Project Final Report

Award: NA10NES4400007

Title: Research in Support of Radiance Assimilation of Clouds and Precipitation

PI: Tom Greenwald

Co-I: Ralf Bennartz

Reporting period: 6/1/2010-5/31/2014

Proposed work:

This project addressed open issues in the Community Radiative Transfer Model (CRTM) that had a direct impact on its performance within a system that assimilates satellite radiance data in cloudy and precipitating regions. Originally, the project had several objectives:

1) Optimize the multi-stream radiative transfer (RT) solvers
2) Improve the reliability of microwave single-scattering properties using Anomalous Diffraction Theory (ADT)
3) Develop and test cloud overlap schemes
4) Test performance and bias characteristics of the GFS linearized cloud/convective schemes and study adjoint sensitivities for microwave sensor brightness temperatures

We chose, however, to focus our efforts on objective #1 since it would have a significant impact on the operational data assimilation system's performance as these calculations are by far the most time-consuming in the CRTM and since developing the optimization and refactoring the forward/tangent linear/adjoint CRTM code would require substantial work. Moreover, while the ADT approach proposed in objective #2 would be more reliable, it would be less accurate overall than what is currently used in the CRTM. Also, other JCSDA researchers were already working on or planning to address objectives #3 and #4.

Work accomplished:

These are the main accomplishments of the project:

- Developed an improved method to predict the optimum number of streams needed by the CRTM multi-stream RT solvers for clouds and precipitation
- Significantly modified the CRTM forward/tangent linear/adjoint code to integrate the new method
- Tested and delivered the modified code as applied to microwave sensors (planned for inclusion in CRTM v2.2)
- Added a new option to allow users to set the number of streams (included in CRTM v2.1)
- Completed final integration and testing of the Successive Order of Interaction (SOI) RT solver (included in CRTM v2.1)

Optimization development

In this project, optimizing the multi-stream RT solvers in the CRTM means predicting the minimum number of streams needed to achieve a desired accuracy for a given cloudy atmospheric profile. The idea is that more streams (i.e., angular resolution) are usually needed to maintain accuracy as more scattering occurs because the scattering phase function needs to be better resolved. Thus, if one can find a parameter that quantifies the amount of scattering in the atmospheric column, then one can estimate the optimum number of streams.

The previous approach used in the CRTM to quantify the degree of scattering was based on the Mie parameter (i.e., ratio of maximum particle size to incident wavelength) – what we refer to here as a scattering indicator (SI). However, this parameter more often than not greatly overestimated the number of streams needed, which considerably slowed down the scattering calculations. Our aim was to improve upon this by developing a new SI.

Early in the project we published an article in the Quarterly Journal of the Royal Meteorological Society (Bennartz and Greenwald 2011) that proposed a candidate SI. While it worked well in many cases, it was later found to have limitations for very optically thin clouds. Consequently, an alternative SI was developed to estimate the number of times (n) a photon is scattered based on successive order of scattering (Stephens 1994). A simple expression can be derived as:

$$n = \frac{[\ln \Delta + \ln(1 - \eta\, \omega_{eff})]}{\ln(\eta\, \omega_{eff})}$$

where

$$\eta = 1 - \exp(-\tau/\cos\theta)$$

and ω_{eff} is the effective single-scattering albedo for the column, τ is the total optical depth, θ is the zenith angle and Δ is the accuracy of the radiance solution, assumed here to have a value of 0.001 (i.e., 0.1%). We made a further assumption that

$$\omega_{eff} = \frac{\sum_{i=1}^{N} K_i \omega_i}{\sum_{i=1}^{N} K_i}$$

where K_i is the total transmittance weighting function and ω_i is the single-scattering albedo for layer i and N is the total number of layers.

