P3.1 EXPLORING THE UTILITY OF CRTM IN ASSIMILATING CLEAR AND CLOUDY RADIANCES FOR FORECAST MODEL INITIALIZATION

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1. INTRODUCTION

The validation of radiative transfer model capabilities is the foundation for research in cloudy satellite radiance data assimilation. In this study, the Community Radiative Transfer Model (CRTM) version 2.0.2 forward model (forward/observation operator) and the K-Matrix model are evaluated in the infrared range of the Geostationary Operational Environmental Satellite (GOES) Imager. The sensors span broadly used infrared ranges, GOES Channel 2, 3, and 4 which central wavelengths are 3.9, 6.5, and 10.7 μm, respectively.

2. FORWARD MODEL CHECK OUT

2.1 Input data

The CRTM forward model (forward operator or observation operator) simulates radiances (or brightness temperatures) from given atmospheric temperature and absorber profiles, surface conditions, and hydrometeor parameters (where clouds exist) and precipitation occurs (Joint Center for Satellite Data Assimilation, 2010). Since our previous study shows the simulated radiance or brightness temperature is very sensitive to the surface condition, land surface type is considered for the forward model checkouts. In addition, high and low solar altitudes are assumed to have the solar zenith angle effect in the near infrared region.

We studied the June 13 2002 storms during the International H2O Project (IHOP) campaign over the Central Great Plains of the United States with the Weather Research and Forecasting (WRF) model. The corresponding event is studied by Liu and Xue (2008), Tanamachi et al. (2008), and Weckwerth et al. (2008).

The initial time is June 12 2002 00 UTC. The domain is 249 x 249 x 35 grid points covering Oklahoma and the extended area. The horizontal resolution is approximately 4 km and the water surface points are fractional and processed as land surface area in this study. The extracted WRF variables used in the CRTM forward function in this experiment are:

- Land use category
- Cloud (hydrometeor) types
- Surface skin temperature [K]
- Cloud water mixing ratio [kg/kg]
- Water vapor mixing ratio [kg/kg]
- Temperature [K]
- Pressure [Pa]
- Geometry information

Land use category index in the WRF output is following U.S. Geological Survey (USGS) Land Use/Land Cover System Legend (Modified Level 2). The CRTM land surface types are assumed to be corresponding to the USGS category as shown in Table 1.

As the primary absorbing gases are water vapor and ozone, they are necessary variables in this model. The presence of aerosols is excluded in this experiment. Since ozone amounts are not predicted in the WRF model, a modified US standard atmosphere ozone profile using the Local Analysis and Prediction System (LAPS, Albers et al. 1996) algorithm. The modification depends on the location and time as shown in Fig. 1. As the CRTM climatological option, the US standard Atmosphere is chosen to adjust absorbers above the given profiles of WRF data.

The WRF data contains four hydrometeor types (water, rain, ice, and snow). The horizontal distributions of individual hydrometeors are shown in Fig. 2. The default effective radius of each

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hydrometeor is implemented to the forward model since they are not predicted in the WRF model.

USGS Code	CRTM Category
Urban and Built-Up Land	URBAN_CONCRETE
Dryland Cropland and Pasture	TILLED_SOIL
Irrigated Cropland and Pasture	IRRIGATED_LOW_ VEGETATION
Mixed Dryland/Irrigated Cropland and Pasture	TILLED_SOIL
Cropland/Grassland Mosaic	TILLED_SOIL
Cropland/Woodland Mosaic	TILLED_SOIL
Grassland	MEADOW_GRASS
Shrubland	SCRUB
Mixed Shrubland/Grassland	GRASS_SCRUB
Savanna	BROADLEAF_BRUSH
Deciduous Broadleaf Forest	BROADLEAF_FOREST
Deciduous Needleleaf Forest	BROADLEAF_PINE_ FOREST
Evergreen Broadleaf Forest	BROADLEAF_PINE_ FOREST
Evergreen Needleleaf Forest	PINE_FOREST
Mixed Forest	BROADLEAF_PINE_ FOREST
Water Bodies	-
Herbaceous Wetland	WET_SOIL
Wooded Wetland	WET_SOIL
Barren or Sparsely Vegetated	COMPACTED_SOIL
Herbaceous Tundra	TUNDRA
Wooded Tundra	TUNDRA
Mixed Tundra	TUNDRA
Bare Ground Tundra	TUNDRA
Snow or Ice	-

Table 1. WRF(USGS)-CRTM match-up table

To evaluate the dependency on the solar zenith angle, images of simulated brightness temperature at 12 and 18 local standard time are compared. The corresponding high and low zenith angles at Norman, OK as the representative location of the domain are 13.6° and 71.1°, respectively.

