Community Radiative Transfer Model (CRTM): Current model and development status

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Community Contributions

- Community Research: Radiative transfer science
  - UWisc – Successive Order of Iteration
  - University of Colorado –DOTLRT
  - UCLA – Delta 4 stream vector radiative transfer model
  - Princeton Univ – snow emissivity model improvement
  - NESDIS – Advanced doubling and adding scheme, surface emissivity models, LUT for aerosols, clouds, precip
  - AER – Optimal Spectral Sampling (OSS) Method
  - UMBC – SARTA
- Core team (ORA/EMC): Smooth transition from research to operation
  - Maintenance of CRTM
  - CRTM interface
  - Benchmark tests for model selection
  - Integration of new science into CRTM

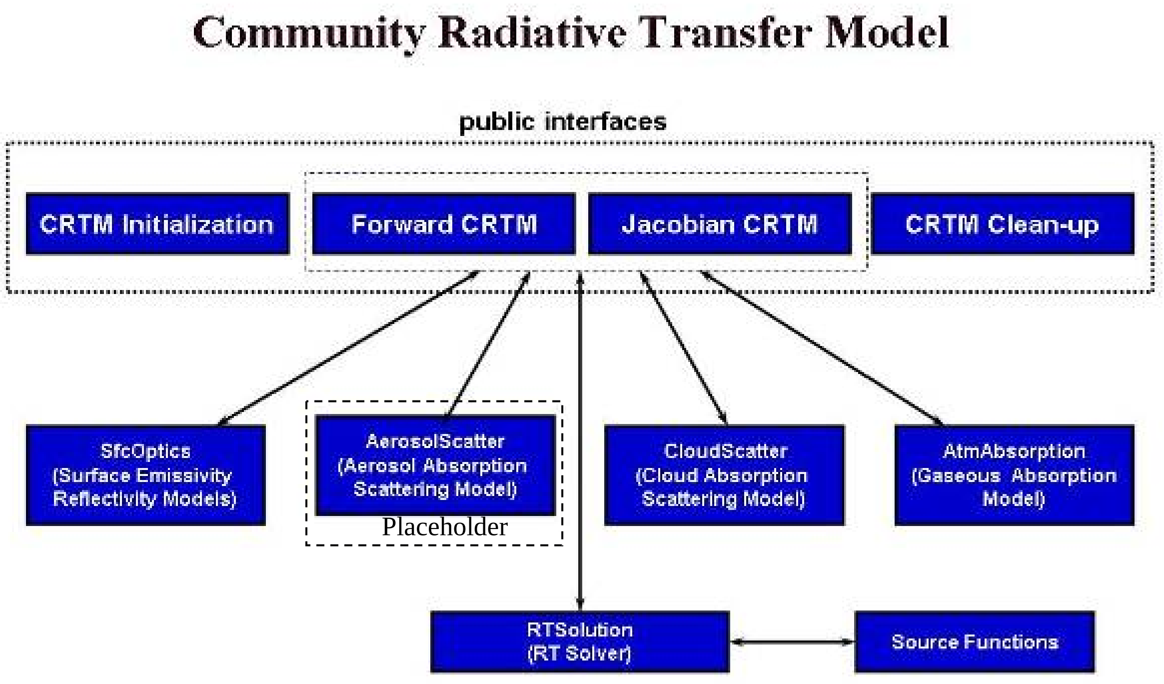
Areas in which CRTM may apply

- Satellite radiance data assimilations for NWP
- Radiometric data impact assessment in Observing System Simulation Experiments (OSSEs)
- Radiometric instrument design, calibration and monitoring
- Physical retrievals of atmospheric and surface state variables
- Air-quality monitoring and forecast
- Scientific research and education

CRTM Capability (operational)

Supported Instruments

- **TIROS-N to NOAA-18 AVHRR**
- **TIROS-N to NOAA-18 HIRS**
- **GOES-8 to 13 Imager channels**
- **GOES-8 to 13 sounder channel 08-13**
- **GOES-R ABI**
- **Terra/Aqua MODIS Channel 1-10**
- **METEOSAT-SG1 SEVIRI**
- **Aqua AIRS**
- **Aqua AMSR-E**
- **Aqua AMSU-A**
- **Aqua HSB**
- **NOAA-15 to 18 AMSU-A**
- **NOAA-15 to 17 AMSU-B**
- **NOAA-18 MHS**
- **TIROS-N to NOAA-14 MSU**
- **DMSP F13 to15 SSM/I**
- **DMSP F13,15 SSM/T1**
- **DMSP F14,15 SSM/T2**
- **DMSP F16 SSMIS**
- **NPP ATMS**
- **Coriolis Windsat**
- **METOP-A AMSUA, MHS, HIRS, AVHRR**



- Input profiles: temperature, water vapor and ozone profiles at user defined layers, and optionally, water content and mean particle size profiles with up to 6 cloud types.
- Surface emissivity: computed internally or supplied by user.
- Frequency coverage: MW and IR

Radiative transfer solver

- Currently in operational code:
  - Advanced Adding and Doubling (ADA) method.
- Other methods being considered:
  - Successive Order of Iteration (UWisc)
  - Discrete Ordinate Tangent Linear Radiative Transfer (University of Colorado)
  - Delta 4 stream vector radiative transfer model (UCLA)

Gaseous transmittance model (1)

- Currently in operation:
  - OPTRAN-compact

- Ongoing development:
  - Integration of multiple transmittance models (OPTRAN-compact, OPTRAN-v7, RTTOV and SARTA)

    Prototype completed; operational code under development
  - Implementation of OSS-based CRTM

    Prototype completed; 75% OSS database software transferred to JCSDA
  - Fast transmittance model for SSMIS upper-atmosphere sounding channels affected by Zeeman-splitting

    Algorithm completed and validated; being integrated into CRTM
  - Validation

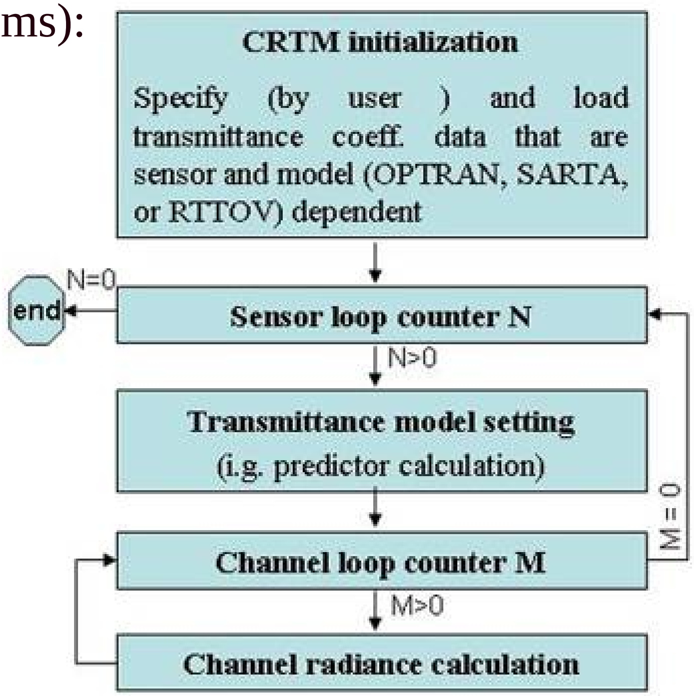
Gaseous transmittance model (2)

Integration of multiple transmittance models

- Motivation: allow users to dynamically select the transmittance algorithms that best meet their needs (e.g. computing environments).

- Basic requirements: computational efficiency must not be reduced; computer codes must not be complicated.

- Models (all passband-averaged transmittance algorithms):
  - OPTRAN-v7: fixed levels of integrated absorber amount (easy to be extended to include more variable trace gases).
  - OPTRAN-compact: fixed levels of integrated absorber amount + vertical smooth (very efficient in computer memory use, good for hyperspectral sensors).
  - UK RTTOV: fixed pressure levels (a well known model).
  - UMBC SARTA: water vapor - OPTRAN; other gases - fixed pressure levels (tuned with AIRS observations).



CRTM initialization

Specify (by user) and load transmittance coeff. data that are sensor and model (OPTRAN, SARTA, or RTTOV) dependent

Sensor loop counter N

Transmittance model setting

(i.g. predictor calculation)

Channel loop counter M

Channel radiance calculation

Gaseous transmittance model (3)

Validation of SARTA implementation

Comparisons between observations and simulations

Clear-sky observations:

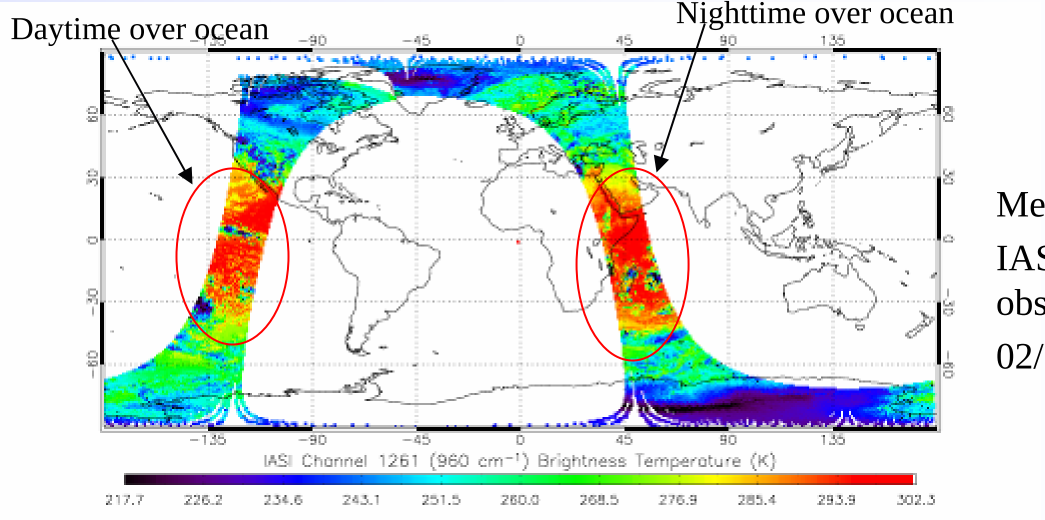
–Clear detection algorithm: Ocean, in the ±40 degree latitude range;

–The brightness temperature variances over the 4 IFOVs in the EFOV < 0.3 K for three wavenumbers 961.0, 1096.0 & 1232.0; BT2616-BT961 < 3.3 and BT2616-BT961 > 0.7 to remove the cirrus and low cloud.

