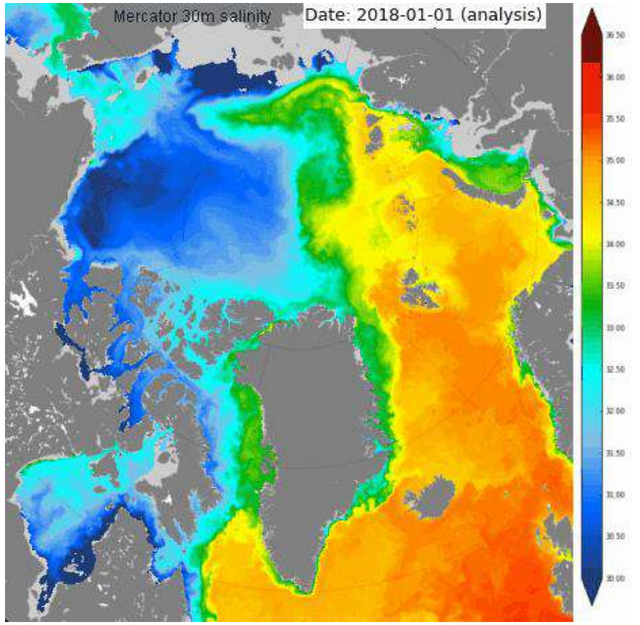
Sea Surface Salinity and Ocean Surface Wind Vector Retrieval Capabilities of the CIMR Instrument

Nicolas Reul & Joe Tenerelli



2024 European polar science week
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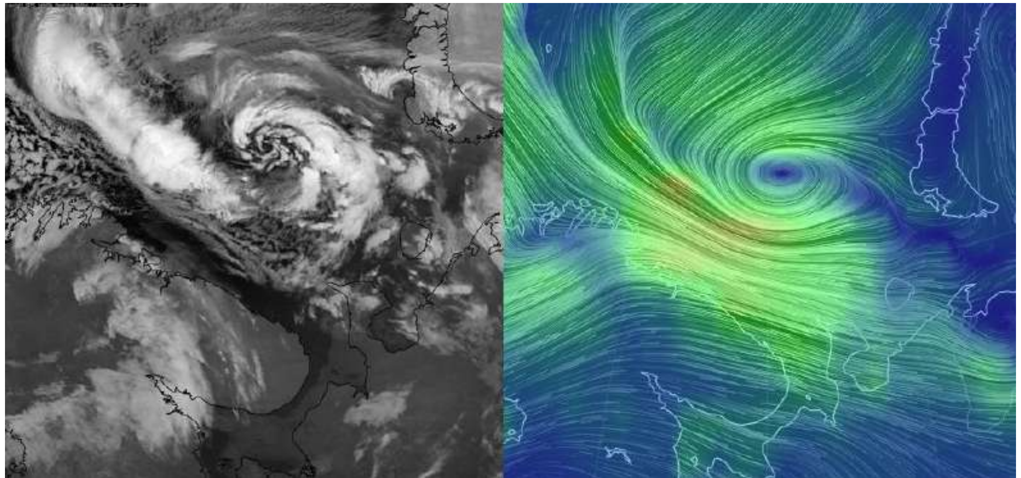
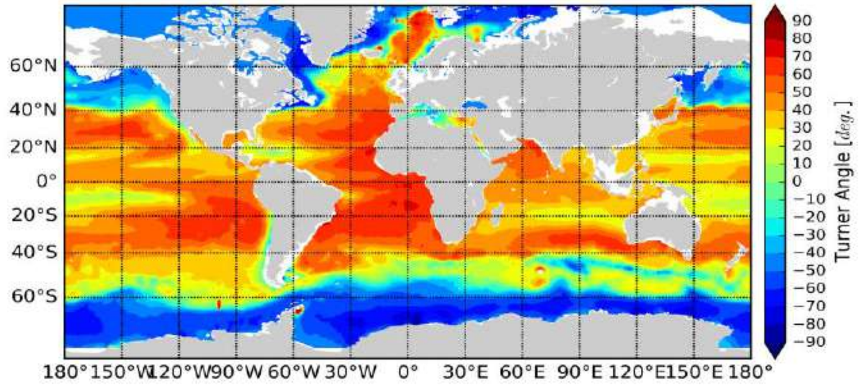


Why measuring Sea Surface Salinity (SSS) from Space in the poles is Important ?
=> Key role of Salinity at high latitudes

- ❑ Dominant impact of salinity on polar water mass **density & global thermohaline circulation**

Stratification T/S ratio

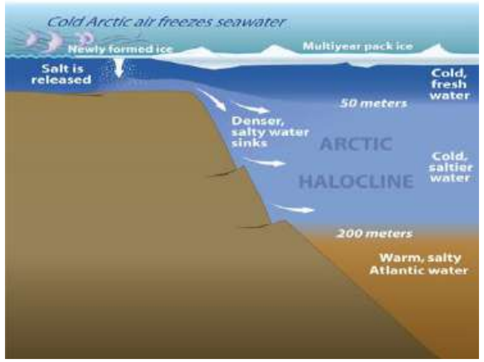


Temperature dominates density

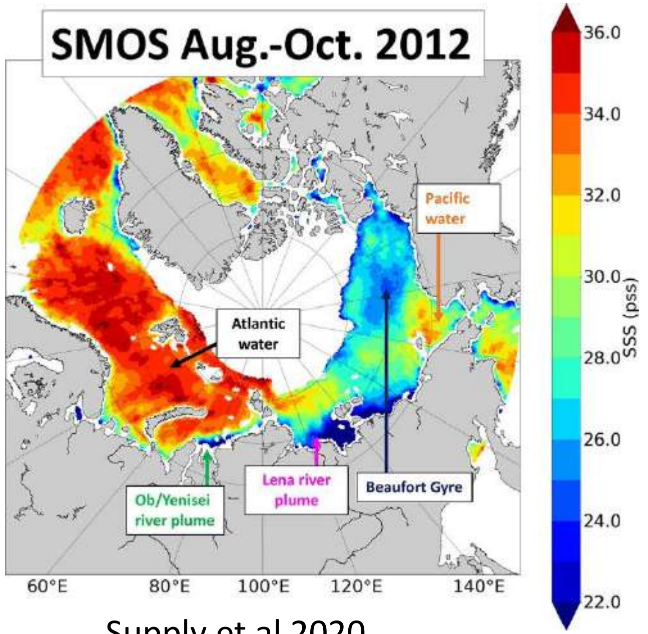
Salinity dominates density

Nicolas Kolodziejcyk 2020

- ❑ Strong salinity **impact on vertical density stratification in polar waters** & subsequent **air-sea-ice exchanges of** heat, momentum and gas **(CO_2)**

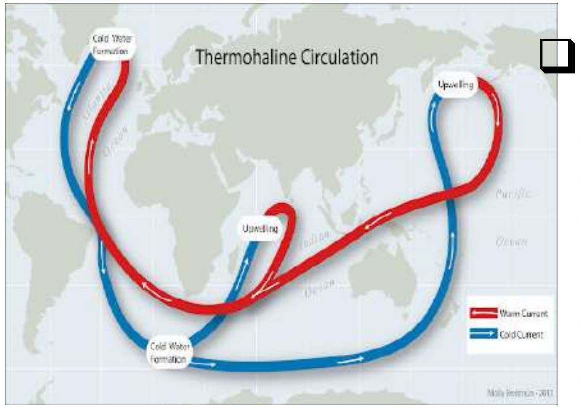


(Illustration by Jayne Doucette, WHOI)

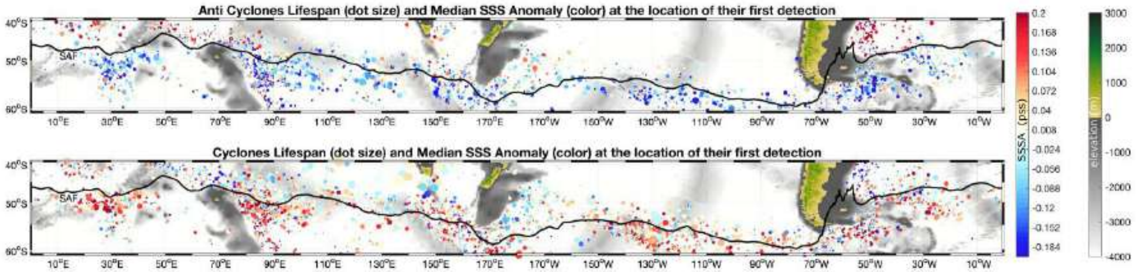


Supply et al 2020

- **A key tracer of the fresh water exchanges at the following interfaces**
  - ❑ Sea ice& glaciers ⇔ocean(melting),
  - ❑ atmosphere⇔ ocean (Precipitations) &
  - ❑ Land ⇔ocean (freshwater river discharge)



- ❑ Key role in **frontal dynamics** & **eddy driven transport**



Hasson et al 2020

Salinity changes are observed & expected in Arctic environment.

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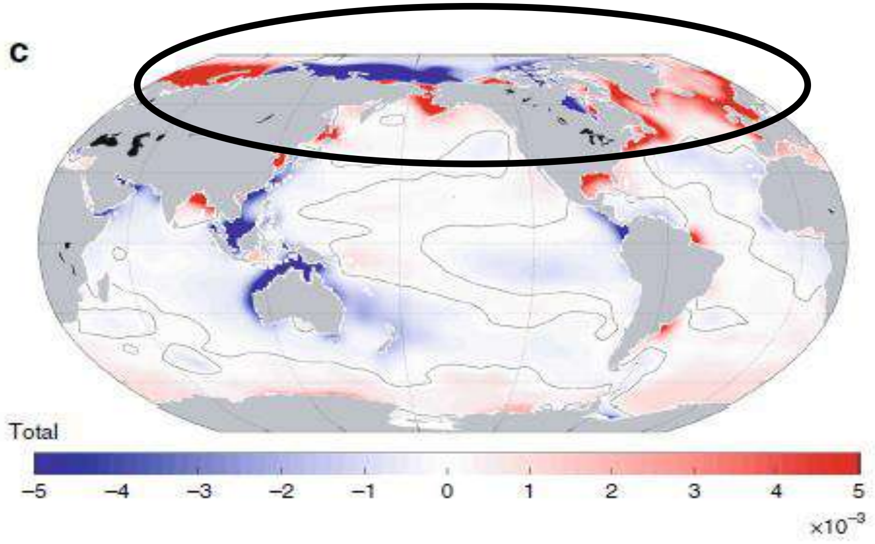
Article | Open Access | Published: 01 August 2019

Vertical redistribution of salt and layered changes in global ocean salinity

Chao Liu, Xinfeng Liang ✉ Rui M. Ponte, Nadya Vinogradova & Ou Wang

Nature Communications **10**, Article number: 3445 (2019) | Cite this article



***a** 22-year (Jan. 1993—Dec. 2014) trends (psu year^{-1}) of ocean salinity averaged over the whole water column*

- **Significant salinity trends have been observed in the Arctic over the last 20 years**

AGU100 ADVANCING EARTH AND SPACE SCIENCE

JGR

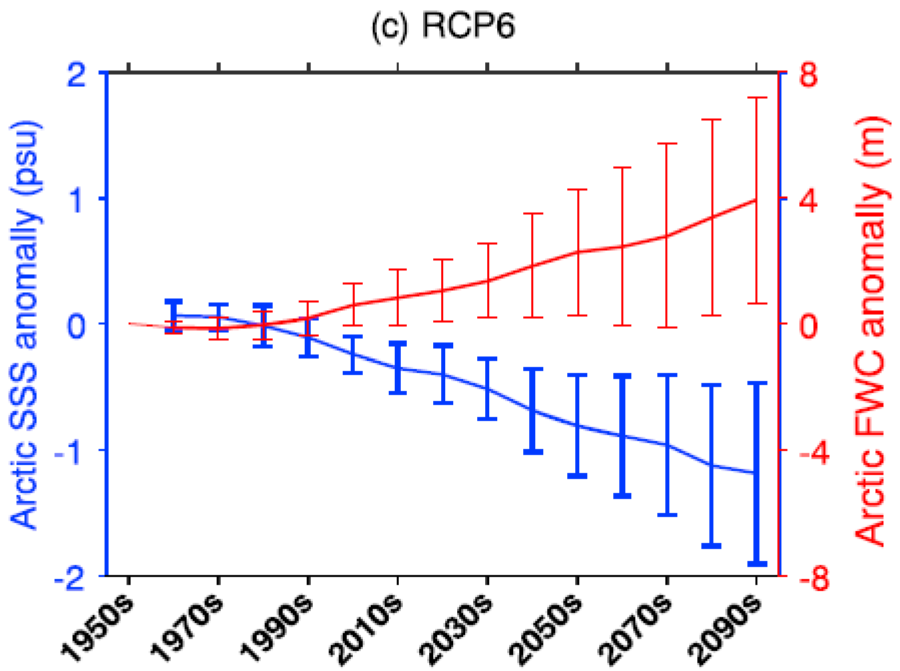
Journal of Geophysical Research: Oceans

RESEARCH ARTICLE

10.1029/2018JC014036

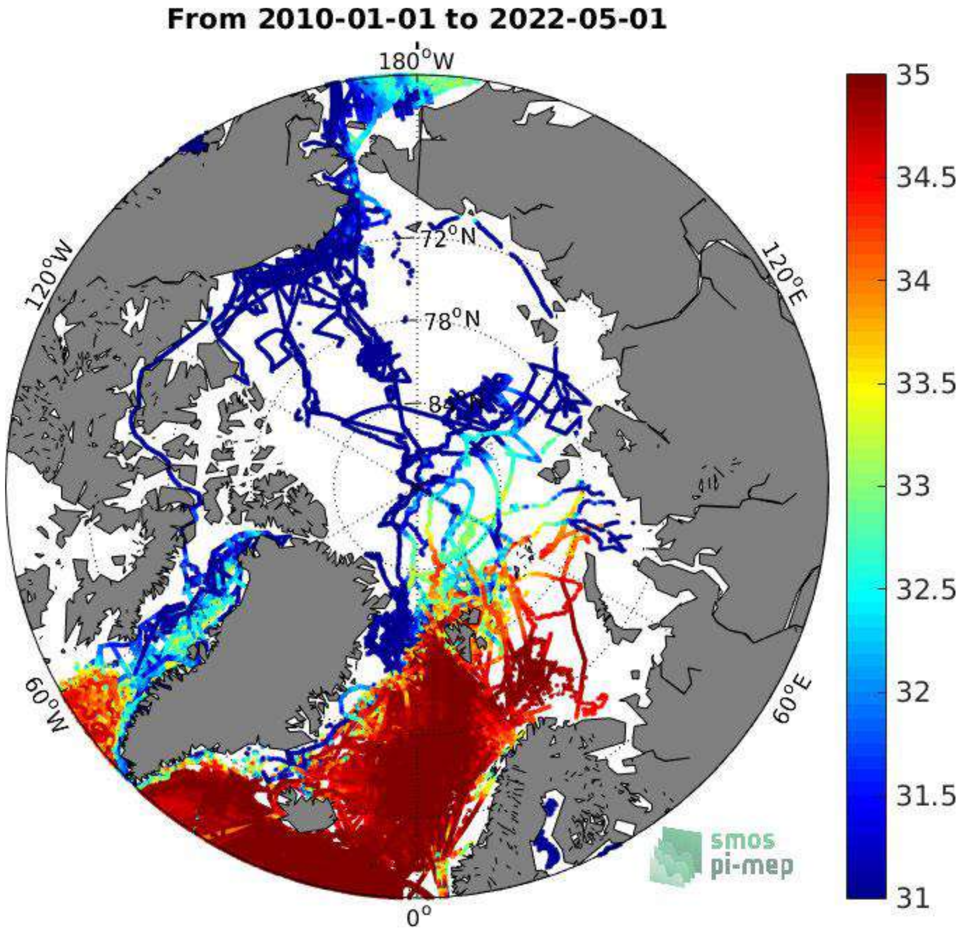
Projected Freshening of the Arctic Ocean in the 21st Century

