A reference model for middle atmosphere ozone in 1992–1993

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Abstract. An ozone climatology for the period April 1992 to March 1993 and covering pressures from 0.1 to 100 hPa and from 80°N to 80°S is derived from satellite-based measurements by the Stratospheric Aerosol and Gas Experiment (SAGE), the Halogen Occultation Experiment (HALOE), and the Microwave Limb Sounder (MLS). At pressures <1 hPa, separate distributions are given for daytime and nighttime conditions. From 0.46 to 32 hPa the accuracy of the distribution is estimated to be 5%, and the precision is also ~5%. Estimates of atmospheric variability are provided on the basis of standard deviations of the measurements within months. Distributions of ozone monthly means and standard deviations are also given in a potential temperature, equivalent latitude coordinate system. This data set is included in the UARS reference atmosphere, and it is accessible through that web site.

1. Introduction

Ozone is one of the most important trace gases in the atmosphere. It plays an important role in the Earth's radiation budget and temperature. Stratospheric ozone is also beneficial to human health by absorbing biologically damaging ultraviolet sunlight, so-called UVB radiation, before it reaches the Earth's surface. Ozone has been observed from ground-based or balloon-borne instruments on a fairly widespread basis since the 1950s [e.g., *Dutsch*, 1971]. More recently, various satellite experiments have greatly improved our understanding of the global distribution of ozone. By combining Limb Infrared Monitor of the Stratosphere (LIMS), solar backscattered ultraviolet (SBUV), Stratospheric Aerosol and Gas Experiment (SAGE I), and SME ozone data between 1978 and 1983, *Keating et al.* [1996] constructed a reference model for ozone between 70 and 0.003 hPa (17 and 90 km).

It has been shown by satellite measurements that ozone has decreased by 4–10% per decade in the upper stratosphere since the late 1970s and early 1980s, with largest downward trends in high latitudes around 40 km and smallest trends in the tropics [*Hood et al.*, 1993; *Hollandsworth et al.*, 1995; *Wang et al.*, 1996; M. J. Newchurch et al., Upper stratospheric ozone trends, 1979–1998, submitted to *Journal of Geophysical Research*, 1998). Total Ozone Mapping Spectrometer (TOMS) total ozone measurements, which are dominated by ozone in the lower stratosphere, also show similar latitudinal dependence of ozone loss. Between 1978 and the 1990s, there was no significant total ozone loss in the tropics, while negative annual mean ozone trends of 8–9% per decade and 2–4% per decade are found at 60°S and 60°N, respectively [*Stolarski et al.*, 1991; *McPeters et al.*, 1996].

The purpose of this study is to present an update of the vertical distribution of ozone, given by *Keating et al.* [1996], for

the early 1990s by combining multiple satellite data sets from the Stratospheric Aerosol and Gas Experiment II (SAGE II), the Halogen Occultation Experiment (HALOE), and the Microwave Limb Sounder (MLS). More particularly, the motivation for this work is the Upper Atmosphere Research Satellite (UARS) Reference Atmosphere Project. That project's objective is to provide a comprehensive data set for atmospheric variables (O_3, H_2O, CH_4, N_2O, aerosols, etc.) in the stratosphere and mesosphere based primarily on UARS measurements. The time period chosen for this project is between April 1992 and March 1993 when UARS Cryogenic Limb Array Etalon Spectrometer (CLAES) and the Microwave Limb Sounder (MLS) 183-GHz sensor were still operating. It should be noted that this period contains high aerosol concentrations following the Mount Pinatubo eruption in mid-1991. Unfortunately, these satellite limb sensors, in almost all cases, only provide trace gas measurements at pressures <100 hPa. This climatology therefore only extends downward to 100 hPa.

Both SAGE and HALOE ozone measurements have shown a positive bias in the lower stratosphere during the high Pinatubo aerosol period [*Cunnold et al.*, 1996a; *Hervig et al.*, 1995]. Moreover, both these sets of measurements were obtained by solar occultation. In order to provide sufficient data to estimate mean monthly values from these sensors and because of the aerosol contamination of the low-altitude ozone measurements, it is necessary to obtain the SAGE and HALOE ozone values for the desired 12-month period by using an empirical model fit to the 1992–1996 measurements. MLS ozone measurements are not affected by Pinatubo aerosol [*Barath et al.*, 1993]. They are, however, biased in the lower stratosphere at 46 and 100 hPa [*Froidevaux et al.*, 1996]. Ozone measurements from MLS for the 1992–1993 period have therefore been combined with the HALOE/SAGE empirical model fits to produce a best estimate of the ozone climatology from 100 to 0.1 hPa for the period between April 1992 and March 1993. A brief

description of each instrument and of the ozone data quality is provided in section 2, followed by detailed discussions of how all three data sets have been combined. Monthly mean ozone mixing ratios and standard deviations are presented on both latitude-pressure and equivalent latitude-isentropic surfaces.

The motivation for presenting the ozone distribution on equivalent latitude-isentropic surface coordinates is that ozone acts as a tracer throughout most of the lower stratosphere. Using equivalent latitudes defined by the potential vorticity distribution on isentropic surfaces provides a way to separate reversible motion associated with the translation of the polar vortex from irreversible motion which occurs, for example, when the vortex is breaking up during major stratospheric warmings. Ozone variability is expected to be less in this coordinate system, which attempts to remove the effects of reversible motions, than in the latitude-pressure coordinate system. Because of the difficulty of inferring accurate vertical motions, many models used for analyzing trace gas observations (three-dimensional chemical-transport models [e.g., *Lary et al.*, 1995]) now use isentropic surfaces for their "horizontal" coordinate system. The data presented here can then be used to test the abilities of those models to represent the irreversible atmospheric processes.

2. Satellite Data Used for Reference Model

2.1. SAGE II

The SAGE II instrument was launched onboard Earth Radiation Budget Satellite (ERBS) in October 1984. It uses the solar occultation technique to measure ozone, aerosol, NO_2, and H_2O [*McCormick et al.*, 1989]. During each satellite sunrise or sunset event the transmission at seven wavelengths, between 0.385 and 1.02 μm, is measured as a function of tangent altitude as the sunlight reaching the satellite has been attenuated by scattering and absorption by various atmospheric species. Total transmission at 0.6 μm is primarily used to retrieve ozone after removing the contributions from Rayleigh scattering and from other species. A detailed discussion of the SAGE ozone retrieval is given by *Chu et al.* [1989].

An advantage of the solar occultation technique is that using the bright Sun as a source allows the instrument's fields of view to be small, thus providing high vertical resolution. The reported vertical resolution of SAGE ozone data is 1 or 2 km below 50 km and 5 km above ~50 km altitude [*Chu et al.*, 1989; *Cunnold et al.*, 1989]. The accuracy of SAGE II ozone profiles is estimated to be 6% above 25 km [*Cunnold et al.*, 1989] (and no drift of the measurements has been found [*Cunnold et al.*, 1999]) and the precision of the measurements from 25 to 50 km altitude is also ~6%. Below this altitude, the accuracy decreases due to the small ozone amount and larger aerosol interference in this region [*Cunnold et al.*, 1996a; *Steele and Turco*, 1997; D. M. Cunnold et al., SAGE (version 5.96) ozone trends in the lower stratosphere, submitted to *Journal of Geophysical Research*, 1998, hereinafter referred to as Cunnold et al., submitted manuscript, 1998].

An improved SAGE ozone data set from a new retrieval algorithm (version 5.96) is used in this study. The interference from aerosols is better characterized in this version, resulting in improved removal from the ozone retrievals. In general, SAGE ozone from this new retrieval in the lower stratosphere is of better quality than in previous versions, although there still seem to be residual aerosol effects during the high Pinatubo aerosol loading period in 1991–1993 [*Cunnold et al.*, 1999, also submitted manuscript, 1998].

2.2. HALOE

HALOE also uses the solar occultation technique, but at infrared wavelengths, to measure the vertical profiles of ozone, temperature, pressure, and other gases. There are a total of eight channels, between 2.45 and 10 μm, on the HALOE instrument. Four of them are gas filter channels that measure extinction due to HCl, HF, CH_4, and NO. The other four channels are broadband radiometer channels that measure CO_2, NO_2, H_2O, and O_3. A detailed description of the HALOE experiment and instrument is given by *Russell et al.* [1993]. HALOE started measuring ozone a few months after the eruption of Mount Pinatubo. The broadband infrared radiometer channels are also affected by aerosols but less so than those from ultraviolet/visible instruments. A description of the aerosol correction procedure for O_3, NO_2, and H_2O channels is given by *Hervig et al.* [1995]. Owing to limitations of the aerosol correction scheme, HALOE ozone data prior to 1993, however, could still be affected by the Pinatubo aerosol [*Bhatt et al.*, 1999]. The altitude range for HALOE ozone data extends from 10 to 90 km. The best precision of ozone data (version 17) is between 25 and 55 km, where the precision at most heights is close to 5% [*Bruhl et al.*, 1996]. HALOE systematic errors are better than 10% at pressures <10 hPa but may increase to ~18% at 46 hPa [*Bruhl et al.*, 1996]. Above 60 km altitude, the uncertainty of the ozone measurements increases due to small signal to noise ratios. Comparisons between HALOE and correlative measurements show HALOE ozone (version 17) agrees well (within 5%) between 30 and 1 hPa region, with a tendency to be low [*Bruhl et al.*, 1996; *Cunnold et al.*, 1996b].

