Investigating the Influence of Carbon Dioxide and the Stratosphere on the Long-Term Tropospheric Temperature Monitoring from HIRS

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ABSTRACT

Contrary to a midtropospheric warming trend detected from Microwave Sounding Unit (MSU) measurements, High-Resolution Infrared Radiation Sounder (HIRS) temperature (15 μm) channels, sensitive to the thermal emission from the troposphere, produce distinct cooling trends for the period 1980–99. This apparent discrepancy in the tropospheric temperature trend is investigated through radiative transfer simulations using Geophysical Fluid Dynamics Laboratory climate model output and the profiles of the standard model atmospheres. Radiative simulations with time-invariant carbon dioxide concentration throughout the entire analysis period produce trends that are qualitatively similar to that obtained from the MSU observations, implying that the observed cooling trends of the HIRS temperature channels are attributable to increased carbon dioxide concentration over the 20-yr period. Additional simulations with the observed time-varying concentration of carbon dioxide confirm this basic result. Whereas temperature fluctuations dominate variability on monthly to interannual time scales, carbon dioxide changes dominate the decadal trends in both the observations and model simulations. Further simulations examined the sensitivity of the brightness temperature change with respect to the changes in tropospheric and stratospheric temperature. These calculations indicate that the influences of stratospheric temperature on the measured radiances are greater for the HIRS temperature channels relative to the MSU midtropospheric channel. These results highlight the contributions of time-varying carbon dioxide concentrations and stratospheric temperature to the HIRS 15-μm (temperature channel) radiance record and underscore the importance of accurately accounting for these changes when using HIRS measurements for long-term monitoring.

1. Introduction

Accurate measurements of atmospheric temperature profiles are a fundamental prerequisite not only for reliable weather forecasting, but also for global-scale monitoring of climate change (e.g., Gaffen et al. 2000; Fu et al. 2004; Mears and Wentz 2009; Chung and Soden 2010). For several decades, atmospheric temperature profile datasets have been constructed mainly through the operational radiosonde network observations. However, radiosonde stations are confined mainly over the continents of Northern Hemisphere, leaving the vast parts of the earth as data-void regions. Moreover, instrument types and observing conventions have been frequently changed, raising doubts on the reliability of radiosonde observations for documenting long-term trends (e.g., Gaffen et al. 2000; Sherwood et al. 2005, 2008; Sherwood 2007).

Temperature sounding instruments onboard polar-orbiting satellites have complemented the radiosonde soundings by providing better spatiotemporal coverage, and thereby can enable a more reliable analysis of long-term atmospheric temperature trends. In particular, since the end of 1970s, atmospheric temperatures for the lower troposphere to the stratosphere have been retrieved through the measurements of the High-Resolution Infrared Radiation Sounder (HIRS) and Microwave Sounding Unit (MSU) on board National Oceanic and Atmospheric Administration (NOAA) operational polar-orbiting satellites. The HIRS and MSU utilize 15-μm carbon dioxide (CO₂) absorption band and oxygen (O₂) absorption band around 60 GHz, respectively.

However, impediments such as diurnal sampling bias arising from satellite orbital drift and problems associated with combining data from different satellites have hindered the use of satellite-retrieved atmospheric temperature profiles for deriving long-term trends (e.g., Gaffen...
et al. 2000; Fu and Johanson 2005). Although recent efforts have significantly resolved these impediments (e.g., Jackson and Soden 2007; Mears and Wentz 2009), uncertainties caused by other factors such as the increase of anthropogenic greenhouse gases (e.g., Keeling et al. 1995; Gurney 2009; Mercado et al. 2009; Chung and Soden 2010) and the influence of the stratosphere have not been investigated for HIRS temperature channels, in comparison with the MSU temperature channels (e.g., Fu et al. 2004; Fu and Johanson 2004).

It is noted that HIRS produces atmospheric temperature information with a better vertical resolution than that of MSU, and the CO₂-slicing techniques based on radiance measurements associated with the 15-μμm CO₂ absorption band are frequently used for defining cloud-top pressure and effective cloud amount (e.g., Menzel et al. 2008). In addition, the HIRS temperature measurements are routinely assimilated into reanalyses products (Kalnay et al. 1996; Uppala et al. 2005). Therefore, it is important to examine the factors affecting the measured radiances of the HIRS temperature channels. In this study, we investigate the contributions of time-varying CO₂ concentration and temperature variation of the stratosphere on the long-term tropospheric temperature monitoring from HIRS.

