Developments of Community Radiative Transfer Model (CRTM) for Satellite Data Assimilation

Fuzhong Weng
NOAA/NESDIS/Office of Research and Applications

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JCSDA Road Map (2002 - 2010)

By 2010, a numerical weather prediction community will be empowered to effectively assimilate increasing amounts of advanced satellite observations

The radiances can be assimilated under all weather conditions with the state-of-the science NWP models

NPOESS sensors (CrIS, CMIS, ATMS…) GOES-R (HES, ABI)

Advanced JCSDA community radiative transfer model, Advanced data selection techniques for hyperspectral

The CRTM includes scattering & polarization from cloud, precip and surface

AIRS, ATMS, CrIS, VIIRS, IASI, SSM/IS, AMSR, more products assimilated

The radiances from advanced sounders will be used. Cloudy radiances will be tested under rain-free atmospheres, and more products (ozone, water vapor winds) are assimilated

Improved JCSDA data assimilation science

A beta version of JCSDA community radiative transfer model (CRTM) transfer model will be developed, including non-raining clouds, snow and sea ice surface conditions

AMSU, HIRS, SSM/I, Quikscat, AVHRR, TMI, GOES assimilated

The radiances of satellite sounding channels were assimilated into EMC global model under only clear atmospheric conditions. Some satellite surface products (SST, GVI and snow cover, wind) were used in EMC models

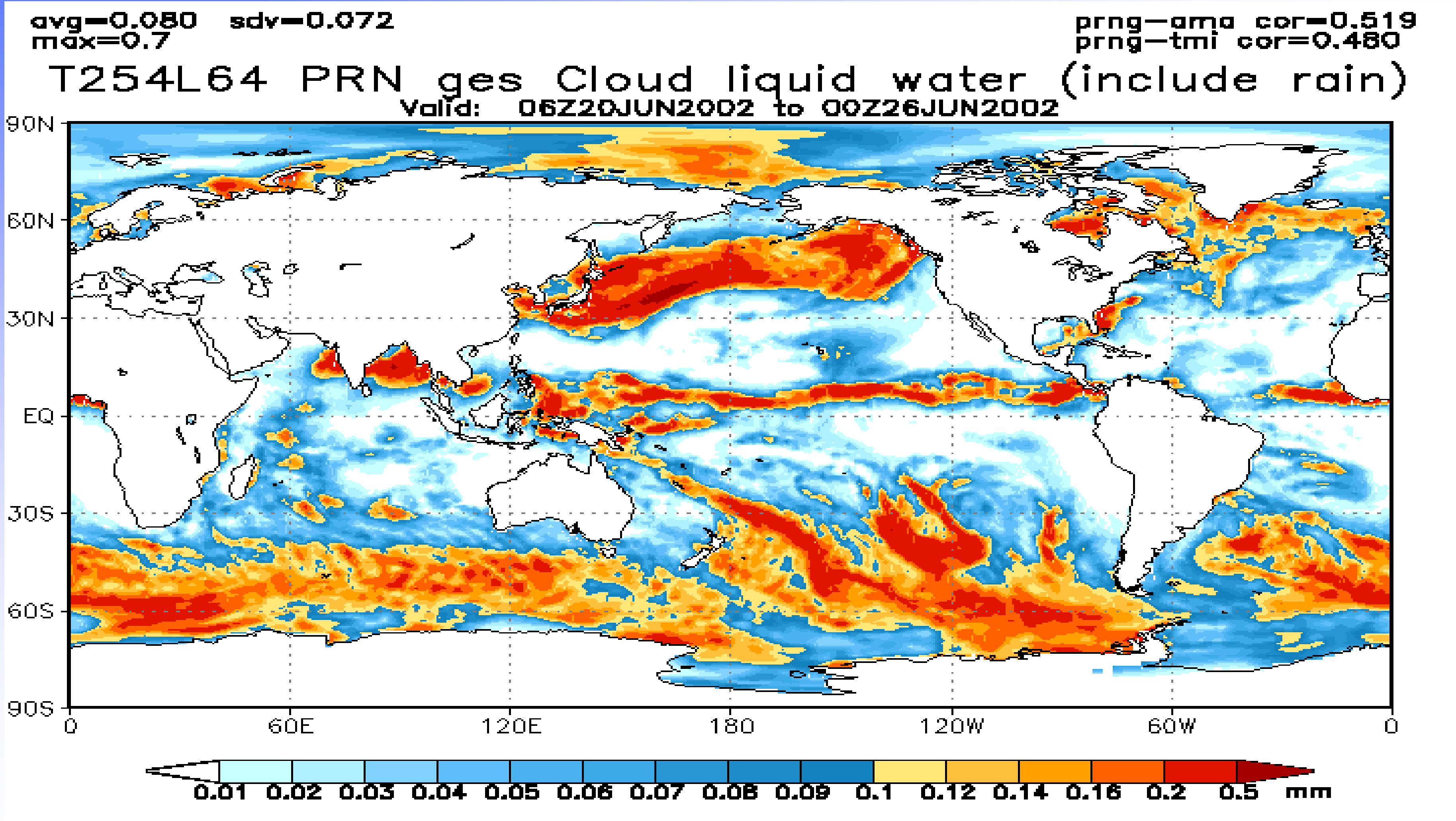
Pre-JCSDA data assimilation science

Radiative transfer model, OPTRAN, ocean microwave emissivity, microwave land emissivity model, and GFS data assimilation system were developed

Science Advance

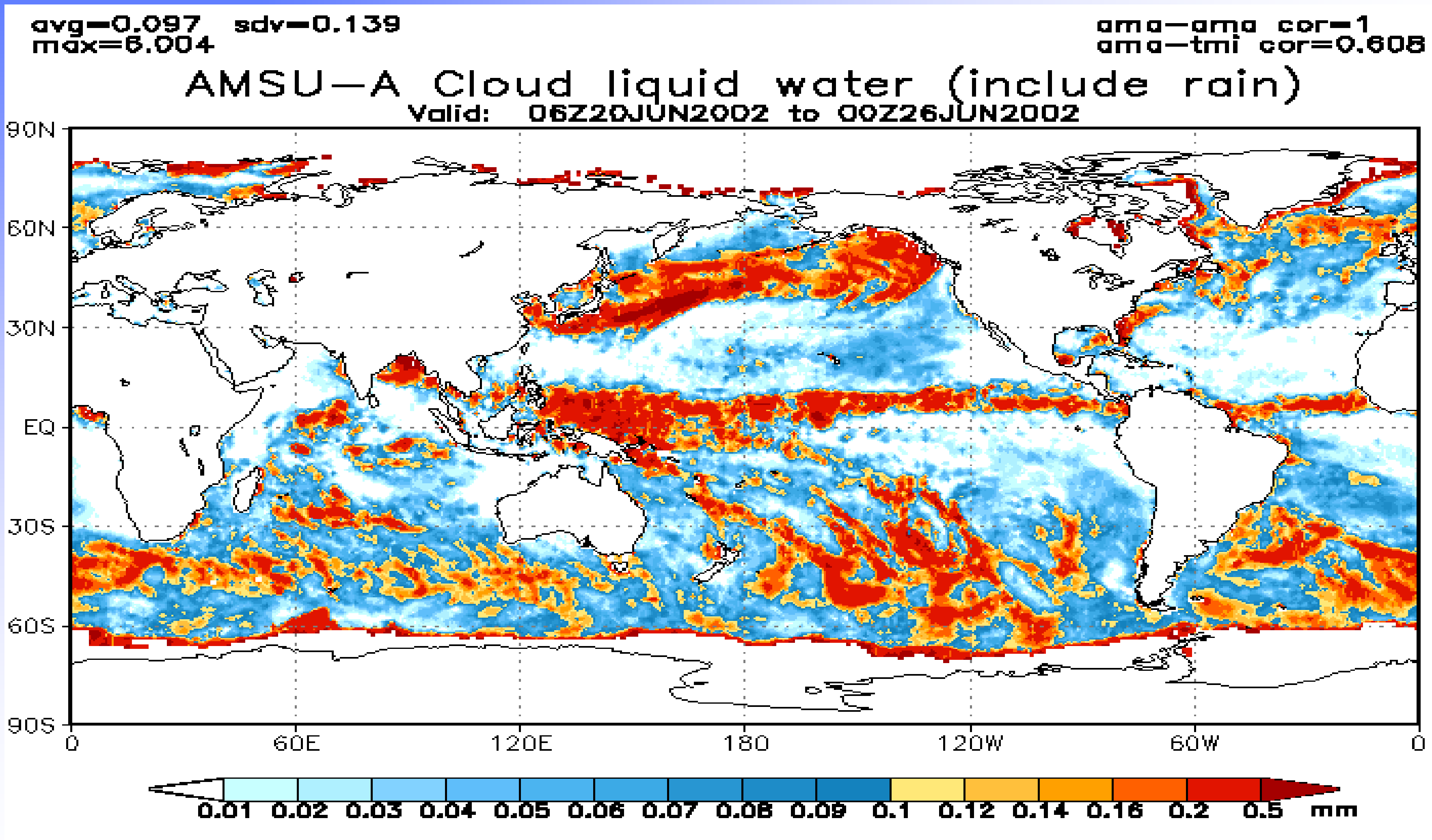
2002 2003 2004 2005 2007 2008 2009 2010

GFS Prediction of Cloud Liquid Water



From Russ Treadon, NCEP

AMSU Retrieval of Cloud Liquid Water

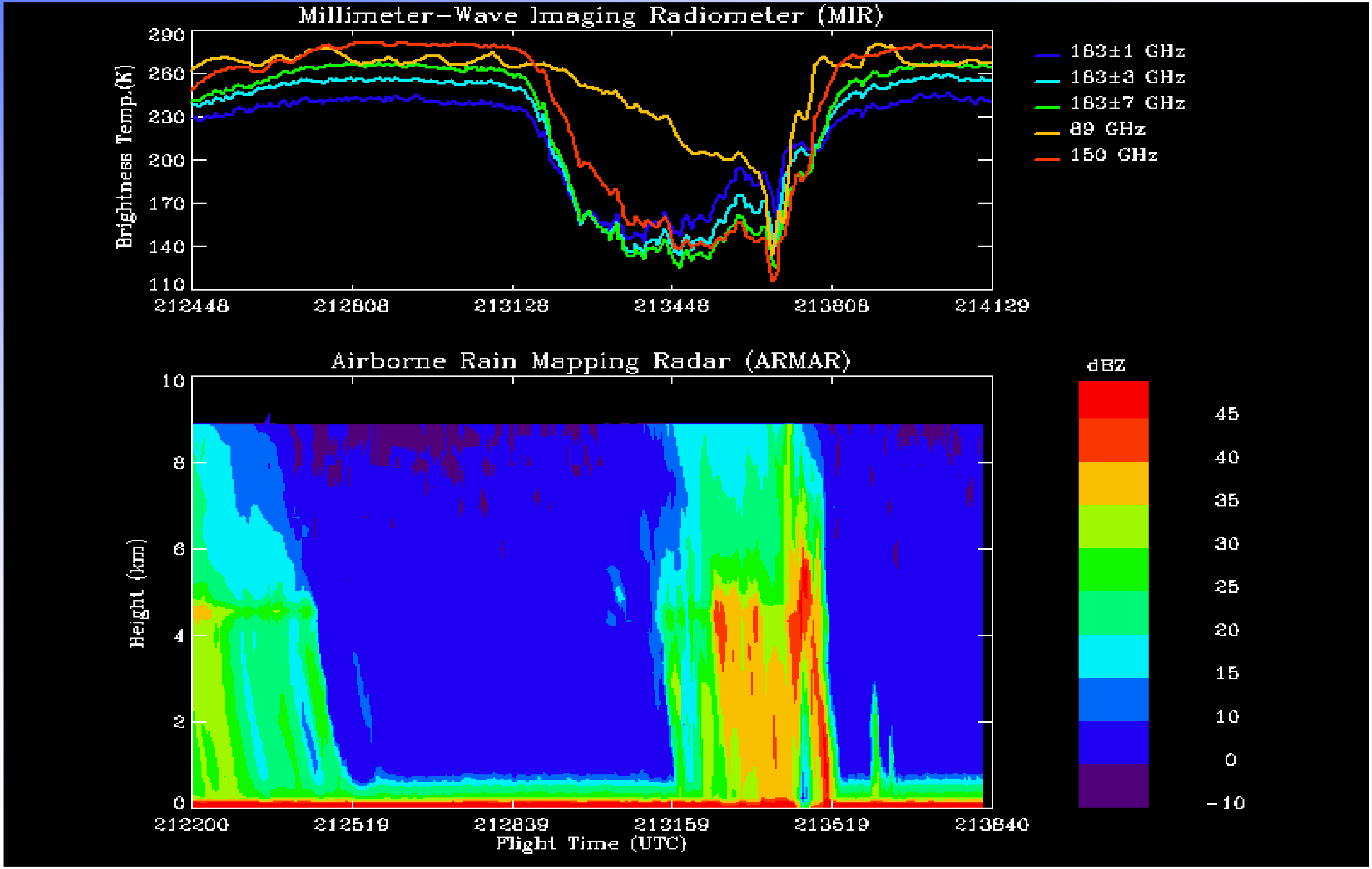


From Russ Treadon, NCEP

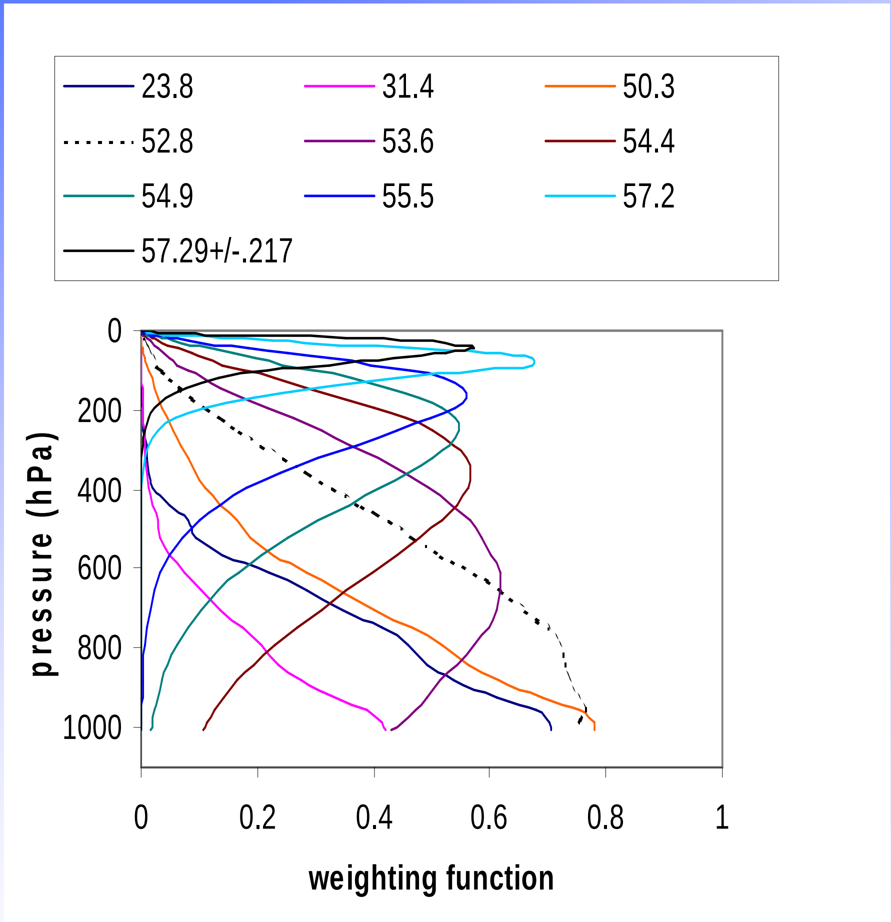
Requirements for Better RT Models

- Accelerated uses of satellite observations
  - Direct radiance assimilation (less dependent on product validation)
  - Unified satellite data assimilation infrastructure
- Advanced satellite instruments
  - Interferometer sounding technology with a few thousand channels
  - Polarimetric from visible to microwave
  - Uses of channels sensitive to surface
  - Inclusion of spectral response functions/field of views
- NWP specific drivers
  - Speed, accuracy and storage
  - Radiances/Jacobian
  - Coupling with forecast modeling

