中国气象局地球系统数值预报中心
CMA EARTH SYSTEM MODELING AND PREDICTION CENTRE

Progress in Advanced Radiative Transfer Modeling System (ARMS)

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Major Updates

ARMS has been upgraded to version 1.5. The main updates include:

- ☐ **Gaseous Absorption:**

  Optimize Atmospheric Transmittance Training for Hyperspectral IR Sounder

  MONORTM-based Microwave Transmittance

- ☐ **Microwave Land Surface Emissivity Database:**

  1DVAR retrieval based on FY-3D MWRI

- ☐ **Non-spherical particle scattering LUT using DDA**

- ☐ **Passive and Active Scattering and Emission Model over Ocean**

  Polarized BRDF Coupled to VDISORT at Lower Boundary condition

- ☐ **ARMS Capabilities for Ground-Based Microwave Radiometer**

Optimize Atmospheric Transmittance Training for Hyperspectral IR Sounder

Old Approach: Variable Gases (6): H2O, CO2, O3, N2O, CH4, CO

$$\Gamma_{i,j}^{\mathrm{tot}} = \Gamma_{i,j}^{\mathrm{con}}\Gamma_{i,j}^{\mathrm{fix}}\Gamma_{i,j}^{\mathrm{H2O},*}\Gamma_{i,j}^{\mathrm{O3},*}\Gamma_{i,j}^{\mathrm{CH4},*}\Gamma_{i,j}^{\mathrm{N2O},*}\Gamma_{i,j}^{\mathrm{CO},*}\Gamma_{i,j}^{\mathrm{CO2},*}$$

Disadvantages:

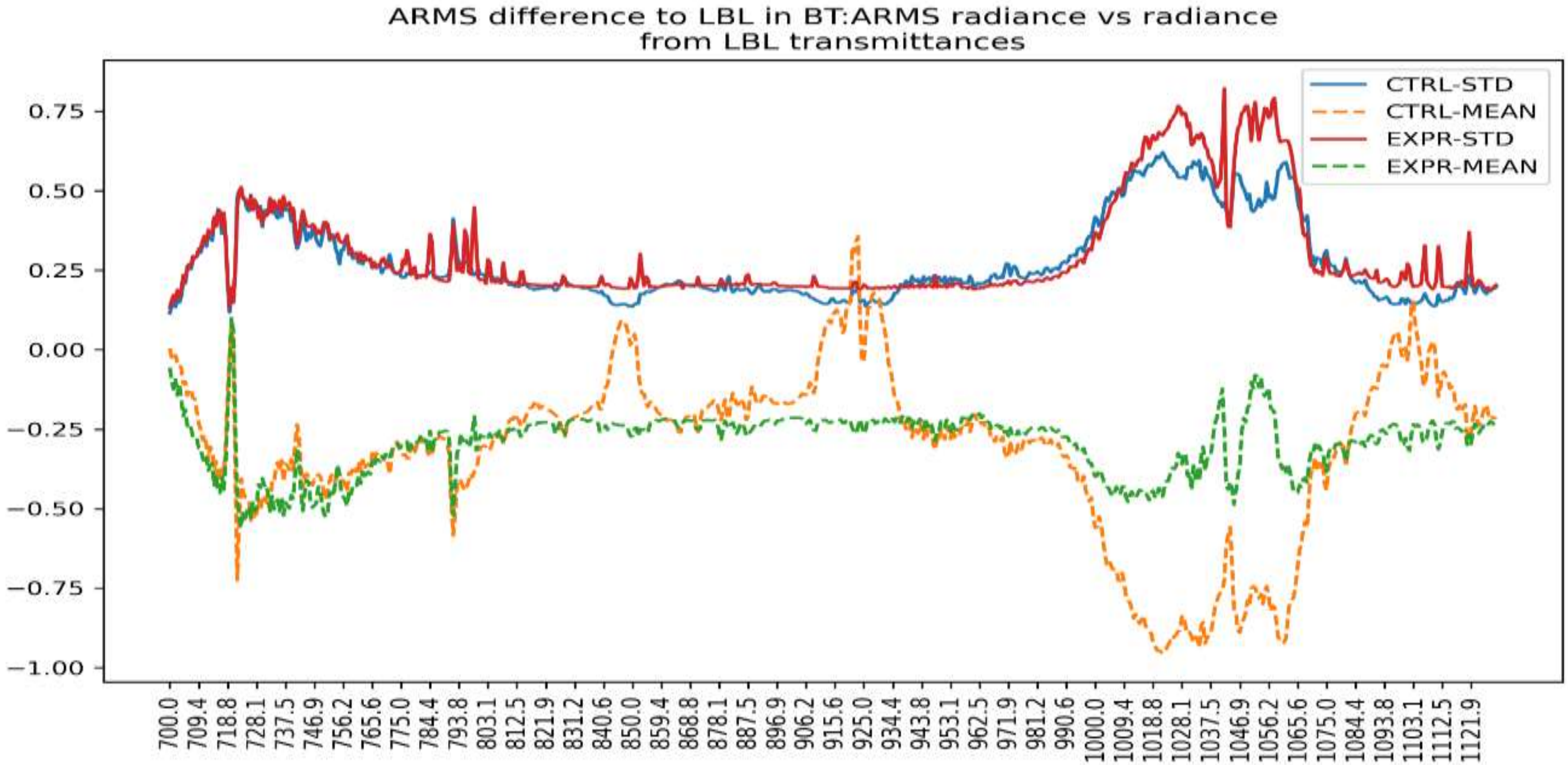
1) Effective transmittance becomes uncertain in cases where specific gas transmittances are zero.

2) The computation of effective transmittance for each gas coefficient requires twice the usual time.

New Method: Variable Gases (7): H2O, CO2, O3, N2O, CH4, CO, SO2

$$\Gamma_{i,j}^{\mathrm{tot}} = \Gamma_{i,j}^{\mathrm{con}}\Gamma_{i,j}^{\mathrm{fix}}\Gamma_{i,j}^{\mathrm{H2O}}\Gamma_{i,j}^{\mathrm{O3}}\Gamma_{i,j}^{\mathrm{CH4}}\Gamma_{i,j}^{\mathrm{N2O}}\Gamma_{i,j}^{\mathrm{CO}}\Gamma_{i,j}^{\mathrm{CO2}}\Gamma_{i,j}^{\mathrm{SO2}}\Gamma_{i,j}^{\mathrm{corr}}$$

ARMS vs LBLRTM Simulation



Bias is more uniform across the spectral domain and much smaller near O3 absorption (1037 wavenumber)

Optimize Atmospheric Transmittance for MW Sensors

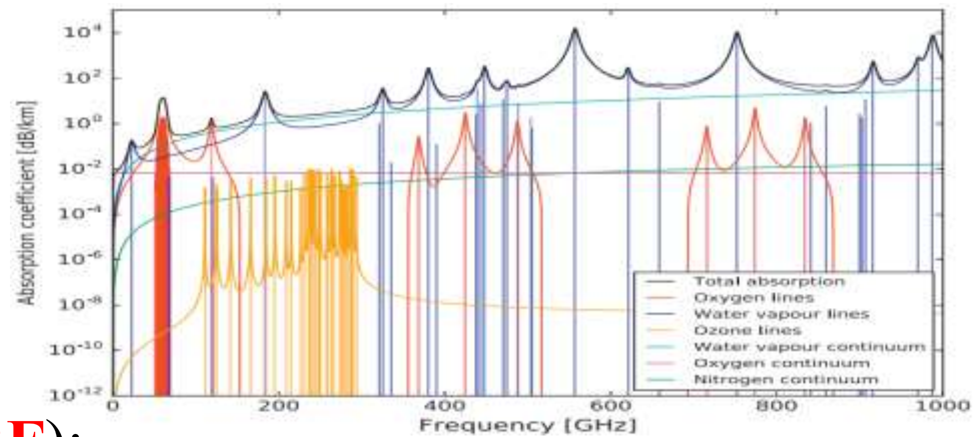
Major Updates (Training)

- Line-by-Line RTM:

MPM* → MonoRTM

* MPM is the Millimeter-wave Propagation Model

O3 absorption is added by this change.

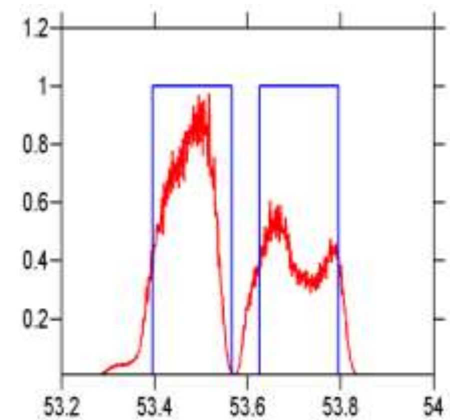


From Turner et al., 2019

- Channel Transmittance (**SRF**):

$$\Gamma_{ch,j} = \frac{\int_V \Gamma(\upsilon)d\upsilon}{\int_V d\upsilon} \Rightarrow \Gamma_{ch,j} = \frac{\int_V \Gamma(\upsilon)\mathrm{SRF}(\upsilon)d\upsilon}{\int_V \mathrm{SRF}(\upsilon)d\upsilon}$$

MWTS FY3F
Ch 7 SRF



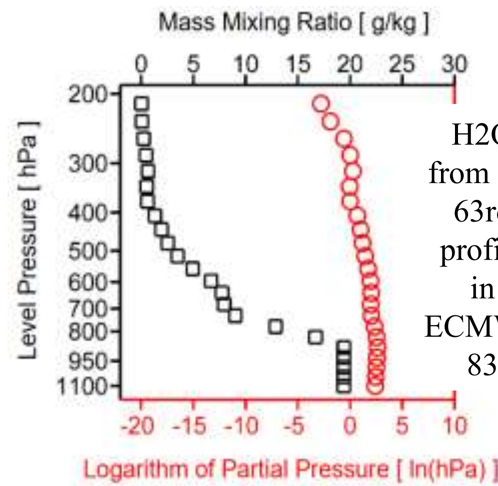
- Predictors:
  - ✓ Add Predictors for Mixed Gas
  - ✓ Separate H2O Continuum Component and Line Component in Regression.