Of the two available transmittance models for use in the CRTM version 2, the Optical Depth in Pressure Space (ODPS) algorithm is used. It is similar to the RTTOV-type of transmittance algorithm and showed better performance to manually derive Jacobians in our preliminary study compared to Optical Depth in Absorber Space (ODAS) algorithm.

2.2 Result

The GOES-8 Imager Channel 2, 3, and 4 observations and the simulated brightness temperature of the GOES-12 are shown in Figure 3. The channel 3, and 4 virtually show the same brightness temperature over the domain at the both solar zenith angles. The observed cloud top brightness temperature is very similar to the simulated result. The channel 2 results show that the warmer brightness temperature at local noon due to the higher solar zenith angle where clouds don't exist. However, the observed cloud top brightness temperature is significantly warmer than the simulated values.

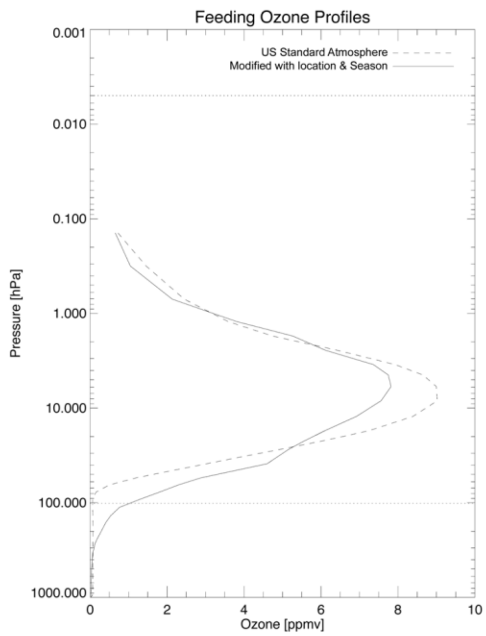


Fig. 1. Ozone profiles of the US Standard Atmosphere and the one used in this experiment.

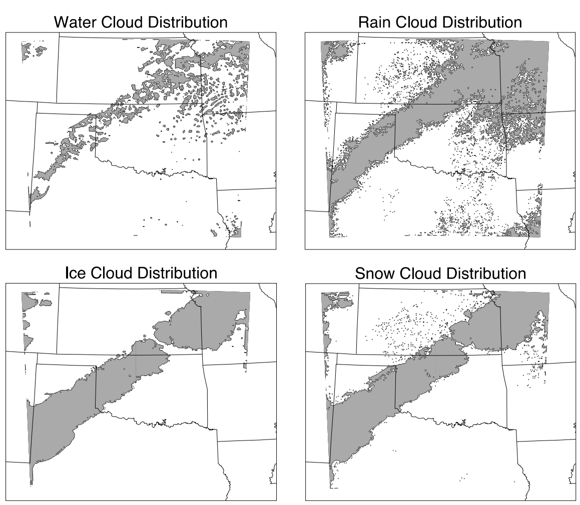
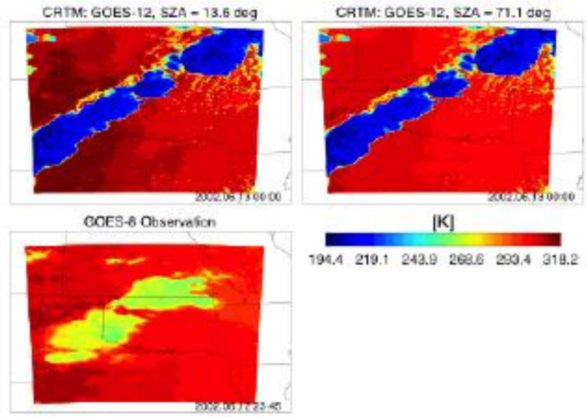
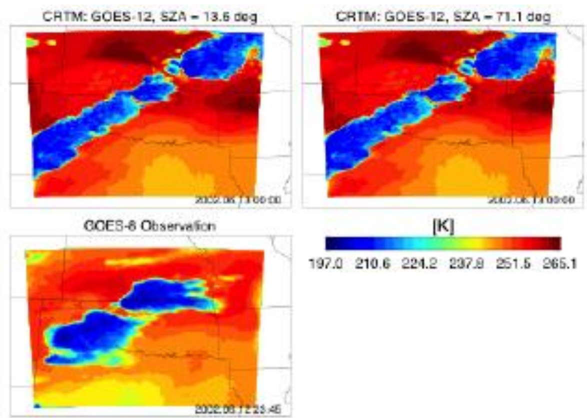


