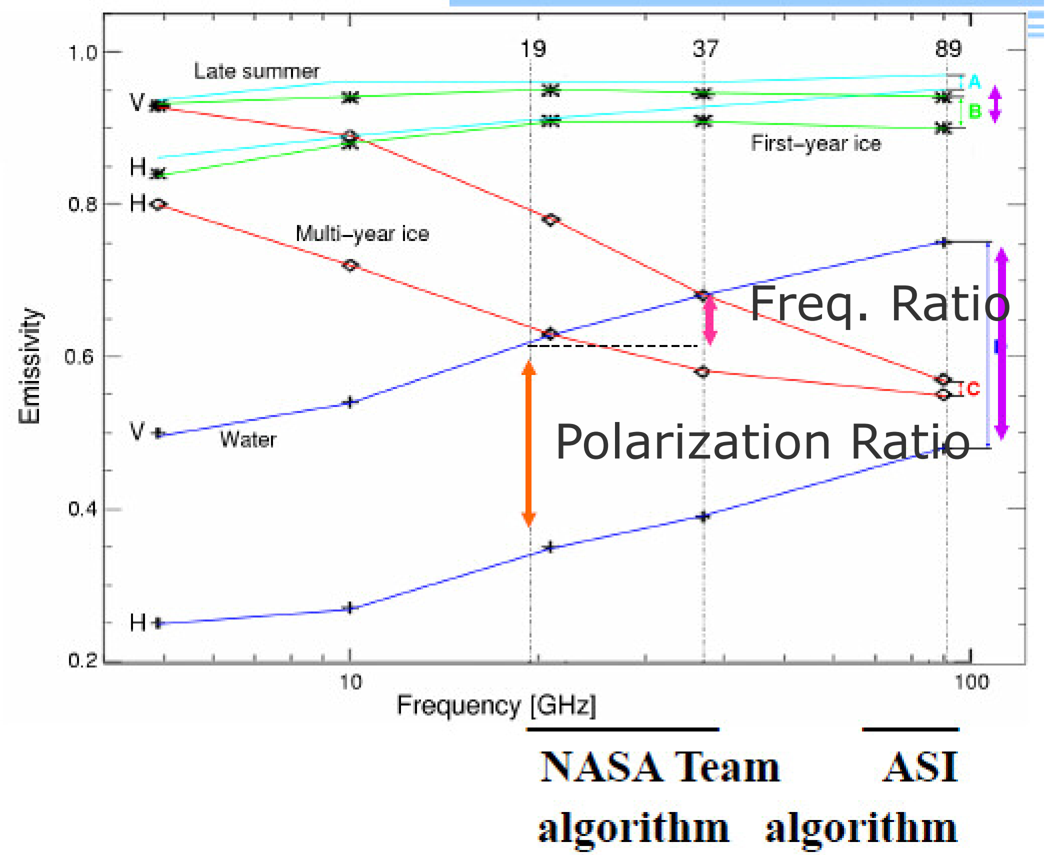
$$T_b = eT$$

T_b brightness temperature

= emitted radiation

e emissivity

T physical temperature



- **Indices** (combination of TBs) are commonly used
- **Tie points** : typical radiometric meas. for sea ice and open water -> Empirically obtained

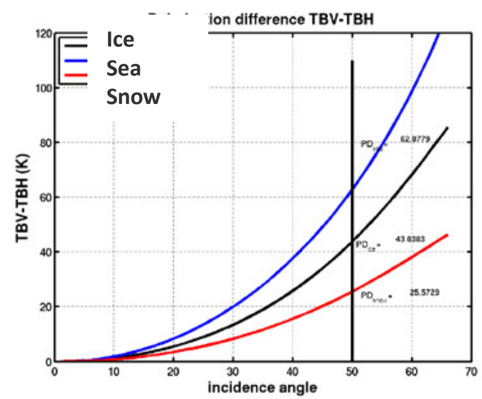
Determination of indices: based on **theoretical** models

Theoretical Models

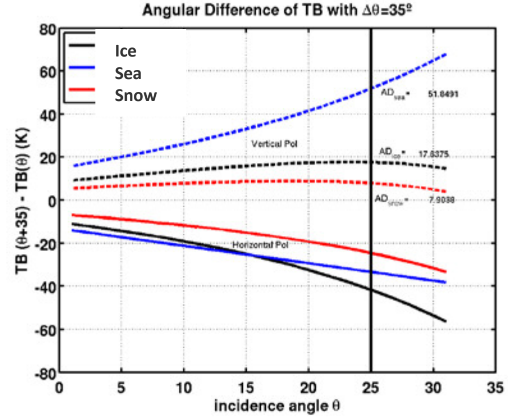
- State of the Art models used to describe TB from ICE: Vant et al. , Cox and Weeks, Leppäranta & Manninen, Burke et al. -> even theoretical models are not much reliable for ice.

- Indices used with SMOS: → Are less sensitive to geophysical conditions changes?

Polarization Differences:
TBv - TBh at θ=50º



Angular Differences:
TBv(θ+Δθ) - TBv(θ)
at θ=25º and Δθ=35º



Determination of indices: based on **theoretical** models

- Sensitivity of TB and indices to geophysical parameters **based on theoretical models**

Sensitivity	Sea Temp.	Sea surf. Salinity	Ice Temp	Ice salinity
TB sea	0.52 K/ºC	0.51 K/pss		
PD sea	0.26 K/ºC	0.21 K/pss		
AD sea	0.20 K/ºC	0.12 K/pss		
TB ice			0.85 K/ºC	1 K/psu
PD ice			0.66 K/ºC	0.35 K/psu
AD ice			0.35 K/ºC	0.25 K/psu

PD and AD have lower sensitivity to temperature and salinity changes

→ **Better to use indices**

SMOS Barcelona Expert Centre

Dataset & Validation

- Data set: SMOS
  - SMOS L1B 503, transformed to BOA, outlier filtered, inter/extrapolated to all incidence angles
  - Average of 3 days for each month in 2014
  - EASE Northern Hemisphere grid, equal area projection, at 25Km
  - ASC + DES orbits

Tie Points from SMOS

- Algorithm validation: No in situ measurements. There is a data base, but from 2006 to 2009.
  - Comparison with OSI-SAF algorithm with SSMIs: uses 19 and 37GHz.

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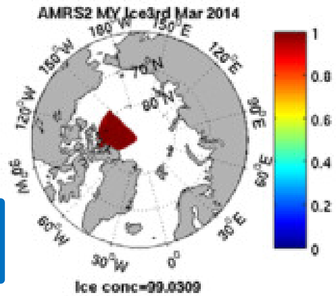
Determination of empirical tie points values

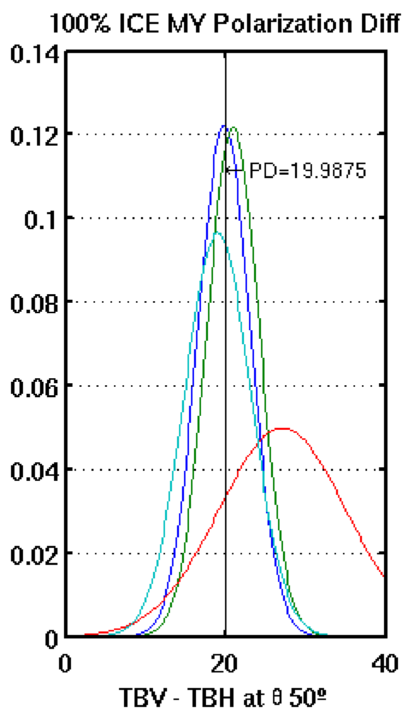
➤ Temporal stability in ice region

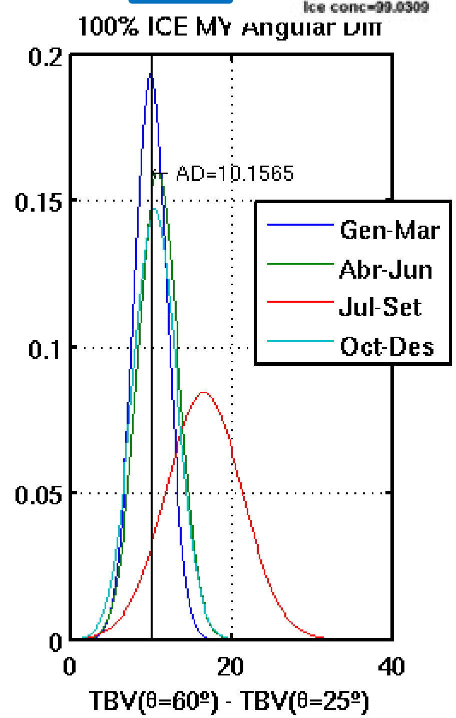
MY ICE



PD

AD

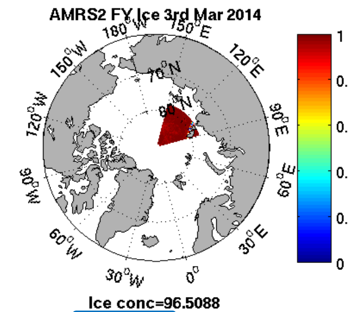




Winter+: σ^2_PDice=2.0 σ^2_ ADice=1.3

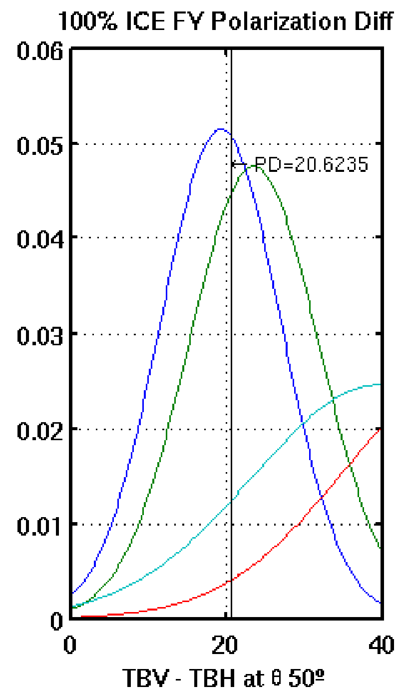
Summer: σ^2_PDice=3.7 σ^2_ ADice=2.3

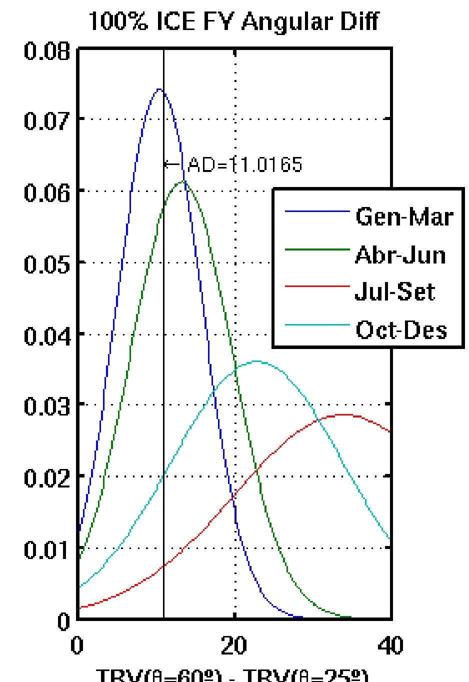
FY ICE



PD

AD

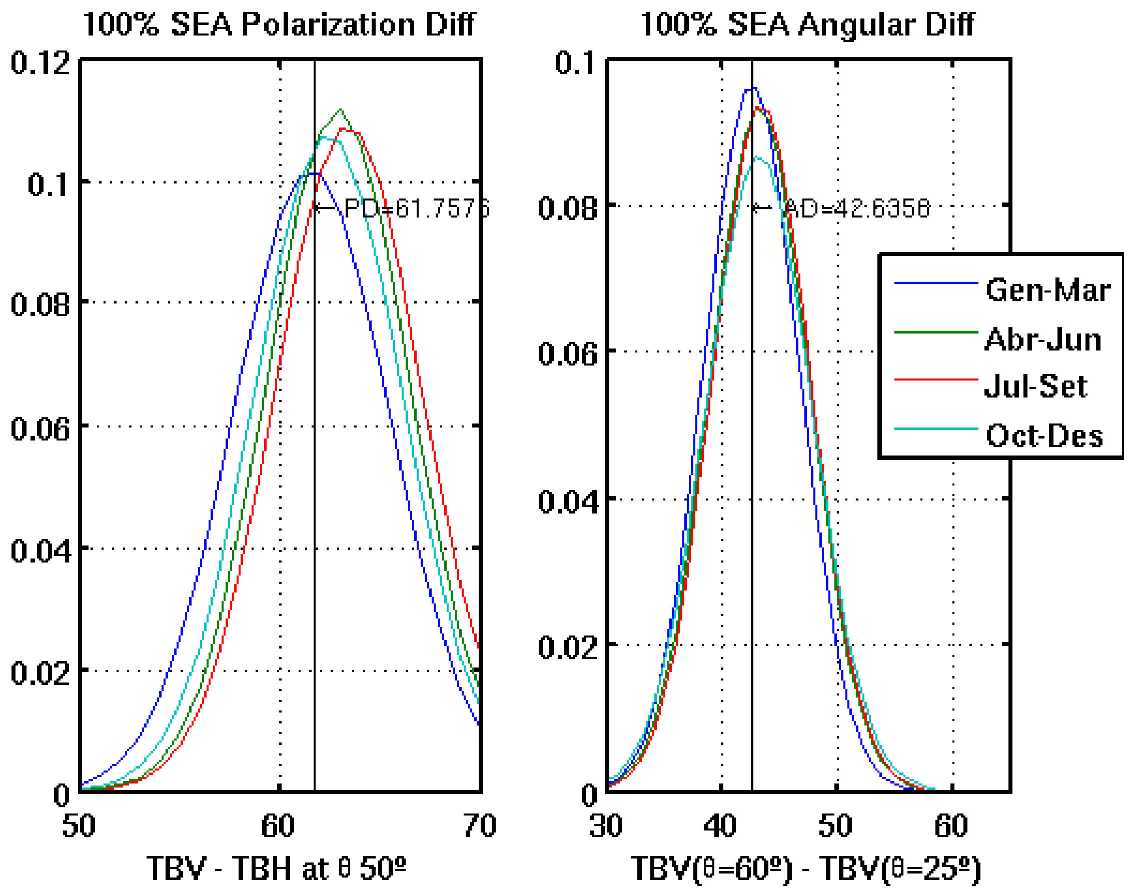


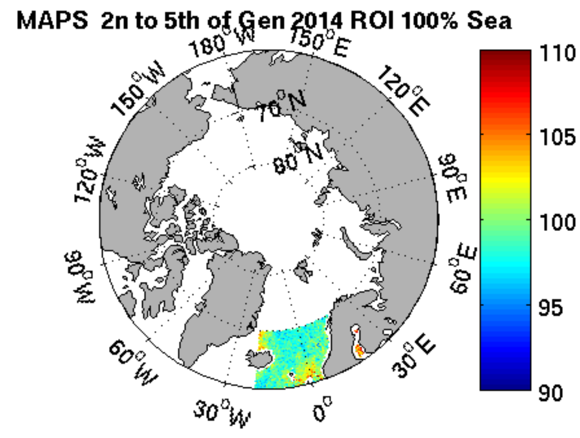


σ^2_ PDice=4.24 σ^2_ ADice=2.7

Determination of empirical tie points values

Temporal stability in Sea region





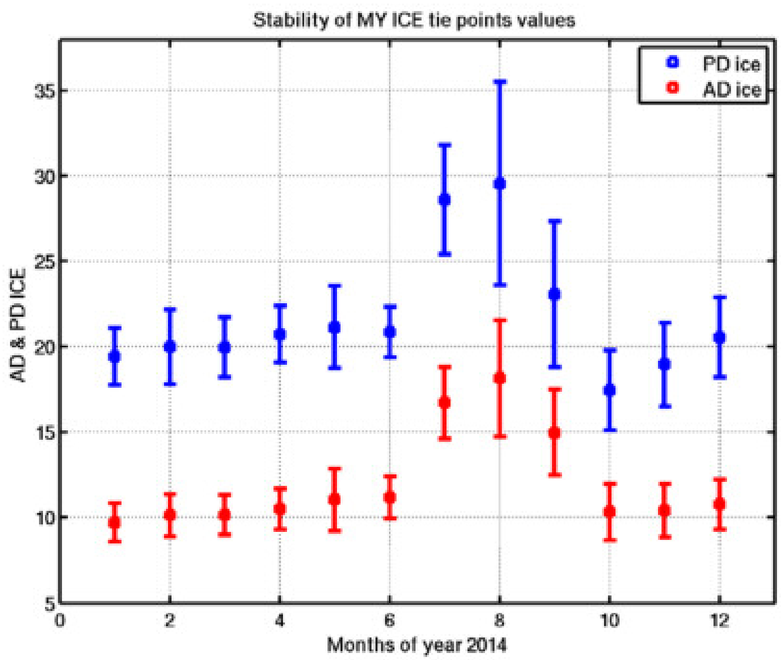
ROI Tie Point
100% SEA

σ^2_ PDsea=2.1 σ^2_ ADice=2.5

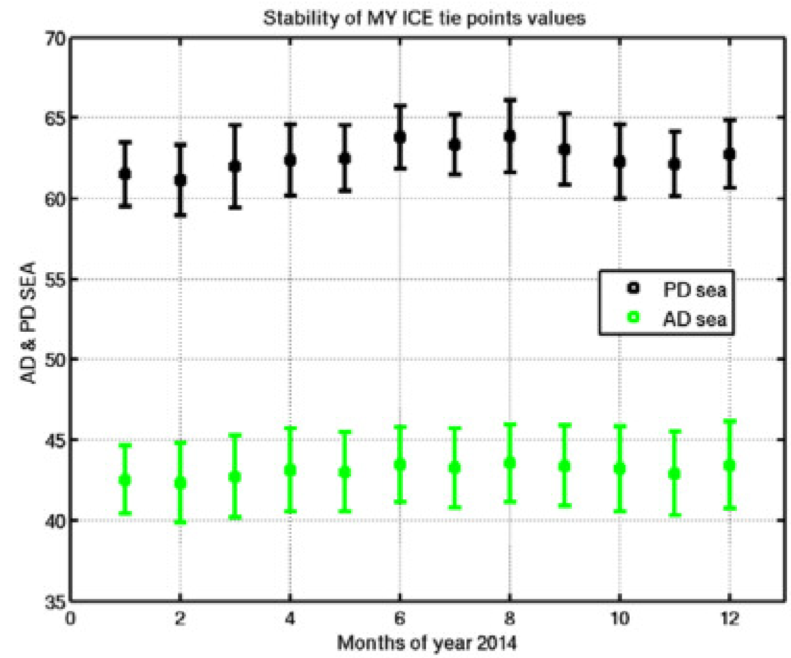
Determination of empirical tie points values

