Temperature trends derived from Stratospheric Sounding Unit radiances: The effect of increasing CO_2 on the weighting function

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[1] Stratospheric Sounding Units (SSU) on the NOAA operational satellites have been the main source of near-global temperature trend data above the lower stratosphere. They have been used extensively for comparison with model-derived trends. The SSU senses in the 15 μm band of CO_2 and hence the weighting function is sensitive to changes in CO_2 concentrations. The impact of this change in weighting function has been ignored in all recent trend analyses. We show that the apparent trends in global-mean brightness temperature due to the change in weighting function vary from about -0.4 Kdecade^{-1} to 0.4 Kdecade^{-1}, depending on the altitude sensed by the different SSU channels. For some channels, this apparent trend is of a similar size to the trend deduced from SSU data but ignoring the change in weighting function. In the mid-stratosphere, the revised trends are now significantly more negative and in better agreement with model-calculated trends. **Citation:** Shine, K. P., J. J. Barnett, and W. J. Randel (2008), Temperature trends derived from Stratospheric Sounding Unit radiances: The effect of increasing CO_2 on the weighting function, *Geophys. Res. Lett.*, *35*, L02710, doi:10.1029/2007GL032218.

1. Introduction

[2] The Stratospheric Sounding Unit (SSU) has been a component of TIROS Operational Vertical Sounders on NOAA operational meteorological satellites since 1979. Although primarily designed to provide data for weather forecasting purposes, the SSU also provides the only near-global source of data on temperature trends above the lower stratosphere over such a long period; it has been extensively used in assessments of those trends, and their possible causes [e.g., *Nash and Forrester*, 1986; *Ramaswamy et al.*, 2001; *Shine et al.*, 2003; *World Meteorological Organization* (*WMO*), 1988, 2007].

[3] There are formidable problems in deriving trends from SSU measurements (see especially *Nash and Forrester* [1986] and *Nash* [1988]). Over the 25 year period, data from the SSUs on 10 different satellites have been used to produce trend analyses. These satellites have varying orbits (and hence have different equatorial crossing times), the equatorial crossing times for individual satellites drift, and there is often quite scant overlap between different instruments to allow intercalibration. Hence corrections have to

be made to account for differences in calibration, and for the significant diurnal and semi-diurnal tidal variations in temperature in the middle atmosphere. In addition, because the SSU is a pressure modulator radiometer, an on-board cell of carbon dioxide is used in spectral filtering [see, e.g., *Houghton et al.*, 1984]; leaks in this cell can cause a time-varying change in signal. However, an advantage of the technique, compared to methods which use a spectral response defined by just a band-pass filter, is that the weighting function is only weakly affected by filter drifts.

[4] Since the radiances measured by the SSU are due to emission by CO_2, the weighting functions of its different channels are also subject to time-varying changes, as the amount of CO_2 in the atmosphere increases. The impact of changes in CO_2 on the weighting functions, and hence the measured radiances, for the SSU have not been assessed in any recent analyses of stratospheric temperature trends. The purpose of this letter is to address this issue. The effect of increasing CO_2 will be to move the weighting functions to higher altitudes; since the SSU senses mostly in the stratosphere (where temperatures increase with height), a higher weighting function translates into higher temperatures. If uncorrected, this would result in spurious positive temperature trends, superimposed on any true geophysical trend, which is expected to be negative throughout the stratosphere [e.g., *Ramaswamy et al.*, 2001; *Shine et al.*, 2003].

[5] The SSU has three channels, denoted 25, 26 and 27, which have peaks in the weighting function at about 29, 38 and 44 km respectively. Trend analyses have utilised the near-nadir (5°) data from these channels; in addition a number of so-called synthetic channels (henceforth X channels) have been utilised (see especially *Nash* [1988]) which use the differences between combinations of near-nadir and 35° scans to construct weighting functions that increase the vertical resolution of derived temperatures and trends–those used here are referred to as 15X, 26X, 36X and 47X (which peak at about 23, 35, 45 and 50 km, respectively). There are additional problems in utilising these X channels. They are much more sensitive to changes in orbital parameters than the nadir channels, such as, for example, the decay in satellite orbit height, in a similar manner to the Microwave Sounding Unit [*Wentz and Schabel*, 1998]. Hence, we have greater confidence in our results for the near-nadir measurements.