2. Data and method

a. HIRS/2 data

Cross-tracking HIRS scanners have flown on board the NOAA operational polar-orbiting satellites since 1978. For the purpose of atmospheric temperature sounding, HIRS has seven infrared channels associated with the CO₂ absorption band centered at 15 μm. The central wavelengths of channels 1–7 are as follows: 15.0, 14.7, 14.5, 14.2, 14.0, 13.7, and 13.4 μm. Whereas channels 1 and 2 are sensitive to the thermal emission from the stratosphere, channels 4–6 have a weighting function peak in the free troposphere. In addition, channels 3 and 7 are closely associated with the temperature at the tropopause and the boundary layer, respectively. An example of weighting function for these channels can be found in Jackson and Soden (2007).

The HIRS diurnal sampling bias caused by satellite orbital drift has recently been addressed by Jackson and Soden (2007). They also intercalibrated all NOAA operational polar-orbiting satellites prior to NOAA-15 carrying the HIRS/2 scanner to NOAA-10 equatorial local crossing times for both the ascending and descending nodes. Because water vapor and lapse rate feedbacks are significantly affected by tropospheric temperature trends (e.g., Held and Soden 2000), we choose to focus our analysis on the free-tropospheric temperature channels (i.e., channels 4–6). In this study, monthly mean clear-sky gridded data with a spatial resolution of 2.5° × 2.5° are analyzed for the period from January 1980 to December 1999.

b. MSU data

Since November of 1978, the NOAA operational polar-orbiting satellites have carried an MSU sensor, which measures the thermal emission from atmospheric oxygen, with four channels located in the oxygen absorption band near 60 GHz. Weighting functions indicate that channels 2 and 4 have a peak in the middle troposphere and the lower stratosphere, respectively (e.g., Fu et al. 2004; Mears and Wentz 2009). The intercalibrated monthly mean MSU dataset (version 3.2) processed by the Remote Sensing Systems Company (Mears and Wentz 2009) is employed to compare with the long-term trends of brightness temperature derived from HIRS observations.

c. GFDL model output

Geophysical Fluid Dynamics Laboratory (GFDL) Atmospheric Model 2 (AM2) simulations were conducted to examine the influence of CO₂ concentration on the brightness temperature trends determined from the HIRS temperature channel measurements. Using observed sea surface temperatures, time-varying trace gases and aerosols, and volcanic aerosols, four model runs were integrated for the period 1979–99 (e.g., Soden et al. 2002). A profile-to-radiance approach is adopted to avoid uncertainties associated with the inversion of satellite-measured radiances into geophysical quantities; that is, model outputs are inserted into a radiative transfer model to simulate the brightness temperature that satellite instruments would have observed under those conditions (e.g., Chung and Soden 2009). The GFDL Global Atmospheric Model Development Team (2004) provides detailed information on dynamics and parameterization schemes adopted in GFDL AM2.

d. Analysis method

To investigate the contribution of time-varying CO₂ concentration on the HIRS-derived brightness temperature trends, we conducted radiative transfer simulations using vertical profiles of temperature, humidity, and ozone and surface variables produced from GFDL AM2 runs in conjunction with constant CO₂ concentration throughout the entire analysis period. We also conducted separate radiative transfer simulations using time-varying CO₂ concentration for comparison with the constant-CO₂ cases and the satellite observations. Radiative transfer simulations are performed for the
temperature channels of both HIRS and MSU for each GFDL simulation, and then ensemble means of four simulations are used to construct the time series for the period 1980–99.

In the second step, the influence of temperature changes in the troposphere and the stratosphere on the radiances of the HIRS temperature channels is examined by radiative transfer simulations with the profiles of the standard tropical atmosphere, the standard midlatitude summer atmosphere, and the standard midlatitude winter atmosphere (McClatchey et al. 1972).

3. Influence of time-varying CO₂ concentration on the long-term tropospheric temperature monitoring

Figure 1 shows the time series of the observed brightness temperature anomalies of HIRS channels 4–6 for the period 1980–99. Brightness temperature anomalies for each channel were produced at each grid point by removing the mean seasonal cycle, and then averaged over three geographical domains with a weight proportional to area, that is, globe (Fig. 1a), tropics (30°N–30°S; Fig. 1b), and tropical ocean (Fig. 1c). The time series of brightness temperature anomaly of these channels exhibit sporadic spikes with larger amplitude over the tropics relative to higher latitudes. These spikes denote atmospheric warming events primarily associated with El Niño that occurred in 1982–83, 1986–87, 1991–92, and 1997–98 (e.g., Wielicki et al. 2002). These sporadic warming events are also clearly evident in the MSU T2MT records (red lines)—MSU T2MT is a linear combination of MSU channel 2 and 4 (Fu et al. 2004; Fu and Johanson 2004).