Due to the urgency in JCSDA's plans to assimilate satellite microwave data in all sky conditions within NOAA's new hybrid ensemble/variational global data assimilation system, we first applied the new SI to the microwave spectrum. To do this required finding thresholds or "selection rules" that set a range of SI values for each of the possible optimum number of streams in the CRTM: 0 (emission only), 2, 4, 6, 8, and 16. We believe the best way to produce a database of CRTM-computed microwave brightness temperatures needed for the analysis over a wide range of cloud conditions was to use high-resolution Weather Research and Forecasting (WRF) model simulations, which were readily available here at CIMSS for Hurricane Katrina, marine stratocumulus, among others.

However, before the work could proceed we needed to add an option to the CRTM that would allow users to set the number of streams themselves, which would supersede any internally computed value. This would make it possible to generate a complete set of synthetic brightness temperatures for each number of streams. This option was eventually included in the v2.1 release of the CRTM.

Once the database of synthetic brightness temperatures was generated it was straightforward to determine the optimum number of streams for different assumed solution accuracies of 0.1, 0.5, 1.0, and 2.0 K using the 16-stream solution as truth. Figure 1 shows an example of the process of determining these thresholds for a solution accuracy of 0.5 K. Table 1 summarizes the global selection rules derived from the histogram analysis.

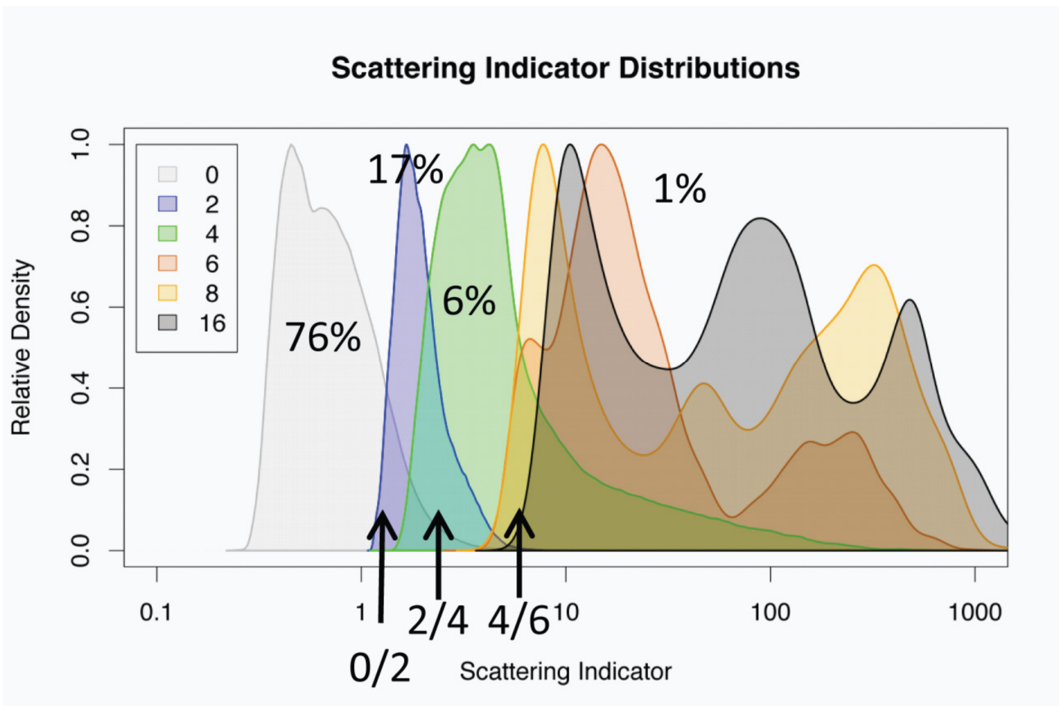

Fig. 1: Histograms of the scattering indicator for different optimum number of streams (assuming a target accuracy of 0.5 K), where 0 streams refers to emission-only calculations and the percentages indicate the percentage of data that are identified with each stream (for streams larger than 4 the percentage represents the combined 6, 8, and 16 streams). Also shown are the thresholds chosen for switching to different streams. Calculations were done for the conically-scanning (fixed zenith angle of 53^{o}) Global Precipitation Measurement Microwave Imager (GMI) and Special Sensor Microwave Imager Sounder (SSMIS), which together have a frequency range of 10 to 183 GHz.

