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Evaluation of ozone and water vapor fields from the ECMWF reanalysis ERA-40 during 1991–1999 in comparison with UARS satellite and MOZAIC aircraft observations

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[1] The European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year Reanalysis (ERA-40) ozone and water vapor reanalysis fields during the 1990s have been compared with independent satellite data from the Halogen Occultation Experiment (HALOE) and Microwave Limb Sounder (MLS) instruments on board the Upper Atmosphere Research Satellite (UARS). In addition, ERA-40 has been compared with aircraft data from the Measurements of Ozone and Water Vapour by Airbus In-Service Aircraft (MOZAIC) program. Overall, in comparison with the values derived from the independent observations, the upper stratosphere in ERA-40 has about 5–10% more ozone and 15–20% less water vapor. This dry bias in the reanalysis appears to be global and extends into the middle stratosphere down to 40 hPa. Most of the discrepancies and seasonal variations between ERA-40 and the independent observations occur within the upper troposphere over the tropics and the lower stratosphere over the high latitudes. ERA-40 reproduces a weaker Antarctic ozone hole, and of less vertical extent, than the independent observations; values in the ozone maximum in the tropical stratosphere are lower for the reanalysis. ERA-40 mixing ratios of water vapor are considerably larger than those for MOZAIC, typically by 20% in the tropical upper troposphere, and they may exceed 60% in the lower stratosphere over high latitudes. The results imply that the Brewer-Dobson circulation in the ECMWF reanalysis system is too fast, as is also evidenced by deficiencies in the way ERA-40 reproduces the water vapor "tape recorder" signal in the tropical stratosphere. Finally, the paper examines the biases and their temporal variation during the 1990s in the way ERA-40 compares to the independent observations. We also discuss how the evaluation results depend on the instrument used, as well as on the version of the data.

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1. Introduction

[2] During the last three decades satellites have been an important source of atmospheric data. They have been providing measurements for a range of atmospheric species, with good temporal and geographical coverage. These measurements may, however, have substantially different accuracies; they are not uniformly distributed in space or time; and data suppliers commonly release upgraded products, so that research findings may need to be checked.

[3] The above shortcomings have been ameliorated, to some extent, as a result of improved methods in data assimilation. The latest reanalysis, European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year Reanalysis (ERA-40) [*Uppala*, 2001], is based on the use of a single, 3-D (variational) data assimilation scheme, which has processed data from September 1957 to August 2002 in a consistent manner. Together with the reanalysis from National Center for Atmospheric Research/National Centers for Environmental Prediction (NCEP/NCAR), which spans the period from 1948 onward [*Kalnay et al.*, 1996; *Kistler et al.*, 2001], ERA-40 provides global analyses of the atmosphere during this period. For atmospheric ozone and water vapor, ERA-40 currently represents the largest continuous data sets available. ERA-40 was set up in order to improve further the results of the previous reanalysis, ERA-15, which was also produced by ECMWF covering the period January 1979 to February 1994 [*Gibson et al.*, 1997].

[4] Even though several difficulties are still encountered in data assimilation schemes, they are considered an indispensable scientific technique, particularly when applied in weather forecasting and environmental monitoring. A principal question regarding the output of such schemes is to what extent the reanalysis results are trustworthy, especially

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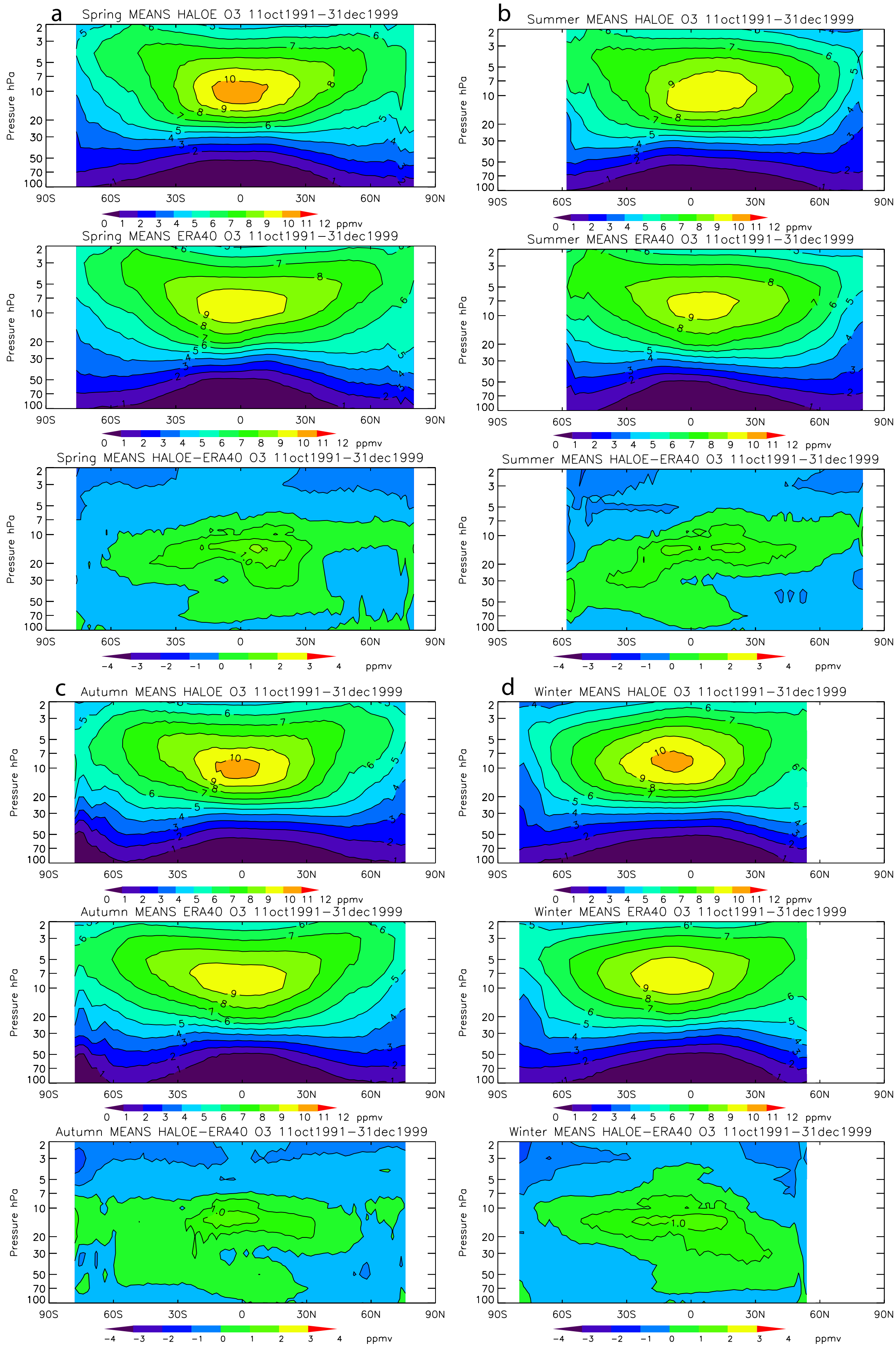
a
Spring MEANS HALOE O3 11oct1991–31dec1999
Spring MEANS ERA40 O3 11oct1991–31dec1999
Spring MEANS HALOE–ERA40 O3 11oct1991–31dec1999
b
Summer MEANS HALOE O3 11oct1991–31dec1999
Summer MEANS ERA40 O3 11oct1991–31dec1999
Summer MEANS HALOE–ERA40 O3 11oct1991–31dec1999
c
Autumn MEANS HALOE O3 11oct1991–31dec1999
Autumn MEANS ERA40 O3 11oct1991–31dec1999
Autumn MEANS HALOE–ERA40 O3 11oct1991–31dec1999
d
Winter MEANS HALOE O3 11oct1991–31dec1999
Winter MEANS ERA40 O3 11oct1991–31dec1999
Winter MEANS HALOE–ERA40 O3 11oct1991–31dec1999
Pressure hPa
90S 60S 30S 0 30N 60N 90N
0 1 2 3 4 5 6 7 8 9 10 11 12 ppmv
–4 –3 –2 –1 0 1 2 3 4 ppmv

Figure 1

in areas and times where no observations are assimilated into the data assimilation system. To answer this question, the reanalysis results need to be validated against independent sets of data, i.e., those data that have not been used in producing the reanalysis.

[5] The purpose of the present work is to provide a systematic evaluation of the ERA-40 ozone and water vapor products, two of the most fundamental and widely used in research atmospheric species. To do so, the ERA-40 ozone and water vapor fields during the 1990s are compared with two sets of independent measurements that were not utilized in generating the reanalysis. The first are measurements from the Halogen Occultation Experiment (HALOE) and Microwave Limb Sounder (MLS) instruments on board the Upper Atmosphere Research Satellite (UARS), which was launched in September 1991. These observations are used to evaluate their counterparts in ERA-40 in the stratosphere (1 to 100 hPa). The second set derives from the Measurement of Ozone and Water Vapour by Airbus In-Service Aircraft (MOZAIC) project. The MOZAIC measurements are used for the ERA-40 evaluation in the upper troposphere/lower stratosphere (UTLS) region, typically between 195 and 290 hPa, where data availability is scarce owing to limitations of remote sensing and unreliability at these altitudes of sondes.

[6] The aims of the present study are as follows: (1) to derive the ERA-40 climatologies of ozone and water vapor; (2) to provide a quantitative reference of the ERA-40 performance for ozone and water vapor in comparison with the UARS and MOZAIC observations; (3) to examine the seasonal and geographical variations of these differences in the stratosphere and the UTLS region; (4) to investigate the existence of any biases and their temporal variation in the reanalysis ozone and water vapor products throughout the 1990s; and (5) to study how ERA-40 captures specific phenomena of interest, such as the Antarctic and Arctic ozone holes and the tape recorder signal in water vapor over the tropics.

[7] The ECMWF ERA-40 ozone and water vapor data assimilation schemes are briefly described in section 2, along with the observations assimilated into the system. Section 3 describes the measurements against which ERA-40 is evaluated, and section 4 describes the method used. The results of the comparison for ozone and water vapor are given in sections 5 and 6, respectively. Results are discussed in section 7 and summarized in section 8.

2. ERA-40 Data Assimilation Scheme

[8] ERA-40 used a 3D-variational data assimilation system based on the Integrated Forecasting System (IFS) developed jointly by ECMWF and Météo-France [*Rabier et al.*, 1998]. ERA-40 has T159 spectral resolution in the horizontal and 60 levels in the vertical, of which 26 are in the stratosphere. The system produces a variety of three-dimensional fields, including ozone and water vapor.

[9] In ERA-40 the production and loss of ozone in the stratosphere are governed by an updated version of the chemistry parameterization scheme originally developed by *Cariolle and Déqué* [1986]. The scheme assumes that the chemical changes in ozone can be described by a linear relaxation toward photochemical equilibrium, and the parameterization makes use of the stratospheric equivalent content of chlorine (for further details, see *Dethof and Hólm* [2002, 2004]). To minimize the model bias, ERA-40 makes use of the ozone climatology derived from observations following *Fortuin and Langematz* [1994]. In order to represent some diurnal variability in the ozone field, the parameterization scheme is on only during daylight. Ozone destruction by chlorine activated on polar stratospheric clouds is parameterized when the temperature drops below the 195 K threshold.

[10] With regard to the water vapor field, prior to 1999 and in a preoperational test version of the ECMWF model, the water vapor values in the tropical upper stratosphere and throughout much of the extratropical stratosphere were found to be too low [*Simmons et al.*, 1999]. To avoid an unrealistic drying of the stratosphere, ERA-40 adopted a simple parameterization of the upper stratospheric moisture source due to methane (CH_4) oxidation and more details on this scheme can be found in the ECMWF IFS documentation (http://www.ecmwf.int/research/ifsdocs/) regarding both the scheme used in ERA-40 (Cycle 23r4), as well as the later operational versions of the scheme.

[11] The ozone observations assimilated into ERA-40 are only from satellites and no conventional data are included in the scheme (surface, ozonesonde, profiler, pilot or aircraft measurements). ERA-40 assimilates (1) total column ozone (version 7 data) retrieved from the Total Ozone Mapping Spectrometer (TOMS) [*McPeters et al.*, 1996] and (2) ozone vertical profiles derived from the nadir-viewing solar backscatter ultraviolet (SBUV) [*Bhartia et al.*, 1996].

[12] The water vapor data assimilated into ERA-40 are humidity profiles from radiosondes, which only provide a very limited amount of information in the stratosphere, and radiances from a number of instruments. The radiance data come from the following instruments: (1) the Vertical Temperature Profile Radiometer (VTPR) on board NOAA 2–5 satellites [*McMillin et al.*, 1973]; (2) the Special Sensor Microwave Imager (SSM/I) on board the NOAA satellites of the Defense Meteorological Satellite Program (DMSP) [*Hollinger*, 1990; *Hollinger et al.*, 1990]; and (3) the High Resolution Infrared Radiation Sounder (HIRS/2 and HIRS/3) instruments from both TIROS Operational Vertical Sounding (TOVS) and Advanced TOVS (ATOVS). Nevertheless, the stratospheric humidity fields from ERA-40 are completely unaffected by assimilation of humidity observations. This is because the analysis increments were forced to be zero above a diagnosed model tropopause and the stratospheric humidity was changed by the analysis procedure

Figure 1. Three-monthly HALOE, ERA-40, and HALOE–ERA-40 ozone zonal means for HALOE version 19 combined sunrise and sunset measurements during the period 11 October 1991 to 31 December 1999 for (a) March-April-May (MAM), (b) June-July- AuJJA, (c) SON, and (d) DJF. The contour range for both HALOE and ERA-40 ozone fields is [0, 12] ppmv with a 1 ppmv step. The contour range for the HALOE–ERA-40 differences is [−4, 4] ppmv with a 0.5 ppmv step.