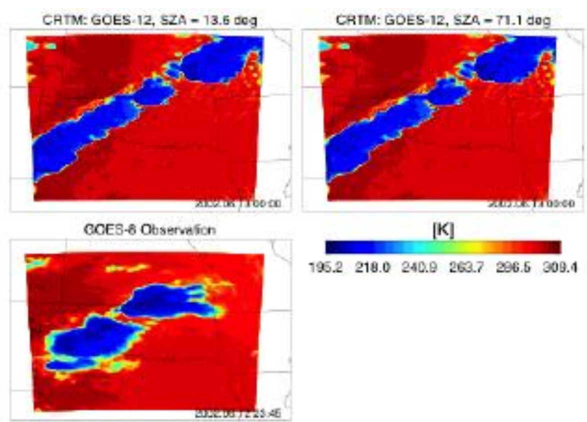
Fig. 2. Horizontal distributions of WRF hydrometeors at 00UTC on June 12 2002.



(a) Channel 2



(b) Channel 3



(c) Channel 4

Fig. 3. Simulated brightness temperature of the GOES-12 Imager (a) channel 2, (b) channel 3, and (c) channel 4 and the corresponding GOES-8 observed brightness temperature. Among each panel, the top-left shows simulated brightness temperature when the sun elevation is at local noon. The top-right image is when the sun is at local 6 pm. The bottom image shows observed brightness temperature by GOES-8 Imager at local 1145 am.

3. K-MATRIX MODEL CHECKOUT

3.1 Theoretical Approach

It is known that atmospheric state of the model is assembled as a column matrix $\mathbf{X}$, which is referred as the state vector. The necessary variables to be used in the CRTM functions are surface temperatures (T_{sfc}), atmospheric temperatures (T), water vapor amounts (q), and ozone amounts (O_3). Since $\mathbf{X}$ can be regarded as a collection of vertical layers, one atmospheric profile can be represented with a scalar variable, T_{sfc} and vectors of state variables, $\mathbf{T}$, $\mathbf{q}$, $\mathbf{O_3}$.

Accordingly, the forward model is expressed as;

$$\mathbf{R} = \mathbf{F}(\mathbf{T}, \mathbf{q}, \mathbf{O_3}, T_{sfc}) \quad (1)$$

where $\mathbf{F}$ is the CRTM forward function. $\mathbf{R}$ is simulated radiance or brightness temperature for a certain assigned satellite sensor. When the surface temperature is assumed to be a focal prognostic/dependent variable of the experiment, the above equation can be replaced as;

$$\mathbf{R} = \mathbf{F}(T_{sfc}) \quad (2)$$

Equally, the radiance changes with respect to temperature variations can be produced with the CRTM K-Matrix operator, $\mathbf{K}$;

$$\frac{\partial \mathbf{R}}{\partial \mathbf{T}} = \mathbf{K}(\mathbf{T}, \mathbf{q}, \mathbf{O_3}, T_{sfc}) \quad (3)$$

$$\text{i.e. } \frac{\partial \mathbf{R}}{\partial T_{sfc}} = \mathbf{K}(T_{sfc}) \quad (4)$$

Jacobians with respect to surface temperature variations can be manually derived with the CRTM forward function based on a finite-different method. The central difference form was selected here due to the simplicity as the following;

$$\frac{\partial R}{\partial T_{sfc}} \approx \frac{R(T_{sfc} + \Delta T) - R(T_{sfc} - \Delta T)}{2\Delta T} \quad (5)$$

Note that other implemented variables into the forward model remained to be the initial values. Jacobians with respect to atmospheric temperature or moisture (specific humidity) variations can be manually derived in the same approach. Thus, the actual values of manually derived Jacobian have high order residual terms as;

$$\frac{R(T + \Delta T) - R(T - \Delta T)}{2\Delta T} = \frac{\partial R(T)}{\partial T} + O\left((\Delta T)^2\right) + \ldots$$

(6)

where O shows the order of magnitude and the residual terms are assumed to be negligible.