Table 1: Thresholds for the scattering indicator in switching from emission-only to 2 streams (0/2), 2 to 4 streams (2/4) and 4 to 6 streams (4/6) for the four assumed target accuracies.

Target Accuracy	0/2 streams	2/4 streams	4/6 streams
0.1 K	1.00	1.45	3.57
0.5 K	1.25	2.07	5.71
1.0 K	1.42	2.65	7.02
2.0 K	1.66	3.76	34.5

The global selection rules were applied to the new SI for our high-resolution (1.5-2 km) WRF model simulations of marine stratocumulus off Baja California (4 June 2005) and Hurricane Katrina in the Gulf of Mexico (28 August 2005). Results show that the method correctly predicted the optimum number of streams over 90% of the time for marine stratocumulus across all frequencies and over 70% of the time for the Katrina case when the target accuracy was 0.5 K or greater (Figure 2). The lower predictability in both cases for the accuracy of 0.1 K is thought to be due to the greater overlap that exists in the histograms. It is noted that we eventually chose the selection rules for 0.5 K for use in the CRTM code since this value represents a typical noise value for satellite microwave radiometers.

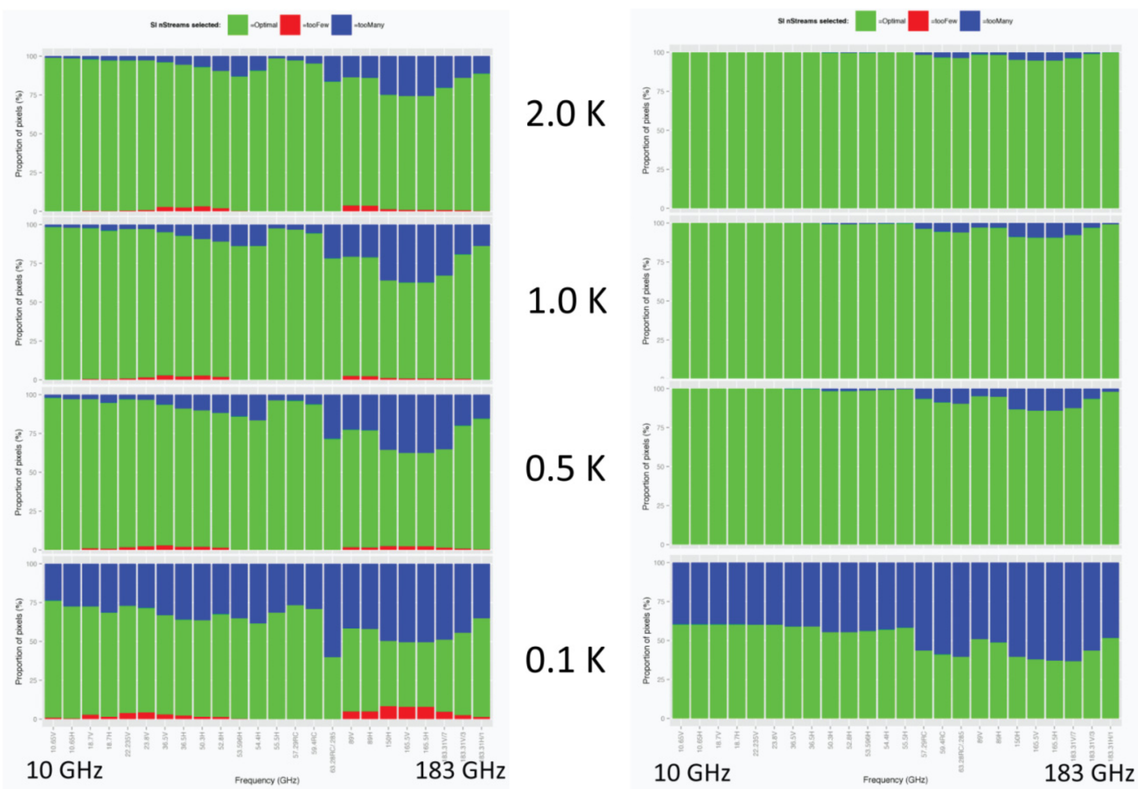

Fig. 2: Percentage of points where the optimum number of streams were correctly predicted (green), where too many streams were predicted (blue) and where too few streams were predicted (red) for the Hurricane Katrina simulation (left column) and marine stratocumulus simulation (right column) using calculations for channels from the Global Precipitation Measurement Microwave Imager and Special Sensor Microwave Imager Sounder. Results are shown for target accuracies of 2.0, 1.0, 0.5 and 0.1 K.

A similar analysis was done in the infrared spectrum for the same two WRF model simulations (Figure 3). Results for the target accuracy of 0.2 K reveal that the method, as expected, works best at the strong absorption wavelengths used in temperature/water vapor soundings but in window regions performs about as well or marginally better than the previous Mie parameter method used in the CRTM. The new method also has a higher frequency of predicting too few streams as compared to the previous method, especially for Hurricane Katrina and larger zenith angles. We suspect the problem lies in how the effective single-scattering albedo is computed, which may not be valid at these wavelengths. Nevertheless, further work would be necessary to improve the approach so that it performs as well throughout the infrared spectrum as in the microwave spectrum.