Qi Shu[1,2,3], Fangli Qiao[1,2,3], Zhenya Song[1,2,3], Jiechen Zhao[4], and Xinfang Li[1]

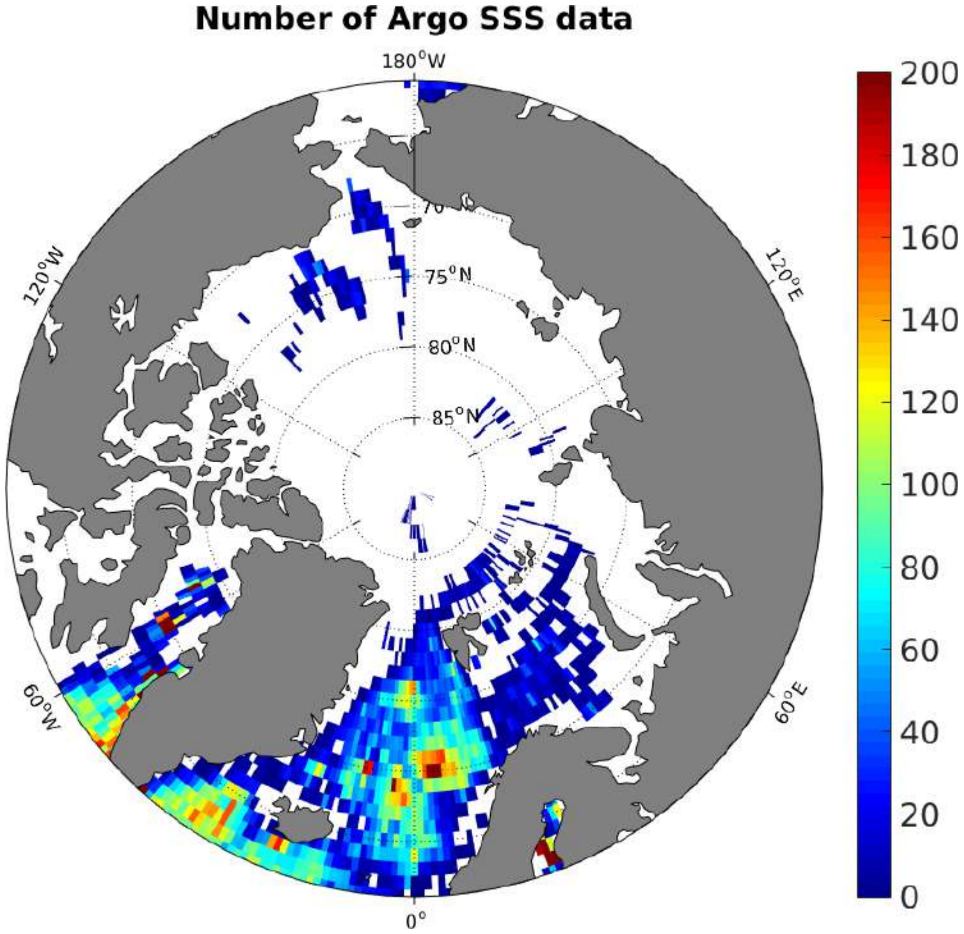


- The **upper Arctic Ocean likely to freshen considerably in the future.** Arctic Ocean average sea surface salinity is projected to decrease by 1.5 ± 1.1 psu and the liquid freshwater column is projected to increase by 5.4 ± 3.8 m by the end of the 21st century

But we got very little in situ SSS data there !

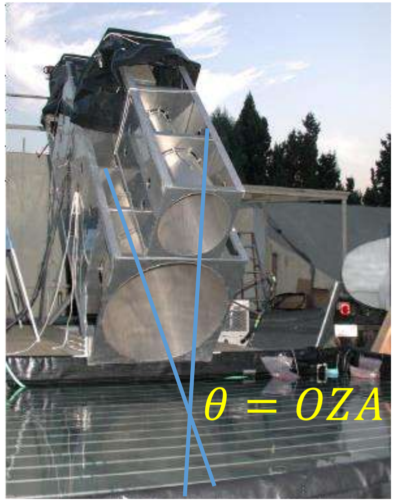


Ensemble of in situ data since 2010



Number of Argo float profile data since 2010
In 1°x1° boxes

Basics of SSS measurements from Space with L-band radiometers



Brightness of a perfectly flat sea water surface:

$$T_{Bp} = \boldsymbol{T}.\, e_p(\theta, f, \boldsymbol{S}, \boldsymbol{T}) = \boldsymbol{T}.\left(1 - \left|R_p(\theta, f, \boldsymbol{S}, \boldsymbol{T})\right|^2\right)$$

$\boldsymbol{f}$: electromagnetic frequency

S: Salinity

T: Temperature

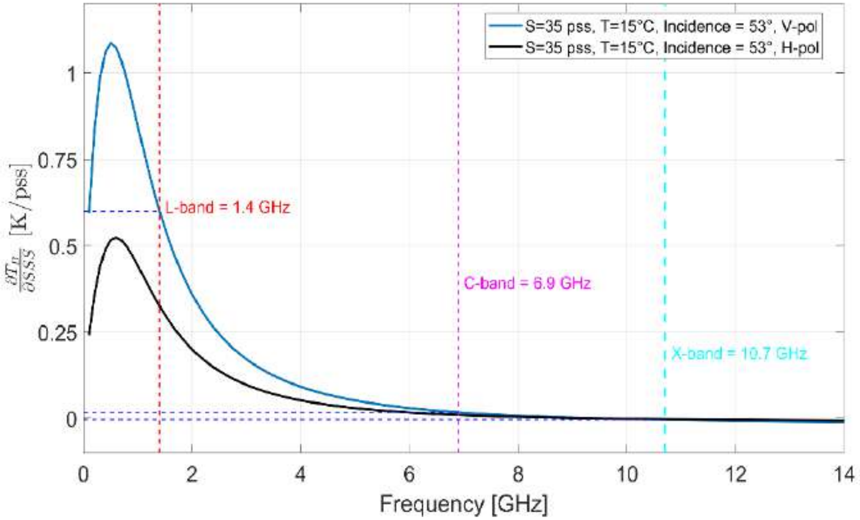
$\varepsilon_{sw}(f, S, T)$ is the dielectric constant of sea water.

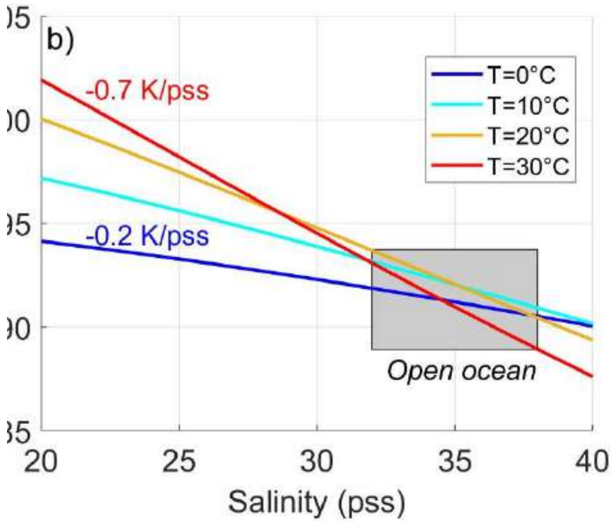
$$\begin{cases} R_v(\theta, f, S, T) = \dfrac{\sqrt{\{\varepsilon_{sw} - \sin^2\theta\}} - \varepsilon_{sw}\cos\theta}{\sqrt{\{\varepsilon_{sw} - \sin^2\theta\}} + \varepsilon_{sw}\cos\theta} \\ R_h(\theta, f, S, T) = \dfrac{\sqrt{\{\varepsilon_{sw} - \sin^2\theta\}} - \cos\theta}{\sqrt{\{\varepsilon_{sw} - \sin^2\theta\}} + \cos\theta} \end{cases}$$

$$\varepsilon = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)}{1 + i\omega\tau} - i\frac{\sigma}{\omega\varepsilon_0}$$

SSS retrieval from radiometer data T_{Bp} involves 1) **auxilliary SST** 2) **accurate model for $\boldsymbol{\varepsilon_{sw}}$**

❑ **Sensitivity to SSS is optimal at L-band**
(10 times more than at C-band)
1.4 GHz is protected for radio-astronomy

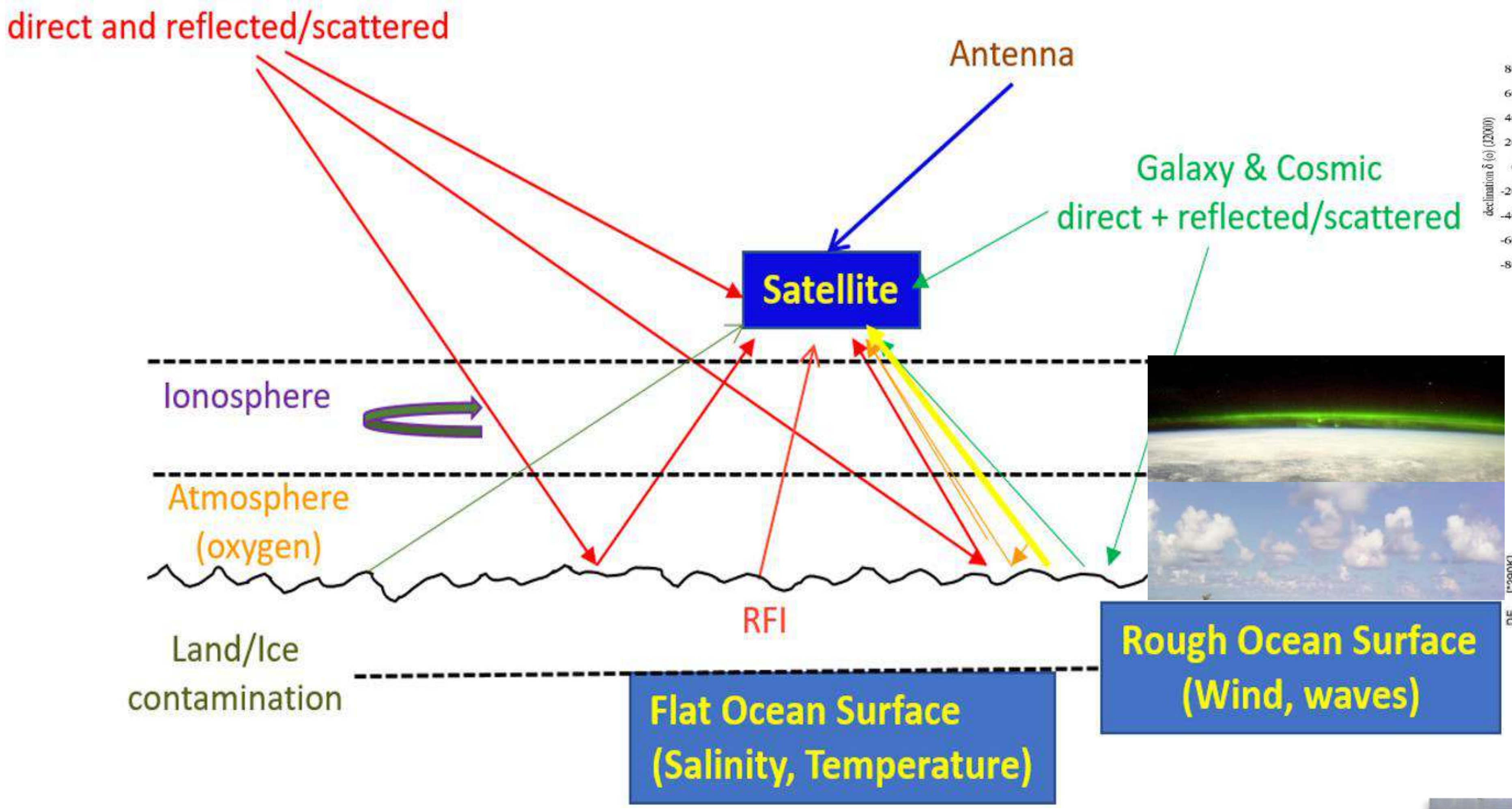




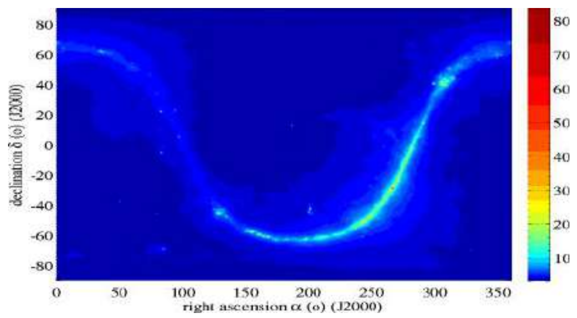
(a) sensitivity of the ocean surface microwave brightness temperature to Salinity (First Stokes parameter) as a function of electromagnetic frequency and incidence angle (blue V-pol, black H-pol) and for a water body with salinity of 35 pss and temperature of 15 °C. (b) Brightness temperature ((TH + TV)/2) changes at 1.4 GHz and nadir as a function of salinity (x-axis) and temperature (colors). The gray domain indicates the range of SSS values mostly encountered in the open ocean.

