9.1 INTERANNUAL AND LONG-TERM CHANGES IN MIDDLE ATMOSPHERE TEMPERATURE FROM HALOE

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1. INTRODUCTION

Radiative models of the middle atmosphere indicate that the largest temperature response due to steadily increasing amounts of atmospheric CO2 should occur at pressure-altitudes between 1 and 0.1 hPa (about 48 to 64 km) and be of the order of –0.5 to –0.6 K/decade on a pressure surface (e.g., Akmaev and Fomichev, 2000). Such a rate assumes that there is no trend in ozone or in the dissipation of wave activity for that region of the middle atmosphere. This rate of cooling is only of the order of 0.20 to 0.25% per decade, which is a small trend to discern from observations.

We have analyzed the 11-year, Version 19 (or V19) temperature versus pressure profile (or T(p)) time series from the UARS Halogen Occultation Experiment (HALOE) for such trends at selected pressure levels. The HALOE T(p) time series are being obtained using CO2 transmission data centered at 2.8 micrometers and from a single instrument that uses the limb solar occultation measurement geometry, which provides significant advantages for the calibration of its single profiles (Russell et al., 1993).

Retrieved T(p) values for the HALOE dataset have a vertical resolution of 3 to 4 km, and they are determined uniquely from the measured transmission profiles from about 5 hPa to just above the 0.01-hPa level. Remsberg et al. (2002a) reported on the good quality of the V19 T(p) for the mesosphere. HALOE adjustments have already been included at its retrieval stage for an annual increase of the CO2 mixing ratio of 1.50 ppmv per year, as recorded for the troposphere at Mauna Loa Observatory. The HALOE profiles include a merger with and an extension to lower altitudes from co-located estimates of the T(p) in the NCEP analyses and are entirely based on NCEP at and below the 5-hPa level. The retrieved NCEP T(p) profile segments also account for changes in CO2 with time.

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2. ANALYSIS APPROACH

Multiple linear regression (MLR) techniques have been applied to the HALOE time series in the manner of Remsberg et al. (2002b). Separate MLR models were generated for time series of the zonal average sunrise (SR) and sunset (SS) points for 10-degree latitude bins and at 12 pressure levels from 5 hPa to 0.01 hPa. The nature of the HALOE T(p) time series for 40N and their MLR models are given in Remsberg et al. (2002b, their Figure 1). The MLR models include semi-annual (SAO) and annual (AO) terms and, possibly, quasi-biennial (800-day), sub-biennial (688-day), and solar cycle (4015-day or SC) periodic terms. The phase of the SC term is determined by specifying its period (4015 days) and then conducting a Fourier fit of the time series residual after accounting for all the other significant, shorter-period terms. Only terms near and above the 95% confidence interval were retained for the final models.

The models also include a lag-1 autoregression (AR-1) term and perhaps a significant trend term. The AR-1 term can effectively account for a slight but systematic mismatch, for example, of a seasonal term to the data points of the time series for a particular year. The residual for each model was checked to see if it was free of any remaining correlated structure before that model was accepted. We looked for continuity of model terms at adjacent latitudes and altitudes as a further check of the results. HALOE measurements occur less frequently at latitudes poleward of about 55 degrees of both hemispheres, and their seasonal cycles are less accurate as a result. Therefore, we did not analyze for longer period and trend terms at the high latitudes.

If significant longer-period, interannual (IA) and solar cycle (SC) terms are present in the time series but have not been accounted for accurately, their effects will alter or amplify any underlying trend term. Exclusion of the AR-1 term may also have an adverse effect on derived trends. Therefore, an AR-1 term is present in every model, and we tested for significant IA and SC terms. Details of our approach to the generation of and the acceptance testing for the final models are given in Remsberg et al. (2002b).

3. RESULTS AND DISCUSSION

For brevity we limit the results in this report to a listing of the SC terms and a statement of the significant trends for the range of middle and low latitudes (40S to 40N) and for 12 pressures levels. Table 1 shows the amplitude (in K) of the 4015-day periodic terms from those models. Table 2 contains the phase of those supposed SC terms in years since the beginning of 1991, which is our estimate of the occurrence of the solar maximum for SC 22.

With the extension of the HALOE T(p) time series to 11 years we have been able to extract significant, decadal-scale periodic terms for more levels and latitudes than was the case in Remsberg et al. (2002b), although these updated SC amplitudes have not changed from what they reported by much. The SC-like term in the upper mesosphere (0.03 to 0.01 hPa) has an amplitude that ranges from 0.6 K to 1.8 K, values that are in good agreement with the modeled response of temperature to the SC variations of the solar uv-flux (Huang and Brasseur, 1993). However, there is a definite lag for the HALOE-observed SC temperature maximum of about 1 to 3 years that is more noticeable for the northern hemisphere. An SC in-phase relationship in Table 2 is indicated by a 'lag' near zero or near 11 years. The amplitude of the decadal-scale term is also somewhat greater in the northern versus the southern hemisphere, indicating that there may be an additional, underlying dynamical forcing term that is bringing about an observed temperature maximum around 1993 (see also She et al. (1998)). Part of the lag in the T(p) maximum in our time series may also be related to the fact that the uv-flux maximum for SC 22 was fairly flat and extended across the entire year of 1991, rather than peaking in January 1991.

The SC amplitude is either weak or statistically insignificant at most latitudes of the middle mesosphere, a finding that is also in good agreement with the temperature response in the model of Huang and Brasseur (1993). At northern middle latitudes of the lower mesosphere the decadal-scale term is in-phase with the SC-flux maximum. However, the amplitude of the SC term near the stratopause from HALOE is about half that expected. Finally, at 5 hPa it appears that the 11-year term is nearly out-of-phase with solar maximum and may be unrelated to the solar forcing.

