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

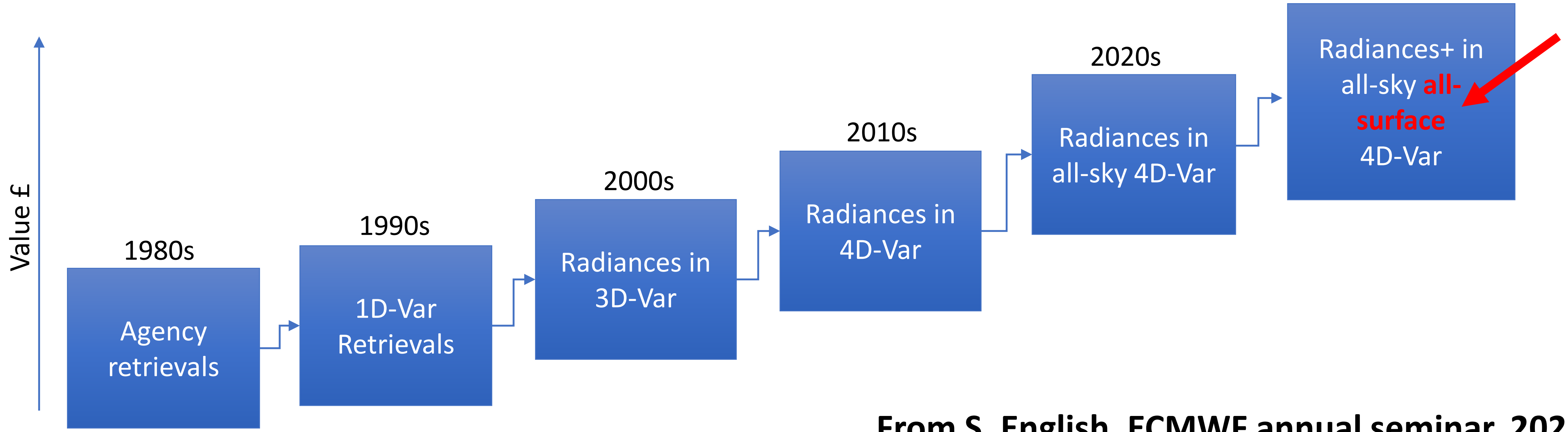
Catherine Prigent
CNRS, Observatoire de Paris, and Estellus

+ Carlos Jimenez, Lise Kilic, Iris de Gelis, Filipe Aires
+ the ISSI group for the Ocean Emissivity model
+ many other collaborators





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



From S. English, ECMWF annual seminar, 2021

That clearly requires an accurate estimation of the surface contribution

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

Outline of this talk

1) General considerations

2) Ocean

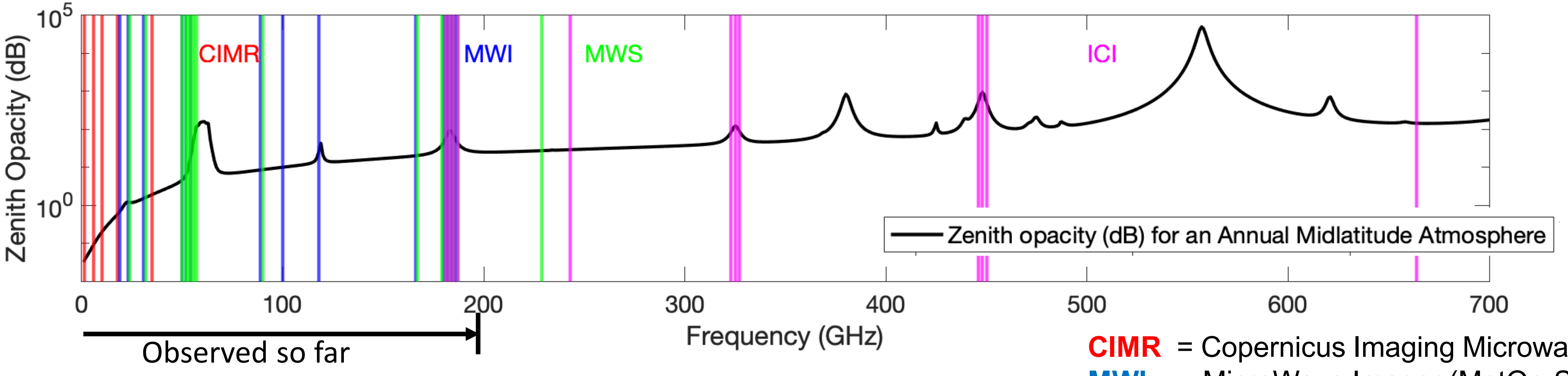
   Physically-based models, and their fast version

3) Other surfaces

   Physically-based model??

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

The bright future of passive microwave observations in Europe



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**

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

Atmospheric ‘windows’ for **surface characterization**. 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; Kilic et al., ESS, 2023).

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

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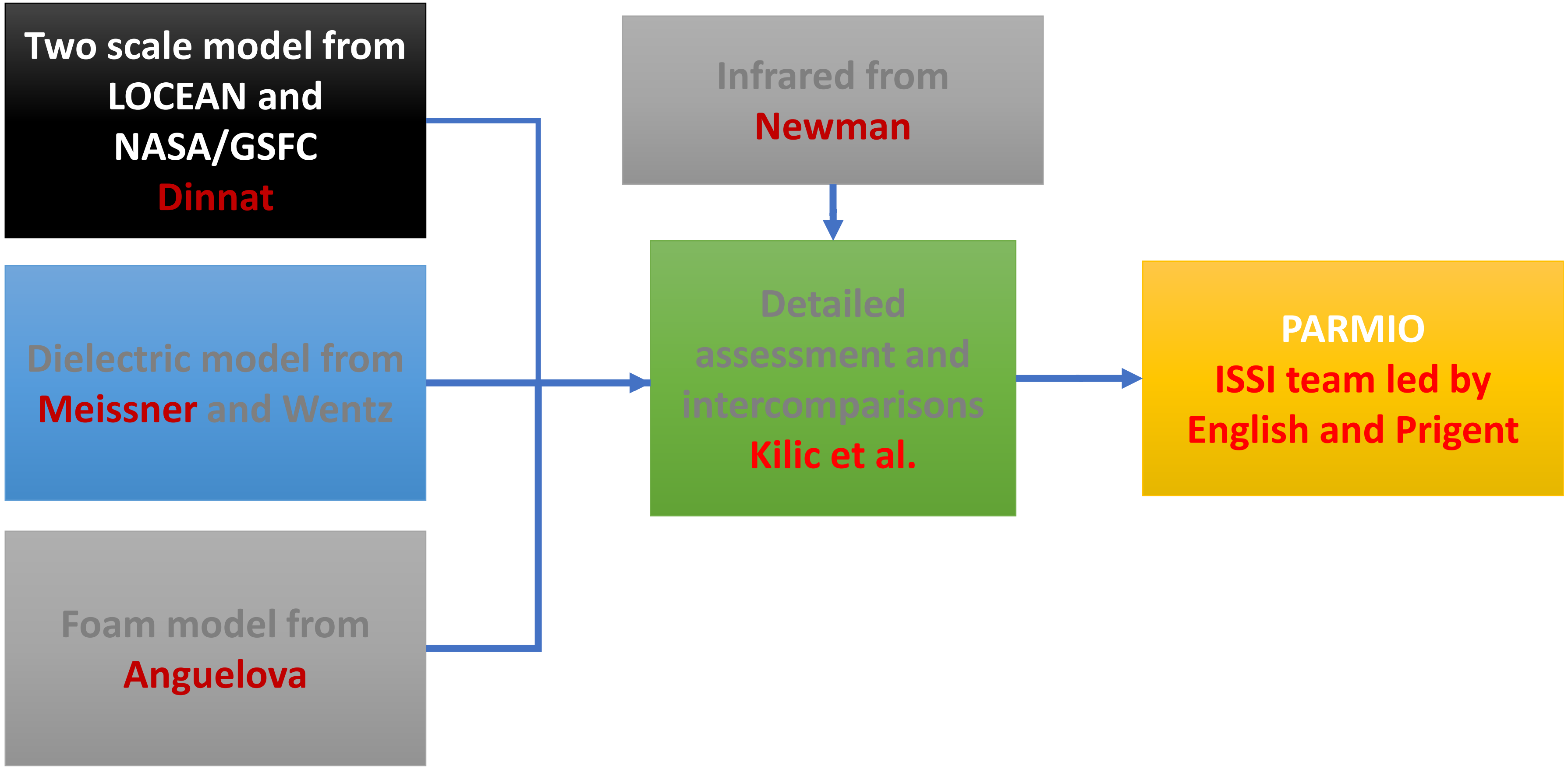
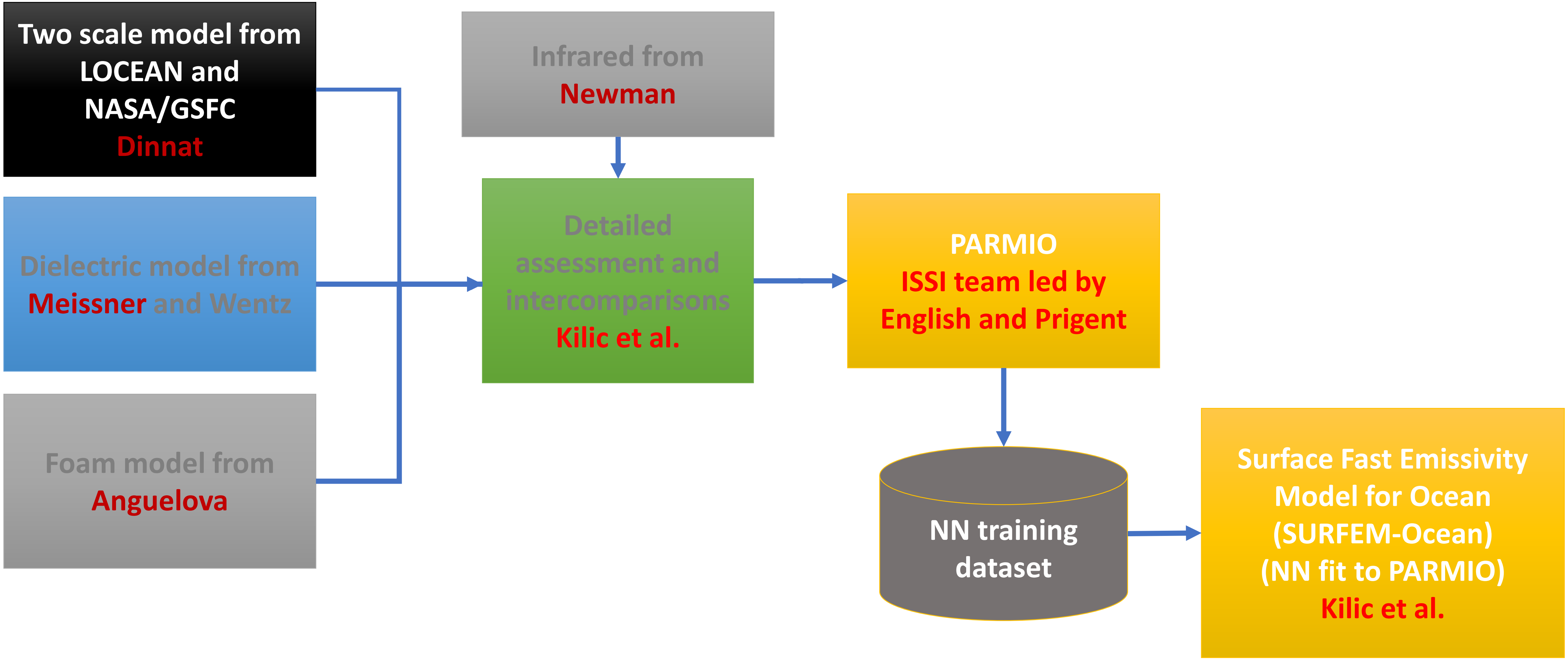
- **Adjustments made to the initial model to better fit the observations under cold temperatures and for high wind speeds.**

