Stratospheric Sounding Unit (SSU) Radiance Modeling and Applications

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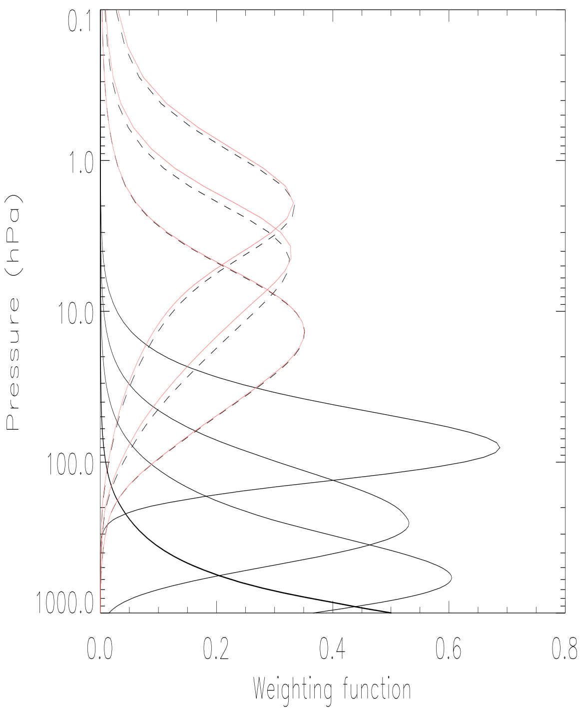
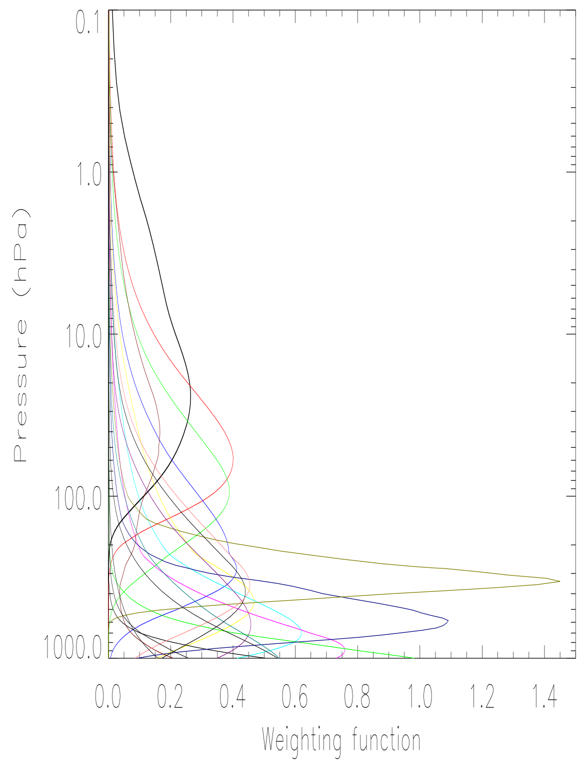
Satellite Data for Reanalysis and Climate Studies

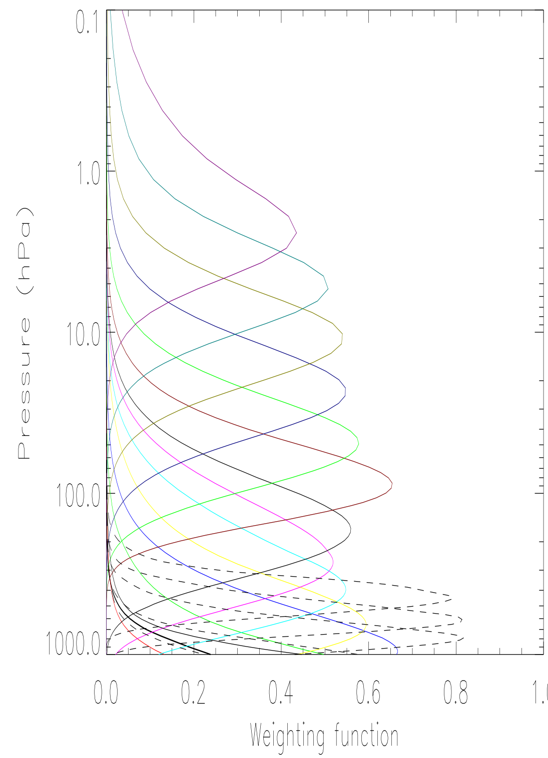
TOVS (1978-2006) **ATOVS (since 1998)**



SSU+MSU



HIRS



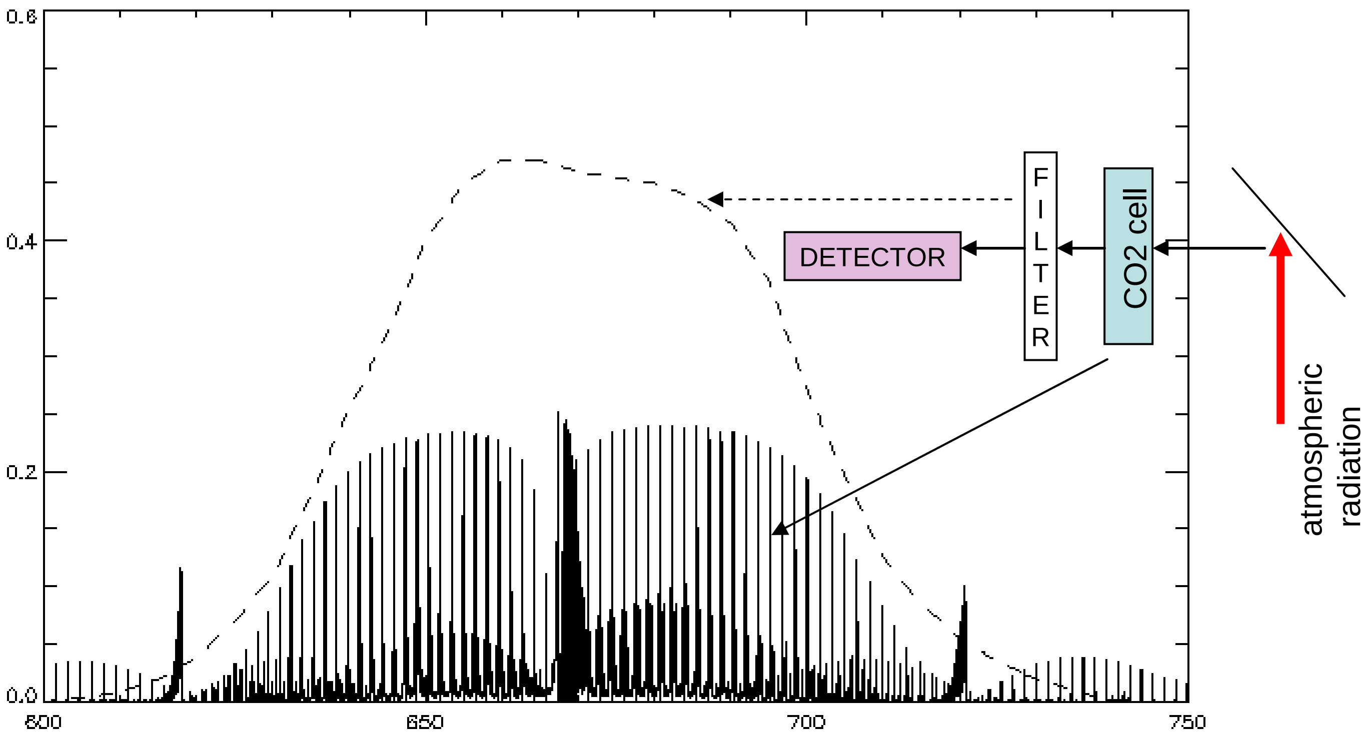
AMSU

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.

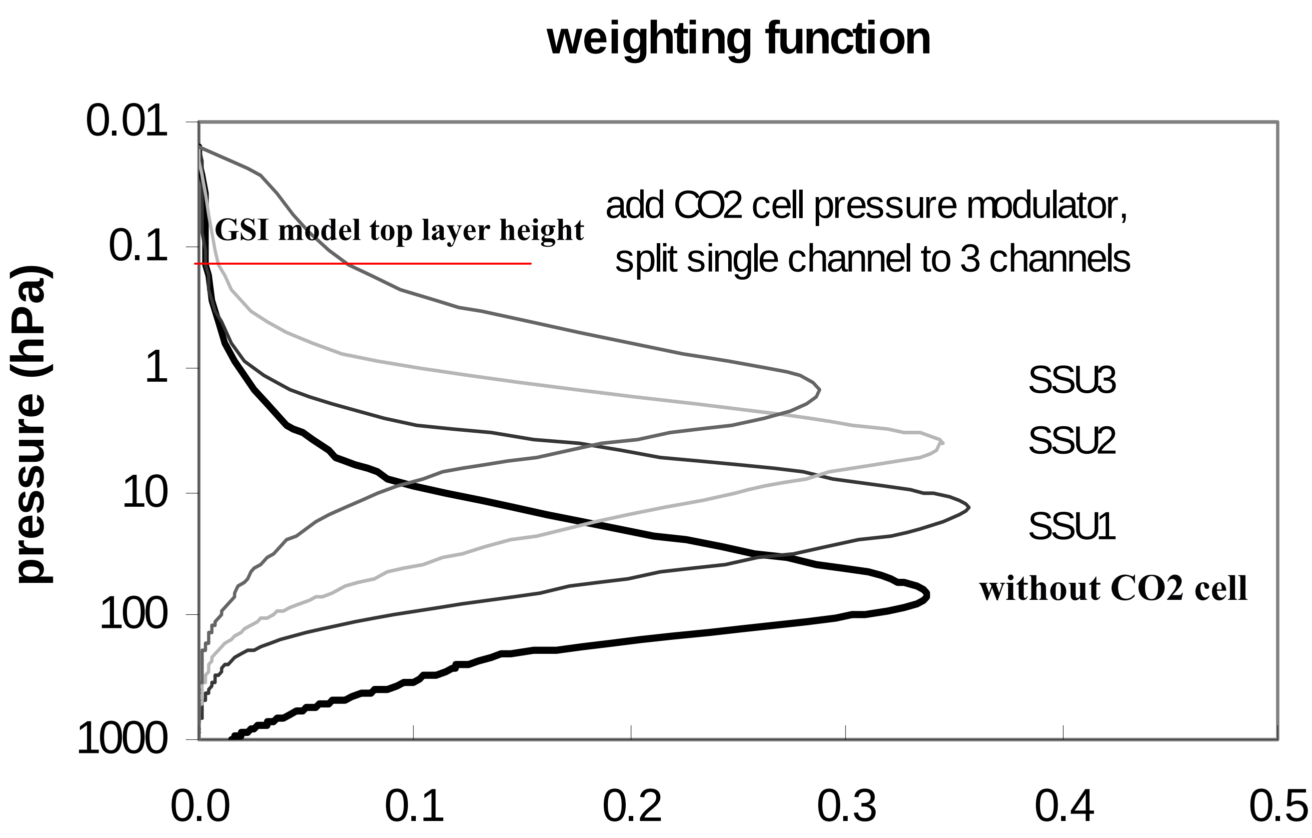
Sensor Response Function (SRF)