➢ SMOS Temporal stability of the TP

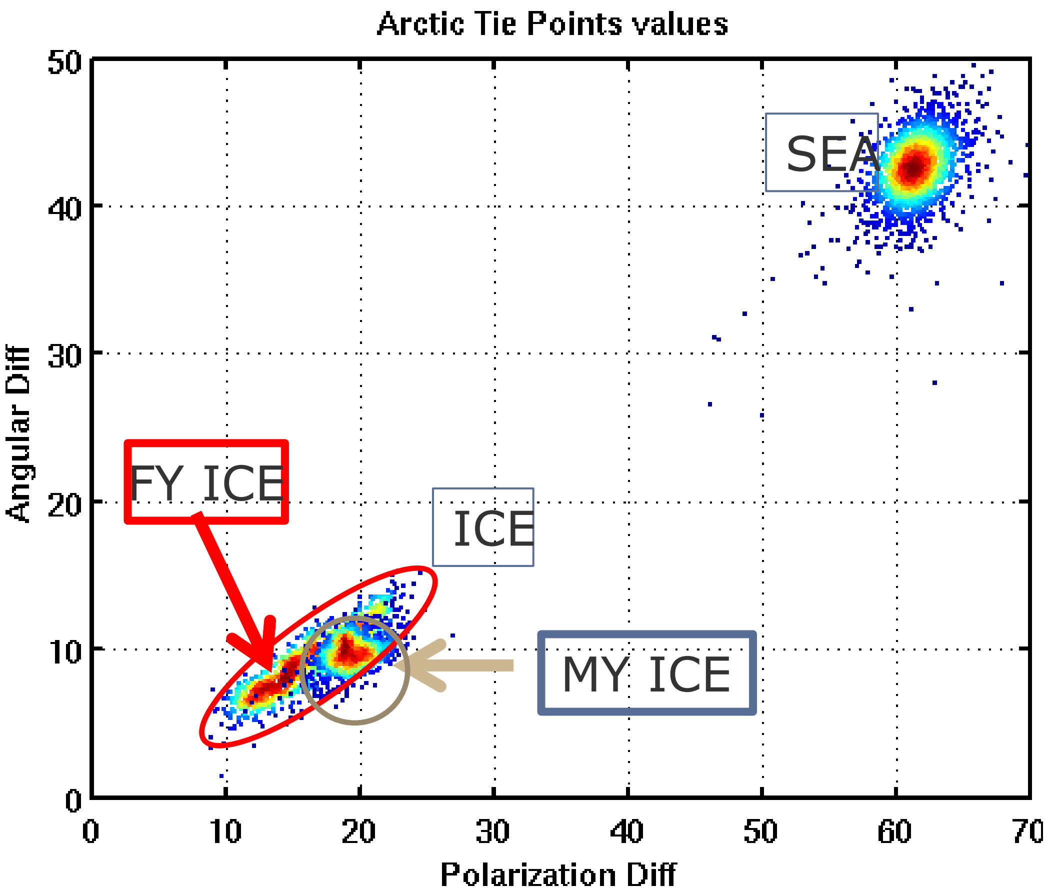
MY ICE



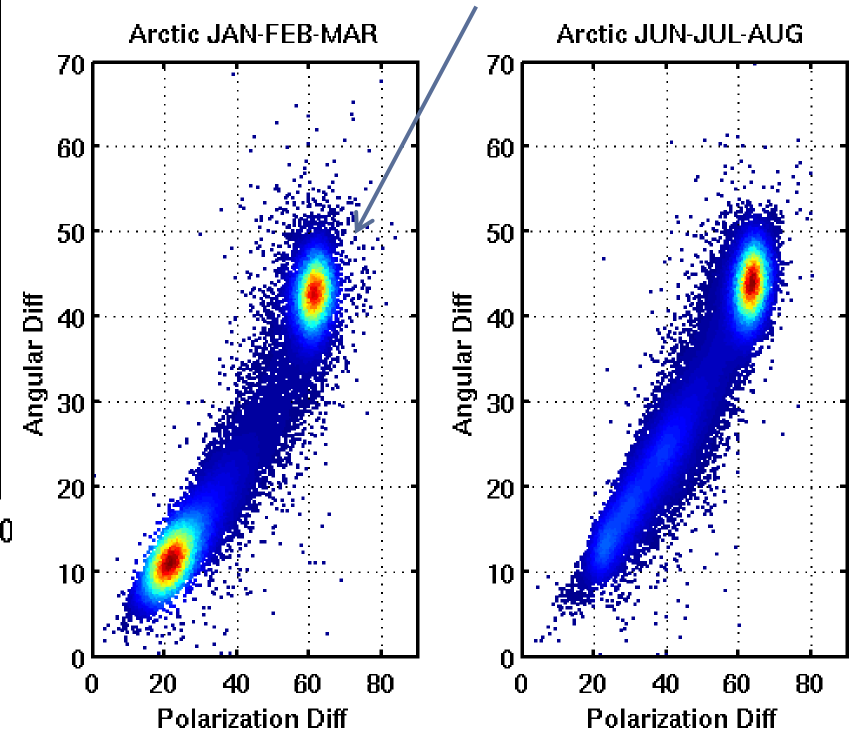
SEA



Determination of empirical tie points values



Assume linear combination



FY and MY ice can not
be distinguished at 1.4 GHz

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Determination of empirical tie points values

- Comparison between Theoretical and empirical Tie Points

Tie Points	Theoretical	SMOS empirical
PD ice + snow (winter & autumn)	25	20
AD ice + snow	8	10
PD sea	63	62
AD sea	44	42

Small differences, about 20% on Ice, less on Sea

Inversion Algorithm

Method 1: Direct linear inversion:

- $PD = c \cdot PD_{ice} + (1 - c) \cdot PD_{sea}$
- $AD = c \cdot AD_{ice} + (1 - c) \cdot AD_{sea}$

- Where c is ice concentration value
- PD_ice/sea and AD_ice/sea are empirical Tie Points: the most frequent value in 100% of SEA/ICE region -> widely used

Inversion Algorithm

Method 2: Maximum Likelihood Estimation, define a normal distribution and assume a linear combination between ICE and Water Tie Points, for the mean and Std Dev of the Tie Points -> **Efficient and unbiased**.

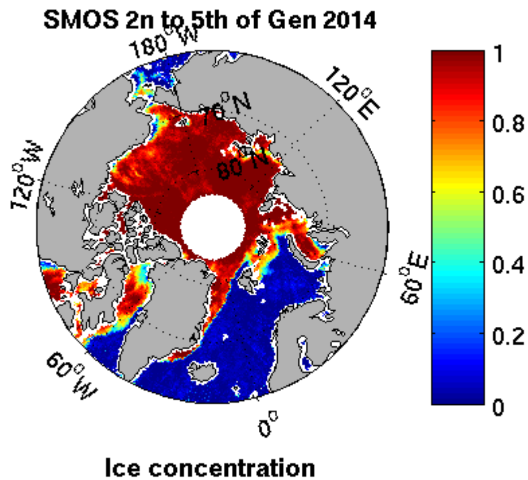
- $\rho_{PD} = N(\mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{1}{2}\frac{(x-\mu)^2}{\sigma^2}} =$
  $N((cPD_{ice} + (1-c)PD_{sea}), \sqrt{c^2\sigma_{PD\_ice}{}^2 + (1-c)^2\sigma_{PD\_sea}{}^2} \;)$

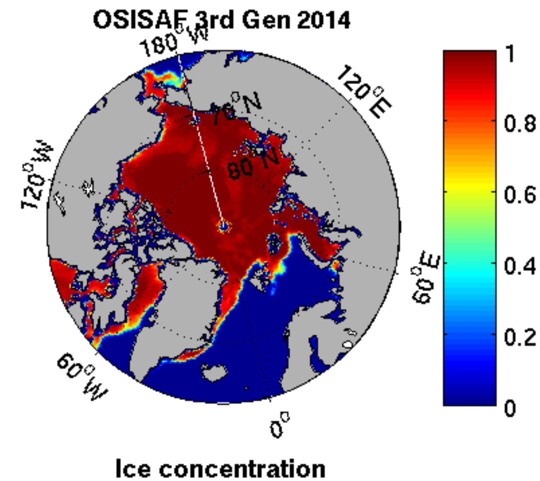
- $\rho_{AD} = N((cAD_{ice} + (1-c)AD_{sea}), \sqrt{c^2\sigma_{AD\_ice}{}^2 + (1-c)^2\sigma_{AD\_sea}{}^2} \;)$

- MLE→ $\max \quad L = \ln(\rho_{PD}(c)) + \ln(\rho_{AD}(c))$ to get ice conc (c).

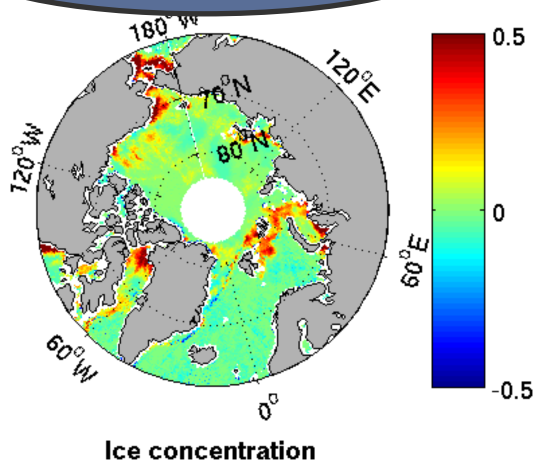
Results and comparison

MLE





SSMI-SMOS



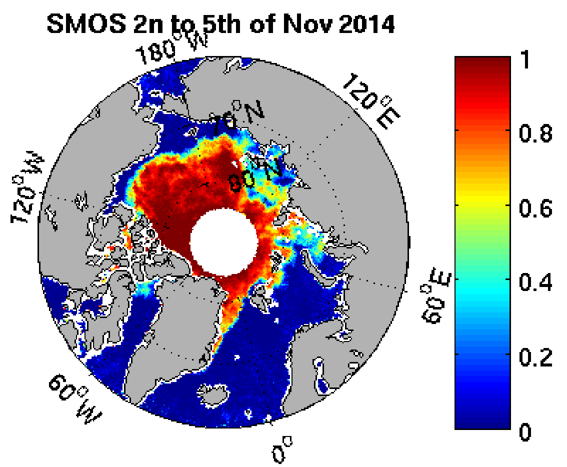
Lower ice concentration values respect OSISAF algorithm (19-37GHz)

Differences are found at the THIN ICE region , due to different penetration

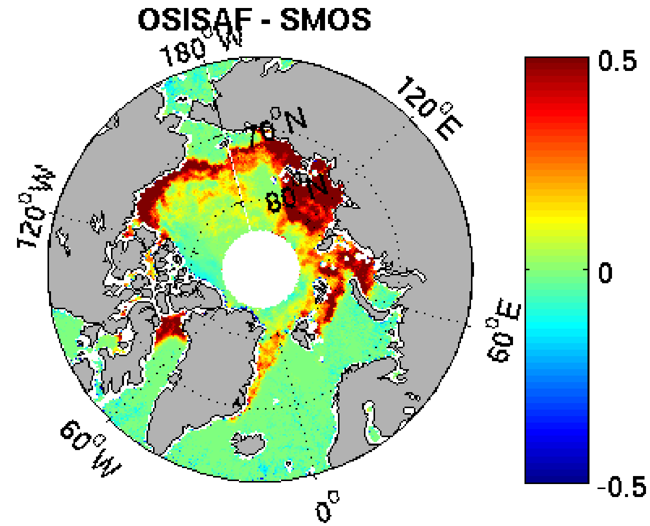
Results and comparison

- Main differences due to thin ice

2-5 Nov 2014

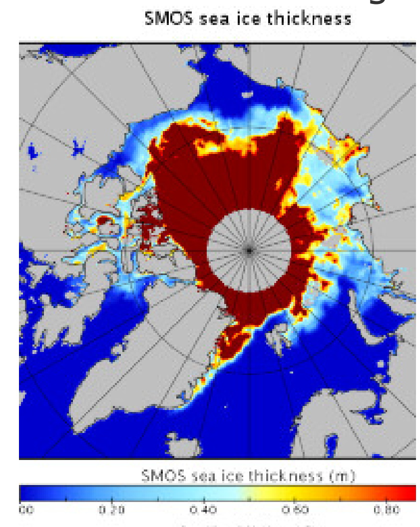


Ice concentration

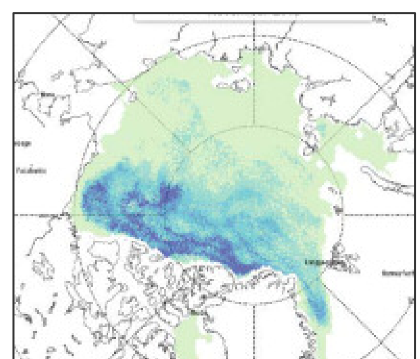


Ice concentration

SMOS Sea Ice thickness from U. Hamburg

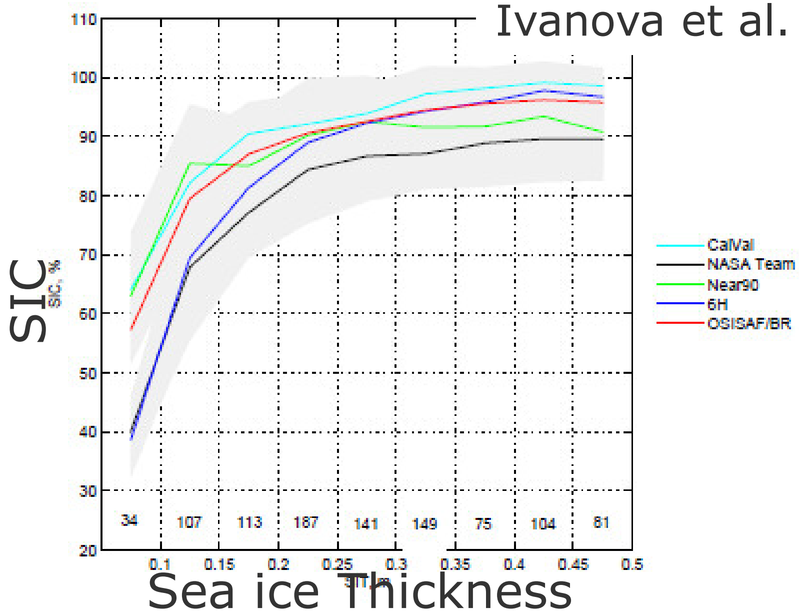


3 Nov 2014

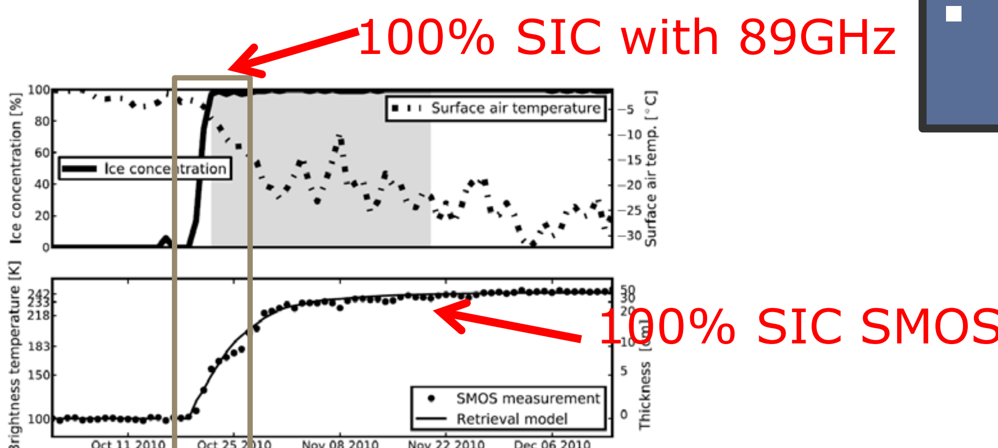


NASA Ice Age Nov 2014

Results and comparison



Ivanova et al. 2015

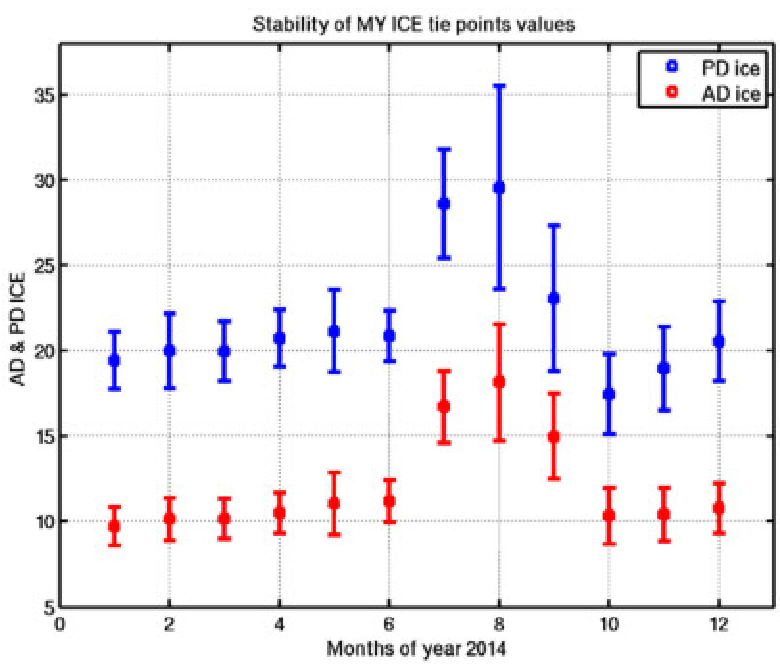


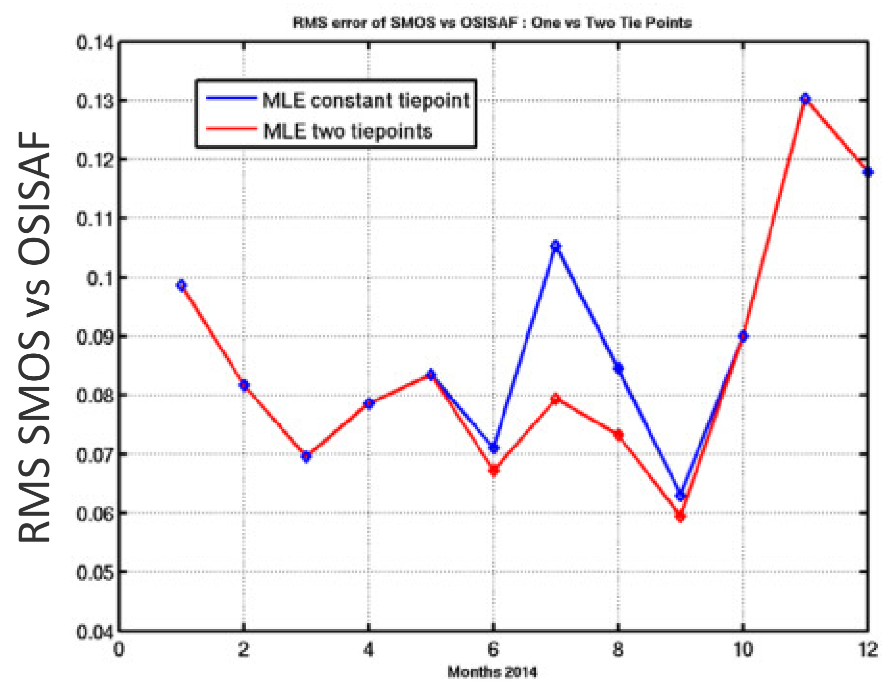
Kaleschke et al. 2012

- SMOS higher penetration than higher freq. 19 /37/89 Ghz
- If thick ice =15 cm:
  - AMSR2 100% ice pixel (89 GHz)
  - SMOS : mixed ice-sea pixel
- Different SIC in thin ice regions

Results and comparison

- Comparison **static vs dynamic tie point** on ICE:
  - **Static:** 1 Tie-Points: averaged TB (Dec to May data) for all year data
  - **Dynamic:** 2 Tie-points:
    - **Winter TP**: averaged TB from Dec to May and applied from Oct to May
    - **Summer TP**: averaged TB Jun to Sep and applied from Jun to Sep

