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An assessment of the quality of Halogen Occultation Experiment temperature profiles in the mesosphere based on comparisons with Rayleigh backscatter lidar and inflatable falling sphere measurements

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[1] Bias errors for retrieved temperature profiles $T(p)$ from the Halogen Occultation Experiment (HALOE) are evaluated by pairing with nearby soundings from ground-based Rayleigh lidar and from inflatable falling spheres. Findings for the mesosphere must be based on large sets of pairings because an individual HALOE $T(p)$ measurement is somewhat noisy and may not view the same atmospheric structure. Simulated estimates of total bias errors for the HALOE profiles are of the order of 2% (or 5 K). The average biases with the lidar profiles at 44°N, 6°E are within 3 K from 33 to 66 km and 4 K to 74 km, at least when zonal easterlies (and reduced wave activity) prevail. Tidal effects can account for most of that difference. Comparisons with shipboard lidar soundings that begin near 100 km indicate no significant bias even in the 77 to 85 km range. Similar comparisons with falling sphere profiles at Cape Canaveral and Wallops Island indicate no significant bias from 40 to 66 km and 71 to 85 km. HALOE profiles are warmer than sphere values from 67 to 70 km, but this is also the altitude region where the sphere profile has greater uncertainties. For those months when the lidar soundings indicate inversion layers the sets of profiles paired with lidar indicate that the HALOE $T(p)$ is somewhat colder in the upper mesosphere, in part owing to the effects of limb path averaging of horizontal structure by HALOE and its inability to completely resolve the inversion layer maximum. On the basis of the combined sets of findings it is concluded that most of the error in a single HALOE $T(p)$ is random, except where there is a sharp inversion. Daily zonal averages of the HALOE profiles are accurate and useful for defining the seasonal and longer-term variations of $T(p)$ in the mesosphere. *INDEX TERMS*: 0340 Atmospheric Composition and Structure: Middle atmosphere—composition and chemistry; 0350 Atmospheric Composition and Structure: Pressure, density, and temperature; *KEYWORDS*: mesospheric temperatures, Rayleigh backscatter lidar, inflatable falling sphere, HALOE temperature comparisons

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1. Introduction

[2] The Halogen Occultation Experiment (HALOE) [Russell *et al.*, 1993] on the Upper Atmosphere Research Satellite (UARS) has provided 10 years of middle atmosphere temperature versus pressure (or T(p)) profiles based on limb solar occultation transmittances from its CO₂ channel centered at 2.8 μm . The original temperature validation paper of Hervig *et al.* [1996] contains examples of the quality of those profiles for the HALOE Version 17 (V17) data set. Note that V17 was the first general public release version of the HALOE data for scientific study. Since that time, improvements have been made to the profile pressure-registration algorithm, CO₂ line parameter data, and the analyses of the HALOE measurement “lock-down position” onto the Sun’s image. These Version 19 (V19) profiles are part of the third (current) public release data set. This report describes the quality of the V19 temperatures in terms of their comparisons with profiles obtained with two standard correlative measurement techniques. Findings are focused on the mesosphere and the uppermost stratosphere.

[3] Our primary objective is to validate individual HALOE T(p) values. Many argue, however, that it is impossible to achieve that goal because of limitations for the effective coincidence of solar occultation and correlative data sets. There are inherent differences due to scan times or integration times for the respective measurements (random and short-term variations), to spatial scales for the samples (effects of gravity waves and inversions), and to time of day for the observations (tides). All three data sets resolve similar vertical scales but are representative of differing horizontal scales and timescales. Each limitation is considered when attempting to verify the known random and systematic error mechanisms for HALOE T(p). First, we have relied on ensembles of individual HALOE/correlative profile pairings. This analysis approach provides an average difference profile, reducing the effects of random measurement errors and of the rapidly varying, local-scale changes that often characterize the mesosphere. We segregated the profile ensembles according to the easterly versus westerly zonal wind regime of the upper stratosphere because strong easterlies effectively filter out the planetary waves and, to some extent, the gravity waves that propagate upward and perturb the mesosphere. We also examined the HALOE data set for its characteristic tidal effects, which can impart a bias between the HALOE/correlative pairs if the comparison data are consistently obtained at a different time of the day (e.g., nighttime for Rayleigh lidar versus sunrise or sunset for HALOE). We then focused on the standard deviation of the average differences for the set of individual profile pairs. Any significant average difference is then evaluated against known biases for the HALOE and the correlative profiles.

[4] Two well-characterized, long-term correlative data sets for middle atmospheric temperature are the ground-based Rayleigh lidar measurements at Haute-Provence Observatory (OHP) (44°N, 6°E) and at Biscarrosse (44°N, 1°W) [Keckhut *et al.*, 1993] and the rocket-based measurements with the inflatable falling sphere [Schmidlin *et al.*, 1991]. A detailed intercomparison of the lidar at Biscarrosse and the falling sphere, among other measurements, was undertaken as part of the Dynamics Adapted Network for

the Atmosphere (DYANA) campaign of January through March 1990, and the results were reported by Luebken *et al.* [1994]. In general, those comparisons were excellent between 35 and 65 km; the mean of the differences was less than ± 3 K. Between 65 and 77 km the falling sphere values were systematically lower than the Rayleigh lidar temperatures by ~ 5 K. There are significant uncertainties in the standard drag coefficients used to correct the falling sphere measurements of atmospheric density (and derived temperature) in the flow regime around Mach 1 speed near 68 km [Quiroz and Gelman, 1976; Schmidlin, 1976]. Model profile initialization errors impart top-of-profile biases to the sphere profiles, normally above the mesopause. The Rayleigh lidar temperatures have biases in the upper mesosphere due to residual background signals, profile initialization effects, and/or the presence of Mie scatterers at top of profile, but that latter effect is believed to be small. Lidar biases have also been reported from 30 km to ~ 40 km due to the presence of aerosols, transmitter/receiver misalignment, and signal-induced noise and pulse pile-up effects [Keckhut *et al.*, 1993; Singh *et al.*, 1996; LeBlanc *et al.*, 1998].

