Challenges in the Modeling / Parameterization of the Surface Contribution in the Microwaves

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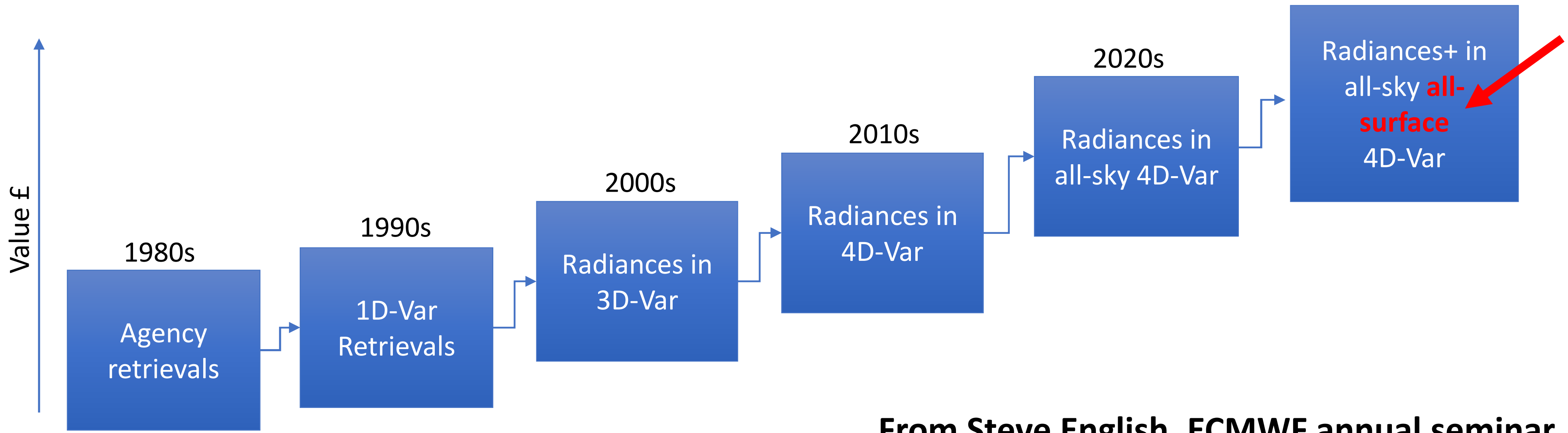
With contributions from Carlos Jimenez, Lise Kilic, Filipe Aires, Iris de Gelis and many other collaborators





The next key challenge in Numerical Weather Prediction (NWP): the assimilation of all-surface radiances



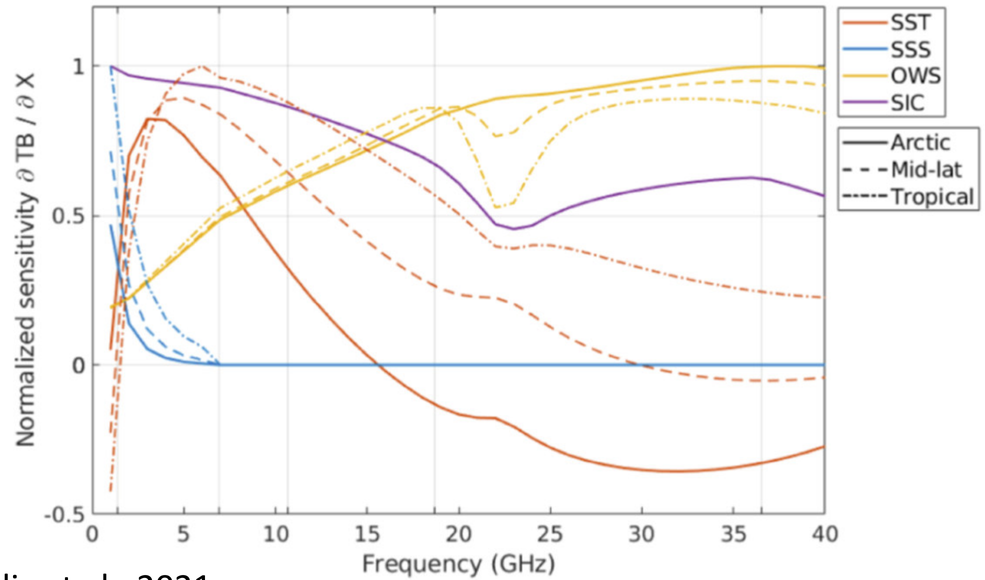
From Steve English, ECMWF annual seminar, 2021

That clearly requires an accurate estimation of the surface contribution

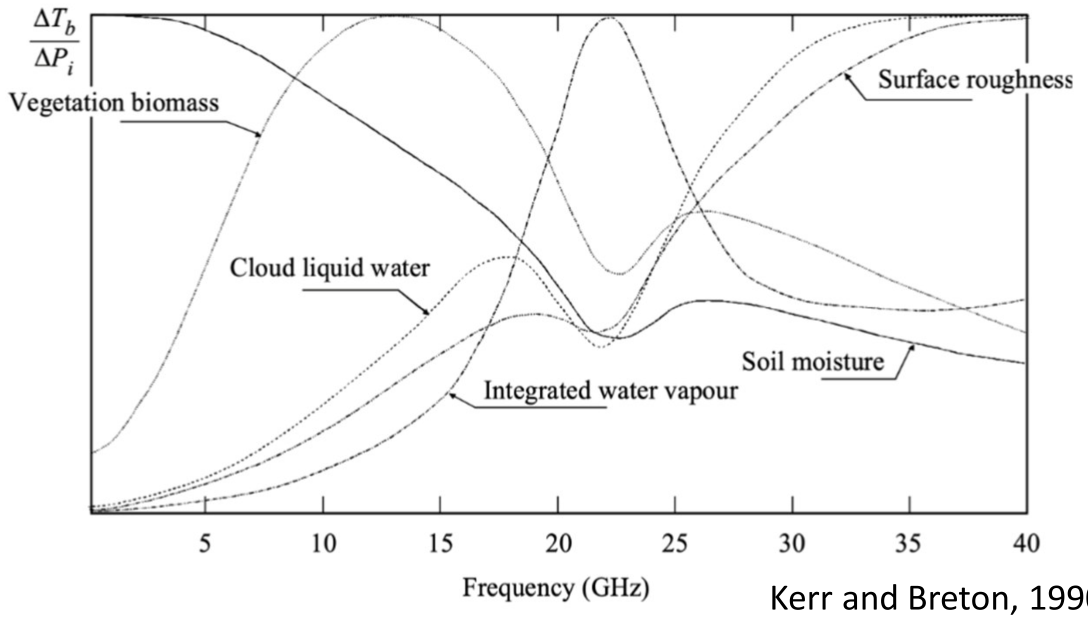
- **for all surface-sensitive observations**
- **for all surfaces**

Necessity to model / parameterize the surface radiative transfer for the retrieval of surface parameters

Normalized sensitivities of satellite measurements to geophysical variables as a function of frequency



Kilic et al., 2021



Kerr and Breton, 1990

Over ocean

Over land

Outline of the talk

1) General considerations

2) Ocean

   Physically-based models, and their fast version

3) Land, snow, and sea ice

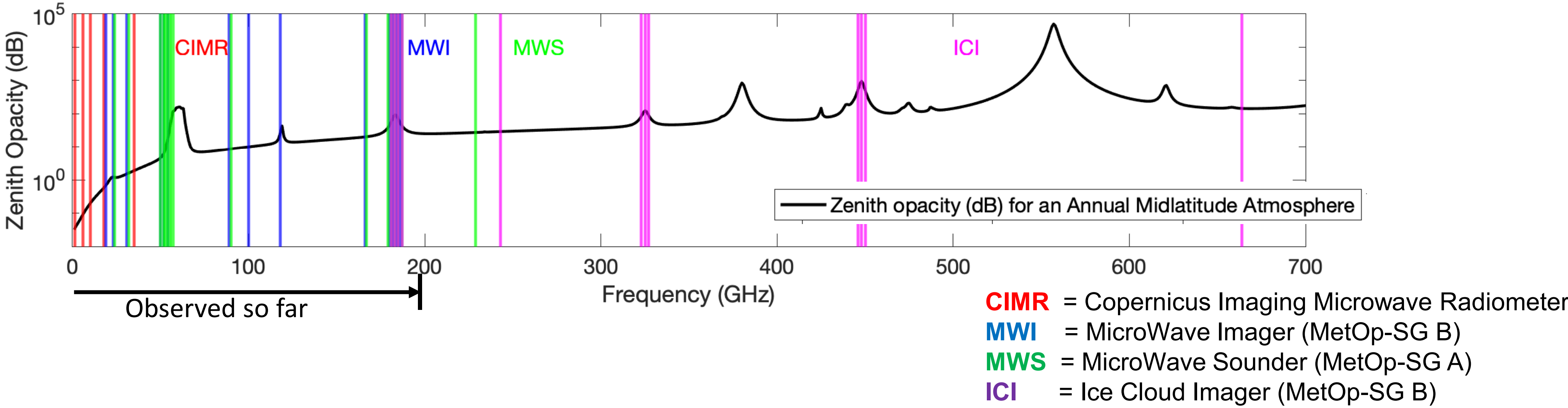
   Physically-based model?