3.2 Input Data

The experimental domain covering the Gulf of Mexico and the extended area consists of 257 x 257 x 56 grid points. Each grid is assumed to be covered by ocean water for the sake of convenience. As an additional assumption, no clouds as hydrometeors exist in the domain. Thus, the primary variables used in this experiment are surface temperatures, atmospheric temperatures, water vapor amounts, and ozone amounts, which are required to run the CRTM functions. Implemented atmospheric temperature and water vapor profiles are obtained from LAPS and corresponds to the time when Hurricane Katrina was moving toward the Gulf of Mexico. Those data are obtained from the LAPS. The input ozone amounts are the modified US standard atmosphere ozone profile following the first experiment, which depends on the latitude and the season.

3.3 Results

The manually derived Jacobian and the CRTM K-matrix results at a pressure level are plotted and compared. Figure 4 shows the GOES-12 Channel 2 radiance variations with respect to the surface temperature perturbation. The perturbation, ΔT, shown in (5) is set at 1K. Both images look very similar over the domain. As other GOES IR channel comparisons are very similar (not shown here), the K-Matrix function performance with respect to surface temperature perturbation is to be good at.

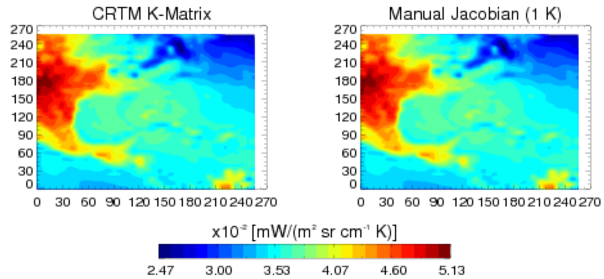


Fig. 4. GOES-12 Channel 2 CRTM K-matrix results with respect to surface temperature perturbations and the corresponding Jacobian values derived manually.

Figure 5 shows the profiles of K-matrix values with respect to atmospheric temperature at the domain using two transmittance algorithms. Both maximum values are appeared at the lowest level. Since the K-Matrix values or Jacobians are related to the sensitivity with respect to the used perturbation variable, the plotted K-Matrix values at the lowest level can represent the properties of those two channels.

Consequently, Fig. 6 shows the GOES-12 radiance variations with respect to the temperature perturbation at 1007 hPa. The atmospheric temperature perturbation is set at 0.5 K. Each color scale is individually optimized to effectively show image features. In general, larger values over the land and smaller values over the ocean are shown.

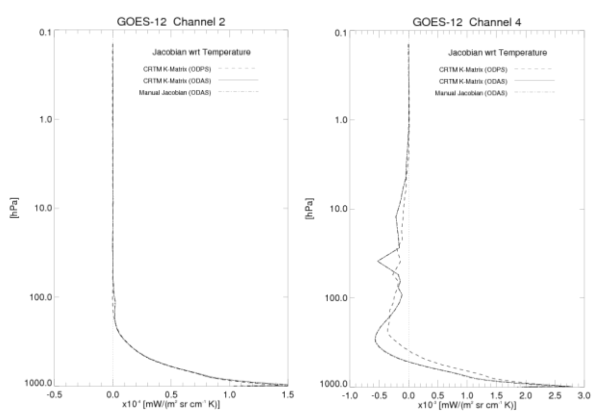
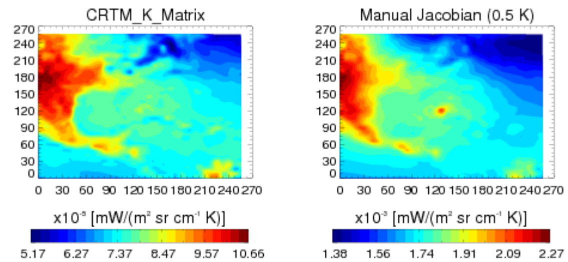
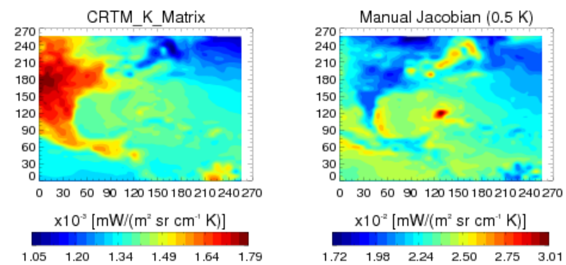


Fig. 5. GOES-12 channels 2 (left) and 4 (right) CRTM K-matrix values at the center point of the domain with respect to each layer atmospheric temperature perturbations.

