CMA Plan for Developing Advanced Radiative Transfer Modeling System (ARMS)

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Outline

- Review of current radiative transfer models
- Current participated organizations for ARMS developments
- ARMS framework design and software engineering
- Initial demonstration of ARMS capabilities
- ARMS future developments
- Summary

Requirements on Radiative Transfer Model for NWP and Remote Sensing Applications

Data assimilation is a process of incorporating all observations into weather forecast models to produce the "*best*" description of the atmospheric state at a desired resolution. Physical understanding of observations, weather structures and applicable mathematical optimal control and statistical estimate theories are important for any success of satellite data assimilation.

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}_b)^T \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b) + \frac{1}{2}(F(\mathbf{x}) - \mathbf{I}^{obs} - \mu)^T (\mathbf{E}_o + \mathbf{E}_F)^{-1}(F(\mathbf{x}) - \mathbf{I}^{obs} - \mu)$$

$$J(\mathbf{x}_a) = \min_{\mathbf{x}} J(\mathbf{x}) \quad \forall \mathbf{x} \text{ near } \mathbf{x}_b$$ <—— Maximum likelihood Estimate

- $\mathbf{x}$ – analysis variable
- $\mathbf{x}_a$ – final analysis
- $\mathbf{x}_b$ – background
- $\mathbf{B}$ – background error covariance

- μ — bias
- $\mathbf{y}^{obs}$ – observations
- $\mathbf{E}_o$ – observation error covariance
- F – Forward operator
- $\mathbf{E}_F$ – forward operator error covariance

1) Forward operator is required for performing fast computations over NWP model domains for all the channels that are assimilated and 2) the uncertainties of forward operators in simulating satellite radiances must be quantified for all the sensors and channels under various atmospheric and surface conditions

CRTM as an Example

- Atmospheric gaseous absorption
  - Band absorption coeff. trained by LBL spectroscopy data with sensor response functions
  - Variable gases (H2O, CO2, O3 etc) .
  - Zeeman splitting effects near 60 GHz
- Cloud/precipitation scattering and emission
  - Fast LUT optical models at all phases including non-spherical ice particles
  - Gamma size distributions
- Aerosol scattering and emission
  - multiple aerosol species (dust, sea salt, organic/black carbon,)
  - Lognormal distributions
- Surface emissivity/reflectivity
  - Two-scale microwave ocean emissivity
  - Large scale wave IR ocean emissivity
  - Land mw emissivity model/data base
  - Land IR emissivity data base
- Radiative transfer scheme
  - Discrete ordinate, doubling and adding, and successive order of iteration
  - Tangent linear and adjoints
  - Inputs and outputs at pressure level coordinate

Primary Performance Issues of Current Fast RT Models

- Large uncertainties are found in simulating radiances at microwave frequencies in scattering atmosphere.

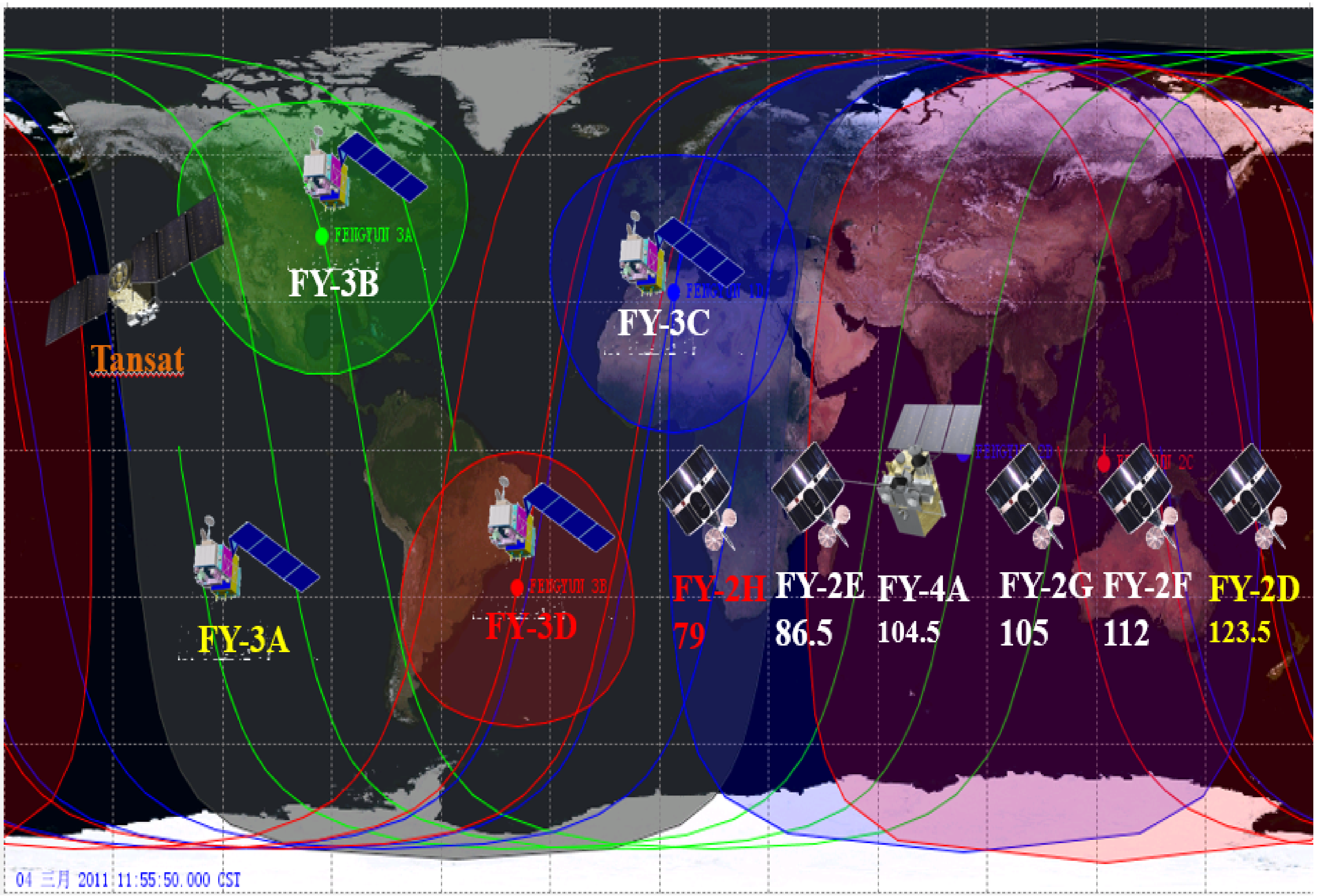
- Large biases (O-B) are observed when simulating radiances at surface sensitive channels for all instruments.

- There are some strange angular-dependent bias (O-B) at microwave sounding channels even under clear conditions.

- Both RTTOV and CRTM are a scaler model and only solve for the radiative intensity. Those instruments such as UV, visible, and microwave polarimetric imagers require a full vector RT model.

- Very slow computation speeds are found when the model runs in strong scattering conditions.