[5] Rocket (datasonde) thermistor measurements are reliable below ~ 55 km [Schmidlin, 1981]. Hervig *et al.* [1996] reported HALOE comparisons with a small set of datasondes and found good agreement for the V17 data set. However, there have not been many datasonde soundings during the 1990s. Instead, we rely on the larger, semi-continuous French lidar data sets for comparisons over the much greater altitude range of 37 to above 80 km. The present report contains HALOE V19 sunrise (SR) and sunset (SS) comparisons with sets of OHP lidar profiles for the middle and late 1990s and with a set of shipboard (R/V *Henri Poincaré*) lidar measurements above the North Atlantic in late 1991. Results from the less frequent HALOE/sphere pairings are intended for the mesosphere only. Whereas the lidar and HALOE soundings represent integrations over time or space, respectively, the sphere soundings are more like snapshots of the local mesosphere. We show pairings with six sphere profiles from Cape Canaveral (29°N, 279°E) obtained from July 1992 through April 1993 and 27 profiles from Wallops Island (38°N, 285°E) from late 1991 through early 1995.

[6] Section 2 is an update on the HALOE T(p) retrieval algorithm and the simulated uncertainties for V19. In addition, we estimate the amplitudes of the tidal variations in the HALOE data set based on its SS/SR differences with pressure-altitude. The HALOE/lidar and the HALOE/sphere comparisons are shown and evaluated in sections 3 and 4, respectively. Section 3 explains how our sets of HALOE/correlative pairings were selected and defines the profile of average differences and its standard deviation. Section 5 contains a summary discussion based on the findings.

2. HALOE Version 19 T(p) Data Set

[7] Each HALOE V19 temperature profile is the result of a complex iterative retrieval algorithm using the 2.8 μm transmittance signals, an a priori National Center for Environmental Prediction (NCEP) T(p) profile containing its recommended adjustments of 1992 and interpolated linearly

in $\log(p)$ from its analysis levels [Finger *et al.*, 1993], and an initial high-altitude profile from the Mass Spectrometer Incoherent Scatter (MSIS) model [Hedin, 1987]. Initially, the measured transmittance profile is placed on an altitude grid based on the HALOE measurements versus zenith angle, and a pressure registration is performed. That process shifts the measurement altitude grid until the error between the observed and calculated transmittance is minimized over the 29 to 40 km altitude range. This first pressure registration assumes the a priori NCEP $T(p)$ profile for the transmittance calculation. Next, the temperatures and corresponding hydrostatic pressures are retrieved from 33 to 89 km at 1.5 km spacing, extending isothermally above this. Because the transmittance model for this HALOE channel is not very accurate below ~ 34 km, the retrieved $T(p)$ profile is merged into the NCEP data from 34.5 (pure NCEP) to 43.5 km (pure HALOE retrieval). A merge was made with the MSIS model from 76.5 km (pure HALOE retrieval) to 99 km (pure MSIS) and then extended with MSIS to 150 km. Pressures are calculated for this hybrid profile using the hydrostatic assumption. The HALOE Level 1 $T(p)$ retrieval and merge process is updated after retrieval of water vapor, which is a significant interfering species for the CO_2 channel. The final pressure profile is used to register the transmittance profiles from all the other HALOE channels. In the same manner, two successive $T(p)$ retrievals are conducted anew in the Level 2 algorithm, such that the final weighting of the NCEP or MSIS profiles versus HALOE is nonlinear through their respective regions of overlap. We consider that the profiles are nearly all HALOE for the altitude range of 37.5 to 87.5 km (or ~ 4 hPa to 0.003 hPa).

[8] Each HALOE V17 temperature profile was judged accurate to 5 K up to 75 km with an effective vertical resolution of ~ 3 to 4 km [Hervig *et al.*, 1996]. At 80 km the uncertainty for a single HALOE V17 profile is 12 K owing to its random measurement error. Updated error estimates have been obtained for the HALOE V19 temperatures and include the effects of an improved pressure registration and more accurate CO_2 line parameters at $2.8 \mu\text{m}$ [Devi *et al.*, 1998]. Random uncertainties for individual HALOE V19 profiles are estimated to be <3 K below 45 km, of the order of 3 to 5 K from 45 km to 75 km, and increasing to 15 K at 80 km. Estimates of total bias error are mainly due to uncertainties for the calculated transmission model (1%) and for the pressure registration ($<2\%$) or ~ 5 K. Account was made for the increasing CO_2 with time. There may be a slight bias in the band model approximations to the CO_2 line parameters for the HALOE forward model. However, it is expected that such a bias would be apparent for the HALOE transmittances throughout a profile. The fact that HALOE $T(p)$ agrees so well with the lidar measurements below 63 km (see section 3) indicates that this error source must be small. HALOE temperatures may also be biased cold at the highest altitudes owing to the assumption of a uniform CO_2 profile for its retrieval, especially at high latitudes of the winter hemisphere where it is likely that there is descent of air of low CO_2 values into the upper mesosphere.