In the ozone climatology presented here, HALOE version 18 (V18) retrievals have been used. The main improvement in V18 retrievals is better altitude registration in the transmission profiles. The accuracy of the ozone measurements in the lower stratosphere, where ozone has a large vertical gradient, is improved. *Lu et al.* [1997] have shown that HALOE V18 ozone concentrations are systematically larger than V17 retrievals by ~5% for altitudes above 20 km and by 5–20% between 15 and 20 km. *Bhatt et al.* [1999] further showed that HALOE V18 ozone and ozonesonde measurements agree within 10% down to the 100-hPa level. They also provide a filtering technique that can be used to improve HALOE results at pressure >100 hPa.

2.3. MLS

The Microwave Limb Sounder (MLS) is the first experiment using the limb sounding technique at microwave frequencies. Measurements are made by vertically scanning the thermal emission from the atmospheric limb. Three channels, centered at frequencies of 63, 183, and 205 GHz, are used to measure vertical profiles of O_3, ClO, H_2O, pressure, and temperature [*Barath et al.*, 1993]. Measurements at these wavelengths have the advantage of not being degraded by ice, clouds, or volcanic aerosol.

Latitudinal coverage for MLS observations alternates with the UARS satellite yaw maneuver which occurs approximately every 36 days. It covers from 80° on one side of the equator to 34° on the other side of the equator. The vertical coverage of MLS O_3 data is from 100 to 0.1 hPa. Ozone is measured at both 183 and 205 GHz. Ozone data from 183- and 205-GHz channels are better used in the mesosphere and stratosphere, respectively [*Froidevaux et al.*, 1996; *Ricaud et al.*, 1996]. An MLS O_3 (version 3) validation study [*Froidevaux et al.*, 1996] showed that the best accuracy of the ozone data (205 GHz) is between 22 and 2.2 hPa with an estimated error bar of ~5%. The estimated accuracy decreases to ~10% at 1 hPa and 15% at 0.46 hPa. The largest inaccuracy is expected to be at 100
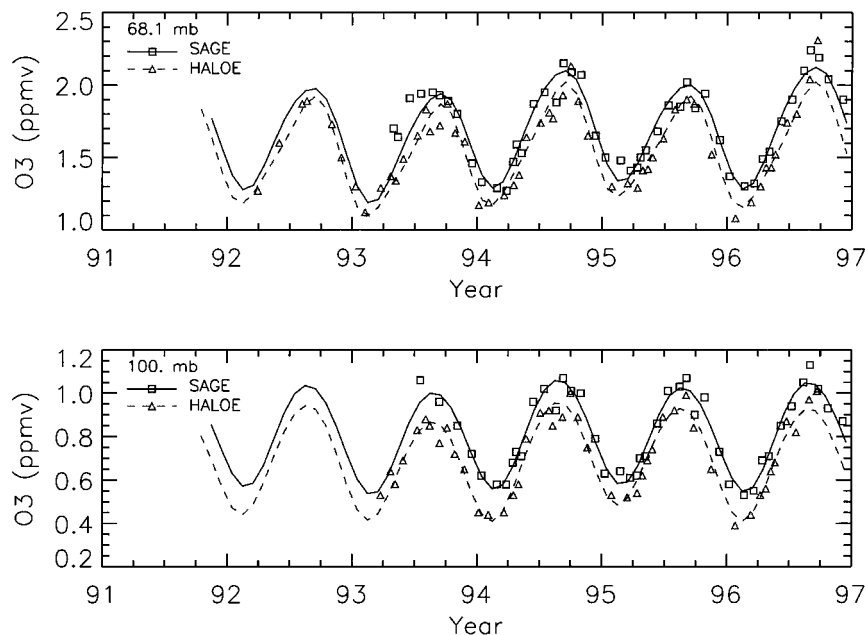
Figure 1. Time series of monthly zonal mean ozone (ppmv) from SAGE (V5.96) (squares) and HALOE (V18) (triangles) at 68 and 100 hPa and between 45 and 50°S. Values are plotted at the midtime of the measurements. The curve fits, which are dominated by the seasonal cycle, are indicated by the solid and dashed lines.

hPa, with a magnitude >50%. Ozone retrieved from 183-GHz radiometer radiances has better quality in the mesosphere. Estimated inaccuracies increase from 10% to 30% between 0.46 and 0.1 hPa. The precision of the MLS measurements is ~5% (or better) from 0.46 to 32 hPa [*Froidevaux et al.*, 1996].

MLS version 4 ozone data are used in this study. In general, V4 ozone is 1–2% lower than V3 data between 22 and 0.46 hPa. At 46 and 100 hPa the differences between MLS V4 and V3 ozone show strong latitudinal dependence with largest differences in tropics and smallest in high latitudes. V4 ozone are typically smaller than V3 by 15–25% at 46 hPa but, in compensation, are larger than V3 ozone at 100 hPa by 50% or more (~0.5 ppmv). There is an indication that MLS V4 ozone at low latitudes is too small at 46 hPa and too high at 100 hPa by comparison with ozonesondes [*Hofmann et al.*, 1998]. At other latitudes and altitudes the V4 ozone data, however, are slightly improved over V3 data.

3. A Model of Ozone Vertical Structure

The ozone data from MLS (V4), HALOE (V18), and SAGE II (V5.96) are used to construct monthly mean ozone values for levels between 100 and 0.1 hPa for the period from April 1992 to March 1993. Final ozone results are presented as distributions both on pressure and latitude cross sections and on isentropic and equivalent latitude surfaces. The ozone climatology from each instrument was first analyzed individually. The best estimates of the ozone climatology were then generated by combining the results from all three satellite measurements. Procedures for processing and combining the O_3 data are described below.

3.1. Ozone on Pressure and Latitude Surfaces

MLS ozone 3AT data (3AT indicates that each profile is presented on a common UARS time grid ~4° apart in latitude and corresponding to the 62-s UARS measurement cycle), at every

UARS level (~2.5 km apart), are averaged to produce monthly zonal mean values in 4° latitude bins. All ozone profiles have been filtered by removing those with negative quality (error bar) values or based on other MLS supplied quality indicators [*Waters et al.*, 1996]. The time period used is from April 1992 to March 1993. Because of the UARS yaw maneuver, MLS observations over high-latitude regions are sparse in some months. For a specific month and latitude bin, when there are no measurements, or the total number of sample points is less than the total expected number of measurements for a 10-day period, interpolated values from a seasonal cycle fit to the 1 year of data are used to provide better estimates for the missing data period. The 183-GHz MLS data are processed separately during daytime and nighttime to reflect the diurnal cycle of ozone in the mesosphere. The daytime and nighttime measurements are identified by local solar zenith angles <87° and >93°, respectively. It seems useful to provide just daytime average and nighttime average climatologies because the diurnal cycle of ozone between 1 and 0.1 hPa can typically be approximated by a square wave [*Ricaud et al.*, 1996]. At 1 hPa and below, day/night differences are <5%, and a combined day/night climatology is calculated.

Unlike the MLS instrument, both SAGE and HALOE are solar occultation sensors which provide at most 15 sunrise and sunset profiles per day. Each profile is separated by ~24° in longitude. The latitudinal coverage during a day varies by <1° at turnaround in middle to high latitudes to 5°–8° in the tropics, and there are typically only one day of sunrises and one day of sunsets in a 4° latitude bin per month. We chose to increase the latitudinal bin sizes to 5° so that even in the tropics, bins for most months contain at least 10 sunrises and 10 sunsets. Unfortunately, solar occultation measurements cannot provide a comprehensive climatology from a single year of measurements because of their limited coverage. For this project we have therefore based results from HALOE and SAGE on a number of years

of measurements (October 1991 to December 1996). Both SAGE and HALOE ozone data are first averaged to UARS levels. For SAGE, translating the observations from altitudes to pressure levels is achieved using the National Center for Environmental Prediction (NCEP) temperatures supplied with each SAGE profile. The uncertainty in the NCEP temperatures and in the geopotential heights will add to uncertainties in the SAGE ozone distribution, but an uncertainty of ±100 m in geopotential height only contributes an uncertainty of $\pm2\%$ in ozone (for an ozone mixing ratio scale height of 5 km). Below ~25 km altitude, both SAGE and HALOE O_3 measurements are affected by Pinatubo aerosols, as already indicated; retrieved ozone values below 25 km altitude for SAGE have been included in the time series consistent with the discussion by *Cunnold et al.* [1999]. For example, SAGE data at 46 hPa at midlatitudes is not used before 1993 [see *Hofmann et al.*, 1998]. Some early HALOE data have also been excluded at low altitudes.

To derive estimated ozone values for SAGE and HALOE between April 1992 and March 1993, a regression model is applied to ozone data (not impacted by Pinatubo aerosol) between October 1991 and December 1996 (i.e., Figure 1). Regression coefficients are then used to calculate O_3 between April 1992 and March 1993. In addition to the seasonal cycle the Quasi-Biennial Oscillation (QBO) and long-term trend terms are also included in the regression model to account for natural variability and ozone loss between 1991 and 1996. Finally, the SAGE and HALOE monthly means for April 1992 to March 1993 derived from the regression model were linearly interpolated to the 4° latitude bins used for MLS.