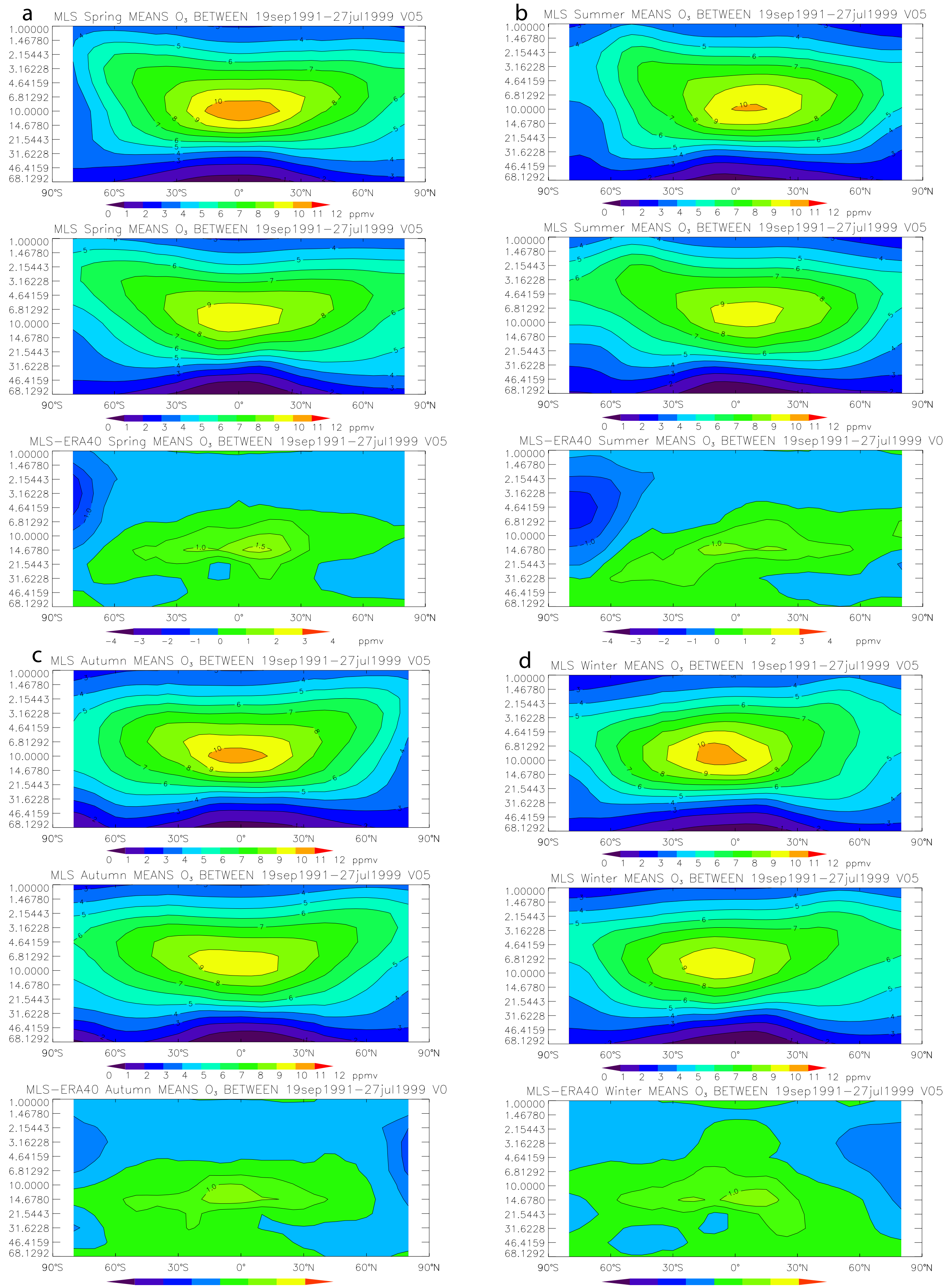
a
MLS Spring MEANS O3 BETWEEN 19sep1991–27jul1999 V05
MLS Spring MEANS O3 BETWEEN 19sep1991–27jul1999 V05
MLS–ERA40 Spring MEANS O3 BETWEEN 19sep1991–27jul1999 V05
b
MLS Summer MEANS O3 BETWEEN 19sep1991–27jul1999 V05
MLS Summer MEANS O3 BETWEEN 19sep1991–27jul1999 V05
MLS–ERA40 Summer MEANS O3 BETWEEN 19sep1991–27jul1999 V0
c
MLS Autumn MEANS O3 BETWEEN 19sep1991–27jul1999 V05
MLS Autumn MEANS O3 BETWEEN 19sep1991–27jul1999 V05
MLS–ERA40 Autumn MEANS O3 BETWEEN 19sep1991–27jul1999 V0
d
MLS Winter MEANS O3 BETWEEN 19sep1991–27jul1999 V05
MLS Winter MEANS O3 BETWEEN 19sep1991–27jul1999 V05
MLS–ERA40 Winter MEANS O3 BETWEEN 19sep1991–27jul1999 V05
1.00000 1.46780 2.15443 3.16228 4.64159 6.81292 10.0000 14.6780 21.5443 31.6228 46.4159 68.1292
90°S 60°S 30°S 0° 30°N 60°N 90°N
0 1 2 3 4 5 6 7 8 9 10 11 12 ppmv
−4 −3 −2 −1 0 1 2 3 4 ppmv

Figure 2

only if it was necessary to remove supersaturation caused by an analysis increment in temperature.

[13] The ERA-40 3D-variational assimilation system adopts a univariate scheme for ozone, in which the background errors of ozone are assumed uncorrelated with background errors in other variables. The ozone background errors are calculated using the method developed by *Fisher and Anderson* [2001]. For water vapor, calibrated (level 1c) radiances are assimilated directly [*Andersson et al.*, 1998], except for total column water vapor derived from the SSM/I radiances, which are assimilated via a 1D-variational scheme, and the TOVS and VTPR measurements that are converted from level 1b (raw radiances) to calibrated level 1c radiances. The major changes undertaken in the ECMWF system and their advantages are summarized by *McNally et al.* [1999].

3. Independent Observations Used for the ERA-40 Validation

3.1. Ozone and Water Vapor Data From the UARS Satellite

[14] The UARS satellite, launched in September 1991, orbits at an altitude of 600 km observing almost the entire globe from 80°N to 80°S. Instruments on board include HALOE and MLS [*Reber*, 1993]. HALOE makes daily 15 sunrise and 15 sunset solar occultation measurements, giving global coverage typically in 3–4 weeks. Its operation has been very stable; *Flaud et al.* [1990], *Russell et al.* [1993] and *Marshall et al.* [1994] give details of the HALOE retrieval algorithm and its errors, and *Brühl et al.* [1996] and *Hervig et al.* [1996] give details of the instrumental errors. The HALOE solar tracking system has performed stably enough to believe that ozone and water vapor trends observed by HALOE are not severely influenced by either the instrument's orbital geometry or any small changes in the azimuth tracking. The eruption of Mount Pinatubo in 1991 released aerosols into the atmosphere that strongly affected the ozone channel below 25 km. The estimation of errors in HALOE data used in this paper includes aerosol-related error. The HALOE processing removes this error with better than 90% accuracy [*Steele and Turco*, 1997]. The official repository for UARS HALOE data is the NASA Goddard Space Flight Center's Distributed Active Archive Center (DAAC). The HALOE archive can be downloaded after registration on http://daac.gsfc.nasa.gov/data/dataset/UARS/HALOE/.

[15] The MLS instrument, also on board UARS, takes day and night measurements [*Jarnot et al.*, 1996]. It comprises three radiometers operating at 63, 183 and 205 GHz [*Barath et al.*, 1993; *Waters*, 1993; *Waters et al.*, 1999]. The MLS retrieval algorithms [*Read et al.*, 2001; *Rodgers*, 1976] produce different levels of output data (J. R. Burke and T. A. Lungu, Upper Atmosphere Research Satellite, Microwave Limb Sounder standard formatted data units, 1996, distributed with MLS data, and available from the MLS home page at http://mls.jpl.nasa.gov/). Despite the high-resolution specifications, MLS experienced several problems during its operation that resulted into periods of sparse or even complete lack of data (see *Livesey et al.* [2003] for the full MLS calendar coverage). Given the problems and data uncertainties encountered in the MLS records, particularly in the LS, and since MLS retrievals were found to be affected by various error sources [*Froidevaux et al.*, 1996], several data versions have been produced in order to improve the quality of the MLS archive. A few changes were made between version 3 [*Froidevaux et al.*, 1996] and version 4 (V4). The latest version 5 (V5) has improved the accuracy and precision of various species in the LS, though the overall precision for ozone data is poorer (except at 100 hPa) compared with V4 [*Livesey et al.*, 2003]. A further version 7.02 is available for water vapor, derived from the MLS 183 GHz radiances [*Read et al.*, 2004a]. Aerosols are believed to have a negligible effect on the MLS data because the signature of Mount Pinatubo is not observed in the measured MLS radiances, thus making MLS extremely valuable to correct other data sets affected by aerosols, such as the SAGE II observations [*Cunnold et al.*, 1996a, 1996b]. Furthermore, studies suggest a 0.1–0.2%/year MLS stability (at least >25 km) when compared with SAGE II and HALOE, as well as when comparing MLS temperatures in the tropics with the NCEP archive [*Stratospheric Processes and their Role in Climate (SPARC)*, 1998]. In the LS, however, the MLS uncertainties are large and depend on the version used. The official repository for the UARS MLS data is DAAC, where MLS data can be directly download from http://daac.gsfc.nasa.gov/data/dataset/UARS/MLS/.

3.2. Ozone and Water Vapor Data From the MOZAIC Program

[16] MOZAIC offers a unique opportunity to evaluate ERA-40 in the UTLS region, where data from the MLS and HALOE instruments are either unreliable or discontinuous in time at aircraft cruise levels. The MOZAIC program of the European Commission was originally developed to study atmospheric chemistry in the UTLS. MOZAIC makes use of commercial flights from four European airlines: Lufthansa, Air France, Austrian Airlines and Sabena (operated by Lufthansa since February 2003). For the purposes of the program, Airbus A340 aircraft have been equipped with specially designed devices that measure in situ ozone [*Marenco et al.*, 1998] and relative humidity (RH), from which the water vapor mass mixing ratio is calculated by applying the Goff-Gratch formula [*Helten et al.*, 1998].

[17] The MOZAIC program extends from January 1993 up to the present. It became fully operational on 1 August 1994 and consists of three phases: (1) MOZAIC-I from January 1993 to June 1996: the ozone and water vapor devices were developed, tested and installed on board the MOZAIC aircraft (see *Helten et al.* [1998] for the humidity sensors and *Thouret et al.* [1998] for the ozone sensors);

Figure 2. Three-monthly MLS, ERA-40, and MLS–ERA-40 ozone zonal means for MLS version 5 measurements during the period 19 September 1991 to 27 July 1999 for (a) MAM, (b) JJA, (c) SON, and (d) DJF. The contour range for both MLS and ERA-40 ozone fields is [0, 12] ppmv with a 1 ppmv step. The contour range for the MLS–ERA-40 differences is [−4, 4] ppmv with a 0.5 ppmv step.

