National Environmental Satellite, Data, and Information Service

Development and Improvement of Community Surface Emissivity Model (CSEM) System

Ming Chen[1,2] and Fuzhong Weng[1]

1.NOAA Center for Satellite Applications and Research
2. Joint Center for Satellite Data Assimilation

Outline

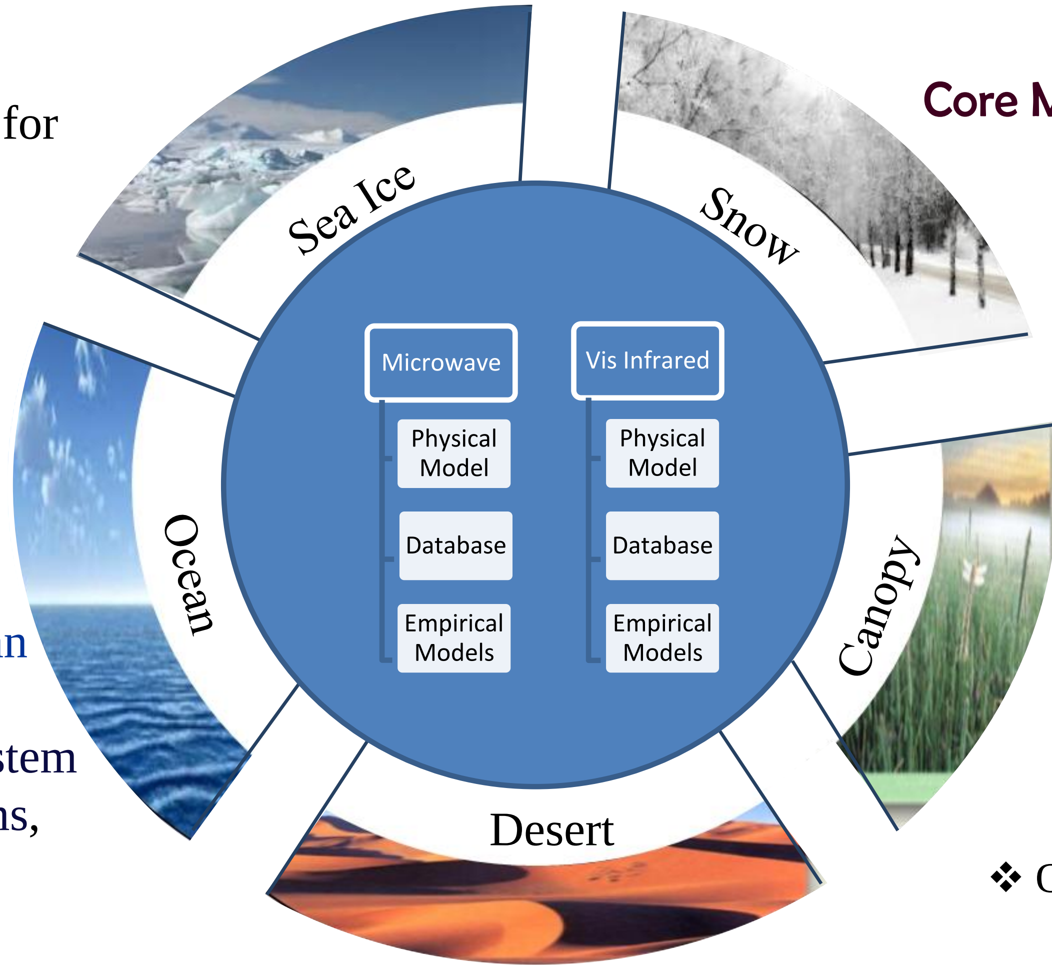
1. An introduction to CSEM — Model design and system features
2. Improvements of model physics and the impacts on CRTM forward simulation, GFS forecasting
3. Ongoing research and model improvement efforts
4. Summary

Community Surface Emissivity Model (CSEM)

❖No longer a subsystem dedicated for use in CRTM

❖An open-system with optional models for research and operational applications

❖It may be used as an independent model system or as a subsystem of upper-level systems, e.g. CRTM.



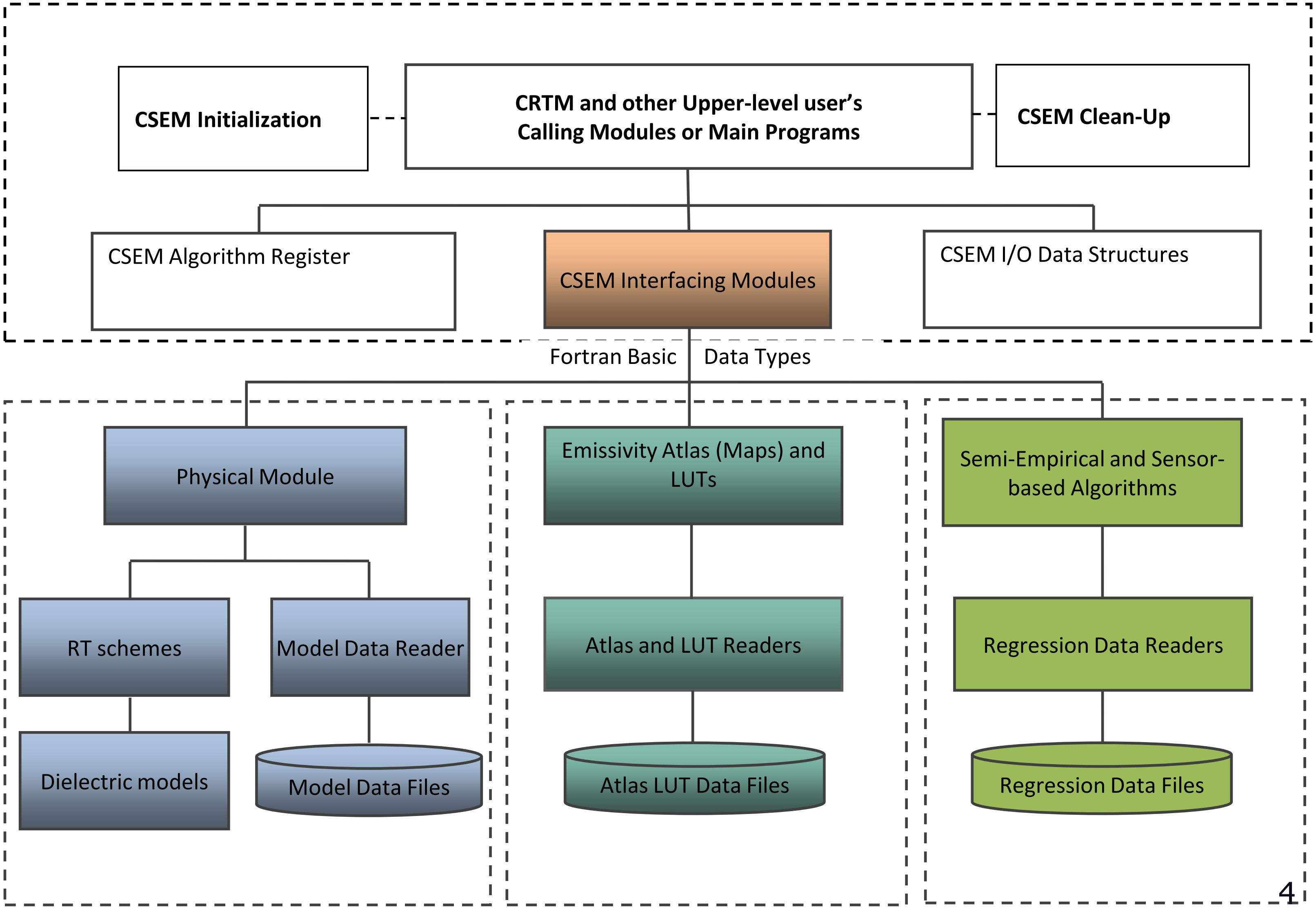
Core Modules

❖ OOP Design

❖A platform where optional research algorithms (models) may be easily developed, added, tested and used besides those that have been chosen for operational use.

❖Forward, tangent-linear, and adjoint operators

Diagram of Unit CSEM Infrastructure and CRTM-CSEM Interfacing Design



CSEM Microwave Land Emissivity Models

	Models	Model Features	Spectral Range	Angular
1	NESDIS Physical Model V1 *Weng et al., 2001*	• Two-stream isothermal three-layer (Air-Canopy-Soil) model structure (Weng et 2l, 2001) • Physical Leaf & Canopy optical property model based on stacked-leaves (*Wegmu¨ller et al., 1995; Ulaby et al., 1981)* • Fresnel Soil emission with top 10cm soil layer T, SMC • Soil surface roughness correction (*Choudhury et al., 1979)*	19 ~ 200 GHz	Any zenith angles No azimuthal dependency
2	NESDIS Physical Model V2 *Chen & Weng, 2015*	• Two-stream non-isothermal three-layer (Air-Canopy-Soil) model structure • Physical Leaf & Canopy optical property model based on arbitray leaf inclination distribution models • Multi-layer soil RT, Fresnel • Multiple soil surface roughness models	1.4 ~ 200 GHz	Any zenith ang No azimuthal dependency les
3	TELSEM *Aires et al., 2007*	• Gridded Monthly emissivity maps (0.25°x0.25°) anchored at SSMI polarized 17, 22,37, 85GHz channels • Applicable for other sensors with the provided interpolators	10 ~ 190 GHz Linear frequency interpolator	0^o ~ 60^o Empirical angular dependency interpolator
4	CNRM *Karbou et al., 2005*	• Gridded emissivity maps (0.5°x0.5°) at AMSU-A & B at 23.8,31.4,50.3,89.0 GHz • Monthly & weekly • Specific for AMSU-A & B	All AMSU-A &B Channels with the linear frequency interpolator	$>40^o$ or $<40^o$

CSEM Infrared Land Emissivity Models

	Models	Model Features	Spectral Range
1	NESDIS Physical Model V1 *Chen et al., 2013*	• Physical leaf optical model based on PROSPECT model (Jacquemou et al., 1990) • Physical canopy RT model based on the scattering and extinction of Arbitrary Inclined Leave, SAIL (Verhoef, 1984) • Kramers-Kronig analysis of leaf refractive index spectral (Chen & Weng, 2012)	0.4um ~ 15um
2	NPOESS Type-based Spectra LUT	• 24 Type-based reflective spectra LUT • Global surface type mapping based on 24 NPOESS type classification	0.2um ~ 15um
3	RTTOV-UWIREmis Database *Seemann & Borbas, 2008*	• Monthly emissivity maps (0.05°x0.05°) with 416 spectral points between 3.6 and 14.3 μm. • Accuracy depdends on UW/CIMSS baseline-fitted emissivity DB, MODIS MYD11 data and the set of laboratory spectra used for the statistical PC regression/projection.	3.6um ~ 14.3um
4	IASI Emissivity Database *Zhou et al., 2011*	• Monthly Gridded emissivity maps (0.5°x0.5°) • Based on 8461 IASI channels 645 – 2760 (cm^{-1}) measurements	3.6um ~ 15.5um

CSEM Ocean Emissivity Models

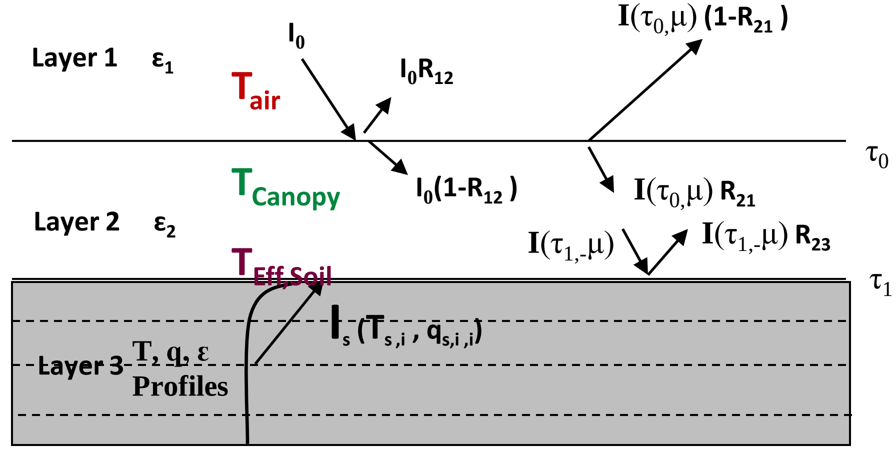
		Models	Model Features	Spectral Range	Angular
MW	1	*FASTEM 5 & 6*	• Geometric Optics (GO) assumption (*English et al, 1998*) •Two-scale ocean wave model (*Durden and Vesecky, 1985*) • Double Debye Permittivity Model (*Ellison et al, 1998*) • Foam effects (*Kazumori et al., 2008*) • Large-scale & small-scale corrections of Fresnel reflection • Full Stokes components • Azimuthal dependency	1.4 ~ 200 GHz	Zenith angle 0^{o} ~ 65^{o} Azimuth angle 0^{o} ~ 360^{o}
Vis/IR	1	Nalli.IRwater	• Nalli et al., 2008 • Geometric Optics (GO) assumption • Cox-Munk and Ebuchi-Kizu wave slope PDFs • Ocean wave shadowing • Accounting for the downwelling atmospheric radiance	3.3um ~ 16.7 um	Zenith angle 0^{o} ~ 75^{o}
	2	WuSmith.IRwater	• Wu et al., 1997 • Geometric Optics (GO) assumption • Seawater refractive index fixed for temperature, salinity, and cholorinity. • Cox-Munk wave slope PDFs • Ocean wave shadowing	3.3um ~ 16.7 um	Zenith angle 0^{o} ~ 75^{o}