Figure 2 illustrates the monthly mean ozone mixing ratios from MLS, SAGE, and HALOE (at 205 GHz). It shows that all three instruments exhibit similar distributions of monthly zonal mean ozone except in the lowermost stratosphere. Compared to SAGE and HALOE, tropical MLS ozone values are much smaller at 46 hPa and larger at 100 hPa. Similar results were previously indicated in comparisons between MLS (Version 3) and ozonesonde measurements [*Froidevaux et al.*, 1996]. The MLS anomaly in the lower stratosphere is evident in Figure 3, which shows differences between MLS and the other two sensors based on collocated measurements. In addition, there are systematic differences between the SAGE and the HALOE measurements which exceed 5% (SAGE higher) at 46 hPa and higher pressures in the tropics and at 68 and 100 hPa at midlatitudes. Because ozonesondes are in better agreement with the HALOE data [*Bhatt et al.*, 1999] than with the SAGE data (Cunnold et al., submitted manuscript, 1998), only the HALOE data will be used in the reference distribution at these locations (see Figure 4).

Between 1 and 32 hPa the differences between the three sets of measurements do not exceed ~5% (using sunrise-sunset averages for the occultation measurements). The average of the three sets of measurements is therefore used in the reference distribution over this height range. This was preferred over a weighted average because there are small (roughly 5%) systematic differences between the measurements which would have received spatially and temporally variable weighting. The stated accuracy of all three measurements over this height range is better than 10%. The accuracy of the combination is therefore expected to be ~5%.

At pressures <4.6 hPa the MLS (183 GHz) measurements are reported to be more precise than the MLS (205 GHz) measurements [*Froidevaux et al.*, 1996]. This is illustrated in Figure 5, which shows a comparison of the monthly ozone standard deviations derived from the binned individual profile
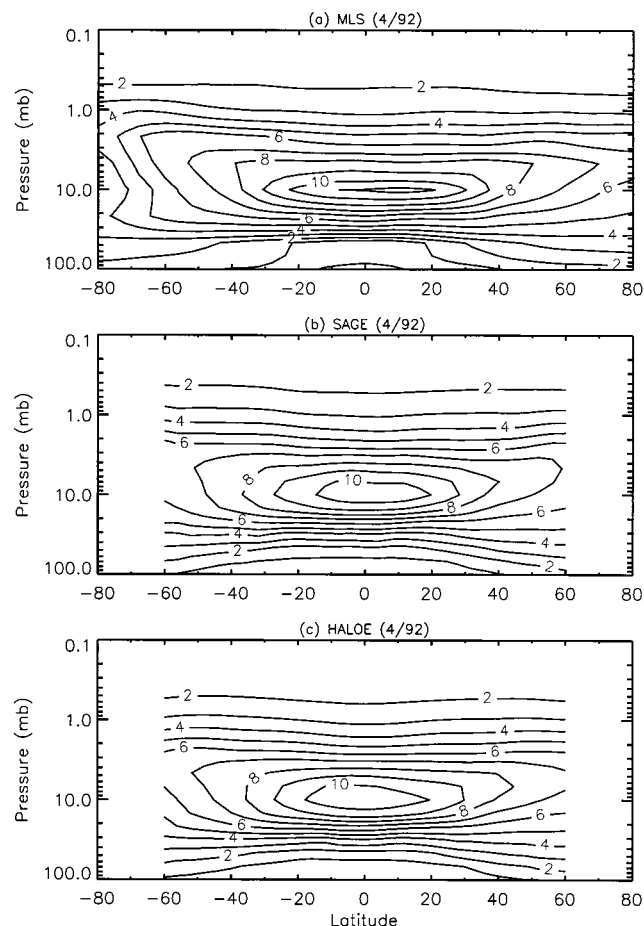

Figure 2. Monthly zonal mean ozone mixing ratios (ppmv) for (a) MLS, (b) SAGE, and (c) HALOE in latitude and pressure cross section for April 1992 obtained directly for MLS (205 GHz) and by curve fit extrapolations similar to those illustrated in Figure 1 for SAGE and HALOE.

measurements in the two channels for April 1992. Not only are the standard deviations above 4.6 hPa at 183 GHz a factor of 2 or more less than those at 205 GHz (consistent with *Froidevaux et al.* [1996]), but SAGE and HALOE standard deviations are even smaller than the MLS (183 GHZ) values at these upper levels. The differences in the latter statement are particularly dramatic above 0.46 hPa, and this is consistent with Table 2a of *Froidevaux et al.* [1996], which gives precisions of 17% at 0.22 hPa and 30% at 0.1 hPa for the 183-GHz measurements. We therefore conclude that measurement imprecision in the individual profile measurements is dominating the monthly standard deviations in the 183-GHz channel above ~0.46 hPa and in the 205 GHz channel above 2.1 hPa. However, *Froidevaux et al.* [1996] also have noted that the accuracy of the 205-GHz measurements is better than that of the 183-GHz measurements at 1 hPa and lower altitudes. We have therefore chosen to use the 205-GHz values for the MLS measurements up to, and including, 1 hPa and to use the 183-GHz values above 1 hPa. This results in some overestimation of ozone variability from MLS measurements due to measurement imprecision from 2.1 to 1.0 hPa, but it is expected to yield the most accurate MLS ozone values. The accuracy of the 183-GHz measurements is 10% at 0.46 hPa, but it decreases to 35% at 0.1 hPa [*Froidevaux et al.*, 1996]. The accuracy of the
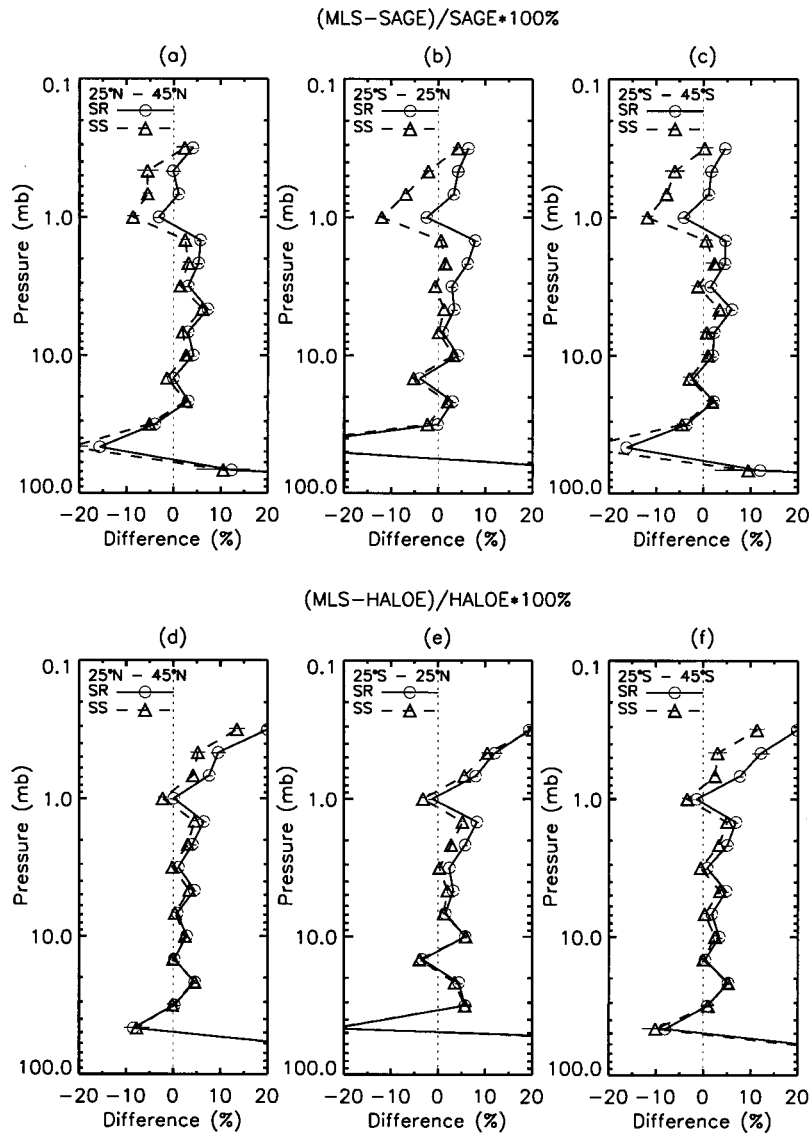
(MLS−SAGE)/SAGE*100%

(MLS−HALOE)/HALOE*100%

Figure 3. (a–c) MLS/SAGE II and (d–f) MLS/HALOE differences in coincident measurements expressed as percentages in the form (MLS-other)/other × 100% over the period 1991–1996 but excluding SAGE aerosol-contaminated data. Solid lines show the sunrise occultation differences, and the dashed lines are for the sunset occultations. Only MLS nighttime measurements at 205 GHz were used in these calculations. The data were placed in three separate bins that extended from 25°N to 45°N, 25°S to 25°N, and 25°S to 45°S. The error bars are twice the standard error of the differences.

MLS (183 GHz), HALOE, SAGE combination (each of which has an accuracy of 10% or better) is expected to be ∼5% at 0.68 and 0.46 hPa and to decrease rapidly at lower pressures.

