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Overview of UARS ozone validation based primarily on intercomparisons among UARS and Stratospheric Aerosol and Gas Experiment II measurements

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Abstract. Comparisons among Stratospheric Aerosol and Gas Experiment (SAGE) II, microwave limb sounder (MLS) (version 3), cryogenic limb array etalon spectrometer (CLAES) (version 7), improved stratospheric and mesospheric sounder (ISAMS) (version 10), and Halogen Occultation Experiment (HALOE) (version 17) ozone profiles are reported with the emphasis being on the periods of January 9–11, April 15–20, and August 25–30, 1992, which were selected for analysis at four UARS validation workshops. The differences with respect to SAGE II are consistent with the conclusions of those workshops. MLS values are found to be systematically approximately 5% larger than SAGE II values except at 1 mbar (where they are approximately 5% smaller) and at 46 mbar in the tropics where they are approximately 20% too small (perhaps with some time dependence to this difference). HALOE values are systematically approximately 5% lower than SAGE II values, with a tendency for this difference to increase slightly in the upper part of the altitude range. CLAES values are approximately 15% high near 4.6 mbar and at 46 mbar in the tropics and are approximately 20% low near 0.32 mbar but show small differences near 1 and 10 mbar. ISAMS produced considerably more variable differences with respect to the other sensors both in space and in time. There remains clear evidence of Pinatubo aerosol contamination of ISAMS values at 10 mbar (the lowest level of the v10 retrievals) in January. The standard deviations of the differences between the coincidentally measured ozone profiles are generally consistent with the prescribed profile error bars of better than 5% from approximately 46 to 0.46 mbar for HALOE and from 1.5 to 15 mbar for MLS (and to approximately 0.46 mbar for the 183-GHz measurements). For ISAMS also, the error bars of 10–15% are consistent with the standard deviations of the differences, but for CLAES, the precision seems to be approximately 10% and would be approximately 20% if the relatively systematic, vertical structure differences were to be included in the error bars.

1. Introduction

The Upper Atmosphere Research Satellite (UARS) was launched into a 58° inclined orbit in September 1991; it has provided a wealth of data on a wide array of atmospheric trace species since that time. An important goal of the measurements is to provide a database for understanding dynamical/chemical interactions important to the assessment of changes in stratospheric ozone, such as ClO-induced ozone changes in the Antarctic vortex. Four of the UARS instruments measure ozone; the validation of these ozone measurements has been reported on and documented at several UARS workshops (the last two workshop reports are being published as NASA reports [see *Grose and Gille*, 1995a, b]. The ozone validation for the individual instruments are reported separately in this special issue of the *Journal of Geophysical Research*. This paper provides an intercomparison between the ozone measurements by the UARS instruments based particularly upon the validation workshop which was held at NASA Langley Research Center from September 19 to 22, 1994 [*Grose and Gille*, 1995b], and supported by comparisons against coincident Stratospheric Aerosol and Gas Experiment (SAGE) II ozone measurements.

During the validation activities the UARS ozone measurements have been compared against measurements by SAGE II, ozone lidars, the ground-based microwave instrument at Table Mountain Observatory, ozonesondes, larger balloon measurements (e.g., the ultraviolet measurements by J. Margitan), and SBUV/2 and TOMS measurements in 1992 and 1993. The comparisons have emphasized January 9–11, April 15–20, August 8–11, and August 25–28, 1992. Some time series comparisons have also been made versus SAGE II, the ground-based microwave, ozonesondes [e.g., *Froidevaux et al.*, this issue] and SBUV/2. All four UARS instruments are now providing retrieved ozone values which agree with each other and with the correlative measurements within approximately 10% over much of the stratosphere. The overall agreement is better for some instruments than others, but this degree of agreement is reasonably satisfactory considering that the correlative measurements, when intercomparisons are possible, exhibit differences up to approximately 10%. The comparisons, however, reveal a generally consistent picture of where and under what

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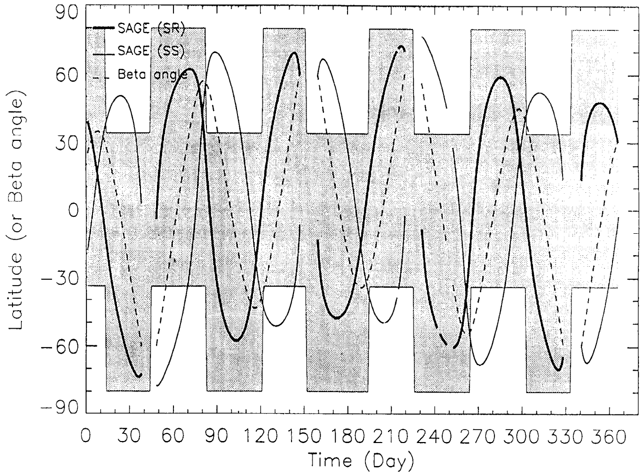


Figure 1. Time series of latitude locations of SAGE II sunrises (thick line) and sunsets (thin line) and the latitudinal coverage of MLS and CLAES (and sometimes ISAMS) ozone measurements in 1992. The β angles of the SAGE measurements are also indicated by a dashed line.

conditions there are limitations in the current UARS ozone data set.

In this paper, comparisons against SAGE II ozone measurements during the selected validation periods are discussed together with intercomparisons between the UARS ozone measurements. The results illustrate and support the conclusions of the UARS ozone validation workshop and of the ozone validation papers in this special issue [*Froidevaux et al.*, this issue; *Connor et al.*, this issue; *Bailey et al.*, this issue; *Bruhl et al.*, this issue; *Ricaud et al.*, this issue].

2. SAGE II Measurements

SAGE II was launched in October 1984 into an orbit inclined at 58° to the ecliptic. It has been taking measurements routinely since that time. Atmospheric trace gas (and aerosol) profiles are measured close to times of spacecraft sunrise and sunset (at ground sunrise and sunset) as the SAGE II telescope views the Sun through the atmosphere (i.e., during solar occultation). Two sets of constituent profiles are thus obtained per satellite orbit, a local (ground) sunrise and one (ground) sunset. Figure 1 shows the latitudes of SAGE II sunrise and sunset measurements in 1992 and the latitudinal coverage provided by several of the UARS instruments in that year. Beta angles (the angle between the orbit plane and the Sun) for the SAGE II measurements are also shown in Figure 1, because not only are SAGE II measurements inaccurate and not reported at beta angles greater than 60° but also, following such periods, there is evidence that SAGE II ozone values are biased at altitudes above roughly 5 mbar until the beta angle decreases to approximately 45° [*Wang*, 1994].

In the SAGE II measurements the trace gas concentrations are inferred by ratioing the measured solar radiation through the atmosphere to that measured outside the atmosphere. The error bars (precision) on retrieved profiles are also estimated separately for each profile based on individual profiles being made up of approximately six scans of the Sun for each altitude on the profile. The precision of an individual SAGE II ozone profile between 24 and 48 km, at 1 km resolution, is better than 7% and if the resolution is reduced to 5 km, this improves to 5% or better [*Cunnold et al.*, 1989]. Above approximately 1 mbar or 48 km the SAGE II profiles are vertically smoothed over 5 km. The systematic uncertainty of the SAGE II ozone profiles is believed to be approximately 6% but with an additional 4% uncertainty introduced at lower altitudes by the presence of aerosols under typical (background) loading conditions [*Cunnold et al.*, 1989].

In performing comparisons of measured profiles against those from the UARS instruments, it is necessary to relate SAGE altitudes to pressures. UARS pressure level i is defined as equal to 1000 $10^{-i/6}$ mbar (for example, 100, 68.1, 46.4, 31.6, 21.5, and 14.7 mbar are UARS levels). This conversion is performed for the SAGE II data using the individual profile National Weather Service (NWS) temperature data which also provide hydrostatically derived altitudes. The SAGE II mixing ratios are first interpolated to pressure levels differing by a factor of $10^{-1/18}$ in pressure which is approximately equivalent to the 1-km altitude resolution of the SAGE measurements. Three of these "sub-UARS layers" then make up a "UARS layer" for which the end point pressures differ by $10^{-1/6}$. The average SAGE II mixing ratio in the UARS layer is then calculated in such a way that the columnar ozone is conserved and the ozone column contribution from an individual UARS layer is just the sum of the three sublayer contributions. Thus SAGE II ozone profiles are being degraded to the UARS layer resolution using

$$\bar{\chi}_j = \frac{\sum_{i=1}^{3} \chi_i \Delta p_i}{\sum_{i=1}^{3} \Delta p_i}$$

where Δp_i is the pressure difference between the boundaries of the sub-UARS layers and χ_i is the mixing ratio in the sub-UARS layer.

An uncertainty in the SAGE II ozone data in the lower stratosphere results from the need to separate the ozone contribution at 0.6 μm from the aerosol contribution. These two contributions are approximately equal under typical aerosol conditions [e.g., *Chu et al.*, 1989]. During the UARS mission, stratospheric aerosol concentrations were exceptionally high because of the Mount Pinatubo eruption, and there is strong evidence that SAGE II ozone profiles are being positively biased by aerosol contamination [*Cunnold et al.*, this issue].

3. UARS Ozone Retrievals

The UARS ozone retrievals are still being improved. The comparisons and validation activities reported on here are based on version 3 microwave limb sounder (MLS) retrievals, version 7 cryogenic limb array etalon spectrometer (CLAES) retrievals, version 10 improved stratospheric and mesospheric sounder (ISAMS) retrievals, and version 17 (or version 16) Halogen Occultation Experiment (HALOE) retrievals. Both the 205-GHz (supposedly the more accurate channel) and the 183-GHz MLS retrievals are discussed. However, only the preferred (blocker 9) retrievals from CLAES are included. The vertical resolution of the CLAES and ISAMS profiles (at levels 3 in the stratosphere) is one UARS layer (approximately 2.5 km), but HALOE level 2 data possesses better vertical resolution. The version 3 MLS profiles possess a resolution of two

UARS layers with the intermediate layer values in the retrievals being given simply as an average of the values above and below [*Froidevaux et al.*, this issue]. The intermediate layer MLS version 3 ozone values are therefore of little scientific value and they have been included in the comparisons only because they are present on the level 3 files which are generally available to the user community. Above 1 mbar, only nighttime ozone profiles are reported for ISAMS because of concerns about nonlocal thermodynamic equilibrium effects during the daytime [*Connor et al.*, this issue].