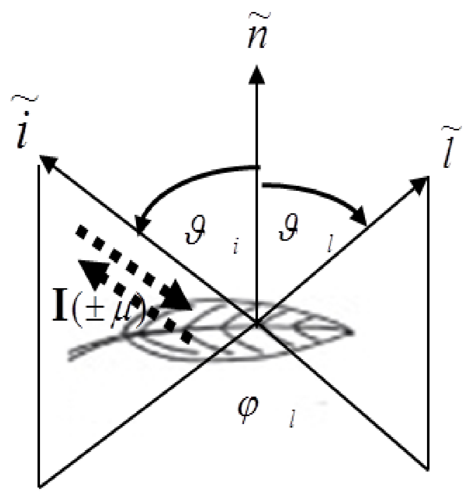
Snow/Sea Ice Emissivity Models

		Models	Model Features	Spectral Range	Angular
MW	1	NESDIS Physical Model V1 *Weng et al., 2001*	• Two-stream isothermal three-layer (Air-Soil-Snow) model structure (Weng et al, 2001) • Dense media scattering and absorption coefficients (*Tsang et al., 1985)* • Fresnel Soil emission with top 10cm soil layer T, SMC	19 ~ 89 GHz	Any zenith angles
MW	2	Empirical Models	• Regression model based on sensor window-channel Tbs • Sensor specific • Implemented for sensor: AMSU-A & B, MHS, SSMI, SSMIS, AMSRE	Specific sensor channels	Specific sensor view angle
MW	3	Semi-Empirical Models *Chen & Weng, 2013*	• 16 Type-based snow lab emissivity spectra LUT • Real-time adjustment based on one or two window-channel TB with a simplified RT analytical model • Implemented for ATMS, AMSR2	Specific sensor channels	Specific sensor view angle
Vis/IR		NPOESS Type-based Spectra LUT	• Fresh snow, old snow and sea ice reflective spectra LUT • Global surface type mapping based on 24 NPOESS type classification	0.2um ~ 15um	N/A

CSEM Physical Land Microwave Emissivity Model

- The two-stream canopy RT model (Weng et al , 2001) was refined to account for the thermal deference of air, canopy and underlying soil layers.
- Enhanced canopy volume scattering scheme accounting for the multiple scattering among leaves with arbitrary leaf inclination distributions.

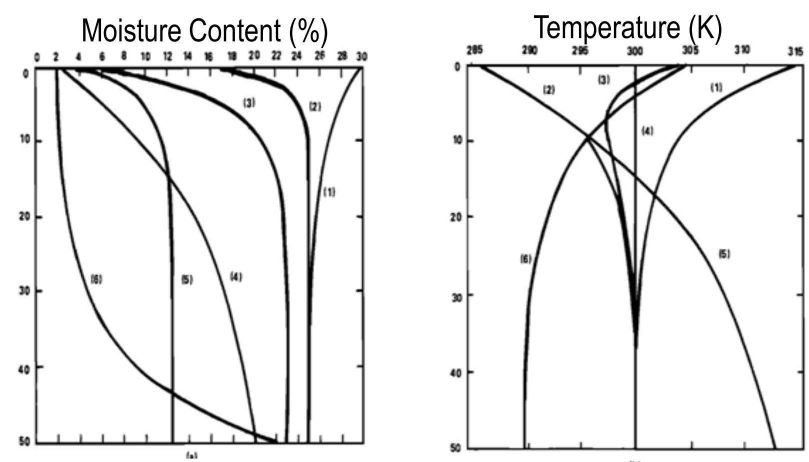




$$T_{scat} = f_{i1}(\tau f_{i1} + \rho f_{i2}) + f_{i2}(\tau f_{i2} + \rho f_{i1}), \text{ forward scattering}$$

$$R_{scat} = f_{i1}(\rho f_{i1} + \tau f_{i2}) + f_{i2}(\rho f_{i2} + \tau f_{i1}), \text{ backward scaterring}$$

- Multi-layered soil RT Models and Profiling Model



Moisture and temperature profiles representative of various soil moisture conditions [from Njoku and Kong, 1977].

Physical Microwave Soil Emission Modeling

Microwave soil emission modeling provides necessary "boundary conditions" for the upper-level radiative transfer models (e.g., canopy and atmosphere). Soil emission is very sensitive to **soil moisture content**, **soil temperature**, **soil texture**, and **surface roughness,** especially at low-frequency bands. Several efforts have being made to optimize the CSEM performance so that CRTM may cover the radiance assimilations of low-frequency L, C and X bands.

	Implementation in CSEM
1) Soil dielectric constant	❑ **Weng et al 2001, Chen & Weng 2015** ❑ Wang et al, 1980 ❑ Mironov et al, 2004 ❑ Dobson et al., 1985
2) Soil Radiative transfer scheme	❑ **Fresnel** ❑ Burke, 1979 ❑ **Wilheit,1980**
3) Surface roughness correction	❑ **Wang & Choudhury 1981** ❑ **Chen & Weng, 2015** ❑ Wegmuller 1999 ❑ Coppo, 1991

Multi-layer MW Soil RT Model Vs. Fresnel Model

A Trade-off Between Computing Cost and Accuracy

	SMC			Temperature			Fresnel (Weff)		Fresnel (Wsoil 1mm)		Truth (Wilheit 120lys)	
F(GHz)	0-10cm	Weff Wilheit	1mm	0-10cm	Teff Wilheit	1mm	H-pol	V-Pol	H-pol	V-Pol	H-pol	V-Pol
1.4	0.2	0.190	0.15	305	306.1	311.5	0.3890	0.2013	**0.3345**	**0.1561**	0.3408	0.1610
5.4	0.2	0.170	0.15	305	308.9	311.5	0.3803	0.1938	**0.3233**	**0.1475**	0.3231	0.1474
10.4	0.2	0.158	0.15	305	310.2	311.5	0.3727	0.1873	**0.3173**	**0.1429**	0.3181	0.1435
23.4	0.2	0.151	0.15	305	311.1	311.5	0.3429	0.1625	**0.2939**	**0.1255**	0.2932	0.1250
89.4	0.2	0.148	0.15	305	311.4	311.5	0.2292	0.0827	**0.2001**	**0.0660**	0.2002	0.0661

Exponential Weff Model

$$Wmm = B + C\left(1 - e^{\frac{3z}{D}}\right), where$$

$$B = B(Wair) \quad C = C(Wsoil1)$$

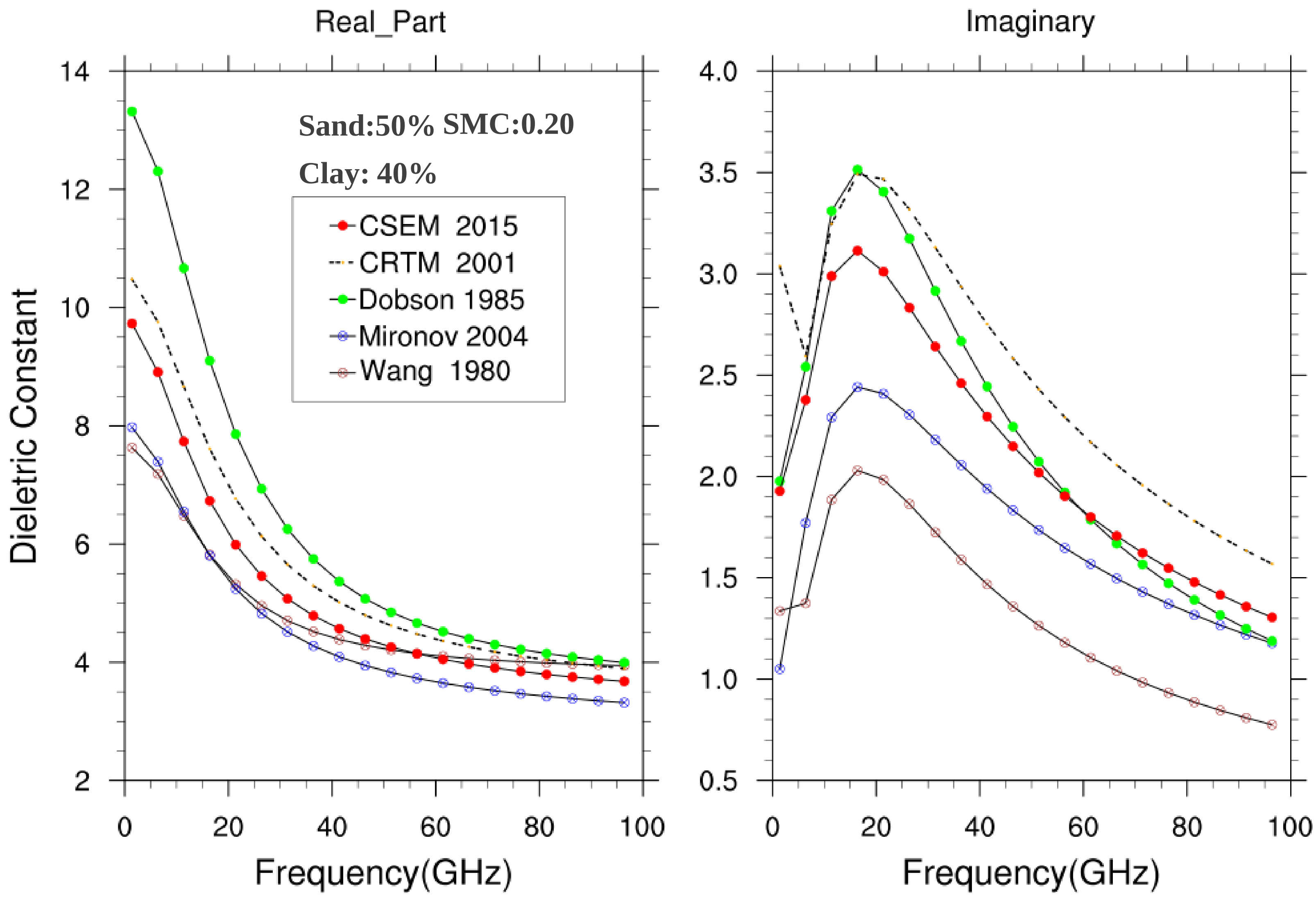
$$D = D(Wsoil1, \Delta T)$$

Linear Mixture Teff Model

$$Teff = (1 - A) * Tsurf + A * Tsoil1, where$$

$$A = A(freq, Wsoil1)$$

Optimization of MW Soil Dielectric Model



MW Attenuation and Polarization Mixing Over Rough Soil Surfaces

$$R_p = [(1-Q)r_p + Qr_q]P$$

❑Roughness Attenuation P-Function

$$P(k,\vartheta;\sigma) = \frac{1}{2}[A + B\tanh\left(\frac{x-x_0}{w_0}\right) + C\tanh\left(\frac{x-x_1}{w_1}\right)]$$

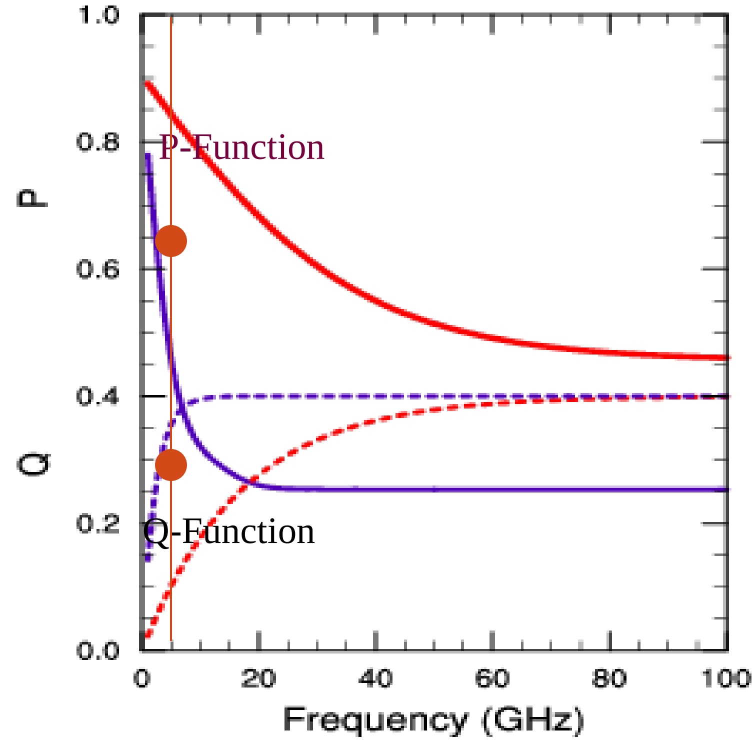
$$x(k,\vartheta;\sigma) = 2k\sigma\cos(\vartheta) \quad k = 2\pi f/30$$

