Abstract

To better use the Stratospheric Sounding Unit (SSU) data for reanalysis and climate studies, issues associated with the fast radiative transfer (RT) model for SSU have recently been revisited and the results have been implemented into the Community Radiative Transfer Model version 2. This study revealed that the spectral resolution for the sensor’s spectral response functions (SRFs) calculations is very important, especially for channel 3. A low spectral resolution SRF results, on average, in 0.6-K brightness temperature (BT) errors for that channel. The variations of the SRFs due to the CO2 cell pressure variations have been taken into account. The atmospheric transmittance coefficients of the fast RT model for the Television and Infrared Observation Satellite (TIROS)-N, NOAA-6, NOAA-7, NOAA-8, NOAA-9, NOAA-11, and NOAA-14 have been generated with CO2 and O3 as variable gases. It is shown that the BT difference between the fast RT model and line-by-line model is less than 0.1 K, but the fast RT model is at least two orders of magnitude faster. The SSU measurements agree well with the simulations that are based on the atmospheric profiles from the Earth Observing System Aura Microwave Limb Sounding product and the Sounding of the Atmosphere using Broadband Emission Radiometry on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics satellite. The impact of the CO2 cell pressures shift for SSU has been evaluated by using the Committee on Space Research (COSPAR) International Reference Atmosphere (CIRA) model profiles. It is shown that the impacts can be on an order of 1 K, especially for SSU NOAA-7 channel 2. There are large brightness temperature gaps between observation and model simulation using the available cell pressures for NOAA-7 channel 2 after June 1983. Linear fittings of this channel’s cell pressures based on previous cell leaking behaviors have been studied, and results show that the new cell pressures are reasonable. The improved SSU fast model can be applied for reanalysis of the observations. It can also be used to address two important corrections in deriving trends from SSU measurements: CO2 cell leaking correction and atmospheric CO2 concentration correction.

1. Introduction

The Stratospheric Sounding Unit (SSU) on board the National Oceanic and Atmospheric Administration (NOAA) operational meteorological satellites since
1978 measures the earth’s radiance at three infrared channels in the CO2 15-μm absorption band and provides a unique near-global source of data on temperature above the lower stratosphere from 1978 to 2006. The SSU data have been extensively used to study the temperature trends in the stratosphere as well as their possible causes [e.g., Nash and Forrester 1986; Ramaswamy et al. 2001; Shine et al. 2003; World Meteorological Organization (WMO) 1988, 2007; Liu and Weng 2009; Randel et al. 2009]. The SSU is a pressure-modulated radiometer (PMR) (Taylor et al. 1972; Miller et al. 1980) in which an on-board cell of CO2 is used in spectral filtering. The CO2 leaking in this cell can cause a time-varying change in signal and thus variations of the spectral sensor response function. If the cell pressure shift is small for the satellite observation period, using a constant cell pressure value over the period may produce negligible effects on brightness temperature (BT). For example, Brindley et al. (1999) reported that the calculated effects on BT ratio due to the cell pressure shifts are less than 0.1% for SSU channel 1 from 1979 to 1994. However, they also admitted that the temporal progression of this ratio factor can substantially reduce the temperature trends seen in the observed data.

There are formidable problems in simulating the brightness temperature when considering the cell pressure shift in a line-by-line (LBL) radiative transfer (RT) model with global coverage and over the SSU observation periods. An LBL RT model such as LBLRTM (Clough et al. 2005) is computationally expensive because it requires the averaging of multiple monochromatic calculations within a spectral band. When the spectral response functions (SRFs) change, the entire LBL computation has to be recalculated. Development of a SSU fast radiative transfer model is driven by the computational requirements of operational systems for reanalysis and climate study at NOAA. The previous version SSU fast RT model was developed at the Joint Center for Satellite Data Assimilation (JCSDA) in 2007 using the Compact–Optical Path Transmittance (OPTRAN) algorithm concept (McMillin et al. 2006; Chen et al. 2010) and a SRF spectral sampling of $2.5 \times 10^{-3}$ cm$^{-1}$, only included the CO2 absorption (Liu and Weng 2009), and assuming plane-parallel atmosphere. Atmospheric CO2 was the only absorber in the earlier model and its concentration was fixed at the average level over the mission lifetime of any particular sensor. The variations of the cell pressures that caused variations in the SRFs were taken into account and handled dynamically at runtime by input the cell pressures directly to the code. As the CO2 concentration was held constant during the sensor observation period, the impact of changes in atmospheric CO2 on the SSU simulated brightness temperature was ignored. This impact is important for longer measurement periods as indicated by Shine et al. (2008), such as NOAA-I1 (from 1988 to 2003, corresponding to CO2 change from 350 to 375 ppmv) and NOAA-I4 (from 1995 to 2006, corresponding to CO2 change from 360 to 381 ppmv).