   Or emissivity parameterization based on the available surface information and satellite-derived emissivity?

   A sea ice emissivity parameterization, as an example

4) Conclusion

The bright future of passive microwave observations in Europe



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

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

For **surface characterization,** selection of atmospheric ‘windows’ and the surface contribution is the **information.**

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

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

- **across frequencies**: from low microwaves to millimeter waves. Possibly including the infrared.
- **across observing conditions**: incidence angle, polarization. For both passive instruments (emissivity) and active instruments (backscattering).
- **across applications**: for NWP, for atmospheric retrieval as well as for the retrieval of surface properties.

Consistency required to optimize the exploitation of multi-frequency, multi-instrument capability, for both atmospheric and surface characterizations

Toward coupled land / ocean / atmosphere assimilation systems

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 physically-based radiative transfer models exist.

Microwave sea surface emissivity models

Physically-based models

two-scale models valid from long microwaves to IR

(examples: Yueh, 1997; Dinnat et al., 2003; Yin et al., 2012; Dinnat et al., 2023)

Fast models parameterized from physically-based models

(examples: FASTEM, TESSEM^2, SURFEM-Ocean)

distributed with RTTOV or CRTM

Models fitted to satellite observations

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

They all include:

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

An international team was formed, 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**

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

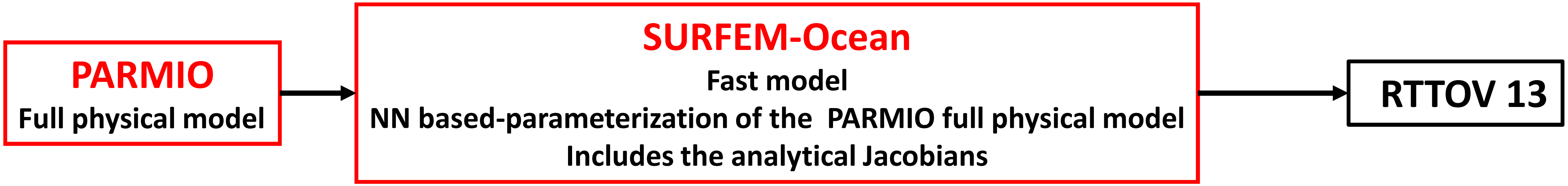
English et al., BAMS, 2020; Dinnat et al., BAMS, 2023

- **A physically-based reference ocean model** was **selected:**
  PARMIO (Passive and Active Reference Microwave to Infrared Ocean)
  (Dinnat et al., 2003; Yin et al., 2012, 2016; Dinnat et al., 2023)

- **Extensively evaluated with multiple observations at global scale** (SMAP, AMSR, GMI, ATMS) (Kilic et al., JGR, 2019).

- **Adjustments made to the initial model to better fit the observations under cold temperatures and for high wind speeds.**

- **A fast code derived from this model,** with similar inputs as FASTEM, along with Jacobians and error estimates, **SURFEM-Ocean**, included in RTTOV 13 (Kilic et al., ESS, 2023) and successfully tested at ECMWF (Geer et al., 2024) for activation in the next operational cycle.



BAMS
Meeting Summary

PARMIO

A Reference Quality Model for Ocean Surface Emissivity and Backscatter from the Microwave to the Infrared

Emmanuel Dinnat, Stephen English, Catherine Prigent, Lise Kilic, Magdalena Anguelova, Stuart Newman, Thomas Meissner, Jacqueline Boutin, Ad Stoffelen, Simon Yueh, Ben Johnson, Fuzhong Weng, and Carlos Jimenez

https://doi.org/10.1175/BAMS-D-23-0023.1

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Earth and Space Science

RESEARCH ARTICLE
10.1029/2022EA002785

Development of the SURface Fast Emissivity Model for Ocean (SURFEM-Ocean) Based on the PARMIO Radiative Transfer Model

Lise Kilic[1,2], Catherine Prigent[1,2], Carlos Jimenez[1,2], Emma Turner[3], James Hocking[3], Stephen English[4], Thomas Meissner[5], and Emmanuel Dinnat[6]

[1]Observatoire de Paris, CNRS, LERMA, Sorbonne Université, Université PSL, Paris, France, [2]Estellus, Paris, France, [3]Met Office, Exeter, UK, [4]European Centre for Medium-Range Weather Forecasts, Reading, UK, [5]Remote Sensing Systems, Santa Rosa, CA, USA, [6]NASA Goddard Space Flight Center, Greenbelt, MD, USA

Key Points:

- An international team of experts has converged on the selection of a Passive and Active Reference Microwave to Infrared Ocean model
- A fast version of the ocean microwave emissivity model has been developed, named SURFace Fast Emissivity Model for Ocean (SURFEM-Ocean)
- SURFEM-Ocean is evaluated by comparisons with a large database of passive microwave satellite observations

Abstract A Passive and Active Reference Microwave to Infrared Ocean (PARMIO) physical radiative

Technical Memo

ECMWF
European Centre for Medium-Range Weather Forecasts

915

SURFEM-ocean microwave surface emissivity evaluated

Alan J. Geer, Cristina Lupu, David Duncan, Niels Bormann and Stephen English
(Research Department)

February 2024

LAND, SNOW, ICE, SEA ICE




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

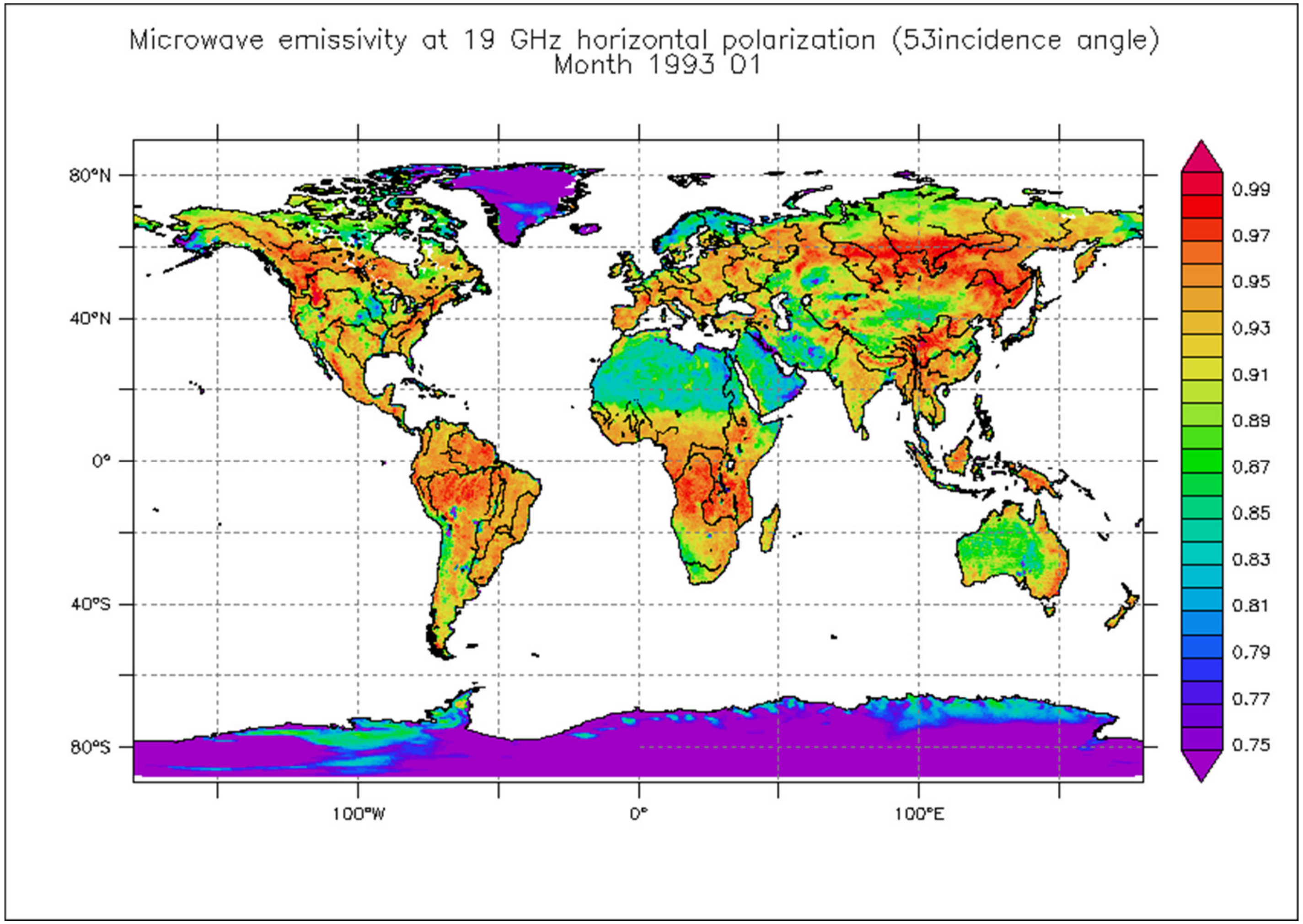
Open ocean: a rather homogeneous surface
=> Robust radiative transfer models exist