$P = 0.3$ CRTM2. 1. 3

❑Polar Mixing Q-Function

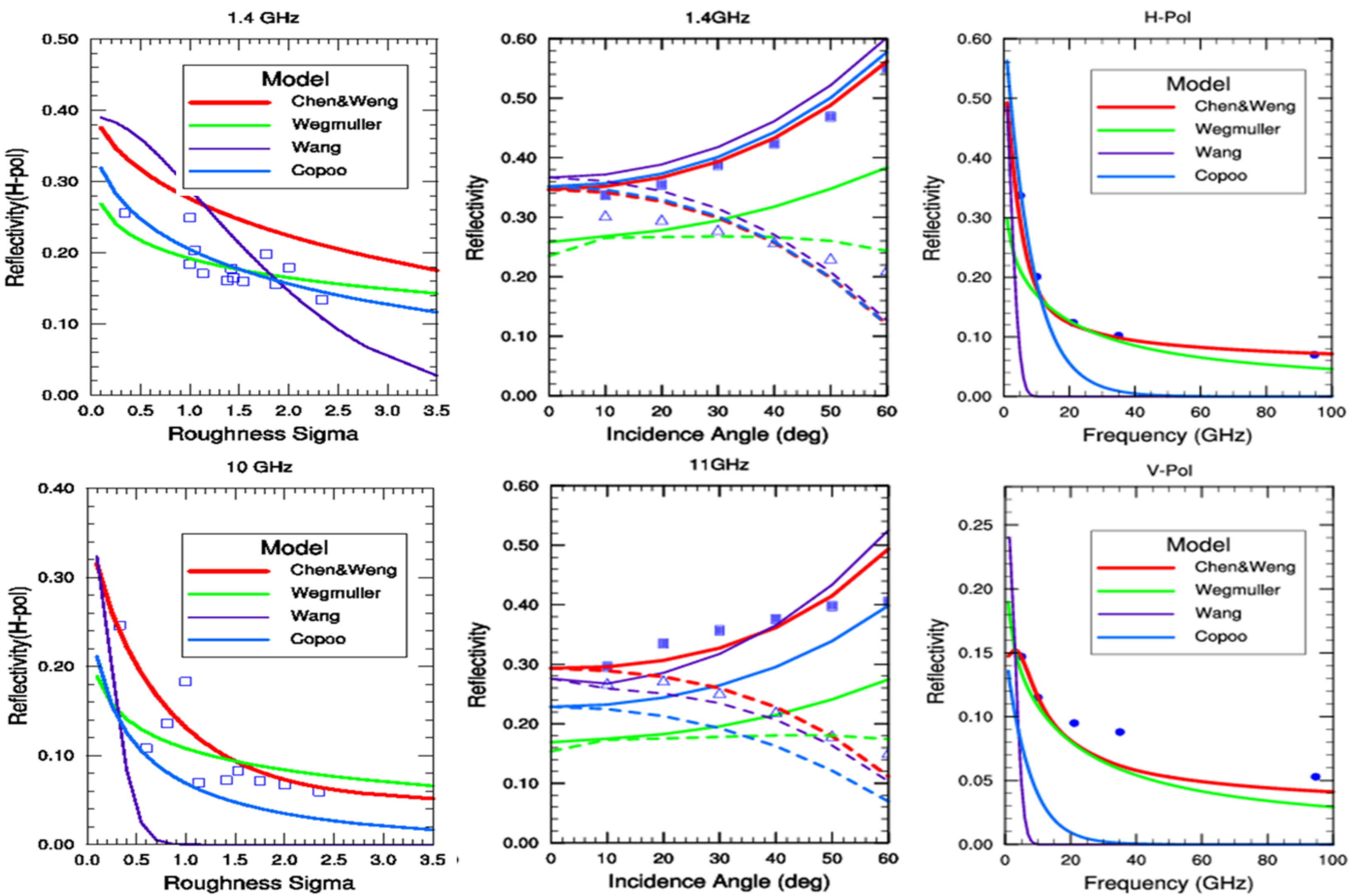
$$Q(k,\vartheta;\sigma) = 0.35(1.0 - e^{-15.0x})$$

Soil Roughness Correction



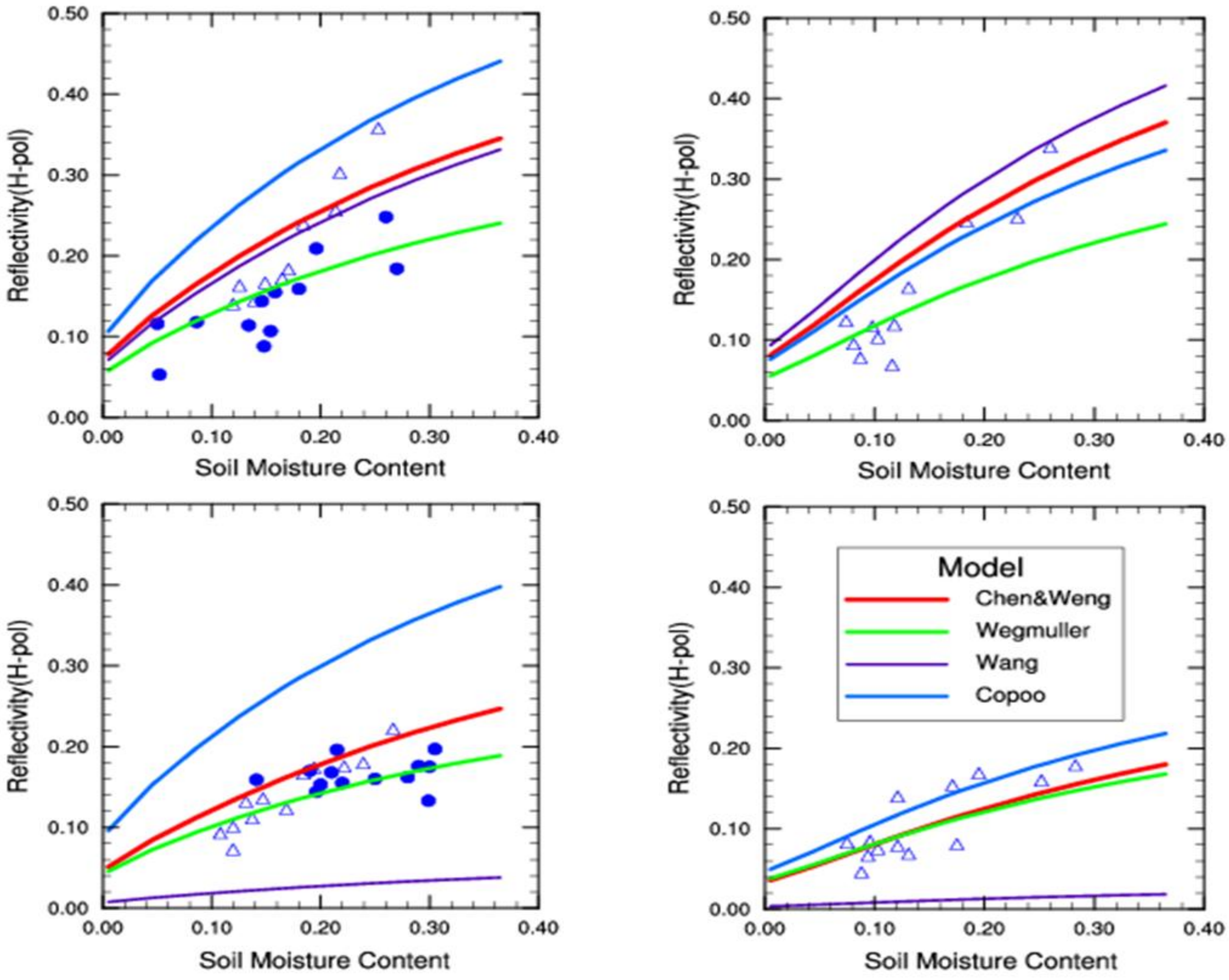
$$\frac{P_{CSEM}}{P_{CRTM2.1.3}} = \frac{R_{CSEM}}{R_{CRTM2.1.3}} = \frac{1-\varepsilon_{CSEM}}{1-\varepsilon_{CRTM2.1.3}} \approx 2.0 \Rightarrow \frac{\varepsilon_{CSEM}}{\varepsilon_{CRTM2.1.3}} \approx 0.5 - 1.0$$

Verification of MW Soil Emission Model With Ground Measurements (1)



National Environmental Satellite, Data, and Information Service

Verification of MW Soil Emission Model With Ground Measurements (2)



Verification of MW Soil Emission Model With 3D Numerical Maxwell Model Simulations (3)

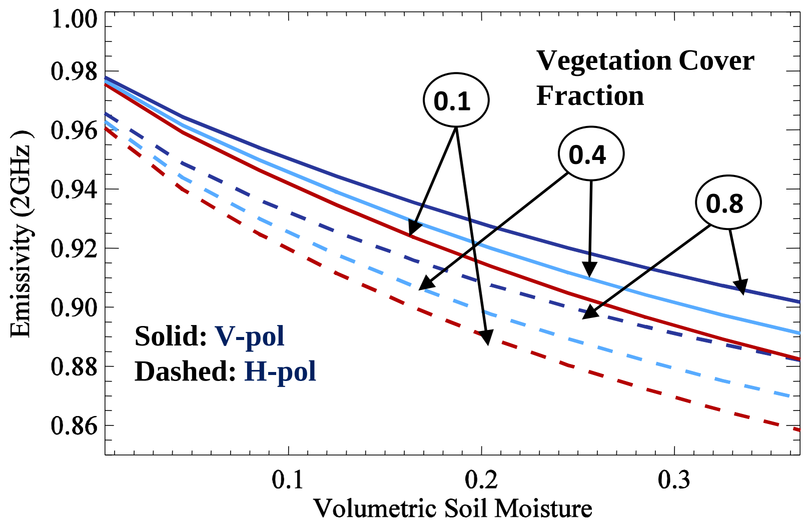
L. Tsang, I. Koh, T. Liao, S. Huang, X. Xu, E.G. Njoku, and Y. Kerr, "Active and Passive Vegetated Surface Models With Rough Surface Boundary Conditions from NMM3D", IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 6, pp. 1698-1709 , 2013.

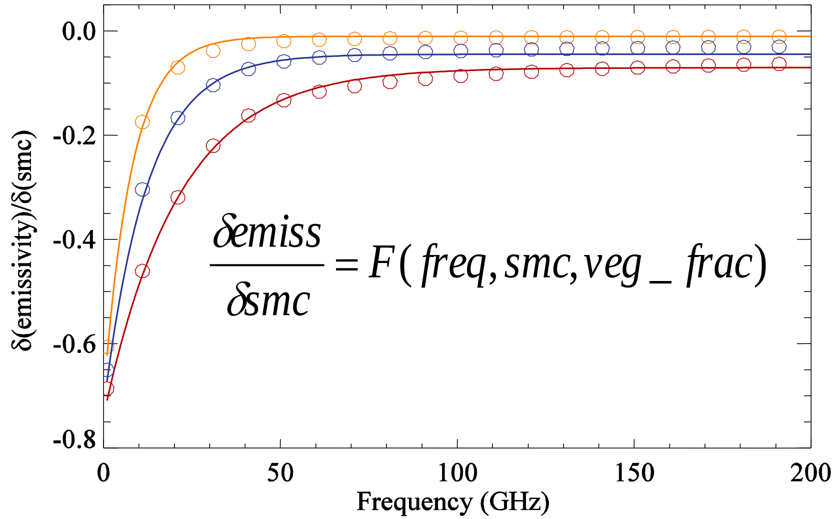
20% Soil Moisture **(H-Pol)**					
Sigma(cm)	NMM3D	C&W	Coppo	Wegmul.	Wang
1	0.40	**0.34**	0.24	0.23	0.38
2	0.35	**0.28**	0.19	0.20	0.21
3	0.31	**0.24**	0.15	0.18	0.08
4	0.28	**0.21**	0.13	0.16	0.02
30% Soil Moisture**(H-Pol)**					
1	0.47	**0.40**	0.28	0.26	0.44
2	0.41	**0.33**	0.22	0.23	0.24
3	0.37	**0.29**	0.18	0.20	0.09
4	0.33	**0.25**	0.15	0.19	0.02

20% Soil Moisture**(V-Pol)**					
Sigma(cm)	NMM3D	C&W(1)	Coppo	Wegmul.	Wang
1	0.23	**0.22**	0.14	0.19	0.21
2	0.21	**0.21**	0.10	0.16	0.12
3	0.20	**0.19**	0.08	0.15	0.04
4	0.18	**0.18**	0.07	0.14	0.01
30% Soil Moisture**(V-Pol)**					
1	0.29	**0.29**	0.18	0.22	0.28
2	0.27	**0.26**	0.14	0.19	0.15
3	0.25	**0.24**	0.11	0.17	0.06
4	0.23	**0.22**	0.09	0.16	0.01

Development of LandMW_TL and LandMW_AD

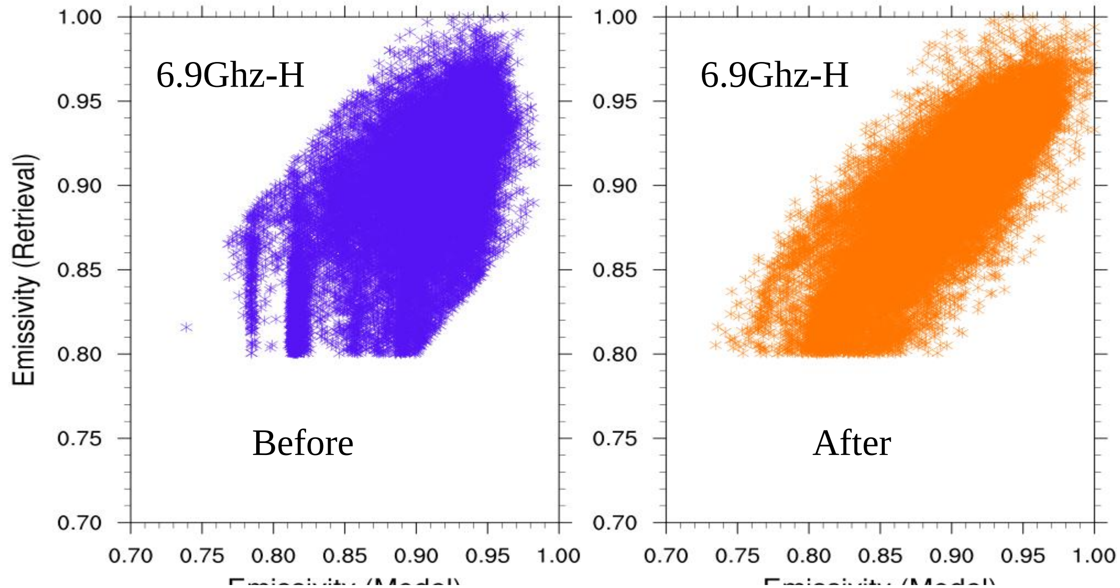
- ❑Analytic TL/AD model may be built up over reduced model state space, where only a few sensitive parameters or model variables are used in model property analysis, and high-order differential regression models are derived.
- ❑Such analytic TL/AD model may be used in GSI, meanwhile it provides the relationship between the sensitivities of different channels, which may be used to quantify the uncertainty of sensitive model inputs from few channels.
- ❑"Real-time" model I/O correction analysis may be performed with the observations of one or two channels.