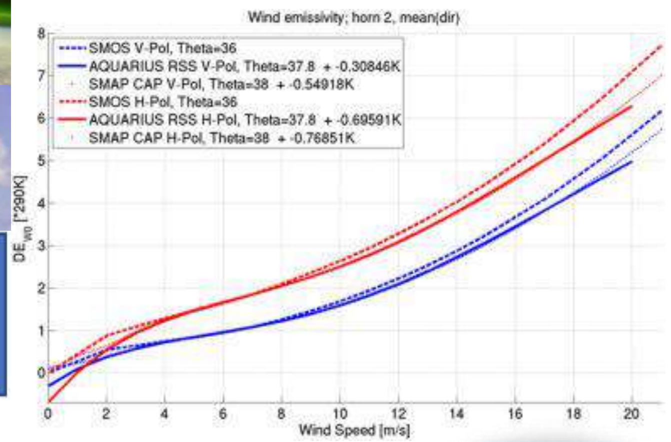
❑ **Sensitivity to SSS at L-band drops with decreasing surface temperature**
~0.2 K /practical salinity scale in Arctic Waters (SST=0°C)
=> Demanding requirements on NeDT

An ensemble of external contributions to antenna Tb that need to be corrected for SSS retrieval

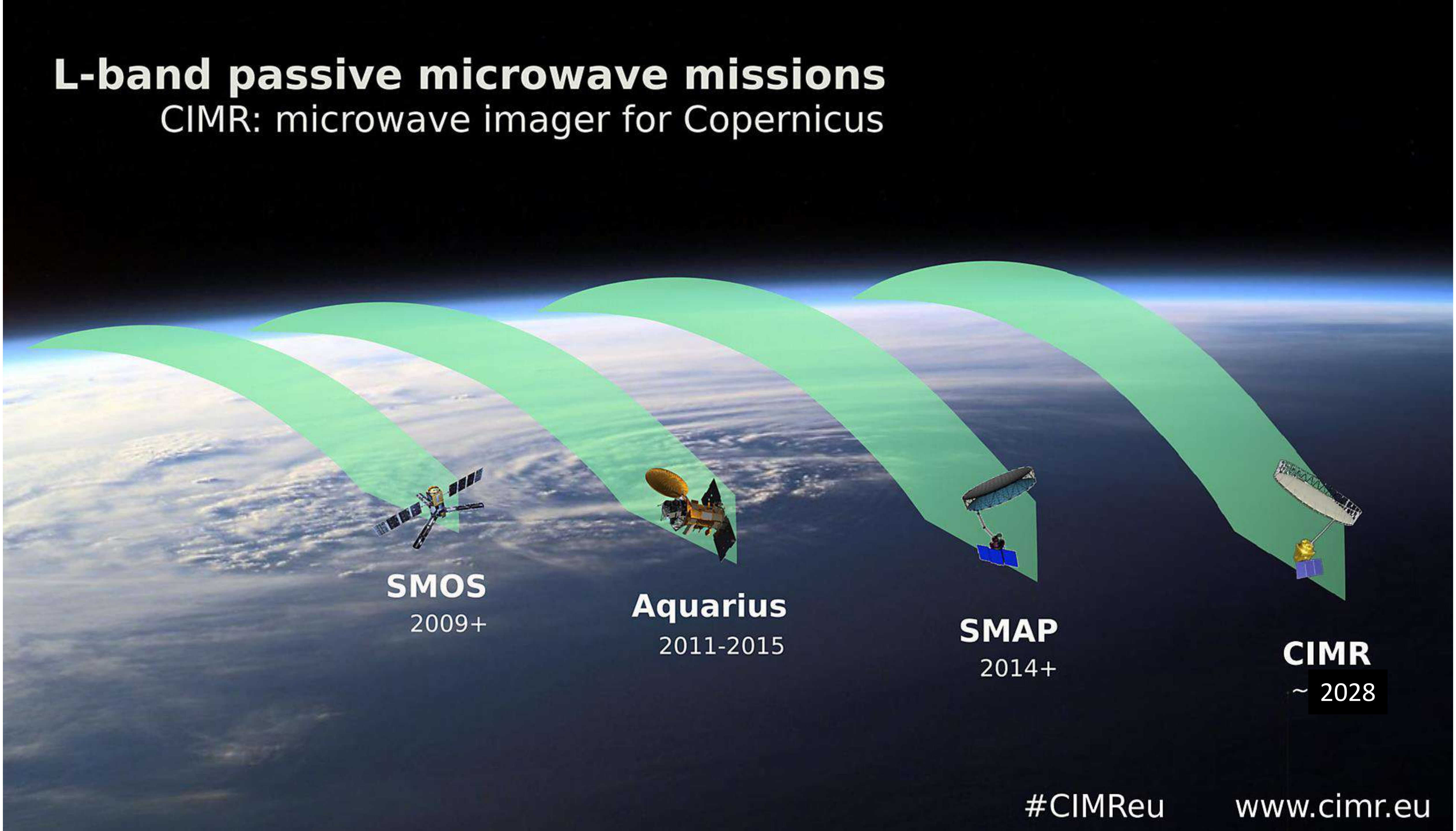


Sky Brightness





Complete and accurate Radiative forward Transfer Model needed


L-band passive microwave missions
CIMR: microwave imager for Copernicus
SMOS
2009+
Aquarius
2011-2015
SMAP
2014+
CIMR
~ 2028
#CIMReu
www.cimr.eu

CIMR Mission requirements

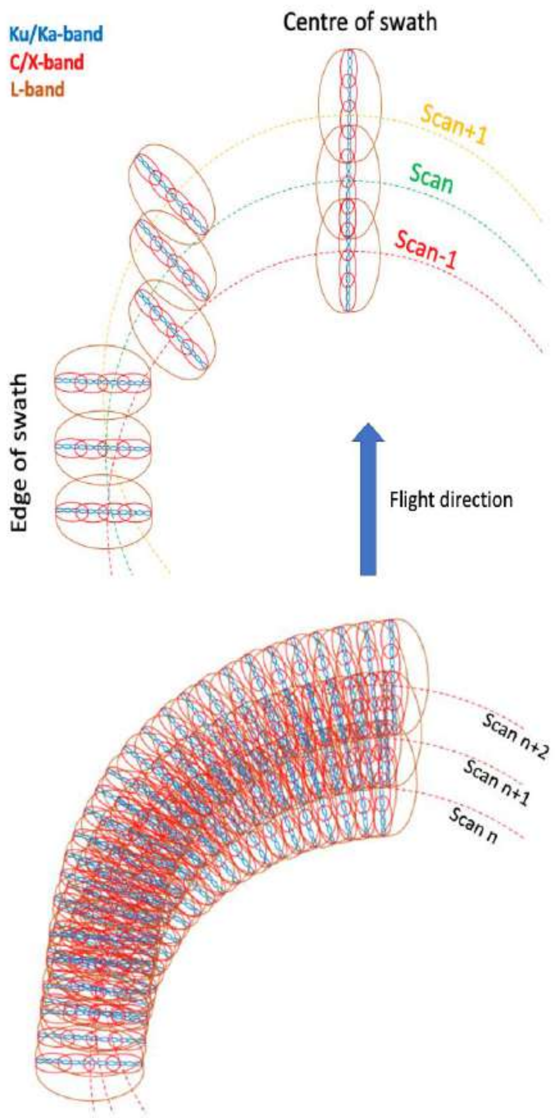
Measure **Sea Surface Salinity (SSS)** over the global ocean from space with a target gridded spatial resolution of 40 km and uncertainty ≤0.3 pss over monthly time-scales

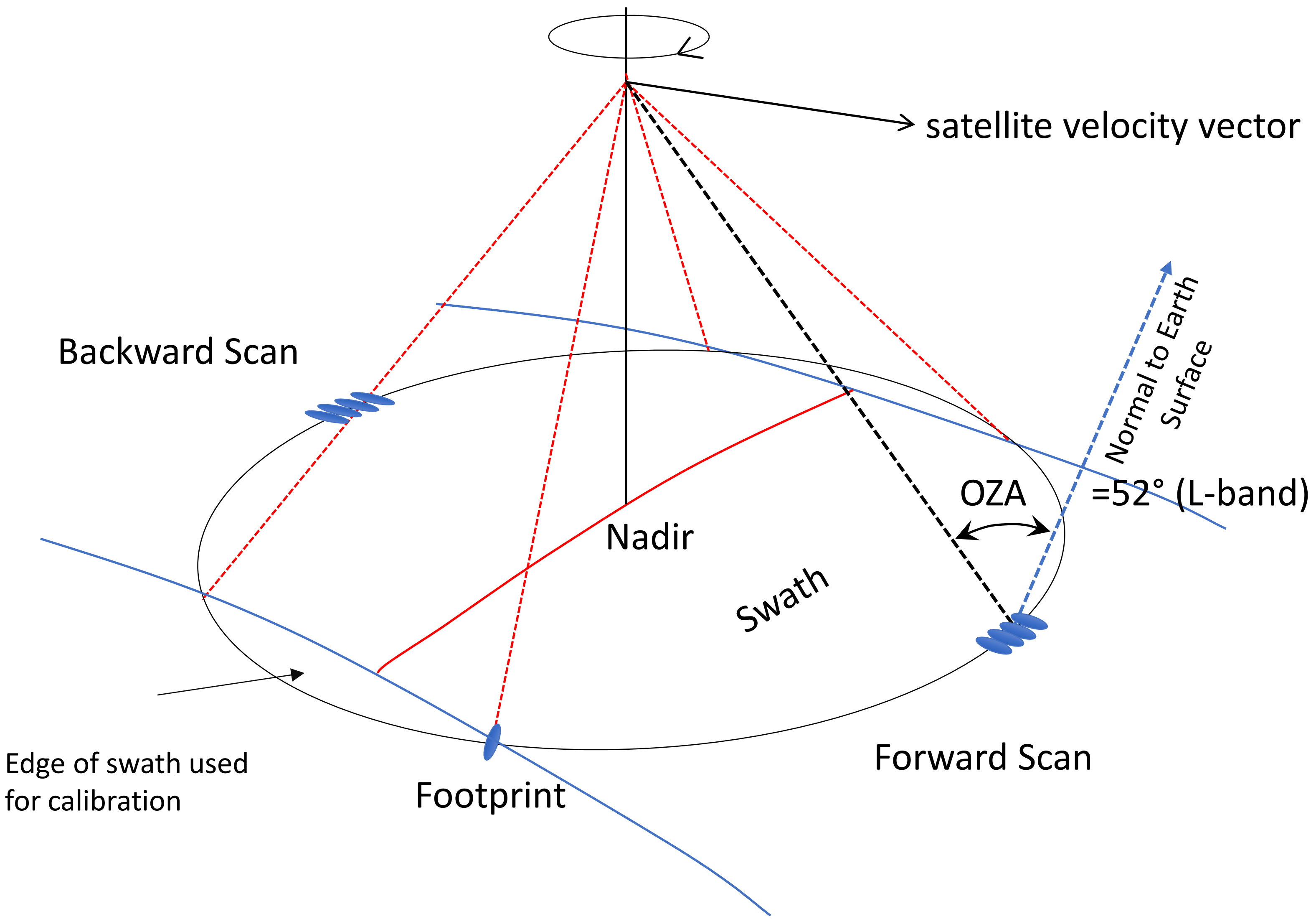
SSS

SST, Surface Wind Vector,SIC, SIT, SI drift,..

Channels (GHz, Full Stokes):	**1.4**	**6.9**	**10.65**	**18.7**	**36.5**
Resolution (km):	**<60**	**≤15**	**≤15**	**≤5.5**	**≤5** (g:4km)
NEΔT (K @150K):	**≤0.3**	**≤0.2**	**≤0.3**	**≤0.4**	**≤0.7**
Tot. Standard Uncertainty(K):	≤0.5	≤0.5	≤0.5	≤0.6	≤0.8
Swath width:	**>1900 km**				

CIMR a Conical Microwave Imaging Radiometer

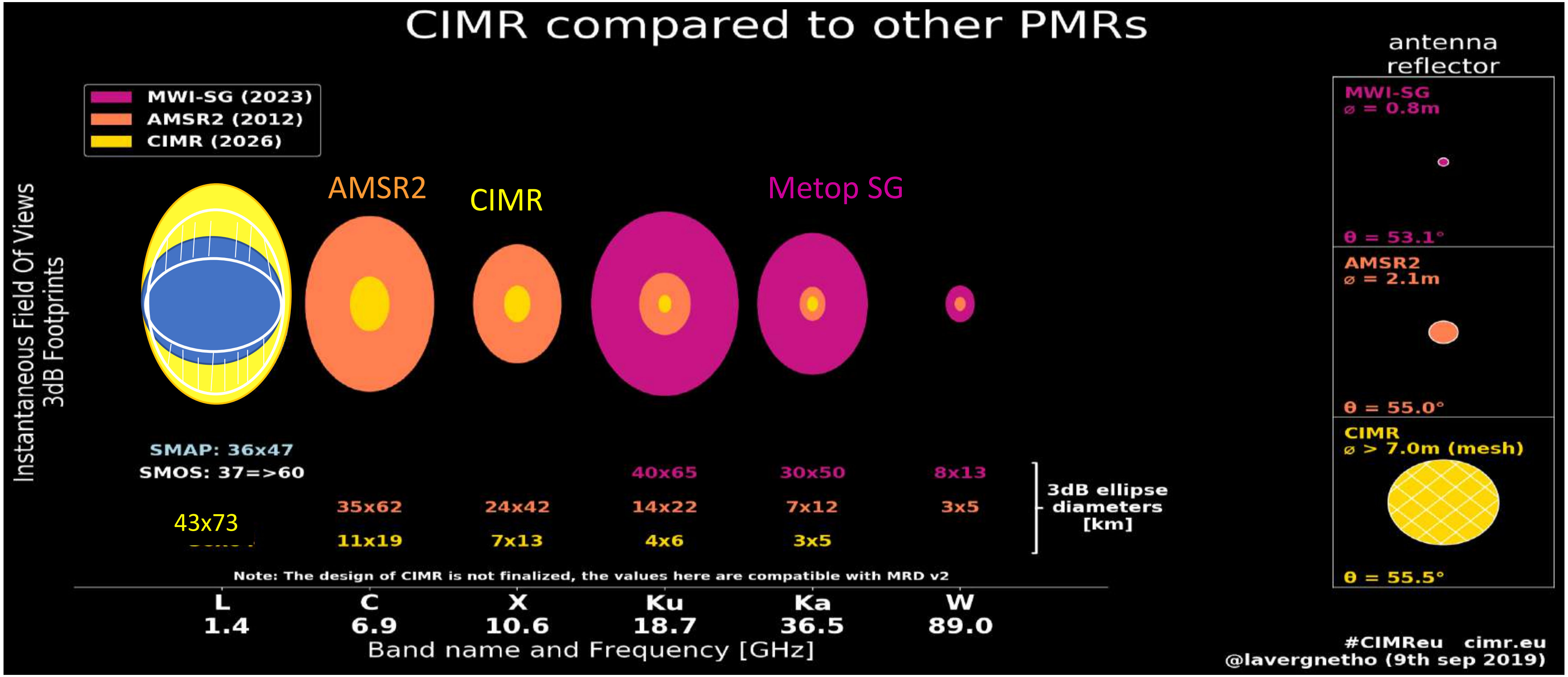




L-band channel CIMR Spatial Resolution: comparaison with other PMRs

- we lose a bit of spatial resolution at L-band with respect SMOS & SMAP

  CIMR L-band 3dB footprint is 43 x 73 km



But we **gain in radiometric accuracy** & **spatio-temporal coverage**

Instrument	Frequency(GHz)	Spatial resolution [km x km] (3-dB footprint size)	Earth Incidence angle (◦)	NeΔT*(K)	Polarizations	Swath Width (km)
CIMR	1.4 (L-band)	43 x 73 km	52°	0.3	H, V, 3rd & 4th Stokes	>1800 km
SMAP	1.4 (L-band)	39 x 47 km	40°	1.3	H, V, 3rd & 4th Stokes	~1000 km
SMOS	1.4 (L-band)	37=>60 km (synthetic beam)	0°-60°	1.5-4 K	H, V, 3rd & 4th Stokes	~1500 km