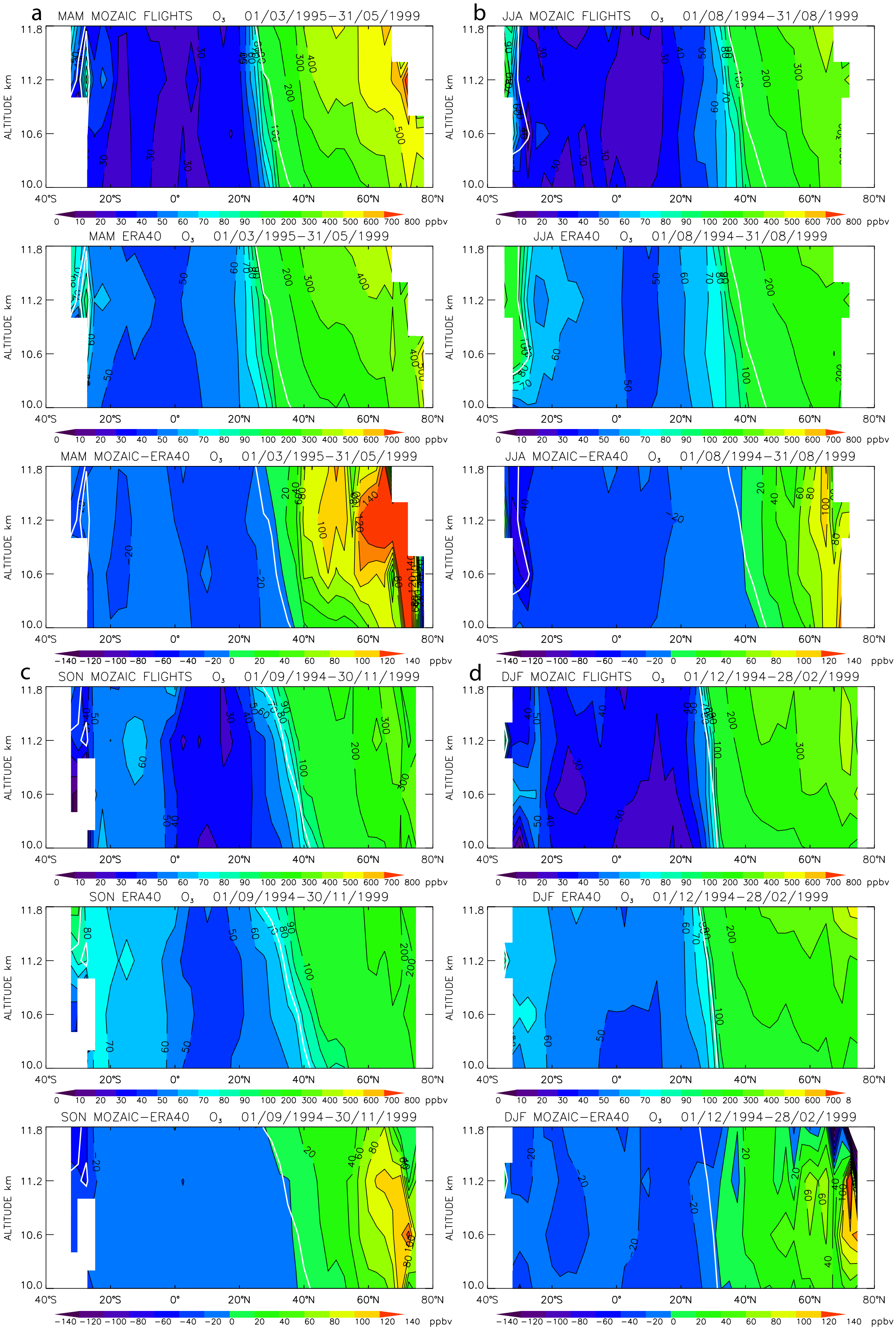
a
MAM MOZAIC FLIGHTS O₃ 01/03/1995–31/05/1999
MAM ERA40 O₃ 01/03/1995–31/05/1999
MAM MOZAIC–ERA40 O₃ 01/03/1995–31/05/1999
b
JJA MOZAIC FLIGHTS O₃ 01/08/1994–31/08/1999
JJA ERA40 O₃ 01/08/1994–31/08/1999
JJA MOZAIC–ERA40 O₃ 01/08/1994–31/08/1999
c
SON MOZAIC FLIGHTS O₃ 01/09/1994–30/11/1999
SON ERA40 O₃ 01/09/1994–30/11/1999
SON MOZAIC–ERA40 O₃ 01/09/1994–30/11/1999
d
DJF MOZAIC FLIGHTS O₃ 01/12/1994–28/02/1999
DJF ERA40 O₃ 01/12/1994–28/02/1999
DJF MOZAIC–ERA40 O₃ 01/12/1994–28/02/1999
ALTITUDE km
40°S 20°S 0° 20°N 40°N 60°N 80°N
0 10 20 30 40 50 60 70 80 90 100 200 300 400 500 600 700 800 ppbv
−140 −120 −100 −80 −60 −40 −20 0 20 40 60 80 100 120 140 ppbv

Figure 3

Table 1. HALOE–ERA-40 Ozone Differences

	HALOE–ERA-40 Ozone Differences[a]				
Pressure, hPa	Global, ppmv	Tropics,[b] ppmv	Midlatitudes,[c] ppmv	NH High Latitudes,[d] ppmv	SH High Latitudes,[e] ppmv
2	−0.56 (−11.6%)	−0.41 (−8.4%)	−0.63 (−12.2%)	−0.68 (−15.2%)	−0.83 (−20.0%)
4	−0.28 (−4.3%)	−0.22 (−2.9%)	−0.30 (−4.4%)	−0.26 (−4.4%)	−0.53 (−9.9%)
10	0.20 (2.1%)	0.37 (3.8%)	0.05 (0.4%)	0.20 (3.7%)	0.003 (−0.3%)
20	0.28 (4.0%)	0.50 (7.2%)	0.22 (3.5%)	−0.16 (−4.3%)	0.004 (−0.4%)
50	0.006 (2.5%)	0.20 (15.4%)	−0.10 (−5.6%)	−0.23 (−9.2%)	−0.16 (−7.8%)
70	−0.02 (−4.4%)	0.09 (21.6%)	−0.12 (−9.7%)	−0.10 (−5.4%)	−0.06 (−2.4%)
100	−0.06 (−26.5%)	−0.04 (−33.8%)	−0.09 (−19.5%)	0.005 (−0.9%)	−0.08 (−46.6%)

[a]HALOE combined sunrise and sunset version 19 measurements for the period 11 September 1991 to 31 December 1999. In total, 2235 days of valid measurements have been used for the validation, which represent 67,050 HALOE sunrise and sunset profiles (30 per day).
[b]Tropics, 30°S to 30°N.
[c]Midlatitudes, 30°–60°N and 30°–60°S.
[d]Northern Hemisphere high latitudes, >60°N. No HALOE data are available during NH winter (DJF).
[e]Southern Hemisphere high latitudes, >60°S. No HALOE data are available during SH winter (JJA).

(2) MOZAIC-II from October 1996 to September 1999: the ozone and water vapor measurements from MOZAIC-I were continued and also evaluated; and (3) MOZAIC-III from February 2000 to the end of 2004: CO devices were installed in all five MOZAIC aircraft between May 2001 and February 2003 and one NO_y measuring device was installed on board one MOZAIC aircraft.

[18] The MOZAIC aircraft routes provide good spatial coverage in the UTLS around the tropics and midlatitudes, with the majority of the flights (in total 20,963 processed and available flights up to 31 August 2003) being over the North Atlantic air corridor: North America (48%), the Caribbean (4%) and Central America (8%), South America (8%), Africa (8%), the Middle East, Southern and Southeast Asia (18%), and the Far East (China, Hong-Kong, Japan, 18%). The MOZAIC data refer to five standard cruise altitudes: 9 km (285–290 hPa), 10 km (263–248 hPa), 10.6 km (242–237 hPa), 11.2 km (223–215 hPa) and 11.8 km (207–195 hPa), with the majority of the flights between 10.6 and 11.2 km.

[19] Most of the MOZAIC devices are now considered well calibrated and most of the intercomparisons have shown an excellent agreement between different MOZAIC aircraft when they are sufficiently close in time. The MOZAIC ozone probes provide a detection limit of 2 ppbv and a precision of ±2 ppbv (or ±2%) in the troposphere [*Marenco et al.*, 1998]. Higher ozone discrepancies are, however, found in the stratosphere for flights comparable in time and space [*Thouret et al.*, 1998]. The MOZAIC ozone measurements agree by 3–13% with ozonesondes in the troposphere and above the boundary layer, but larger differences exist in the UTLS region where ozonesondes are unreliable as calibration devices. During the MOZAIC program the relative humidity (RH) instruments provide water vapor information with a detection limit of 20 ppmv; and the water vapor calculations are within ±4% and ±7% of the RH in the middle troposphere and the UTLS, respectively. Comparisons of the MOZAIC RH devices with other RH measuring techniques indicate a ±(5–10)% agreement [*Helten et al.*, 1998].

4. Methodology

[20] In the present study, we use ERA-40 products on pressure levels and at full temporal resolution (i.e., at 6-hour intervals: 0000, 0600, 1200, and 1800 UTC each day). The ERA-40 data are then interpolated to the positions and times of the satellite or aircraft measurements by using a cubic interpolation scheme in the horizontal (see http://www.ecmwf.int/research), a logarithmic spline interpolation in the vertical, and a simple linear interpolation in time.

[21] The HALOE retrieval algorithm was designed for the stratosphere and above. With most problems affecting the HALOE ozone retrievals now considered solved, little improvement is expected beyond the current version of the HALOE data. The present study makes use of version 19 level 2 HALOE data. Here we consider only the HALOE profiles down to 100 hPa, in order to keep a vertical data homogeneity for the ERA-40 versus HALOE comparison throughout the period from 11 October 1991 to 31 December 1999, and also in order to compare ERA-40 with measurements from both HALOE and MLS. ERA-40 is available up to, and including, the highest model level of 0.1 hPa, though accuracy declines close to the top model level, and ERA-40 products interpolated to standard pressure levels are available to users only up to 1 hPa. For these reasons, and also the fact that the HALOE profile measurements are not given at set pressure, the ERA-40 evaluation against HALOE goes up only to 2 hPa.

[22] The MLS ozone measurements have good temporal coverage till June 1995, when MLS started operating with alternate on and off periods for power savings. Here the period of the ozone ERA-40 versus MLS evaluation is between the start of the MLS operation on 19 September 1991 up to 27 July 1999, after which date no processed MLS data are publicly available at present. The Level 3AT MLS products are supplied in 37 preset pressure levels from

Figure 3. Three-monthly MOZAIC, ERA-40, and MOZAIC–ERA-40 ozone zonal means during the period 1 August 1994 to 31 December 1999 for (a) MAM, (b) JJA, (c) SON, and (d) DJF. The contour range for both MOZAIC and ERA-40 ozone fields is [0, 600] ppmv with a 50 ppmv step. The contour range for the MOZAIC–ERA-40 differences is [−300, 100] ppmv with a 0.25 ppmv step. PV = 2 pvu (thick white line). White areas represent data gaps.

Table 2. MLS – ERA-40 Ozone Differences

Pressure, hPa	MLS(V5) – ERA-40 Ozone Differences[a]				
	Global, ppmv	Tropics, ppmv	Midlatitudes, ppmv	NH High Latitudes, ppmv	SH High Latitudes, ppmv
1	−0.07 (−2.0%)	0.02 (0.6%)	−0.10 (−2.8%)	−0.05 (−1.6%)	−0.26 (−8.6%)
2.154	−0.36 (−7.1%)	−0.16 (−3.0%)	−0.39 (−7.1%)	−0.51 (−10.3%)	−0.79 (−17.5%)
4.641	−0.25 (−4.6%)	−0.03 (−0.4%)	−0.20 (−3.0%)	−0.45 (−8.5%)	−0.91 (−19.4%)
10.0	0.29 (2.1%)	0.69 (7.0%)	0.20 (2.4%)	−0.09 (−2.5%)	−0.37 (−10.1%)
21.54	0.19 (2.6%)	0.33 (5.2%)	0.30 (5.4%)	−0.27 (−6.8%)	−0.14 (−4.5%)
46.46	0.08 (4.9%)	0.26 (14.8%)	−0.03 (−1.8%)	−0.08 (−2.8%)	0.04 (0.8%)
68.13	0.16 (18.8%)	0.27 (40.5%)	0.05 (3.2%)	0.13 (5.5%)	0.15 (8.7%)

[a]MLS version 5 measurements for the period 19 September 1991 to 27 July 1999. In total, 1403 days of valid measurements have been used for the validation. Latitudinal zones are defined as in Table 1.

464 to 0.000464 hPa, though here we use only the ozone MLS files between 1 and 68 hPa. This vertical range is appropriate for scientific applications because the MLS ozone data at 100 hPa have significant uncertainty of larger than 50% (see Table 10 from *Livesey et al.* [2003]). Only data flagged as good quality are used here. Several MLS data versions have been produced owing to some instability in instrument performance. For comparison with the ERA-40 ozone field, we focus on the MLS V5 data.

[23] The procedure described above for the MLS ozone validation is also implemented for the MLS water vapor data obtained from the 183 GHz radiometer, which provided measurements for 19 months from 19 September 1991 to mid-April 1993 when the instrument failed. Although this period is quite short, the data are still useful for evaluating ERA-40 water vapor. We use the recently released version 7.02 (referred to as V7) for the 183 GHz channel. This version is preferred to V5 and V4 because V7 fills the gap around 100 hPa that exists in the previous MLS data versions. Although V7 supplies data between 46 and 316 hPa, we follow the recommendations of the UARS team [*Read et al.*, 2004a]: (1) use data between 56 and 147 hPa; (2) since there is no cloud screening, reject any data for which the goodness of the radiance fit between radiance measurements and calculated radiances is greater than a certain threshold; and (3) increase the MLS values water vapor at 147 hPa and 100 hPa by 30% and 20%, respectively, in order to minimize the biases in the tropics.

[24] The MOZAIC observations used here cover the period from 1 August 1994 to 31 December 1999. The MOZAIC ozone archive contains in situ ozone aircraft measurements, and the water vapor archive contains data that the MOZAIC scientific team has derived from the RH in situ aircraft observations by using the method of *Helten et al.* [1998]. Both MOZAIC ozone and water vapor data sets are now consider fully calibrated. Since the MOZAIC aircraft take readings every 4 s, in contrast to the ERA-40 six-hour interval, several artefacts appear in the ERA-40 ozone and water vapor fields when interpolating ERA-40 to the space and time of the aircraft measurements. Furthermore, such a short interpolation time step was found computationally expensive. Following initial tests with various ERA-40 interpolation time steps, it was finally decided to consider the average value of continuous (when available) aircraft observations over a 4-min interval. In terms of typical MOZAIC flight speeds and altitudes, this represents an average horizontal distance of between half to one third of the distance between two ERA-40 horizontal grid points. Apart from the condition for the MOZAIC measurements to be continuous during the 4-min interpolation step, a further condition was set by monitoring the aircraft vertical speed and pressure in order for the data to refer to the same pressure level, and not to be affected by any abrupt changes in the aircraft altitude. Results of the ERA-40 comparison with MOZAIC are grouped into 2.5° × 2.5° longitude/latitude boxes and into the five MOZAIC cruise levels. Data from the 9.4 km cruise altitude were not used because data continuity was inadequate. Finally, the tropopause is defined here as the PV = 2 potential vorticity units (pvu) surface.