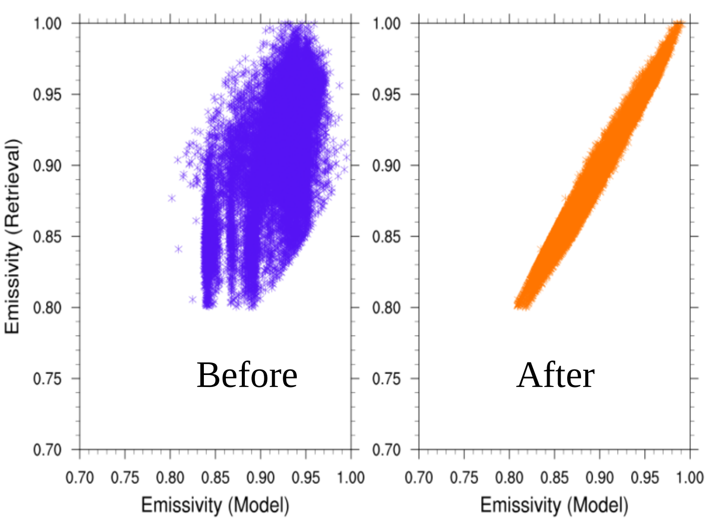


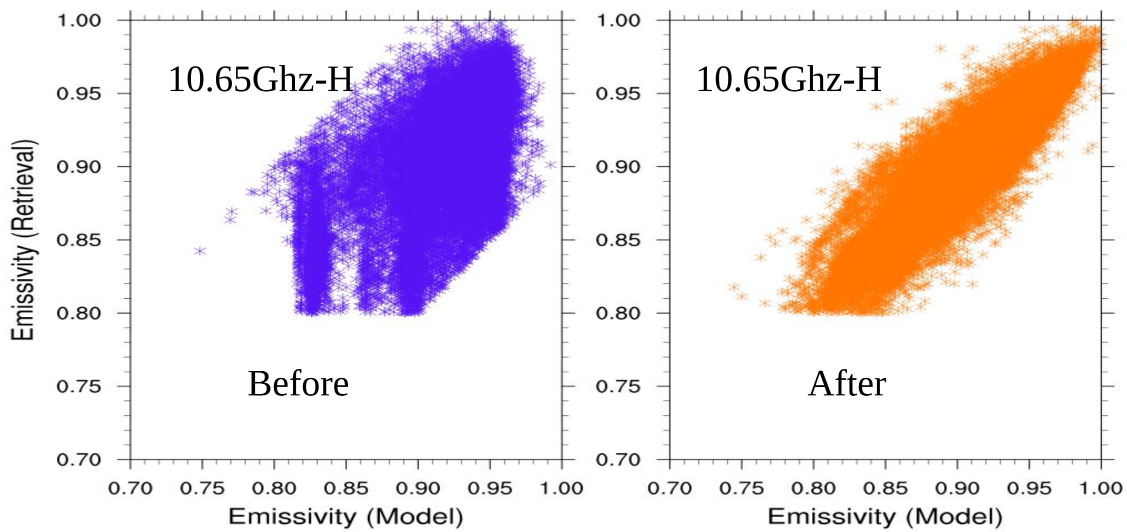
Emissivity Scatter Plots of AMSR-2 (Model Vs. NRT Retrival)

Correction analysis with observation of only one channel (23.8GHz) applied to all other channels



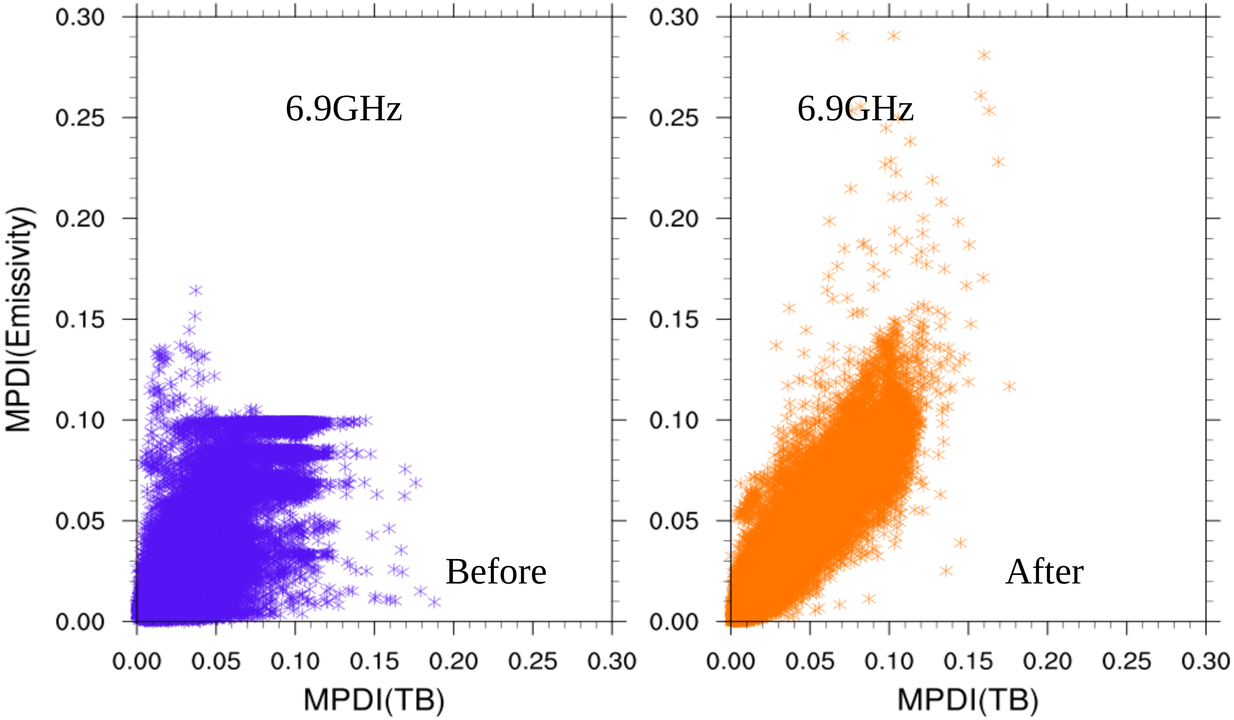
23.8GHz-H





MPDI Scatter Plots of AMSR-2

Microwave Polarization Difference Index (MPDI)

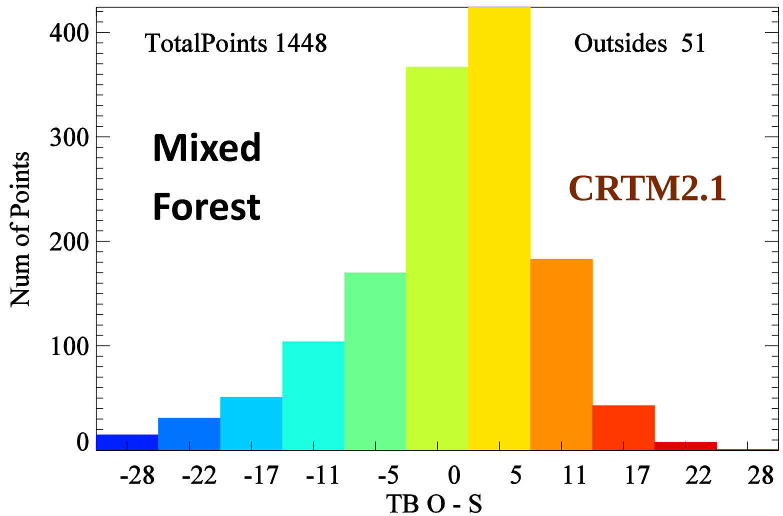


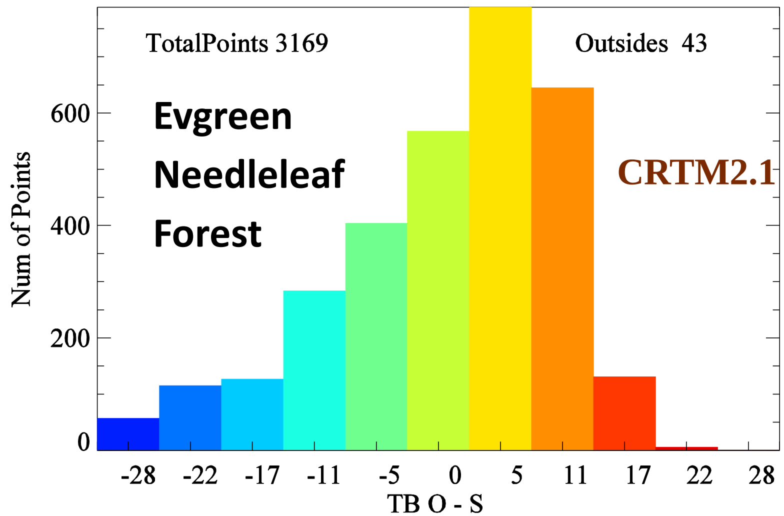
$$\begin{cases} MPDI_{Tb} = \dfrac{\mathrm{Tb_v} - \mathrm{Tb_h}}{\mathrm{Tb_v} + \mathrm{Tb_h}} \\ MPDI_{\varepsilon} = \dfrac{\varepsilon_v - \varepsilon_h}{\varepsilon_v + \varepsilon_h} \end{cases}$$

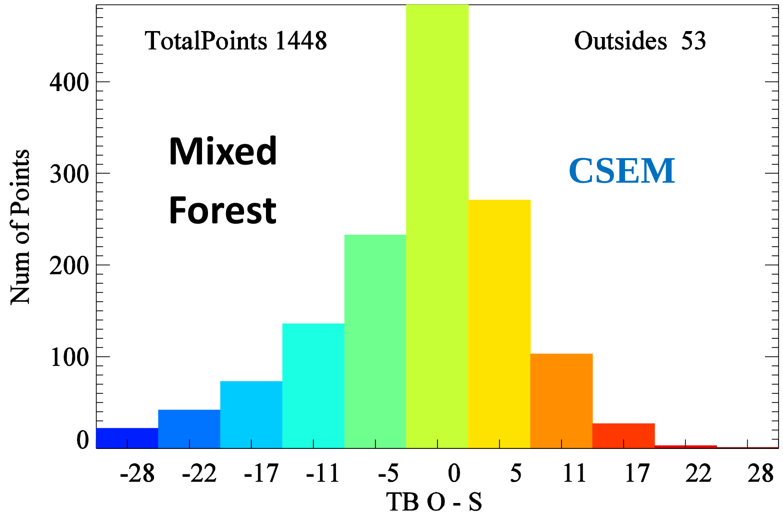
$$if: Tb \approx \varepsilon T$$

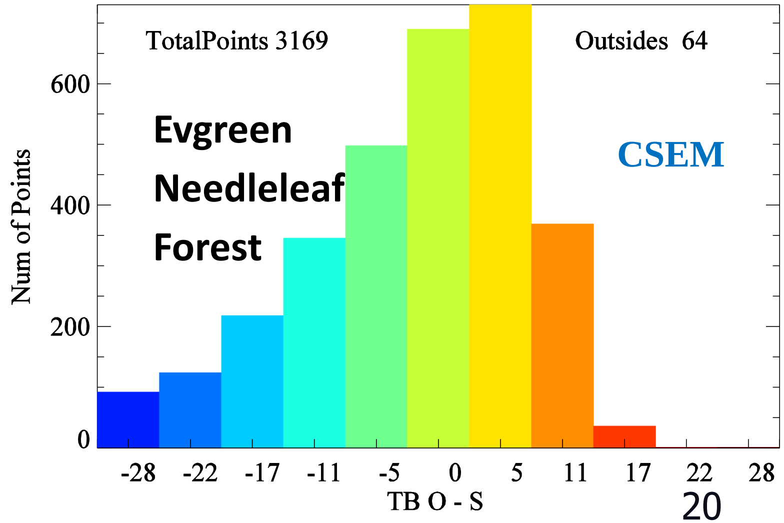
$$then\ MPDI_{Tb} \approx MPDI_{\varepsilon}$$