- **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), successfully tested at ECMWF (Geer et al., 2024) and now activated in the operational cycle.

Selection of the physically-based reference ocean model, its evaluation and its adjustments



A fast model derived from PARMIO, based on NN parameterization.



PARMIO
Full physical model

→

SURFEM-Ocean
Fast model
NN based-parameterization of the PARMIO full physical model
Including the analytical Jacobians

→

RTTOV 13

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

Corresponding author: Emmanuel Dinnat, emmanuel.dinnat@nasa.gov

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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

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Technical Memo

ECMWF
European Centre for Medium-Range Weather Forecasts

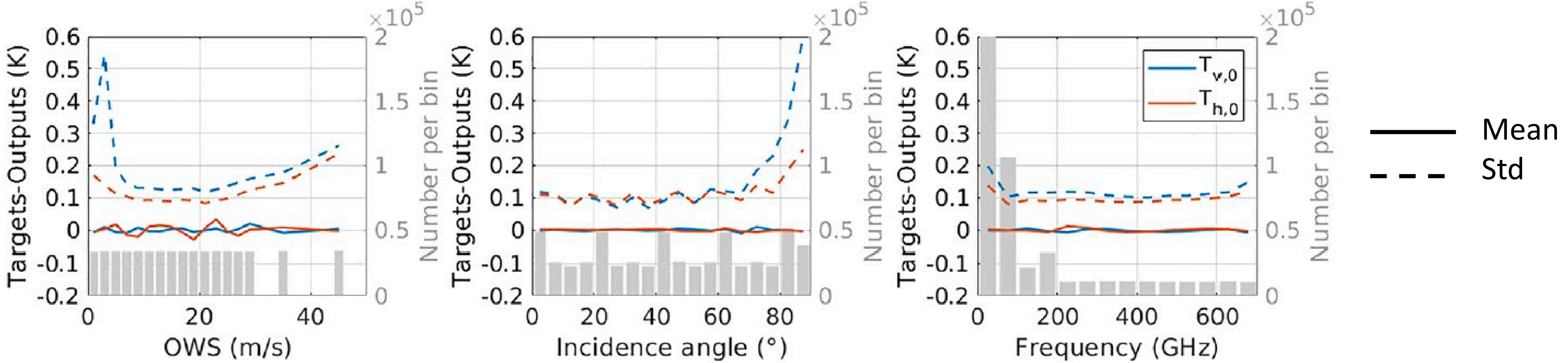
915

SURFEM-ocean microwave surface emissivity evaluated

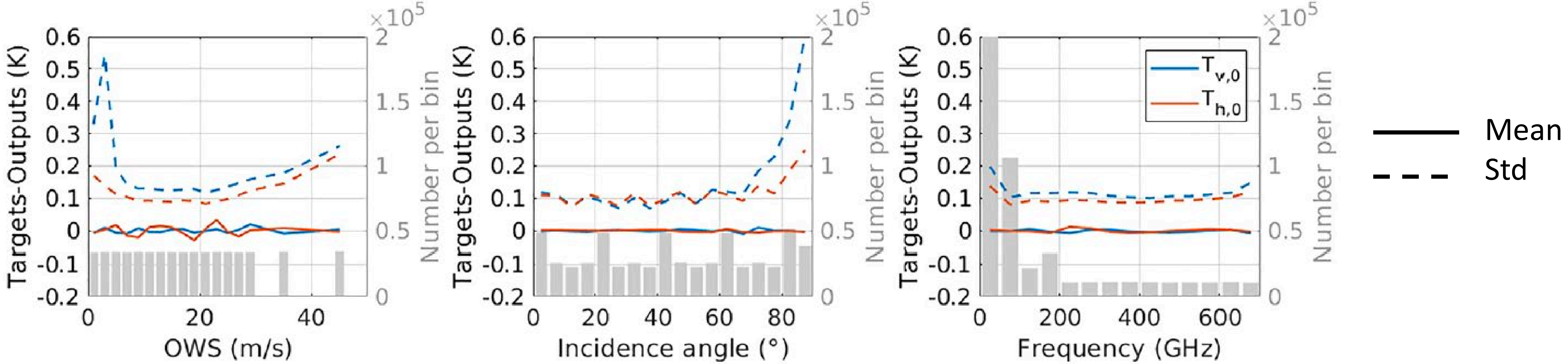
Alan J. Geer, Cristina Lupu, David Duncan, Niels Bormann and Stephen English
(Research Department)

February 2024

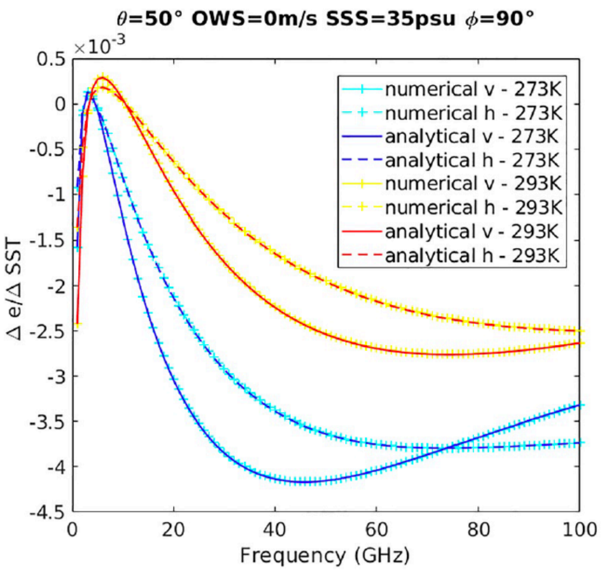
SURFEM-Ocean reproduces well the PARMIO model

