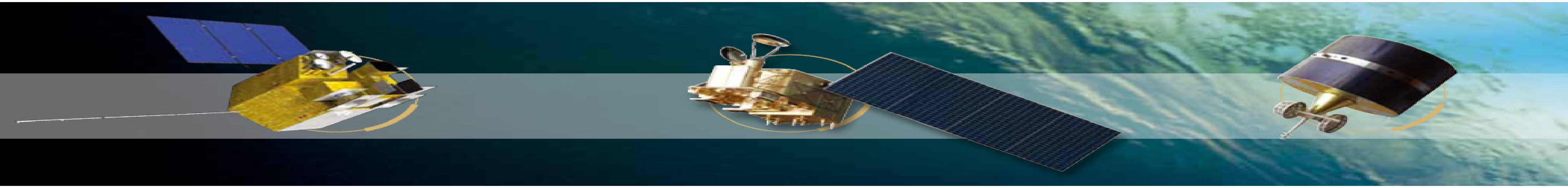

Recent Developments and Applications of Advanced Radiative Transfer Modeling System (ARMS)

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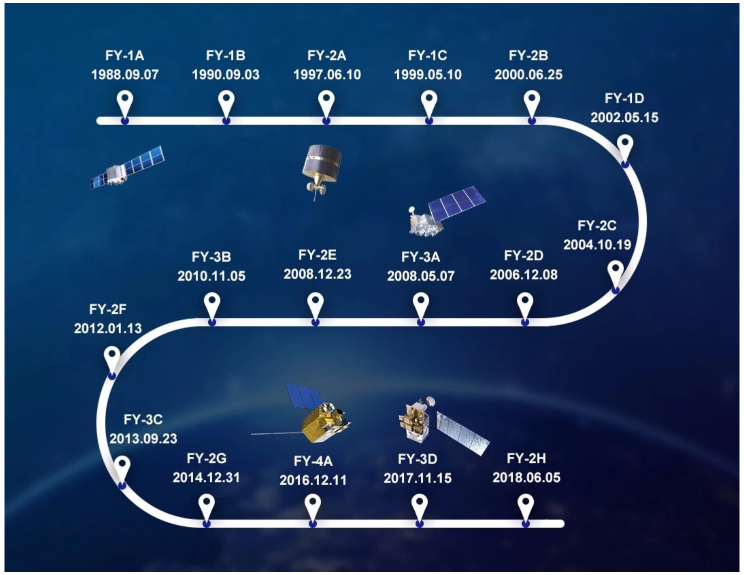
Outline

Application Demand of Fengyun Satellite Promotes the Development of ARMS

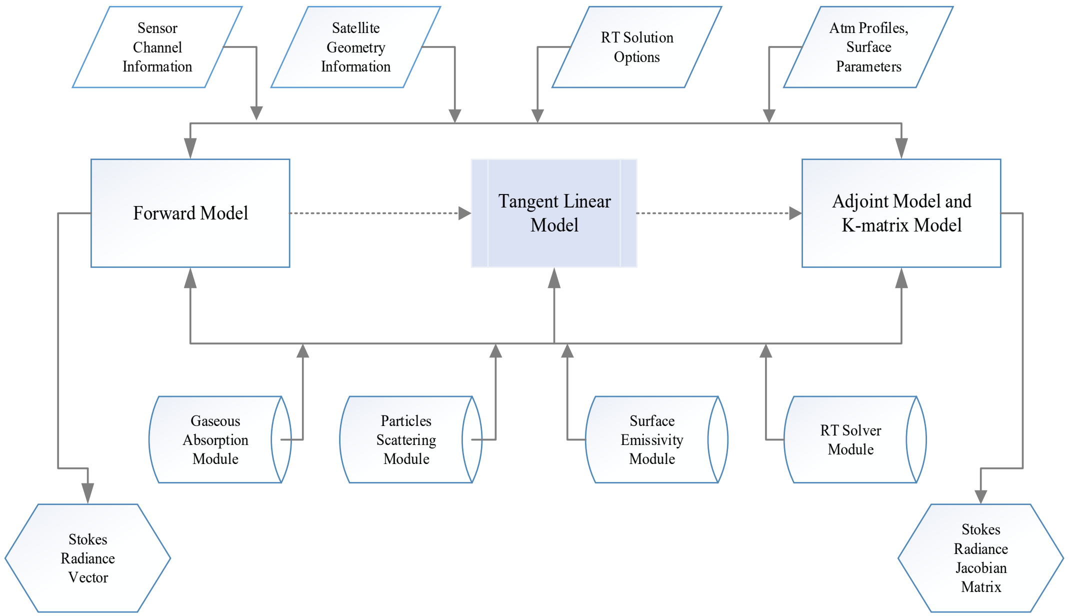


Since 1988, China has launched a series of polar orbiting and geostationary meteorological satellites.

There are eight Fengyun satellites operating in orbit, and many other satellites will be launched in near future.

The **payloads have expanded** from a single optical instrument to a full-spectrum and the observation **parameters have also expanded** from surface and atmosphere to space weather .

Advanced Radiative Transfer Modeling System (ARMS） Software Framework



Weng et al., 2020 **Yang et al., 2020**

Kan et al., 2020 **Shi et al., 2021**

Bi et al., 2020 **Yi et al., 2020**

ARMS is compatible with vector solvers.

In the particle scattering module, the expansion of six elements **scattering phase matrix** need to be considered.

$$\mathbf{P} = \begin{bmatrix} P_{11} & P_{12} & 0 & 0 \\ P_{12} & P_{22} & 0 & 0 \\ 0 & 0 & P_{33} & P_{34} \\ 0 & 0 & -P_{34} & P_{44} \end{bmatrix}$$

In the surface emissivity module, the **reflection matrix** also need to consider the changes of 16 elements with azimuth.

$$\mathbf{R} = \begin{pmatrix} |S_2|^2 & |S_3|^2 & \mathrm{Re}(S_2S_3^*) & -\mathrm{Im}(S_2S_3^*) \\ |S_4|^2 & |S_1|^2 & \mathrm{Re}(S_1S_4^*) & -\mathrm{Im}(S_4S_1^*) \\ 2\,\mathrm{Re}(S_2S_4^*) & 2\,\mathrm{Re}(S_1S_3^*) & \mathrm{Re}(S_1S_2^* + S_3S_4^*) & -\mathrm{Im}(S_2S_1^* - S_3S_4^*) \\ 2\,\mathrm{Im}(S_2S_4^*) & 2\,\mathrm{Im}(S_3S_1^*) & \mathrm{Im}(S_2S_1^* + S_3S_4^*) & \mathrm{Re}(S_1S_2^* - S_3S_4^*) \end{pmatrix}$$

Supporting Fengyun Satellite Payloads and Future Instrument Development is the Main Purpose of ARMS

Fast Atmospheric Transmittance Model for the Four types of Fengyun Satellite payloads：

- ✓ **Microwave** FY-3D MWTS/MWHS/MWRI/CMWS、 FY-4GEOM GMWS： MonoRTM、 Channel spectral response function.
- ✓ **Infrared hyperspectral** FY-3D HIRAS、FY-4A GIIRS： LBLRTM、FFT、 Apodization、FFT^{-1}、ODPS。
- ✓ **Broadband infrared** FY-4A AGRI： LBLRTM、 Channel spectral response function 、ODPS。
- ✓ **Visible** FY-4A v_AGRI： LBLRTM、 Channel spectral response function 、ODAS。

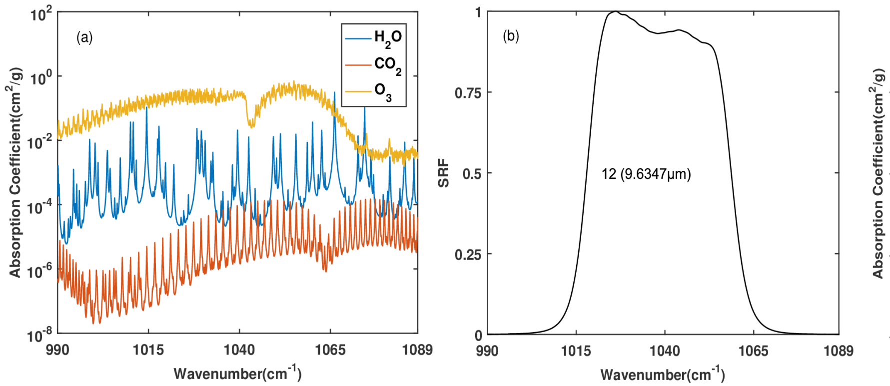
- FY-3A MWTS
- FY-3A MWHS
- FY-3B MWTS
- FY-3B MWHS
- FY-3C MWTS-2
- FY-3C-MWHS-2
- FY-3D MWTS-2
- FY-3D MWHS-2
- FY-3 B/C/D MWRI
- FY-3 B/C VIRR
- FY-3C MERSI
- FY-3C IRAS
- FY-3D MERSI-2
- FY-3D HIRAS
- FY-4A GIIRS
- FY-4A AGRI
- **FY-4M GMIS**
- **FY-3E MWTS**
- **FY-3E MWHS**
- **FY-3E-HIRAS**
- **FY-4B AGRI**
- **FY-4B GIIRS**
- **FY-4B GHI**

- NOAA 15 to 19 AMSU-A
- NOAA 18-19 MHS
- NOAA 18-19 HIRS
- NOAA 15-19 AVHRR
- SNPP/NOAA-20 ATMS
- SNPP/NOAA-20 CrIS
- SNPP/NOAA-20 VIIRS
- METOP-A to C IASI
- METOP-A to C IASI
- METOP-A to C AMSU-A
- METOP-A to C AVHRR
- JAXA AMSR2
- NASA GMI
- EOS Aqua AIRS
- EOS Terra/Aqua MODIS

ARMS supported payloads

Kan et al., 2020

Alternate Mapping Correlated k-Distribution (AMCKD) for Broadband Infrared



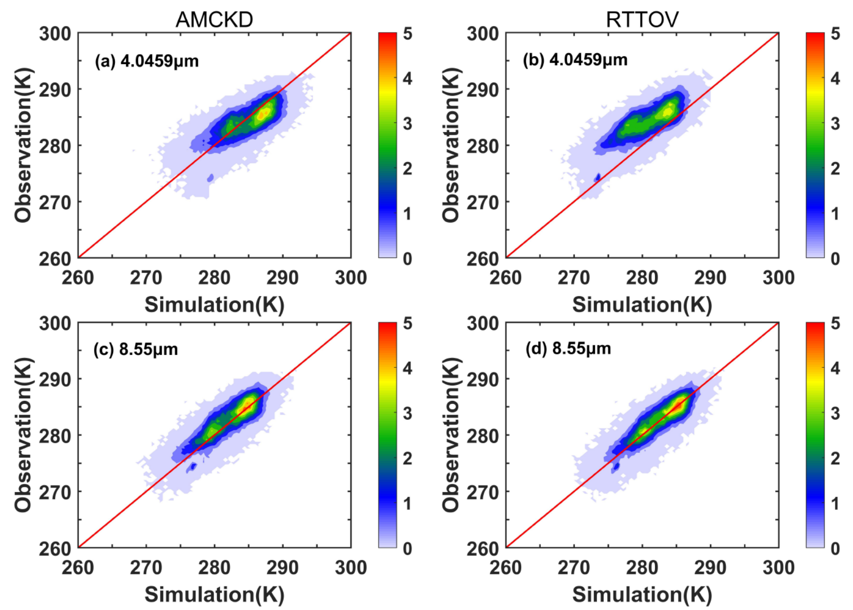
Treatment of gas absorption in Himawari AHI channel 12 using AMCKD

(a) Variation of gas absorption coefficient with wavenumber;

(b) Spectral response function of channel 12;

(c) Cumulative probability function of absorption coefficient.