In this study, we focus on improving the previous SSU fast radiative transfer model using the Optical Depth in Pressure Space (ODPS) method to compute atmospheric transmittance profiles (Chen et al. 2010). The ODPS transmittance model is an optional transmittance model, along with the Compact-OPTRAN model, implemented within the multiple transmittance algorithms framework in the JCSDA Community Radiative Transfer Model (CRTM) version 2. The CRTM is a sensor-channel-based radiative transfer model (Weng et al. 2005; Han et al. 2006; Chen et al. 2008) used in satellite data assimilation and remote sensing applications. It includes components that compute the radiation from gaseous absorption, absorption and scattering of radiation by hydrometeors and aerosols, and emission and reflection of radiation by ocean, land, snow, and ice surfaces.

The ODPS transmittance model can have up to six user input variable absorbers: H2O, CO2, O3, N2O, CO, and CH4. The improved SSU fast model treats the CO2 and O3 as variable gases, uses the SRFs with an increased spectral resolution, and considers the earth curvature effects by varying the zenith angle with height. Also, as with the previous model of Liu and Weng (2009), the model takes into account the variations of the SRFs due to the CO2 cell pressure variations. This fast radiative transfer model can be used to assimilate the SSU measurements in operational systems for reanalysis. To derive temperature trends from SSU measurements, corrections have to be made to account for CO2 cell pressure leaking in SSU PMR, change in atmospheric CO2 concentration, limb adjustment, and diurnal and semidiurnal tidal variations in the middle atmosphere. The first two corrections can be addressed by using the improved CRTM SSU fast radiative transfer model in this paper. The study is split into the following five main sections. Section 2 provides a brief discussion of the SSU instrument response, followed by an in-depth assessment of the sensitivity of spectral resolution and atmospheric gaseous absorption on SSU simulated radiances. Section 3 focuses on the improved SSU fast RT model. In section 4, the fast RT model is validated with observations. The impact of cell pressure shift on brightness temperature is detailed in section 5, and the conclusions to be drawn from this study are presented in section 6.

2. SSU spectral response functions

The SSU instrument is a pressure-modulated CO2 radiometer designed to measure the radiance emitted by
stratospheric carbon dioxide within the 15-μm $v_2$ band (Miller et al. 1980). The PMR employs a cell containing CO$_2$ as a filter. The pressure of the cell is periodically modulated, resulting in the selection of thermal radiation from the carbon dioxide absorption spectrum. An interference filter then confines the spectral response, and contributions from any other radiation not originating from within the 15-μm region are neglected.

Unlike other typical satellite radiometers, the SSU SRF requires that a line-by-line radiative transfer model be involved to calculate the high-frequency CO$_2$ gas cell response. The LBLRTM version 11.3 was employed to realistically simulate the response of SSU PMR in this study. Following the approach outlined by Brindley et al. (1999), the high-frequency gas cell response $H_v$ can be modeled using a two-cell approximation:

$$H_v = \tau_v^{\text{cell min}} - \tau_v^{\text{cell max}},$$

where $\tau_v^{\text{cell min}}$ and $\tau_v^{\text{cell max}}$ are the transmittances at minimum cell pressure and maximum cell pressure, respectively. The resulting high-resolution transmission filter is then convolved with the wideband interference filter after interpolating at the same resolution to obtain the SSU SRF.