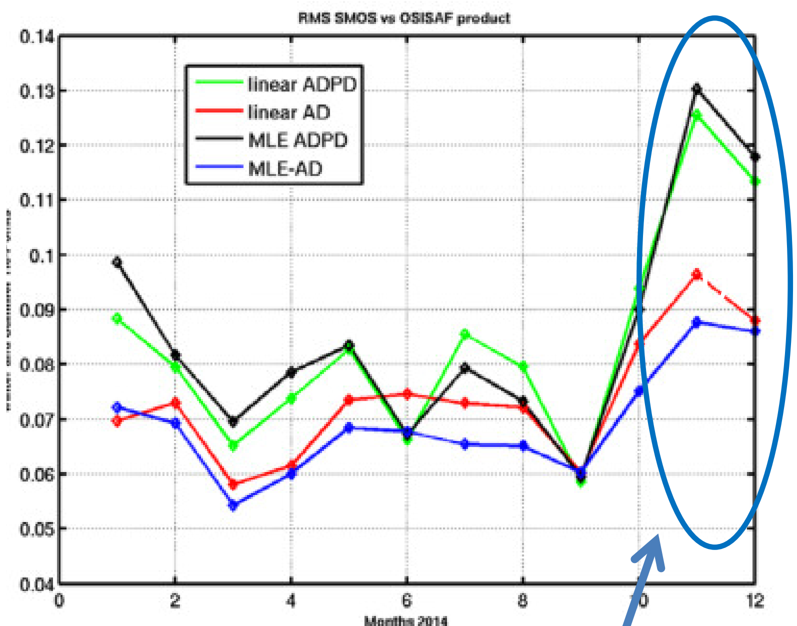




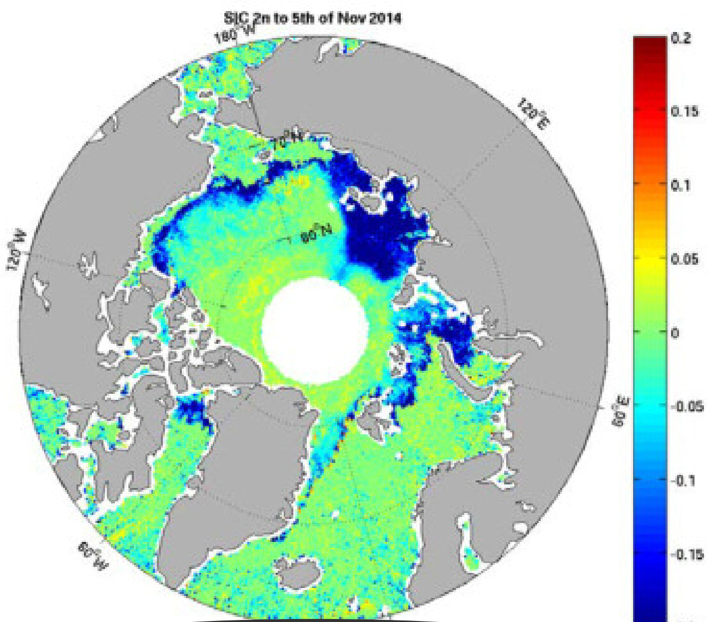
Results and comparison

- Comprison of MLE vs linear and using AD/PD/Both

RMS SMOS vs OSISAF



Best results (vs OSISAF):
- MLE (lower RMS and noise)
- Only with AD -> main diff. on thin ice



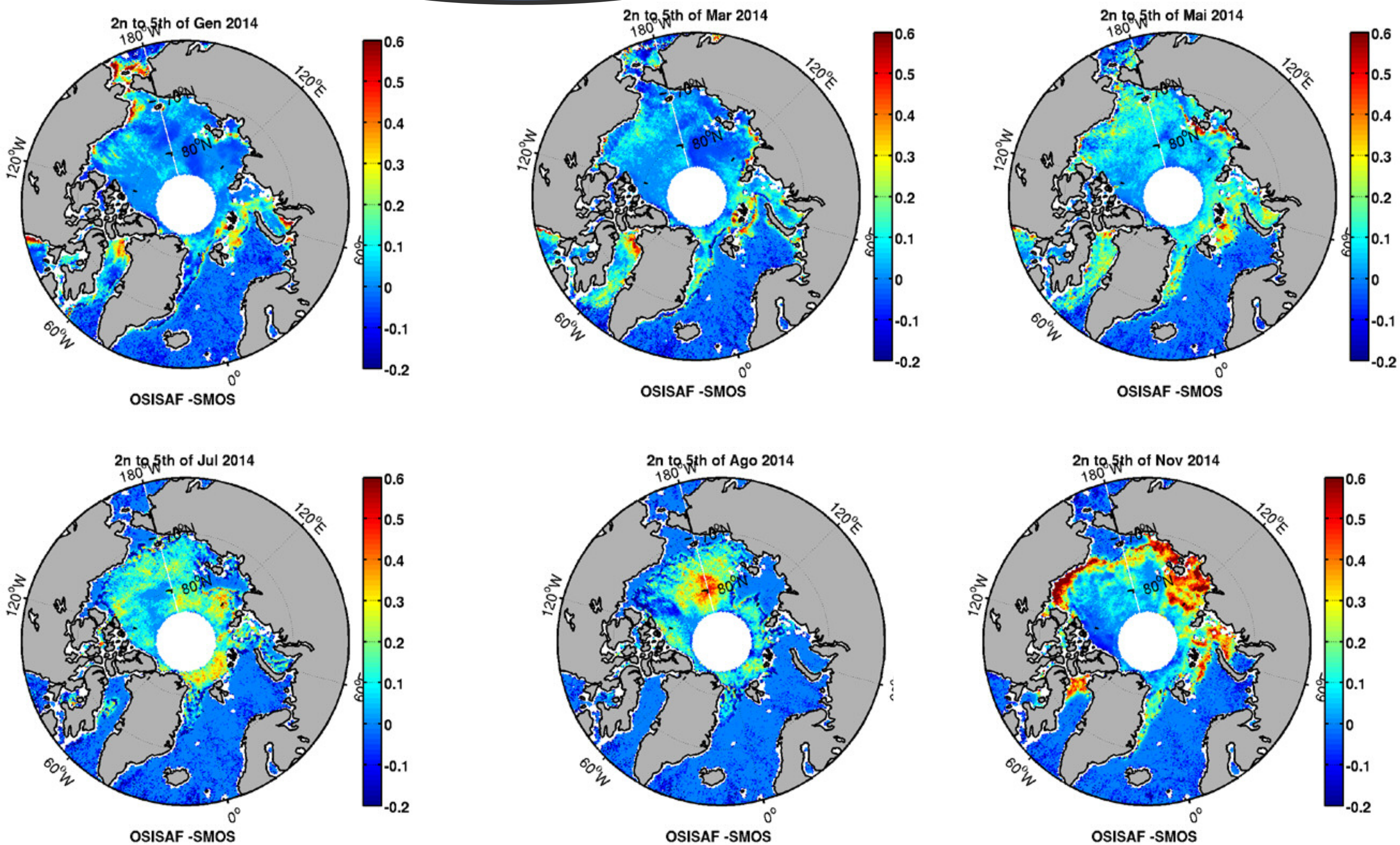
Larger AD vs ADPD diff
-> when max extension
of thin ice. AD is less sensitive
to thin ice

MLE ADPD –MLE AD

Results and comparison

- SMOS SIC best configuration: MLE (AD) + 2 TP

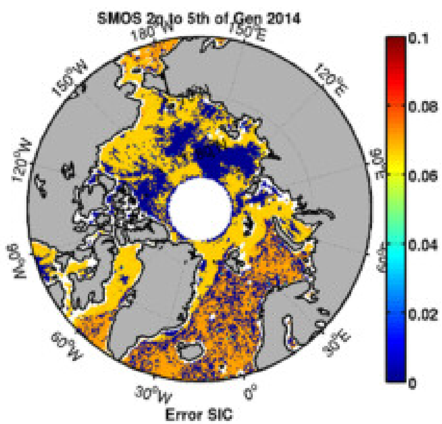
OSISAF-SMOS



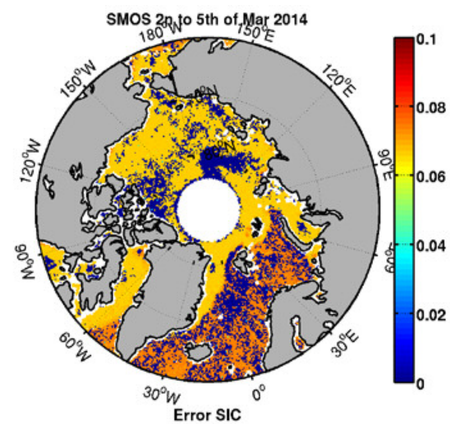
Results and comparison

- **A priori Error**: propagation error from MLE weighted by σAD_sea, σAD_ice & σTB

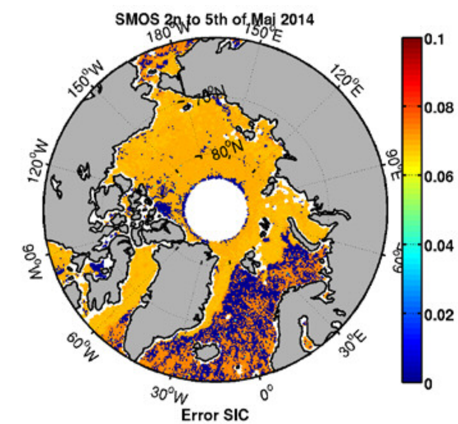
Jan 2014



March 2014



Mai 2014



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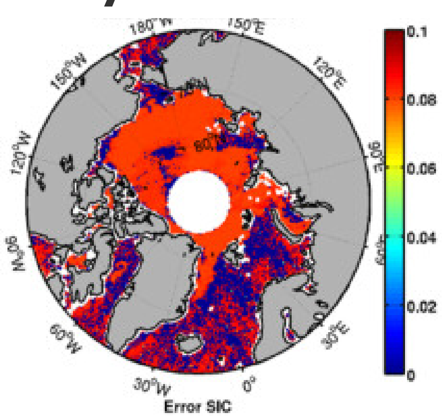
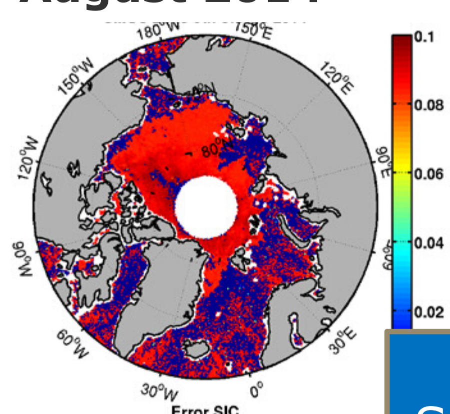
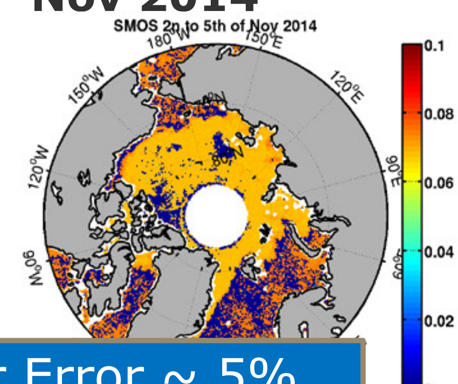


August 2014



Nov 2014



Winter Error ~ 5%
Summer error ~ 10%

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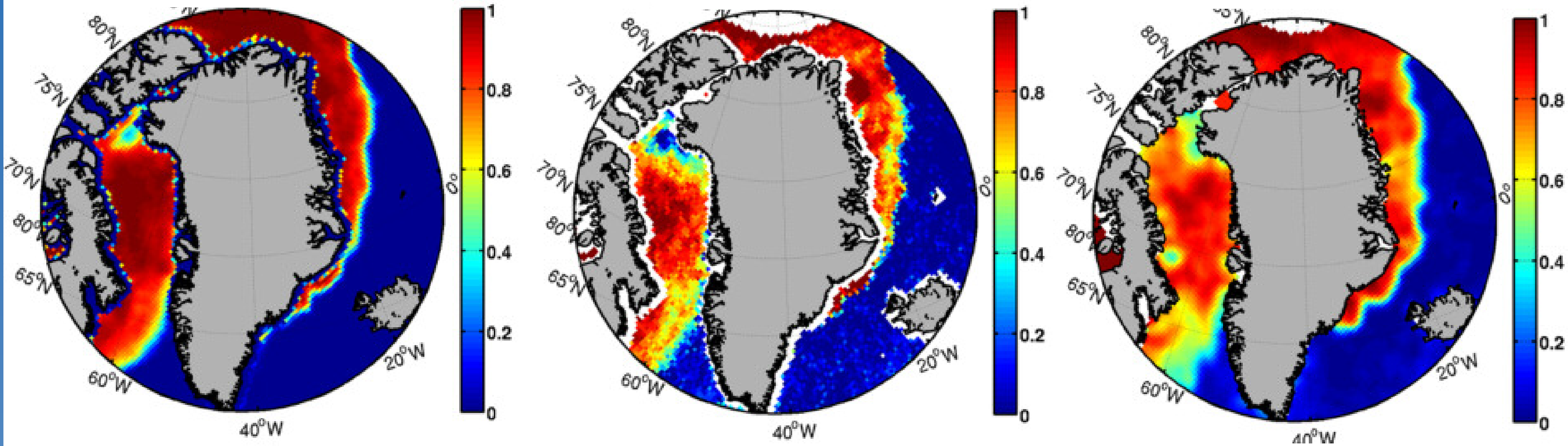
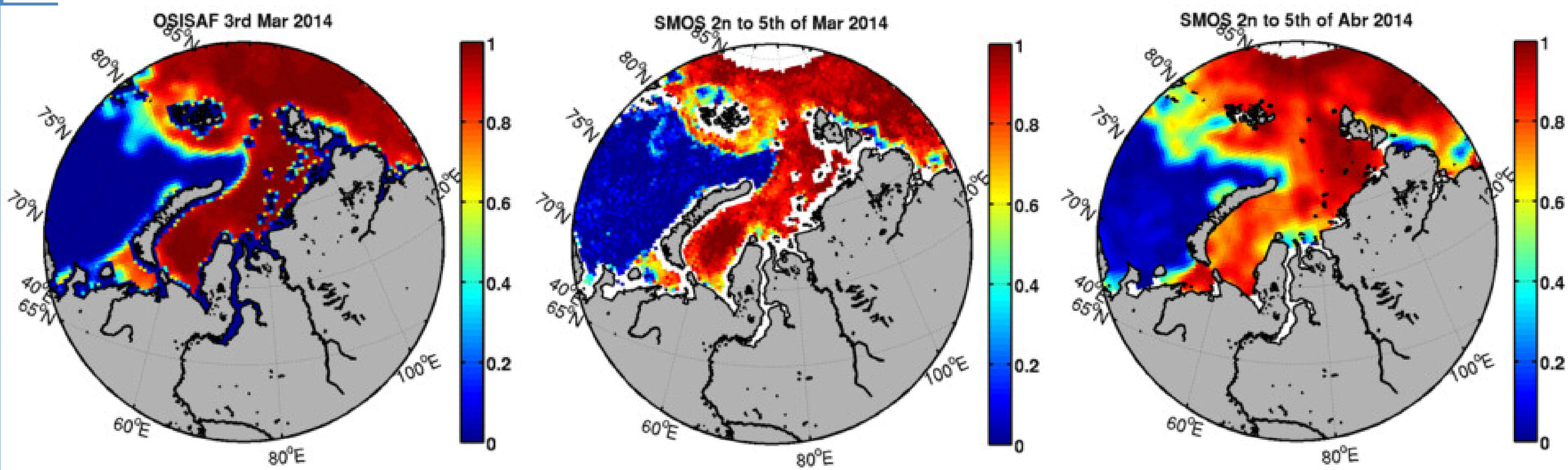
Results and comparison

OSI_SAF | **SMOS** | **SMOS Hamming**

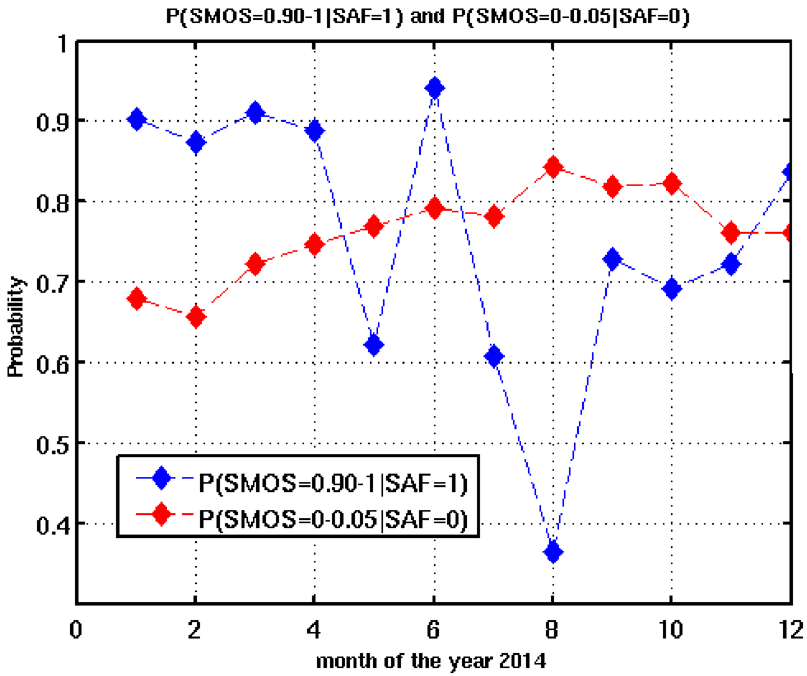


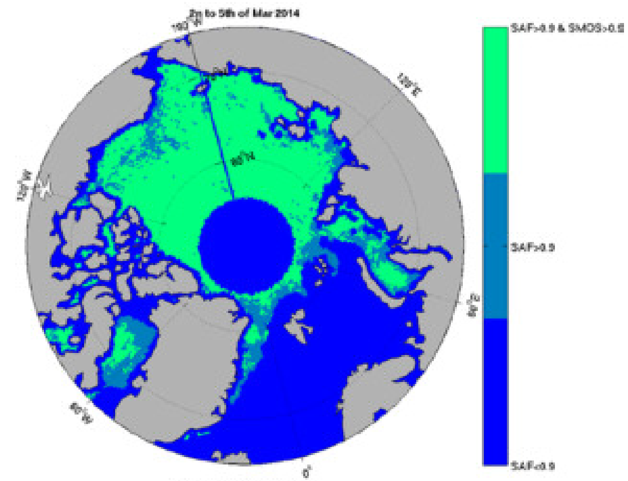


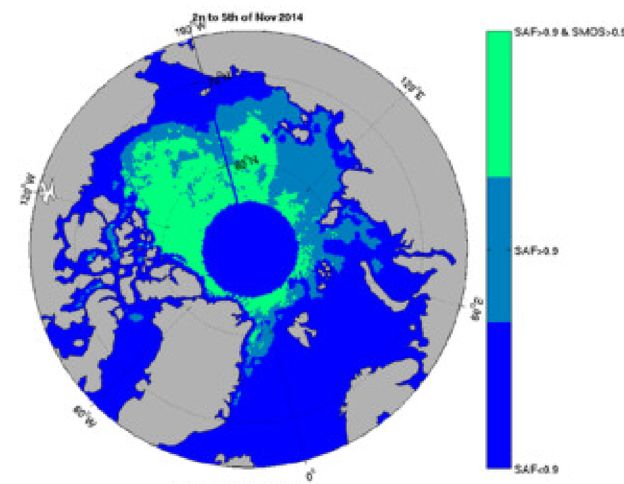
3 Mar 2014 | **2-5 Mar 2014** | **2-5 Mar 2014**