Optimize Atmospheric Transmittance for MW Sensors

☐ Major Updates (Simulations)

- H2O Vertical Interpolation Mode:

Interpolate Mass Mixing Ratio → Interpolate Log of Partial Pressure



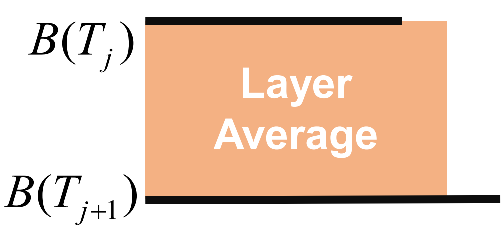
H2O from the 63rd profile in ECMWF 83

The partial pressure is directly used for the line strength calculations. (Emma Turner et al., 2019 JQSRT)

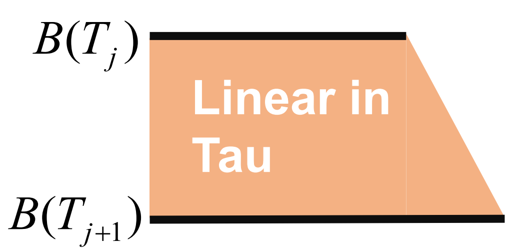
Compared to that of mass mixing ratio, the vertical variation of the logarithm of water vapor partial pressure is more smooth.

- Planck Vertical Distribution:

Layer Averaged → Linear in Tau



linear in tau can describe Planck distribution well



ARMS vs MonoRTM

101L / 54L ECMWF 83

7 angles from 0 - 70.5 degree.

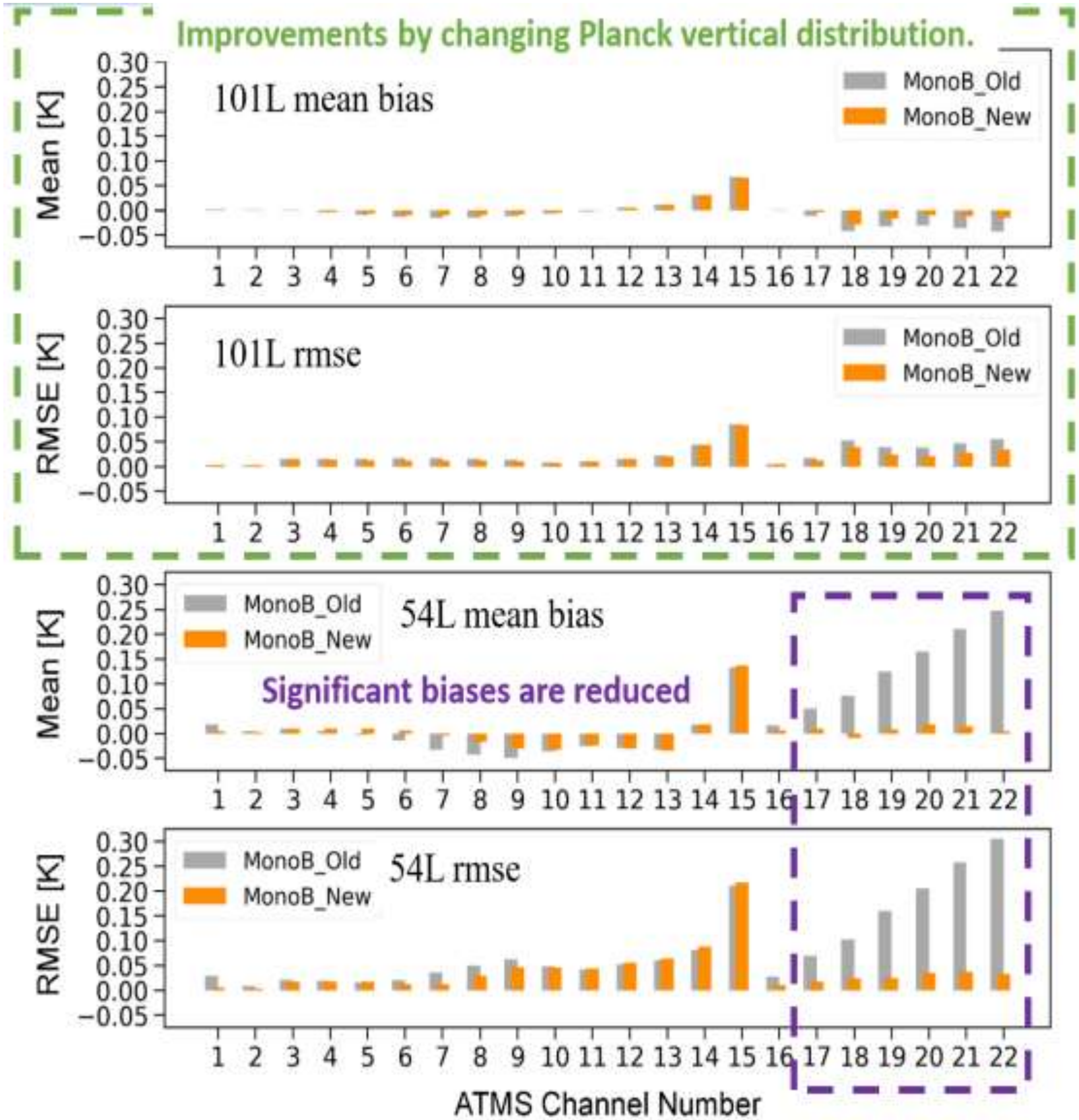
Benchmark:

$$rad_{ch} = \frac{\int_V rad(v)SRF(v)dv}{\int_V SRF(v)dv}$$

$rad(v)$ is from MonoRTM

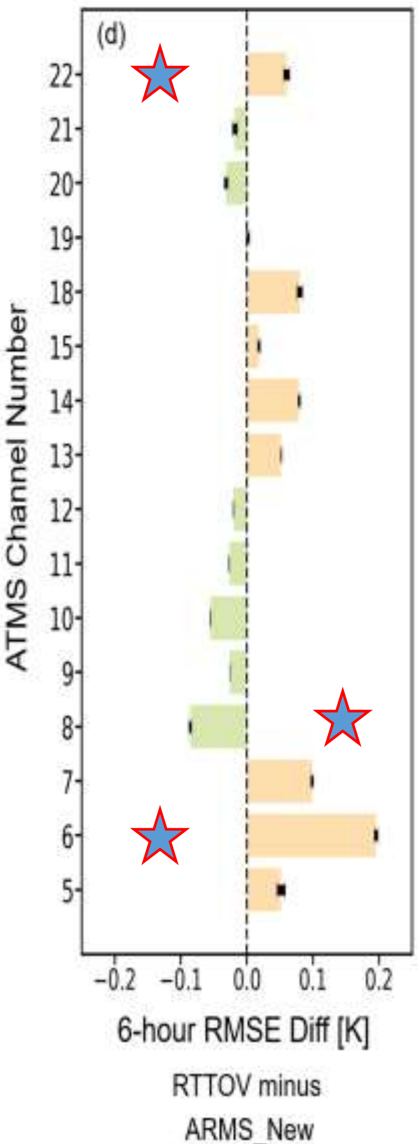
Old Interpolation:
Layer averaged Planck