Different from a conventional sensor response function, the SSU SRF is a product of traditional broadband and the CO_2 cell absorption line responses.

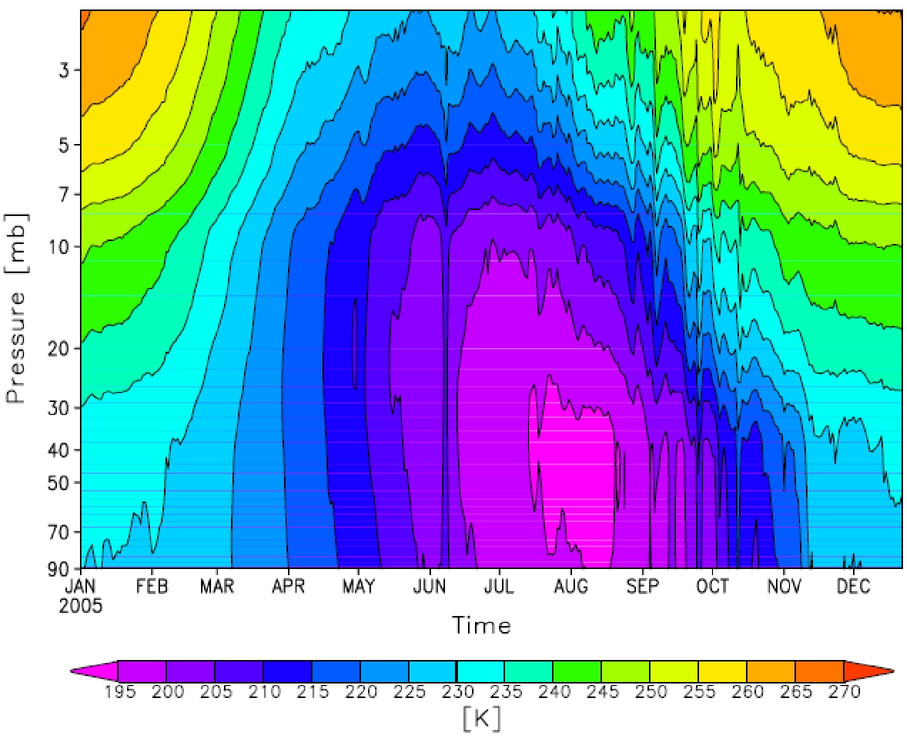


Weighting Function

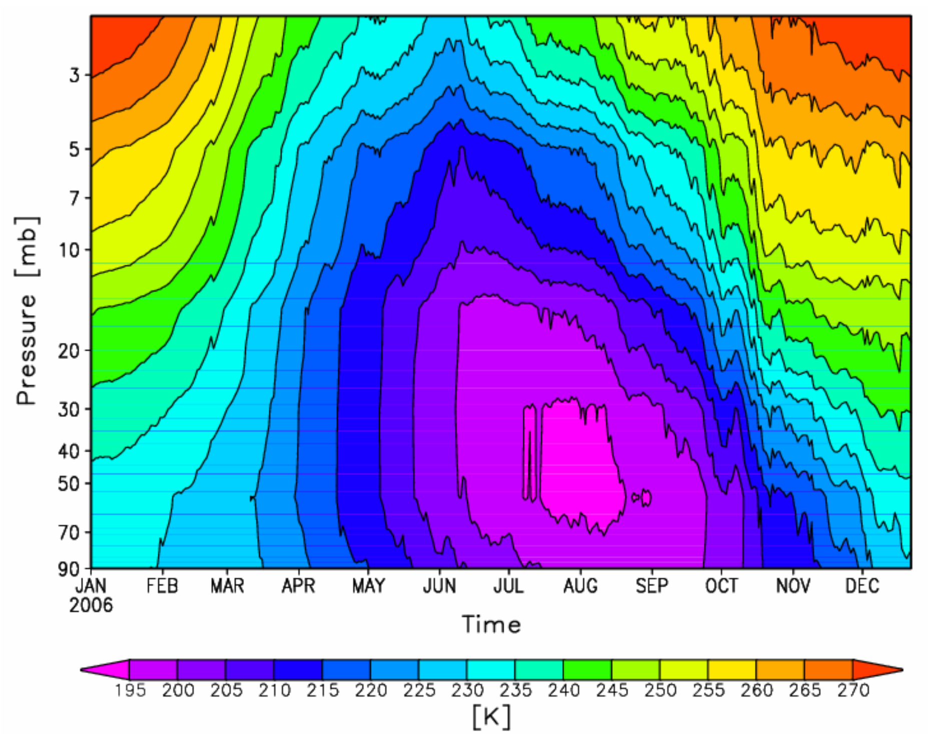
Split into 3 channels and shifted upward middle and upper stratosphere



Multi-channel brightness temperatures averaged from 60º S to the South pole



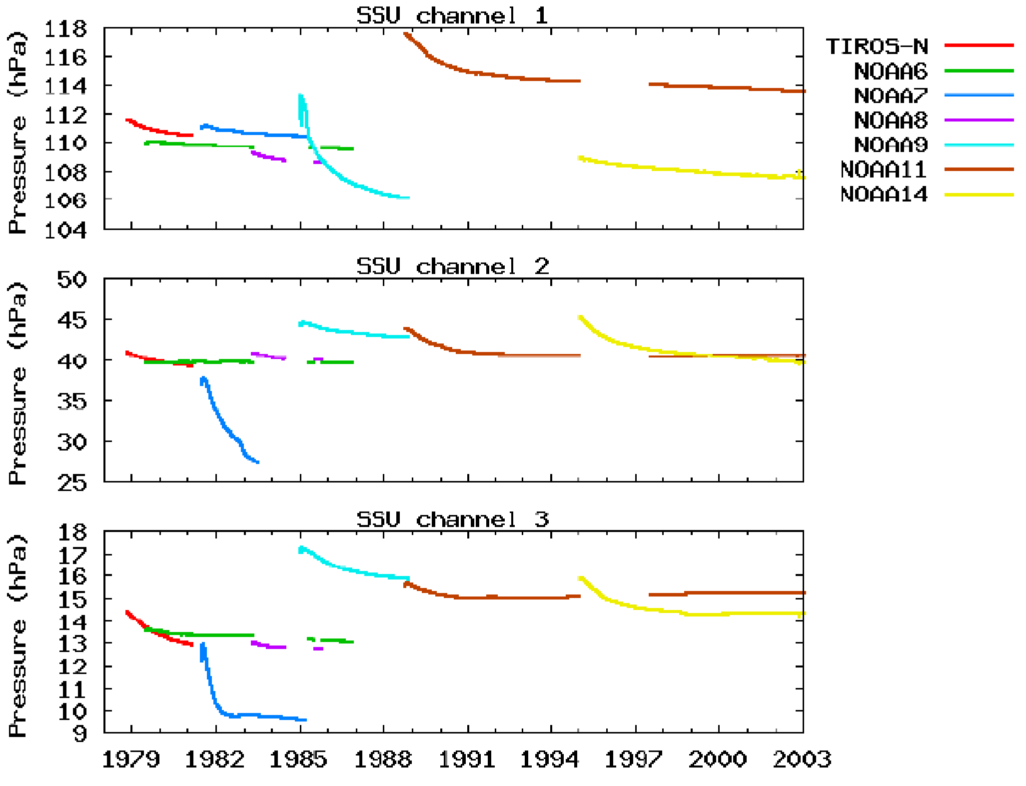
A composite of 3 SSU channels and MSU channels 3 and 4, for 2005



A snapshot of a time series of the interpolated brightness temperatures at SSMIS channels 22, 23, 24, 7, 6, and 5 for 2006.