Model:

–CRTM-SARTA for IASI; CRTM-OPTRAN for MHS.

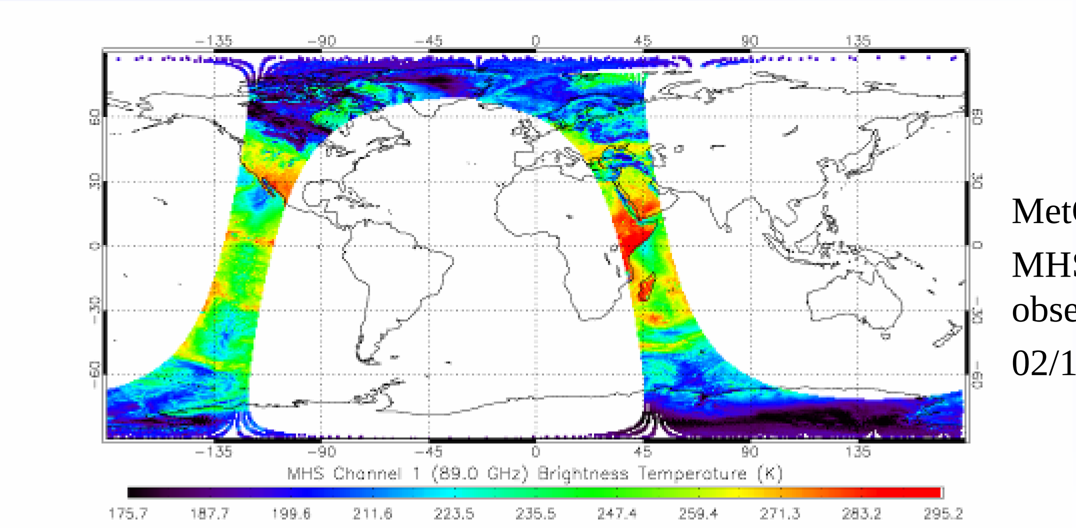
–GDAS profiles interpolated on locations of IFOVs.



Daytime over ocean

Nighttime over ocean

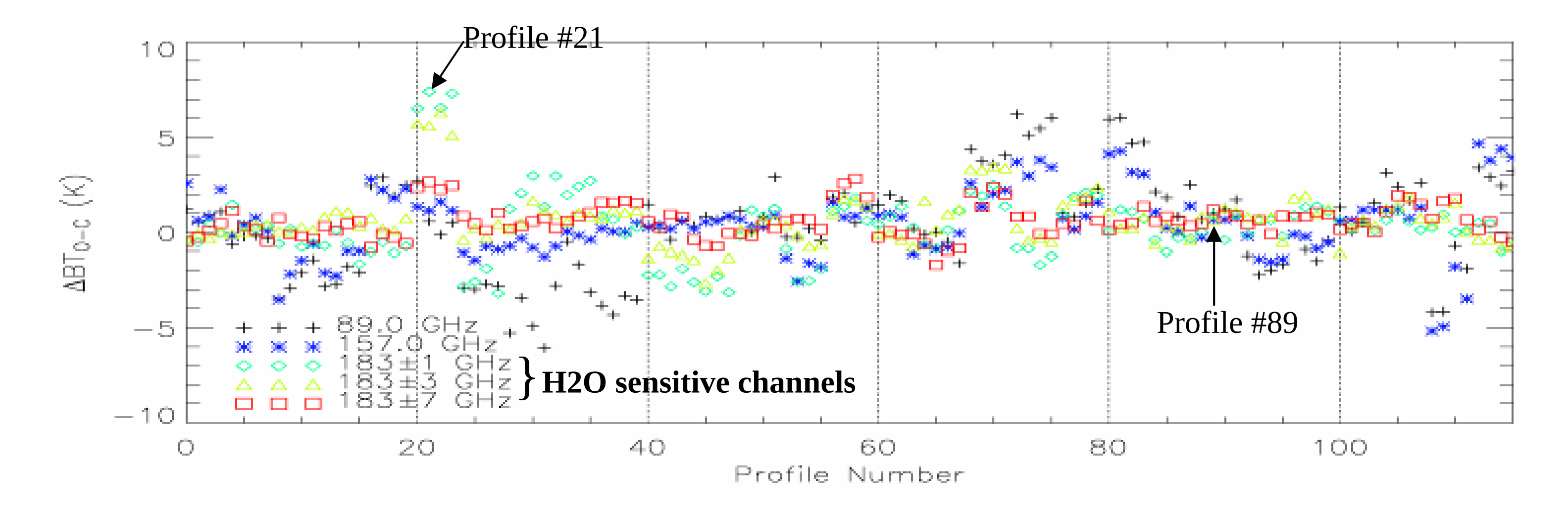
MetOp-a
IASI
observation
02/11/2007



MetOp-a
MHS
observation
02/11/2007

Comparison between observations and simulations

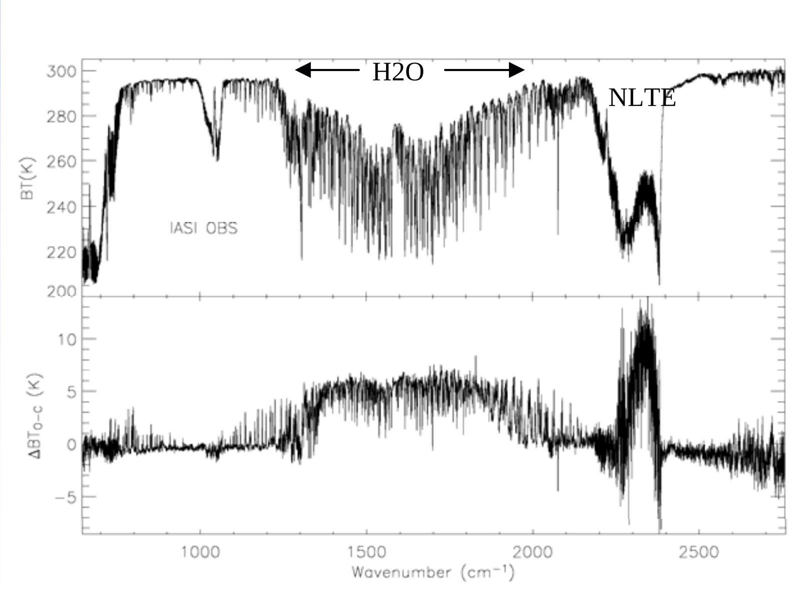
MHS



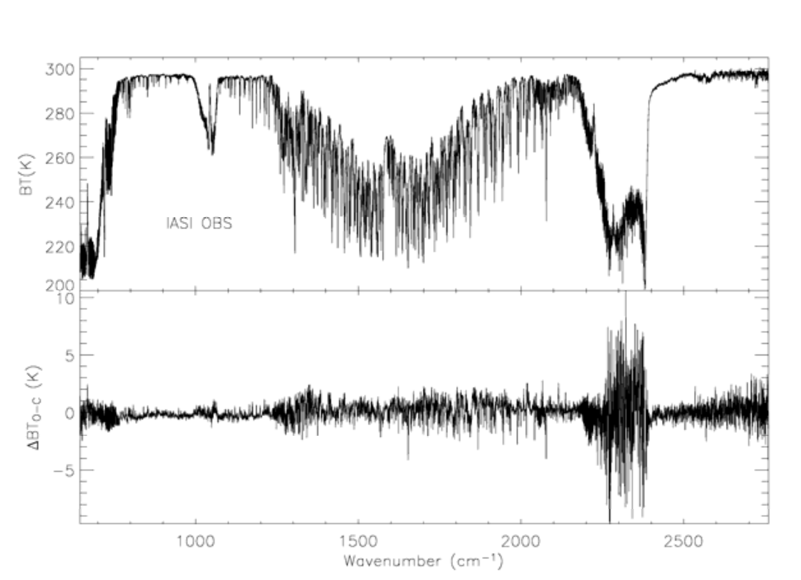
Day time

Night time

IASI



Problem with the input water vapor profile (profile #21)

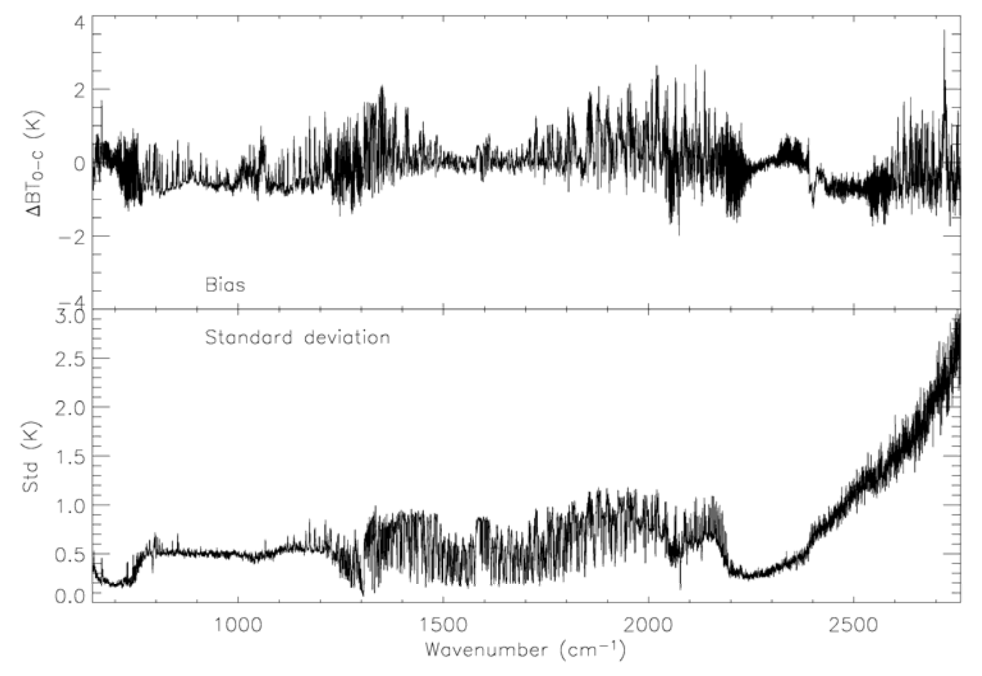


Both IASI and MHS observations agree well with calculations (profile #89 is used).