Requirements of ARMS from China



ARMS Project Kick-Off

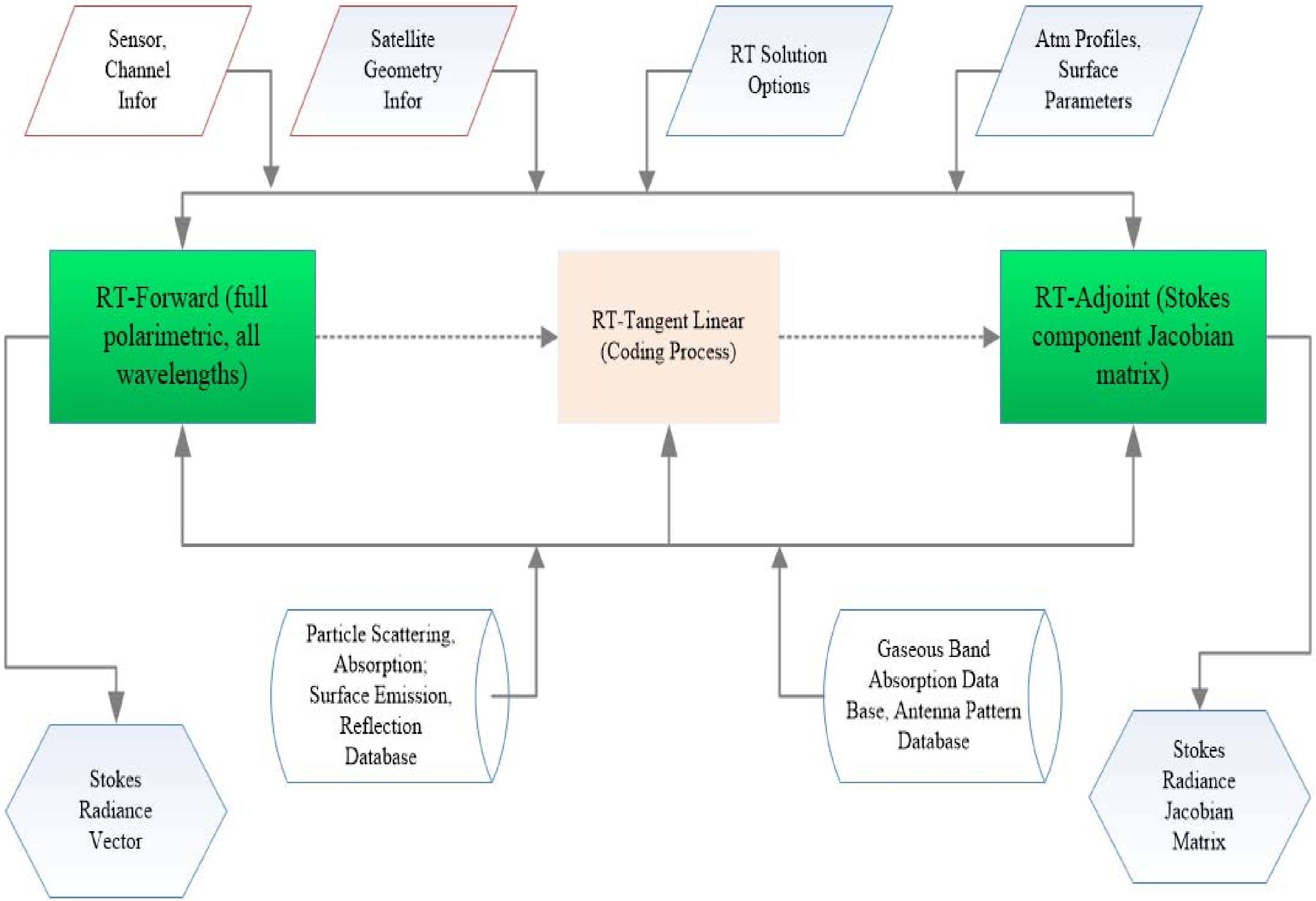
- On June 12-13, 2018：CMA held its first workshop on “new generation of fast and accurate radiative transfer model”. 13 organizations and 120 people attended the meeting. The purpose of this workshop
  - Understand the requirements on fast and radiative transfer models and current capability in China
  - Formulate a working group and develop a work plan for fast RT model developments



Current Participated Organizations

- Chinese Academy of Meteorological Sciences (CAMS)
- National Satellite Meteorological Centre (NSMC)
- National Meteorological Centre (NMC)
- Chinese Academy of Sciences (CAS)
- Nanjing University of Information Science & Technology (NUIST)
- Nanjing University (NJU)
- Zhejiang University (ZJU)
- Sun Yat-sen University (SYSU)
- Fudan University (FDU)

Advanced Radiative Transfer Modeling System (ARMS）



Radiative transfer equation: from scalar to vector

Scalar

$$\frac{dI(\tau,\mu,\phi)}{d\tau} = -I(\tau,\mu,\phi) + J(\tau,\mu,\phi) + S(\tau,\mu,\phi,\mu_0,\phi_0)$$

1. Extinction

I: Intensity

2. Multiple scattering

$$J = \frac{\omega}{4\pi}\int_0^{2\pi}\int_{-1}^{1} P(\tau,\mu,\phi;\mu',\phi')I(\tau,\mu',\phi')d\mu' d\phi'$$

3. First scattering &thermal emission

$$S(\tau,\mu,\phi,\mu_0,\phi_0) = \frac{\omega F_{\odot}}{4\pi}\exp(-\tau/\mu_0)\, P(\mu,\phi,\mu_0,\phi_0) + (1-\omega)B[T(\tau)]$$

Vector

$$\frac{d\boldsymbol{I}(\tau,\mu,\phi)}{d\tau} = -\boldsymbol{I}(\tau,\mu,\phi) + \boldsymbol{J}(\tau,\mu,\phi) + \boldsymbol{S}(\tau,\mu,\phi,\mu_0,\phi_0)$$

$\boldsymbol{I}$: Stokes vector $\boldsymbol{I} = [I, Q, U, V]$ or $\boldsymbol{I} = [I_r, I_l, U, V]$

$$\boldsymbol{J} = \frac{\omega}{4\pi}\int_0^{2\pi}\int_{-1}^{1} \boldsymbol{M}(\tau,\mu,\phi;\mu',\phi')\boldsymbol{I}(\tau,\mu',\phi')d\mu' d\phi'$$

$$\boldsymbol{S}(\tau,\mu,\phi,\mu_0,\phi_0) = \frac{\omega F_{\odot}}{4\pi}\exp(-\tau/\mu_0)\begin{bmatrix} M_{11}(\phi,\mu_0,\phi_0) \\ M_{12}(\phi,\mu_0,\phi_0) \\ M_{13}(\phi,\mu_0,\phi_0) \\ M_{14}(\phi,\mu_0,\phi_0) \end{bmatrix} + (1-\omega)\boldsymbol{B}\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

