CRTM including aerosols and historical sensors

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OUTLINE

- Extension of the CRTM for UV/Visible sensors
- Aerosol radiance assimilation
- Historical sensors for reanalysis
- Summary

Extension of CRTM for UV+VIS

Operational CRTM is for IR and MW where source is the thermal emission. To extend CRTM for UV+VIS, solar source has to be included. The extension is composed of:

1. Gaseous transmittance models for consideration

a. OPTRAN
b. Correlated k-distribution method
c. Optimal Spectral Sampling

2. Extension of Look-up tables

a. Aerosols
b. Clouds, ice cloud part from P. Yang
c. Surface emissivity/reflectivity

3. Solver for RTSolution

a. Add a loop over Fourier component for azimuth angle.
b. Add TOA solar irradiance

Transmittance Models for UV+VIS

For UV and VIS bands, reflection and scattering determine satellite measurements.

1. OPTRAN

OPTRAN transmittance is path-dependent. The scaling of the optical depth depending on the secant of the viewing angle is not valid. OPTRAN is a good approximation for emission dominated radiation, for example for IR and MW.

2. Correlated k-distribution method

Grouping gaseous spectral transmittances according to the absorption coefficient k. The concept of the method behind is that the wavenumber integration may be replaced by an integration over the k space. It is a fast method for the computation of long-wave and short-wave radiation. However, for the selected k values and associated weights, we no longer identify the corresponding position in the spectral space (i.e. wavenumber). We cannot consider sensor spectral response function and the spectral variation of cloud, aerosol, and surface within the band.

3. Optimal Spectral Sampling (OSS)

The common base for the exponential fit, k-distribution and OSS is very similar. OSS method can take account for sensor spectral response function and the spectral variation of cloud, aerosol, and surface within the band. ***We are testing the computation efficient between k-distribution and OSS for UV and VIS channels.***

CRTM Baseline Solver +solar radiation

(Advanced Doubling-Adding, ADA)

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

$$\mathbf{r}(\delta_0) = \delta_0 \boldsymbol{\beta} \qquad \mathbf{t}(\delta_0) = \mathbf{E} + \boldsymbol{\alpha}\delta_0 \qquad \delta = \delta_n = 2^n \delta_0$$

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

2. Compute layer source functions

$$\mathbf{S_u} = [(\mathbf{E} - \mathbf{t} - \mathbf{r})B(T_1) - (B(T_2) - B(T_1))\mathbf{t} + \frac{B(T_2) - B(T_1)}{(1 - \varpi g)\delta}(\mathbf{E} + \mathbf{r} - \mathbf{t})\mathbf{u}]\boldsymbol{\Xi} + \frac{\varpi F_0}{\pi}\exp(-\frac{\tau_{k-1}}{\mu_0})[(\mathbf{E} - \mathbf{t}\exp(-\frac{\delta}{\mu_0}))\Psi_u - \mathbf{r}\Psi_d]$$

$$\mathbf{S_d} = [(\mathbf{E} - \mathbf{t} - \mathbf{r})B(T_1) + (B(T_2) - B(T_1))(\mathbf{E} - \mathbf{r}) + \frac{B(T_2) - B(T_1)}{(1 - \varpi g)\delta}(\mathbf{t} - \mathbf{E} - \mathbf{r})\mathbf{u}]\boldsymbol{\Xi} + \frac{\varpi F_0}{\pi}\exp(-\frac{\tau_{k-1}}{\mu_0})[(\exp(-\frac{\delta}{\mu_0})E - \mathbf{t})\Psi_d - \mathbf{r}\exp(-\frac{\delta}{\mu_0})\Psi_u]$$

$$\begin{bmatrix}\Psi_d \\ \Psi_u\end{bmatrix} = -\frac{\varpi F_\lambda}{(1+\delta_{0m})\pi}\begin{bmatrix}\boldsymbol{\alpha} + E/\mu_0 & \boldsymbol{\beta} \\ -\boldsymbol{\beta} & -\boldsymbol{\alpha} + E/\mu_0\end{bmatrix}^{-1}\begin{bmatrix}\phi(\mu_i,\mu_0) \\ \phi(-\mu_i,\mu_0)\end{bmatrix}$$

3. Vertical integration

$$\mathbf{I_u}(n) = \varepsilon B(T_s) + \frac{F_\lambda \exp(-\tau_N/\mu_0)}{(1+\delta_{0m})\pi}R_s(\mu_0)$$

$\mathbf{R}(n)$ **the surface reflection matrix, loop k from n → 1**

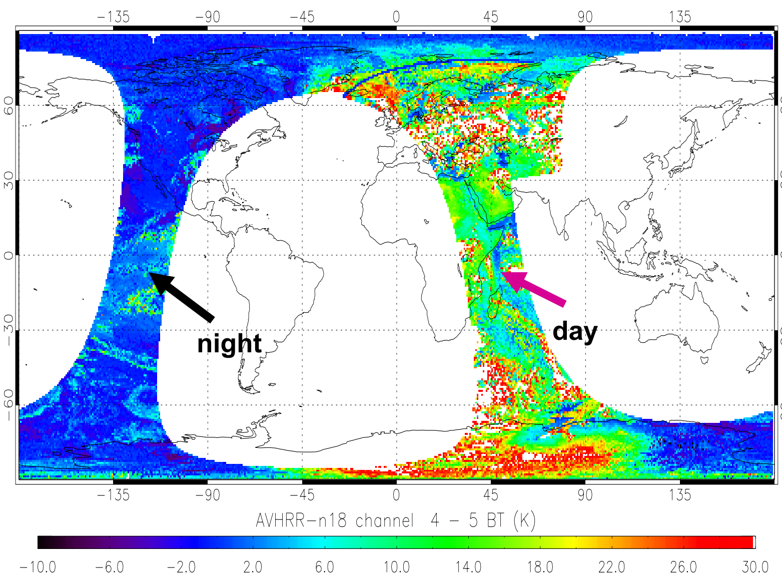
$$\begin{aligned}\mathbf{I_u}(k-1) &= \mathbf{S_u}(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\ \mathbf{R}(k)\mathbf{S_d}(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\ \mathbf{I_u}(k) \\ &= \mathbf{S_u}(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\ [\mathbf{R}(k)\mathbf{S_d}(k) + \mathbf{I_u}(k)]\end{aligned}$$

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

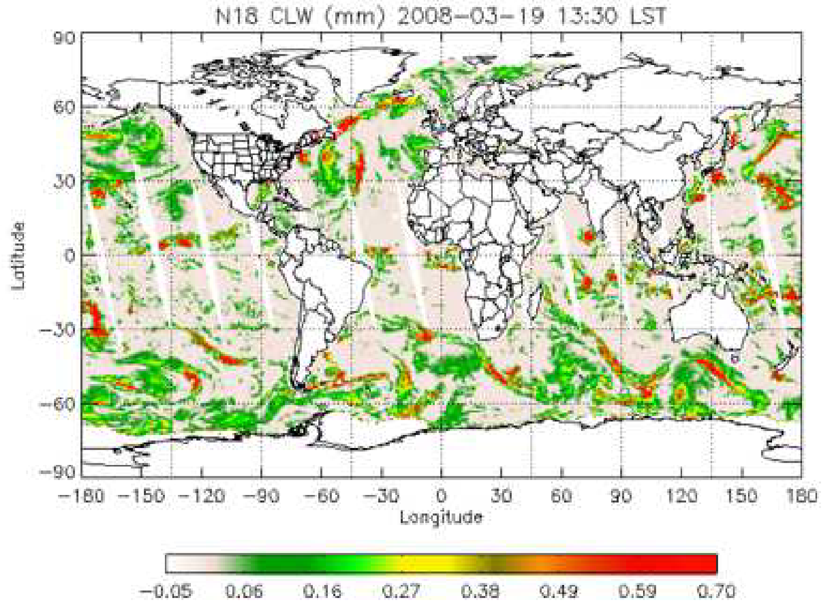
4. Final TOA radiance

$$\mathbf{R}adiance = \mathbf{I}_u(0) + \mathbf{R}(0)\mathbf{I}_{sky}$$

Solar radiation effect on AVHRR 3.7 µm, 9:00



For clear atmosphere, the brightness temperature Difference between AVHRR channels 4 and 5 is small. The large difference for the ascending orbit is resulted from reflected solar radiation at channel 4. The white color in the orbit represents values exceed 30 K.



