Challenges in microwave radiative transfer parameterization of the Earth surface, for both atmosphere and surface characterizations

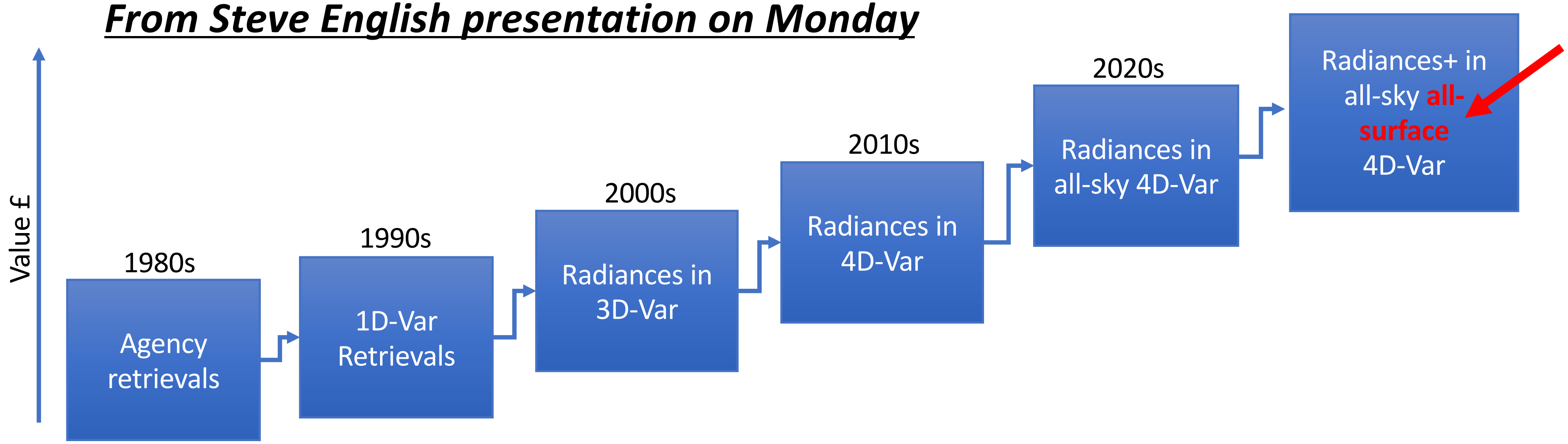
Catherine Prigent
CNRS, Observatoire de Paris, Estellus

With contributions from Filipe Aires, Carlos Jimenez, and many other collaborators




One of the next challenges in NWP: the assimilation of all-surface radiances

<u>From Steve English presentation on Monday</u>

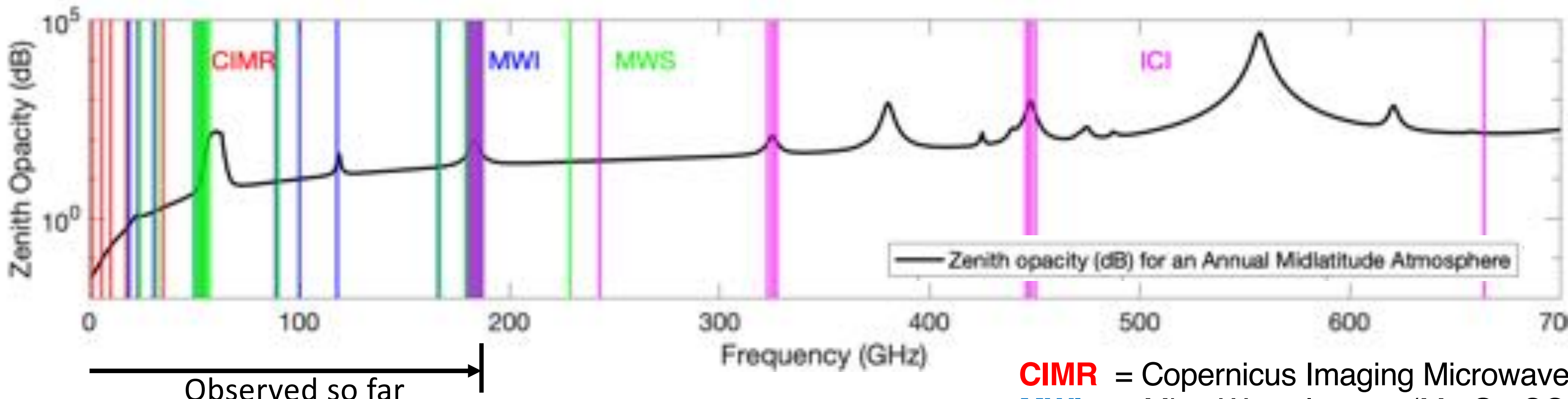


That clearly requires an accurate estimation of the surface contribution

- **for all surface-sensitive observations**
- **for all surfaces**

Beginning of a golden era
for passive microwave Earth observations in Europe

The future European microwave instruments will cover the full microwave spectrum



CIMR = Copernicus Imaging Microwave Radiometer
MWI = MicroWave Imager (MetOp-SG B)
MWS = MicroWave Sounder (MetOp-SG A)
ICI = Ice Cloud Imager (MetOp-SG B)

- Extension of the frequency range up to 664 GHz, with **ICI**
- Simultaneous observations between 1.4 and 36 GHz, with **CIMR**

Outline of this talk

1) General considerations about the microwave surface contribution

2) Ocean

Physicaly-based model, and their fast version

3) Land, snow, ice, sea ice

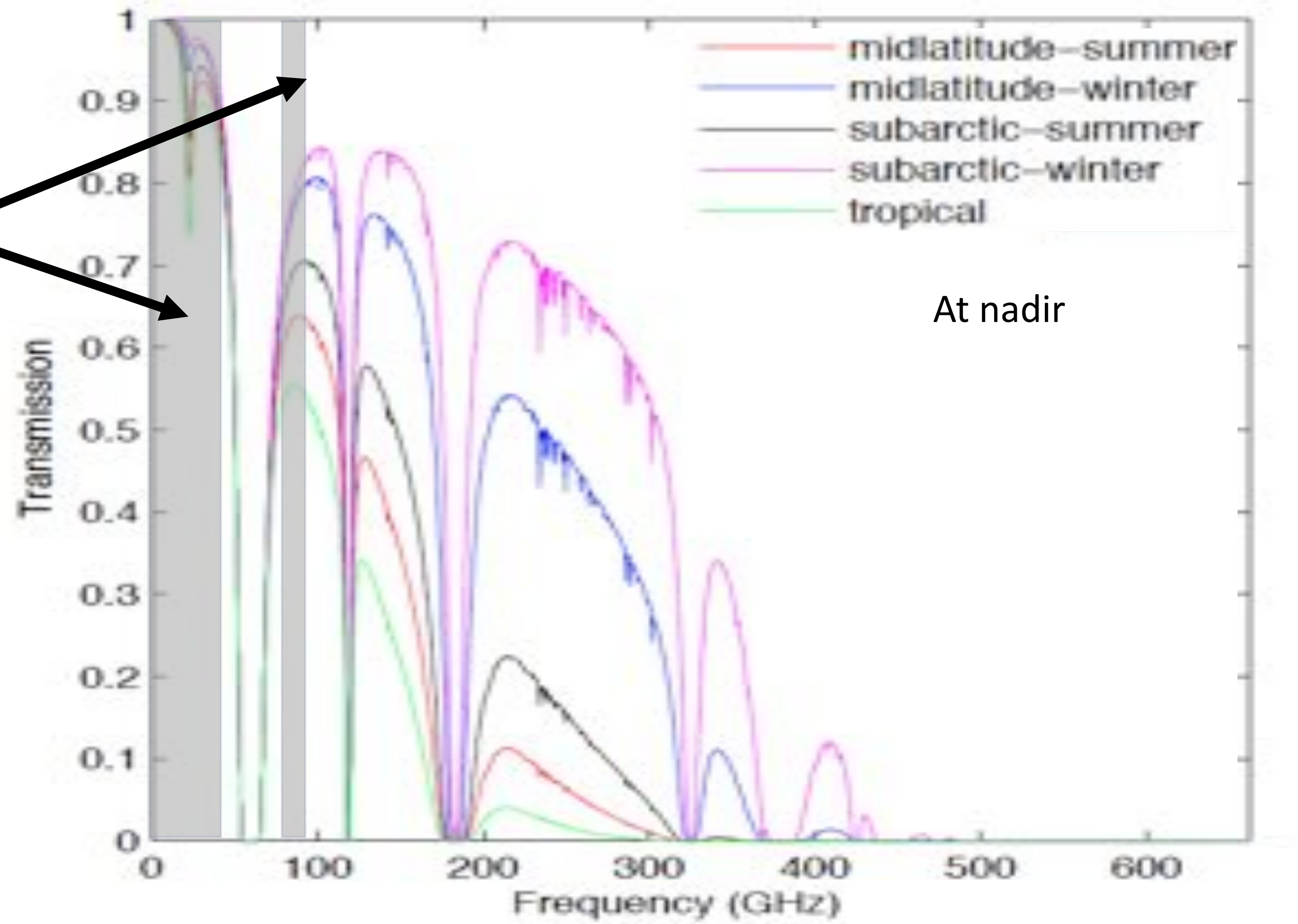
Physicaly-based model or satellite-derived estimation ?

An analysis over sea ice
An analysis over desert
A few words about soil and vegetated surfaces

3) Conclusion

Atmospheric transmission in the microwaves

Atmospheric 'windows' for surface characterization. The surface contribution is the **information.**



At nadir

Atmospheric transmission in the microwaves

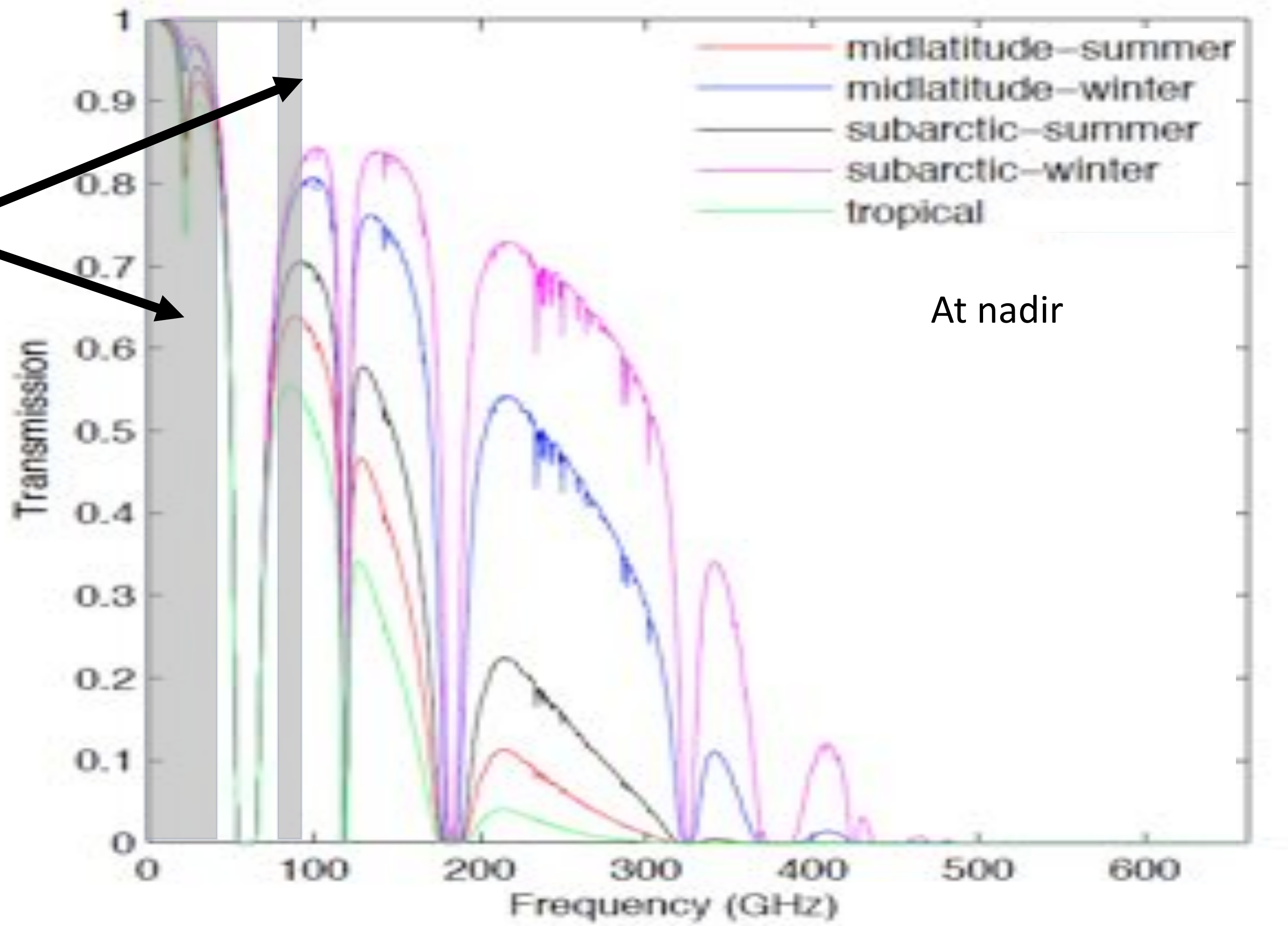
Atmospheric 'windows' for surface characterization. The surface contribution is the **information.**

SMOS, SMAP…

- soil moisture
- sea surface salinity
- vegetation information
- ice thickness…

AMSR, SSMI, GMI…

- sea surface temperature
- ocean wind speed
- sea ice concentration
- snow water equivalent
- land surface temperature
- soil moisture
- vegetation information….



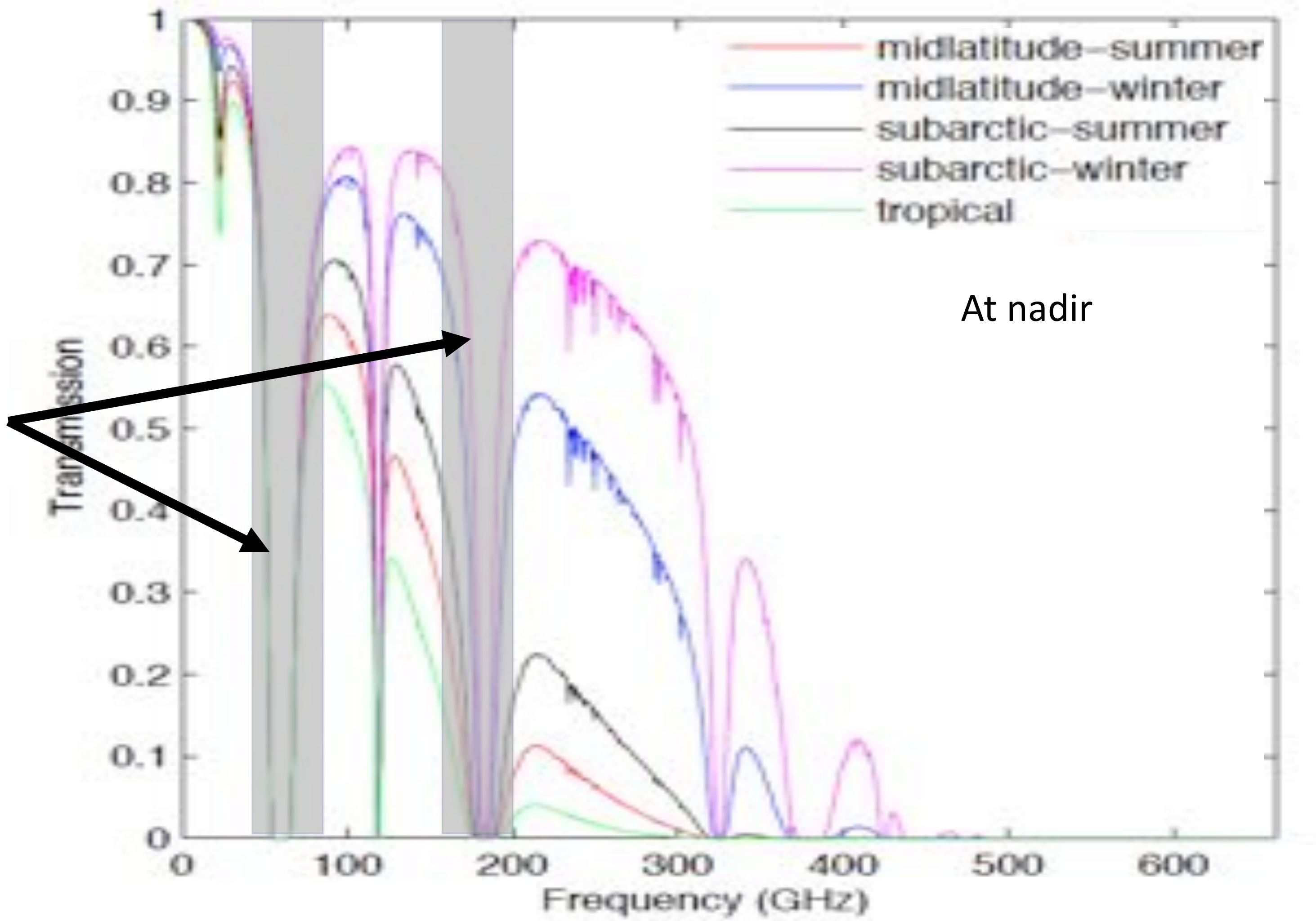
Atmospheric transmission in the microwaves

Atmospheric 'windows' for surface characterization: The surface contribution is the **information**

For atmospheric characterization, the surface contribution is a source of **noise.**

For sounders such as **AMSU, MHS, ATMS…**

NB: Still some contribution up to 300 GHz (ICI), for very cold and dry atmosphere

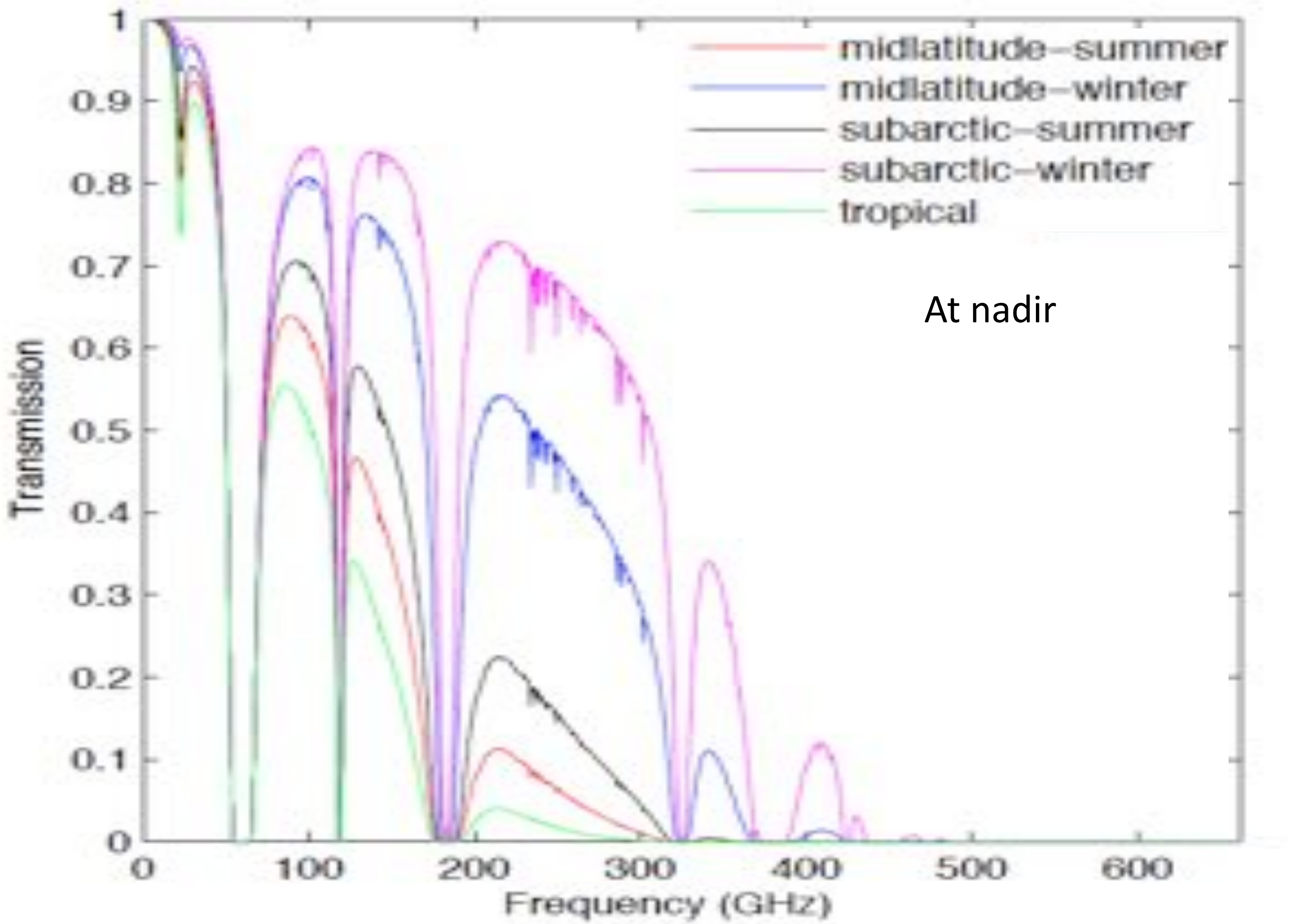


Atmospheric transmission in the microwaves

Atmospheric 'windows' for surface characterization. The surface contribution is the **information**

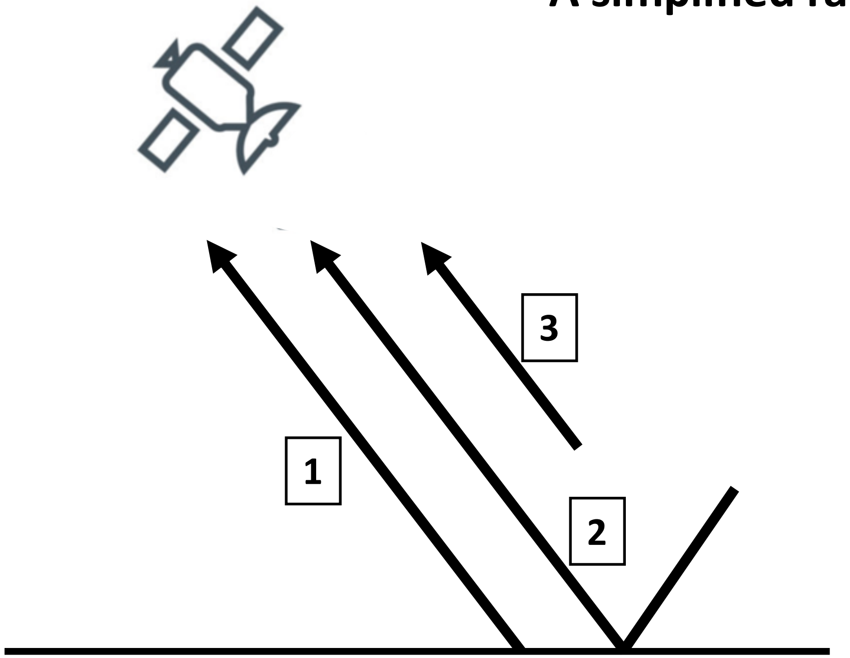
For atmospheric characterization, the surface contribution is a source of **noise.**

In both cases, the surface contribution has to be quantified!