[6] The impact of changes in CO_2 on SSU weighting functions appears to have been first considered by the 1988 International Ozone Trends Panel [*WMO*, 1988, chapter 6]. The impact of an 8 ppmv change in CO_2 was computed (corresponding to the change from 1979 to 1985)–it was concluded, in the context of the then rather short period of data for trend analysis, that the effect was minor. Subsequently, *Brindley et al.* [1999] considered the impact of

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changes in both temperature and CO_2 on the changes in Channel 25 radiances corresponding to the period of 1865 to 2045. The results derived here are consistent with those that can be inferred from these previous studies.

2. Weighting Function Calculations

[7] Weighting functions are calculated using the GENLIN line-by-line radiative transfer code; this code is the forerunner of the GENLN2 code [*Edwards*, 1992], and is used here as it was set up for the SSU Pressure Modulator Radiometer calculations. CO_2 volume mixing ratios of 350 and 370 ppmv were used, equivalent to about 13 years worth of change at current rates of increase [*Forster et al.*, 2007]. The weighting functions were calculated using the CIRA (COSPAR International Reference Atmosphere) 30°N standard atmosphere [*Fleming et al.*, 1990] (with the ozone profile taken from the US Standard Atmosphere). Since ozone absorbs in the same spectral region as sensed by the SSU, the effect of this absorption is included for all calculations presented here, but its influence on the brightness temperature (T_B) is small. If ozone is neglected, the changes range in magnitude from 0.016 to 0.4 K, depending on channel; the impact of any ozone trends will be one to two orders of magnitude lower.

[8] Various instrument and satellite orbit parameters have to be specified in such a calculation. For the instrument, the pressure of CO_2 in the cells is required. Since the radiances in the temperature series used in recent assessments (extended from *Nash and Forrester* [1986]) have been adjusted to take in to account changes in cell pressures, they are assumed constant here, to isolate the effect of changes in atmospheric CO_2. The values used are 100, 40 and 15 hPa for channels 25, 26 and 27 respectively. A single wide-band transmission filter is used for all 3-channels, to isolate the signal from the 15 μm band–the filter function presented by *Brindley et al.* [1999] is used here. Orbital parameters include the height of the satellite and the local cross-track radius of curvature of the Earth. Weighting functions are calculated for an equatorial case (satellite altitude 830 km and local cross-track radius of curvature of 6378 km) and a polar case (852 km and 6400 km). The cell length and temperature are taken as 10 mm and 302.6 K respectively, and the pressure modulation amplitudes are taken as 0.177, 0.266 and 0.299 for channels 25, 26 and 27 respectively. The uncertainty in these values [see, e.g., *Brindley et al.*, 1999] has negligible impact on the effect of changes in CO_2 calculated here–a 10 K change in cell temperature for channel 26 changes the result by less than 1%.

[9] The weighting functions depend on the instrument scan angle (here 5° and 35° are used) and also whether Doppler shifting between CO_2 lines in the cell and CO_2 lines in the atmosphere is accounted for; the Doppler shift is largest for the equatorial case, and zero for polar cases–this Doppler shifting was neglected in the analysis of *Nash* [1988]. Here we include the Doppler shifting due to the Earth's rotation, but neglect any component due to the wind.