[25] Results of the ERA-40 evaluation for ozone (section 5) and water vapor (section 6) are arranged so that initially a short introduction is presented on the major scientific findings. This is followed by five subsections. The first three subsections show the validation results for the stratosphere arranged into three geographical areas: tropics (30°N to 30°S), midlatitudes (60°–30°N and 30°–60°S), and high latitudes (>60°N, >60°S). The remaining two subsections discuss (1) the evaluation of ERA-40 within the UTLS based on MOZAIC data and (2) the evaluation of any bias with respect to independent data, and whether the bias varies with time during the 1990s. In addition, at the beginning of sections 5 and 6 we present tables summarizing the ERA-40 evaluation results (both actual values and percentages), and we present figures of the seasonal variation of the percentage differences between ERA-40 and UARS at selected pressure levels and geographical regions. We also show plots of the 3-monthly ozone and water vapor zonal means. For the Northern Hemisphere, spring is defined as March to May, summer as June to August,

Table 3. MOZAIC – ERA-40 Ozone Differences

Altitude, km	MOZAIC – ERA-40 Ozone Differences[a]		
	Tropics,[b] ppbv	NH Midlatitudes, ppbv	NH High Latitudes,[c] ppbv
11.8	−19.7 (−56.3%)	33.6 (9.9%)	24.8 (3.8%)
11.2	−19.3 (−54.2%)	42.1 (12.4%)	123.8 (25.3%)
10.6	−19.7 (−65.8%)	37.0 (13.5%)	88.1 (24.4%)
10.0	−18.6 (−61.2%)	16.2 (7.9%)	67.2 (23.4%)

[a]MOZAIC flights for the period 1 August 1994 to 31 December 1999. Total number of flights is 12,816.
[b]Tropics, 30°S to 30°N.
[c]NH high latitudes, >60°N.

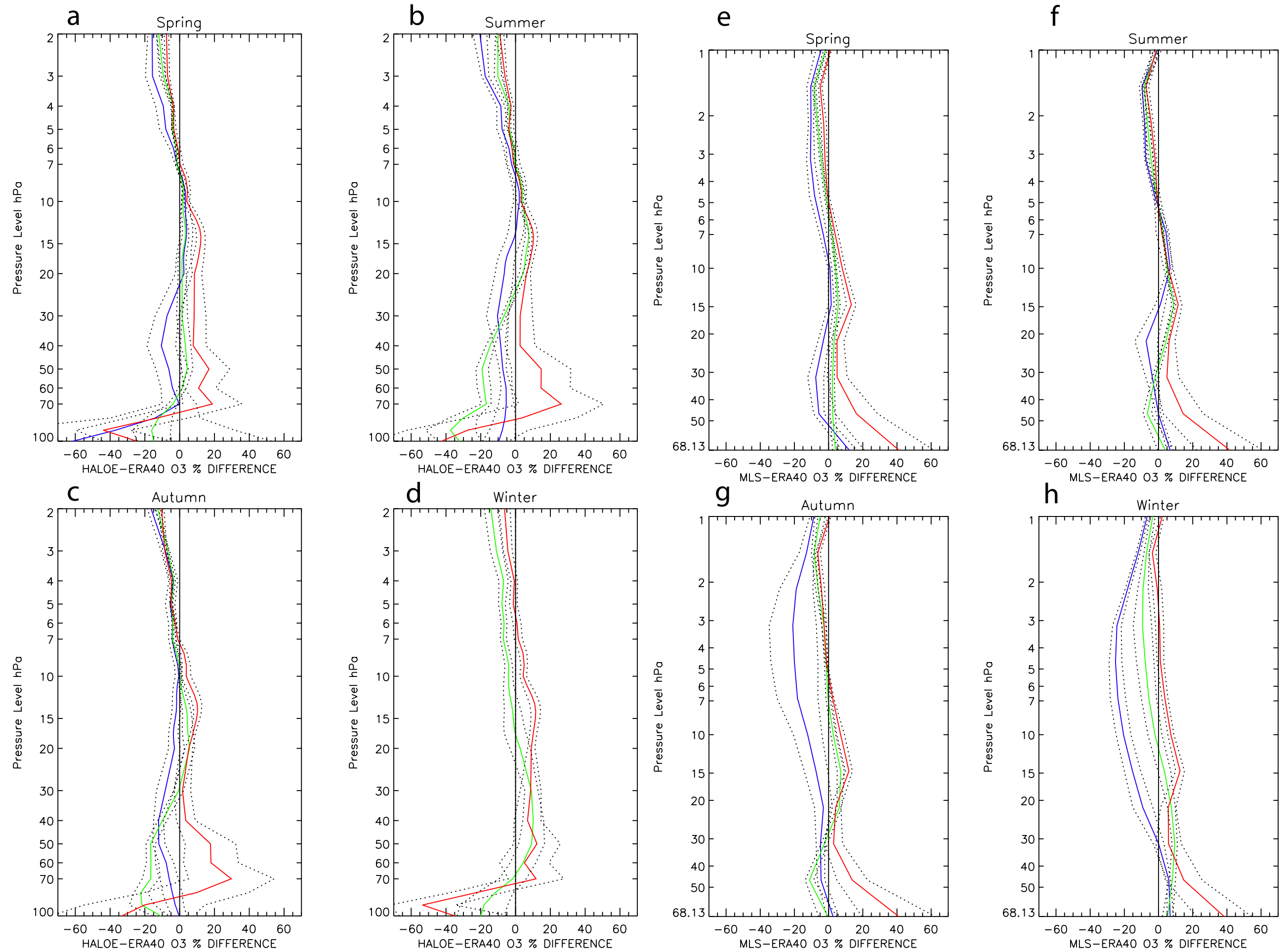

Figure 4. UARS−ERA-40 ozone seasonal zonal mean differences expressed as percentage of the original UARS measurements for (a–d) HALOE V19 sunrise and sunset measurements for the period 11 October 1991 to 31 December 1999 and (e–h) MLS V5 for the period 19 September 1991 to 27 July 1996. Spring is MAM for NH and SON for SH, summer is JJA for NH and DJF for SH, autumn is SON for NH and MAM for SH, and winter is DJF for NH and JJA for SH. Latitudinal zones: tropical (30°N to 30°S, red line), midlatitudes (60°–30°N and 30°–60°S, green line), and high latitudes (>60°N and >60°S, blue line). Dotted lines indicate the standard deviations. HALOE has no coverage poleward of 60° during winter for both hemispheres.

autumn as September to November, and winter as December to February.

5. ERA-40 Ozone Validation

[26] The global ozone climatology has been well established by previous studies and used either as the a priori information for both the UARS ozone retrievals and the ERA-40 fields, or it has been reconstructed on the basis of the UARS measurements themselves [*Wang et al.*, 1999]. The ozone distribution is now known to be affected by both long-term processes, such as the solar cycle, and stratospheric circulation that lead to ozone changes of interannual, decadal and seasonal scales, including the stratospheric quasi-biennial oscillation (QBO). UARS data showed conclusive evidence that chlorofluorocarbons (CFCs), rather than other anthropogenic or natural emissions, are the dominant ozone depletion constituent over Antarctica [*Russell et al.*, 1996]. Estimations of the chemical loss of polar ozone in the LS became possible by using UARS measurements of chemical species, such as MLS ClO [*Wu and Dessler*, 2001]. Besides the initial focus on ozone over Antarctica, equally important UARS findings have been reported over the Arctic LS [*Manney et al.*, 1997]. On the basis of the above results, it is of particular interest how ERA-40 captures the ozone tropical maximum and both the Antarctic and Arctic ozone holes.

[27] ERA-40 reproduces realistically the ozone field when compared with both the satellite and the aircraft observations. Shown here is the seasonal variation of the zonal means of the ERA-40 ozone comparison with HALOE V19 (Figure 1), MLS V5 (Figure 2), and MOZAIC (Figure 3). In addition, Tables 1–3 present both the actual and percentage differences at selected pressure levels and geographical areas of the ERA-40 ozone comparison with HALOE (Table 1), MLS (Table 2), and MOZAIC (Table 3) throughout the entire period of the observations used from each of these three data sources. Also, Figure 4 presents the

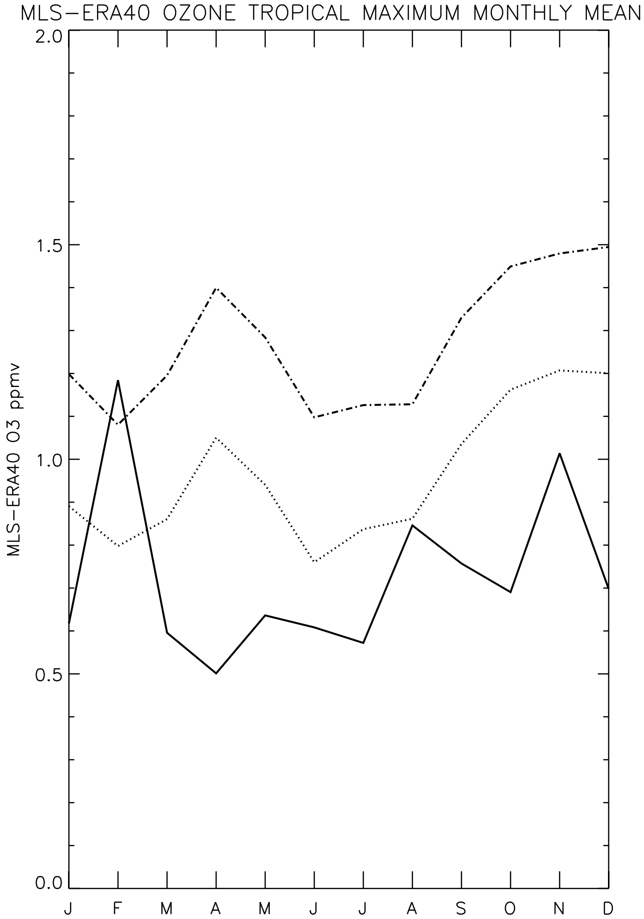

Figure 5. Monthly mean differences of UARS–ERA-40 at the ozone tropical maximum in ppmv for HALOE combined sunrise and sunset measurements (solid line) during the period 11 October 1991 to 31 December 1999 and for MLS version 5 data (dashed line) and version 4 data (dash-dotted line) during the period 19 September 1991 to 27 July 1999.

seasonal variation of the UARS–ERA-40 ozone percentage differences arranged in three geographical areas (i.e., tropics, middle and high latitudes). In comparison with UARS ERA-40 overestimates by 5–10% the ozone concentration on a global scale in the upper stratosphere but underestimates it by 5–10% over the tropics at the level of the ozone tropical maximum (i.e., slightly above 10 hPa or 30–35 km) and down to 30 hPa (20–25 km, Figure 4). Below 30 hPa in the middle stratosphere, and in the LS over the middle and high latitudes, results of the ERA-40 ozone comparison with independent data become highly dependent on both season and altitude (Figure 4).

5.1. Tropical Stratospheric Ozone

[28] At the level of the tropical ozone maximum, the ERA-40 deviations from the UARS measurements seem to have a seasonal variation over the equator, with positive UARS–ERA-40 differences being larger to the north (south) of the equator during northern (southern) winter to early spring months (Figures 1 and 2). Regarding the actual value of the tropical ozone maximum, ERA-40 captures it consistently lower than UARS by typically 0.5–1.2 ppmv (~4%) compared to HALOE and by 0.8–1.2 ppmv (~8%) compared to MLS V5 (Figure 5). A seasonal dependence can be detected in the way ERA-40 reproduces the tropical ozone maximum, with largest UARS–ERA-40 differences occurring from late October to February and smallest differences encountered from late April to early June (Figure 5).

[29] Furthermore, from May to August during the 1990s, ERA-40 places the tropical ozone maximum at a lower height than does the UARS data. A similar situation regarding the altitude of the ozone maximum is also found over the South Pole [*Dethof*, 2003] where in comparison with ground based observations during the SH spring months prior to 1979 the ozone maximum is located at lower altitude in ERA-40 than in the observations.

[30] Below the level of the ozone tropical maximum and down to 70 hPa, ERA-40 consistently underestimates ozone over the tropics compared with the independent data. More precisely, between 10 hPa and 50 hPa ERA-40 underestimates the ozone concentration over the tropics by 5–10% in comparison with HALOE (Figures 4a–4d) and MLS (Figures 4e–4h). At the levels between 50 hPa and 70 hPa we find the maxima positive deviations from the UARS measurements of 20–30% in comparison with HALOE, particularly during summer and autumn, and of 30–40% throughout the year in comparison with MLS. However, in the layer 20–50 hPa, ERA-40 occasionally overestimates tropical ozone by over 1 ppmv (20%). Although this tendency does not seem to depend on season, it is confined over the tropical Atlantic and Indian Ocean. At the tropical tropopause level (i.e., 100 hPa), ERA-40 seriously overestimates the ozone concentration by 40–60% in comparison with HALOE.

5.2. Midlatitude Stratospheric Ozone

[31] In the upper stratosphere and down to 7 hPa ERA-40 consistently overestimates the ozone concentration over midlatitudes by the order of 10% in comparison with HALOE (Table 1) and by only a few percent in comparison with MLS (Table 2). At the levels of 7–10 hPa the general tendency of ERA-40 to underestimate the ozone concentration spreads also over the midlatitudes in both hemispheres, though with greater variations and seasonal dependence than over the tropics. Nevertheless, during winter ERA-40 between 7 and 10 hPa slightly overestimates the ozone concentration over the midlatitudes by less than 5% in comparison with UARS (Figures 4d and 4h).