The measured microwave brightness temperature

A simplified radiative transfer equation



$$Tb_p = \underbrace{T_{surf} \times \epsilon_p \times e^{-\tau(0,H)/\mu}}_{1} + \underbrace{T_{atm}^{\downarrow} \times (1-\epsilon_p) \times e^{-\tau(0,H)/\mu}}_{2} + \underbrace{T_{atm}^{\uparrow}}_{3}$$

In transparent channels: $Tb_p = T_{surf} \times \epsilon_p$

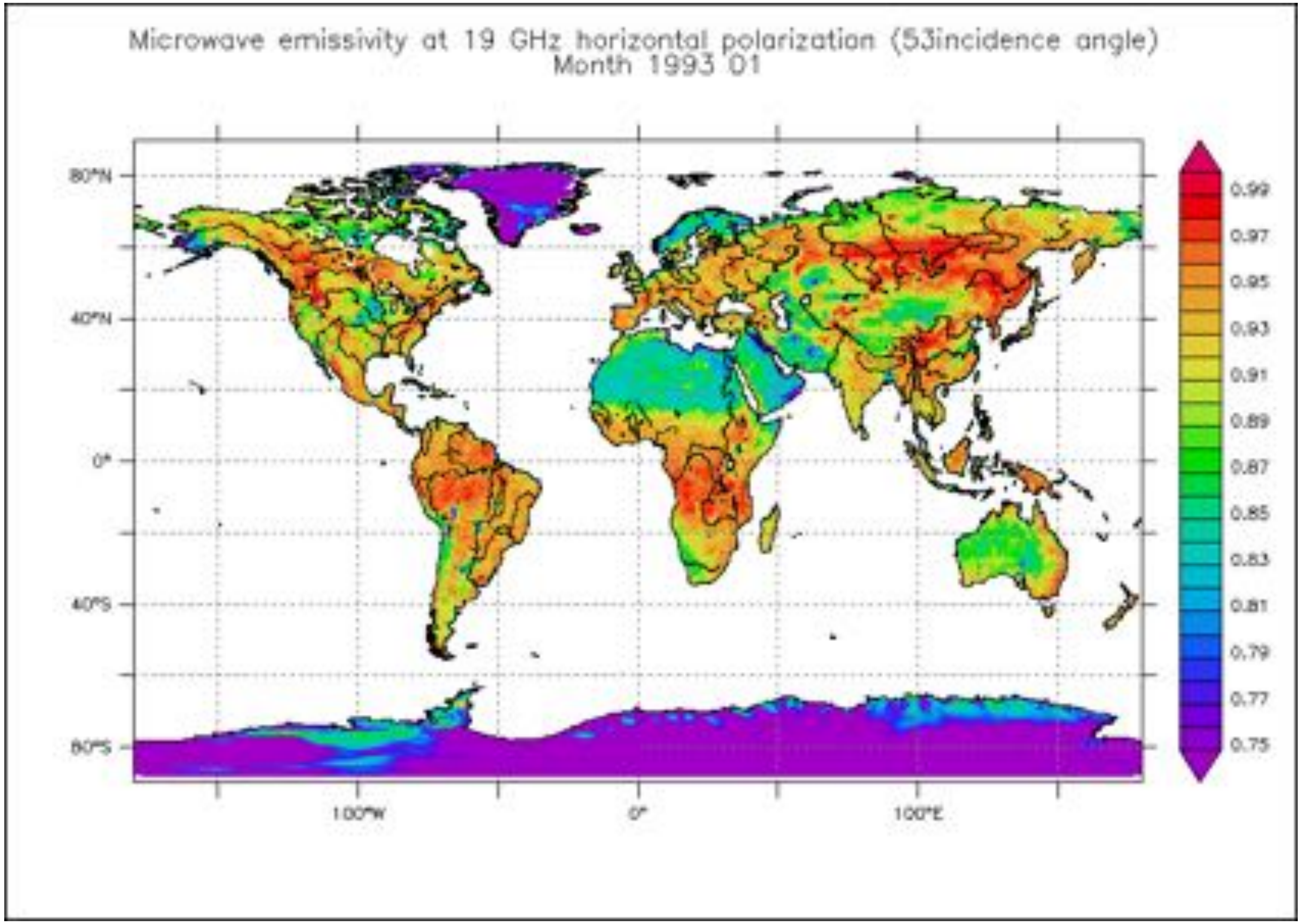
Surface temperature (T_{surf}) **Emissivity** (ϵ_p)

But it is not always that simple …

Surface reflection and scattering, as well as volume scattering, depending on the medium

The space and time variability of the microwave surface emissivity

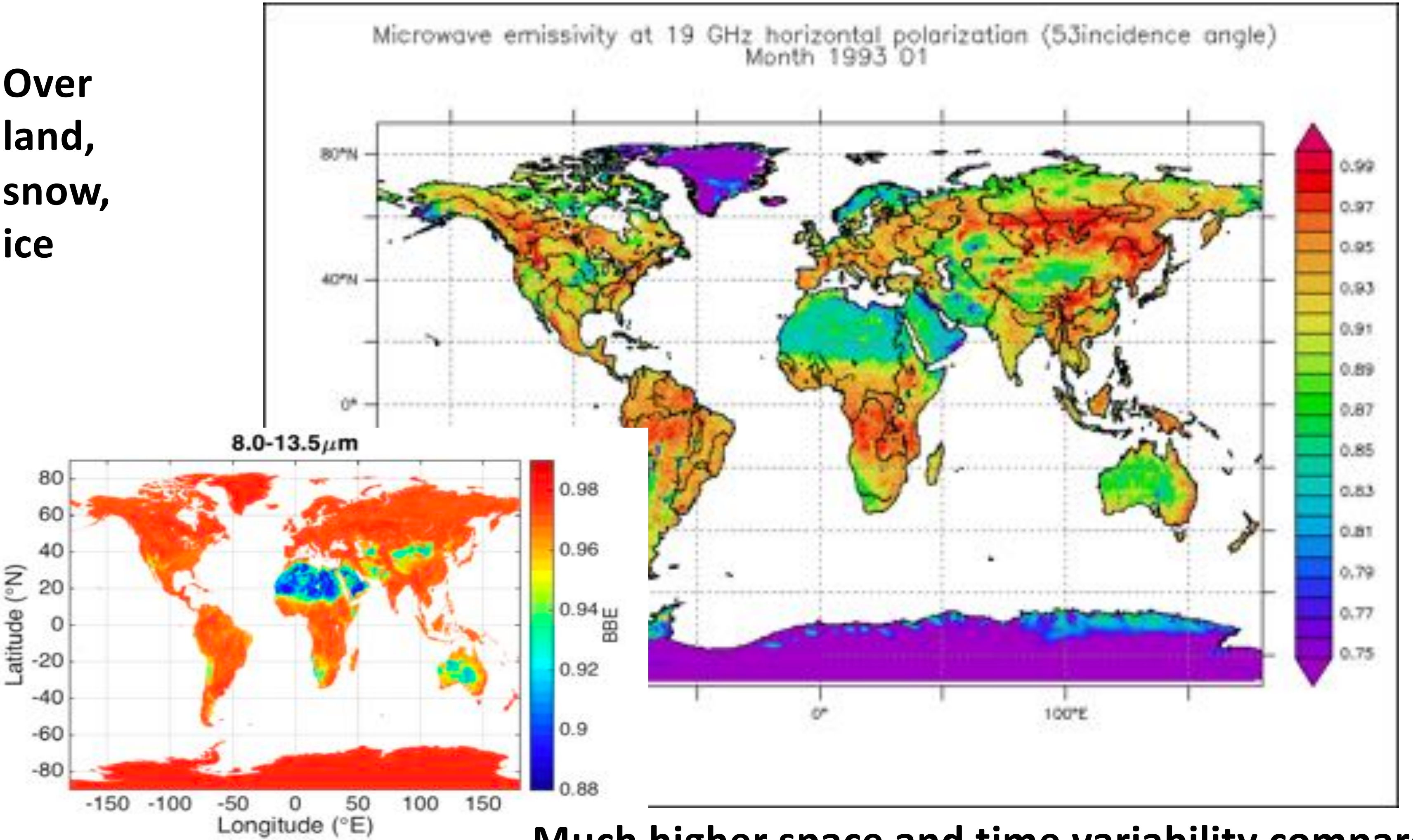
Over land, snow, ice



As observed from a microwave imager in a window channel (19 GHz, H polarization, 53°), over a year

The space and time variability of the microwave surface emissivity

Over land, snow, ice



Much higher space and time variability compared to the infrared

An accurate estimate of the surface contribution is needed in the microwaves, at global scale

- **across frequencies**: from low microwaves to millimeter waves
- **across observing conditions**: incidence angle, polarization
- **across applications**: for atmospheric retrieval as well as for the retrieval of surface properties

Consistency required to exploit multi-frequency, multi-instrument capacity, for both atmospheric and surface characterizations

Toward coupled land / ocean / atmosphere assimilation systems

(see also Patricia de Rosnay presentation later today)


OCEAN

How to accurately estimate the surface contribution in the microwaves at global scale?

Open ocean: a rather homogeneous surface (at least compared to the other surfaces)

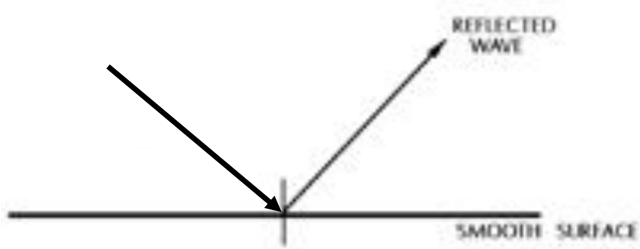
=> Robust radiative transfer models exist.

Land, snow, ice, sea ice: high heterogeneity and complex interaction with the radiation

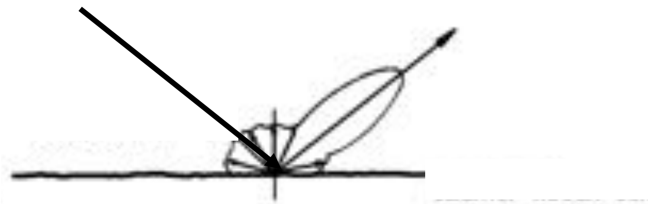
=> Modeling very challenging.

Microwave sea surface emissivity models

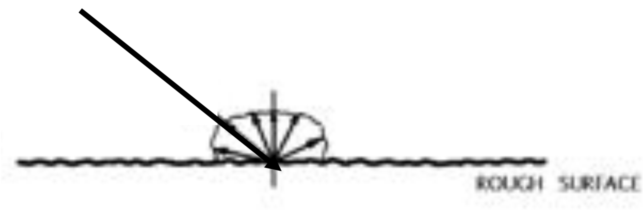
For a flat ocean surface, specular reflection applies, with **dielectric properties** related to the **surface temperature and its salinity**.



When the **wind** increases, the **surface roughness** increases, with relationship between the wind speed and the **wave spectrum**.

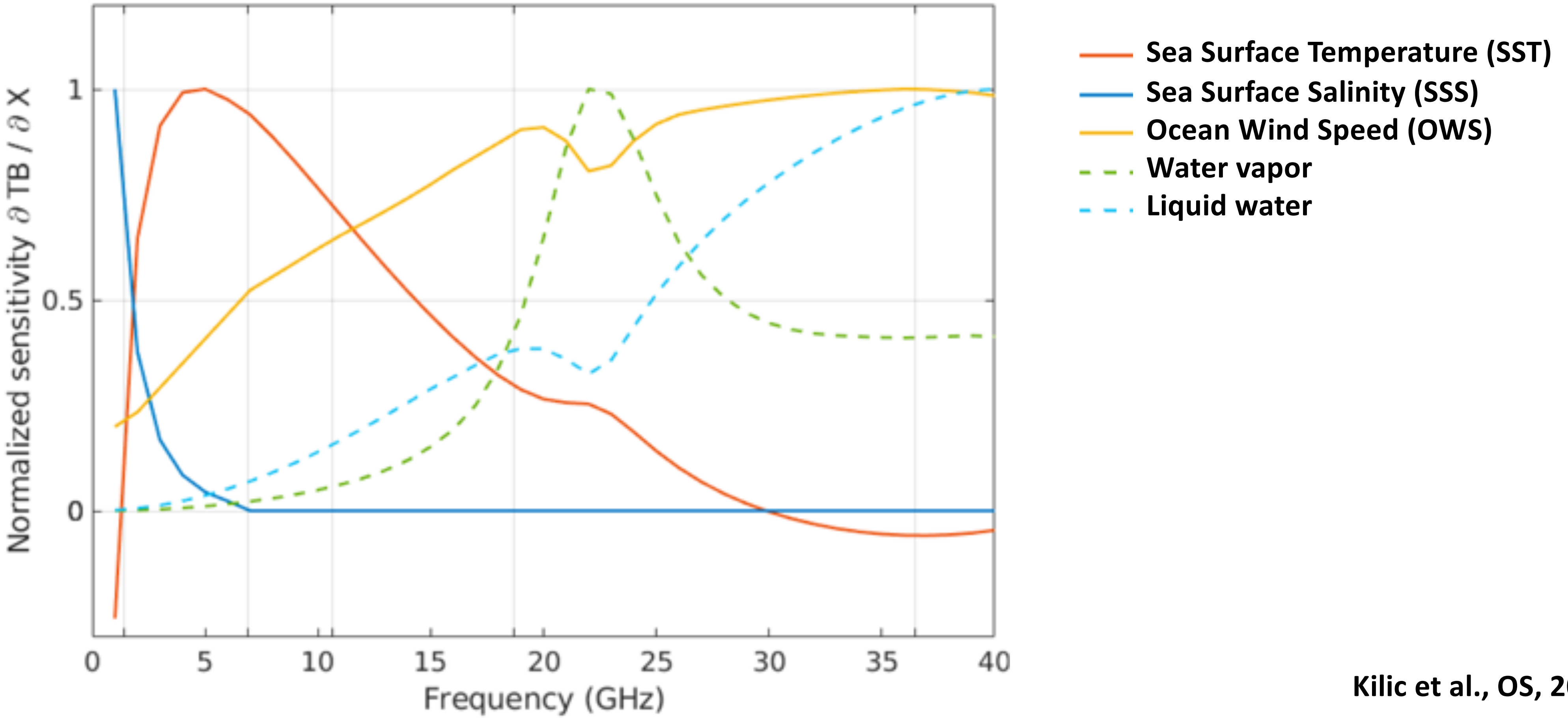


When the wind keeps increasing, foam is produced, with **foam** having a high emissivity compared to sea water.



Microwave sea surface emissivity models

Normalized sensitivity of the passive microwave observations to the ocean parameters: a revisit of the famous figure from Wilheit (1979)



Kilic et al., OS, 2021

Microwave sea surface emissivity models

Physically-based models

(examples: Yueh, 1997; Dinnat et al., 2003; Yin et al., 2012, 2016)

currently no such model available to the community

Fast models parameterized from physically-based models

(examples: FASTEM, TESSEM^2)

distributed with RTTOV or CRTM

Models fitted to satellite observations

(example: Remote Sensing System model, Meissner et al., 2012, 2014)

They all include:

- **a dielectric model**
- **a wind-driven roughness model**
- **a foam model (extent and emissivity)**

Microwave sea surface emissivity models

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An international team has been formed (supported by **ISSI**), to work on the development of a

Reference Quality Model for Ocean Surface Emissivity and Backscatter

- **Physically-based**
- **From the microwaves to the infrared**
- **For both active and passive modes**

A Reference Quality Model For Ocean Surface Emissivity And Backscatter From The Microwave To The Infrared

ISSI Team led by S. English (UK) & C. Prigent (FR)

INTERNATIONAL SPACE SCIENCE INSTITUTE

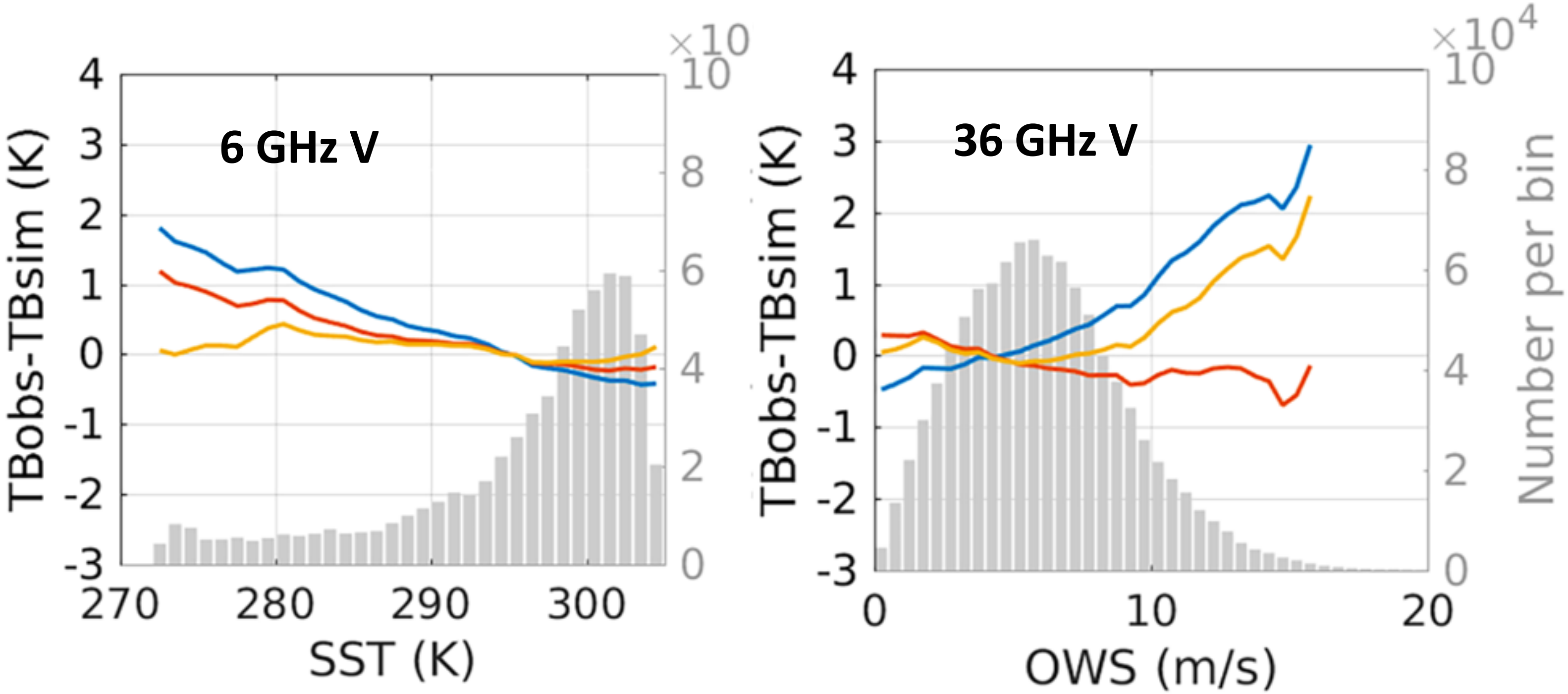
https://www.issibern.ch/teams/oceansurfemiss/

English et al., BAMS, 2020

First action: evaluation of the current models

Three ocean radiative transfer models have been evaluated, by comparison with SMAP, AMSR2, GMI, ATMS observations, over a year.