[9] HALOE SR minus SS differences were examined when those separate measurements occurred at nearly the same latitudes and longitudes and only a half day apart. Figure 1 shows the average results for an ensemble of 117 such March/April pairings for Northern Hemisphere middle

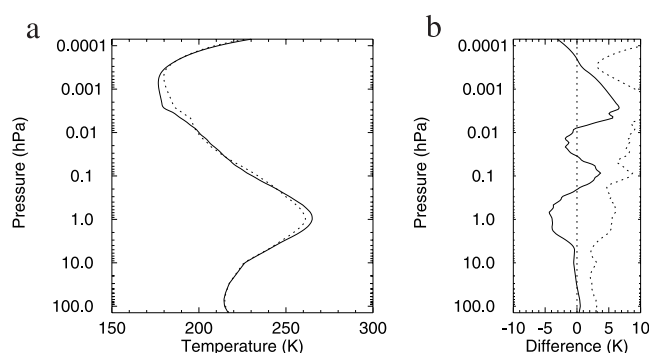


Figure 1. Halogen Occultation Experiment (HALOE) average sunrise (SR) (dotted) and sunset (SS) (solid) temperature comparisons for March/April periods at Northern Hemisphere middle latitudes when the HALOE SR/SS orbital crossovers occur ~ 12 hours apart. (a) Averages for the SR and the SS profiles; (b) Solid profile is the average of 117 paired SR minus SS differences and the dotted curve is the RMS profile for the paired differences.

latitudes obtained over a 6-year HALOE period. Figure 1a displays the average SR and SS profiles. Figure 1b contains the average profile of the SR minus SS differences for the upper stratosphere and mesosphere, plus the profile of the RMS differences. The average profile is a first-order estimate of the diurnal and, to a lesser extent, the semidiurnal temperature tides near 47°N . The effects of their combined tidal amplitudes vary between ± 6 K, and successive minima or maxima are separated by 22 to 30 km in the profile average. A similar plot for low latitudes (not shown) gives a vertical wavelength of 20 to 25 km with amplitude range of ± 7 K. The increasing RMS profile of the upper mesosphere is mainly due to the random noise of individual HALOE profiles. The kink near 0.003 hPa in Figure 1a reflects the tie-in to MSIS; differences above that level are not real and should be ignored.

[10] Remsberg *et al.* [2002] conducted separate SR and SS time series analyses for 9.5 years of HALOE temperatures at 12 pressure levels and for 10° -wide latitude zones. Figure 2 shows the SR minus SS profiles based on their separate time series averages; results are shown for 40°N , 30°N , and the tropics. The implied tidal amplitudes in the multiyear averages are somewhat smaller for 40°N and 30°N , but the phases are very similar to those of the NH middle latitudes of Figure 1. The tropical difference profile in Figure 2 is nearly out of phase with the ones at middle latitudes. These tidal-induced differences are considered when interpreting results from any HALOE comparisons with correlative measurements that have a consistent time-of-day separation with HALOE.

3. HALOE/Lidar Comparisons

[11] The Rayleigh lidar profiles are normally averages over 1 to 3 hours obtained just prior to midnight, and they have an estimated accuracy of 3 K at 80 km and 1 K at 70 km on the basis of an initial upper altitude of 90 km for their top-down retrieval [Keckhut *et al.*, 1993]. Background noise can limit the highest altitudes achieved. The character of the background noise varies seasonally and night to night and is

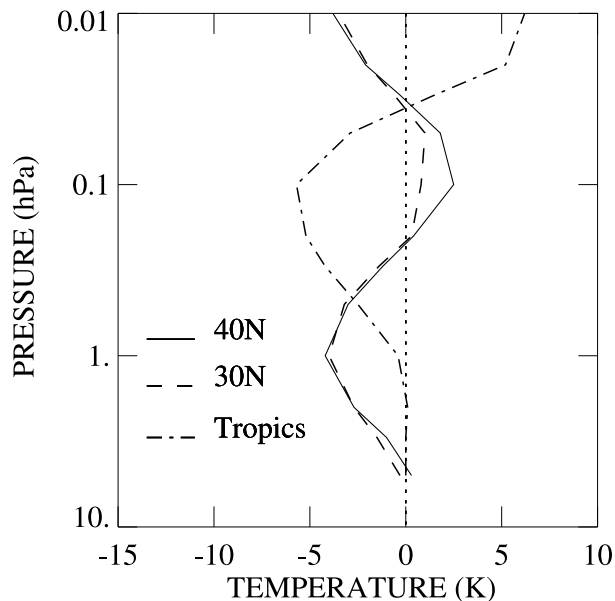


Figure 2. Average profiles of the HALOE SR minus SS temperatures (K) for the three latitude zones of 40°N, 30°N, and the tropics.

hard to diagnose [Singh *et al.*, 1996; Leblanc *et al.*, 1998]. Planetary and gravity wave-breaking effects can lead to biases in any comparison results that do not have similar spatial averaging scales for their measurements [Keckhut *et al.*, 1996]. Initially, we assume that those instances are occurring in a fairly random-like way from pair to pair. Because the profile data have an effective vertical resolution of ~ 3 km and are averages over several hours, only the profile features (often inversions) due to the effects of sustained wave-breaking activity are retained fully in the nightly lidar averages.

[12] Coincidence in time is a particularly difficult issue for comparisons with solar occultation measurements. In section 2 we estimated the effects of tidal variations for the HALOE temperatures. However, Schmidlin [1981] found that there are shorter-period variations of the order of 4 K at 55 km and 3 K at 30 to 50 km based on 45 pairs of datasonde profiles, where the time differences for a pair ranged from 5 minutes to about an hour. It is likely that those short-period differences would have been larger for the upper mesosphere. On the other hand, if those paired datasonde differences are a result of variations in the small-scale vertical structure of the atmosphere, both the lidar and the HALOE data sets will tend to average such features. It is concluded that the greatest uncertainty for an individual HALOE $T(p)$ for the mesosphere is due to its random noise, and we cannot verify any smaller-magnitude HALOE bias errors by examining individual HALOE/correlative pairs. Therefore we have relaxed our goal of excellent coincidence in favor of evaluating average differences from large sets of paired comparisons.