SSS retrieval algorithm for CIMR

Auxilliary Data (first guess):
Surface Wind vector, SST, SSS,
Atmospheric parameters:T(z), …

L2 SST^p
SSS^p

Seawater L-band dielectric constant estimate

Flat sea surafce Brightness Temperatures
T_{Flat} (h,v,U,V)

L2 U^p_{10},Φ^p_w

Add Surface Roughness Effects

Sea-Surface Total Brightness Temperatures
T_{Surf} (h,v,U,V)

ECMWF P_{surf}, Tair, CWV

Add atmospheric contributions
(O_2, cloud and H_2O Absorption)

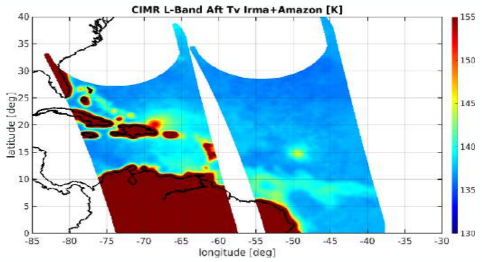
Sum of the Forward model solutions
Four Stokes L-band parameters aft and fore views

Top of the Atmosphere RTM
(surface pol basis)

Maximum Likelihood Inversion Method

L2 SSS
aft and fore views

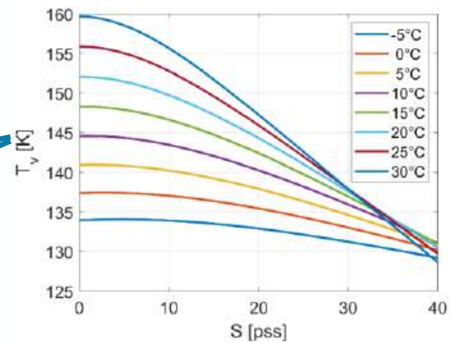
Iterations



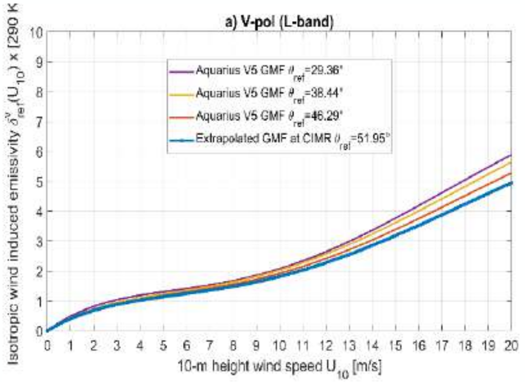
CIMR Level 1C resampled TOA
Four Stokes L-band parameters
aft and fore views
(surface pol basis)

Corrected for solar & Sky radiations
& Faraday rotation & RFI filtered

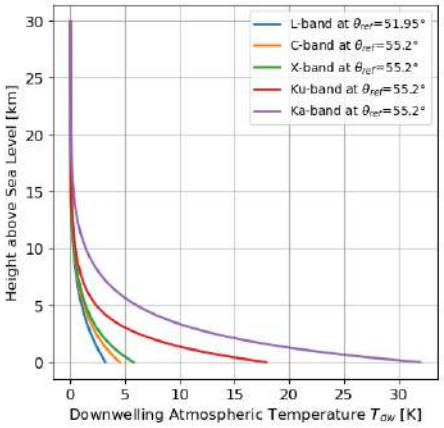
Sea water dielectric cst
Zhou et al (2021)



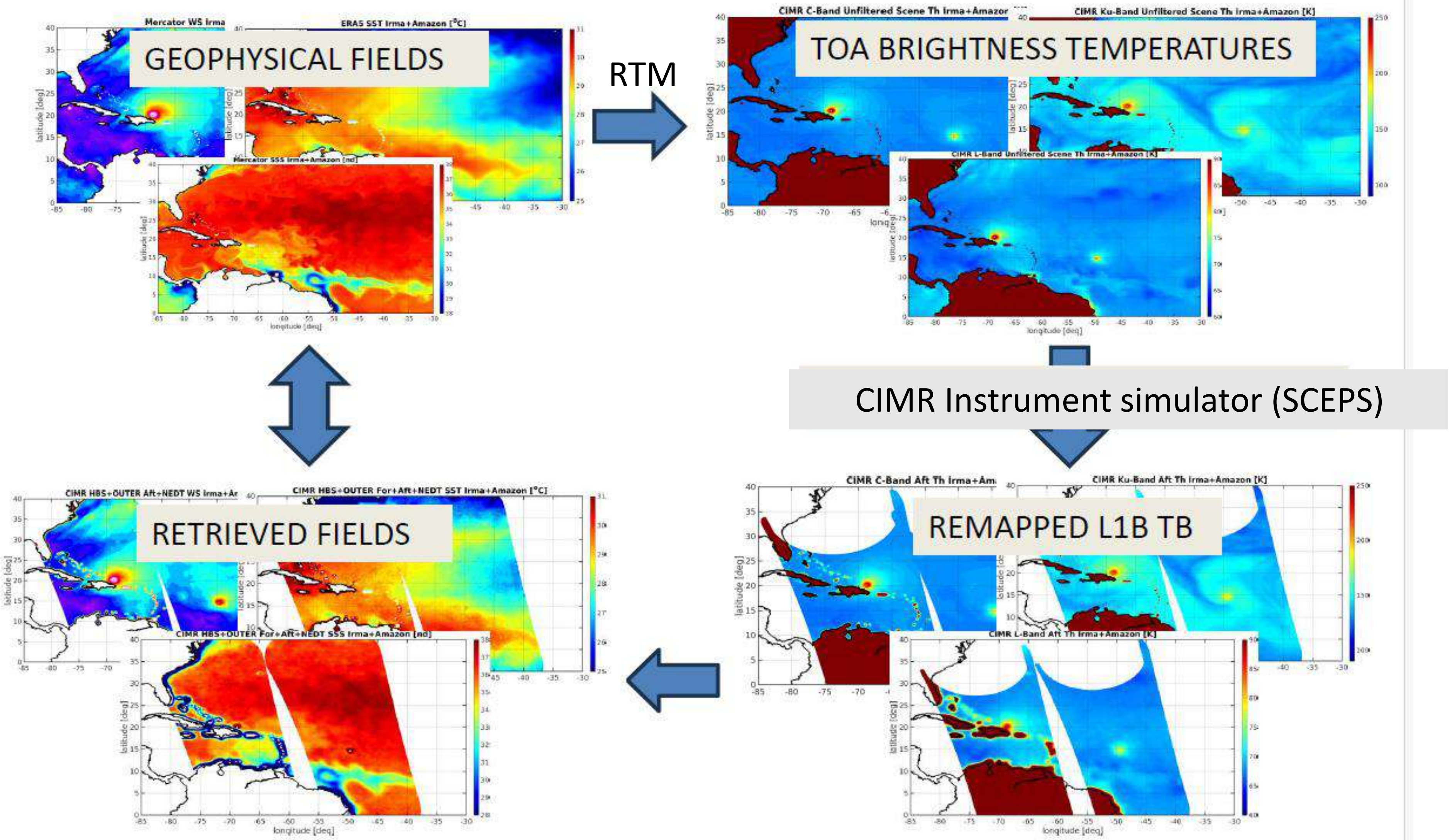
Aquarius's GMF extrapolated at 52°



Atmospheric impacts (Liebe 1993)



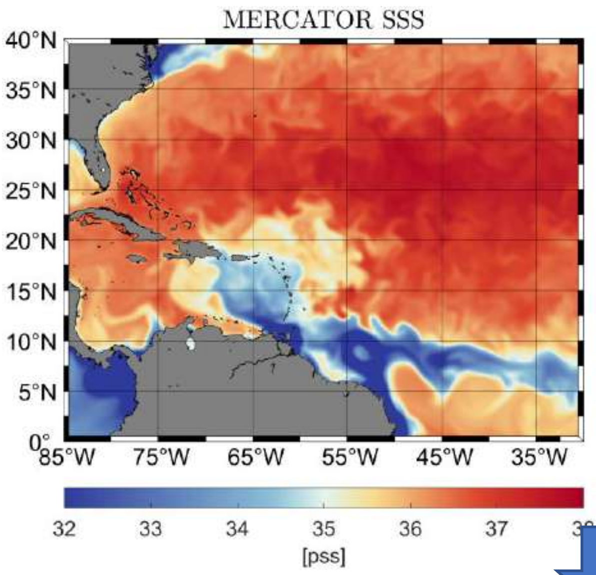
SSS retrieval simulations for CIMR



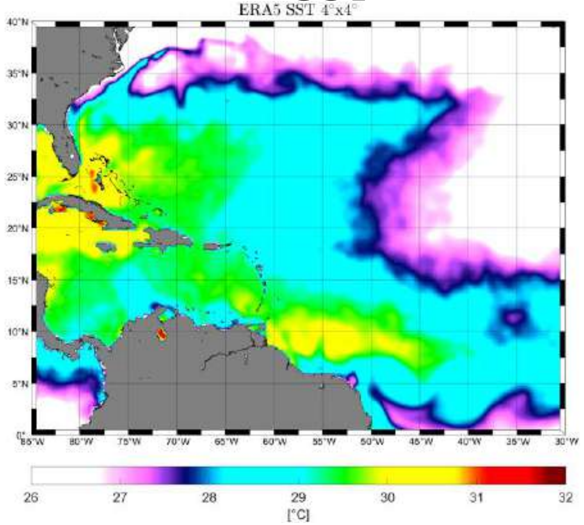
Integrated over
full antenna patterns
+ NEDT
+resampled
Aft & Fore views

SSS Retrieval tests over a large tropical scene:

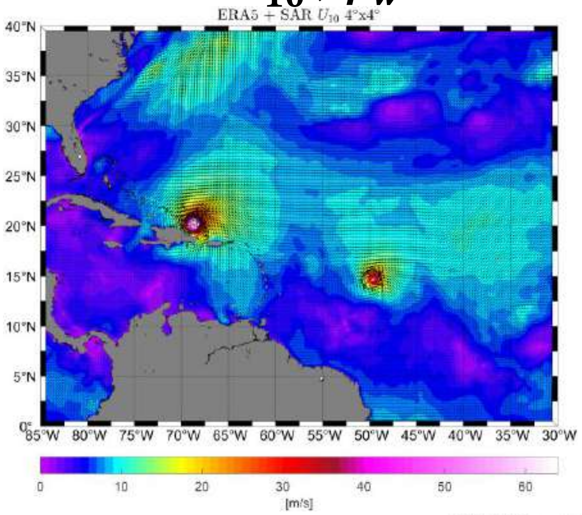
Inputs data$= [\mathrm{T_H^L}; \mathrm{T_V^L}; U^L; V^L; \boldsymbol{U_{10}^{ret}}, \boldsymbol{SST^{ret}}, \boldsymbol{\phi_w^{ret}}]$