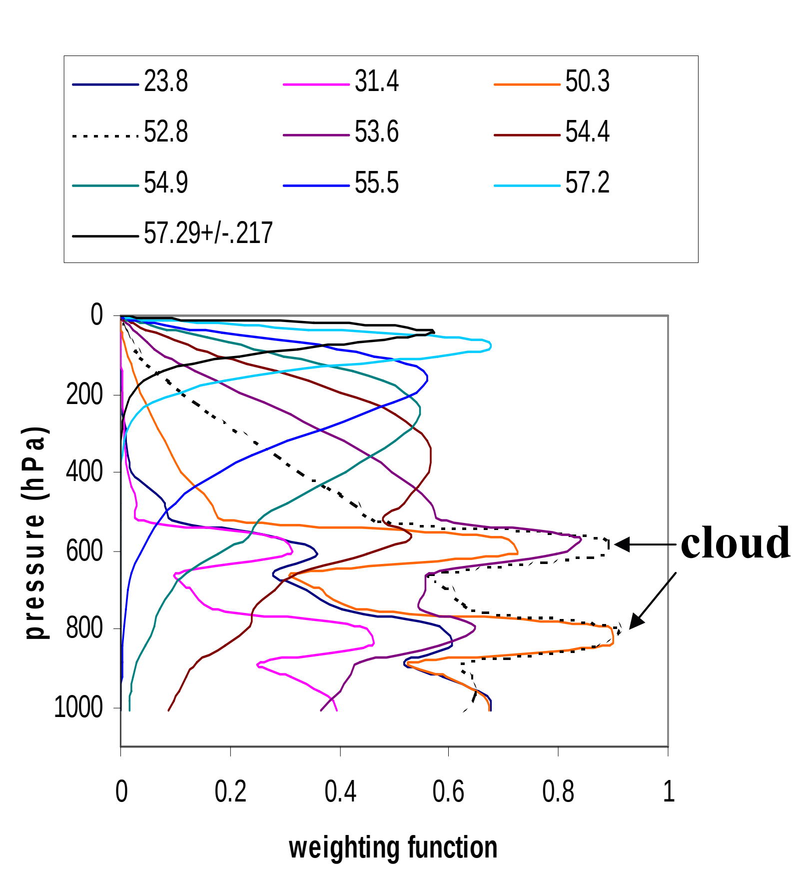
ER-2/DC-8 Measurements during TOGA/CORE (2/2)



Clouds Modify AMSU Weighting Function

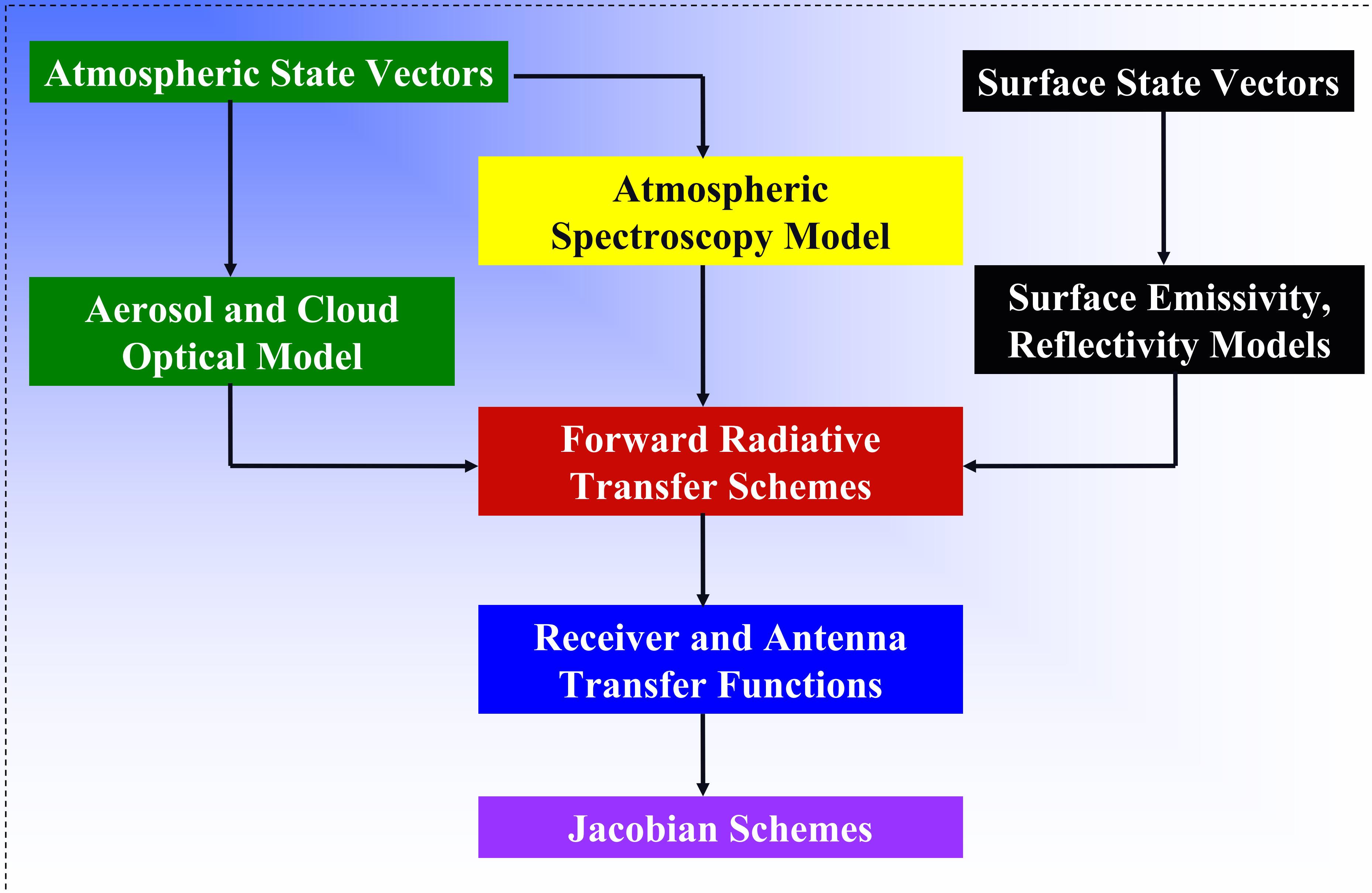


Clear condition



Include two separated cloud layers at 610 and 840 hPa with 0.5 g m^{-3} liquid water.

Community Radiative Transfer Model



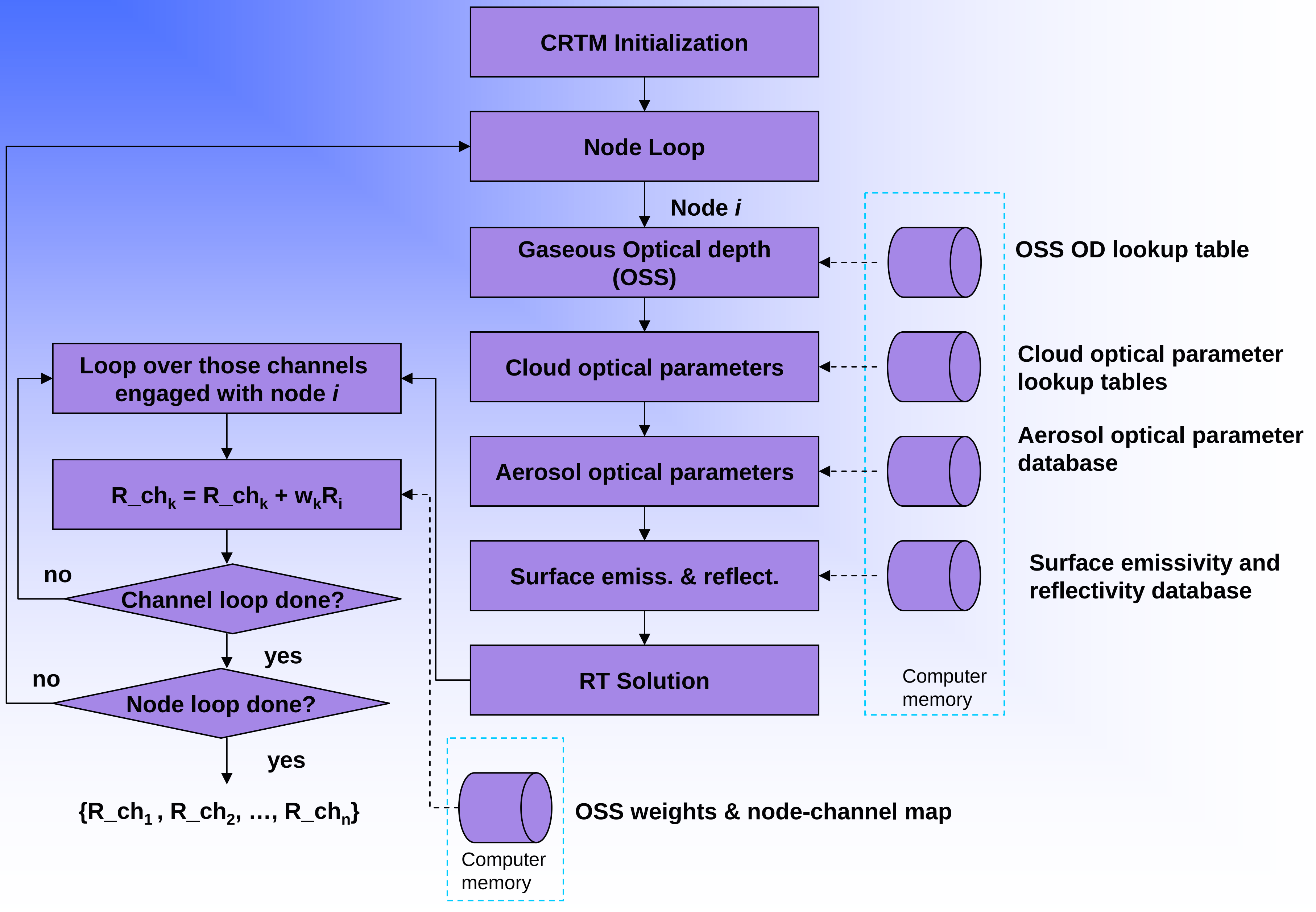
Community Contributions

- Community Research: Radiative transfer science
  - AER. Inc: Optimal Spectral Sampling (OSS) Method
  - NRL – Improving Microwave Emissivity Model (MEM) in deserts
  - NOAA/ETL – Fully polarmetric surface models and microwave radiative transfer model
  - UCLA – Delta 4 stream vector radiative transfer model
  - UMBC – aerosol scattering
  - UWisc – Successive Order of Iteration
  - CIRA/CU – SHDOMPPDA
  - Langley/Hampton Univ – principal component radiative transfer
  - Princeton Univ – snow emissivity model improvement
  - NESDIS/ORA – Snow, sea ice, microwave land emissivity models, vector discrete ordinate radiative transfer (VDISORT), ocean polarimetric, scattering models for all wavelengths
- Core team (ORA/EMC): Smooth transition from research to operation
  - Maintenance of CRTM (OPTRAN/OSS coeff., Emissivity upgrade)
  - CRTM interface
  - Benchmark tests for model selection
  - Integration of new science into CRTM

The CRTM Framework

- The radiative transfer problem is split into various components (e.g. gaseous absorption, scattering etc). Each component defines its own structure definition and application modules to facilitate independent development.
- Minimize or eliminate potential software conflicts and redundancies.
- Components developed by different groups can “simply” be dropped into the framework.
- Faster implementation of new science and algorithms
- At the simplest level, it’s a collection of structure definitions, interface definitions, and stub routines.
- There are User and Developer interfaces, Shared Data interface, Test Software, Utilities/Feedback

Beta Version CRTM flowchart



Computation & Memory Efficiency

Time needed to process 48 profiles with 7 observation angles

	OPTRAN-V7 Forward, Jacobian+Forward	OPTRAN-comp Forward, Jacobian+Forward	OSS Jacobian+Forward
AIRS	7m20s, 22m36s	10m33s, 35m12	3m10s
HIRS	4s, 13s	5s, 17s	9s

Memory resource required (Megabytes)

	OPTRAN-V7 single, double	OPTRAN-comp double precision	OSS Single precision
AIRS	33, 66	5	97
HIRS	0.26, 0.5	0.04	4

Current Forward CRTM Interface

```
Error_Status = CRTM_Forward( Atmosphere, &
                             Surface, &
                             GeometryInfo, &
                             ChannelInfo, &
                             RTSolution )
```

- All data contained in structures.
- Additional "arguments" can be added as required to the requisite structures.
- No impact on calling routine.

Allowable dimensionality

L = number of channels; M = number of profiles

INPUTS			OUTPUTS
Atmosphere	Surface	GeometryInfo	RTSolution
Scalar	Scalar	Scalar	L
M	M	M	$L \times M$

Current K-Matrix CRTM Interface

```
Error_Status = CRTM_K_Matrix( Atmosphere, &
                              Surface, &
                              RTSolution_K, &
                              GeometryInfo, &
                              ChannelInfo, &
                              Atmosphere_K, &
                              Surface_K, &
                              RTSolution )
```

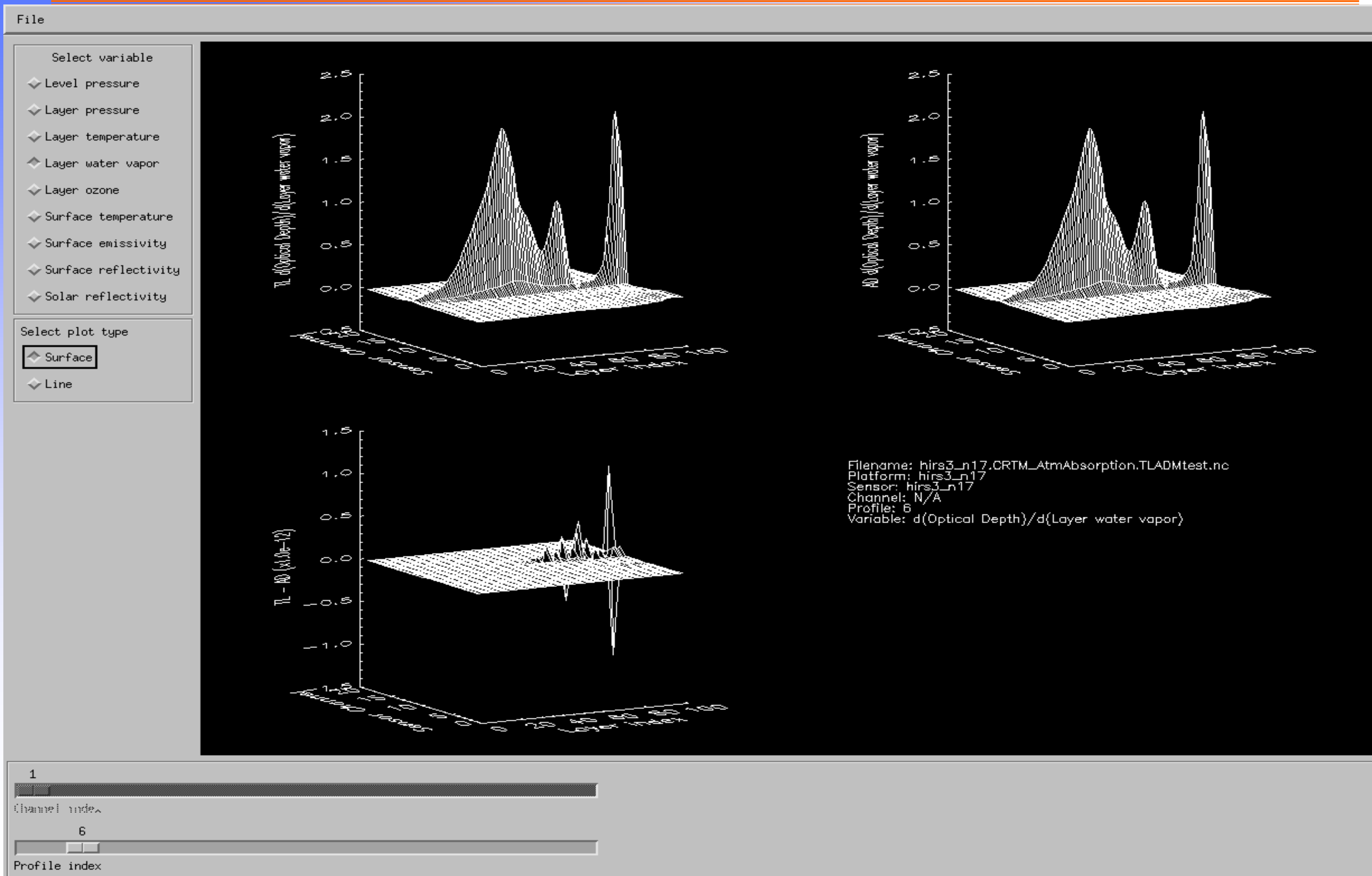
- Same structure definitions for both the forward and K-matrix structures.
- Channel dependencies are handled via the structure array dimensions.