Quality of the retrieved SIC

Conditioned probability







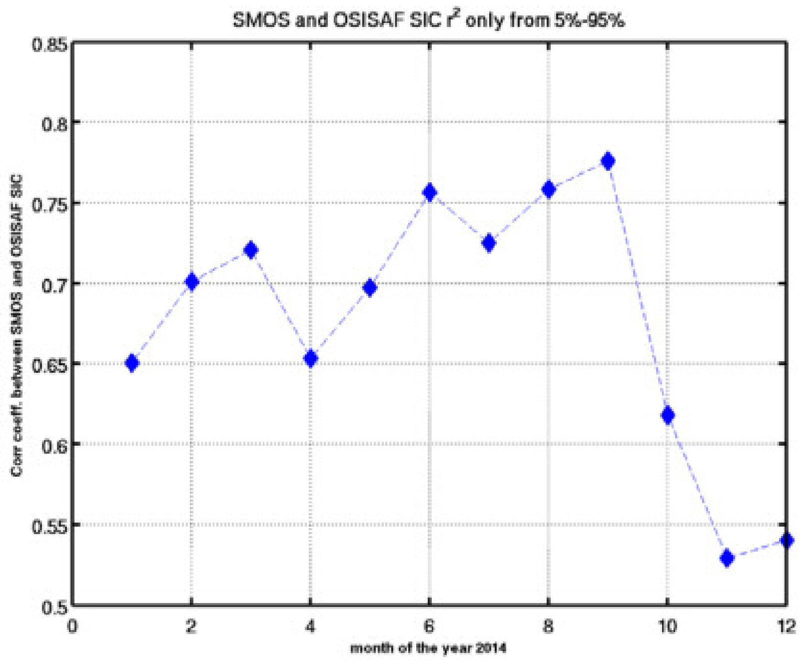
Algorithm used: MLE AD+2TP

Both have similar ability to detect 100% sea
Good performance in winter, during summer and autumn -> snow gets wet -> differences for the dynamic tie points of SAF algo, every 2 weeks

Results and comparison

Quality of the retrieved SIC

Correlation factor r²

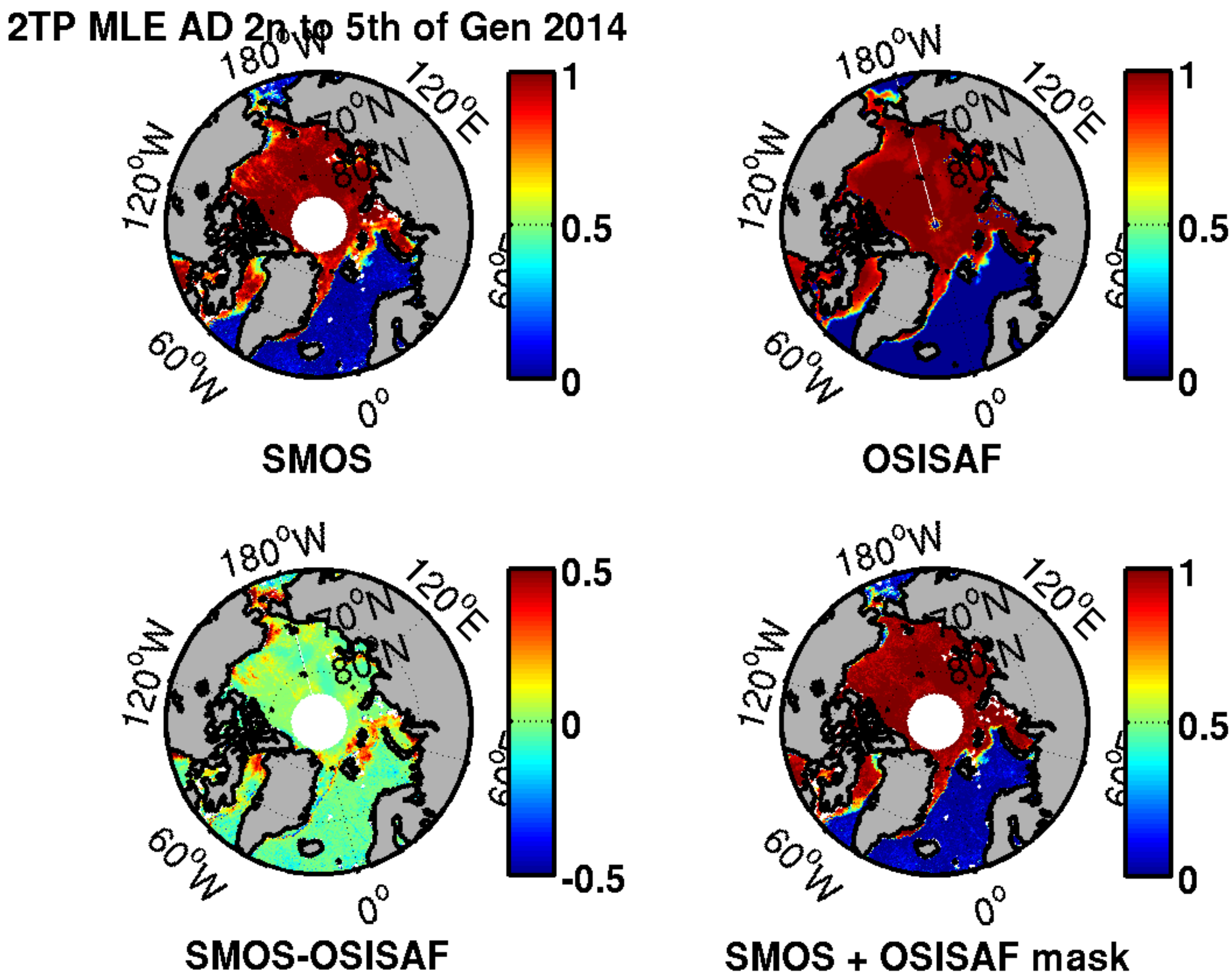


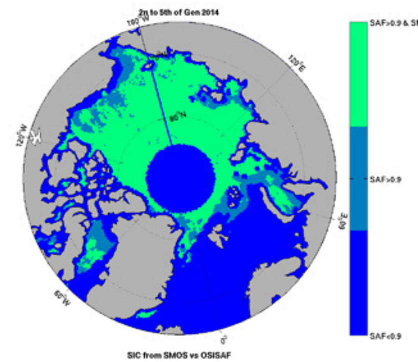
Correlation avoiding regions with many points, of 0% and 100% which would dominate the statistics.