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

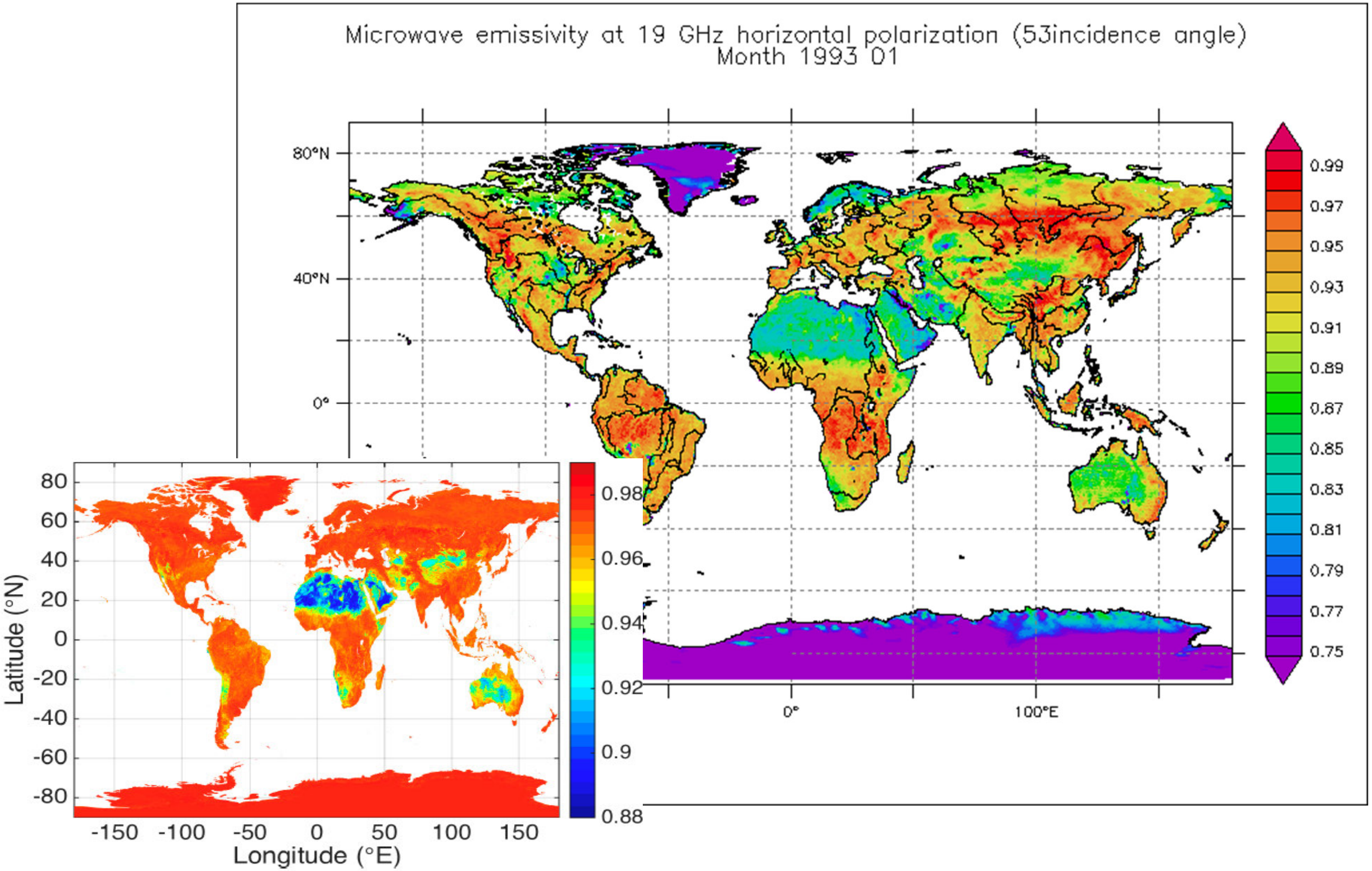
- How to realistically simulate these surface contributions at satellite observation scales?
- How to capture the major geophysical parameters that drive their variability?
- How to develop the forward operator, as a function of these geophysical parameters?




Space and time variability of the microwave land surface emissivity



Space and time variability of the microwave land surface emissivity



Generic land surface microwave emission models

Community Microwave Emission Model (CMEM) at ECMWF

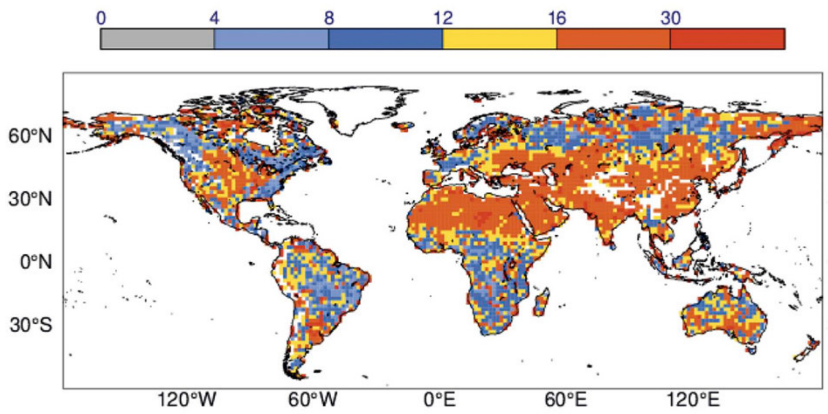
(Drusch et al., JHM, 2009, de Rosnay et al., RSE, 2020)

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)

Specific work at 1.4 GHz, for SMOS

Before bias correction

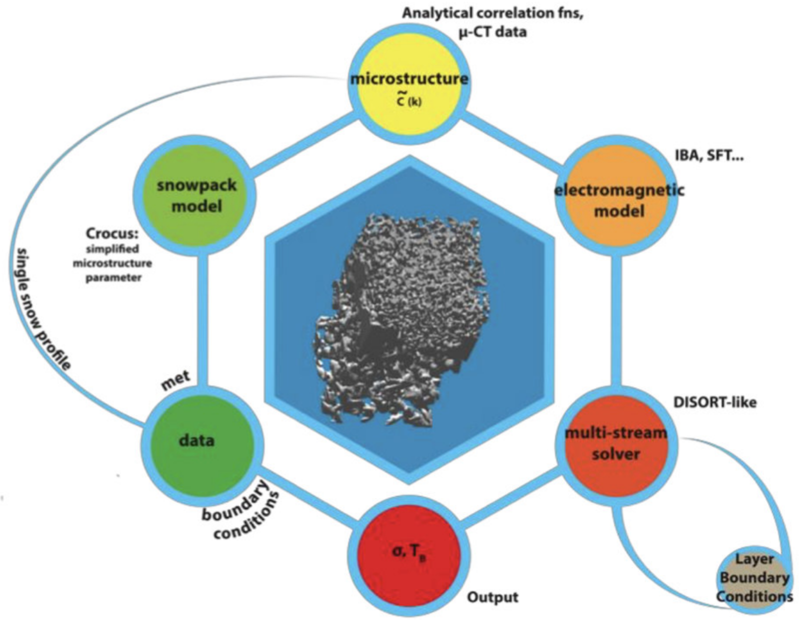


RMSE (K)

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

Specific microwave emissivity physical models

For snow, ice, sea ice



An ISSI team for microwave snow and se ice emissivity modeling

INTERNATIONAL SPACE SCIENCE INSTITUTE

Snow/Sea Ice Emission and Backscatter Modelling

ISSI Team led by Sandells M. & Mätzler C.