Allowable dimensionality

L = number of channels; M = number of profiles

INPUTS			OUTPUTS	
Atmosphere Surface	RTSolution_K	GeometryInfo	Atmosphere_K Surface_K	RTSolution
Scalar	L	Scalar	L	L
M	L×M	M	L×M	L×M

TL/AD test results for `AtmAbsorption`



Fast Gaseous Absorption Model

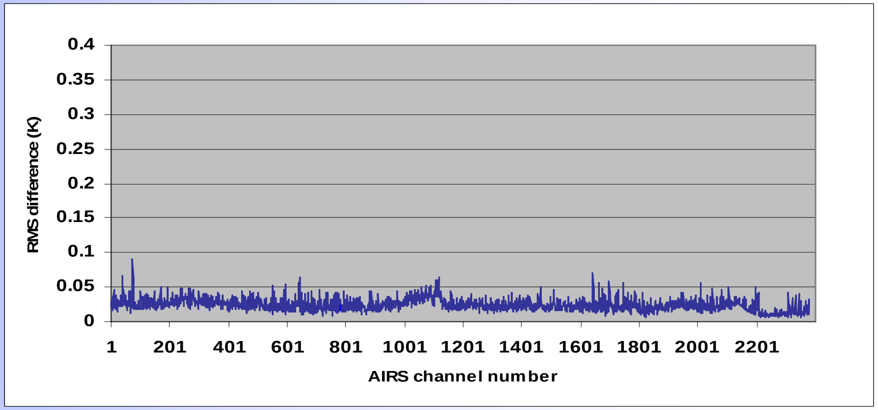
- OSS (Optimal Spectral Sampling) method (Moncet and Uymin, 2003; Moncet *et al.* 2001) models the channel radiance as

$$\overline{R} = \int_{\Delta\nu} \phi(\nu) R(\nu) d\nu \cong \sum_{i=1}^{N} w_i R(\nu_i); \qquad \nu_i \in \Delta\nu$$

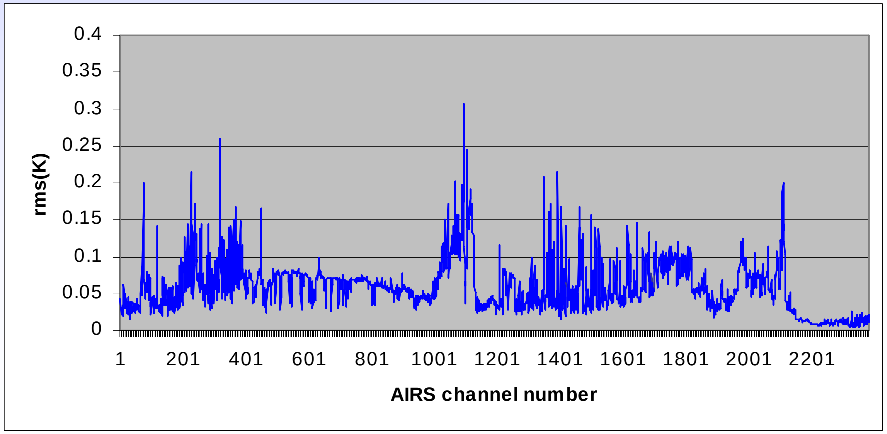
- Wavenumber ν_i (nodes) and weights w_i are determined by fitting "exact" calculations (from line-by-line model) for globally representative set of atmospheres (training set)

- Monochromatic RT (using look-up tables of absorption coefficients for relevant species stored at the selected nodes)
  - Maximum brightness temperature error with current LUT < 0.05K in infrared and <~0.01K in microwave

OSS
Trained with ECMWF set
Tested with UMBC set

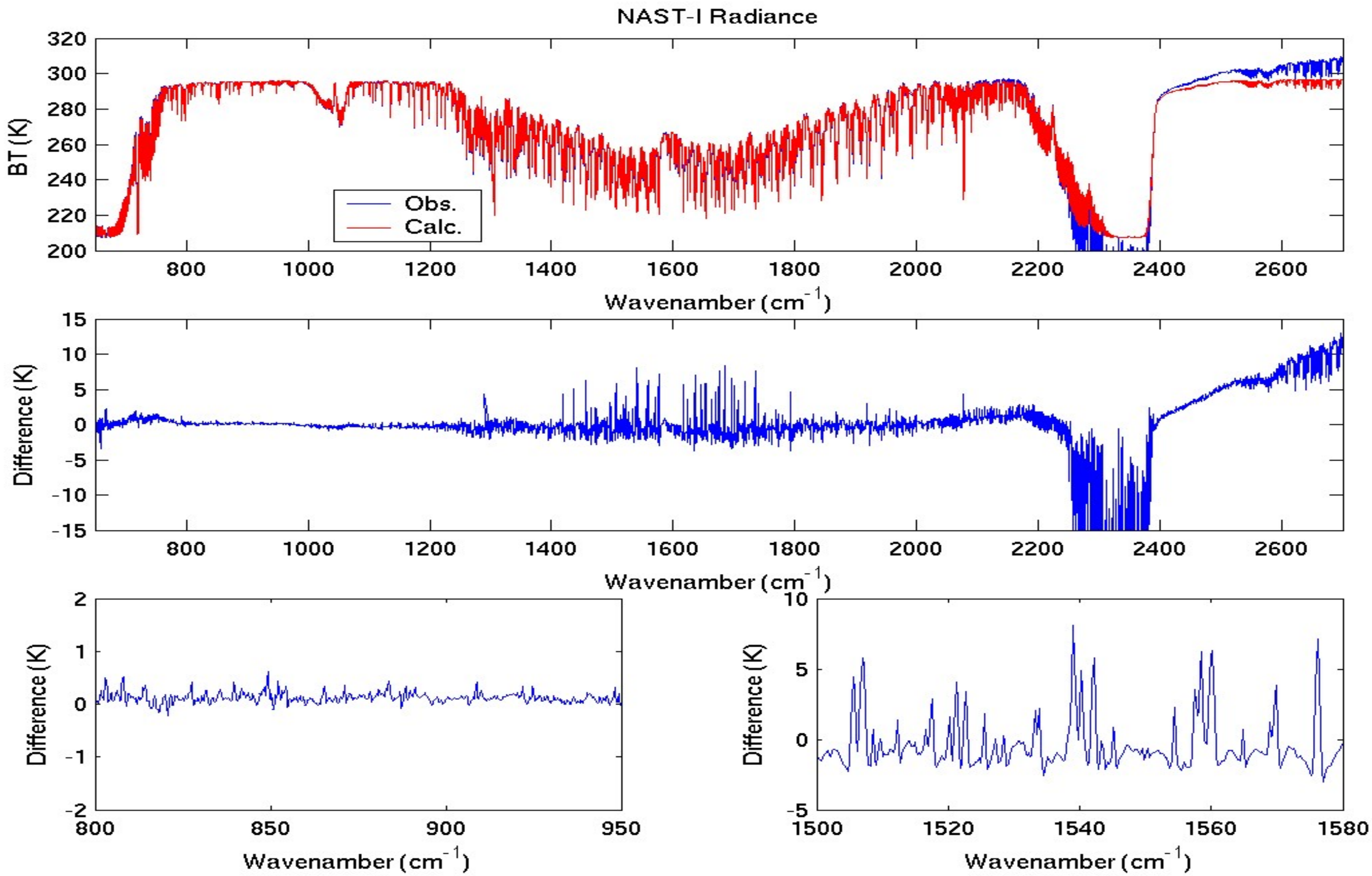


OPTRAN
Trained with UMBC set
Tested with ECMWF set



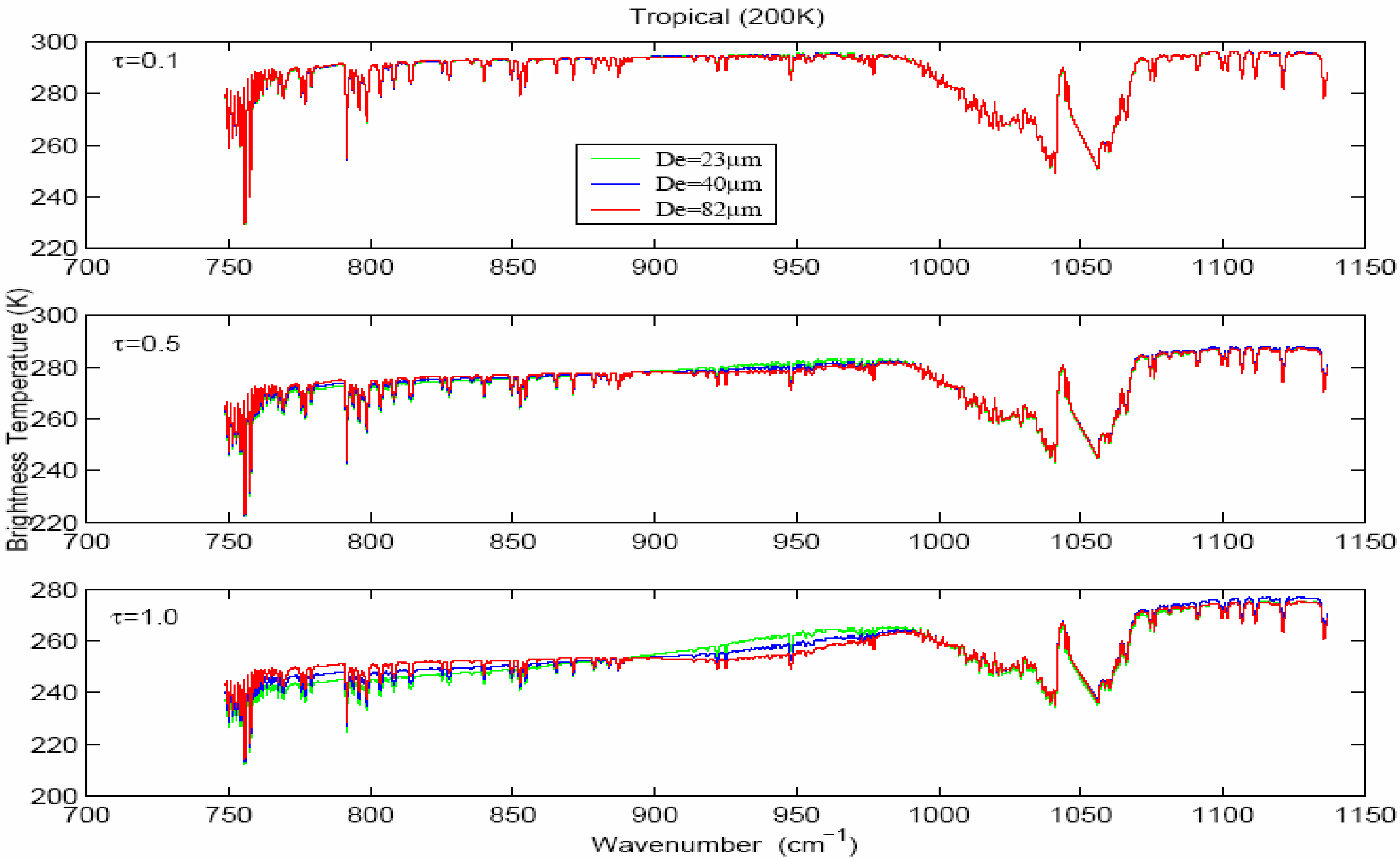
Provided by Y. Han (NESDIS) and J. Moncet (AER)

Principal Component Radiative Transfer



Provided by Xu Liu and Bill Smith

AIRS Sensitivity to Cirrus Clouds



Provided by K.N. Liou and S. Ou

Ocean Emission/Scattering Model

Phenomenology.

- Large gravity waves, whose wavelengths are long compared with the radiation wavelength.
- Small capillary waves, which are riding on top of the large-scale waves, and whose RMS height is small compared with radiation wavelength.
- Sea foam, which arises as a mixture of air and water at the wind roughened ocean surface, and which leads to a general increase in the surface emissivity.

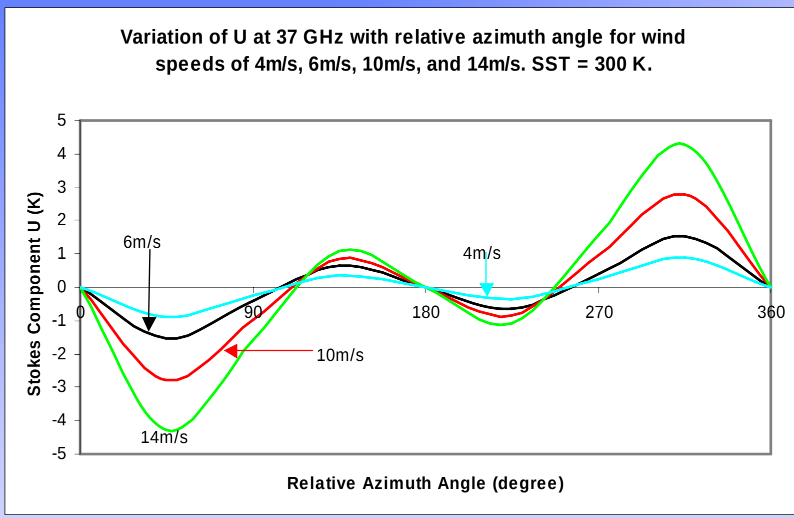
Methodology: two-scale model

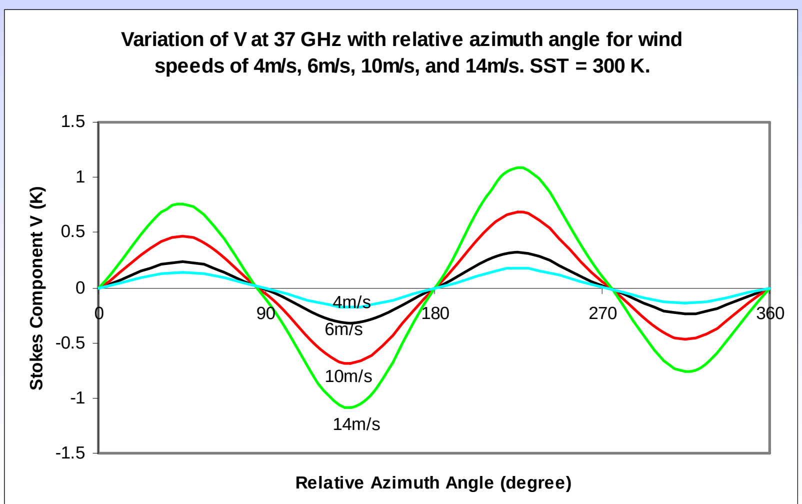
• Gravity wave is simulated as an ensemble of tilted facets each acting as an infinitely large specular surface

•Capillary wave is approximated by small perturbation theory

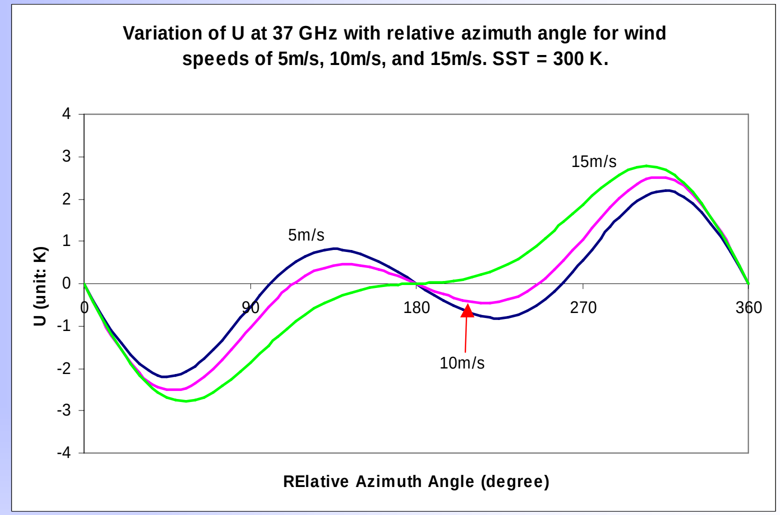
Oceanic Emission Model vs Observations

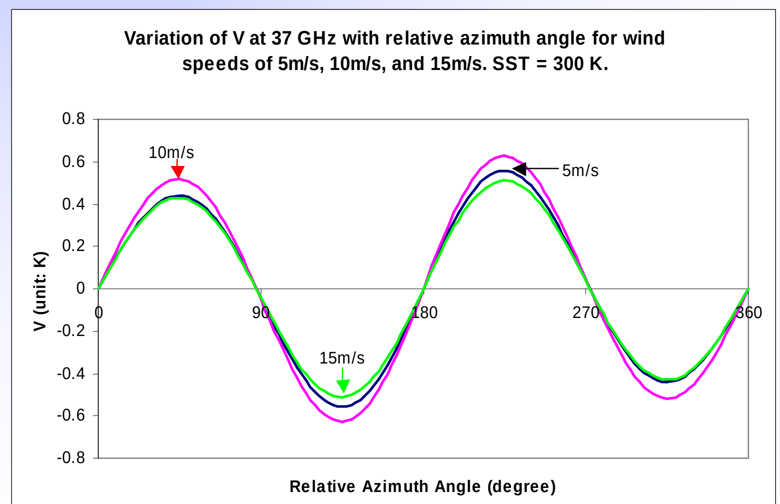
Simulation





Measurement





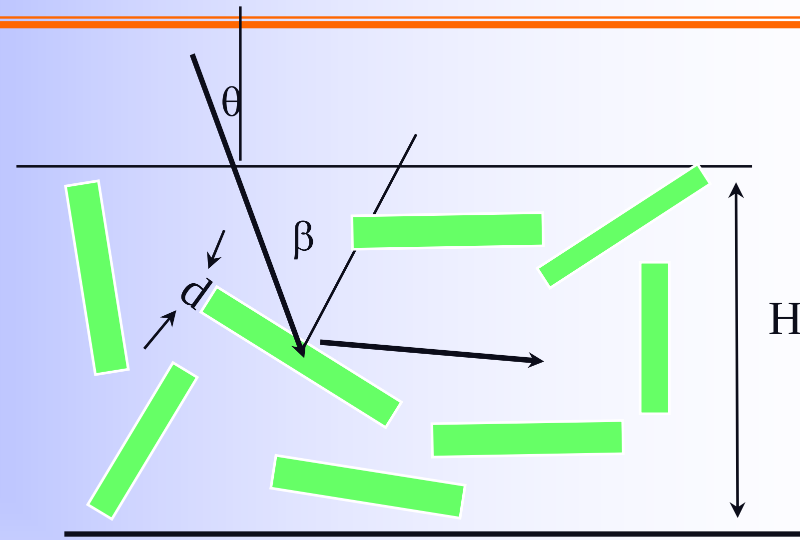
From Poe and St. Germain (1999)