O-B Histogram Of Different Surface Types

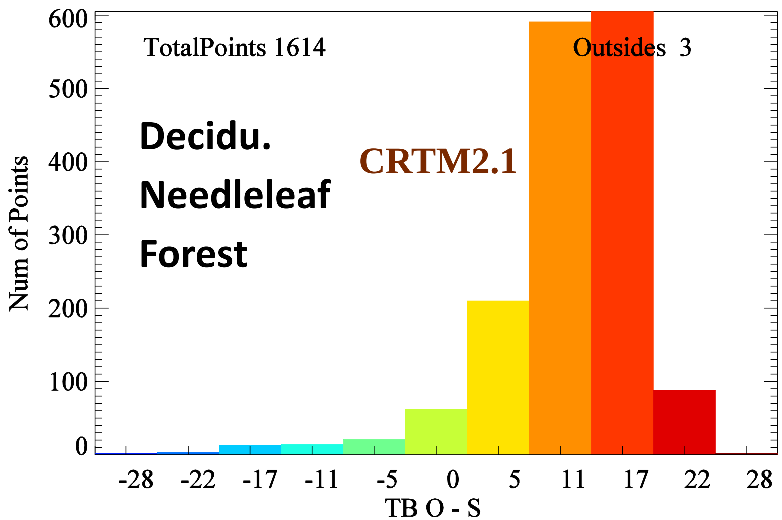


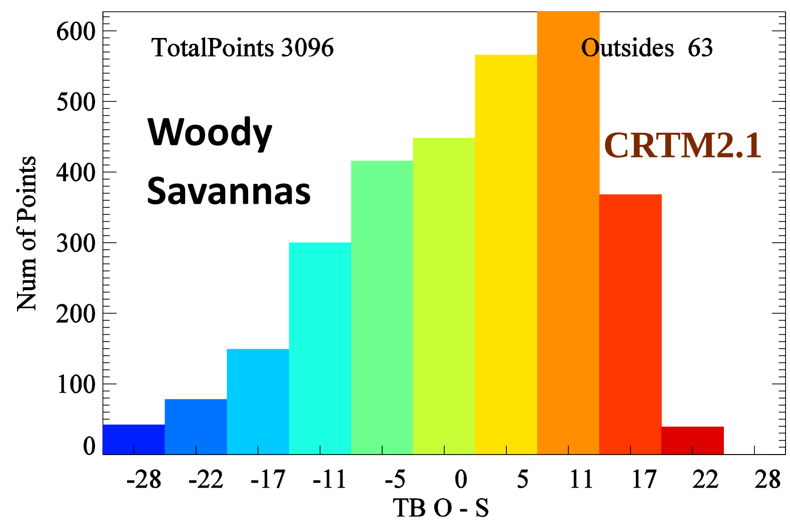


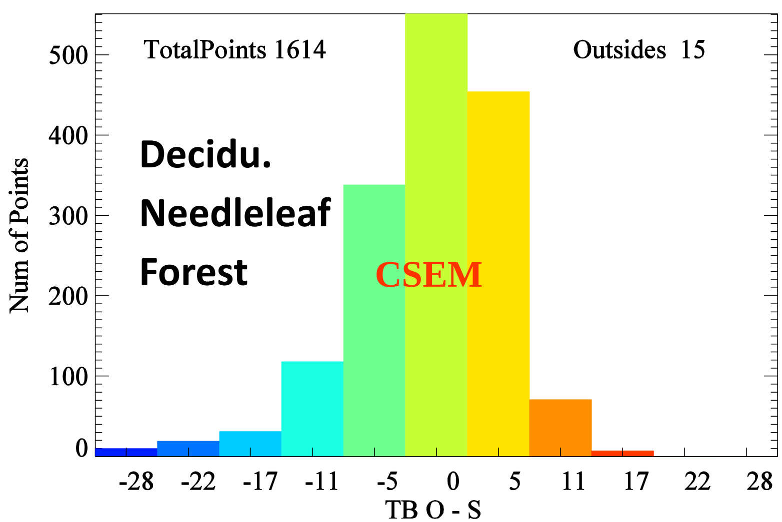


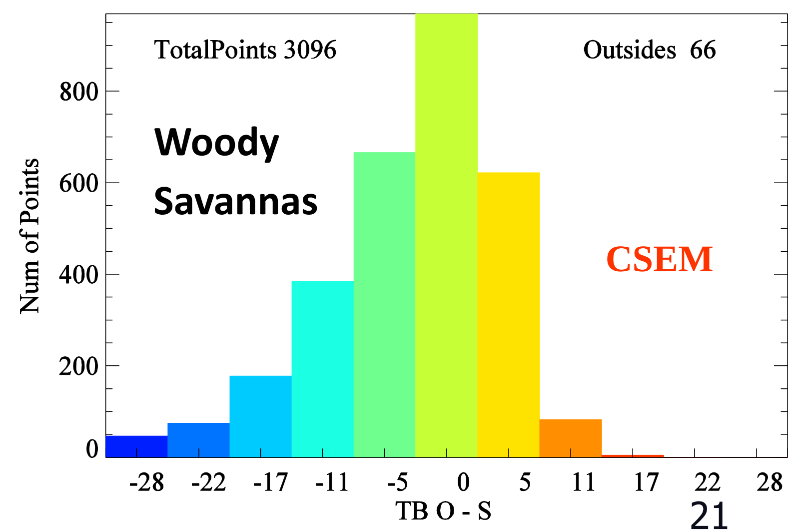


O-B Histogram Of Different Surface Types (3)



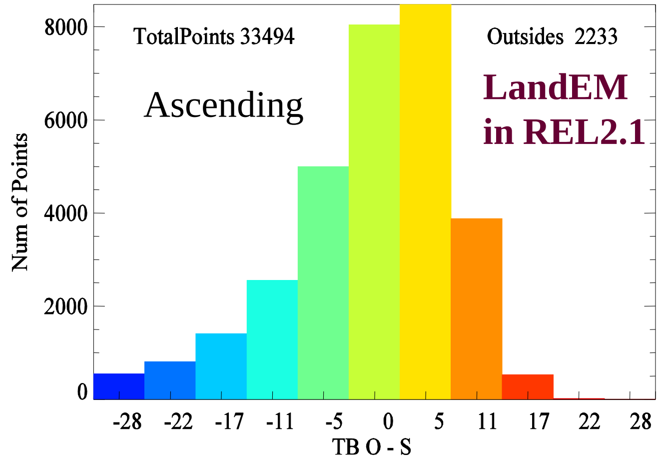


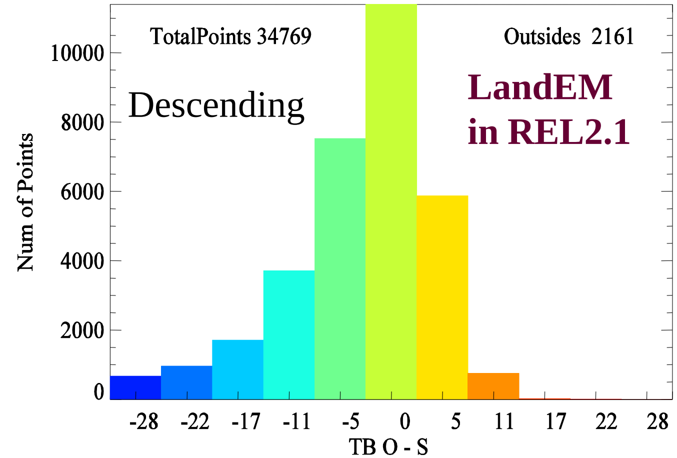




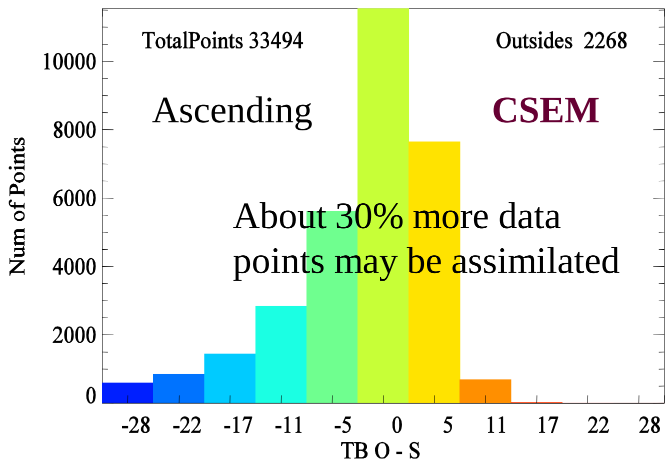
Impact of Model Improvements on TB O – B (CRTM)
LandEM in REL-2.1 vs. CSEM

