CRTM extension for UV/Visible Sensors

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Abstract

The CRTM visible radiative transfer (RT) algorithm is developed and implemented. This development allows users to simulate and assimilate radiance/reflectance for ultraviolet and visible sensors. The new solver is also used in the microwave and infrared radiance simulations and assimilation, and it reduces computation time and achieves a very accurate jacobian calculation under aerosol and cloudy conditions. For microwave and infrared sensors, the difference in the forward calculations between the baseline solver and the new solver is negligible (< 0.001 K). The accuracy in the jacobian calculation fro the baseline solver depends on a selection of a delta optical depth, the smallest sub-layer optical depth in the algorithm.

The UV/Visible simulation capability enables us to study the impact of aerosol vertical distribution on satellite radiance measurements. The vertical distribution of aerosols is important for air quality forecasting. The aerosol mass at a high altitude can statistically be transported for a long distance.

Theoretical Basis

UV/Visible sensors measure backscattered solar radiation that depends on atmospheric gaseous absorption, scattering/absorption of molecules, aerosols, and clouds, as well as surface reflectance. The backscattering depends on geometry parameters including relative an azimuth angle between sun and sensor viewing directions.

CRTM Baseline Solver +solar radiation

(Advanced Doubling-Adding, ADA)

1. Compute layer transmission and reflection (loop i from 0→ n-1)

baseline $\mathbf{r}(\delta_0) = \delta_0 \boldsymbol{\beta}$ $\mathbf{t}(\delta_0) = \mathbf{E} + \boldsymbol{\alpha}\delta_0$ $\delta = \delta_n = 2^n \delta_0$ $\mathbf{t}(\delta_{i+1}) = \mathbf{t}(\delta_i)[\mathbf{E} - \mathbf{r}(\delta_i)\mathbf{r}(\delta_i)]^{-1}\mathbf{t}(\delta_i)$

$\mathbf{r}(\delta_{i+1}) = \mathbf{t}(\delta_i)[\mathbf{E} - \mathbf{r}(\delta_i)\mathbf{r}(\delta_i)]^{-1}\mathbf{r}(\delta_i)\mathbf{t}(\delta_i) + \mathbf{r}(\delta_i)$

new $\mathbf{t} = (A_{22})^{-1}$ $\mathbf{r} = A_{12}\mathbf{t}$ **where** $\exp(A\delta) = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$ **and A is the phase matrix.**

2. Compute layer source functions

$$\mathbf{S}_u = [(\mathbf{E} - \mathbf{t} - \mathbf{r})B(T_1) - (B(T_2) - B(T_1))\mathbf{t} + \frac{B(T_2) - B(T_1)}{(1 - \varpi g)\delta}(\mathbf{E} + \mathbf{r} - \mathbf{t})]\mathbf{u} \equiv \text{[illegible]}$$

$$\mathbf{S}_d = [(\mathbf{E} - \mathbf{t} - \mathbf{r})B(T_1) + (B(T_2) - B(T_1))(\mathbf{E} - \mathbf{r}) + \frac{B(T_2) - B(T_1)}{(1 - \varpi g)\delta}(\mathbf{t} - \mathbf{E} - \mathbf{r})]\mathbf{u} \equiv \text{[illegible]}$$

$$\begin{bmatrix} \Psi_d \\ \Psi_u \end{bmatrix} = \text{[illegible]}$$

3. Vertical integration

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

$$\mathbf{I}_u(k-1) = \mathbf{S}_u(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\mathbf{R}(k)\mathbf{S}_d(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\mathbf{I}_u(k)$$
$$= \mathbf{S}_u(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}[\mathbf{R}(k)\mathbf{S}_d(k) + \mathbf{I}_u(k)]$$

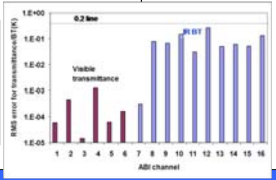
$$\mathbf{R}(k-1) = \mathbf{r}(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\mathbf{R}(k)\mathbf{t}(k)$$