Canopy Scattering Model

Canopy Scattering Model

Factors

- Leaf coverage
- Canopy water content
- Stem population
- Underlying soil moisture content



Methodology: geometric optics is applied because the leaf size is typically larger than wavelength

d - leaf thickness

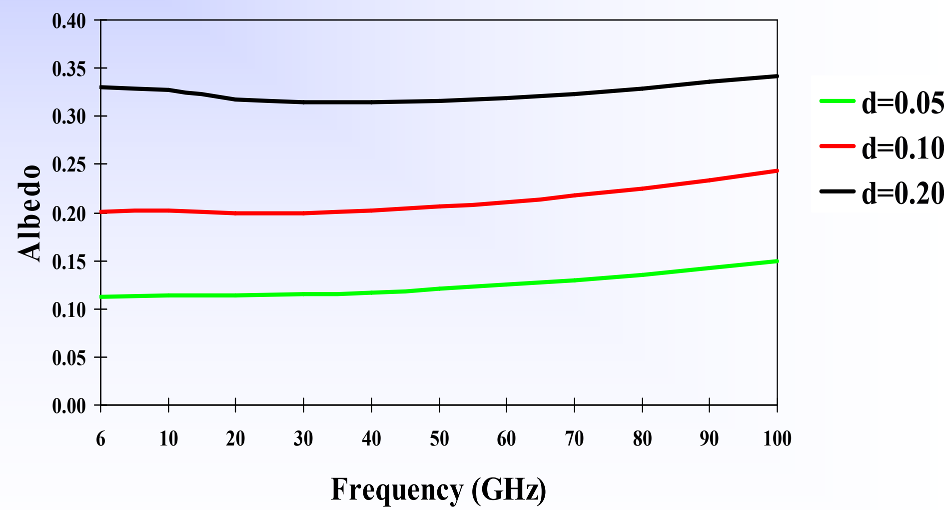
H - canopy height

LAI - leaf area index

m_d - dry matter content

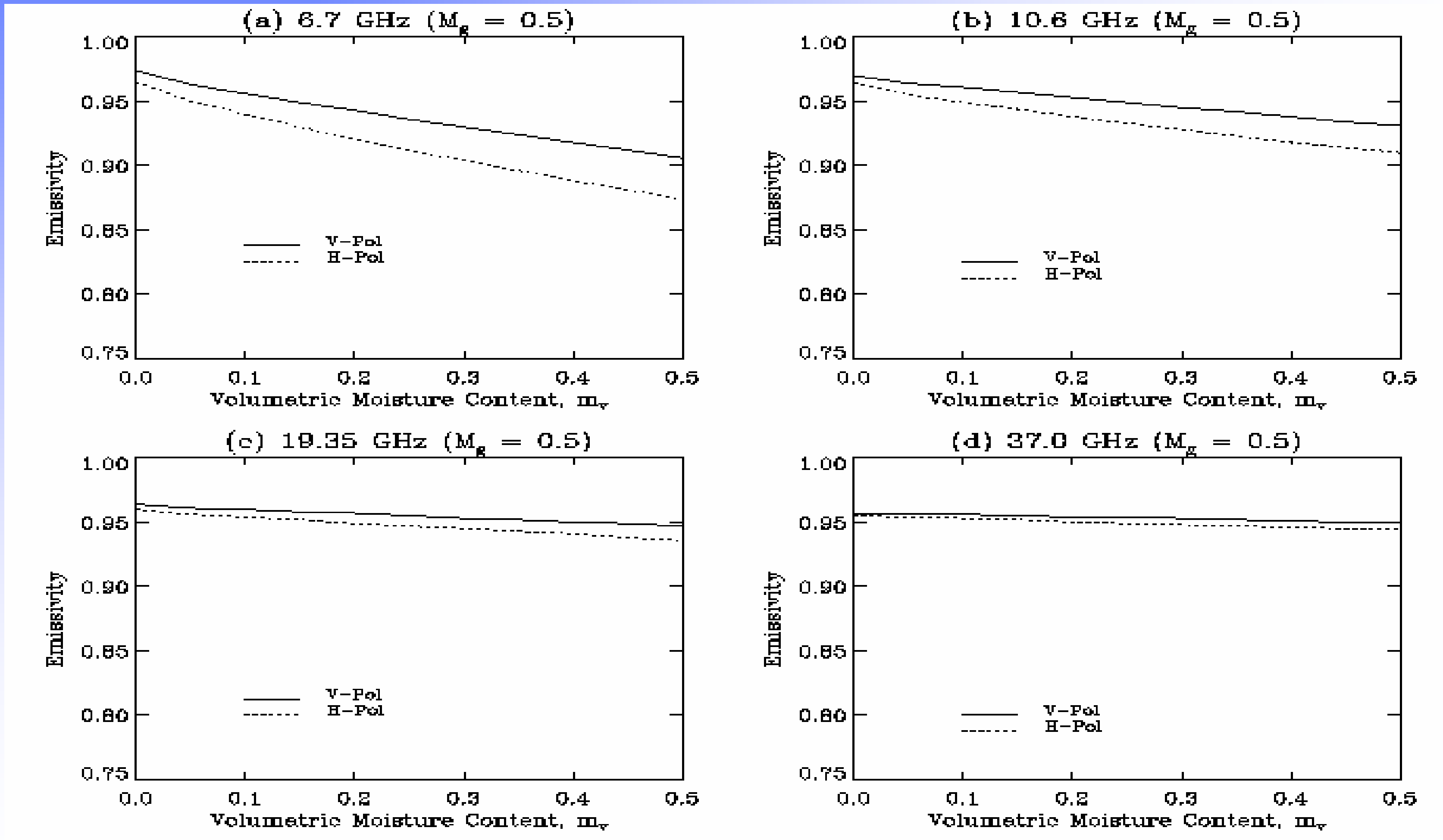
β – leaf orientation angle

θ – incident angle of EM wave

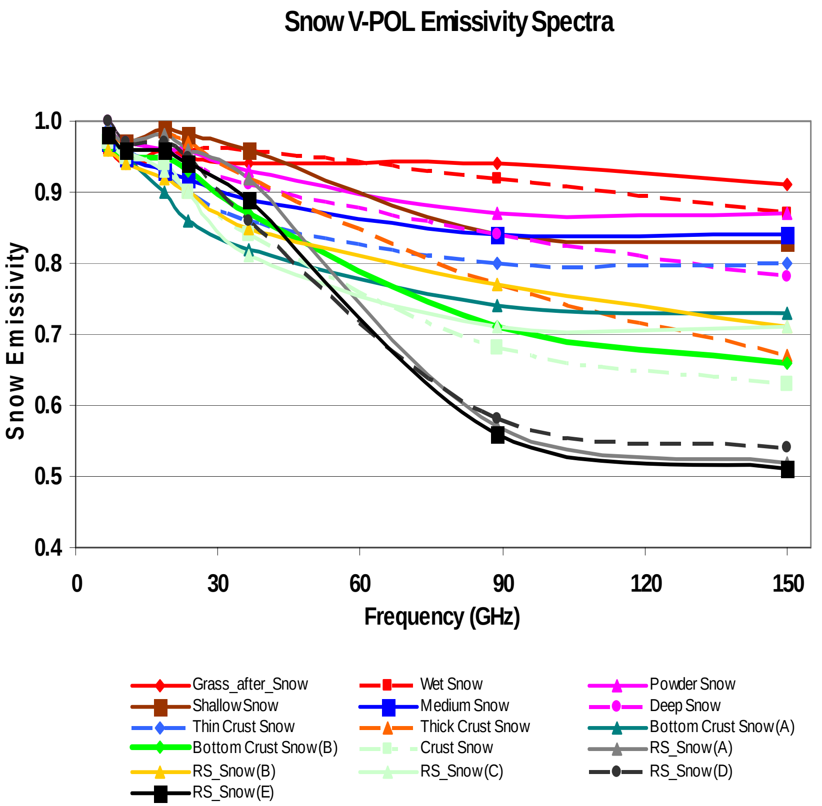


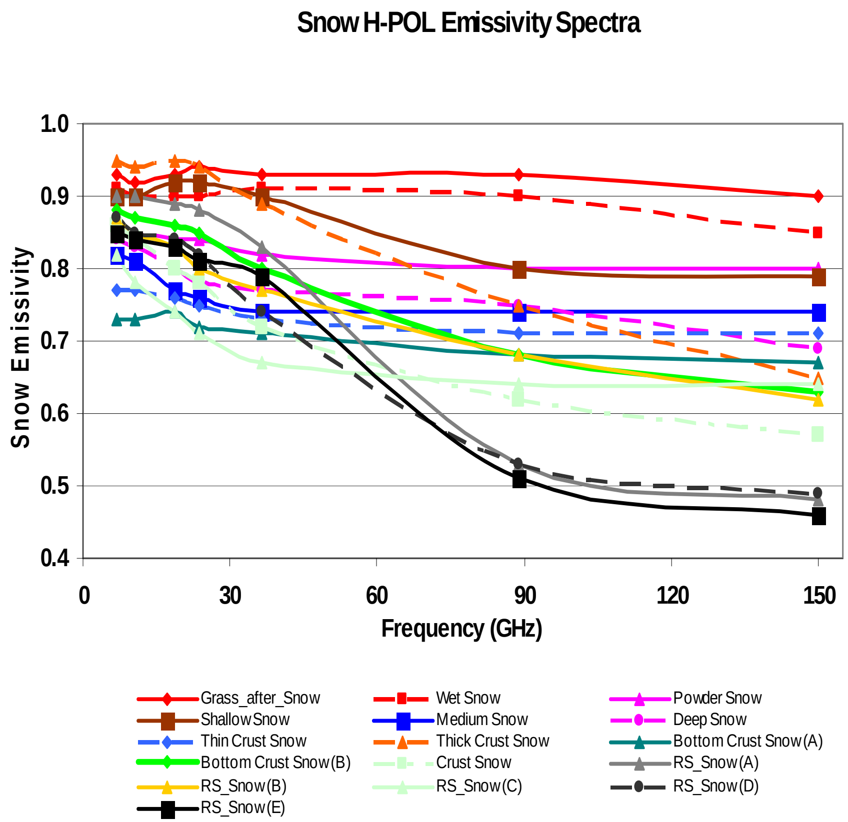
Emissivity-Soil Moisture

with canopy



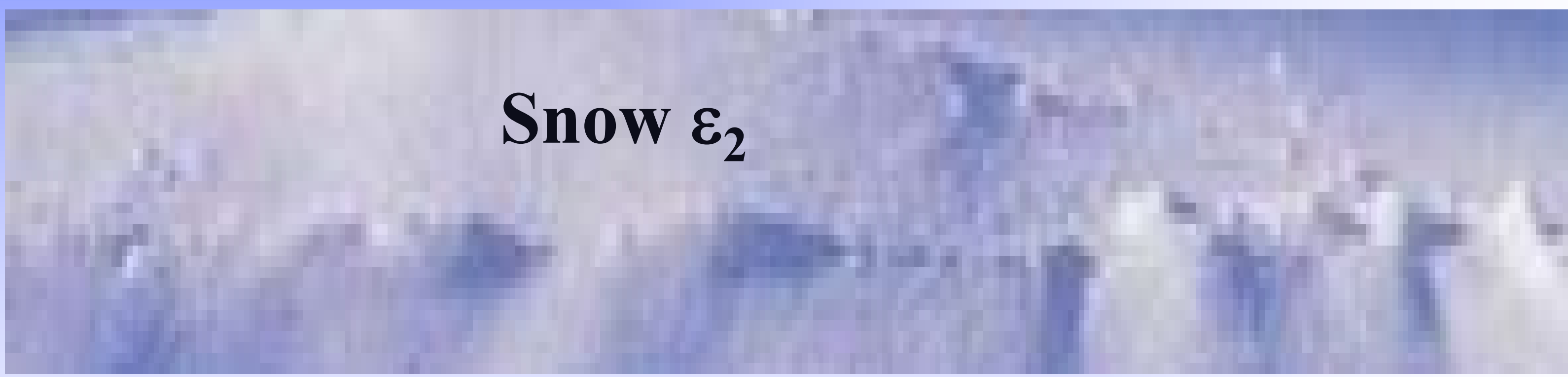
Snow Microwave Emissivity Spectra





Snow Emissivity Model

Air ε_1



Subsurface ε_3

- Dielectric constant within snow is perturbed and a function of volume fraction of scattering particles
- Reflection occurs at interface

Optical Properties of Dense Medium

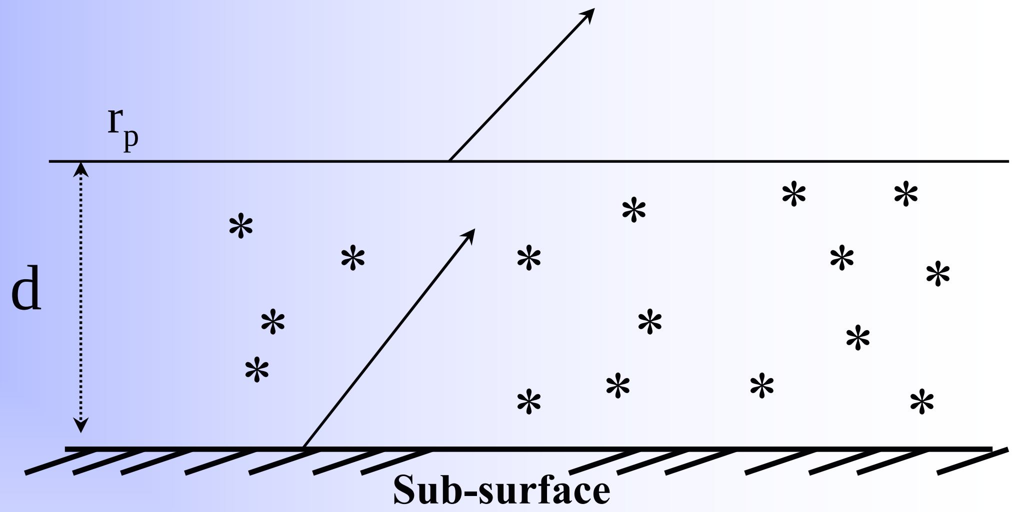
Strong fluactuation theory
(Tsang at al., 1985)