MSPPS cloud liquid.

Improving the CRTM Computation Efficiency

1. **Fast model**
2. **Selection of an optimal number of scattering angles (two/four/eight streams).**
3. **Optimal coding (machine dependent??), for example IBM machine is "memory usage" sensitive.**
4. **Our matmul –vs- IBM intrinsic matmul** was about 9 times faster.

Table 1. CPU time usage for operational algorithm (op), operational algorithm with the fast matrix manipulation (rev-op), new four-stream and new two-stream methods.

	op	rev-op	Four-stream + observation angle	Two-stream + observation angle
Single CPU	100	69	26	17
32 CPUs for GSI	100	66	29	18

Applications of CRTM including Aerosols

Aerosols are suspended particles in the atmosphere. Its size ranges from less than 100 nm to several microns. Aerosols mainly interacts with electromagnetic at ultraviolet, visible and infrared, microwave ranges.

1. **Air Quality/health, depending on aerosol concentration**
2. **SST, uploaded Sahara dust affects IR radiance**
3. **Ozone, aerosol correction for ozone retrieval**
4. **Radiation, net radiation budget for atmospheric heating/cooling, and for climate studies**
5. **CCN (cloud condensation nuclei), for cloud and precipitation, aerosols having small size absorb water vapor and reduce precipitation, while aerosols having large size increase rain.**

Aerosols and Air Quality

Particulate mass with the size smaller than 2.5 µm (PM2.5) are found in smoke and haze, vehicles and power plants pollution, and burning (Al-Saadi et al., BAMS 2005). U.S. EPA uses PM2.5 as a measure of air quality.

TABLE 1. The U.S. EPA Air Quality Index for Particulate Matter.

Index Values	Category	Cautionary Statements	$PM_{2.5}$ ($\mu g\ m^{-3}$)	PM_{10} ($\mu g\ m^{-3}$)
0–50	Good	None	0–15.4	0–54
51–100	Moderate	Unusually sensitive people should consider reducing prolonged or heavy exertion	15.5–40.4	55–154
101–150	Unhealthy for sensitive groups	Sensitive groups should reduce prolonged or heavy exertion	40.5–65.4	155–254
151–200	Unhealthy	Sensitive groups should avoid prolonged or heavy exertion; everyone else should reduce prolonged or heavy exertion	65.5–150.4	255–354
201–300	Very unhealthy	Sensitive groups should avoid all physical activity outdoors; everyone else should avoid prolonged or heavy exertion	150.5–250.4	355–424

Source: US EPA, 1997

Needs of Radiance Assimilation for Air Quality Forecast

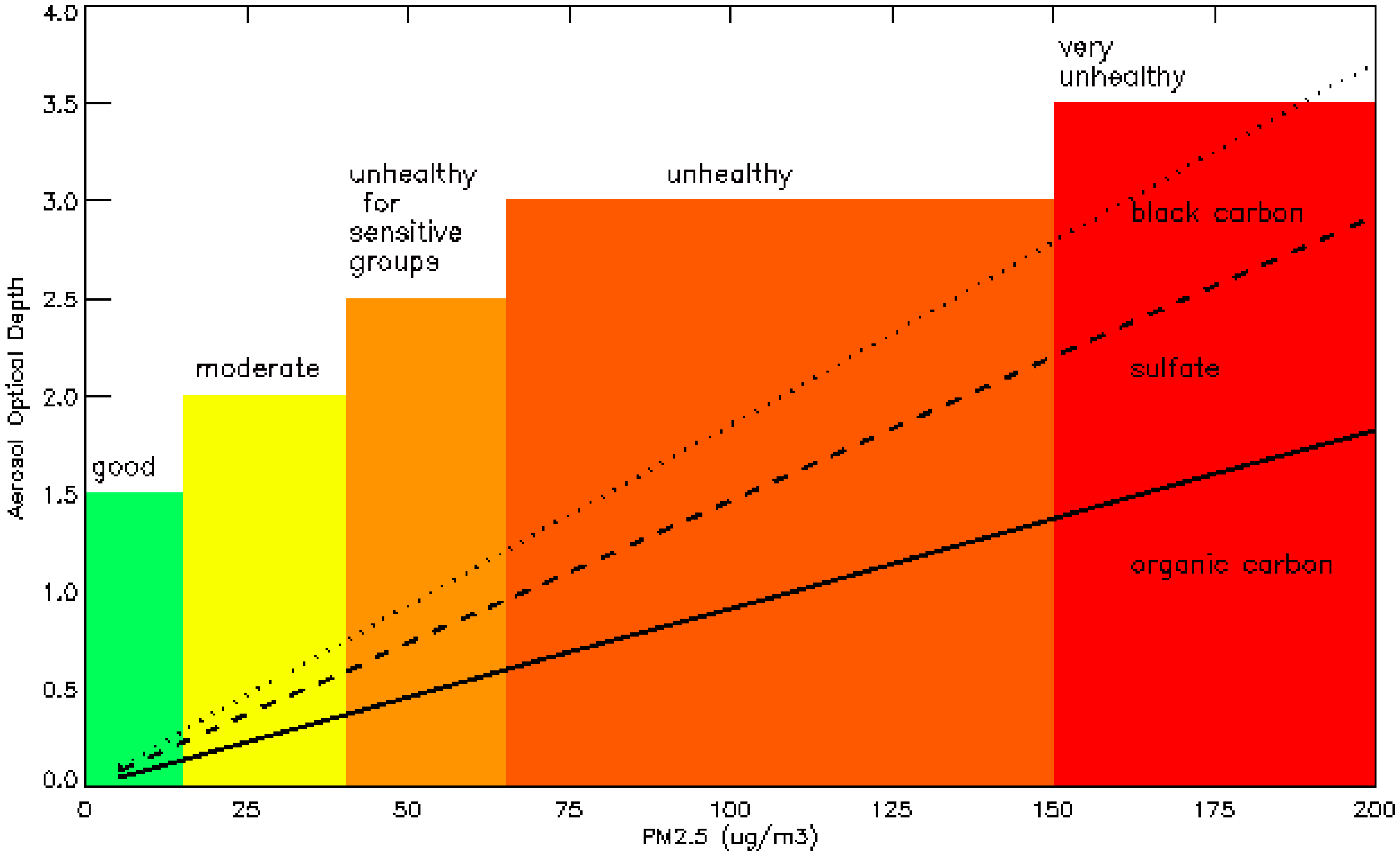
Current aerosol optical depth (AOD) product lacks of the vertical distribution and detailed chemical compounds of aerosols. AOD has no relation to surface PM2.5 when aerosol is entirely aloft.