$\boldsymbol{SST^{ret}}$

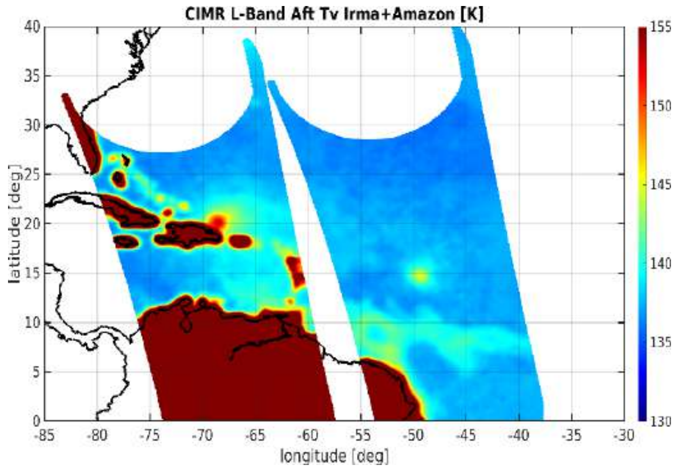


$\boldsymbol{U_{10}^{ret}}, \boldsymbol{\phi_w^{ret}}$

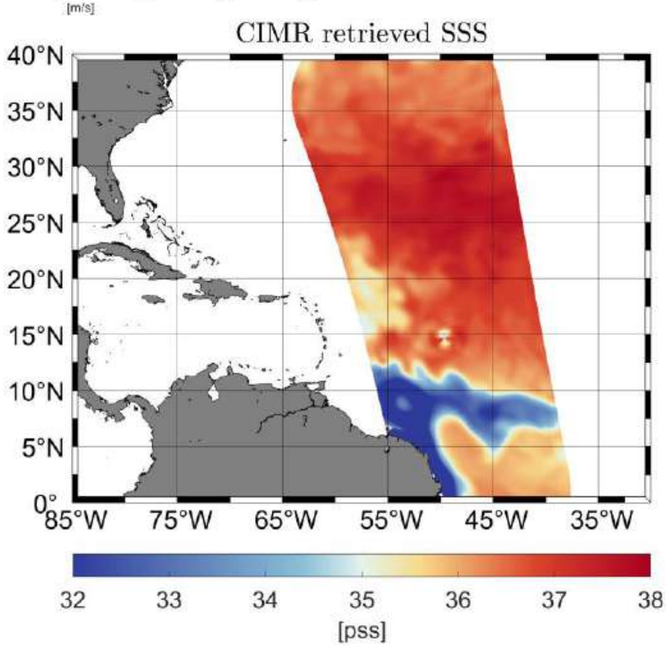


1 km resolution

Simulated CIMR L-band TOA Tbs

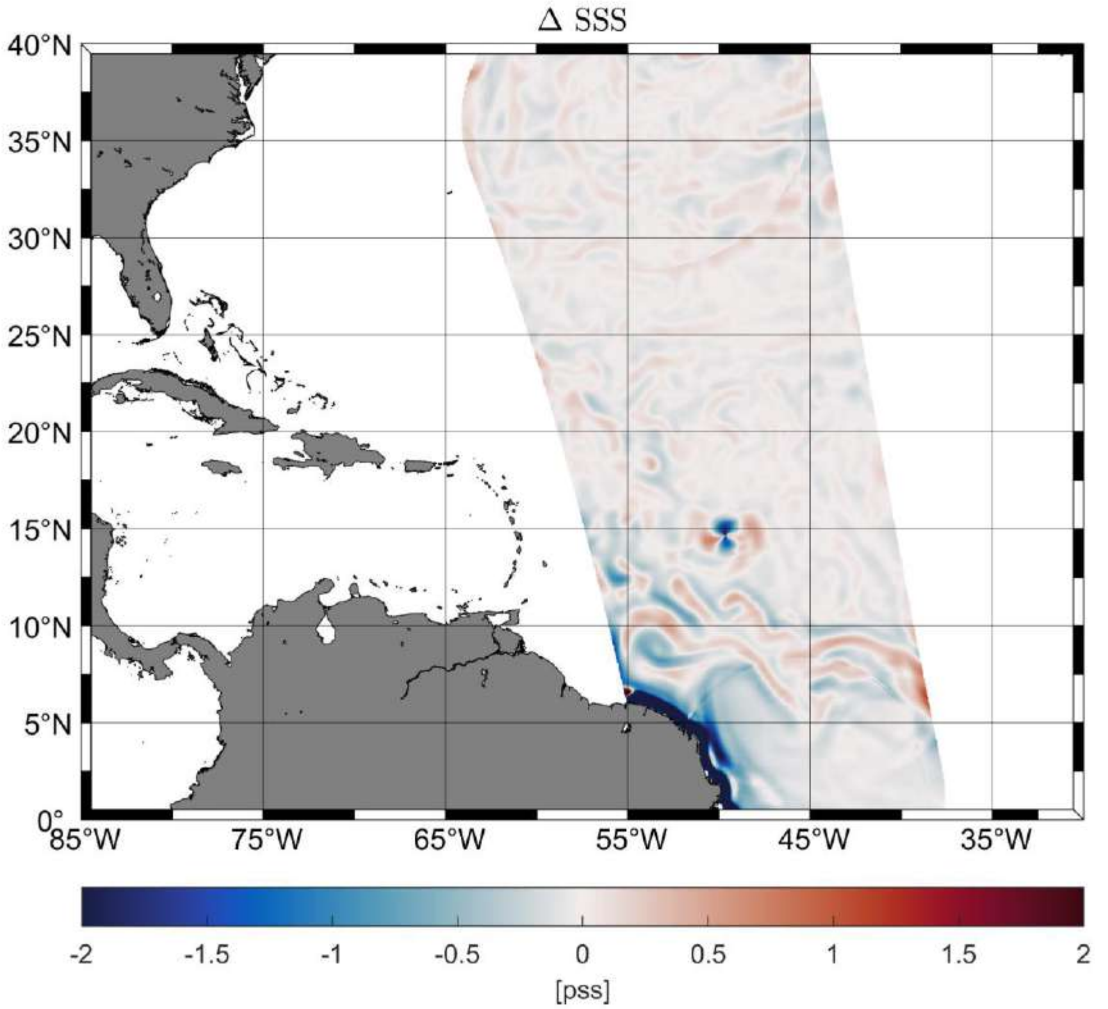


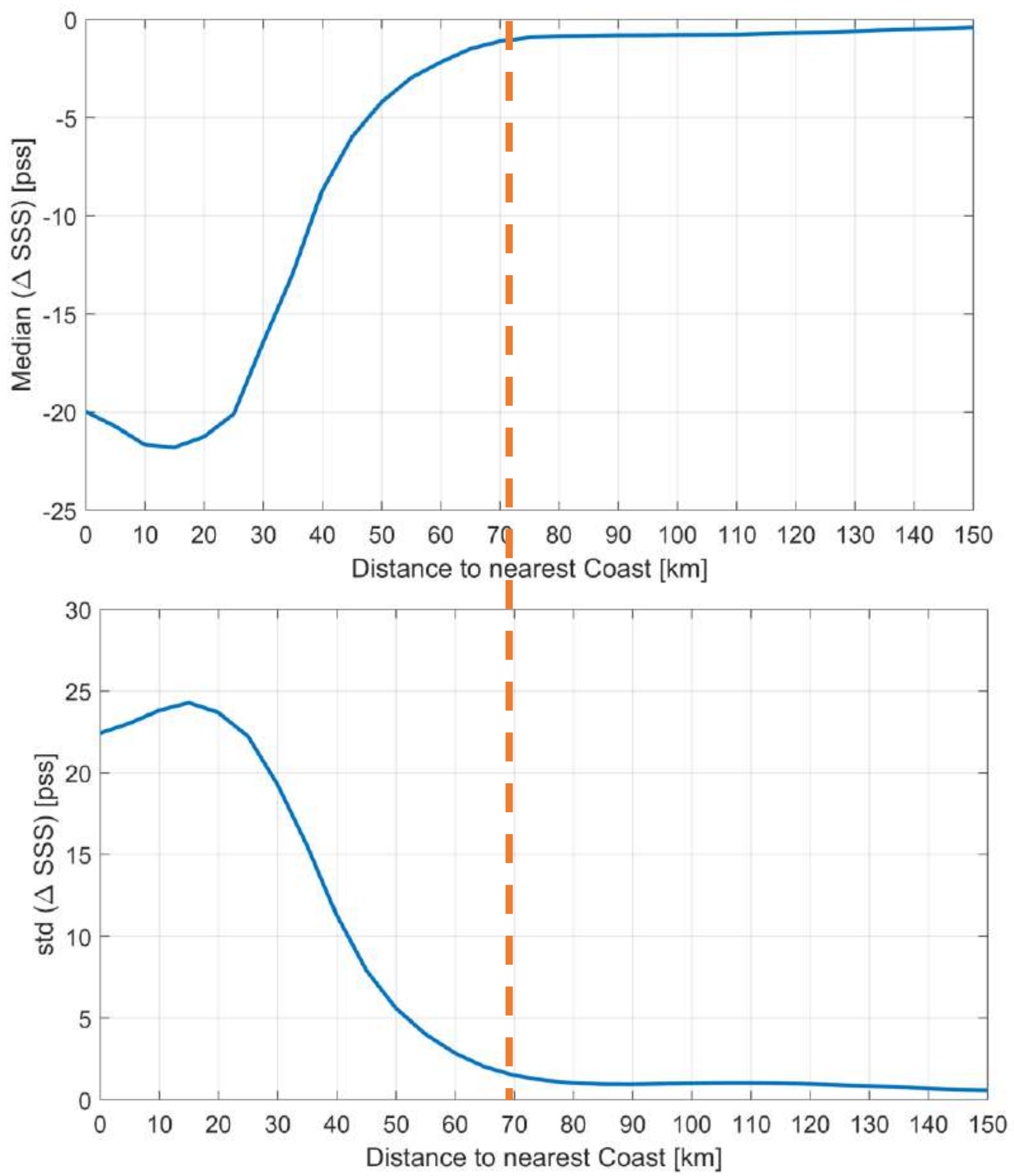
Retrieval Algorithm



~60km resolution

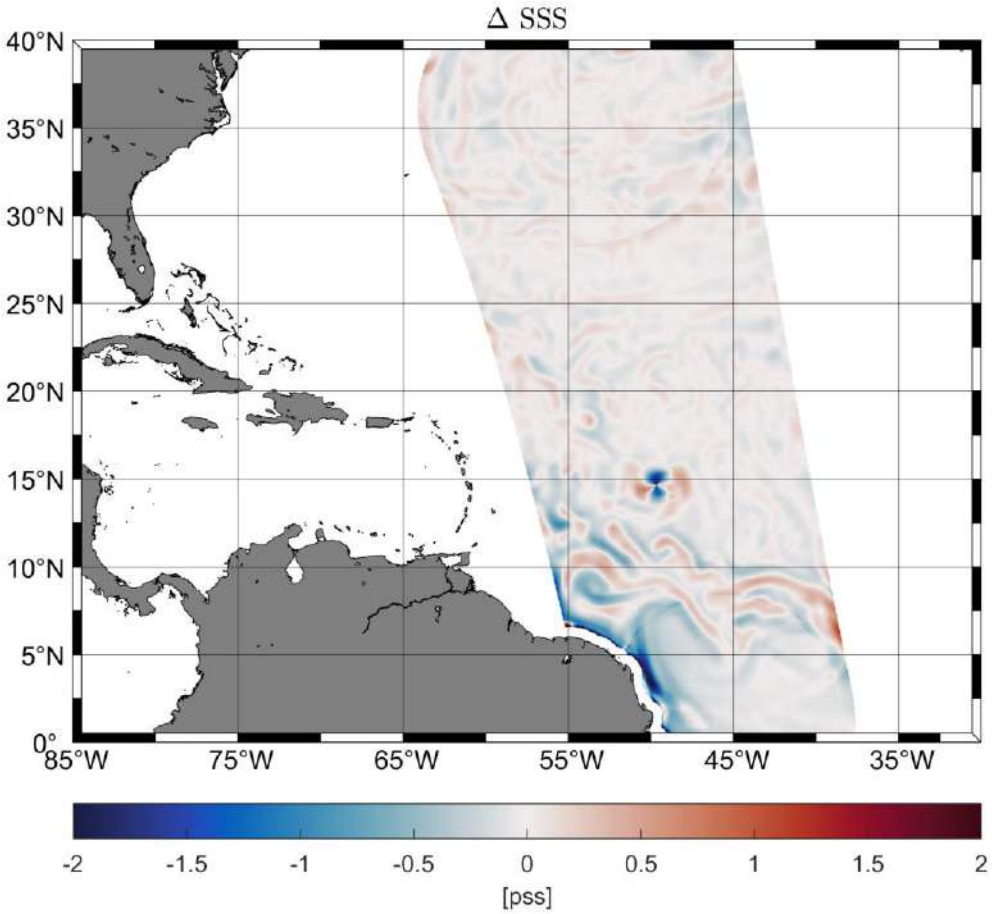
SSS Retrieval: land Contamination

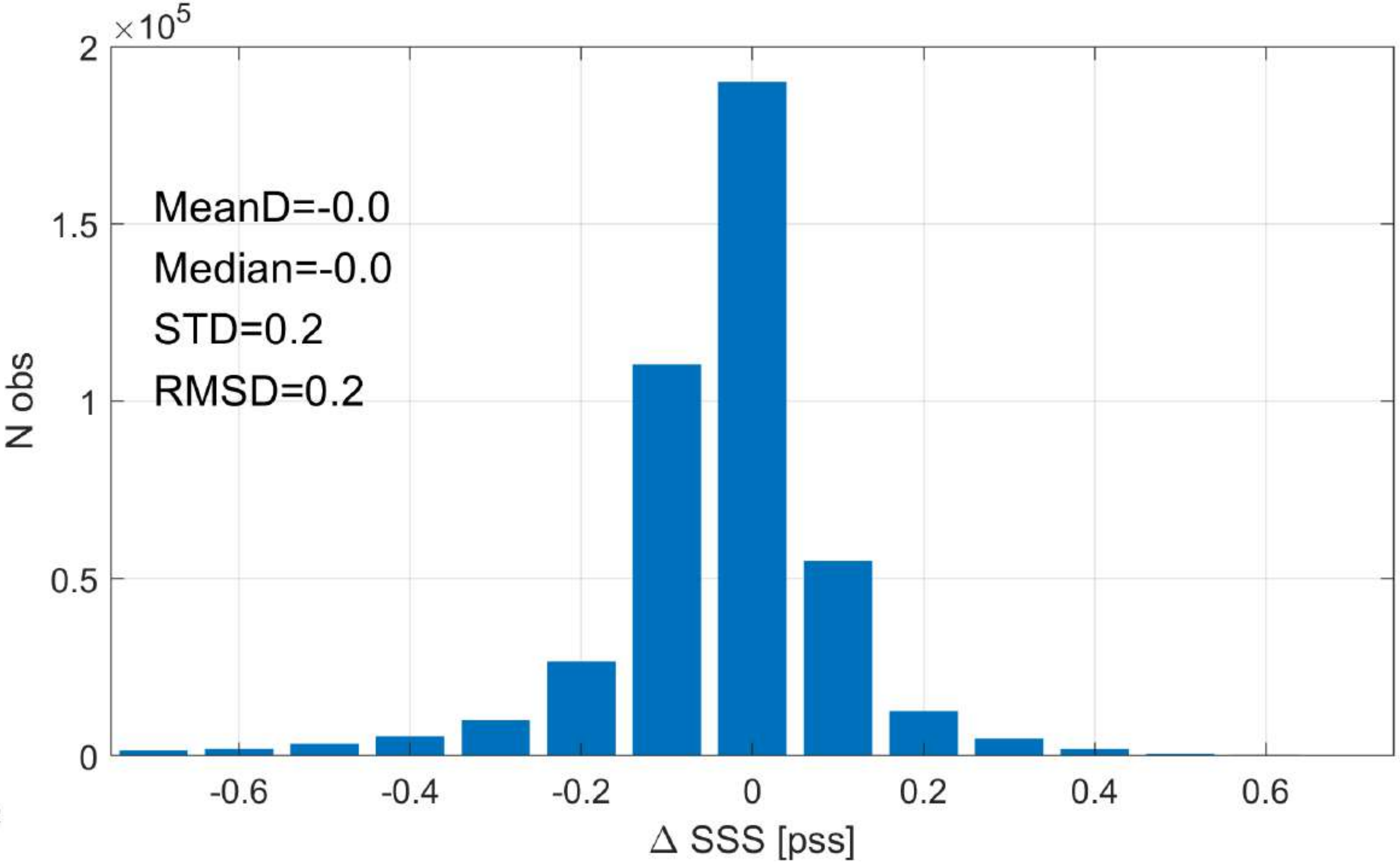




Significant Land contamination observed within ~70 km from coasts => impact of land Tbs in sidelobes & main lobe

Step 6 :SSS Retrieval: after land Contamination Filtering (distance to coasts > 70 km)





High resolution features (North Brazilian current induced SSS fronts and TC center) not well resolved by the ~60 km resolution L-band footprint