All the UARS ozone sensors except MLS are affected by the large aerosol concentrations resulting from the Pinatubo eruption. The interference, however, is broadband and it appears that the HALOE and CLAES retrieval algorithms have been largely successful in removing the effects. On the other hand, the ISAMS (version 10) retrievals remain affected where the aerosol concentrations were particularly high because of their effects on the temperature retrievals and thereby on the ozone retrievals. Accordingly (version 10) ISAMS ozone retrievals are only reported at pressures less than or equal to 10 mbar.

Several of the UARS retrieval algorithms, especially the MLS and the ISAMS, utilize a mix of both measurement and a priori information. The data user should therefore be aware that portions of the retrieved profiles may contain little measurement information. In the case of MLS and ISAMS regions where the a priori contribute more than 25% of the retrieved mixing ratios are indicated by negative error bars (e.g., generally above 0.46 mbar for the MLS 205-GHz channel and above 0.2 mbar for ISAMS). In regions where the a priori provides an important constraint on the profiles, standard deviations of differences between such UARS profiles will generally be less than what is implied by the error bars. This will also be true if profile smoothing constraints are not adequately reflected in the error bars. The MLS and CLAES error bars contain contributions from systematic errors but the HALOE and ISAMS error bars do not.

4. UARS Comparisons Against SAGE II During Validation Periods

SAGE II measurements have been compared against UARS measurements during UARS team-selected validation periods based on a coincidence criteria of 12 hours in time, 2° in latitude, and 14° in longitude. There were no HALOE comparisons against SAGE II during these periods which satisfied these coincidence criteria.

SAGE II ozone profiles have thus been compared against coincident measurements by MLS, CLAES (blocker 9), and ISAMS over the periods January 9–11, 1992 (45 UARS profiles between 5°S and 10°N and 45 UARS profiles between 21° and 34°N), April 15–17 (42 profiles between 22° and 36°N and 42 profiles between 53° and 58°S), and April 18–20 (45 UARS profiles between 5° and 22°N and 44 UARS profiles between 53° and 45°S). Comparisons were also made for August 25–28, 1992 (56 MLS profiles between 44° and 53°S), but CLAES data were not available for August 27 and ISAMS was no longer operating. The time differences between the SAGE II and the UARS measurements varied between 0 and 7 hours (averaging 3 hours) and the spatial collocation differences varied within each comparison period over the range 0° to 14° longitude (averaging ~7°) and 0° to 2° in latitude (average ~1°). Data were only utilized if the error bars at the individual levels being compared were each less than 50% of the measured ozone mixing ratios. As a result of the diurnal cycle in ozone, the most appropriate comparison between UARS and SAGE II measurements between 1 and 0.32 mbar occurs for nighttime UARS measurements. Therefore only nighttime UARS measurements have been used in the comparisons against SAGE II.

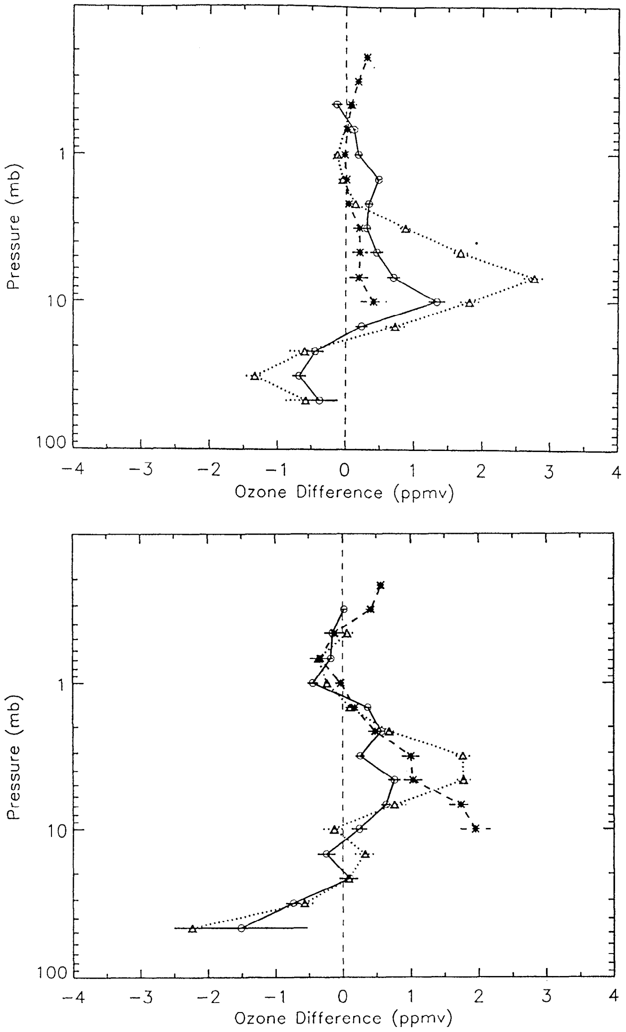
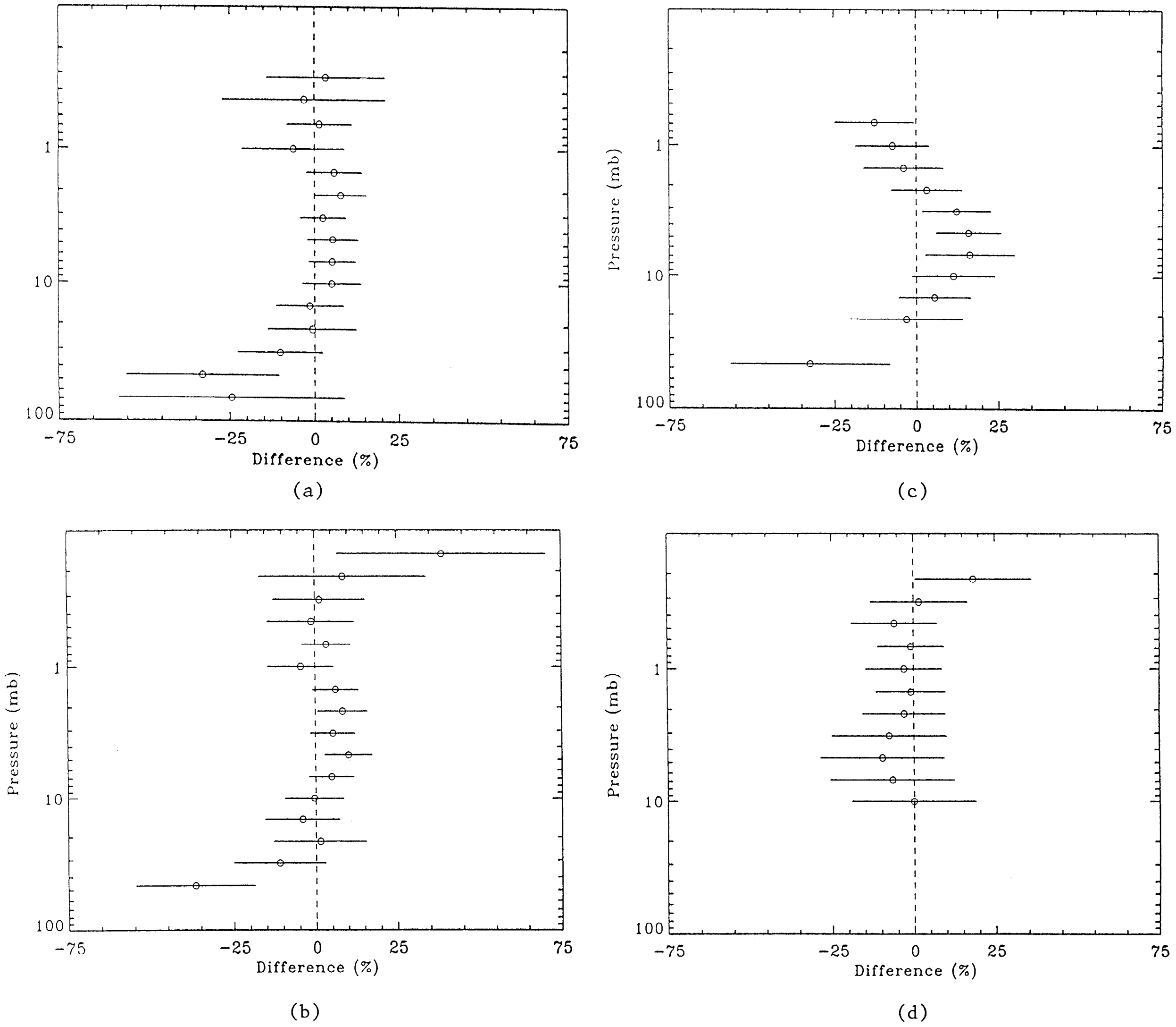


Figure 2. Means and standard errors (parts per million by volume) of the ozone measurement differences among MLS (circles), CLAES (triangles), and ISAMS (asterisks) and coincident SAGE II profiles for (top) April 15–17, 1992, near 29°N (45 profiles) and (bottom) for January 9–11, 1992 near 28°N (45 profiles).

Differences between the UARS and the SAGE II measurements (expressed in ppm) for two of the selected periods are shown in Figure 2 together with the standard errors of the differences. Figure 3 shows the means and standard deviations of all the indicated profile differences with respect to SAGE II (expressed in percent) over all the validation periods.

SAGE II/MLS Comparisons

Starting with the summary of the MLS/SAGE II differences shown in Figure 3, MLS values are seen to be approximately 5% larger than SAGE II values from 1.5 to 10 mbar. This difference is absent at 15 mbar and MLS values are slightly smaller than SAGE II values at 1 mbar. At pressures less than 1.5 mbar, the differences oscillate with altitude probably be-



(a) (c) (b) (d)

Figure 3. Mean differences between UARS measurements and SAGE II ozone profiles over the periods January 9–11, April 15–20, and August 25–30, 1992, expressed as a percentage of the SAGE II values: (a) MLS (205 GHz), (b) MLS (183 GHz), (c) CLAES, and (d) ISAMS.

cause MLS is only retrieving at 1 and 0.46 mbar (and 0.22 mbar) with the other values being given by linear interpolation in $\ln(p)$, where p is the pressure. It is for this reason that the standard deviations at the intermediate levels are smaller than those at 1 and 0.46 mbar. The reason for the relatively smaller MLS ozone values at 1 mbar is not known at this time.