Compared for MERSI Channels under clear sky



AMCKD improves the efficiency of computation by reducing the number of simulations of radiative transfer in satellite channels.

Zhang et al, 2019

ARMS Radiative Transfer Solvers

- There are four solvers in ARMS: polarimetric two-stream approximation (**P2S**), vector doubling adding (**VDA**), hybrid radiative transfer scheme (**HRTS**) and advanced doubling adding (**ADA**).
- Of these solvers, P2S and HRTS are recommended as the preferred solvers to simulate the Stokes vector and scalar intensity, respectively.

Extinction, Source, Multiple scattering

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

$$\mathbf{I} = [I, Q, U, V]$$

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

$$\cos i_1 = \frac{-\mu + \mu' \cos\Theta}{\pm(1-\cos^2\Theta)^{1/2}(1-\mu'^2)^{1/2}}$$

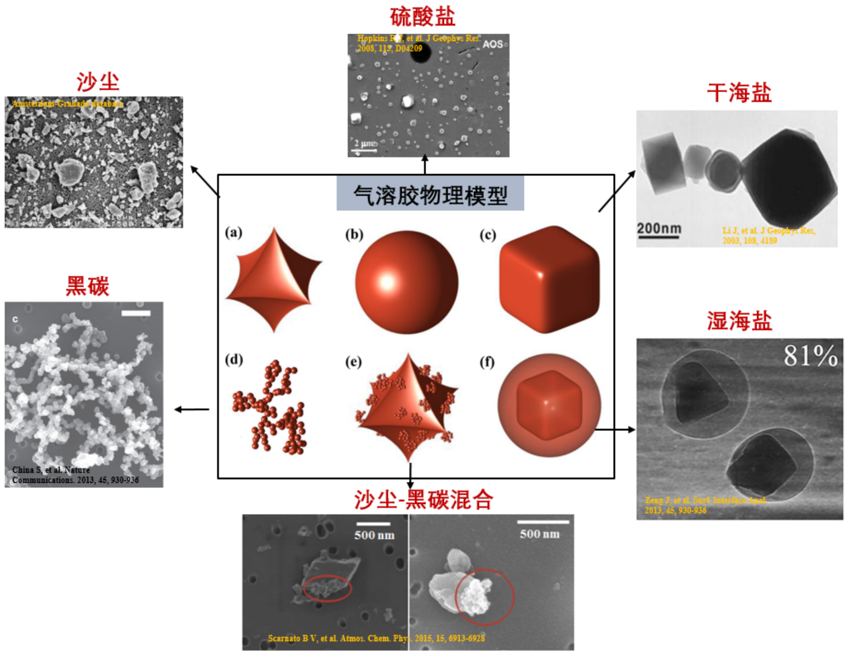
$$\cos i_2 = \frac{-\mu' + \mu \cos\Theta}{\pm(1-\cos^2\Theta)^{1/2}(1-\mu^2)^{1/2}}$$

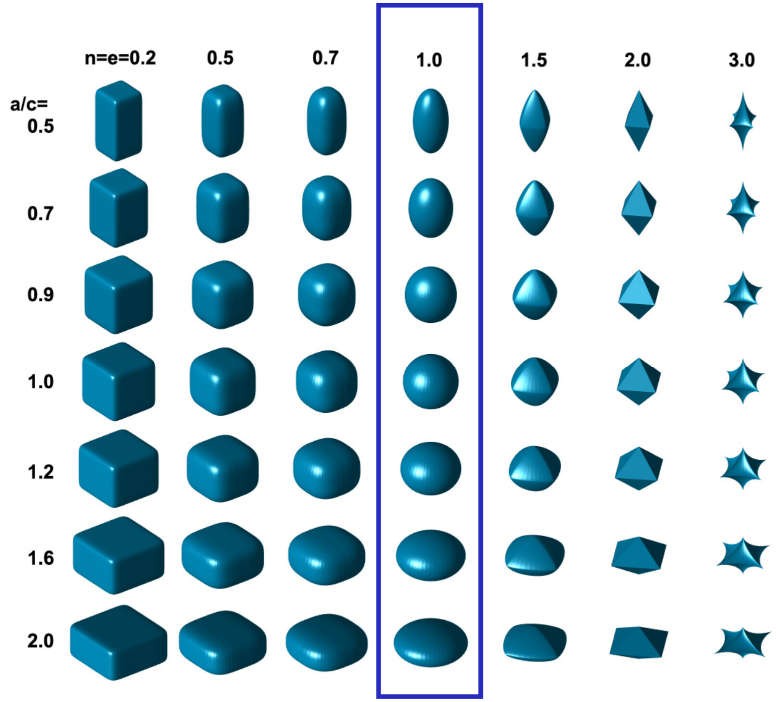
Phase matrix

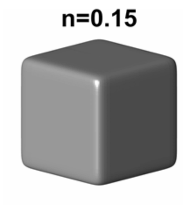
$$\mathbf{M}(\tau,\mu,\phi;\mu',\phi') = \begin{bmatrix} P_{11} & P_{12}\cos 2i_1 & -P_{12}\sin 2i_1 & 0 \\ P_{12}\cos 2i_2 & P_{11}\cos 2i_1 \cos 2i_2 - P_{33}\sin i_1 \sin 2i_2 & P_{11}\sin 2i_1 \cos 2i_2 - P_{33}\cos i_1 \sin 2i_2 & -P_{34}\sin 2i_2 \\ P_{12}\sin 2i_1 & P_{11}\cos 2i_1 \sin 2i_2 + P_{33}\sin i_1 \cos 2i_2 & -P_{11}\sin 2i_1 \sin 2i_2 + P_{33}\cos i_1 \cos 2i_2 & P_{34}\cos 2i_2 \\ 0 & -P_{34}\sin 2i_1 & -P_{34}\cos 2i_2 & P_{33} \end{bmatrix}$$

$$\mathbf{P} = \begin{pmatrix} P_{11} & P_{12} & P_{13} & P_{14} \\ P_{21} & P_{22} & P_{23} & P_{24} \\ P_{31} & P_{32} & P_{33} & P_{34} \\ P_{41} & P_{42} & P_{43} & P_{44} \end{pmatrix}$$

Non-spherical Aerosol Particle Scattering Scheme in ARMS







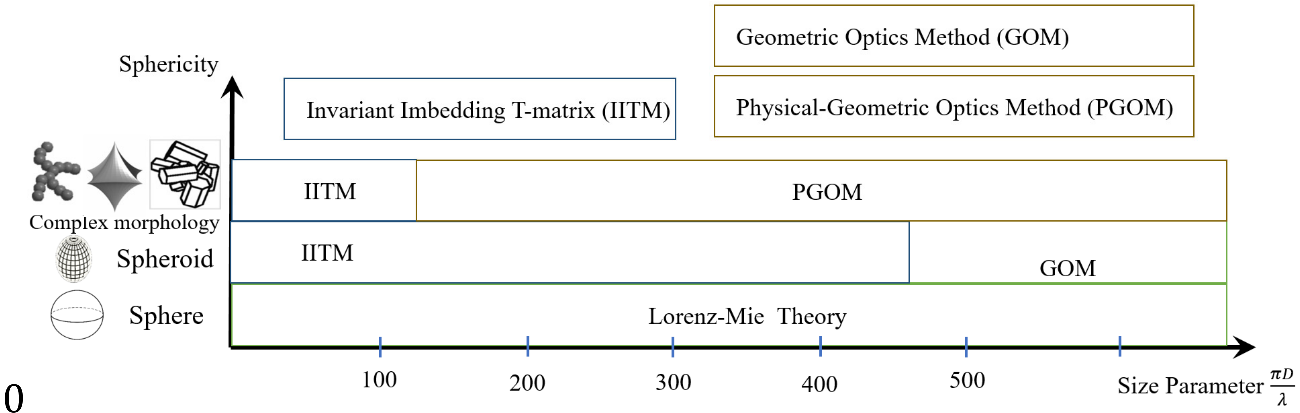
a/c, Indicates the ratio of the horizontal and vertical axis of the particle

Roundness n, Reflects the unevenness of the particle surface

Advantage: Compared with traditional spherical particles, super ellipsoid has one more degree of freedom, which is convenient for characterizing various complicated particle shapes in the atmosphere.