AOD assimilation may not improve PM2.5 prediction compared with using model only, due to lack of constraints of vertical profile and composition (Mian Chin, Hongbin Yu, D. Allen Chu, 2005).

Satellite measurements alone are not sufficient to retrieve aerosols over bright surface and coast area.

By aid of wind, humidity, surface information and other observations, satellite radiance in data assimilation systems may be useful in determining the vertical distribution of PM2.5 and in improving air quality forecasting.

Air Quality vs Aerosol Optical Depth



Satellite Measurements for Aerosols

AVHRR 4-km Global Area Coverage (GAC), single channel algorithm, VIS

GOES aerosol product, VIS

MODIS 1-km Global Area Coverage, 0.66 μm and 2.2 μm, VIS.

GOME-2 (Global Ozone Monitoring Experiment), UV+VIS

AIRS (Advanced Infrared Radiation Sounder), IR,

Pierangelo, Atmos. Chem. Phys. 2004.

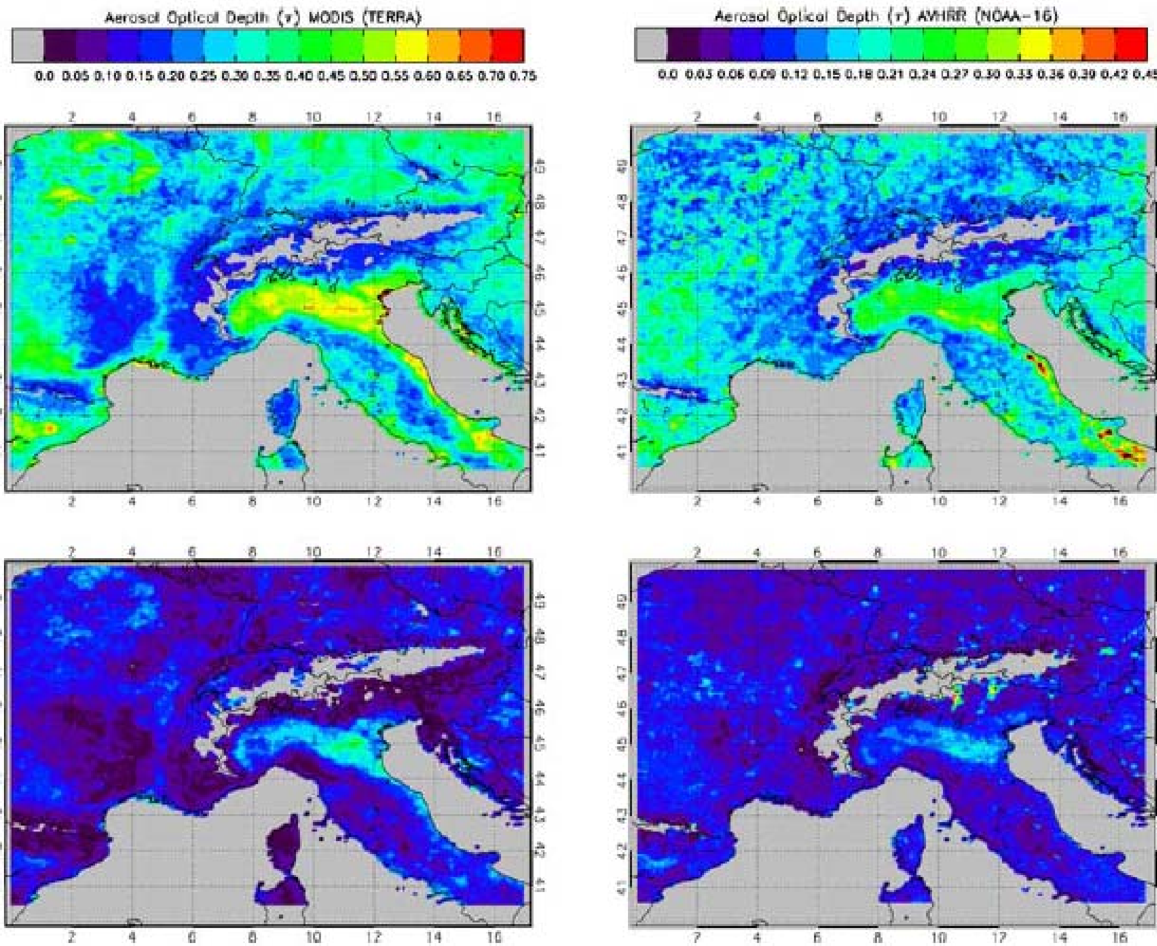
MLS (Microwave Limb Sounder), stratospheric aerosol, MW

