National Environmental Satellite, Data, and Information Service

Advances in Surface Emissivity Modeling at Microwave Frequencies

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Outline

- Overview of CSEM Status
- Improvements on the Microwave Land Emissivity Model
- Progress on developing the Two-Scale Ocean Microwave BRDF Model
- Testing of the Microwave Land Emissivity Model in GSI
- Summary and Conclusions

Overview of CSEM Status

- Completed all the CSEM infrastructure modules which includes, but not limited to, all the IR/VIS/MW Land/Snow/Ice/Water surface emissivity models from CRTM Except for the IR-Water and the MW-Water (FASTEM) codes, almost all the previous CRTM surface models were restructured and recoded to fit them into the CSEM OOP framework and to facilitate the development of the related tangent linear and adjoind modules.
- A thorough code review was performed for the original CRTM IR-Water and MW-Water modules. Bugs were identified and fixed.
- Implemented all the interfacing modules for the integration of CSEM with CRTM and other host model.
- Developed the utility programs to facilitate CSEM configuration, maintenance and management.
- Completed the first-round software development cycle, which led to the first clean working version ready for CRTM-CSEM integration.
- Established the CSEM subversion (SVN) repository on NOAA EMC machine.
- Committed the first CSEM working version to CSEM SVN Trunk

Performance Difference between CSEM and CRTM due to Software Structure Change

Wind_Speed=15m/s Wind_Speed_TL=1.5m/s						
Zenith Angle (Deg)		15	30	45	60	75
Emissivity V-Pol		Foreward Finite Difference (dFWD)				
	CSEM	5.73773120E-03	4.38642750E-03	2.33623870E-03	-3.91807230E-04	-4.70703030E-03
	CRTM	5.73773120E-03	4.38642750E-03	2.33623870E-03	-3.91807240E-04	-1.95699440E-03
		Tangent Linear (TL)				
	CSEM	5.72381710E-03	4.37551330E-03	2.33326710E-03	**-3.76395150E-04**	**-4.65548530E-03**
	CRTM	5.43762620E-03	4.15673770E-03	2.21660370E-03	**-3.57575400E-04**	**-1.80962340E-03**
		dFWD/TL				
	CSEM	1.002	1.002	1.001	1.040	1.011
	CRTM	1.056	1.056	1.053	1.096	1.081
Reflectivity VV		Foreward Finite Difference (dFWD)				
	CSEM	-1.31041890E-03	-7.18180490E-04	-3.36994780E-04	-9.21585700E-04	-3.16925300E-02
	CRTM	-1.31041890E-03	-7.18180500E-04	-3.36994790E-04	-9.21585690E-04	-1.57361260E-02
		Tangent Linear (TL)				
	CSEM	-1.29445610E-03	-7.05764620E-04	-3.33582340E-04	-9.36545610E-04	-3.16298320E-02
	CRTM	-1.22973330E-03	-6.70476400E-04	-3.16903230E-04	-8.89718330E-04	-1.48873600E-02
		dFWD/TL				
	CSEM	1.012	1.017	1.010	1.016	1.002
	CRTM	1.065	1.071	1.063	1.036	1.057
Wind_Speed_AD: 1.69324746775181E-03 (CSEM) 8.73819151597255E-04(CRTM)						

Improvements on Microwave Emissivity Modeling

- Improved the MW soil emission modeling to support the radiance data assimilations of low-frequency L, C and X bands.
- Developed the physical MW ocean surface model which provides both ocean surface emissivity and BRDF simulations for the upper-level CRTM multi-stream scattering scheme. We have established the core modules for both emissivity and BRDF simulations.
- Analyzed the sensitivity of the BRDF model to each of the model inputs. The analysis results will be used to reduce model dimensions and to establish an efficient regression model for future use in GSI.
- Developed the MW land surface tangent-linear and adjoint modules to support the variational analysis of land skin temperature, soil moisture and vegetation fraction in radiance data assimilation.

Assessments of Multi-layer MW Soil Emissivity Model

- Two multi-layer MW soil RT models (Burke, 1979; Wilheit, 1980) are implemented in CSEM to account for the soil profile impacts on the net thermal emission leaving the soil surface.
- The multi-layer soil models are computationally expensive, and not apt for operational applications.
- Fresnel model with the effective soil temperature and the moisture of the top mm layer may retain computational simplicity, meanwhile account for the soil profile impacts.
- Effective soil temperature and moisture models were developed by fitting to multi-layer model simulations