Difference and standard deviation of IASI spectral calculations from observations

Brightness temperature difference between observed radiances and those computed using GDAS data. The results have been scaled to an effective observation temperature of 280K.

Standard deviation between observed brightness temperatures and those computed using GDAS data. The results have been scaled to an effective observation temperature of 280K.



Night time only, sample size = 76

Gaseous transmittance model (4)

Fast transmittance model for SSMIS Zeeman affected channels

Energy level splitting:

In the presence of an external magnetic field, each O2 energy level associated with the total angular momentum quantum number J is split into 2J+1 levels corresponding to the azimuthal quantum number M = -J, …, 0, …,J

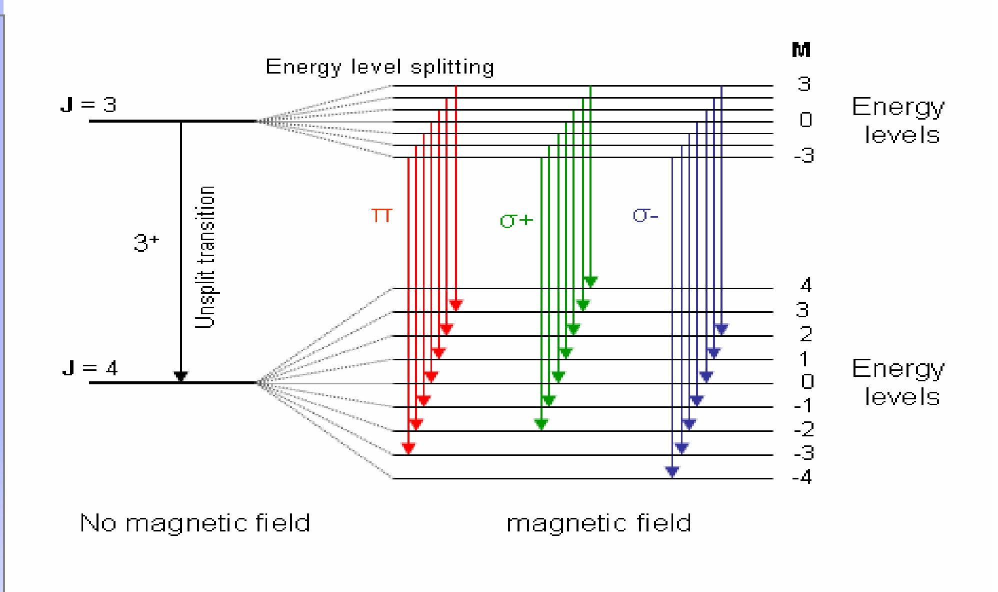
Transition lines (Zeeman components) :

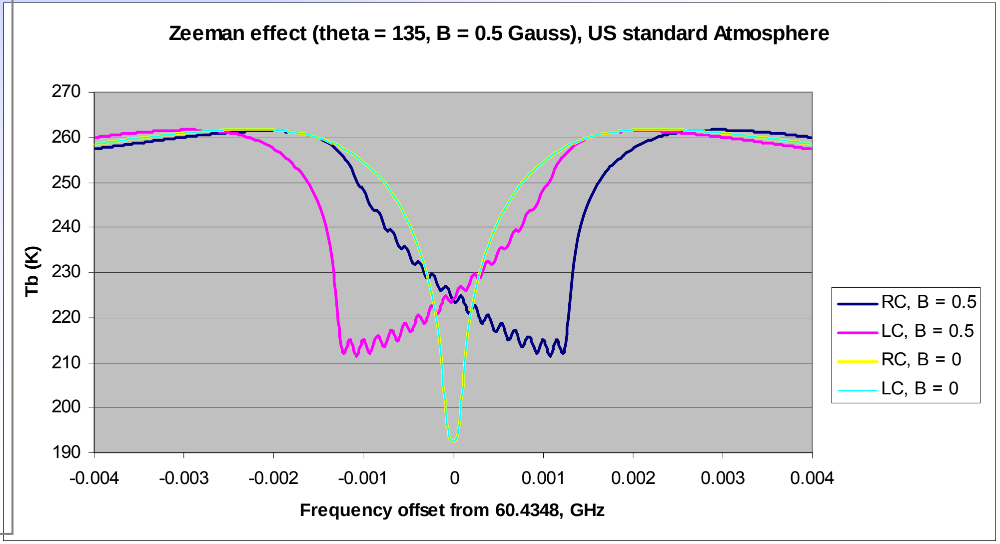
The selection rules permit transitions with $\Delta J = \pm 1$ and $\Delta M = 0, \pm 1$. For a change in J (i.e. J=3 to J=4, represented by 3^+), transitions with

$\Delta M = 0$ are called π components,
$\Delta M = 1$ are called σ+ components and
$\Delta M = -1$ are called σ- components.

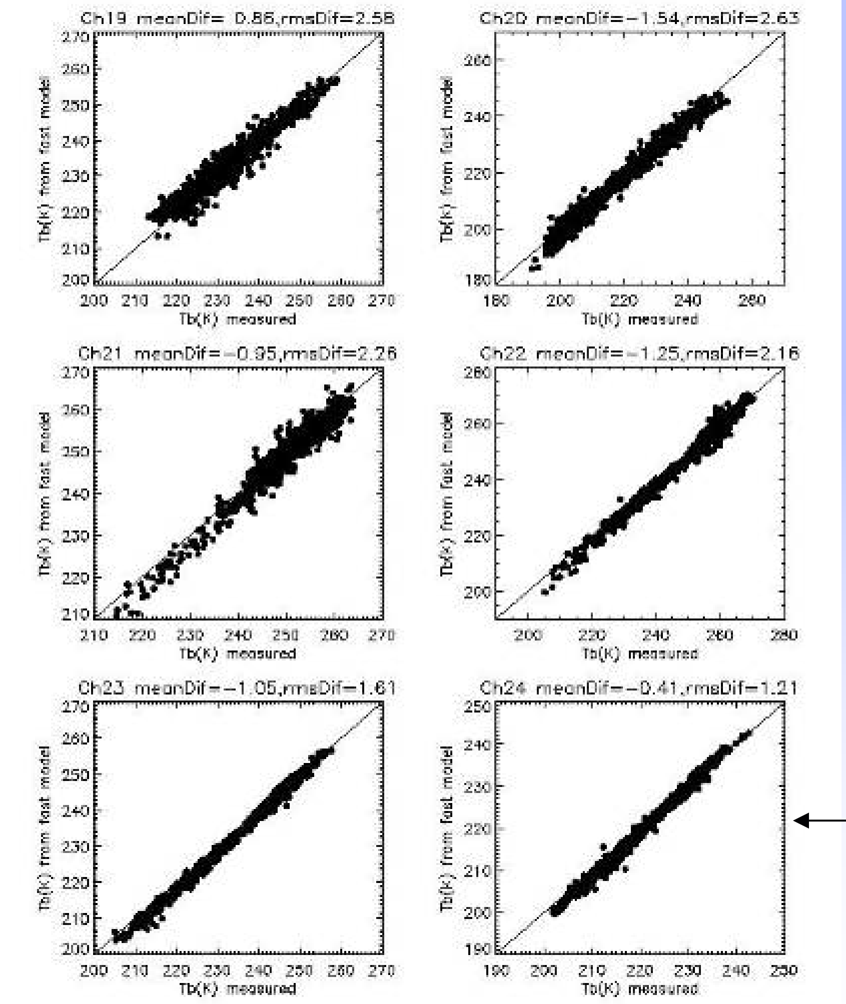
Polarization:

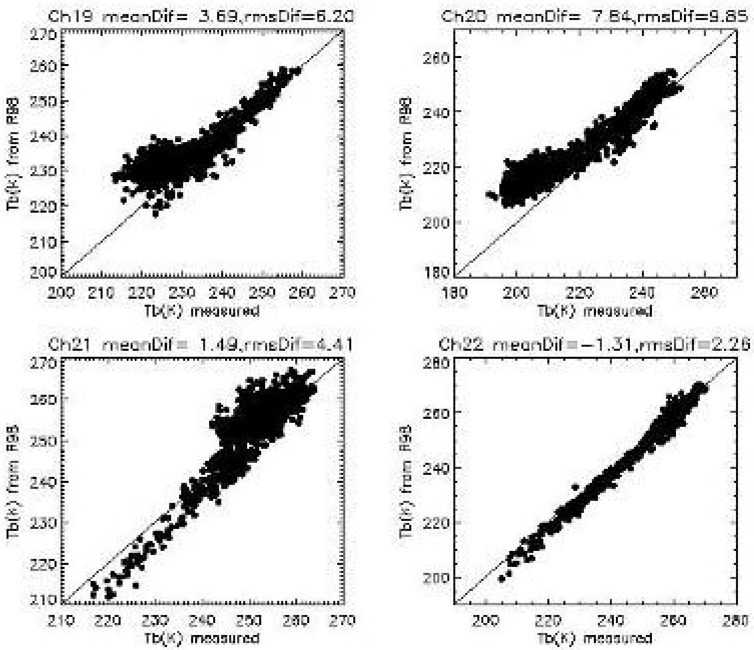
The three groups of Zeeman components also exhibit polarization effects with different characteristics. Radiation from these components received by a circularly polarized radiometer such as the SSMIS upper-air channels is a function of the magnetic field strength |**B**|, the angle θ_B between **B** and the wave propagation direction **k** as well as the state of atmosphere, not dependent on the azimuthal angle of **k** relative to **B**.