Above 1 hPa and up to 0.1 hPa the ozone distribution is derived separately during daytime and nighttime periods. For daytime distributions, only MLS ozone (183 GHz) data are used because both SAGE and HALOE are intrinsically nighttime measurements between 1 and ∼0.3 hPa [e.g., *Chu*, 1989; *Chu and Cunnold*, 1994]. For the nighttime case, monthly mean ozone values from all three measurements are averaged at 0.68, 0.46, and 0.31 hPa, and only MLS ozone values are used for levels above 0.31 hPa (where the effective time of the HALOE and SAGE measurements is less clear).

In order to obtain the most consistent ozone distribution, discontinuities in the ozone distribution associated with switching between measurement data sets (see Figure 4) should be

avoided as much as possible. Figure 6 shows the ratios of the ozone measurements in the two MLS channels for several months. The 183-GHz values are typically 5% smaller than the 205-GHz values, but at 1 hPa, where the transition between the two MLS channels is made, the differences are closer to zero. Moreover, slightly smaller ozone values at 0.68 and 0.46 hPa, as seen in the 183-GHz data, are more consistent with the HALOE measurements, as may be seen by referring back to Figure 3. Therefore we have made no adjustments to any data at the 1-hPa transition. However, there is an obvious problem with one of the two MLS data sets poleward of 60°S near 1 hPa in July 1992. Since the problem area is in complete darkness at that time, the occultation measurements are unable to indicate which MLS channel is correct. We are therefore forced to rely on the horizontal and temporal continuity of the contours to decide that it is the 183-GHz measurements which are in error.
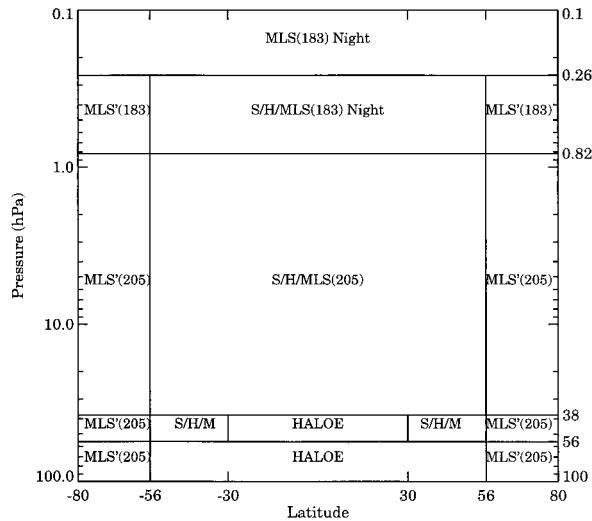
Figure 4. The data use pattern employed in creating the nighttime reference distribution. S/H/M means that the data from all three sensors are averaged. MLS' indicates that the data have been adjusted by a factor close to unity to reduce the possibility of latitudinal discontinuities. The daytime reference distribution is identical up to 1.0 hPa, but above that pressure level it is based entirely on the 183-GHz MLS measurements.

Accordingly, in May, June, and July 1992 we use the 205-GHz measurements at 0.68 hPa poleward of 60°S.

The occultation measurements do not provide complete annual coverage poleward of 56° latitude. Hence at high latitudes

only the MLS observations are used to define the reference distribution. In order to avoid a discontinuity at the transition latitude the ratios between the means at 56° latitude and the MLS values have been calculated (Figure 7). Figure 7 shows that these ratios typically lie between 0.95 and 1.05; this is another indication of the excellent consistency between the MLS, SAGE, and HALOE ozone data sets. Ratios have also been calculated at 48°, 52°, and 60° latitude; these calculations indicate that the ratios shown in Figure 7 are essentially independent of latitude. Therefore poleward of 56° latitude, in order to avoid the possibility of a small discontinuity there, the MLS values have been multiplied by the factors shown in Figure 7. Note that at 100 hPa the factors decrease to 0.7 in the spring. This is associated with the questionable quality of the MLS data at this level, and it results in significant uncertainty in the reference ozone distribution at 100 hPa poleward of 56° latitude, where the MLS data are used, and in an overestimation of ozone variability poleward of 56° latitude below 46 hPa because of the large imprecision of the MLS measurements there. Elsewhere, up to 0.46 hPa, the three sets of measurements (as shown in Figures 3 and 7) are consistent with the accuracy of the reference distribution being ~5%. Above 0.31 hPa where only the MLS values are used, the stated accuracy of the MLS (183 GHz) measurements is ~25% [*Froidevaux et al.*, 1996].

The reference ozone distribution created using the procedures described above, which are summarized in Figure 4, is shown in Figure 8. It contains several well-known features. For example, the upward and poleward extension of the 7-ppmv contour in winter may be noted. This arises from the reduced,
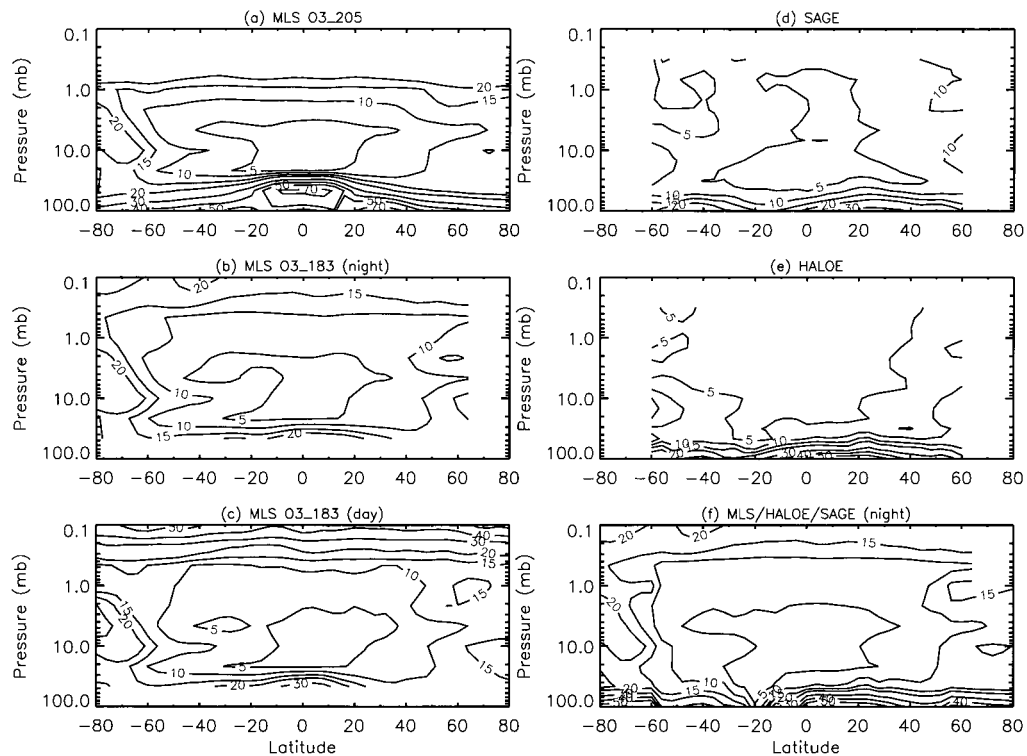

Figure 5. Standard deviations about monthly zonal mean ozone for April 1992 from (a) MLS (205 GHz), (b) MLS (183 GHz) nighttime measurements, (c) MLS (183 GHz) daytime measurements expressed as percentages of the monthly mean values for each sensor, (d) SAGE and (e) HALOE measurements. (f) The reference atmosphere, combined standard deviations for April. Note that the standard deviations above 0.31 hPa are dominated by the imprecision of the MLS (183 GHz) measurements.
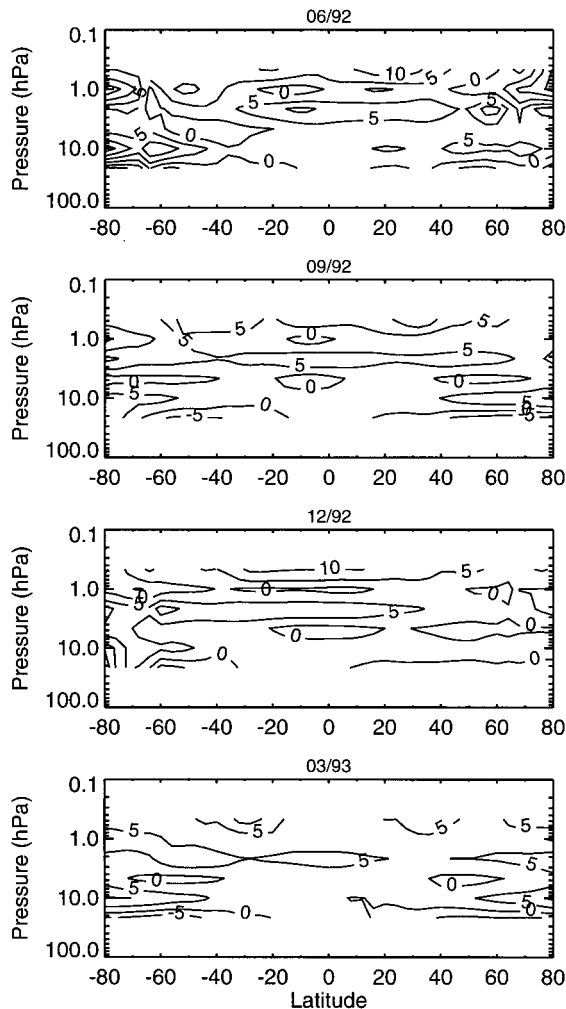
Figure 6. The ratio of differences between MLS measurements of zonal monthly means of ozone at 205 GHz and at 183 GHz (nighttime) expressed as a percentage of the 183-GHz values. Distributions are shown for June, September, and December 1992 and for March 1993.

and strongly temperature-dependent, ozone loss rate in winter which possesses a stronger latitudinal variation at ~2 hPa than does the photochemical ozone production process [*Cunnold et al.*, 1976; *Frederick et al.*, 1984; *Perliski et al.*, 1989]. The ozone maximum at 10 hPa, which is photochemically produced, may be seen to move back and forth across the equator with the Sun, and the area of the 10-ppmv contour, for example, is maximum at the equinoxes [*Perliski et al.*, 1989]. The Antarctic ozone hole is also evident in the upturned ozone contours in the low stratosphere in September and October poleward of 60°S. The smaller daytime concentrations of ozone above 1 hPa than at night are also evident; note, however, that the separation into daytime and nighttime values means that the contours contain gaps at these levels poleward of 60° latitude at the solstices.