The parameters needed to simulate the SSU radiometric SRF are cell pressure, cell temperature, cell length, and pressure modulation amplitude. In this study, the cell length and temperature are same for each channel and every SSU sensors [Television and Infrared Observation Satellite (TIROS)-N, NOAA-6, NOAA-7, NOAA-8, NOAA-9, NOAA-11, and NOAA-14], taken as 1 cm and 302.6 K, respectively. The pressure modulation amplitudes are taken as 0.177, 0.266, and 0.299 for channels 1, 2, and 3, respectively. The uncertainty on these three parameters induces an effect of less than 0.01% on BT changes (Brindley et al. 1999), and can be negligible compared to the impact of the cell pressure changes, which can be on an order of 1 K. The assessment of the effects of the cell drifts upon measured BTs is discussed in section 5. Figure 1 illustrates the three SSU channel’s cell pressures progression from 1979 to 2003 (data from Kobayashi et al. 2009). Channel 1 cell pressures range from 106 to 118 hPa, channel 2 from 27 to 46 hPa, and channel 3 from 9.6 to 17 hPa. The weighting function peak height for a CO$_2$ PMR (Taylor et al. 1972) may be analytically expressed as

$$p_{\text{peak}} = \left[\frac{4(1+\beta)L}{a}\right]^{1/2}p_0,$$

where $1 + \beta$ is a correction for the self-broadening effect in the pure CO$_2$ for the cell length $L$. The variable $a$ is the thickness that the total column of atmospheric CO$_2$ would have if it were compressed to standard temperature and pressure, and $p_0$ is the mean pressure within the absorption cell. From Eq. (2), the peak of the weighting function associated with a given SSU channel is determined by the atmospheric carbon dioxide amount and $p_0$. For a given $p_0$, increases (decreases) in atmospheric CO$_2$ lead to a decrease (increase) in the pressure where the weighting function peaks. For a given atmospheric CO$_2$ amount, decreases (increases) in $p_0$ would decrease (increase) $p_{\text{peak}}$. Since the SSU senses mostly in the stratosphere where the temperatures increase with height, the reductions (increases) in $p_{\text{peak}}$ translate into higher (lower) measured brightness temperature.

Figure 2 gives the three SSU channel weighting functions by using average cell pressures from Fig. 1 (the values used are 110.9, 39.9, and 14.2 hPa for channels 1, 2, and 3, respectively, all the sensitivity studies are using these cell pressures) for 5 model atmospheres (Anderson et al. 1986) including the midlatitude summer (MMLS), midlatitude winter (MLWL), subarctic summer (MSAS), subarctic winter (MSAW), and tropical atmosphere (MTROP). The weighting function without PMR (using

FIG. 1. Measured cell pressures for (top to bottom) SSU channels 1–3 from 1978 to 2003 (data from Kobayashi et al. 2009).
only the wideband interference filter) is also shown. The average peak heights for each channel are given by the dashed lines. With the three modulated cells, the weighting function of the original 15-μm carbon dioxide absorption band (with peak at around 70 hPa) is shifted up and split into 3 weighting functions with peak pressures of approximately 14.6, 4.6, and 1.9 hPa. The three SSU channels measure middle stratosphere, upper stratosphere, and upper stratosphere–lower mesosphere, respectively.

Sensitivity studies were carried out to assess the effects of spectral resolution, and atmospheric gaseous absorption on the modeled SSU three channel radiances. The reference case uses a spectral resolution of 1 \times 10^{-4} \text{ cm}^{-1}, and seven absorbers (H2O, CO2, O3, N2O, CO, CH4, and O2) in LBLRTM. The University Maryland, Baltimore County (UMBC) 48 atmospheric profile set (Strow et al. 2003) is used in these calculations. Three other spectral resolutions (5 \times 10^{-4}, 1 \times 10^{-3}, and 2.5 \times 10^{-3} \text{ cm}^{-1}) are used for the comparison. The differences and standard deviations related to the reference are summarized in Table 1. In all cases, Table 1 shows that the spectral resolution impact on channels 1 and 2 BT (less than 0.035 K) is minimal. However, the spectral resolution is very important for channel 3 with the mean BT difference being approximately -0.693 K for resolution 2.5 \times 10^{-3} \text{ cm}^{-1} compared to the reference resolution. The width of any spectral line originating at a height of 60 km in the atmosphere is less than 1 \times 10^{-3} \text{ cm}^{-1} and usually much less (Taylor et al. 1972), and SSU channel 3 has weighting function peak at about 45 km. To accurately model such a line, the spectral resolution must be better than 1 \times 10^{-3} \text{ cm}^{-1}. If the spectral resolution is coarser, the simulated radiance measurement will sound lower levels in the atmosphere as opposed to higher levels for finer resolution. Lower levels in the stratosphere means lower BT (since the lapse rate is positive), which will result in a negative bias on BT compared to the finer resolution. Based on these results, the response functions used in this paper utilize a spectral resolution of 5 \times 10^{-4} \text{ cm}^{-1} for all SSU 3 channels.