Bi et al., 2018

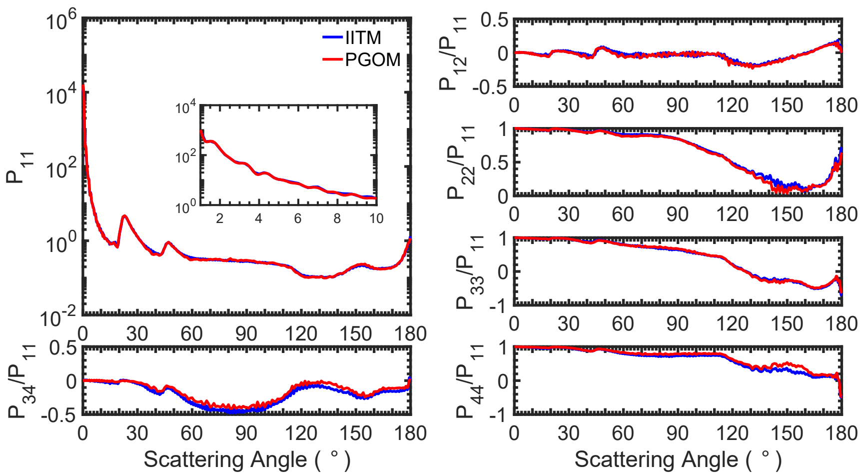
Non-spherical Particle Scattering Using Invariant Imbedding T-Matrix (IITM)



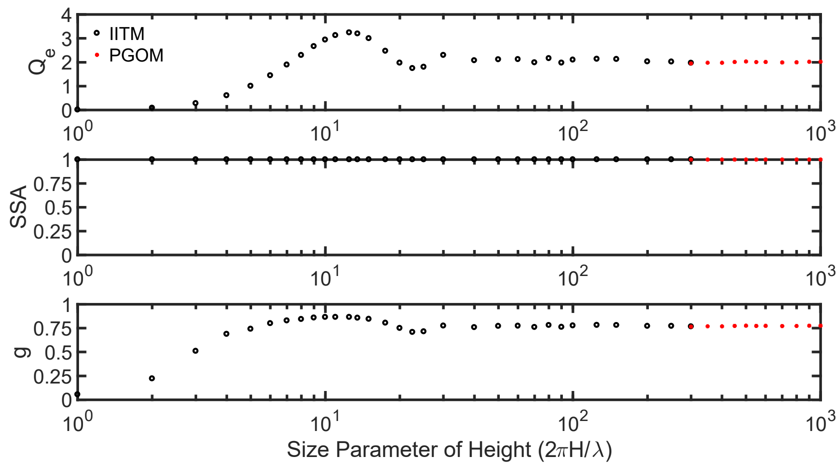
Spherical particle: Mie

Non-spherical particle: IITM

$$\frac{2\pi R}{\lambda} = 300$$



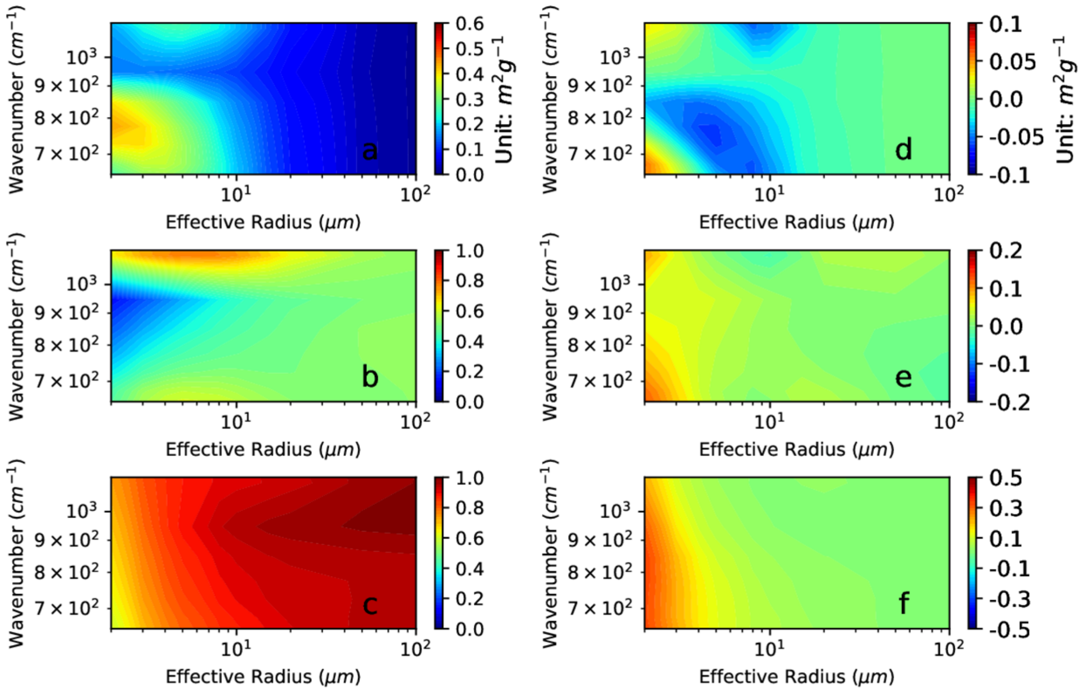
IITM method has good stability



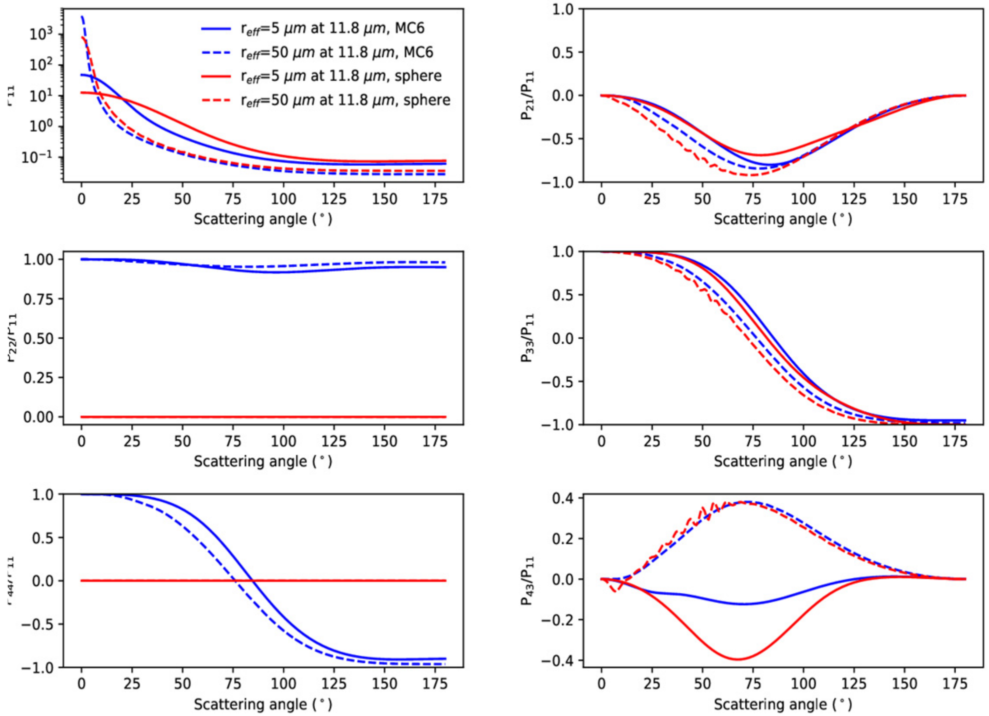
IITM realizes the transition from numerically accurate solution to approximate solution

Bi et al., 2014
Sun et al., 2019

Non-spherical Cloud Particle Scattering Scheme in ARMS（IITM）



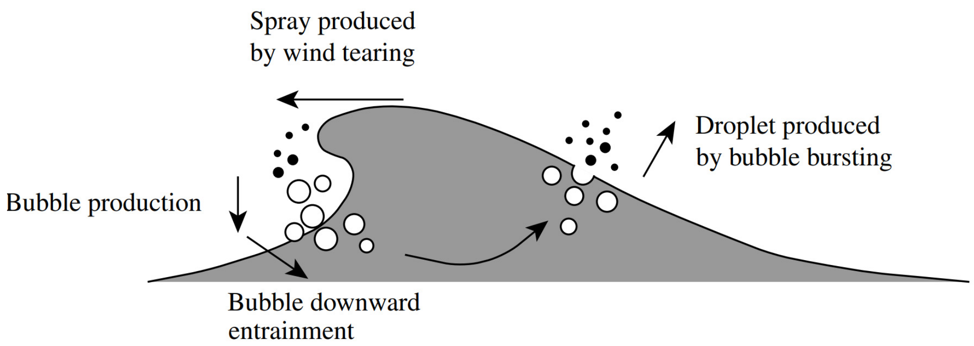
Comparison of bulk optical properties of ice cloud between updated MC6 parameterization and the one with spherical ice cloud assumption for **HIRAS** spectral range of 650–1135 cm $^{-1}$
(a) mass extinction coefficient, (b) single-scattering albedo, (c) asymmetry factor, and (d–f) the corresponding spherical version minus updated version differences of (a–c).



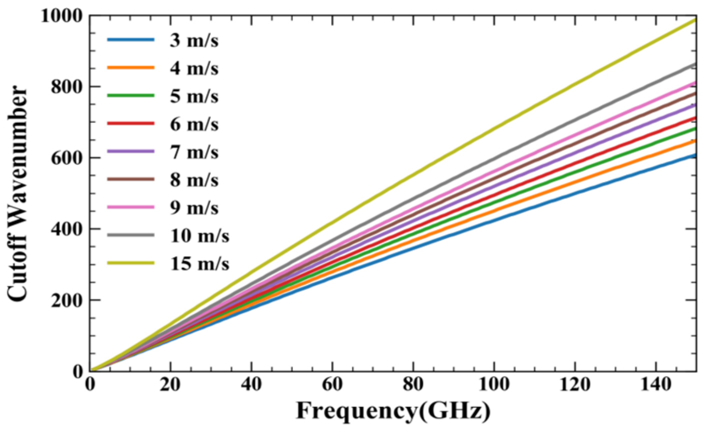
Comparison of scattering phase matrix of **ice cloud** between **MC6** and **spherical particle** assumption with effective radii of 5 and 50 μm at the wavelength of 11.8 μm.

Yi et al., 2020

Microwave Ocean Surface BRDF Matrix



The large-scale roughness is dependent on the gravity waves and whereas the small irregularities is affected by capillary waves.