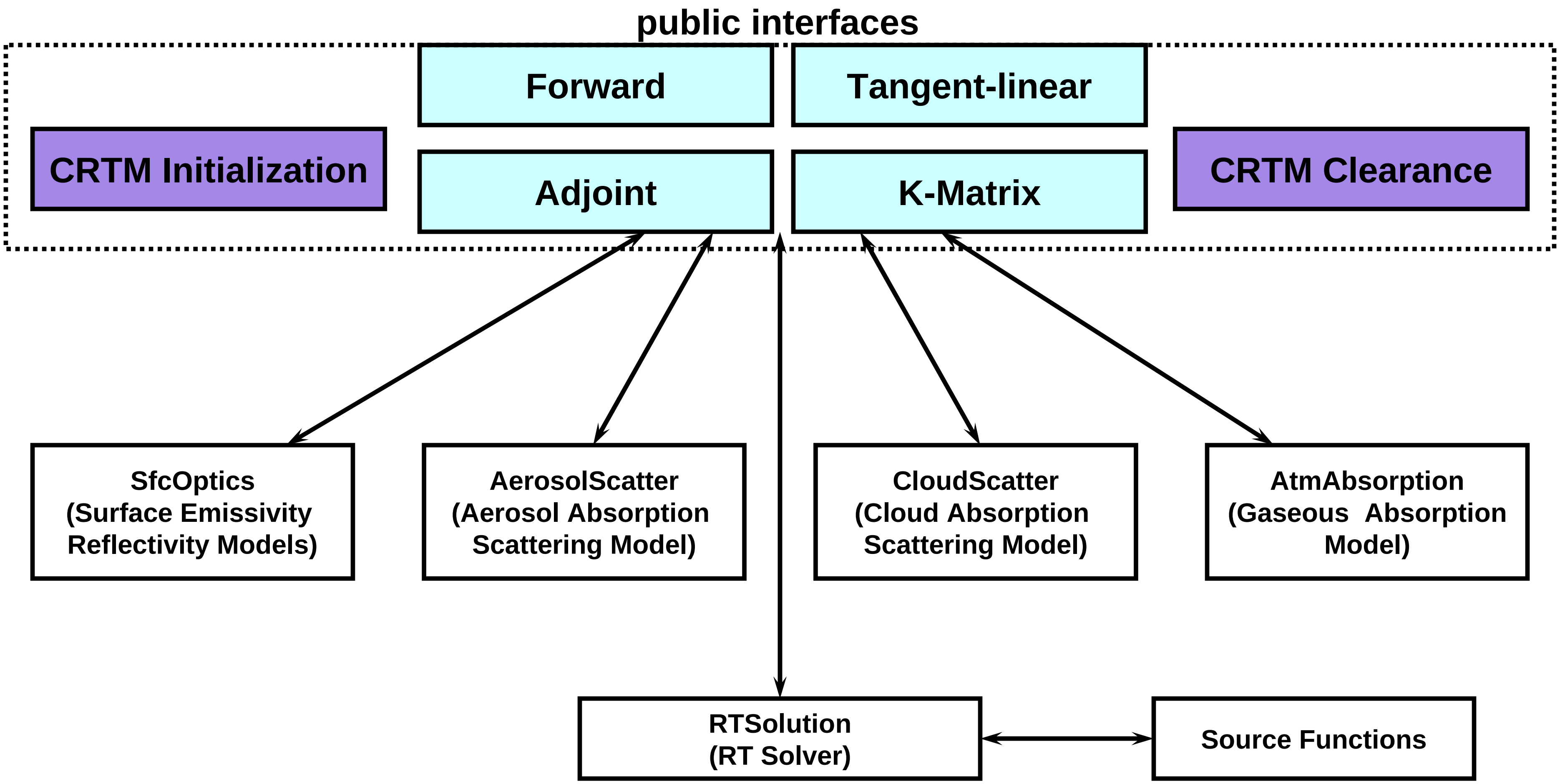
Liu et al., GRL 2007.

CO2 Leaking in cell pressure modulator



This figure is from Dr. Shinya Kobayashi at ECMWF.

CRTM Major Modules



Weng, 2007 JAS

Han et al., 2007, NOAA Tech. Report

CRTM Baseline Solver (Advanced Doubling-Adding, ADA)

Layer transmission and reflection

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

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

Layer source function

$$\mathbf{S_u} = [(\mathbf{E} - \mathbf{t} - \mathbf{r})B(T_1) - (B(T_2) - B(T_1))\mathbf{t} + \frac{B(T_2) - B(T_1)}{(1-\varpi g)\delta}(\mathbf{E} + \mathbf{r} - \mathbf{t})\mathbf{u}]\boldsymbol{\Xi}$$

$$\mathbf{S_d} = [(\mathbf{E} - \mathbf{t} - \mathbf{r})B(T_1) + (B(T_2) - B(T_1))(\mathbf{E} - \mathbf{r}) + \frac{B(T_2) - B(T_1)}{(1-\varpi g)\delta}(\mathbf{t} - \mathbf{E} - \mathbf{r})\mathbf{u}]\boldsymbol{\Xi}$$

Vertical integration

$\mathbf{I_u}(n) = \varepsilon B(T_s)$ $\quad \mathbf{R}(n)$ **the surface reflection matrix, loop k from n → 1**

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

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

TOA radiance

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

Liu and Weng, 2006 JAS

CRTM + solar part

Method 1. Add downward solar source at TOA and treat sun direction as additional stream

$$\mathbf{R}adiance = \mathbf{I}_u(0) + \mathbf{R}(0)[\mathbf{I}_{sky} + \mu_0 \mathbf{S}olar\_i]$$

Method 2. Add solar source in layer source function

$$\mathbf{S_d} = [(\mathbf{E}-\mathbf{t}-\mathbf{r})B(T_1) + (B(T_2)-B(T_1))(\mathbf{E}-\mathbf{r}) + \frac{B(T_2)-B(T_1)}{(1-\varpi g)\delta}(\mathbf{t}-\mathbf{E}-\mathbf{r})\mathbf{u}]\mathbf{\Xi}$$

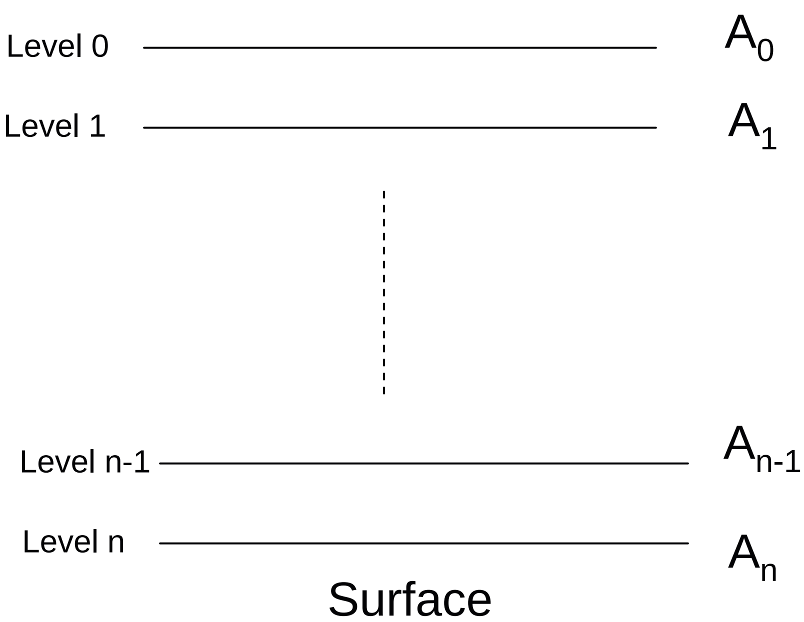
$$+\frac{\varpi F_0 \mu_0}{\pi}[\mathbf{r}\exp(-\frac{\tau}{\mu_0})]\Psi_u + [\exp(-\frac{\tau}{\mu_0}) - \mathbf{t}]\Psi_d$$

$$\mathbf{S_u} = [(\mathbf{E}-\mathbf{t}-\mathbf{r})B(T_1) - (B(T_2)-B(T_1))\mathbf{t} + \frac{B(T_2)-B(T_1)}{(1-\varpi g)\delta}(\mathbf{E}+\mathbf{r}-\mathbf{t})\mathbf{u}]\mathbf{\Xi}$$

$$+\frac{\varpi F_0 \mu_0}{\pi}[\mathbf{E}-\mathbf{t}\exp(-\frac{\tau}{\mu_0})]\Psi_u + [\exp(-\frac{\tau}{\mu_0}) + \mathbf{r}]\Psi_d$$