SMRT (Snow Microwave Radiative Transfer)

(Picard et al., GMD, 2018,

https://www.smrt-model.science/documentation.htm)

- Can handle several physical scattering assumptions, as well as multiple geophysical conditions.
- Passive and active microwaves
- A user friendly inter-active version available

- Help explain processes and interprete the observations
- Suitable for continental / global applications, for operational implementation?

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

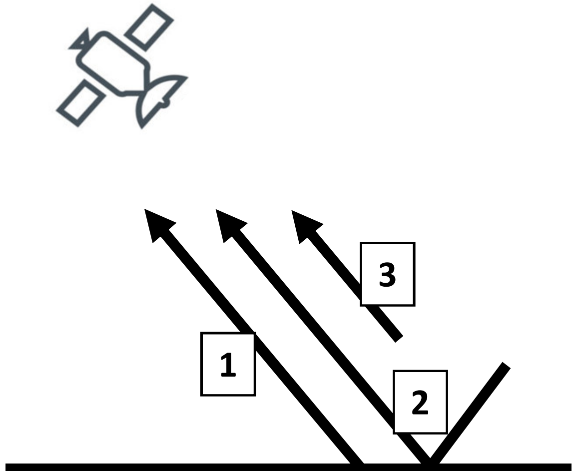
- Difficulty to capture the high spatial and temporal heterogeneity

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

- Difficulty 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.

TELSEM^2

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)

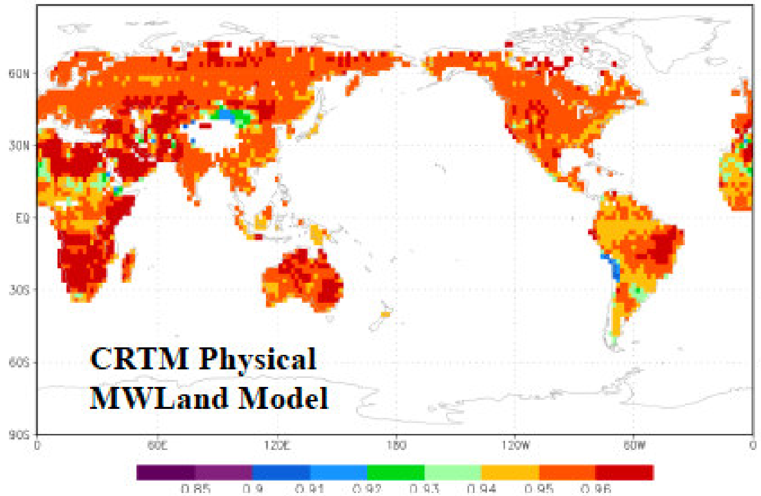
- It provides global atlases of emissivity for all continental and sea-ice surfaces, from 18 to 700 GHz, monthly mean, at 25 km resolution.
- **Inputs:** **lat, lon, month, frequency, and incidence angle.**
- **Outputs:** **emissivities in V and H polarizations, along with error covariances**
- Realistic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

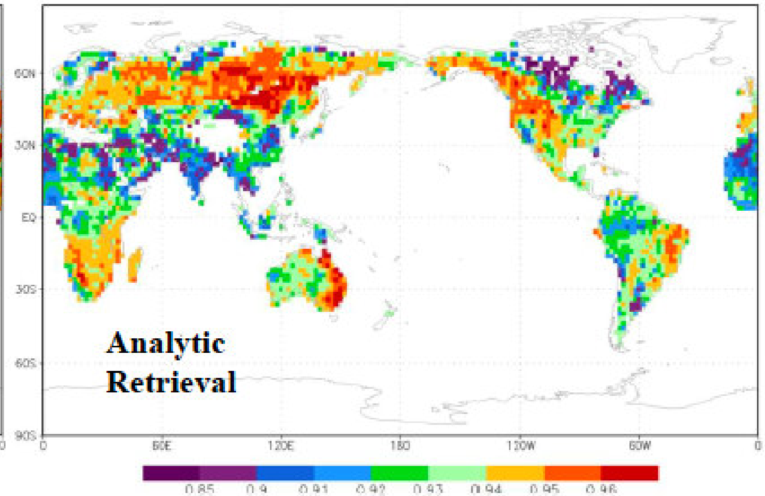
Updating needed with new emissivity estimates, especially below 18 GHz
(AMSR + SMAP + SMOS)

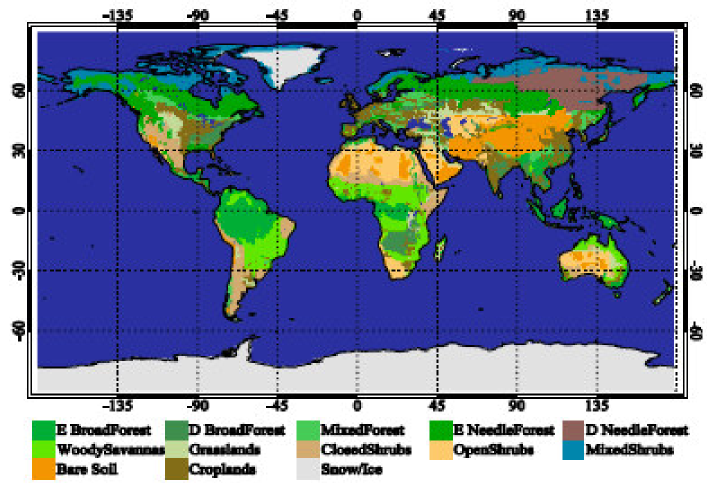
Comparison between modeled and satellite-derived emissivities

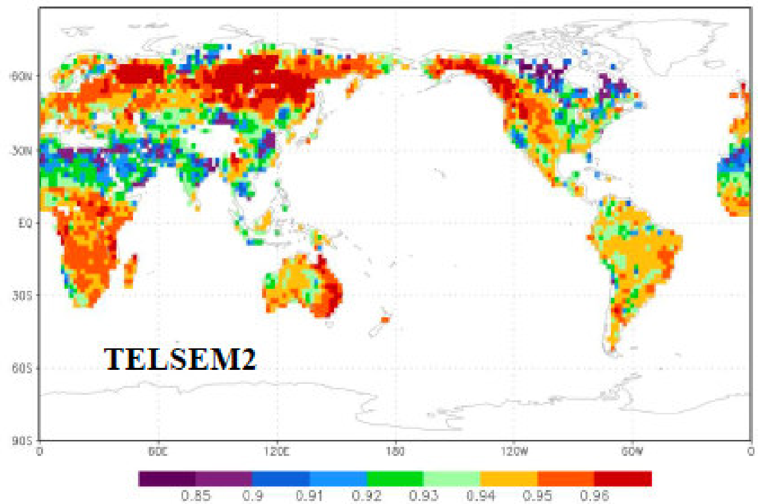
At NOAA
(Chen et al., 2019)

Very challenging to reproduce the observed emissivities with a radiative transfer model at global scale









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 L1 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…

Suggested method :

1) Revise and extent the satellite-derived emissivity database

- Satellite-derived emissivity calculated for the full time series of SSM/I, SSMIS, AMSR2, SMAP, and SMOS, over the continents and sea ice