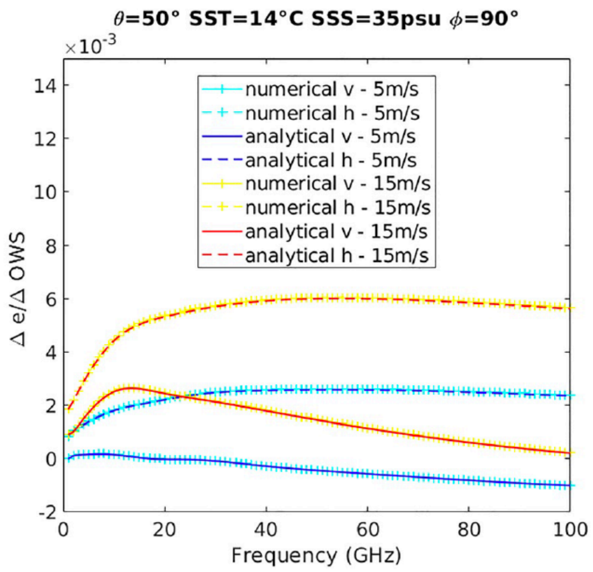


SURFEM-Ocean reproduces well the PARMIO model



Analytical Jacobians are calculated

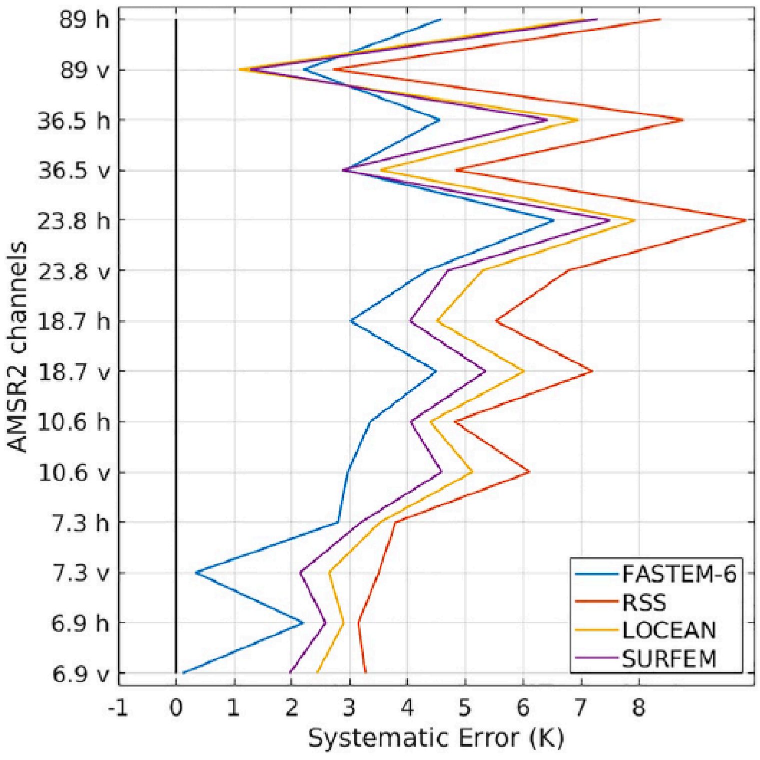




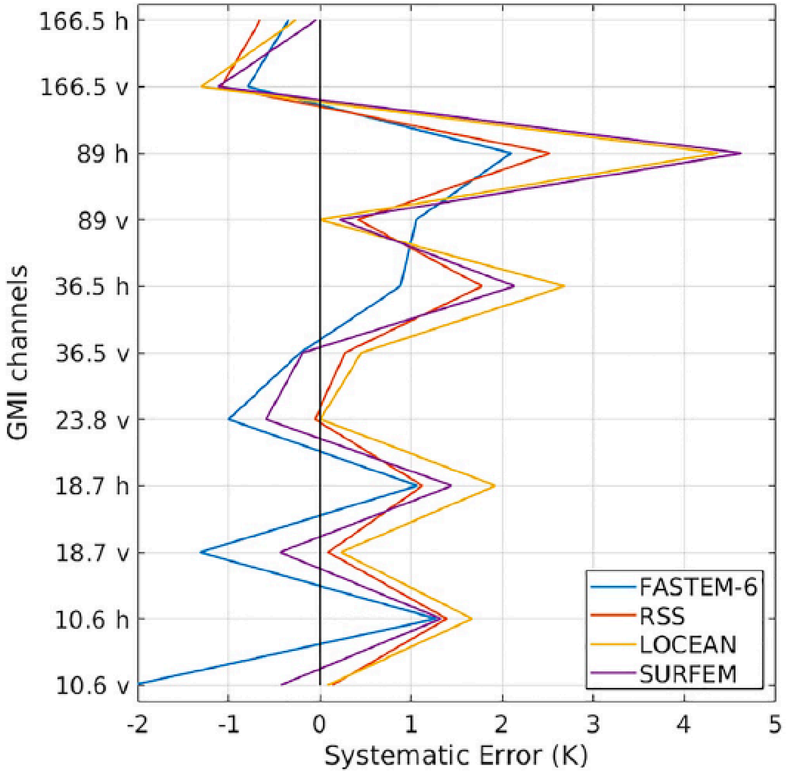
(Kilic et al., ESS, 2023)

Test of SURFEM-Ocean with multiple satellite observations: Biases with observations

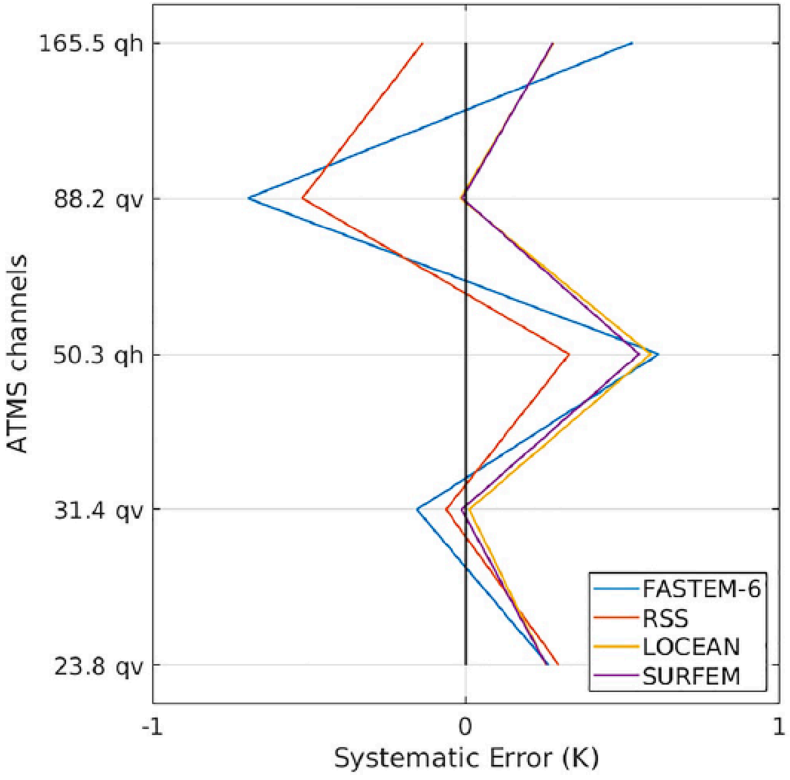
AMSR2



GMI



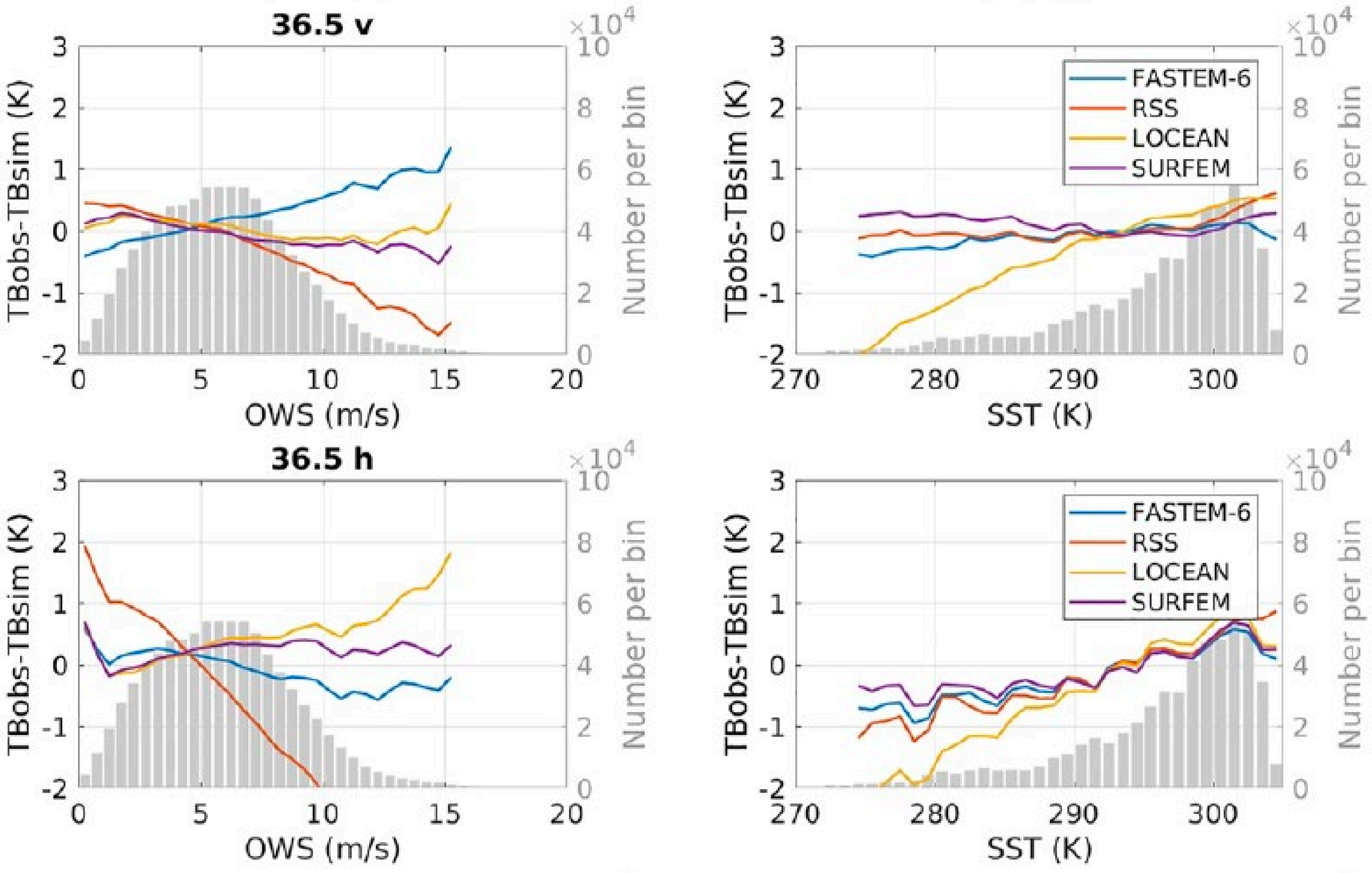
ATMS



(Kilic et al., ESS, 2023)

Test of SURFEM-Ocean with multiple satellite observations: Dependence with ocean parameters

GMI



With SURFEM-Ocean:

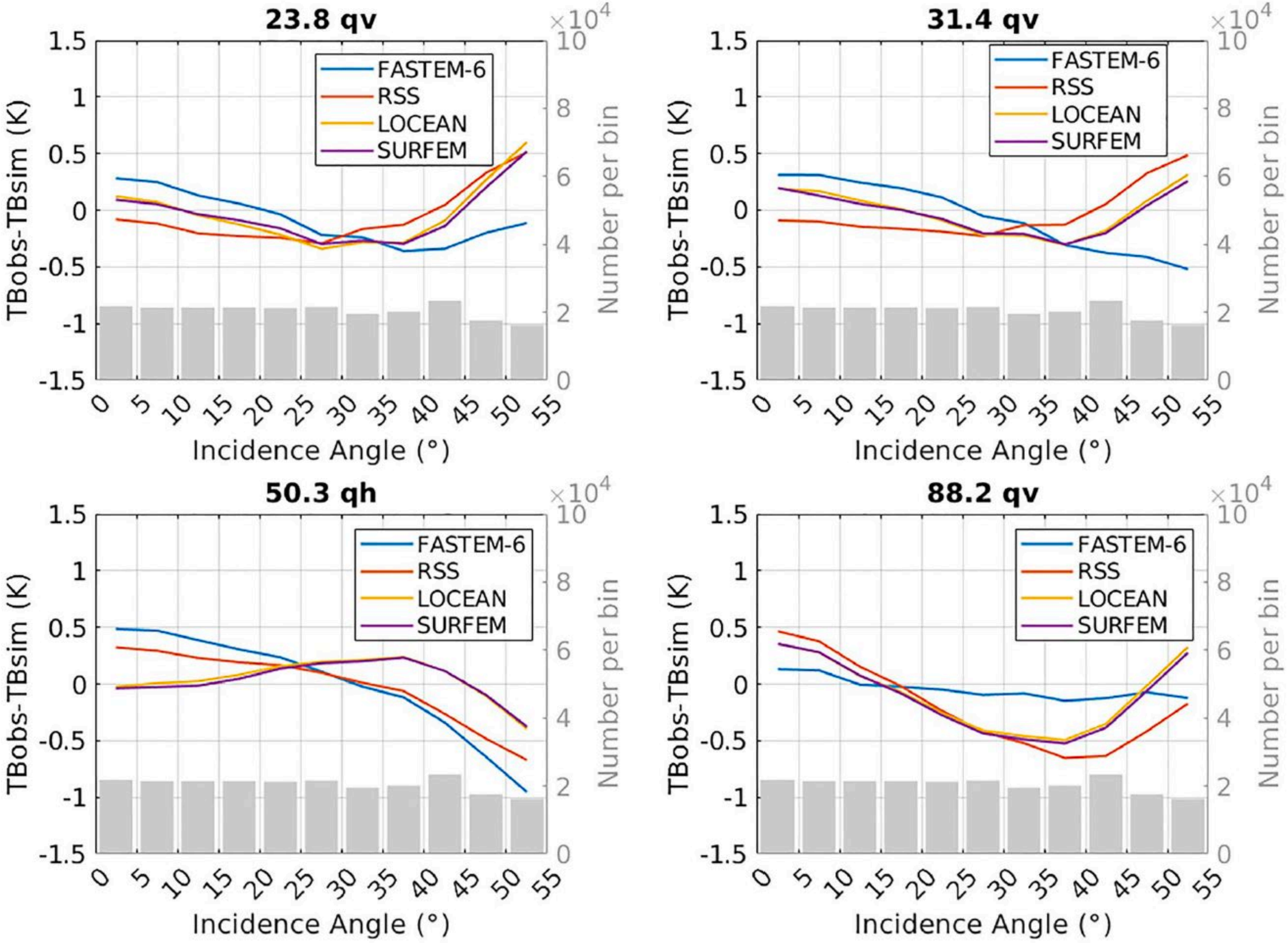
limited error at high OWS

limited error at low SST

(Kilic et al., ESS, 2023)

Test of SURFEM-Ocean with multiple satellite observations: Dependence with incidence angle

ATMS



Conclusion over ocean

- Rather robust radiative transfer models exist.
- A reference physical model (PARMIO) with maintenance insured over time, available at https://gitlab.com/nwpsaf/parmio.
- Preliminary testing for infrared emissivity and for active microwaves.
- A corresponding fast emissivity model developed for passive microwaves, based on NN (SURFEM-Ocean).
- SURFEM-Ocean incorporated into RTTOV 13 and operational at ECMWF now.
- More info at https://www.issibern.ch/teams/oceansurfemiss/


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

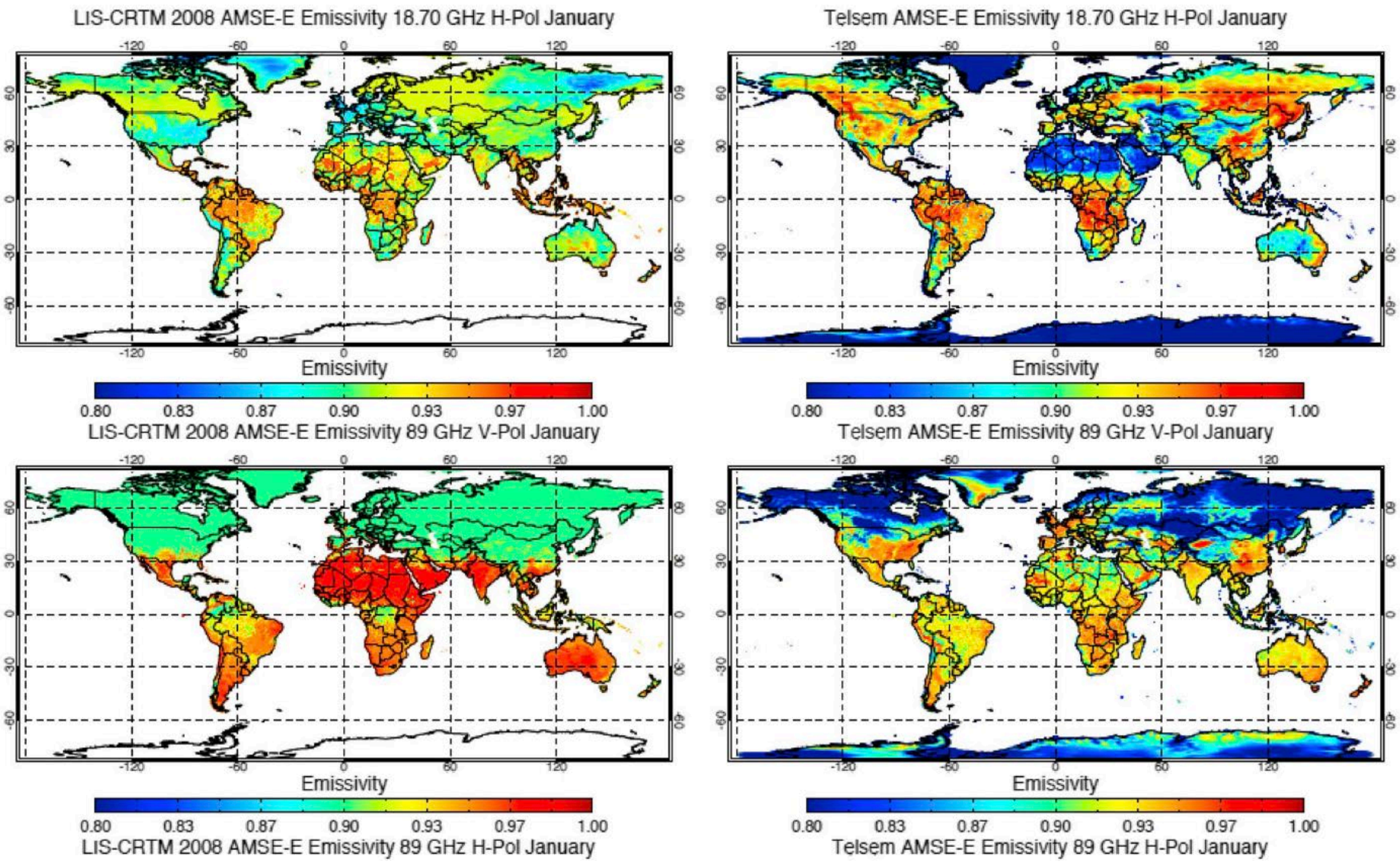



The challenge of calculating emissivities with radiative transfer models at global scale

CRTM | **Satellite-derived**

18GHz H

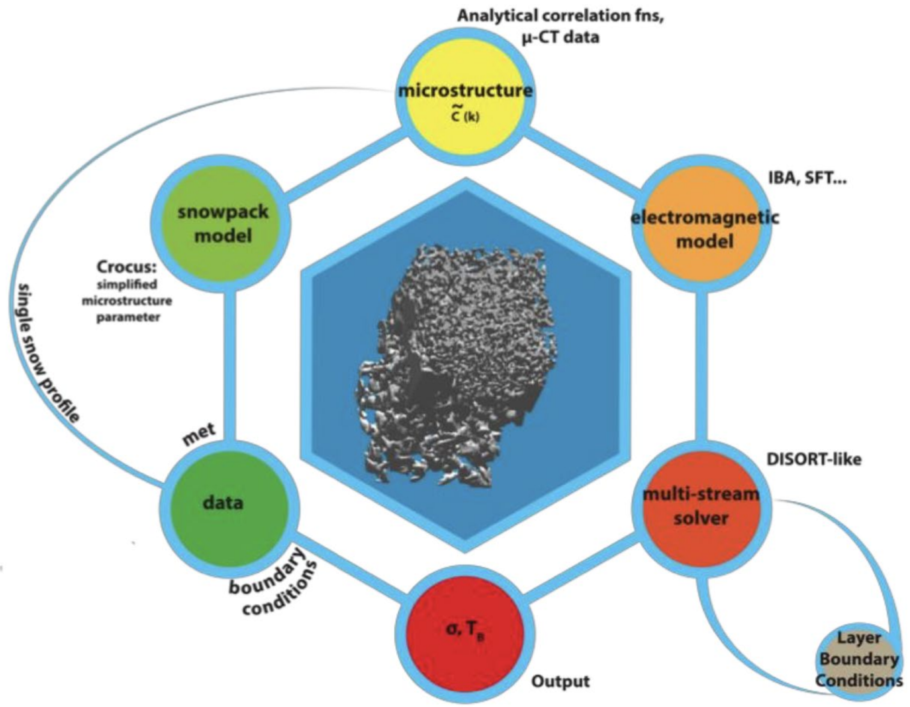
89GHz V



(Prigent et al., JGR, 2015)

Specific microwave emissivity physical models

For snow, ice, sea ice



SMRT (Snow Microwave Radiative Transfer)

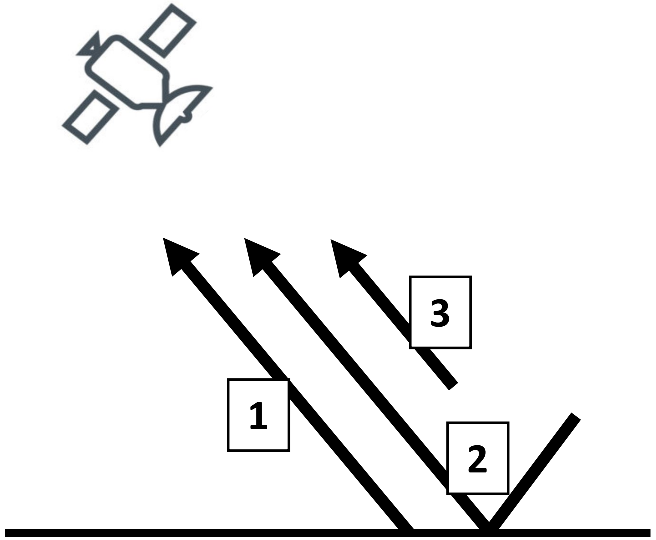
(Picard et al., GMD, 2018, https://www.smrt-model.science/documentation.htm)

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

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 for 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… (**Effective emissivities)**
- 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 (Prigent et al., IEEE, 2008).