Physical model
LOCEAN / PARMIO
Fast model
FASTEM
Empirical model
RSS



Major discrepancies were found:

- **for cold temperatures**
- **for high wind speeds**

Kilic et al., JGR, 2019

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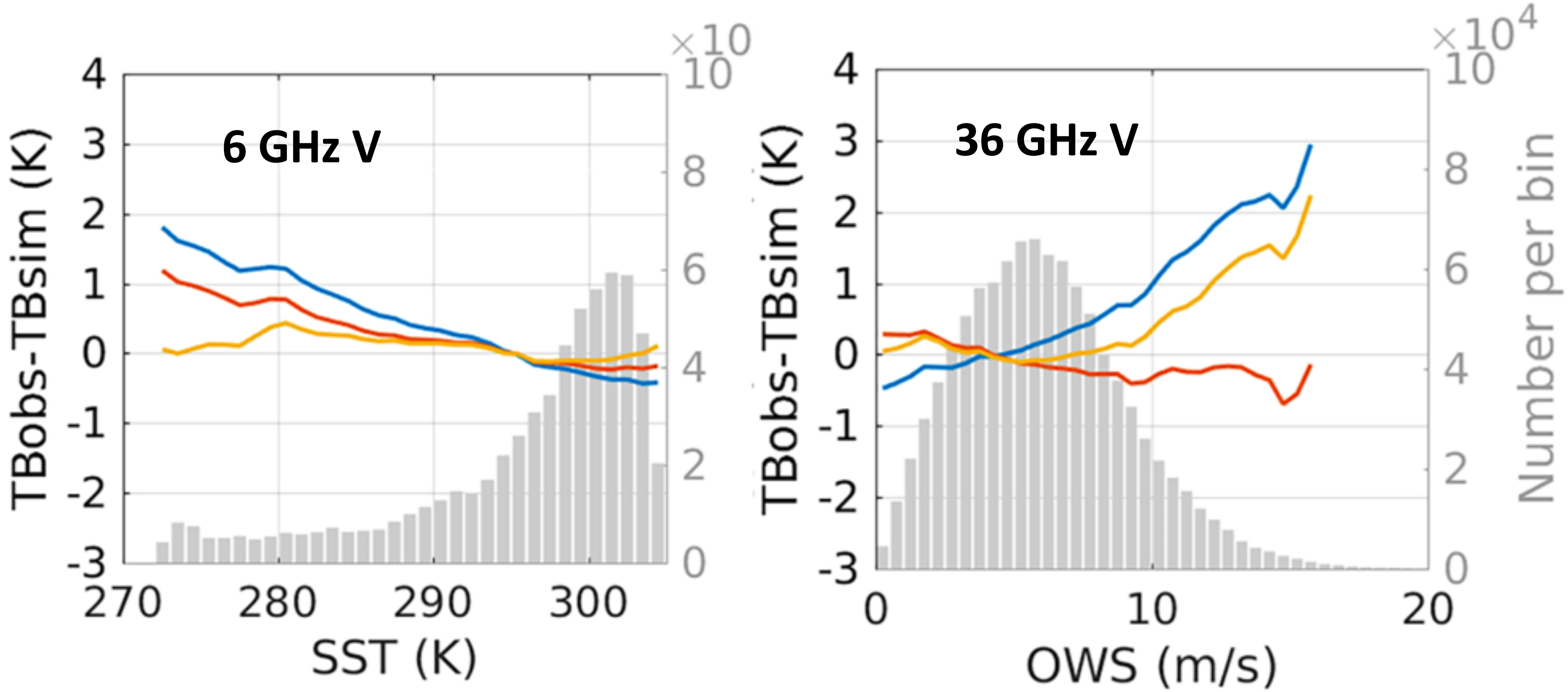


Major discrepancies were found:

- **for cold temperatures** ***=> sea dielectric properties?***
- **for high wind speeds** ***=> foam modeling?***

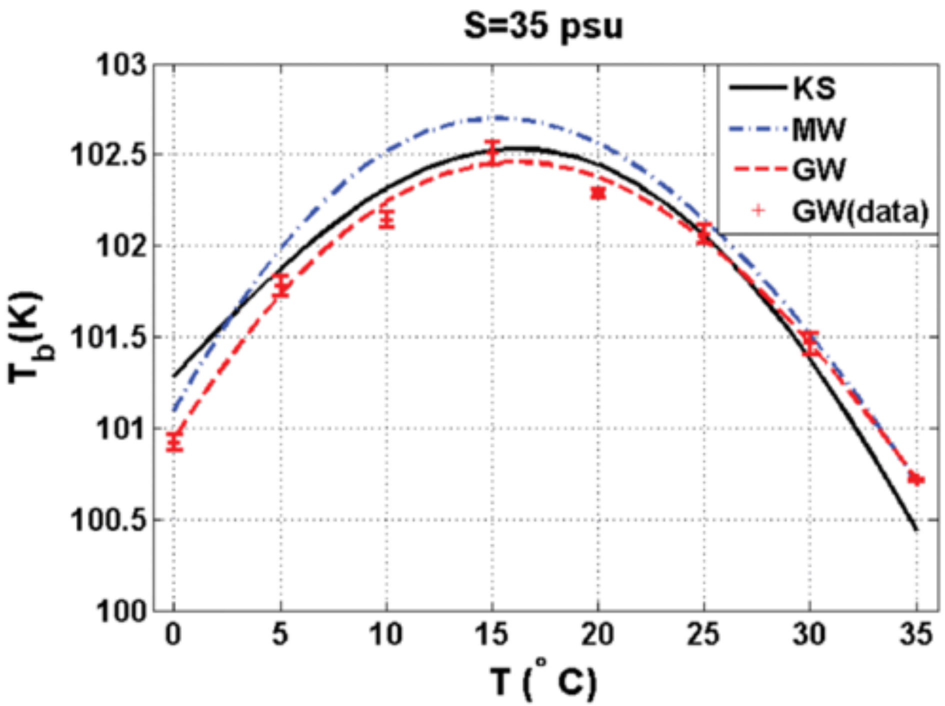
Kilic et al., JGR, 2019

Microwave sea surface emissivity: *the sea dielectric properties*

Particularly critical at:

- **1.4 GHz (L band), where high accuracy is required for salinity retrieval (<0.1K)**
- **6 GHz (C band), that is the key frequency for sea surface temperature retrieval**

Developments mostly at 1.4 GHz so far (SMOS and SMAP)

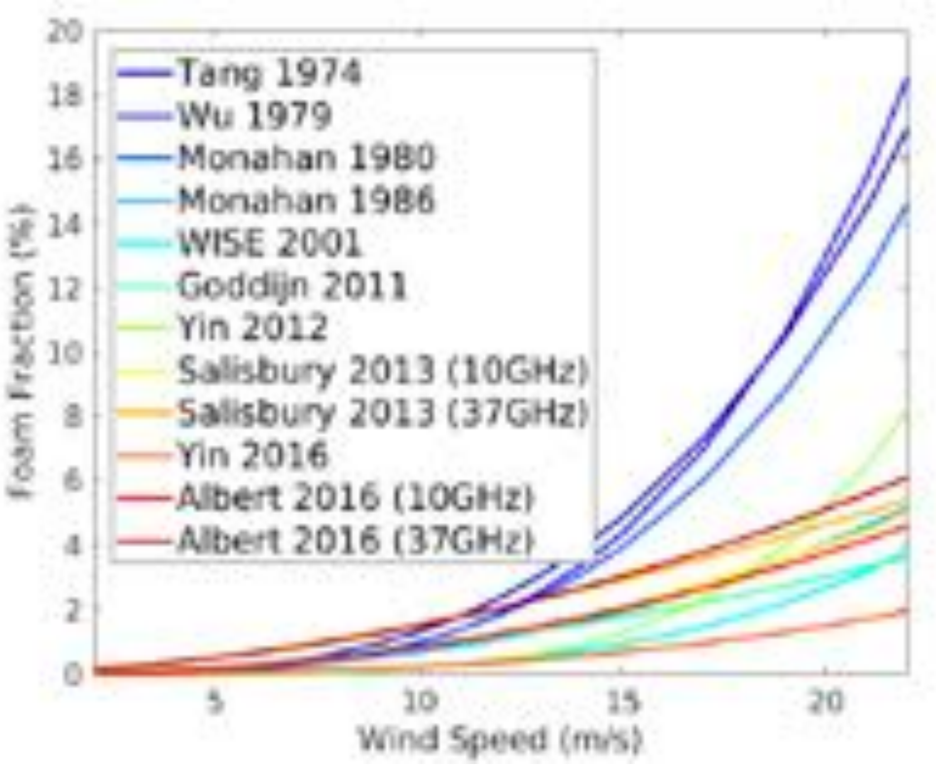


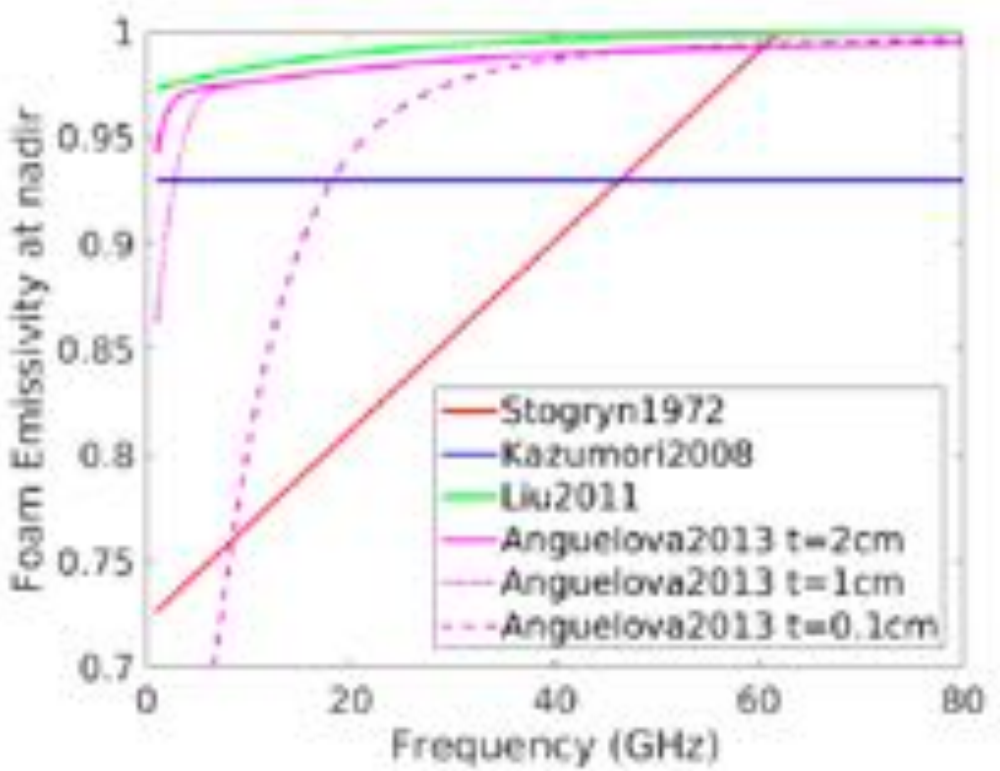
KS = Klein and Swift
MW = Meissner and Wentz
GW = George Washington University, Zhou et al., 2017

Zhou et al., IEEE, 2017, 2021

Microwave sea surface emissivity: *the foam emissivity and coverage*

A large variety of models for both foam coverage and foam emissivity…

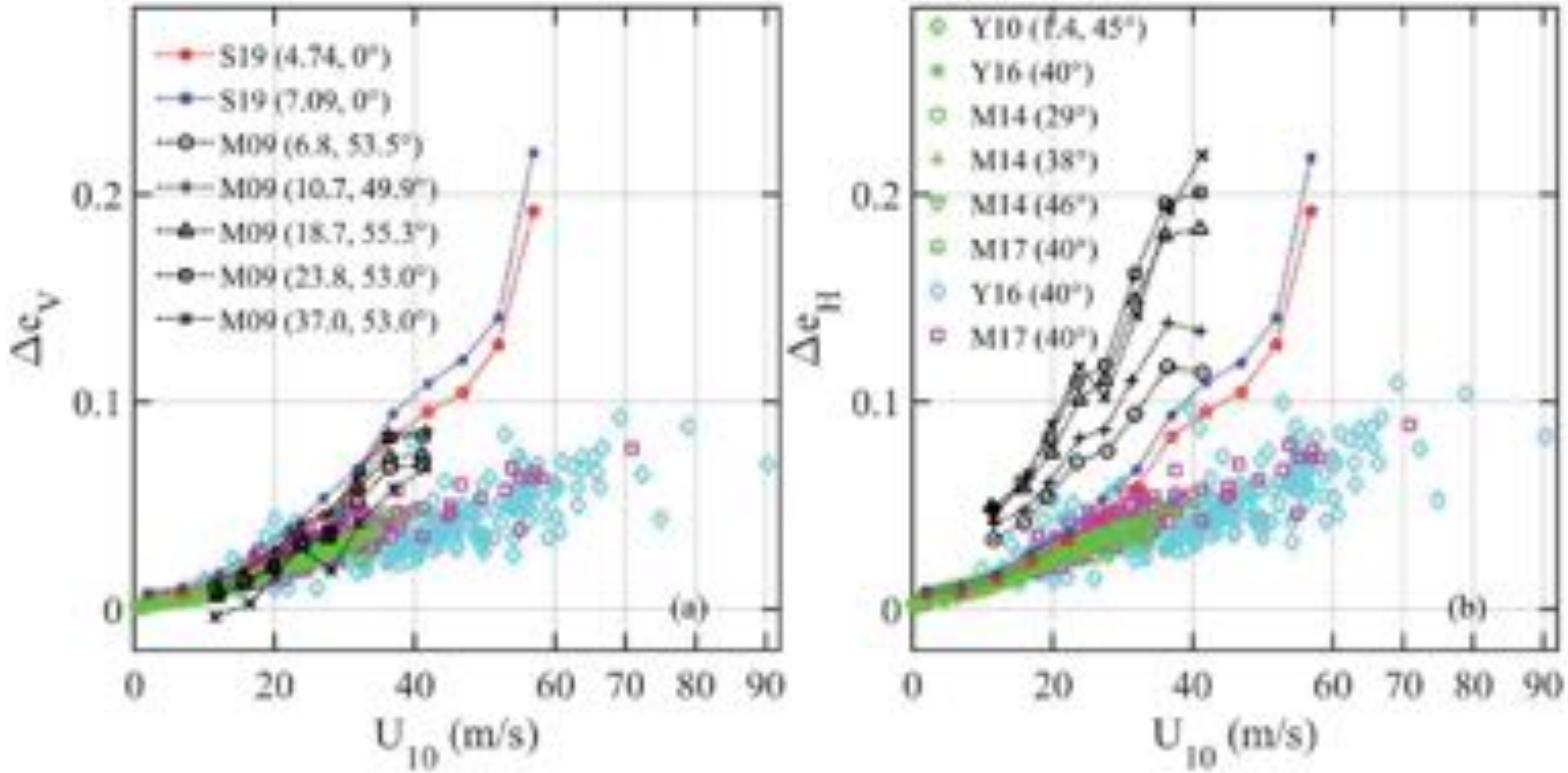




Kilic et al., JGR, 2019

Microwave sea surface emissivity: *the foam emissivity and coverage*

Sea surface emissivity keeps increasing with wind speed, due to the foam presence



Hwang et al., IEEE, 2019

A Reference Quality Model For Ocean Surface Emissivity And Backscatter From The Microwave To The Infrared

INTERNATIONAL SPACE SCIENCE INSTITUTE

https://www.issibern.ch/teams/oceansurfemiss/

- **A physically-based reference ocean model has been selected:**
  PARMIO (Passive and Active Reference Microwave to Infrared Ocean)
  (Dinnat et al., 2003; Yin et al., 2012, 2016)

- **It has been extensively evaluated with multiple observations at global scale (SMAP, AMSR, GMI, ATMS). Adjustments are made to the initial model to better fit the observations under cold temperature and for high wind speed.**

- **The development of a NN fast code is underway, derived from this model,** with similar inputs as FASTEM, along with Jacobians and error estimates.

LAND SNOW, ICE, SEA ICE

How to accurately estimate the surface contribution in the microwaves at global scale?

Open ocean: a rather homogeneous surface
=> Robust radiative transfer models exist

Land, snow, ice, sea ice: high heterogeneity and complex interaction with the radiation
=> Radiative transfer modeling very challenging
surface reflection and scattering + volume scattering

- How to realistically simulate these surface contributions?
- How to capture the major geophysical parameters that drive their variability?
- How to develop the forward operator, as a function of these geophysical parameters?

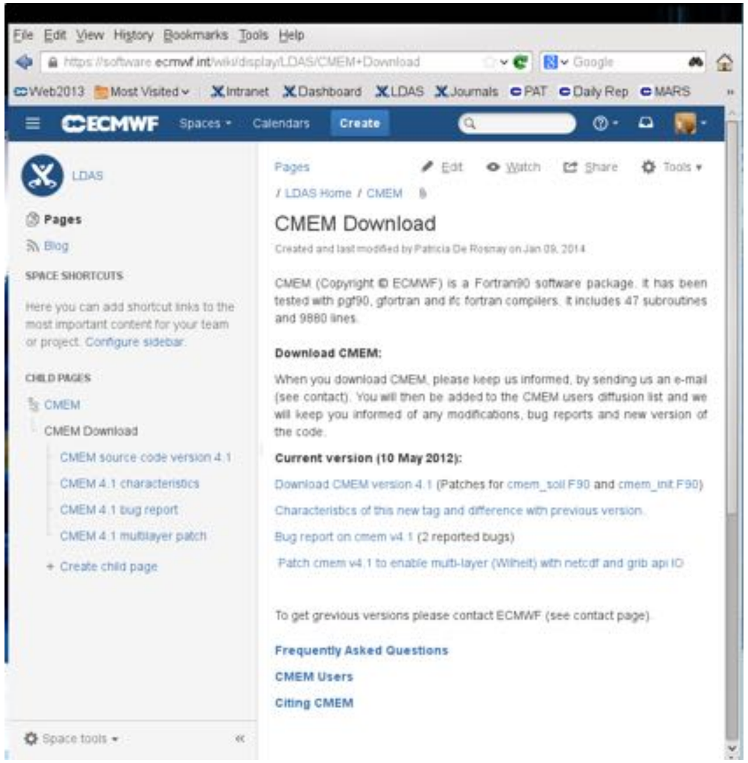



Generic land surface microwave emission models

Community Microwave Emission Model (CMEM) at ECMWF

(Drusch et al., JHM, 2009, de Rosnay et al., RSE, 2020)

https://software.ecmwf.int/wiki/display/LDAS/CMEM



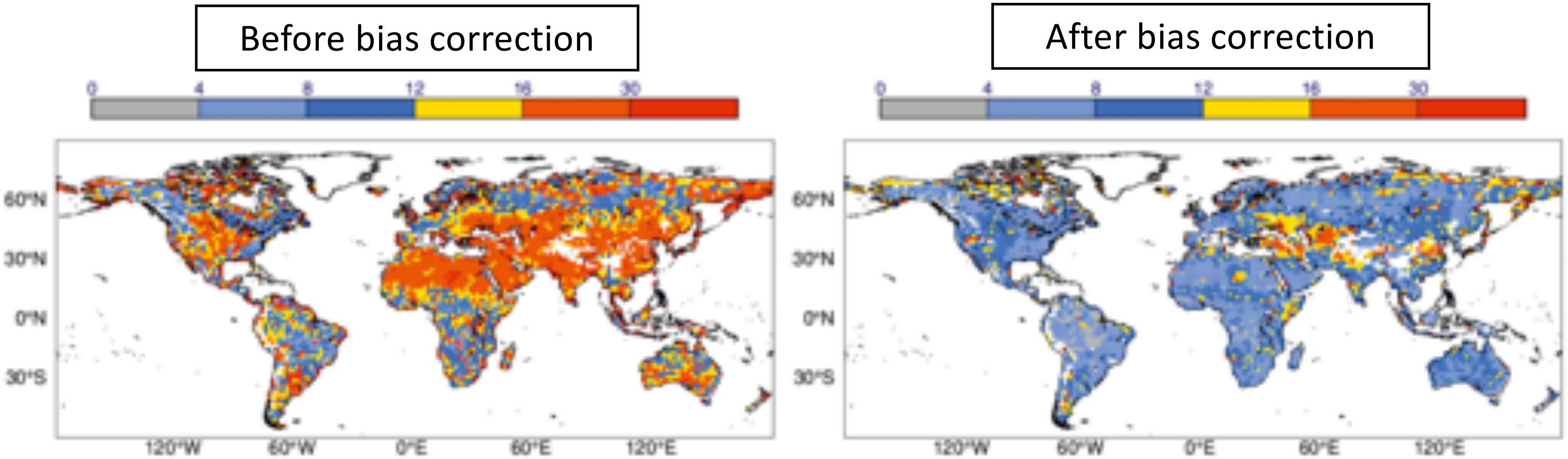
Modular configuration of CMEM. For each module components, a choice of parameterizations is available. Parameterizations in bold are those used in this paper. Different combinations of CMEM using three different dielectric models, four roughness models and three vegetation optical depths models are compared, leading to 36 configurations evaluated against SMOS observations.