The sensitivity of SSU channels’ brightness temperatures to the gaseous absorbers included in the LBLRTM calculations is shown in Table 2. The reference case includes the previously mentioned seven molecules in the LBLRTM calculation. The other two cases included CO2 and O3, and CO2 only, respectively. A spectral resolution 5 \times 10^{-4} \text{ cm}^{-1} is employed for all cases. The results indicate that other gaseous absorbers except CO2 and O3 either do not contribute to the received radiation or are effectively rejected within the 15-μm band by employing the PMR technique. The O3 absorption via the 701 cm^{-1} band cannot be neglected because of the O3 absorption line overlay with those from CO2, especially for SSU channel 1 with mean difference about negative 0.1 K.

Fig. 2. (right) The SSU 3 channel weighting functions by using average cell pressures from Fig. 1 for (left) 5 model atmospheres including the MMLS, MMLW, MSAS, MSAS, and MTROP. The no PMR (using only the wideband interference filter) weighting function is also shown. The average peak heights for each channel are given by the dash lines.
The impact of atmospheric CO2 concentration change on SSU brightness temperatures is shown in Fig. 3 by using a CO2 concentration of 360 ppmv as a reference. The increase in CO2 leads to an increase in brightness temperature for model atmospheres of MTROP and MSAW because of the peak of the weighting function shifting to higher atmospheric levels. The BT change due to a 25 ppmv increase in CO2 can be greater than 0.1 K and even as large as 0.4 K. These findings are consistent with results from Shine et al. (2008).

Based on the sensitivity studies, the improved fast RT model for SSU developed in this study utilizes a spectral resolution of $5 \times 10^{-3} \text{ cm}^{-1}$, with CO2 and O3 as variable gases. The fast model also takes account of the variations of the cell pressures.

### 3. SSU fast RT model

#### a. Fast model with fixed CO2 cell pressure

The transmittance model for the SSU uses the Optical Depth at Pressure Space method (Chen et al. 2010). The simulation of transmittances at prescribed fixed atmospheric pressure levels is based on a regression scheme with a variety of predictors from the profile variables that are related to the $i$th layer optical depth $\sigma_i$. The regression is actually performed in terms of its departure from a reference profile (mean profile from the training dataset) for all variable gases. The fast model can be written as

$$\sigma_i = c_{i,0} + \sum_{j=1}^{N_p} c_{i,j} X_{i,j},$$

where $N_p$ is the number of predictors at layer $i$; $c_{i,j}$ and $X_{i,j}$ are the regression coefficients and the predictors, respectively. The predictors in the model are related to atmospheric gaseous concentrations, temperatures, and zenith angles. For the fast model, the atmosphere is divided into 100 layers and the highest level pressure is set to 0.005 hPa, which has the required height for SSU channels.

In the training process, transmittance spectra with spectral resolution of $5 \times 10^{-4} \text{ cm}^{-1}$ are computed from LBLRTM using a set of diverse set of atmospheric profile at seven different zenith angles for which the secant has equally spaced values from 1 to 2.25 plus an additional value of 3.0. From these transmittance spectra the channel transmittances are calculated by convolution with the channel SRF, computed with the LBLRTM version 11.3 and at a specified CO2 cell pressure. The resultant transmittances are then converted to the layer optical depths used as the predictand in the training (dependent) dataset. In this study, the European Centre for Medium-Range Weather Forecasts (ECMWF) 83 profiles in 101 vertical pressure levels (Chevallier et al. 2006; Matricardi 2008) are used as training profiles. Since the carbon dioxide concentration in the atmosphere increased from 335 to 381 ppmv from 1978 to 2006 during the SSU observation period, the CO2 profiles in the training set have been adopted and extended to the required CO2 concentration ranges from their original values by scaling.