Many other sensors

Future Sensors

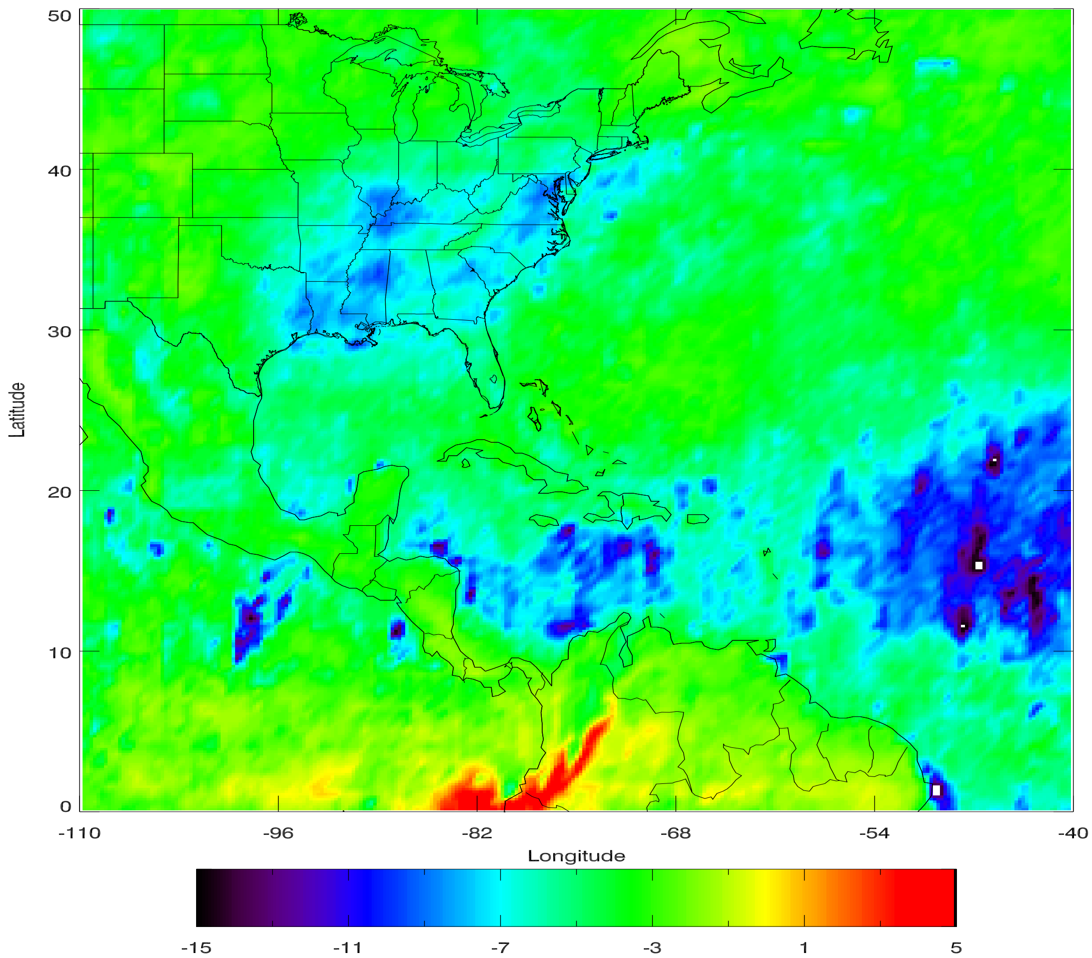
GOES-R, ABI, NPOESS VIIRS, CrIS, OMPS

AOD (MODIS vs AVHRR)



Hauser et al., 2005, GRL

Aerosol Radiative Forcing



Global monthly mean aerosol Forcing for August 2005 is 2.3 Watt/m2, which is significant to the global annually net radiation of about 0.5 Watt/m2 (BADC).

Aerosol Models

Global Model, Goddard Chemistry Aerosol Radiation and Transport (GOCART)

Dust
Sea Salt
Organic carbon
Black carbon
Sulfate

Regional Model WRF-NMM, Community Multiscale Air Quality (CMAQ)

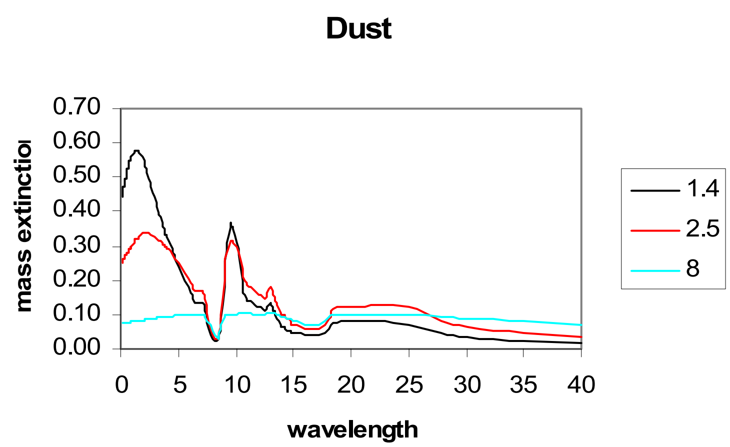
Sulfate mass
Ammonium mass
Nitrate mass
Organic mass
Unspecified anthropogenic mass
Elemental carbon mass
Marine mass
Soil derived mass

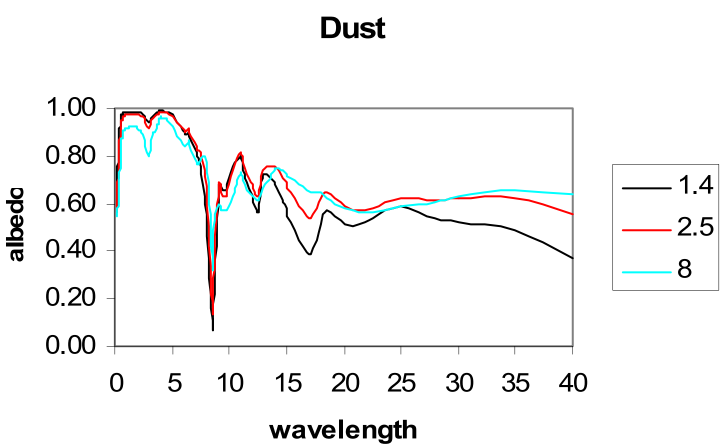
CRTM Model for GOES-R Applications (preliminary)

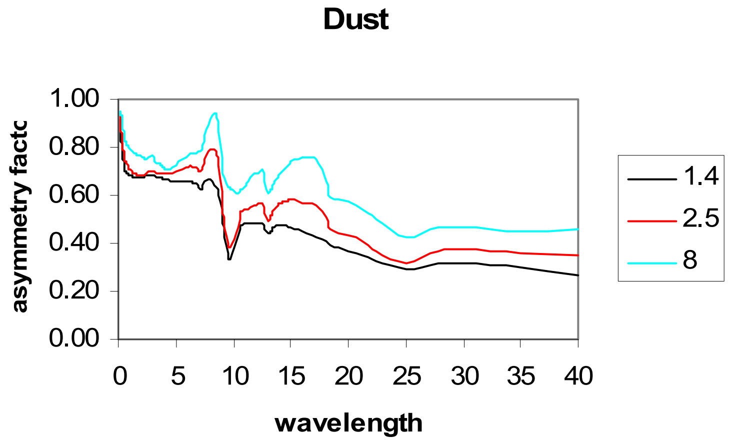
Continental
Urban
Generic 1
Heavy smoke 1
Dust

5 Coarse mode aerosol
4 Fine mode aerosol

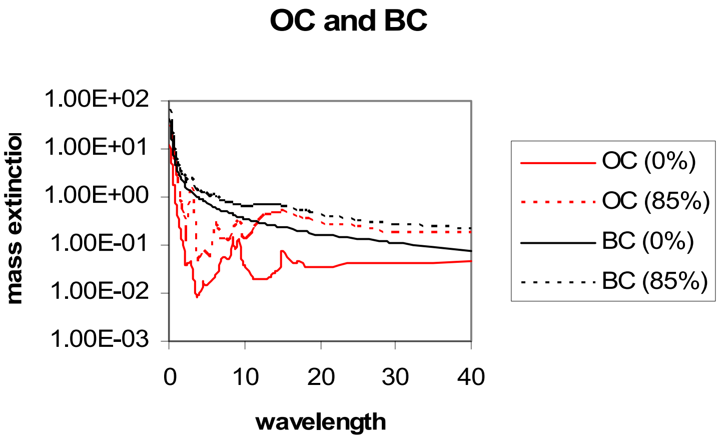
Aerosol Optical Properties (1)