Cutoff wavenumber varies with frequency and wind speed

Each element has **coherent and incoherent** components. The reflection matrix of the two-scale model can be decomposed into

$$\mathbf{S}=\begin{pmatrix} S_2 & S_3 \\ S_4 & S_1 \end{pmatrix}=\mathbf{S}_{co}+\mathbf{S}_{in}=\begin{pmatrix} R_{vv}^{(0)}+R_{vv}^{(2)}+R_{vv}^{(1)} & R_{vh}^{(2)}+R_{vh}^{(1)} \\ R_{hv}^{(2)}+R_{hv}^{(1)} & R_{hh}^{(0)}+R_{hh}^{(2)}+R_{hh}^{(1)} \end{pmatrix}$$

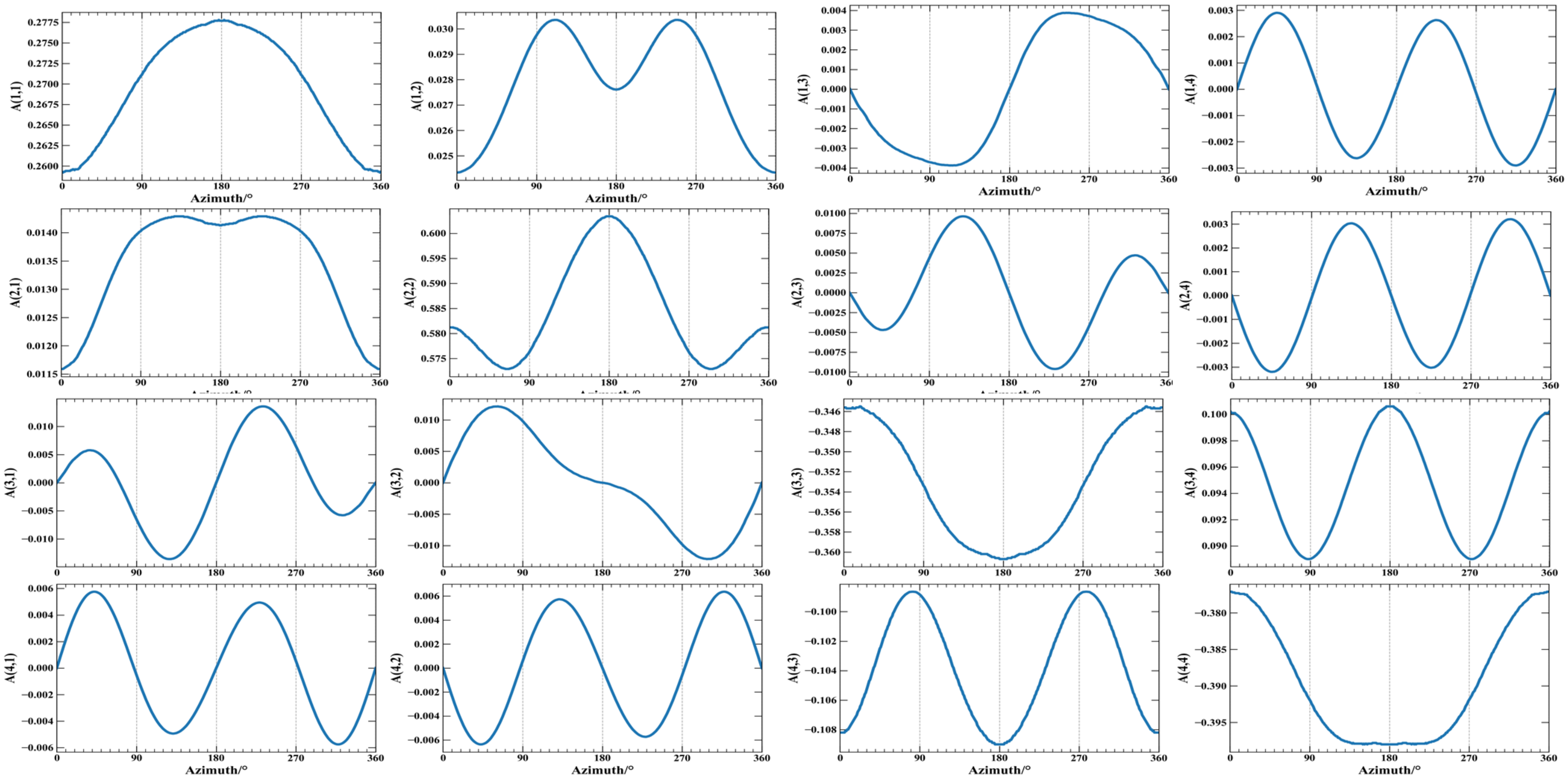
Reflection matrix elements represented by stokes vector

(I_v, I_h, U, V)

$$\mathbf{R}=\begin{pmatrix} |S_2|^2 & |S_3|^2 & \mathrm{Re}(S_2S_3^*) & -\mathrm{Im}(S_2S_3^*) \\ |S_4|^2 & |S_1|^2 & \mathrm{Re}(S_1S_4^*) & -\mathrm{Im}(S_4S_1^*) \\ 2\,\mathrm{Re}(S_2S_4^*) & 2\,\mathrm{Re}(S_1S_3^*) & \mathrm{Re}(S_1S_2^*+S_3S_4^*) & -\mathrm{Im}(S_2S_1^*-S_3S_4^*) \\ 2\,\mathrm{Im}(S_2S_4^*) & 2\,\mathrm{Im}(S_3S_1^*) & \mathrm{Im}(S_2S_1^*+S_3S_4^*) & \mathrm{Re}(S_1S_2^*-S_3S_4^*) \end{pmatrix}$$

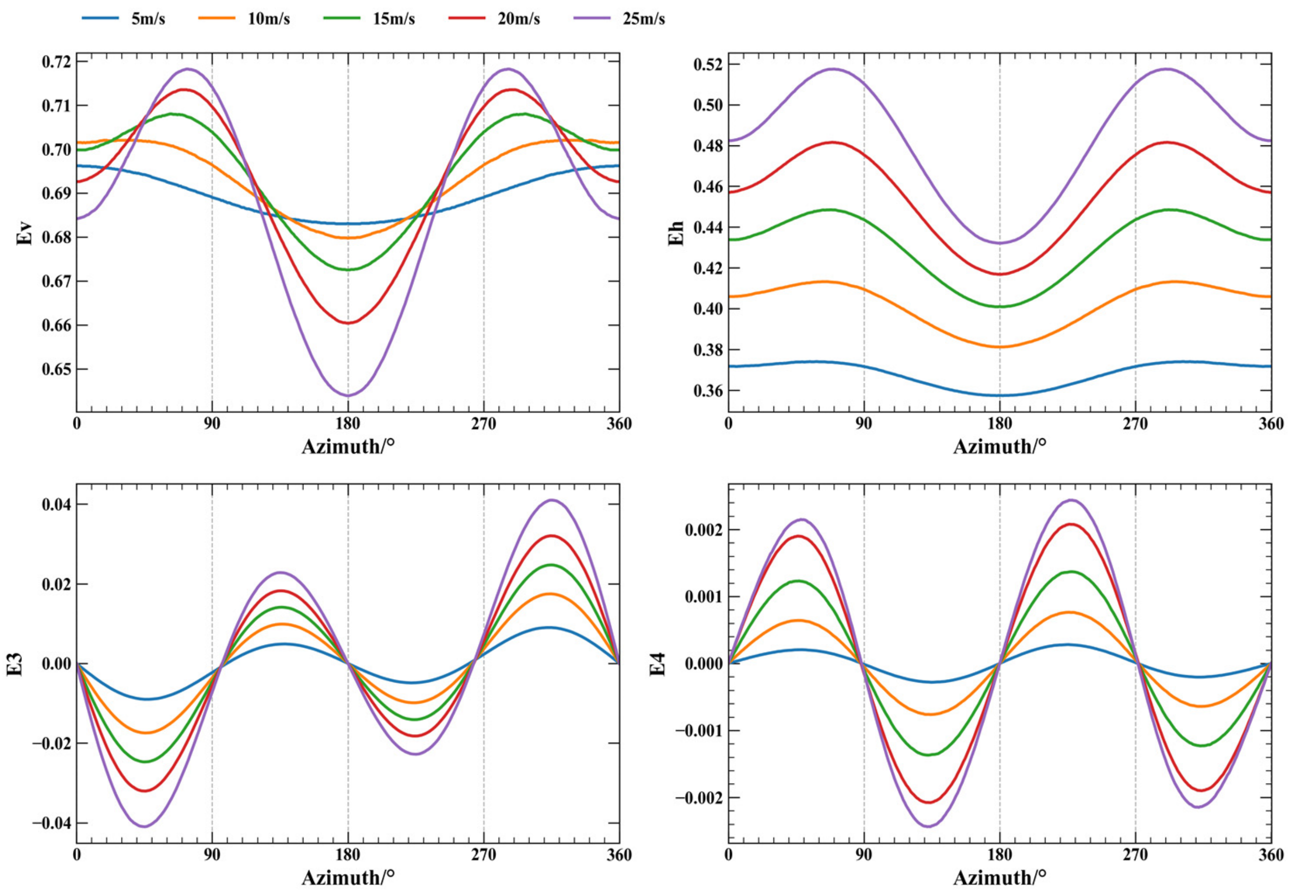
01 **Development Status of ARMS**

Variation of Reflectance Matrix Elements with Azimuth



Viewing angel =55° Frequency= 37GHz SST= 285K Salinity=35‰

Variation of Each Component in Surface Emissivity with Azimuth



$$\bar{e}(\theta,\phi) = \overline{I}_i - \int \left(\overline{\overline{R}}^c + \overline{\overline{R}}^i\right) \cdot \overline{I}_i d\Omega_i$$

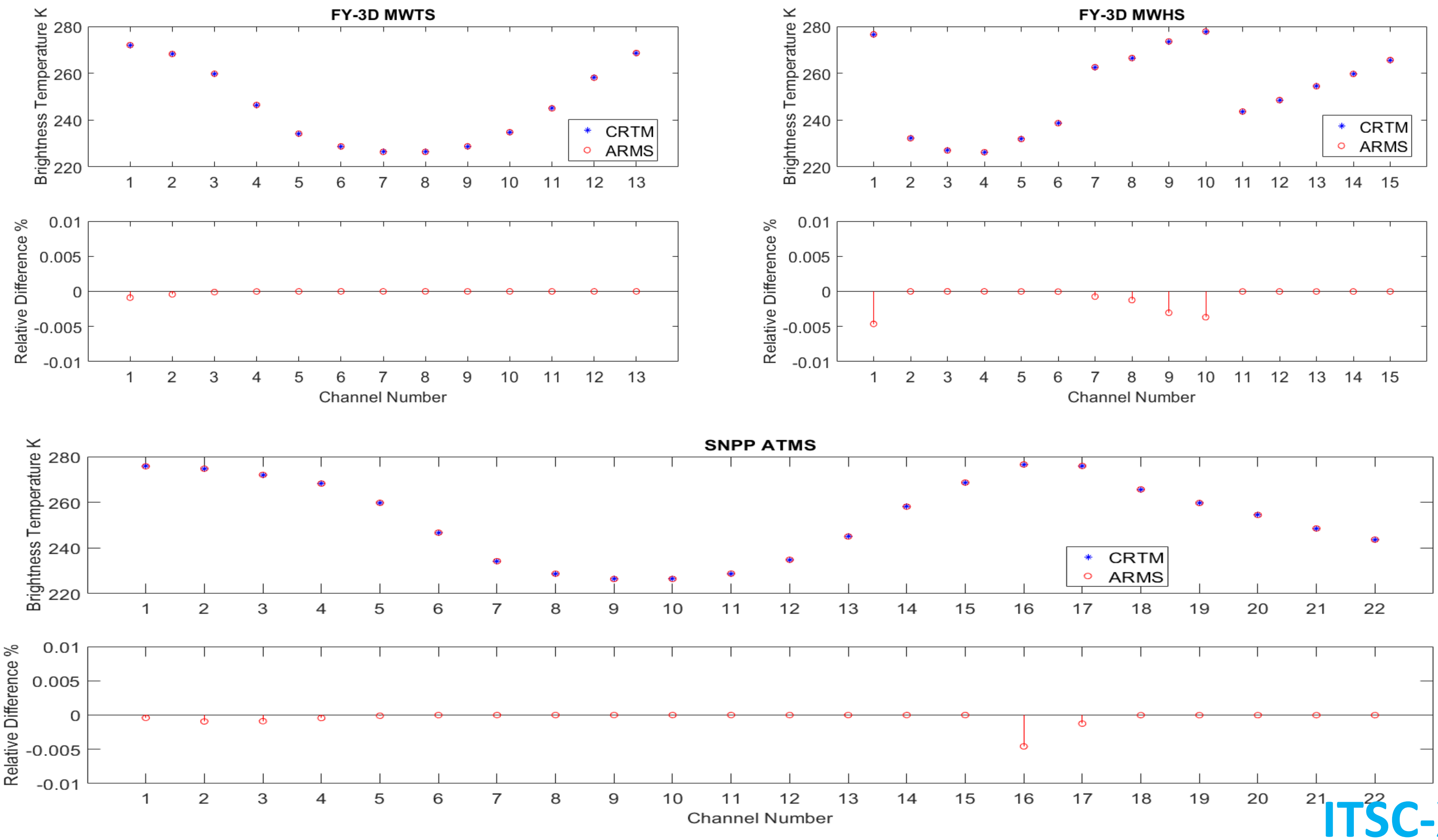
$$= \overline{I}_i - \int_0^{\pi/2} \sin\theta_i d\theta_i \int_0^{2\pi} d\phi_i \left(\overline{\overline{R}}^c + \overline{\overline{R}}^i\right) \cdot \overline{I}_i.$$