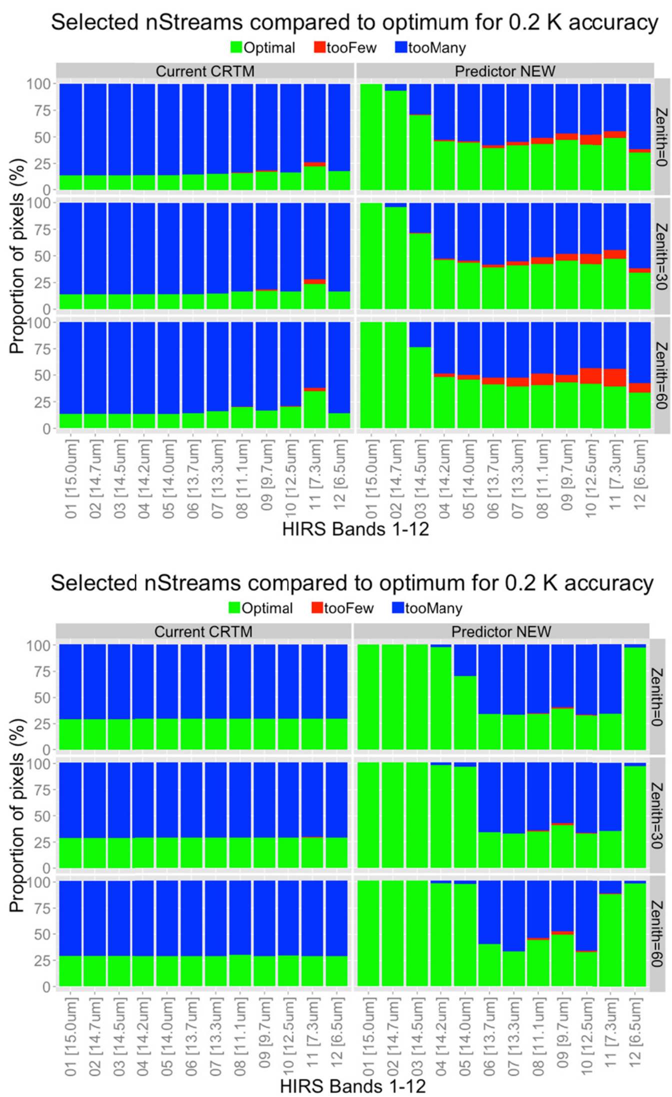

Fig. 3: Percentage of points where the optimum number of streams was correctly predicted (green), where too many streams were predicted (blue) and where too few streams were predicted (red) for the current CRTM (left) and new approach (right) for Hurricane Katrina (top) and marine stratocumulus (bottom). Results are shown for zenith angles of 0^o, 30^o and 60^o using calculations for channels from the High-resolution Infrared Radiation Sounder (HIRS).

Integration of optimization method

The challenge in incorporating the new method into the CRTM code was that the code was not organized in a way that would easily allow this. The basic issue was that functions that computed atmospheric absorption and cloud/aerosol scattering properties needed in calculating the new SI were called *after* the function that computes the number of streams (CRTM_Compute_n_Streams). However, the functions that computed cloud/aerosol scattering properties were themselves dependent on the number of streams (n) so they could not simply be called before the call to CRTM_Compute_n_Streams. The solution was to break up the cloud/aerosol scattering property functions into separate functions that were dependent on n (i.e., the scattering phase function) and independent of n (i.e., single-scattering albedo and extinction). The creation of these new functions and their rearrangement were done for the forward, tangent linear and adjoint code, which underwent extensive testing so as not to change the results from the original code. The schematic below illustrates the transformation for the forward module code.

Old code (v2.1)		New code (v2.2)
		CALL AtmAbsorption
CALL n_Streams(n)		CALL CloudScatter
CALL AtmAbsorption	⟹	CALL AerosolScatter
CALL CloudScatter(n)		CALL n_Streams(n)
CALL AerosolScatter(n)		CALL CloudScatter_PhaseFnc(n)