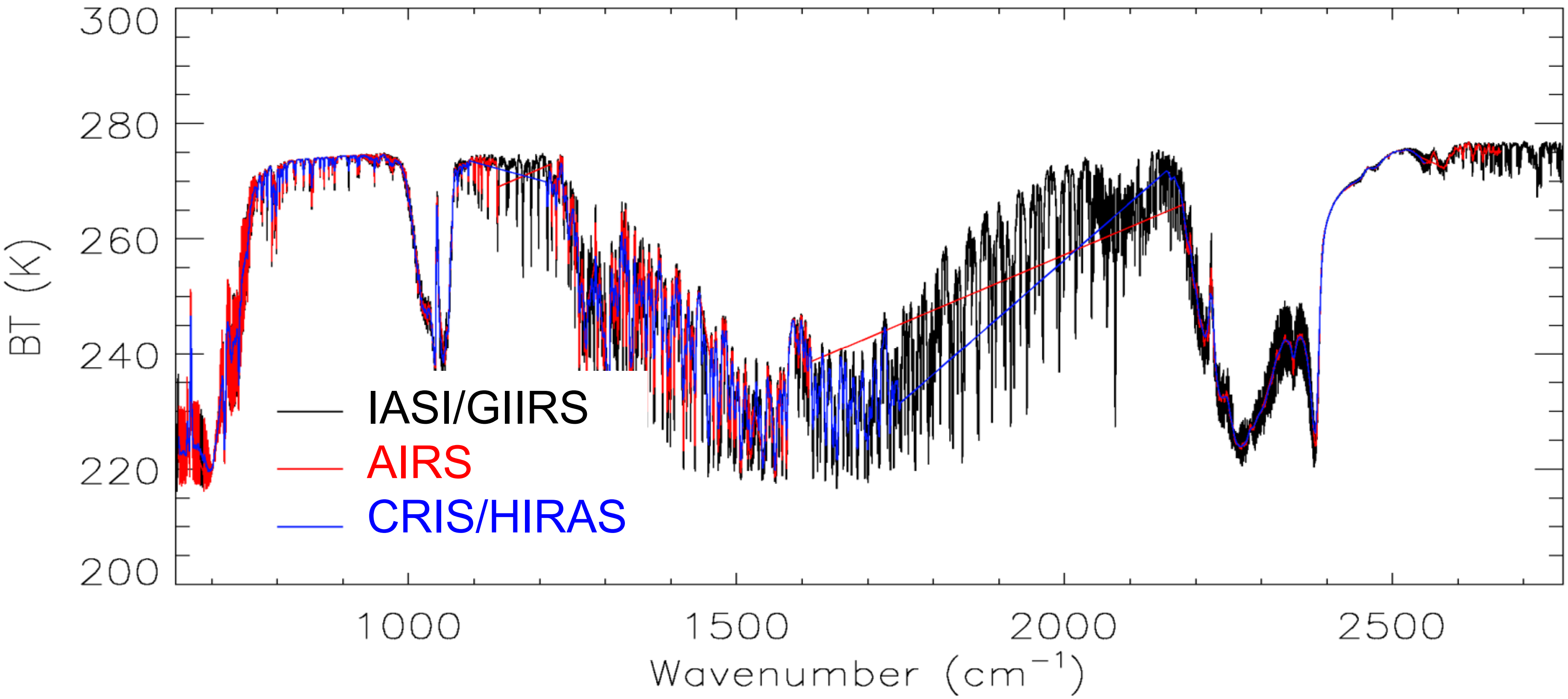
ARMS Software Engineering

- Designing with the state-of-the-art radiative transfer sciences, cutting edge software engineering, and flexible interfaces with other fast models.
- Modular development for easy teamwork
- Optimize ARMS software design by using Python, Fortran and C computer languages to achieve a more flexible interface to user applications.
- Developing a GPU and cloud versions of ARMS to improve computational speeds

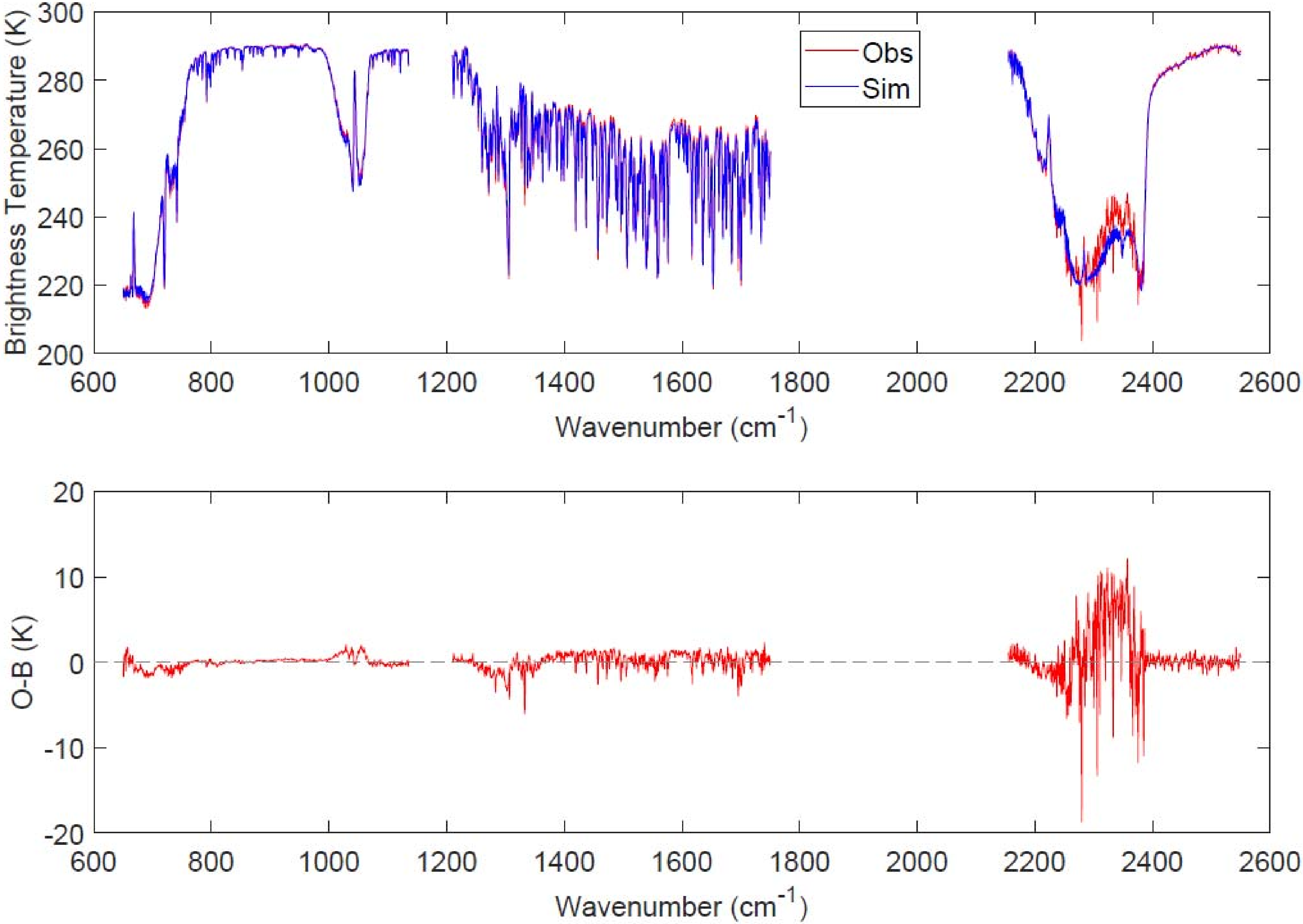
Completed ARMS Modules

- Integrate polarized two steam radiative transfer solver (P2S) into ARMS
- Test vector doubling and adding model, and start integration into ARMS
- Fix some software bugs in Vector Discrete Ordinate Transfer Model (VDISORT)
- Introduce CRTM aerosols, clouds and precipitation scattering database
- Test UNL-VRTM/VLIDORT for proxy data simulation
- Complete FY-3 HIRAS and FY-4 GIIRS fast transmittance model
- Integrate the surface roughness model into microwave land emissivity model
- We are expected to release a beta version of ARMS later this year.