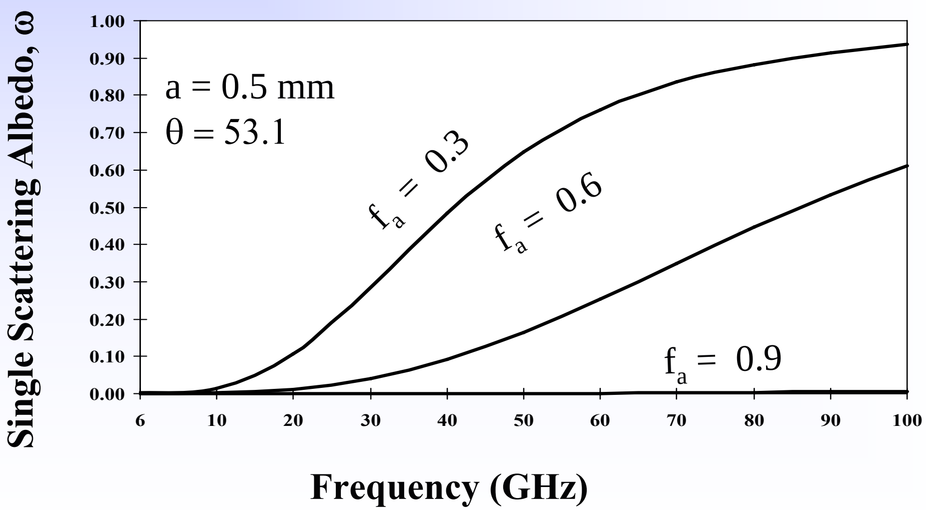
$$\varepsilon_{eff} = \frac{1+2f_a y}{1-f_a y} + i\frac{2f_a y^2(\kappa a)^3(1-f_a)^4}{(1-f_a y)^2(1+2f_a)^2}$$

$$\kappa = \sqrt{3(1-\omega)(1-\omega g)}$$

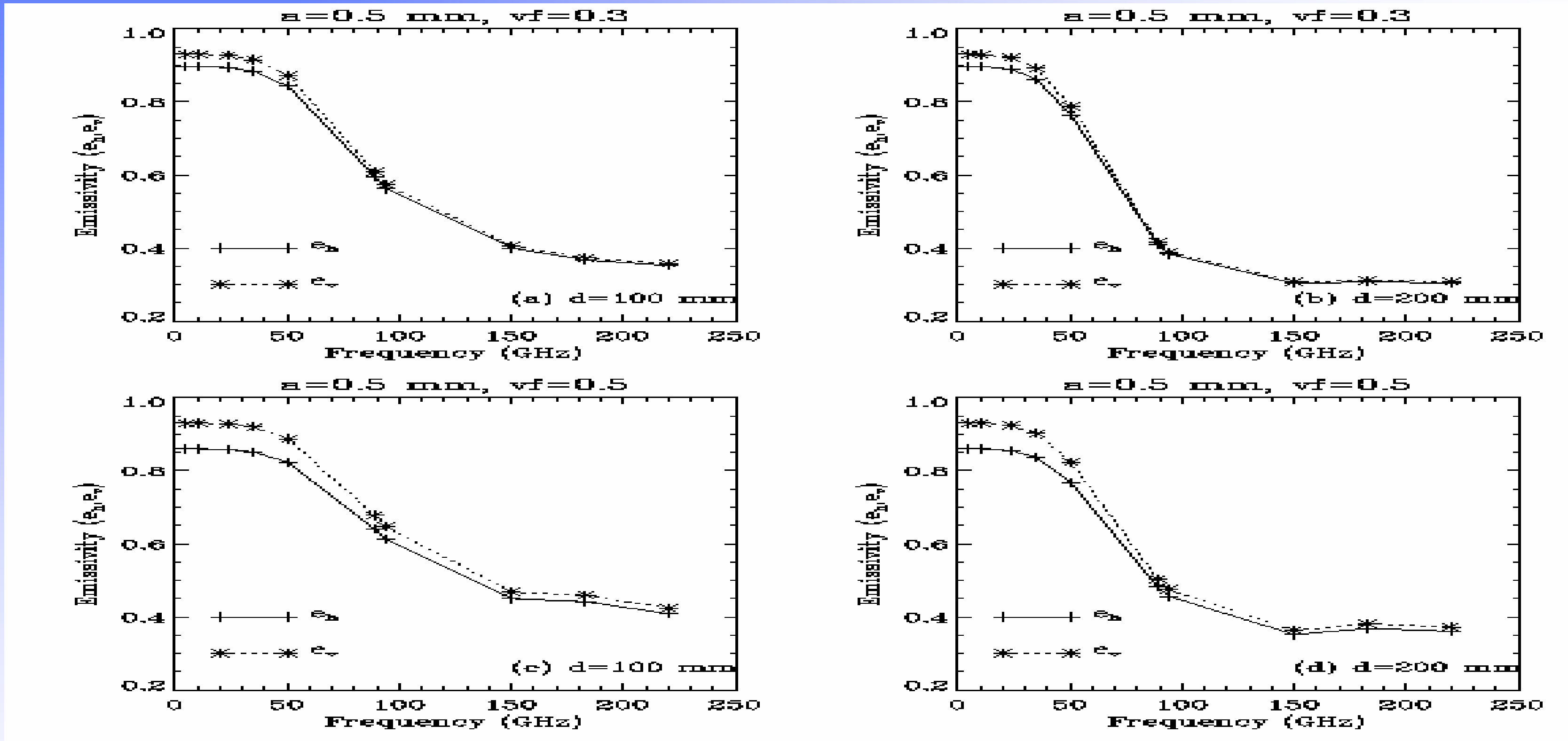
$$y = \frac{\varepsilon_s - \varepsilon}{\varepsilon_s + 2\varepsilon}$$

f_a - ice-volume fraction
d - snow depth
a - snow particle size





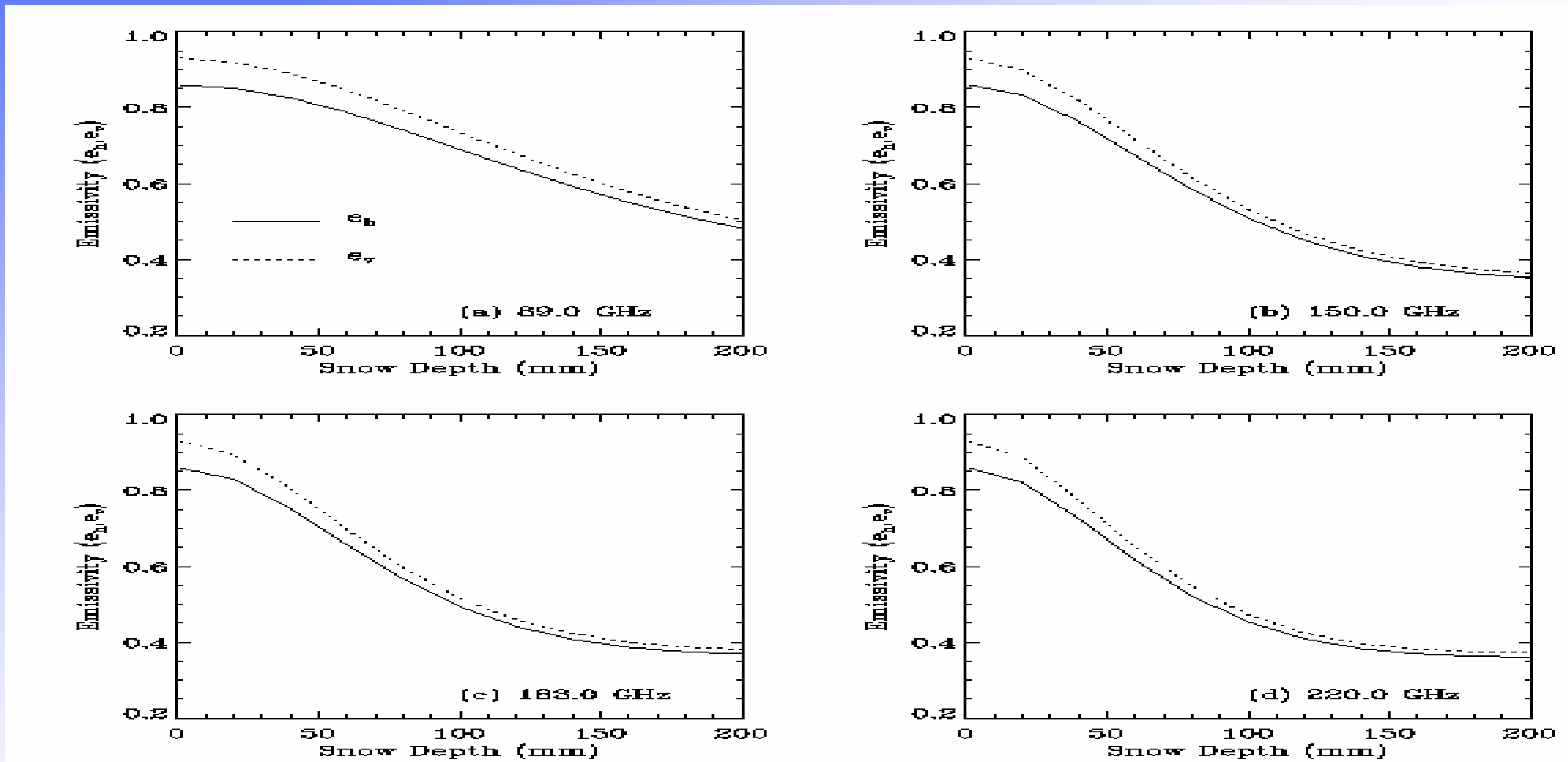
Snow Emissivity Spectra



Parameters:

- Snow depth
- Volume fraction
- Grain size/bulk density

Emissivity vs. Snow Depth

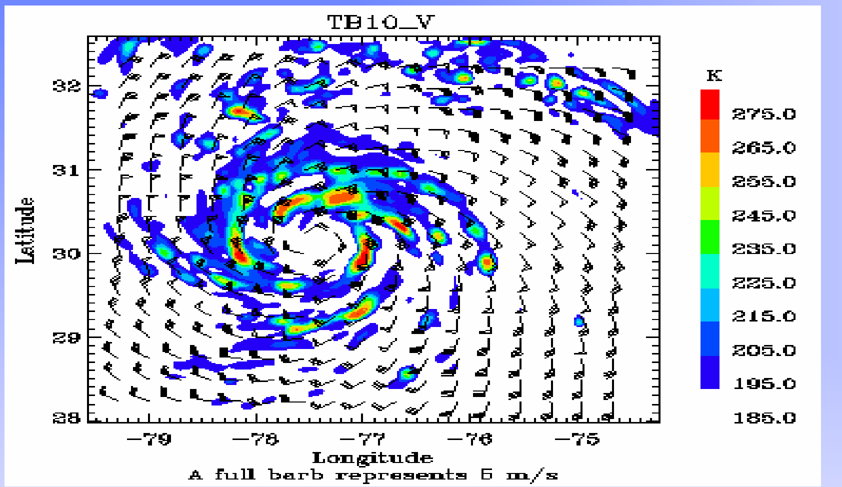


Need Improvements for:

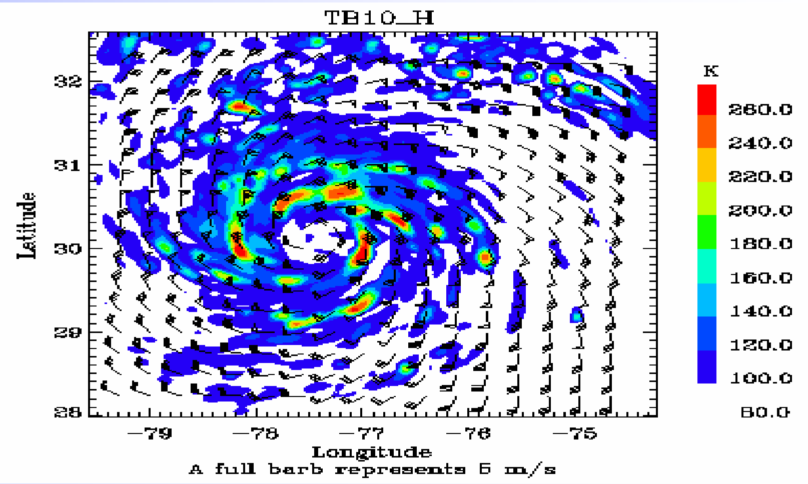
- Snow stratification
- Melting/refrozen
- Metamorphosis process

Stokes Radiance Simulations at Microwave Wavelength, Preparation for NPOESS/CMIS

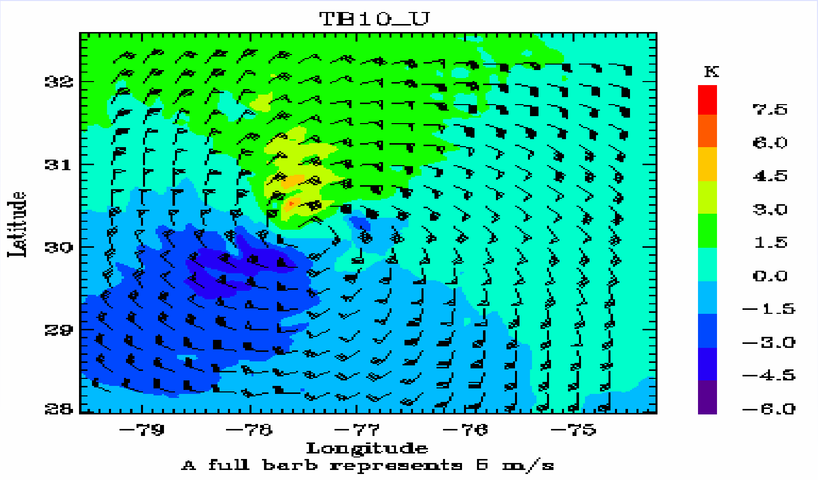
10.7_V



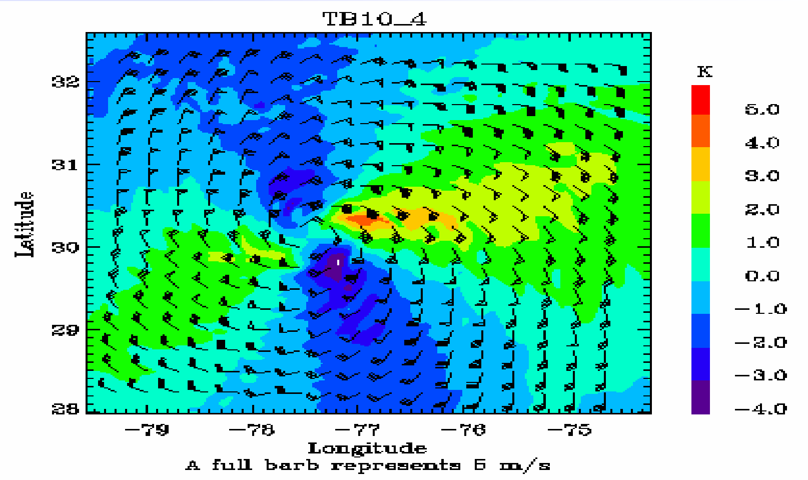
10.7_H



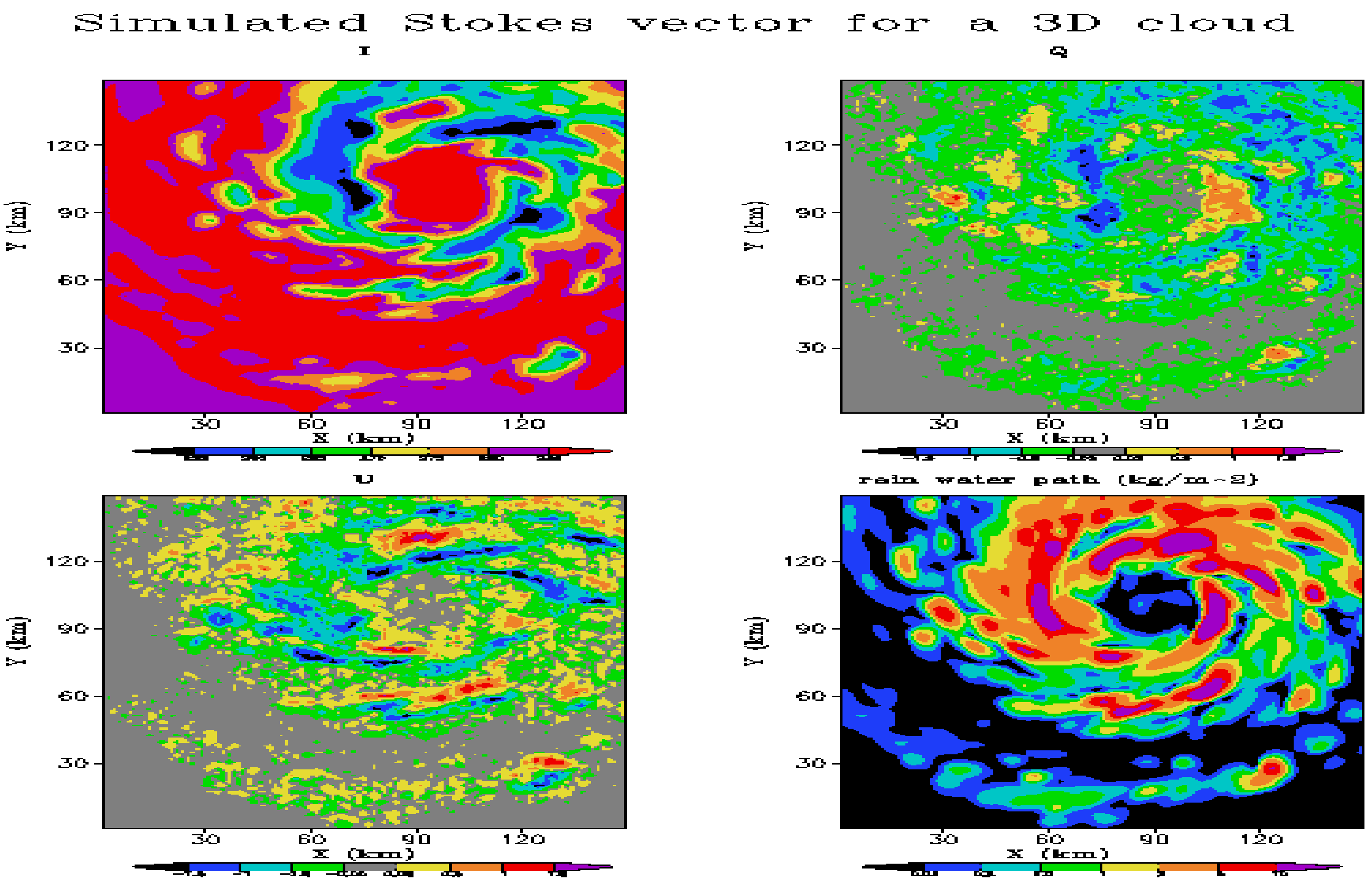
10.7_U



10.7_4



3D Clouds Produce Third Stokes Component at 10.7 GHz



Analytic Jacobian

Jacobian to surface parameters (e.g. surface temperature, soil moisture) can be written as (Weng and Liu, 2003, JAS):

$$\frac{\partial \mathbf{I}_1(\mu)}{\partial x_s} = \sum_{j=1}^{4N} \mathbf{K}_L(\mu, j)\{B(T_s)\frac{\partial \boldsymbol{\varepsilon}}{\partial x_s} + \frac{\partial B(T_s)}{\partial x_s}\boldsymbol{\varepsilon} + \frac{\partial \mathbf{R}}{\partial x_s}\overline{\mathbf{E}}\mathbf{s}_L(\tau_L) + \frac{\partial \mathbf{R}_0}{\partial x_s}\frac{F_0}{\pi}\exp(-\tau_L/\mu_0)\overline{\boldsymbol{\Xi}}\}_j \qquad (1)$$

$$+\sum_{j=1}^{4N} \mathbf{K}_L(\mu, j)\{\frac{\partial \mathbf{R}}{\partial x_s}\overline{\mathbf{E}}\exp[\mathbf{A}_L(\tau_L - \tau_{L-1})]\,\mathbf{c}_L\}_j$$