A linear trend term was also fitted to the 11-year time series. That term is negative (an average cooling rate over 11 years) and significant at several latitudes and pressure-altitudes. Trends occurred in the mesosphere at 10N (-1.0 K at 0.5 hPa), at 20S (-1.0 K at 0.02 hPa and -1.3 K at 0.05 hPa and at 0.1 hPa), at 30S (-2.1 K at 0.1 hPa), and at 40S (-1.4 K at 0.03 hPa). All those trend terms were significant at or near the 95% confidence interval. Significant cooling was also found at 5 hPa at 30N (-1.7 K) and 20S (-1.5 K). On the other hand, no highly significant trend was found at any level for 40N, 20N, Equator, or 10S. For about half of the cases that exhibited a significant trend, there was also a significant decadal-scale or SC term. In those instances it is unlikely that those long-period terms are being aliased into the trend term. If one excludes the trends found at 5 hPa (which are really derived from the time series of NCEP data), then the majority of the HALOE-observed trends occur in the southern hemisphere subtropics of the middle mesosphere. The cooling is in the range of 0.9 K to 1.4 K per decade at 20S; that observed magnitude is about twice what has been found from radiative model studies of the effects of steadily increasing CO_2.

4. CONCLUDING REMARKS

Based on our findings to date, it is concluded that a significant cooling trend due to increasing greenhouse gases is being found in the lower and middle mesosphere, as predicted. There are several reasons why such a trend may be observable first in the southern hemisphere (SH) subtropics. First, it is important that the time series residual have low 'measurement and short-period, geophysical noise' after accounting for the significant periodic terms, so that one can extract a significant trend term. Tidal amplitudes are generally not so large in the subtropical mesosphere, and it is likely that tidal interactions with planetary waves will be less pronounced for the SH with its weaker wave activity. In addition, stratospheric warming events occur more regularly in the southern than in the northern hemisphere. Their late winter effects ought to be characterized better by the AO terms of the MLR models for the SH. Because the amplitudes of the periodic terms (including the SC) are generally small in the lower mesosphere, slight mismatches of those terms to the data points will impart less bias to the time series residual. An unidentified and unmodeled decadal-scale, dynamical-forcing term may be present due to the interaction of the QBO and the annual cycle, but it ought to be less of an issue for the SH subtropics because the amplitude of the QBO-term is smaller in the SH (Remsberg et al., 2002b). Time-series residuals also tend to be less noisy in the lower than the upper mesosphere because vertical temperature structure is not so enhanced (or incompletely resolved) with HALOE at the lower altitudes (Leblanc et al., 1998).

Finally, there may be unmodeled long-term changes in T(p) due to a decreasing trend in the effects of the dissipation of planetary and gravity waves once they have propagated upward through the stratosphere (Hu and Tung, 2003). Those effects should be less pronounced in the lower mesosphere, or below their 'wave-breaking region'. However, such a trend could modulate the amplitude of the SC term near the stratopause and at the same time impart an extra cooling trend within the mesosphere. It should be clear from this initial study of the HALOE temperatures that the measurement, retrieval, analysis, and interpretation of the variations in T(p) is not so straightforward even for the mesosphere--the region for which early signs of global change due to the increases in CO2 have been predicted. As the HALOE measurements continue, it is anticipated that better estimates of the decadal-scale and trend terms will be obtained.

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Table 1—Amplitude of SC Term (K)

P(hPa)	40S	30S	20S	10S	Eq	10N	20N	30N	40N
0.01	0.9	1.6	0.6	--	--	--	1.1	1.5	1.1
0.02	0.6	0.7	1.1	--	--	--	1.5	1.8	1.5
0.03	0.8	0.8	1.2	1.1	--	--	1.0	1.6	1.3
0.05	--	0.9	0.5	0.7	0.9	--	--	0.5	1.1
0.10	--	1.1	--	--	--	--	0.3	0.8	--
0.20	--	0.3	--	--	--	--	0.4	--	--
0.30	--	--	--	--	--	--	--	0.6	0.8
0.50	--	--	--	--	--	--	--	0.5	0.7
1.00	--	--	--	0.4	0.5	--	0.4	--	0.4
2.00	--	0.2	--	--	--	--	--	--	0.5
3.00	--	--	--	0.3	0.3	0.4	--	0.6	0.5
5.00	0.7	0.7	0.6	0.9	0.7	0.6	0.5	--	--

Table 2—SC Maximum (in yrs) past January 1991

P(hPa)	40S	30S	20S	10S	Eq	10N	20N	30N	40N
0.01	10.9	9.7	0.1	--	--	--	1.2	1.8	1.8
0.02	1.8	1.8	2.0	--	--	--	1.8	2.2	2.5
0.03	0.1	1.9	2.6	1.9	--	--	1.8	2.4	3.2
0.05	--	1.8	1.9	1.9	1.8	--	--	3.5	3.7
0.10	--	10.5	--	--	--	--	3.8	5.4	--
0.20	--	9.8	--	--	--	--	3.6	--	--
0.30	--	--	--	--	--	--	--	9.9	10.7
0.50	--	--	--	--	--	--	--	10.5	10.4
1.00	--	--	--	2.1	1.8	--	9.0	--	10.7
2.00	--	2.8	--	--	--	--	--	--	0.3
3.00	--	--	--	7.9	8.5	7.9	--	9.0	10.5
5.00	5.4	6.3	8.5	6.9	6.9	7.0	7.3	--	--