The standard deviations of monthly mean ozone (expressed as percentages of the mean) were shown for April in Figure 5; the SAGE and HALOE standard deviations were obtained by fitting seasonal cycle terms to the time series of monthly standard deviations of the binned individual profiles from October 1991 to 1996. Over the 31 to 3.1 hPa pressure range, there is a

tendency for the MLS standard deviations to be larger than those from SAGE and HALOE. This is probably due to the limited sampling each month associated with the occultation instruments. The reference model standard deviations have been obtained by applying the data combinations indicated in Figure 4 to the standard deviations obtained from the individual instruments (i.e., by averaging the individual standard deviations). Because of the 10% imprecision of the 205-GHz MLS measurements at 1 hPa [*Froidevaux et al.*, 1996] the combination is likely to result in a small overestimation (e.g., 2%) of the standard deviations there; more importantly, above 0.31 hPa the standard deviations are similar to the imprecision of the MLS (183 GHz) measurements and are unlikely to provide any information on ozone variability. This is further illustrated in Figure 5 by the exceptionally large daytime standard deviations at the uppermost levels which, expressed in ppmv, are similar to nighttime values but which appear to be much larger when expressed as percentages because of the smaller mean concentrations in the daytime. The measurement precision associated with the standard deviations as already discussed is roughly 5% from 0.46 to 32 hPa. This means that the reported standard deviations in the summer and in the tropics may be influenced by measurement noise. Below 46 hPa the HALOE observations have a precision of roughly 10%, but the precision of the high-latitude MLS observations is expected to be considerably poorer.

The standard deviations obtained by combining the results from the individual sensors are shown for each month of the year at selected latitudes in Figure 9. The standard deviations are <5% over a broad region extending from ~20 to 2 hPa over the tropics and middle and high latitudes in the summertime. At these levels they reach ~15% in the winter at middle and high latitudes (poleward of 50°). Below 20 hPa the standard deviations increase with decreasing height, reaching 30–50% below 46 hPa. There are local minima in the standard deviations at midlatitudes near 3–5 and 30 hPa, especially in winter. The former is associated with a transition in the phase relationship between ozone and temperature variations [e.g., *Douglass et al.*, 1985; *Newchurch et al.*, 1995], while the latter is near the ozone concentration maximum. Substantial variability may also be noted at the time and location of the antarctic ozone hole in October.

The daytime reference distribution of ozone from these measurements is the same as the nighttime distribution at pressures >1 hPa. The differences above the corresponding altitude are illustrated in Figure 10, which shows the ratio of the nighttime to the daytime ozone mixing ratios; these ratios (based on HALOE/SAGE/MLS measurements) are not noticeably different if they are obtained from the MLS measurements only. It is apparent that the latitudinal variation in this ratio is small.

3.2. Ozone on Isentropic and Equivalent Latitude Surfaces

The potential vorticity on an isentropic surface can be treated as a conservative tracer for adiabatic and frictionless motion; thus the potential vorticity contour is essentially a streamline for the flow. It has been used as a diagnostic for large-scale dynamical processes such as evolution of the vortex [*McIntyre and Palmer*, 1983, 1984; *Butchart and Remsberg*, 1986]. Equivalent latitude is defined as the latitude which encloses the same polar area as the potential vorticity contour [*Norton*, 1994; *Lary et al.*, 1995]. Using equivalent latitude as the horizontal coordinate is especially useful when the polar
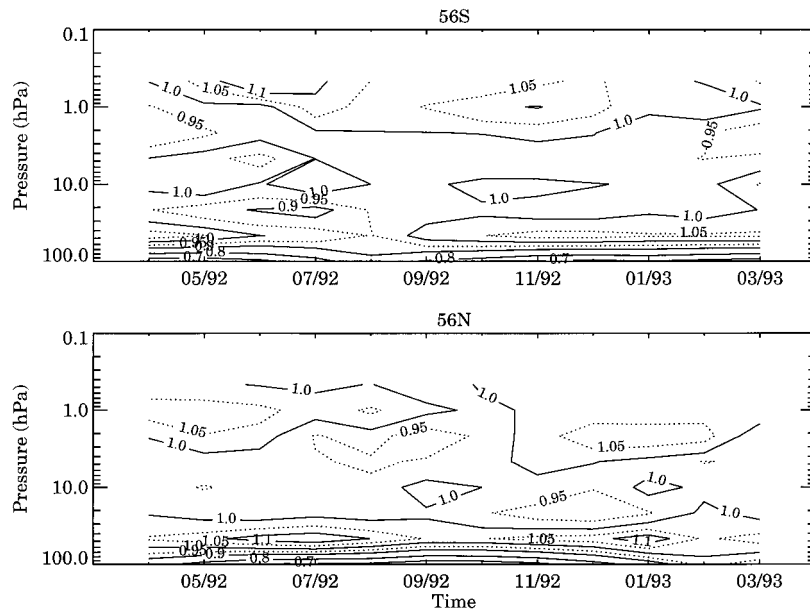
Figure 7. The monthly adjustment factors used to multiply MLS values at latitudes beyond 56° where HALOE and SAGE values are not used. The factors are equal to the ratio of monthly mean ozone between the SAGE/HALOE/MLS averaged values and MLS ozone values at 56°S and 56°N latitude.

vortex is far from symmetrically located over the pole. For example, when the vortex is displaced from the pole or it is distorted without change of size [*McIntyre*, 1983; *Zurek et al.*, 1996], conventional Eulerian zonal means around latitude circles typically include air masses located both inside and outside the vortex. This results in larger variations in potential vorticity and conservative trace gases around the latitude circle [*Randel et al.*, 1998]. Representing ozone in an equivalent latitude and isentropic surface (i.e., modified Lagrangian mean) coordinate system can provide important complimentary information to ozone on pressure and latitude surface, particularly in the lower stratosphere.

Ozone is long-lived in the lower stratosphere and will typically exhibit less variability along flow lines on isentropic levels (i.e., lines of constant potential vorticity (PV)) than in a latitude and pressure presentation. However instead of presenting the results as a function of PV and potential temperature, it is more common to replace PV by the equivalent latitude. There is a one-to-one correspondence between PV and equivalent latitude at a specified time but using equivalent latitude instead of PV removes the effect of seasonal changes in PV amplitudes.

The same ozone data as in previous sections (Figure 4) are used in this analysis. Since the potential vorticity approach is only beneficial in the lower stratosphere where ozone has a long chemical lifetime, only MLS ozone data at 205 GHz are used together with SAGE and HALOE ozone data. The procedure used to process the ozone data is as follows: for each MLS ozone profile, MLS reported temperature values are used to derive potential temperatures at the UARS levels. Ozone values are then linearly interpolated to 14 predefined potential temperature levels. These predefined levels are 420, 465, 520, 585, 655, 740, 840, 960, 1100, 1300, 1500, 1700, 1900, and 2100 K; these values are chosen to approximate the UARS levels between 100 and 0.68 hPa. For each day the potential vorticities were first calculated from U.K. Meteorological Office (UKMO) data on the isentropic surfaces indicated above. The

equivalent latitudes were then assigned to the PV values. The potential vorticities (and corresponding equivalent latitudes) at MLS measurement locations then could be obtained by interpolation from the UKMO gridded fields.

Both SAGE and HALOE report temperature data along with ozone profiles. For SAGE data the temperature profiles are generated based on the NCEP data. HALOE retrieves its own temperatures from the 2.8-μm CO_2 band but only for altitudes above 35 km [*Park et al.*, 1979; *Hervig et al.*, 1996]. Below 35 km the NCEP temperatures are also used. Ozone and temperature profiles from SAGE and HALOE are first vertically averaged to UARS levels. Again potential vorticities and hence equivalent latitudes at SAGE and HALOE measurement locations are assigned on the isentropic levels using the UKMO gridded PV fields.