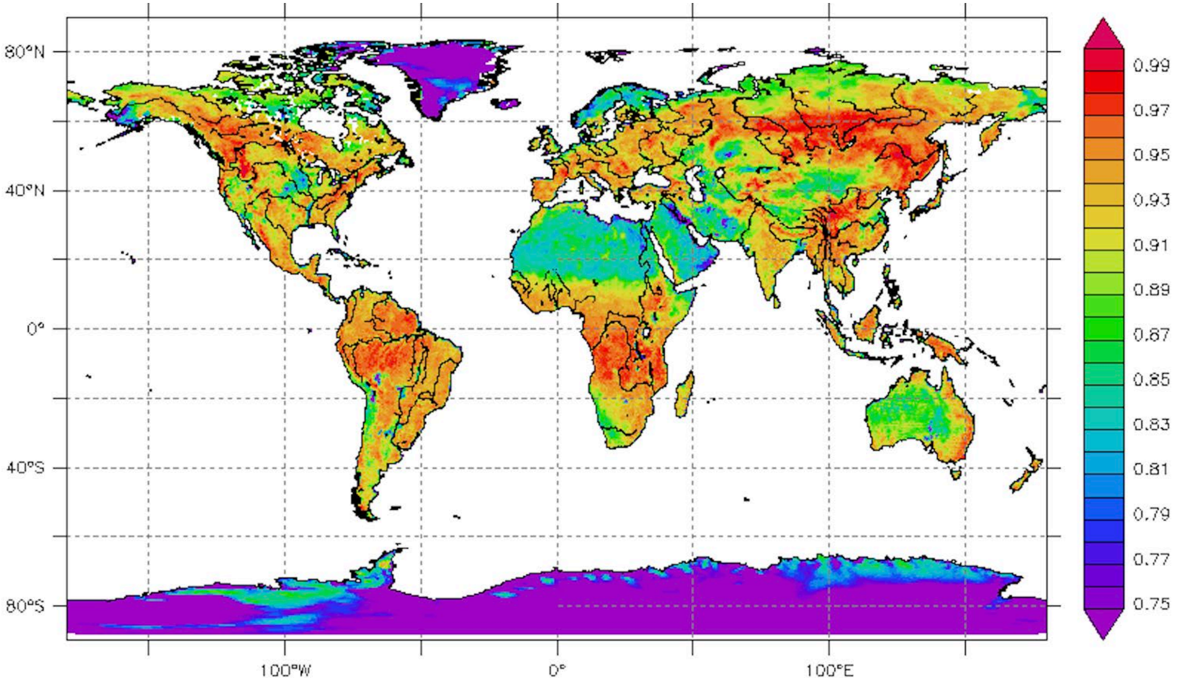
TELSEM^2

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)

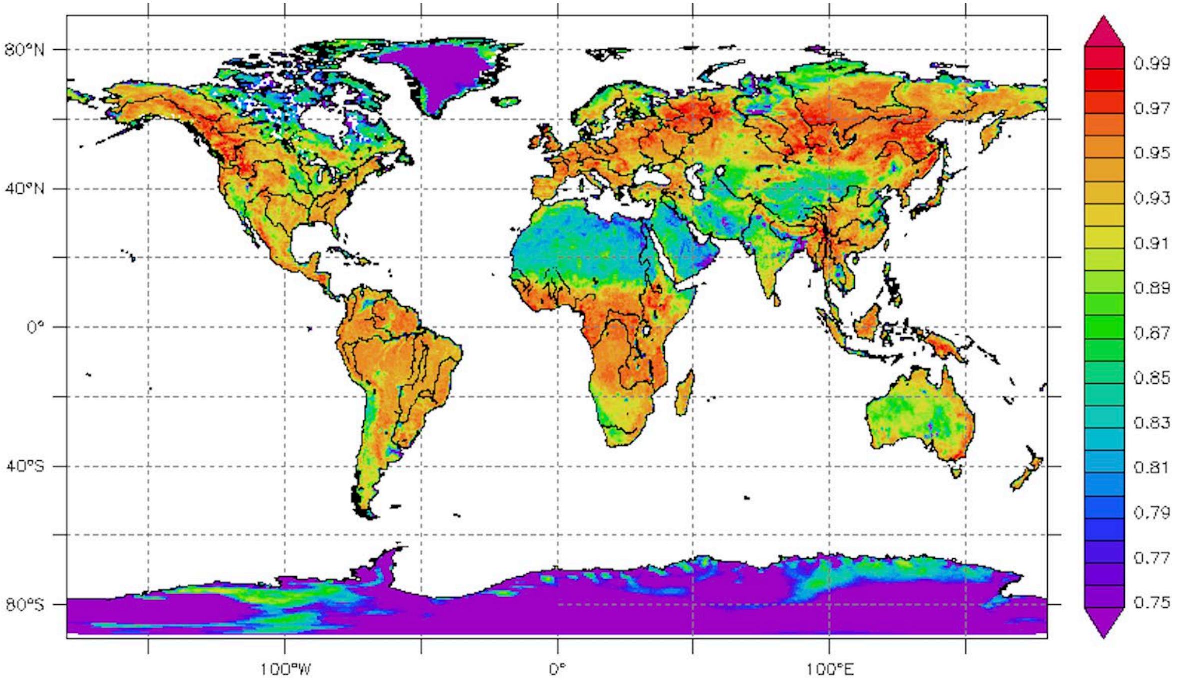
- Global atlases of emissivity for all continental and sea-ice surfaces, from 18 to 700 GHz, monthly mean, at 25 km resolution.
- **Inputs:** **lat, lon, month, frequency, and incidence angle.**
- **Outputs:** **emissivities in V and H polarizations, along with error covariances**
- Realistic **FIRST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

Space and time variability of the microwave land surface emissivity

Emissivity, 19GHz, H polarization, 53° incidence angle
January



Emissivity, 19GHz, H polarization, 53° incidence angle
July



Space and time variability of the microwave land surface emissivity

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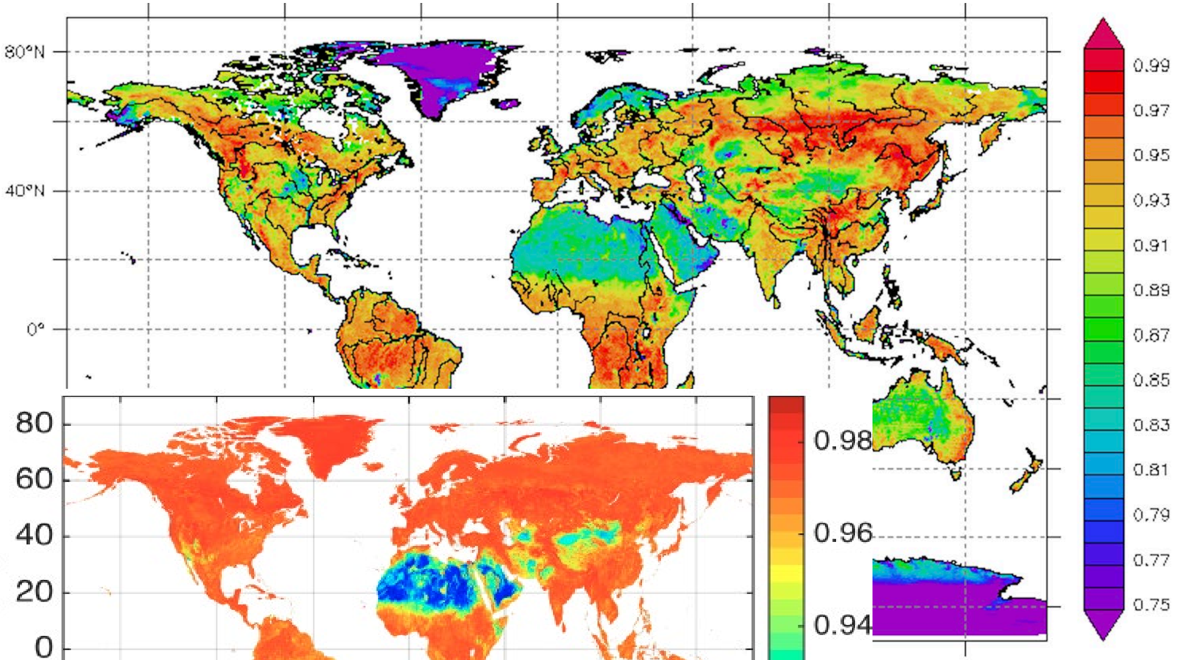

Emissivity, 19GHz, H polarization, 53° incidence angle
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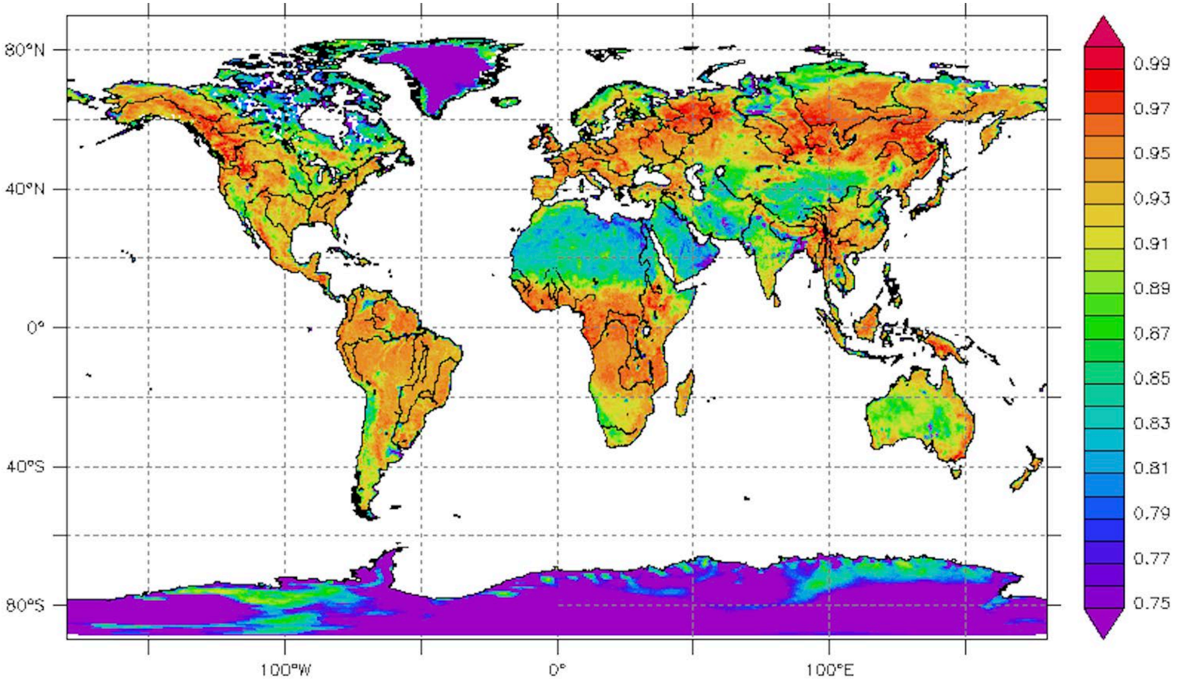