A considerably more extensive comparison between MLS and SAGE II ozone observations is reported by *Cunnold et al.* [this issue]. The summary figure for those comparisons shows a vertical structure similar to that shown in Figure 3. At pressures greater than 10 mbar, it is demonstrated in that paper that the SAGE II ozone retrievals are too high, particularly in the tropics, because of a failure to completely remove the effects of the Pinatubo aerosols. However, it is also shown that after the aerosol concentrations have decreased sufficiently at individual levels, MLS values are larger than SAGE II values by approximately 5%; that is, they are consistent with the differences in the 1.5- to 10-mbar range. *Cunnold et al.* [this issue] also note that HALOE/MLS comparisons also indicate that MLS ozone values at 1 mbar are slightly reduced, relative to the values at the other levels.

The MLS/SAGE II individual period difference profiles shown in Figure 2 are basically similar to the mean differences given in Figure 3 (except for the 1 ppm difference at 10 mbar in April). Among all the periods analyzed, the mean difference profile for January 9–11 at 5°S to 10°N (not shown) is most atypical; it suggests that SAGE II values are anomalously larger (by 10–15%) at altitudes below the 3-mbar level at that time. In detailed comparisons between SAGE II and SBUV measurements from 1984 to 1990, it has been found that the largest differences (both plus and minus) occur in January in the tropics [*Wang*, 1994]. The January SAGE II anomaly is evident also in Figure 12 which will be discussed for another reason below, in which comparisons between sunrise and sunset measurements at approximately the same latitude and longitude and within a single 24-hour period have been made. The differences are seen to be much larger in January than at any other time of the year; it has been speculated that there might be SAGE II reference height errors [*Wang*, 1994], but it is unclear why these should maximize in January.

Within an individual validation period it is interesting to examine the correlated and the residual variances in order to

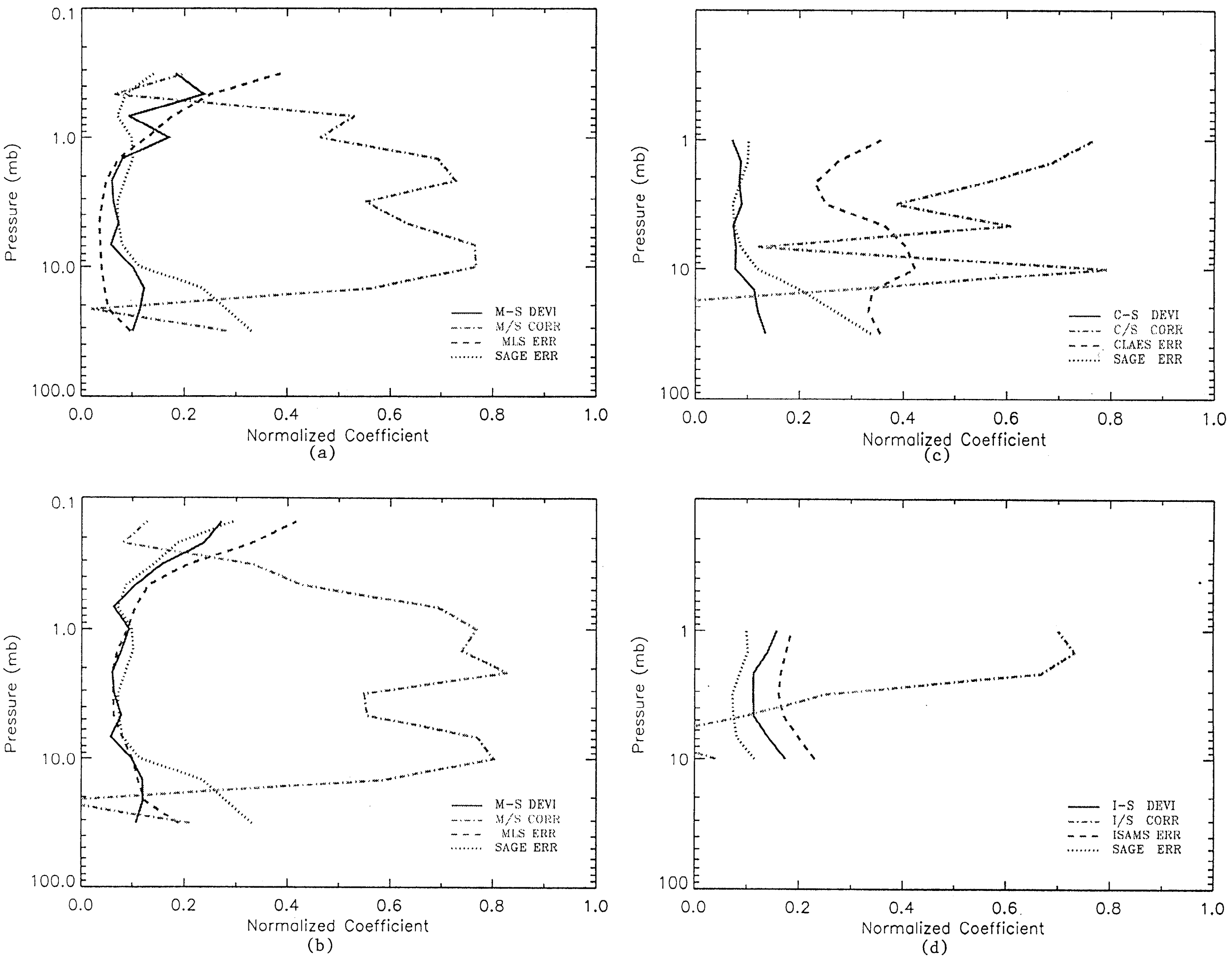


Figure 4. Correlations, standard deviations of differences, and stated mean profile error bars for the 45 UARS/SAGE II coincident profiles near 28°N for January 9–11, 1992: (a) MLS (205 GHz), (b) MLS (183 GHz), (c) CLAES, and (d) ISAMS.

examine the consistency with the reported profile error bars. Figure 4 illustrates the results for the January validation period, which was typical of the periods studied (in contrast the April period which had atypically small variability). The standard deviations of the MLS/SAGE II differences are approximately consistent with the MLS and SAGE II profile error bars and with a correlation coefficient uncertainty of $1/\sqrt{45}$ or 0.15. At altitudes above 1.5 mbar the MLS error bars are larger and the standard deviations of the differences follow the increase of the MLS error bars with increasing height (random errors dominate the MLS error bars in this region). The oscillation in the standard deviations is the result of the MLS linear interpolation procedure [*Froidevaux et al.*, this issue]. Since the MLS values given at levels (e.g., 0.68 mbar) intermediate between the retrieval levels are simply averages of the values above and below, the variability (from whatever cause) at MLS retrieval levels which is uncorrelated between levels will be a factor of $\sqrt{2}$ less at the intermediate levels (and there will be a corresponding decrease in the reported random error component there). At altitudes below 1.5 mbar the SAGE II error bars are larger than the MLS error bars and the standard deviations of the differences tend to follow the SAGE II error bars. It should be noted, however, that both sets of error bars are expected to overestimate the actual errors: for SAGE II the error bars have not been reduced to reflect the vertical smoothing of the profiles over approximately 2.5 km (this could lead to a factor of approximately 1.2 reduction in the error bars [*Cunnold et al.*, 1989]), giving a precision of approximately 6% in the middle of the profile. Second, although a rough attempt has been made to increase the SAGE II error bars for both random and systematic errors as a result of interference from Pinatubo aerosols, even allowing for the inclusion of systematic errors, it is apparent from the difference standard deviations that the SAGE II error bars at altitudes below 10 mbar are roughly a factor of 2 too large. The MLS error bars are also somewhat larger than random errors alone [*Froidevaux et al.*, this issue], because of the influence of a priori and systematic errors. In particular, systematic errors make larger contributions to the MLS error bars than random errors from 2.2 to 22 mbar and a priori contributions become dominant at altitudes above 0.46 mbar at 205 GHz and below 22 mbar at 183 GHz.

A typical standard deviation of both and MLS measurements on January 9–11, 1992, at 27°N is approximately 10%. The standard deviations are smallest at 3.2 mbar (for comparable model results on the vertical structure of ozone variability, see *Newchurch et al.* [1995]), and the correlation coefficient is smaller there. There are no obvious differences in correlation between the levels at which MLS retrieves ozone and the intermediate levels for which ozone is specified by interpolation. For most purposes these results indicate that the SAGE II and MLS precision estimates are fairly realistic.

Because of the rapid reduction in the precision of the MLS profiles with height above 1 mbar, it is recommended that the 183-GHz MLS observations be used in place of the 205 GHz above 1 mbar [*Froidevaux et al.*, this issue]. Figure 3b shows the results for the 183-GHz channel which may be directly compared against the 205-GHz results shown in Figure 3a. The smaller standard deviations at altitudes above 2.2 mbar confirm the better precision of the 183-GHz observations at these levels; below that level, there is no evidence from these results of any difference in the precision and accuracy of the 183- and 205-GHz channels. Note, however, that the 183-GHz results agree with the 205-GHz profiles in showing closer agreement with SAGE II from 1 to 0.32 mbar in contrast to the approximately 5% differences shown at altitudes below 1 mbar. Since the SAGE II retrieval algorithm includes vertical smoothing over 5 km at altitudes above approximately 1 mbar, it is possible that SAGE II smoothing could be playing a role in the apparent transition in the differences at this level. At altitudes above 0.32 mbar the transition to nighttime ozone values is significantly delayed beyond a 90° solar zenith angle (and by different amounts at sunrise and sunset); therefore nighttime MLS ozone concentrations are expected to exceed the SAGE II sunrise and sunset values.

The standard deviations of the SAGE II/MLS differences are between 5 and 10% from 1.5 to 10 mbar in the individual periods (Figure 2) and similar standard deviations are exhibited when the periods are combined (Figure 3). This is also true up to 0.68 mbar if the 183-GHz MLS channel results are used. The precision of the average profiles for individual periods are similar to the precisions of the individual profiles.