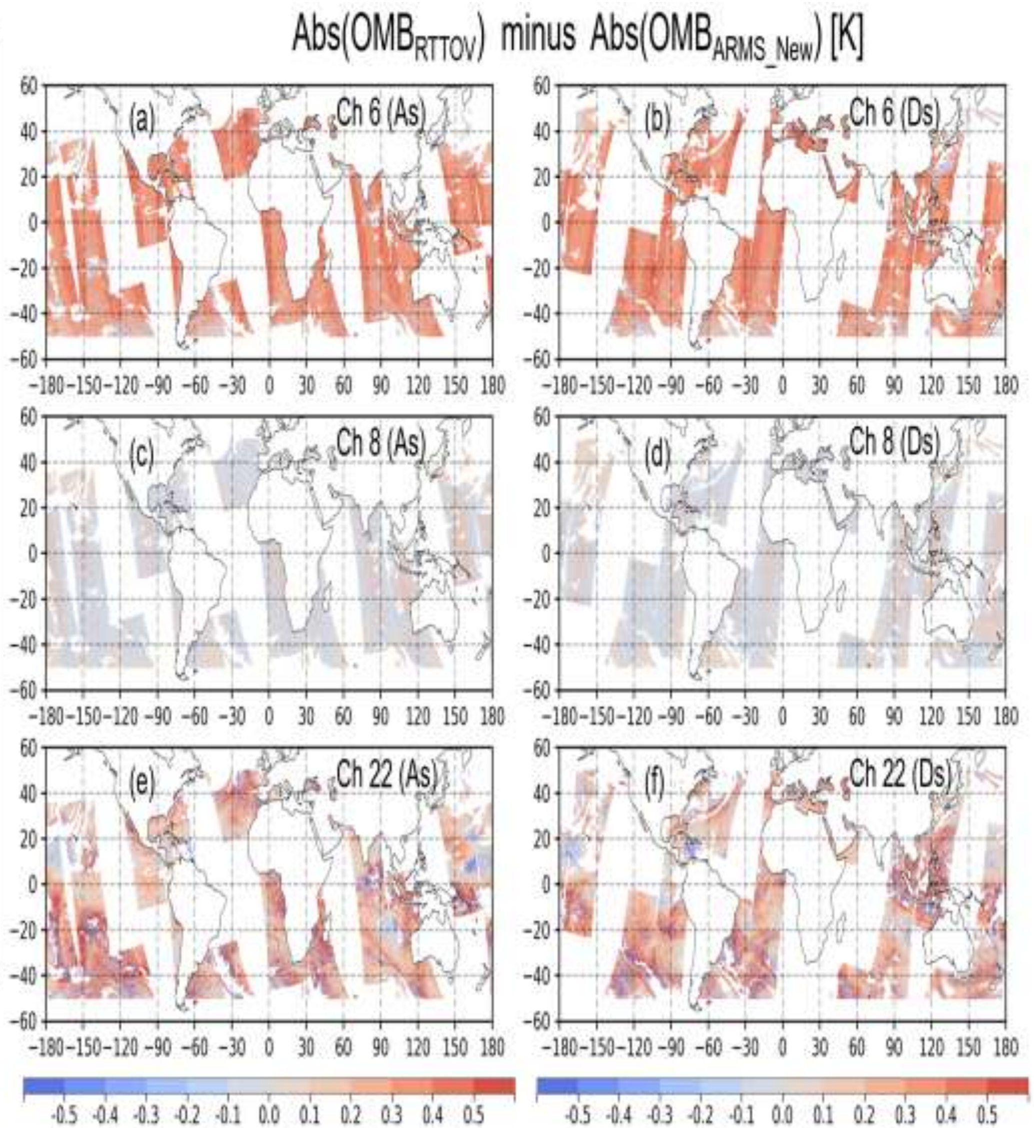
New Interpolation:
Linear in tau Planck



Lambertian Emissivity: 0.98

ARMS vs RTTOV13.2



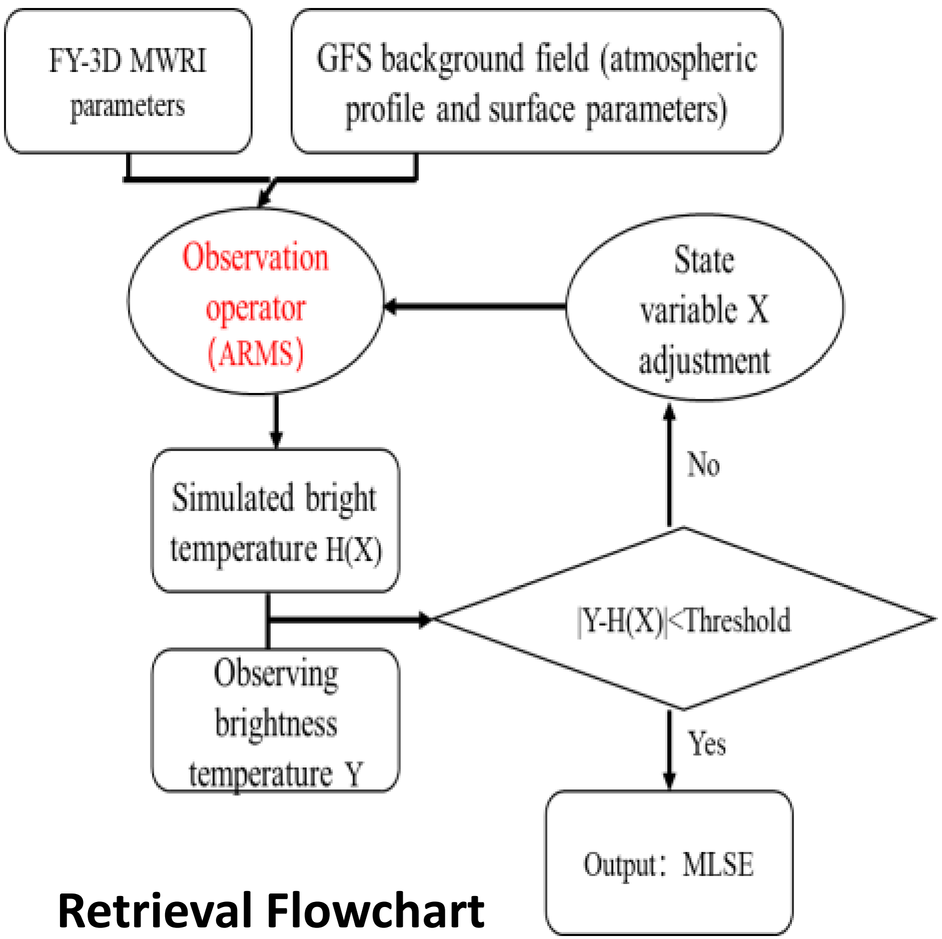


The global distribution of OMB diffs between ARMS and RTTOV follows a consistent pattern in channel 6 and channel 8

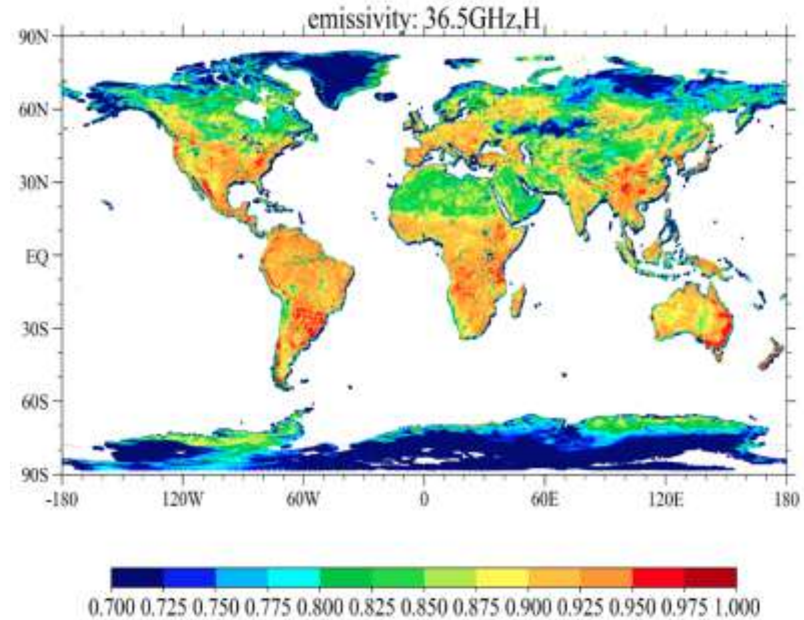
A significant disparity between ARMS and RTTOV is observed in channel 22, where the maximum difference can reach 0.5 K..

Microwave Land Surface Emissivity Database

FY-3D MWRI based Land Emissivity Atlas



Retrieval Flowchart



FY-3D MWRI Channel Characteristics

Frequency (GHz)	Polarization	Bandwidth (MHz)	Calibration accuracy (K)	Resolution (km×km)
10.65	V.H	180	1.0	≤51x85
18.7	V.H	200	2.0	≤30x50
23.8	V.H	400	2.0	≤27x45
36.5	V.H	900	2.0	≤18x30
89	V.H	2x2300	2.0	≤9x15
150	V.H	2x1500	2.0	≤7.5x12