[13] In order to examine the role of atmospheric variations due to planetary and gravity waves on the comparisons, we consider periods when the zonal winds in the stratosphere are westerly (Figure 3) versus easterly (Figure 4). A set of HALOE/OHP lidar comparisons is shown in Figure 3 for profiles from the winter/spring periods of January 1997

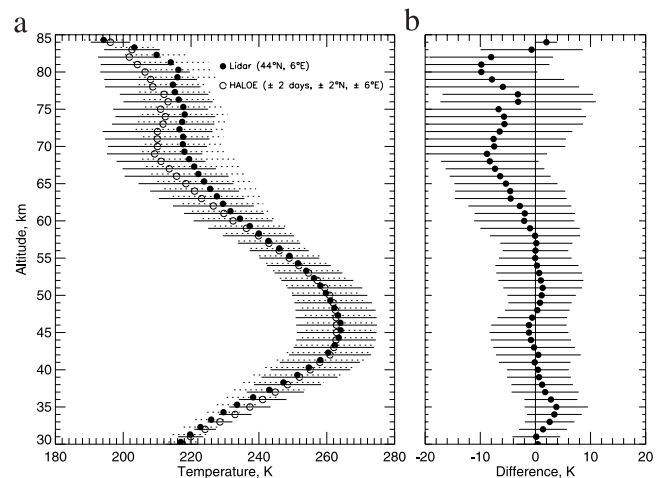


Figure 3. HALOE SR and SS versus Haute-Provence Observatory (OHP) lidar temperature comparisons for the period January 1997 through April 1999. Coincidence is within 2 days, 2° of latitude, and 6° of longitude. (a) Averages for the HALOE and the lidar profiles; horizontal lines represent the standard deviations of the profiles from their average. Profile points are offset vertically for clarity. (b) Average profile of the differences for a set of 66 paired soundings, HALOE minus lidar; horizontal lines represent the standard deviation of the paired differences about their mean value.

through April 1999. A computer search was conducted for the HALOE profiles that were colocated with the lidar soundings of those months using a fairly strict criteria of being within 2° of latitude and 6° of longitude. However, in order to obtain more than a few profile pairs, the separation in time was allowed to be up to 2 days. Many of the 38 lidar profiles were paired with two adjacent HALOE profiles, effectively reducing the effect of HALOE noise by $\sqrt{2}$ and giving a total of 66 pairs. We accessed NETCDF HALOE profiles of temperature and altitude from the HALOE

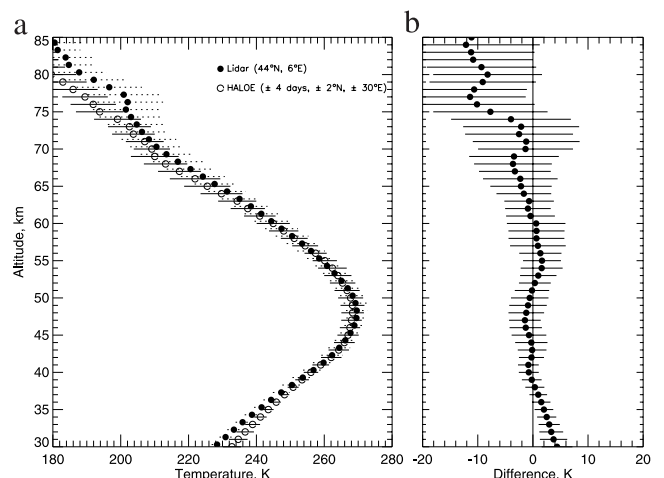


Figure 4. As in Figure 3, except for 54 profile pairs at OHP during May through August periods of 1994–1996. Coincidence criteria have been expanded to 4 days, 2° of latitude, and 30° of longitude.

website; they are the hydrostatically determined Level 2 profiles with a vertical spacing of ~ 0.5 km. The nighttime average lidar profiles are available from the Network for Detection of Stratospheric Change (NDSC) website. Both the HALOE and lidar $T(z)$ profiles were then interpolated to a common 1 km altitude grid. Both SR and SS HALOE profiles were included in this statistical sample. By combining SR and SS samples into a single set we obtained a more representative mean difference, although the standard deviations for this set of differences are somewhat larger than within the separate SR and SS comparison sets. It was also expected that wintertime inversions induced by wave effects at 44°N , 6°E would lead to much larger-amplitude temperature variability than from tides [Wilson *et al.*, 1991; Meriwether and Gardner, 2000; LeBlanc and Hauchecorne, 1997; Salby *et al.*, 2002]. Several “outlier” point pairs were screened from the comparison set near the mesopause, when their individual paired differences exceeded ± 30 K, most likely owing to the combination of wave-breaking effects, a lack of good coincidence in time, and HALOE noise effects.

[14] Statistical results were generated as follows. Figure 3a shows the average of the HALOE profiles versus the average for the lidar profiles. Horizontal bars for HALOE and lidar profiles in Figure 3a represent the standard deviations for those two data sets. Those bars are very similar in magnitude, indicating that they are recording the same intraseasonal temperature variations. Effects of the random noise and small-scale variations are effectively minimized. However, in Figure 3b we show the average of the differences (solid dots) for the individual paired profiles; the horizontal bars are the standard deviations for those paired differences, and they are rather large and increase with altitude. Deviations in the upper stratosphere and lower mesosphere are of the order of 7 K or about twice the estimated random error for HALOE at 45 km. Most likely, the observed excess is due to subpar coincidence and the effects of the winter/spring time planetary wave breaking [Sassi *et al.*, 2002]. Standard deviations for the differences in the upper mesosphere can be explained by the combined effects of the HALOE noise (5 K up to 75 km and increasing to 15 K at 80 km), the spatial smoothing of temperature structure by HALOE (see also section 5), plus a noncoincidence for the local effects of the wave dissipation.

[15] The average of the differences for the two data sets in Figure 3b is within the 1 standard deviation range at all altitudes. That average is within 3 K from 37 km to 62 km or of the order of the estimated bias error for HALOE. The good agreement over that altitude range supports the finding of no significant biases in the parameters for sets of CO_2 or H_2O lines. Karen Keppler-Albert (private communication, 2001) has recently made laboratory measurements and redetermined the line parameters for H_2O , which is a major interfering gas at $2.8 \mu\text{m}$ in the midstratosphere. A transmissivity data table was prepared for H_2O using those new parameters, but they only cause the retrieved HALOE temperatures to become colder (by up to 1 K) in the lower mesosphere.