SAGE II/CLAES Comparisons

Figure 3 indicates that for the 1992 validation periods there are significant differences in the vertical structure of ozone in the upper stratosphere between the SAGE II and the CLAES measurements. Specifically, CLAES (B9) gives larger ozone values at 6.8 mbar by approximately 15%, smaller values than SAGE II at altitudes above 2 mbar, and gives mean CLAES/SAGE II differences roughly similar to MLS/SAGE II differences at altitudes below 20 mbar. The vertical structure of the CLAES/SAGE II differences is similar in the individual periods depicted in Figure 2, except that there is some variability in the altitude at which the difference maximizes.

The standard deviations of the differences in the individual periods suggest that CLAES (B9) precision is not quite so good as MLS (which is providing less vertical resolution) but is in the 5–10% range over at least the 1- to 10-mbar range. *Bailey et al.* [this issue] report short-term CLAES precisions of better than 10% from 1 to 100 mbar (decreasing to approximately 30% at 0.3 mbar), based on comparisons between CLAES ozone profiles obtained near latitudinal extremes of the satellite orbit. Consistent with these results, the correlations between SAGE II and CLAES shown in Figure 4 are slightly weaker than those between SAGE II and MLS. When all the periods are combined, the standard deviations of the differences (Figure 3) are seen to be approximately 25% larger than the SAGE II/MLS standard deviations at altitudes below 1 mbar (but the SAGE II/CLAES standard deviations do not increase at the higher altitudes, although this is not shown in this particular figure). The profile error bars reported for CLAES (version 7) include allowances for possible systematic errors; however, even allowing for the mean differences in the profiles shown in Figure 3, the error bars are too large. An error has recently been found in assessing the systematic component; the error will be corrected in future versions of the CLAES algorithm. It may be noted that the correlations are poorest at those heights where the mean differences are largest, so that not only are there inaccuracies there, but the CLAES values are also more variable at these levels.

ISAMS/SAGE II Differences

Figure 3 indicates that in the January and April comparisons the ISAMS (version 10) ozone values agree with SAGE II values within 10% in the mean with the ISAMS values being smaller at 4.6 mbar. However, the standard deviations of the SAGE II/ISAMS differences are larger than most of those seen in the CLAES and MLS comparisons. The standard deviations are 10–20% with the smallest standard deviations occurring at the 1.5-, 1.0-, and 0.68-mbar levels. The April period shows much better agreement between ISAMS and SAGE II than the January period (Figure 2). The standard deviations of the differences in the individual periods are 10–15% from 0.46 to 10 mbar (Figure 3), but the correlations are insignificant from 4.6 to 10 mbar (where ISAMS is being influenced by aerosols). The best agreement between SAGE II and ISAMS occurs around the 1-mbar level. The ISAMS error bars are dominated by random errors due to radiance uncertainties and inferred temperature errors [*Connor et al.*, this issue]. The reported error bars appear to be slightly conservative. More extensive comparisons between ISAMS and SAGE II measurements between 1 and 10 mbar are reported by *Connor et al.* [this issue], but the mean differences are similar to those shown in Figure 3. Time series comparisons between the ISAMS and the ground-based microwave measurements (loco citato) show better agreement at 10 mbar in April and May 1992 than in November 1991 to January 1992.

5. MLS/CLAES/ISAMS Comparisons for January 9 and April 15, 1992

Figure 5 shows the zonal mean ozone values measured by MLS, CLAES, and ISAMS on January 9–11, 1992, and Figure 6 shows the percentage differences expressed in terms of the means of the two instruments. The zonal mean ozone structure is similar for all three instruments except for more latitudinal waviness in the ISAMS measurements above 0.46 mbar and a strong latitudinal structure in the MLS/CLAES differences below 32 mbar. The ozone mixing ratio peak is located at slightly higher altitudes for CLAES than for the other instruments and the peak values are smaller for ISAMS.

The percentage differences figure shows that CLAES values are larger than MLS values by approximately 10% from 2.2 to 4.6 mbar in the tropics but with somewhat smaller differences poleward of 40°N. CLAES values are also larger than MLS values at altitudes below 22 mbar and latitudes less than 40°, with differences reaching approximately 50% in the tropics at 46 mbar. At 0.46 mbar, CLAES values are approximately 10% less than the MLS values. The mean MLS/CLAES profile differences are consistent with the reported differences based on the SAGE II comparisons except that those comparisons

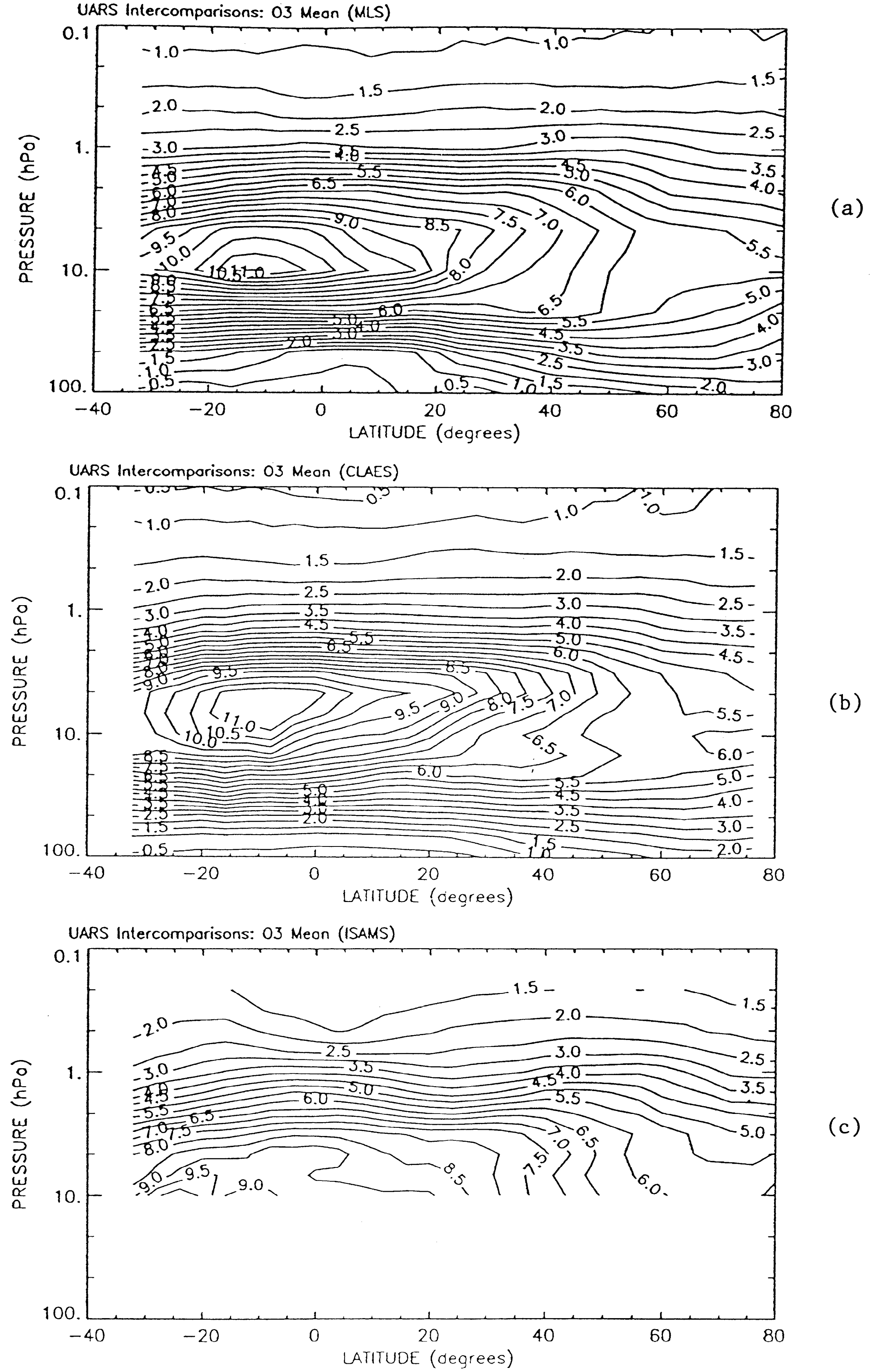


Figure 5. Zonal mean UARS ozone profiles (ppmv) for January 9–11, 1992: (a) MLS, (b) CLAES, and (c) ISAMS.