	Soil Moisture			Temperature			Fresnel (Teff, W-1mm)		Truth (Wilheit 120lys)	
GHz	0-10cm	Weff	1mm	0-10cm	Teff	1mm	H-pol	V-Pol	H-pol	V-Pol
1.4	0.2	0.190	0.15	305	306.1	311.5	**0.334**	**0.156**	0.340	0.161
5.4	0.2	0.170	0.15	305	308.9	311.5	**0.323**	**0.147**	0.323	0.147
10.4	0.2	0.158	0.15	305	310.2	311.5	**0.317**	**0.142**	0.318	0.143
23.4	0.2	0.151	0.15	305	311.1	311.5	**0.293**	**0.125**	0.293	0.125
89.4	0.2	0.148	0.15	305	311.4	311.5	**0.200**	**0.066**	0.200	0.066

Exponential Weff Model

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

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

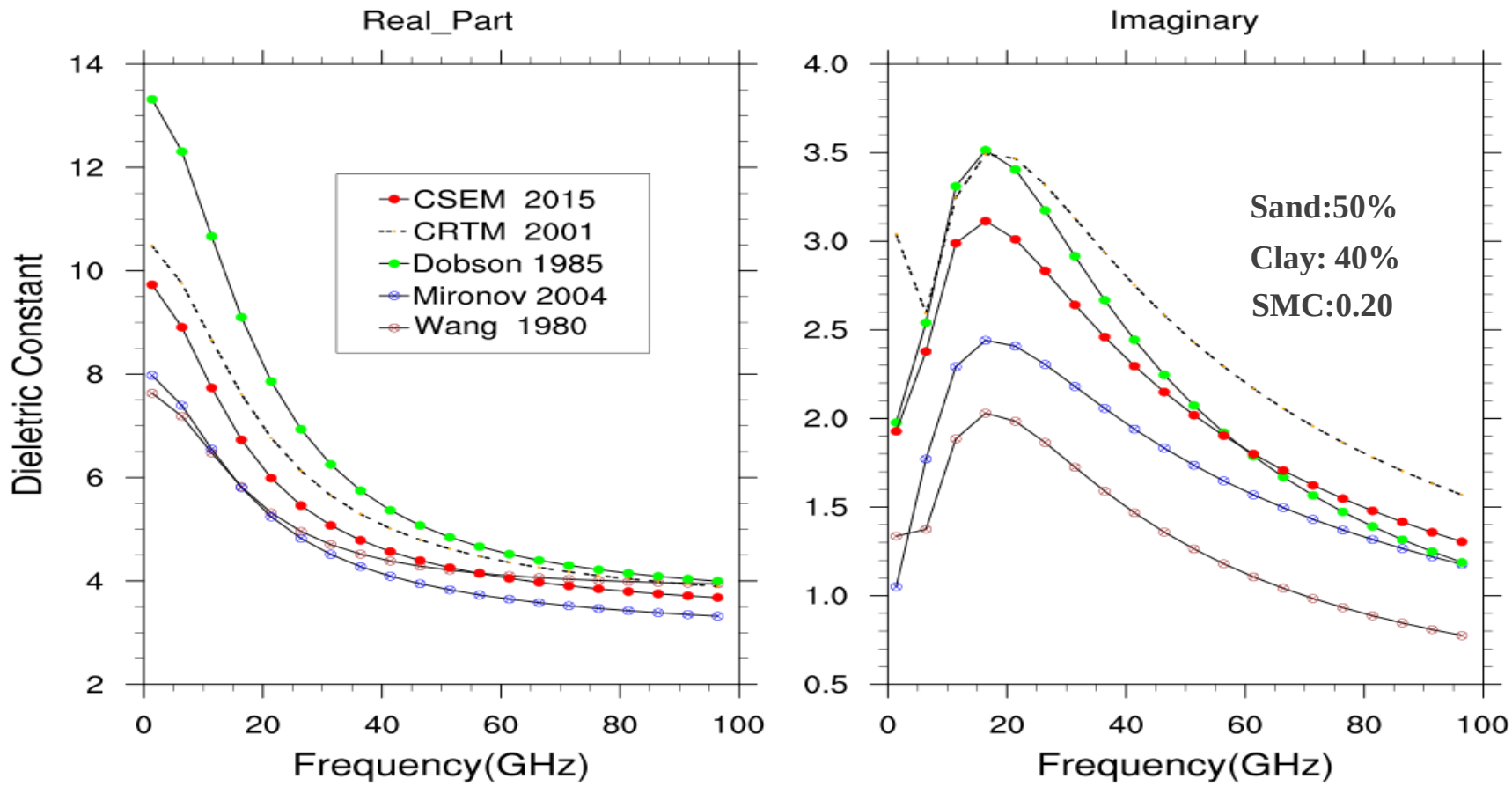
$$D = D(Wsoil1, \Delta T)$$

Linear Mixture Teff Model

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

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

Optimization of MW Soil Dielectric Model



There also exists large uncertainty in the calculation of the MW soil permittivity. Several soil MW permittivity models (Weng et al 2001; Wang et al, 1980; Mironov et al, 2004; Dobson et al., 1985) are implemented in CSEM for research purpose and model optimization purpose.