[10] The weighting functions for the near-nadir views, and their dependence on changes in CO_2, are insensitive (within 1 mK for Channels 25 and 26, and 8 mK for Channel 27) to the choice of orbital parameters and whether Doppler shifting due to Earth's rotation is included. The

same is not true for the 35° views, and hence the X channels; in particular, the weighting function for 47X shows a much stronger response in the upper mesosphere, in the equatorial case. It is for this reason that we have more confidence in the analysis for the nadir channels; however, as will be shown, the effect of changes in CO_2 is reasonably similar for the X channels, whether an equatorial or polar weighting function is chosen. While, in principle, latitude-dependent weighting functions could be derived for the X channels, this is a formidable job and is not attempted here; any attendant trend analysis would have to take in to account the latitudinal variation in tidal corrections [see *Nash*, 1988] that are applied.

3. Results

[11] Figure 1 shows the weighting functions for channels 25, 26 and 27, and the change in weighting function for the 20 ppmv increase in CO_2. The effect of the increase in CO_2 can be characterized by computing the change in the "centroid" of the weighting function. This is defined as the vertical integral of z multiplied by the weighting function, where z is the scale height ($z = -\ln(p/p_o)$ where p is pressure and p_o is a reference pressure of 1013 hPa). For all channels, the centroid increases by 0.028 ± 0.001 scale heights except for 36X and 47X which increase by 0.035 scale heights. This translates to an increase of about 0.2 km (0.25 km for 36X and 47X) in the height of the weighting function.

[12] The impact of the CO_2-induced changes in the weighting function on T_B is computed using the zonal and monthly mean temperatures from the 1986 CIRA [*Fleming et al.*, 1990] with a 5° latitudinal resolution. Since the weighting function acts on the radiance field [e.g., *Houghton et al.*, 1984; *Nash*, 1988], rather than the temperature field as is sometimes assumed, the temperatures are converted to radiances, using the Planck function appropriate for 668 cm^{-1} and then weighted using the appropriate weighting function. They are then inverted using the Planck function to produce T_B. The procedure is repeated for both CO_2 mixing ratios.

[13] Figure 2 shows the effect on T_B of the 20 ppmv change in CO_2 for the near-nadir views, for January, July and the annual mean. As expected, the increase in CO_2 leads to an increase in T_B of 0.2 to 0.4 K. The seasonal dependence is due to the change in temperature profile between these months. On the whole this seasonal variation is modest, except in the southern extra-tropics, where seasonal variations in temperature are most marked. We refer to the trend in temperature due solely to the weighting function change as the "apparent trend". The annual and global-mean apparent T_B trends are 17.0, 17.5 and 9.3 mK ppmv^{-1} for channels 25, 26 and 27 respectively. These translate into apparent trends of about 0.26, 0.27 and 0.14 K decade^{-1}, respectively, assuming a 15.4 ppmv decade^{-1} change in CO_2 [*Forster et al.*, 2007].

[14] Figure 3 shows the annual-mean changes in T_B for the synthetic channels–the computations are repeated using both the equatorial and polar weighting functions. In general, the impact of the choice of weighting function is quite modest (0.1 K or less), although when the change in T_B is near zero (e.g. for 15X near the poles), the percentage
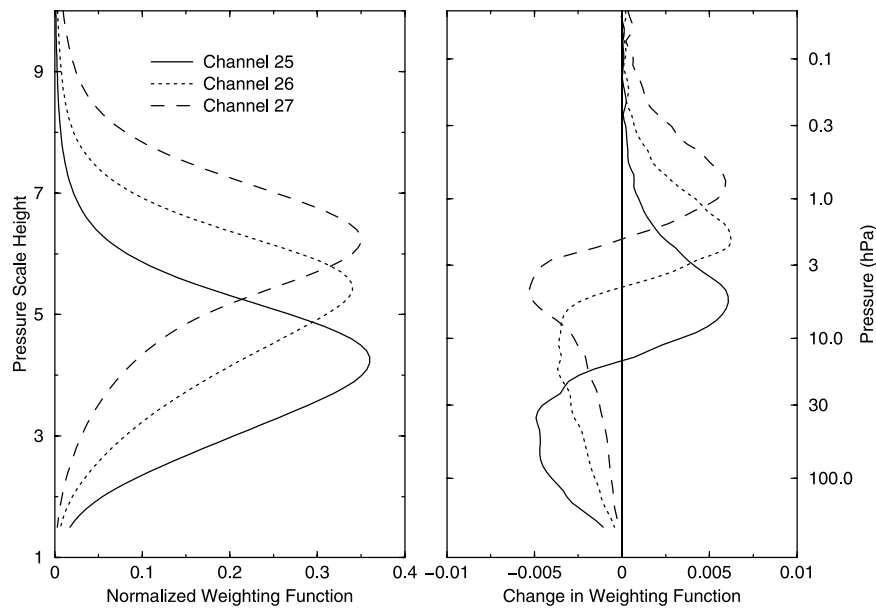
Figure 1. (left) The normalized weighting functions for SSU channels 25, 26, and 27, for a CO_2 mixing ratio of 350 ppmv. (right) Change in weighting function (370 minus 350 ppmv) due to a 20 ppmv increase in CO_2.