[32] In the layers below 10 hPa the UARS–ERA-40 differences show a strong seasonal signal and they also depend on the UARS retrieval against which the reanalysis is validated. More precisely, between 30 hPa and 70 hPa over the midlatitudes ERA-40 tends to underestimate ozone by up to 10% during winter (Figures 4d and 4h) but overestimates it by up to 20% during summer (Figures 4b and 4f) and autumn (Figures 4c and 4g) in each hemisphere. Particularly at 68 hPa (the lowest vertical level considered here for the MLS ozone), ERA-40 compares very well with the MLS measurements over the midlatitudes where ERA-40 underestimates the ozone concentration by up to 0.05 ppmv (~5%, Figures 4e–4h); but over the midlatitudes ERA-40 overestimates the concentration in comparison

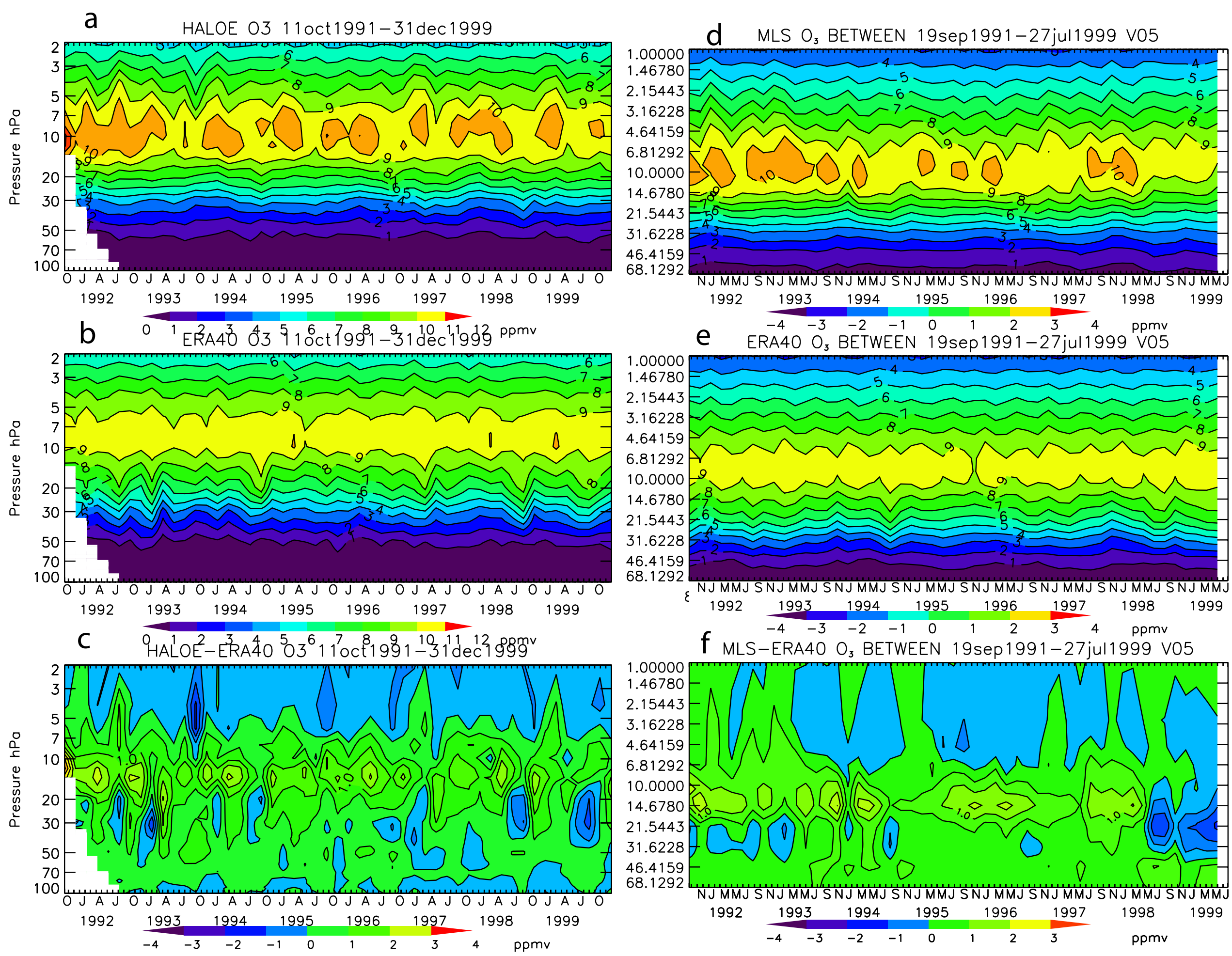

Figure 6. Time series of the UARS versus ERA-40 ozone comparison between 12°N and 12°S for (a–c) HALOE V19 sunrise and sunset measurements during the period 11 October 1991 to 31 December 1999 and (d–f) MLS version 5 data during the period 19 September 1991 to 27 July 1999. Shown are UARS ozone (top panels), ERA-40 ozone interpolated to the time and location of the UARS observations (middle panels), and the UARS–ERA-40 difference (bottom panels). The contour range for both UARS and ERA-40 ozone fields is [0, 12] ppmv with a 1 ppmv step. The contour range for the UARS–ERA-40 differences is [−4, 4] ppmv with a 0.5 ppmv step. For the UARS–ERA-40 differences the contour step is every 0.50 ppmv.

with HALOE by 0.15 ppmv (10–20% depending on season, see Figures 4a–4d).

5.3. High-Latitude Stratospheric Ozone

[33] The tendency of ERA-40 to overestimate the ozone concentration in the upper parts of the model is more pronounced over the high latitudes where in comparison with UARS ERA-40 in general overestimates ozone by typically 5–10% (see for example the overall validation results round the 2 hPa level in Tables 1 and 2). We also find that ERA-40 ozone in the upper stratosphere compares better with UARS over the northern than over the southern high latitudes. At levels between 7 and 10 hPa, in comparison with UARS, ERA-40 underestimates the ozone concentration over the high latitudes by 5% during summer (Figure 4b and 4f) but overestimates it by up to 35% during polar autumn (Figures 4c and 4g) and especially during southern polar winter (Figure 4h). In addition, when compared with UARS, the ERA-40 ozone over the high latitudes appears to be highly dependent on altitude, season and satellite sensor. For example, during polar spring (Figures 4a and 4e) and autumn months, when both UARS instruments provide similar coverage over the high latitudes, in the upper stratosphere and down to 10 hPa ERA-40 ozone compares better with HALOE (Figures 4a and 4c) than with MLS (Figures 4e and 4g).

[34] During the Antarctic ozone hole from September to October, ERA-40 reproduces realistic low ozone in the layer 50–70 hPa where the core of the Antarctic ozone hole can be found. In comparison with UARS at 70 hPa the reanalysis in general underestimates the ozone concentration by up to 20%, but at 50 hPa ERA-40 overestimates it by 10% (Figure 2c). Nevertheless, at the 50–70 hPa levels there seem to be significant differences when comparing ERA-40 with the two MLS data versions: ERA-40 ozone differs by <10% compared to MLS V5 and by ~30% compared to MLS V4 (not shown here). In the Antarctic middle strato-

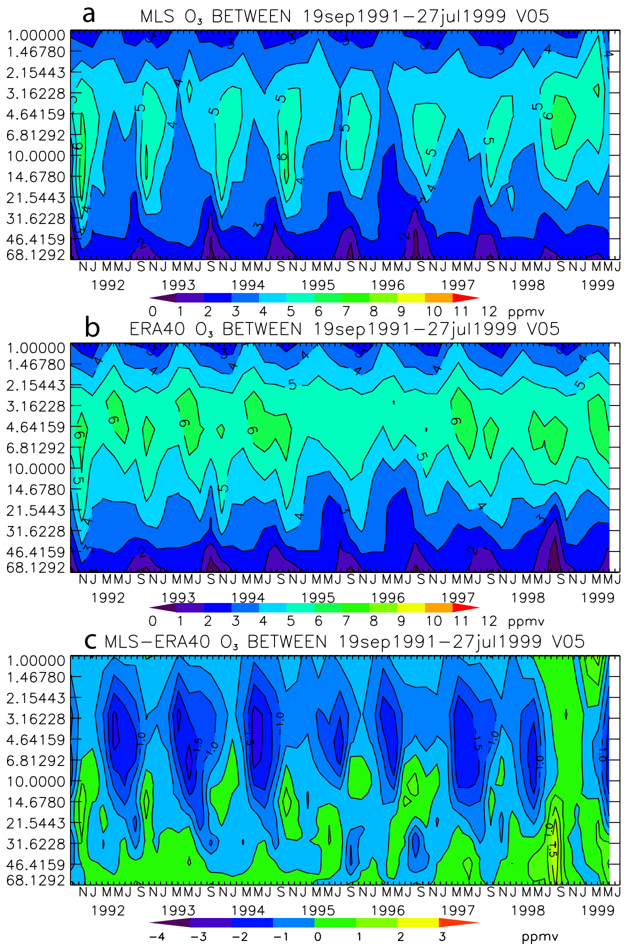

Figure 7. Time series of the MLS V5 versus ERA-40 ozone comparison between 1990s and 70°S during the period 19 September 1991 to 27 July 1999. (a) MLS ozone, (b) ERA-40 ozone interpolated to the time and location of the MLS observations, and (c) MLS−ERA-40 difference. The contour range for both MLS and ERA-40 ozone fields is [0, 12] ppmv with a 1 ppmv step. The contour range for the MLS−ERA-40 differences is [−4, 4] ppmv with a 0.5 ppmv step.

sphere (typically 20–50 hPa) in September, in comparison with HALOE and both MLS versions, ERA-40 consistently overestimates ozone by 10–15%. Finally, at the levels below the Antarctic ozone hole (near 100 hPa), during polar spring ERA-40 seriously overestimates the ozone amounts by 60% (and >100% particularly over Antarctica) in comparison with HALOE (Figure 4a).

[35] There are differences in the way the ERA-40 ozone field compares with the satellite observations between the NH and the SH high latitudes. For example, above 10 hPa ERA-40 ozone is overall about 10% closer to the UARS measurements over the northern than over the southern high latitudes (see Tables 1 and 2). In comparison with MLS ERA-40 over the northern high latitudes consistently overestimates ozone by typically 10–15% throughout the year and at all vertical levels, except during northern summer and near the 7–14 hPa layer, where ERA-40 underestimates ozone by 5–10% (Figure 2b). As also seen for the southern high latitudes, over the northern high latitudes ERA-40 significantly overestimates ozone in the middle and upper stratosphere, with maximum deviations of ERA-40 from the UARS measurements reaching 20% during northern winter at 4 hPa (Figure 4h). In addition, we find that over the northern high latitudes and at all vertical levels ERA-40 ozone seems to compare considerably better with MLS V5 than with V4 data (not shown here).

5.4. UTLS Ozone

[36] By examining the ERA-40 PV field interpolated onto the MOZAIC measurements, we find that, during most of the validation period, the MOZAIC aircraft cross into the LS over northern middle and high latitudes (typically north of 30°N at 11.8 km and north of 40°N at 10.0 km cruise levels), while over the tropics and subtropics (typically between 30°S and 30°N), the aircraft fly constantly in the UT (Figure 3). During northern summer and early autumn the "tropospheric" part in the MOZAIC aircraft routes extends further north up to 40°–42°N (Figures 3b and 3c).

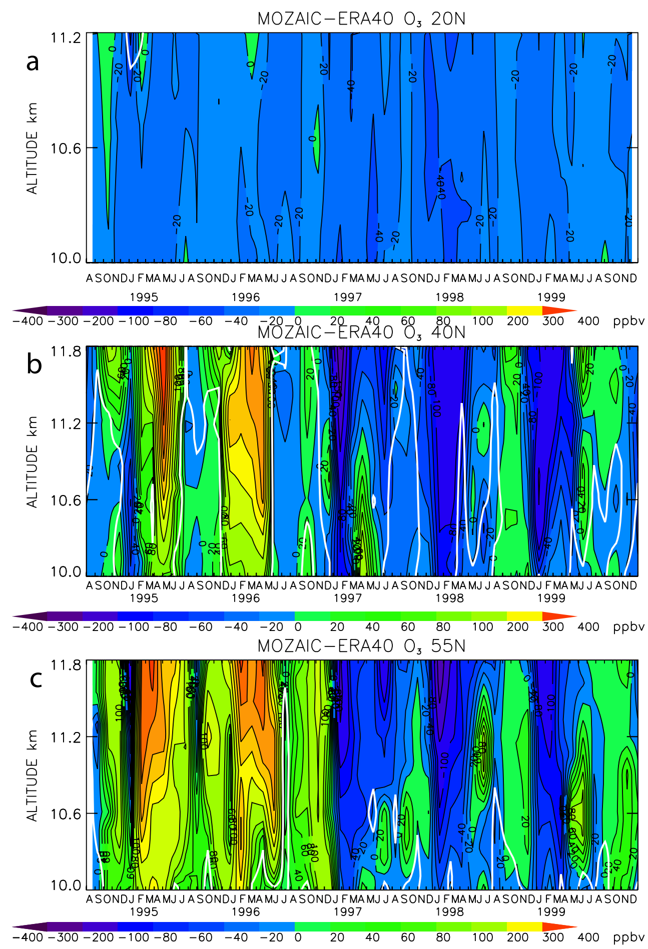

Figure 8. Time series of the vertical variation of the MOZAIC−ERA-40 ozone differences for the period 1 August 1994 to 31 December 1999 at (a) 20°N, (b) 40°N, and (c) 55°N. The contour range is [−400, 400] ppmv with a 50 ppmv step. PV = 2 pvu (thick white line). White areas represent data gaps. The top cruise level of 11.8 km at 20°N is not considered here because at this level over 20°N the MOZAIC measurements are discontinuous.