Microwave Land Surface Emissivity Database

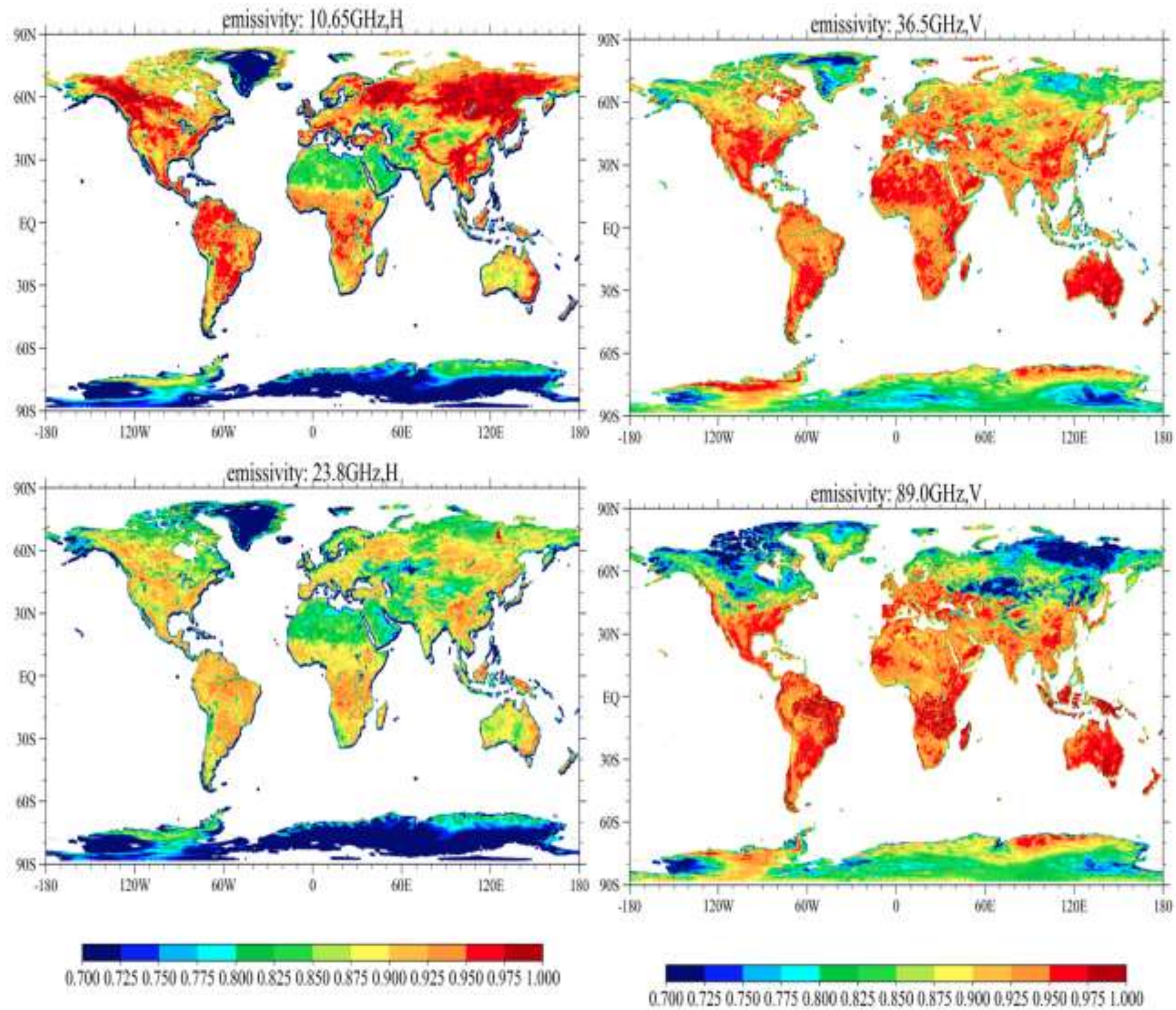
Basic Information

Frequency

- 10.65 GHz
- 18.7 GHz
- 23.8 GHz
- 36.5 GHz
- 89 GHz

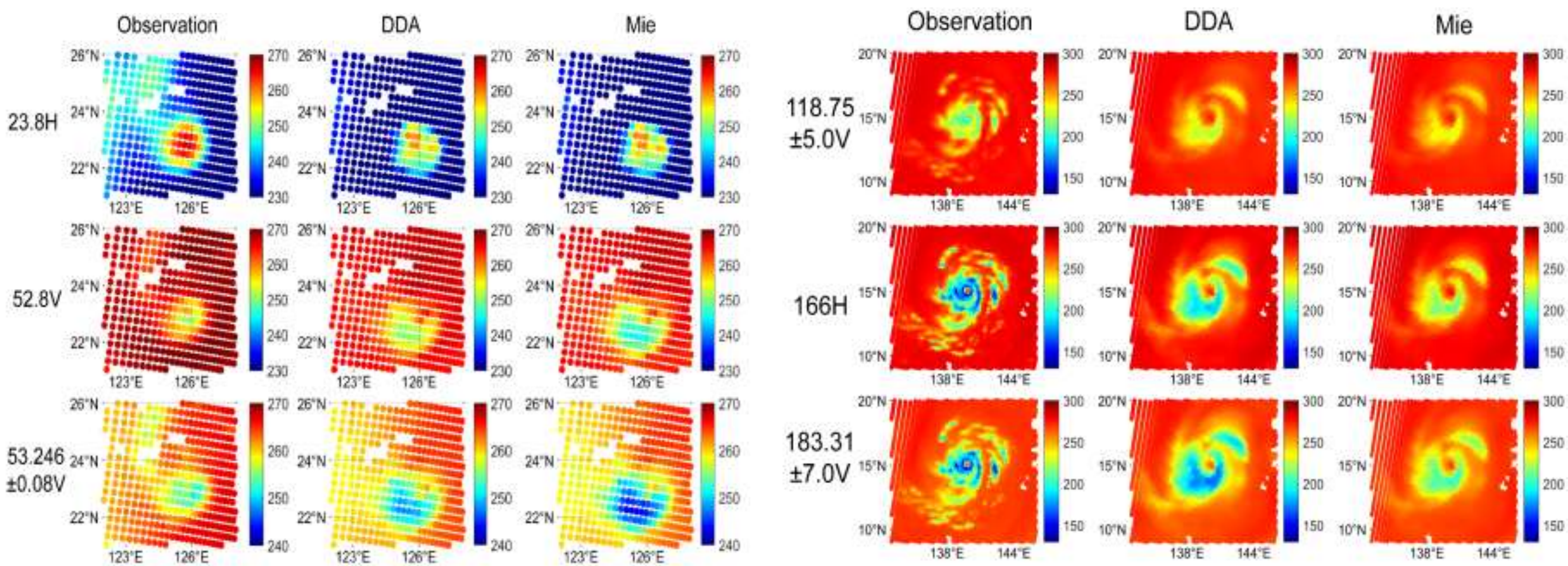
Resolution

- Spatial:0.25×0.25
- Ten day average



LUT of Cloud Particle Optics

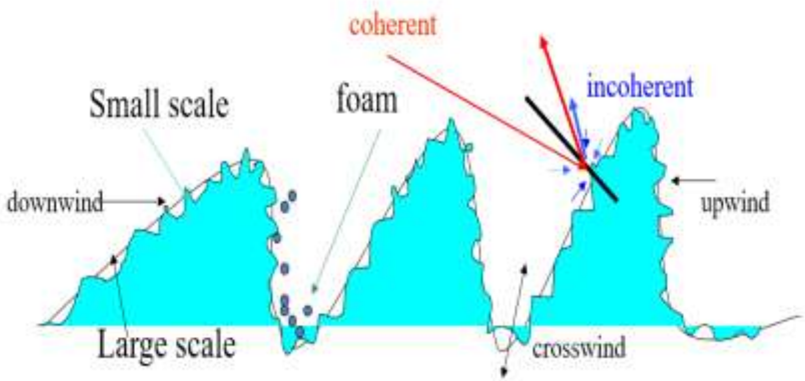
- **Comparison of scattering between Mie and DDA**

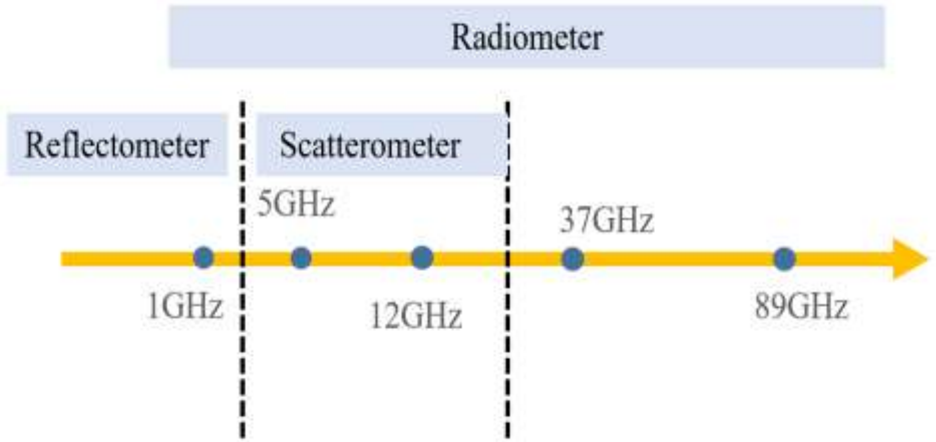


- The spherical assumption of ice cloud particles will generate excessive scattering at low frequencies and insufficient scattering at high frequencies.
- The simulation results of non-spherical scattering based on DDA are closer to observations.

Passive and Active Scattering and Emission Model over Oceans

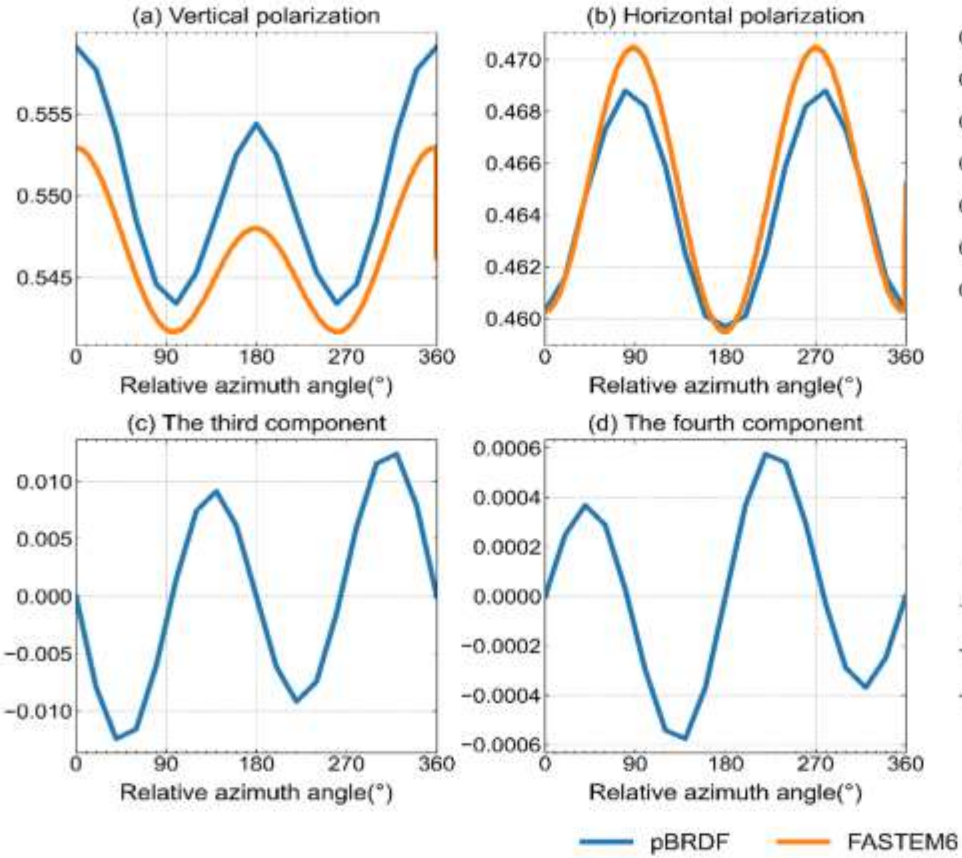
Two-Scale Model (TSM)