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

- The calibration and verification of MW soil model were performed with extensive ground-based measurements (Chen & Weng, 2015).

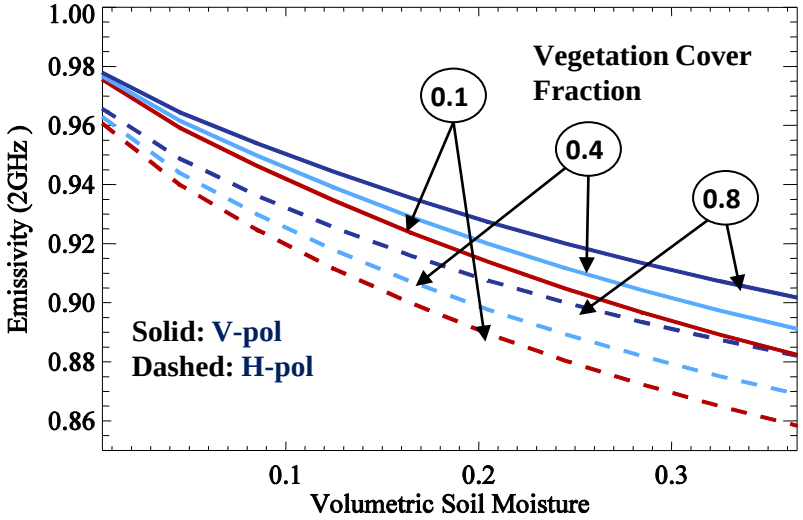
- Verification with the 3D numerical Maxwell model simulations also indicated that the current CSEM MW soil model has very reliable performance over a variety of soil surfaces.

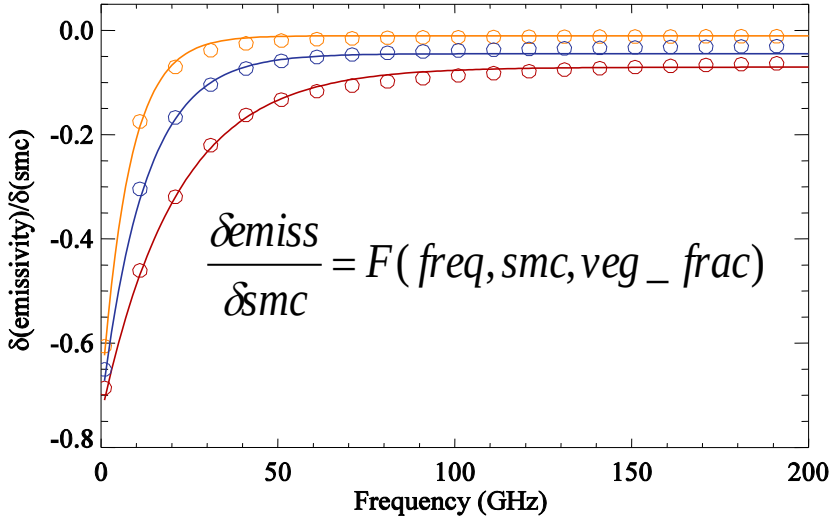
20% Soil Moisture **(H-Pol)**					
Sigma(cm)	NMM3D	C&W	Coppo	Wegmul.	Wang
1	0.40	**0.34**	0.24	0.23	0.38
2	0.35	**0.28**	0.19	0.20	0.21
3	0.31	**0.24**	0.15	0.18	0.08
4	0.28	**0.21**	0.13	0.16	0.02
30% Soil Moisture**(H-Pol)**					
1	0.47	**0.40**	0.28	0.26	0.44
2	0.41	**0.33**	0.22	0.23	0.24
3	0.37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

- Two different LandMW TL-AD sets were developed. One is in the original land-surface model space, the other is in a reduced model space.
- 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.





Development of MW Ocean Surface 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

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

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

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

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.