#### b. Method to handle CO2 cell pressure variations

The CO2 leaking in the SSU PMR can cause a time-varying change in signal and thus variations in the SRFs. The method to handle the CO2 cell pressure variations is to use a series of the transmittance coefficient sets for each sensor at different values of CO2 cell pressure with its corresponding SRF. Each set of coefficients are generated in a similar process as described in section 3. The transmittances at an arbitrary value of CO2 cell pressure are obtained through linear interpolation from

### Table 1. Sensitivity of SSU 3 channels’ BTs to spectral resolution.

<table>
<thead>
<tr>
<th>Molecules included</th>
<th>Resolution (cm$^{-1}$)</th>
<th>Mean difference from reference (K)</th>
<th>Std dev (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Channel 1</td>
<td>Channel 2</td>
</tr>
<tr>
<td>First 7</td>
<td>$5 \times 10^{-4}$</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>First 7</td>
<td>$1.0 \times 10^{-3}$</td>
<td>0.002</td>
<td>0.006</td>
</tr>
<tr>
<td>First 7</td>
<td>$2.5 \times 10^{-3}$</td>
<td>0.016</td>
<td>0.032</td>
</tr>
</tbody>
</table>

### Table 2. Sensitivity of SSU 3 channels’ BTs to gaseous absorbers.

<table>
<thead>
<tr>
<th>Gases included</th>
<th>Resolution (cm$^{-1}$)</th>
<th>Mean difference from reference (K)</th>
<th>Std dev (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2, O3</td>
<td>$5 \times 10^{-4}$</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>CO2 only</td>
<td>$5 \times 10^{-4}$</td>
<td>0.099</td>
<td>0.046</td>
</tr>
</tbody>
</table>

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the transmittances computed at two adjacent CO₂ cell pressure nodes that bracket the desired value. The series of SSU transmittance coefficient sets for each of the sensors TIROS-N, NOAA-6, NOAA-7, NOAA-8, NOAA-9, NOAA-11, and NOAA-14 have been generated by training with the LBLRTM model. To study the impact of cell pressure change and especially for fitting the cell pressures for SSU NOAA-7 channel 2 in section 5, a SSU pseudo sensor with cell pressure range covering all SSU sensors (cell pressures range from 105 to 118 hPa for channel 1, 14.8 to 46 hPa for channel 2, and 5 to 18 hPa for channel 3) has also been created and its transmittance coefficients generated. The SSU fast RT model has been implemented into CRTM version 2 under the CRTM module of multiple transmittance algorithms framework. By comparing to the detailed LBLRTM calculation, the root-mean-square (RMS) errors due to the fitting and interpolation of the CO₂ cell pressure in the fast transmittance model are less than 0.1 K for the ECMWF 83–dependent profile set.

4. Model validation

a. Comparison with the LBL model for independent dataset

Since the SSU fast model is trained with ECMWF 83 profiles, it is necessary to test BT against the base LBLRTM on an independent data ensemble, the UMBC 48 atmospheric profile set. Both profile sets are diverse and represent well real atmospheric conditions, with the ECMWF profiles having larger ranges of surface temperatures and integrated water amount than the UMBC profiles (Chen et al. 2010). Figure 4 shows the independent test BT results of CRTM SSU simulations compared with those from LBLRTM. The simulations from LBLRTM are using a spectral resolution of $5 \times 10^{-4}$ cm$^{-1}$ and the first 7 molecules in LBLRTM by using UMBC 48 atmospheric profiles for (top to bottom) channels 1–3. The dots show the results for training spectral resolution $5 \times 10^{-4}$ cm$^{-1}$ and absorber gases including CO₂ and O₃, whereas the triangles show the results for spectral resolution $2.5 \times 10^{-3}$ cm$^{-1}$ and only including CO₂ gas.
b. Comparison with observations

Liu and Weng (2009) validated the previous SSU fast RT model against the SSU measurements by use of the input temperature profiles from the Earth Observing System (EOS) Aura Microwave Limb Sounder (MLS) product for November 2004. We use the same dataset here to check the effects of model improvements. The comparison results are given in Table 4. We should point out that when considering the earth curvature effects by varying the zenith angle with height, the improved CRTM SSU model (version 2) always produces larger BTs than the previous version under same conditions. Since channel 2 in Liu and Weng (2009) already shows positive bias, the bias increasing for CRTM SSU from 0.062 to 0.114 K is mainly due to the earth curvature effects. Except for channel 2, the biases for channels 1 and 3 are improved. The standard deviations for all three channels are slightly increased, which may be due to the use of a single ozone profile from the 1976 U.S. Standard Atmosphere.