Figure 11 shows the calculated MLS adjustment factors (as in Figure 6) in this coordinate system at 56°S, 56°N, and 64°N. These factors show a seasonally varying pattern at 64° latitude, but only a slight tendency for a similar pattern at 56° latitude. This suggests sampling and precision differences between the satellite measurements. The largest differences are found at the winter solstice. Because of wave activity, potential vorticity contours are often not centered over the pole in winter, and at altitudes above 10 hPa and at most latitudes, ozone is controlled more by chemistry than by transport. Polar air that gets advected to subtropical latitudes in winter will be quickly affected by the photochemical conditions characteristic of the subtropics. Because of limitations of the solar occultation technique associated with the satellite orbit inclination, the majority of both SAGE and HALOE observations (especially in winter) are for latitudes equatorward of 55°. On the other hand, MLS, which uses the limb emission technique, provides more evenly distributed latitudinal coverage (from 80°N to 80°S). Therefore, when comparing the results at high latitudes (i.e., for equivalent latitudes poleward of 60°) in winter, HALOE and SAGE are mostly observing air that has been exposed to photochemical conditions characteristic of lower lat-
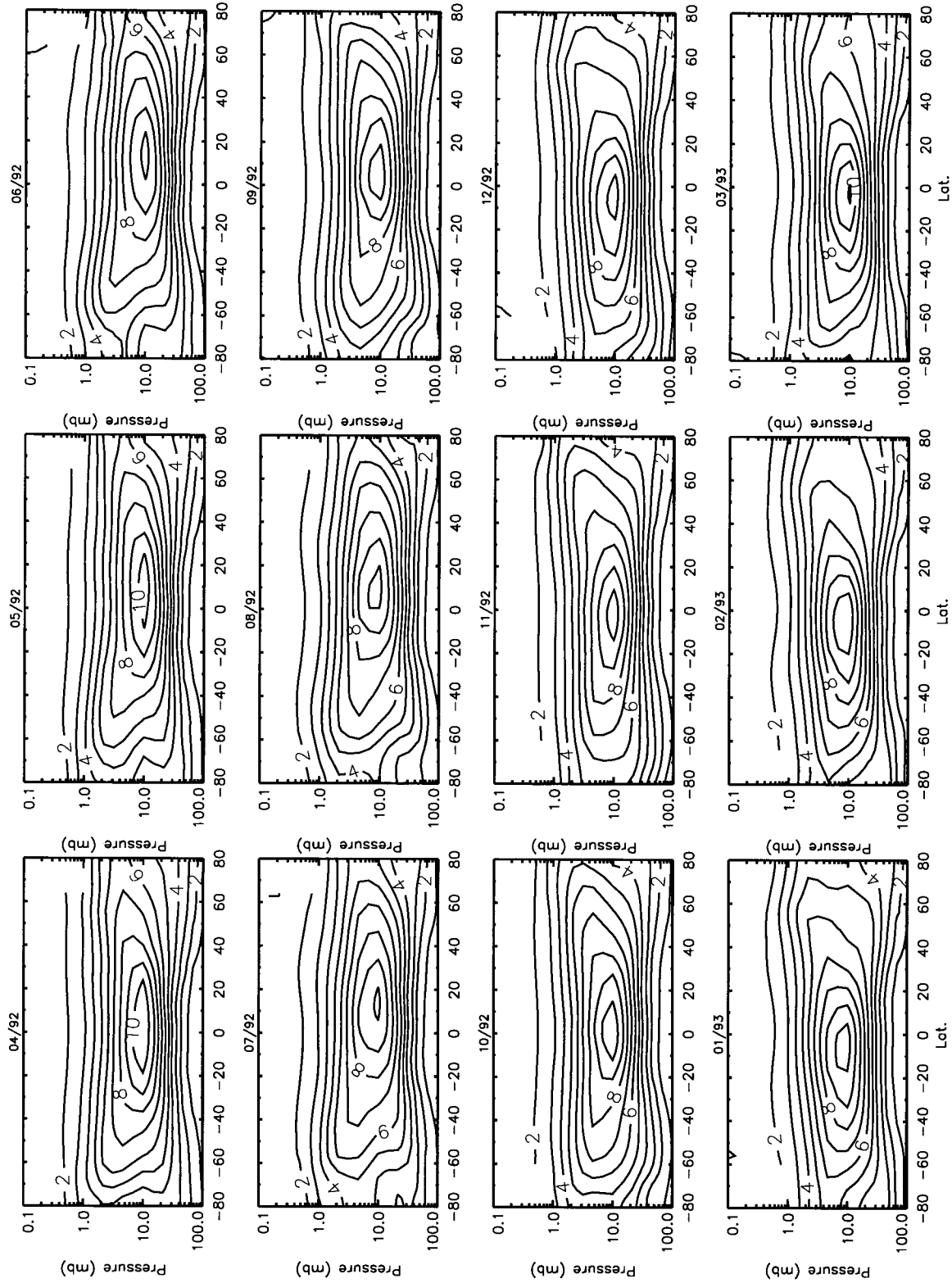
Figure 8. Monthly zonal mean ozone mixing ratios (ppmv) from the combined SAGE, HALOE, and MLS measurements in pressure and latitude coordinates for each month from April 1992 to March 1993. Above 1 hPa, nighttime ozone values are shown. This is the reference atmosphere ozone distribution for nighttime.
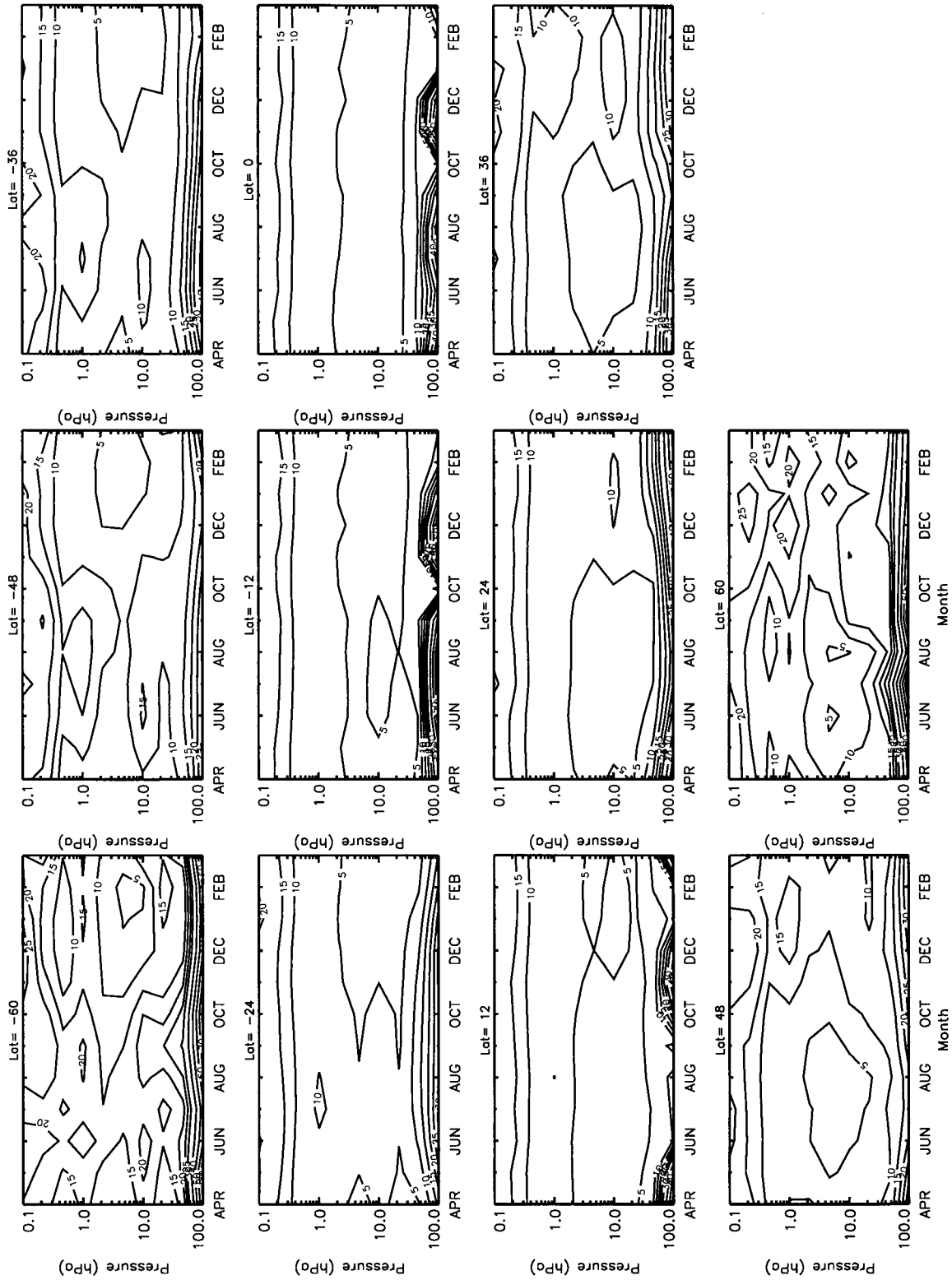
Figure 9. Monthly standard deviations at selected latitudes expressed as percentages of monthly mean ozone obtained by averaging the standard deviations based on the data combinations indicated in Figure 4. Above 1 hPa, nighttime values are shown. Note that the standard deviations contain both natural variability and measurement imprecision and that the latter contribution is likely to be particularly large above 0.31 hPa and below 46 hPa poleward of 56° latitude.
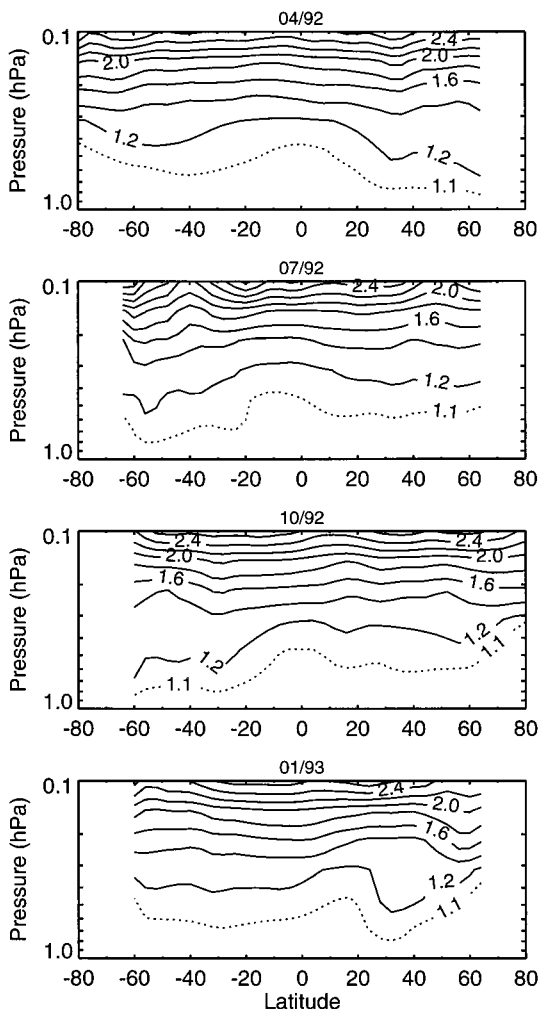
Figure 10. The ratio of the average of the nighttime ozone measurements by MLS (183 GHz) and from SAGE and HALOE occultation (effectively nighttime) measurements up to 0.31 hPa to the MLS (183 GHz) daytime measurements.