Ψ_u, Ψ_d **are phase vectors computed from layer phase matrix.**

Gaseous Transmittance Model
Compact OPTRAN



$$\ln(k_{ch}(A)) = c_0(A) + \sum_{j=1}^{6} c_j(A) P_j(A)$$

$$c_j(A) = \sum_{m=0}^{n} a_{j,m} \ln(A)^m, \; j = 0,6, \; n < 10$$

$$\tau_{ch} = \exp(-k_{ch}\delta A)$$ estimate layer transmittance

$$\tau_{ch} := \int \tau_\nu \phi_\nu d\nu$$ Channel transmittance definition

ϕ_ν – spectral response function

K – absorption coefficient of an absorber

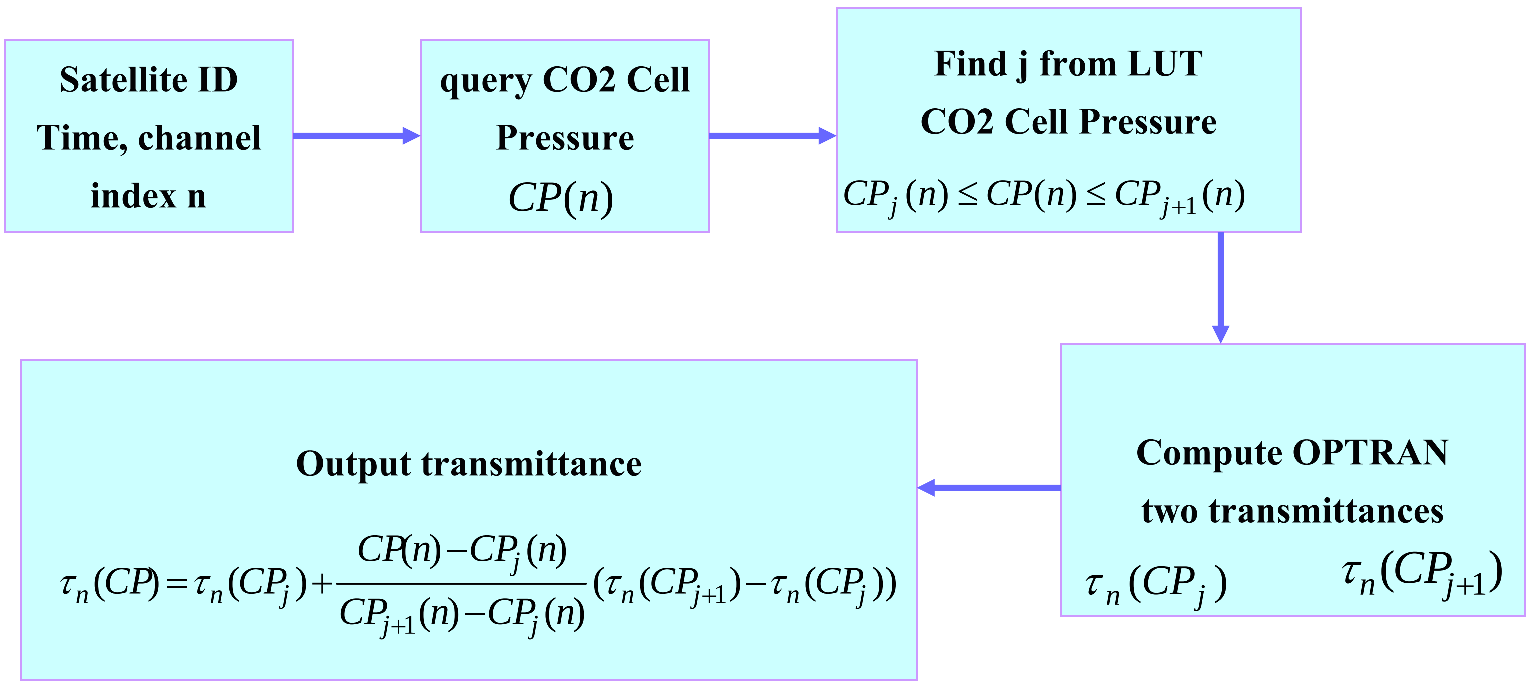
A – integrated absorber amount

P_j – predictors

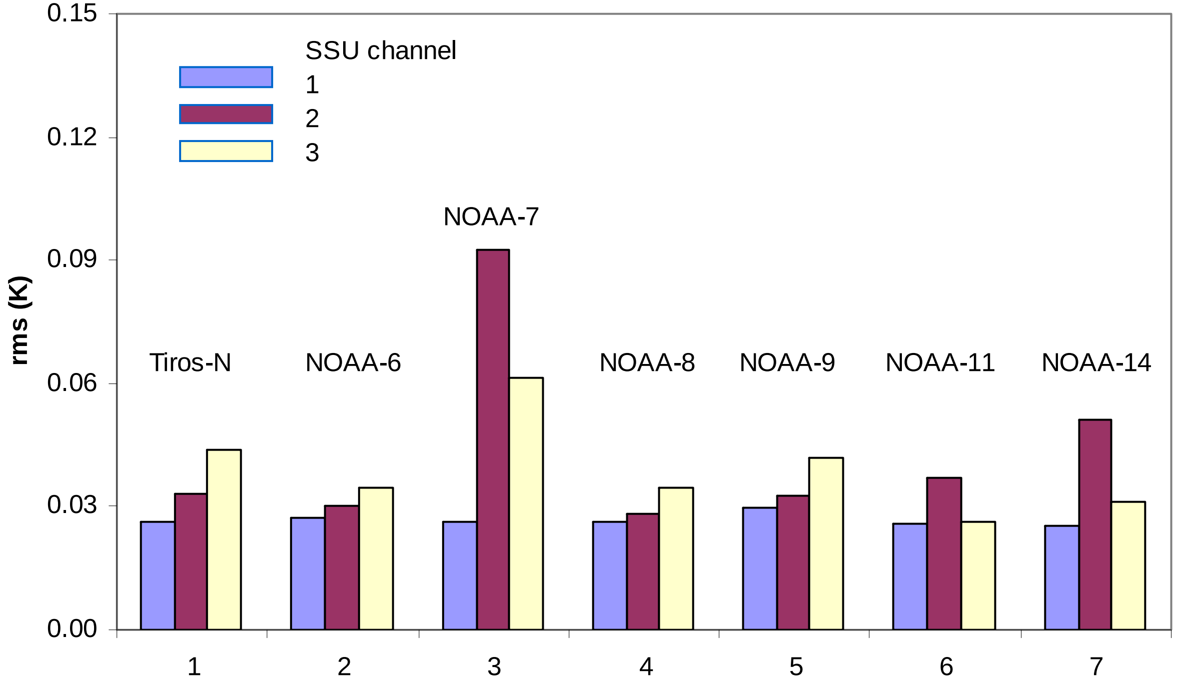
a_j – constants obtained from regression

- Currently water vapor and ozone are the only variable trace gases and other trace gases are “fixed”.
- The model provides good Jacobians and is very efficient in using computer memory