Comparison between SSMIS observations and simulations with/without Zeeman-effect





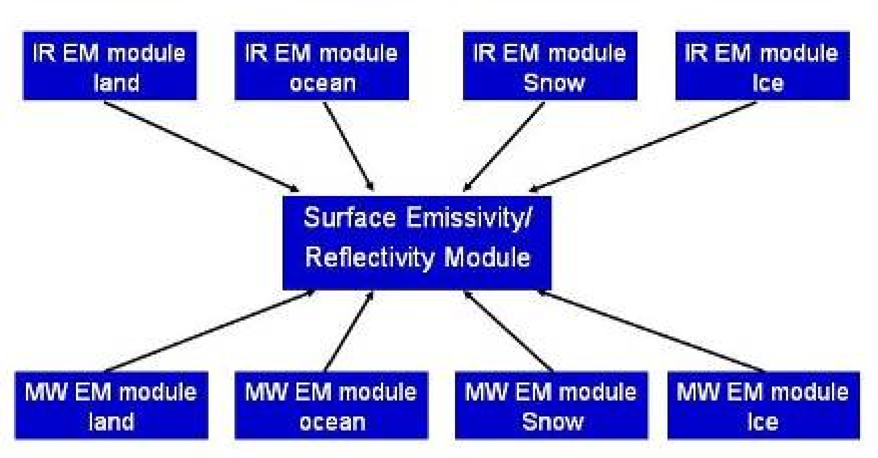
Without including Zeeman-effect in the model.

Channels 23 & 24 are not affected by Zeeman-splitting

Collocated temperature profiles for model input are retrievals form the SABER experiment.

Sample size: 1097 samples

Surface emissivity/reflectivity model (1)



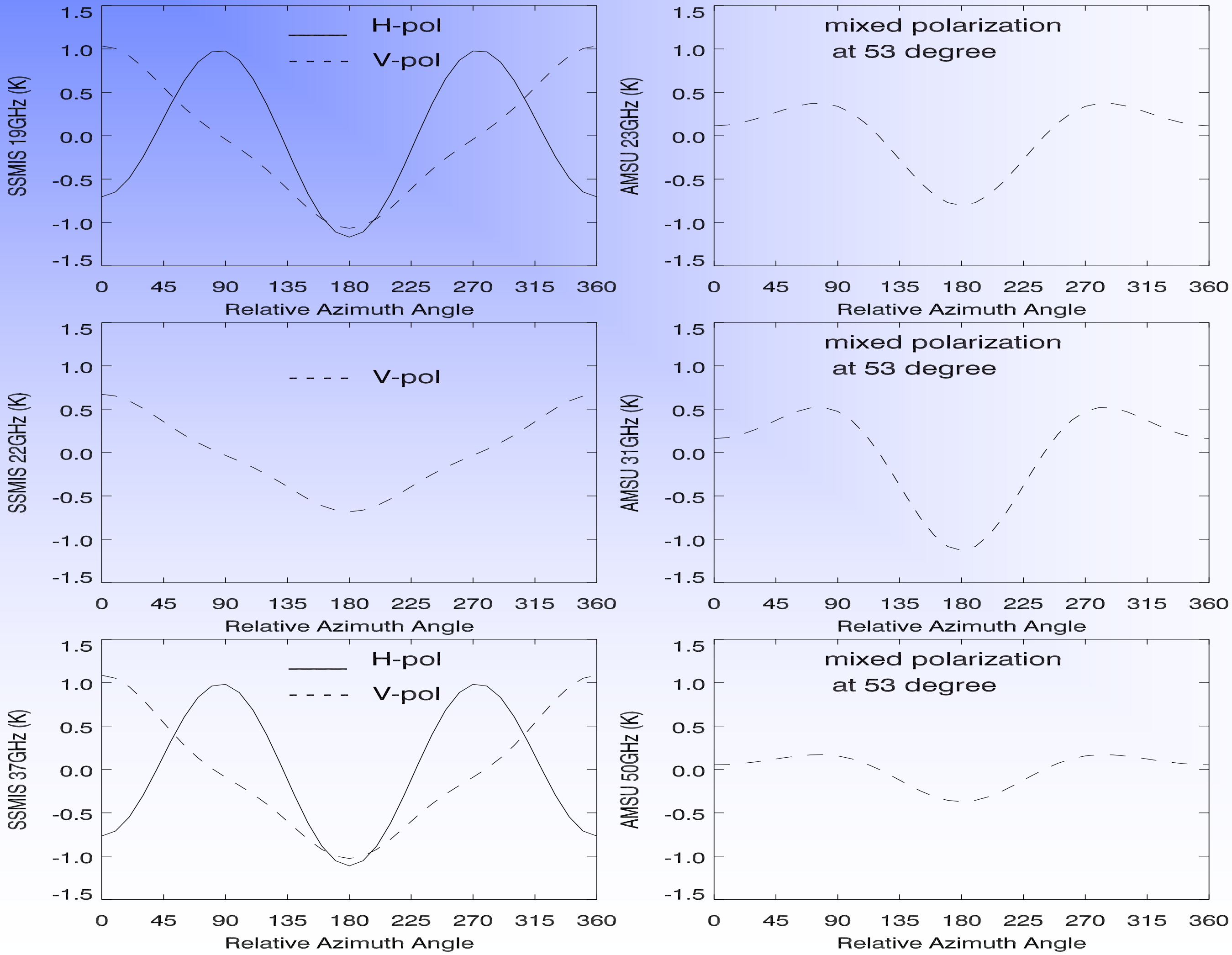
The CRTM surface emissivity module is split into 8 sub-modules in order to accommodate new model implementations and model improvement.

- **Currently in operation:**
  - – MW over ocean: UK FASTEM-1.
  - – MW over land, snow and ice: NESDIS microwave land emission model (LandEM); MW empirical snow and ice surface emissivity model for several sensors.
  - – IR over ocean: fast sea surface emission model (IRSSE), based on Wu-Smith (1997).
  - – IR over land, snow and ice: lookup table with 24 surface types (Carter et al., 2002) mapped to 13 GFS surface types.
- **Ongoing development:**
  - – Implementation of NESDIS polarimetric ocean surface emissivity model (preliminarily implemented; is being tested and evaluated);
  - – Improvement of microwave ocean emissivity model in low MW frequency region (algorithm completed, validated and implemented);
  - – New lookup table for 13 GFS surface types using data from JPL emissivity database.

Surface emissivity/reflectivity model (2)

Polarimetric ocean surface model

Microwave polarimetric emissivity model has been preliminarily implemented in CRTM. The model allows users not only to simulate polarimetric sensor WINDSAT, but also the wind-directional variation for SSMIS and AMSU.



Surface emissivity/reflectivity model (3)

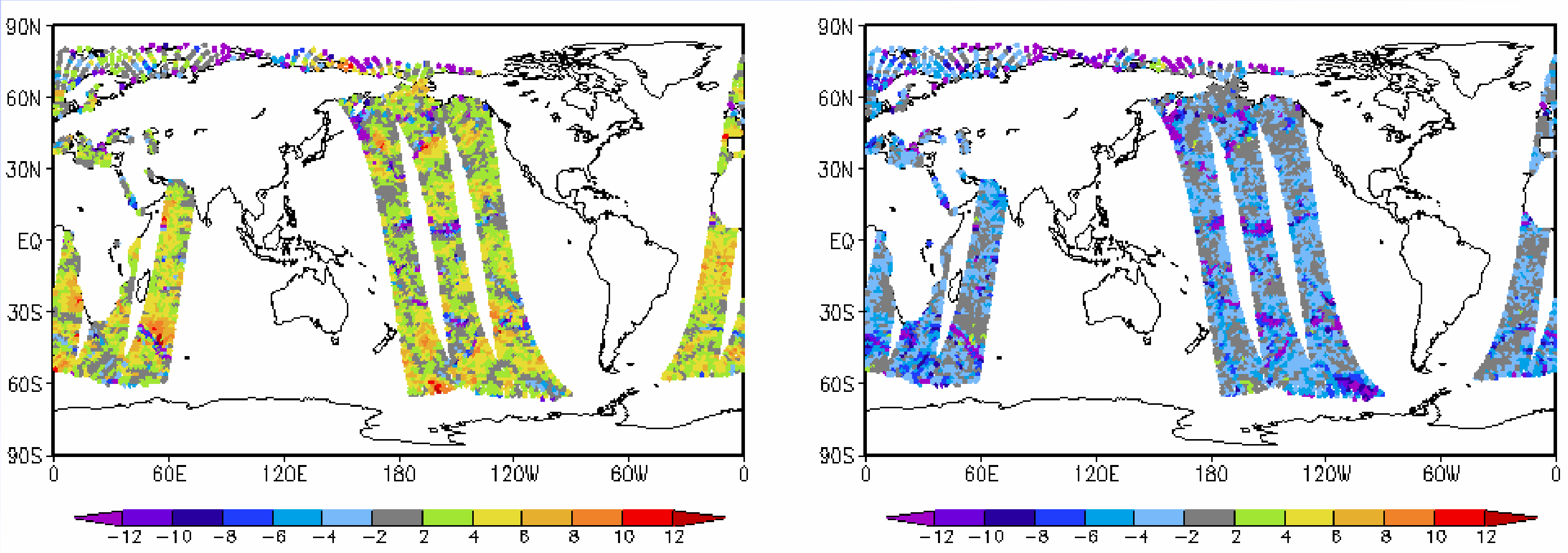
Development of Low Frequency MW Sea Surface Emissivity Model (LowFrequency_MWSSE)

(Masahiro Kazumori, visiting scientist from JMA)

- Community Radiative transfer model (CRTM) has two options for Microwave Ocean Emissivity Model

1. FASTEM (Developed by UKMO) ← operational use
2. NESDISEM (Developed by NESDIS)

TBcal – Tbobs (AMSR-E)



FASTEM

NESDISEM

00z 16 August 2005

Both models have large bias(about 3K) in 10.65GHz (H).