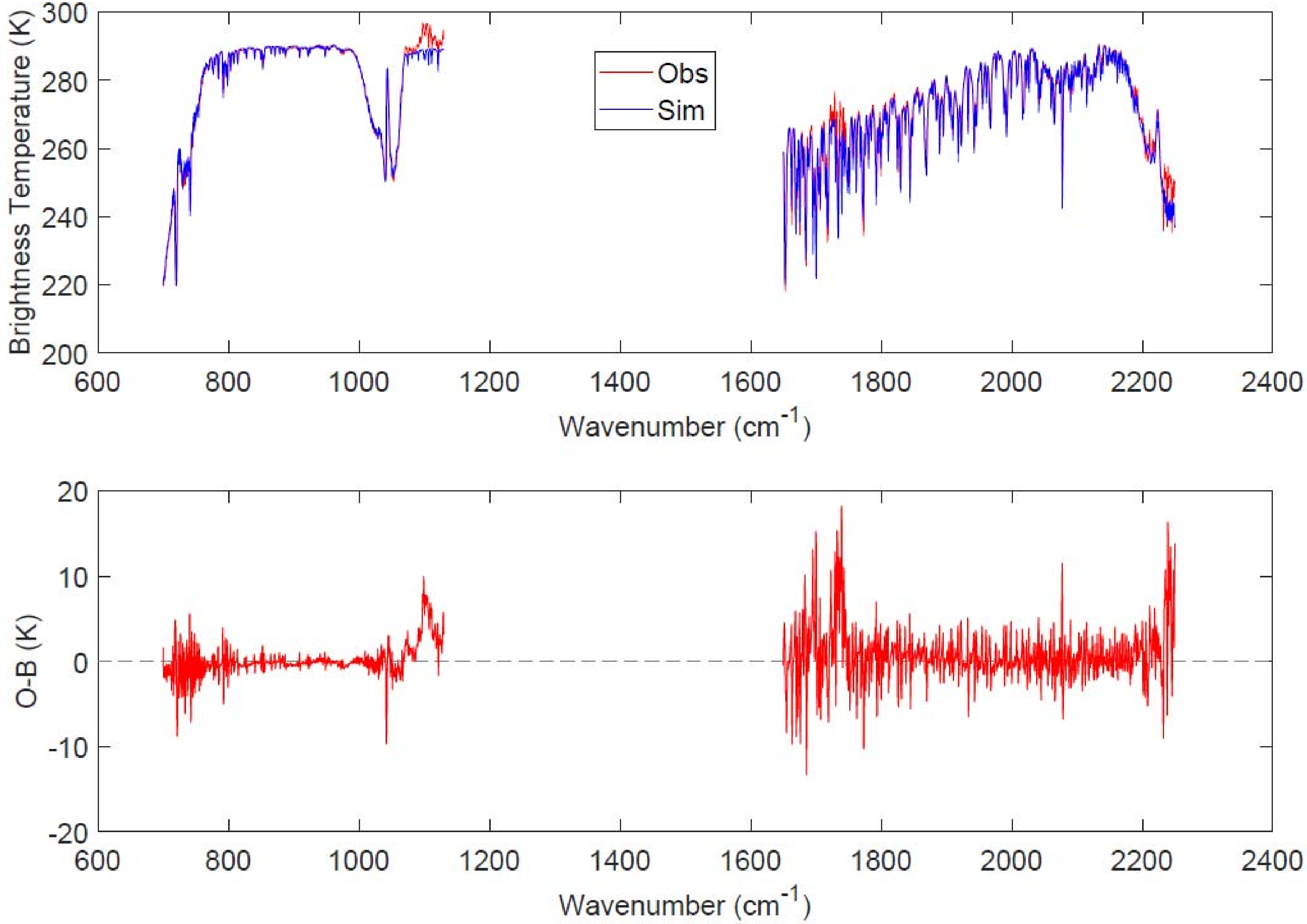
ARMS Infrared Spectroscopy Database



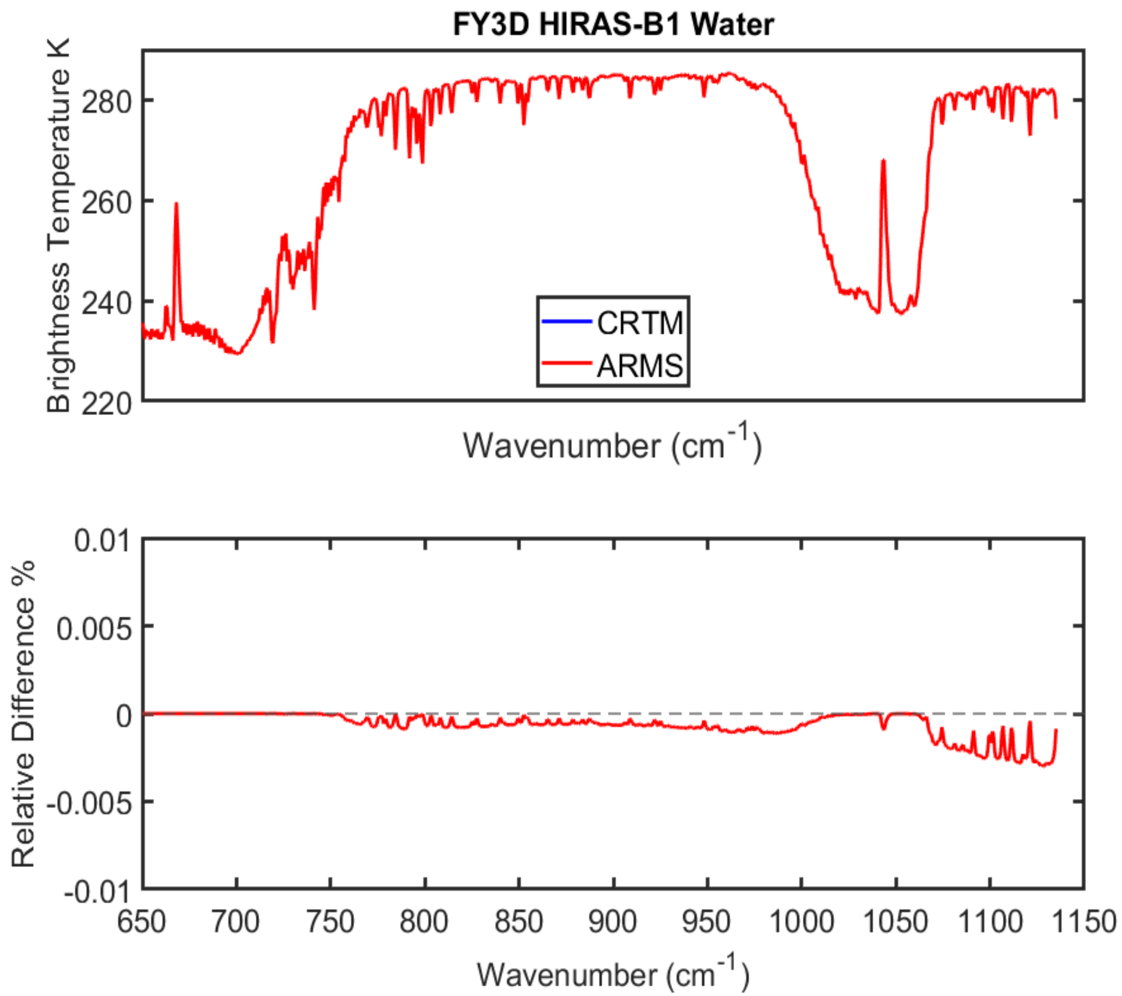
ARMS HIRAS Transmittance Module



ARMS GIIRS Transmittance Module

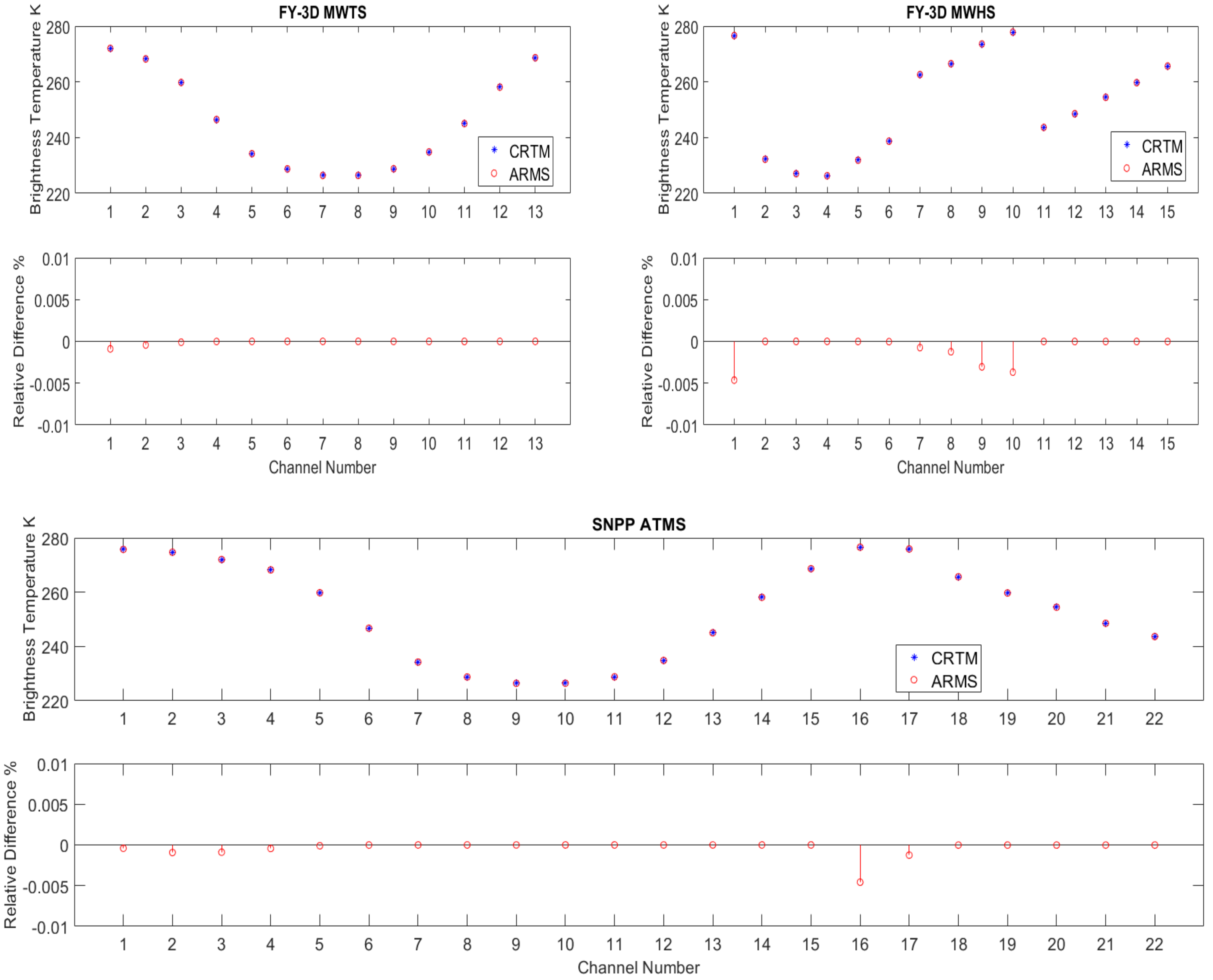