OPTRAN Extension for SSU

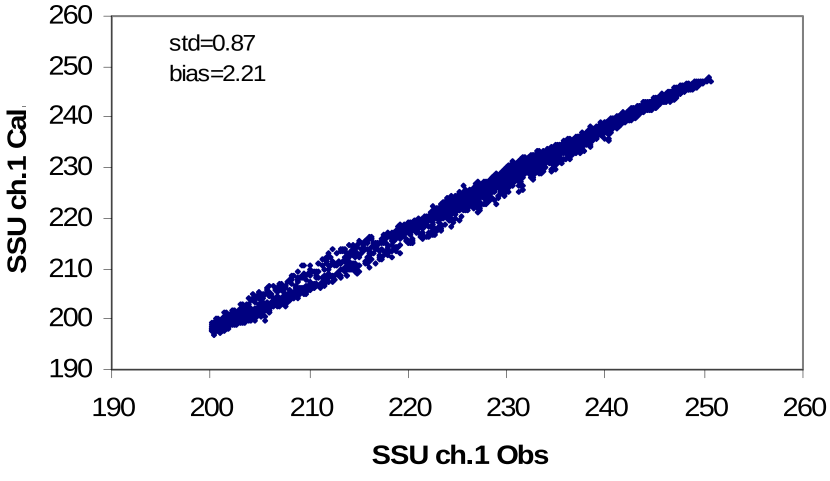


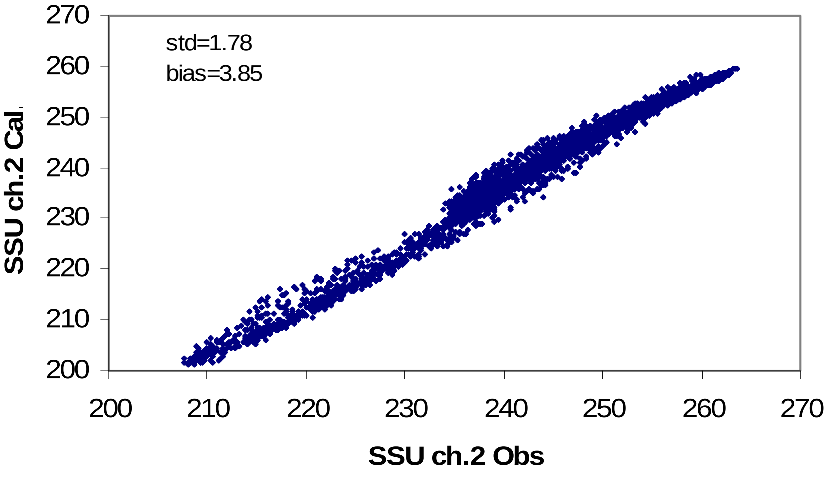
Comparison between LBL and OPTRAN-SSU

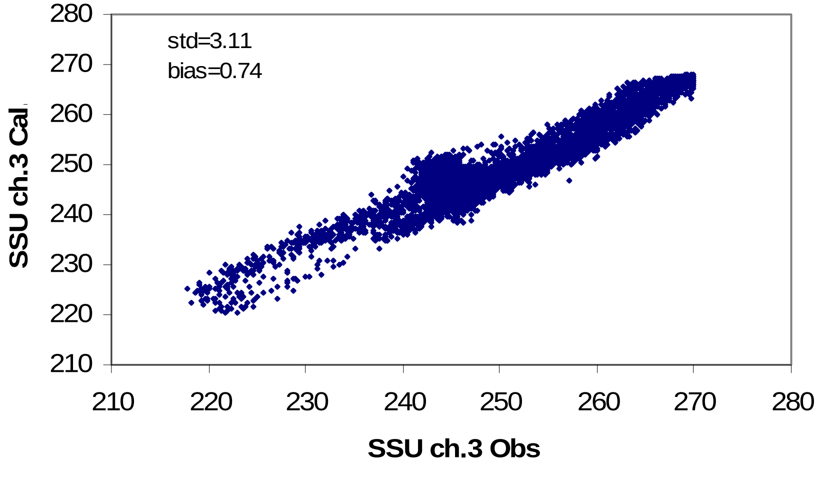


Fitting error + interpolation error for CO2 cell pressure

Comparisons between observation and modeling





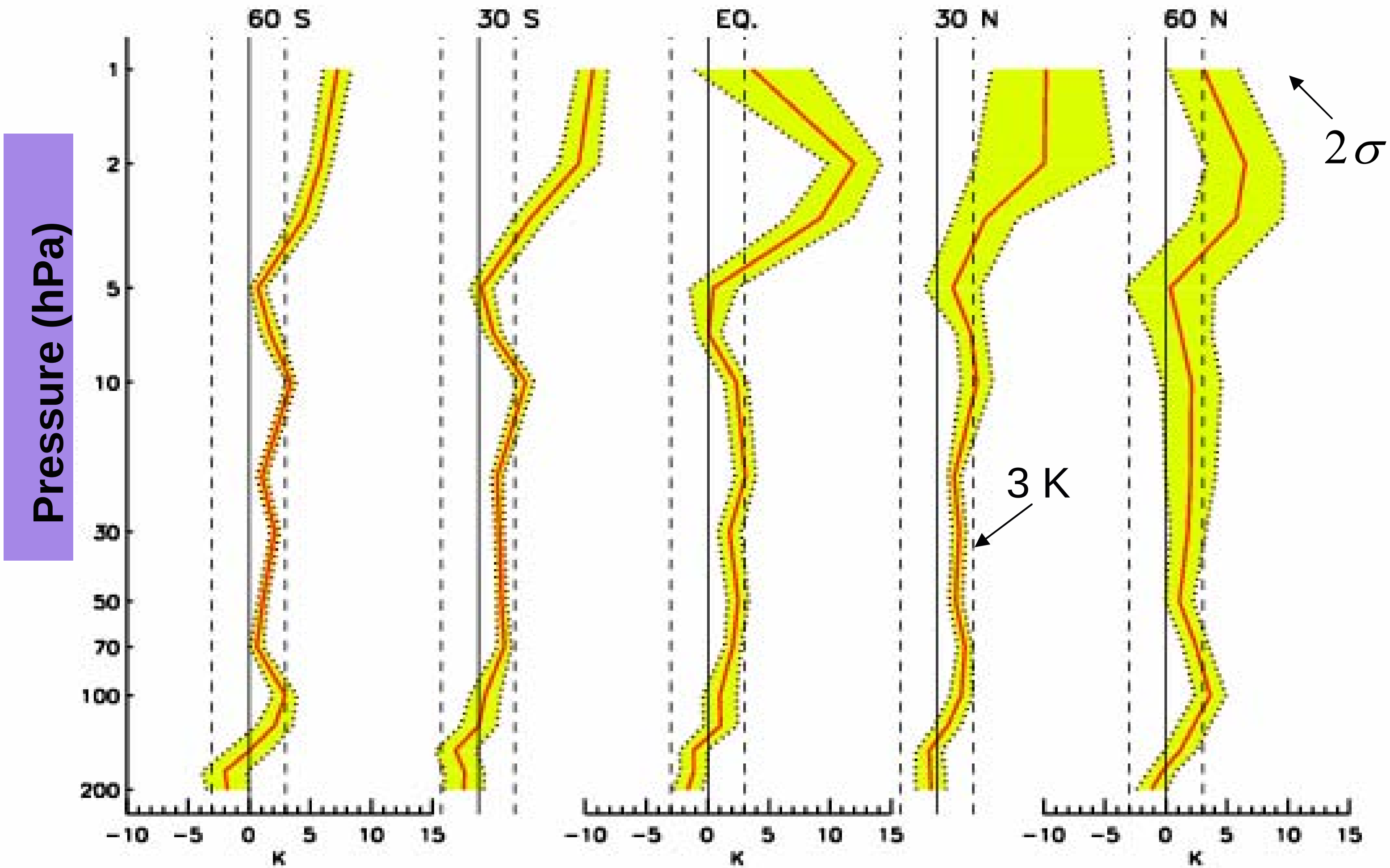


The peaks of the SSU weighting function approximately locate at 15, 5, and 1.5 hPa. The simulated BT bias at channels 1 and 2 could be caused by a cold bias in stratosphere in the NCEP analysis.

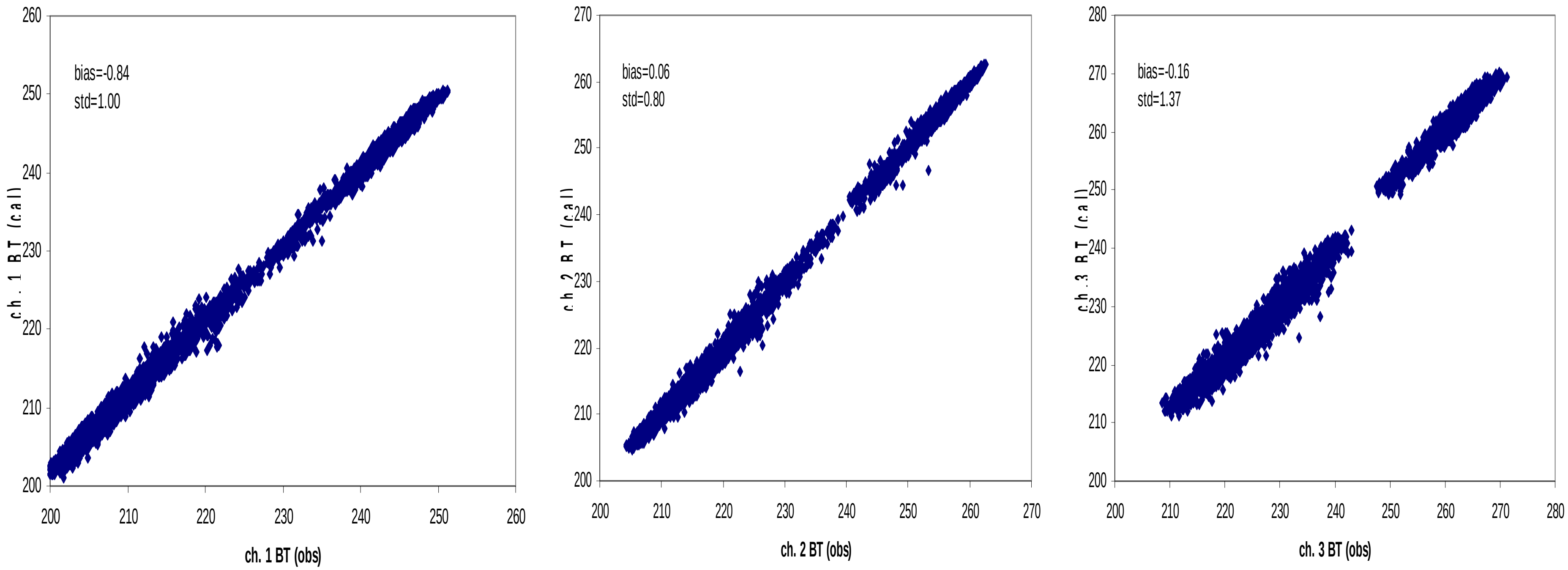
The large scatters for channel 3 is partly due to the limited top height (~ 0.2 hPa) in analysis.

Shuntai Zhou, Craig S. Long, Alvin. J. Miller,Lawrence E. Flynn and Trevor Beck

MLS – GDAS **January 2006**



Validation using Microwave Limb Sounding Product



SSU and MLS data for 11/2004,

All match-up data points are plotted.

Error budget

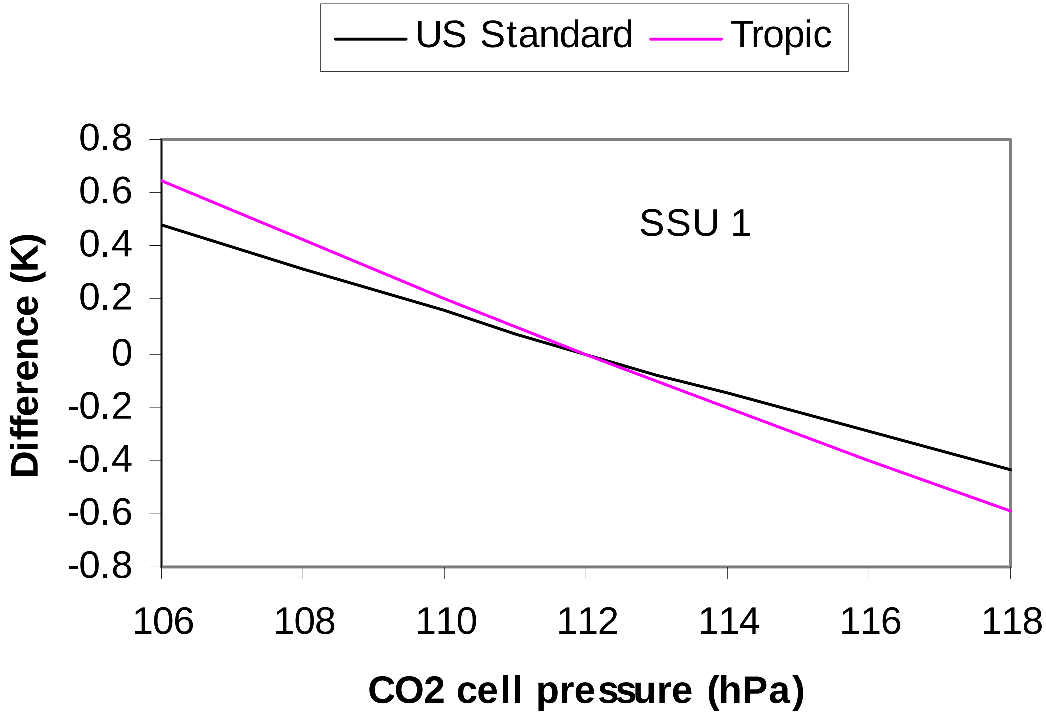
Brindley et al. (1999) showed the variation of SSU brightness temperature at channel 1 due to the leaking is between -0.3 and 0.3 K during entire SSU mission. But, the variation for SSU channels 2 and 3 can be between 0.5 ~ 1.5 K for single mission.
By considering the CO_2 cell pressure as a variable in the CRTM, this part error is < 0.1 K.