Necessary to develop a new microwave ocean emissivity model

Algorithm of new microwave ocean emissivity model

Two-Scale Ocean roughness model

- –Small Scale correction (Liu1998, Bjerkaas1979)
- –Large Scale correction (Modified Storyn1972)
- –Foam emissivity and foam fraction (Modified Storyn1972,Rose2004)

$$\left|R_{\mathrm{v}}\right|^2 = \left|R_{\mathrm{v,Fresnel}}\right|^2 \underline{\exp(-4k^2\varsigma_{\mathrm{R}}^2\cos^2\theta)} + \underline{(a_1 + a_2\theta + a_3\theta^2)W_s\, f(\nu)}$$

$$f(\nu) = \frac{\nu}{c_1 + c_2\nu}$$

$$\left|R_{\mathrm{h}}\right|^2 = \left|R_{\mathrm{h,Fresnel}}\right|^2 \underline{\exp(-4k^2\varsigma_{\mathrm{R}}^2\cos^2\theta)} + \underline{(b_1 + b_2\theta + b_3\theta^2)W_s\, f(\nu)}$$

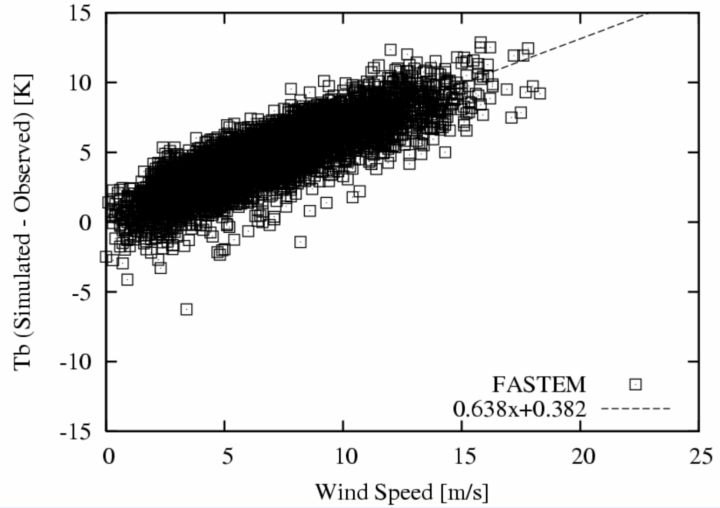
$$a_1 = b_1$$

Small scale correction Large scale correction

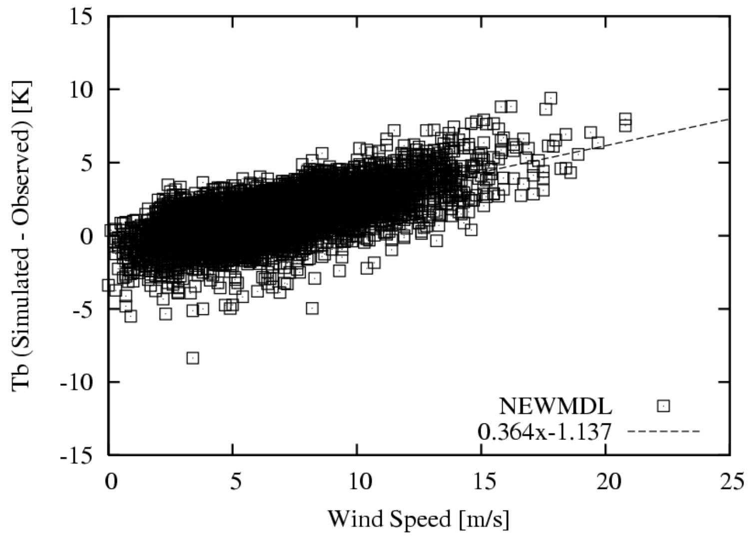
Coefficients were obtained from the fitting to the satellite measurements (AMSR-E,SSMI and AMSU-A)

Tb_{cal}-Tb_{obs} vs Wind Speed AMSR-E 10.65 GHz (H)

FASTEM



LowFrequency_MWSSEM

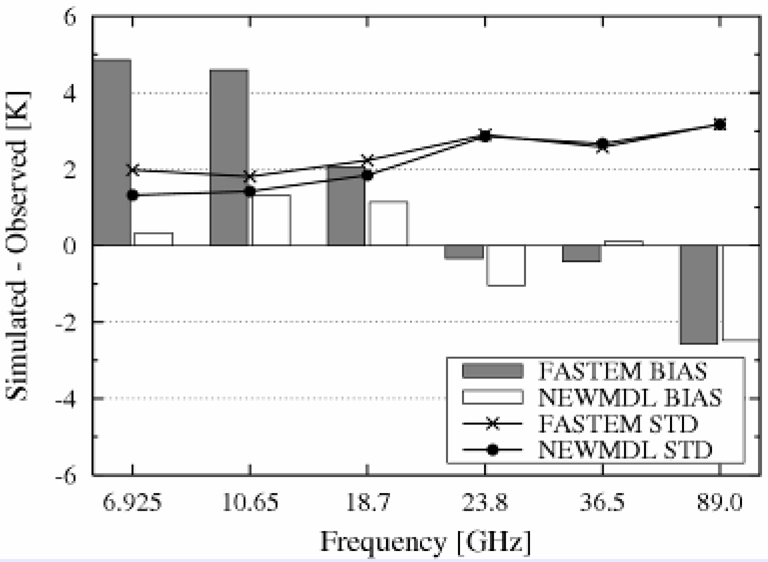


Bias is dependent on surface wind speed.

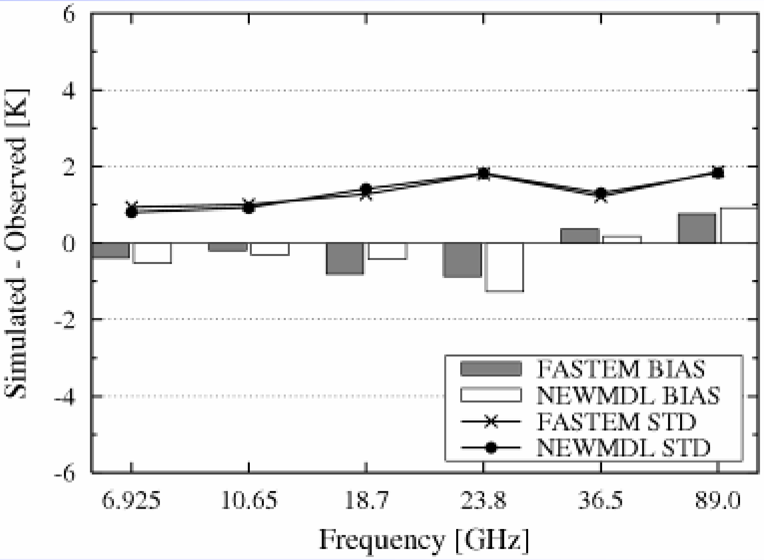
New model has smaller bias than the operational (FASTEM-1).

Comparison between FASTEM & LowFrequency_MWSSEM in AMSR-E channels

Horizontal-polarization



Vertical-polarization



Statistic period:1-5 December 2005

Bar: BIAS

Line:STD

▨ FASTEM

☐ New Model

New model is better in the low frequency (< 20GHz).