itudes, whereas MLS provides a more complete sampling of the ozone at each equivalent latitude. By making the data transition as in Figure 4 at 56° latitude, the aliasing of the mean of the data sets is very small.

The combined reference ozone distribution in this coordinate system is shown in Figure 12. Differences between these distributions and those on pressure-latitude surfaces (Figure 8) are small except for a flattening of the contours towards the isentropes which is evident in the lower stratosphere. This is further illustrated in Figure 12 in the ratios of the monthly mean ozone values at equivalent latitude/potential temperature grid points to the values at similar latitude and (latitudinally averaged) equivalent pressure locations. The differences in the lower stratosphere are caused by the combination of potential temperature surfaces which cross pressure levels and the strong vertical gradients of ozone.

The expectation of the potential temperature/equivalent latitude approach is to obtain smaller standard deviations particularly in the winter and early spring at mid and high latitudes. The combined standard deviations are shown in Figure 13. The differences between this approach and the pressure-latitude distributions are illustrated in Figure 13 (right) which shows

the ratios of the pressure-latitude standard deviations to the potential temperature-equivalent latitude values. Monthly ozone variations in the lower stratosphere in winter at mid and high latitudes are reduced significantly compared to the latitude-pressure plots. For example, between 420 and 520 K (100 to 46 hPa) and at all levels in winter the magnitude of ozone variations from SAGE and HALOE measurements are about one half those in pressure and latitude coordinate. On the other hand, in summer the variability increases in this coordinate system. This must be because PV values are small in summer and the analyzed PV fields do not provide an accurate indication of the location of individual air masses at that time.

4. Differences From the *Keating et al.* [1996] Results

A detailed comparison of the ozone distribution compiled by *Keating et al.* [1996] and that presented here was reported by *Wang and Cunnold* [1998]. In brief, the differences are as follows: overall, the differences are up to 10% in ozone mixing ratio, which in significant part reflects the atmospheric ozone losses from the early 1980s to 1992–1993. The results presented here are, however, more extensive in latitude and extend to higher pressures (100 hPa). There are substantial differences
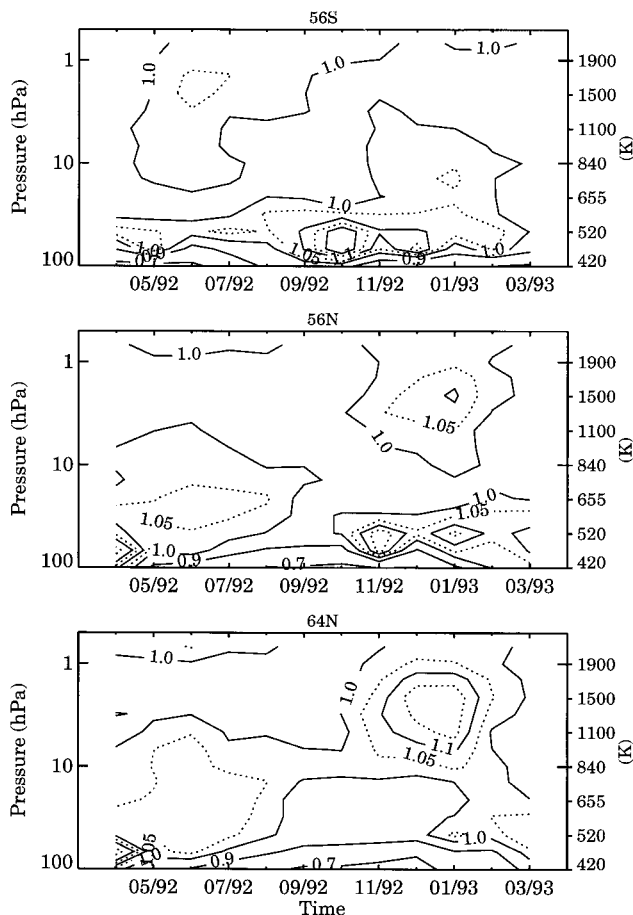

Figure 11. The ratio of averaged monthly mean ozone from SAGE, HALOE, and MLS to MLS ozone values alone at 56°S, 56°N, and at 64°N. The factors at ±56° are used to multiply the MLS values at latitudes greater than 56° in order to reduce the possibility of discontinuities in the distributions.
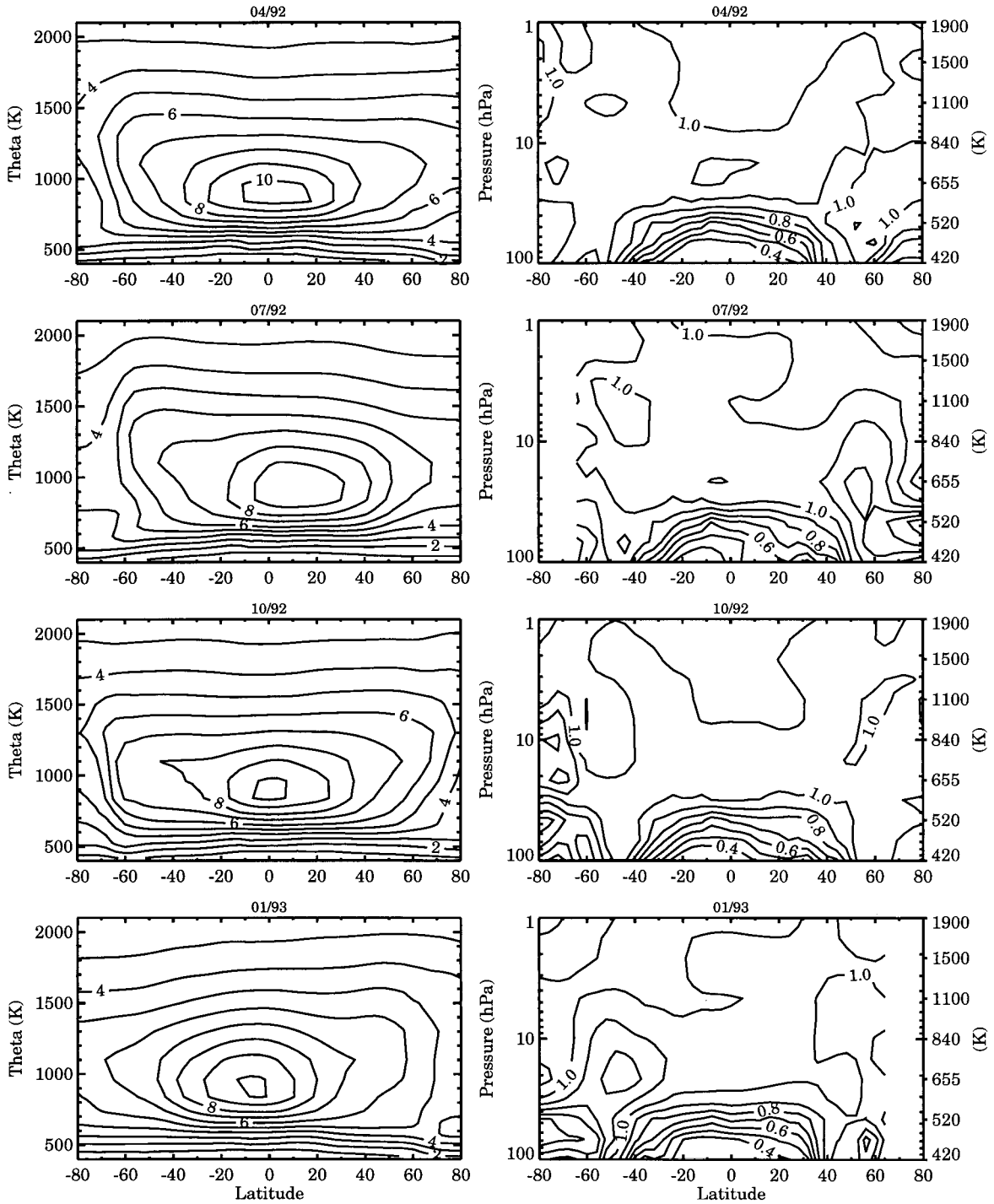
Figure 12. (left) Combined monthly mean ozone mixing ratios (ppmv) from SAGE, HALOE, and MLS measurements in an isentropic and equivalent latitude coordinate system for April, July, and October 1992 and for January 1993. (right) The ratios of the monthly means in Figure 8 to values in Figure 12 (left); these ratios are based on a mean pressure being assigned to each potential temperature level and on latitudes and equivalent latitudes being treated as equivalent.