The CRTM SSU fast RT model is also tested against the SSU measurements by using temperature and ozone profiles retrieved from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics satellite launched in December 2001 (Russell et al. 1999). SABER provides profile data near globally on a daily basis with a good vertical resolution (~0.4 km), especially above the stratosphere. The temperature and ozone profiles generally reach the level required by our RT model (up to 0.000 01 hPa), although the highest pressure (lowest altitude) level only reaches around 200 hPa. The retrieval temperatures in the stratosphere were compared against products from the Met Office analysis with the differences within about 2 K (Remsberg et al. 2003). SABER has generally warm biases of ~2 K relative to MLS, and the ECMWF and Goddard Earth Observing System, version 5 (GEOS-5) analyses below 10 hPa (Schwartz et al. 2008).

The SSU and SABER data are matched on the following criteria: A SSU scan angle 5° pixel (near nadir) field of view (FOV) was collocated with a SABER profile (using time and location at ~5 hPa, near the SSU channel 2 weighting function peak) if the absolute differences of latitudes and longitudes between the two data points were less than 2.5°, their distance was a minimum among all the data pairs and less than 200 km, and the absolute time difference was less than 2 h. Data were taken from SSU Sensor Data Records (SDRs) and SABER products version 1.07 for January, April, July, and October 2003 to consider the seasonal and global coverage. A total of 10562 matched samples were collected for the comparison. Of these samples, 1786 are in January, 3771 are in April, 1969 are in July, and 3036 are in October. In simulating the radiances in CRTM, only the profile data below 0.005 hPa data are used, and the profiles are extended to surface using the 1976 U.S. Standard Atmosphere when SABER profiles do not have lower level atmosphere. The CO2 concentration variation with times and locations are considered by using 2003 CO2 global monthly-mean observed data (available online at WMO Global Atmosphere Watch Web site http://gaw.kishou.go.jp) specified at 15° spacing in longitude and latitude. Figure 5 shows the scatterplots and statistics of the comparisons between the simulations and measurements. The impact on these biases without the supplementary data to extend the SABER profiles to surface are very small, about 0.1, 0.05, and 0.007 K for channels 1–3, respectively. Since all three SSU channel weighting functions peak above 300 hPa (see Fig. 2), the impact of clouds on the channel BTs should be very small, especially for channels 2 and 3. The agreement is good if we consider the uncertainties in the

<table>
<thead>
<tr>
<th>Gases included</th>
<th>Resolution (cm⁻¹)</th>
<th>Mean difference from LBLRTM (K)</th>
<th>Std dev (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Channel 1</td>
<td>Channel 2</td>
<td>Channel 3</td>
</tr>
<tr>
<td>CO₂, O₃</td>
<td>5 × 10⁻⁴</td>
<td>0.016</td>
<td>-0.083</td>
</tr>
<tr>
<td>CO₂ only</td>
<td>2.5 × 10⁻³</td>
<td>-0.066</td>
<td>-0.160</td>
</tr>
</tbody>
</table>

Table 3. Independent test results of CRTM SSU simulations compared with those from LBLRTM for UMBC 48 profile set.

<table>
<thead>
<tr>
<th>Model</th>
<th>Mean difference from measurement (K)</th>
<th>Std dev (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Channel 1</td>
<td>Channel 2</td>
</tr>
<tr>
<td>CRTM SSU</td>
<td>-0.596</td>
<td>0.114</td>
</tr>
<tr>
<td>Liu and Weng (2009)</td>
<td>-0.844</td>
<td>0.062</td>
</tr>
</tbody>
</table>

Table 4. CRTM SSU simulations against measurements compared with those from Liu and Weng (2009) by use of MLS product for 7006 data points.
SABER temperature retrievals (Remsberg et al. 2003; Schwartz et al. 2008) and measurement uncertainties in the SSU channels.