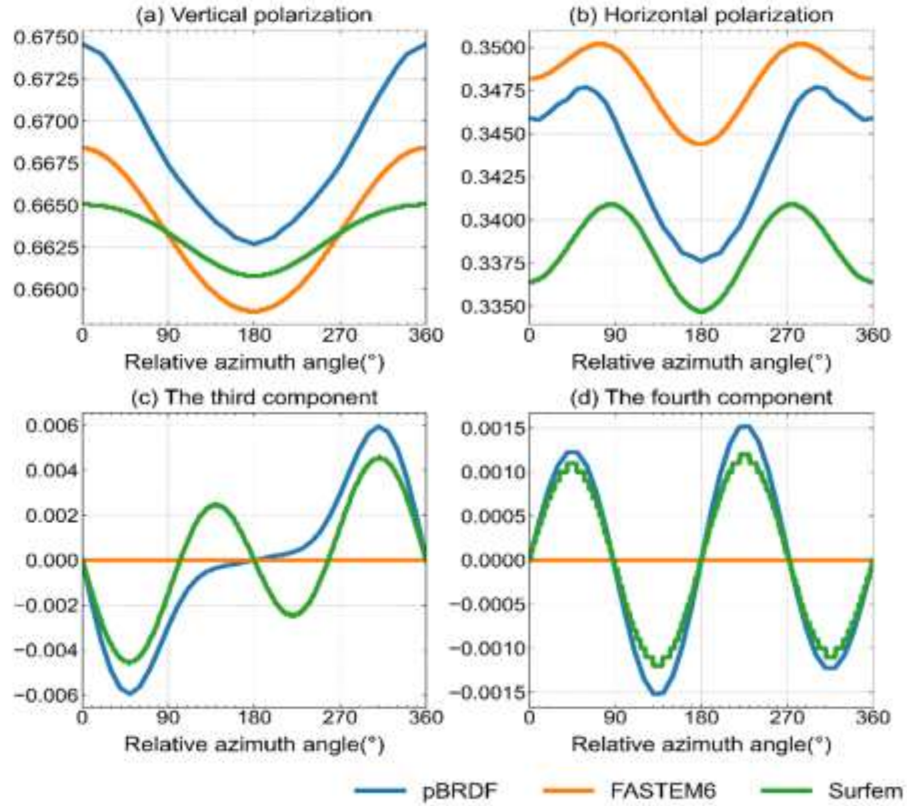


- Large scale roughness is generated gravity wave and small scale roughness is related capillary waves
- Coherent and non-coherent reflection and scattering from both scales
- Coherent term is derived from geometric optics
- Non-coherent is derived from small perturbation model (SPM)
- TSM is valid for small to medium incidence angles and moderate wind speed

Emissivity Vector (*E*) from pBRDF (*R*) Matrix

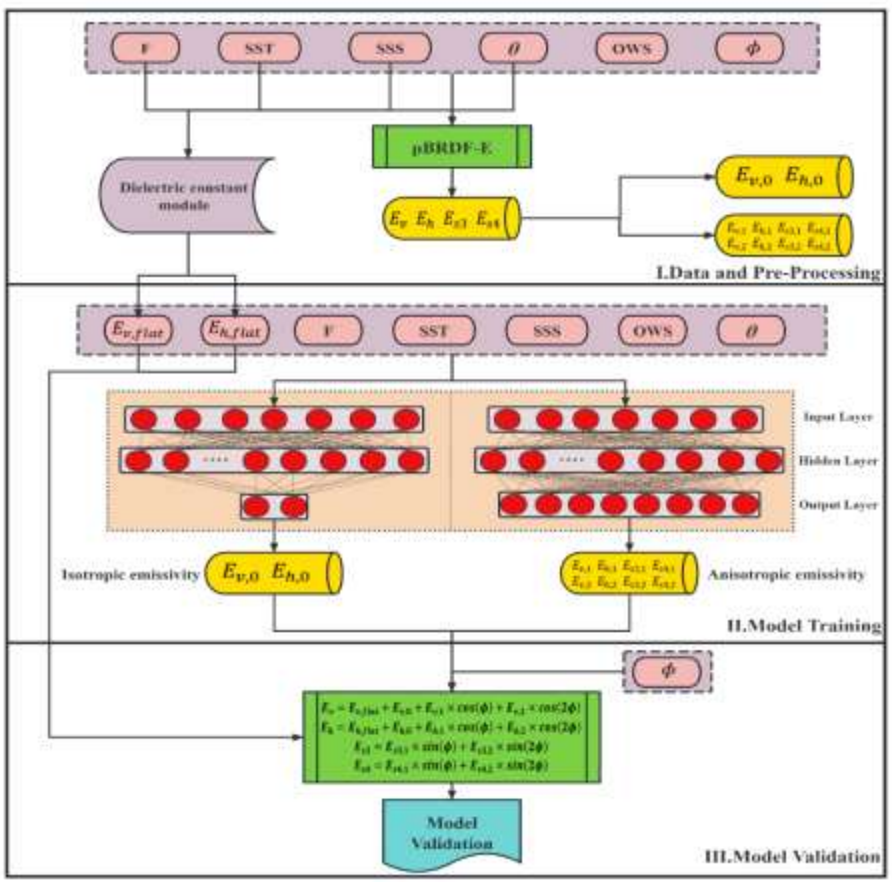


Zenith angle =30° ; wind speed = 5m/s; f=37GHz



Zenith angle =55° ; wind speed = 5m/s; f=37GHz

Fast Ocean Emissivity Model (OceanEM) Based on pBRDF



A fast ocean emissivity model (OceanEM) is developed based on the emissivity data output from the pBRDF-E model by using the **multilayer perceptron (MLP)** neural network.

Physical Model Setup

Incidence angle:

0 − 80°

Wind speed:

2 − 50 m s^{-1}

Sea surface temperature:

−2 − 30°C

Salinity:

0−40 psu

Frequency:

1.4−410 GHz

Dielectric constant model:

Liu et al.(2011)

Wave spectrum model:

Durden and Vesecky (1985) with a0×2

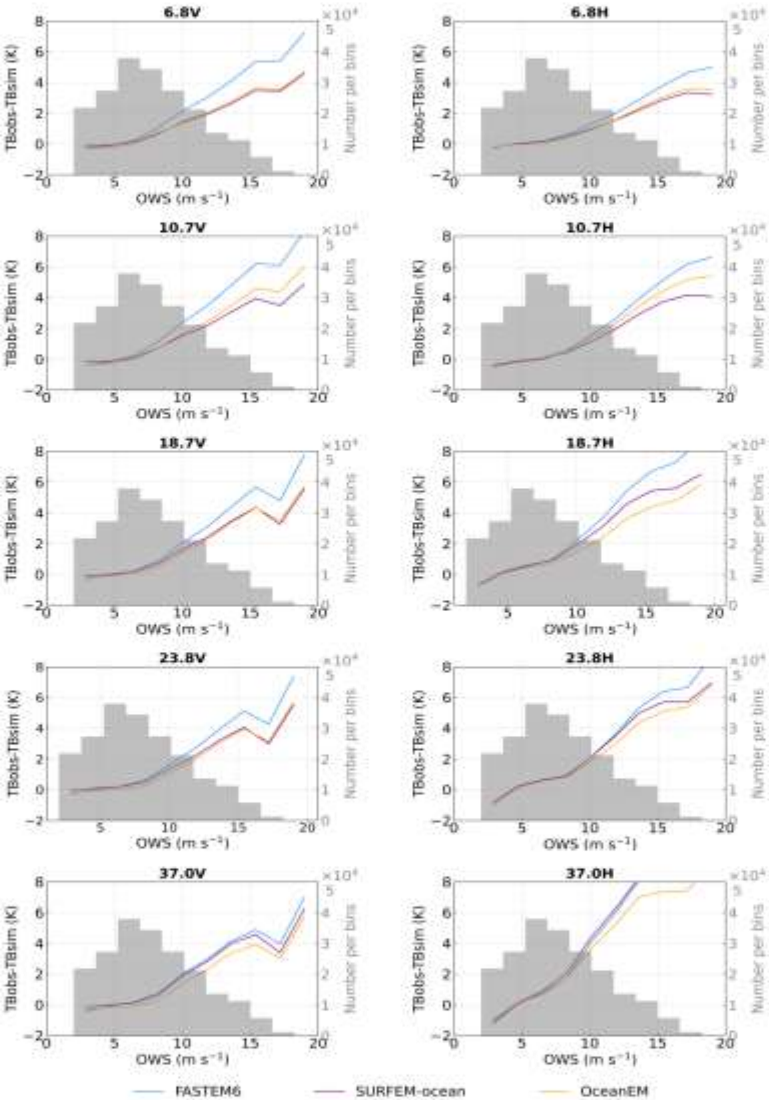
Foam cover model:

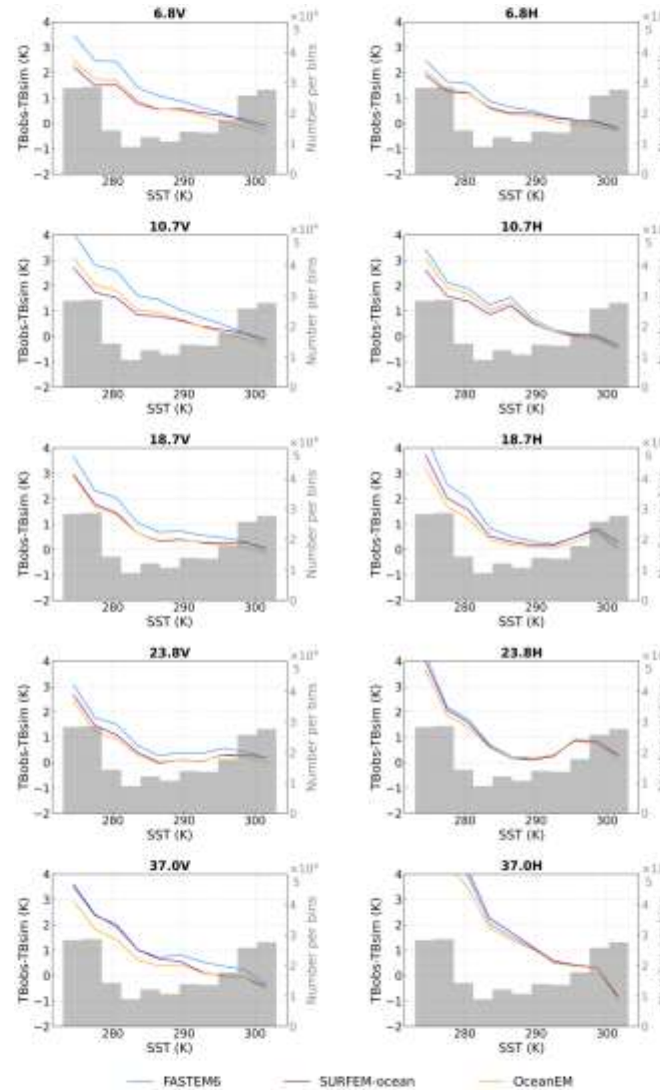
Monahan and O'Muircheartaigh (1986)

Foam emissivity model:

Kazumori et al. (2008) with Stogryn (1972)

Evaluation of the OceanEM (WindSat)





Both SurfEM and OceanEM perform better than FASTEM6 with small biases at high wind speeds, with FASTEM6 underestimating the simulated brightness temperature compared to the other two models.

Both SurfEM and OceanEM perform better than FASTEM6 with respect to the SST, and OceanEM has the lower biases at lower SST conditions in channel with 18.7/23.8/37 GHz.

VDISORT Lower Boundary Scheme

$$\mathbf{I}(\mu,\phi) = \mathbf{E}\mathbf{S}_t + \int_0^{2\pi}\int_0^1 \mathbf{R}(\mu,\phi;-\mu',\phi')\mu'\mathbf{I}(-\mu',\phi')d\mu' d\phi' + \mathbf{R}(\mu,\phi;-\mu_0',\phi_0')\mu_0\mathbf{S}_b \exp(-\tau_L/\mu_0)$$

where emissivity vector (***E***) and BRDF (***R***) are related to each other; $\boldsymbol{S_t}$ and $\boldsymbol{S_b}$ are thermal Stokes vector and solar Stokes vector respectively

$$\mathbf{R}(\theta^i,\varphi^i;\theta^s,\varphi^s) = \begin{pmatrix} R_{llll} & R_{lrlr} & \mathrm{Re}(R_{lrll}) & \mathrm{Im}(R_{lrll}) \\ R_{rlrl} & R_{rrrr} & \mathrm{Re}(R_{rrrl}) & \mathrm{Im}(R_{rrrl}) \\ 2\,\mathrm{Re}(R_{llrl}) & 2\,\mathrm{Re}(R_{lrrr}) & \mathrm{Re}(R_{llrr}+R_{lrrl}) & \mathrm{Im}(R_{rrll}+R_{rllr}) \\ 2\,\mathrm{Im}(R_{llrl}) & 2\,\mathrm{Im}(R_{lrrr}) & \mathrm{Im}(R_{llrr}+R_{lrrl}) & \mathrm{Re}(R_{rrll}-R_{rllr}) \end{pmatrix}$$

Polarized BRDF matrix

$$\mathbf{E}(\mu,\varphi) = \mathbf{N} - \int_0^{2\pi}\int_0^1 \mathbf{R}(\mu,\varphi;-\mu',\varphi')\mu' d\mu' d\varphi'$$

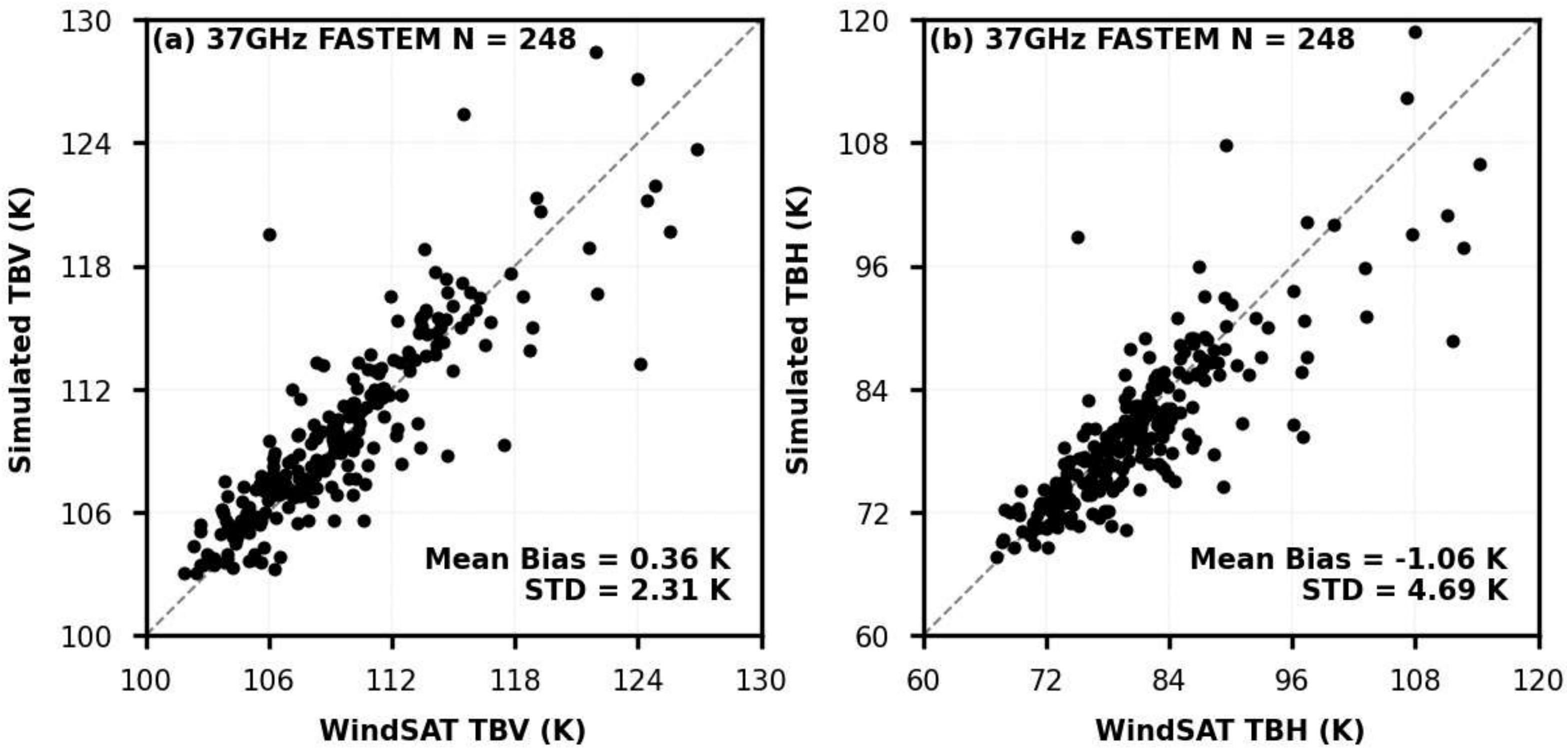
For an absorption surface, Kirchhoff's Law is generalized to compute the emissivity matrix as follows:

Liu, Q. , F. Weng and S. English, 2011: An Improved Fast Microwave Water Emissivity model: *IEEE Trans. Geosci. Remote Sens.,* 1238-1250, DOI: 10.1109/ TGRS.2010.2064779.

He, L. and F. Weng, 2023: Improved Microwave Emissivity and Reflectivity Model derived from Two-scale Roughness Theory, *Adv Atmos. Sci.,40,1923-1938*

$$\boldsymbol{R}(\mu_s,\varphi_s,\mu_i,\varphi_i) = \sum_{m=0}^{\infty}\left\{\boldsymbol{R}_m^c(\mu_s,\mu_i,\varphi_s)\,cosm(\varphi_i-\varphi_s) + \boldsymbol{R}_m^s(\mu_s,\mu_i,\varphi_s)\,sinm(\varphi_i-\varphi_s)\right\}$$

VDISORT Simulations vs. WindSAT Observations



- ☐ NRL Windsat data are collocated with ERA5 data (Temperature, humidity, hydrometeor profiles, surface temperature, surface wind.
- ☐ The all sky vertically (left) and horizontally (right) brightness temperatures at 37 GHz are simulated with VDISORT. The surface emissivity model is based on FASTEM-6.