  => **a huge emissivity database**…

- With ERA5 inputs for the atmosphere and the surface temperature (Tskin)

Suggested method :

1) **Revise and extent the satellite-derived emissivity database**

2) **Select potential predictors for the parameterization of the emissivities**

   - Avalaible easily over long time series
   - Preferably from reanalysis (ERA5)
   - From well-recongized community models when reanalysis information not enough

Suggested method :

1) **Revise and extent the satellite-derived emissivity database**

2) **Select potential predictors for the parameterization of the emissivities**

3) **Statistically relate the satellite-derived emissivities to the relevant geophysical parameters available at global scale**

   - Use of machine learning method, to account for complex relationships between geophysical parameters and emissivity

   - Neural Network parameterization suggested

Suggested method :

1) **Revise and extent the satellite-derived emissivity database**

2) **Select potential predictors for the parameterization of the emissivities**

3) **Statistically relate the satellite-derived to the relevant geophysical parameters available at global scale**

4) **Derive a physics-aware statistical parameterization of the surface emissivity**
   - as a function of :
     - instrument characteristics (frequency, incidence angle, polarization)
     - geophysical variables from reanalysis, Land Surface Model / Sea Ice Model

Suggested method :

1) **Revise and extent the satellite-derived emissivity database**

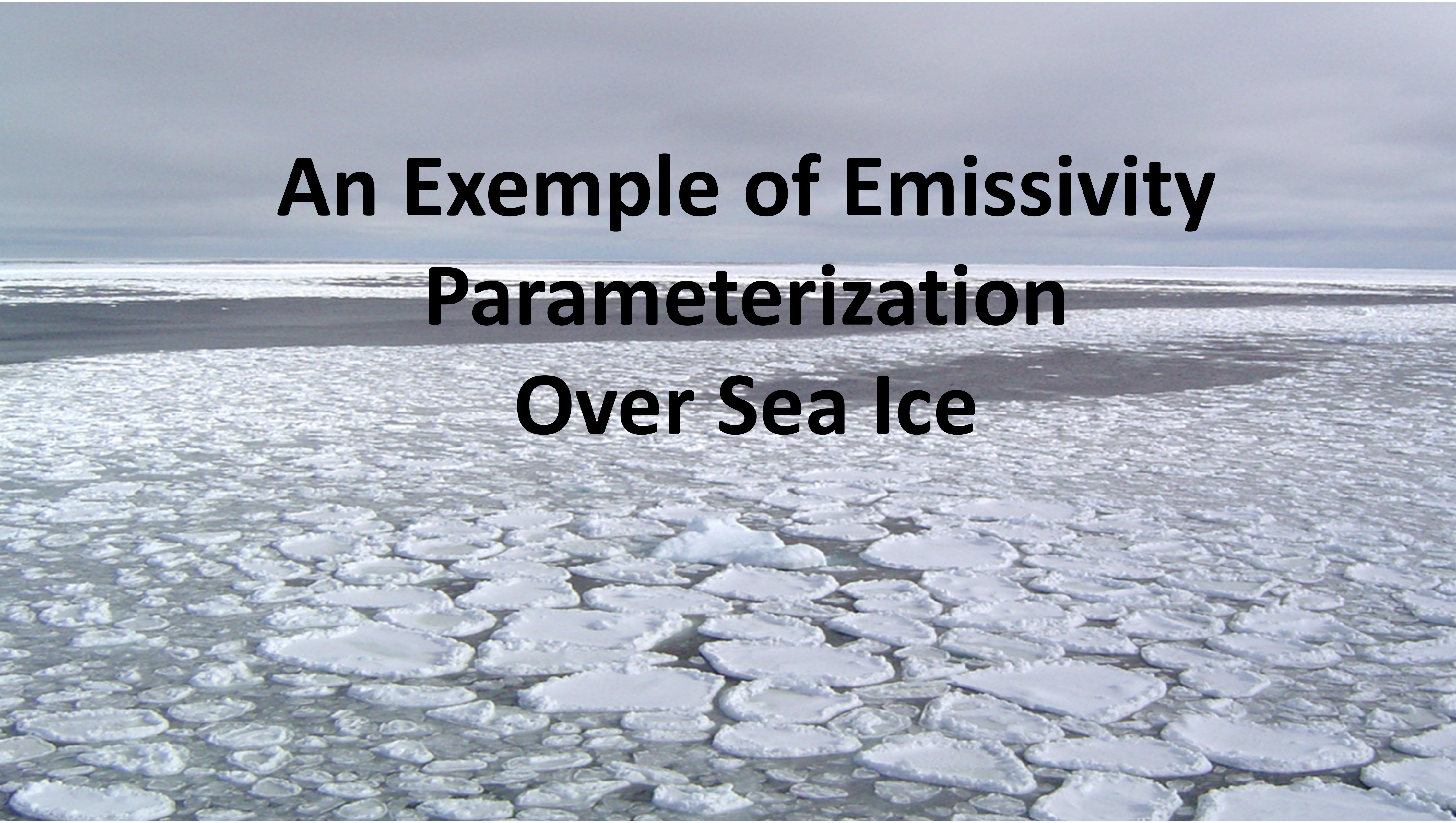
2) **Select potential predictors for the parameterization of the emissivities**

3) **Statistically relate the satellite-derived to the relevant geophysical parameters available at global scale**

4) **Derive a physics-aware statistical parameterization of the surface emissivity**

=> An example for the sea ice emissivity parameterization

An Exemple of Emissivity Parameterization Over Sea Ice



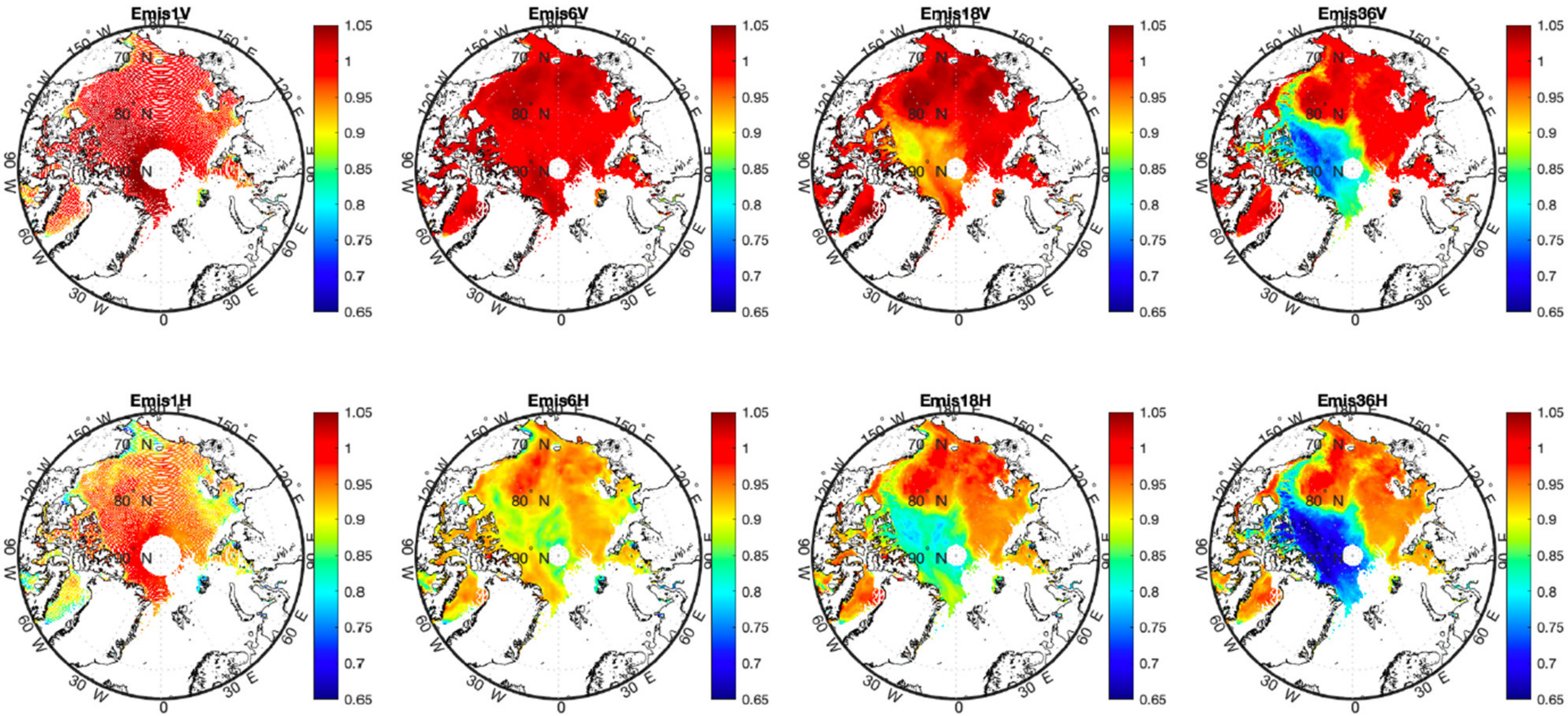
Sea Ice emissivity

The satellite-derived emissivity database

1.4GHz SMAP | 6GHz AMSR2 | 18GHz AMSR2 | 36GHz AMSR2

V polarization

H polarization



Example for 20-31 December 2018

Sea Ice emissivity

The geophysical parameters

- ERA5 variables: very limited. Only the sea ice concentration, Tskin and the atmospheric info Nothing more at that point. Developments underway at ECMWF.