By choosing a constant CO_2 concentration in a mission (e.g. NOAA-14), the brightness temperature change for CO_2 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.

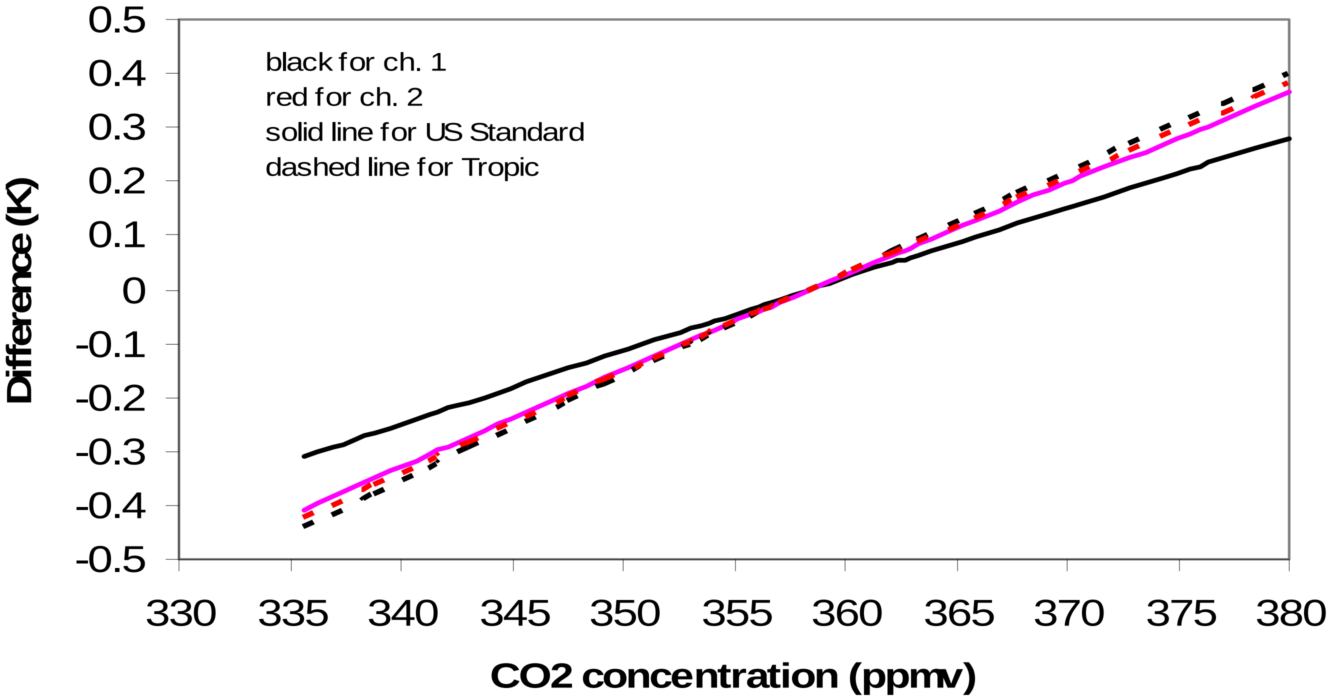
CO2 cell pressure effect on SSU observation



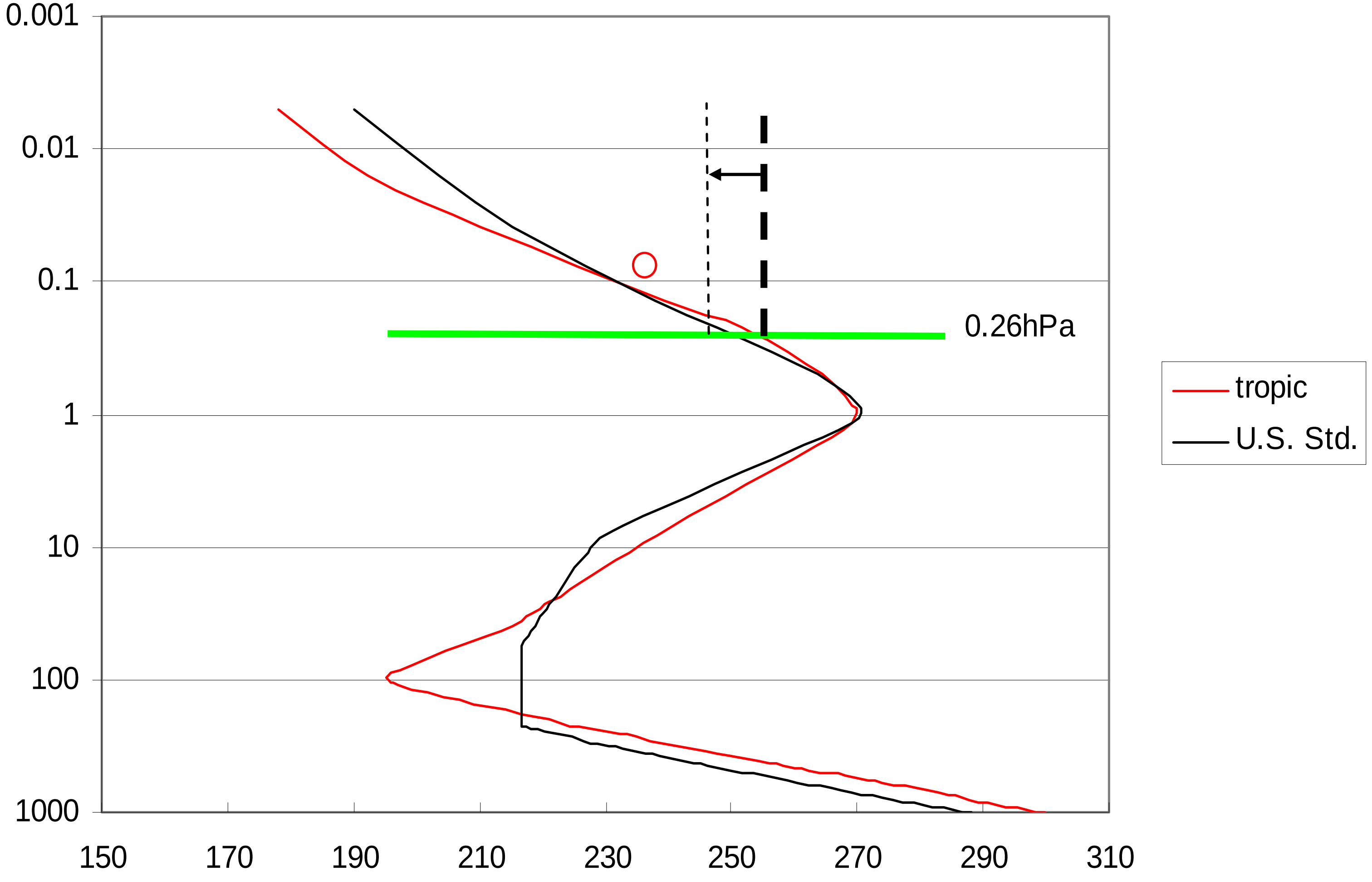
Channel 1

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

Correction on atmospheric CO2 concentration



Atmospheric Temperature Profiles



Infrared Radiance for Climate Studies

Microwave radiance have been successfully used for climate studies

(e.g. Spencer and Christy, 1990; Fu et al., 2004; Vinnikov and Grody, 2003; Zou et al., 2006).

For infrared CO2 absorption channels like on SSU, the effective atmospheric temperature depends also on CO2 concentration in the atmosphere, and it may be written as:

$$BT_n(t) = T_{eff}(n, t, CO2) \qquad \textbf{(1)}$$

where n is a channel index for the infrared sensor. The variation of the global mean brightness temperature to time t is defined as:

$$\frac{dBT_n(t)}{dt} = \frac{\partial T_{eff}(n, t, CO2)}{\partial t} + \frac{\partial T_{eff}(n, t, CO2)}{\partial CO2}\frac{\partial CO2}{\partial t} \qquad \textbf{(2)}$$

The trend, we are interested in, is the trend in atmospheric temperature only, that is

$$trend = \frac{\partial T_{eff}(n, t, CO2)}{\partial t} \qquad \textbf{(3)}$$

$$= \frac{dBT_n(t)}{dt} - \frac{\partial T_{eff}(n, t, CO2)}{\partial CO2}\frac{\partial CO2}{\partial t}$$

Corrections to SSU brightness temperatures

1. Correction to CO2 cell pressures, reference values of 110, 40, 14.5 hPa are applied for the SSU channels 1, 2, and 3, respectively.
2. Correction to atmospheric CO2 effect.
3. Studies in orbit drift and diurnal variation.