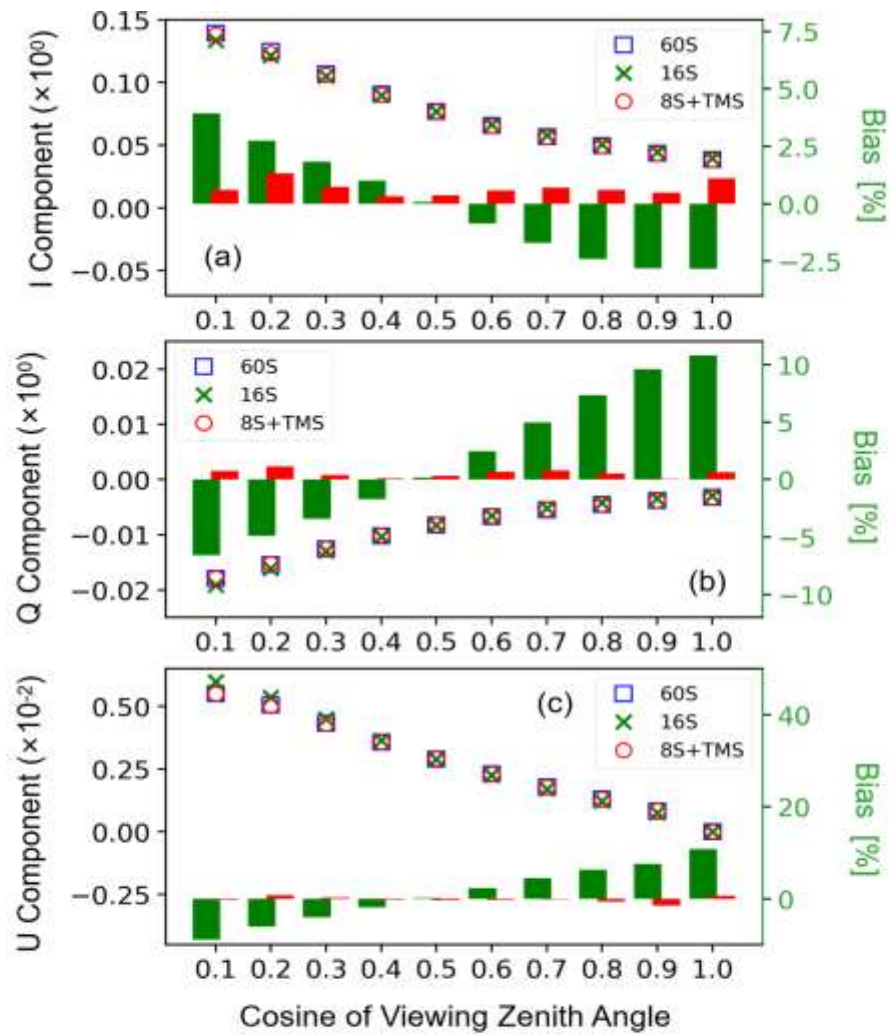
VDISORT Acceleration Technique

TMS correction has been applied into VDISORT to accelerate single layer RT solver

Truncated Multiple and Single (TMS) Scattering Correction (Nakajima, 1988):

$$\mathbf{L}(\tau,\mu,\phi) = \mathbf{L}_{\mathrm{SS}}(\tau,\mu,\phi) - \mathbf{L}_{\mathrm{SS}}(\tau_*,\mu,\phi) + \mathbf{L}_{\mathrm{VDOM}}(\tau_*,\mu,\phi)$$

After applying TMS Correction, the accuracy of 8-stream VDISORT can exceed the performance from 16-stream VDISORT.



VDISORT Jacobian Development

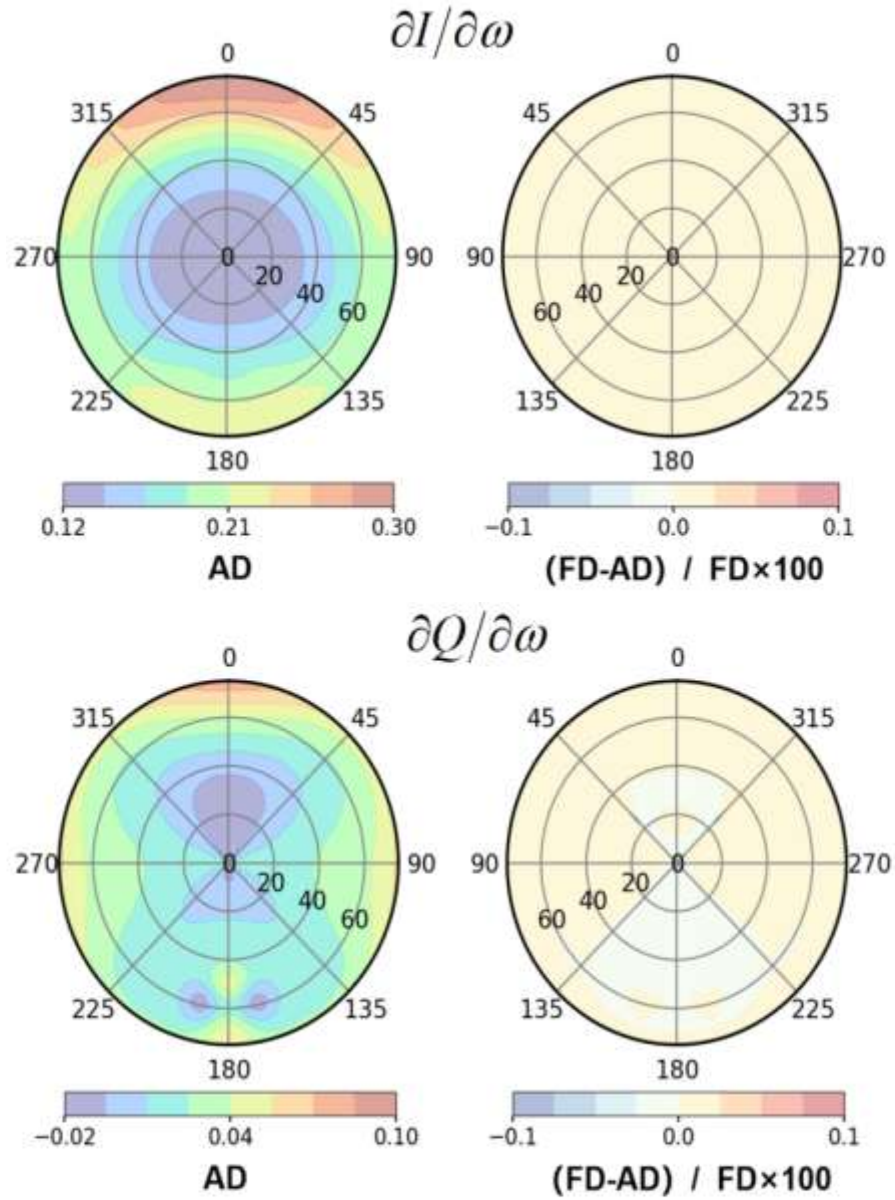
The Jacobian Module of VDISORT are developed following Tangent-Linear and Adjoint rules.

The Jacobian results are examined by comparing Adjoint results (AD) to the finite difference method (FD)

The finite difference method (FD)

$$\frac{\partial F(x)}{\partial x} = \frac{F(x+\delta x) - F(x)}{\delta x}$$

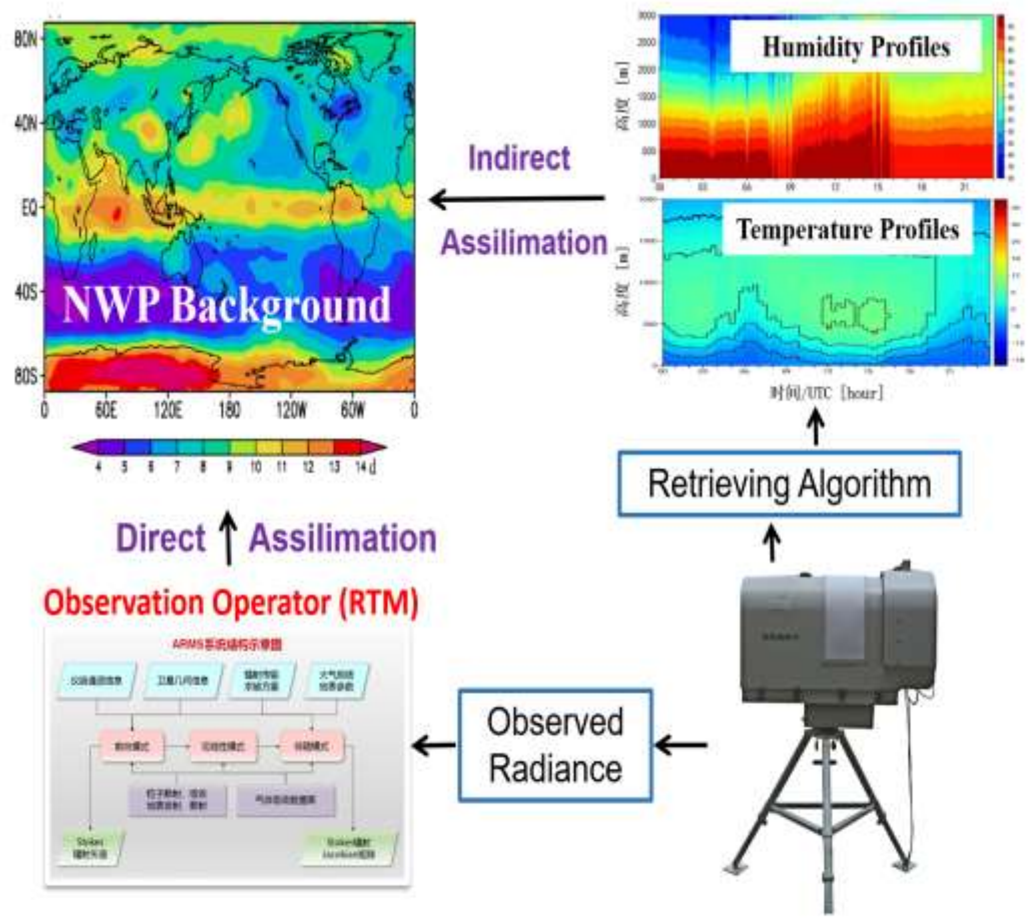
The relative biases between AD to FD less than 0.1%.