Major souces of SSS retrieval errors in cold waters

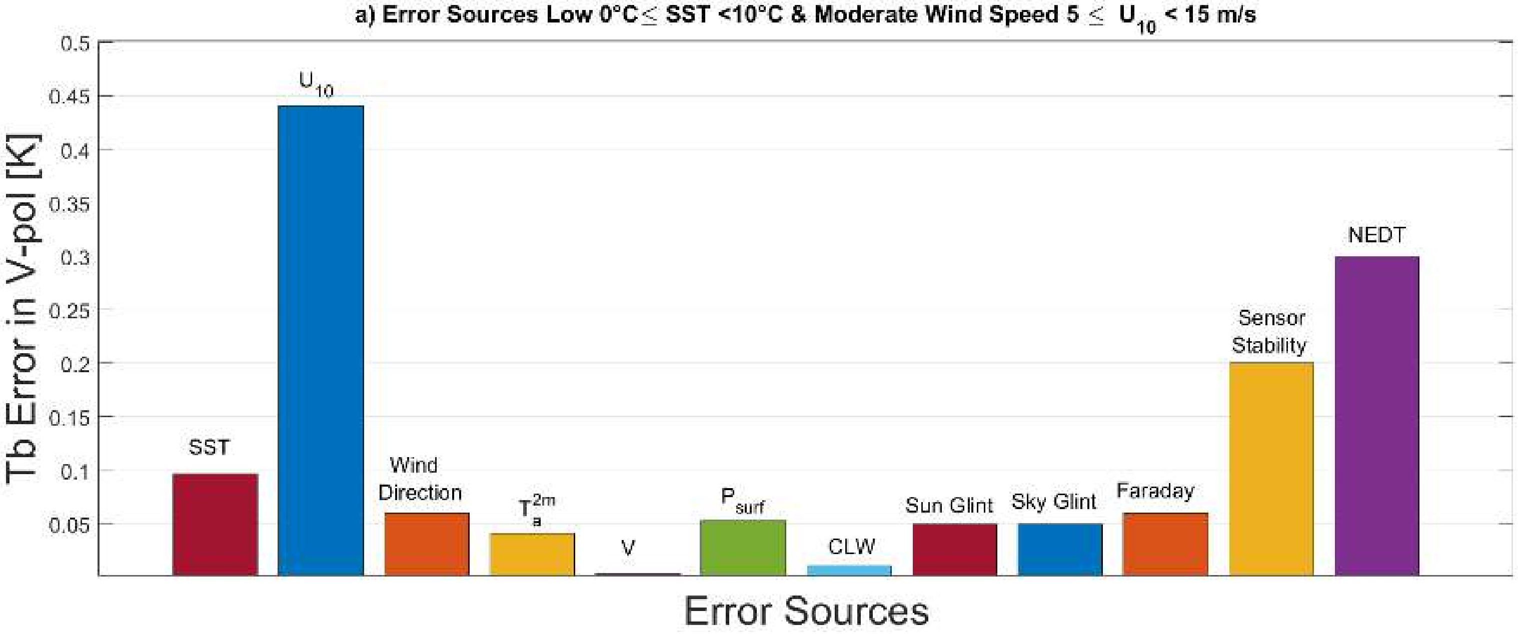


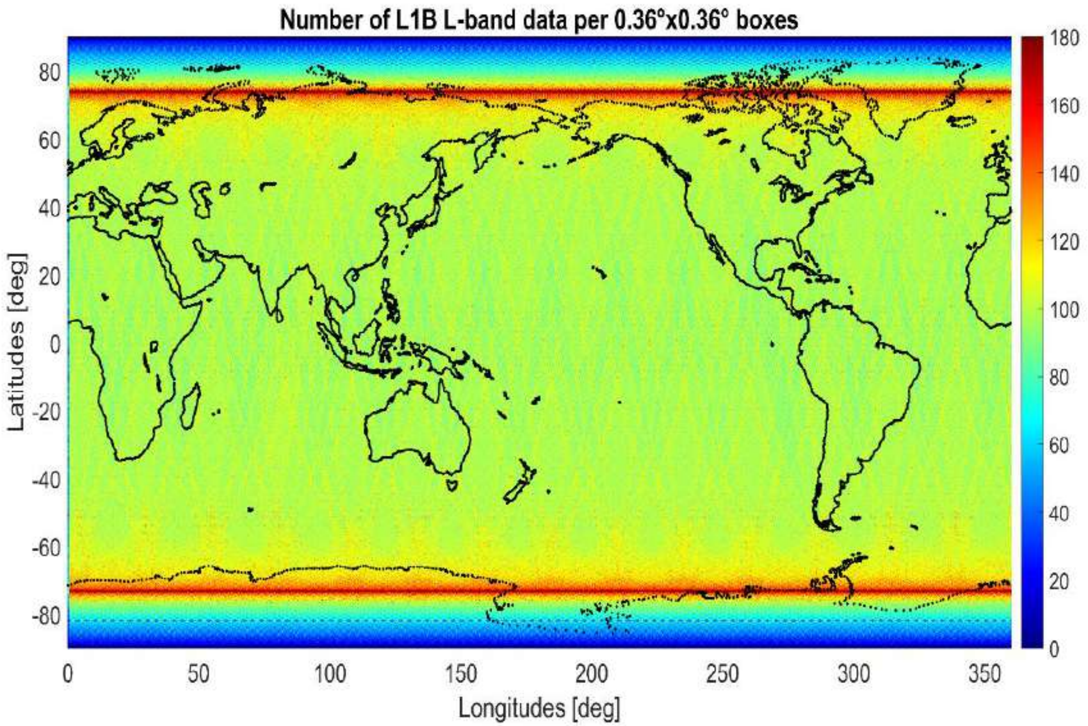
Figure 34: *Distribution of uncertainties in the modeling of the V-polarization L-band Tbs at incidence angle of 52° in a) cold sea condition and b) warm sea conditions. The wind speed is moderate with 5 m/s* $\leq U_{10} < 15$ *m/s.*

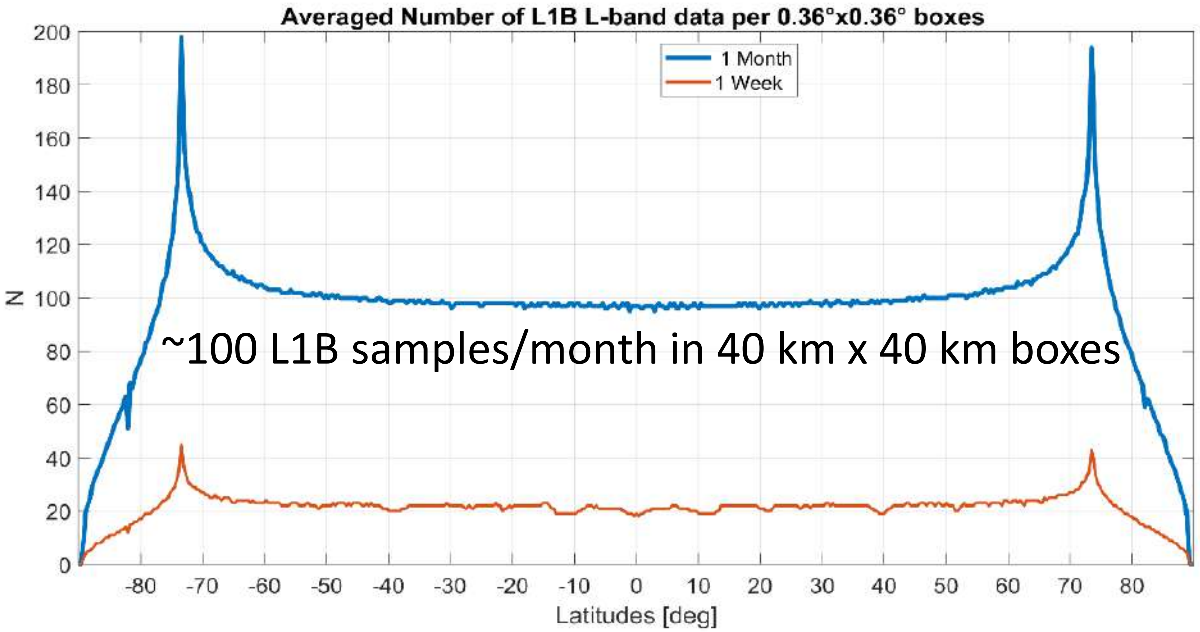
In reality, uncertainties on auxilliary data and corrections will be source of retrieved SSS errors

In V-polarization, the **expected accuracy of instantaneous retrievals ranges from ~0.9 pss to ~3.5 pss** depending on wind speed and SST conditions.

Far away from coasts & ice-edges, dominant sources of errors are uncertainties in **wind speed, NEDT and sensor stability**

Monthly Number of L1B data in 40 km^2 boxes





The number of independent L1B samples required to reduce the error to 0.3 pss after temporal averaging has been evaluated

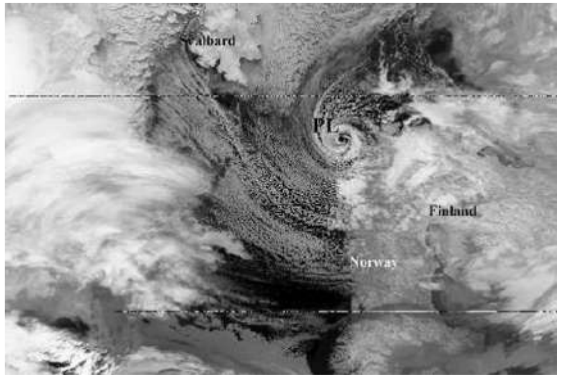
⇒ It is about 50 for very cold waters (with V-polarization data) and

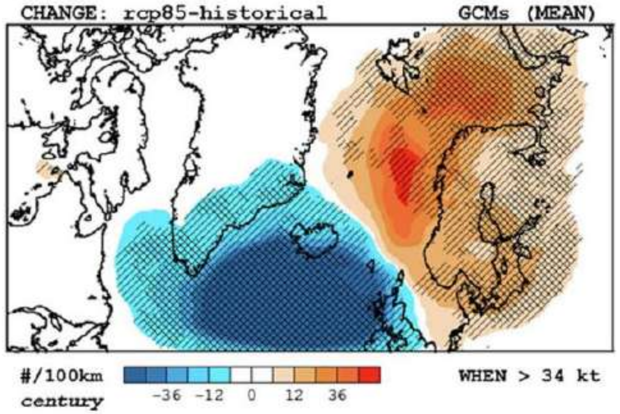
⇒ diminishes to ~5 passes for Tropical regions.

One month sampling with the CIMR polar-orbiting L-band instrument results in about 100 passes.

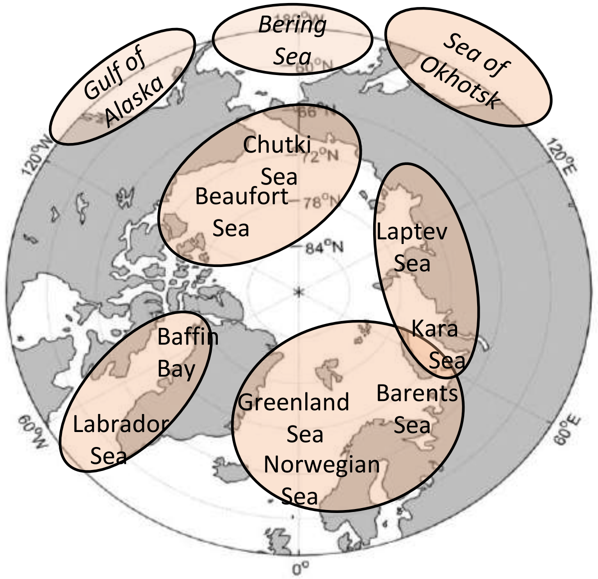
This suggests that a monthly averaged SSS of 0.3 pss is clearly achievable at distances > 70 km from coasts and ice edges

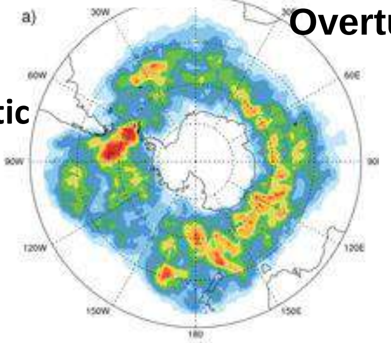
Why measuring surface winds at high latitudes is important: The Polar lows' threat





Change in PL track density between the historical and the future periods. The PL track density is the number of storms per century within a radius of 100km. From Romero and Emanuel (2017)





Areas of occurrence of polar lows in the Arctic & Antarctic

- **Polar Lows (PL)** are **short-living intense meso-scale maritime atmospheric low pressure weather systems**
- exhibit **short lifetime**: (average 15÷20 hours) & **small size**: 100÷1000 км
- => these events are therefore **very difficult to detect**
- **High surface wind speed**: > 15 m/s (some time > 30 m/s) associated with **heavy snowfalls**
- **Typically marine phenomenon**: polar lows rapidly break down over land and ice cover
- one of the **most frequent reason of ship icing**
- Polar lows represent **threat to** coastal communities and to such businesses as **oil and gas exploitation, fisheries and shipping**
- **With global warming (sea ice extent decrease)** the **regions of PL activity will shift northwards, frequency of PLs will decrease (**Romero and Emanuel, 2017) **and this might weaken the Atlantic Meridional Overturning Circulation (AMOC).**

Polar lows are highly complicated phenomena: their study, timely detection, tracking and forecasting is still a challenge for Earth sciences !
=> Polar lows often occur in sparsely populated regions, but they have led to deaths. Therefore, **we must improve our ability to monitor these abrupt and intense storms.**

CIMR requirements on Ocean Wind Vector retrievals

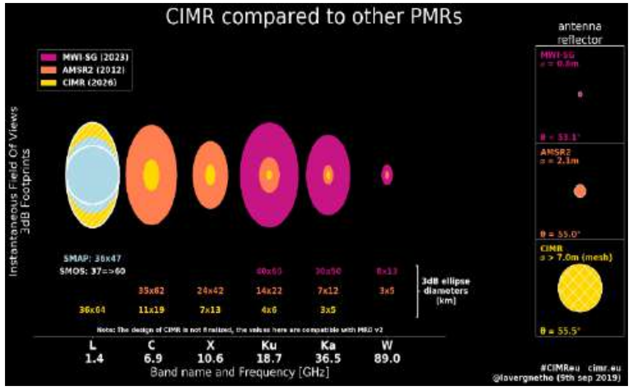
MRD-990

CIMR shall generate daily L2 products of wind speed and direction over 95% global ocean at a resolution of ~40 km and a standard total uncertainty of ≤2 ms^{-1} and 20° in direction at wind speeds >6 ms-1.