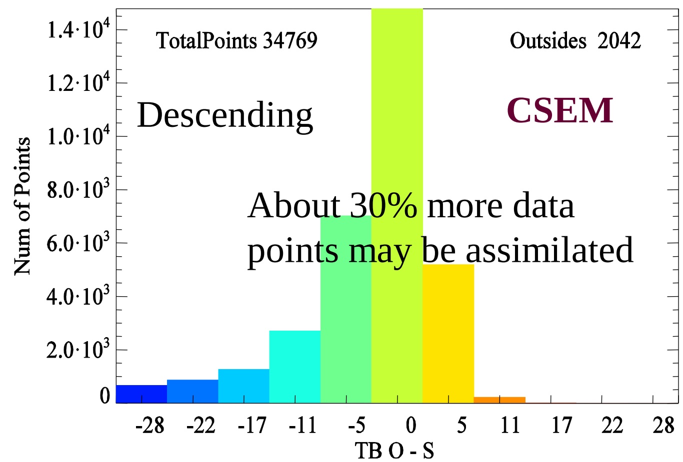
AMSUA-N18 23.8GHz





AMSUA-N18 23.8GHz

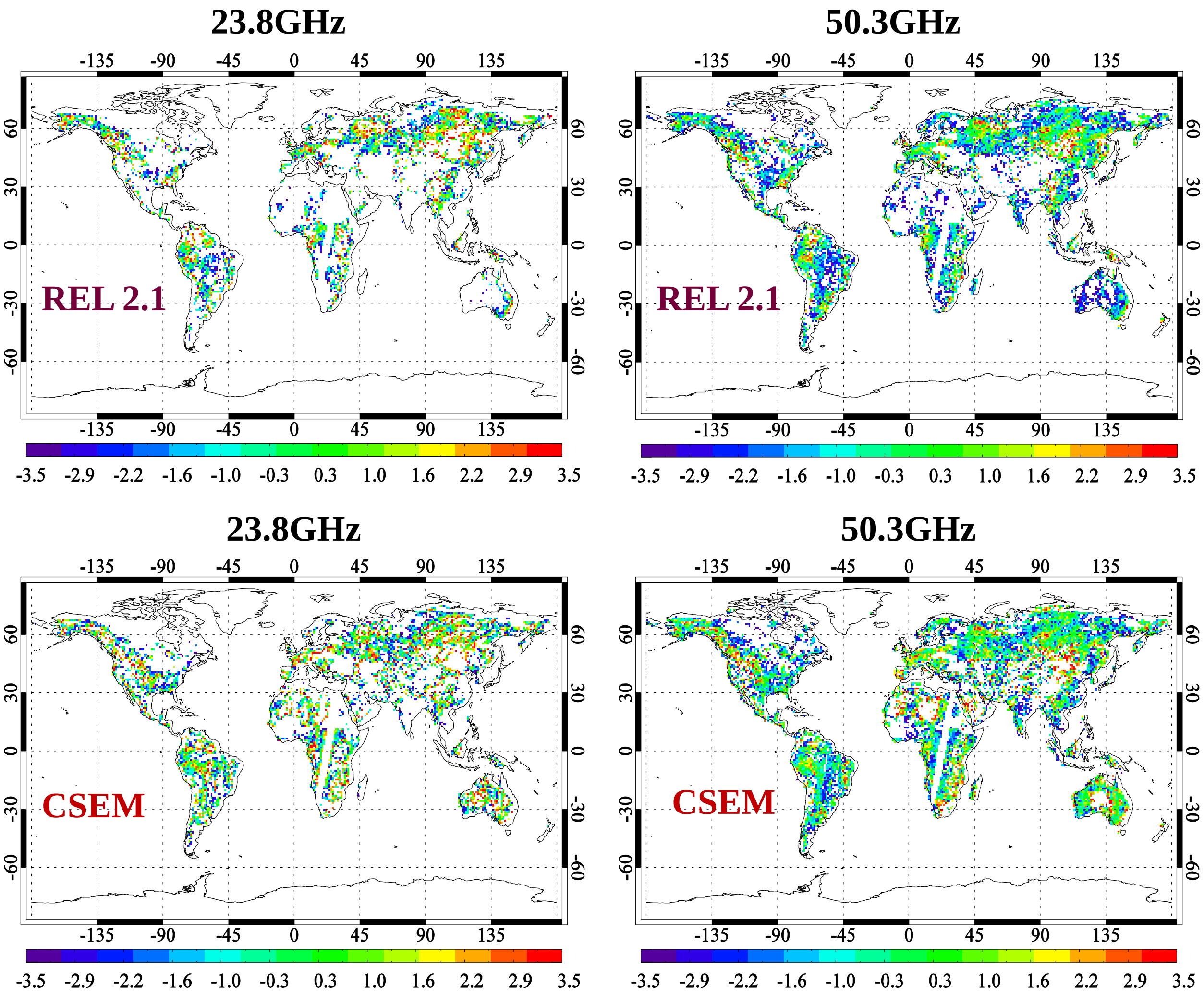




Impact of Model Improvements on TB O – B (AMSUA)
LandEM in REL-2.1 vs. CSEM

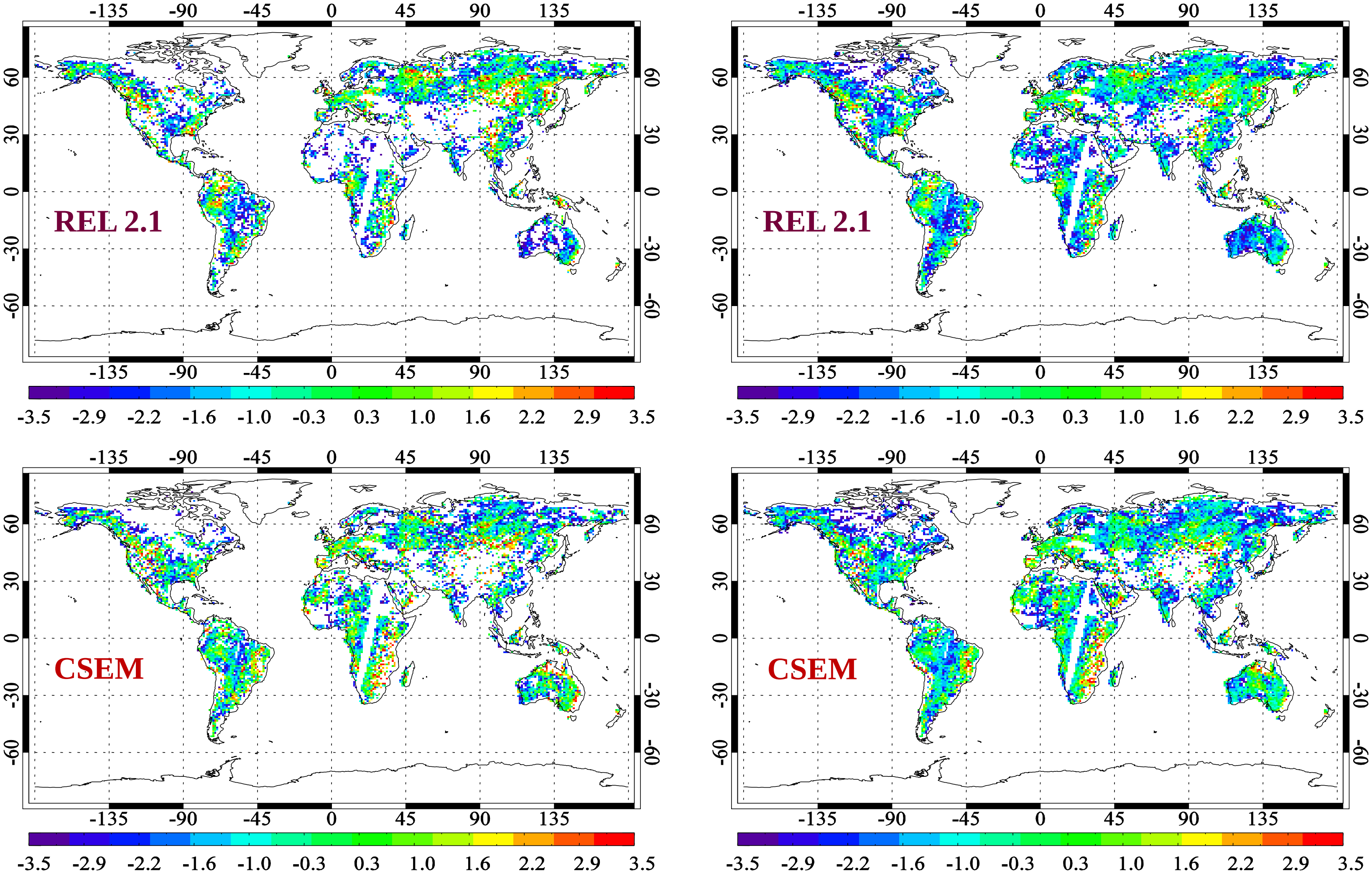
In comparison with the LandEM in REL-2.1, the ongoing improvements have significantly increased the data points that are possibly assimilated, especially over desert / bare soil regions.

Both window-channel and surface sensible sounding channels are improved.