CMEM modules	Choice of parameterizations	
	Short name	Reference
Soil module:		
Dielectric mixing model	**Dobson**	(Dobson et al., 1985),
	Mironov	Mironov et al. (2004)
	Wang	Wang and Schmugge (1980)
Effective temperature model	Surface temperature forcing	
	Choudhury	Choudhury et al. (1982)
	Wigneron	Wigneron et al. (2001)
	Holmes	Holmes et al. (2006)
Soil roughness model	**Choudhury**	(Choudhury et al., 1979),
	Wign07	Wigneron et al. (2007)
	Wign01	Wigneron et al. (2001)
	Texture dependent	citepatbd:10
	Wegmüller	Wegmüller and Mätzler (1999)
Vegetation module:		
Vegetation optical depth model	Wegmüller	(Wegmüller et al., 1995),
	Jackson	Jackson and O'Neill (1990)
	Kirdyashev	Kirdyashev et al. (1979)
	Wigneron	Wigneron et al. (2007)
Snow module:		
Snow emission model	HUT single layer model	Pulliainen et al. (1999)

Generic land surface microwave emission models

Community Microwave Emission Model (CMEM) at ECMWF

Specific work at 1.4 GHz, for SMOS



RMSE (K)

- **Large errors before adjustements at 1.4 GHz**
- **Significant improvement after bias correction**
- **Applicable to other frequencies, with consistent hypotheses and inputs?**

de Rosnay et al., RSE, 2020

Specific microwave emission models

Example for sea ice:
(Burgard et al., TC, 2020)

based on the MEMLS model
(*already discussed by Gunnar Spreen on Monday*)

Complex structure and large number of inputs

Incidence angle	55°
Ocean temperature	−1.8 °C
Incoming microwave radiation from the atmosphere	0 K
Ice ocean reflectivity for V polarization	0.25
Brine pocket form	spherical
Correlation length first-year ice	0.35 mm for depth < 20 cm, 0.25 mm for depth > 20 cm
Correlation length multiyear ice	1.5 mm
Snow thickness	as computed by SAMSIM
Snow density	$300\ kg\ m^{-3}$
Snow correlation length	0.15 mm
Snow salinity	$0\ g\ kg^{-1}$
Snow temperature	as computed by SAMSIM

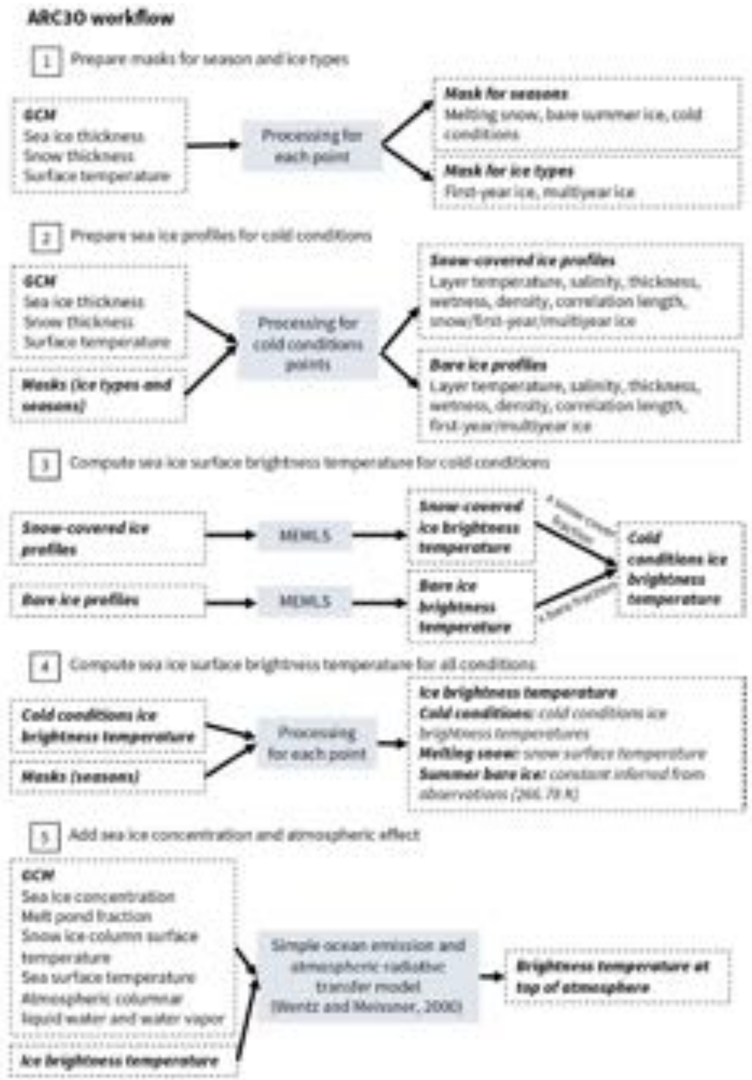


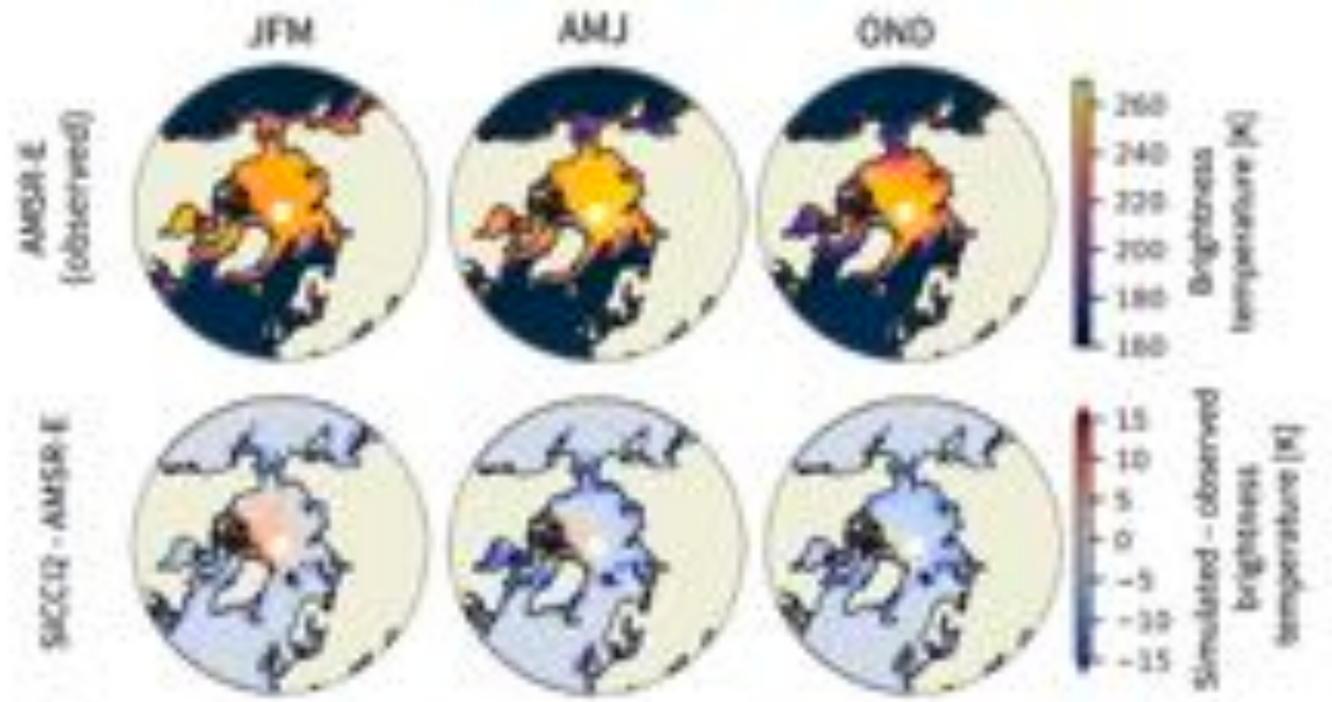
Figure 1. Workflow of the Arctic Ocean Observation Operator ARC3O.

Specific microwave emissivity models

Example for sea ice
(Burgard et al., TC, 2020)

Comparison with AMSR observations at 6.GHz, V pol, 53°

Applicable to H polarization, and to the other AMSR frequencies?



(after debaising)

Physically-based microwave emissivity models are very challenging for global applications, over land, snow, ice, and sea ice

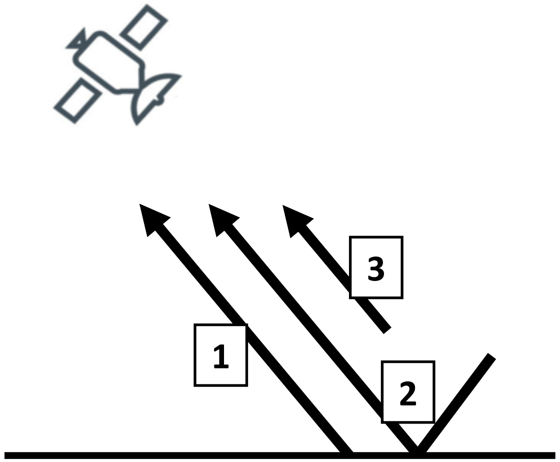
- Difficulty to capture the high spatial and temporal heterogeneity

- Complex interaction between the signal and the surfaces
  surface reflection and scattering + volume scattering… at the same time

- Difficulties to access the necessary input parameters to the model

- Which are the key drivers of the signal variability?
    - Are they included in the model inputs?
    - Are they available at large scale?

Satellite-derived microwave emissivity



$$Tb_p = \underbrace{T_{surf} \times \epsilon_p \times e^{-\tau(0,H)/\mu}}_{1} + \underbrace{T_{atm}^{\downarrow} \times (1 - \epsilon_p) \times e^{-\tau(0,H)/\mu}}_{2} + \underbrace{T_{atm}^{\uparrow}}_{3}$$

$$\epsilon_p = \frac{Tb_p - T_{atm}^{\uparrow} - T_{atm}^{\downarrow} \times e^{-\tau(0,H)/\mu}}{e^{-\tau(0,H)/\mu} \times (T_{surf} - T_{atm}^{\downarrow})}$$

Applied to window channels for SSM/I, AMSU, AMSR, GMI…. under clear sky only or imbedded into a full retrieval of the atmosphere and surface

E.g., Prigent et al., 1997, 2006; Aires et al., 2001; Karbou et al., 2005, Boukabara et al.,, 2018; Munchack et al., 2020…

In operational mode:

- **Emissivities are calculated on line in window channels and propagated to other channels**
- **Or emissivity atlases are used**

Satellite-derived microwave emissivity

$$\epsilon_p = \frac{Tb_p - T_{atm}^{\uparrow} - T_{atm}^{\downarrow} \times e^{-\tau(0,H)/\mu}}{e^{-\tau(0,H)/\mu} \times (T_{surf} - T_{atm}^{\downarrow})}$$

Sources of errors:

The surface temperature T_{surf}

- Tsurf=Tskin? Tskin from NWP model? From IR estimates (under clear sky conditions) ?
- Sub-surface contribution? Tsurf=Teff. Depends upon the frequency…
- Clearly, the **dominant error**

The atmospheric contribution

- especially at high frequency
- adjusted when calculation within a full surface / atmosphere inversion model (as in NWP centers)

Specular approximation

- always valid? Is there a need to add a Lambertian contribution close to nadir and at high frequency, especially over snow and ice? (Matzler, GRSL, 2005; Karbou et al., GRSL, 2005; Harlow, IEEE, 2009)

Satellite-derived microwave emissivity

An analysis of emissivities has been derived from multiple satellites, to parameterize the frequency, angle, and polarization dependence, of the emissivity for NWP applications.

TELSEM²

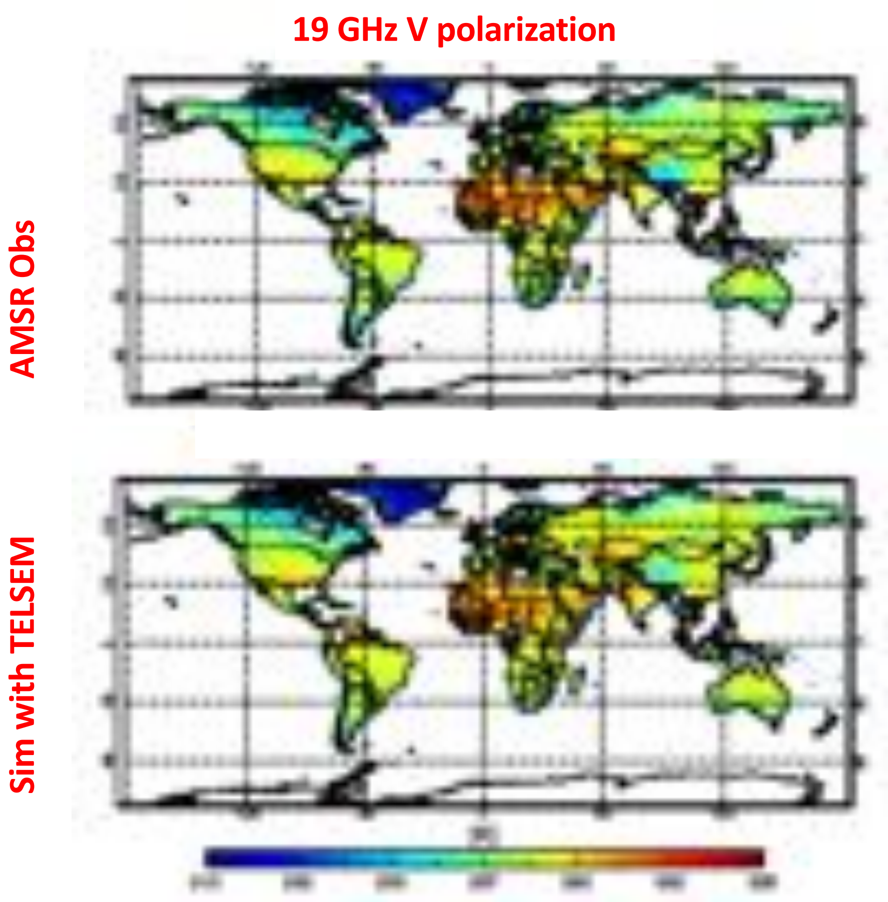
Tool to Estimate Land Surface Emissivities at Microwaves and Millimeter waves
(**distributed with RTTOV and CRTM)** (Aires et al., JQSRT, 2011; Wang et al., JAOT, 2017)

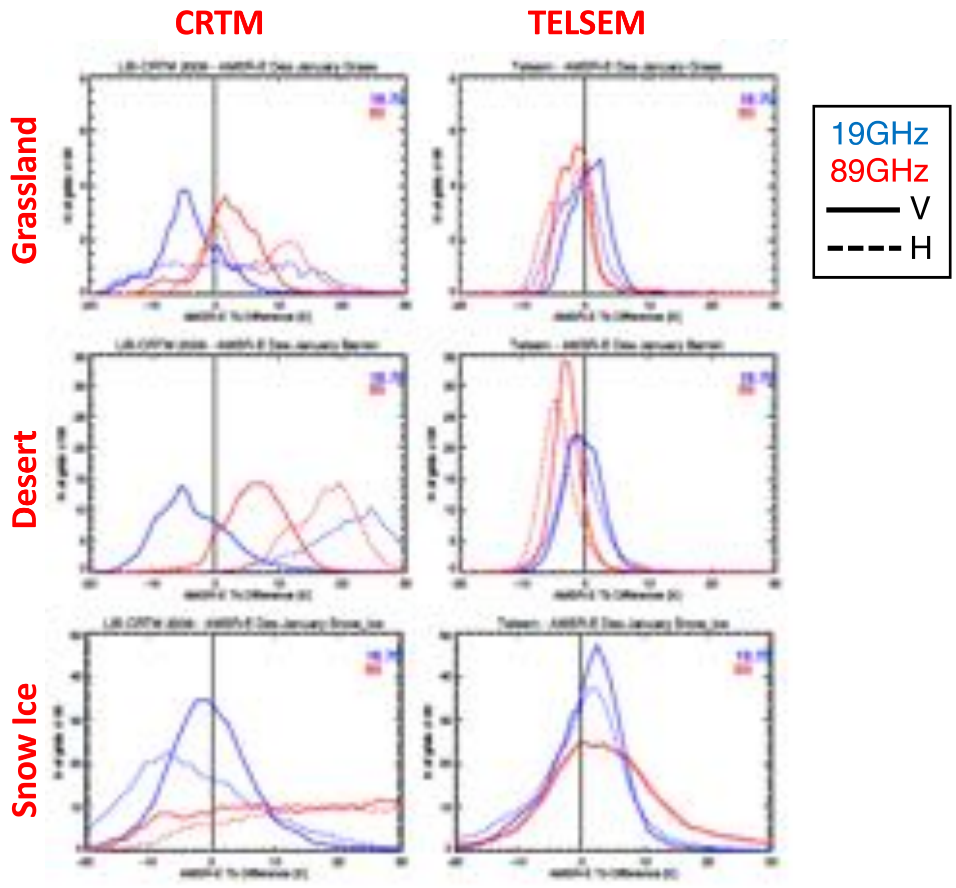
- It provides global atlases of emissivity for all continental and sea-ice surfaces, from 18 to 700 GHz, monthly mean, at 25 km resolution.
- **Inputs:** **lat, lon, month, frequency, and incidence angle.**
- **Outputs:** **emissivities in V and H polarizations, along with error covariances**
- Realistic **FIRST GUESS** estimates

Could be updated with new emissivity estimates, especially below 18 GHz (AMSR + SMAP + SMOS)

Comparison between modeled and satellite-derived emissivities

CRTM from NOAA (with LIS inputs) and TELSEM
Comparison at Tb level, with AMSR satellite observations





Differences between AMSR observations and simulations

Prigent et al., JGR, 2015

Comparison between modeled and satellite-derived emissivities

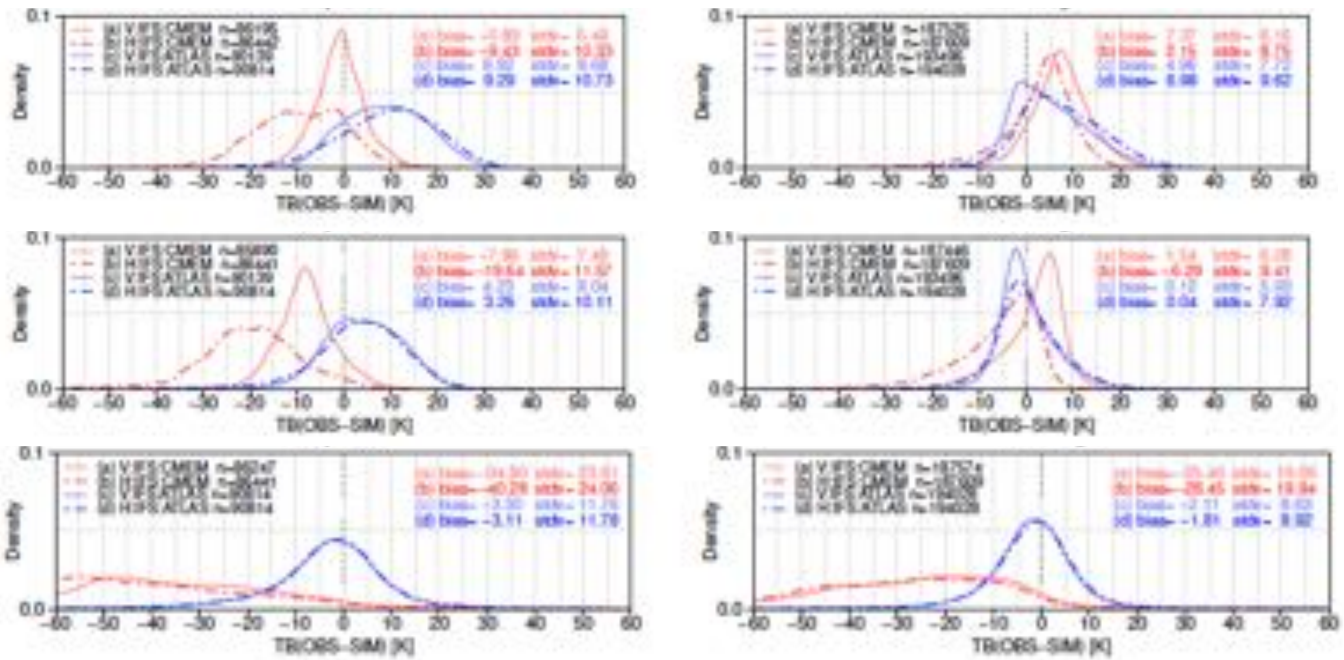
Snow modeled emissivity (CMEM) and satellite-derived emissivity (TELSEM²) at ECMWF compared to AMSR observations

Only snow | **Snow with vegetation**

6.9GHz*

18.7GHz

89.0GHz



Satellite-derived emisivity

Snow radiative transfer model

* Outside the interpolation range for TELSEM²

——— V pol

- - - - - H pol

Hirahara et al., RS, 2020

As expected, the satellite-derived land surface emissivity provides reasonable spatial and temporal variabilities, as well as frequency co-variabilities

But they do not tell about the key geophysical parameters that drive their variability…

For consistent surface and atmospheric inversion, how to relate the satellite-derived surface contribution to the geophysical parameters?