- Viewing angel =55°
- Frequency= 37GHz
- SST= 285K
- Salinity=35‰

01

Development Status of ARMS

High Precision Simulation of Microwave Instruments Using ARMS



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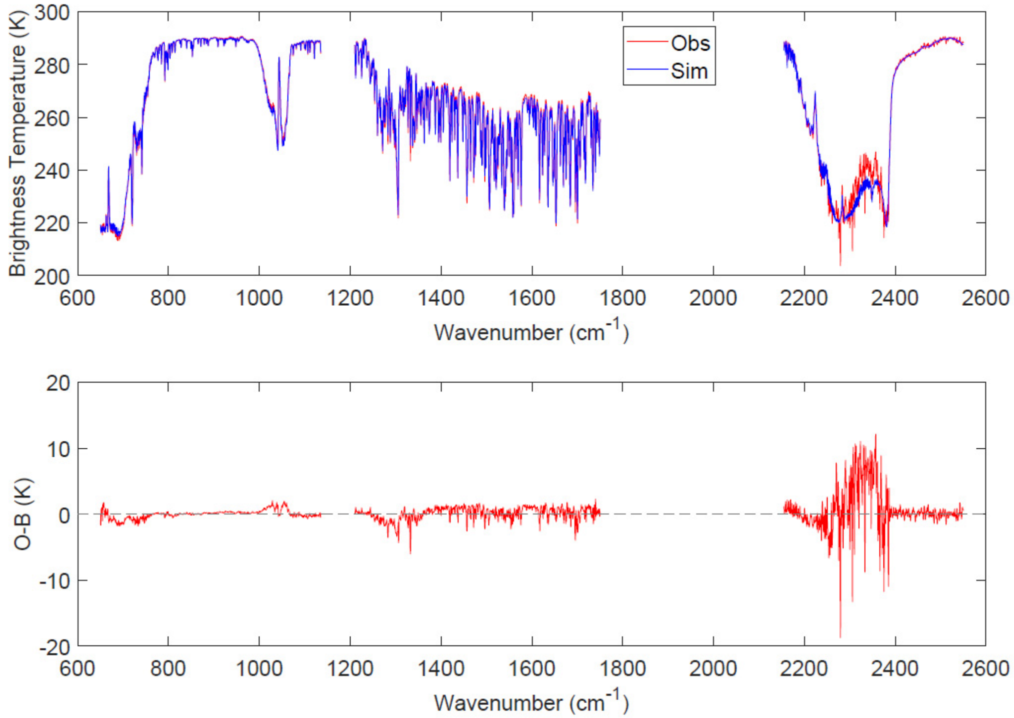
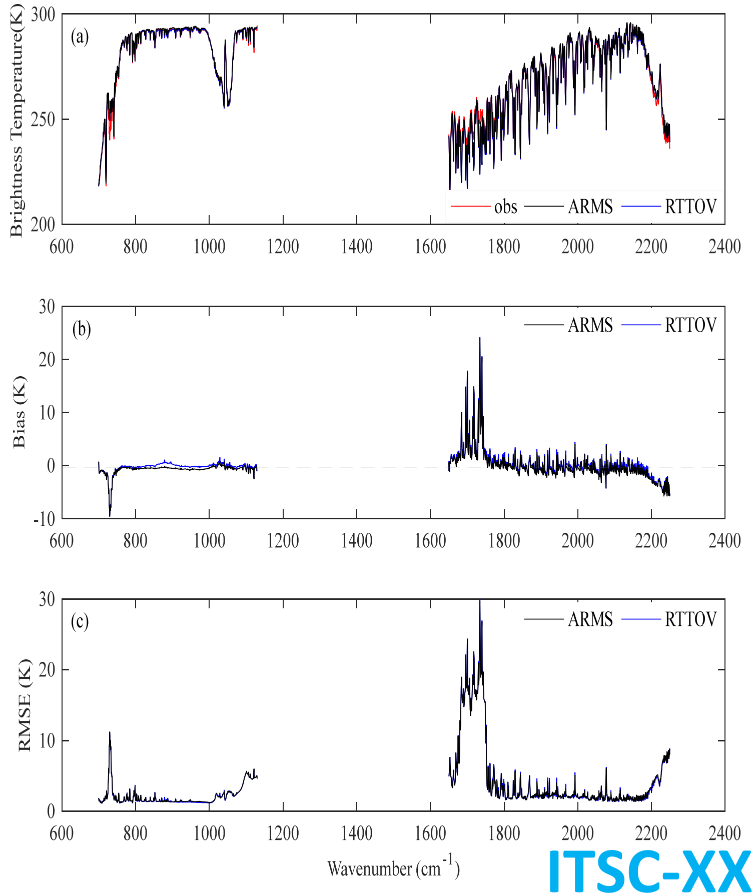
01 **Development Status of ARMS**