CIMR Instrument as Compared to the Characteristics of Current radiometer Instruments With ... nas

Instrument	Frequency(GHz)	Spatial resolution [km x km] (3-dB footprint size)	Earth Incidence angle (∘)	NeΔT*(K)	Polarizations	Swath Width (km)
CIMR	1.4 (L-band)	36 x 64	52	0.3	H, V, 3rd & 4th Stokes	
	6.9 (C-band)	11 x 19	55	0.2	H, V, 3rd & 4th Stokes	>1900 km
	10.65 (X-band)	7 x 13	55	0.3	H, V, 3rd & 4th Stokes	
	18.7 (K-band)	4 x 6	55	0.3	H, V, 3rd & 4th Stokes	
	36.5 (Ka-band)	3 x 5	55	0.7	H, V, 3rd & 4th Stokes	
SMAP	1.4 (L-band)	39 x 47 km	40	0.9	H, V, 3rd & 4th Stokes	~1000 km
AMSR-2	6.9 (C-band)	35 x 62	55	0.3	V,H	
	7.3 (C-band)	35 x 62	55	0.3	V,H	
	10.65 (X-band)	24 x 42	55	0.6	V,H	
	18.7 (K-band)	14 x 22	55	0.6	V,H	
	23.8 (K-band)	11 x 19	55	0.6	V,H	~1450km.
	36.5 (Ka-band)	7 x 12	55	0.6	V,H	
	89.0 (W-band)	3 x 5	55	1.1	V,H	
WindSat	6.8 (C-band)	39 x 71	53.8	0.48	V,H	
	10.7 (X-band)	25 x 38	50.1	0.37	V,H,P,M,L,R	
	18.7 (Ku-band)	16 x 27	55.6	0.39	V,H,P,M,L,R	~950 km
	23.8 (K-band)	20 x 30	53.2	0.55	V,H	
	37 (Ka-band)	8 x 13	53.2	0.45	V,H,P,M,L,R	
SSM/I	19.35 (Ku-band)	43 x 69	50.3	0.42	V,H	
	23.235 (K-band)	40 x 50	50.3	0.74	V	
	37.0 (Ka-band)	28 x 37	50.3	0.38	V,H	~1400km
	85.5 (W-band)	15 x 13	50.3	0.69	V,H	

L+C+X
Simultaneously for the first time



C- and X-band
At unprecedented
spatial resolution

L, C and X
All fully polarimetric

Wind Speed dependencies of the surface emission

Physics

Increase of the microwave ocean emissivity with wind speed U_{10} at frequency f and incidence angle θ

⇔ surface wave & foam change impacts on all Stokes parameters as wind speed increase

⇔ Can be decomposed into azimuthal harmonics of ϕ_s, the relative azimuthal direction between the wind direction and the radiometer look direction

$$\begin{pmatrix} E_{h,f}^{surf} \\ E_{v,f}^{surf} \\ E_{U,f}^{surf} \\ E_{V,f}^{surf} \end{pmatrix} = \begin{pmatrix} e_{sh,f}^{(0)} + \boldsymbol{\Delta e_{h,f}^{(0)}}(\boldsymbol{U_{10}}) + \boldsymbol{\Delta e_{h,f}^{(1)}}(\boldsymbol{U_{10}})\cos\phi_s + \boldsymbol{\Delta e_{h,f}^{(2)}}(\boldsymbol{U_{10}})\cos 2\phi_s \\ e_{sv,f}^{(0)} + \boldsymbol{\Delta e_{v,f}^{(0)}}(\boldsymbol{U_{10}}) + \boldsymbol{\Delta e_{v,f}^{(1)}}(U_{10})\cos\phi_s + \boldsymbol{\Delta e_{v,f}^{(2)}}(\boldsymbol{U_{10}})\cos 2\phi_s \\ \boldsymbol{\Delta U_f^{(1)}}(\boldsymbol{U_{10}})\sin\phi_s + \boldsymbol{\Delta U_f^{(2)}}(\boldsymbol{U_{10}})\sin 2\phi_s \\ \boldsymbol{\Delta V_f^{(1)}}(\boldsymbol{U_{10}})\cos\phi_s + \boldsymbol{\Delta V_f^{(2)}}(\boldsymbol{U_{10}})\sin 2\phi_s \end{pmatrix}$$

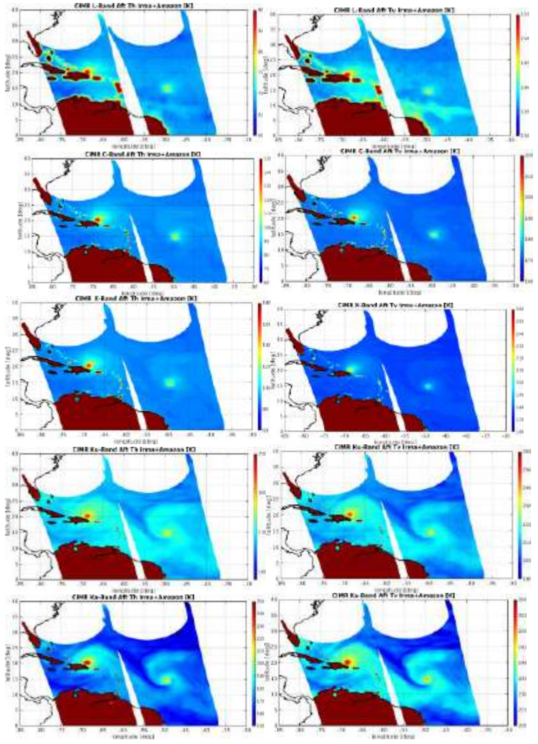
$e_{p,f}^{(0)}(SSS, SST, \theta)$:**Perfectly flat ocean surface emission** (dependent on SST, SSS, incidence angle θ and EM frequency *f*)

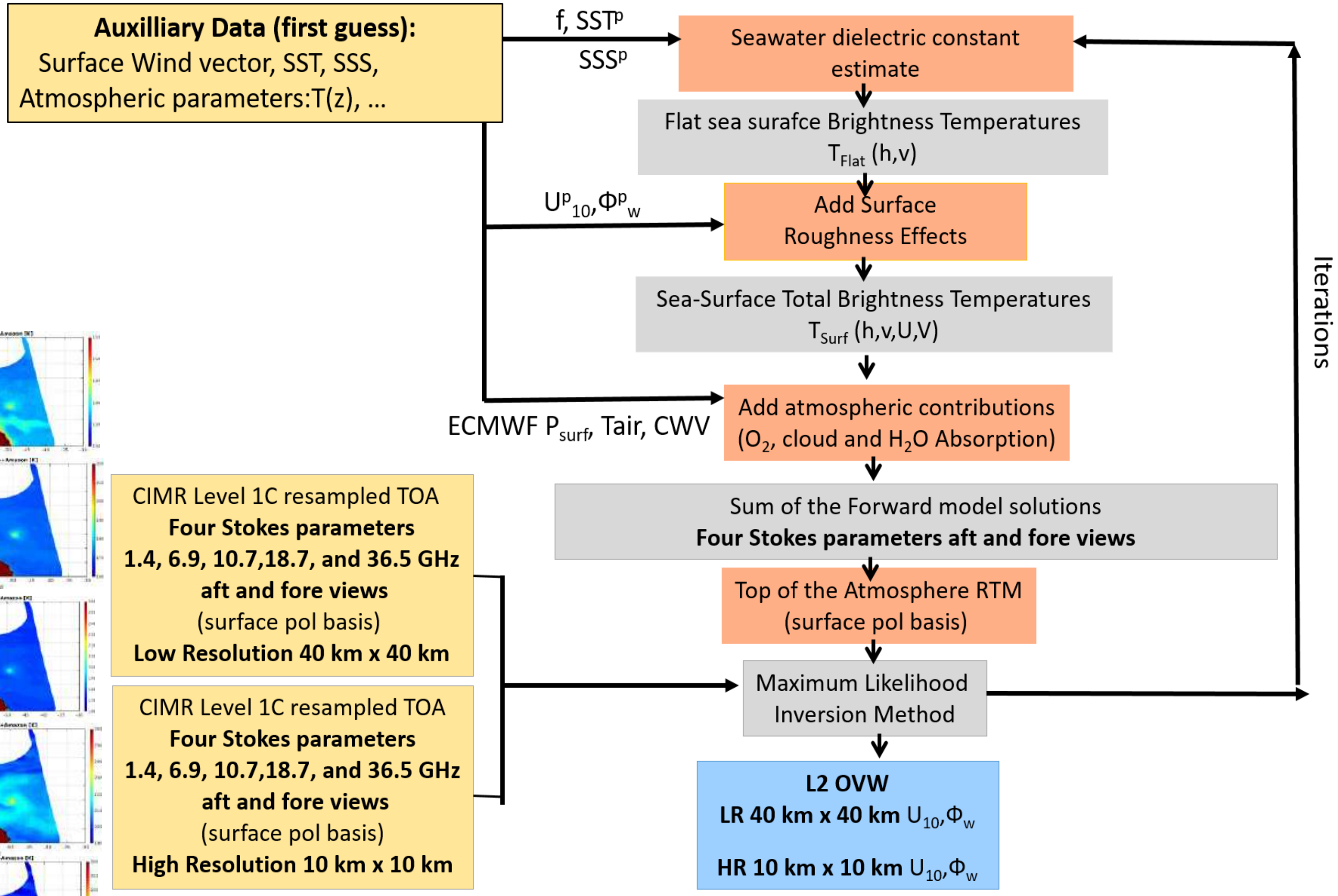
$\Delta e_{p,f}^{(0)}(U_{10}, \theta)$: **isotropic wind-induced emissivity** at 10m-height surface wind speed U_{10}, polarization p=h,v, frequency *f*, EIA=θ

$\Delta e_{p,f}^{(1)}(U_{10}, \theta)$: **anisotropic upwind/downwind asymmetry** in emissivity at 10m-height surface wind speed U_{10}, polarization p and *f*

$\Delta e_{p,f}^{(2)}(U_{10}, \theta)$: **anisotropic upwind/crosswind asymmetry** in emissivity at 10m-height surface wind speed U_{10}, polarization p and *f*

Ocean Wind Vector retrieval algorithm for CIMR



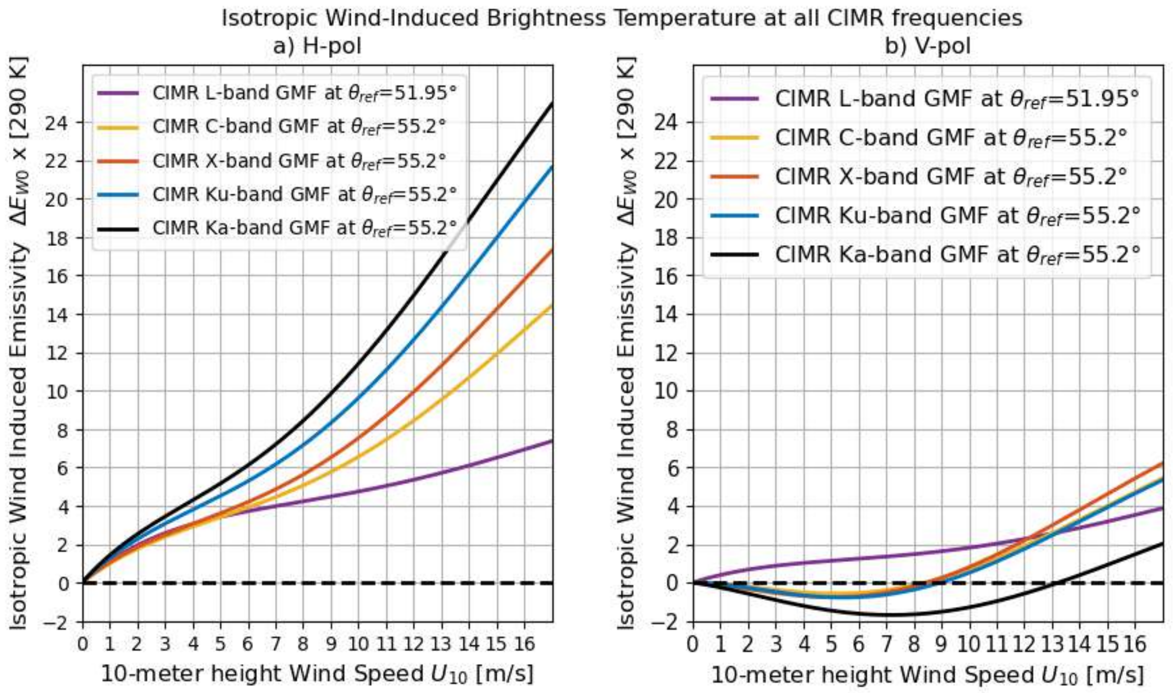


Wind Speed dependencies of the surface emission

Physics

Increase of the microwave ocean emissivity with wind speed U_{10} at frequency f and incidence angle θ
⇔ surface wave & foam change impacts as wind speed increase

- **Wind response = Isotropic Wind induced (excess) emissivity** $\Delta T_B = T_{B\ rough} - T_{B\ flat}$
- GMF from AMSR-E, WindSat & SSM/I, AMSR-2, SMOS, Aquarius and SMAP (Meissner and Wentz, 2012; Meissner *et al.* [2018])
- **H-pol much more sensitive to U_{10} than V-pol** (factor ~3)
- The higher the frequency, the more sensitive to U_{10}
- **Above 10 m/s: mainly sea foam impact**
- **Mostly linear at high winds, no reduced sensitivity.**
- Isotropic emission models $\Delta T_{o,p}(U_{10}, \theta)$ are rather consistent between various Algorithms
- Remaining differences in the low & high wind regimes



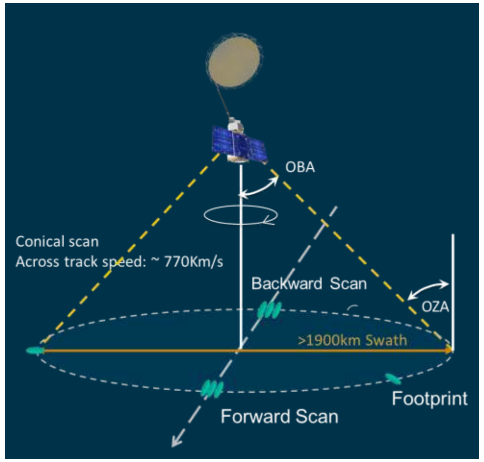
Wind direction dependencies of the surface emission