It is noted that the MSU T2MT (also MSU channel 2) records show a warming trend of brightness temperature anomaly consistent with previous studies that reported a decadal warming trend with magnitudes ranging over 0.1–0.2 K (10 yr)⁻¹ (e.g., Fu et al. 2004; Fu and Johanson 2004; Mears and Wentz 2009). Other tropospheric temperature records and climate model predictions also indicated a qualitatively similar tropospheric warming trend (e.g., Bengtsson et al. 1999; Gaffen et al. 2000). Unlike the MSU T2MT, the brightness temperature anomalies of HIRS temperature channels exhibit a distinct cooling trend over the 1980–99 period. Table 1 lists the linear trends for the global mean time series from both the HIRS and MSU records. Considering that the HIRS channel 5 has a nearly similar weighting function peak to that of the MSU T2MT (and MSU channel 2) as shown in Fig. 2, the marked difference in trend is not associated with differences in the vertical sampling, but rather reflects the effects of increasing atmospheric CO₂ concentration on the HIRS temperature channels (e.g., Chung and Soden 2010).

To examine further the discrepancy of brightness temperature trend between HIRS and MSU, the impact of enhanced CO₂ on the HIRS brightness temperatures is investigated through radiative transfer simulations in which the CO₂ concentration is set to the value in January of 1980 for the entire analysis period. Brightness temperatures are simulated by inserting model outputs from GFDL AM2 runs into a radiative transfer model [Radiative Transfer for Television and Infrared Observation Satellite Operational Vertical Sounder (RTTOV); Saunders et al. 2009] with the constant value of CO₂ concentration. Figure 3 shows the time series of the simulated brightness temperature anomaly of both MSU channel 2 (red lines) and T2MT (dark red lines) for three spatial domains. Although the times series of simulated MSU T2MT brightness temperatures exhibit a slightly larger warming trend when compared with observations for the global mean case, the time series from radiative simulations with GFDL model output are generally consistent with satellite observations. It is also noted that substantial warming signals associated with El Niño events are captured well in the simulation.

On the other hand, the distinct cooling trends found in HIRS observations are not reproduced in the time series of simulated HIRS brightness temperature anomaly. Rather, the simulated time series are qualitatively similar to those of MSU T2MT. Furthermore, HIRS channel 6 (violet lines) even exhibits a warming trend with a magnitude of around 0.1 K (10 yr)⁻¹. These results imply that time-varying CO₂ concentration causes the HIRS temperature channel measurements to produce a distinct cooling trend in the free troposphere, distorting a true warming trend of the free troposphere detected in other measurements (e.g., Gaffen et al. 2000; Mears and Wentz 2009; Chung and Soden 2010).

As a sensitivity test, radiative transfer computations for the standard midlatitude summer atmosphere (McClatchey et al. 1972) were performed using Moderate Resolution Atmospheric Transmittance and Radiance (MODTRAN) code (Berk et al. 1999) with four values of CO₂ concentration (Fig. 4). For wavenumbers covering the 15-μm CO₂ absorption band, simulated equivalent blackbody brightness temperatures gradually decrease as CO₂ concentration increases from 315 to 390 ppmv in agreement with results shown in Huang and Ramaswamy (2009), confirming that the impact of the increased CO₂ concentration during the recent decades (e.g., Keeling et al. 1995; Gurney 2009; Mercado et al. 2009) on the observed radiances of HIRS temperature channels.

The radiances of HIRS temperature channels are influenced by both atmospheric temperature change and
the variation of CO₂ concentration. To compare the contribution of each factor, we simulated brightness temperatures for three cases: 1) time-varying atmospheric temperature with constant CO₂ concentration over the entire analysis period (same as in Fig. 3), 2) time-varying CO₂ concentration and the atmospheric temperature profiles of 1980, and 3) time-varying atmospheric temperature and time-varying CO₂ concentration. The CO₂ concentrations used in the last two cases linearly increase from 337 ppmv in January 1980 to 368 ppmv in December 1999.

Over the tropical ocean, Fig. 5 shows that the second case (green lines) produces a gradual decrease in brightness temperature anomalies with approximately constant slopes for the three HIRS temperature channels. The brightness temperature differences between January 1980 and December 1999 are 0.7–0.9 K. Similar results are obtained over the globe (not shown). Comparisons of

![Graphs showing monthly mean brightness temperature anomalies](image)

**Fig. 1.** Area-weighted domain average of observed monthly mean brightness temperature anomalies for three HIRS temperature channels and MSU T2MT (a linear combination of MSU channels 2 and 4) for the period 1980–99: (a) globe, (b) tropics, and (c) tropical ocean. Anomalies are calculated by removing the mean seasonal cycle over the period 1980–99.