Simulation of Infrared Hyperspectral Instruments Using ARMS

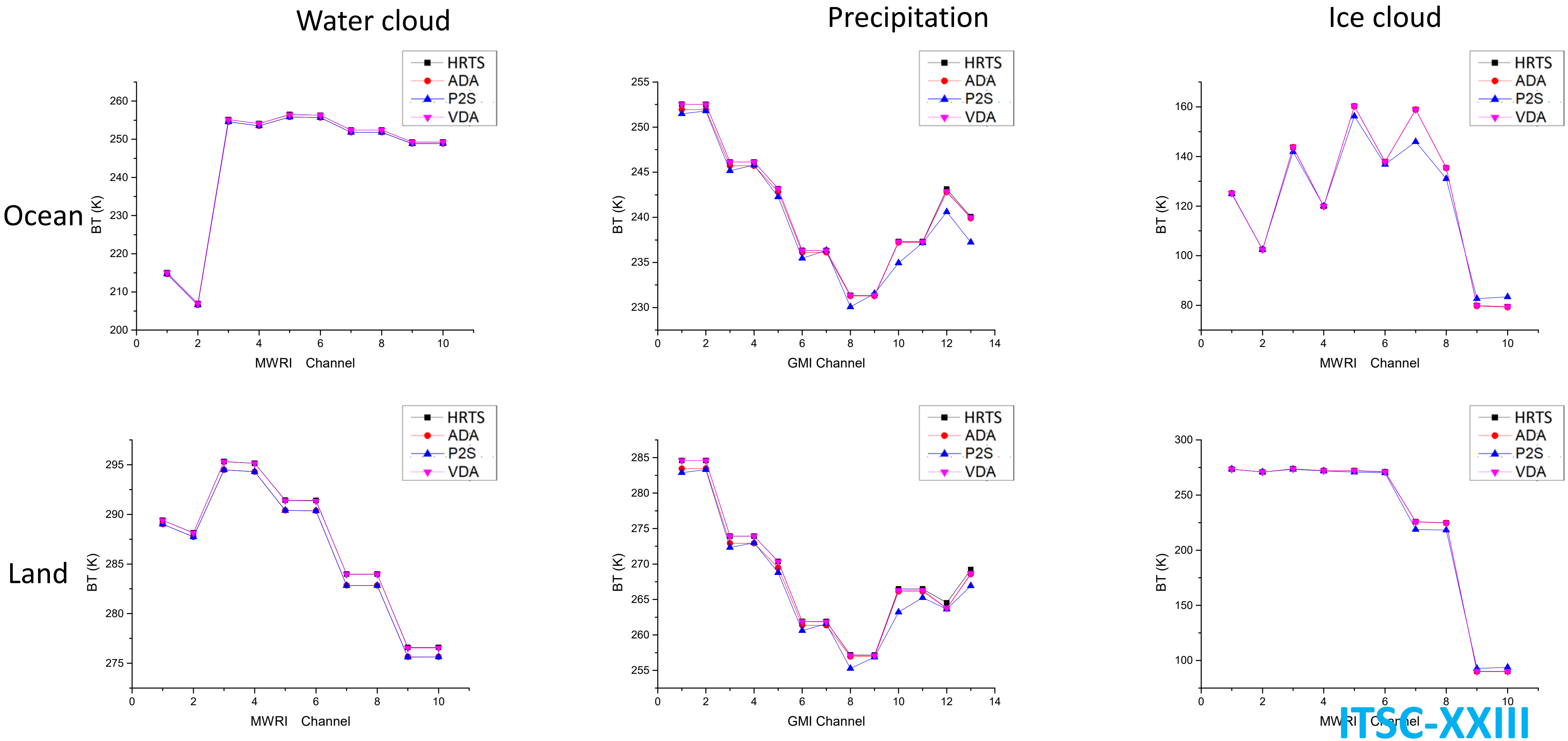
FY-3D HIRAS



FY-4A GIIRS



Comparison of Four Solvers in ARMS



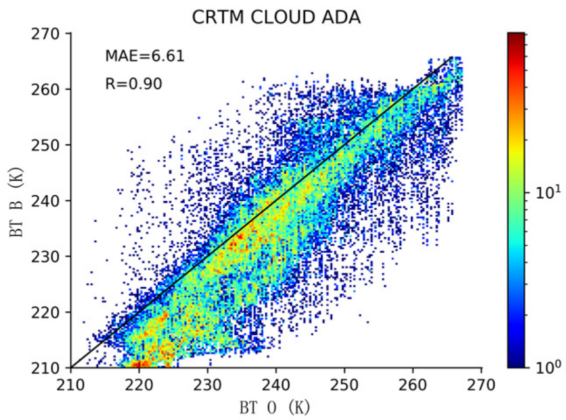
02 Typical Applications of ARMS

ARMS O-B Test

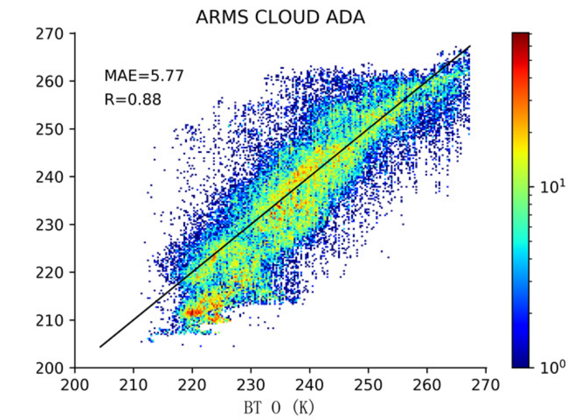
Sensor: FY-3D MWTS
Atmosphere profile: ERA5 hourly 0.25°
Hydrometeors profile: GPM GPROF
Distance threshold: 30 km
Time threshold: ±15min
Date: 2018-06-02/2018-07-02/
2018-08-02/2018-09-02
12401 profiles were collocated over ocean

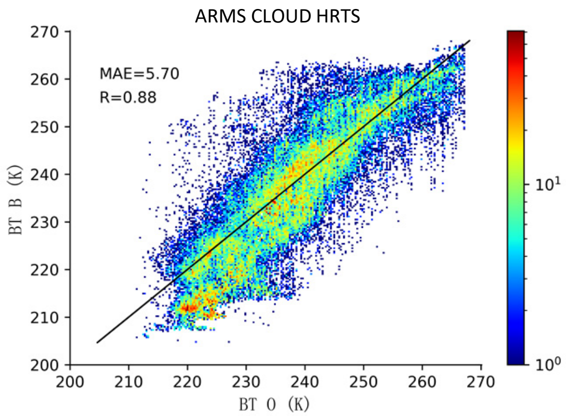
Model	Solver	Test name	MAE
ARMS	ADA	ARMS CLOUD ADA	5.77
	HRTS	ARMS CLOUD HRTS	5.70
	P2S	ARMS CLOUD VTWO	6.13
CRTM	ADA	CRTM CLOUD ADA	6.61