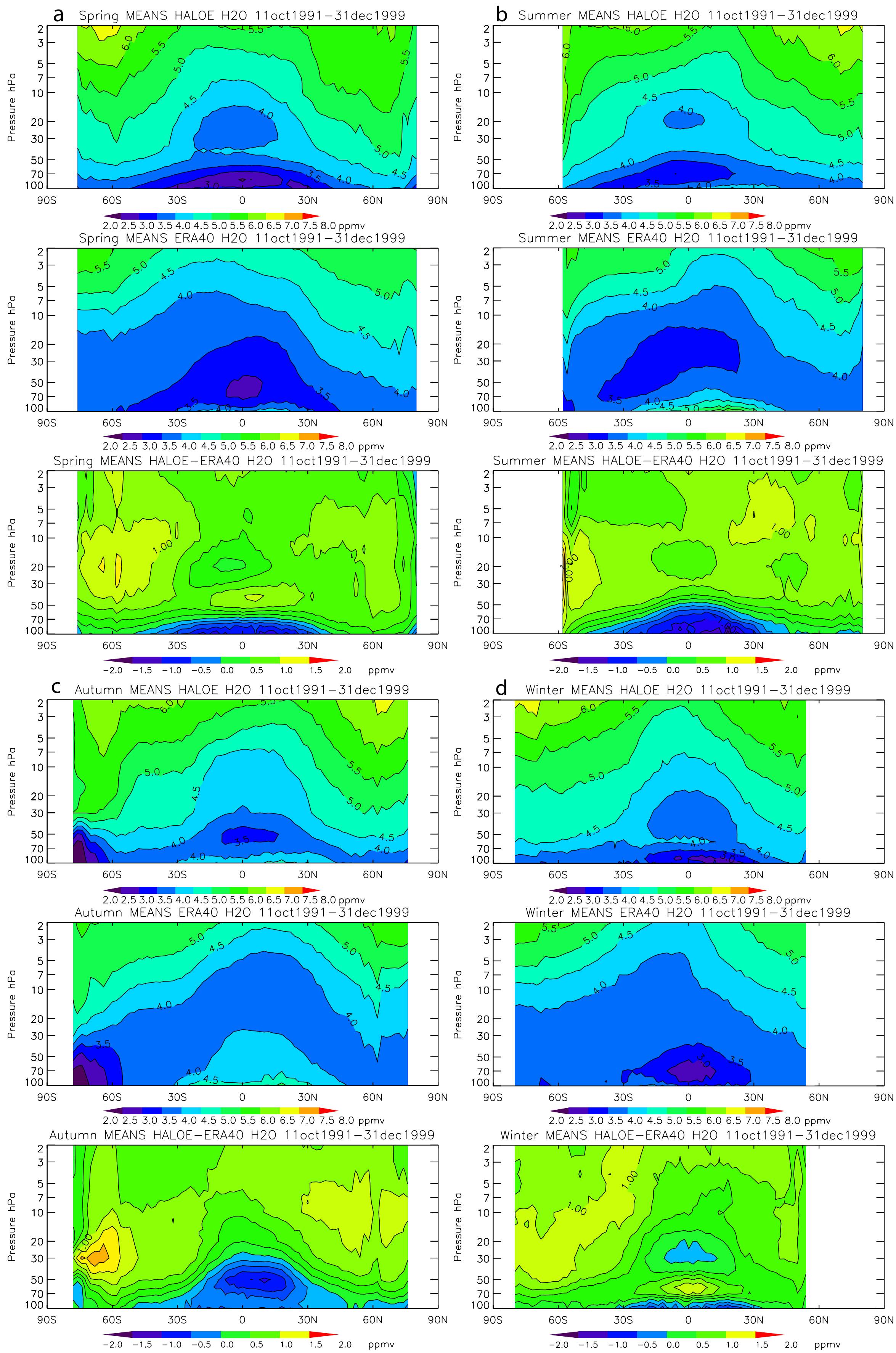
a
Spring MEANS HALOE H2O 11oct1991–31dec1999
Spring MEANS ERA40 H2O 11oct1991–31dec1999
Spring MEANS HALOE–ERA40 H2O 11oct1991–31dec1999
b
Summer MEANS HALOE H2O 11oct1991–31dec1999
Summer MEANS ERA40 H2O 11oct1991–31dec1999
Summer MEANS HALOE–ERA40 H2O 11oct1991–31dec1999
c
Autumn MEANS HALOE H2O 11oct1991–31dec1999
Autumn MEANS ERA40 H2O 11oct1991–31dec1999
Autumn MEANS HALOE–ERA40 H2O 11oct1991–31dec1999
d
Winter MEANS HALOE H2O 11oct1991–31dec1999
Winter MEANS ERA40 H2O 11oct1991–31dec1999
Winter MEANS HALOE–ERA40 H2O 11oct1991–31dec1999
Pressure hPa
90S 60S 30S 0 30N 60N 90N
2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 ppmv
−2.0 −1.5 −1.0 −0.5 0.0 0.5 1.0 1.5 2.0 ppmv

Figure 9

[37] Throughout the entire validation period and at all cruise altitudes of MOZAIC aircraft, ERA-40 reproduces the UTLS ozone field with a typical deviation from MOZAIC of 20–60% depending on cruise level, latitude and season (Table 3).

[38] A clearer picture of the UTLS ERA-40 ozone field is obtained when using the PV = 2 pvu criterion to define the tropopause (Figure 3). ERA-40 consistently overestimates ozone in the tropical UT by typically 20 ppbv (~60%, Table 3). This tendency applies throughout all seasons, and appears to be especially pronounced during northern winter and spring, when ERA-40 around 20°N tends to overestimate ozone by >100% in comparison with the MOZAIC observations. In the LS throughout the year ERA-40 tends to underestimate ozone over the northern midlatitudes by typically 10% and over the northern high latitudes by typically 25–30% (Figure 3 and Table 3). Since in the LS the ERA-40 ozone field is ~30% closer to the MOZAIC measurements than in the tropical UT, throughout the year ERA-40 shows a much stronger ozone gradient across the tropopause than the one captured by the MOZAIC observations.

5.5. ERA-40 Ozone Biases Compared With Independent Data and Their Temporal Variation

[39] In recent years, several investigators have combined measurements from ground-based stations, numerous satellite instruments and, in some cases, data assimilation systems in order to estimate ozone variations and trends. The overall conclusion is that global ozone was fairly constant during the 1990s [*SPARC*, 1998]. After the major volcanic eruption of Mount Pinatubo in 1991, however, a record low in stratospheric ozone was observed, especially over the northern middle and high latitudes [*Gleason et al.*, 1993]. In this study, we examine the presence of possible biases and their variation with time for both the ozone and water vapor (section 6) ERA-40 fields.

[40] When examining time series of the ERA-40 ozone comparison with the independent observations we find that there is a gradual improvement in the way ERA-40 reproduces the tropical ozone maximum throughout the 1990s. In particular, when considering time series of the equatorial stratospheric ozone between 12°N and 12°S at the level of the tropical ozone maximum (10 hPa), we find that ERA-40 consistently underestimates ozone in comparison with HALOE by 2 ppmv (20%) in the early 1990s (Figures 6a–6c). These differences become ~1.5 ppmv (15%) after January 1994, and they reduce to <1.0 ppmv (<10%) toward the end of 1996. At the levels below the tropical ozone maximum and in comparison with HALOE, ERA-40 throughout the 1990s underestimates the ozone concentration by 10–20% between 10 and 40 hPa and by 30–50% between 40 and 70 hPa but ERA-40 overestimates ozone by 40–60% round the tropical tropopause (70–100 hPa).

[41] Results are significantly different when ERA-40 is compared with MLS. For the levels above the tropical ozone maximum, and for the period September 1991 to the end of 1992, ERA-40 tends to underestimate ozone in comparison with MLS by typically 0.5–1.0 ppmv (5–10%) (Figures 6d–6f). This situation is reversed at the beginning of 1993, after which date ERA-40 seems to consistently overestimate the tropical ozone field in the upper stratosphere. Nevertheless, one should be cautious when examining the temporal evolution of ERA-40 in comparison with MLS, since there were several problems encountered in the performance of the MLS instrument during the selected period, and data collection became more problematic and less frequent especially after June 1995 [*Livesey et al.*, 2003].

[42] In agreement with previous observational studies [e.g., *SPARC*, 1998], ERA-40 does not show any significant decadal trend in the ozone values during the 1990s. Over the tropics in ERA-40, between 10 hPa and 20 hPa the isopleths of ozone mixing ratio appear to descend further down into the middle stratosphere (i.e., down to 30–40 hPa; Figures 6b and 6e) typically in August/September. As a result, in the layer 20–40 hPa from August till December ERA-40 has about 20% more ozone than UARS. This feature is especially pronounced in ERA-40 in 1994 and 1998, but it is not found in the UARS observations. The above ERA-40 tendency in the ozone field over the tropics and between the 10 and 40 hPa levels is not, however, encountered over the middle and high latitudes (Figure 7).

[43] The way that ERA-40 reproduces the Antarctic ozone holes, as described in section 5.3, remains consistent throughout the 1990s when comparing the reanalysis with the MLS observations (Figure 7). Especially for the Southern Hemisphere ozone holes of 1995 and 1996, ERA-40 overestimates the ozone concentration within the core of the Antarctic ozone hole in comparison with MLS (Figure 7c). For the 1998 case, however, ERA-40 underestimates the ozone concentration in the entire stratosphere compared with MLS by >1.5 ppmv (40%) at the edge of the Antarctic ozone hole (i.e., at 46 hPa). Similar results are found for the same years when ERA-40 is compared with the HALOE observations during the Antarctic ozone hole (not shown here).

[44] In the UTLS region during the 1990s, the differences in ozone between ERA-40 and MOZAIC have a seasonal dependence and substantial variations. The time series of the MOZAIC–ERA-40 ozone differences are calculated at three different latitudes where there exist continuous aircraft observations: 20°N, 40°N and 55°N (Figure 8). (At 20°N the highest cruise level of 11.8 km is not considered here since, at this altitude, the MOZAIC data over the tropics are discontinuous.)

[45] There was a change in the ERA-40 UTLS ozone field after autumn 1996 when modifications in the ERA-40 ozone system took place [*Dethof and Hólm*, 2004]. In

Figure 9. Three-monthly HALOE, ERA-40, and HALOE–ERA-40 water vapor zonal means for HALOE version 19 combined sunrise and sunset measurements during the period 11 October 1991 to 31 December 1999 for (a) MAM, (b) JJA, (c) SON, and (d) DJF. The contour range for both HALOE and ERA-40 water vapor fields is [2, 8] ppmv with a 1 ppmv step. The contour range for the HALOE–ERA-40 differences is [−2, 2] ppmv with a 0.25 ppmv step.

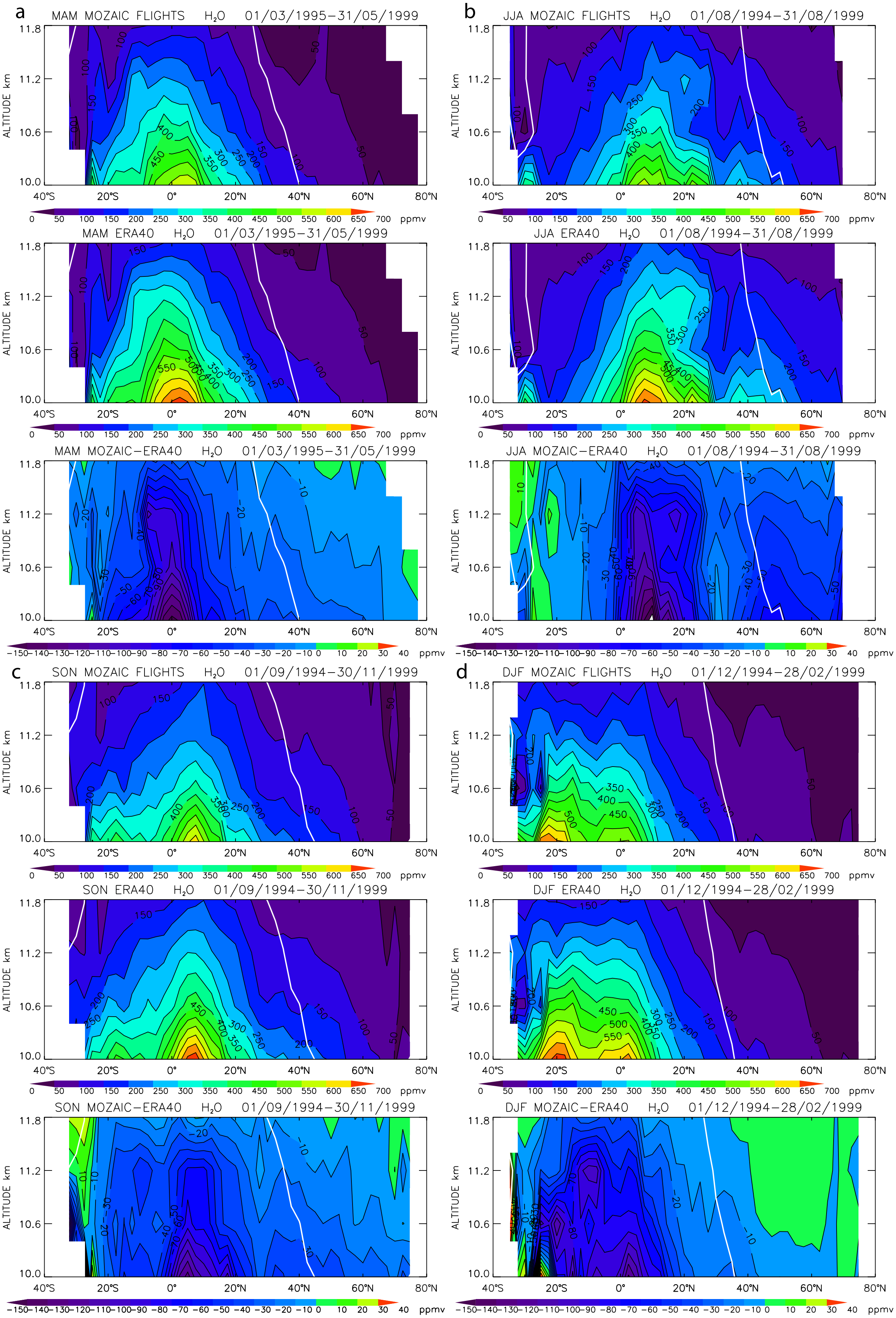
a
MAM MOZAIC FLIGHTS H2O 01/03/1995–31/05/1999
MAM ERA40 H2O 01/03/1995–31/05/1999
MAM MOZAIC–ERA40 H2O 01/03/1995–31/05/1999
b
JJA MOZAIC FLIGHTS H2O 01/08/1994–31/08/1999
JJA ERA40 H2O 01/08/1994–31/08/1999
JJA MOZAIC–ERA40 H2O 01/08/1994–31/08/1999
c
SON MOZAIC FLIGHTS H2O 01/09/1994–30/11/1999
SON ERA40 H2O 01/09/1994–30/11/1999
SON MOZAIC–ERA40 H2O 01/09/1994–30/11/1999
d
DJF MOZAIC FLIGHTS H2O 01/12/1994–28/02/1999
DJF ERA40 H2O 01/12/1994–28/02/1999
DJF MOZAIC–ERA40 H2O 01/12/1994–28/02/1999
ALTITUDE km
11.8
11.2
10.6
10.0
40°S
20°S
0°
20°N
40°N
60°N
80°N
ppmv