Simulations between ARMS vs CRTM

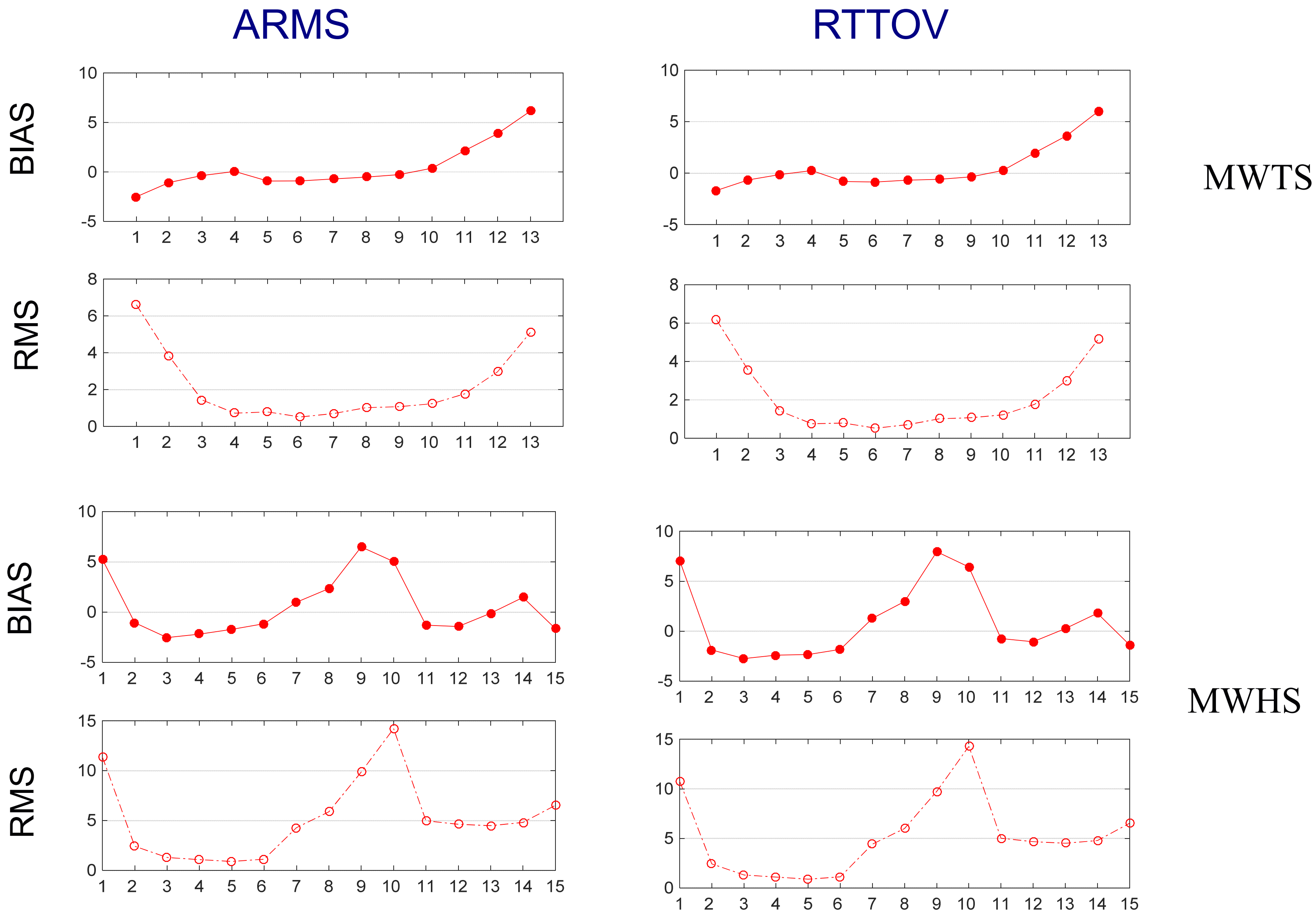


Surface Type: Water; The Local zenith angle is 50.208 degree. Surface temperature=288.0 K.
Wind_Speed: 10.0 m/s. Wind_Direction 10.0 degree. Salinity: 33 ppt