[16] There is no HALOE/lidar bias at 30 km in Figure 3. However, HALOE temperatures are warmer than lidar by ~ 4 K at 35 km, though that difference is within 1 standard deviation. However, the HALOE temperatures below ~ 37 km are the result of a tie-in to profile segments derived from

the NCEP analyses. J. D. Wild (NOAA, private communication, 2002) also finds no clear bias at 10 hPa and about a 3-K warm bias at 5 hPa for “adjusted” NCEP profiles from NOAA 14 versus the nightly lidar soundings at the location of OHP. Thus our independent comparisons are consistent for both altitudes.

[17] From 62 to 69 km the average of the HALOE temperatures in Figure 3 is increasingly cooler than lidar with altitude by up to 9 K. Some of the individual pairs in the set show intense inversion layers in the mesosphere in both the HALOE and lidar soundings (e.g., LeBlanc and Hauchecorne [1997], their Figure 2), while the structure in other pairs clearly disagrees. Because of the localized inversion layers, we conclude that a much better collocation in time and space is required (see also Lehmacher *et al.* [2000]). The lidar measurements capture more of the inversion layer amplitude, especially when the dissipation of the wave energy is continuing and occurring at the same altitudes for over several hours [LeBlanc and Hauchecorne, 1997]. Although the HALOE $T(p)$ retrievals must be regarded as sounding “events,” they are the result of a tangent path average of several hundred kilometers. Furthermore, the retrieved HALOE profiles do not fully resolve the amplitudes of inversion layers whose vertical wavelengths are typically < 10 km; simulations of this smoothing effect were reported for the UARS Improved Stratospheric and Mesospheric Sounder (ISAMS) experiment, as well [Dudhia and Livesey, 1996, their Figure 2]. Both spatial smoothing effects will lead to a HALOE warm bias at the base of the inversion layer (between 60 and 70 km) and a cold bias at its top (some 5 to 10 km higher), primarily during wintertime at middle latitudes when inversions are more frequent and the waves break at lower altitudes. No such alternating bias signature is apparent in Figure 3, indicating that inversions are not so frequent or persistent in this set. However, part of the cold bias for HALOE versus lidar at these altitudes could still be because HALOE underestimates the peak of any temperature inversion. It is also possible that there is an overall warm bias in the lidar results in the upper mesosphere due to residual background noise and/or top of profile initialization effects from MSIS during winter [LeBlanc *et al.*, 1998; Rapp *et al.*, 2001].

[18] During summer the stratospheric and lower mesospheric winds are easterly at 44°N , inhibiting the propagation of planetary waves, and the generation of mountain-induced gravity waves is reduced [Salby *et al.*, 2002]. Thus the frequency and amplitude of inversion layers at 44°N is reduced considerably, and they tend to occur 5 to 10 km higher in summer than in winter [Hauchecorne *et al.*, 1987]. It is expected that comparisons for summer should be more repeatable and indicative of any biases. However, there are fewer HALOE measurements near 44°N for summer than the other seasons. Furthermore, the UARS solar array was in a fixed position beginning in May 1997, leading to power constraints for HALOE for a longer period around each UARS yaw event. As a result, HALOE obtained even fewer measurements near 44°N for the summer seasons of 1997 onward. Therefore a second set of pairings was obtained for the months of May through August of 1994–1996; improvements had also been made to the alignment of the OHP transmitter/receiver by 23 August 1994. In order to obtain a significant number of pairings, we expanded our

colocation criteria to be within 30° of longitude and 4 days in time. Because planetary wave amplitudes are small during summer, this relaxation of the term “coincidence” does not add much to the effects of the noise in the HALOE profiles.

[19] Results for this second set of 54 pairs are shown in Figure 4. The summertime temperature variations for the stratosphere in Figure 4a are much less than in Figure 3, and the standard deviations for the pairings in Figure 4b are only of the order of 3 K in the upper stratosphere. The effects of noise in the HALOE temperatures can explain all of the increase of the paired standard deviations with altitude. The agreement for the average of the paired differences (dots in Figure 4b) is within 3 K from 33 to 66 km and within 4 K up to 74 km. The average HALOE and lidar profiles still diverge above 75 km, although at slightly different rates for the SS versus SR comparisons (not shown). Tidal effects can account for half of that HALOE/lidar difference. For example, a cold bias for HALOE versus lidar in the upper mesosphere is consistent with the tidal models of *Zhu et al.* [1999], which show midlatitude maxima in both the diurnal and semidiurnal tides occurring at night. The warm bump in the average lidar profile (Figure 4a) above 75 km would correspond with the tides but may be a result of other factors too. The overall good comparison in Figure 4 for most of the mesosphere indicates that the average HALOE results are accurate and that the larger HALOE/lidar differences in Figure 3 are most likely due to poor coincidence during wintertime and an inability of HALOE to fully resolve the amplitude of mesospheric inversion layers.

[20] There is a significant temperature bias at 30 km in Figure 4, where the HALOE profile segment is based on the NCEP analyses. We have determined that the bias does not change appreciably when we (1) tighten the coincidence criteria or (2) eliminate the pairs for the lidar data before 23 August 1994, prior to upgrades for the OHP system. However, independent comparisons between the NCEP analyses for 10 hPa and the lidar soundings at OHP indicate a warm bias for NCEP of ~ 3 K and then 2 K, respectively, during the mid 1990s when NOAA 11 and then NOAA 14 was operating (J. D. Wild, NOAA, private communication, 2002). There are also warm biases for NCEP versus lidar at 5 hPa, perhaps partly owing to tides. As for Figure 3, there is consistency between these two independent analyses of the NCEP/lidar bias.