Figure 10

Table 4. HALOE–ERA-40 Water Vapor Differences[a]

	HALOE–ERA-40 Water Vapor Differences				
Pressure, hPa	Global, ppmv	Tropics, ppmv	Midlatitudes, ppmv	NH High Latitudes, ppmv	SH High Latitudes, ppmv
2	0.75 (12.6%)	0.79 (14.0%)	0.72 (11.9%)	0.63 (9.8%)	0.76 (11.7%)
4	0.77 (13.9%)	0.73 (14.3%)	0.81 (14.1%)	0.73 (11.9%)	0.74 (12.2%)
10	0.87 (17.1%)	0.75 (16.2%)	0.95 (18.0%)	0.98 (17.4%)	0.94 (17.1%)
20	0.75 (15.9%)	0.52 (12.1%)	0.91 (18.5%)	0.83 (16.2%)	1.09 (21.2%)
50	0.54 (12.1%)	0.28 (6.5%)	0.70 (15.7%)	0.71 (15.2%)	0.82 (18.4%)
70	0.21 (4.8%)	−0.07 (−2.5%)	0.39 (9.4%)	0.46 (10.6%)	0.44 (11.0%)
100	−0.30 (−8.4%)	−0.72 (−20.0%)	−0.006 (−0.5%)	−0.05 (−1.6%)	0.10 (3.1%)

[a]Total period, number of HALOE measurements used, and definition of latitudinal zones as in Table 1.

general, ERA-40 in the tropical UT (near 20°N) tends to overestimate ozone by 20–40 ppbv (30–60%) compared with MOZAIC data (Figure 8a). At 20°N the effect of the modifications in the reanalysis system can be seen only at the MOZAIC cruise level of 11.2 where prior to October 1996 there are cases for which ERA-40 underestimates the ozone concentration, whereas post-October 1996 ERA-40 consistently overestimates it. In the UTLS over the northern middle and high latitudes, however, the change in the ERA-40 performance is significant after October 1996. For example, at 40°N, ERA-40 tends to underestimate ozone before October 1996 but tends to overestimate it after October 1996 (Figure 8b). In addition, post-October 1996 over the northern middle and high latitudes, the size of the MOZAIC–ERA-40 differences are substantially reduced at all cruise levels from a typical maximum of 400 ppbv (100%) to 100–150 ppbv (25–30%), with most of the improvement encountered in the LS over the northern high latitudes.

6. ERA-40 Water Vapor Validation

[46] According to the upper troposphere water vapor climatologies obtained from satellite sensors [*Chiou et al.*, 1997; *SPARC*, 2000], maximum water vapor concentrations are encountered in three prominent regions: (1) the maritime continent near 90°E; (2) the region over South America around 60°W; and (3) the tropical west and central Africa. The MOZAIC flight paths (especially at 10.0 and 10.6 km) can provide information about the water vapor field in the last two of these three tropical monsoon systems.

[47] In the stratosphere, HALOE and MLS have provided information regarding the water vapor cycle. In addition to establishing features such as the occurrence of a stratospheric water vapor minimum over the tropics, Southern Hemisphere springtime dehydration was observed by HALOE, with the horizontal extent of the dehydrated area at 465 K (i.e., where the polar ozone decrease becomes maximum) comprising up to 35% of the total vortex area north of 80°S, which is the limit of the HALOE observations [*Pierce et al.*, 1994; *Rosenlof et al.*, 1997]. Other relevant findings include the indication that water vapor has, broadly speaking, increased in the LS over the last 45 years [*Rosenlof et al.*, 2001], and the significant discovery of the so-called tape recorder in water vapor mixing ratios in the tropical stratosphere [*Mote et al.*, 1996].

[48] Here we show the seasonal variation of the zonal means of the ERA-40 water vapor comparison with HALOE V19 (Figure 9) and MOZAIC (Figure 10). In addition, we present both the actual and percentage differences at selected pressure levels and geographical areas of the ERA-40 water vapor comparison with HALOE (Table 4), MLS V7 (Table 5), and MOZAIC (Table 6) throughout the entire period considered for each of these sets of independent observations. In addition, Figure 11 presents the seasonal variation of the UARS–ERA-40 water vapor percentage differences arranged in three geographical areas (i.e., tropics, middle and high latitudes).

[49] The most striking feature in the ERA-40 water vapor seasonal cycle is the inability of the reanalysis to reproduce a realistic water vapor tropical minimum (Figure 9). Overall, ERA-40 is consistently drier in the upper and middle stratosphere by 10–20% down to 30 hPa at all latitudes and seasons. At the levels between 30 hPa and 70 hPa ERA-40 remains consistently drier than UARS by 10–20% over middle and high latitudes but at these levels the ERA-40 water vapor performance has a strong seasonal dependence over the tropics and extratropics (Tables 4 and 5). In the UTLS, ERA-40 is consistently wetter than MOZAIC by typically 20% over the tropics and northern midlatitudes and by over 60% in the LS over the northern high latitudes (Figure 10 and Table 6). ERA-40 is in agreement with HALOE measurements indicating that, in the time mean, the NH is wetter than the SH, though the reanalysis has a drier SH than does HALOE, particularly in the southern polar vortex.

6.1. Tropical Stratospheric Water Vapor

[50] According to the HALOE observations, the water vapor minimum over the tropics occurs in the LS. It is located between 70 and 100 hPa from January to May (northern winter and spring, Figures 9a and 9d) and between 50 and 70 hPa from June to September (northern summer and autumn, Figures 9b and 9c). In contrast, ERA-40 produces a weaker water vapor minimum than HALOE, which extends significantly higher into the tropical middle stratosphere rather than being confined within the tropical LS. As a result, in the tropical LS ERA-40 between 70 and

Figure 10. Three-monthly MOZAIC, ERA-40, and MOZAIC–ERA-40 water vapor zonal means during the period 1 August 1994 to 31 December 1999 for (a) MAM, (b) JJA, (c) SON, and (d) DJF. The contour range for both MOZAIC and ERA-40 ozone fields is [0, 600] ppmv with a 50 ppmv step. The contour range for the MOZAIC–ERA-40 differences is [−300, 100] ppmv with a 0.25 ppmv step. PV = 2 pvu (thick white line). White areas represent data gaps.

Table 5. MLS–ERA-40 Water Vapor Differences for MLS 183 GHz Version 7.02 During the Period 19 September 1991 to 15 April 1993[a]

	MLSV7.02–ERA-40 Water Vapor Differences				
Pressure, HPa	Global, ppmv	Tropics, ppmv	Midlatitudes, ppmv	NH High Latitudes, ppmv	SH High Latitudes, ppmv
56.23	0.63 (14.2%)	0.27 (6.5%)	0.81 (17.9%)	0.97 (20.0%)	0.94 (22.3%)
68.13	0.46 (10.8%)	0.17 (4.3%)	0.60 (14.0%)	0.73 (16.1%)	0.69 (17.2%)
82.54	−0.20 (−5.6%)	−0.44 (−12.4%)	−0.12 (−3.4%)	0.001 (0.01%)	0.13 (4.2%)
100.00	−0.09 (−2.2%)	−0.20 (−5.2%)	−0.11 (−3.2%)	0.001 (−0.001%)	0.27 (8.5%)
121.15	−0.17 (2.4%)	−2.0 (−26.2%)	0.77 (15.9%)	1.21 (24.0%)	1.56 (33.2%)
146.78	0.20 (5.8%)	−0.31 (−1.2%)	0.59 (10.5%)	0.41 (8.4%)	0.50 (12.0%)

[a]In total, 517 days of valid measurements have been used for the validation. The latitudinal zones are defined as in Table 1.

100 hPa is constantly wetter than HALOE by typically 10–20%, whereas between 50 and 70 hPa ERA-40 is drier than HALOE by up to 20% during northern winter and spring, but becomes moister than HALOE by up to 15% during northern summer and autumn (Table 4 and Figure 11). Above 40 hPa over the tropics ERA-40 is constantly drier by 10–15% in comparison with HALOE, and this dry bias in the tropical middle and upper stratosphere extends also over middle and high latitudes throughout the entire year (Figure 9).

[51] The HALOE observations over the tropical LS also revealed that in January, dehydrated air passing through the tropical tropopause gradually spreads poleward, so that by April it covers much of the LS between 60°N and 60°S [*SPARC*, 2000]. Although ERA-40 captures this phenomenon, in January ERA-40 seems to bring up to the tropical tropopause (100 hPa) wetter air than UARS (by 20% than HALOE and by 5% than MLS V7) and then spreads it by April within the LS over the tropics and subtropics but not over the midlatitudes (Figures 9 and 11). As a result, over the midlatitudes and throughout the entire stratosphere, ERA-40 remains consistently drier than HALOE by typically 10–20% (Figure 9).

[52] Around the tropical tropopause (100 hPa), the MLS V7 data from the 183GHz instrument provide more information than HALOE, as shown in Table 5 and Figure 11. At levels above the tropical tropopause between 56 and 82 hPa the comparisons of the ERA-40 water vapor field with MLS V7 and HALOE agree very well with each other, both qualitatively and quantitatively. In the tropical UT (100 hPa to 150 hPa), however, the ERA-40 water vapor field compares much better with the MLS V7 than with the HALOE observations, particularly at the tropical tropopause and at 146 hPa. In general, in the tropical UT ERA-40 tends to be wetter than MLS V7 by only a few percent, except at 121 hPa where ERA-40 seems significantly wetter than MLS V7 by 20–30%. This wet bias in ERA-40 over the tropical UT agrees well with the results from the comparison with the MOZAIC data (Figure 10). Taking into account the fact that the MLS V7 measurements at 147 hPa and 100 hPa are increased by 30% and 20%, respectively, by the data providers in order to minimize the biases in the tropics [*Read et al.*, 2004a], it is possible that the above discrepancies found in the water vapor field between MLS V7 and ERA-40 at the 121 hPa level over the tropics may be due to a bias of the MLS V7 data at this level.

6.2. Midlatitude Stratospheric Water Vapor

[53] Over midlatitudes, the comparison of the water vapor field between ERA-40 and both the UARS and MOZAIC observations remains fairly consistent with season and height. More precisely, throughout all seasons ERA-40 is constantly drier than UARS by 10–20% in the upper and middle stratosphere down to 50 hPa. In the layer 50–80 hPa ERA-40, remains drier than UARS, but only by a few percent (Figures 11a–11d). In the layer 80–100 hPa, ERA-40 becomes wetter than the UARS measurements, but it is in this layer and over midlatitudes where the reanalysis water vapor field seems to compare overall at its best with the MLS V7 data (Figures 11e–11h). Below 100 hPa, in the LS ERA-40 becomes drier than MLS V7 by 10–20% (Table 5), whereas in the UT over midlatitudes ERA-40 is wetter than MOZAIC by 20% (Table 6).

6.3. High-Latitude Stratospheric Water Vapor

[54] HALOE has no coverage poleward of 80 degrees latitude, and especially during winter for both hemispheres HALOE has no coverage poleward of approximately 60 degrees. At high latitudes, HALOE data show that, during the year, the middle stratosphere is wettest during late spring and early summer for the SH (i.e., September to February, Figures 9c and 9d), and during summer to early autumn for the NH (i.e., June to September, Figures 9b and 9c). Although ERA-40 reproduces the above seasonal cycle in water vapor over the high latitudes, however, in the polar middle stratosphere, as well as in the polar upper stratosphere, ERA-40 is consistently drier than HALOE by typically 1.0–1.5 ppmv (~10–20%, Figures 9c and 11). During Southern Hemisphere winter and spring, low water vapor values are observed by ground-based measurements in polar regions of the Southern Hemisphere, associated with dehydration in the Antarctic polar vortex [*SPARC*, 2000]. This dehydration process usually begins in the mid southern winter (July) and continues until the vortex breaks down in December. The effect of dehydration extends over the LS up to ~60°S, with a sharp gradient in water vapor values near the vortex edge. Figure 9c shows that ERA-40 clearly captures the low water vapor mixing ratios of

Table 6. MOZAIC–ERA-40 Water Vapor Differences[a]

	MOZAIC–ERA-40 Water Vapor Differences		
Altitude, km	Tropics, ppmv	NH Midlatitudes, ppmv	NH High Latitudes, ppmv
11.8	−14.1 (−14.6%)	−4.0 (−6.6%)	−0.5 (−0.05%)
11.2	−36.9 (−20.0%)	−13.9 (−17.0%)	−10.3 (−63.5%)
10.6	−40.9 (−16.9%)	−19.4 (−18.7%)	−12.8 (−17.2%)
10.0	−57.8 (−14.1%)	−30.3 (−21.5%)	−22.8 (−94.1%)

[a]MOZAIC flights for the period 1 August 1994 to 31 December 1999. Total number of flights is 12,227. The latitudinal zones are defined as in Table 3.