ARMS-gb Development

Ground-based microwave radiometers (GMRs) can provide near-surface observations with minute-level temporal resolution..

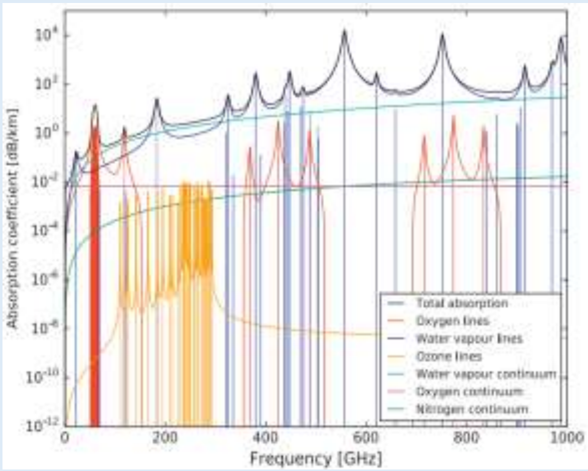
Indirect assimilation of temperature and humidity profiles retrieved from GMRs is an effective approach, but it is difficult to accurately estimate observation errors in indirect assimilation, which limits its effectiveness.



Direct assimilation of GMR-observed brightness temperatures allows for the estimation of observation errors using OMB (Observation Minus Background), but there is a lack of an independently developed and controllable observation operator.

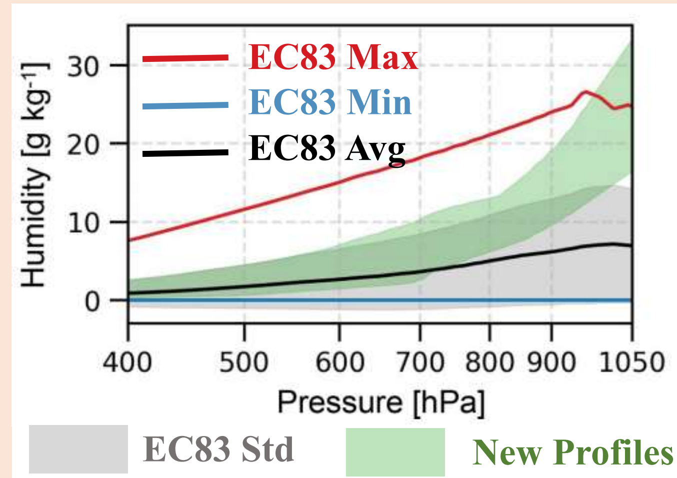
ARMS-gb Development

- MonoRTM-based ODPS gaseous absorption scheme



From Turner et al., (2019)

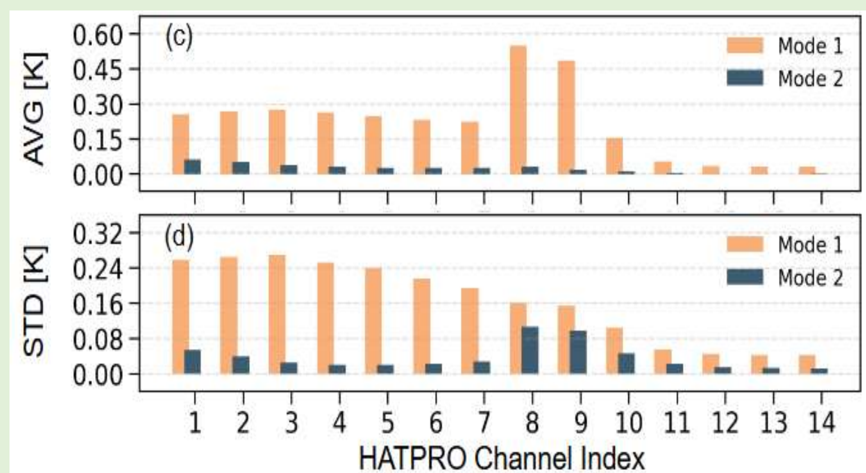
- Optimized Training dataset for low atmosphere, add 7 humidity profiles



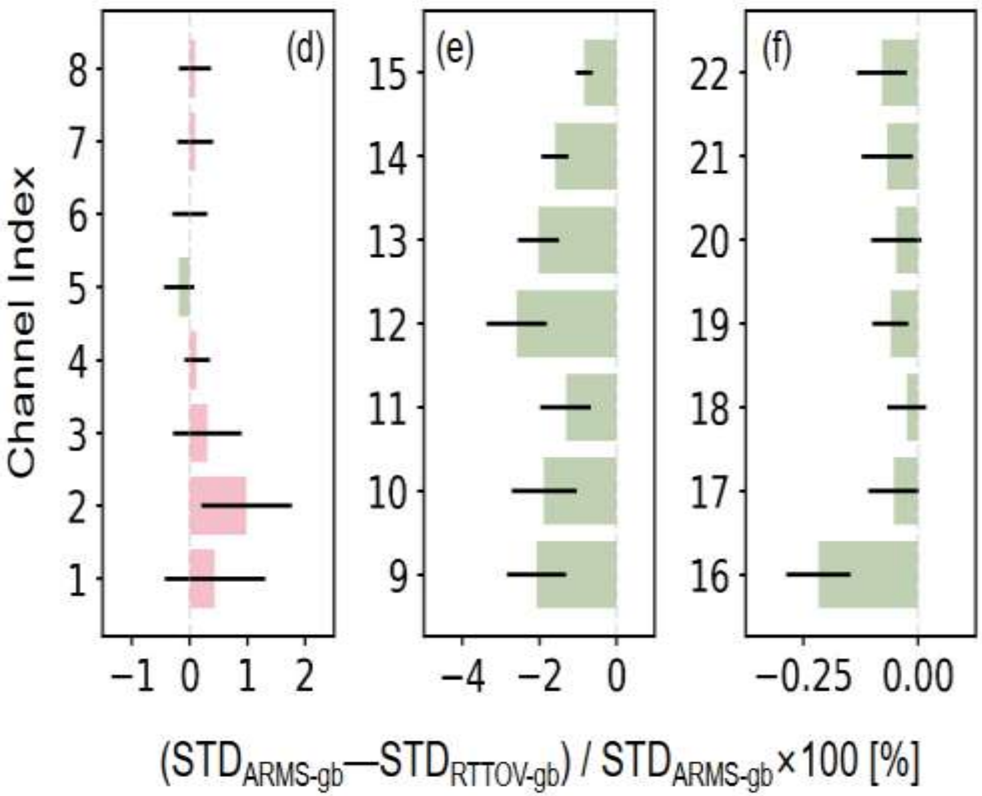
- Used Advanced Water vapor Interpolation scheme to reduce error.

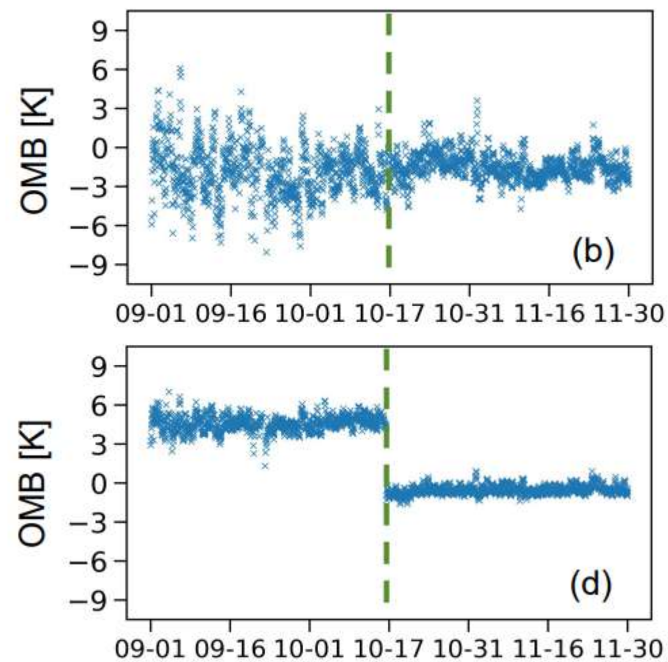
RTTOV-gb Interpolation mode

ARMS-gb Interpolation mode



ARMS-gb vs RTTOV-gb





In Tianjing Tanggu Station, STD of OMB from ARMS-gb much less than that from RTTOV-gb

According to results in Xinjiang Mingfen Station, we can find the characteristics of OMB changed significantly before and after calibration.

Summary and Conclusions

ARMS has been upgraded to version 1.5， the main updates include:

1. In the training of infrared hyperspectral atmospheric transmittance, sulfur dioxide (SO_2) was added as a variable gas, and smaller biases were obtained near 1037 wavenumber.
2. MONORTM was introduced to train microwave atmospheric transmittance, and the spectral response function of the instrument was taken into account during the channel convolution process.
3. A microwave surface emissivity dataset based on 1DVAR inversion was constructed by using the FY-3D MWRI.
4. A scattering database of non-spherical cloud particles in the microwave band was constructed based on the Discrete Dipole Approximation (DDA).
5. A fast ocean emissivity model (OceanEM) is developed based on the emissivity data output from the pBRDF-E model by using the multilayer perceptron (MLP) neural network and coupled to VDISORT as Lower Boundary condition.
6. In response to the application requirements of ground-based microwave radiometers, ARMS-gb was developed, and its simulation accuracy and application effects were preliminarily evaluated.

THANKS!

Earth System Modeling and Prediction Centre
China Meteorological Administration (CMA)