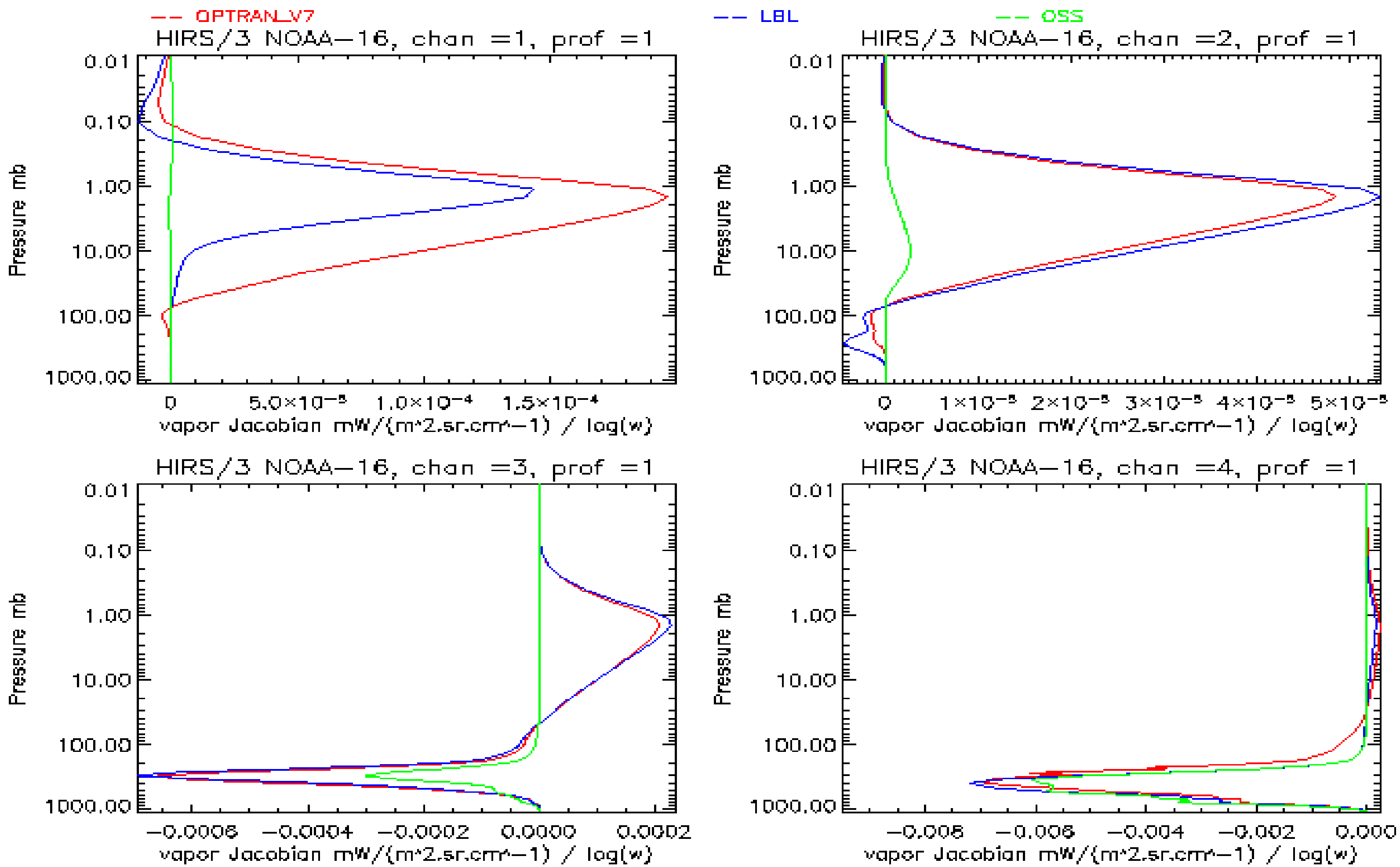
Jacobian to any atmospheric parameters is just a linear sum of the Jacobians to temperature, optical thickness, and phase function/matrix, for example, Jacobian to water vapor,

$$\frac{\partial \mathbf{I}_1(\mu)}{\partial q_l} = \frac{\partial \tau_l}{\partial q_l}\frac{\partial \mathbf{I}_1(\mu)}{\partial \tau_l} + \frac{\partial \varpi_l}{\partial q_l}\frac{\partial \mathbf{I}_1(\mu)}{\partial \varpi_l} = \kappa_l^{abs}\left[\frac{\partial \mathbf{I}_1(\mu)}{\partial \tau_l} - \frac{\varpi_l}{\tau_l}\frac{\partial \mathbf{I}_1(\mu)}{\partial \varpi_l}\right] \qquad (2)$$

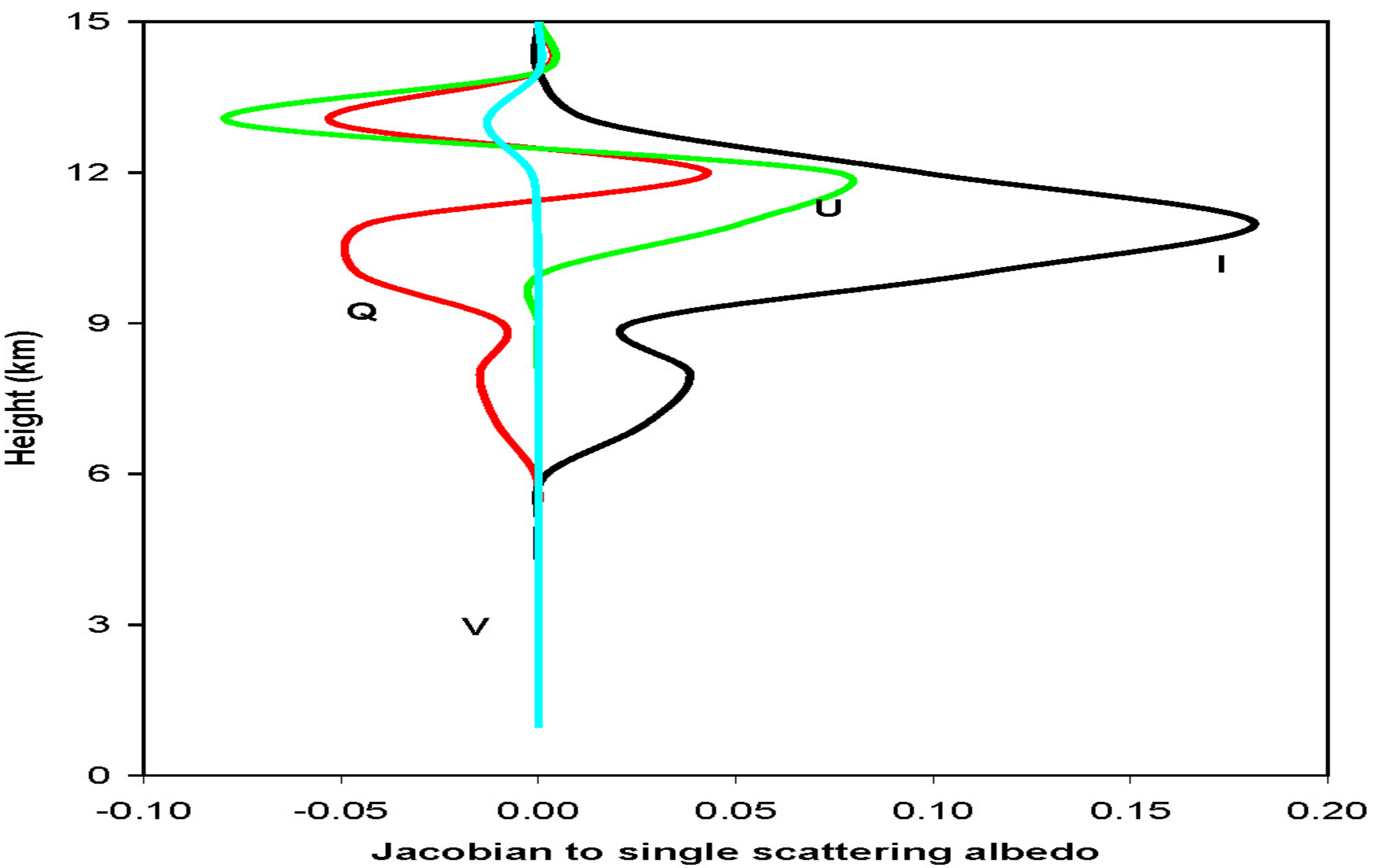
and Jacobian to cloud water,

$$\frac{\partial \mathbf{I}_1(\mu)}{\partial w_l} = \frac{\partial \tau_l}{\partial w_l}\frac{\partial \mathbf{I}_1(\mu)}{\partial \tau_l} + \frac{\partial \varpi_l}{\partial w_l}\frac{\partial \mathbf{I}_1(\mu)}{\partial \varpi_l} = \frac{\tau_l - \kappa_l^{abs} q_l}{w_l}\frac{\partial \mathbf{I}_1(\mu)}{\partial \tau_l} + \frac{\varpi_l \kappa_l^{abs} q_l}{w_l \tau_l}\frac{\partial \mathbf{I}_1(\mu)}{\partial \varpi_l} \qquad (3)$$

Water vapor Jacobians at weak water vapor channels



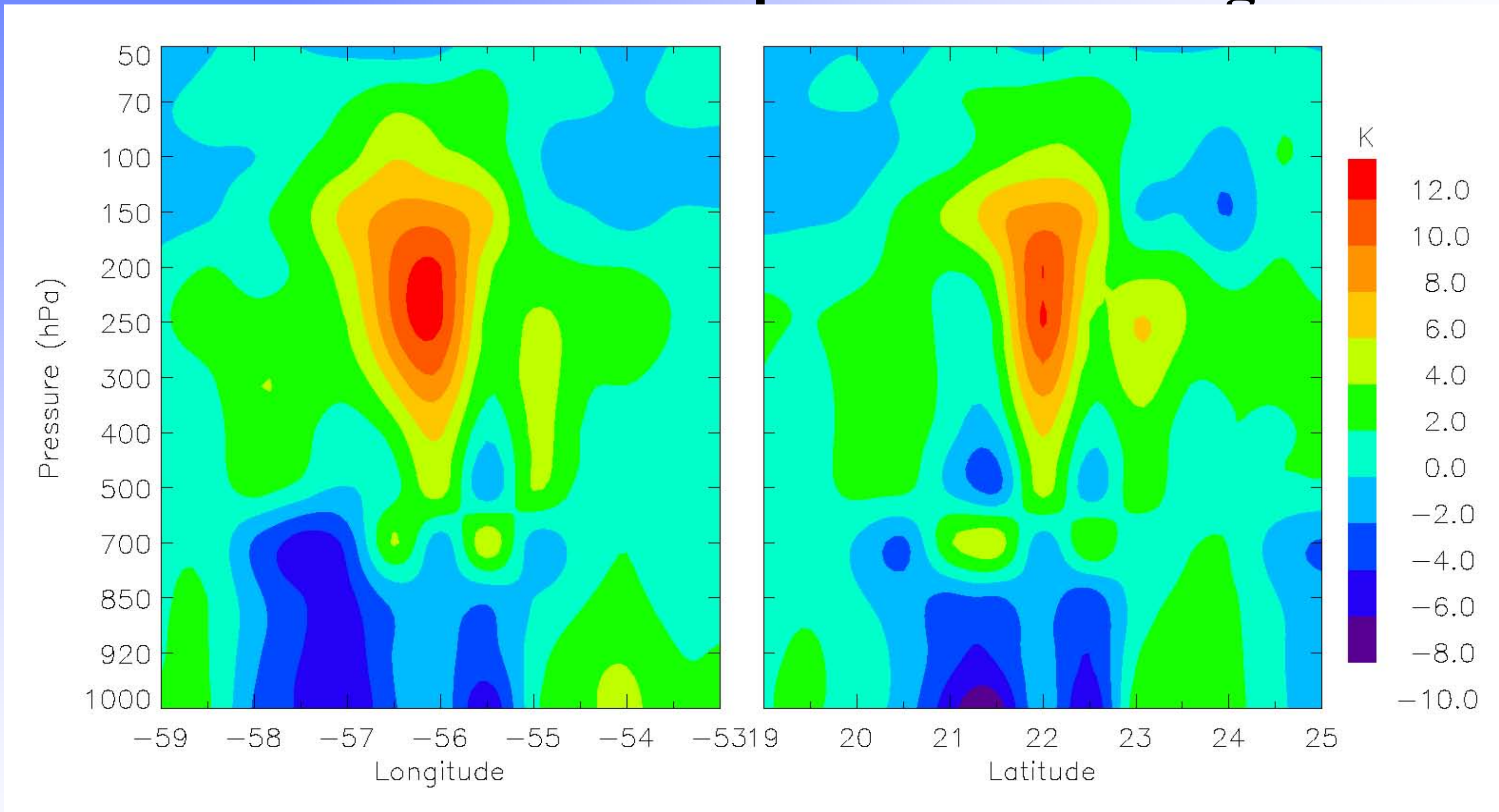
Stokes Jacobians at 0.67 micron Preparation for NPOESS/APS



(Weng and Liu, 2003, JAS)

Hurricane Isabel Temperature Anomaly

With Cloud/Precipitation Scattering

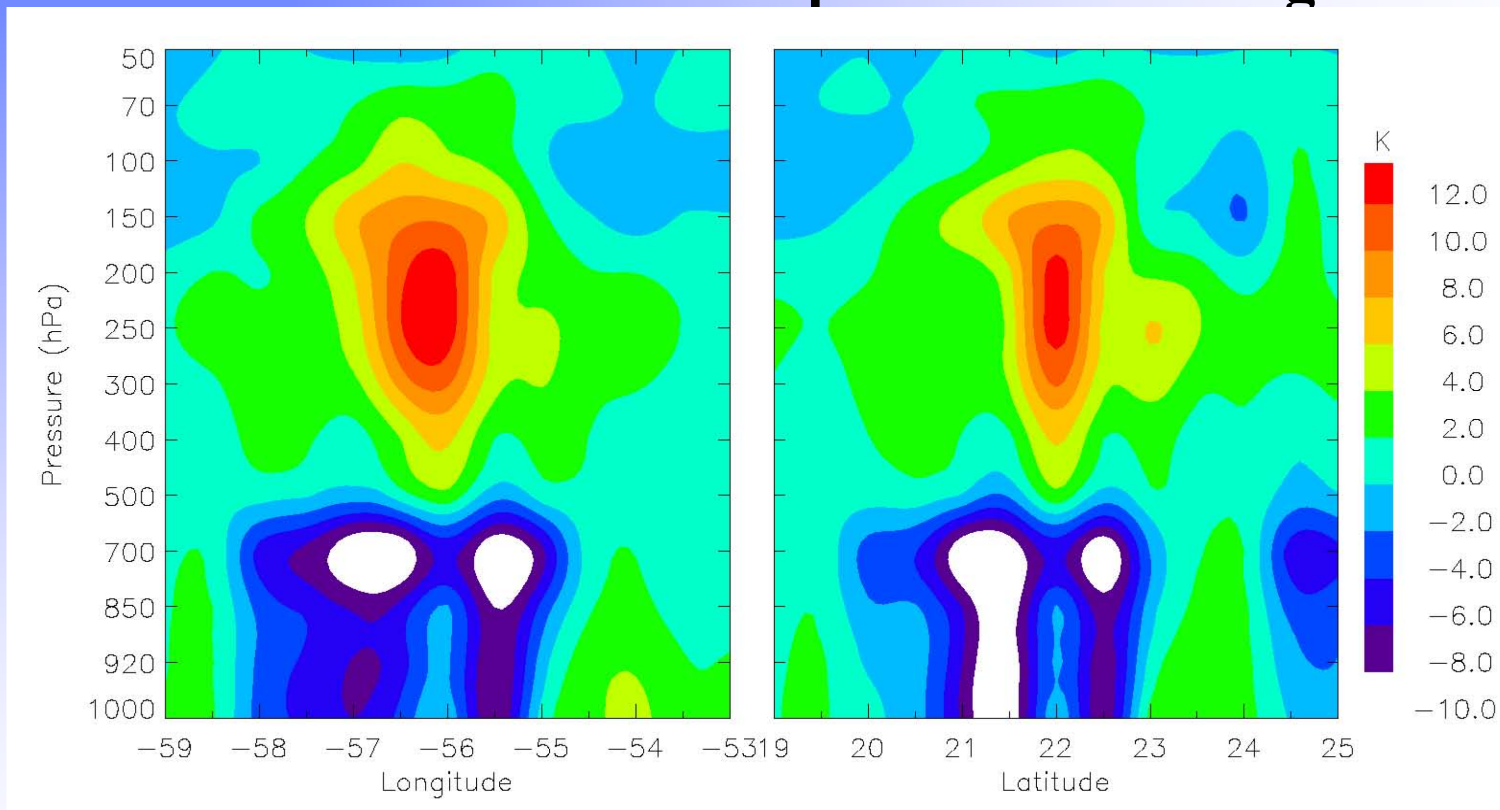


Vertical cross section of temperature anomalies at 06:00 UTC 09/12/2003. Left panel: west-east cross section along 22☜N, and right panel: south-north cross section along 56☜W for Hurricane Isabel

$$\mu \frac{d\mathbf{I}(\tau,\Omega)}{d\tau} = -\mathbf{I}(\tau,\Omega) + \frac{\omega}{4\pi}\int_0^{4\pi} \mathbf{M}(\tau,\Omega,\Omega')\mathbf{I}(\tau,\Omega')d\Omega' + (1-\omega)\mathbf{S}_t$$