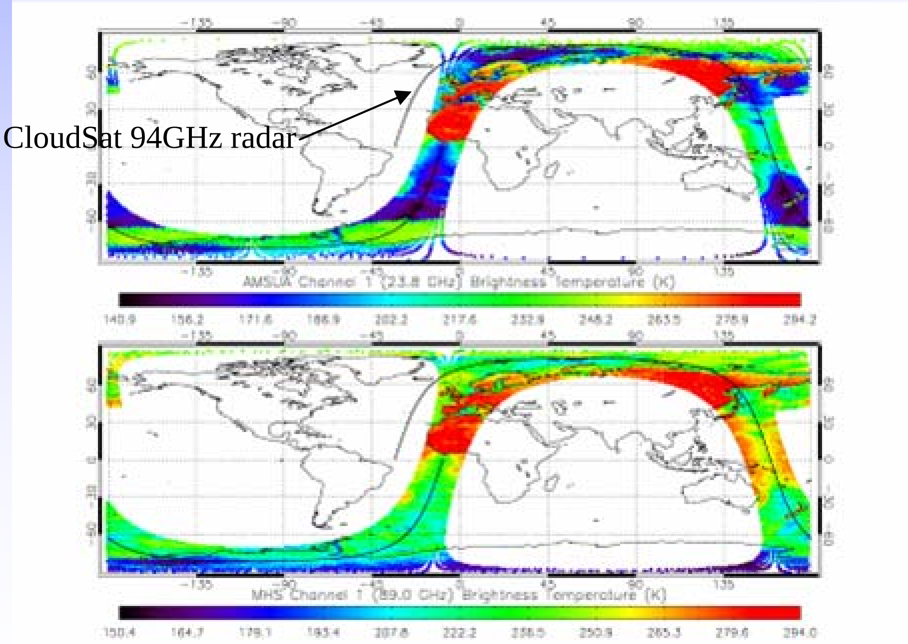
Cloud absorption/scattering model (1)

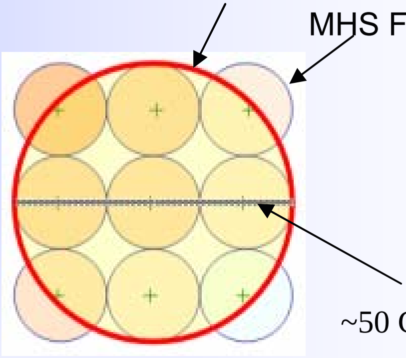
- Currently in operation:
  - Six cloud types: water, ice, rain, snow, graupel and hail
  - NESDIS lookup table: mass extinction coefficient, single scattering albedo, asymmetric factor and Legendre phase coefficients. Sources:
    - IR: spherical water cloud droplets (Simmer, 1994); non-spherical ice cloud particles (Liou and Yang, 1995; Macke, Mishenko et al.; Baum et al., 2001).
    - MW: spherical cloud, rain and ice particles (Simmer, 1994).
- Ongoing development:
  - An improved lookup-table interpolation scheme (completed)
  - Extending lookup table to UV+VIS regions (implemented preliminarily)
  - Validation

Cloud absorption/scattering model (2)

validation using CloudSat data (non-precipitating weather)

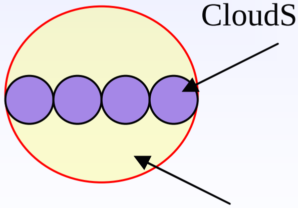
- CloudSat data:
  - Cloud Geometrical Profile
  - Cloud Classification
  - Cloud Liquid Water Content
  - Cloud Ice Water Content
- Temperature, water vapor and O3 profiles and surface state variables:
  - ECMWF analysis data set


CloudSat 94GHz radar


AMSUA FOV (~50km diameter)

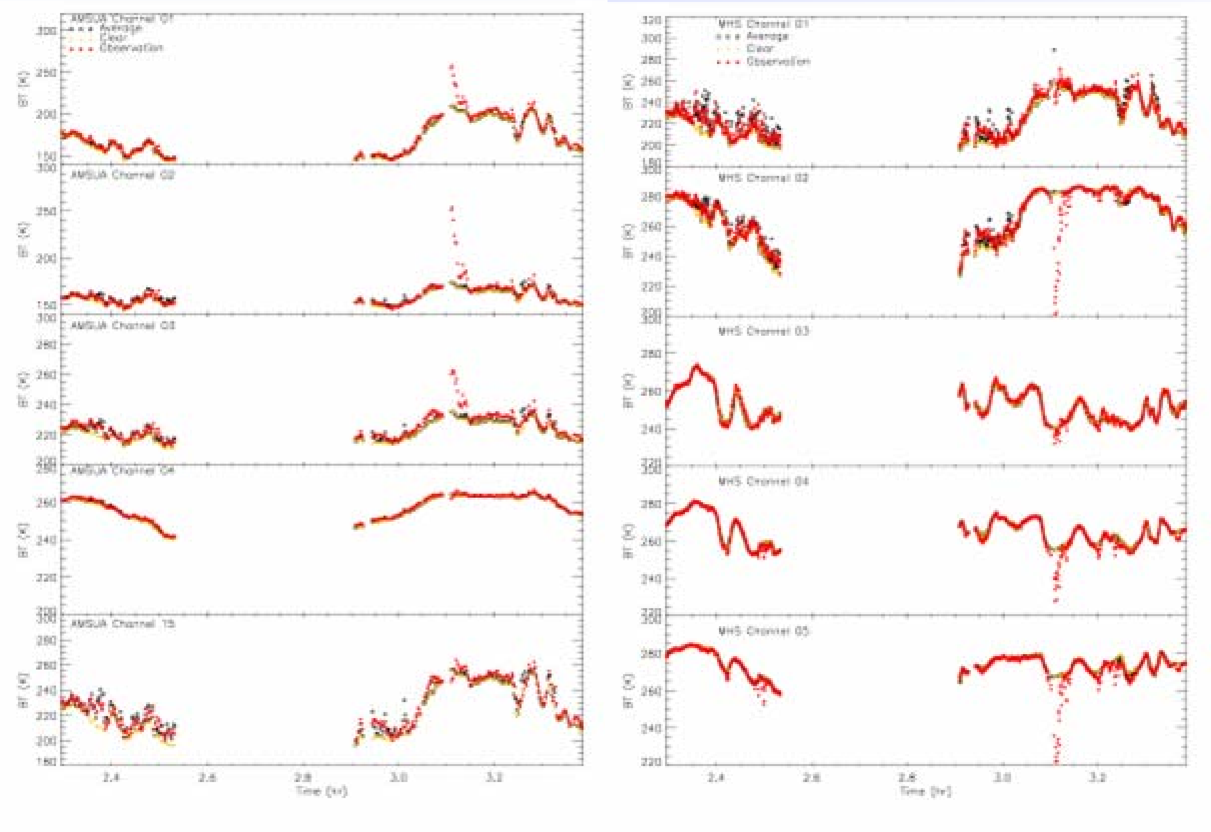
MHS FOV

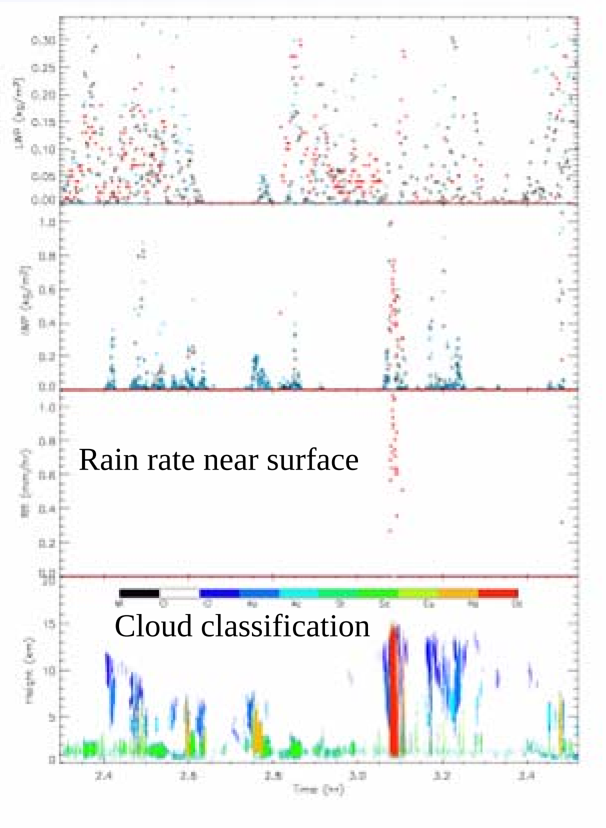
~50 CloudSat FOVs


CloudSat FOV

AVHRR FOV (GAC)
~4km diameter

Time series of AMSU-A, MHS observations versus CRTM simulations using CloudSat data (non-precipitating weather)





Model simulations with cloud component on (black) and off (yellow);
AMSU-A and MHS observations (red), 07/27/2006
Model input: cloud liquid/ice content and particle size profiles from CloudSat

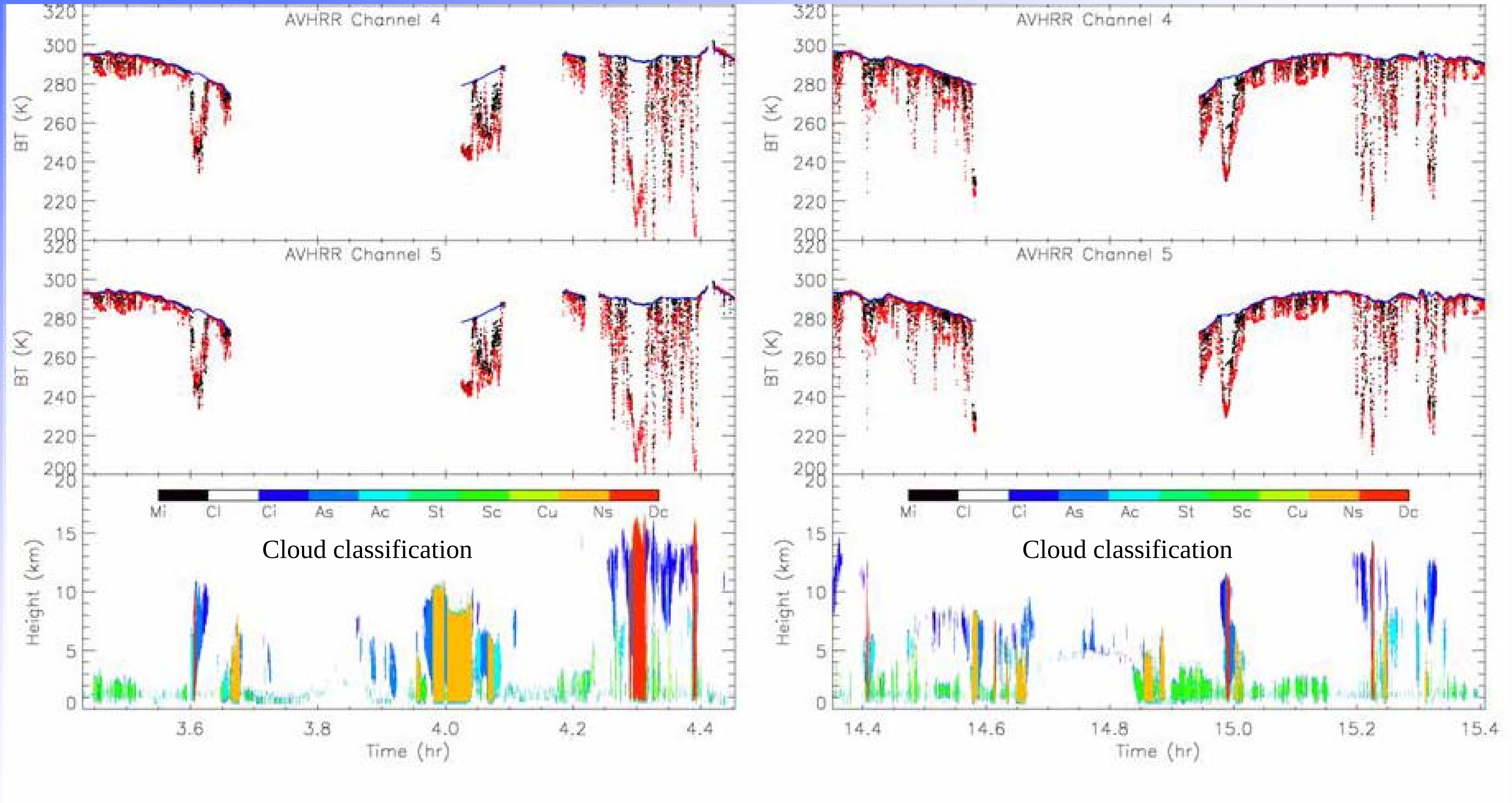
Large differences between Observations and simulations near 3.1 are due to CloudSat data that exclude precipitation.