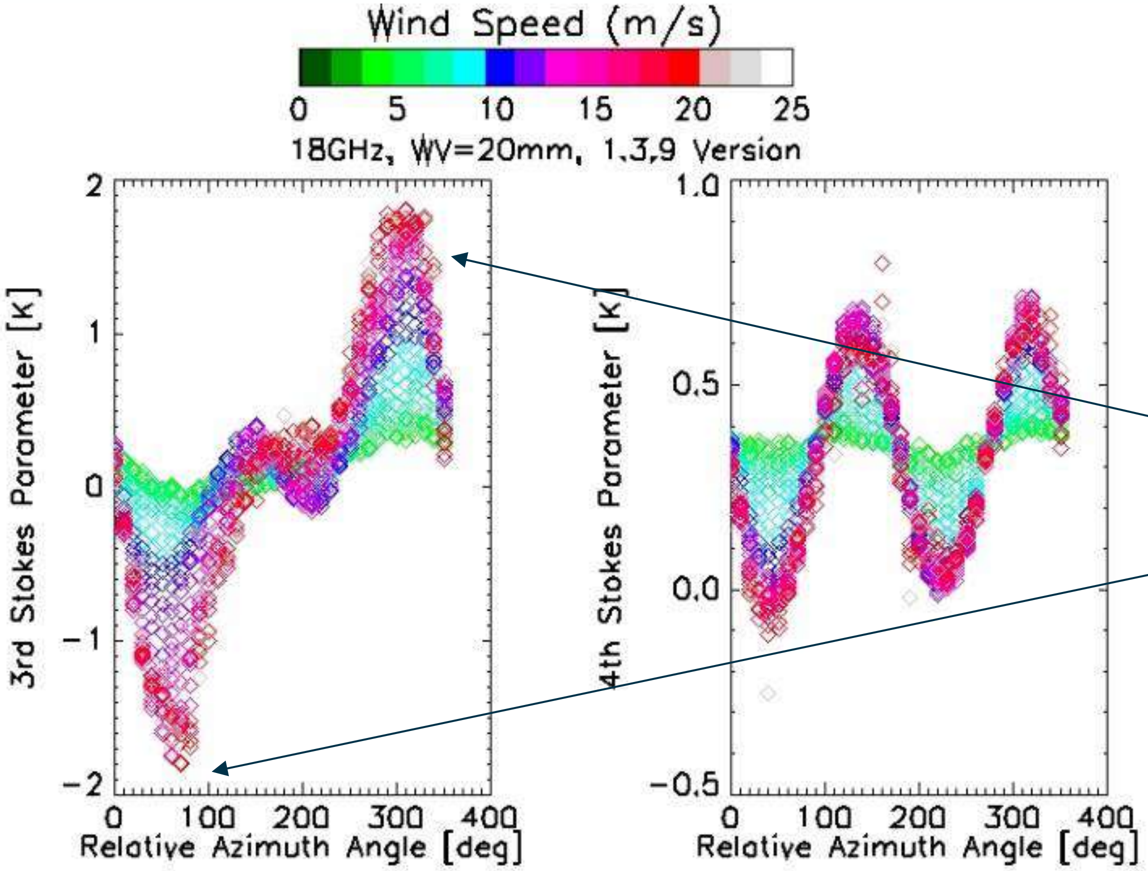
Wind direction dependencies are in all 4 Stokes parameter but 3rd and 4th Stokes at C, X, Ku, Ka are very weakly affected by atmosphere compared to H and V

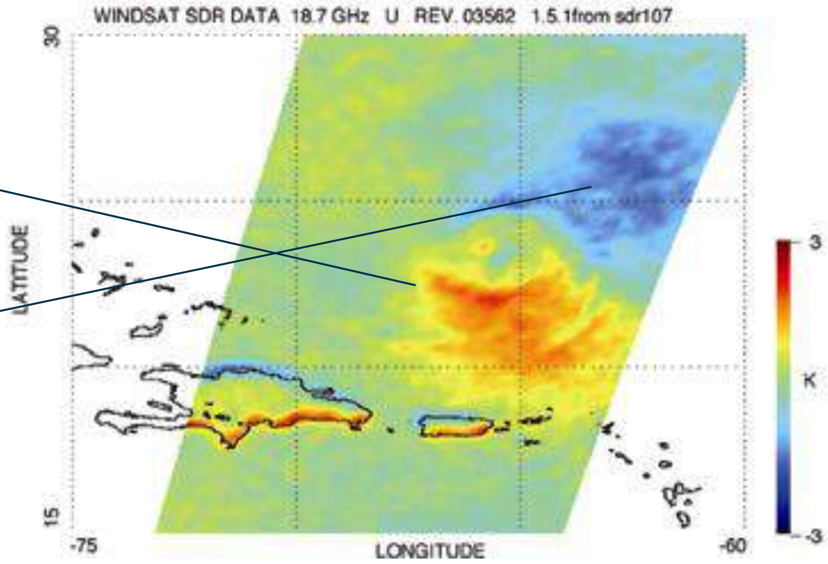
$\Rightarrow$ Are used for wind direction retrieval in WindSat & SMAP

Aft and Fore views can be used to remove directional ambiguities

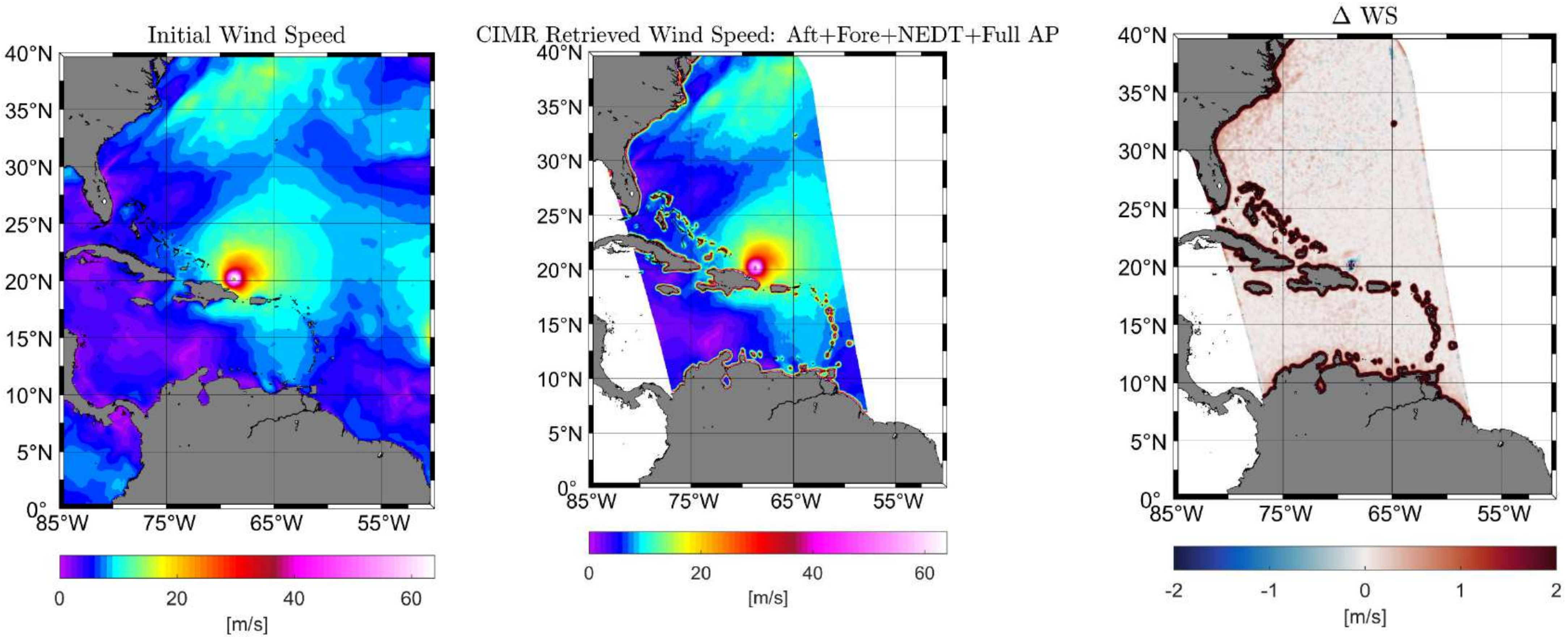
$\Rightarrow$ will Follow the same approach in CIMR





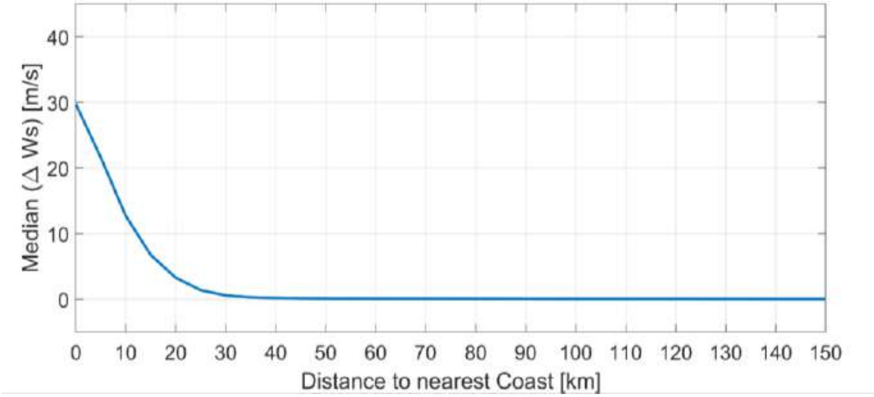


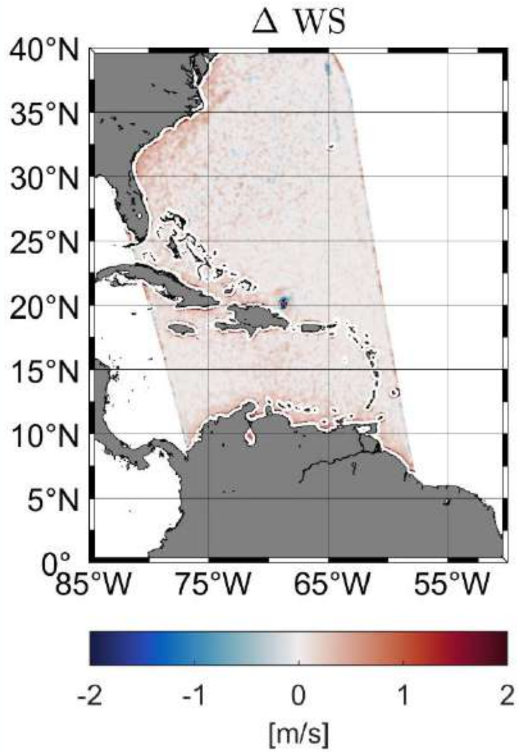
Wind vector retrieval simulations

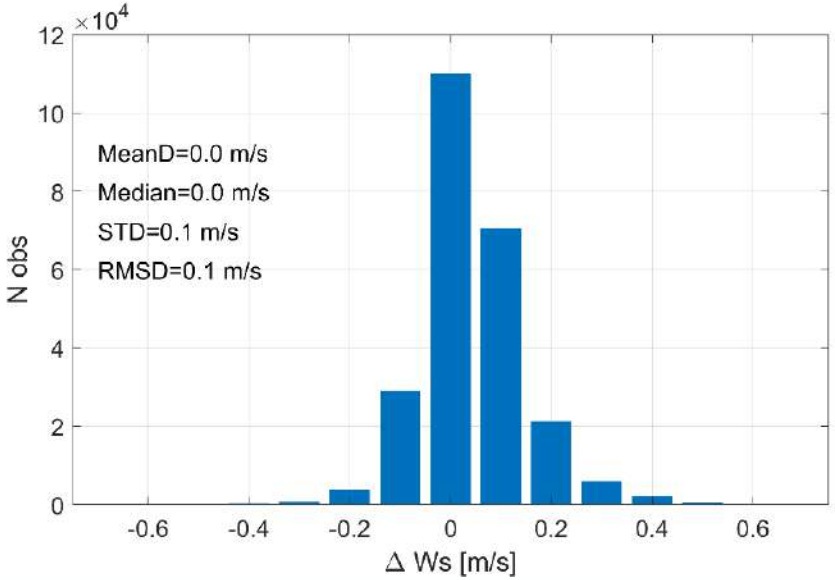


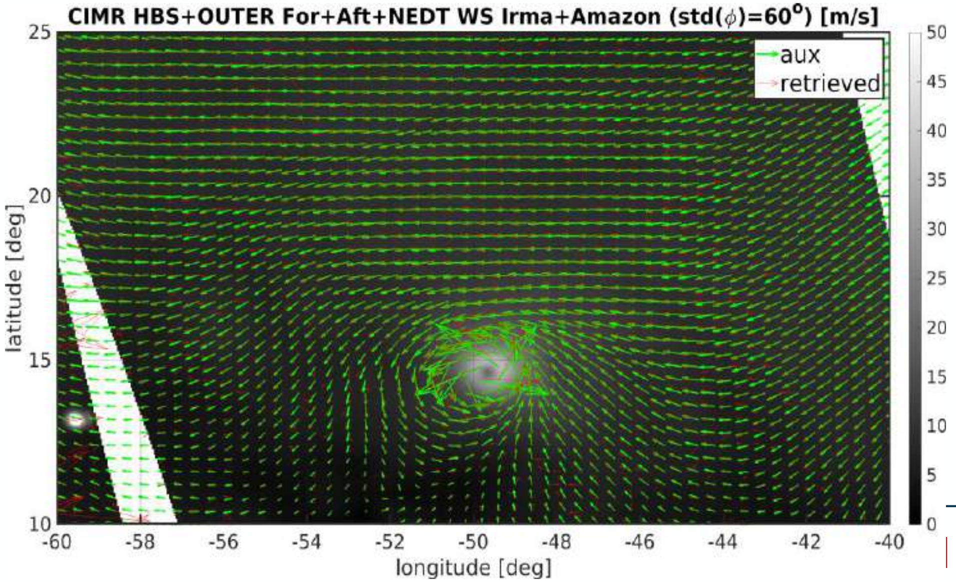
Wind vector retrieval simulations

Land contamination for distance to coast < 30 km









Wind direction retrieval errors~20°

Conclusions:

CIMR will

- provide continuity of L-band passive measurements of the ocean surface
- Improved SSS retrievals in weaker sensitivity high latitudes thanks to better NEDT, high repetitivity and concomittant measurements of SST, Surface wind vector, SIC, etc..
- 30-40 km resolution global wind vector capability,
- Air-sea interaction studies: first instantaneous & concomittant measurements of spaceborne surface density, wind and ice estimator,
- Will have limitations because of
  - land/ice contamination (~70 km and ~30 km from land/ice borders for sss and wind, respect)

    => Can be mitigated using side-lobe corrections (Olmedo et al 2017; Meissner & Manaster, 2021)
  - sun & sky glint will be an issue at high latitudes in the Northern hemisphere for SSS retrievals,
  - Remaining uncertainties on roughness correction (isotropic behaviour at low to moderate wind, anisotropy at high wind, etc..)
  - Sky & sun glint can be mitigated thanks to aft/fore view differences