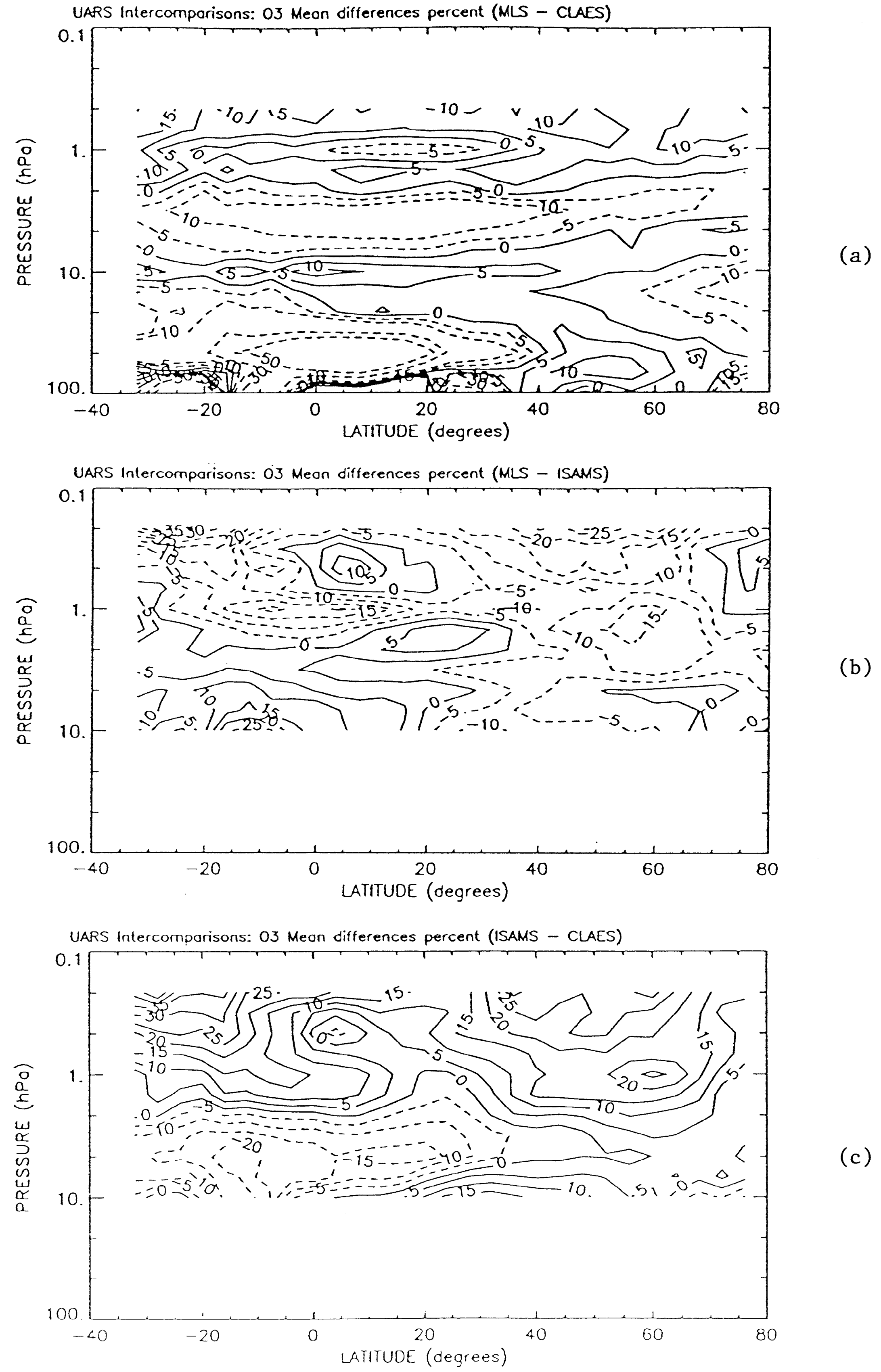


Figure 6. Zonal mean differences between UARS ozone profiles on January 9–11, 1992, expressed as a percentage of the two instrument means: (a) MLS-CLAES, (b) MLS-ISAMS, and (c) ISAMS-CLAES.

did not identify the large MLS/CLAES differences at 46 mbar in the tropics. The latitudinal variations suggest that CLAES values near 4.6 mbar are largest in the tropics and that the MLS anomaly at 1 mbar may be a little larger in the tropics. However, the latitudinal variation in the MLS/CLAES differences is approximately ±5% around the mean values between 0.46 and 10 mbar (and do not exceed ±10% if the region is extended downward to 22 mbar).

The MLS/ISAMS differences show that ISAMS values are approximately 10% larger than MLS values at 1 mbar and almost 20% larger at 0.2 mbar (where the MLS retrievals are significantly affected by the a priori profiles). The most prominent feature, however, is the latitudinal variability in the differences especially at 10 mbar, where the ISAMS tropical values are being influenced toward low values by the aerosols, and above 0.68 mbar. Excluding these two regions, the variation in the latitudinal differences around the means is approximately ±10%. CLAES values are approximately 20% less than ISAMS values at 0.22 mbar.

The zonal mean ozone plots for April 15–20, 1992 (Figures 7 and 8), also show the large CLAES/MLS differences below 32 mbar in the tropics but otherwise fairly similar distributions for these two instruments. The MLS/CLAES percentage differences are approximately 5% larger above 2 mbar than in January and 5% smaller from 2 to 6.8 mbar. They are also approximately 10% smaller at 10 mbar and 10% larger at 22 mbar. The comparisons against SAGE II indicate that most of these vertical structure variations arise from the CLAES measurements and correspond, for example, to some variation in the level at which the CLAES/SAGE II difference is maximum. The latitudinal variation of the CLAES/MLS differences around the latitudinal means is again small and is roughly ±5% between 0.68 and 32 mbar.

The MLS/ISAMS differences in April are fairly consistent over the tropics with the differences again taking their minimum value at 1 mbar. Above that level, MLS is larger than ISAMS in April, whereas it was smaller than ISAMS in January. There are large differences (up to 20%) at middle and high southern latitudes in April associated with a peculiar latitudinal behavior of the ISAMS data at this time. As a result, variations around the latitudinal mean MLS/ISAMS differences are roughly ±15% at most levels. ISAMS values are again approximately 20% larger than CLAES values at 0.22 mbar.

Because of the large differences between MLS and CLAES in the tropics at 46 mbar, it is interesting to see how SAGE II ozone compares. At 32 mbar in the tropics, *Cunnold et al.* [this issue] have shown that MLS values are approximately 5% larger than SAGE II values, but by the end of 1993, aerosol concentrations still tended to be too large to accurately evaluate the corresponding difference at 46 mbar in the tropics. It is therefore useful to compare the recent MLS measurements against pre-Pinatubo SAGE II values. Figure 9 shows such a comparison. The MLS observations are seen to be approximately consistent with the pre-Pinatubo SAGE II values at 15–32 mbar and with the post-Pinatubo values in 1993 (except for the approximately 5% offset between the two instruments). However, the MLS values are clearly lower than the SAGE II value at 46 mbar. The difference at this level (and at the other levels) seem to be time dependent with the smallest ozone values occurring during the first few months of MLS measurements (when aerosol concentrations in this region were largest). The SAGE II mean value at 46 mbar in 1989–1990 is approximately 20% larger than the mean MLS value in 1992/1993. Thus the climatological SAGE II measurements suggest that MLS ozone values in the tropics at 46 mbar are too small, but based on the CLAES/MLS differences shown in Figures 6 and 8, the SAGE II measurements also suggest that CLAES values are too large by roughly 20%. Comparisons between MLS and ozonesonde measurements in the tropics [*Froidevaux et al.*, this issue] have indicated that MLS ozone values at 46 mbar are indeed about 20% lower than the ozonesonde values. All these comparisons also show that differences between the measurement techniques at 46 mbar in the tropics are largest during the first 6 months of UARS operations (October 1991 to March 1992).

6. Comparisons With HALOE Ozone Measurements

Comparisons between HALOE and MLS, CLAES, and ISAMS ozone measurements have been made for the validation periods of January 9–11 (centered at 47°N), April 15–20 (at 8°N), August 8–11 (at 17°S), and August 25–28 (39°N), 1992. Approximately 34 to 75 coincidences were found depending on the period studied using criteria of 2° of latitude, 10° of longitude, and 12-hour time differences. The comparisons contain a mix of UARS daytime and nighttime measurements and therefore the comparisons at altitudes above the 1-mbar level need to be interpreted allowing for the diurnal variation of ozone. The HALOE profile uncertainties range from 6 to 12% from 10 to 0.1 mbar, with the largest errors being primarily systematic due to forward model and pressure registration defects and with the smallest errors occurring in the middle of this pressure range [*Bruhl et al.*, this issue]. However, the uncertainties were larger at the lowest altitudes during high Pinatubo aerosol loading conditions in 1991 and early 1992. The HALOE precisions are better than 5% from 22 to 0.46 mbar. The error bars accompanying each HALOE profile are approximately 1% and are known to underestimate the random errors. They do not include the systematic uncertainties.

Figure 10 shows the mean and standard deviations of the differences between the sunrise ozone measurements by HALOE and the measurements by the other sensors for the April 15–20 period. From 0.46 to 10 mbar, MLS shows 10–20% more ozone than HALOE (it should be recalled that there are just four MLS retrieval levels over this pressure range). Consistent with other comparisons against MLS, the smallest difference in this pressure range occurs at 1 mbar. The difference is close to 10% at 22 mbar but is −10% at 46 mbar. The pattern shown is representative of all the periods, although the January period shows better agreement throughout the profile with less than 7% differences between 3 and 50 mbar (at midlatitudes) with MLS being systematically higher. The standard deviations of the differences typically are approximately 5% from 1.5 to 32 mbar, which indicates that both experiments have precisions of approximately 5% or better over this pressure range. At altitudes above 1.5 mbar the standard deviations increase with altitude consistent with the increase in the MLS error bars (as shown in Figure 4). Based on these results and on the MLS/HALOE comparisons for September 1992 given by *Cunnold et al.* [this issue], it is concluded that MLS ozone values are typically approximately 10–15% larger than HALOE values. However, the difference is smaller at 1 mbar (0–10%) and is approximately −10% at 46 mbar in the tropics according to