Upper two panels:

Red – AMSUA+MHS retrievals

Black – derived from CloudSat Radar

Time series of AVHRR observations versus CRTM simulations using CloudSat data



Cloud classification

Cloud classification

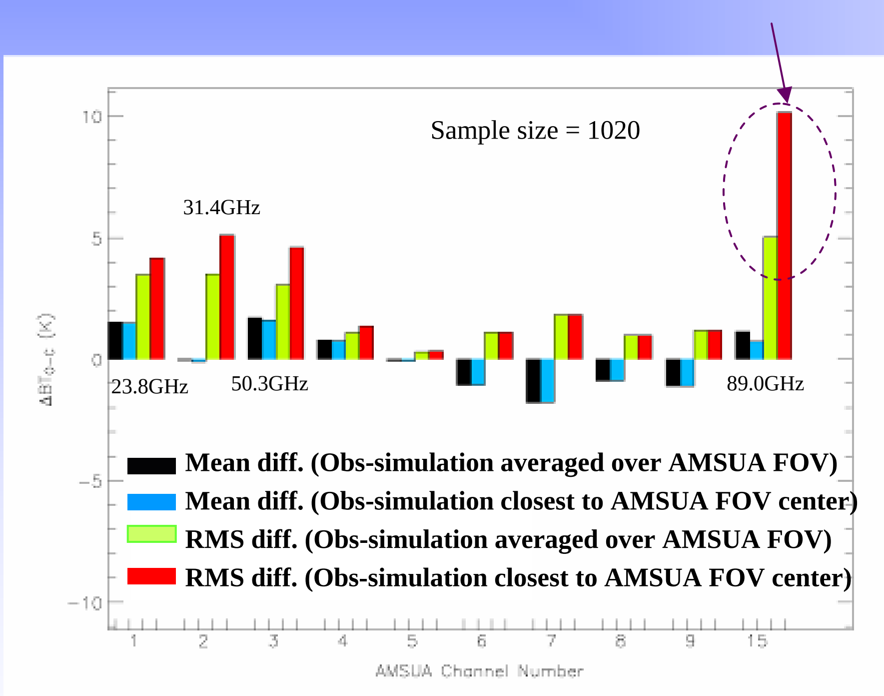
- **Model simulations with cloud component on (black) and off (blue)**
- **AVHRR observations (red)**
- **Model input: cloud liquid/ice content and particle size profiles from CloudSat**

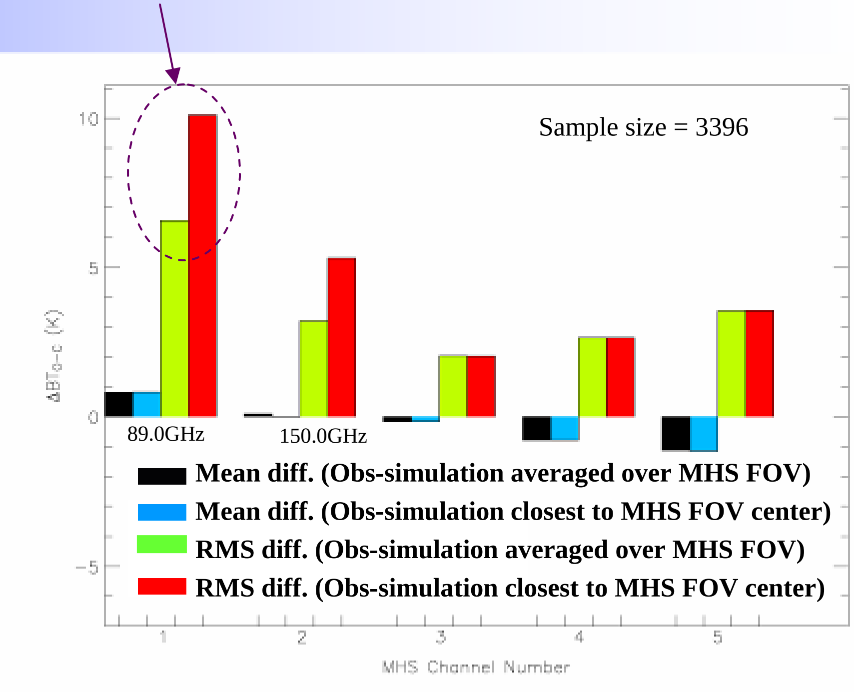
Effect of cloud inhomogeneity

Green bar – RMS difference between AMSU/MHS Obs and simulations averaged over FOVs.

Red bar – RMS difference between AMSU/MHS Obs and single-point simulation.

The significant differences between the Green and Red bars (w/o considering inhomogeneity) demonstrate the importance of modeling the cloud inhomogeneity effect.





Obs. – AMSU-A observations;

Simulation averaged – average of ~50 simulations using CloudSat data over an AMSU-A FOV;

Simulation closest – simulation at the location closest to the AMSU-A FOV center.

Obs. – MHS observations;

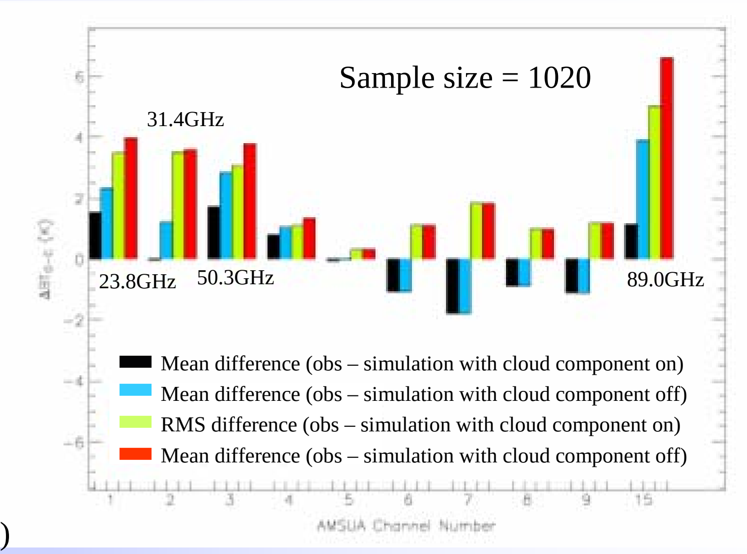
Simulation averaged – average of ~50 simulations using CloudSat data over an MHS FOV;

Simulation closest – simulation at the location closest to the MHS FOV center.

Mean & RMS difference between AMSU-A, MHS & AVHRR observations and simulations under cloudy conditions

The differences between the observations and simulations are significantly reduced with the inclusion of modeling cloud absorption and scattering

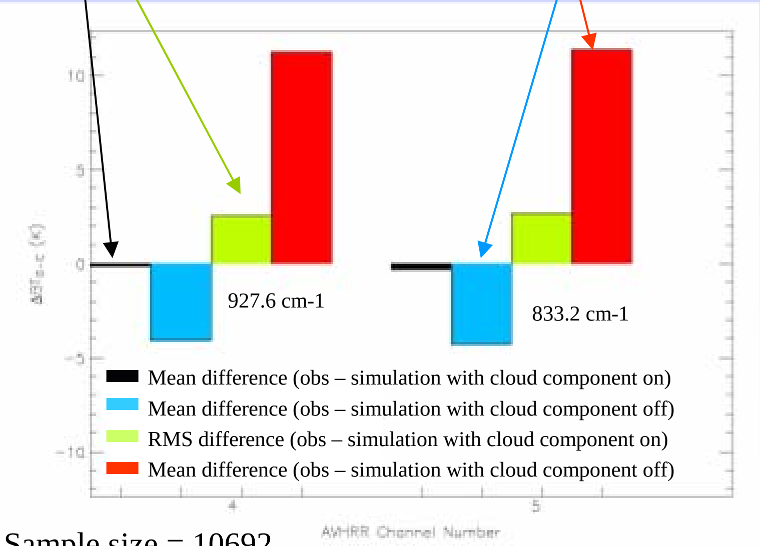
AMSU-A



Mean & RMS Diff. (obs. – simulation w. cloud on)