Given the limitations of the physically-based forward operator over land,

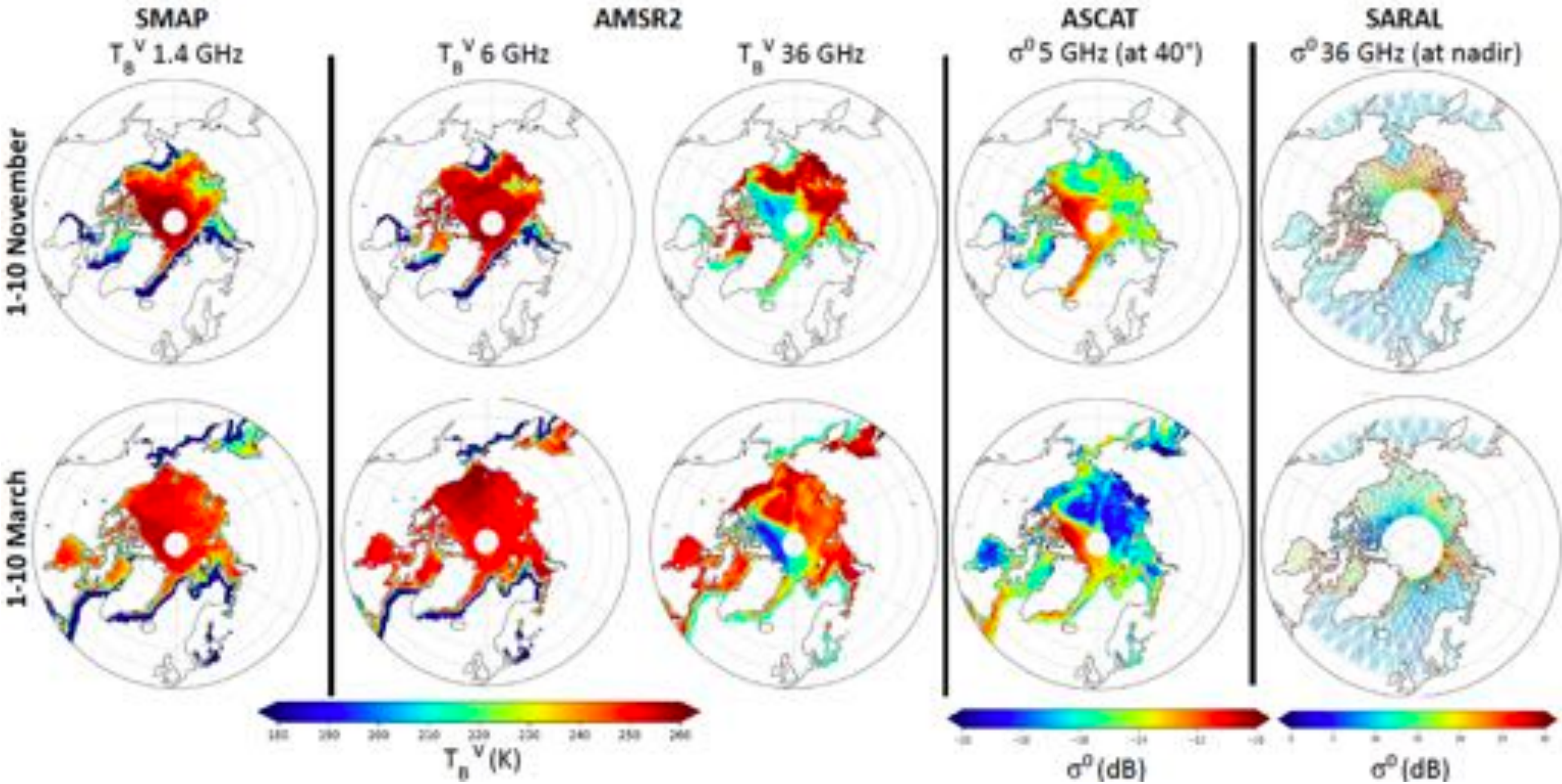
- ***Possibility to derive statistical forward operators anchored to the satellite observations, and consistent for multi-frequency, multi-instrument operation ?***

Toward coupled land atmosphere assimilation system…

An analysis over sea ice

An analysis over sea ice

Collection of observations, all sensitive to sea ice parameters, with high spatial and temporal variability



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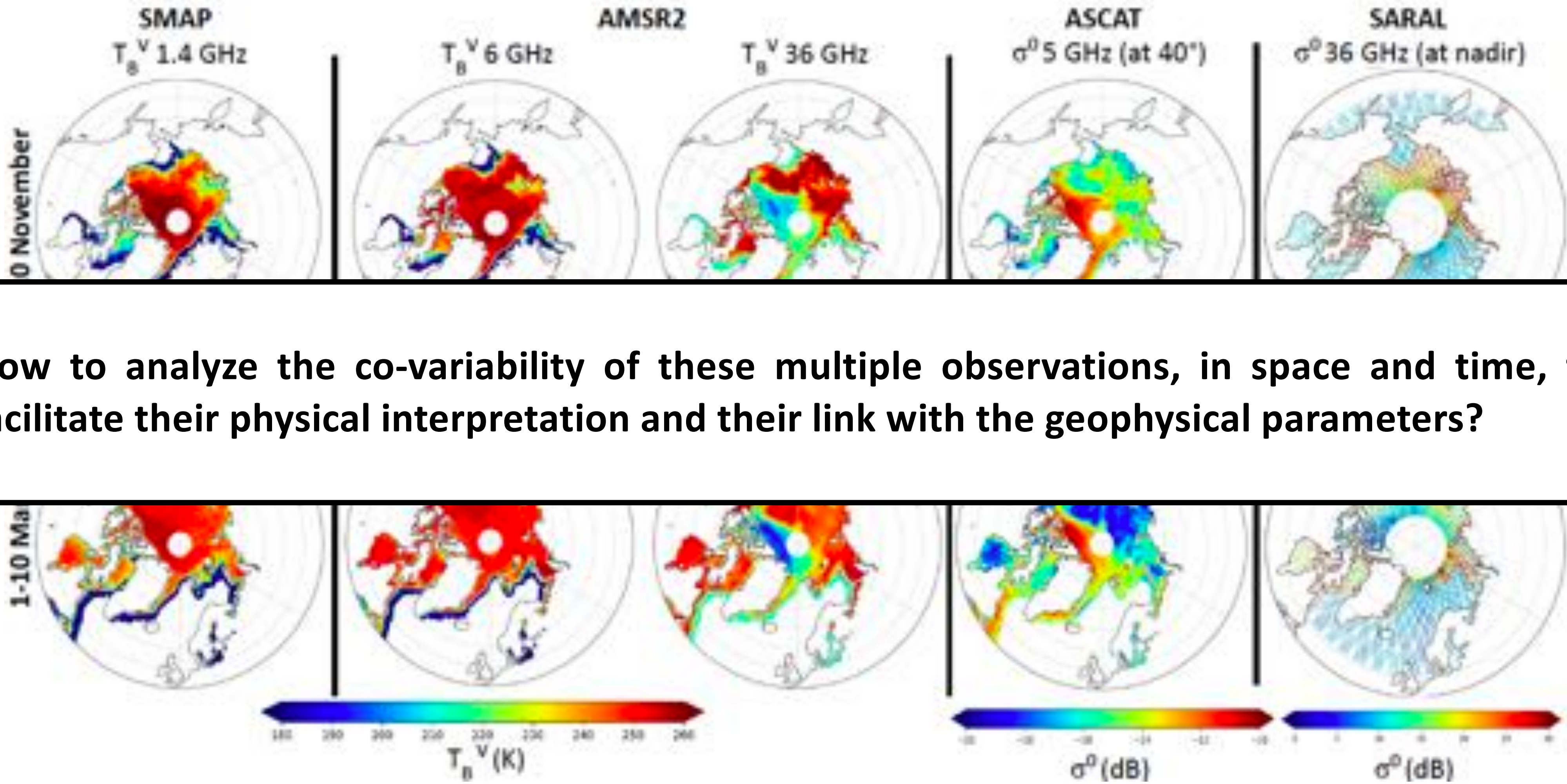
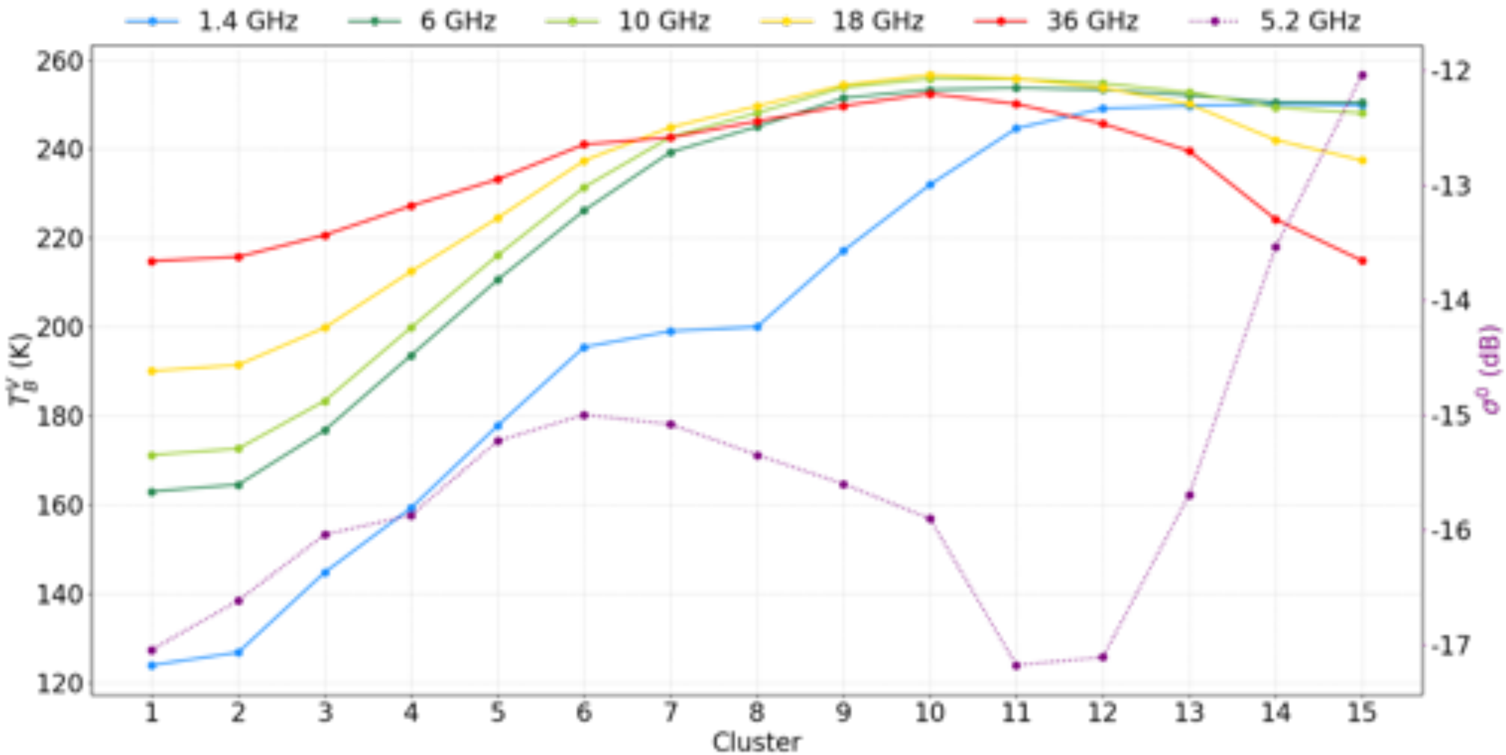


How to analyze the co-variability of these multiple observations, in space and time, to facilitate their physical interpretation and their link with the geophysical parameters?

An analysis over sea ice

Classification of one year of SMAP + AMSR2 (to mimic CIMR) and ASCAT data over the Arctic, to extract the dominant patterns and their co-variabilities (AI self organizing classification)



Soriot, PhD, 2021

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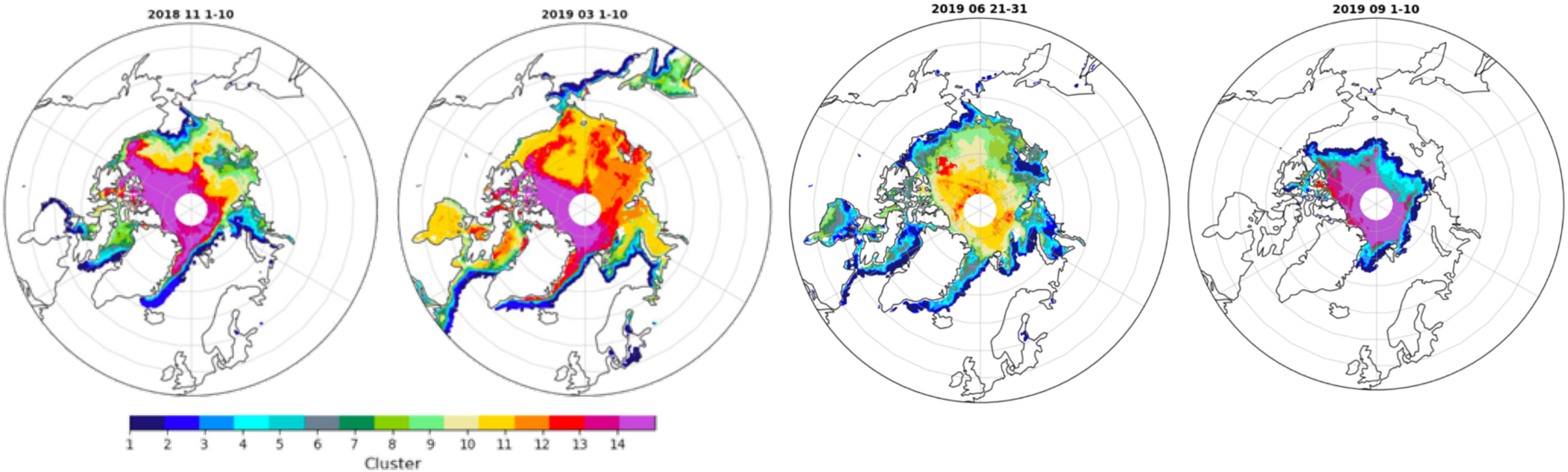
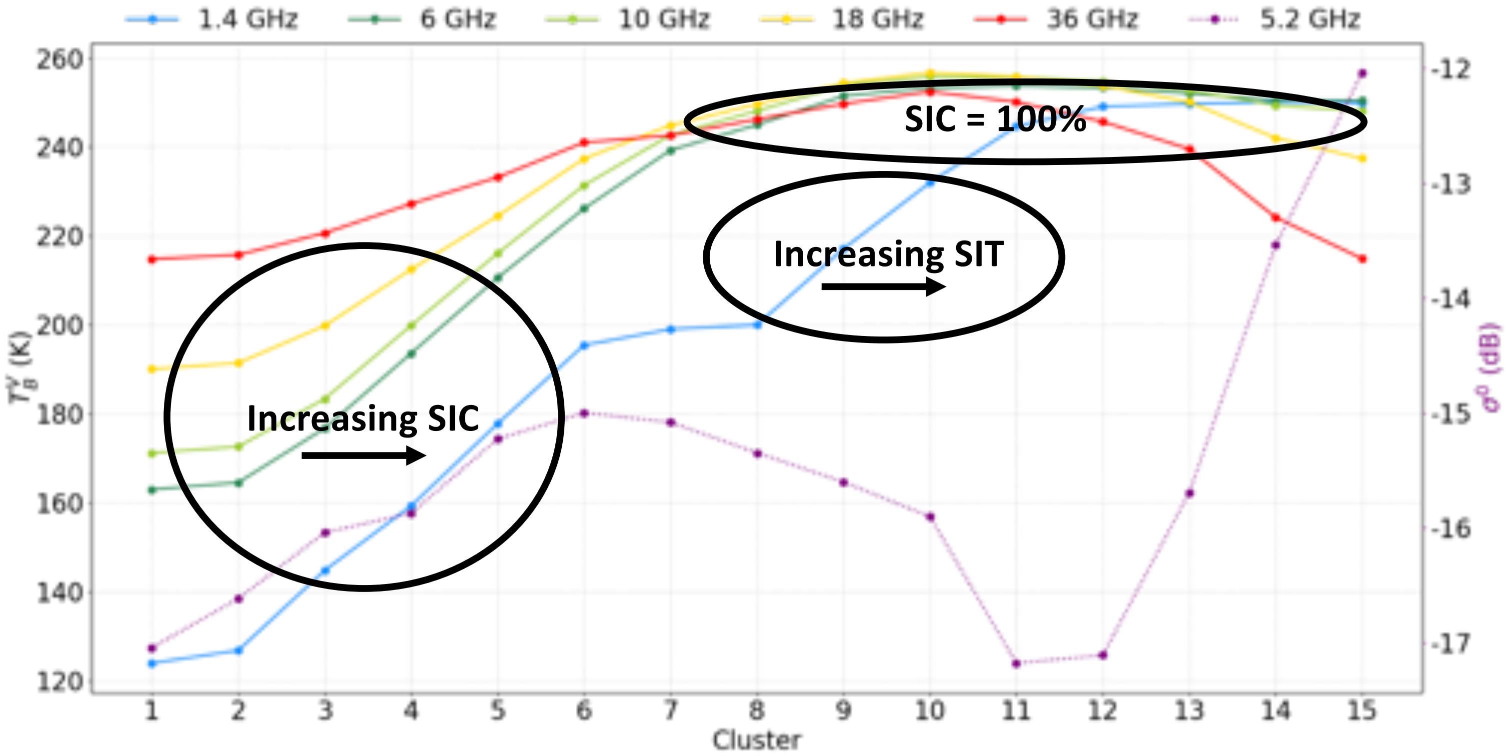


Soriot, PhD, 2021

An analysis over sea ice

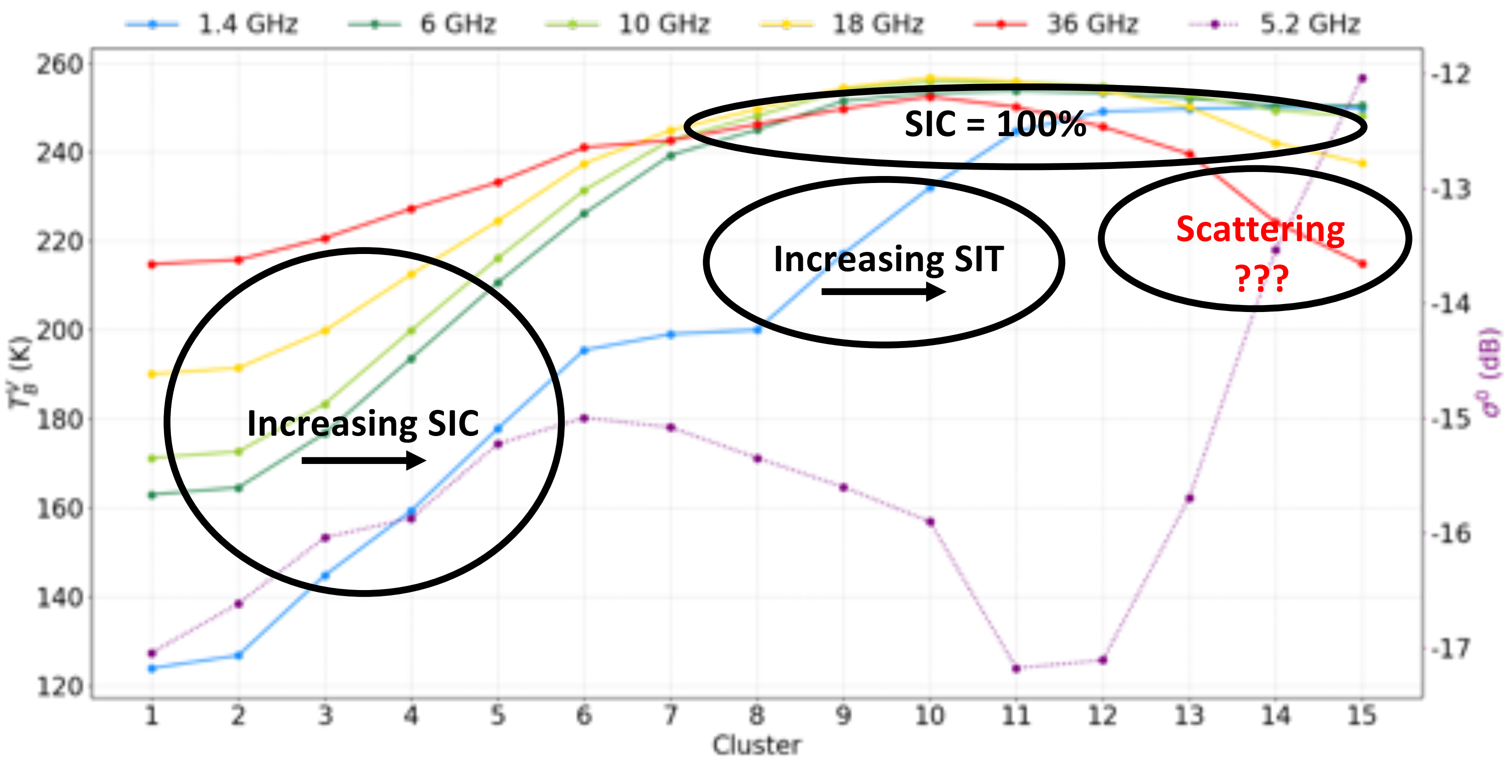
Interpretation of the signatures, in terms of geophysical parameters?
Rather straight forward for some features



Soriot, PhD, 2021

An analysis over sea ice

Interpretation of the signatures, in terms of geophysical parameters?
Rather straight forward for some features, but not for all

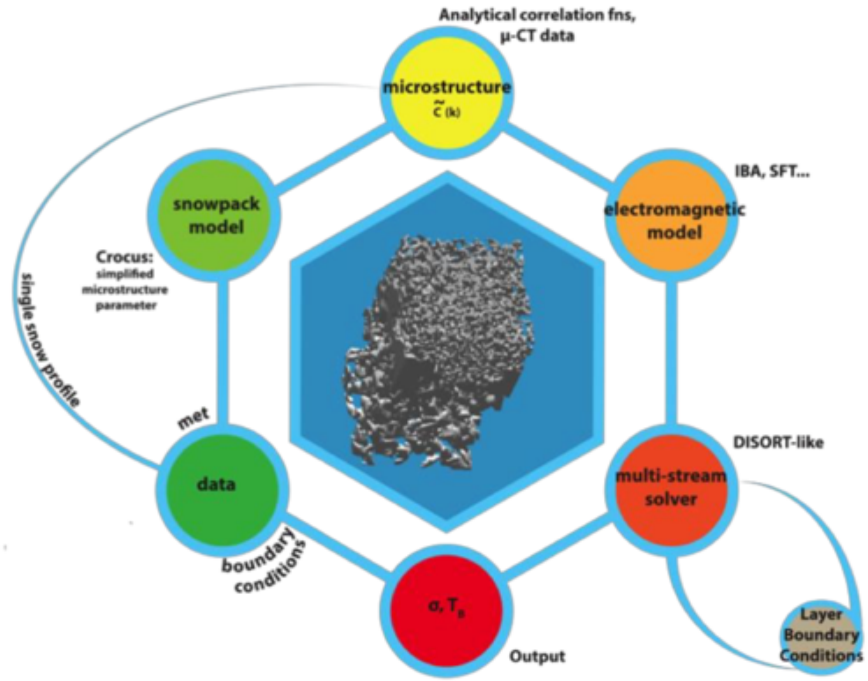


Soriot, PhD, 2021

An analysis over sea ice

Can we explain the dominant variability and co-variability with radiative transfer modeling to better understand the key parameters that drive these variabilities?