CRTM ADA

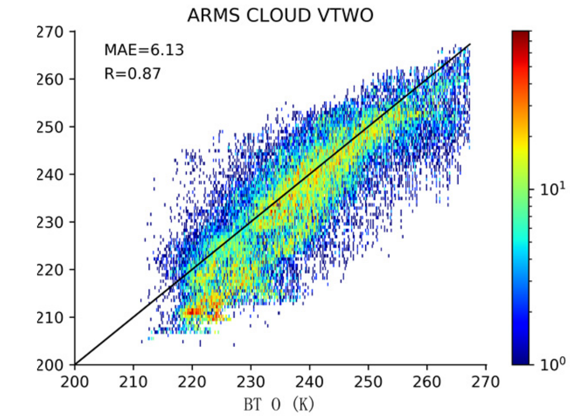


ARMS ADA



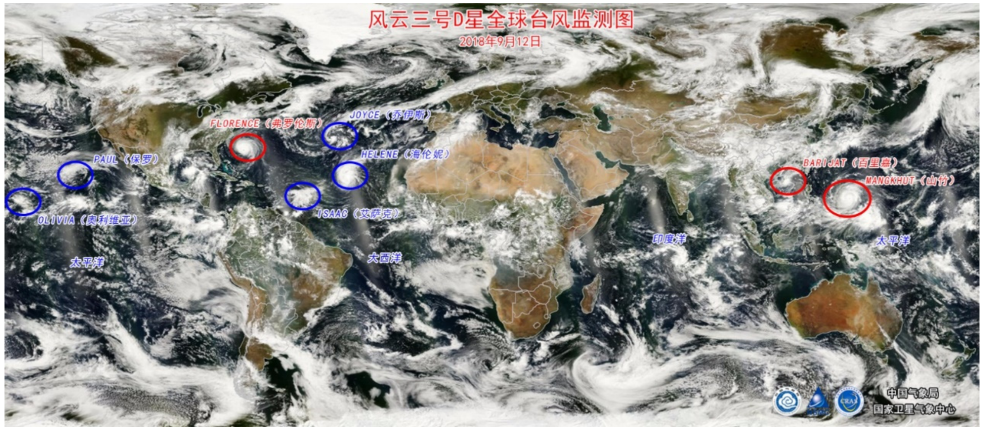


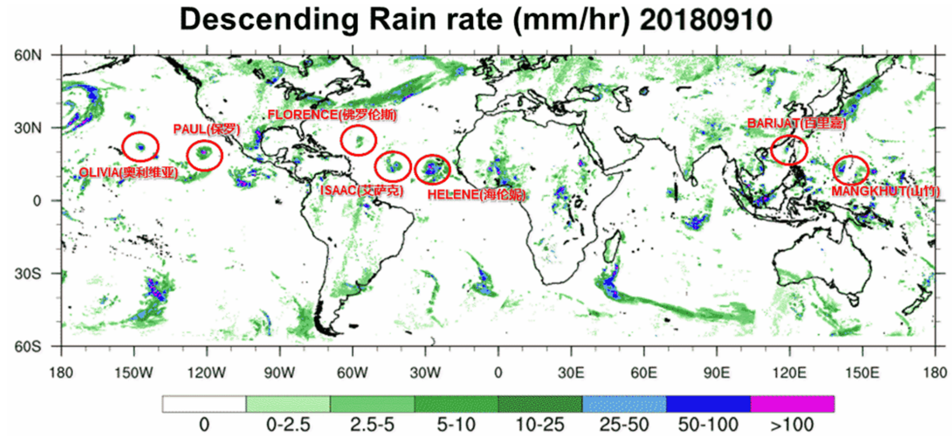
ARMS HRTS

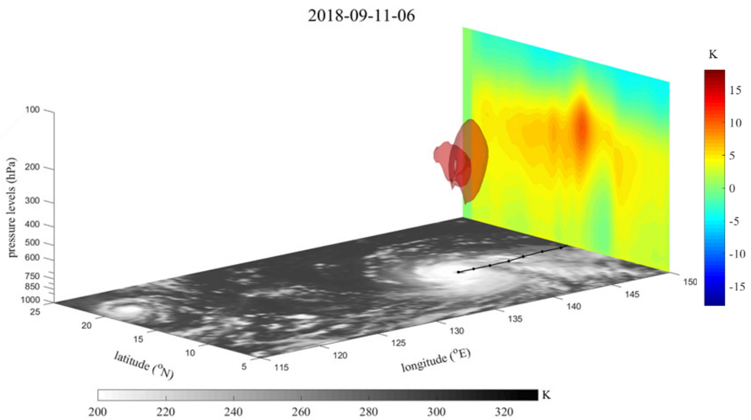


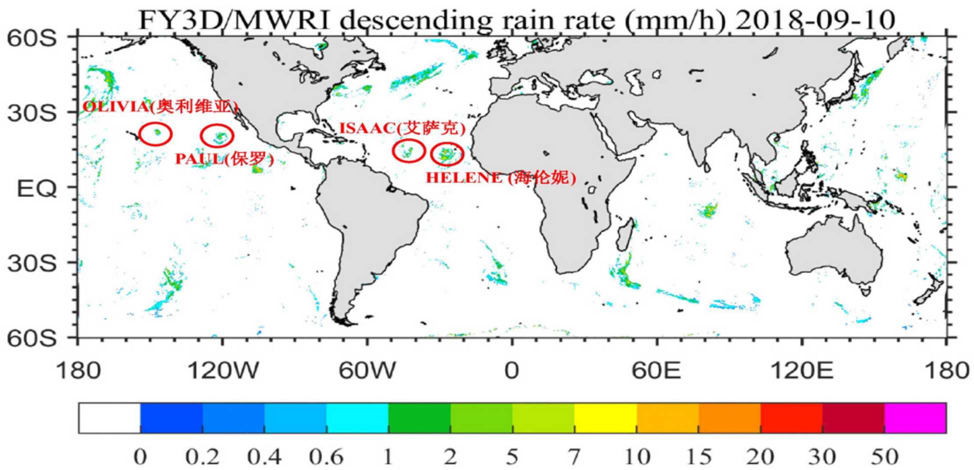
ARMS P2S

ARMS Used for Typhoon Warm Core and Precipitation Rate Inversion



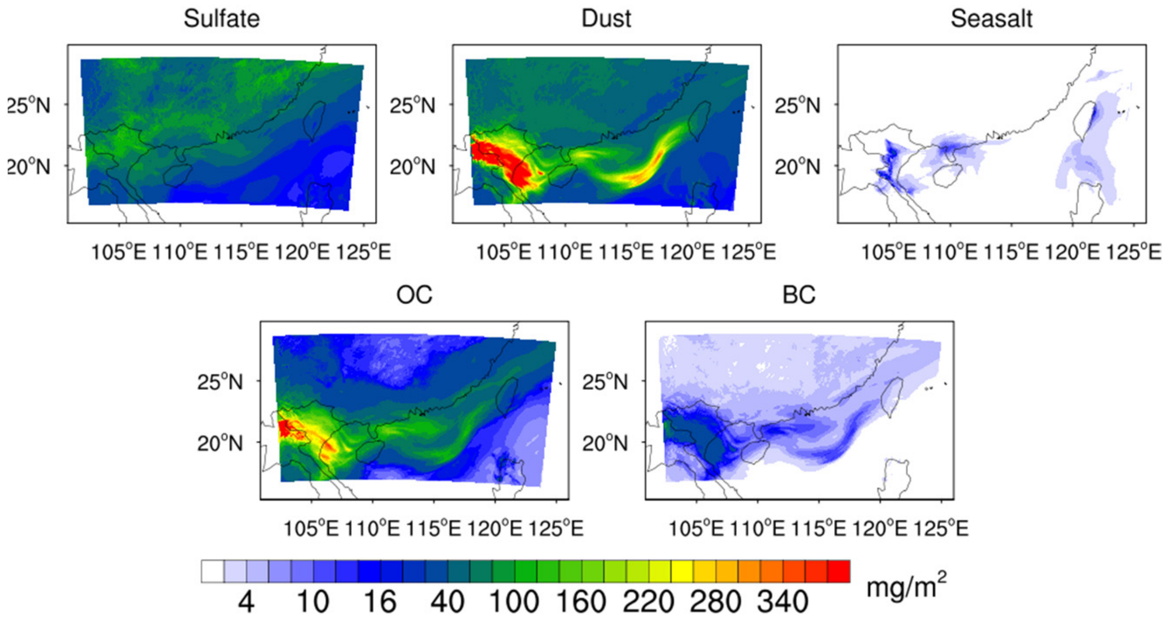




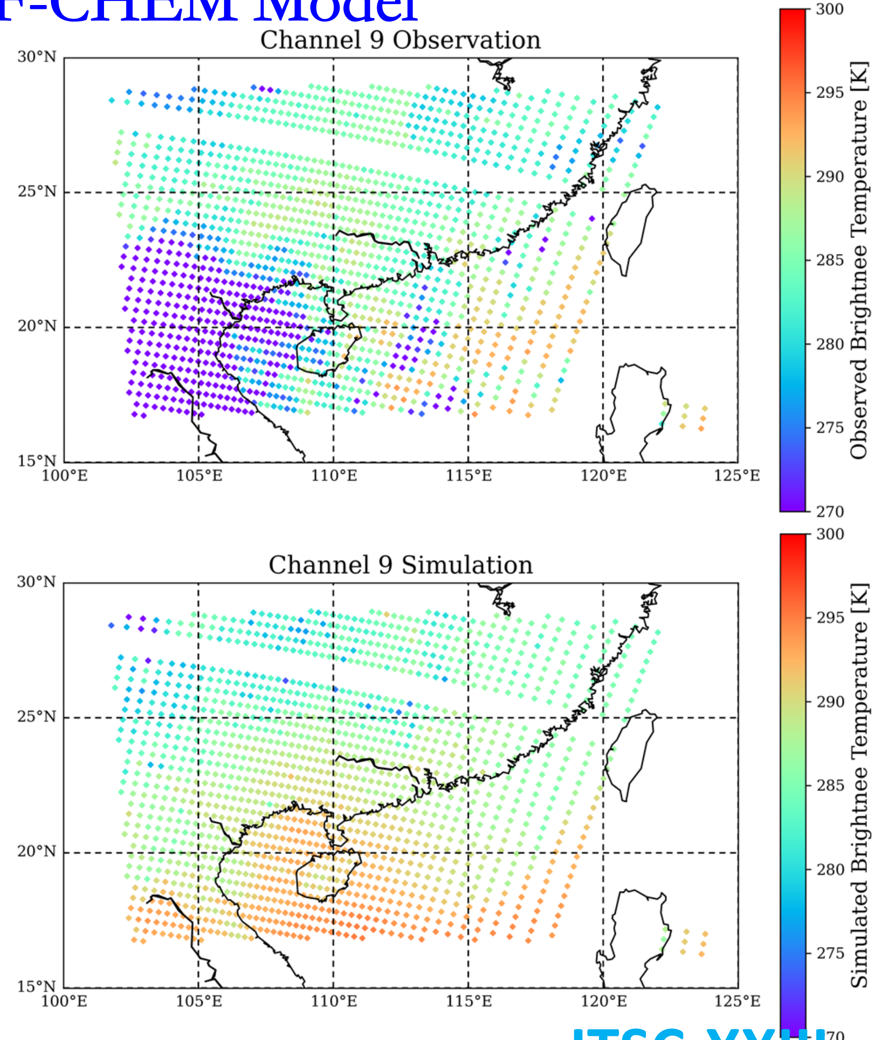


Will be introduced in detail in Dr. Hu's report tomorrow

Diagnostic Analysis of WRF-CHEM Model

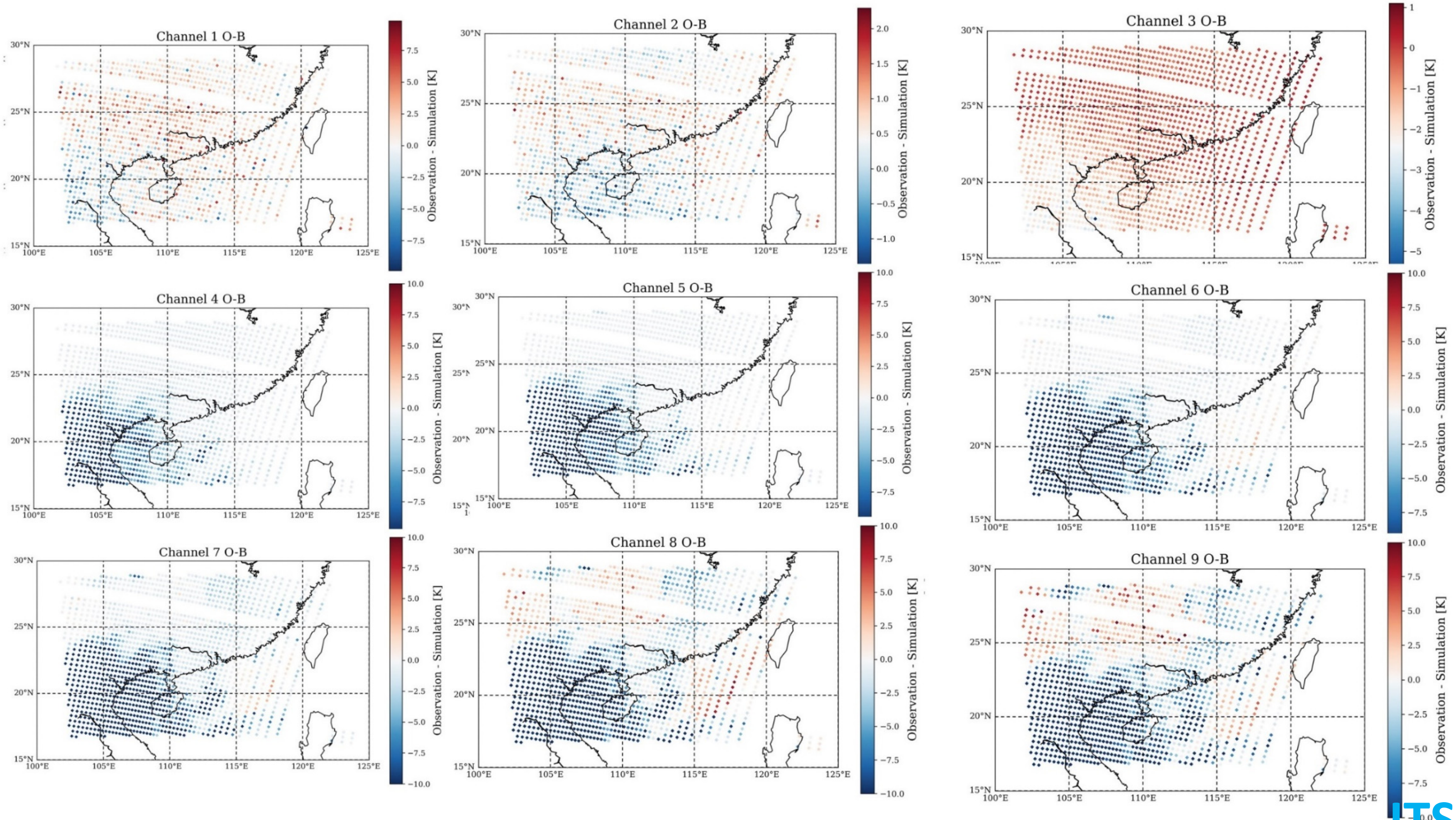


WRF-CHEM output

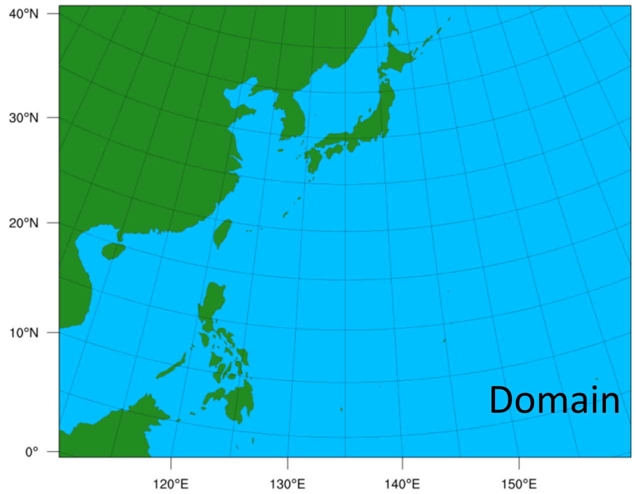


FY-3B IRAS

Diagnostic Analysis of WRF-CHEM Model



Assimilating of FY-3D Microwave Observations in the East China Regional Model

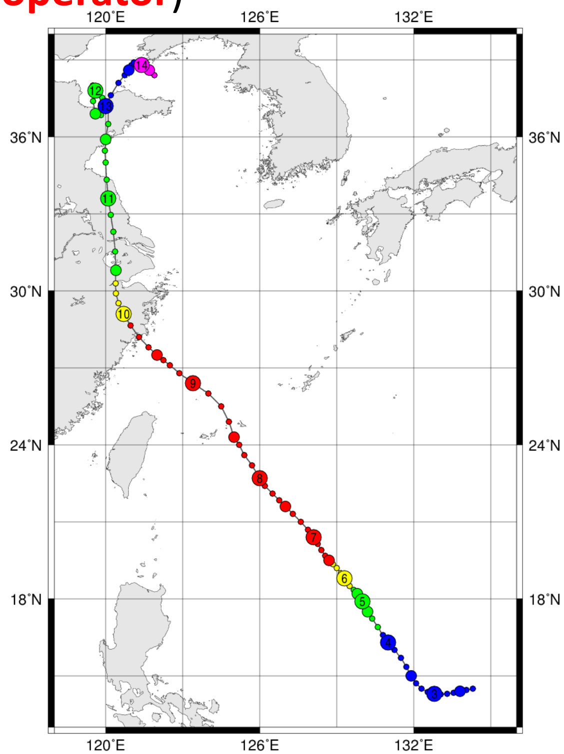


Forecast model： WRF V3.8.1

Data assimilation： GSI V3.7 (**with ARMS as an operator**)