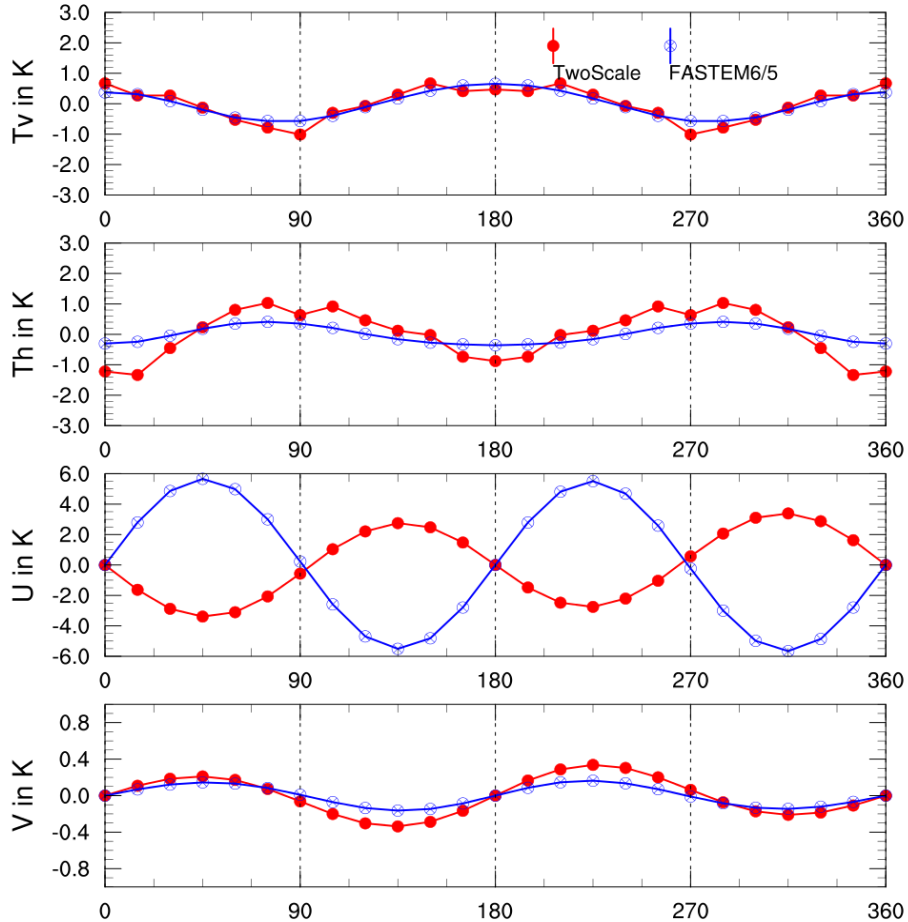
Tangential Plane Approximation
*Stationary Phase Approximation and Geometric Optics (GO) (**FASTEM**)*
Scalar Approximation and Physical Optics (PO)

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

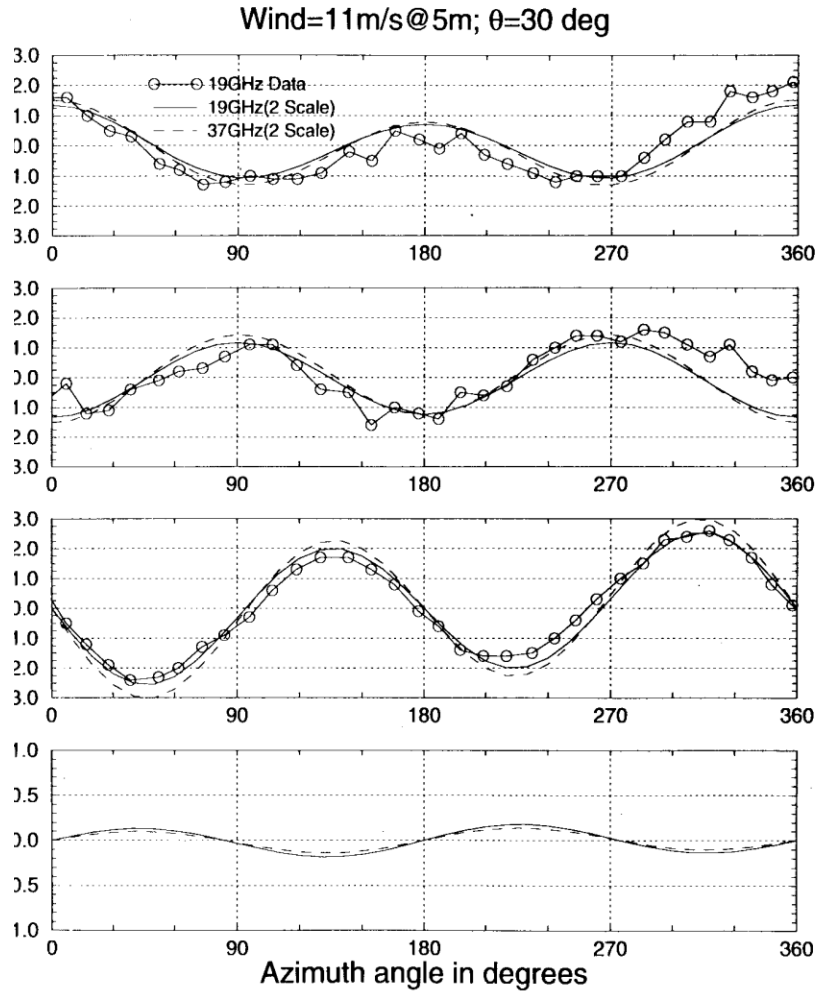
- **Composite Two-scale Model** based on the separation of both the surface and the EM wave into two distinct scales, e.g., Yueh et al., 1997