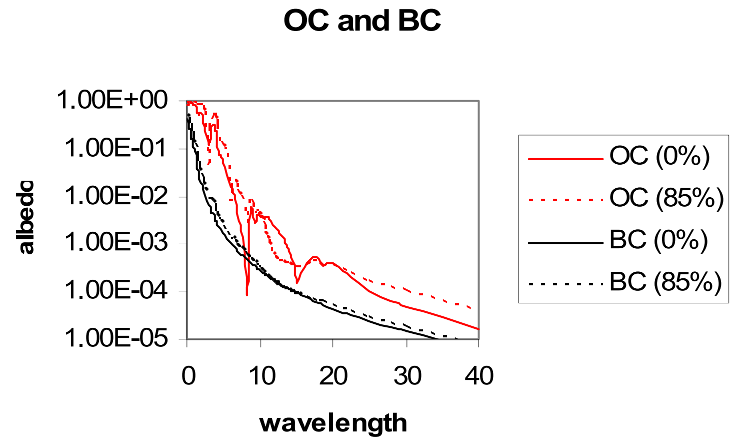


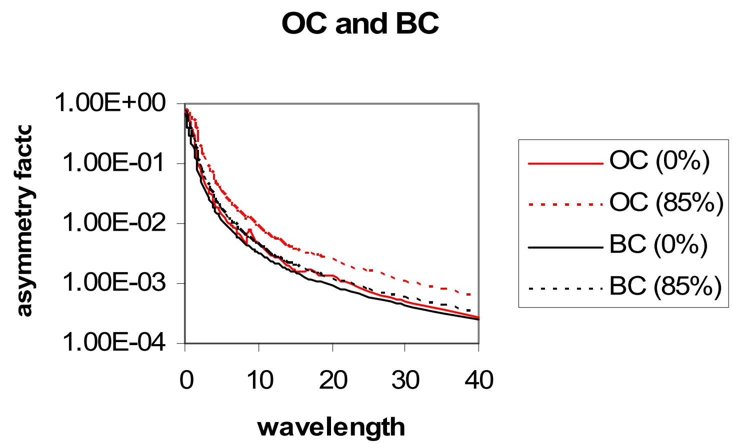




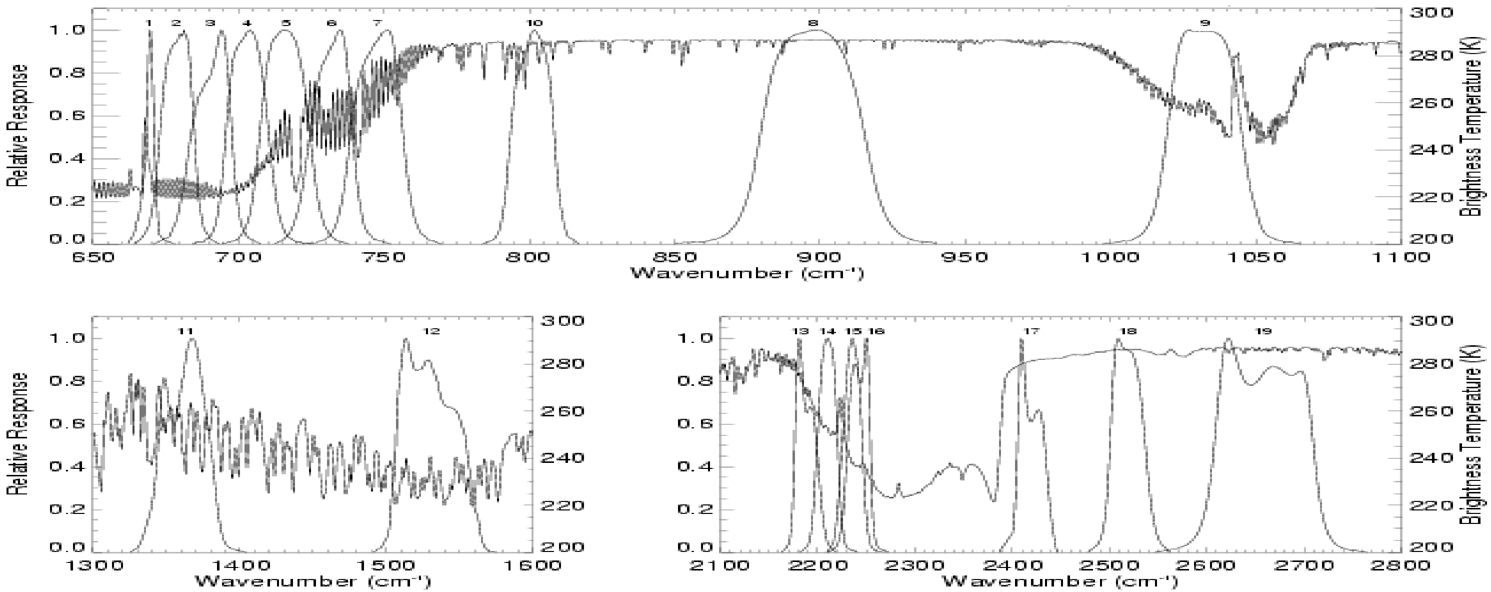
Aerosol Optical Properties (2)