ARMS-P2S vs CRTM

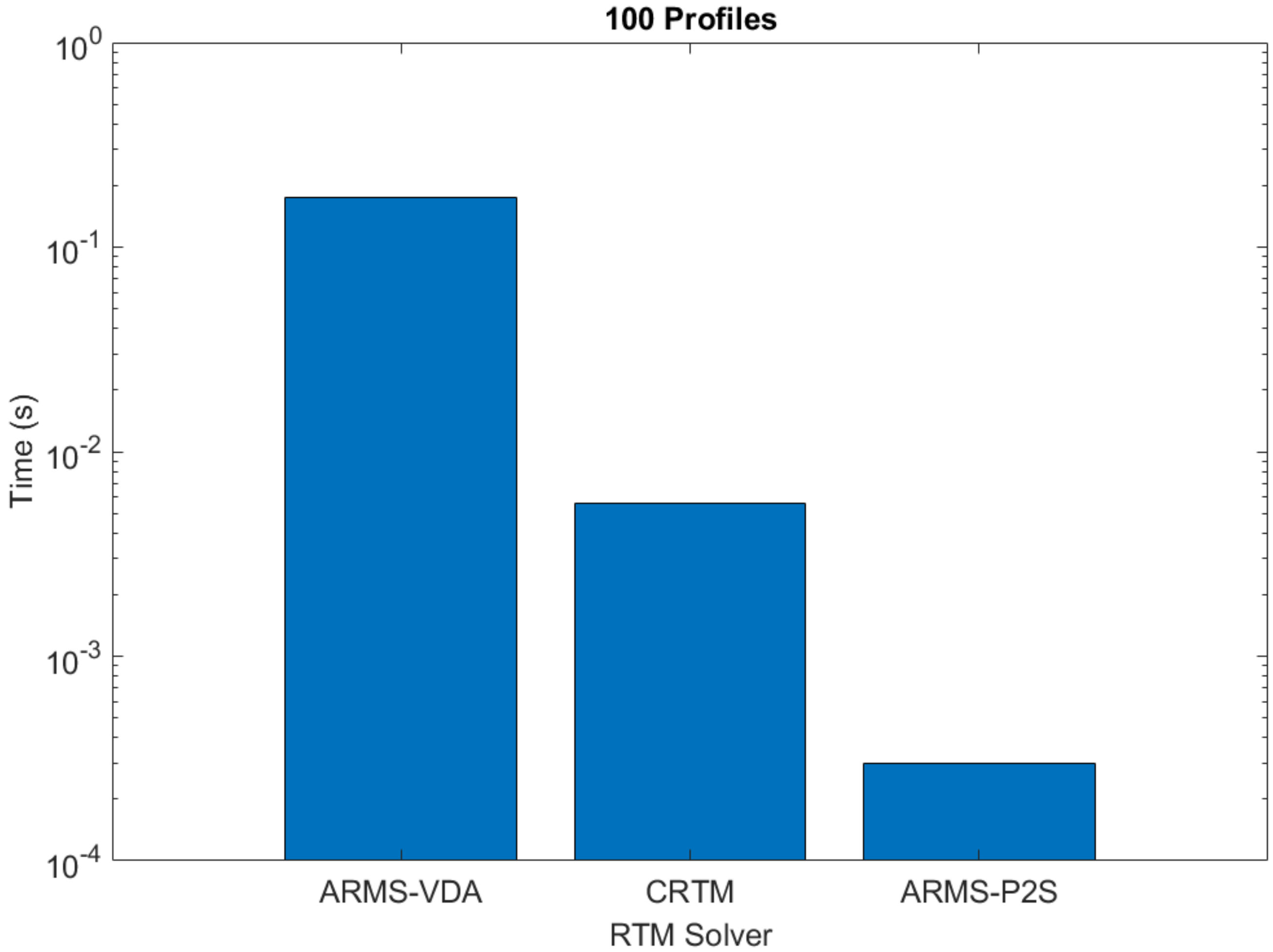


ARMS Simulations Using GNOS Profiles



Surface emissivity =0.6

Speed Comparisons (ARMS vs. CRTM)



Transitioning ARMS into Research & Operations

- Use ARMS to monitor O-B for microwave instrument performance in orbit. NSMC collaborators: Lu Qifeng, Hu Xiuqing, Qi Chengli, Guo Yang
- Integrate ARMS visible channel capability into FY-4A RGB true color image processing. NSMC collaborators: Wei Caiyang, Chen Boyang
- Use ARMS in FY-3 microwave remote sensing testbed (MRT) ground processing to produce a suite of microwave products such as atmospheric temp and moisture profiles, surface and hydrological parameters from MWTS, MWHS and MWRI. NSMC collaborators: Gu Songyan, Han Yang
- Use ARMS in ocean weather monitoring and forecasts. NSMC Collaboration partners: Zhang Peng, Yang Zhongdong, Gu Songyan, Han Xiuzhen
- ARMS in GRAPES, CNWP/NSMC Collaborators: Gong Jian dong, Han Wei, Lijuan, Ma Gang
- ARMS in satellite ecological monitoring and remote sensing: NSMC Collaborators: Han Xiuzhen, Gao Ling
- ARMS in harmonizing AMSU and MWTS data record for climate trends: NCC Collaborator: Guo Yanjun
- Use ARMS in Chinese Ministry of Science and Technology Project. NSMC Collaborators: Yang Jun, Tan Shihao, Han Xiuzhen
- Use ARMS for future instrument proxy and simulation. NSMC Collaborators: Zhang Zhiqing, Lu feng, Hu Xiuqing

Correction for MWTS/MWHS Cross-Scan Asymmetry

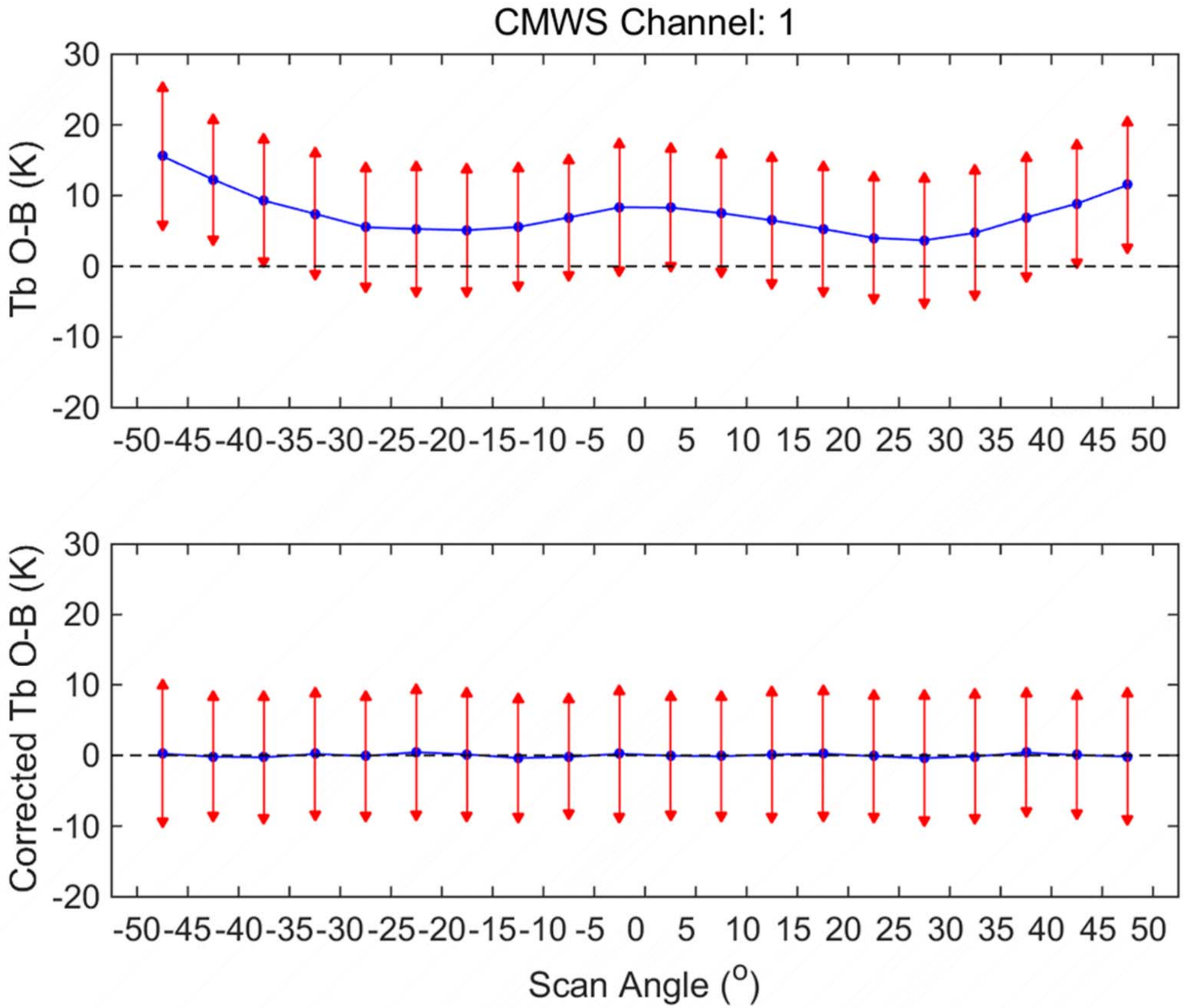
- Following Weng et al. (2003), the bias Tb (O-B) is fit with the equation:

$$\Delta T_b = A_0 exp\left\{-\frac{1}{2}[(\theta_s - A_1)/A_2]^2\right\} + A_3 + A_4\theta_s + A_5{\theta_s}^2,$$

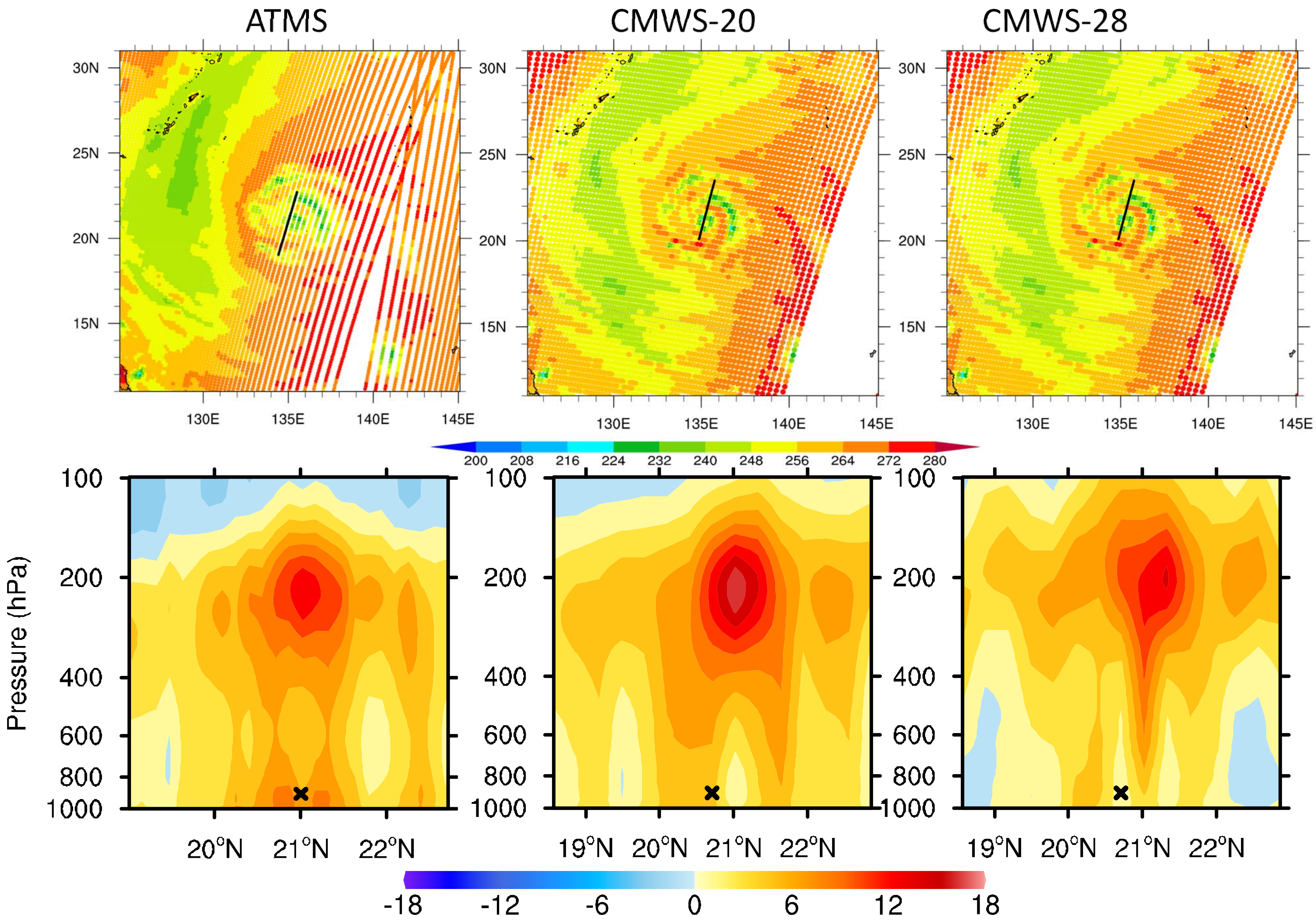
where T_b is the observed brightness temperature and θ_s is the zenith angle. The coefficient A_{0-5} are fitted using ΔT_b and θ_s on Jul-08, 2018 under clear sky condition ($clwp_{era}<0.01$ and $ciwp_{era}<0.01$) over ocean.

- After that, the asymmetry corrected TB is defined as Tb - ΔT_b.

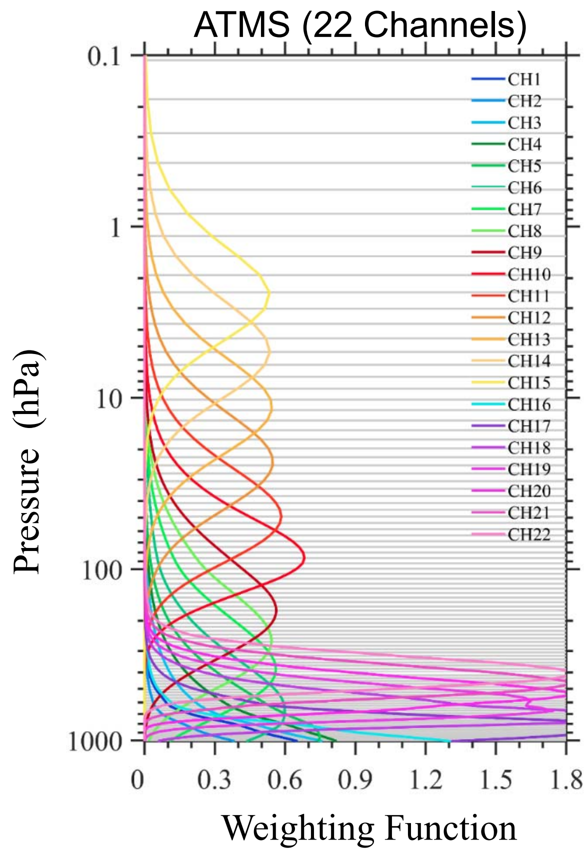
Correction for MWTS/MWHS Cross-Scan Asymmetry