in the diurnal cycle of ozone, which in our analyses is relatively uniform in latitude, probably because Keating et al. had to combine results from two different sensors in order to derive a diurnal variation. Moreover, in contrast to Keating et al., our annual cycle of ozone at midlatitudes shows good hemispheric symmetry. Some of this difference may reflect atmospheric

differences between the two time periods. The Keating et al. standard deviations are also <4% in the tropics from 10 to 0.5 hPa. This reduced variability may reflect the reduced vertical resolution of the SBUV observations (about 8 km) used by Keating et al. versus the 2.5–5 km vertical resolution of the observations used here.
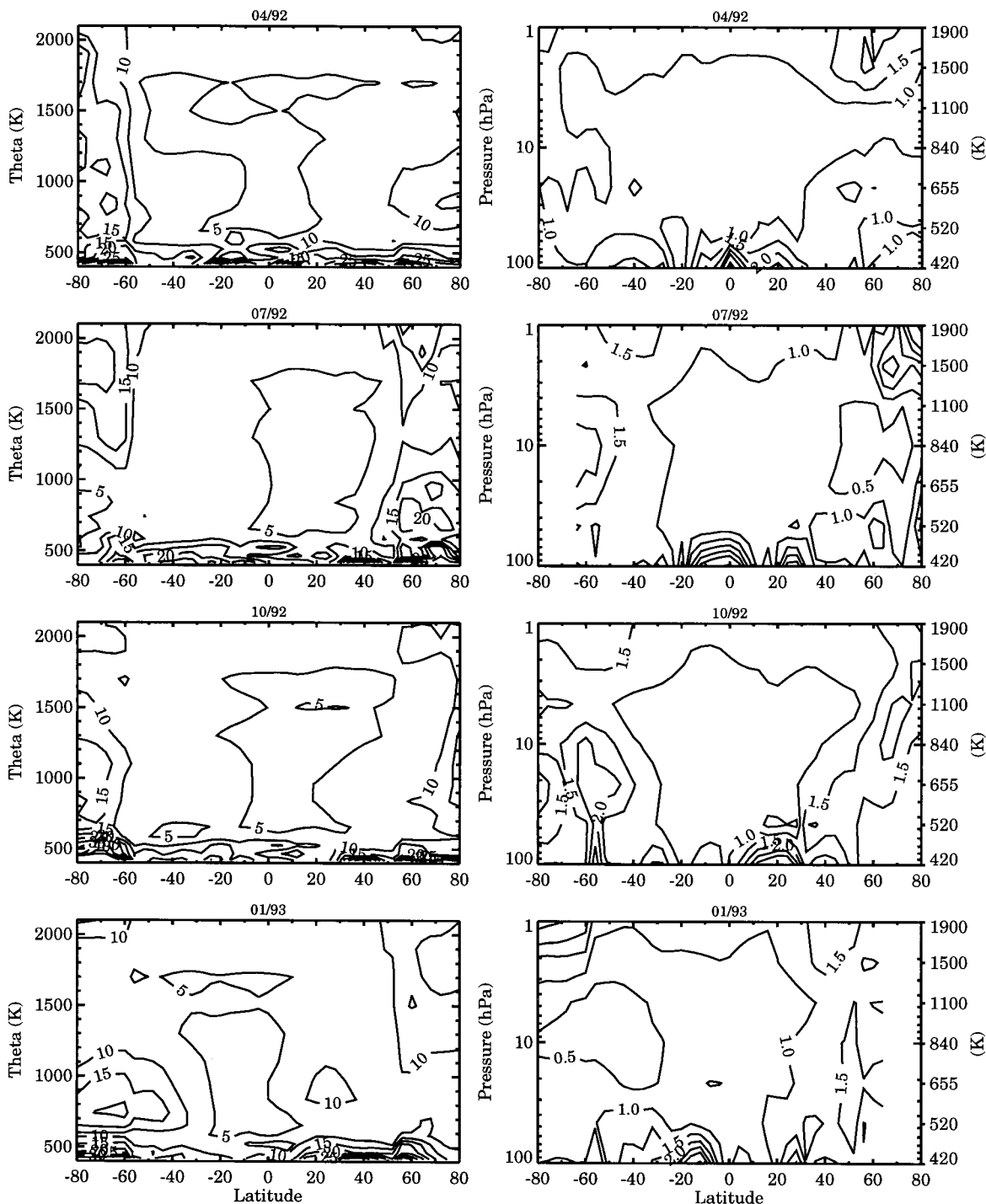
Figure 13. Similar to Figure 12, but for the standard deviations of ozone in percentages of the monthly means.

5. Conclusions

Monthly mean ozone values and standard deviations for April 1992 to March 1993 have been presented in the form of pressure-latitude distributions and of potential temperature-equivalent latitude distributions. The distributions are based on MLS measurements from April 1992 to March 1993 and on SAGE and HALOE measurements from 1991 to 1996. Where differences between the three sets of measurements are ≲10%, the measurements have been averaged to produce best estimates. On the other hand, where there are known limitations in the data sets, for example, MLS values at pressures greater than 40 hPa and SAGE values in the tropics at pressures ≳60 hPa; the questionable measurements have not been included. At pressures <1 hPa, MLS (183 GHz) measurements were used, whereas at higher pressures the MLS (205 GHz) measurements were used. The 183-GHz observations were also used to produce separate high altitude daytime-only distributions. Figure 4 summarizes the data usage pattern.

On the basis of comparisons between data sets and the reported accuracies of the measurements we believe the ozone reference distribution has an accuracy of ~5% from 0.46 to 32 hPa and ~10% at 46 and 0.31 hPa. From 0.22 to 0.1 hPa, only MLS (183 GHz) observations are used, and their accuracy is estimated to be 17–30% [*Froidevaux et al.*, 1996]. At 100 hPa, HALOE observations, which were used everywhere except at latitudes exceeding 56°, have an estimated accuracy of 30% or better [*Bruhl et al.*, 1996]. At higher latitudes where MLS observations are used, we can quote the better than 50% accuracy estimate from *Froidevaux et al.* [1996], but we believe that because the ozone mixing ratios are largest at high latitudes, the accuracy is substantially better than this.

Standard deviations of the MLS ozone values have been calculated from latitudinally binned measurements over individual months from April 1992 to March 1993. The same procedure has been applied to SAGE and HALOE measurements except that the monthly standard deviations were then placed in time series from October 1991 to 1996 and the estimated standard deviations for the months for April 1992 to March 1993 were obtained from an empirical model fit to the 1991–1996 time series. Finally, the combined monthly standard deviations were obtained by averaging the standard deviations from MLS, SAGE, and HALOE (based on Figure 4).

The reported monthly standard deviations are expected to overestimate ozone variability in some locations because of contributions from measurement imprecision. From 0.46 to 46 hPa the measurement precision, associated with combination of the measurements used, is ~5%; for the HALOE measurements used for the reference distribution at 68 and 100 hPa equatorward of 56° the measurement imprecision is estimated to be ~10%. Above 0.31 hPa, and poleward of 56° latitude below 46 hPa, MLS measurement imprecision is expected to dominate the reported variability.

The potential temperature-equivalent latitude monthly mean ozone distributions exhibit barely noticeable differences from the pressure-latitude distributions, but the former do possess less variability in the lower stratosphere (below 20 km altitude) and in winter at middle and high latitudes. Elsewhere, the variability increases slightly, which suggests that the potential temperature-equivalent latitude representation is not particularly useful in summer and in the tropics. This is particularly true in the upper stratosphere where ozone is photochemically controlled. There it has been shown that the solar occultation technique can produce biased monthly means at equivalent latitudes ≳56°. (The reference distributions of both daytime (O3_DAY) and nighttime (03_NIGHT) ozone can be accessed at UARS Reference Atmosphere Project (URAP) Web page at http://hyperion.gsfc.nasa.gov/Analysis/UARS/urap/home.html.)

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