		CALL AerosolScatter_PhaseFnc(n)

Workshop participation and visits:

- 12th JCSDA Technical Review Meeting and Science Workshop on Satellite Data Assimilation, 21-23 May, 2014
  NOAA Center for Weather and Climate Prediction, College Park, MD
  Oral presentation: "*Optimizing Multiple Scattering Calculations in the CRTM: IR Results*"
  Presenter: T. Greenwald
- 11th JCSDA Science Workshop on Satellite Data Assimilation, 5-7 June, 2013
  NOAA Center for Weather and Climate Prediction, College Park, MD
  Oral presentation: "*Optimizing Multiple Scattering Calculations in the CRTM: Update*"
  Presenter: T. Greenwald
- 10th JCSDA Workshop on Satellite Data Assimilation, 10-12 Oct, 2012
  NOAA Center for Weather and Climate Prediction, College Park, MD
  Oral presentation: "*Optimizing Multiple Scattering Calculations in the CRTM*"
  Presenter: T. Greenwald
  T. Greenwald served as co-chair for Session 3 (Cloud and Precipitation Data Assimilation)

- 9th JCSDA Workshop on Satellite Data Assimilation, 24-25 May, 2011
  University of Maryland, College Park, MD
  Oral presentation: "*Current problems in scattering radiative transfer modeling for data assimilation*"
  Presenter: R. Bennartz
  Poster presentation: "*Modifications to Scattering Radiative Transfer in the CRTM*"
  Presenter: T. Greenwald
  R. Bennartz served as co-chair for Session 3 (Cloud and Precipitation Data Assimilation)
- 28 Mar - 1 Apr, 2011; World Weather Building, Camp Springs, MD
  T. Greenwald made a visit to complete final testing of the SOI RT solver

References:

Bennartz, R., and T. Greenwald, 2011: Current problems in scattering radiative transfer modelling for data assimilation. *Q. J. R. Meteorol. Soc.*, **137**, 1952-1962.

Stephens, 1994: *Remote Sensing of the Lower Atmosphere*, Oxford University Press, New York, NY, 523 pp.