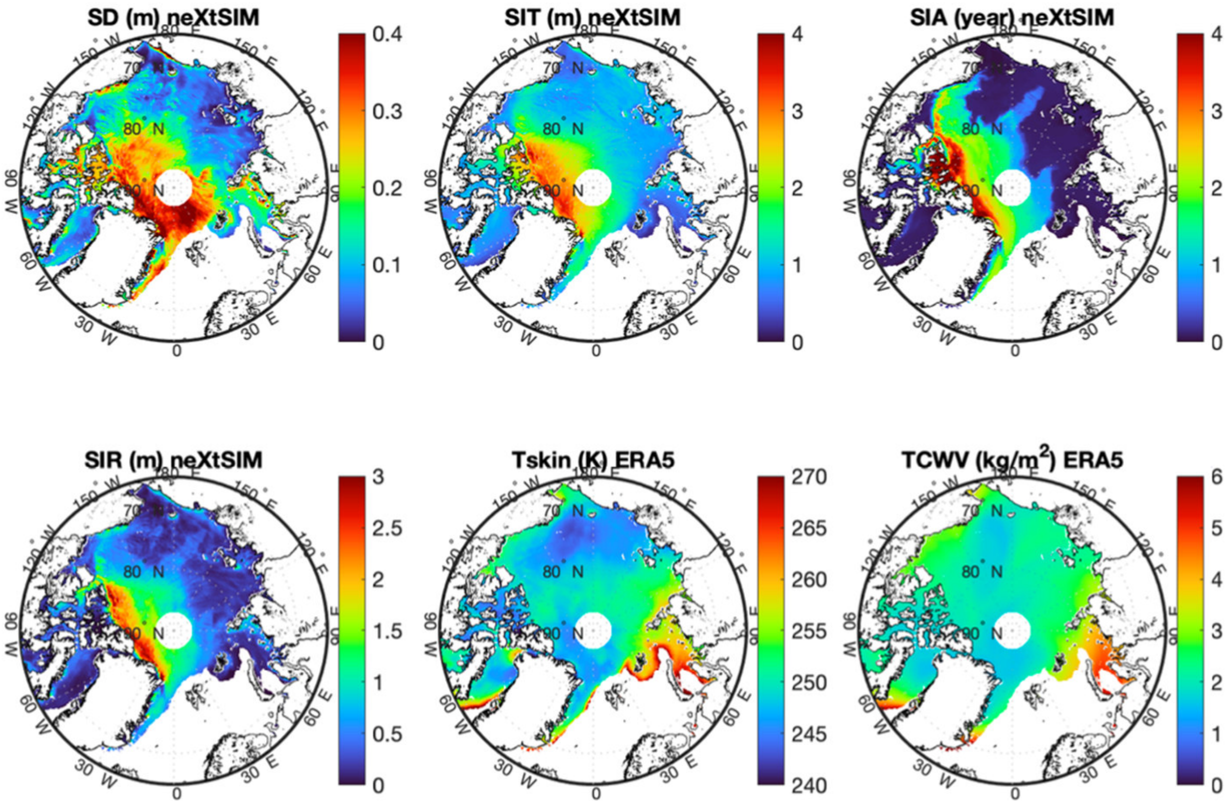
- Information from an ocean / sea ice model needed: NEMO /LIM selected first (Copernicus Ocean Service). Results already shown.

- **neXtSIM** model outputs provided by the NERCS (Anton Korosov), daily, gridded at 3 km (presented at the last MAG by A. Korosov)

Sea Ice emissivity

The geophysical parameters from neXtSIM (NERCS, Anton Korosov)

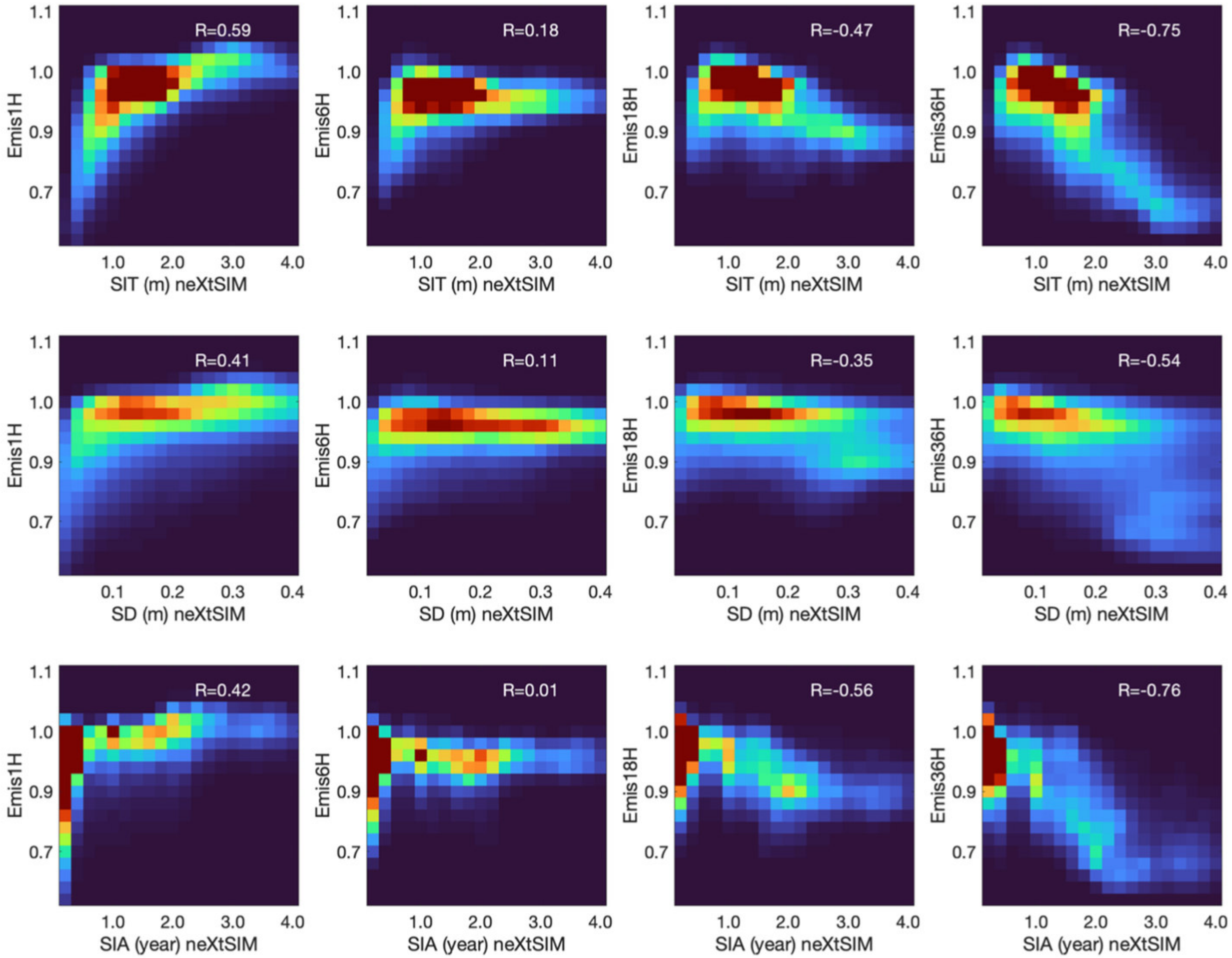
Multiple parameters available to describe the sea ice.