Use of radiative transfer model, along with the expertise of specialists (G. Picard & F. Dominé), to explain the observation variability, and their changes over the seasons

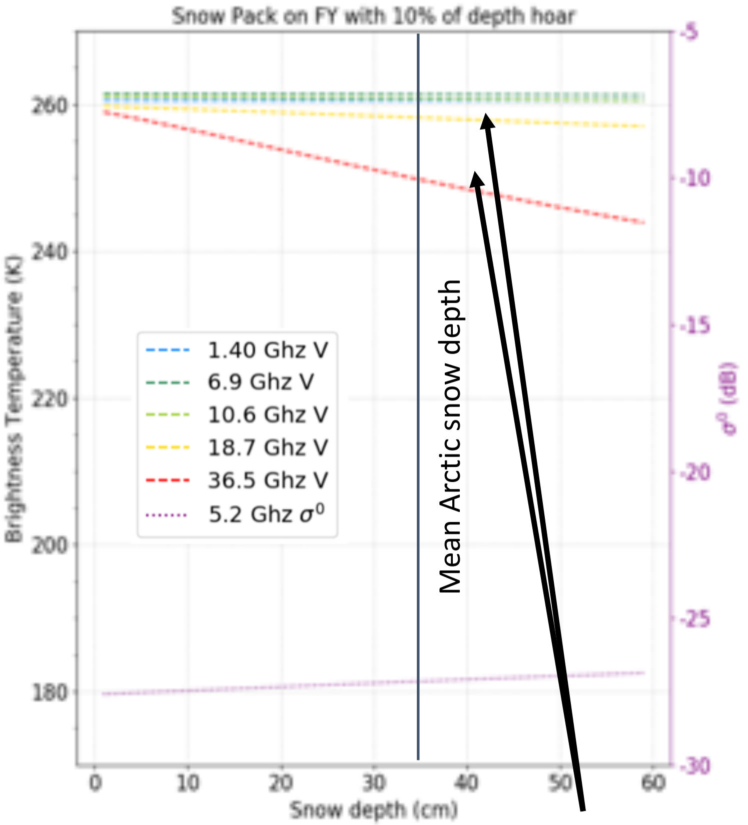


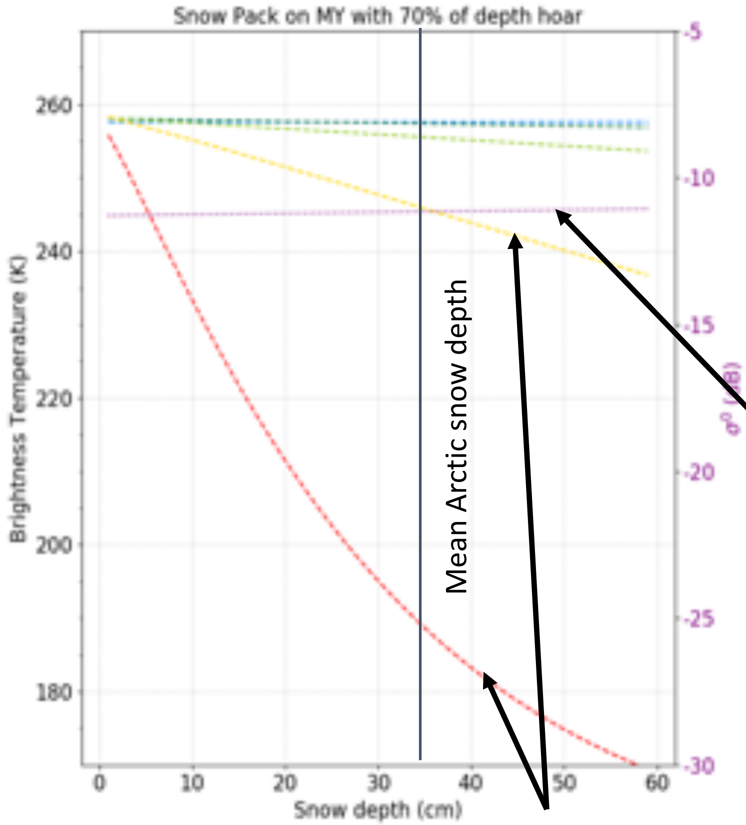
SMRT (Picard et al., GMD, 2018)
See https://www.smrt-model.science/documentation.html

An analysis over sea ice

Simulation of the scattering signals with SMRT

What is the signal sensitive to? Snow depth, Depth hoars, Surface roughness, Ice type?





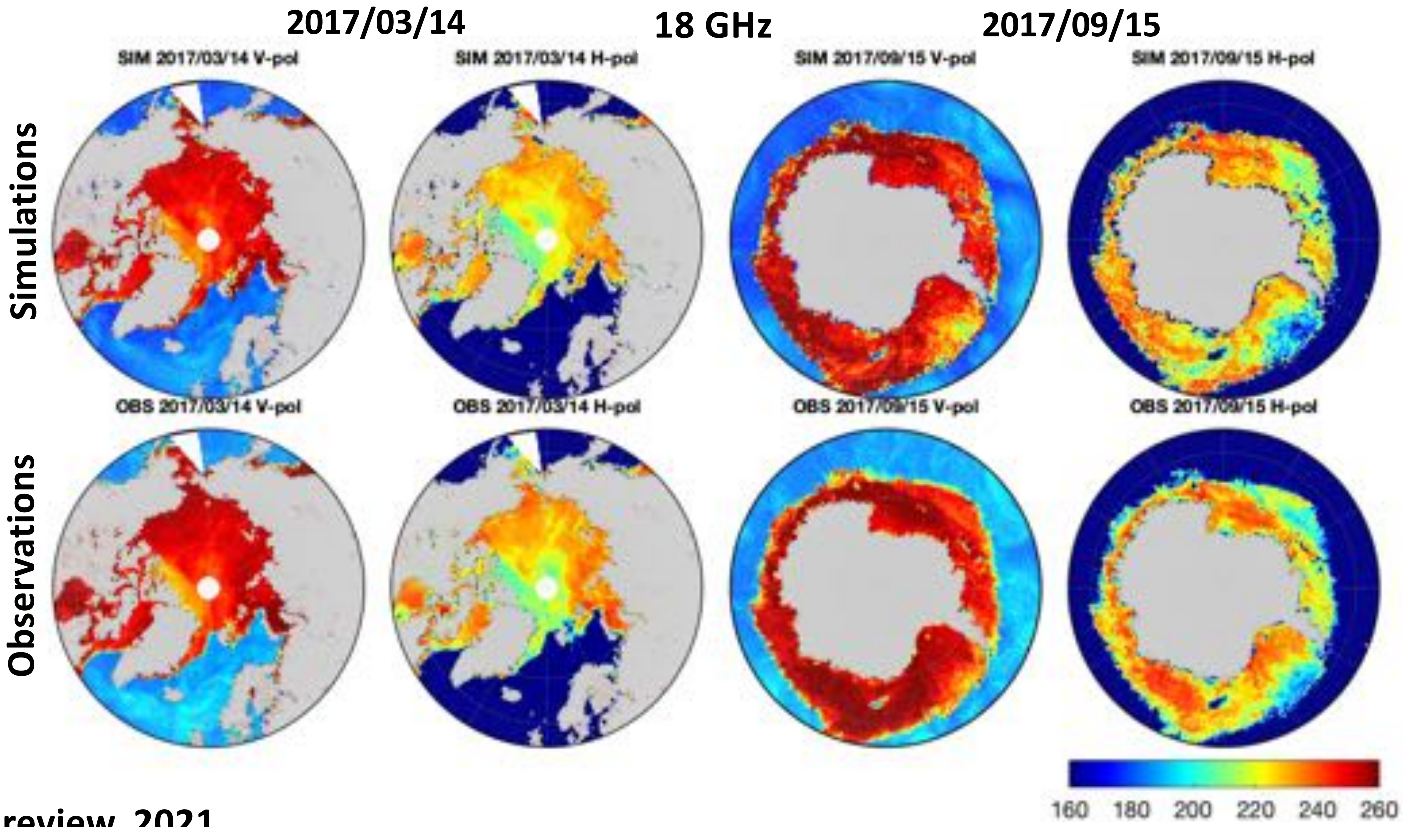
Snow layer with regular small grains cannot scatter the passive observations at 18 and 36 GHz.

Presence of depth hoars over MY ice explain passive observations at 18 and 36 GHz.

The high scattering of σ^0 is not related to the snow nor to the depth hoars, but to surface roughness at the ice snow interface over MY ice.

An analysis over sea ice

<u>Very preliminary</u> sea ice emissivity estimation and tests in Tb space



Jimenez et al., under review, 2021

An analysis over sea ice

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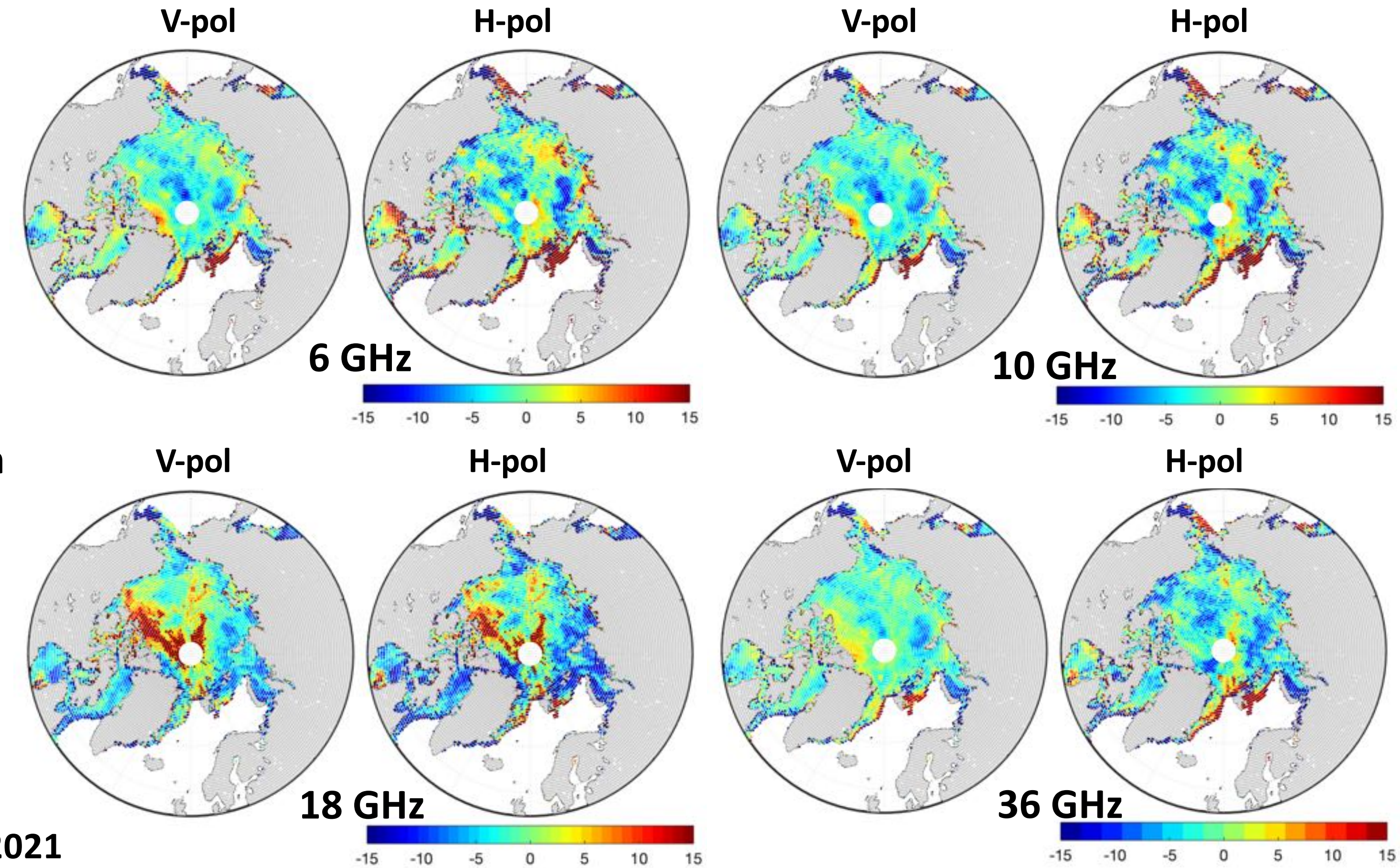


2017/03/04
Simulations - Observation

Jimenez et al., under review, 2021

An analysis over sea ice

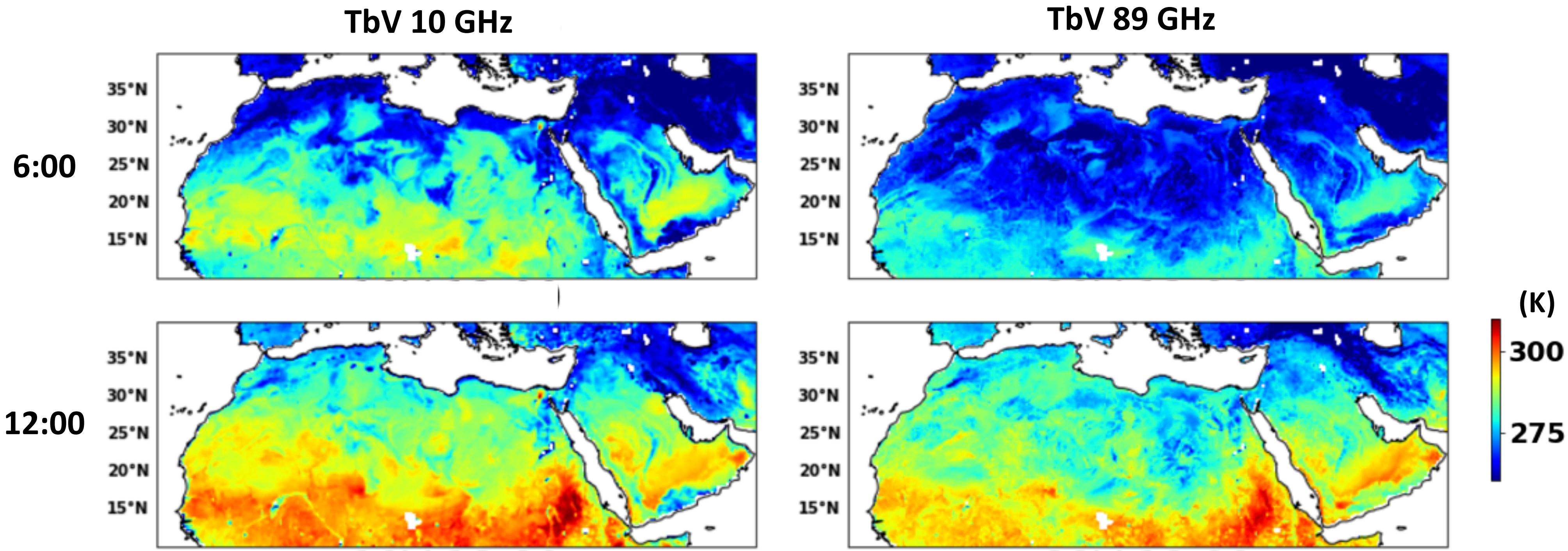
- **Multi frequency, multi instrument analysis of the surface signatures is suggested, to better understand the physics, and isolate the driving geophysical variables.**

- **Once the key driving geophysical variables are isolated, develop a forward model simulator to reproduce the observed signals (possibly based on AI)**

(see also Alan Geer presentation, on Friday)


An analysis over desert

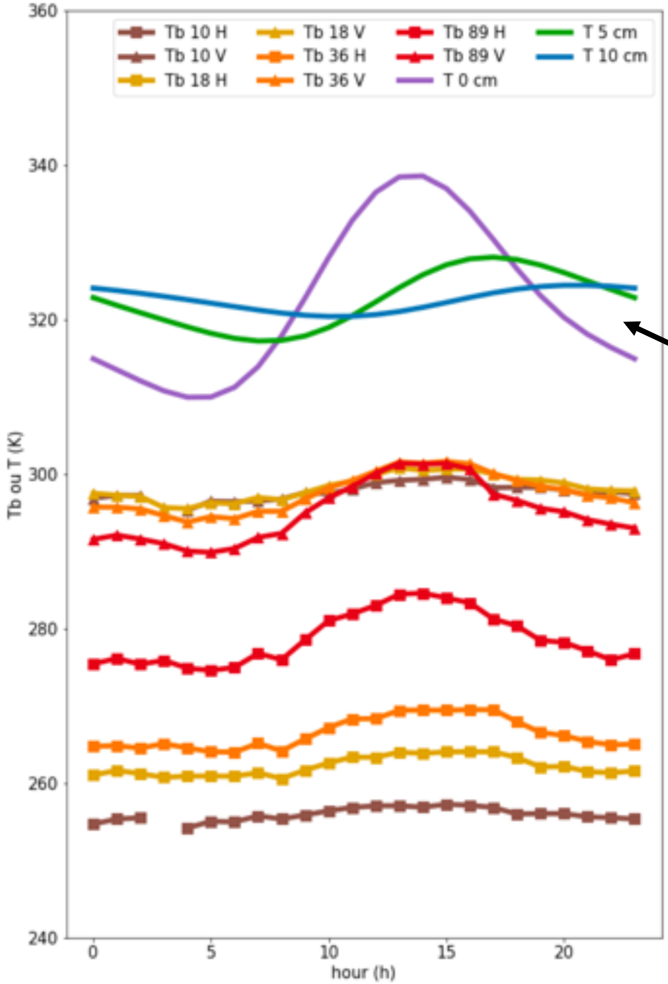
An analysis over desert



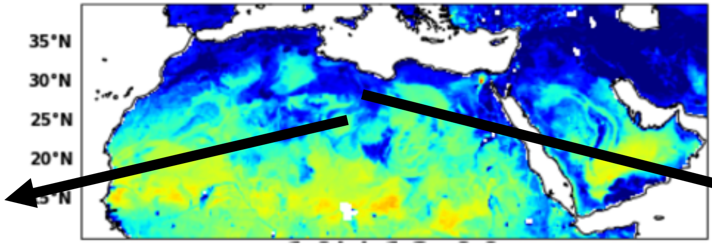
Derived from GMI observations (on non sun-synchronous orbit)