Minimum corr. when thin ice is maximum

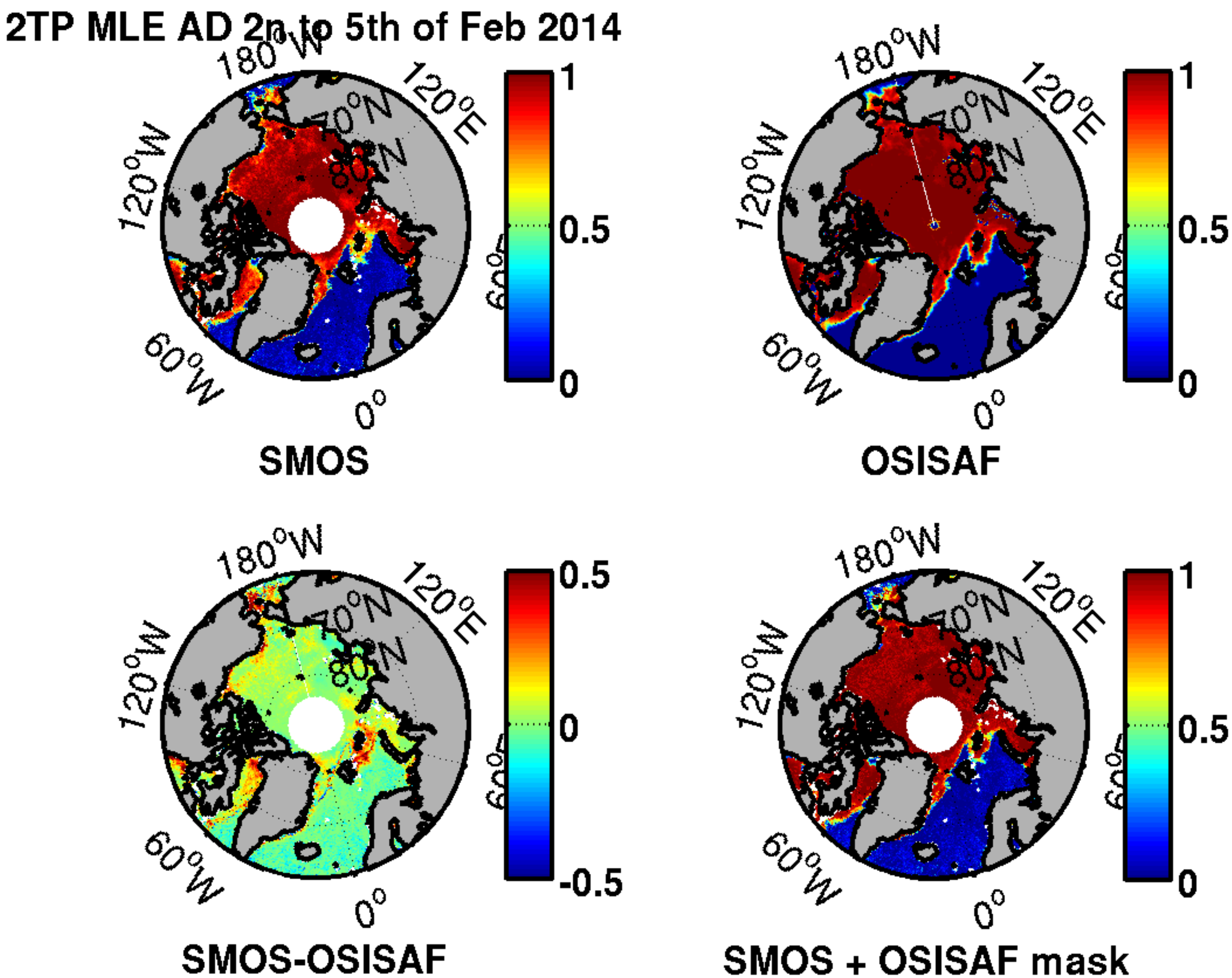
Algorithm used: MLE AD+2TP

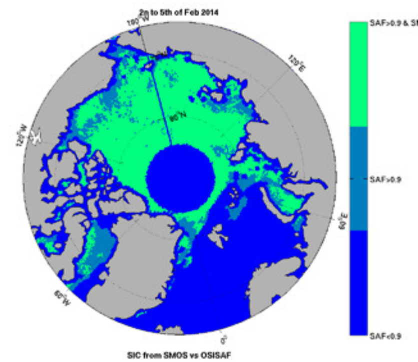
ICE concentration SMOS MLE vs OSISAF



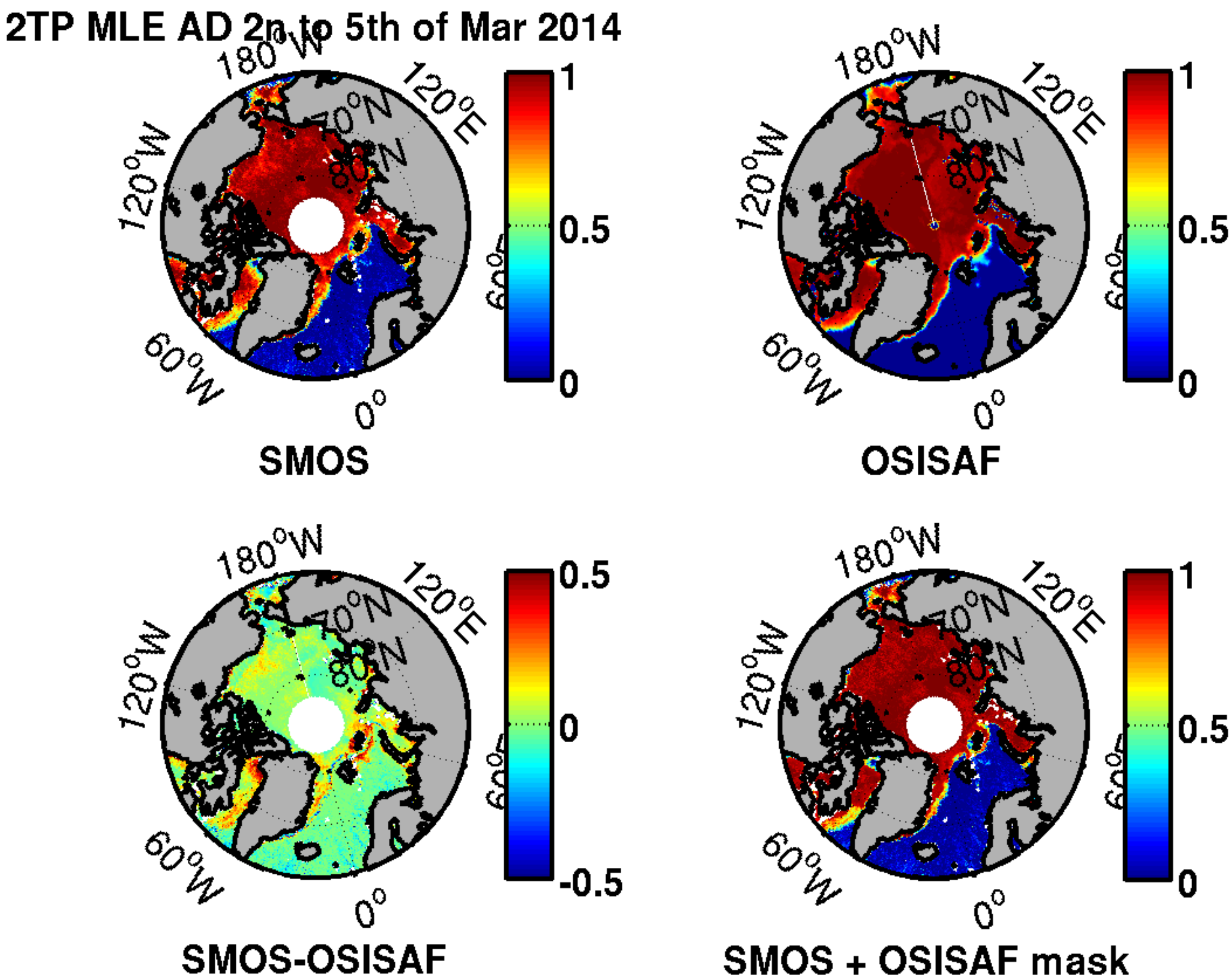


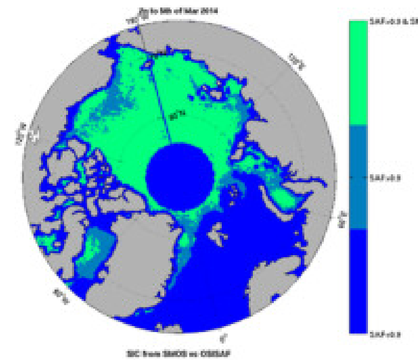
ICE concentration SMOS MLE vs OSISAF



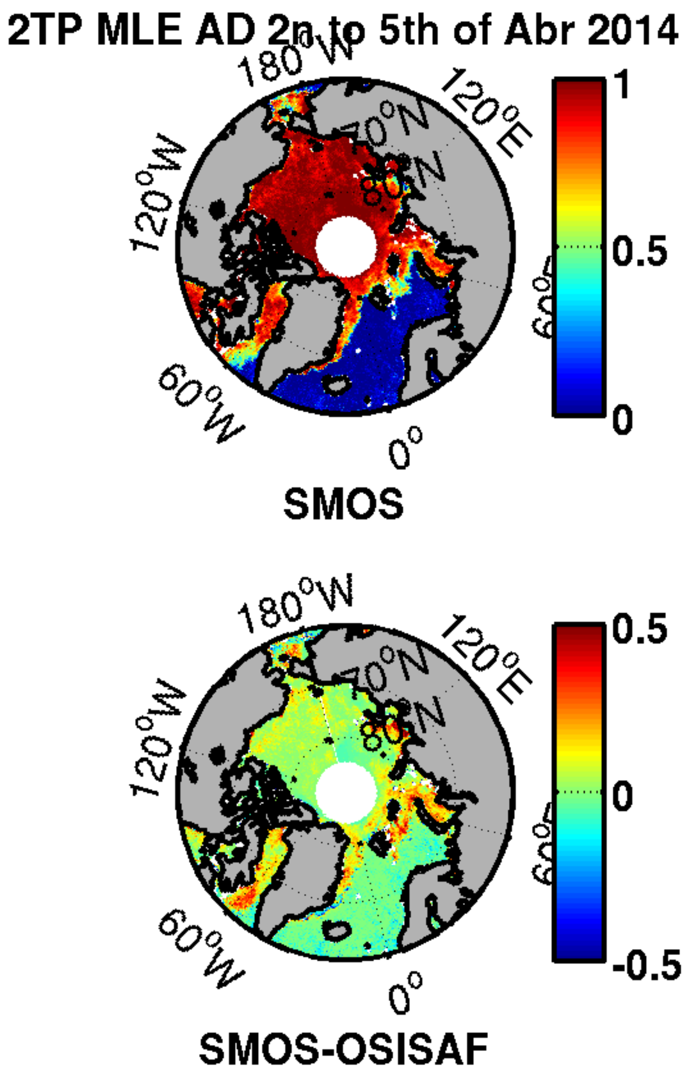


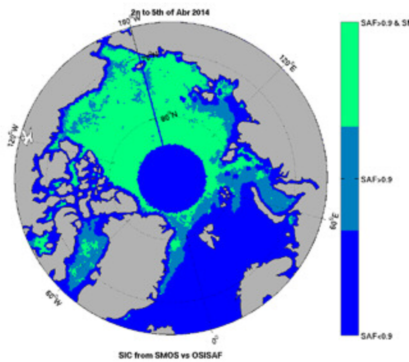
ICE concentration SMOS MLE vs OSISAF



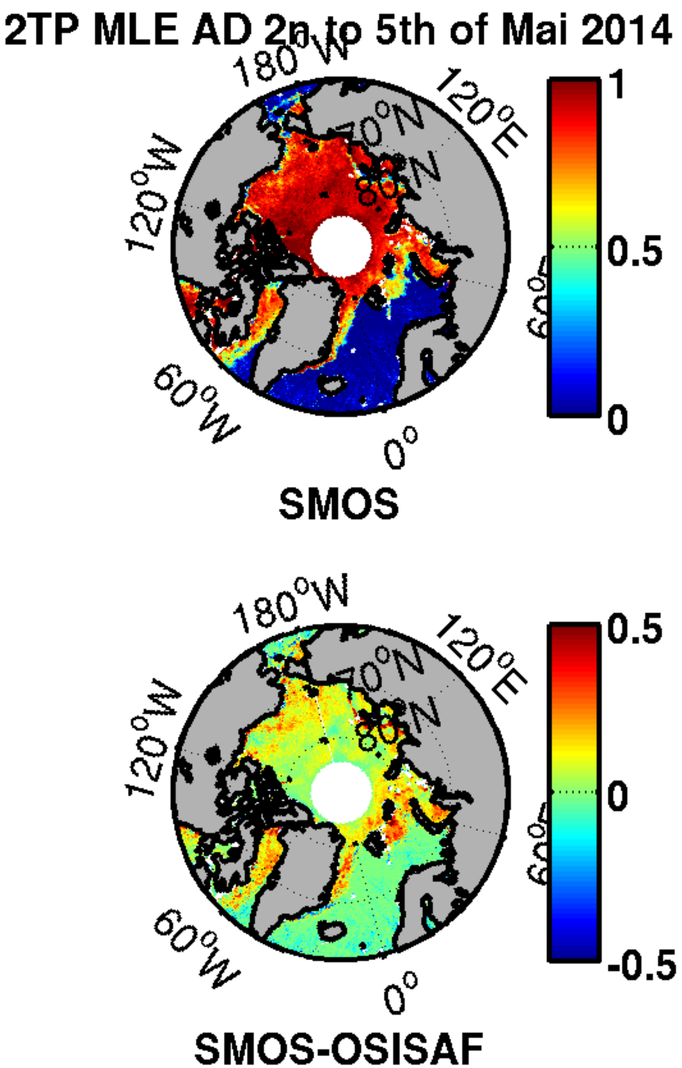


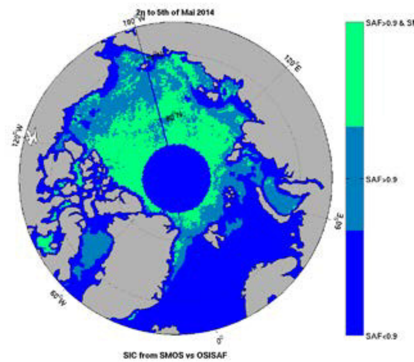
ICE concentration SMOS MLE vs OSISAF





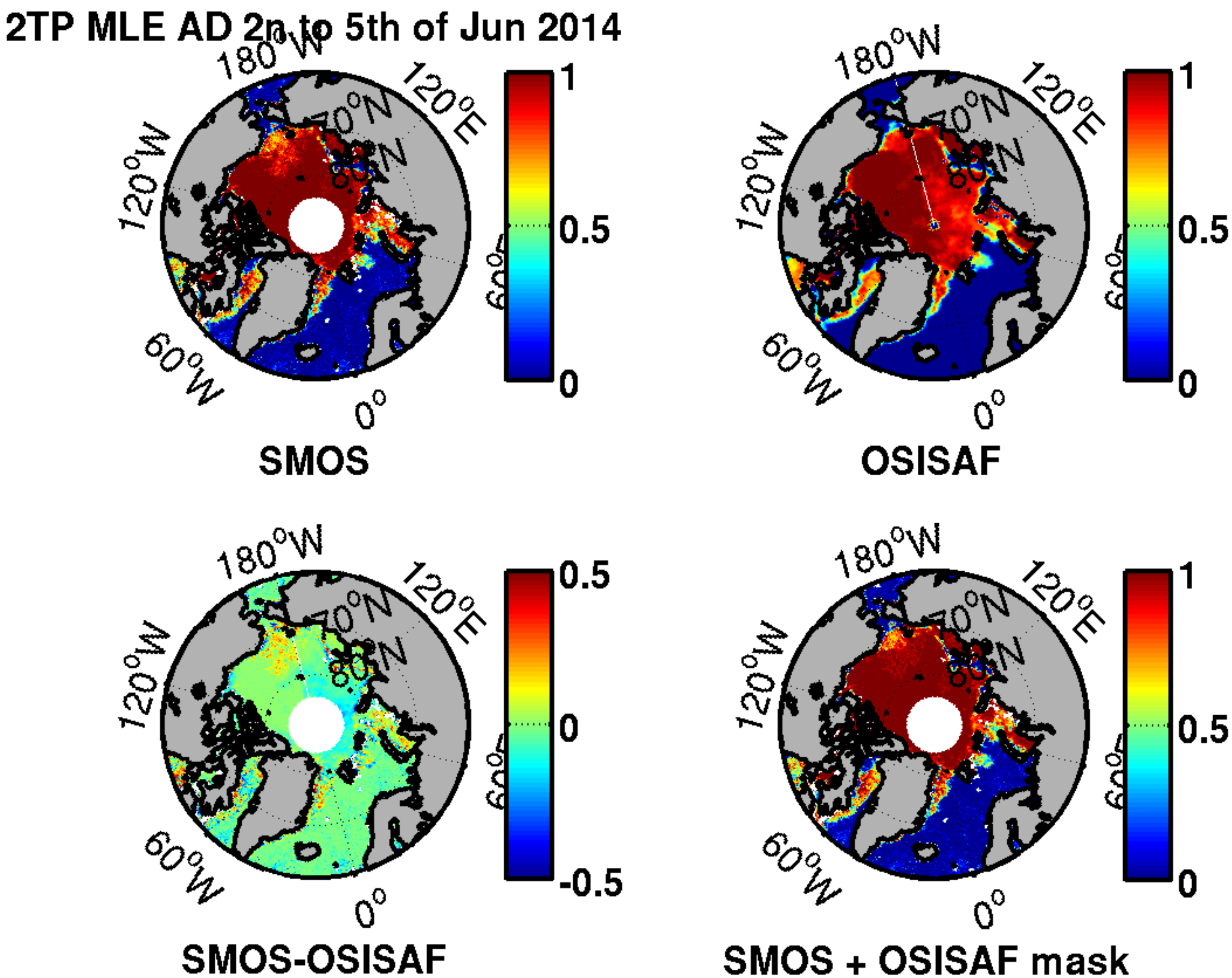
ICE concentration SMOS MLE vs OSISAF

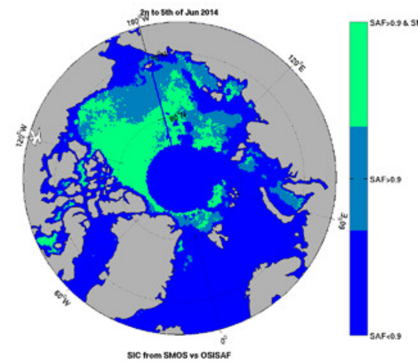




SMOS BARCELONA EXPERT CENTRE

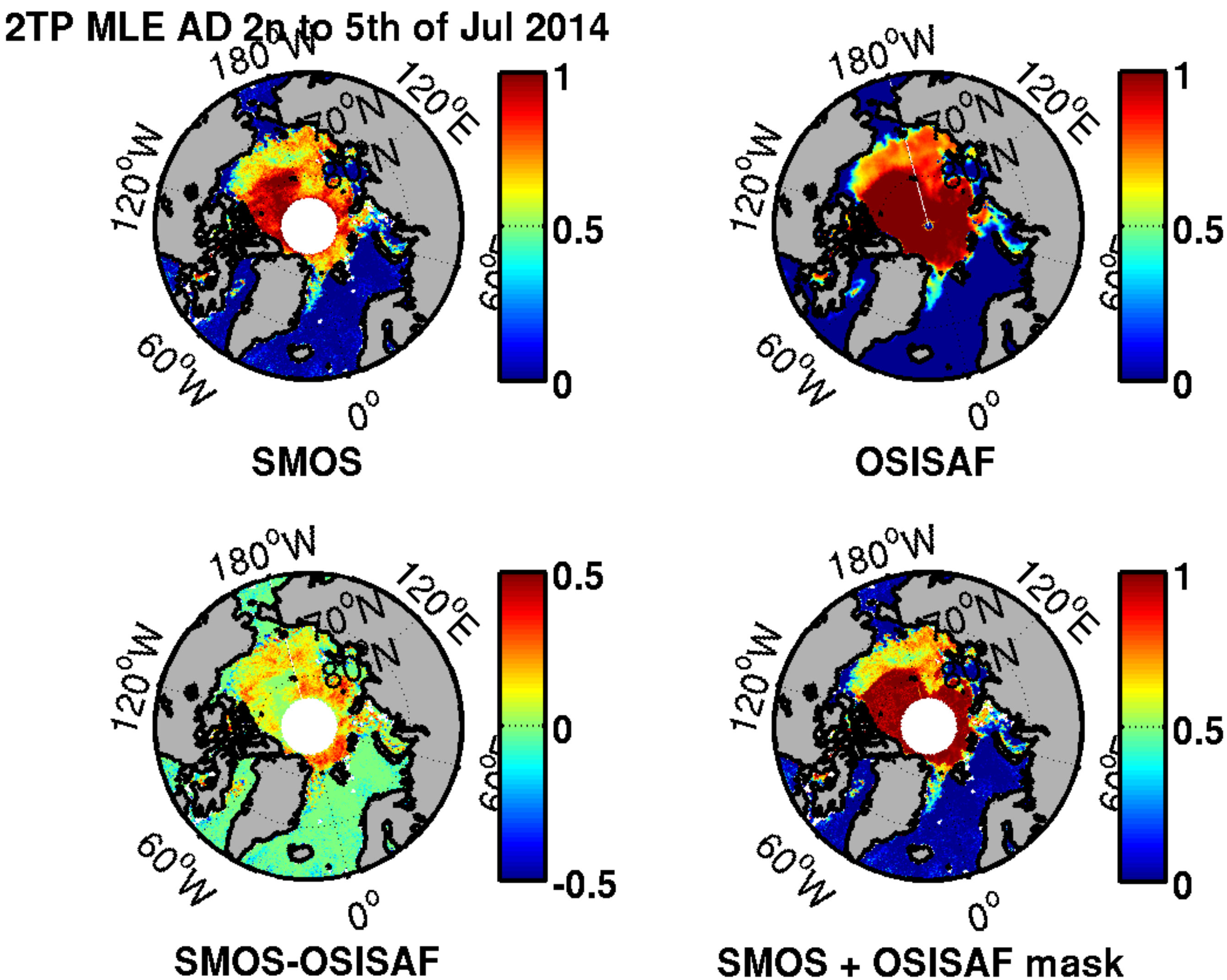
ICE concentration SMOS MLE vs OSISAF

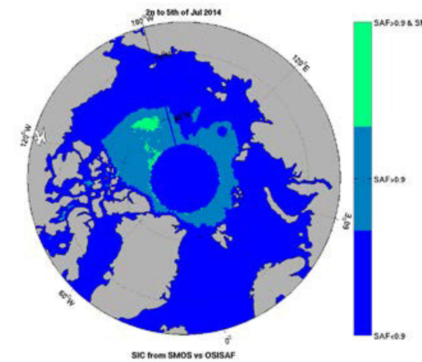




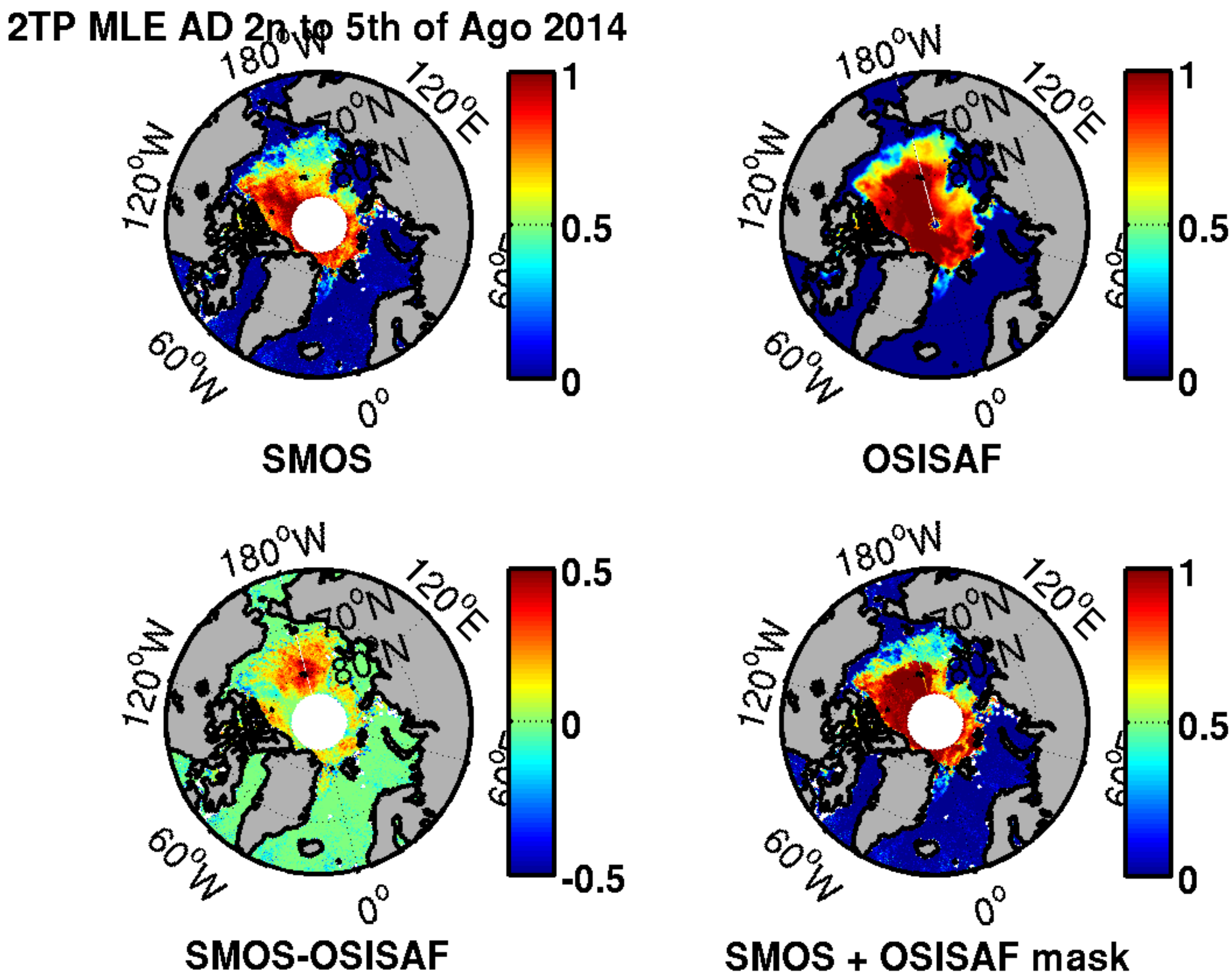
SMOS BARCELONA EXPERT CENTRE

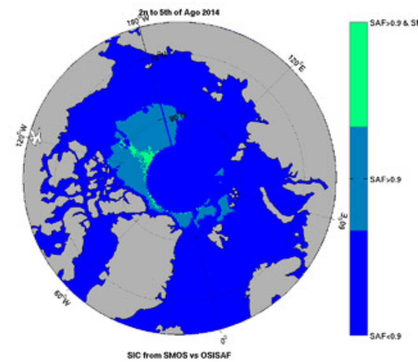
ICE concentration SMOS MLE vs OSISAF



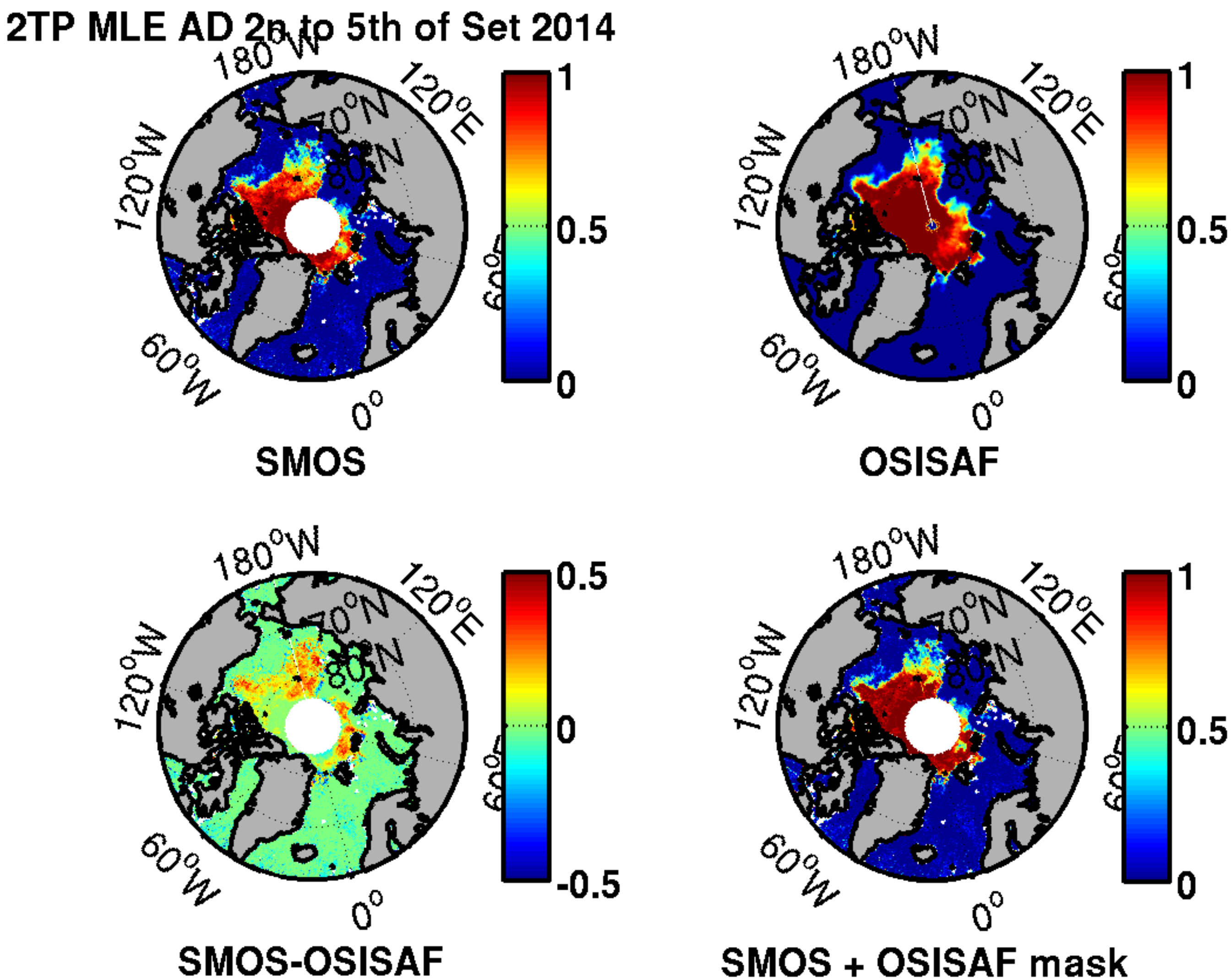


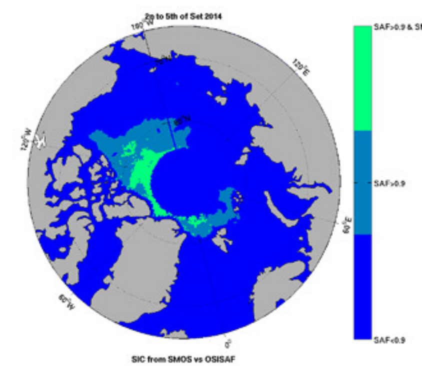
ICE concentration SMOS MLE vs OSISAF



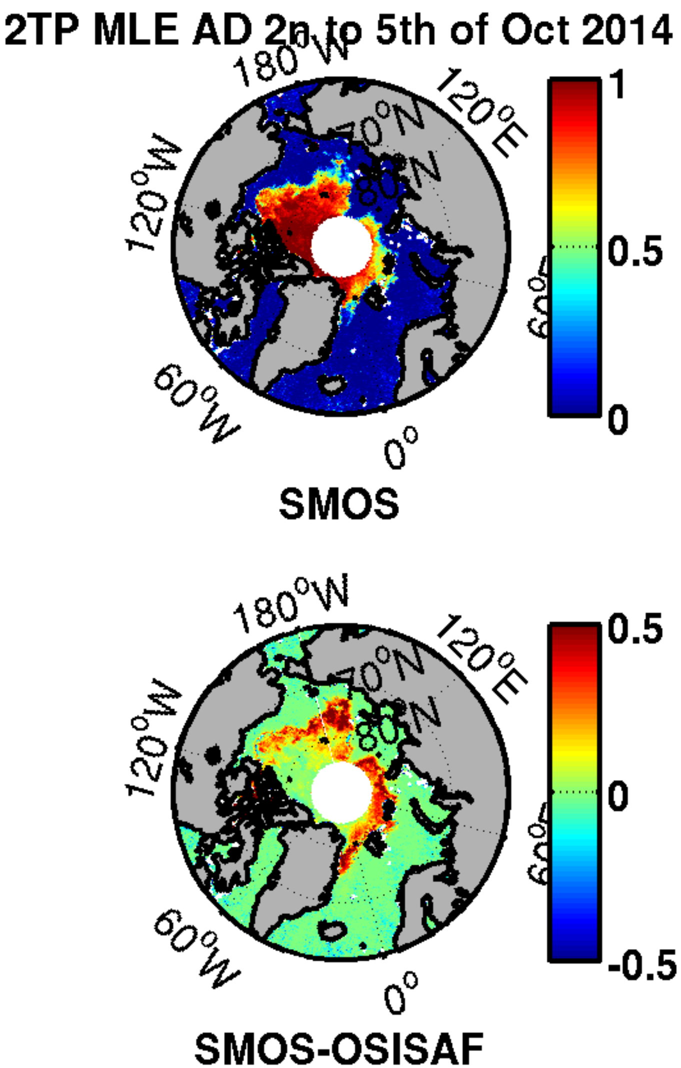


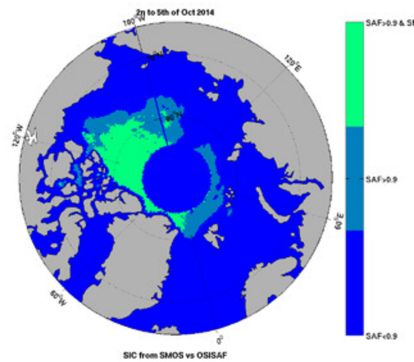
ICE concentration SMOS MLE vs OSISAF



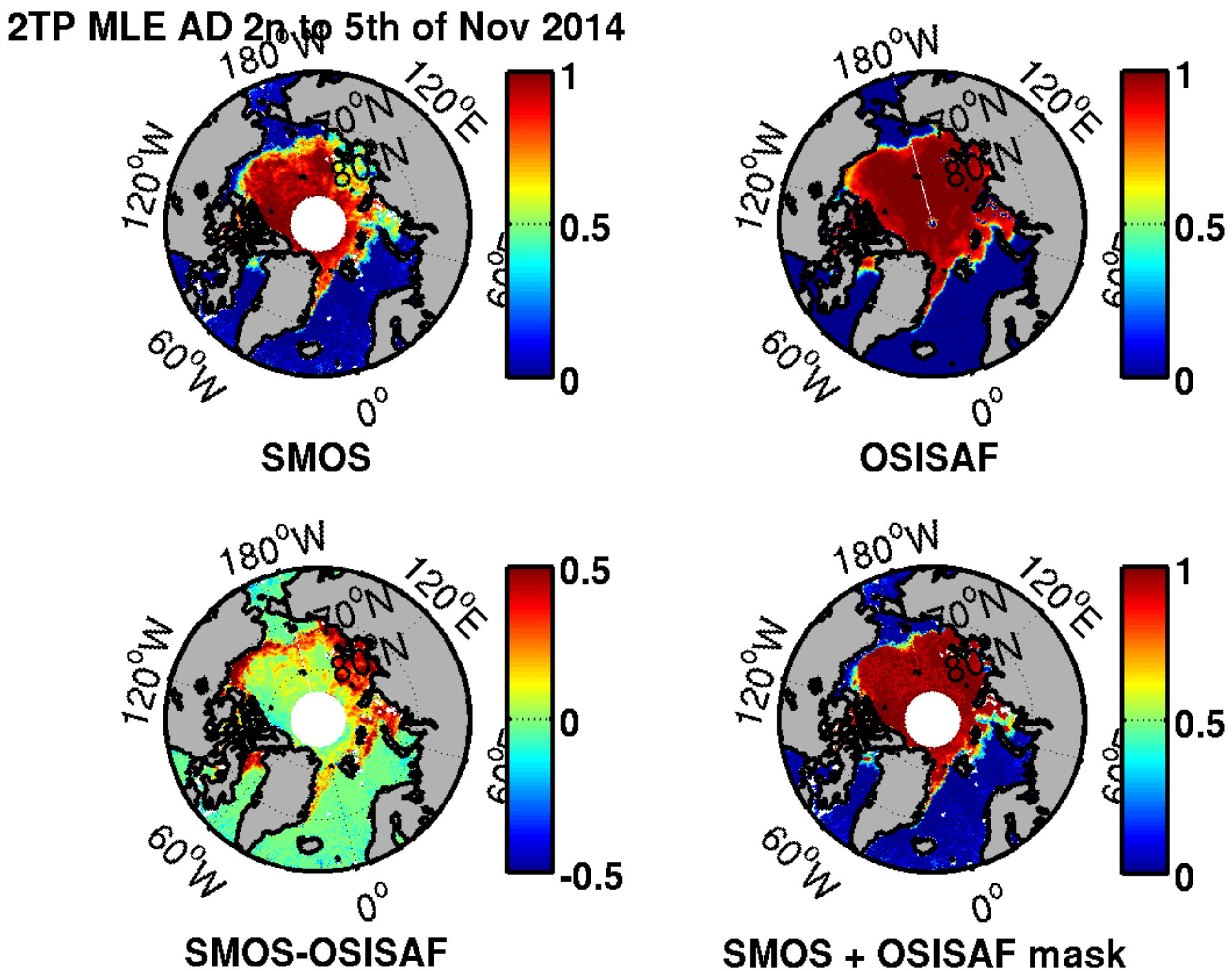


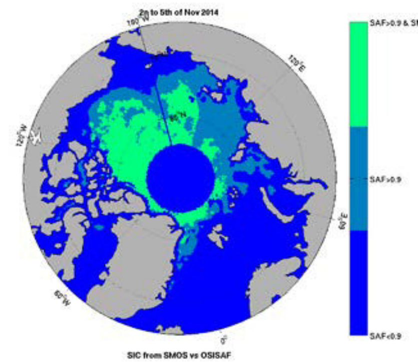
ICE concentration SMOS MLE vs OSISAF



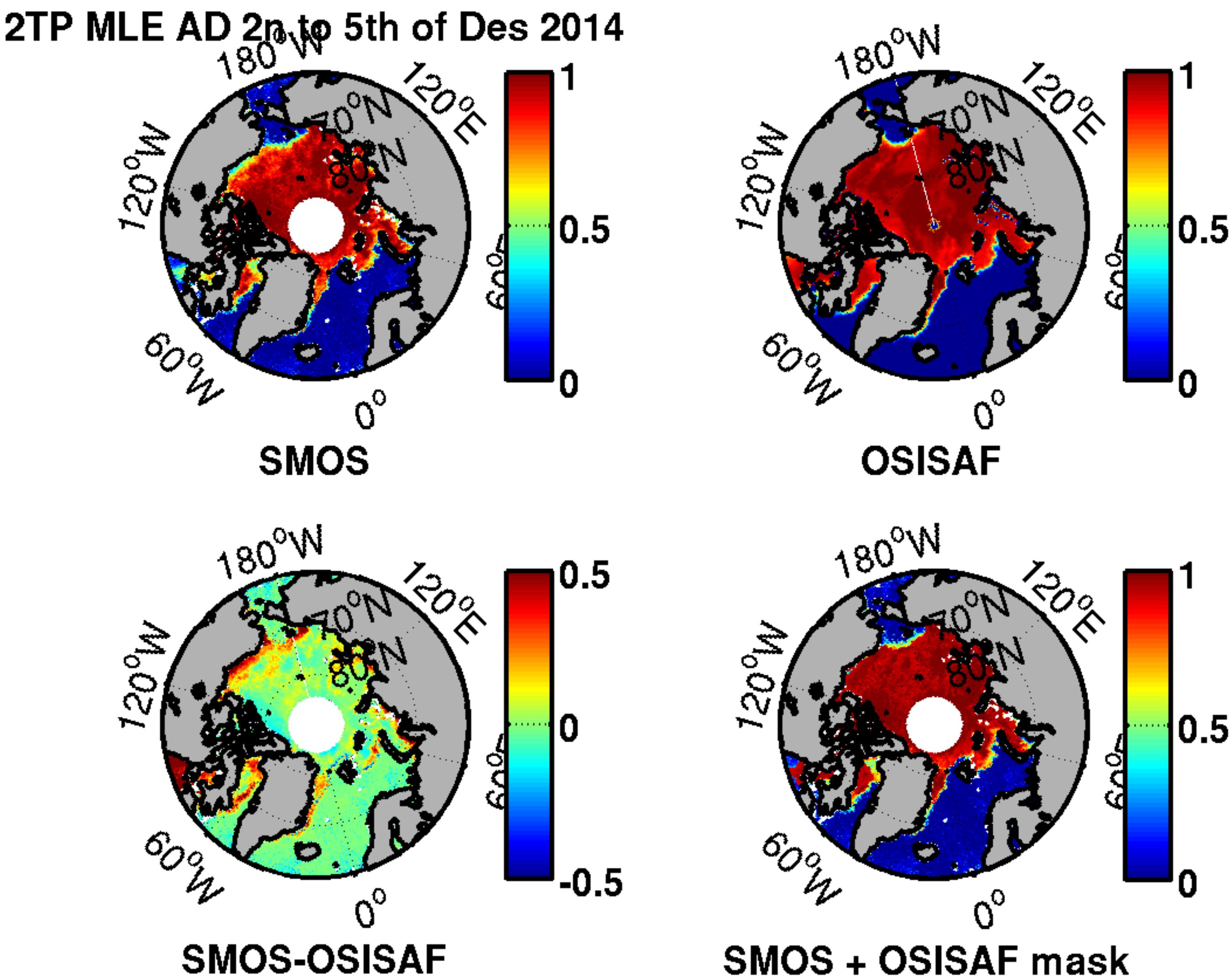


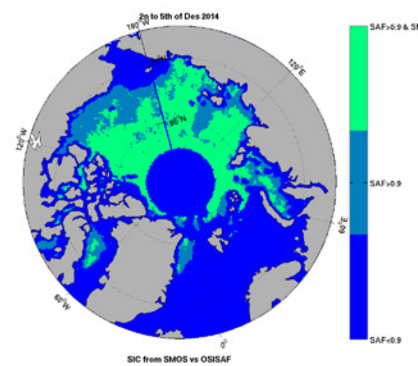
ICE concentration SMOS MLE vs OSISAF





ICE concentration SMOS MLE vs OSISAF



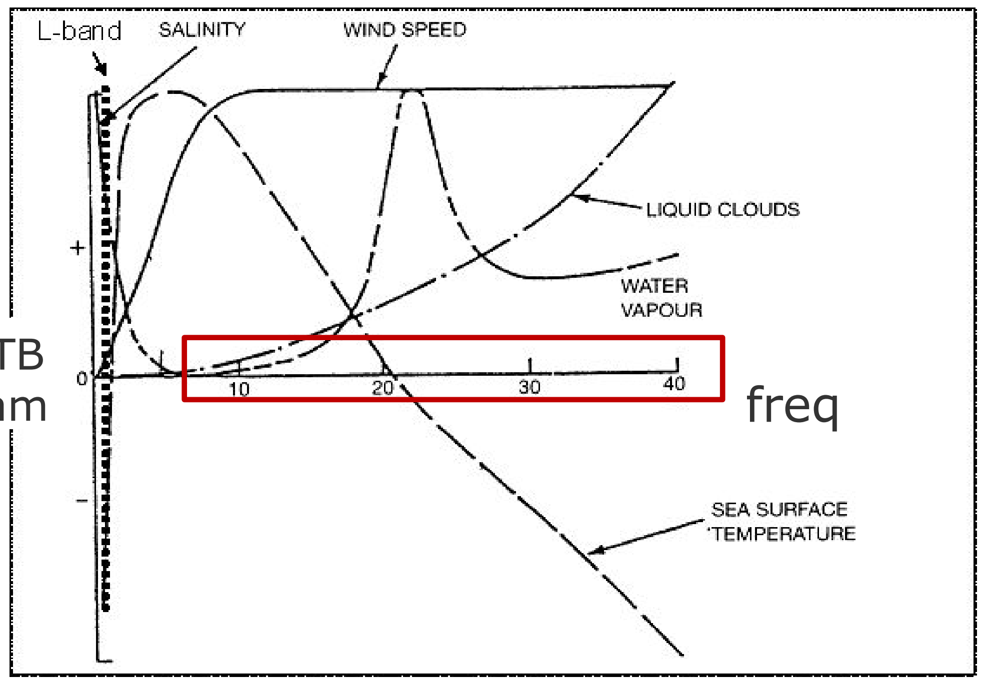


Advantages and drawbacks

- Main drawbacks of SMOS SIC:
  - Underestimation on thin ice -> but detection of thin ice
  - Lower spatial resolution (25km)
- Main problems of other SIC, from Ivanova et al. 2015
  - Atmosphere correction: water vapour and cloud liq[...]al low ice concentration

SMOS almost transparent

Sens. TB to param



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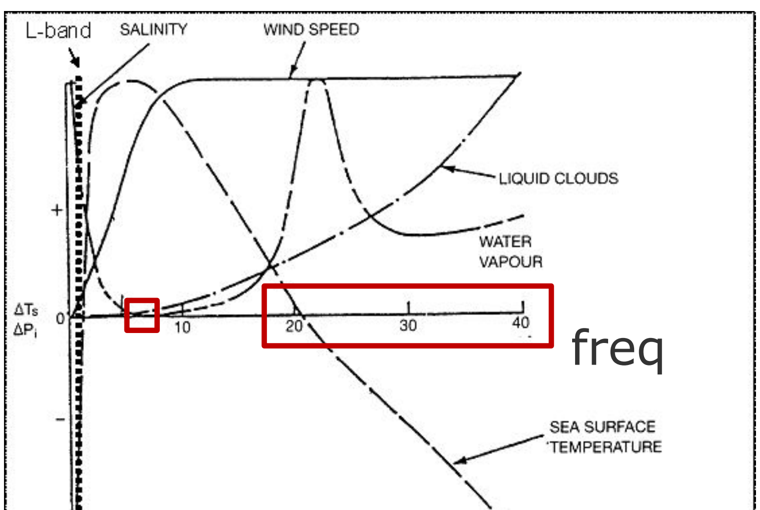
  - Lower spatial resolution (25km)
- Main problems of other SIC, from Ivanova et al. 2015
  - Atmosphere correction: water vapour and cloud liq ... eal low ice concentration
  - Sensitivity wit ... and wind
  - Snow cover thickness -> difficult to determine
  - Seasonal changes on ice tie points of up to 10K

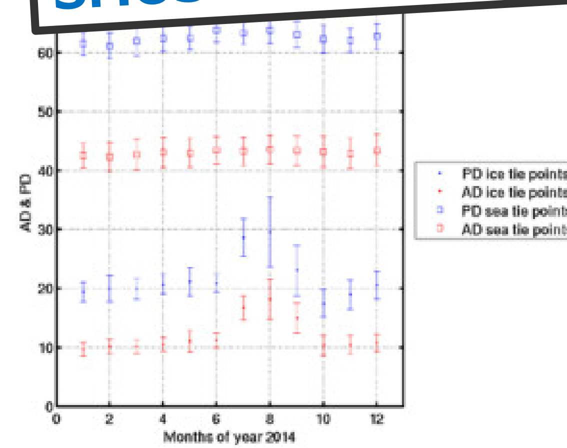
SMOS almost transparent

SMOS is less sensitive

SMOS not affected by snow thickness

SMOS more stable





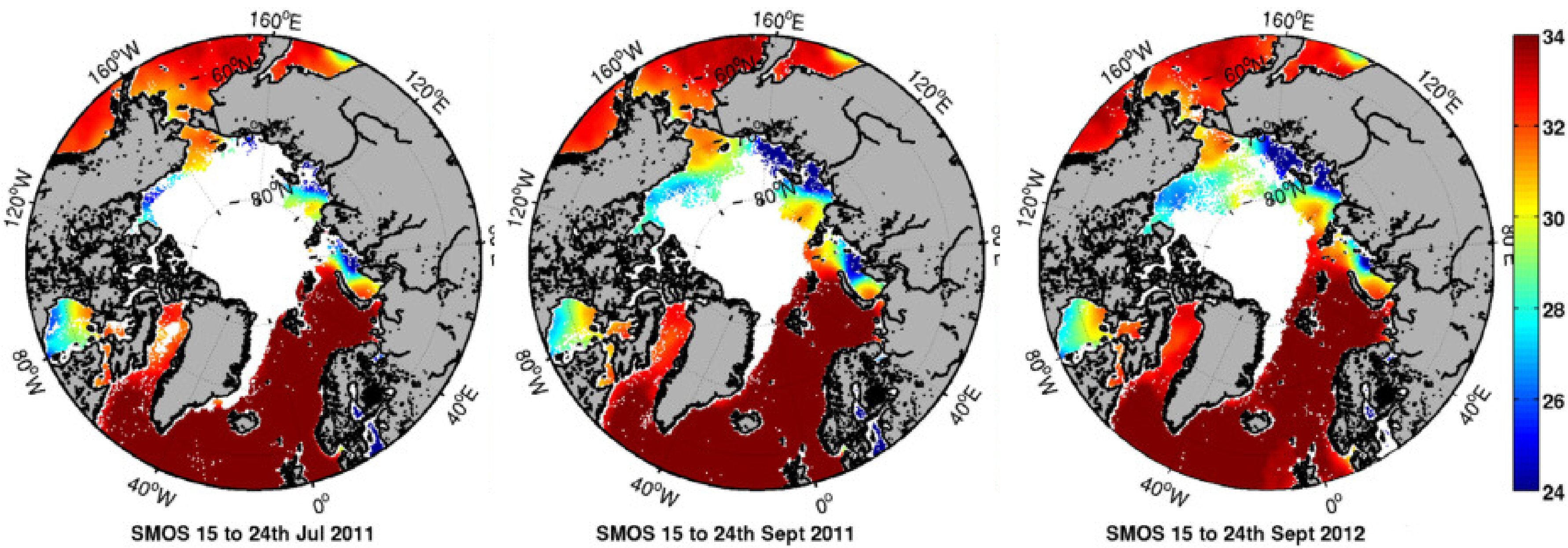
SMOS BARCELONA EXPERT CENTRE

CONCLUSIONS

- **SMOS** (L-band) can **measure SIC with good results**, but it is not suitable to differentiate FY and MY ice.
- AD and PD **are robust indices to retrieve SIC**, more independent to geophysical changes than TB. **AD is less sensitive** to ice thickness.
- **MLE algorithm is better** than linear -> less noisy.
- **SMOS leads to lower SIC than OSISAF on thin ice**, due to its different **penetration**.
- Correlation is high between SMOS and OSISAF SICs.
- SMOS less sensitive to atmosphere and geophysical conditions.
- Need Data for validation (SAR/INSITU)
- Investigate how to retrieve simultaneously SIC and Sea Ice Thickness (SIT) by using both AD and PD indices from SMOS measurements