<table>
<thead>
<tr>
<th>Case Description</th>
<th>HIRS Ch4</th>
<th>HIRS Ch5</th>
<th>HIRS Ch6</th>
<th>MSU T2MT</th>
</tr>
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<tbody>
<tr>
<td>Obs</td>
<td>−0.246</td>
<td>−0.496</td>
<td>−0.343</td>
<td>0.155</td>
</tr>
<tr>
<td>Case 1 (varying temperature and constant CO₂)</td>
<td>−0.099</td>
<td>0.009</td>
<td>0.082</td>
<td></td>
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<tr>
<td>Case 2 (constant temperature and varying CO₂)</td>
<td>−0.293</td>
<td>−0.421</td>
<td>−0.434</td>
<td></td>
</tr>
<tr>
<td>Case 3 (varying temperature and varying CO₂)</td>
<td>−0.401</td>
<td>−0.415</td>
<td>−0.351</td>
<td></td>
</tr>
</tbody>
</table>
case 2 and the time series of observed MSU T2MT (and MSU channel 2) indicate that the increase of CO₂ concentration during the 20-yr period counteracts the warming trend of tropospheric temperature, thereby resulting in the discrepancy in the long-term trend of brightness temperature between MSU and HIRS channel 5 and 6. The case of variations in both atmospheric temperature and CO₂ concentration (case 3) is shown with the red lines. It is interesting to note that the impact of increasing CO₂ on the linear trends is roughly 3 times as large as the impact of increased temperature over this period (Table 1). Thus, it is likely that other factors in addition to time-varying CO₂ concentration must also be considered when interpreting the decadal changes of the HIRS 15-μm brightness temperatures.

Given the fact that MSU channel 2 has a weighting function peak in the middle troposphere (e.g., dashed line in Fig. 2), it is expected that the satellite-observed radiances are mainly determined by the vertical temperature distribution of the troposphere. However, Fu et al. (2004) found that the contribution of stratosphere is significant in the brightness temperature trend of MSU channel 2 and that approximately 15% of the signal comes from the stratosphere. Fu et al. (2004) consequently developed MSU T2MT (a linear combination of MSU channels 2 and 4) to remove the contribution of stratosphere on the tropospheric temperature trend derived from MSU channel 2 measurements (e.g., dash–dot–dotted line in Fig. 2). It was found that the contribution of stratospheric cooling on the decadal trend of MSU channel 2 brightness temperature is approximately $-0.1 \, \text{K (10 yr)}^{-1}$ for the period 1979–2001 (Fu and Johanson 2004). In agreement with Fu et al. (2004) and Fu and Johanson (2004), Fig. 3 clearly shows that MSU T2MT exhibits a greater warming trend when compared with the original MSU channel 2.

As shown in the MSU channel-2 case, careful examinations of the weighting functions of HIRS channels 4–6 suggest that the stratospheric contribution to the measured brightness temperature is not negligible [refer to Jackson and Soden (2007) and solid lines in Fig. 2]. Therefore, we assessed the contribution of stratospheric temperature trend to the observed trend of HIRS 15-μm brightness temperatures by simulating HIRS brightness temperatures for seven temperature channels (i.e., channels 1–7) using the profiles of three standard model atmospheres (McClatchey et al. 1972) as input. Figures 6 and 7 show the brightness temperature changes of HIRS temperature channels as functions of tropospheric temperature change and stratospheric temperature change.
For HIRS channel 1, the changes of brightness temperature are nearly identical to stratospheric temperature changes, indicating that the influence of tropospheric temperature changes is insignificant. Generally similar results are obtained for HIRS channels 2 and 3 (Fig. 6).

On the other hand, the brightness temperature changes of HIRS channels 4–6 are influenced by both tropospheric temperature change and stratospheric temperature change, as can be identified by slanted isopleths (Fig. 7). It is also noted that the contribution of stratospheric temperature change is reduced as a weighting function peaks at lower altitude in the troposphere. These results explain why HIRS channel 6 exhibits larger warming trend than channel 5 in Fig. 3. Meanwhile, HIRS channel 7 exhibits much steeper slopes when compared with HIRS channel 6, indicating the predominant influence of temperature changes in the planetary boundary layer and at the surface consistent with the shape of the channel-7 weighting function (e.g., Jackson and Soden 2007). In addition, channel 7 shows that the influence of stratospheric temperature change is almost negligible for the tropical summer condition.