Favrichon, PhD, 2021

An analysis over desert

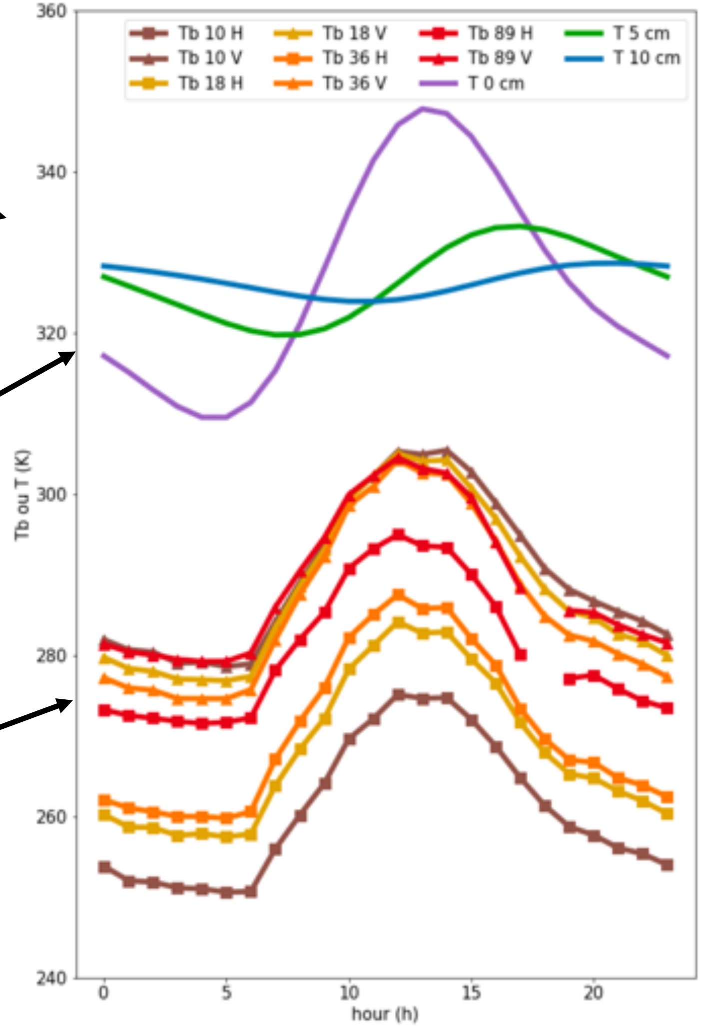


TbV 10 GHz at 6:00



Diurnal cycles of the temperature at the surface and in the sub-surface

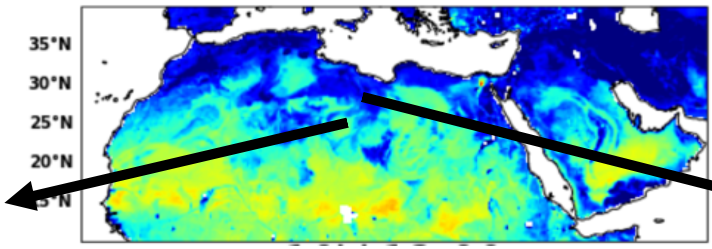
Diurnal cycles of the microwave Tbs from 10 to 89 GHz

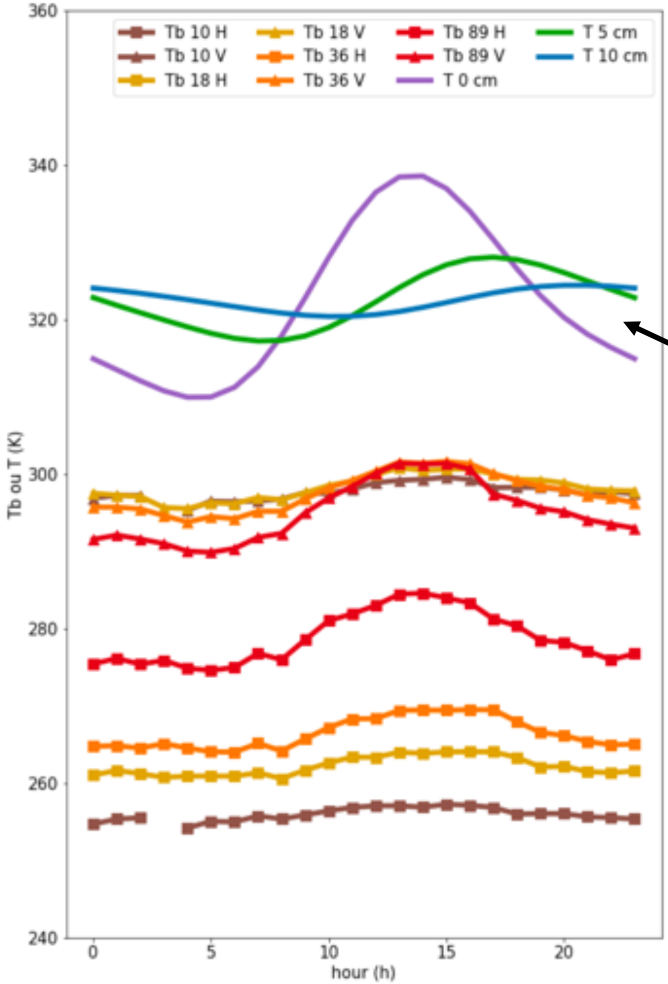


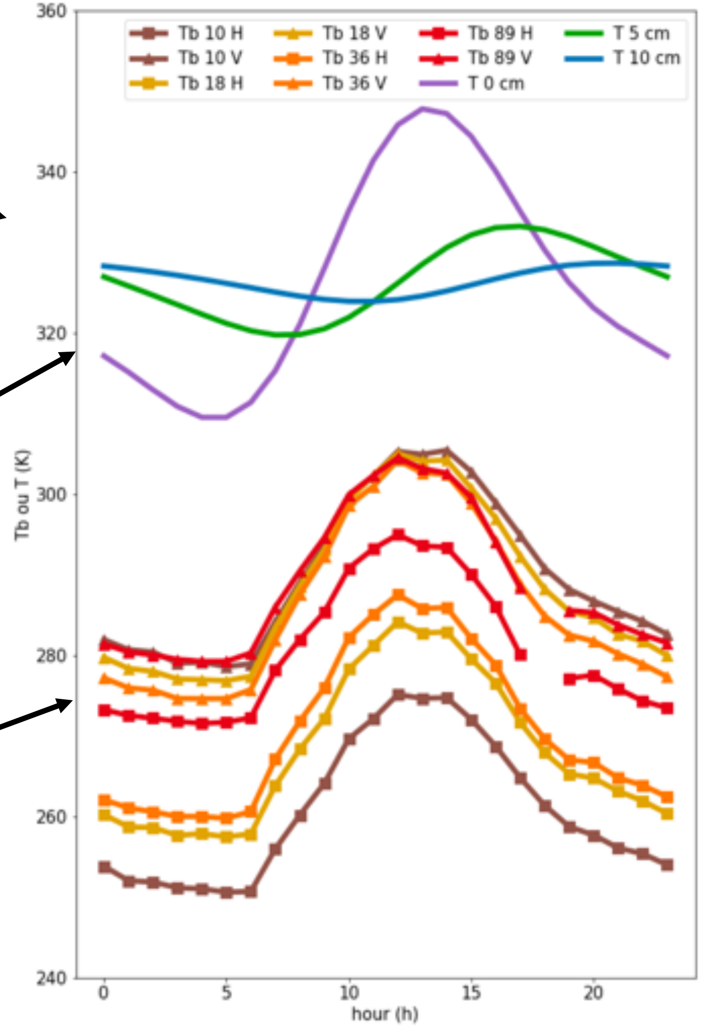
Favrichon, PhD, 2021

An analysis over desert

TbV 10 GHz at 6:00







Diurnal cycles of the temperature at the surface and in the sub-surface

Diurnal cycles of the microwave Tbs from 10 to 89 GHz

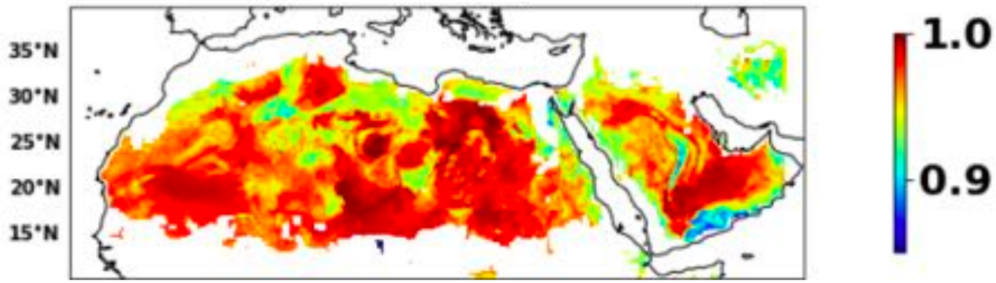
Evidence of the penetration depths of the microwave observations, depending on the frequencies

An analysis over desert

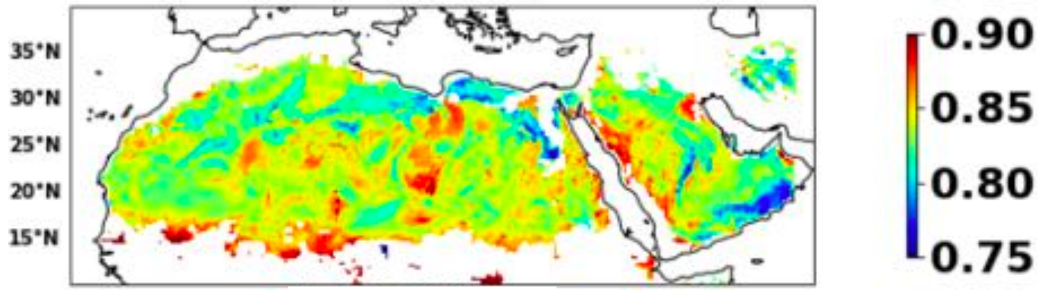
Consistant estimations of emissvities and penetration depths are calculated, using a thermal diffusion model tight to ECMWF surface skin temperature

Emissivity

18 GHz V (55°)

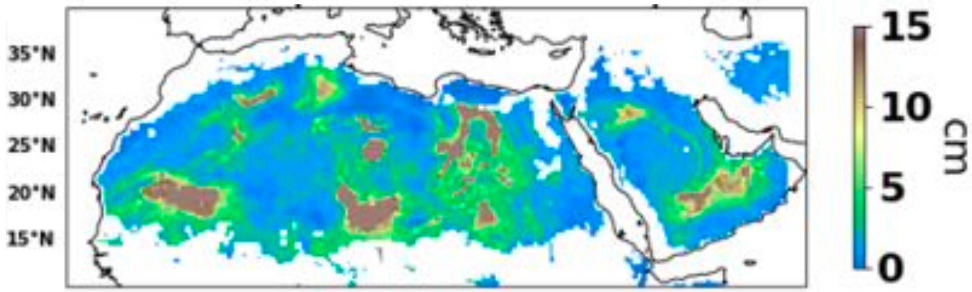


18 GHz H (55°)

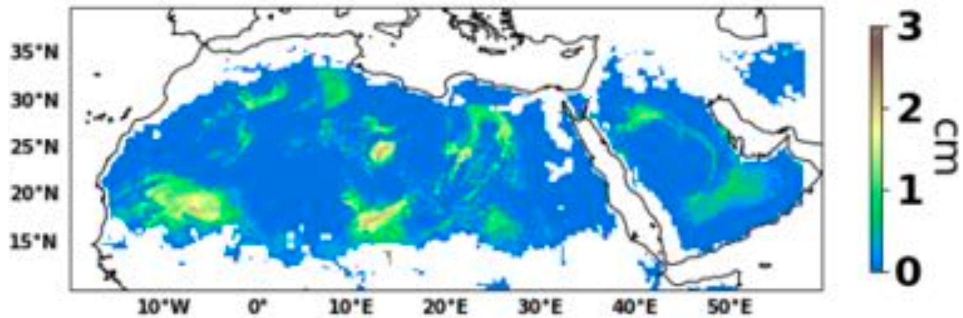


Penetration depth

10 GHz



89 GHz

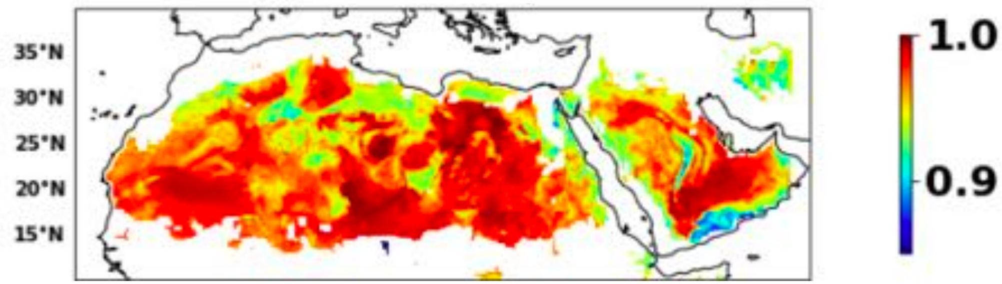


Favrichon, PhD, 2021

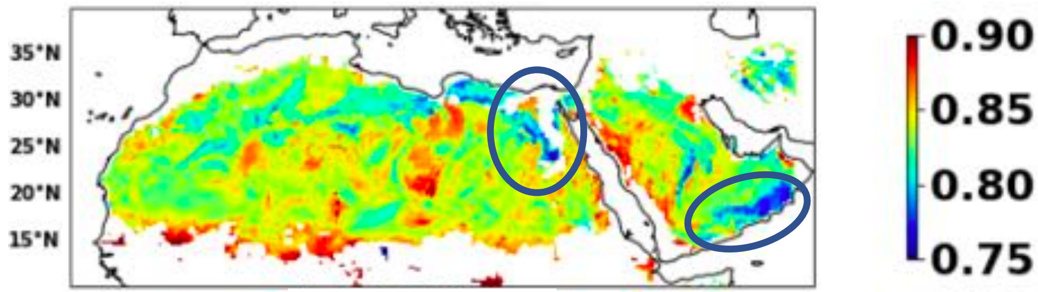
An analysis over desert

Emissivity

18 GHz V (55°)



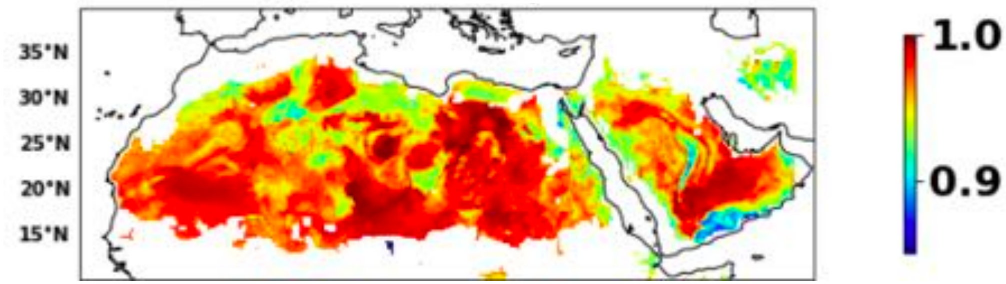
18 GHz H (55°)



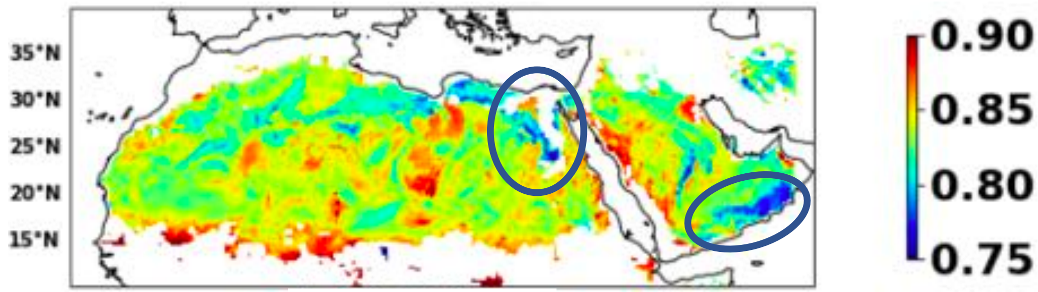
An analysis over desert

Emissivity

18 GHz V (55°)

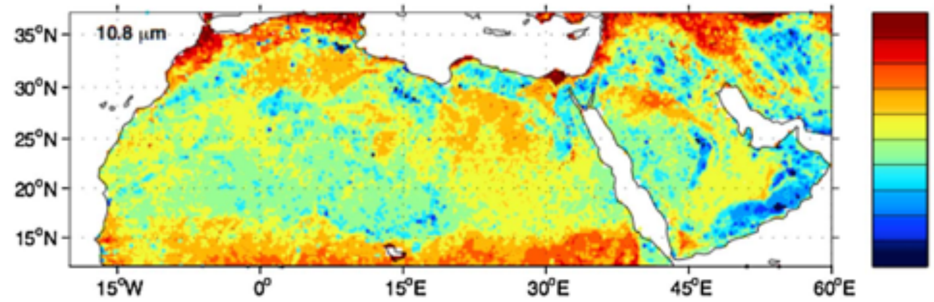


18 GHz H (55°)



The very low microwave emissivities are also visible at 10.8μm in the IR emissivities at the same locations. They are related to the presence of carbonates.

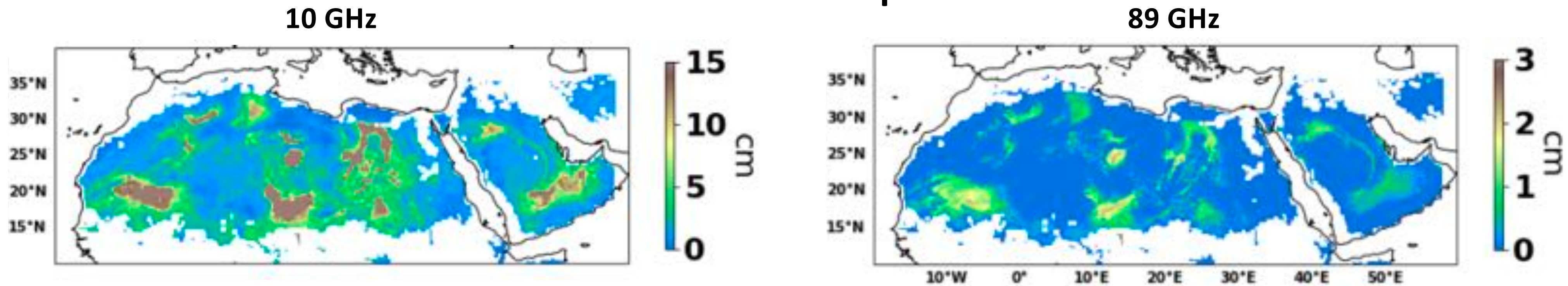
IR emissivity at 10.8μm



Jimenez et al., JGR, 2010; Favrichon, PhD, 2021

An analysis over desert

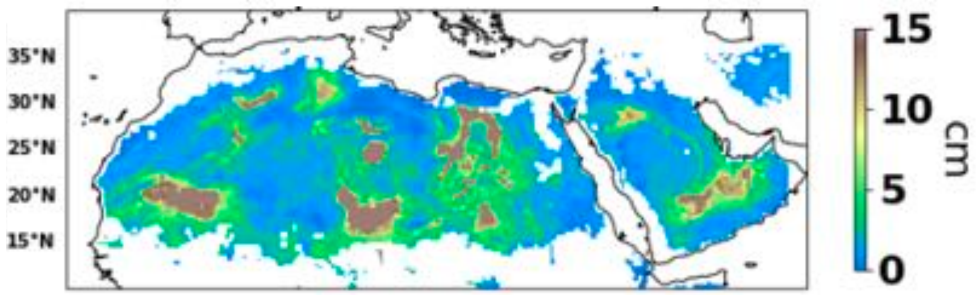
Penetration depth



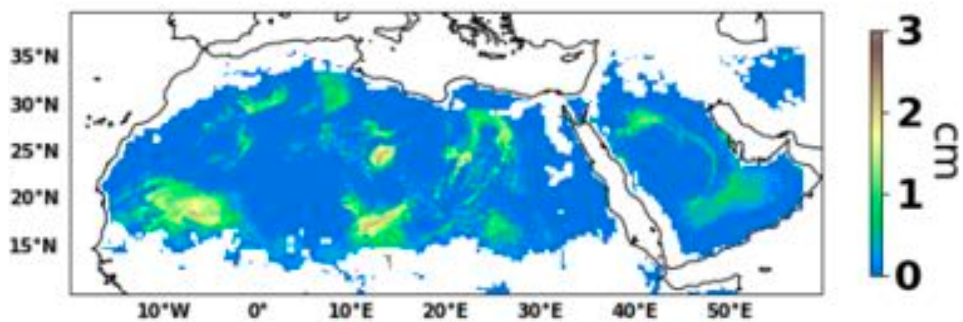
An analysis over desert

Penetration depth

10 GHz

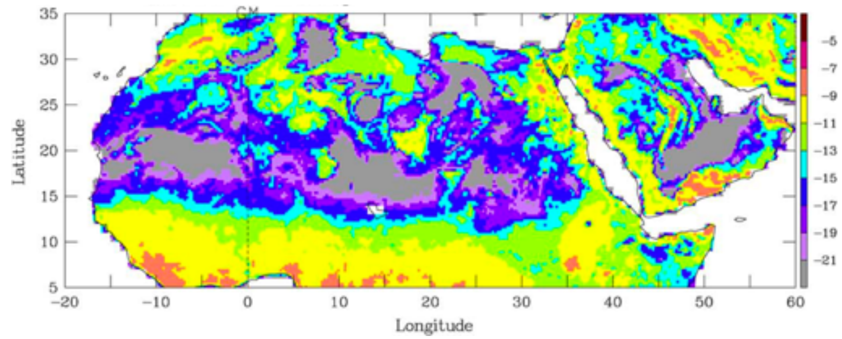


89 GHz



The high penetration depth in the microwaves is also observed with the scattrometers (low backscatter).