SSS at high latitudes

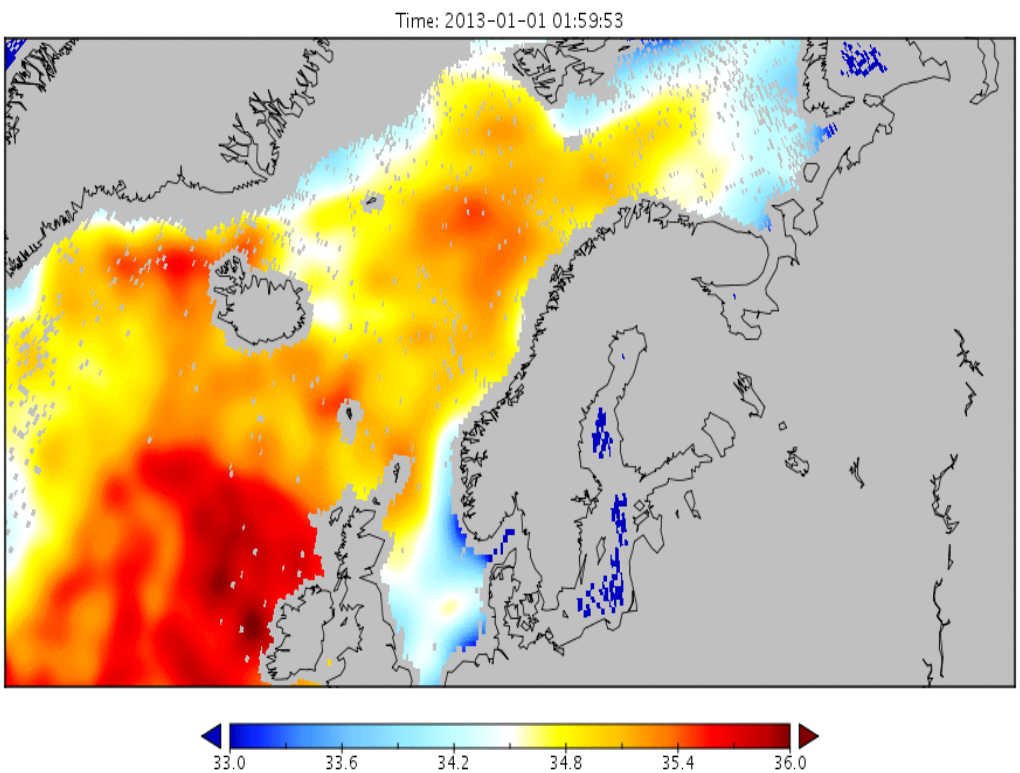
- For the Arctic Ocean, sea water density depends more on salinity than on temperature, and hence the thermohaline circulation mainly determined by salinity.
- An increased level of river discharge to the Arctic Ocean. -> the dynamical impact of such increase remains an enigma

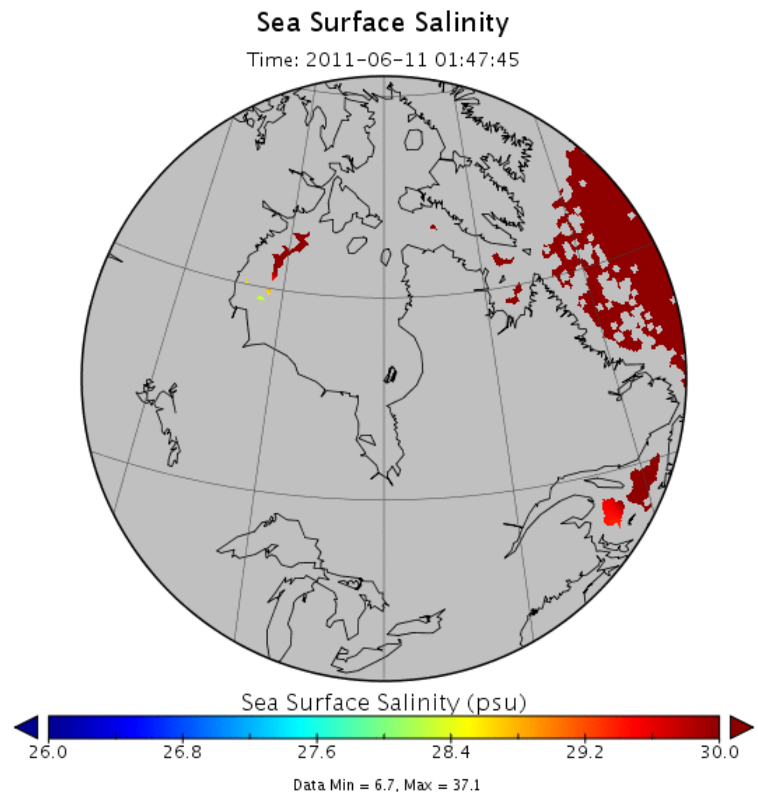


- http://cp34-bec.cmima.csic.es/ <- DATA HERE

SSS at high latitudes

Remote sensing of the Arctic Ocean salinity by SMOS would provide an unprecedented source of information about the salinity and sea ice variability.



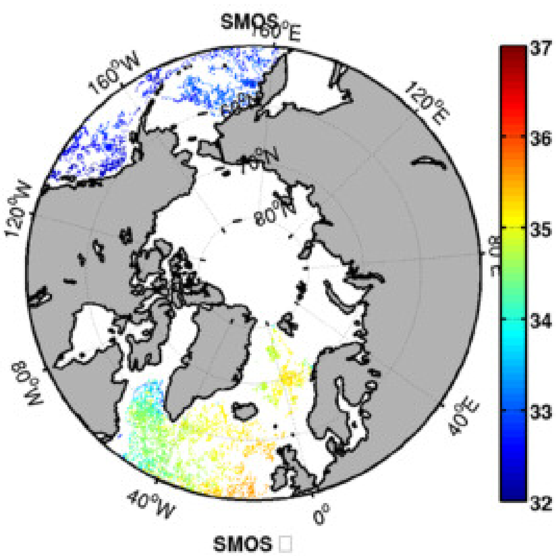


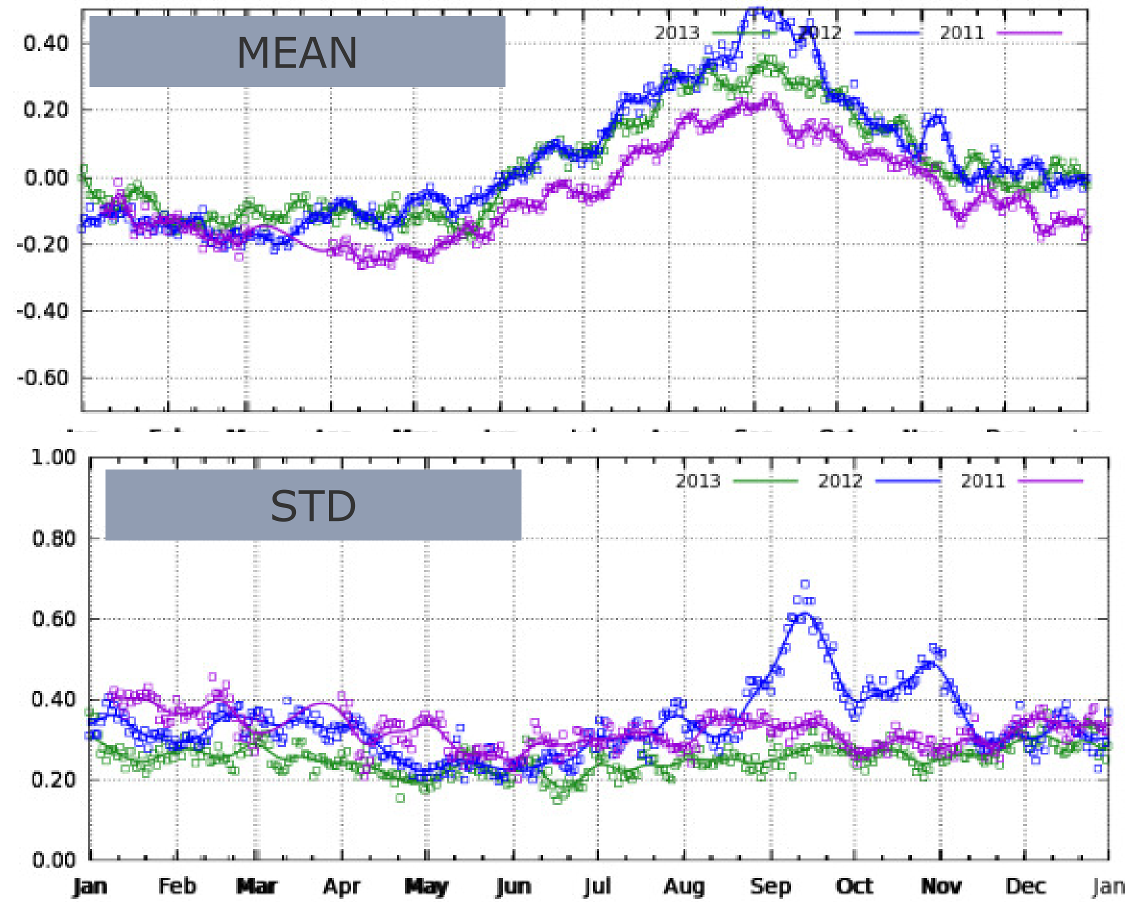
SSS ->Norwegian fjords

SSS Hudson Bay

Quality assessment: comparison with Argo

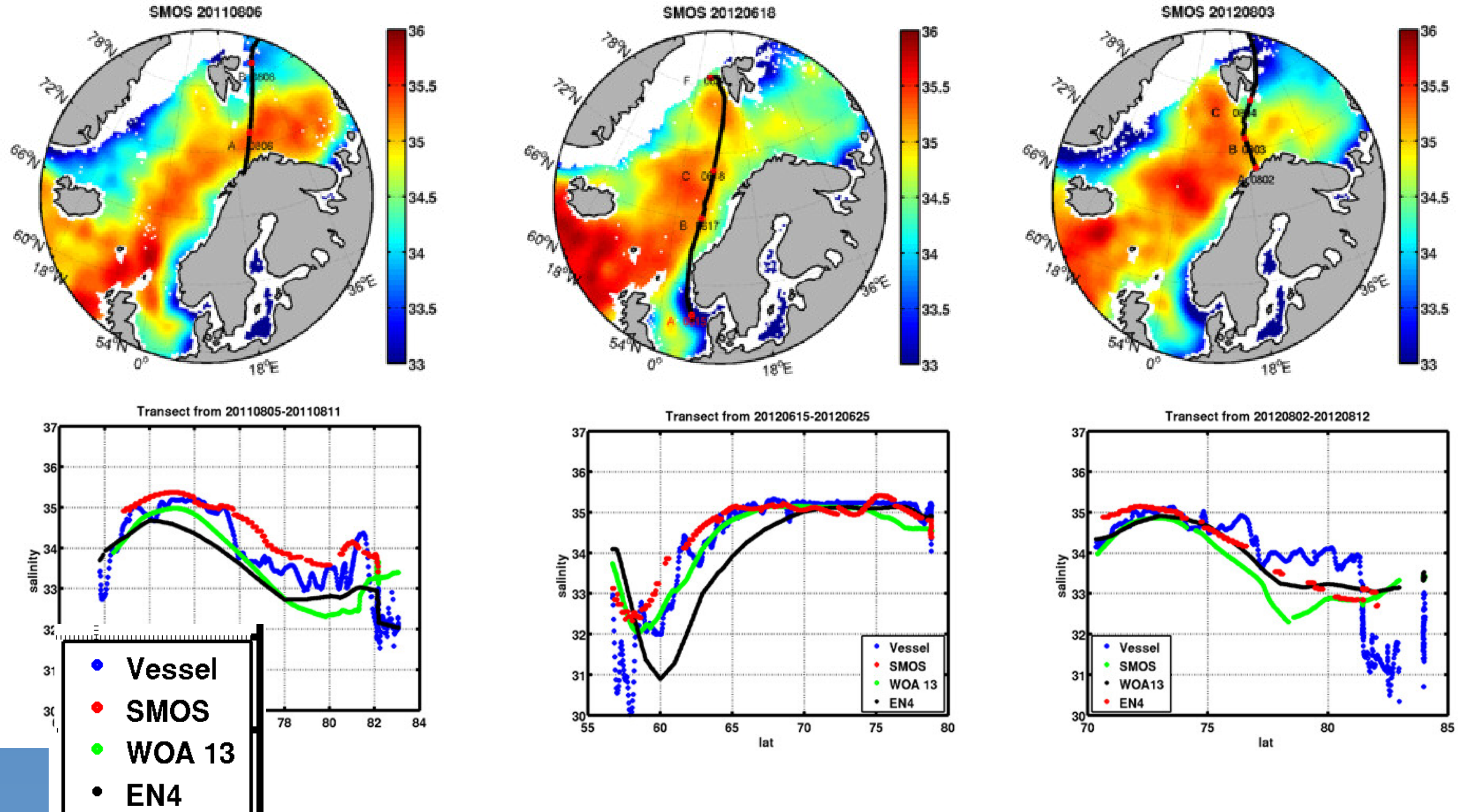
Argo locations 2011





	Mean	Std	RMS
2011	-0.05	0.32	0.35
2012	0.05	0.34	0.38
2013	0.04	0.25	0.29

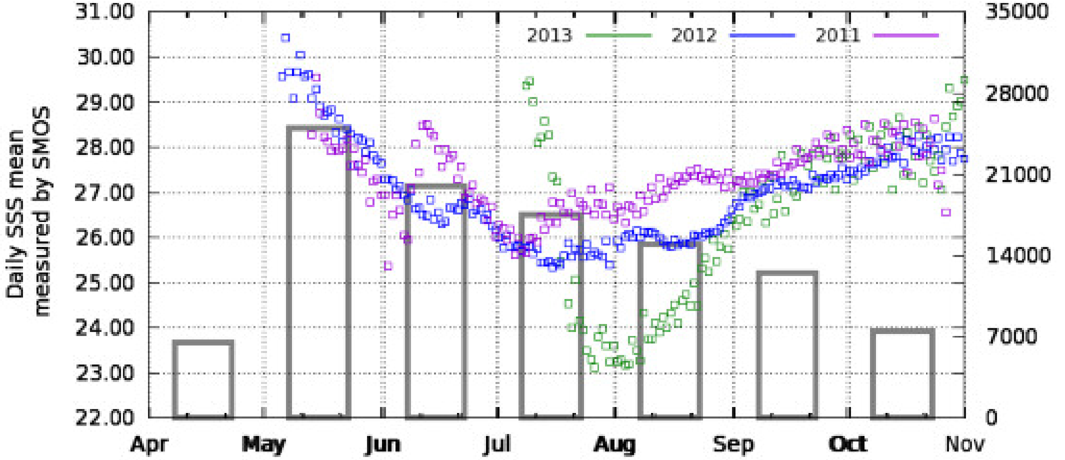
Comparison with transects

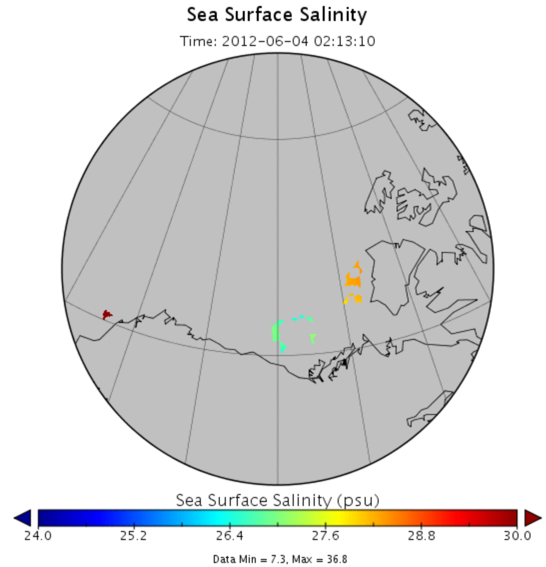


	RMS	RMS	RMS
SMOS-TSG	0.68	0.89	0.78
WOA13-TSG	0.96	0.96	1.18
EN4-TSG	0.80	1.31	1.21

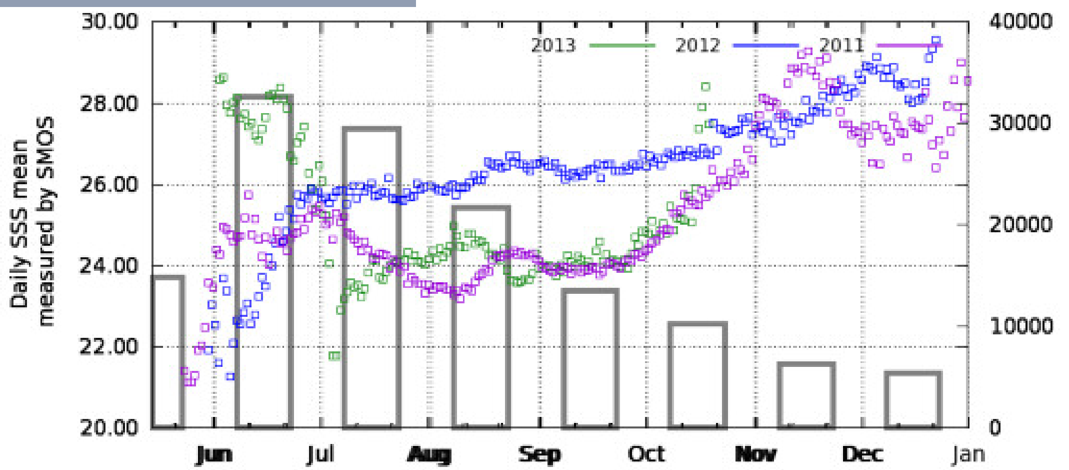
Monitoring the Arctic rivers

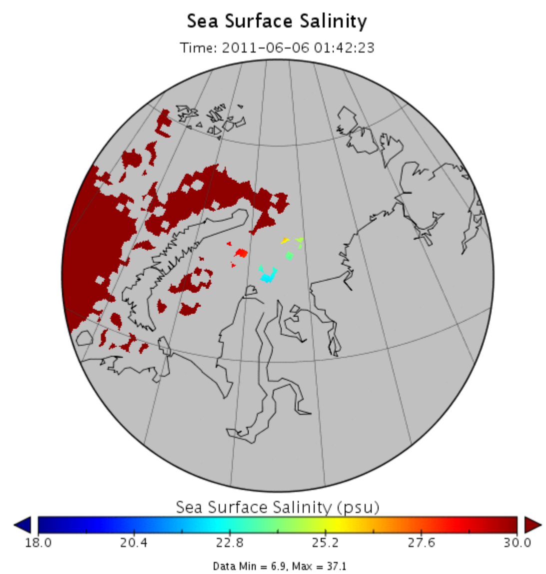
Machenzie





Ob





Monthly river discharge from http://rims.unh.edu

SMOS BARCELONA EXPERT CENTRE

Conclusions

- **SMOS is capable** to measure **Sea Surface salinity** from cold waters with an accuracy aprox 0.35 psu with respect ARGO measurements.
- SMOS is a good tool to **monitor river discharges** in the Arctic Ocean.
- SMOS gives better accuracy SSS data than WOA13 climatology and EN4 datasets.
- Better corrections can be performed using sophisticated processing tools (work going on at BEC).