5. Impact of cell pressure on brightness temperature

a. Time series

The time series impact of the cell pressure leaking on SSU brightness temperature is simulated using the zonal and monthly-mean temperatures profiles from Committee on Space Research (COSPAR) International Reference Atmosphere (Fleming et al. 1988) (CIRA) with a $5^\circ$ latitudinal resolution from $80^\circ$S to $80^\circ$N. Since the main focus here is the cell leaking impact instead of the temperature trend and the impact of any ozone trend will be one to two orders of magnitude lower according to Shine et al. (2008). Therefore the ozone profiles are fixed and taken from the *U.S. Standard Atmosphere, 1976*. However, the atmospheric CO$_2$ concentration variation with time is considered in the simulation. The CIRA temperature profile set consisted of 396 profiles generated from data including ground-based and satellite measurements. The CIRA profile set retains the gross characteristics of the latitudinal and seasonal variations in the temperature field and therefore is useful for simulating the variation features shown in the measurement series. The simulated time series global (average from the 33 zonal data) and monthly-mean brightness temperatures with monthly-mean measured SSU cell pressure for all the SSU sensors according to Fig. 1 are shown in the top three panels of Fig. 6. The bottom three panels of Fig. 6 show the simulated brightness temperature differences between the top panel brightness temperatures and those obtained when the cell pressure was held constant (average cell pressure) over the measurement period for each SSU sensor. The simulated effects on BT of the cell shifts can be as large as $0.6$ K for NOAA-9 channel 1, $0.2$ K for NOAA-7 channel 2, and $0.6$ K for NOAA-7 channel 3. In general, the effects cannot be neglected, and the temporal progress of those effects can substantially reduce the temperature trends seen in the observed data (Brindley et al. 1999) if not considered.

b. Fitting the cell pressures for SSU NOAA-7 channel 2

The cell pressure monitoring for NOAA-7 SSU channel 2 ceased reporting values after June 1983 and in Fig. 1 we see a flat line until January 1985. However, the observed data show the brightness temperatures continued to rise. Based on the behavior of the cell pressure data prior to June 1983, two linear fitting methods were...
proposed to predict the cell pressure after June 1983. The first one uses linear extrapolation based on the cell pressures from period January 1983 to May 1983, and the second one does the same but using the rate of decrease from period November 1982 to January 1983. The cell pressure fittings are shown in Fig. 7.

The simulated time series brightness temperatures from the cell pressure fitting have been compared with SSU observation by using the CIRA profile set, default U.S. Standard Atmosphere ozone profile, and variable CO₂ concentration for the observation period. The observed data are first divided into months and then averaged into 5° latitudinal bins from 80°S to 80°N, the same as the CIRA dataset, to obtain the zonal and monthly-mean data. Finally, time series of the observed global and monthly brightness temperatures are produced for the SSU NOAA-7 observation period. The comparison result for scan angle 5° (scan position 4 and 5) is shown in Fig. 8. The simulated BTs from the CIRA dataset have been shifted by a constant value for each channel (1.15, 4.16, and 2.34 K for SSU channels 1–3, respectively) by using the BT difference between simulations and observations during December 1982, since CIRA profiles are different from the SSU-observed atmospheric profiles. The simulated BTs from the original cell pressures and fitting method 1 are well below those of the observations starting from June 1983. When using fitting method 2, the simulated temperature trend from channel 2 is consistent with the observation. Channels 1 and 3 show similar trends although the magnitude may be different. After removing the seasonal cycles obtained from the simulations using the original cell pressure (Fig. 8, bottom panel), the differences between simulations and observations for the three SSU channels strongly suggest that the predicted cell pressures using fitting method 2 are reasonable. The correlated scatterplots between the simulations and observations for NOOA-7 are also shown in Fig. 9. Fitting method 2 has the greatest correlation between simulations and observations. Since NOOA-7 and NOOA-8 have an overlap time period from May 1983 to June 1984, we used these observations to check the consistency of the fitting cell pressures. The top panel of Fig. 10 shows the global monthly-mean measured brightness temperatures for SSU NOOA-7 and NOOA-8 at scan angle 5° during the overlap period. The BT differences for channels 1 and 3 are small and consistent during this period because their cell pressures remain relatively constant. However, the BT differences for channel 2 are continuously increasing with time, which cannot be explained if the cell pressures are held constant for SSU NOOA-7 as the original cell pressures.
pressure suggested. The global monthly-mean BT double differences ($\Delta BT_{DF}$) between the differences from NOAA-7 simulations (using CIRA model profiles) minus observations and those from NOAA-8 are shown in Fig. 10, bottom panel. Since we included the atmospheric CO$_2$ change and cell pressure variations for the simulations, the BT difference from simulation and observation mainly comes from the mean atmospheric temperature structure between model atmosphere and real atmosphere. The double difference $\Delta BT_{DF}$ between NOAA-7 and NOAA-8 would show the relative performance between the two satellites by removing the model bias introduced from the inputs. The double difference method can validate the predicted cell pressure values for NOAA-7 channel 2 when we check the consistence of the double difference pattern before and after June 1983, since SSU channel 2 senses atmospheric levels with relative constant lapse rate above the stratosphere. For SSU channel 1, the double differences are very small (within ±0.2 K) during the overlap period.