[21] In late 1991, lidar soundings were conducted from the ship R/V *Henri Poincare* in the North Atlantic (41°N to 48°N). This particular lidar provided better performance and S/N at high altitudes. The lidar profiles extend up to ~ 100 km, with bias errors throughout the mesosphere that are potentially smaller than those for the OHP lidar [*Keckhut et al.*, 1993]. Though for an autumn period, the coincidence criteria were relaxed to that for the summertime comparisons of Figure 4. HALOE profiles were paired with 12 separate lidar soundings, and the results of the 51 pairs are shown in Figure 5. Biases are not significant at any level. The average differences are similar to those of Figures 3 and 4 except that they are absent at 78 km and above, which is above the region where inversion layers due to wintertime wave breaking tend to occur. The lack of a clear bias at this upper altitude also suggests that the corrections for the

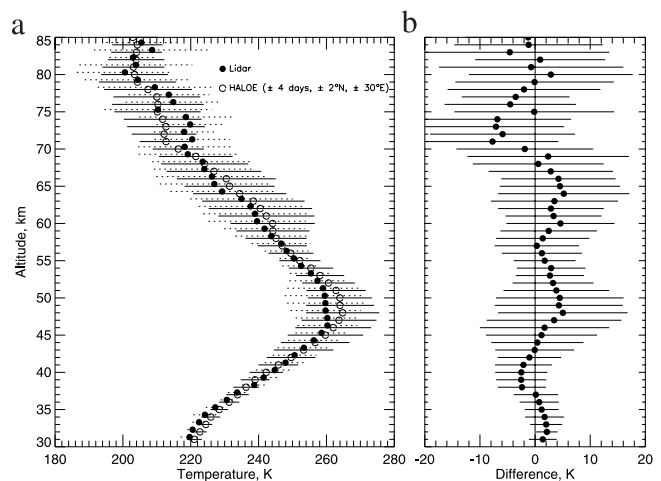


Figure 5. As in Figure 3, except for 51 HALOE/lidar profiles near the location of the R/V *Henri Poincare* lidar in the North Atlantic in late 1991. Coincidence criteria have been expanded according to those of Figure 4.

background signals are accurate for this high-performance lidar and that its top-of-profile error effects are limited to above 85 km. The slight cold bias for HALOE versus lidar from 71 to 77 km may be due to a spatial smoothing by HALOE of the full amplitude of wintertime inversion layers. We infer from Figure 5 that the HALOE temperatures have little bias even up to 85 km.

[22] Individual HALOE comparisons (not shown) were also performed against the lidar measurements of *McGee et al.* [1995] at OHP in 1992 and at Mauna Loa Observatory (19°N) in Hawaii for 1995, and the quality of those results is also good from 38 km to about 65 km. The HALOE temperatures are typically colder than the lidar values at ~ 70 km and higher, and that finding holds for both the SS and the SR comparisons. However, there were many fewer comparison profile pairs in the set, particularly at 19°N , because the HALOE occultations seldom meet our liberal coincidence criteria at tropical latitudes.

[23] At this point we note that there is no evidence in Figures 3–5 for the 3–5 K cold bias that was mentioned for the HALOE Version 17 (V17) profiles between 35 and 50 km [*Hervig et al.*, 1996]. We checked the HALOE V19 temperature comparisons versus the same small set of correlative datasonde and lidar soundings that were used to evaluate the quality of the V17 results, and we found that there is essentially no V19 bias in that altitude range for the SS comparisons and a HALOE cold bias for only half of the SR comparisons, apparently owing to tidal effects. Several of the comparisons in our standard set occurred very early in the HALOE mission when the procedure for locking onto the image of the solar disk was still being optimized, particularly for SR. In addition, the lidar profiles may have been biased in the middle stratosphere at that time by the scattering effects from the volcanic aerosols. The slight discontinuity in the HALOE V17 profiles near 60 km reported by *Hervig et al.* [1996] was also eliminated for V19 by maintaining the same effective vertical resolution of 3–4 km over the entire HALOE profile. The V17 algorithm smoothed over five rather than three 1.5-km layers for altitudes at and above 60

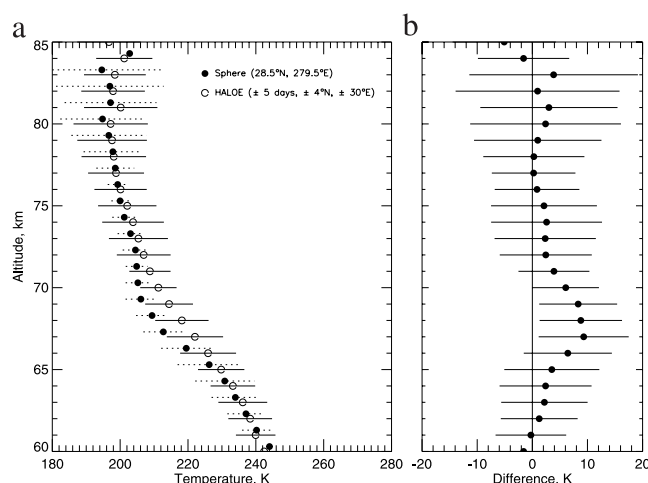


Figure 6. Comparison of HALOE SR and SS and inflatable falling sphere profiles for Cape Canaveral for 1992–1993. Coincidence criteria are 5 days, 4° of latitude, and 30° of longitude. (a) Averages for the HALOE and the sphere profiles; horizontal lines are as defined in Figure 3. (b) Average of the 25 paired differences, HALOE minus sphere; horizontal lines represent the standard deviation of the differences about their mean value.

km, which led to an effective lower resolution for V17 in the middle and upper mesosphere.