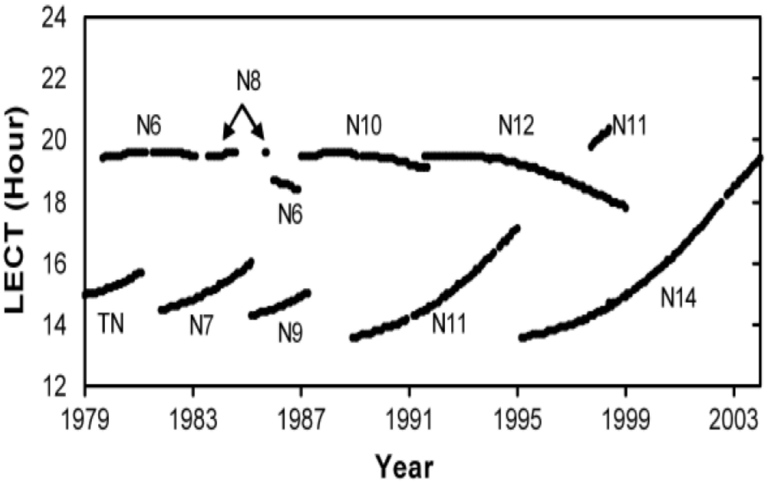
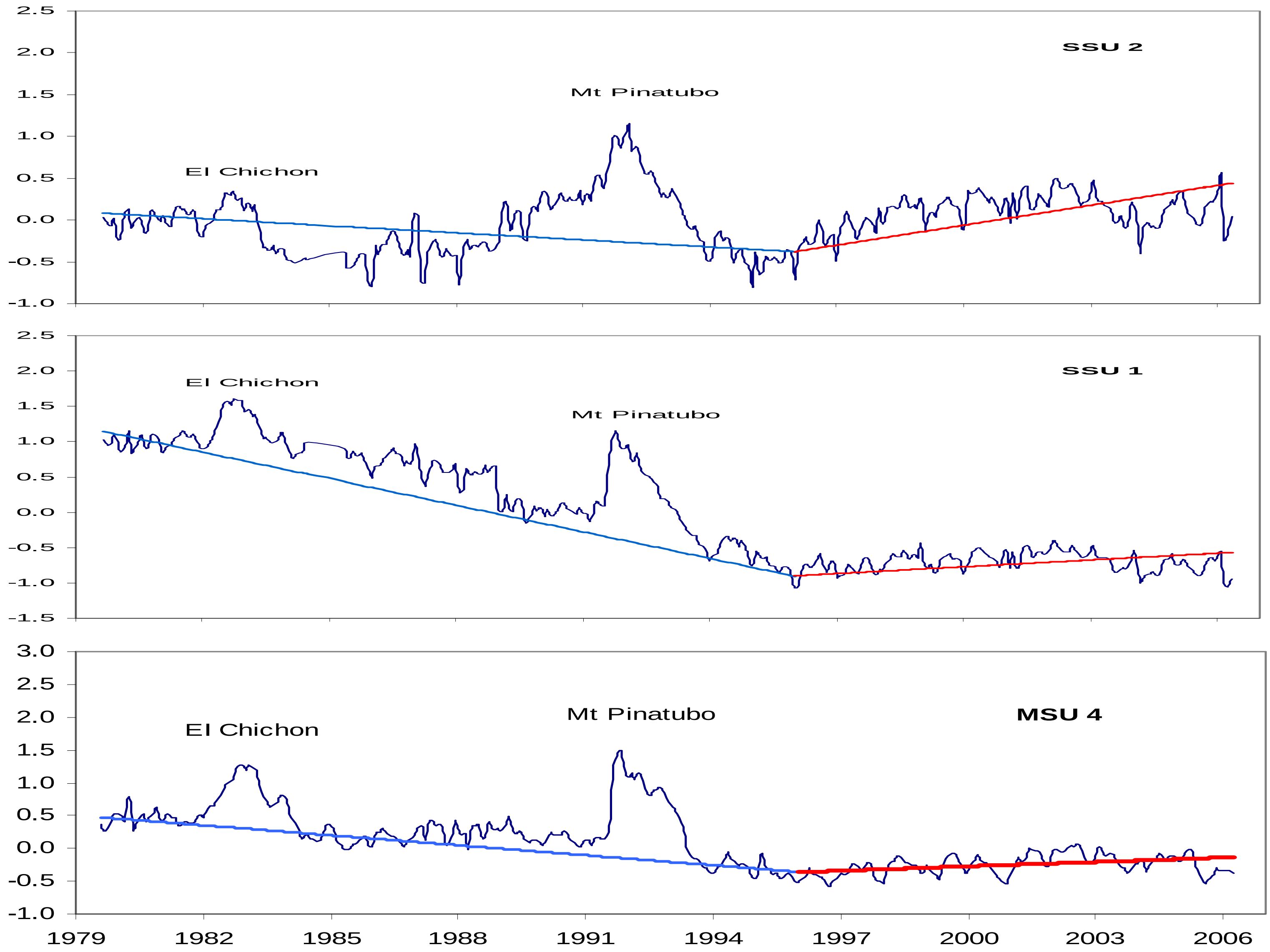


Table 1. CRTM simulations using analysis data in 2005 for NOAA-14 orbiting parameters in 2005 and 1995, respectively

	SSU 1		SSU 2		SSU 3	
	(05)	(05-95)	(05)	(05-95)	(05)	(05-95)
January	225.291	(0.034)	235.686	(0.017)	246.244	(0.153)
April	224.875	(-0.055)	235.278	(-0.075)	246.624	(-0.083)
July	225.222	(-0.032)	235.624	(-0.082)	247.116	(-0.229)
October	225.062	(-0.049)	235.888	(-0.033)	245.026	(0.027)
Annual	225.112	(-0.025)	235.619	(-0.043)	246.252	(-0.033)

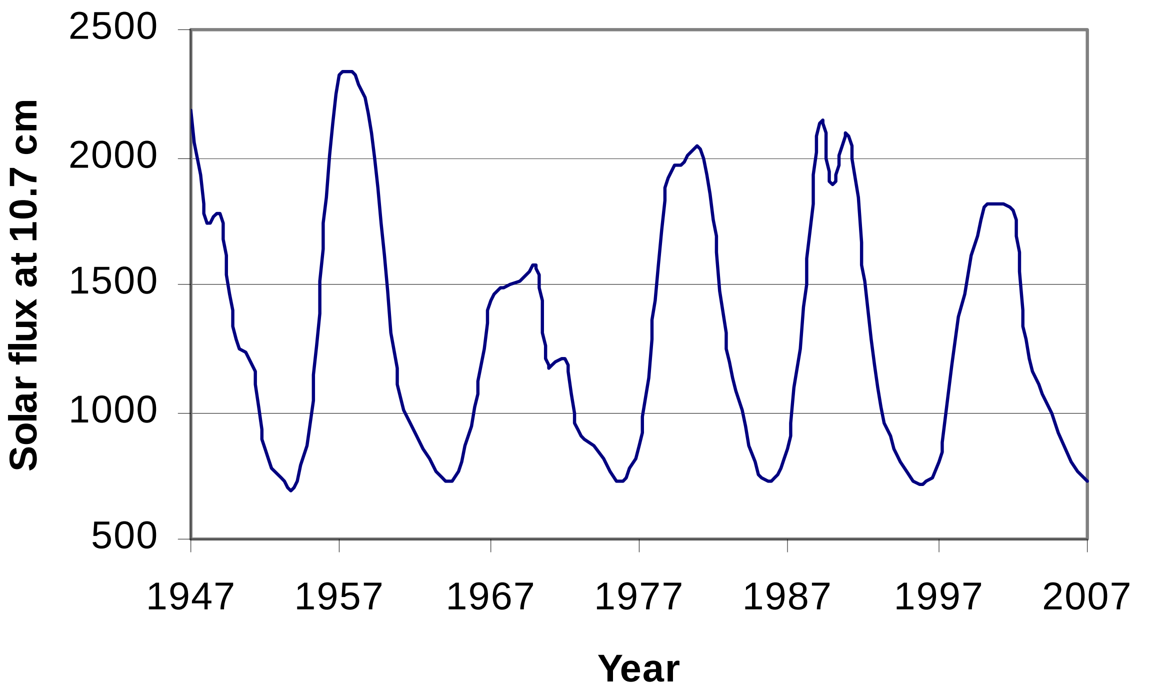
Time series of brightness temperature at MSU 4, SSU 1, and SSU 2



Trendes k/decade

before	after
-0.51	0.22
-1.25	0.32
-0.28	0.78

Solar cycle



Data from NOAA NGDC website

Possible contributors to stratospheric temperature

Solar cycle

The linear correlation coefficients between temperature and F10.7 for the five series fall between 0.02 and 0.31, which suggests that the association between temperature and solar cycle is weak (Adler and Elias,2004). Solar cycle effects are small, about an order of magnitude smaller than ozone changes over the last few decades due to chlorine change (Austin et al., 2007).

Greenhouse gases (CO2, CH4, CFC, N2O)

In comparison to ozone and water vapor, greenhouse gases, CO2, CH4, CFC, N2O, have small effect on Heating rate (Randel et al., 2007).