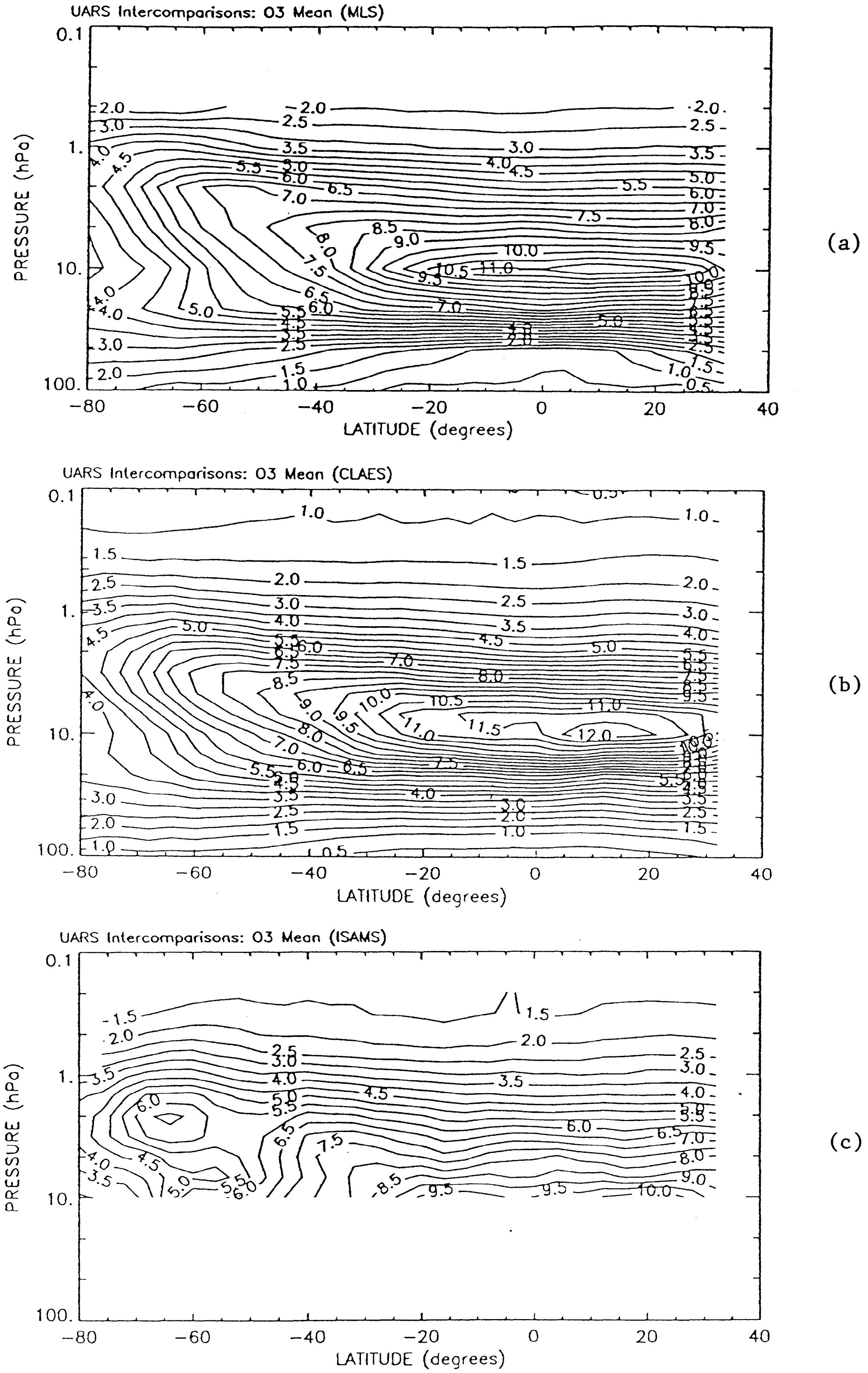


Figure 7. As for Figure 5 but for April 15–20, 1992.

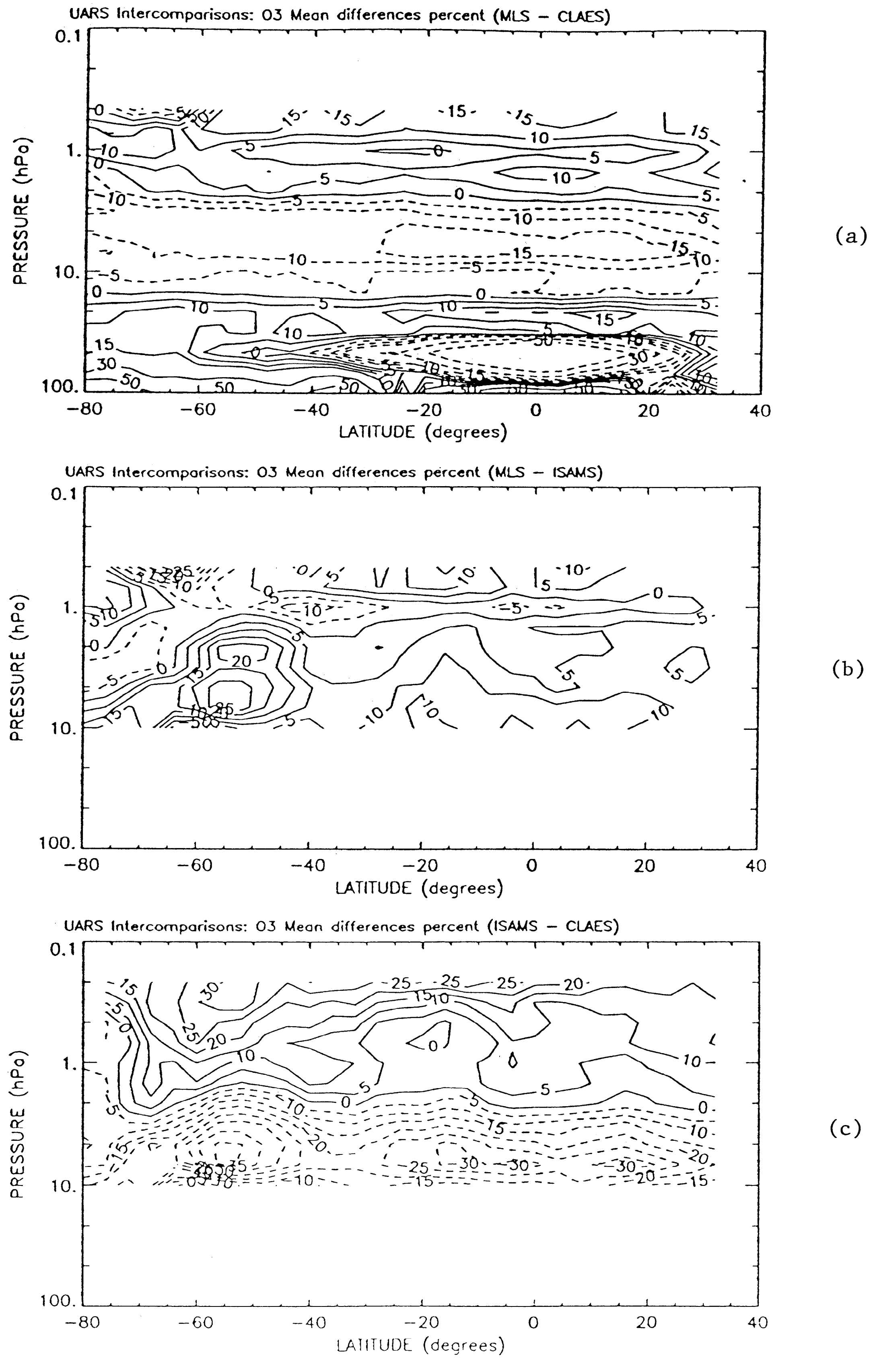


Figure 8. As for Figure 6 but for April 15–20, 1992.

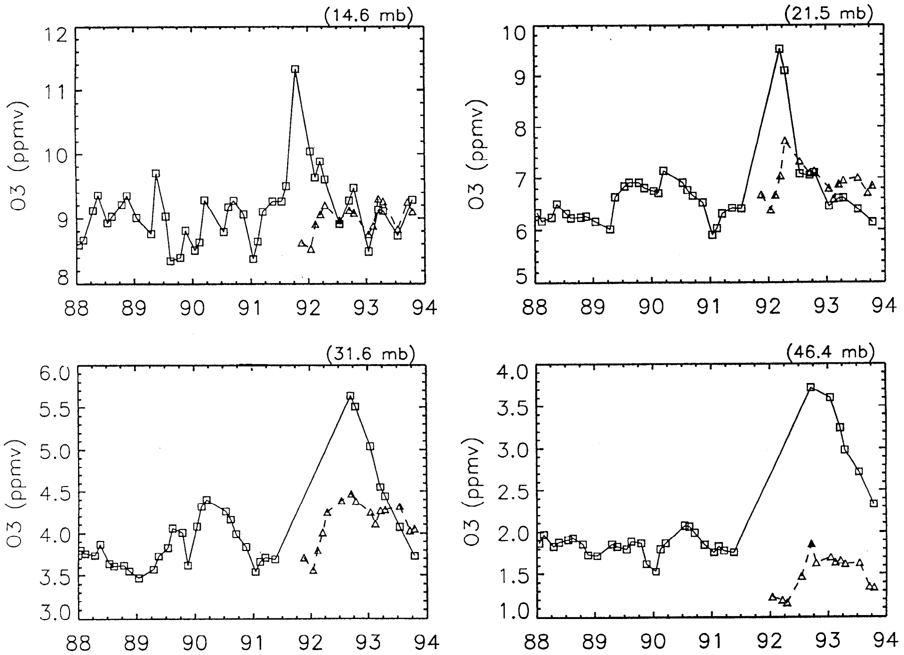


Figure 9. Time series of monthly means of SAGE II (squares) and MLS (triangles) ozone values between −5 and +5% latitude at four UARS levels between 14.6 and 46.4 mbar. The period covered is January 1988 to December 1993 and SAGE II ozone values were not retrievable in the tropics for some (level dependent) period of time after Pinatubo.

Figure 10; the differences are also more variable latitudinally at these levels than at the intermediate levels; but only a few HALOE profiles in the April comparisons extend as low as 46 mbar and those that do were measured outside the tropics.

ISAMS and HALOE data in the April period agree to better than 10% mean difference from 0.46 to 10 mbar with ISAMS being approximately 5% larger on the average over this height range. The standard deviation of the differences are approximately 15% throughout this height range, and the standard deviations are almost uniform with altitude. During the January validation period the agreement between HALOE and ISAMS is much worse with ISAMS exhibiting 10 to 30% larger values over the same height range (at 47°N); this result can be anticipated from the MLS/ISAMS differences seen in Figure 6.

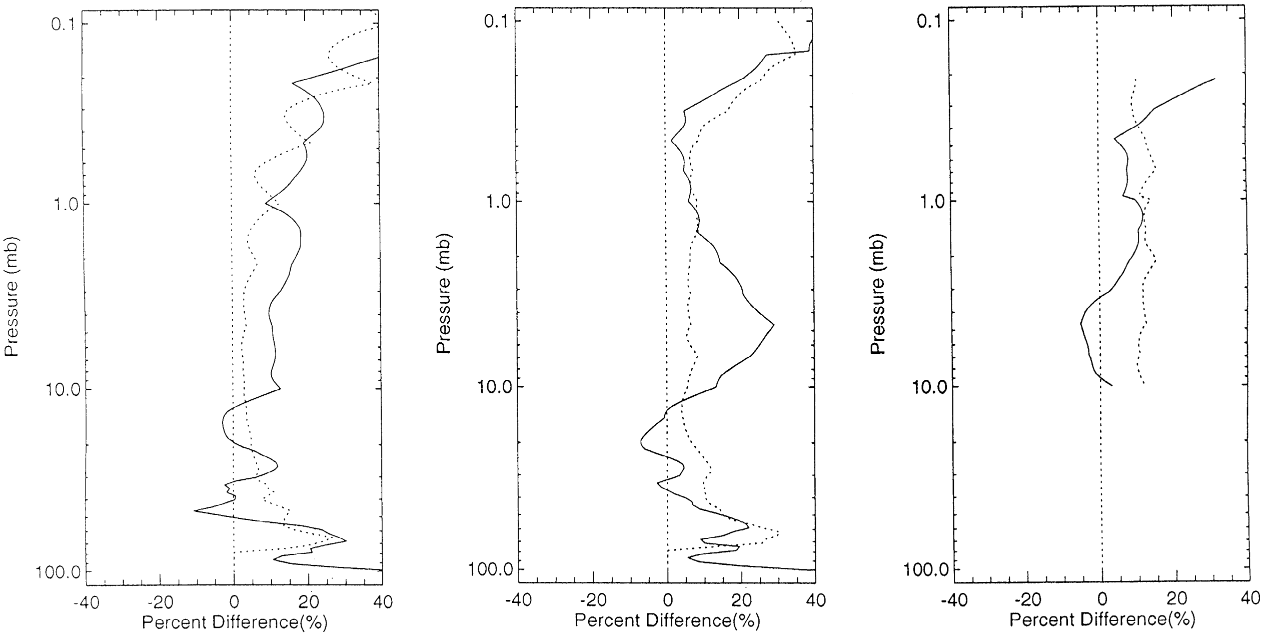


Figure 10. Mean (solid lines) and standard deviations of the differences (dashed lines) among (a) MLS, (b) CLAES, and (c) ISAMS and HALOE sunrise ozone measurements for April 15–20, 1992, near 7°N for approximately 75 coincident profiles. The mean differences are expressed as UARS-HALOE values.