4. HALOE/Falling Sphere Comparisons

[24] Falling sphere temperature profiles have been obtained occasionally at Cape Canaveral (28°N) and more regularly at the Wallops Flight Facility (38°N) in the 1990s, and they have been used as correlative measurements for $T(p)$ from several instruments aboard the space shuttle and on the UARS satellite. Good coincidence in time was not achieved for HALOE in most cases, however. As with the lidar comparisons, the primary uncertainty in the mesosphere for the individual paired comparisons is the effect of the noise in the HALOE $T(p)$. Therefore we evaluated bias errors for HALOE using sets of profile pairs, and we applied liberal HALOE/sphere collocation criteria of within 5 days, 4° of latitude, and 30° of longitude. Average separation time for a pair at Cape Canaveral is 2.7 days, for example. HALOE/sphere differences due to temperature tides should be within ± 5 K at 28°N and 38°N , according to Figures 1 and 2 and the calculations of Zhu *et al.* [1999]. Dudhia *et al.* [1993] determined that the zonal average tidal amplitudes are no greater than 3 K in the mesosphere from 25°N to 40°N , at least for wintertime. We did not partition our small samples of HALOE/sphere comparisons by the zonal wind regime. In addition, it was presumed that gravity wave effects due to air flow over mountains and strong frontal boundaries are much reduced for these two sites versus the OHP site.

[25] More than one HALOE profile was paired with a given sphere profile. At Cape Canaveral the six sphere profiles are from 23 July, 5 and 12 August, and 20 October of 1992 and from 22 January and 6 April of 1993. Vertical interpolations of the separate profiles were made to a 1-km

grid and the paired differences were determined. Figure 6 shows the average and the standard deviation of the differences for the 25 HALOE/sphere pairings. The inference of temperature for the falling sphere technique should be free of bias, except near its top of profile, if the local atmosphere is in hydrostatic balance. Also, Schmidlin *et al.* [1991] reported slight inaccuracies below 60 km due to vertical motions that affect the sphere fall rate. Our comparisons are nearly equally divided between SR and SS pairings. The standard deviations of the differences in Figure 6b are of order 7 K in the midmesosphere owing to HALOE noise and because the sphere soundings do not involve any spatial averaging across horizontal scales. The average of the differences is near zero at 60 km and 80 km. HALOE temperatures are significantly warmer than the sphere values by up to 10 K from 67 to 70 km. A small part of this bias is expected because five of the six sphere measurements were obtained in the afternoon when the tidal amplitudes at those altitudes should be at their coldest value [Zhu *et al.*, 1999; Dudhia *et al.*, 1993]. A larger part may be because of a cold bias for the sphere temperatures near that altitude as a result of uncertainties in the standard drag coefficients near Mach 1 [e.g., Luebken *et al.*, 1994]. Note that the average HALOE profile in Figure 6a exhibits a fairly steady lapse rate through this altitude region. The ISAMS comparisons of Dudhia and Livesey [1996] with five falling sphere measurements from Cape Canaveral showed agreement to within 2 K at the 0.1-hPa (64 km) and 0.01-hPa (80 km) levels, but the ISAMS temperatures were also warmer by ~ 10 K at 0.05 hPa (70 km). Because the ISAMS comparisons were based on coincidences within ± 6 hours, their findings are more indicative of a bias near 70 km in the inferred $T(p)$ for the falling sphere measurements.

[26] We also obtained 109 HALOE/sphere pairings at the Wallops Flight Facility (WFF) location (38°N , 285°E). A total of 27 sphere soundings were used for the late 1991 through early 1995 period. Figure 7 contains the results, and

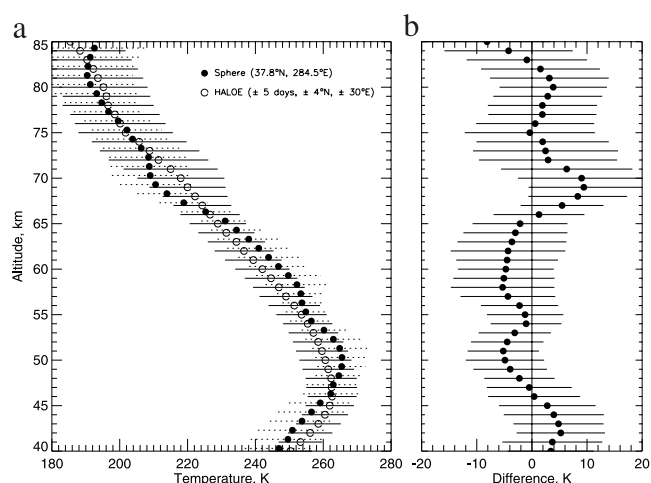


Figure 7. As in Figure 6, except for 109 profile pairs at the Wallops Flight Facility (WFF) location and from December 1991 through February 1995. Average sphere profile points are the solid circles; HALOE are the open circles. The average of the paired differences are the HALOE minus sphere values.

the average of the differences is within their 1 standard deviation value at all altitudes. The average difference profile varies with altitude but is within ~ 5 K from 40 to 66 km and 72 to 83 km. There also seems to be structure in the average sphere profile at 55 km that is not in the combined SS/SR HALOE average. Most of the WFF sphere soundings were made during late morning. Sets of HALOE SR and SS comparisons (not shown) with the WFF spheres indicate that those separate average difference profiles show some change owing to the effects of temperature tides from ~ 45 to 66 km and above 72 km. However, the apparent HALOE warm bias (or sphere cold bias) of up to 10 K near 69 km in Figure 7 was present for both the SR (66 pairs) and the SS (43 pairs) cases.

[27] Falling sphere profiles from WFF have also been compared with and reported by *Lehmacher et al.* [2000] for limb sounding determinations of temperature from the shuttle-deployed Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA) experiment of August 1997, and those coincidences were within minutes and only 33 km apart horizontally. Therefore poor coincidence cannot explain much of any difference. Even so, CRISTA versus sphere differences were present from 66 to 72 km and of similar sign and magnitude to those of our Figures 6 and 7. Because the sphere profiles do not seem to be free of bias in the Mach 1 flow regime and because the HALOE/lidar comparisons do not show the same anomaly, we conclude that the HALOE profiles are experiencing no reduction in accuracy at that altitude.