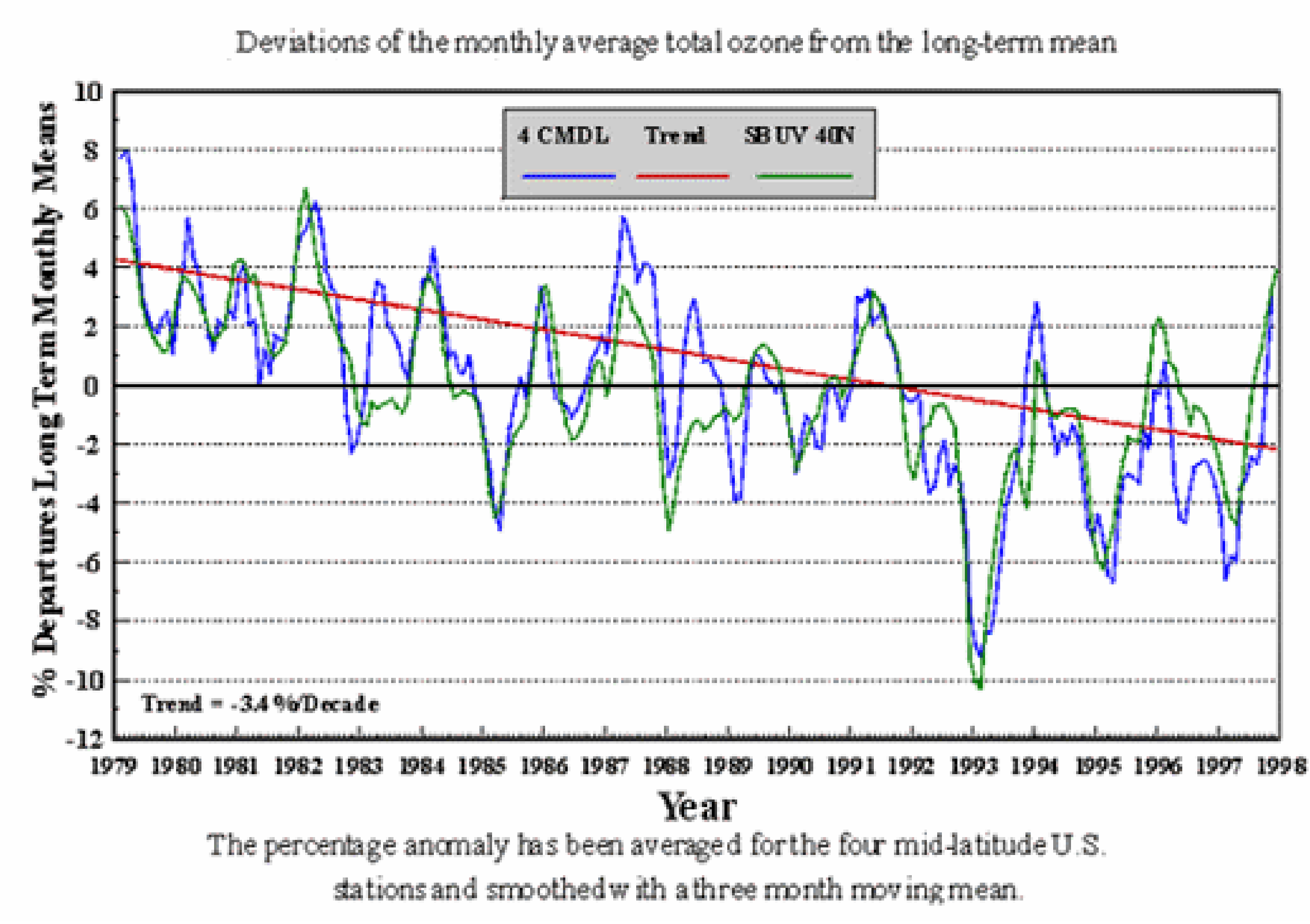
Ozone

Decrease of the ozone results in the decrease of stratospheric temperature. By removing all ozone from the part (0-4 km above tropopause) of the lower stratosphere (Randel et al., 2007).

***Molina and Rowland* found chlorofluorocarbon (CFC) → stratospheric chlorine atoms → destroy (+UV) ozone**

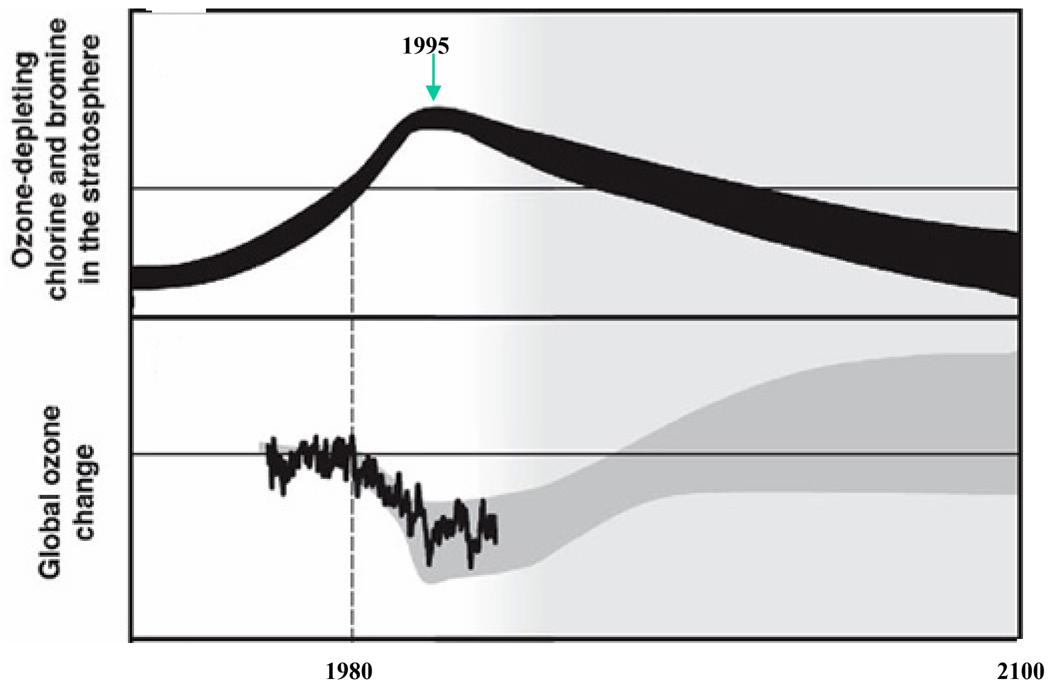
Antarctic ozone depletion appears to be connected with the extremely low prevailing temperatures, which lead to condensation of water and nitric acid to form "polar stratospheric clouds" (PSCs) (*Crutzen* et al.)

Trend in atmospheric ozone concentration



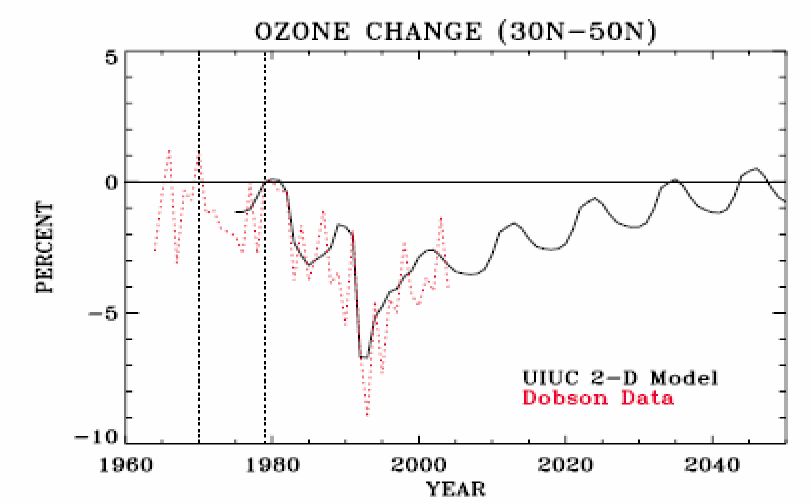
Created by NOAA, http://www.epa.gov/air/airtrends/aqtrnd96/brochure/stratoz.html

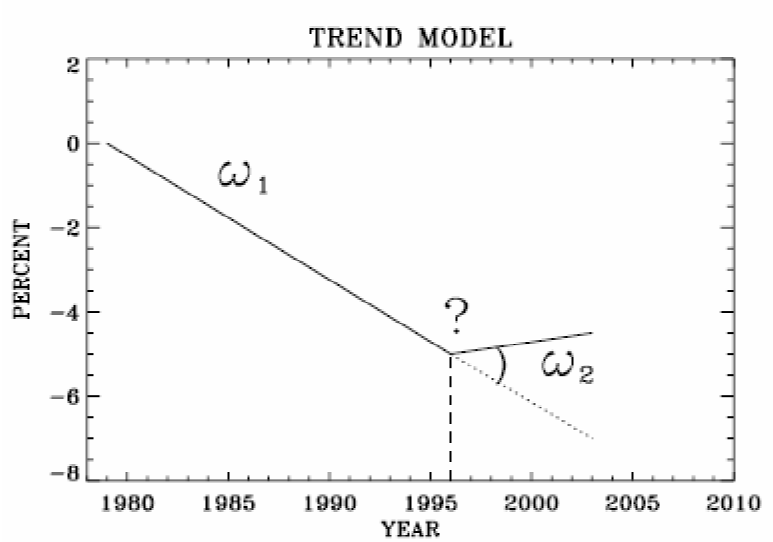
Projected chlorine, bromine, and ozone in the stratosphere



WMO/UNEP Scientific assessment of ozone depletion (2006)

Ozone trend, Miller et al., 2006





Conclusion

1. **SSU data are useful for reanalysis and climate studies in stratosphere.**
2. **The CRTM model takes care of the leaking problem by using a LUT for CO_2 cell pressure calculated from satellite ID and observation time. The CRTM is used for NCEP reanalysis and research.**
3. **Preliminary results provide evidence of the recovery of stratospheric temperature,**
   a possible sign for a recovery of stratospheric ozone concentration.