difference can be very large. For 15X, the apparent warming ranges from near zero at the poles to more than 0.3 K in the tropics. As the lapse rate reverses in the mesosphere, it is expected that the highest channel, 47X, would show an apparent cooling as CO_2 increases. Figure 3 shows an apparent cooling of up to 0.6K. Channel 36X, with its peak near 45 km is generally "mesospheric" (i.e. showing a cooling) in the tropics but becomes "stratospheric" at higher latitudes. The annual and global-mean apparent T_B trends are 12.0, 29.3, -1.35 and -28.2 mK ppmv^{-1} for the equatorial weighting functions for channels 15X, 26X, 36X and 47X respectively. These translate into apparent trends of
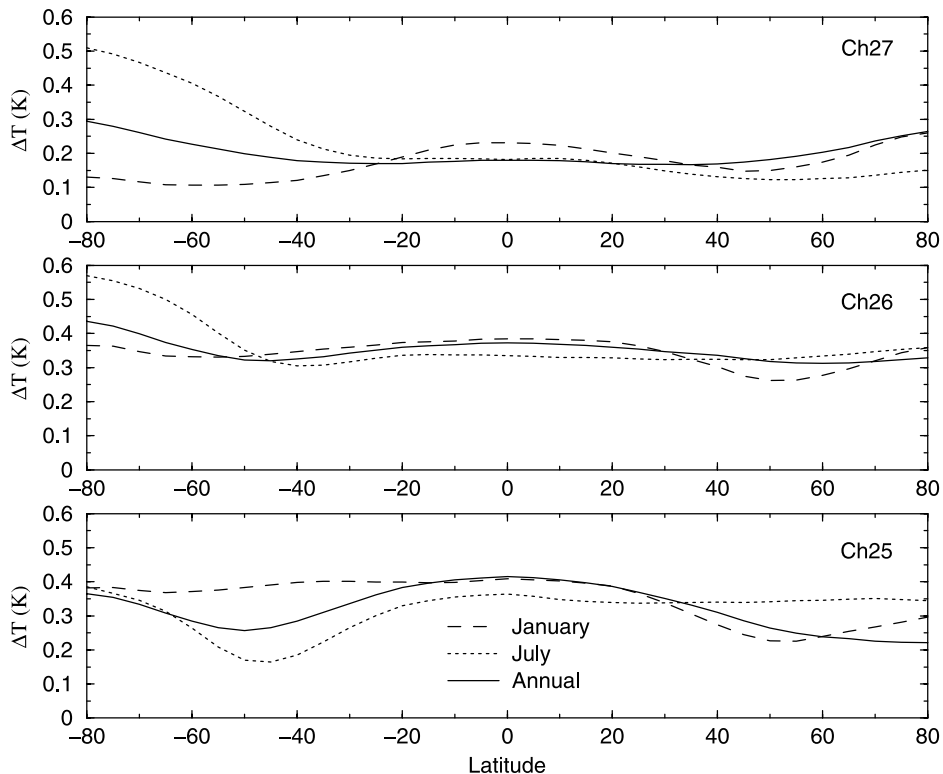
Figure 2. Apparent change in zonal-mean brightness temperature (K) due to a 20 ppmv increase in CO_2 for the near-nadir views for channels 27, 26, and 25, for January, July, and the annual mean.
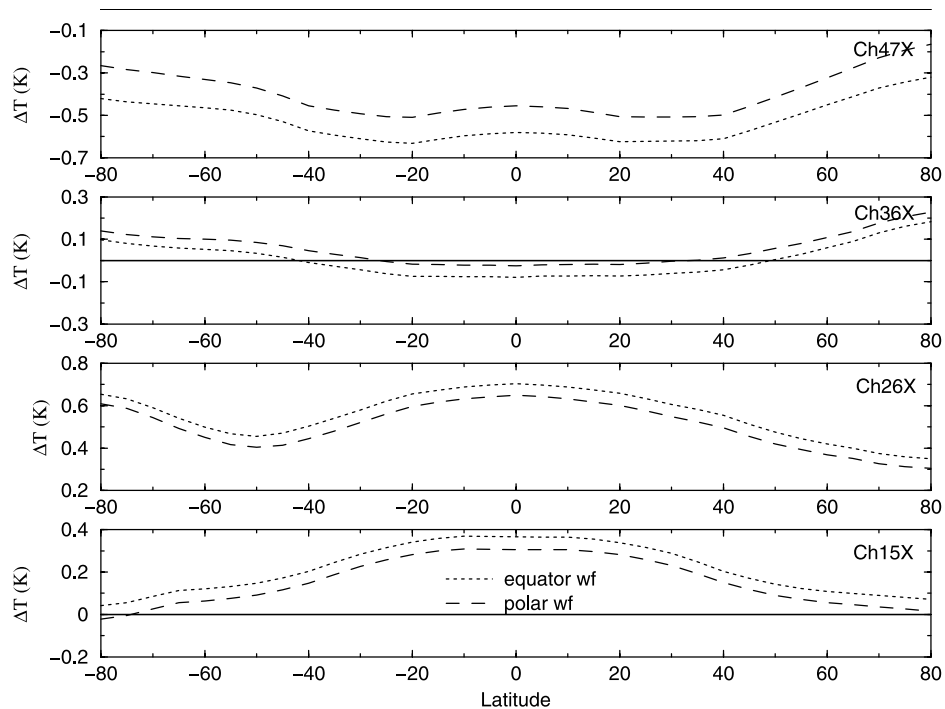
Figure 3. Apparent change in annual and zonal-mean brightness temperature (K) due to a 20 ppmv increase in CO_2 for the synthetic channels 47X, 36X, 26X, and 15X; the dotted line shows the temperature change derived by using the equatorial weighting function and the dashed line shows the change using the polar weighting function–see text for details.