Hurricane Isabel Temperature Anomaly

Without Cloud/Precipitation Scattering



Vertical cross section of temperature anomalies at 06:00 UTC 09/12/2003. Left panel: west-east cross section along 22☜N, and right panel: south-north cross section along 56☜W for Hurricane Isabel

$$\mu \frac{d\mathbf{I}(\tau,\Omega)}{d\tau} = -\mathbf{I}(\tau,\Omega) + (1-\omega)\mathbf{S}_t$$

Summary

- The Community Radiavtive Transfer Model (CRTM) is being developed through the JCSDA satellite data assimilation program
- The CRTM includes vital components required for direct assimilations of current and future operational satellite radiances and will allow for uses of satellite data under all weather conditions in NWP models
- The CRTM is a framework with all interfaces to link university research and is accelerating the transition of new radiative transfer science into US operational NWP data assimilation systems (NASA and DoD are planning to use the same CRTM)

Outstanding Issues

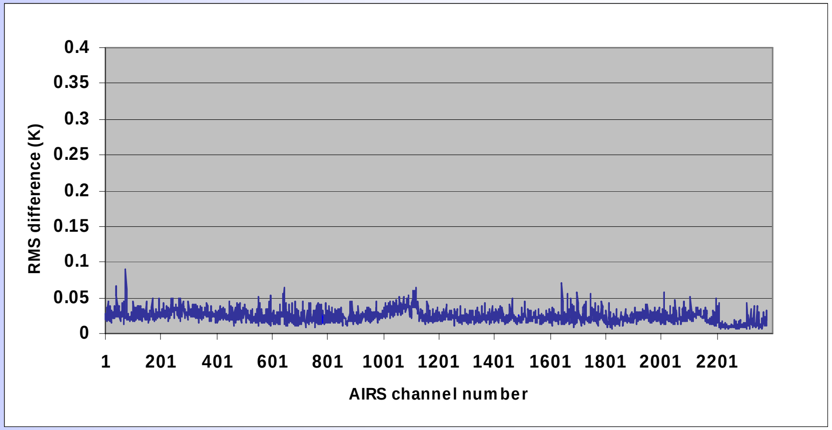
- Lack of schemes for diagnosing the hydrometeors associated with sub-grid convection
- Lack of high quality dataset to validate CRTM under cloudy conditions
- Consistent assumptions in cloud microphysics from visible, infrared and microwave wavelengths used in CRTM with NWP models
- Limited access to operational forecast models outputs
- Surface scattering/emission related to dense medium materials
- Inclusion of spatial inhomogeneity of clouds and precipitation in CRTM
- Infrared emissivity over deserts
- Sea ice emissivity modeling at microwave frequencies

Backup Slides from The JCSDA 3rd Workshop on Satellite Data Assimilation: Radiative Transfer, Clouds & Precip Session

Co-chairs: Fuzhong Weng (NESDIS/ORA)
Lars Peter Riishojgaard (GSFC/GMAO)

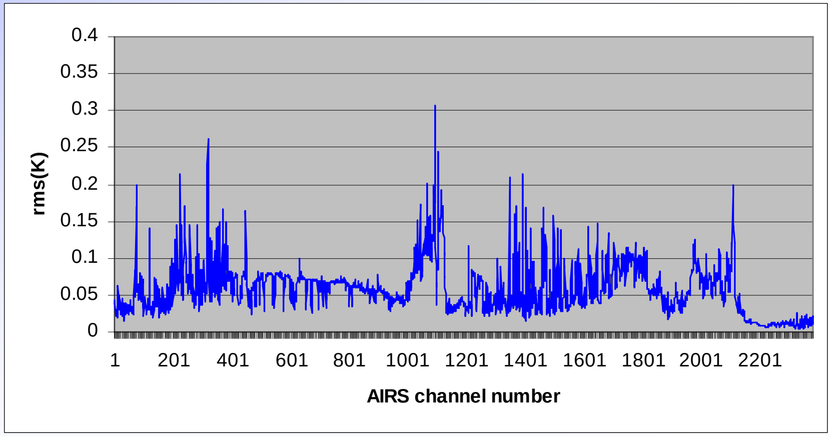
Integrating Community RT Components into JCSDA CRTM – Science

Contributors: Y. Han, Q. Liu and P. van Delst,
F. Weng, T. J. Kleespies and L. M. McMillin



Summary of Accomplishments

- Gaseous absorption modules implemented in CRTM: OPTRAN and OSS
- Cloud optical parameter databases also included: ORA lookup tables
- Surface emissivity and reflectivity module with LandEM, MW Sea Ice/Snow emissivity model, MW Ocean emissivity model, IRSSE, and IR land emissivity database.
- RT solution modules: VDISORT and the following modules or programs : UW SOI, ETL RT Solver and UCLA Vector Delta-4 Stream.



Future Plans

- Delivery of a Beta version of CRTM in June 05

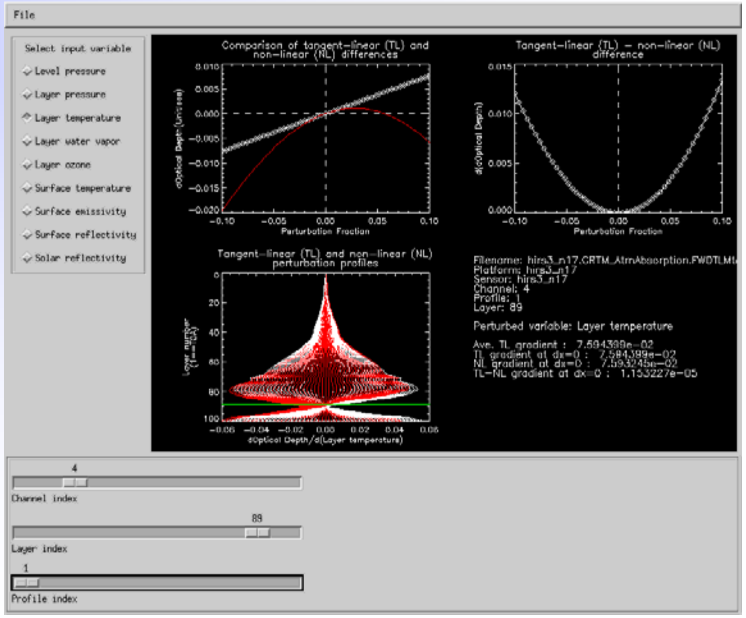
Integrating Community RT Components into JCSDA CRTM – User Interface

Contributors: Y. Han, P. van Delst, Q. Liu

Type Name	Description
`SpcCoeff_type`	Channel frequencies, polarisation, Planck function coefficients, etc.
`TauCoeff_type`	Coefficient data used in the `AtmAbsorption` functions.
`AerosolCoeff_type`	Coefficient data used in the `AerosolScatter` functions.
`ScatterCoeff_type`	Coefficient data used in the `CloudScatter` functions.

Summary of Accomplishments

- All data contained in structures
- Additional "arguments" can be added as required to the requisite structures.
- Visualization tools developed
- CRTM tested on several instruments (AMSU, AIRS, HIRS)



Future Plans

- Test each CRTM component (gaseous absorption, scattering, etc) in each model (Forward, K-matrix, etc) for consistency, as well as the end-to-end test.

Development of RT models based on optimal spectral sampling method (OSS)

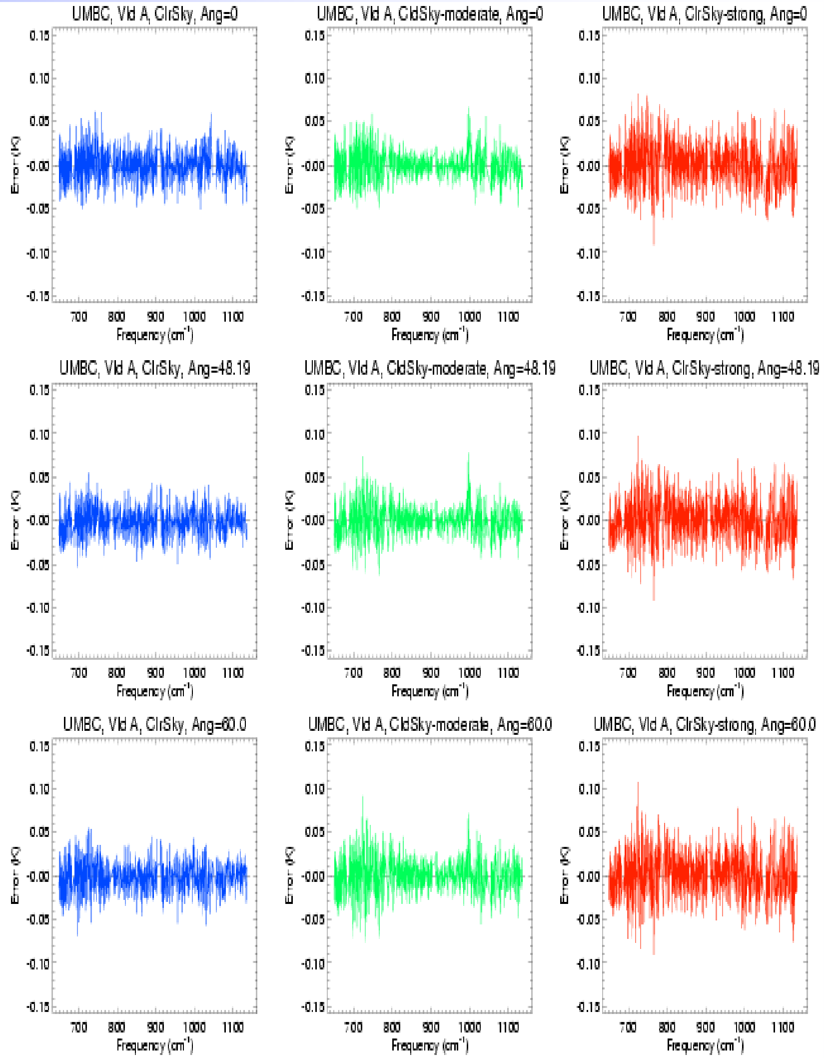
Contributors: **J-L Moncet, Gennadi Uymin and Sid Boukabara (AER)**

Summary of Accomplishments

- Clear-sky comparison (accuracy and timing) with OPTRAN
- Beta version of CRTM with OSS engine delivered
- Explored new approaches for speeding up (and reducing memory requirements) the method in clear and cloudy skies
- Preliminary cloudy validation

Future Plans

- Work with NOAA to finalize the OSS integration into the CRTM
- Work with NOAA to complete OPTRAN comparison and extend to scattering atmospheres (other: complex surface emissivities / solar regime)
- Continue multi-channel selection development in parallel
- Export OSS generation



Microwave Emissivity Model Upgrade

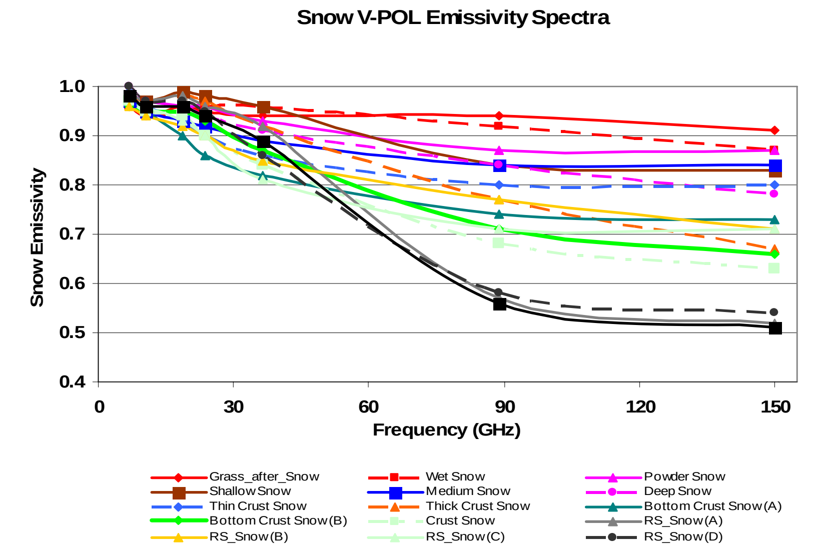
Contributors: ORA: Fuzhong Weng (PI), Banghua Yan; EMC: Kozo Okomoto (EMC visiting scientist)

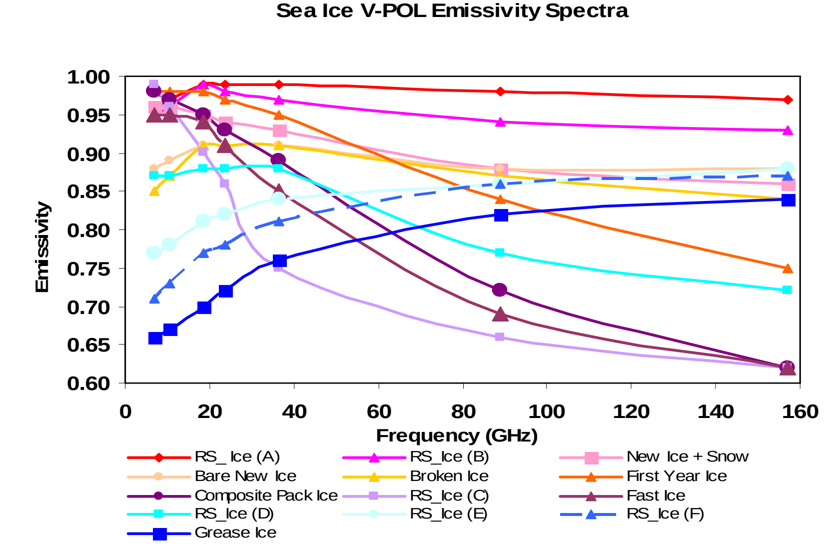
Summary of Accomplishments

- Microwave emissivity models have been updated for new sensors (e.g. SSMIS, MHS) over snow and sea ice conditions
- Microwave snow and sea ice emissivity models are integrated as part of CRTM
- These upgrades improve AMSU data utilization rate in polar atmospheres (200-300% increase)
- Impacts of the emissivity models on global 6-7 forecasts are also assessed and significant

Future Plans

- Investigate large emissivity biases over regions as highlighted by other PIs
- Fix the ocean emissivity model bugs in NCEP at lower frequencies