Horizontal resolution： 9km

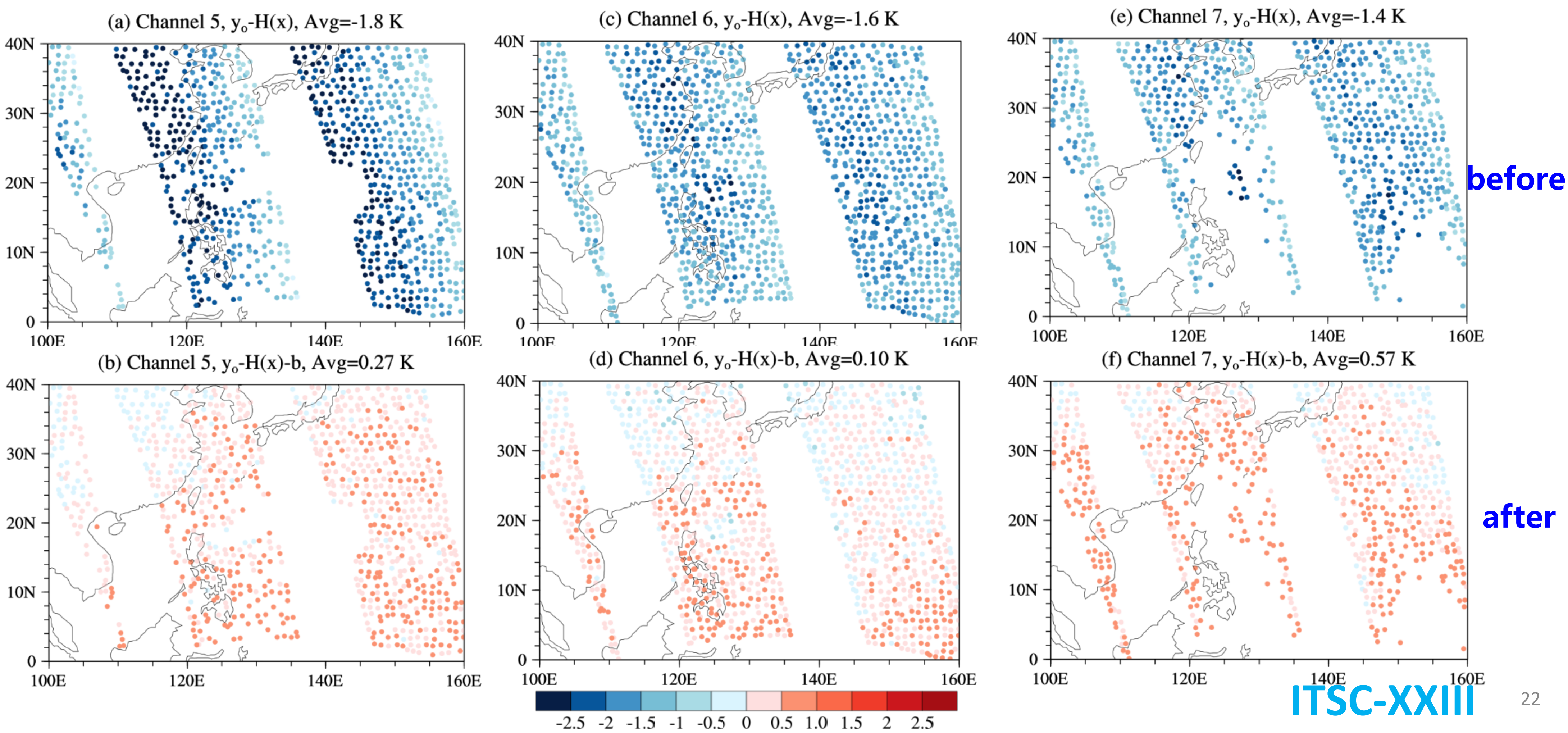
Initial boundary conditions: GFS 6h forecast



Test name	Description
CTRL	Control test， no assimilation of satellite observations
EXP_AD	Same as CTRL， with AMSUA(NOAA15,18,19,MetOp-A/B)
EXP_AMD	Same as CTRL， with AMSUA+ MWHS (FY-3D)

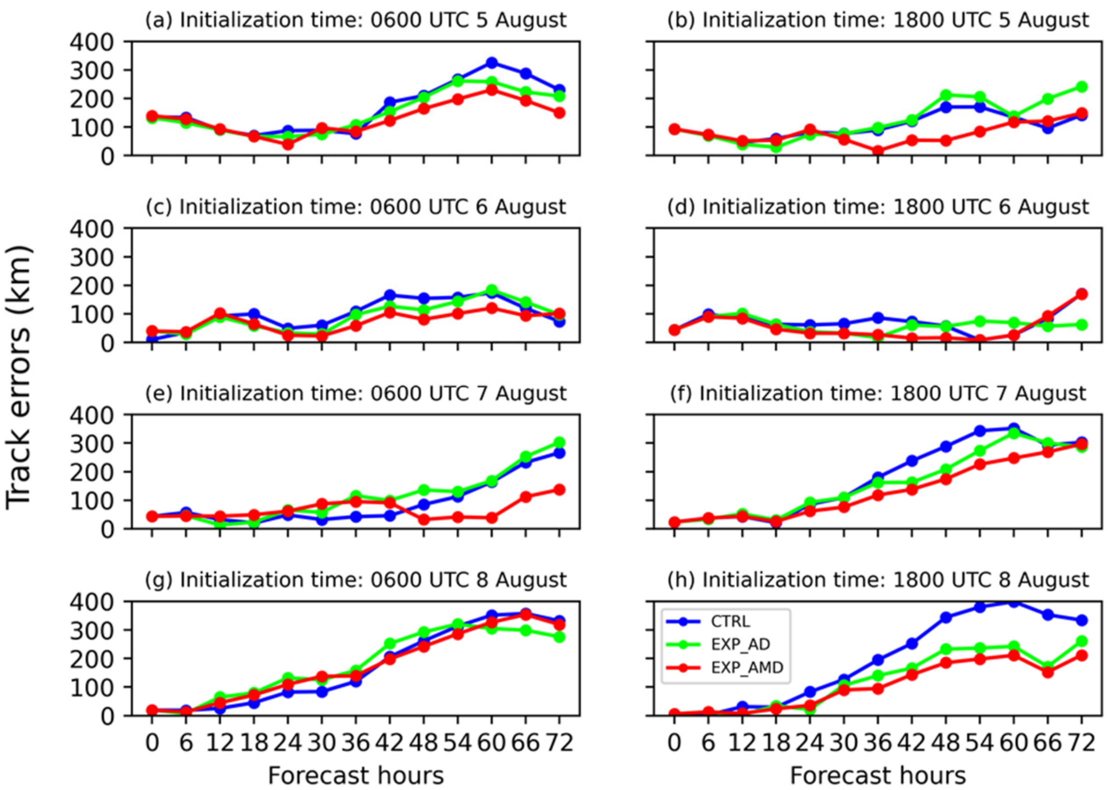
O-B Compared Before and After Bias Correction

Ini: 0600 UTC August 7, 2019

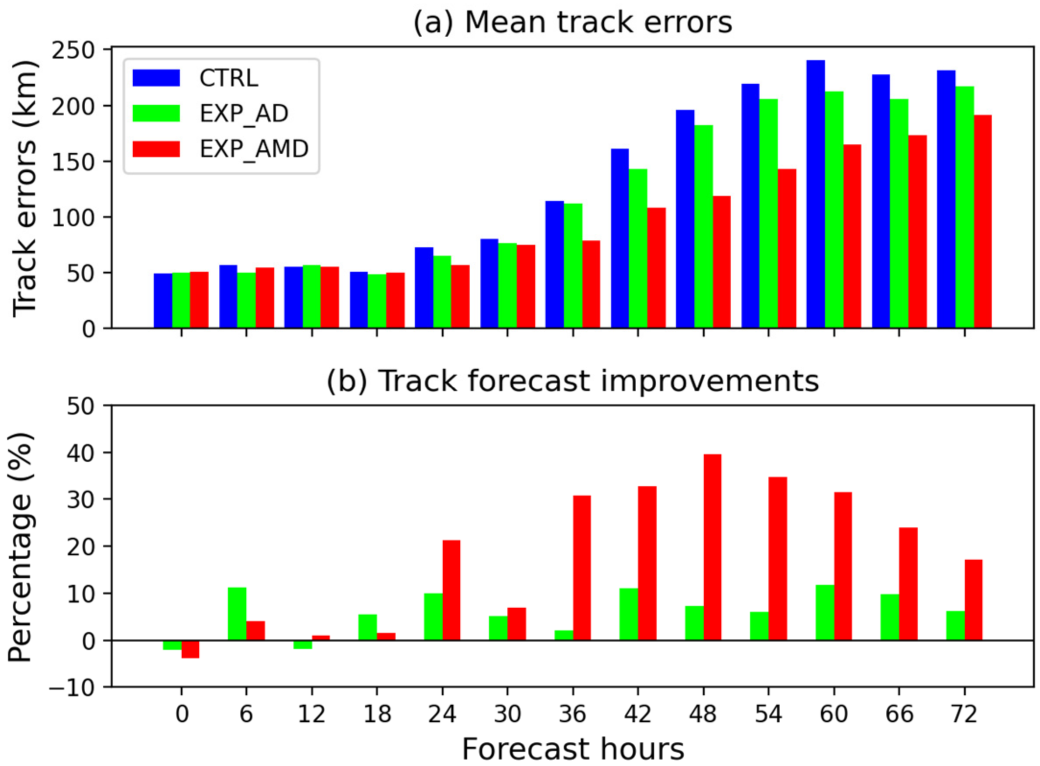


02 Typical Applications of ARMS

Compared of Assimilating Different Satellite Data for Typhoon Track Forecast



Typhoon track errors at different starting times



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03

Summary and Future Plan

ARMS

- An interface is built for ARMS with CMA NWP systems (e.g. 1dvar, GRAPES-4dvar) with a focus on FengYun satellite data assimilation.

- A **consistent particle scattering database** across the entire spectrum will be established based on the super ellipsoid model and invariant imbedding T-matrix (IITM) method.

- Surface **BRDF matrix** will be coupled in ARMS, especially in the microwave frequencies.

- Two new **vector solvers**: vector hybrid radiative transfer scheme(HRTS) and vector discrete ordinate radiative transfer (VDISORT) are being developed in ARMS. These will be the preferred vector solvers in the next version of ARMS.

Thanks for Your Attention!