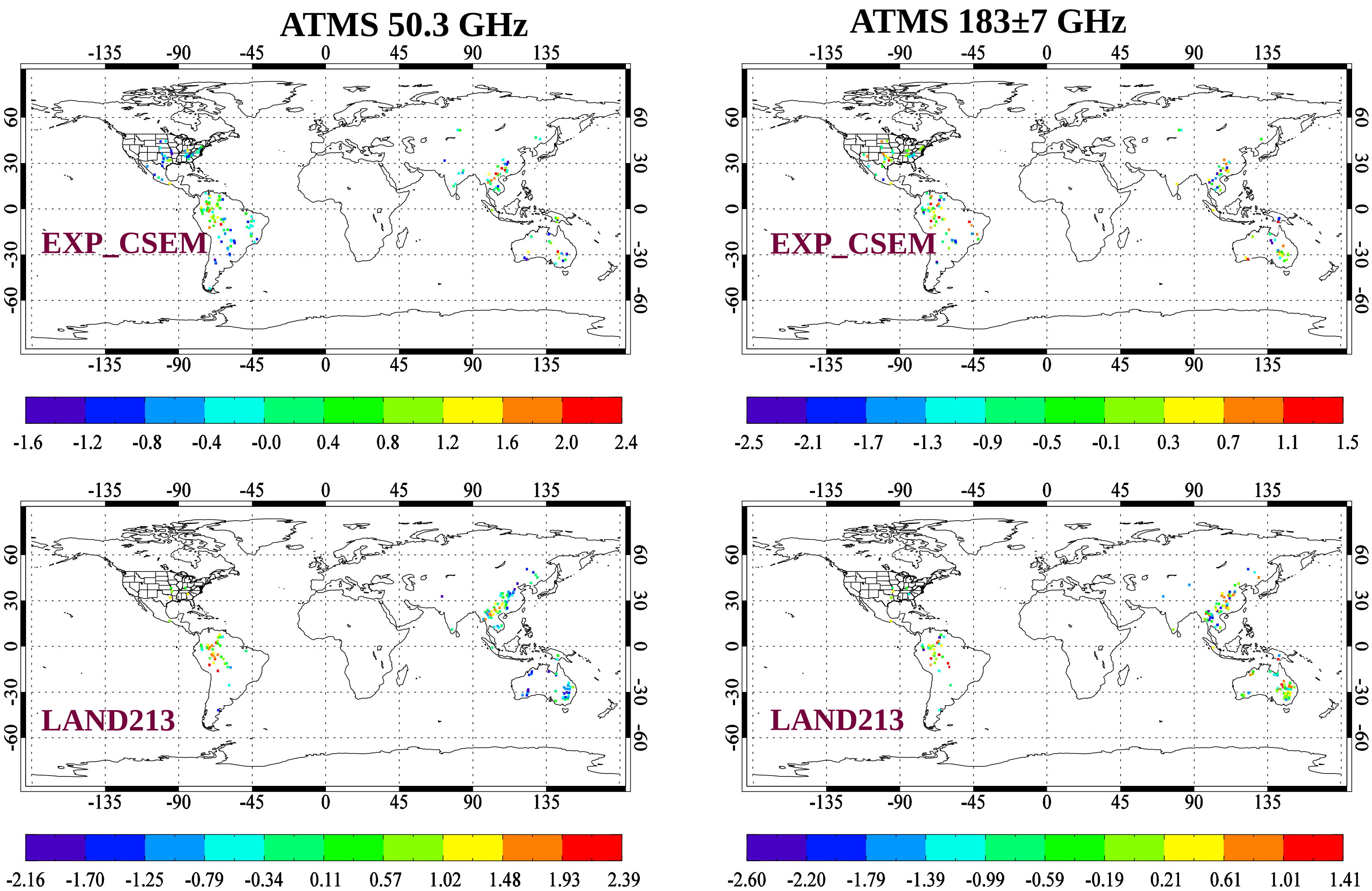


Impact of Model Improvements on TB O – B (ATMS)
LandEM in REL-2.1 vs. CSEM

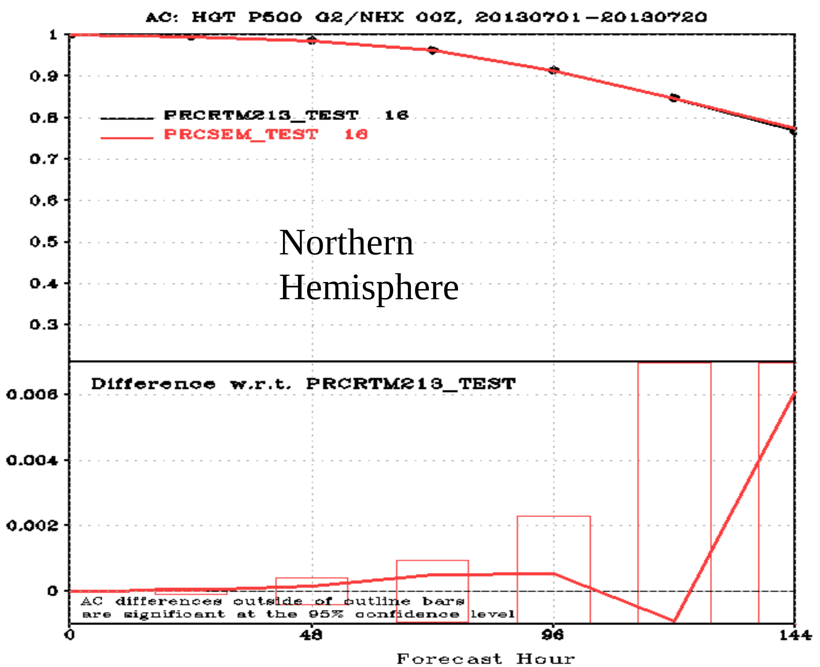
50.3 GHz **51.8 GHz**

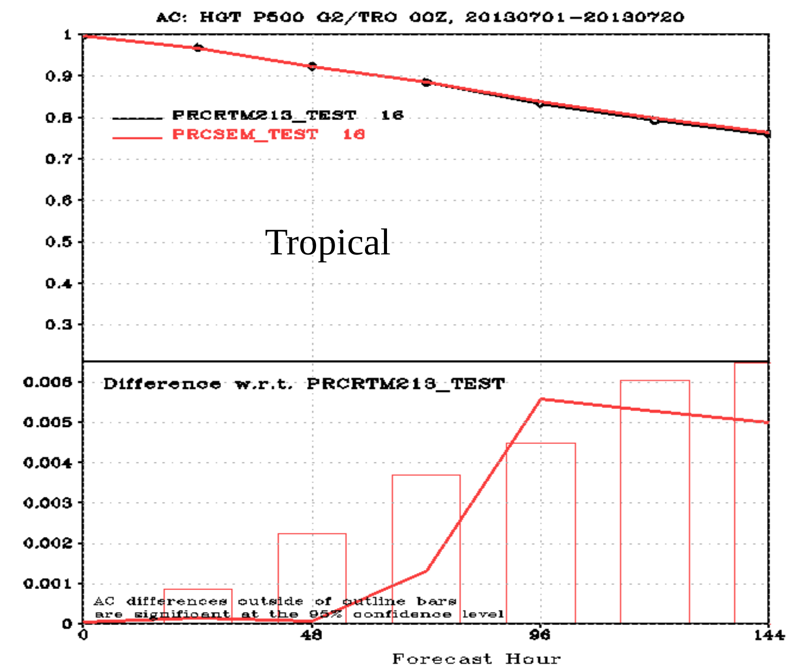


Map & Histogram of TB O – B (FirstGuess) in GSI

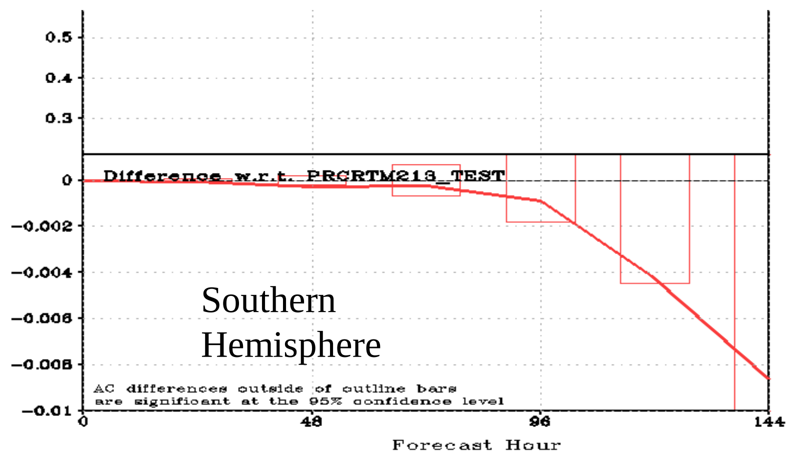


Parallel GFS-GSI Test With the Updated MW Land Emissivity Model

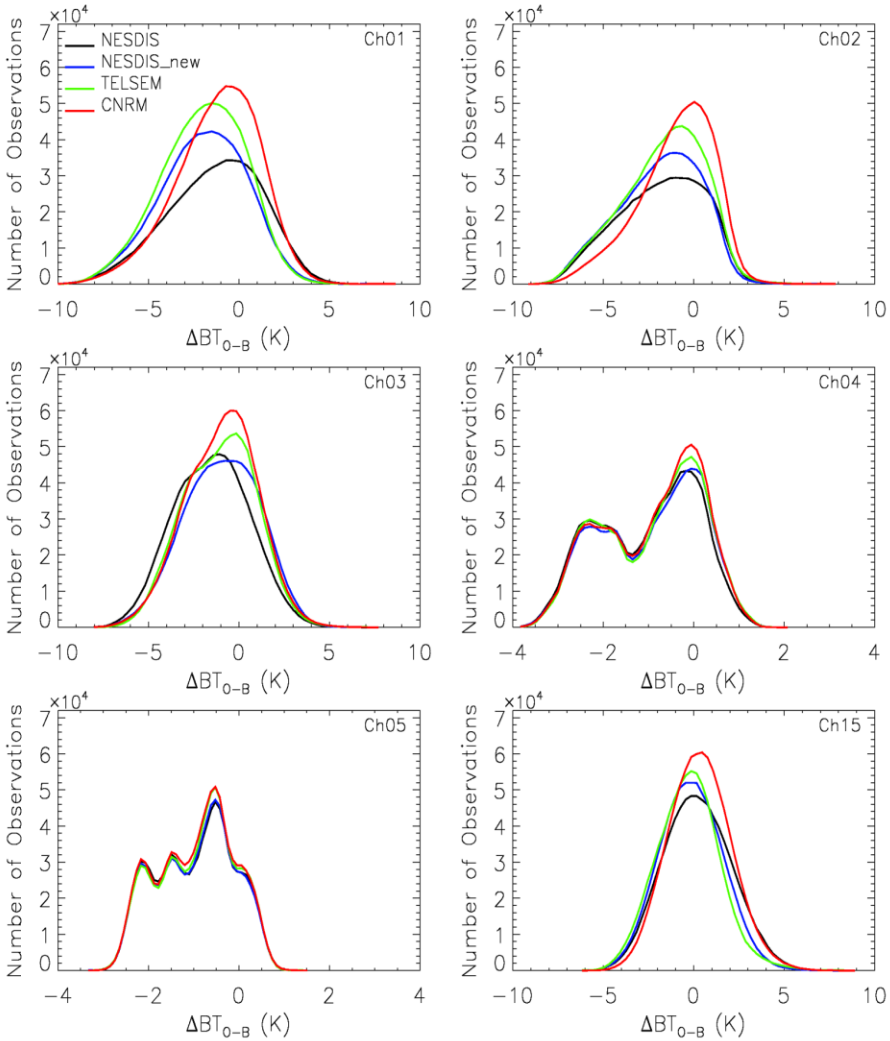




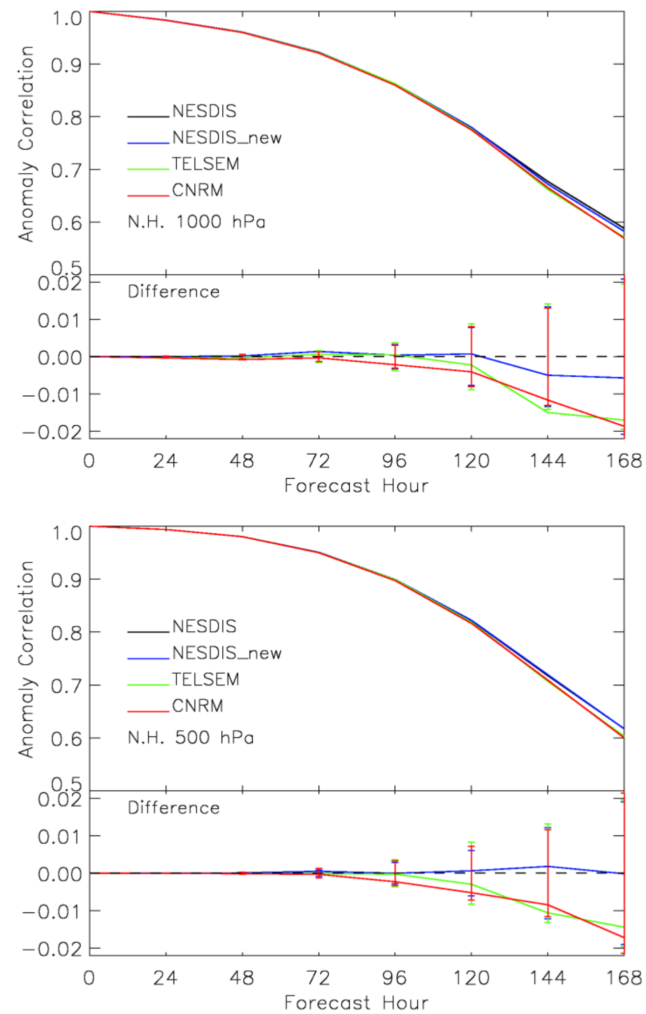
The results are promising, but a consistent retuning of the ocean emissivity model may be essential to ensure a general positive impact on the GFS forecasting.



Assimilated Data Histograms Before Bias Correction



Forecast Impact: Geopotential Height



By Y. Chen

Development of Ocean Surface MW BRDF Model

$$I_{stokes} = \begin{bmatrix} T_v \\ T_h \\ U \\ V \end{bmatrix} \qquad I^s_{stokes} = \sigma(\vec{k}_s, \vec{k}_i) I^i_{stokes}$$

$$\sigma_{pq}(\vec{k}_s, \vec{k}_i) = \sigma_{pq}(\vartheta_s, \varphi_s; \vartheta_i, \varphi_s)$$

$$= \begin{bmatrix} |f_{vv}|^2 & |f_{vh}|^2 & Re(f^*_{vh} f_{vv}) & -Im(f^*_{vh} f_{vv}) \\ |f_{hv}|^2 & |f_{hh}|^2 & Re(f^*_{hh} f_{hv}) & -Im(f^*_{hh} f_{hv}) \\ 2Re(f^*_{hv} f_{vv}) & 2Re(f^*_{hh} f_{vh}) & Re(f^*_{hh} f_{vv} + f^*_{hv} f_{vh}) & Im(f^*_{hh} f_{vv} - f^*_{hv} f_{vh}) \\ 2Re(f^*_{hv} f_{vv}) & 2Re(f^*_{hh} f_{vh}) & Im(f^*_{hh} f_{vv} + f^*_{hv} f_{vh}) & Re(f^*_{hh} f_{vv} - f^*_{hv} f_{vh}) \end{bmatrix}$$

$f_{\alpha\beta}$ *are bistatic coefficirnts* α, β *stands for* v, h

$f^*_{\alpha\beta}$ *is the conjugate*

$$r_p(\vartheta_i, \varphi_i) = \frac{1}{4\pi} \int_0^{2\pi} \int_0^{\pi/2} \left(\sigma_{pp}(\vartheta_s, \varphi_s; \vartheta_i, \varphi_i) + \sigma_{qp}(\vartheta_s, \varphi_s; \vartheta_i, \varphi_i)\right) \frac{\sin\vartheta_s}{\cos\vartheta_i} d\vartheta_s \varphi_s$$

$$= r_p^{coherent}(\vartheta_i, \varphi_i) + r_p^{incoherent}(\vartheta_i, \varphi_i)$$

$$e_p(\vartheta_i, \varphi_i) = 1 - r_p(\vartheta_i, \varphi_i)$$

There are several well-established methods for simulation of electromagnetic scattering from randomly rough surfaces

❑ **Kirchhoff Method (KM)** based on the assumption that the wavelength of the incident wave is much shorter than the horizontal variations of the surface so that the general solution can be regarded as the integration of local plane-boundary reflections.

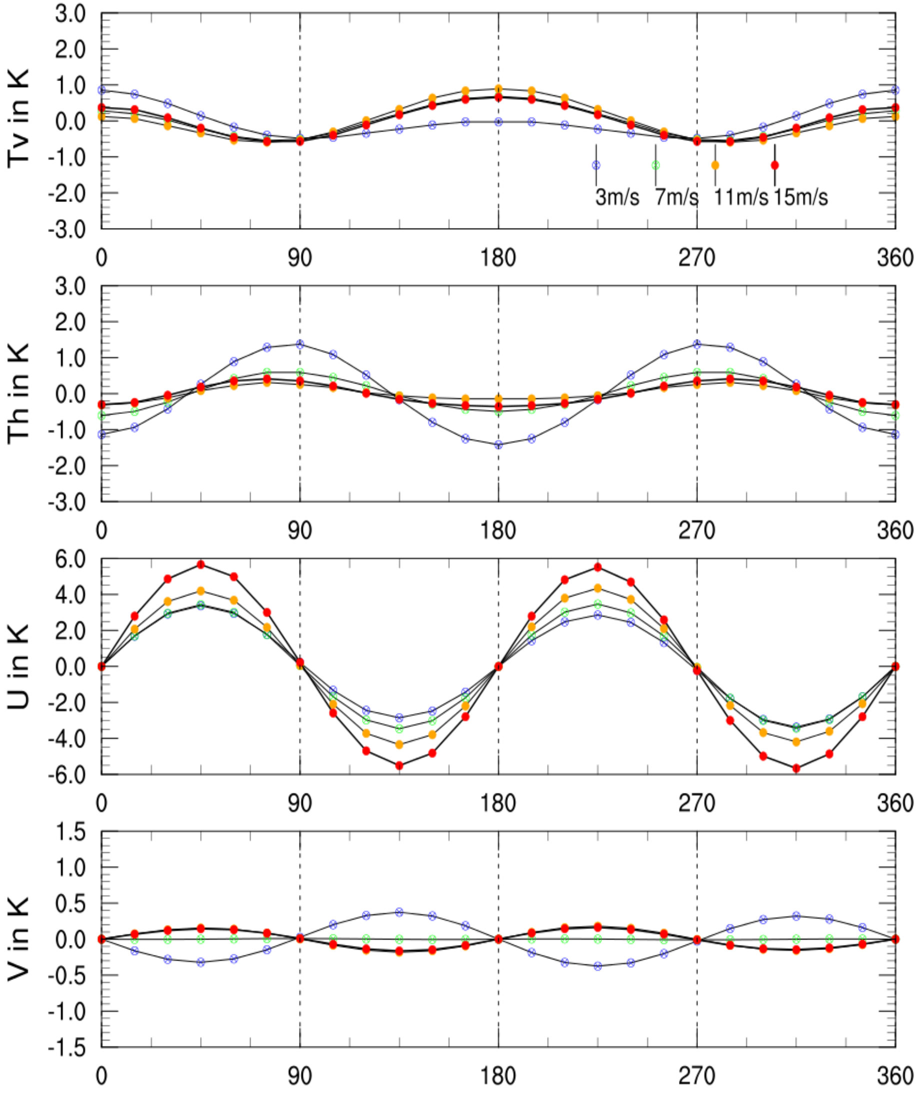
Tangential Plane Approximation
*Stationary Phase Approximation and Geometric Optics (GO) (**FASTEM**)*
Scalar Approximation and Physical Optics (PO)

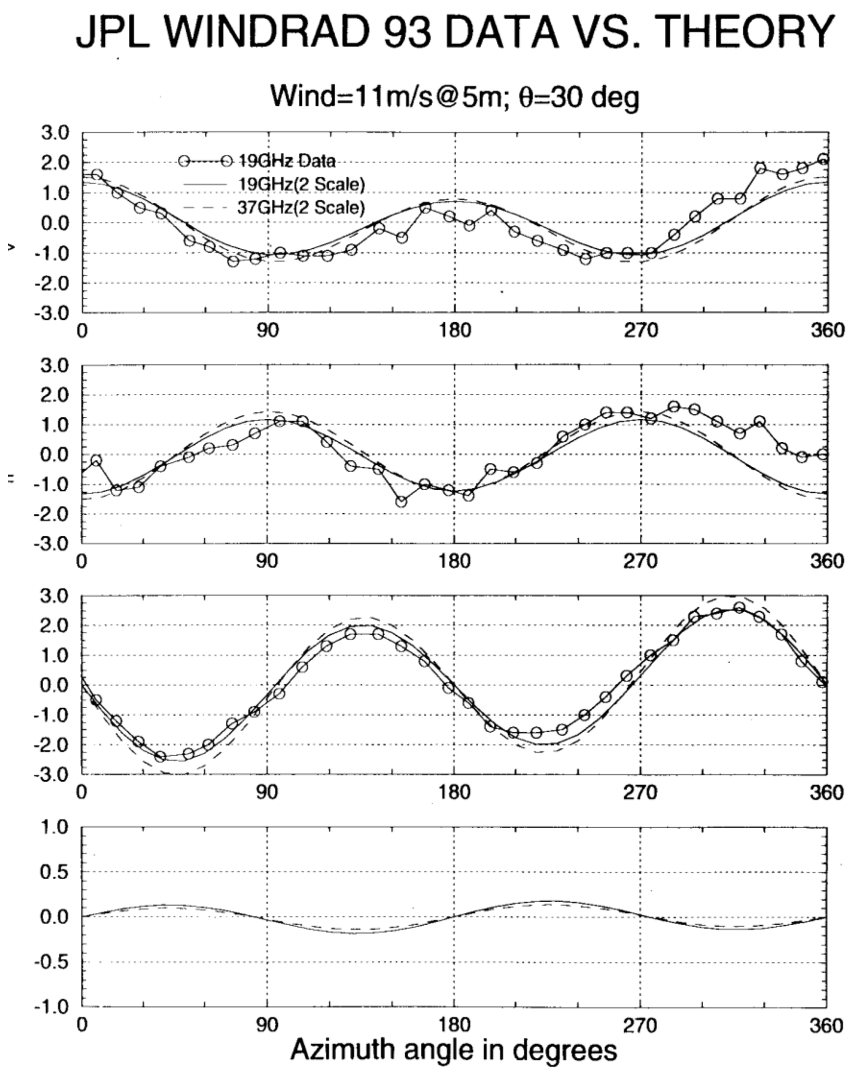
❑ **Small Perturbation Method (SPM)** based on the assumption that the surface correlation length and its standard deviation are smaller than the wavelength (low frequencies).