FIG. 8. (top) Time series for global monthly-mean measured BTs and simulated BTs using the fast model from the CIRA temperature profiles for SSU NOAA-7 channels at scan angle 5°. (bottom) BT differences after removing seasonal cycles obtained from the simulations using the original cell pressure.

FIG. 9. Scatterplot of global monthly-mean measured BTs and simulated BTs using the fast model from the CIRA temperature profiles for SSU NOAA-7 channels at scan angle 5° for (top to bottom) channels 1–3.
because of their small cell pressure differences and the fact that they have almost same weighting function peak height and thus sense the same atmospheric level. For SSU channel 2, the double differences using cell pressures from fitting method 2 after June 1983 for NOAA-7 are consistent with the period before June 1983. There are relative constant $2\text{-K}$ double differences for channel 2 because NOAA-7 and NOAA-8 have larger cell pressure differences and sense different atmospheric levels and because of the relative constant lapse rate above stratosphere. The double BT differences using the original cell pressures and fitting method 1 are obviously inconsistent before and after June 1983. Based on these comparison results, the cell pressure predicted using fitting method 2 would appear to approximate the actual cell pressure. The SSU channel 3 has different double difference pattern compared with the other two channels because this channel senses upper stratosphere–lower mesosphere (lapse rate reverse) and relatively larger cell pressure differences compared to channel 1.

6. Summary and conclusions

SSU observations provide unique data for global stratospheric temperature studies over long periods from 1978 to 2006. To accurately estimate brightness temperatures for the SSU, the RT model must include schemes to model the CO$_2$ cell transmittance for each of the three channels and account for the variations of the SRFs caused by the CO$_2$ cell pressure variations. In addition, the study revealed that the spectral resolution of $2.5 \times 10^{-3} \text{ cm}^{-1}$ for the SRF calculation in channel 3 is not adequate and could result in 0.6 K brightness temperature errors on average. The spectral resolution is increased to $5 \times 10^{-4} \text{ cm}^{-1}$ for the development of the improved fast RT model. The analysis of radiance sensitivities to the variations in the atmospheric CO$_2$ and O$_3$ concentrations have shown that contributions from the two absorbing gases must be taken into account in the RT model. The changes in CO$_2$ can lead to 0.1–0.4-K BT difference due to a 25-ppmv increase in CO$_2$, depending on the SSU channel. Also, the O$_3$ absorption cannot be neglected, especially for SSU channel 1 with mean difference about $-0.1$ K.

The RT model is first validated against LBLRTM using independent UMBC 48 profile sets. It shows that the BT differences between the two models are less than 0.1 K. The fast model is also tested against measurements for NOAA-14, with MLS and SABER sounding profiles as the model inputs. The model results show consistency and improvement compared with results from the previous SSU model using the MLS dataset. The model results also agree well with the measurements for SABER input (RMS difference less than 2 K for all the three channels) if we consider the uncertainties in the SABER temperature retrievals.

The variations of the cell pressures that caused variations of the SRFs have been taken into account in the SSU fast model and handled dynamically via user input cell pressure or satellite observation time. The impact of the CO$_2$ cell pressure shift for SSU has been evaluated by using the CIRA model profiles. It is shown that the impacts can be of the order of 1 K, especially for SSU NOAA-7 channel 2. Two linear fitting methods are proposed to solve the larger brightness temperature gap between observation and model simulation using the available cell pressures for NOAA-7 channel 2 after June 1983. The evaluation of the cell fitting methods is also performed by checking the consistency between NOAA-7 and NOAA-8 during the overlap time period. The results show that the new cell pressures using fitting method 2 are reasonable.

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