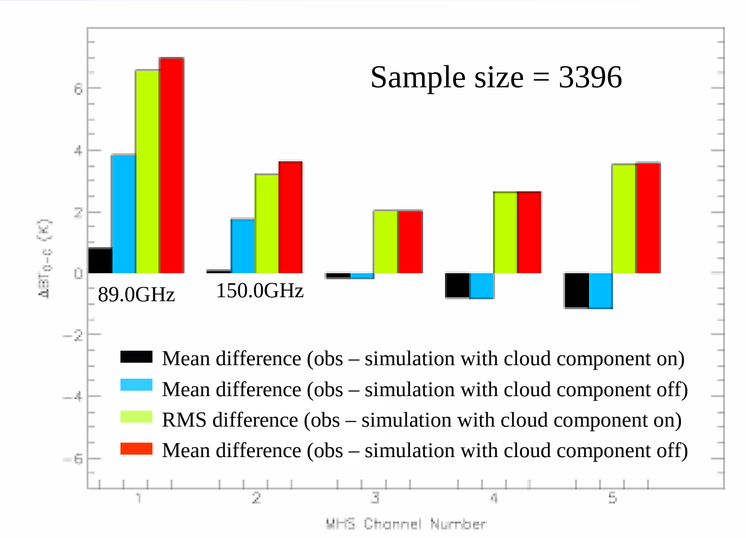
Mean & RMS Diff. (obs. – simulation w. cloud off)

AVHRR



Sample size = 10692

MHS



CRTM extension to include aerosol absorption/scattering and UV+VIS regions (1)

- Aerosol absorption/scattering model (forward and TL models completed):
  - –GOCART aerosol profiles: Dust, Sea Salt, Organic carbon, Black carbon, Sulfate.
  - –Optical parameter lookup table.
  - –Other aerosol models (i.g. Community Multiscale Air Quality (CMAQ) for Regional Model WRF-NMM) are also under consideration.
  - *** **See Quanhua Liu's presentation** for details***
- CRTM extension to UV+VIS (a prototype for GOES-R ABI completed):
  - –Gaseous transmittance model
  - –Optimal Spectral Sampling (OSS) method (Correlated k-distribution method is also under consideration)
  - –Extension of optical parameter lookup table to UV+VIS
    - Aerosols
    - Clouds (ice cloud part from P. Yang)
    - Surface emissivity/reflectivity
- RT solver:
  - –Add a loop over Fourier components for azimuth angle
  - –Add TOA solar irradiance

CRTM extension (2)

Selection of Transmittance Model for UV+VIS

For most UV and VIS channels, reflection and scattering determine the received radiance.

1. OPTRAN

OPTRAN transmittance is path-dependent. The scaling of the optical depth depending on the secant of the viewing angle is not valid when scattered solar radiance makes large contribution to the received energy.

2. Correlated k-distribution method

Grouping gaseous spectral transmittances according to the absorption coefficient k. However, for the selected k values and associated weights, we no longer identify the corresponding position in the spectral space (i.e. wavenumber) and cannot consider sensor spectral response function and the spectral variation of cloud, aerosol, and surface within the band.

3. Optimal Spectral Sampling (OSS)

The base for k-distribution and OSS is similar. But the OSS method can take account for sensor spectral response function and the spectral variation of cloud, aerosol, and surface within the band.

We are testing the computation efficient between k-distribution and OSS for UV and VIS channels.

CRTM extension (3)

Extension of RT solver to UV+VIS

Sharing the same code as for IR and MW (ADA method). Additional loop over Fourier component for azimuth angles, add the solar term in the last equation (highlighted).

Vertical integration

$\mathbf{I_u}(n) = \varepsilon B(T_s)$ $\mathbf{R}(n)$ **the surface reflection matrix, loop k from n → 1**

$$\mathbf{I_u}(k-1) = \mathbf{S_u}(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\ \mathbf{R}(k)\mathbf{S_d}(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\ \mathbf{I_u}(k)$$

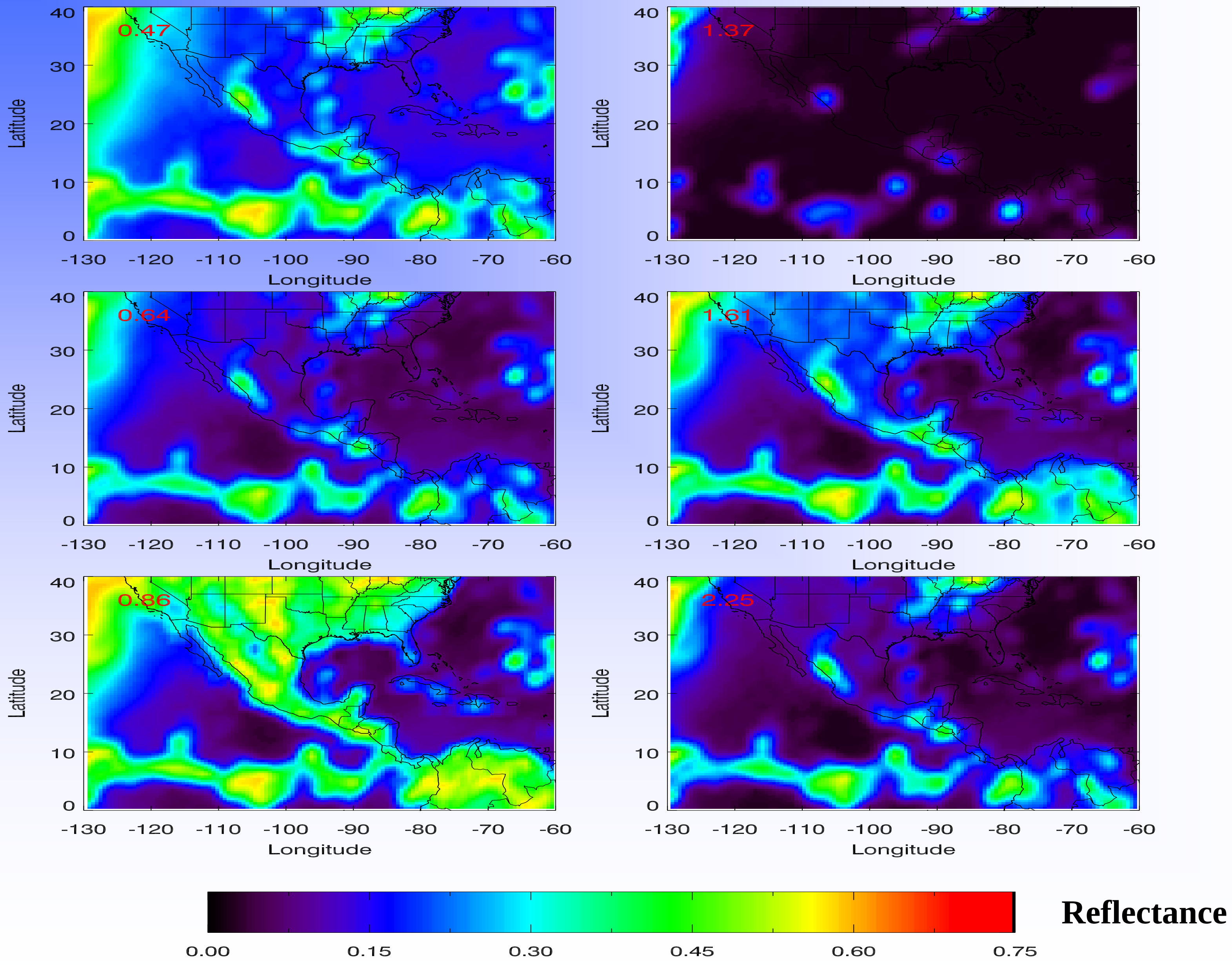
$$= \mathbf{S_u}(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\ [\mathbf{R}(k)\mathbf{S_d}(k) + \mathbf{I_u}(k)]$$

$$\mathbf{R}(k-1) = \mathbf{r}(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\ \mathbf{R}(k)\,\mathbf{t}(k)$$

Liu and Weng, 2006 JAS

TOA radiance $\mathbf{R}adiance = \mathbf{I}_u(0) + \mathbf{R}(0)\,\mathbf{I}c$ $+\mathbf{R}(0)\ \mu_0\,\mathbf{Solar}\_i$

CRTM for GOES-R ABI VIS channel simulation



Summary

- CRTM is a well modularized model, designed as a framework for the purpose of accelerating the transition from research to operation.
- Its current capabilities include Forward, Tangent-linear, Adjoint and Jacobian models for assimilations of clear and cloudy IR and MW radiance observations from satellite over ocean, land, snow and ice surfaces.
- Development and validation efforts in the past year:
  - improvement of currently operational code;
  - integration of fast OPTRAN, UMBC SARTA and RTTOV transmittance models;
  - Development of a fast RT model for SSMIS Zeeman affected channels;
  - extension to aerosol absorption/scattering component;
  - extension to UV and VIS regions;
  - OSS integration and LUT software transition;
  - preparation for MetOp-a sensors and validation for IASI, AMSUA and MHS;
  - validation and assessment of CRTM cloudy radiance simulation capability using CloudSat data;
  - development of a new MW ocean emissivity model for AMSR-E;
  - Development of a new IR emissivity LUT for GFS 13 surface types.

Future Work

- Continue the work on integration of multiple transmittance models, aerosol component, extension for UV and VIS sensors and RT model for SSMIS UAS channels;
- Continue the work on CRTM validations under various environments;
- Improve and enhance surface emissivity models;
- Extend CRTM to include more variable trace gases;
- Extend CRTM to water-leaving radiance simulations for ocean color remote sensing;
- Develop a community-based model for active sensors (e.g. GPS/RO, Lidar, Altimeter, and scatterometers)