5. Summary and Concluding Remarks

[28] The validation of individual satellite temperature profiles in the mesosphere using correlative measurements is difficult at best because of the considerable structure and variability that exists at those altitudes, particularly when planetary and gravity wave breaking is occurring. Individual HALOE temperature profiles in the mesosphere are noisy and tend to mask potential bias errors. A different spatial scale for the satellite versus the correlative measurements is a problem also. These circumstances underscore the need to assemble sets of comparisons in order to judge whether any biases are present. The current HALOE Version 19 data set is improved over previous versions in several minor but important ways, and this report is an update of the first HALOE validation study of $T(p)$ by *Hervig et al.* [1996]. The present study is focused on the mesosphere. We examined sets of paired comparisons of HALOE/lidar and of HALOE/sphere soundings. In order to reduce the effects of tides in the average HALOE result, we included pairings with HALOE SR and SS measurements in each set.

[29] In the absence of pronounced atmospheric temperature structure the accuracy of individual HALOE profiles is dominated by and may be explained by its noise effects. The average of the paired differences should be zero in that case, which is essentially what we found in Figure 4. The mean bias for the paired differences with the OHP lidar is within 3 K from 33 to 66 km and within 4 K to 74 km when the zonal easterlies prevent the vertical propagation of significant wave activity to the mesosphere. This amount of apparent bias is not significant and may be accounted for by the known tidal effects. Further, it is within the envelope

of estimated systematic error effects for the HALOE $T(p)$. The comparisons with soundings from the high-performance lidar indicate no apparent HALOE bias even from 77 to 85 km. Comparisons during the winter/spring seasons (when zonal westerlies prevail) indicate that the HALOE profiles are often colder than those from lidar in the upper mesosphere. Possible explanations include a lack of good coincidence and the prospect that the HALOE measurement and retrieval cannot respond to all of the temperature amplitude of mesospheric inversion layers of rather short scale height.

[30] The HALOE comparisons with the falling spheres do not reveal a significant bias from 71 to 85 km or below 67 km. From 67 to 70 km the HALOE profile is warmer than the sphere by up to 10 K. Most of that difference may be due to the larger uncertainties for $T(p)$ from the sphere measurements in the Mach 1 flow regime, which occurs in this same altitude region.

[31] It is concluded that the HALOE V19 temperature distributions have little to no bias and that single HALOE profiles are accurate to within their estimated total (random plus systematic) error from 37 km to at least 80 km. This finding also implies that the pressure registration of the HALOE constituent profiles is accurate. Exceptions would be near and above the high-latitude mesopause (1) in summer where polar mesospheric clouds (PMC) impart unknown levels of interfering extinction to the transmittance and (2) in winter where the CO_2 mixing ratio profile is decreasing. In the latter case the HALOE temperatures will be biased cold because a uniform CO_2 mixing ratio profile is assumed in the HALOE retrieval of $T(p)$.

[32] The ability of HALOE to resolve mesospheric inversions is similar to the findings reported for the UARS ISAMS experiment [*Dudhia and Livesey*, 1996]. Both the HALOE and ISAMS measurement approach and retrieval tend to underestimate the maximum of the temperature inversion, which can contribute to the apparent cold bias for HALOE versus lidar for the upper mesosphere at OHP in winter and at low latitudes after equinox [*LeBlanc and Hauchecorne*, 1997]. The ISAMS algorithm uses an optimal estimation approach that is weighted toward its a priori profile at high altitudes where its measurements are noisy, while the HALOE algorithm yields temperatures that are not weighted by its initial guess until its tie-in to MSIS. The effect of noise on the HALOE $T(p)$ profile is secondary to not being able to fully resolve atmospheric structure. This conclusion is supported by the fact that the HALOE $T(p)$ profiles decrease smoothly with altitude for midlatitudes of the summer mesosphere.

[33] Similarly, the individual HALOE temperature profiles will not contain all of the tidal structure. Observed tidal amplitudes are affected by the descent of the semiannual oscillation in the mesospheric zonal winds at low latitudes [*Garcia et al.*, 1997]. Equatorial diurnal and semidiurnal tides reinforce at some mesospheric altitudes and have their largest combined amplitude just after equinox [*Zhu et al.*, 1999; *LeBlanc and Hauchecorne*, 1997]. Because HALOE underestimates the tidal-induced inversion maximum, the calculated pressure thickness of the corresponding atmospheric layer is reduced. This consequence leads to an overestimate of the retrieved mixing ratio of a HALOE species for that same layer. The effect should be most

notable for nitric oxide because of its steep vertical mixing ratio gradient and for water vapor because of its nonlinear dependence on changes in its transmittance profile. For example, a 5 K negative bias in HALOE temperature for a 10-km-thick layer leads to a 10 to 15% excess in retrieved water vapor and may explain the anomalously high SR water vapor values near the equator and 70 km of early May and November. Mixing ratios just below that layer would be artificially lowered in compensation, which may contribute to observed equatorial minima in HALOE water vapor near 60 to 65 km that are more pronounced for SR than SS. Further simulation studies are required to fully characterize these effects for HALOE and is outside the scope of this paper.

[34] Daily zonally averaged HALOE temperatures will have random errors that are reduced by \sqrt{N} , where N is the number of SR or SS profiles. Remsberg et al. [2002] determined the seasonal and longer-period variations in middle atmosphere temperature from a 9.5-year time series of zonally averaged HALOE data, at least for the low and middle latitudes where its seasonal sampling is adequate each year. According to the comparisons herein, it is judged that the mean and seasonal terms that they provided for the mesospheric and the upper stratospheric $T(p)$ climatology are accurate and representative of the decade of the 1990s.

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