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

FASTEM6/5 and Two-Scale

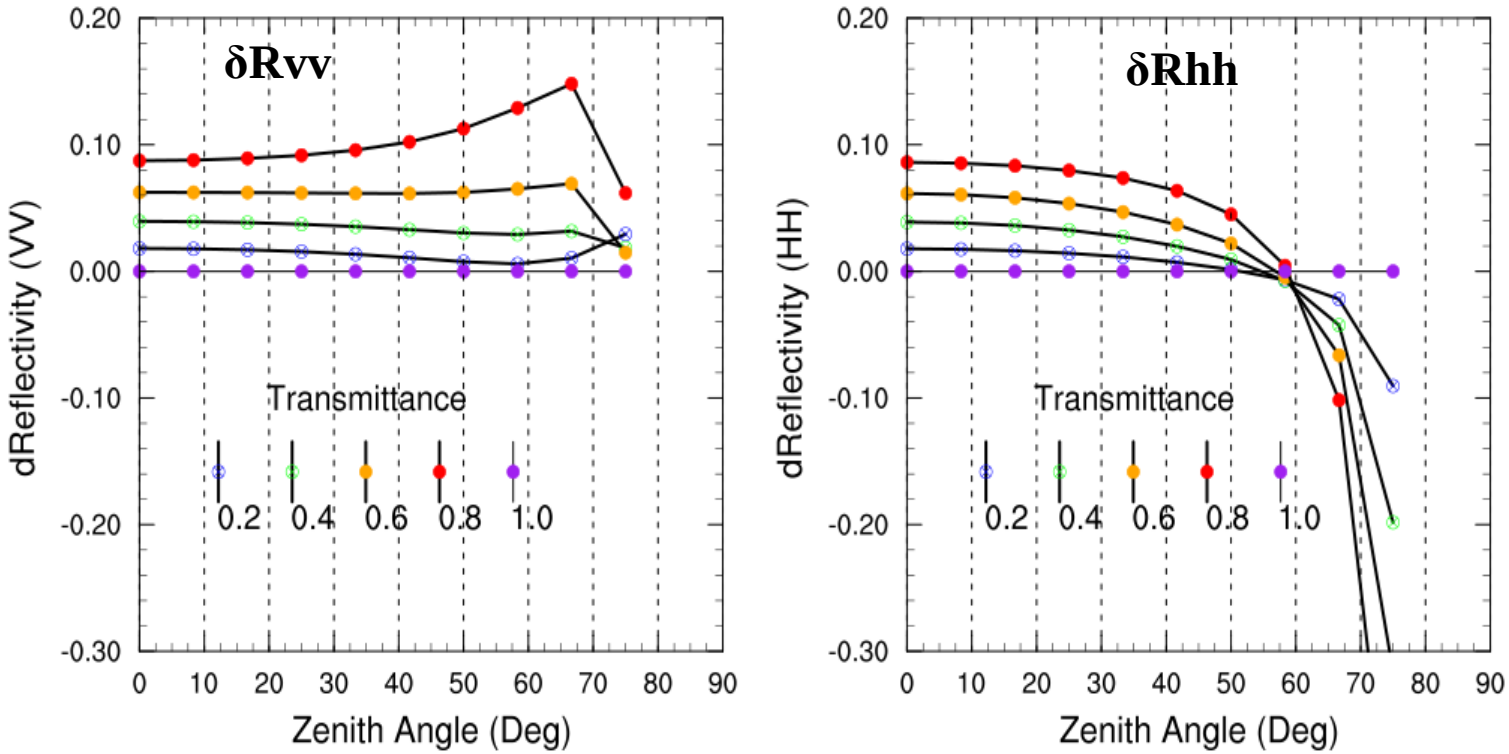


JPL WINDRAD 93 DATA VS. THEORY



Yueh 1997

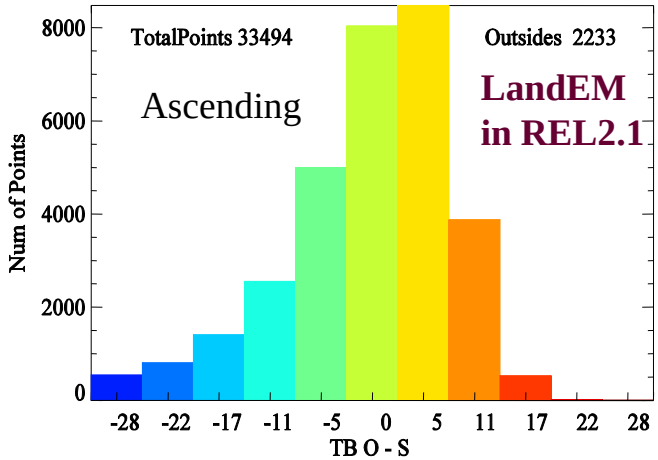
Reflection Correction in FASTEM6/5

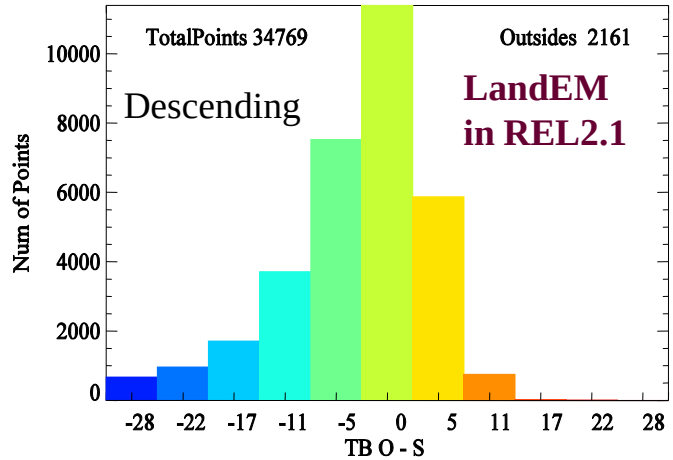


FASTEM reflection correction (**δR(τ) = R(τ) - R(τ=0)**) in