❑ **Composite Two-scale Model** based on the separation of both the surface and the EM wave into two distinct scales, e.g., Yueh et al., 1997

Comparison of FASTEM with JPL WINDRAD Observations (theta=30º)

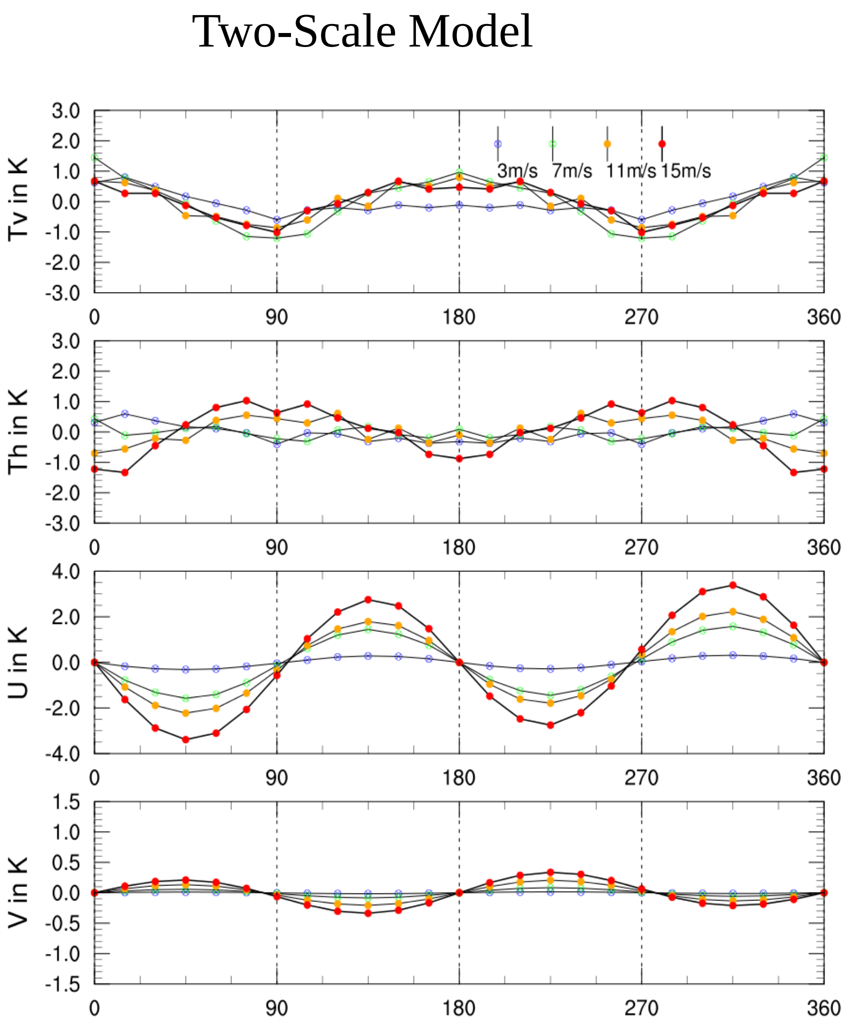
FASTEM 5/6

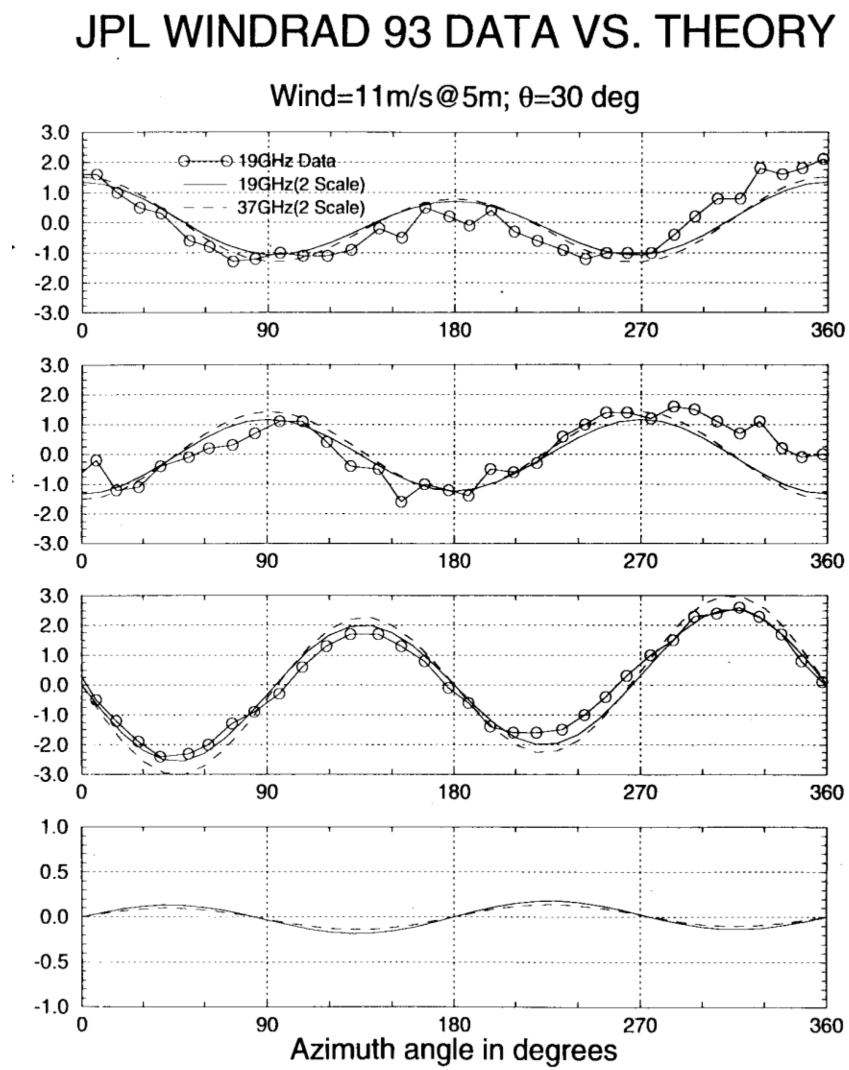




Yueh 1997

Comparison of Two-scale Model with JPL WINDRAD Observations (theta=30°)



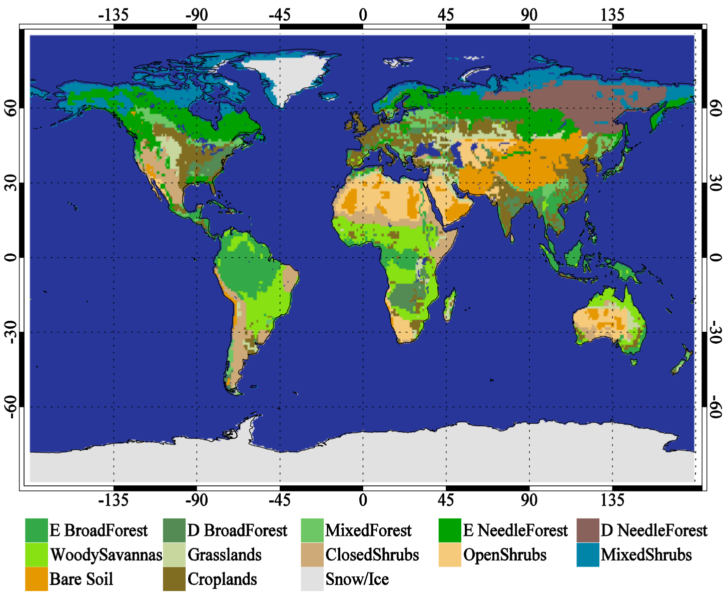


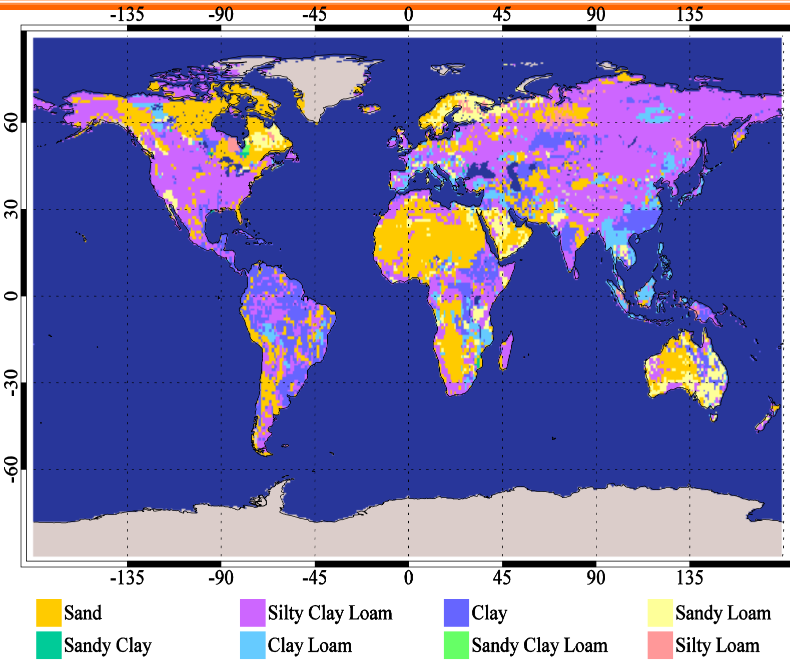
Yueh 1997

Summary

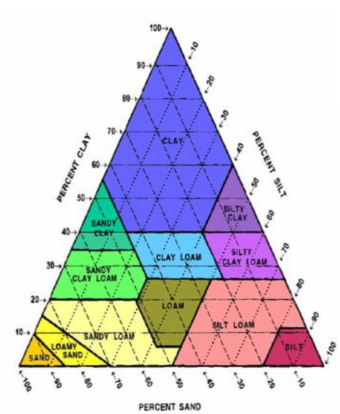
1. CSEM is an open software system for both research and operational applications. It may be used as an independent package for surface emissivity studies or coupled with other upper-level host models for operational purpose. It completely hide s the high-level CRTM complexity from the low-level CSEM developers and users, and vice versa.
2. CSEM is designed to offer such a platform where optional research algorithms (models) may be easily developed, added, tested and used besides those that have been chosen for operational (default) use.
3. CSEM keeps backward compatibility with the earlier CRTM versions.
4. The improvement and refinement of CSEM relies on our in-house and external collaborative research efforts. Some in-house model improvements will be included in the first CSEM official release.
5. Several efforts were made to improve the physical MW land emissivity model, which includes the non-isothermal model formulation, enhanced canopy scattering scheme, the tanh-based roughness correction model, multi-layer soil RT schemes, TL and AD operators. The improvements showed significant impacts on CRTM forward simulations, and neutral/slightly positive impacts on GFS forecasting.
6. Some ongoing in-house efforts include 1) the development of ocean surface MW BRDF/Emissivity model to be coupled with the multi-stream Scattering RT of Cloudy Cases 2) the development of KK-based physical IR land emissivity model 3) the improvement of desert and frozen bare soil emissivity 3) the empirical snow/sea ice models for newly launched sensors.

Unified Surface-Tying Based on Vegetation and Soil Unit-Types





Index	IGBP Name	Percentage
1	E BroadForest	9.1
2	D BroadForest	3.9
3	MixedForest	4.4
4	E NeedleForest	13.6
5	D NeedleForest	6.9
6	WoodySavannas	9.6
7	Grasslands	4.2
8	ClosedShrubs	6.9
9	OpenShrubs	8.1
10	MixedShrubs	12.3
11	Bare Soil	8.6
12	Croplands	12.3



Index	USGS Name	Percentage
1	Sand	25.6
2	Silty Clay Loam	45.2
3	Clay	13.5
4	Sandy Loam	7.1
5	Sandy Clay	0.2
6	Clay Loam	6.8
7	Sandy Clay Loam	0.1
8	Silty Loam	1.5