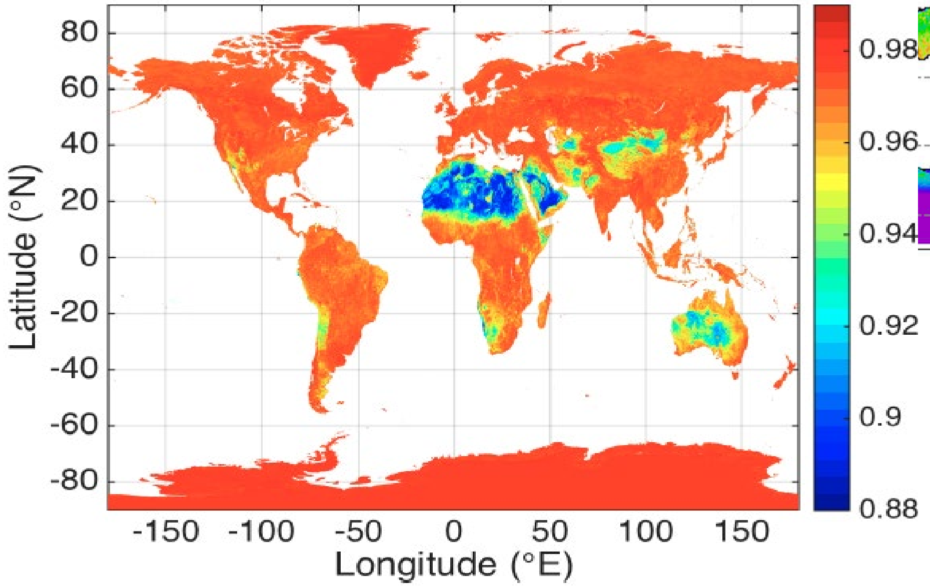

Emissivity in the thermal infrared

Satellite-derived surface emissivity provides reasonable spatial and temporal variabilities, as well as frequency co-variabilities, over land, snow, sea ice.

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…

Suggested method :

1) Revise and extend the satellite-derived emissivity database

- Satellite-derived emissivity calculated for the full time series of SSM/I, SSMIS, AMSR, SMAP, and SMOS, over the continents and sea ice
  => **a large 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-recognized community models when reanalysis information not enough

   - Not always the expected physical parameters that play the key role… Be ready for surprises…

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**

$\Rightarrow$ **An example for snow and sea ice emissivity parameterization.**
See presentation from Iris de Gelis later today.

Conclusion 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 to be shown for snow and sea ice (**Iris de Gélis, later in the day**)

Thank you!

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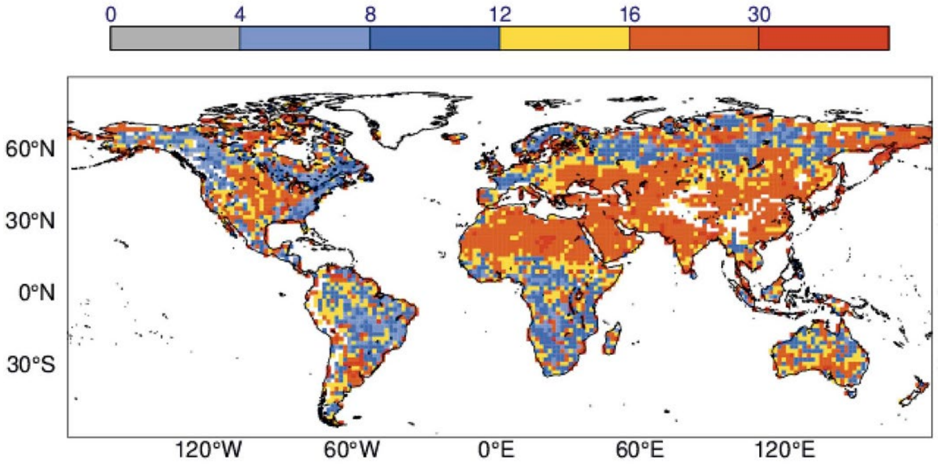
Generic land surface microwave emission models

Community Microwave Emission Model (CMEM) at ECMWF

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

Specific work at 1.4 GHz, for SMOS

Before bias correction



RMSE (K)

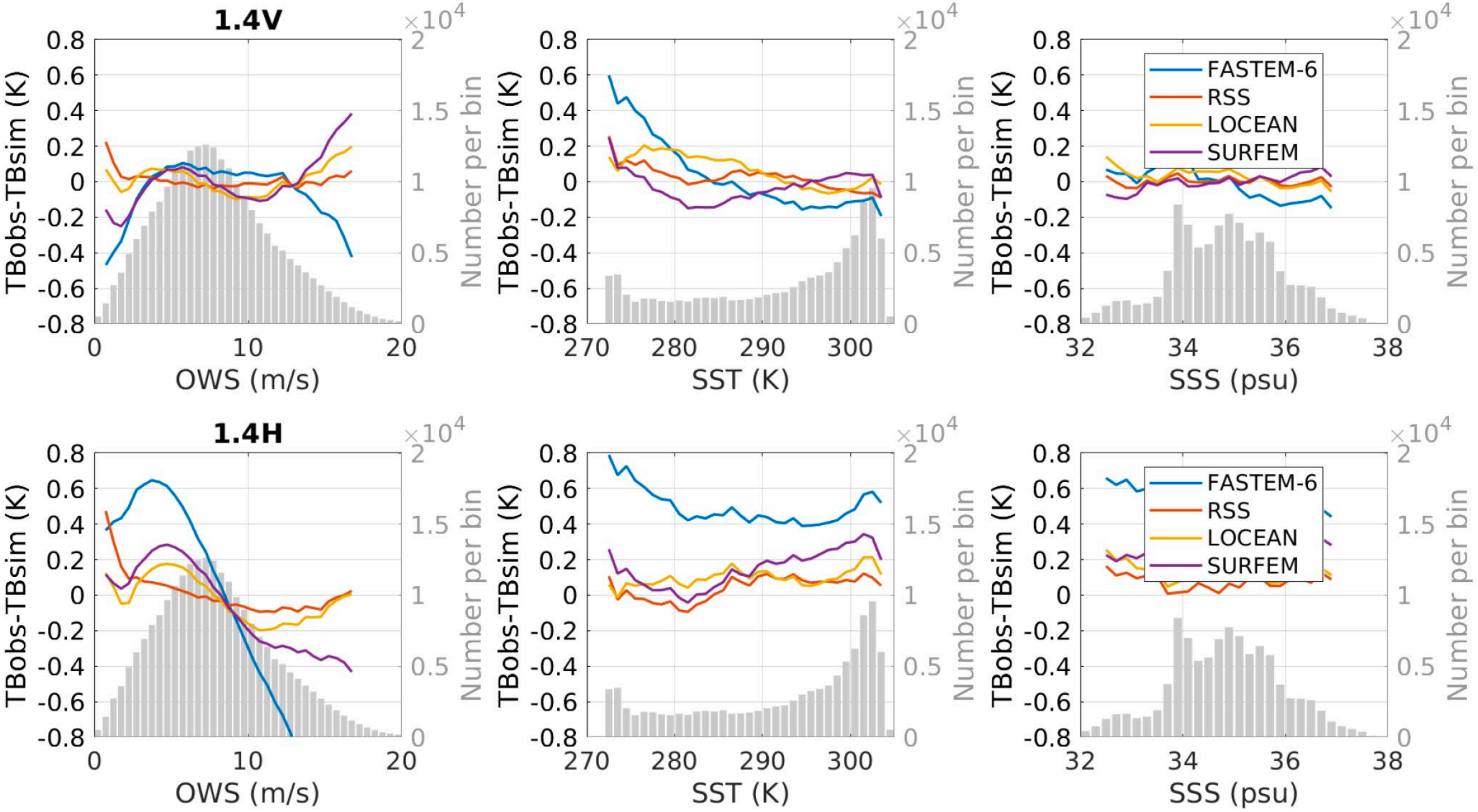
Modular configuration of CMEM. For each module components, a choice of parameterizations is available. Parameterizations in bold are those used in this paper. Different combinations of CMEM using three different dielectric models, four roughness models and three vegetation optical depths models are compared,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

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

Test of SURFEM-Ocean with multiple satellite observations: Dependence with ocean parameters

SMAP



SURFEM-Ocean less precise than LOCEAN or RSS models (that are fitted for L-band).