terms of transmittance appears physically unreasonable. In general, one would expect larger reflection correction in more cloudy cases. FASTEM6/5 shows the opposite way. Correction for zenith >60° is also problematic.

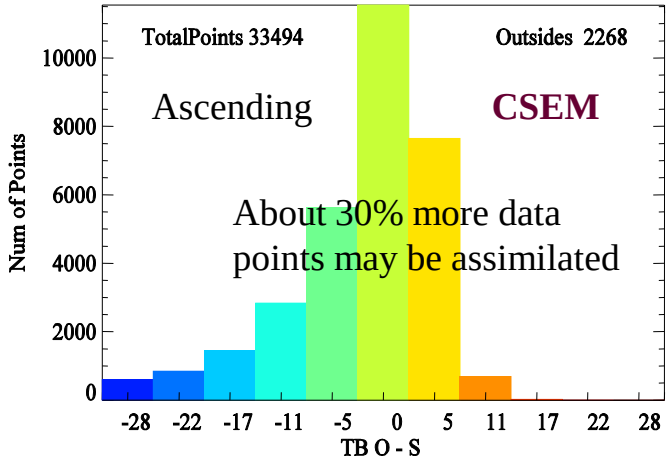
Impact of Model Improvements on TB O – B LandEM in CRTM REL-2.1 vs. CSEM