At the hurricane's central location and the neighborhood, the manually derived Jacobians show much larger values compared to the K-Matrix function results. However, as the no-cloud assumption is far from the actual condition, we can speculate that the differences for both channels are caused by these non-practical assumptions.



(a) Channel



(b) Channel 4

Fig. 6. CRTM K-matrix results with respect to atmospheric temperature perturbations and the corresponding Jacobian values derived manually.

Figure 7 shows a profile of the GOES-12 channel 2 K-matrix values with respect to specific humidity at the domain center. The highest value computed using the ODPS algorithm appears at 136.9 hPa.

Similarly, Fig. 8 shows radiance variations with respect to the specific humidity perturbation (0.5%) at 136.9 hPa. Where specific humidity is zero, the following approximation is used instead of the central difference form;

$$\frac{\partial R}{\partial q} \approx \frac{R(q+\Delta q)}{\Delta q} \qquad (7)$$

The area surrounding the hurricane shows values near zero in the manually derived Jacobians – a contrast to the K-Matrix results.

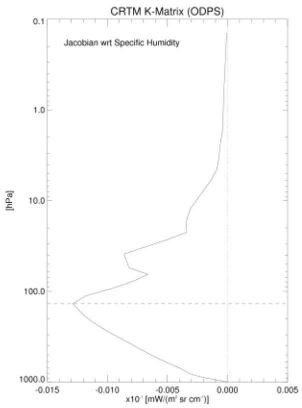


Fig. 7. GOES-12 channels 2 CRTM K-matrix values at the center point of the domain with respect to each layer atmospheric moisture perturbations.

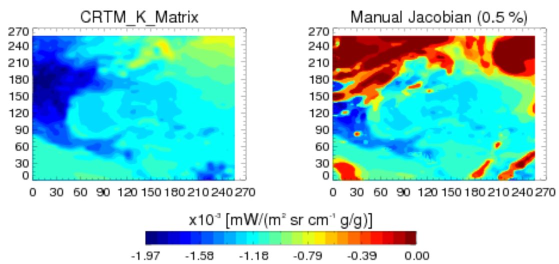


Fig. 8. GOES-12 channels 2 CRTM K-matrix results with respect to atmospheric moisture perturbation (left) and the corresponding manually derived Jacobians (right).

However, those areas agree with very dry areas at the same level as shown in Fig. 9. Accordingly, we speculate that the dry area is not adequate for the evaluation with the approach as shown in Fig. 8.

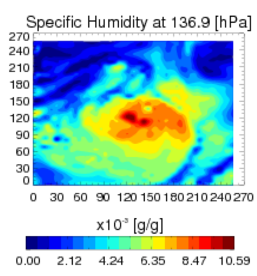


Fig. 9. CRTM K-matrix results with respect to atmospheric temperature perturbations and the corresponding Jacobian values derived manually.

4. FUTURE WORK

Further investigation for GOES Channel 2, located in the near-infrared region, is necessary to understand why the simulated cloud top brightness temperature appears much cooler than the observation. One of the potential causes is that the reflection part of the total radiance is not properly computed in the CRTM forward model.

The CRTM K-Matrix function performance with respect to atmospheric temperature and moisture are needed to study with more specific conditions as contrast with the non-practical assumptions of this study. A case when the domain is hardly covered with clouds is a good atmospheric condition to apply the assumption of this study.

5. SUMMARY

The CRTM forward model is reasonably accurate for brightness temperature or radiance simulations, but near-infrared channel is not accurate as other infrared channels.

The CRTM K-matrix function performs well for Jacobians with respect to surface temperature perturbations. The K-Matrix function with respect to atmospheric temperature and moisture is also expected to show decent agreement with the manually derived Jacobians. However, further investigation with specific experimental conditions is necessary.

Acknowledgement

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