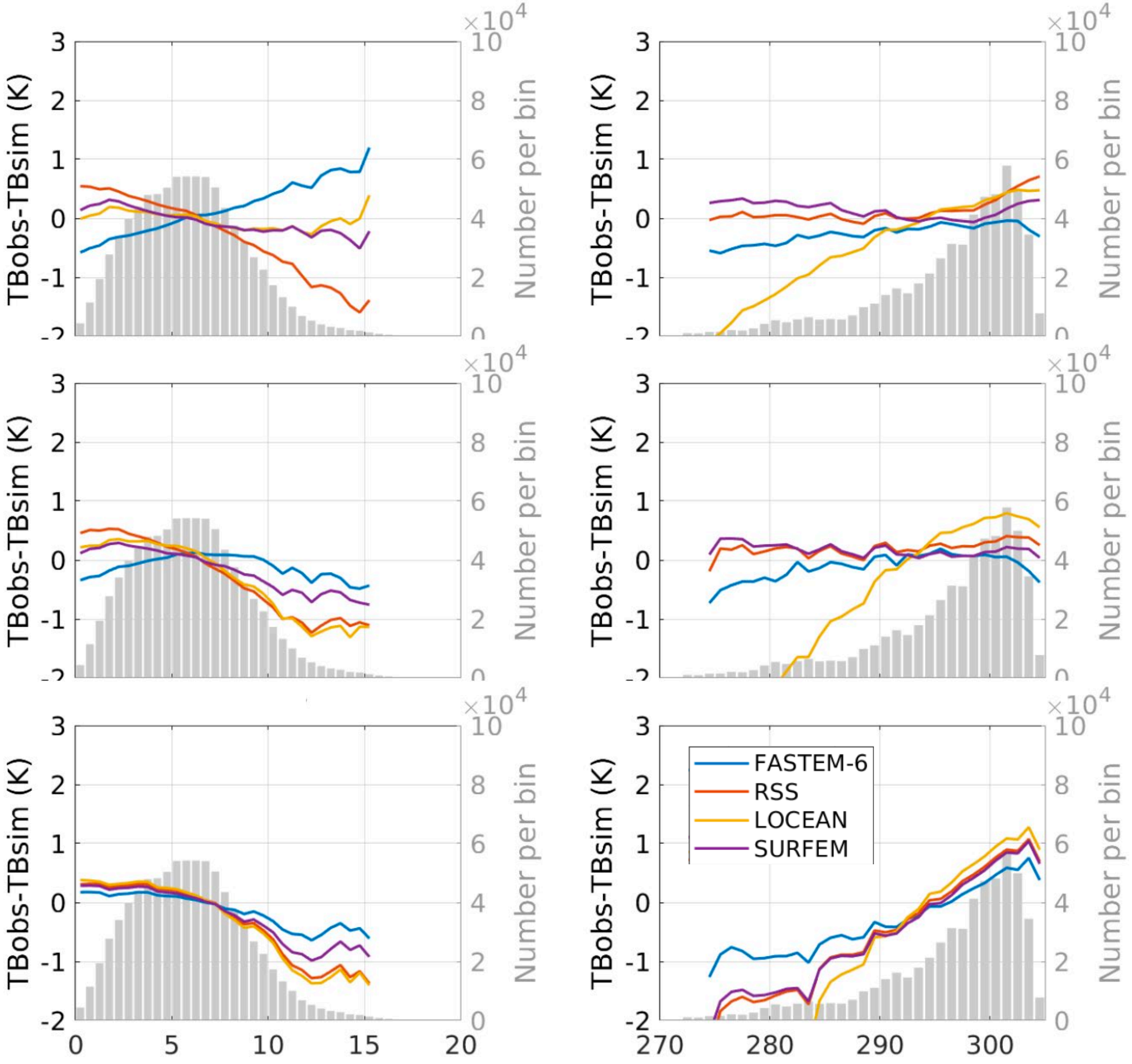
Test of SURFEM-Ocean with multiple satellite observations: Dependence with ocean parameters

GMI

36 V

89V

166V

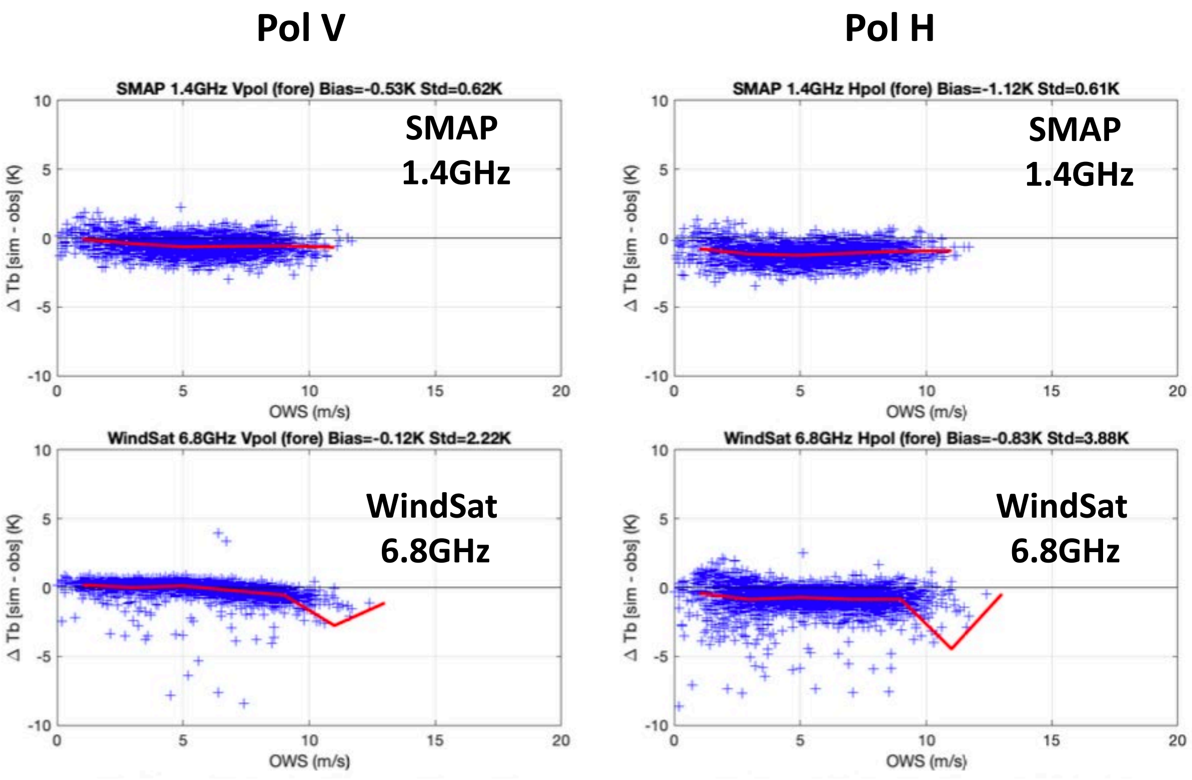


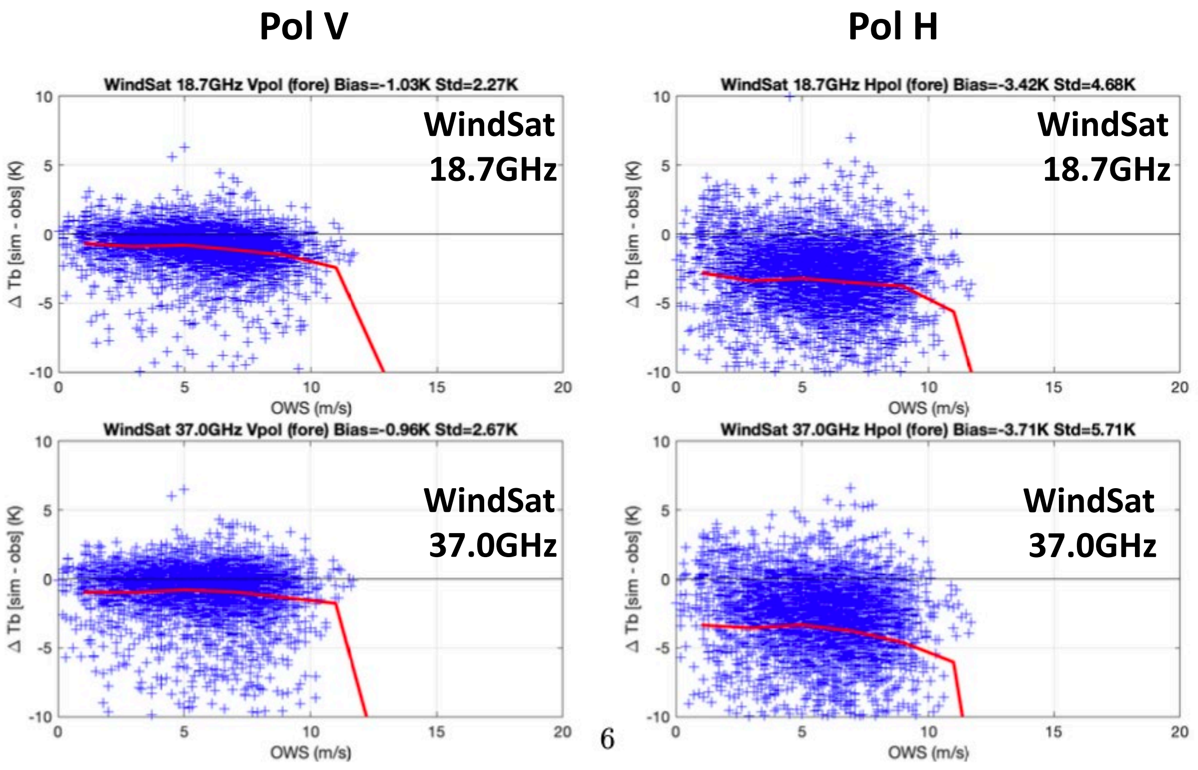
OWS (m/s)

SST (K)