Example for 21-31 December 2018

Sea Ice emissivity

Statistical analysis of the link between the emissivities and the geophysical parameters



Sea Ice Thickness

Snow Depth

Sea Ice Age

Sea Ice emissivity

Parameters selected for the parameterizations of the emissivities

NN1 Sea Ice Thickness (neXtSIM), Snow Depth (neXtSIM), Sea Ice Age (neXtSIM), Sea Ice Roughness (neXtSIM), SkinTemperature (ERA5)

(SIT, SD, SIA, SIR, Ts)

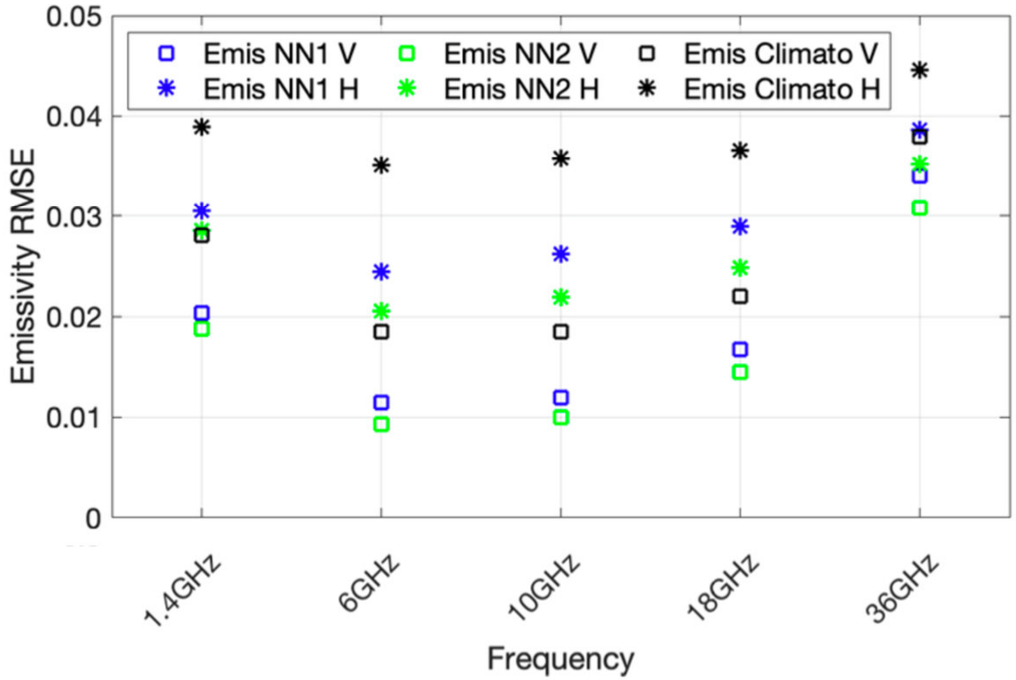
NN2 Same plus Total Column Water Vapor (ERA5) and winter day (calculated from 01/10)

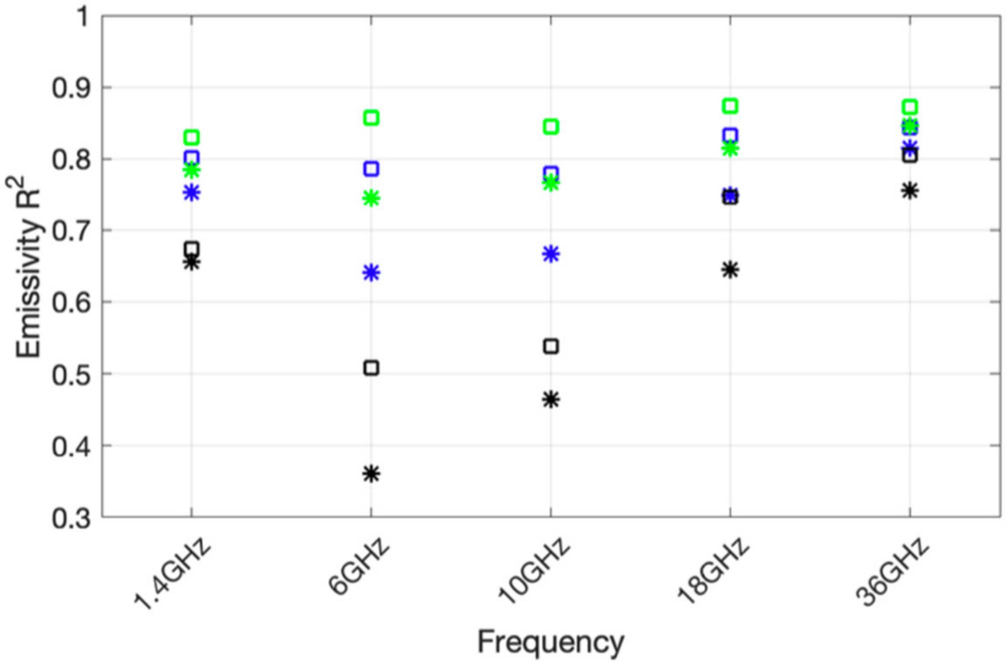
(SIT, SD, SIA, SIR, Ts, TCWV, WD)

Sea Ice emissivity

Training of a NN to reproduce the emissivities, using the geophysical parameter inputs

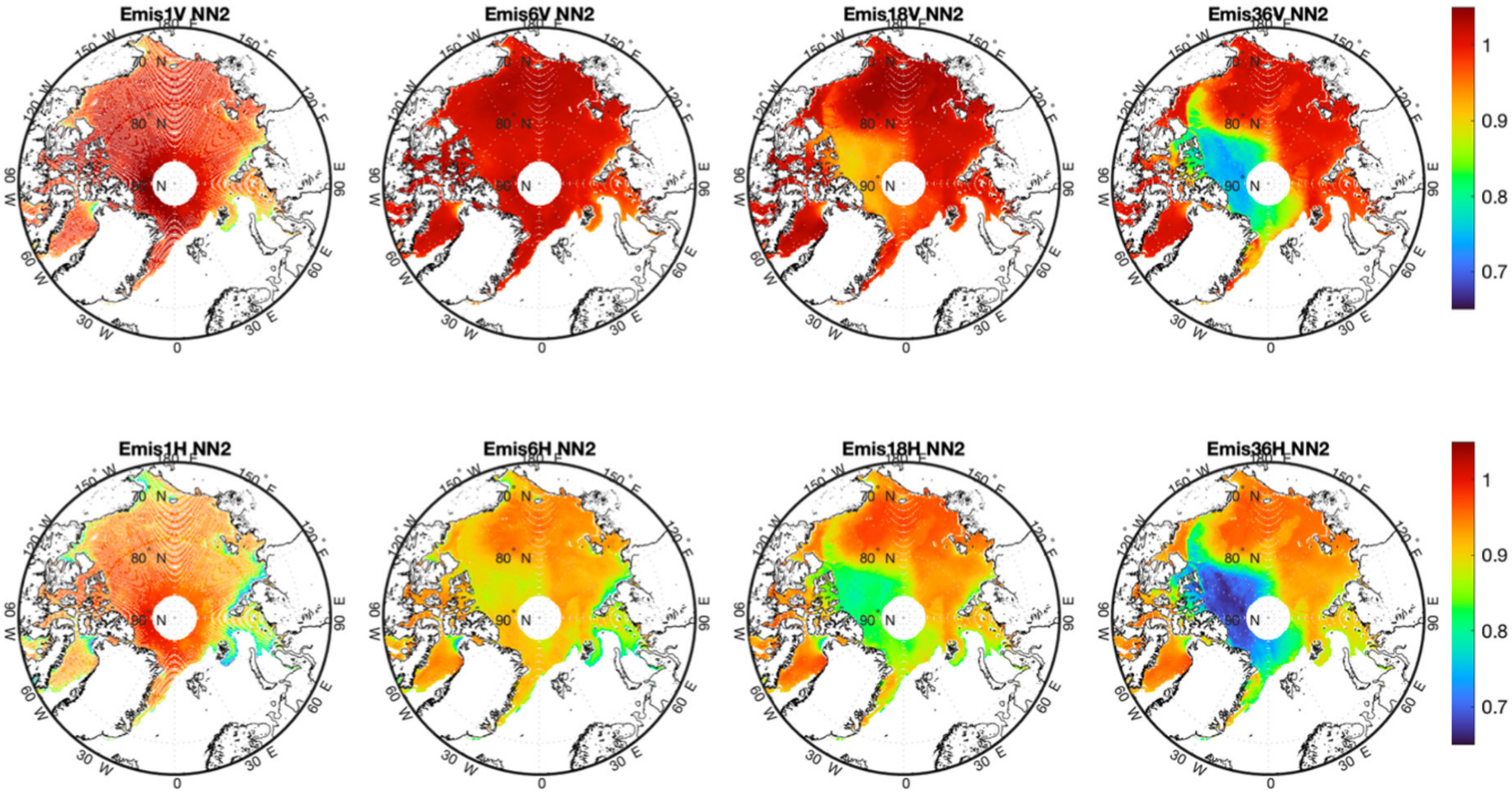
Multiple tests and systematic evaluation of the emissivity parameterization