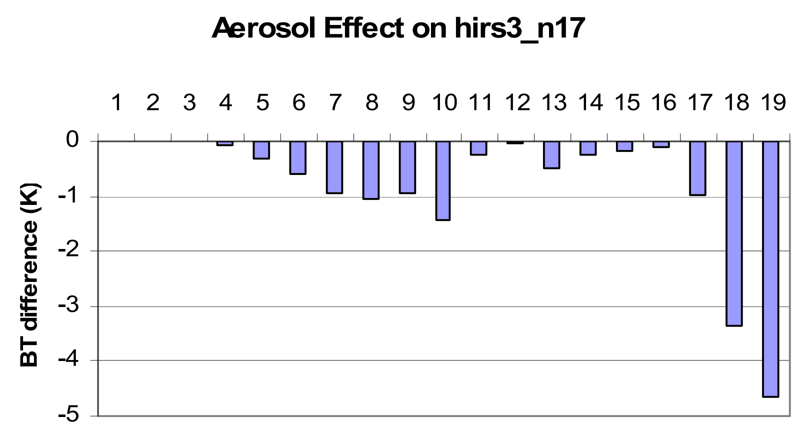






Aerosols' effect on hirs3_n17





No clouds

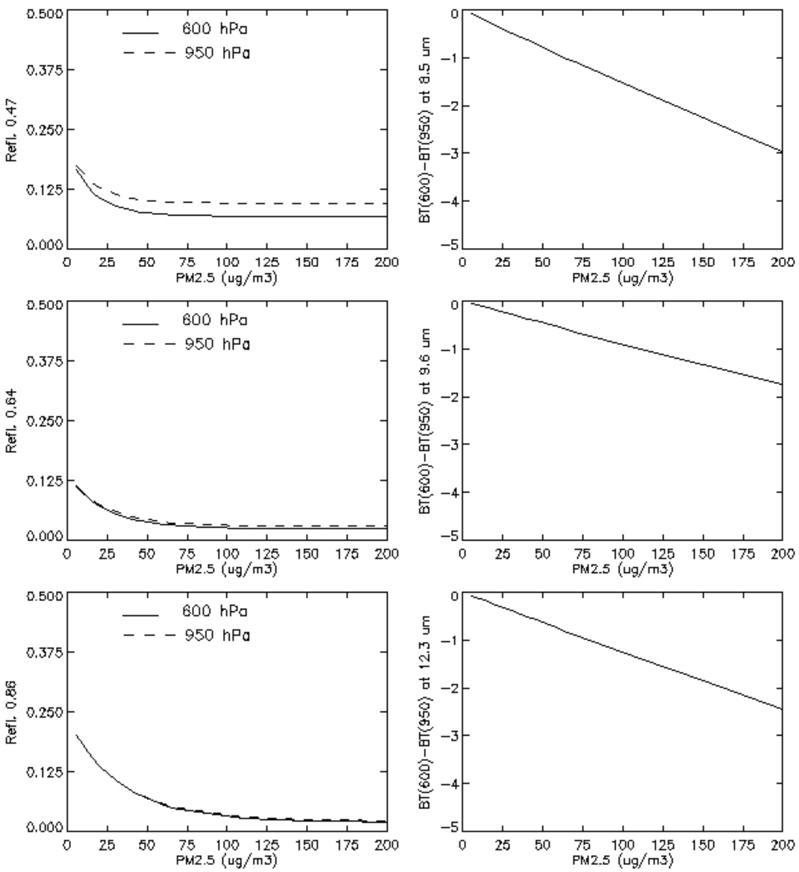
0.1 g/m2 OC aerosol at 300 hPa

0.1 g/m2 Dust aerosol at 600 hPa

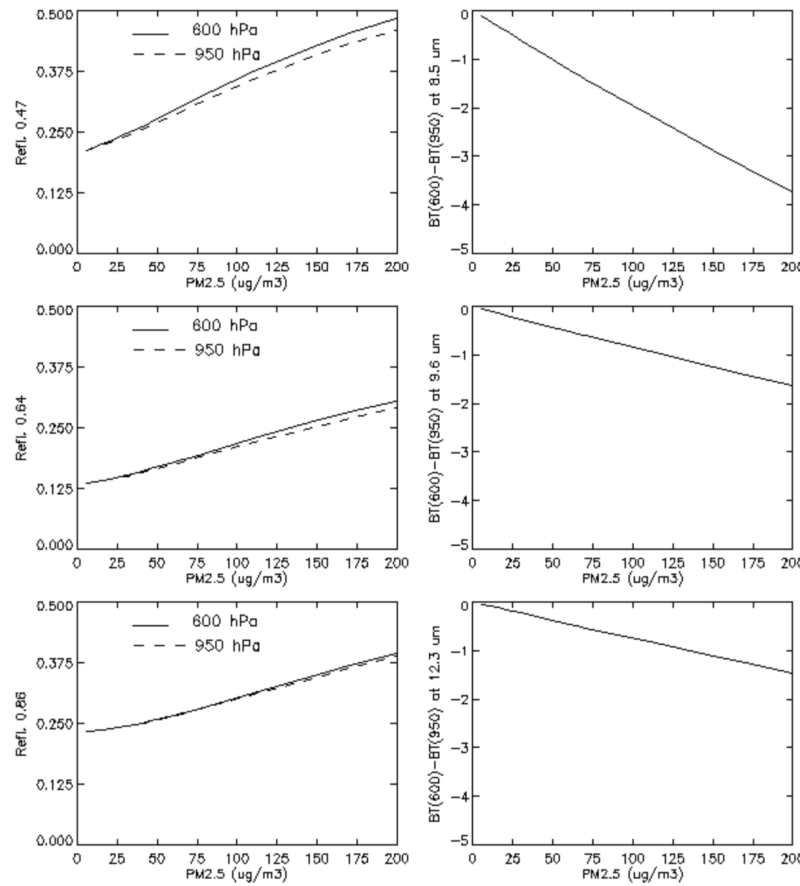
0.1 g/m2 Dust aerosol at 650 hPa

Sensitivity to the aerosol altitude

Black carbon



Sulfate



SSU Data

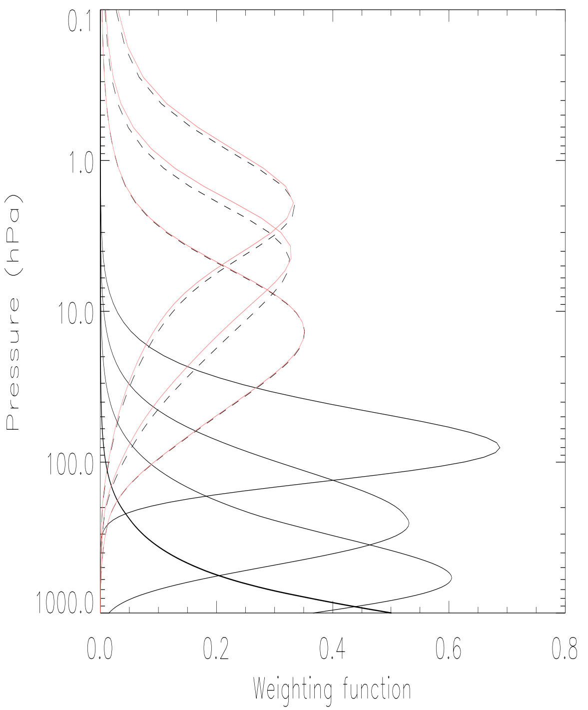
Stratospheric Sounding Unit data is a three-channel sensor onboard NOAA series satellites (started from TIROS-N in 1978 and ended at NOAA-14 in 2006).
The data in past 29 years is unique for middle and upper stratospheric temperatures.

Using CO2 cell pressure modulation onboard satellite, the single CO_2 15 μm is split into 3 channels and shifted up to middle and upper stratosphere.

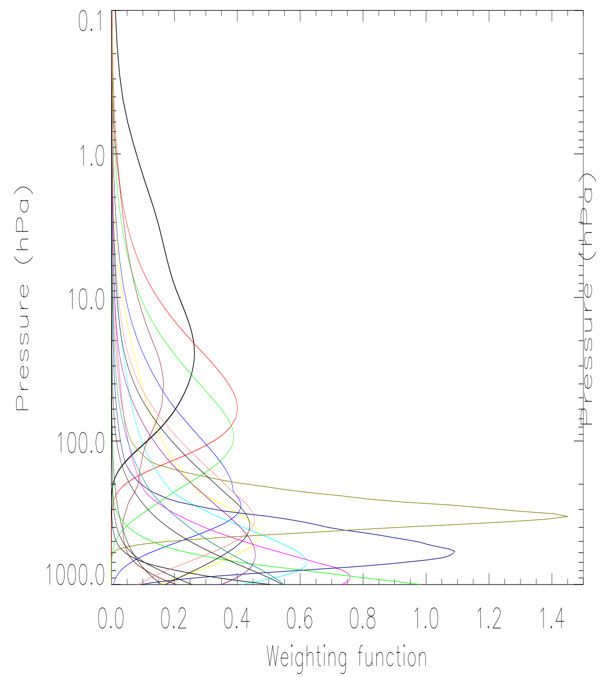
In absent of a fast and accurate transmittance model, the SSU data was not used in NCEP analysis and previous reanalysis.