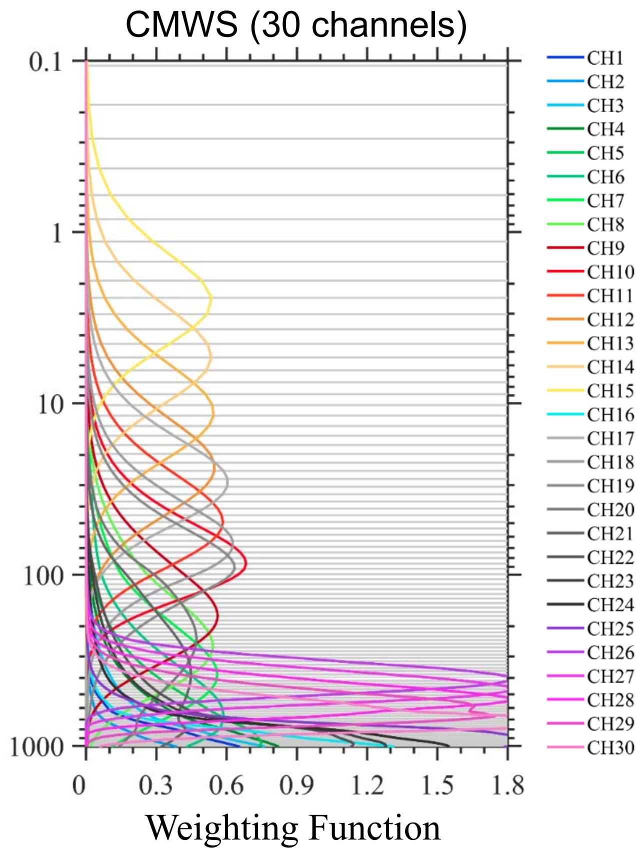


Typhoon Maria Thermal Structure Derived from SNPP-ATMS and FY-3 CMWS



Comparison of FY-3D and NOAA Microwave Sounding Capability

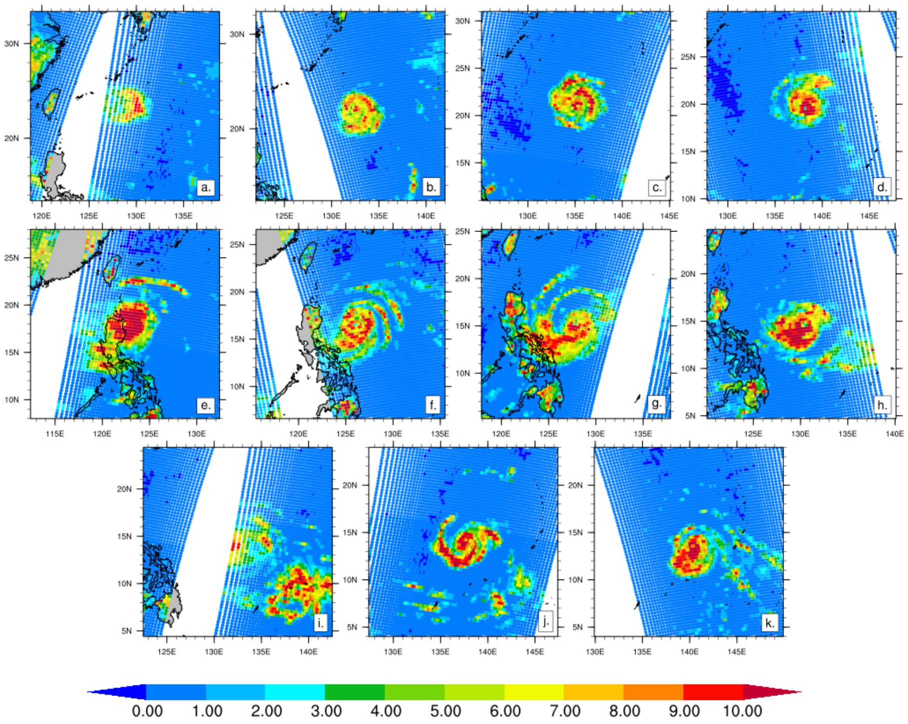




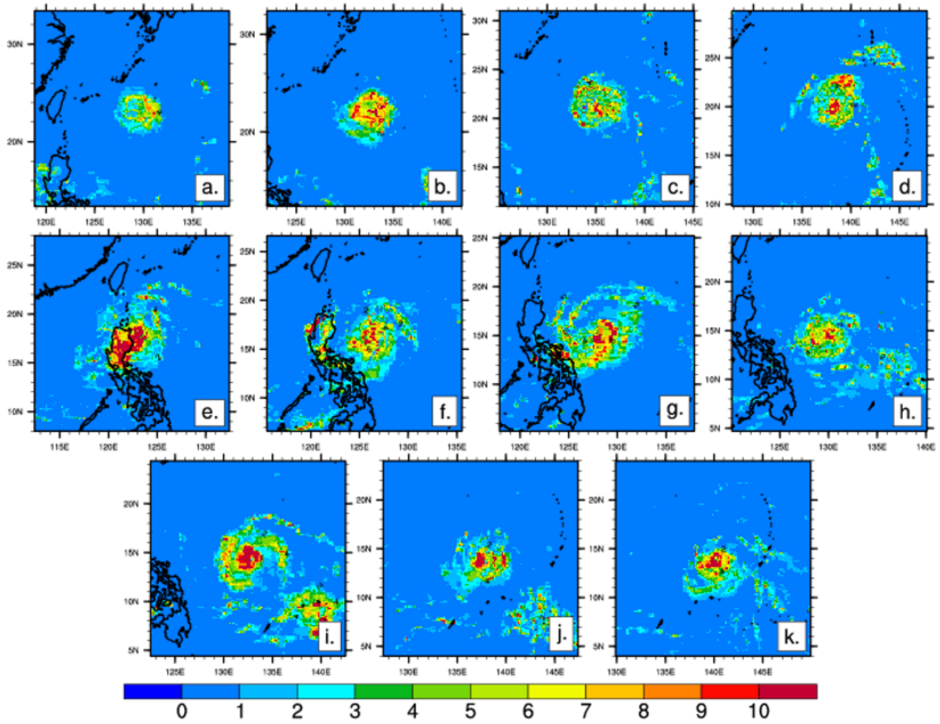
Fully Combined microwave sounders (CMWS) from FY-3D MWTS and MWHS has better vertical resolution for temperature sounding than NOAA ATMS

Typhoon Maria and Mangkhut
Precipitation Retrieved from FY-3 MWTS and MWHS

Precipitation from CMWS-28



Precipitation from CMORPH



FY3-CMWS-28 is combined from MWTS and MWHS
CMORPH is NOAA CPC Morphing Technique

Future Plan

- The developments and updates of ARMS will give more priority to Chinese satellite program
- Establish a complete aerosol, cloud particle scattering database to achieve high-precision radiation transmission simulation. Improvements are needed for simulation of cloudy/precipitation conditions and over high elevations through better scattering tables and surface models
  - ✓ CAMS and NSMC jointly responsible for the development of ARMS
  - ✓ ZJU for particle scattering LUT in Visble/IR
  - ✓ SYSU for particle scattering LUT at Microwave
  - ✓ FDU and CAS for surface emissivity
- More solvers will be integrated into ARMS
  - ✓ CAMS and NUIST for solvers
- Develop a GPU versions of ARMS to improve computational speeds
- Develop active sensor operators for simulating the active sensors（NJU）

Conclusions

- Fast and accurate radiative transfer model is critical for satellite program and affects many applications in sensor simulation, retrievals, and NWP data assimilation
- China has been relying on RTTOV and CRTM to support satellite data applications. We are grateful for their contribution.
- The beta version of ARMS will be released later this year
- ARMS is now being integrated with NWP data assimilation system (1dvar, GSI, GRAPES-4dvar)