about 0.19, 0.45, -0.02 and -0.43 K decade^{-1}, respectively, assuming a 15.4 ppmv decade^{-1} change in CO_2.

4. Impact on Model-Observation Comparisons

[15] The impact of the apparent trends in T_B on our understanding of stratospheric temperature trends is illustrated in Figure 4. For the X channels, the equatorial weighting function trends shown in Figure 3 are used, as these should be more applicable in an area-averaged sense. Figure 4 shows the "consensus" global-mean total stratospheric temperature trend in K decade^{-1} from the multi-model comparison presented by *Shine et al.* [2003]. It also shows the SSU trends as presented in that paper (open diamonds) and these trends (closed circles) corrected for the effect of changes in CO_2 on the weighting function. The change in CO_2 has been taken to be 15.4 ppmv decade^{-1}.

[16] The first important point to note is that the effect of the weighting function change is appreciable, when viewed in the context of the uncorrected observed trends. This is particularly so in the mid-stratosphere (Channel 26), where the correction to the trends is about the same size as the trend itself.

[17] Second, overall, the corrected trend is in better agreement with the models. This is particularly so in the mid-stratosphere; *Shine et al.* [2003] had been unable to account for the fact that the model trends were much more negative than the observed trends, but this problem has now been significantly alleviated. The corrections to channels 25, 27 and particularly 47X also lead to improved agreement between models and observations, although for all

these channels, models and observations agreed within the error bar of the uncorrected trends.

[18] For other channels the situation is not so clear. 36X is barely affected. 15X and 26X show a significantly greater negative trend; the models are now in worse agreement with the satellite observations, albeit still within the error bar of the observed trend. In any case, as noted by *Shine et al.* [2003], there is a particular uncertainty in the model temperature trends in the lower stratosphere because of the possible role of stratospheric water vapour trends in this region. *Shine et al.* [2003] showed that radiosonde data gave a much more negative trend in the lower stratosphere; while the correction to the 15X appears to alleviate this difference to some extent, *Randel and Wu* [2006] show that the sonde data in the tropics may overestimate the cooling trend by around a factor of two, because of discontinuities in the data.

5. Conclusions

[19] Although previous work had identified the possible impact of changes in CO_2 mixing ratio on the weighting functions, and hence T_B, for the SSU near-nadir observations and synthetic channels, their impact on contemporary trends has not previously been evaluated.

[20] We have shown that the changes in CO_2 lead to apparent trends in T_B ranging from about -0.4 K decade^{-1} to $+0.4$ K decade^{-1} depending on the SSU channel. Importantly, such apparent trends are significant compared to the observed trends in T_B of -0.2 to -2 K decade^{-1}. This is particularly so in the mid-stratosphere, where the apparent and measured trends (neglecting the change in
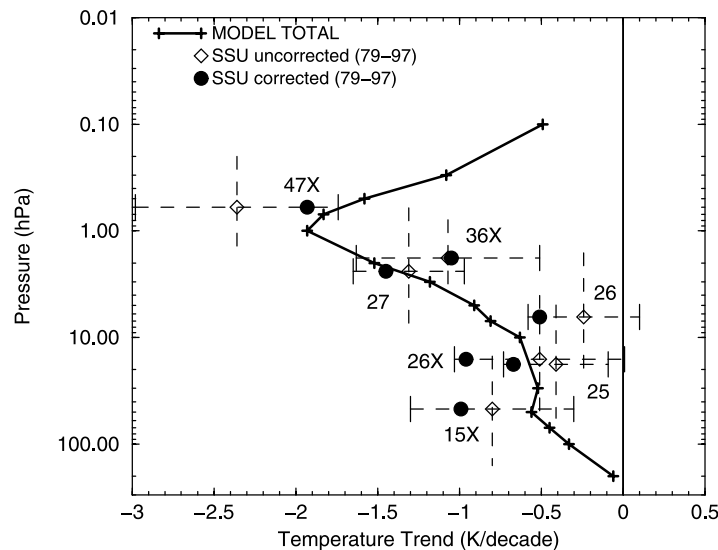
Figure 4. Global mean stratospheric temperature trend (in Kdecade^{-1}) for the period 1979–1997. The solid line shows the "consensus" model-derived total trend from a group of models [*Shine et al.*, 2003]. The open diamonds show the trends derived from SSU, as used by *Shine et al.* [2003], which are uncorrected for the effect of changes in CO_2 on the weighting function. The solid circles show the trends corrected for the change in weighting function. The horizontal lines on the open diamonds on the uncorrected trends show the 2-sigma error bars in the observed trends; the vertical lines are intended to give an approximate altitude range sensed by each channel.

weighting function) are of the same size (but opposite in sign); this indicates that after accounting for the apparent trend, the corrected trend is approximately double that indicated in earlier analyses.

[21] In general, the adjustment of the observed trends to account for the effect of the change in weighting function, leads to an improved agreement between model and observation, although this is not true at all altitudes. Of particular importance is that the discrepancy between models and observations in the mid-stratosphere has been removed via the adjustment to the observed trends.

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