Satellite Data for Reanalysis and Climate Studies

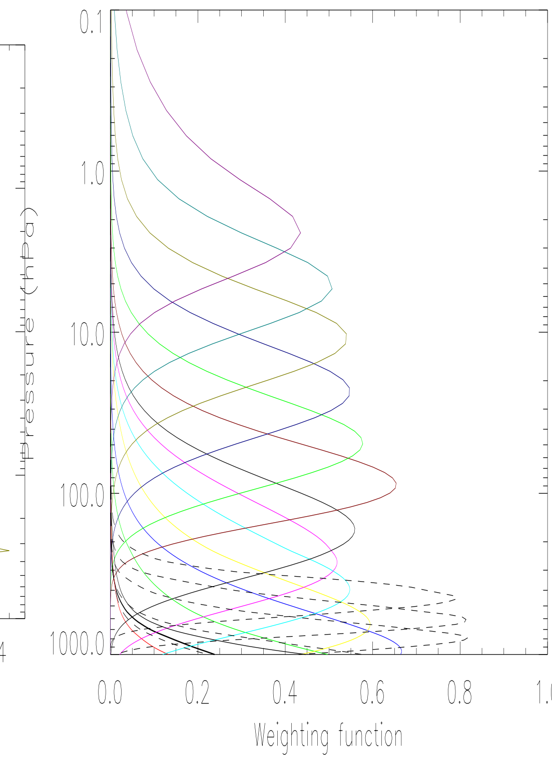
TOVS (1978-2006) **ATOVS (since 1998)**



SSU+MSU



HIRS



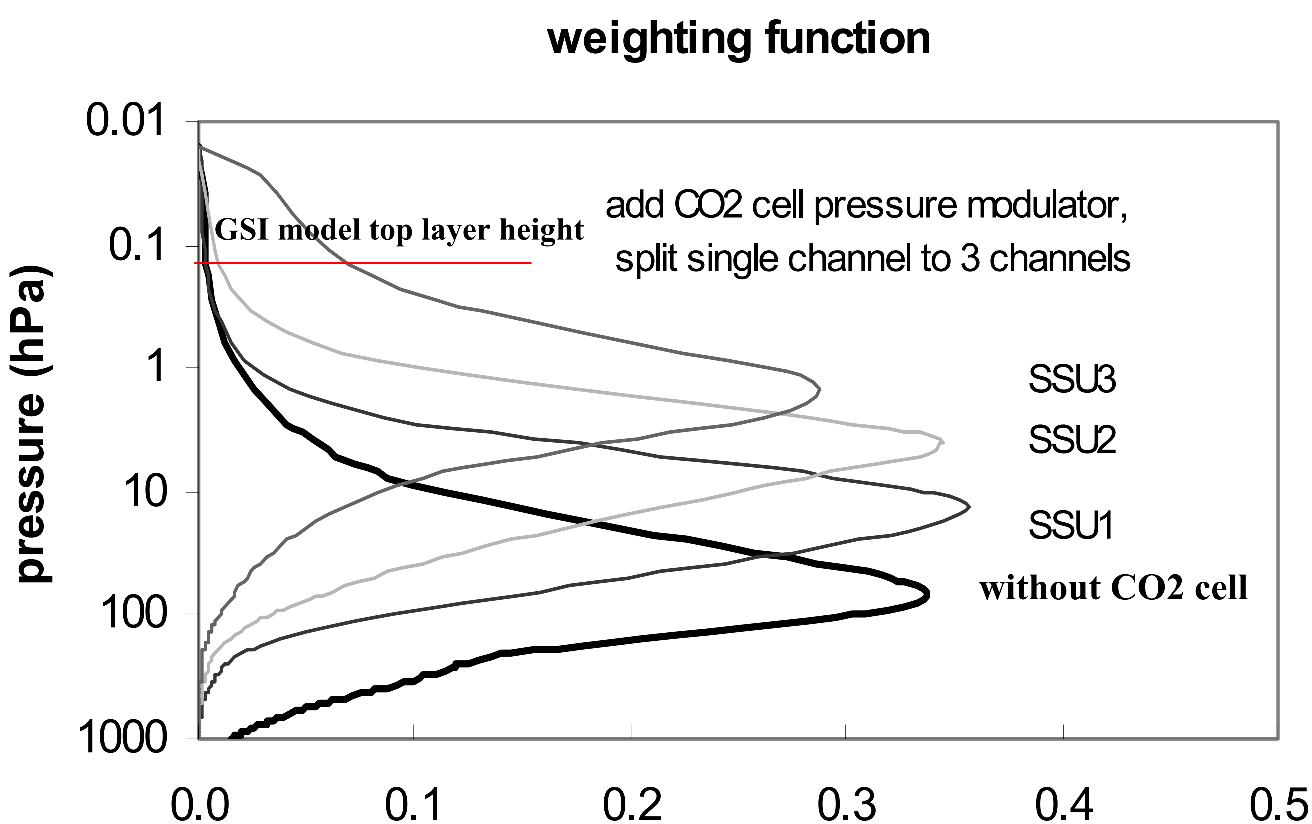
AMSU

SSU part: Dashed line is for 1/1/1995.

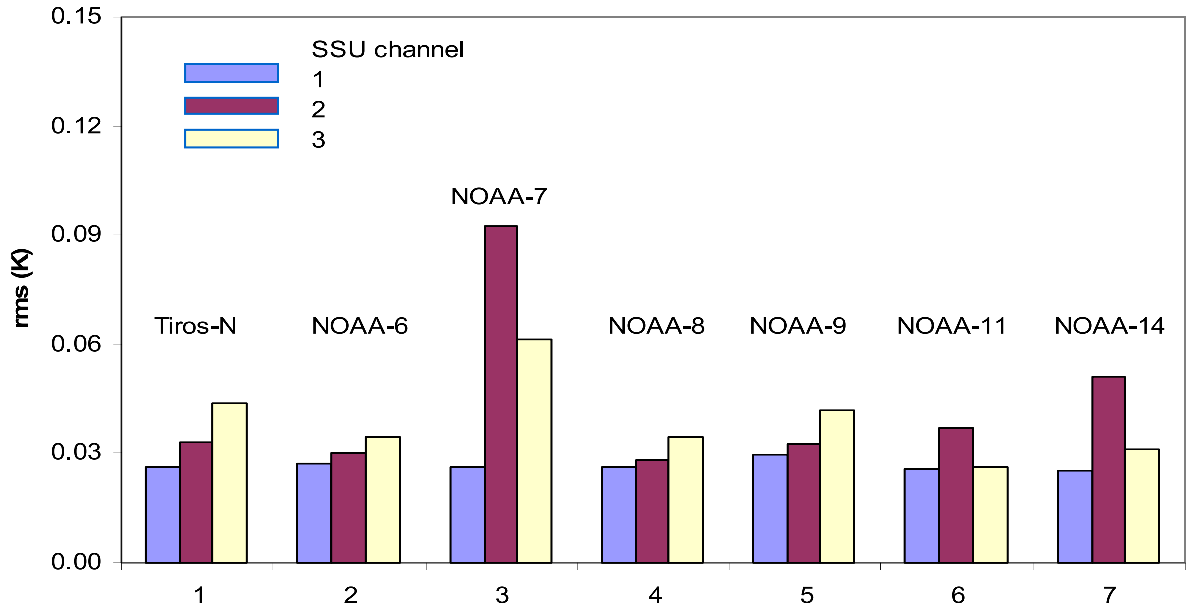
Red line is for 1/1/2003, indicate the shift of the weighting function due to the leaking.