Sea Ice emissivity

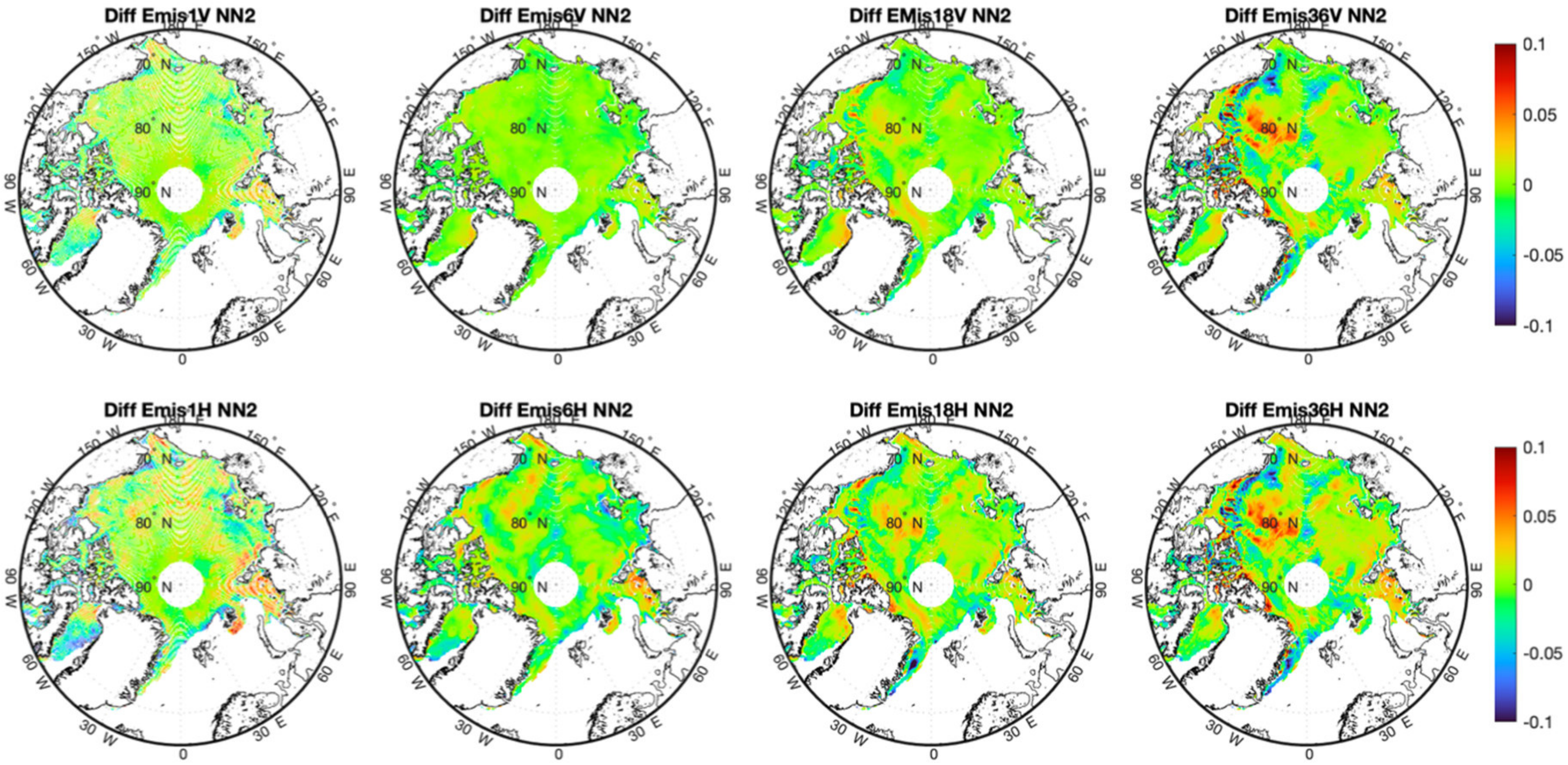
Emissivity maps



21-31 December 2018

Sea Ice emissivity

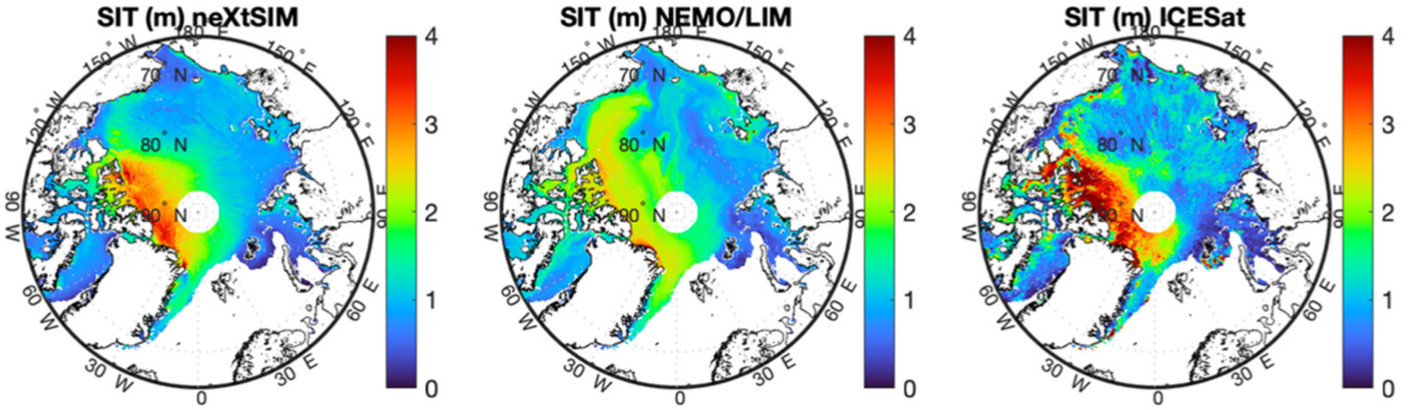
Maps of the emissivity differences between target and parameterization



21-31 December 2018

Sea Ice emissivity

What drives the main differences?



Maps of SIT, for December, 21-31, 2018, over the Arctic, with SIC>95%

CONCLUSION

Conclusion for the surface in the microwaves

Over ocean

- Rather robust radiative transfer models exist
- A reference physical model (PARMIO) and its maintenance should be insured over time.
- A corresponding fast emissivity model has been developed (based on NN): SURFEM-Ocean
- It is already incorporated in RTTOV 13. Operational at ECMWF.

Conclusion for the surface in the microwaves




Over land, snow, ice, sea ice

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

- **Physics-aware ML parameterization of the surface emissivity**
  as a function of :
  - instrument characteristics (frequency, incidence angle, polarization)
  - geophysical variables from reanalysis and from external Land Surface Models or Ocean-Sea ice models, when not enough information available in the reanalysis

Results shown for sea ice (Kilic et al., ESS, 2025). **SURFEM-SeaIce**

Parameterization derived for snow (de Gelis et al., RSE, 2025). **SURFEM-Snow**

Underway for snow-free land

Thank you!

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