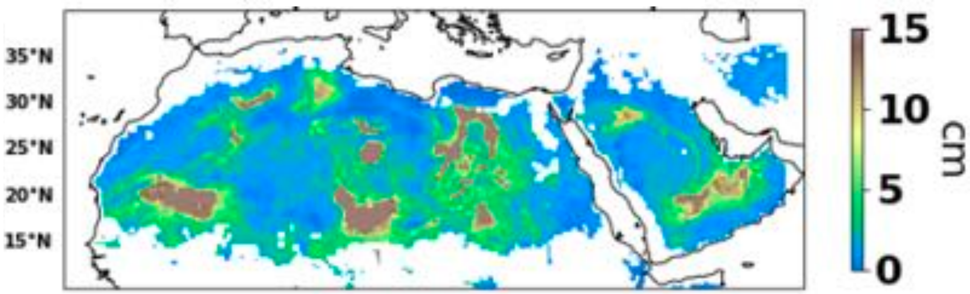
Backscattering at 5 GHz



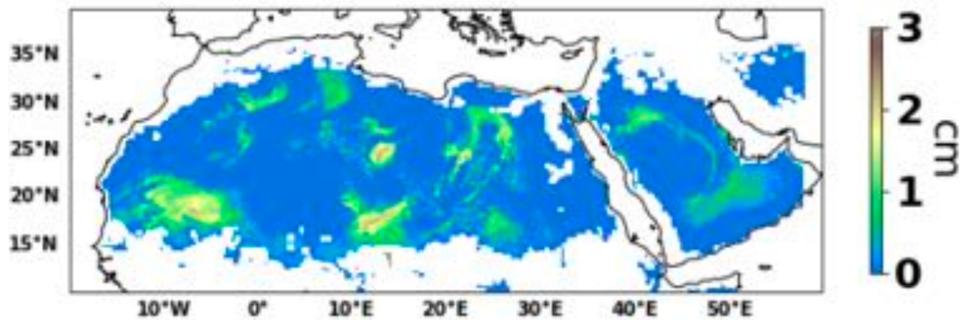
An analysis over desert

Penetration depth

10 GHz

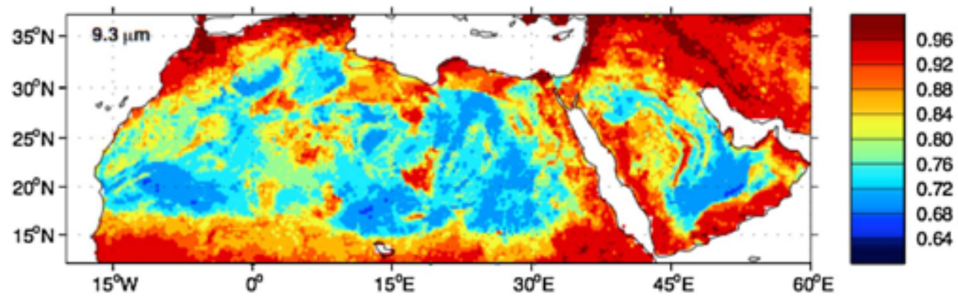


89 GHz

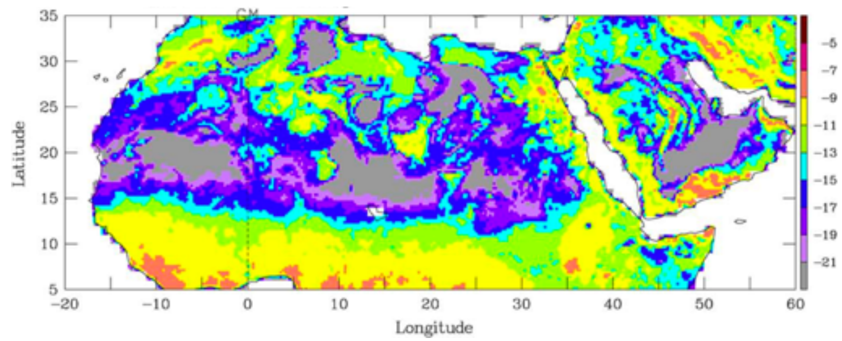


The high penetration depth in the microwaves is also observed with the scattrometers (low backscatter).
It is associated to the presence of dry silicate sands (as also observed with low emissivity in the IR at 9.3 μm).

IR emissivity at 9.3μm



Backscattering at 5 GHz



Jimenez et al., JGR, 2010; Favrichon, PhD, 2021

An analysis over desert

Over deserts, the high variability of the surface contribution is associated to mineral outcrops (not considered in models) and to penetration depth in dry sands.

For the simulation of the microwave surface contribution over desert:

- Climatology of microwave satellite-derived surface emissivity, consistant with IR emissivity

- Development of a thermal diffusion module to estimate the effective emission temperature, tight to the ECMWF surface skin temperature and using pre-calculated penetration depth

SOIL AND VEGETATED SURFACES

Over soil and vegetated surfaces

For soil moisture analysis

Statistical NN inversions for the soil moisture are already in place

- For SMOS / SMAP, but also for ASCAT and simultaneously for multiple instuments.
- The inversion is directly trained on coincident satellite observations and modeled soil moisture

(Aires et al., 2021)

Statistical forward operator are developed or under developments

- For SMOS / SMAP or ASCAT, based on NN
- The operator is directly trained on coincident satellite observations and modeled soil moisture

(Aires et al., 2005; Kolassa et al., 2013, 2017; Rodriguez-Fernandez et al., 2019….)

(Patricia de Rosnay presentation later in the day, and Jana Kolassa presentation on Friday)

Over soil and vegetated surfaces

For vegetation analysis

- Microwave observations sensitive to Vegetation Water Content, to Above Ground Biomass, to vegetation structure...?
- How to relate these variables to the microwave signal in an efficient way, consistent with the surface model? With rather limited vegetation parameters in the model…

Over soil and vegetated surfaces

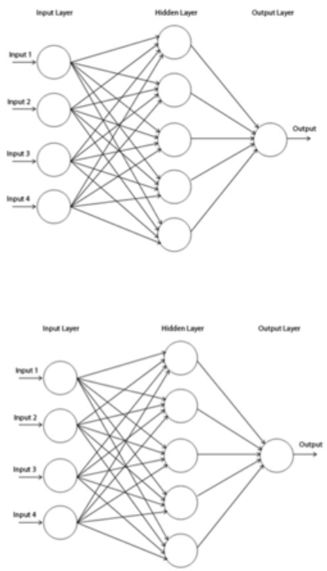
Testing the information content of multi-frequencies and their synergies over the Tropics for vegetation characterization

Passive microwave observations

SMAP
1.4 GHz

AMSR2
6, 10, 18, 36 GHz

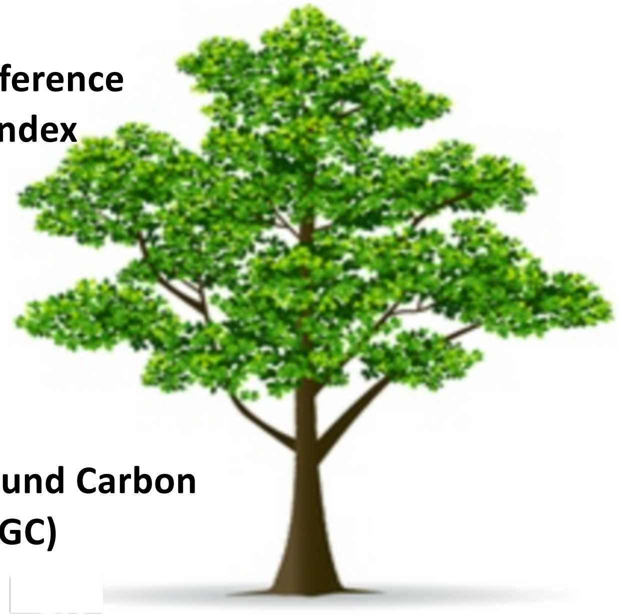
Statistical inversion



Vegetation parameters

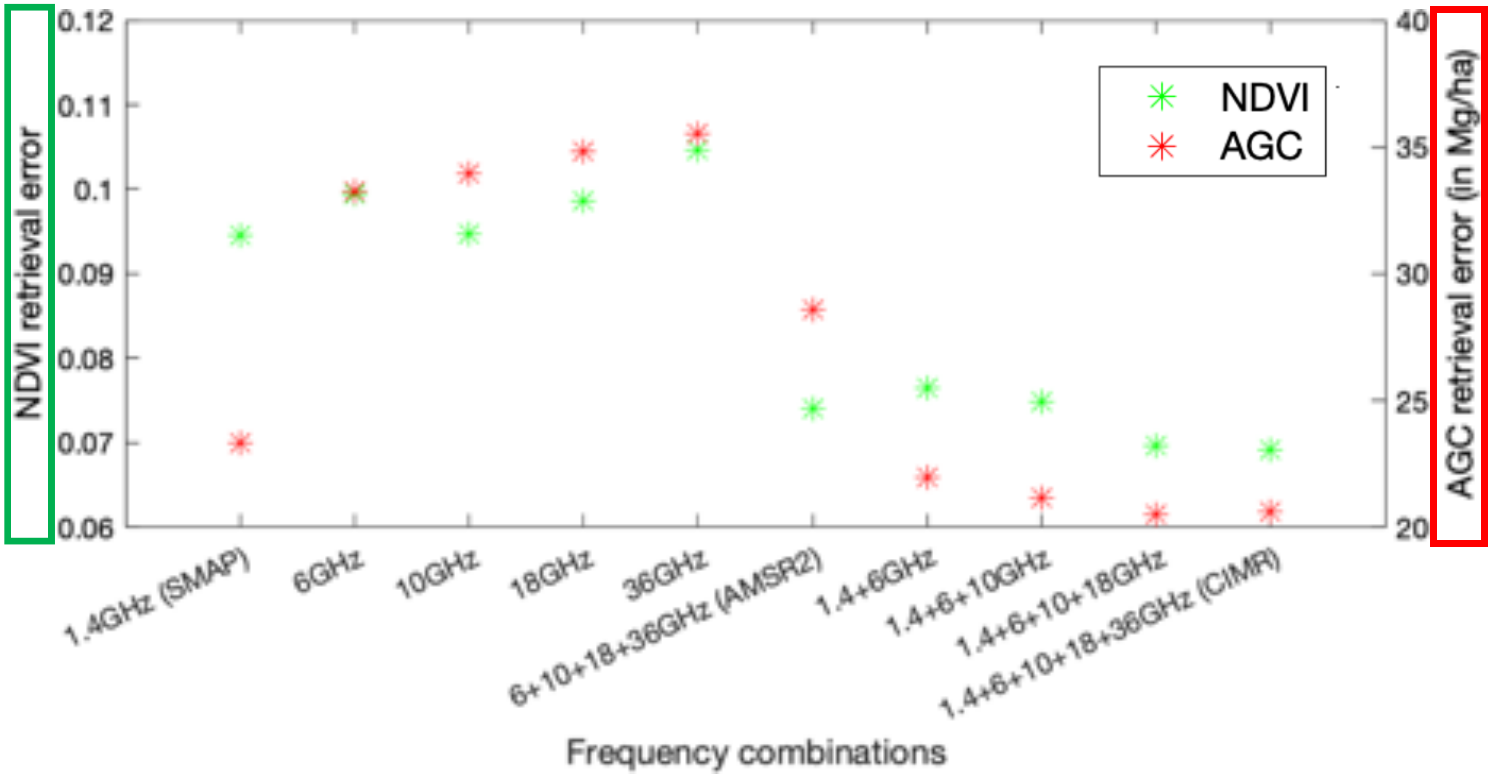
Normalized Difference Vegetation Index (NDVI)

Above Ground Carbon (AGC)



Over soil and vegetated surfaces

Results of the NN inversion of two vegetation parameters,
using different frequency combinations of passive microwave observations, including SMAP, AMSR2

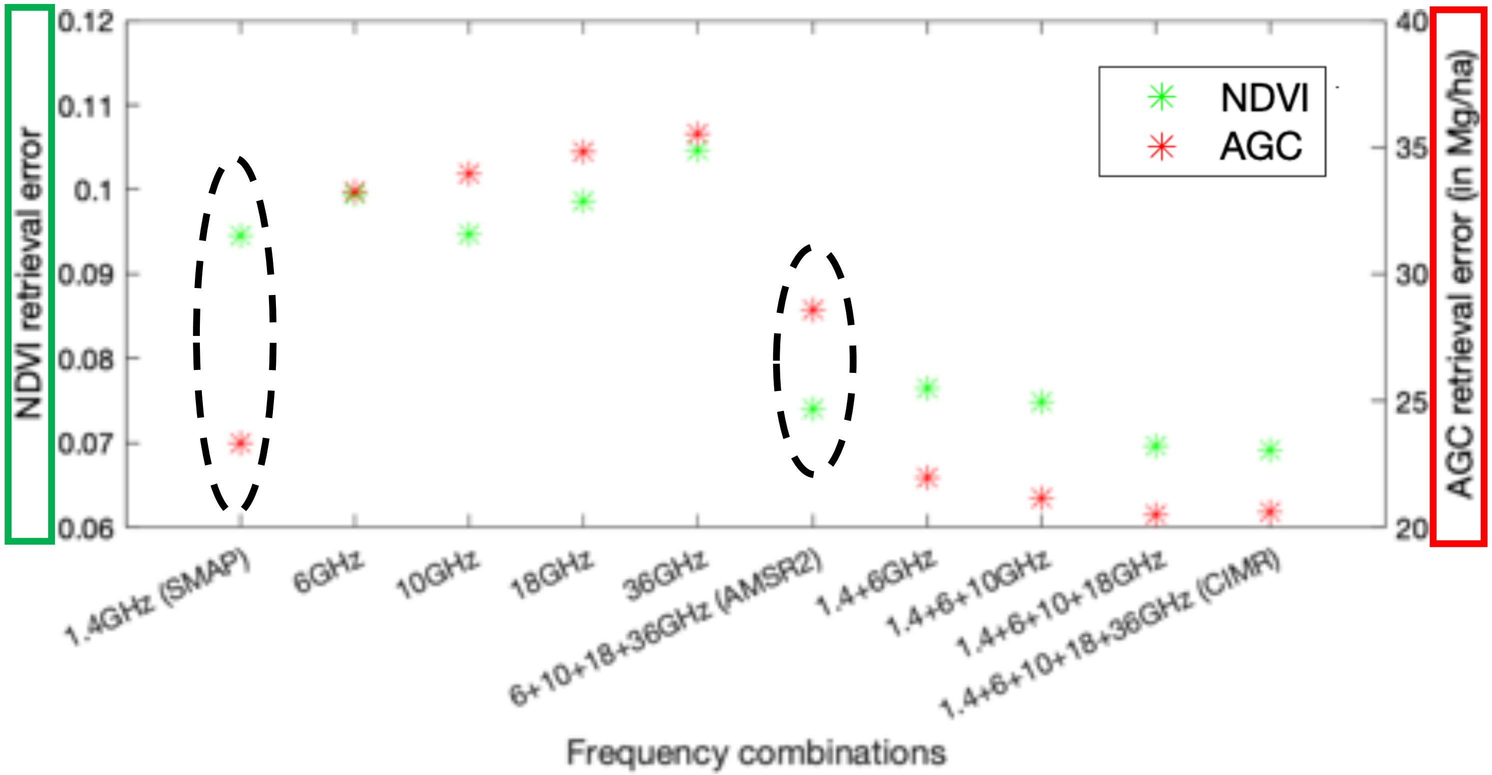


Over soil and vegetated surfaces

Results of the NN inversion of two vegetation parameters,
using different frequency combinations of passive microwave observations, including SMAP, AMSR2

1.4 GHz outperforms the other frequencies alone, for the estimation of biomass in Tropical areas.

AMSR2 frequency combination is efficient to reproduce NDVI (LAI).



Over soil and vegetated surfaces

Results of the NN inversion of two vegetation parameters, using different frequency combinations of passive microwave observations, including SMAP, AMSR2

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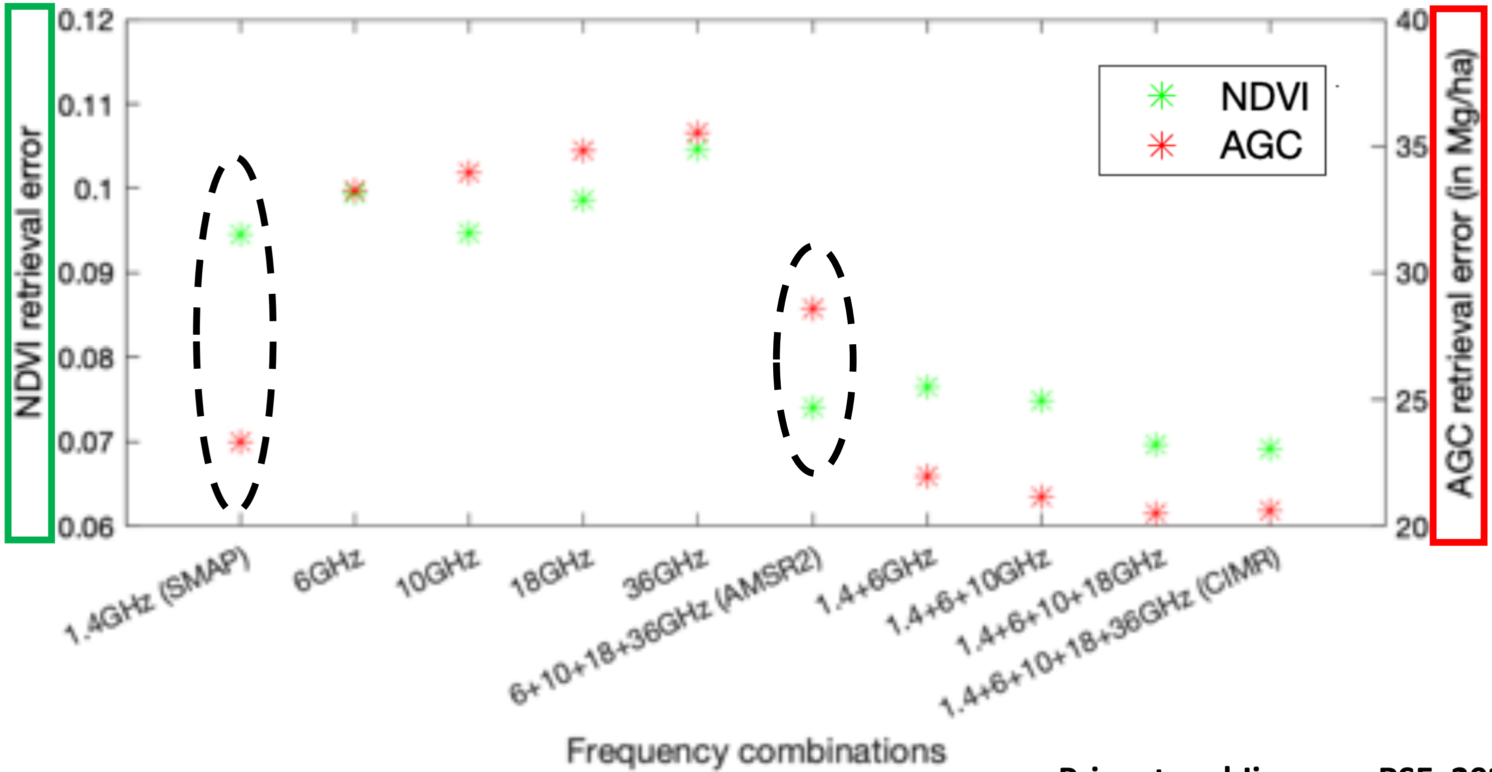
AMSR2 frequency combination is efficient to reproduce NDVI (LAI).

ASCAT tests are underway, with the same methodology

At global scales, soil humidity to be added as input parameter



Prigent and Jimenez, RSE, 2021

CONCLUSION

Conclusion

Over ocean

- **Rather robust radiative transfer models exist**

- **There is an on-going community effort to refine a reference physical model (PARMIO) and to insure its maintenance over time.**

- **The development of the corresponding fast emissivity model is under way (based on NN model).**

Conclusion

Over land, snow, ice, sea ice

- **Phyiscally-based radiative transfer land surface models still very challenging** for large scale applications, under multiple instrument conditions and diverse environments.

- **Satellite-derived emissivity estimates** can provide reasonable first guess **with realistic multi-frequency co-variabilities, spatial patterns and temporal behaviors, at global scale.**

- **Several decades of satellite data** are **available** (multi-frequency, angle, polarization, mode).
  We can learn a lot from this multi-dimension dataset, possibly using AI techniques.

- **Need to gain a thourough understanding of the geophysical parameters that drive the surface contribution variabilities**, consistently at multiple frequencies and observing conditions, with the help of statistical analysis and radiative transfer modeling.

Conclusion



Over land, snow, ice, sea ice

Physics-aware statistical parameterization of the surface contribution ?

as a function of :

- **instrument characteristics (frequency, incidence angle, polarization)**
- **geophysical variables from the Land Surface Model / Ocean model**
- **additional ancillary data (if needed)**

Some already developed or under development for SMOS / SMAP and ASCAT for soil moisture.
More to come?

Consistent forward operator codes to be used for forward and inverse modeling, for coupled assimilation system

(see also presentations by Patricia de Rosnay, Jana Kolassa, and Alan Geer)

Thank you!

catherine.prigent@obspm.fr