Weighting Function

Split into 3 channels and shifted upward middle and upper stratosphere

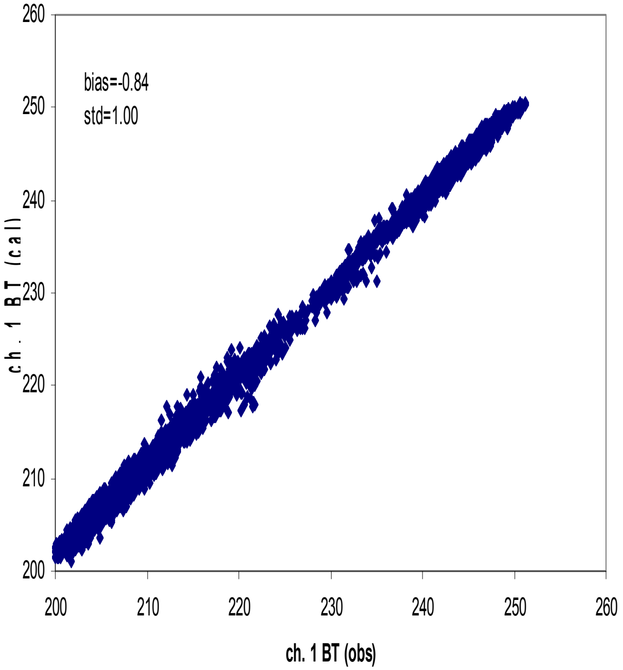


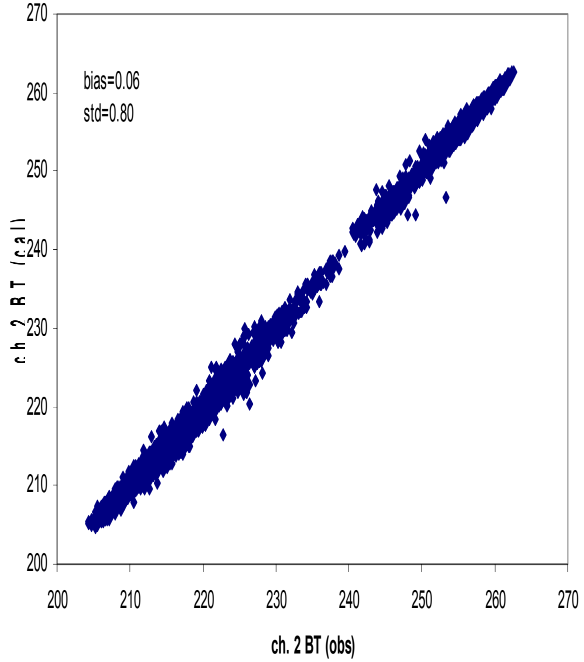
Comparison between LBL and OPTRAN-SSU

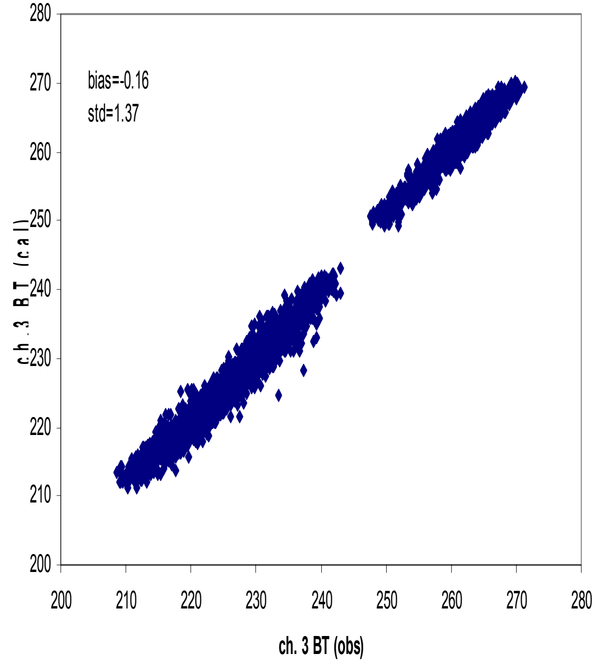


Fitting error + interpolation error for CO2 cell pressure

Validation using Microwave Limb Sounding Product



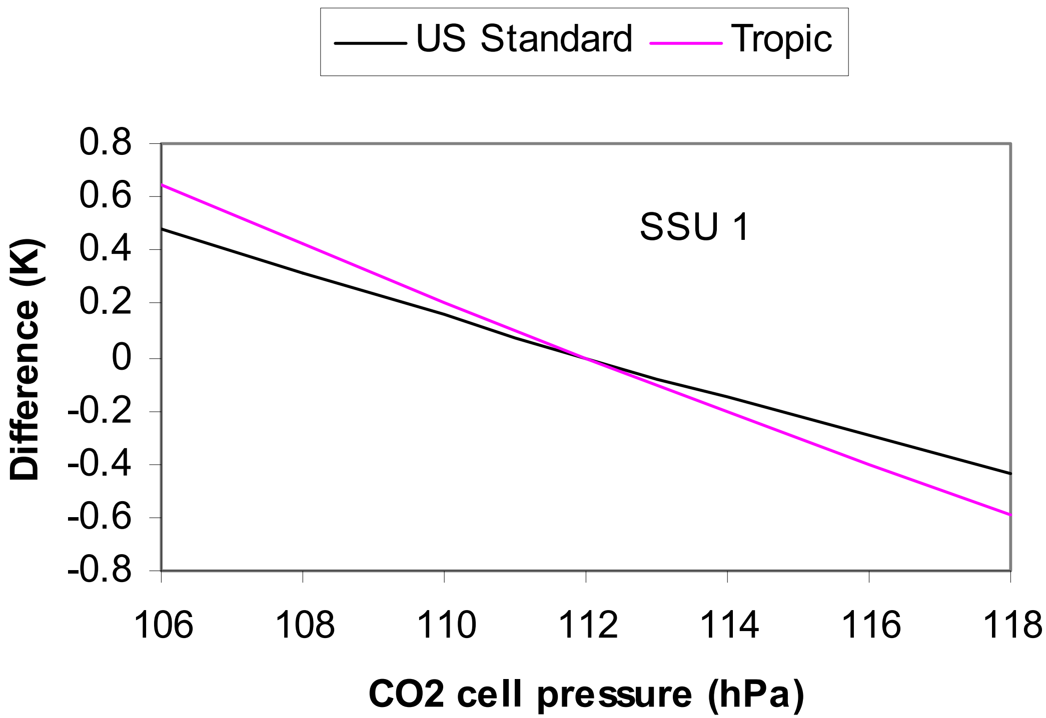




SSU and MLS data for 11/2004,

All match-up data points are plotted.

CO2 cell pressure effect on SSU observation



Channel 1

The difference depends on both cell pressure and atmospheric state.
The difference for channels 2 and 3 are larger.

Error budget

Brindley et al. (1999) showed the variation of SSU brightness temperature at channel 1 due to the leaking is between -0.3 and 0.3 K during entire SSU mission. But, the variation for SSU channels 2 and 3 can be between 0.5 ~ 1.5 K for single mission.
By considering the CO2 cell pressure as a variable in the CRTM, this part error is < 0.1 K.

By choosing a constant CO2 concentration in a mission (e.g. NOAA-14), the brightness temperature change for CO2 between 370 and 380 ppmv is 0.15 K.

The fitting error in the CRTM fast model against line-by-line model is very small (< 0.05 K).

The channel 3 is affected by the input atmospheric profile above the model height (~0.2 hPa). The error is not quantitatively evaluated.

Summary

- The CRTM model takes care of the leaking problem by using a LUT for CO2 cell pressure calculated from satellite ID and observation time. The CRTM is used for NCEP reanalysis.
- The CRTM model is being implemented for UV/Visible radiance simulation.
- CRTM will provide the tool to support the work direct aerosol radiance assimilation,
- Aerosol optical depth is useful for a quick monitor of air quality and a background field of the aerosol, in particular identify the aerosol sources,
- Aerosol type and height are important to the air quality radiance simulation

Acknowledgments

- Thanks to NCEP Sarah Lu, Jeff McQueen for inputs/outputs description of GOCART model and NCEP + GOCART data.

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- Thanks to NASA Mian Chin for providing aerosol refractive indices and helpful discussions!

- JCSDA Supports