4. Final TOA radiance $Radiance = \mathbf{I}_u(0) + \mathbf{R}(0)\mathbf{I}_{sky}$

CRTM Updates

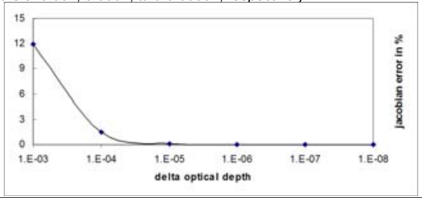
A new loop over Fourier expansion series for azimuth angles is added. The phase matrix is extended with the Fourier component. The RTSolution module is incorporated with the layer source for solar radiation. The operational OPTRAN algorithm is applied for generating absorption coefficients for the fast visible transmittance calculation. For the GOES-R ABI sensor, the accuracy for transmittance is about 0.001 for visible channels and better than 0.2 K for IR channels. The aerosol types are updated (see table). Look-up tables for cloud and aerosol properties are also extended to include the visible part.

previous aerosol names		new aerosol names	
Dust	size bins	Dust	size bins
Seasalt AM	a size	Seasalt AM	a size
Seasalt CM	a size	Seasalt CM1	a size
Dry organic carbon	RH =0	Seasalt CM2	a size
Wet organic carbon	0<RH<=1	Seasalt CM3	a size
Dry black carbon	RH =0	Organic carbon	0<=RH<=1
Wet black carbon	0<RH<=1	Black carbon	0<=RH<=1
Sulfate	a size	Sulfate	a size

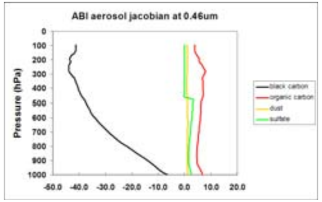


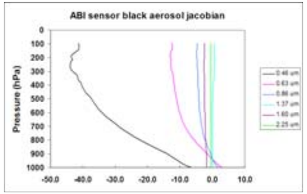
Result

The new repository braches EXP-Visible is created for the CRTM development to include solar radiation for UV/Visible sensors. The new development is validated with the operational CRTM code in the trunk (operational). The operational code uses a delta optical depth of 0.001 for a sub-layer in a layer double-adding method. The new RT solver uses analytical solutions for layer transmittance and reflectance matrices and it may be considered as a reference. For forward IR and MW brightness temperature calculations, the difference between the operational code and this new code is less than 0.001 K and approaches zero for finer delta optical depths. The difference in jacobian calculations depends on the delta optical depth. The following figure shows that the difference may be as large as 12%, 1.5%, 0.1% for the delta optical depths of 0.001, 0.0001, and 0.00001, respectively.



Using this CRTM visible model, we can study the effect of vertical distribution of aerosols on satellite measurements, for example in term of jacobian. The jacobian value describes the radiance sensitivity to each geophysical parameter under clear and cloudy conditions. The weighting function, commonly defined as a derivative of transmittance to a layer thickness, describes a total sensitivity distribution under a clear-sky condition. In the scattering case, the weighting function is expressed as a function of transmittance and reflectance matrices, no longer as a derivative of transmittance to a layer thickness. The following left panel displays the jacobians for black carbon, organic carbon, dust, and sulfate. The sensitivity for the GOES-R channel 1 for black carbon is negative, that indicates a reduction of solar backscattering as an increase of black carbon, because of its strong absorption. Organic carbon shows a positive sensitivity that implies an increase of the backscattering radiance as an increase of the organic carbon, due to its strong scatterings. The GOES-R channels 1 and 2 are used for determining aerosol type and optical depth. For a black carbon, the sensitivity strongly depends on altitudes, because a black carbon layer at a high altitude generally absorbs more backscattering radiance from molecules and surface beneath the layer. The sensitivity depends also on electromagnetic wavelength since molecule scattering decreases rapidly with the increase of the wavelength. The right panel below shows the vertical distribution of the sensitivity for the GOES-R 6 visible channels. For the GOES-R channels 2 and 3, the scattering effect competes with the absorption effect, depending on the altitude of the black carbon layer. The sensitivity at channel 4 (1.38 µm) is small and this channel is used for a cirrus cloud detection. The sensitivity at channel 6 (2.25 µm) is also small and this channel is helpful to estimate surface reflectance.





Conclusion

The CRTM visible module can be useful for both retrieval and assimilation. It shows that aerosol vertical distribution has a significant impact on satellite measurements. For UV/Visible sensors, surface bidirectional reflectance model (BRDF) and molecule/aerosol/cloud polarization are also important. The following developments are under consideration:

1. Surface BRDF models over ocean and land;
2. MODIS-like aerosol LUT and CMAQ LUT;
3. Microwave cloud LUT for non-spherical particles;
4. Molecule/aerosol/cloud Polarization.