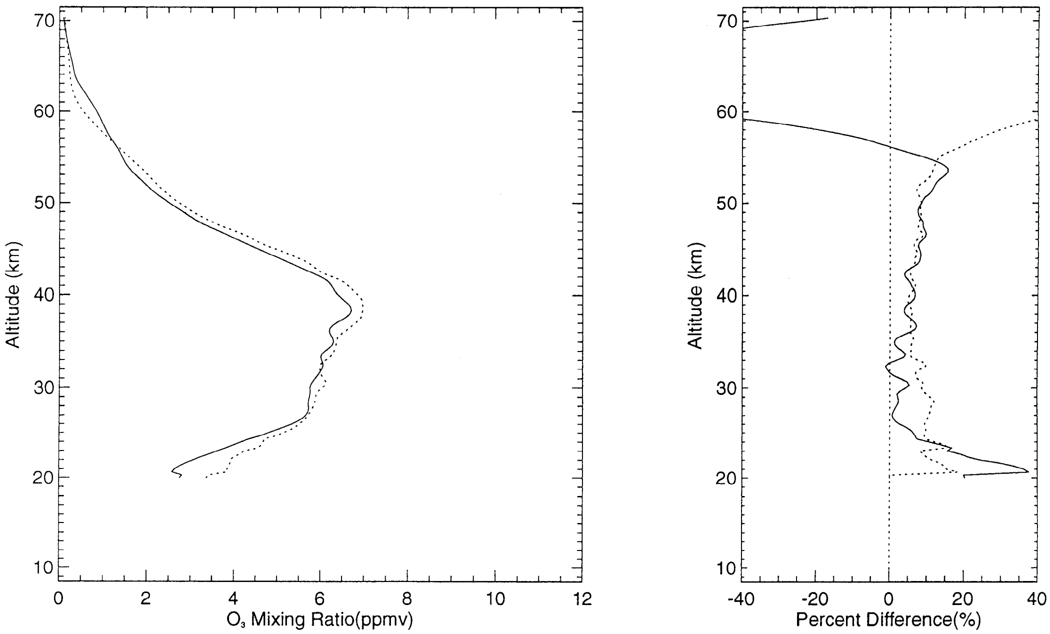


Figure 11. Mean profiles (left) and means (solid line) and standard deviation differences (right) (dashed lines) between SAGE II (sunset) and HALOE (sunrise) ozone measurements near 51°S, May 6, 1992.

CLAES/HALOE differences show the previously identified anomalous vertical structure in the CLAES ozone profiles resulting in a maximum CLAES-HALOE difference of approximately 25% at 4.6 mbar and minimum differences of −7% at 22 mbar and 2% at 0.46 mbar. Both CLAES and MLS show the ozone mixing ratio peak to be at a slightly higher altitude than the HALOE measurements. The standard deviations of the differences are 7% (or less) from 0.68 to 22 mbar.

It is rare that SAGE II and HALOE have made coincident measurements. However, one such example is shown in Figure 11 (from *Bruhl et al.* [this issue] for May 6, 1992 (at 51°S)). It shows that SAGE II values are on average approximately 5% larger than HALOE values over the 25- to 50-height range but that the differences increase somewhat with altitude. Below 25 km the SAGE II profiles are being affected by aerosols. The standard deviation of the differences is less than 10% over this height range.

The differences between HALOE and the other measurements become large above 55 km altitude (or 0.32 mbar). These differences are primarily related to the strong diurnal variation in ozone at these altitudes and to the fact that ozone measurements made at a 90° solar zenith are typical of nighttime conditions at 55 km altitude but are typical of sunlit conditions at 65 km altitude. Moreover, this transition occurs at a higher altitude for sunrises than for sunsets [*Chu*, 1989; *Chu and Cunnold*, 1994]. Therefore at times when sunrise and sunset measurements by SAGE II or HALOE are made at the same latitude on the same day, sunrise ozone values are larger than sunset values from approximately 0.2 to 0.04 mbar (58 to 68 km). These differences are illustrated in Figure 12. HALOE measurements show maximum differences of approximately 25% occurring at approximately 65 km altitude, in good agreement with the results in the works of *Chu* [1989] and *Chu and Cunnold* [1994]. SAGE II ozone retrievals also exhibit the increasing sunrise/sunset ratios with increasing altitude above 55 km, but they do not extend high enough to show the maximum in the ratio. The reason for the more rapid increase in the ratio for SAGE above 55 km altitude is probably related to the 5-km vertical smoothing and to the decreasing information content of the measurements above this altitude. At least part of the difference between SAGE II and HALOE seen in Figure 11 therefore occurs because SAGE II was making sunset observations, whereas HALOE was making sunrise measurements. Moreover, the differences between HALOE (sunrise) and other UARS sensors above approximately 0.32 mbar occur because the selected coincident UARS measurements (in April) were nighttime measurements.

7. Discussion

From a UARS validation viewpoint, SAGE II ozone measurements should be placed in context as one of many techniques against which UARS ozone measurements have been compared. A comparison of SAGE II against the ground-based microwave radiometer values is just a few percent larger than the microwave from 10 to 1.5 mbar (Figure 13). We currently suspect it is a coincidence that the SAGE II/ground-based microwave difference is larger at 1 mbar and, in fact, the mean MLS/ground-based microwave radiometer differences over the period October 1991 to May 1992 show the difference to be approximately 5% less at 1 mbar than at the other levels [see *Grose and Gille*, 1995b]. Based on other comparisons reported at the UARS validation workshops, the ozone lidar measurements at Table Mountain (see Figure 13) and Haute Provence vary from 0 to 10% larger than SAGE II values depending on the equipment used. The SAGE II ozone validation paper [*Cunnold et al.*, 1989] reported no systematic differences versus the ROCOZ and comparisons against ozonesondes have typically shown good agreement (within approximately 5% in the mean) above 20 km altitude [*Veiga et al.*, 1995]. Therefore SAGE II measurements seem to be an excellent standard for comparison and the UARS ozone measurements will be summarized on that basis.

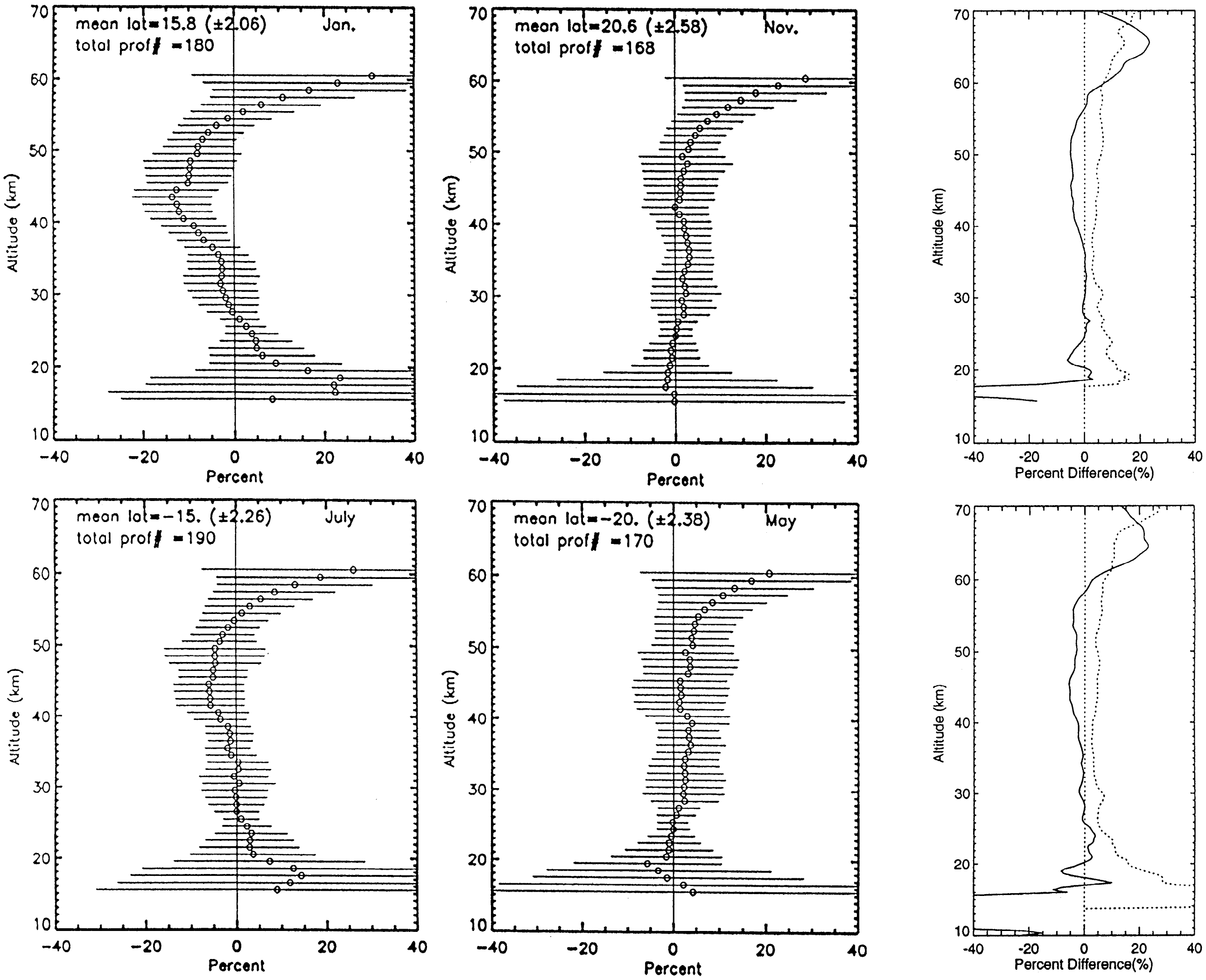


Figure 12. Percentage differences between sunrise minus sunset ozone measurements on the same day at the same tropical latitudes. The top three figures are for approximately 20°N and the bottom three figures are for approximately 20°S. The four figures on the left are from 7 years of SAGE II measurements and the right-hand two figures are from HALOE measurements in 1992 with the November and January periods combined in the top figure and the May and July periods combined in the bottom figure. The SAGE II and HALOE (dashed lines) figures also show standard deviations of the differences.