WP4.1 Radiative transfer

- **Evaluation of codes implemented for the scene simulation and inversions**

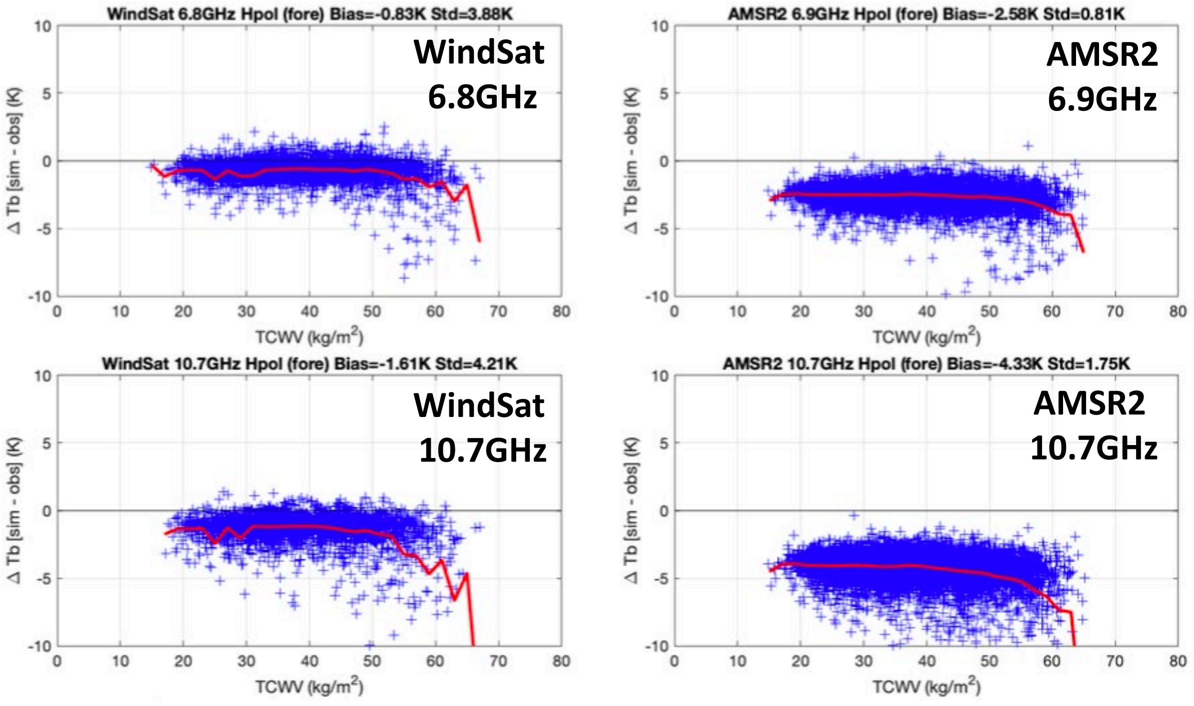




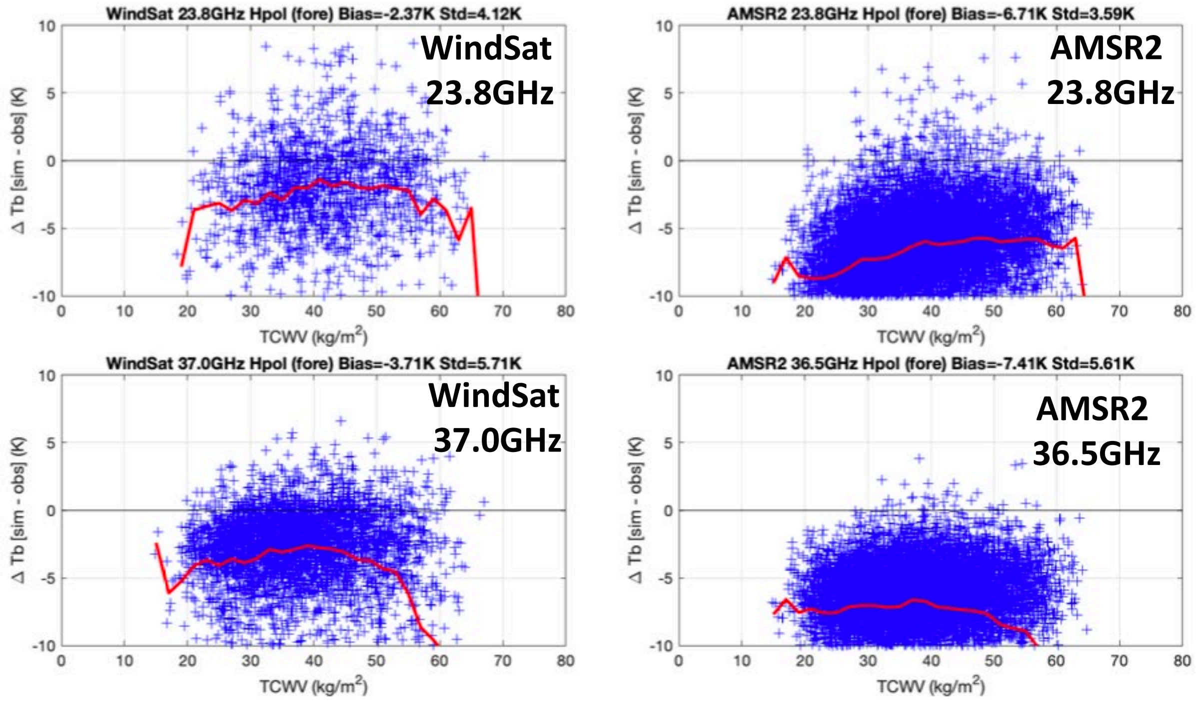
WP4.1 Radiative transfer

- **Evaluation of codes implemented for the scene simulation and inversions**
    - Limited dependence with the TCWV even at higher frequencies with WindSat.
    - Large differences in the behaviours between WindSat and AMSR2.
    - Large biases observed with AMSR2, as already evidenced in previous works (Kilic et al., 2020)

Pol H

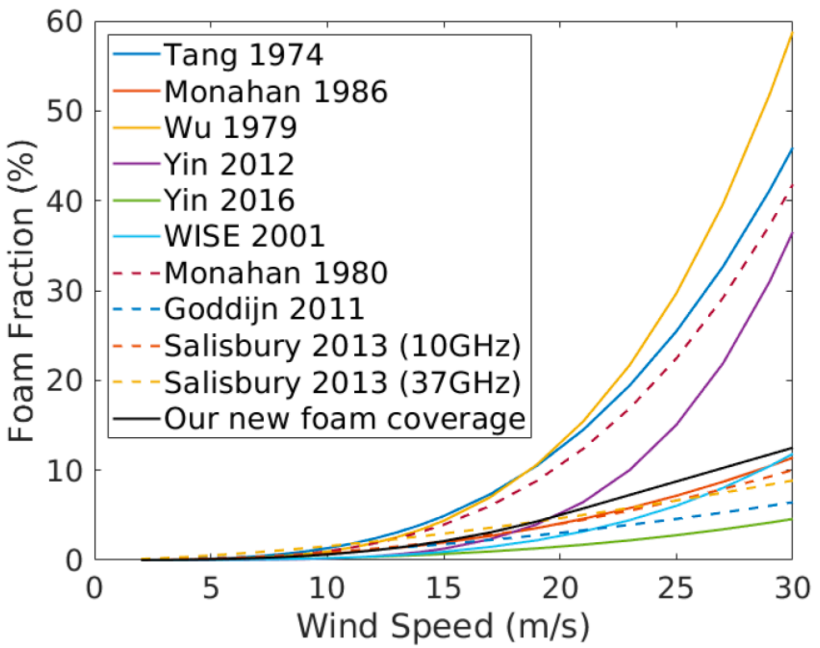


Pol H



Configuration of PARMIO

- Dielectric constants:
  - Meissner and Wentz, 2004 and 2012
- Wave spectrum:
  - Durden and Vesecky, 1985 with the amplitude coefficient multiplied by 1.25.
- Foam coverage:
  - New estimation



$$if\ U_{10} < 20$$
$$Fc = 6.25e^{-6} \times U_{10}^3$$
$$else$$
$$Fc = 3 \times 6.25e^{-6} \times 20^2 \times (U_{10} - 20) + 6.25e^{-6} \times 20^3$$

- Foam emissivity:
  - Anguelova and Gaiser, 2013 with a foam effective thickness of 2mm.

Approach

Within PARMIO the ocean emissivity is decomposed as follows:

$$e_p = e_pN + e_p0 + e_p1 \times \cos(\varphi) + e_p2 \times \cos(2\varphi)$$

For p = V or H polarizations

$$e_q = e_q1 \times \sin(\varphi) + e_q2 \times \sin(2\varphi)$$

For q = S3 or S4 (the 3rd or 4th stokes parameters)

With φ the relative wind direction

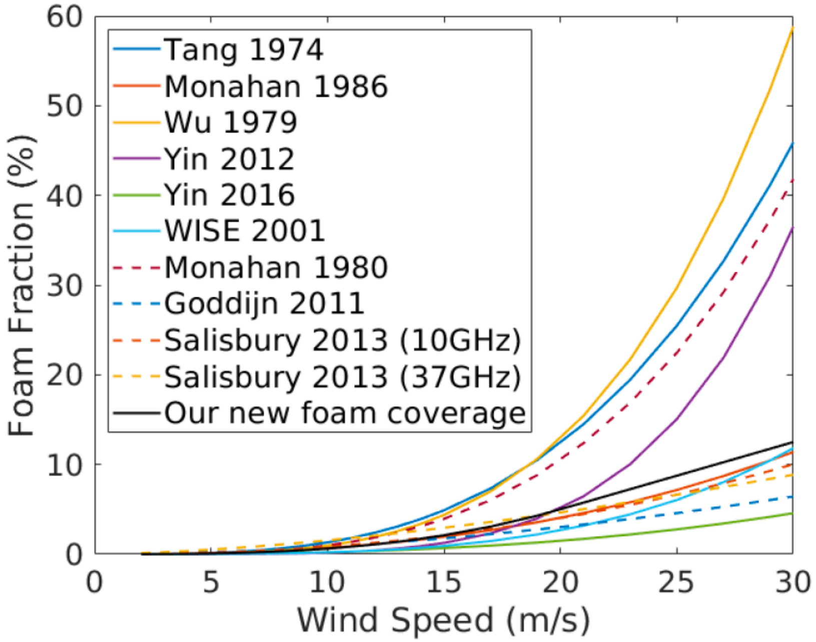
- e_VN and e_HN are the neutral emissivities (i.e. for a flat sea / no wind). They are estimated with the dielectric constant module from Meissner and Wentz [2004, 2012] and the Fresnel equations.

- e_V0 and e_H0 are the isotropic emissivities due to the wind. They are estimated with a neural network (NN).

- e_V1, e_V2, e_H1, e_H2, $e_{S3}1$, $e_{S3}2$, $e_{S4}1$ and $e_{S4}2$ are the anisotropic emissivities due to the wind. They are estimated with a second NN.

Configuration of PARMIO

- **Dielectric constants:**
  - Meissner and Wentz, 2004 and 2012
- **Wave spectrum:**
  - Durden and Vesecky, 1985 with the amplitude coefficient multiplied by 1.25.
- **Foam coverage:**
  - New estimation



$$if\ U_{10} < 20$$
$$Fc = 6.25e^{-6} \times U_{10}^3$$
$$else$$
$$Fc = 3 \times 6.25e^{-6} \times 20^2 \times (U_{10} - 20) + 6.25e^{-6} \times 20^3$$

- **Foam emissivity:**
  - Anguelova and Gaiser, 2013 with a foam effective thickness of 2mm.