Fast Solvers and Polarization in the CRTM

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Project Goals

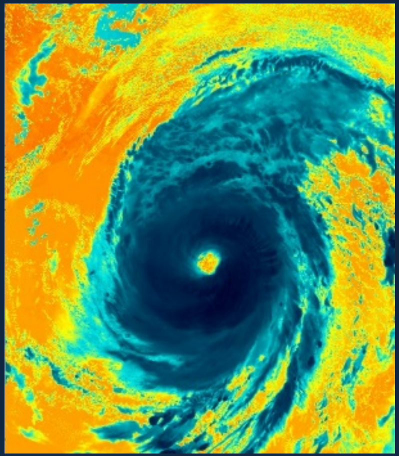
- Exploit very fast analytic radiative transfer solvers to optimize the CRTM in calculating all-sky microwave and IR radiances for clouds, precipitation and aerosols
- Demonstrate the impact of these improvements in the GOES-5 DAS and other systems
- Introduce fully polarized radiative transfer into the CRTM

Year 2 Accomplishments

- Integrated δ-Eddington solver (FWD/TL/AD) into the CRTM
- Integrated multi-stream Successive-Order-of-Scattering (SOS) solver (Greenwald et al. 2005) into the CRTM
  - Improvements include bug fixes, reduced memory requirements and faster calculations for strongly absorbing wavelengths
- Extended benchmark testing to infrared; began developing methods to optimize IR calculations

Forward Model Runtime Performance

- Profiles come from WRF model run of Hurricane Katrina (1.5 km; 948 x 1096)
- Tests for two instruments:
  - GMI (13 channels; 10.6-183 GHz)
  - HIRS-4 (19 channels; 3.76-14.9 μm)



	GMI (θ=52.8°)					HIRS-4 (θ=0°)				
Solver	**2**	**4**	**6**	**8**	**16**	**2**	**4**	**6**	**8**	**16**
SOI	+35	+53	+68	+89	+108	+87	+97	+129	+159	+183
SOS	-45	-38	-36	-35	-37	-49	-46	-38	-34	-22
EDD	-66	-74	—	—	—	-70	-74	—	—	—
EMIS	-80	-85	—	—	—	-86	-88	—	—	—

Forward Model Accuracy

- 4-stream solver performs best over a range of wavelengths and accuracies but is relatively slow
- δ-Eddington solver performs poorly at IR wavelengths, where absorption is stronger

	GMI (θ=52.8°)				HIRS-4 (θ=0°)			
Error	**EMIS**	**EDD**	**2**	**4**	**EMIS**	**EDD**	**2**	**4**
±0.5K	69%	58%	79%	99%	49%	18%	74%	96%
±1K	73%	76%	83%	99.7%	60%	32%	87%	99%
±2K	77%	95%	87%	99.9%	73%	57%	95%	99.9%

Why Consider Polarization?

- Many satellite instruments exploit polarization to sense properties of clouds, precipitation, aerosols, and surface
- Clouds
  - Residual polarization (I,Q,U) in solar measurements (e.g, MODIS, VIIRS) not accounted for in forward models (Yi et al. 2014)
  - Multi-angle polarized reflectance (I,Q,U) measurements (e.g., POLDER; MetOp-SG 3MI) are sensitive to cloud particle size and phase (DiNoia et al. 2019)
  - Lidar linear depolarization (I,Q) measurements (e.g., CALIOP) are sensitive to ice crystal shape and orientation, especially to horizontally oriented crystals (Sassen and Zhu 2009)
  - Sub-mm (183-664 GHz) polarization measurements (I,Q) are sensitive to ice particle shape (MetOp-SG Ice Cloud Imager) (Evans and Stephens 1995; Fox et al. 2019)

Polarization Effects from Precipitation and Aerosols

- Precipitation
  - Polarization signatures (I,Q) generated by large horizontally-oriented non-spherical ice particles have been observed to be significant and very common at microwave frequencies (Galligani et al. 2013; Zeng et al. 2019)
- Aerosols
  - Space-based multi-angle multi-spectral polarimeters (I,Q,U) provide most of the detailed information about aerosols (Dubovic et al. 2018)
  - Particle size (e.g., POLDER, APS/Glory, HARP/Cubesat, 3MI, MAIA/OTB-2, SpexOne/PACE, ScanPol + MSIP)
  - Particle morphology (e.g., POLDER, APS/Glory, 3MI, SpexOne/PACE, ScanPol + MSIP)
  - Complex refractive index (e.g., POLDER, APS/Glory, HARP/Cubesat, 3MI, SpexOne/PACE, ScanPol + MSIP)
  - Single scattering albedo (e.g., POLDER, VNIR-POL, SpexOne/PACE)

Surface Polarization Effects

- Soil moisture and vegetation significantly impact polarization (I,Q) at microwave frequencies (SSMIS, AMSR-E, AMSR2, GMI, etc.)
- The ocean is highly polarized at microwave frequencies. Fully polarimetric passive microwave measurements (I,Q,U,V) of ocean surface are used to detect the wind vector (WindSat)

Year 2 Accomplishments

- Evaluated Vector Adding Doubling (VAD) model (TAMU)
  - Well tested and accurate multi-stream model
  - Solar wavelengths only (no thermal source)
  - Code is very complicated; challenge to write TL/AD models
- Vector SOI solver development (in progress)
  - Default CRTM solver (MOM) deemed too complex
  - SOI FWD/TL/AD models include thermal sources only
  - Assume randomly oriented particles; azimuthal sym.

Vector SOI Development

- Wrote code to develop the vector SOI outside of the CRTM
- Selected test profiles from a high-resolution WRF model simulation of a mid-latitude frontal system
- Patrick Stegmann provided a way to compute phase matrix elements P_{11}, P_{12}, P_{33} using the asymmetry factor
- Borrowed code from rt3 (Evans and Stephens 1991) to generate the phase matrix and rotate it

Year 3 Plans

- Modify existing SOI FWD/TL/AD models for vector radiative transfer
- Other related code development:
  - Polarization scattering matrix (FWD/TL/AD) needed for the vector solver
  - Restructure CRTM to compute radiances for multiple channels using a single RT call; currently limited to one channel per call
- Develop TL/AD models for SOS solver
- Complete IR optimization for multi-stream solvers