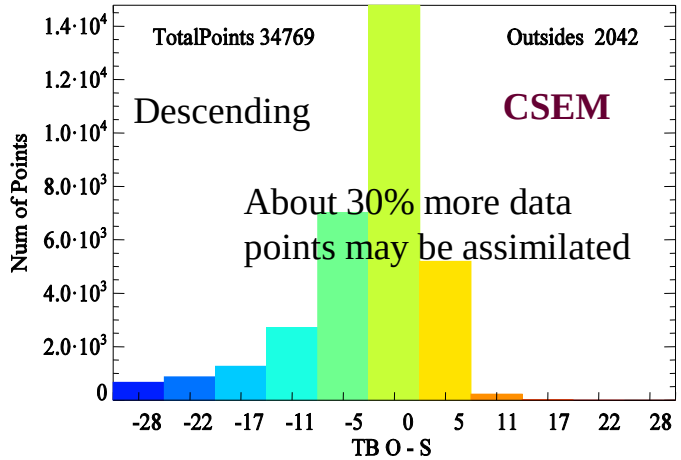
AMSUA-N18 23.8GHz



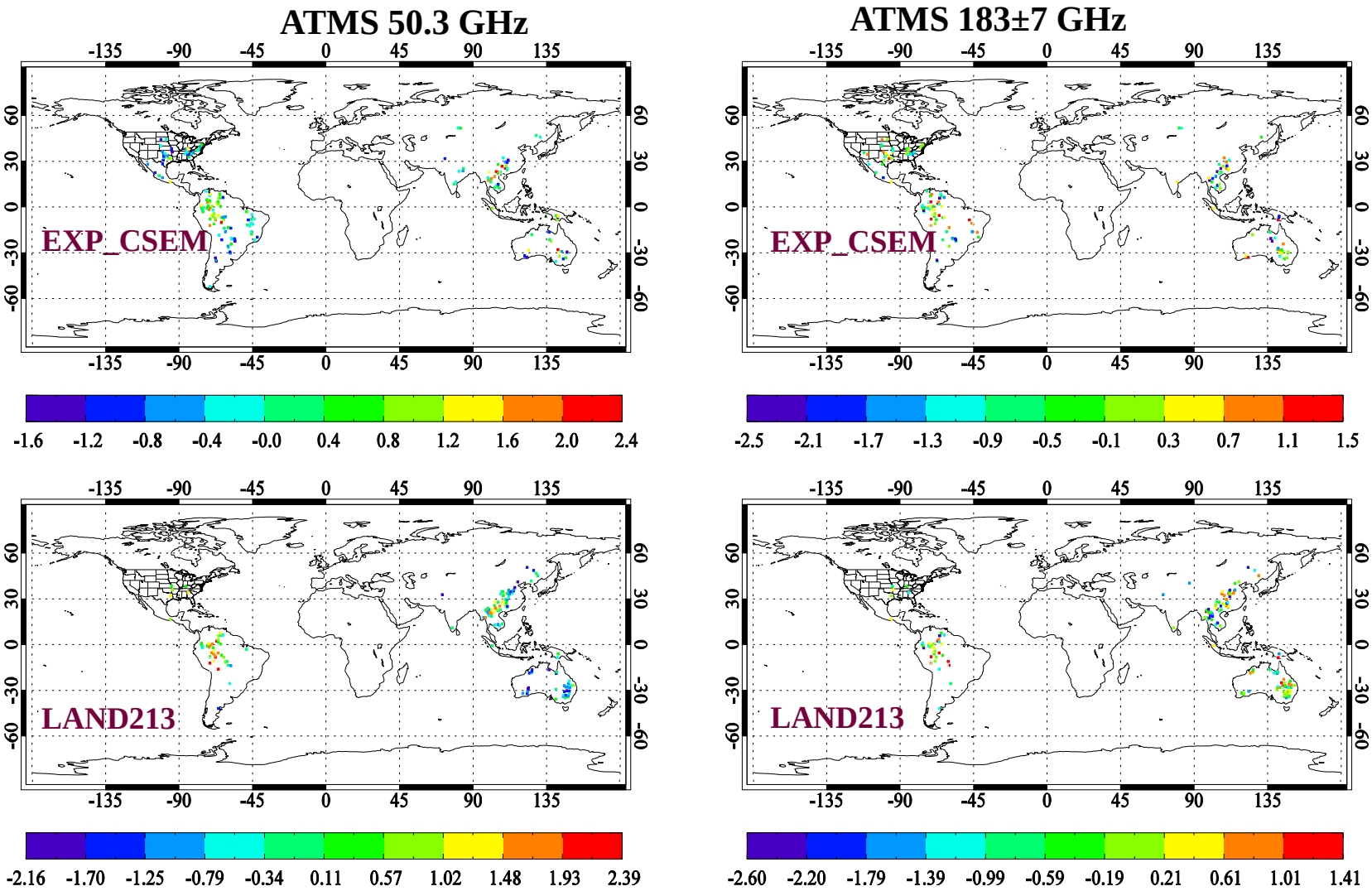


AMSUA-N18 23.8GHz

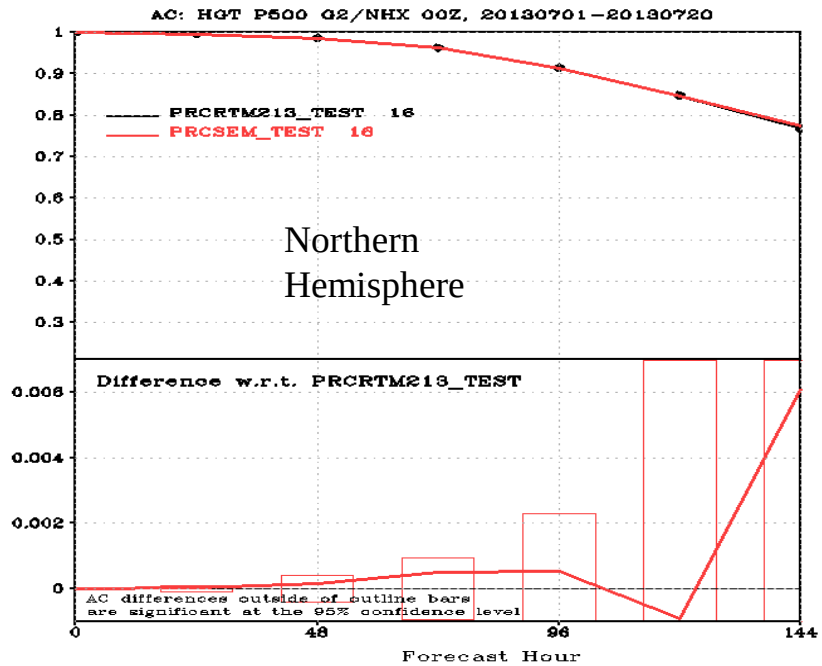


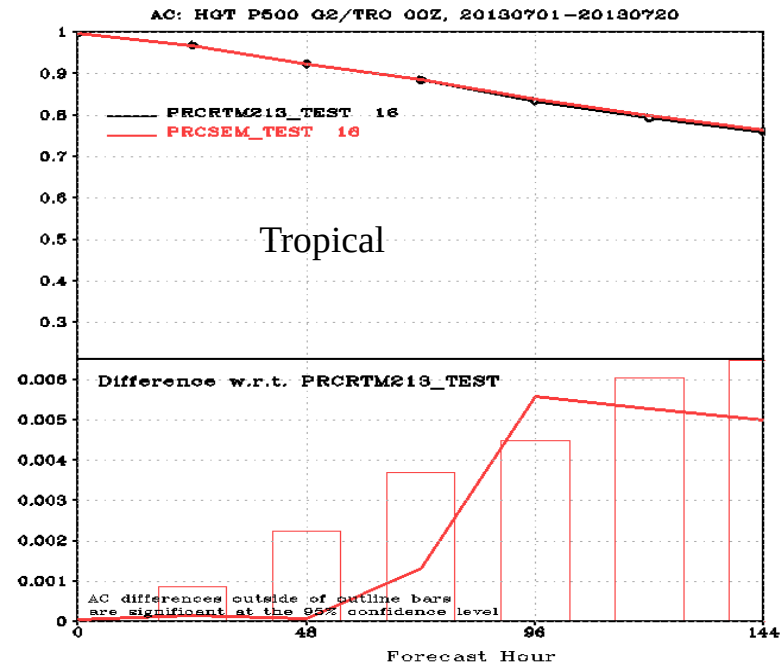


Map & Histogram of TB O – B (FirstGuess) in GSI

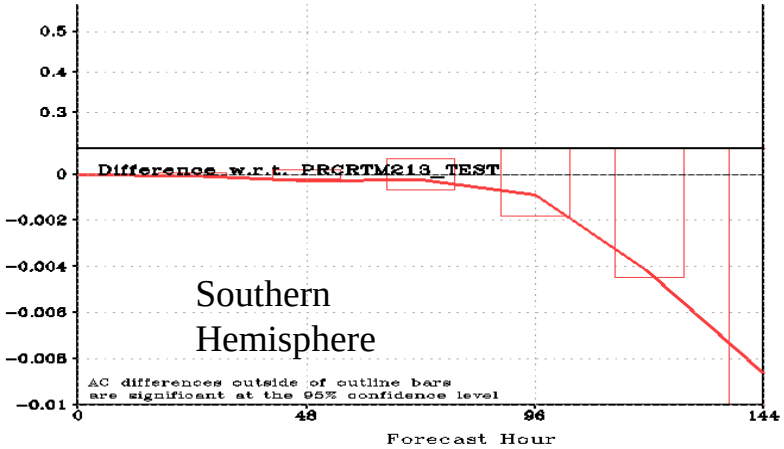


Parallel GFS-GSI Test With the Updated MW Land Emissivity Model





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.



Summary and Conclusions

- The MW land tangent-linear and adjoint modules need to be refined for the purpose of computational efficiency. Testing of the MW TL and AD modules in GSI is still on-going
- Two-scale MW ocean emissivity and BRDF model is being tested for fixing the apparent bugs in FASTEM5/6 (3rd/4th Stokes components)
- The physical IR-Land based on Chen and Weng (2012) KK-analysis is being implemented in CSEM
- The impact of land EM improvements on forecasting skill is neutral but promising. Nevertheless, it seems essential and a must to perform compatible improvements of all other surfaces for GSI to take the full advantage of the land surface model improvements, and vice versa. Compatible adjustments may be also needed in GSI QC algorithms.
- There are very few observations assimilated over desert and frozen-soil surfaces. The relevant model improvements are being performed.