Thank you for your attention

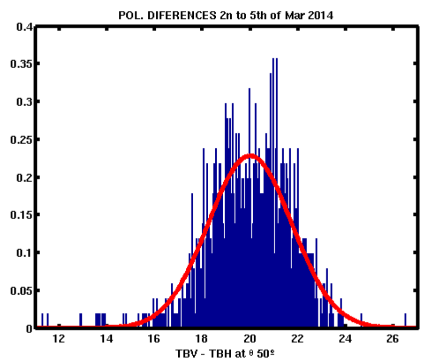
Data in http://cp34-bec.cmima.csic.es/

Distribution of measured PD and AD

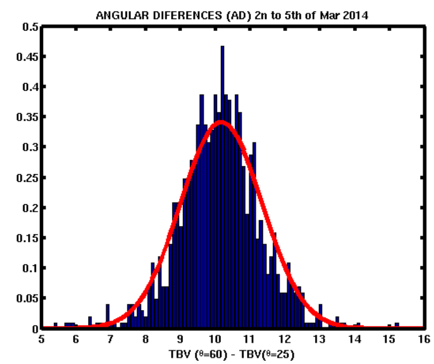
Histograms of measurements inside ROIs:

100% ICE

PD

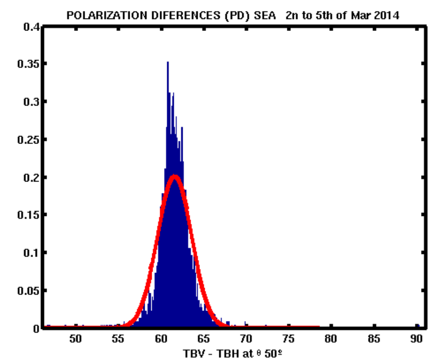


AD

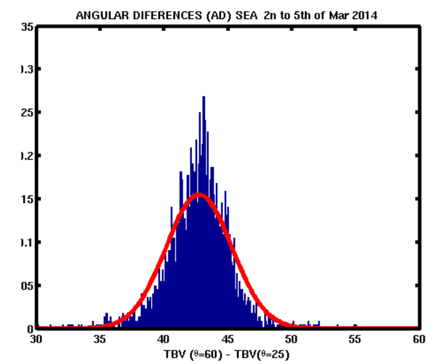


100% SEA

PD

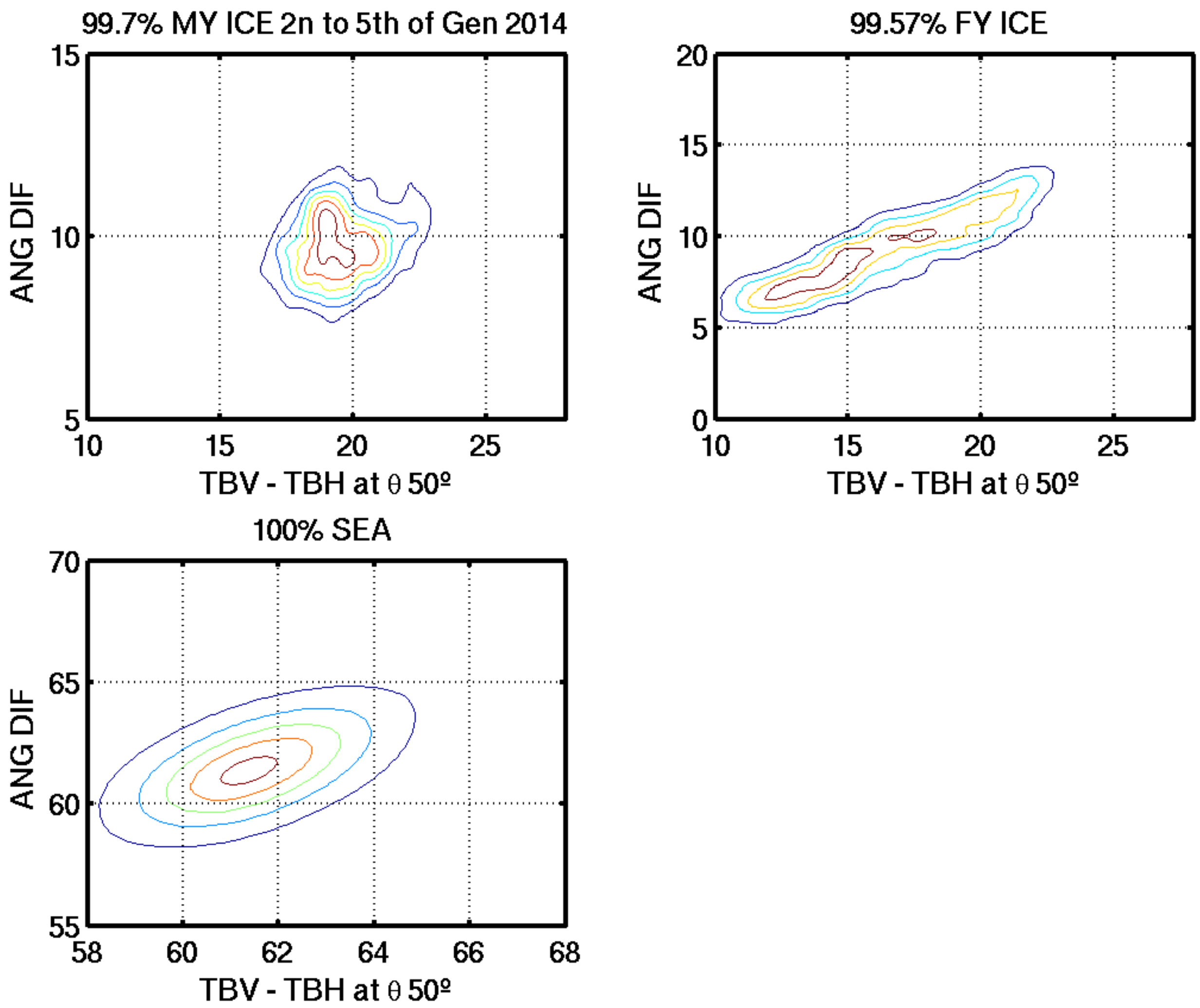


AD



PD & AD distributions are unimodal and symmetric -> can be approximated as Gaussian distributions

Stability of TiePoints with time



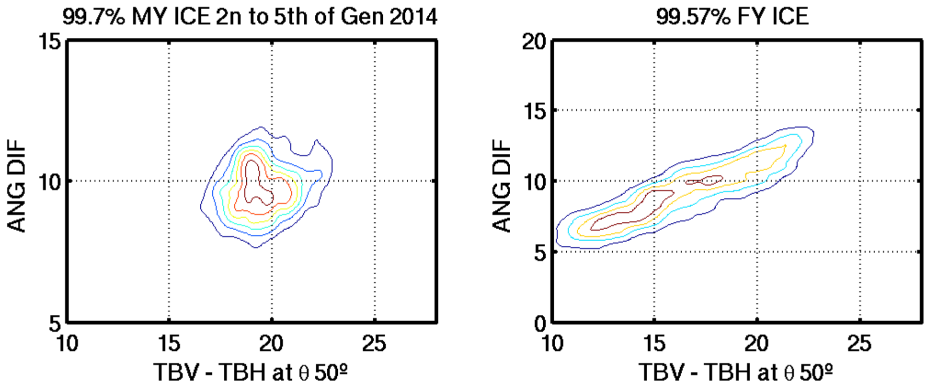
Advantages and drawbacks

- PROS:
  - SMOS less sensitive to atmosphere
  - SMOS less sensitive to temperature / snow / wind

- CONS:
  - Lower spatial resolution
  - Underestimation on thin ice

  However, synergy with high freq radiometres, region of thin ice (less than 70cm) can be masked

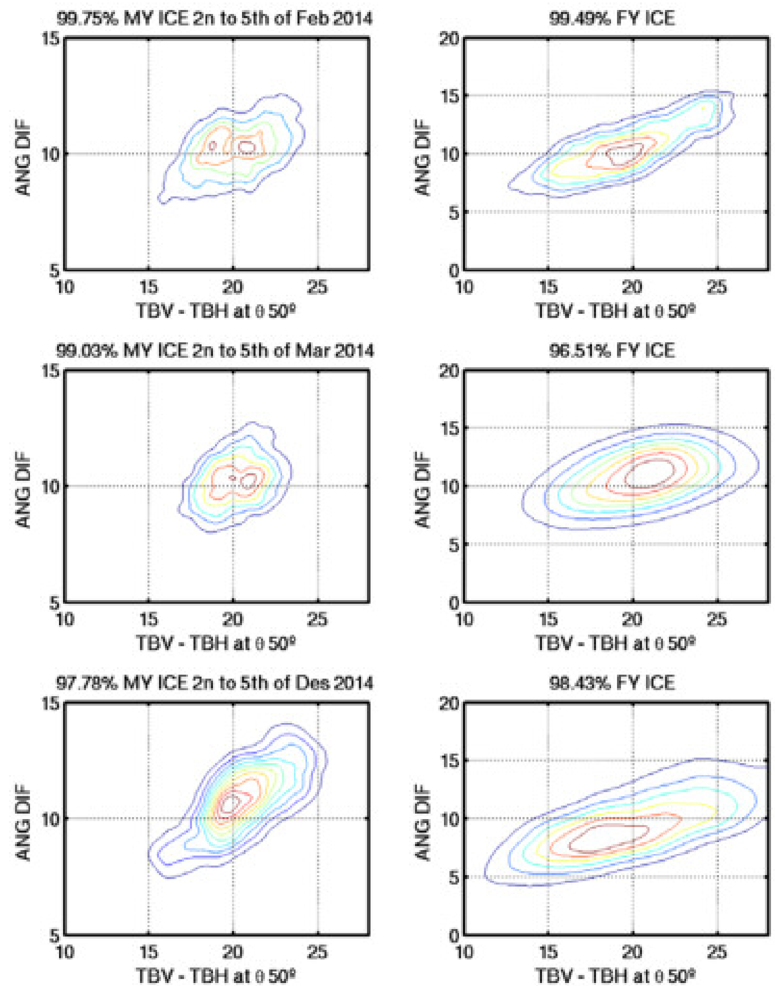
Stability of TiePoints with time



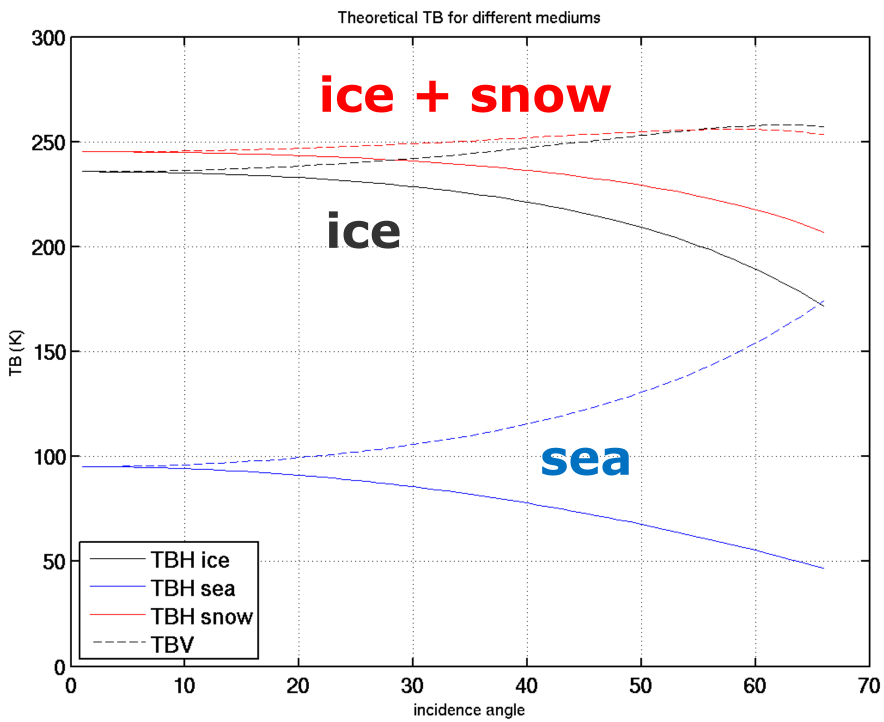
Mean_PD_FY~=mean_PD_MY
Mean_AD_FY~=mean_AD_MY

Std_PD_FY~=2*std_PD_MY
Std_AD_FY~=2*std_AD_MY

- Could it be a proxy for FY/MY ice classification?



Theoretical models



- Sea ice dielectric constant: Vant et al (1978) + Cox & Weeks (1983) + Leppäranta & Manninen (1988)
- Seawater dielectric constant: Klein & Swift
- Ice over seawater: Burke et al. (1979) 3-layer model (snow+ice+water)
- Snow is transparent but effect on the incidence angle (Fresnel)

Differences:

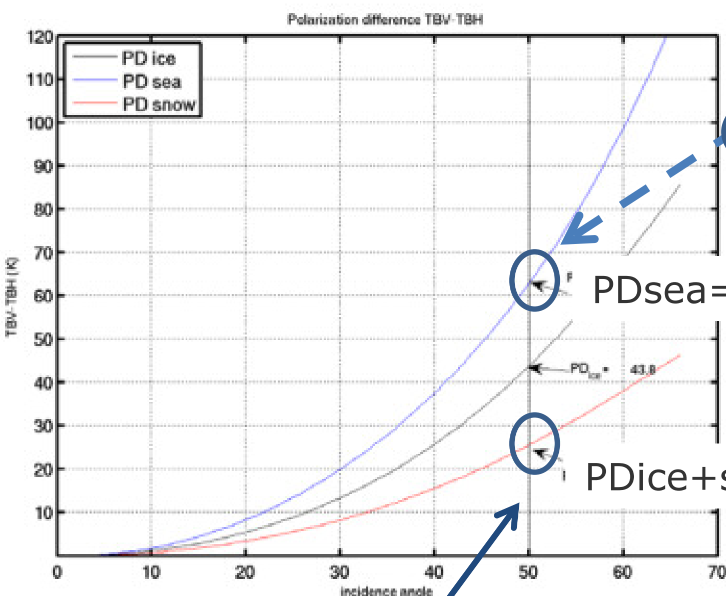
- polarization differences
- TBV

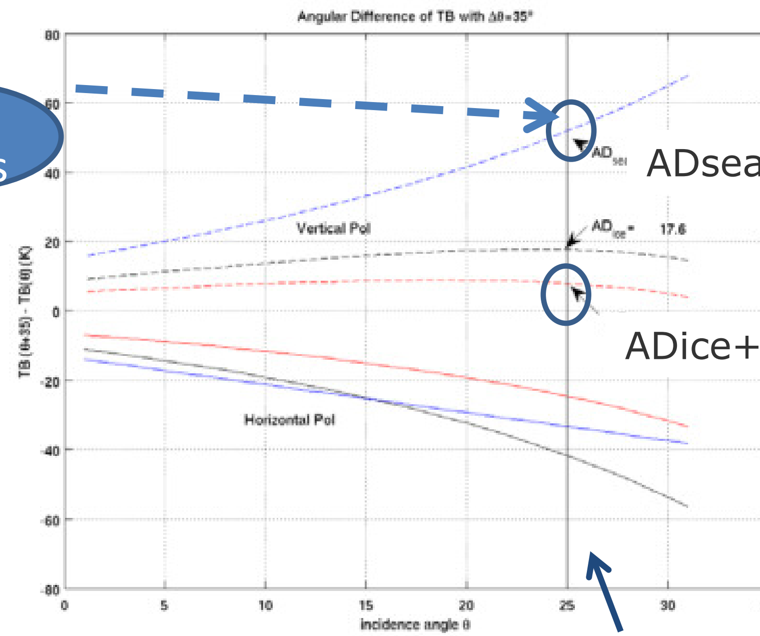
SMOS BARCELONA EXPERT CENTRE

Theoretical behaviour of selected indices

Polarization Difference Index: TBV - TBH

Angular Difference Index: TBV for Δθ=35º





Tie points

PDsea=65

PDice+s=25

ADsea=44

ADice+s=8

TBv(θ=60)-TBv(θ=25)

Value at θ=50º is a good compromise

Theoretical Tie Points

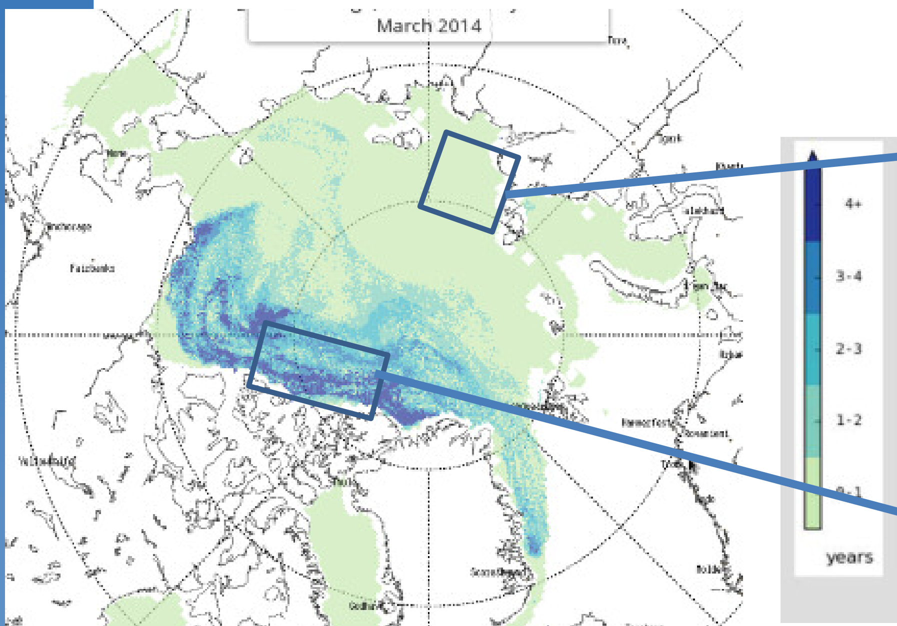
PD_ice+snow=25	AD_ice+snow=8
PD_sea=65	AD_sea=44

Values changes with T, S, wind, etc

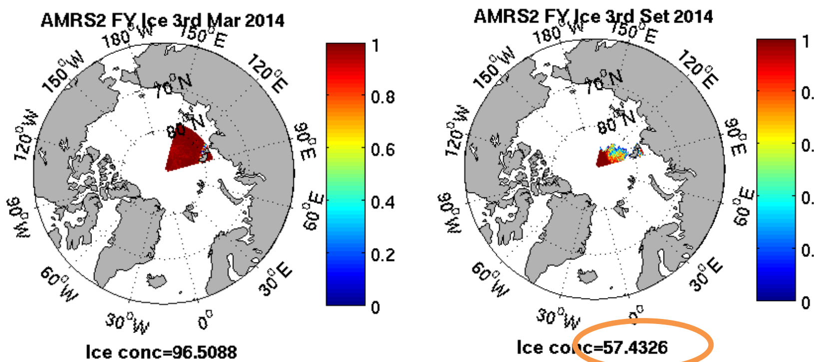
55

Identify ROIs for FY ice and MY ice

ICE AGE

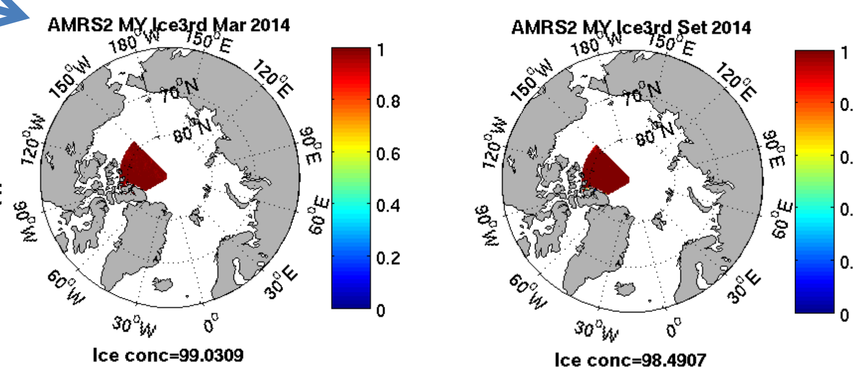


ROI Tie Point FY ICE: thickness < 2m



March SEPT.

ROI Tie Point MY ICE



Source: NASA: satellite observation of Artic Cha
http://nsidc.org/soac