Toward Passive microwave radiance assimilation of clouds and precipitation

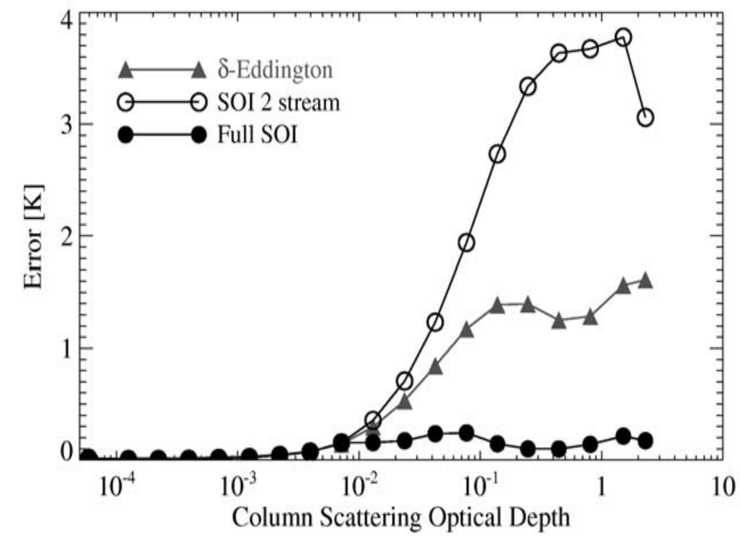
Contributors: R. Bennartz (PI) (UW) T. Greenwald (CIMSS), A. Heidinger (ORA), C. O'Dell (UW), M. Stenge (UW), K. Campana (EMC), P. Bauer (ECMWF)

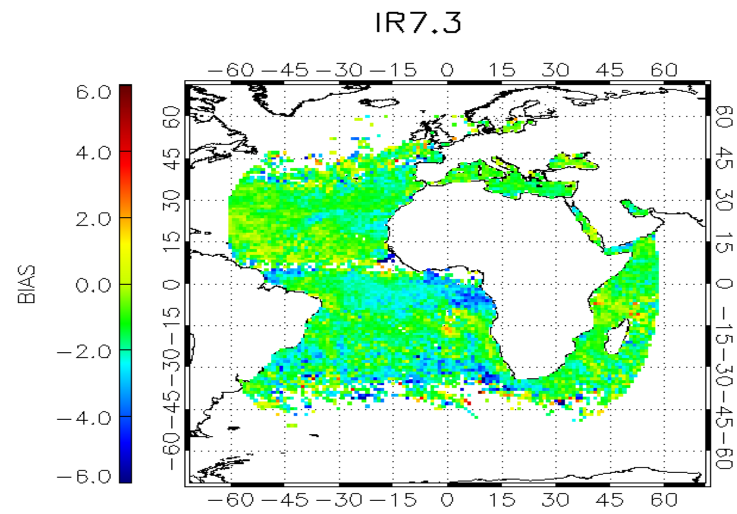
Summary of Accomplishments

- Fast RT models (SOI) developed, tested and integrated in CRTM
- Tangent linear and adjoint model developed, tested, and integrated in CRTM
- Bias statistics for passive microwave
- Initial results also for infrared SEVIRI cloud-free

Future Plans

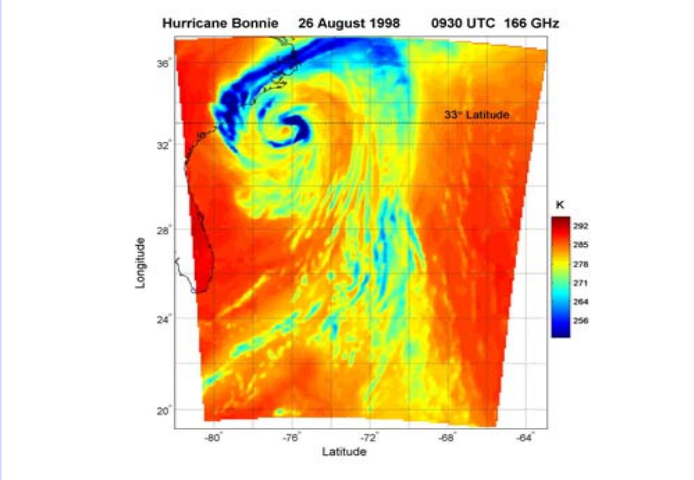
- Monitor bias statistics over longer time period,: fully include scattering (need more complete GFS input data), biases in IR including scattering
- Precipitation assimilation: include cloud diagnostics to generate precipitation rate 1DVAR loop to optimize moisture profiles versus direct assimilation





Discrete Ordinate Tangent Linear Radiative Transfer (DOTLRT) Model for All-Weather Microwave Radiance Assimilation

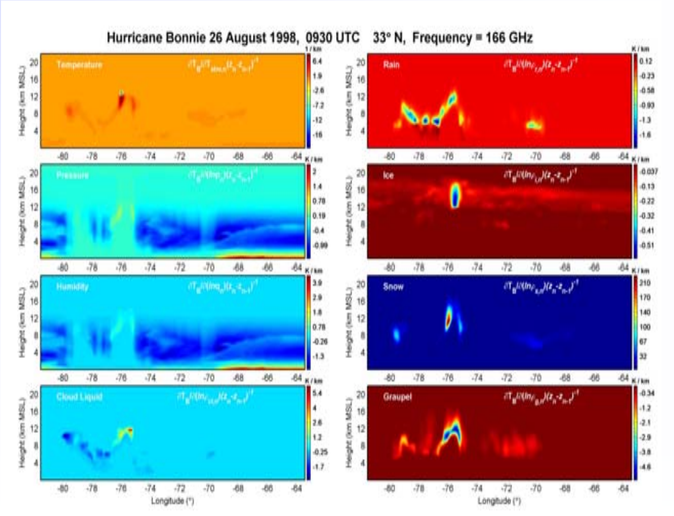
Contributors: Al Gasiewski (PI), Alexander Voronovich, Bob Weber, Dean Smith, Timothy Schneider, Jian-Wen Bao (NOAA/ETL)



Summary of Accomplishments

- DOTLRT interfaced with CRTM, and further tested at JCSDA
- Interface tested/validated using comparisons of T_b and Jacobians
- Improved accuracy of cloud scattering: Henyey-Greenstein phase function approximation replaced with full Mie scattering phase function
- Improved computational speed: Mie scattering library for all microwave frequencies developed
- Two components of Stokes vector developed (horizontal and vertical T_b)

Tb and Analytic Jacobians
CRTM / DOTLRT



Future: - Finish up the Stoke vector development; Interface DOTLRT solver with CRTM Cloud Scatter module for generic stream angles; implement analytic Jacobians in K-matrix; Test/validate CRTM

UCLA Vector Radiative Transfer Model for Application to Satellite Data Assimilation

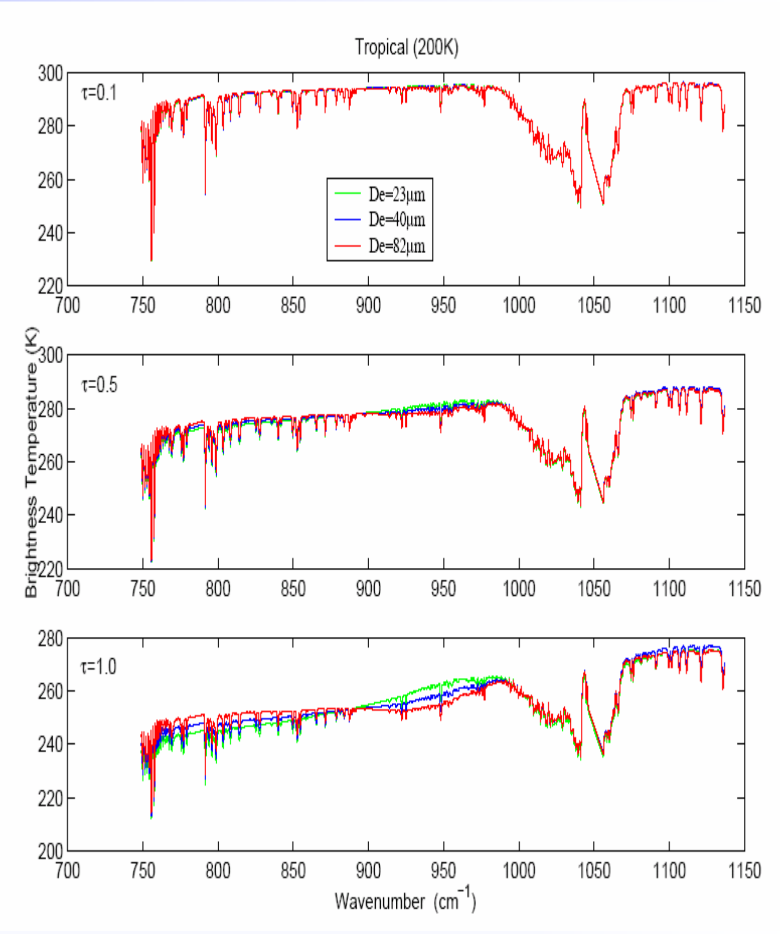
Contributors: K. N. Liou (PI), S. C. Ou and Y. Takano, UCLA

Summary of Accomplishments

- **Completed the development of D4S/A for intensity component;**
- **Verified D4S/A results with those computed from the "exact" doubling method;**
- **Developed an analytical expression of radiance derivatives;**
- **Developed a thin cirrus cloud parameterization in conjunction with OPTRAN; and**
- **Analyzed clear-sky AIRS spectra and compared to OPTRAN calculations.**

Future Plans

- **Continue the development of D4S/A for polarization (Q) component;**
- **Develop a method to compute radiance derivatives with respect to cloud and surface parameters;**
- **Analyze AIRS cloudy spectra and compare to cirrus parameterization/OPTRAN computations; and**
- **Construct a module RTSolution in CRTM.**



Global Microwave Surface Emissivity Error Analysis

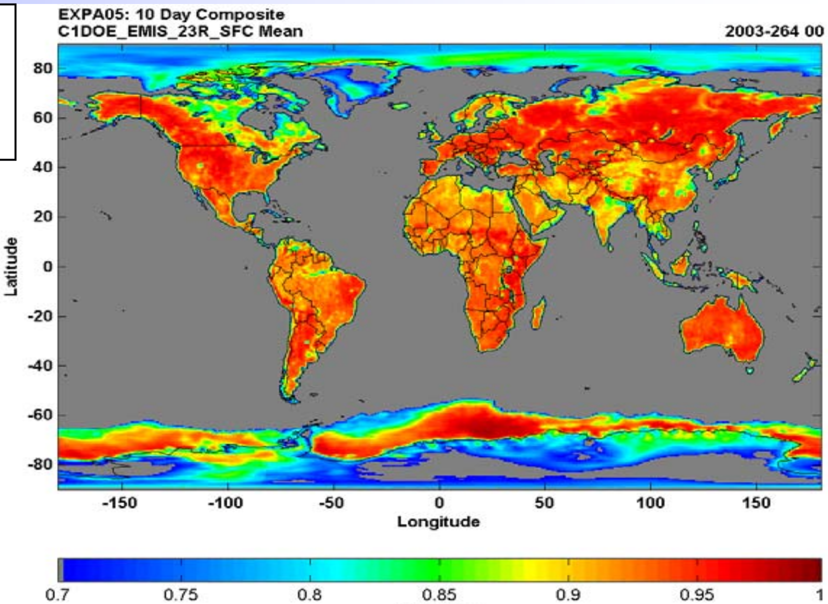
Contributors: A. Jones (PI) P. Shott, J. Forsythe, C. Combs, M. Nielsen, P. Stephens, R. Kessler, T. Vukicevic, T. H. Vonder Haar (CIRA/CSU)

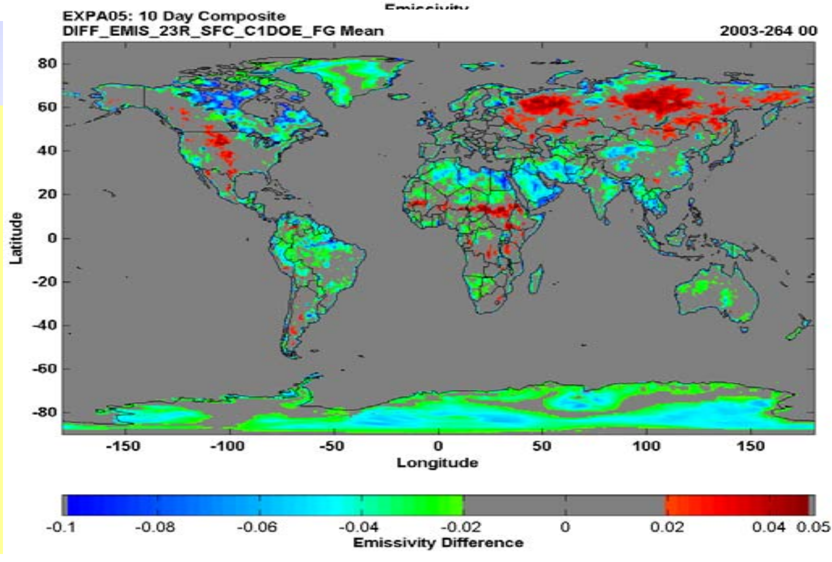
Summary of Accomplishments

- Created and validated the AMSU-B Antenna Pattern Correction module (results in 10-15% bias improvements to AMSU-B upper-water vapor profiles)
- Created a robust near-real-time 1DVAR global emissivity retrieval system suitable for transition to operations using the DPEAS grid computing framework
- MEM intercomparison to 1DVAR emissivity retrievals indicates several regions needing future MEM improvement (particularly desert and coastal regions) differences can be locally large

Future Plans

- Transition the AMSU-B Antenna Pattern Correction module to operations
- Continue emissivity cross-correlation studies and collaborations re: MEM improvements
- Perform intercomparisons with NRL JCSDA emissivity work
- From JCSDA needs, determine the future operational role of the dynamic global 1DVAR emissivity retrieval system





Including atmospheric aerosols in CRTM

Contributors: C. Weaver (PI), UMBC, P. Ginoux, P. Colarco, A. Silva, J. Joiner, P. van Delst

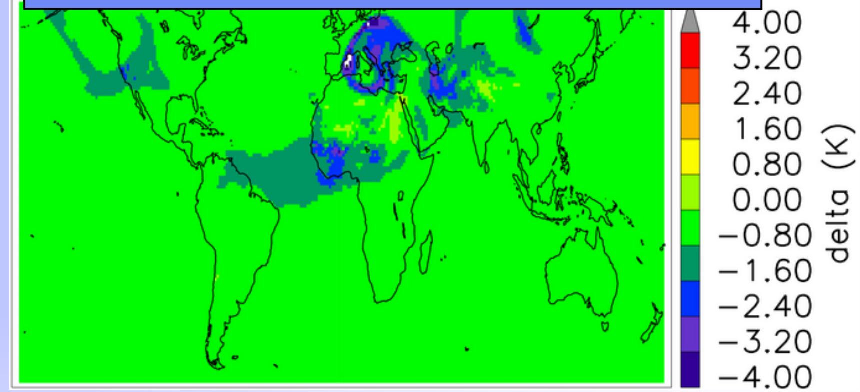
Summary of Accomplishments

- Developed code to generate Aerosol Extinction and Scattering Coefficients for HIRS and AMSU satellites
- Developed version of pCRTM that accounts for aerosol radiative effects.

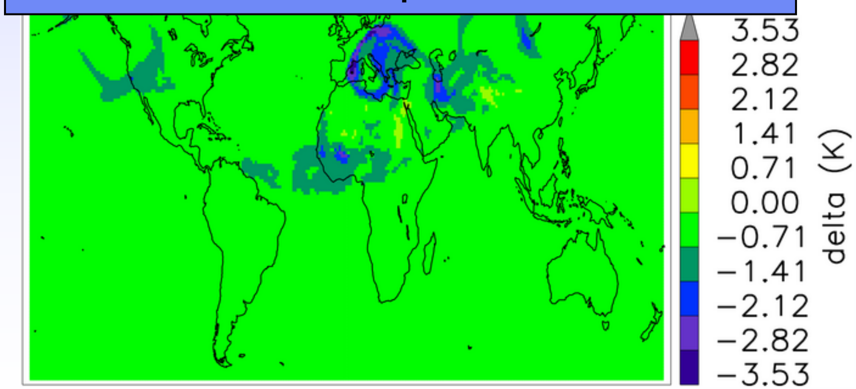
Future Plans

- Testing out two options for 3D model dust fields.
- Investigate Aerosol effect on Observed minus Forecast Brightness temperatures
- Include Sulfate Aerosol

ΔB_t HIRS Channel 8 (11.1 um)
Senses Surface Temperature



ΔB_t HIRS Channel 10 (12.56 um)
Senses Water Vapor 900 mb



Efficient All-Weather (Cloudy and Clear) Observational Operator for Satellite Radiance Data Assimilation

Contributors: M. Sengupta, T. Vukicevic, T.H. Vonder Haar (CIRA/CSU) and K.F. Evans (CU)

Summary of Accomplishments

- Components for gaseous absorption (CRTM), ice and water cloud optical properties (Anomalous Diffraction) and radiative transfer computation (SHDOMPPDA) have been built/adapted.
- The observational operator is currently being upgraded from our previous research version with the components which are newly developed
- SHDOMPPA was tested in 4dvar for assimilating GOES sounder data and results are very optimistic

Future Plans

- Complete Observational operator for operation with any NWP model output. Improve efficiency and provide tools for running on single processor and in parallel.
- Build scattering tables from Mie theory for water droplets and Yang et al. parameterizations for ice crystals.
- Long term plans: Investigate accuracy of single calculations using CRTM in visible satellite bands by comparing with multiple calculations for cloudy cases using correlated-k distributions for gaseous absorption.