Microwave Limb Sounder

MLS (version 3) ozone measurements are of excellent quality and are systematically approximately 5% larger than SAGE II values from 0.32 to 32 mbar except at the 1-mbar level. MLS values are similarly larger than the ground-based microwave measurements (although a discontinuity in the time series differences occurred in January 1992 at 4.6 mbar [see *Grose and Gille*, 1995a], but the lidar measurements show somewhat better agreement with the mean MLS values. Margitan's balloon ultraviolet measurements also indicate that in the mean the MLS measurements give values which are approximately 5% too large. Standard deviations of differences between the MLS measurements and SAGE II and HALOE measurements are consistent with the MLS profile error bars which indicate a precision of better than 5% over the 1.5- to 32-mbar pressure range. Above 1.5 mbar the precision of the MLS 205-GHz measurements decreases to approximately 20% at 0.46 mbar. However, better precision can be obtained over the 1.5- to 0.46-mbar range by using the 183-GHz MLS measurements (diurnal variations inferred from these data are discussed by *Ricaud et al.* [this issue]).

At 1 mbar, SAGE II and HALOE comparisons, in particular, indicate that the MLS values are proportionately approximately 10% smaller than at the other levels; although this is not fully understood, it seems to be a feature of the MLS measurements because a similar feature is seen in the 183-GHz MLS/SAGE II comparisons.

At 46 mbar, ozonesonde comparisons suggest that MLS values are approximately 20% too small in the tropics [*Froidevaux et al.*, this issue]; this results in an excessively steep latitudinal gradient at that level. The HALOE/MLS comparisons for September given by *Cunnold et al.* [this issue] support this result. Furthermore, the mean MLS values are also approximately 20% smaller than the pre-Pinatubo SAGE II ozone values at 46 mbar but are within approximately 5% of SAGE II values from 32 to 10 mbar in the tropics. Both the SAGE II and the ozonesonde comparisons suggest that the tropical MLS differences in the lower stratosphere are decreasing with time.

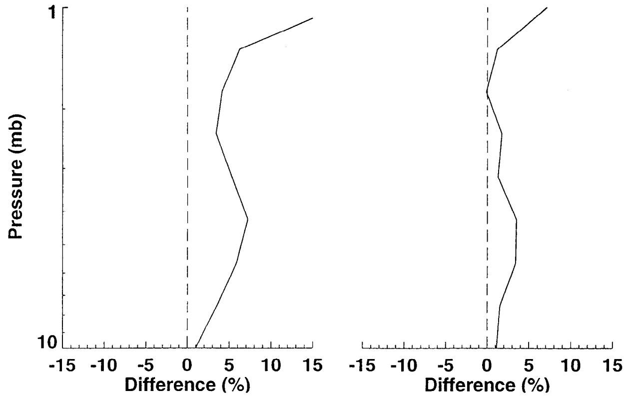


Figure 13. Mean differences in percent between the McDermid ozone lidar and the ground-based microwave radiometer at Table Mountain Observatory over the period October 1991 to June 1992 (65 comparisons (left)) and between the SAGE II ozone measurements and the microwave measurements (26 comparisons (right)) for the same time period. Positive differences indicate that the ground-based microwave values are less than the other measurements (based on *Tsou et al.* [1994]). The standard deviations of all the differences are approximately 5%.

Furthermore, the differences of approximately 50% between MLS and CLAES in this region found in January and April 1992 had decreased to approximately 20% in August 1992 [*Grose and Gille*, 1995b].

Halogen Occultation Experiment

There is only the one day of direct comparisons between HALOE and SAGE II measurements, but the degree of agreement can also be inferred from the comparisons between the two data sets and MLS. HALOE ozone values are approximately 5% smaller than SAGE II values over the height range of 25 to 50 km, with slightly larger differences occurring in the upper part of the height range. HALOE values are also of excellent quality and from the standard deviations of the differences versus SAGE II and MLS, it is inferred that the HALOE errors (other than systematic errors) over the pressure range 1.5 to 32 mbar are approximately 5% or less. Both HALOE and SAGE II show an ozone sunrise/sunset ratio which increases with altitude between 55 and 60 km altitude.

Cryogenic Limb Array Etalon Spectrometer

CLAES (version 7) ozone profiles possess a different vertical structure relative to the other measurements. The profiles possess approximately 15% larger values near 4.6 mbar than the SAGE II profiles, although there is a variability of one or more UARS layers in the location of the maximum relative difference, and they are approximately 20% smaller than ISAMS values near 0.32 mbar (where ISAMS agree in the mean with SAGE II values). CLAES values at 0.32 mbar are similarly low versus other correlative measurements, as documented by *Bailey et al.* [this issue]. Near 1 and below 10 mbar, on the other hand, the CLAES and SAGE II profiles are in better agreement, with CLAES values typically being less than or equal to SAGE II values; but at 46 mbar in the tropics, CLAES values are approximately 10% larger than HALOE and SAGE II values. At heights above this, the differences between CLAES and MLS are fairly uniform with latitude, but there are some changes in the vertical structure of the differences between the January and the April validation periods. The standard deviations of the CLAES/SAGE II differences are approximately 10%, suggesting that the precision of the CLAES ozone measurements is better than 10% over the pressure range of at least 15 mbar to 0.68 mbar. The CLAES ozone error bars are known to be unrealistically large, even allowing for their inclusion of the large systematic offsets in the profiles near 4.6 and 0.32 mbar.

Improved Stratospheric and Mesospheric Sounder

The ISAMS ozone profiles possess marked variability in their differences with respect to the other UARS measurements, both latitudinally and between the January and the April 1992 validation periods. There is a peculiar, large feature in the ISAMS ozone measurements at southern midlatitudes in April, for example, and there is clear evidence of Pinatubo aerosol contamination of the ozone values in the tropics in January at 10 mbar. The SAGE II/ISAMS mean differences for the four sets of comparisons are approximately 5% (ISAMS smaller) all the way up to 0.3 mbar, and even closer agreement in the mean is shown in the more extensive comparisons for November 1991 and April and May 1992, reported by *Connor et al.* [this issue]. The standard deviations of the differences are 10–15%, with the smallest standard deviations being near 1 mbar. These differences are approximately consistent with the ISAMS error bar profiles.

8. Conclusions

This paper has discussed the quality of typical ozone retrievals made by the MLS (version 3), HALOE (version 17), CLAES (version 7), and ISAMS (version 10) instruments on the UARS spacecraft. This discussion has been based on conclusions reached at the UARS validation workshops and coincident comparisons against SAGE II (primarily) and among the UARS instruments, with more detail given in the workshop report [e.g., *Grose and Gille*, 1995a, b].

From 0.46 to 32 mbar the comparisons indicate, with a few exceptions, agreement in the mean within approximately 10%. The MLS measurements give approximately 5% higher values (except at 1 mbar), and the HALOE measurements give approximately 5% lower values than most of the correlative measurements. The next version of the MLS retrievals is expected to yield slightly smaller ozone values. The CLAES ozone values are approximately 15% too large in the middle of the altitude range, but the agreement is closer to ±5% nearer the ends of the range. ISAMS values are biased high by the very high Pinatubo aerosol concentrations in the tropics below 4.6 mbar (and are only being retrieved in version 10 down to 10 mbar). The precision of the HALOE values is better than approximately 5% over this range, and there is a similar precision for the MLS observations (if the 183-GHz measurements are used above 1.5 mbar). The MLS retrieval procedure of using linear interpolation to join alternate UARS level ozone retrievals may be contributing to minor differences versus the other measurements. The CLAES ozone values appear to have a precision of 10% or better over this height range, even if variability in the fairly systematic profile structure is included, and even if the systematic portions of the errors in the vertical profile structure are included, the current (version 7) profile error bars of approximately 40% are too large (because of an error in the assigned error bars). The ISAMS measurements exhibit more variability in the vertical and latitudinal structure compared to the other measurements, but if the aerosol contaminated regions are excluded, the precisions are indicated to be similar to the error bars of 10–15%.

Above 0.46 mbar it is more difficult to validate the ozone profiles because of the strong diurnal variation of ozone and fewer correlative measurements at these heights. HALOE profiles, however, show sunrise/sunset ratios approximately consistent with a photochemical model up to 0.1 mbar and SAGE II measurements show similar tendencies. ISAMS and MLS (183 GHz) measurement ozone values agree with SAGE II in the mean at 0.32 (and with the ground-based microwave), but CLAES values are smaller by approximately 20%. MLS 183-GHz measurements are more sensitive than the 205-GHz data above 0.46 mbar, albeit intrinsically less accurate [*Froidevaux et al.*, this issue].

Below 32 mbar, there are large differences between MLS and CLAES measurements which reached 50% in the tropics in 1992. Ozonesondes and comparisons against SAGE II climatology suggest that MLS values are approximately 20% too small at 46 mbar in the tropics with the smallest values occurring during the first 6 months (October 1991 to April 1992) of the UARS mission. The HALOE ozone values at these altitudes have no obvious problems except that they have larger uncertainties than at higher altitudes because of high aerosol concentrations and were not retrieved under the highest aerosol loading conditions. CLAES values also may be influenced by high aerosol loading and tend to be somewhat high at 46 mbar in the tropics.

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