Figure 7 also displays the brightness temperature changes of MSU channel 2 (thin black lines). Comparison of slopes between MSU channel 2 and HIRS temperature channels indicates that the isopleths of HIRS channel 6 are generally parallel to those of MSU channel 2. By contrast, the slopes of HIRS channels 4 and 5 are gentler than those of MSU channel 2, suggesting that stratospheric temperature change exerts a greater influence on the brightness temperature changes in comparison with MSU channel 2. Thus, weaker warming
trends of the free troposphere derived from radiative transfer simulations for HIRS free-tropospheric temperature channels with constant CO$_2$ concentration (Table 1) can be explained by the greater contribution of stratosphere and the cooling trend of stratosphere over the past several decades (e.g., Houghton et al. 2001; Fu et al. 2004; Ramaswamy et al. 2006; Mears and Wentz 2009; Son et al. 2009). The greater contribution of the stratosphere is also evident following the volcanic eruptions of El Chichón and Mount Pinatubo (March 1982 and June 1991, respectively). These eruptions introduced large amounts of aerosol particles into the stratosphere that remained for several years, warming the stratosphere as a result of the enhanced absorption of solar radiation from the aerosols (e.g., Robock and Mao 1992; Stowe et al. 1992; Trepte et al. 1993; Ramaswamy et al. 2001; Soden et al. 2002; Stenchikov et al. 2002). This transient warming of the stratosphere combined with the greater stratospheric influence on the HIRS channels explains the diverging anomalies with respect to MSU T2MT in the periods of 1982–84 and 1991–94 in Fig. 3.

5. Summary and conclusions
We examined the causes of diverging trends between HIRS and MSU temperature channel measurements. Whereas the MSU brightness temperatures (channel 2 or T2MT) exhibit a warming trend for the period 1980–99, HIRS (15 $\mu$m) temperature channel measurements
indicate a distinct cooling trend over the same period. A series of radiative transfer calculations were performed using GFDL climate model output with both constant and time-varying carbon dioxide concentration. These simulations revealed that, while temperature fluctuations dominate the changes in HIRS brightness temperatures on monthly to interannual time scales, the increased CO$_2$ concentration is dominant on the longer decadal time scales despite the presence of a significant long-term warming of the troposphere over this period. When simulations were performed using constant levels of CO$_2$ a warming trend emerged in the HIRS brightness temperatures; however, this trend is noticeably weaker relative to that simulated for the MSU channels (both T2MT and the original channel 2). Sensitivity calculations of the HIRS and MSU brightness temperatures as functions of tropospheric and stratospheric temperature change demonstrated that the stratosphere exerts a greater influence on the brightness temperature of the HIRS temperature channels than for MSU channel 2.

These results highlight the contributions of time-varying CO$_2$ concentrations and stratospheric temperature to the HIRS 15-$\mu$m (temperature channel) radiance record and underscore the importance of accurately accounting for these changes when using HIRS measurements for long-term monitoring. HIRS sounders provide temperature information for relatively broad layers in comparison with the conventional radiosonde network observations, because of the limited number of
channels. However, high-spectral infrared sounders such as the Atmospheric Infrared Sounder (AIRS) and Infrared Atmospheric Sounding Interferometer are currently in operation, producing atmospheric temperature profiles with a greatly enhanced vertical resolution. Given the fact that the 15-μm CO₂ absorption band is also employed in these high-spectral infrared sounders, the influences of time-varying CO₂ concentration should be considered for long-term climate monitoring through the use of AIRS and similar high-spectral-resolution instruments.

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FIG. 6. Brightness temperature changes (K) of HIRS temperature channels 1–3 with respect to the changes in tropospheric and stratospheric temperatures for (left) the standard tropical atmosphere, (center) the standard midlatitude summer atmosphere, and (right) the standard midlatitude winter atmosphere. Positive and negative values are represented by solid and dashed lines, respectively.
FIG. 7. Brightness temperature changes (K; blue lines) of HIRS temperature channels 4–7 with respect to the changes in tropospheric and stratospheric temperatures for (left) the standard tropical atmosphere, (center) the standard midlatitude summer atmosphere, and (right) the standard midlatitude winter atmosphere. Superimposed thin black lines denote the changes of MSU channel 2 brightness temperatures (K) as functions of the changes in tropospheric and stratospheric temperatures. Positive and negative values are represented by solid and dashed lines, respectively.
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REFERENCES