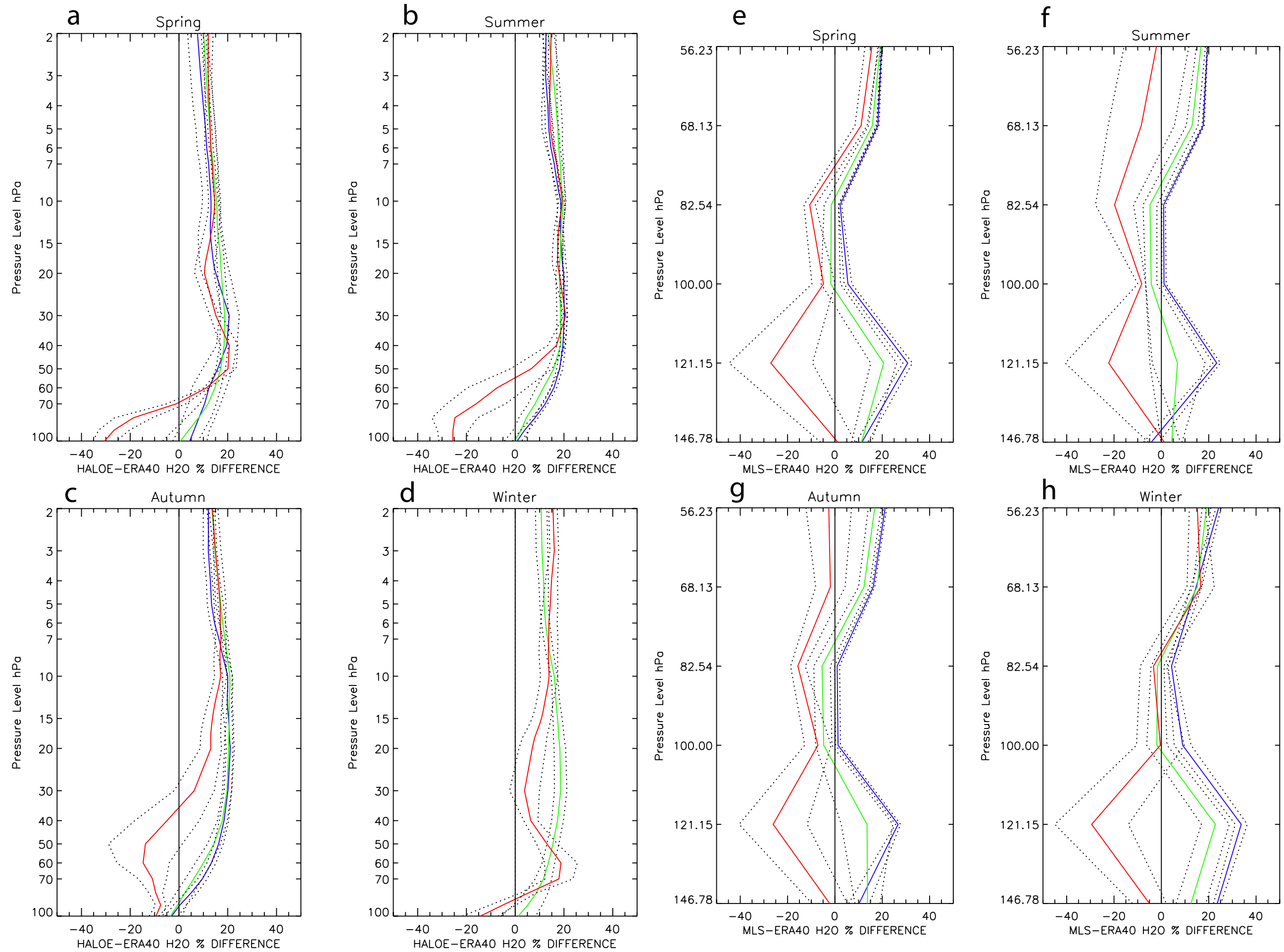

Figure 11. UARS−ERA-40 water vapor seasonal zonal mean differences expressed as percentage of the original UARS observations for (a–d) HALOE V19 sunrise and sunset measurements for the period 11 October 1991 to 31 December 1999 and (e–h) MLS 183 GHz V7.02 for the period 19 September 1991 to 15 April 1993. The definition of seasons and geographical areas is the same as in Figure 4.

southern polar vortex in spring, with the same latitudinal extent as indicated by HALOE. Nevertheless, ERA-40 water vapor values are ~1.0 ppmv (25%) too high in the core of the polar vortex between 70 and 100 hPa from September to November (when HALOE provides coverage to nearly 80°S). Above 50 hPa, however, at southern high latitudes during spring the sign of the difference with HALOE changes and ERA-40 becomes considerably drier than HALOE by up to 1.5 ppmv (15–20%, Figures 9c and 11a).

6.4. UTLS Water Vapor

[55] In the tropical UT and throughout the entire validation period ERA-40 is consistently wetter than MOZAIC by 100–150 ppmv (20–30%) around the equator where the aircraft fly predominantly over the Atlantic Ocean (Figure 10). Over middle and high latitudes, ERA-40 in the UTLS remains predominantly wetter than MOZAIC by typically 15–20 ppmv (Table 6), though with a strong dependence on season and altitude. For example, ERA-40 over the midlatitudes is moister than the aircraft observations by 20–30% during northern spring and by 30–35% during northern summer.

[56] In northern summer, there is a strong signal of locally moist air over the Indian continent during its monsoon, as well as over Central America/Caribbean and also over West Africa. Over these three areas of the UT during northern summer, ERA-40 is consistently wetter than MOZAIC by 10–15%, 20% and 30–35%, respectively. In sharp contrast, in the vicinity of coastal areas ERA-40 in the tropical UTLS may underestimate water vapor amounts by 10–20% particularly during northern winter over the coasts of South and Central America, as well as those of western and southern Africa (e.g., Figure 10d at 35°S).

[57] The very dry regions of the subtropics and their strong seasonal cycle are successfully captured by ERA-40 in the subtropical UT (Figure 10). Both MOZAIC and ERA-40 water vapor data at 11.2 km (223–215 hPa) compare well with the MLS observations at 215 hPa from *Stone et al.* [2000], who report a dry region around the subtropical North Atlantic (i.e., around 20°N) during northern winter. The same feature can be seen in ERA-40 (Figure 10d), though again the reanalysis in the subtropical UT remains wetter than the MOZAIC measurements by 20–30 ppmv (~20%). There is also good agreement in the way the UT water vapor maxima are associated, as noted in previous

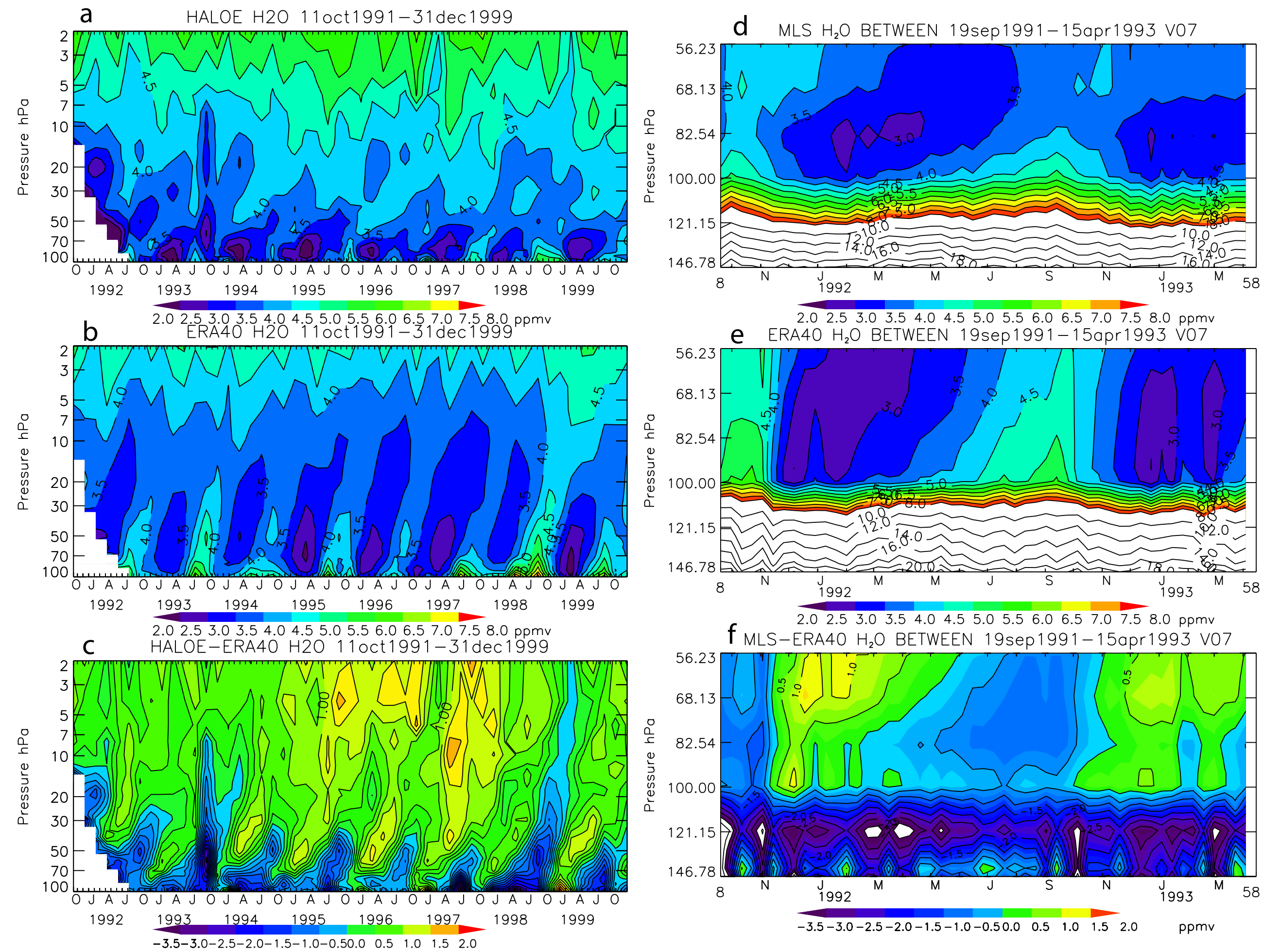

Figure 12. Time series of the UARS versus ERA-40 water vapor comparison between 12°N and 12°S for (a–c) HALOE V19 sunrise and sunset measurements during the period 11 October 1991 to 31 December 1999 and (d–f) MLS 183 GHz version 7.02 data during the period 19 September 1991 to 15 April 1993. Shown are UARS ozone (top panels), ERA-40 ozone interpolated to the time and location of the UARS observations (middle panels), and the UARS–ERA-40 difference (bottom panels). For the UARS–ERA-40 differences the contour step is every 0.25 ppmv. The vertical range is [2, 100] hPa for the HALOE versus ERA-40 validation and [56.23, 146.78] hPa for the MLS V7.02 versus ERA-40 validation following the UARS team recommendations. In order to compare the ERA-40 water vapor validation against both UARS sensors, the same color plates are used in the figures. The contour ranges as in Figure 10. Also plotted are, in Figures 12d and 12e, the MLS V7.02 and ERA-40 water vapor fields for values over 8.0 ppmv using a 2 ppmv interval and, in Figure 12f, the MLS-ERA-40 values less than −3.5 ppmv using a 0.25 ppmv interval.

studies [*Stone et al.*, 2000], with areas of strong upward motion.

[58] Over northern high latitudes, ERA-40 between the cruise levels of 10–11.2 km is typically wetter than MOZAIC; but at the highest cruise level of 11.8 km, ERA-40 is predominantly drier than MOZAIC by 5–10% (Figures 10a, 10c, and 10d). For example, at the 11.8 km cruise level over Canada and the southern tip of Greenland during northern autumn and winter, ERA-40 is drier by 10–15% than MOZAIC. These results for the cruise level of 11.8 km over high latitudes agree very well with the findings derived from the comparison of ERA-40 with MLS V7, showing that the LS over high latitudes in ERA-40 is typically drier than MLS by 10–20% (Figures 11e–11h). Below the 11.8 km cruise level over high latitudes, ERA-40 is typically moister than the aircraft measurements by 10–30% during northern spring and by >100% during northern summer. These results suggest that, especially in the LS over high latitudes, ERA-40 reproduces the water vapor seasonal cycle with a strong wet bias below the cruise level of 11.8 km.

6.5. ERA-40 Water Vapor Biases Compared With Independent Data and Their Temporal Variation

[59] A comprehensive study of the seasonal and long-term variations of water vapor is given by *SPARC* [2000]. The tendency of ERA-40 to be drier than HALOE in the middle and upper tropical stratosphere seems to increase with time (Figure 12). Between 1992 and 1997 progres-

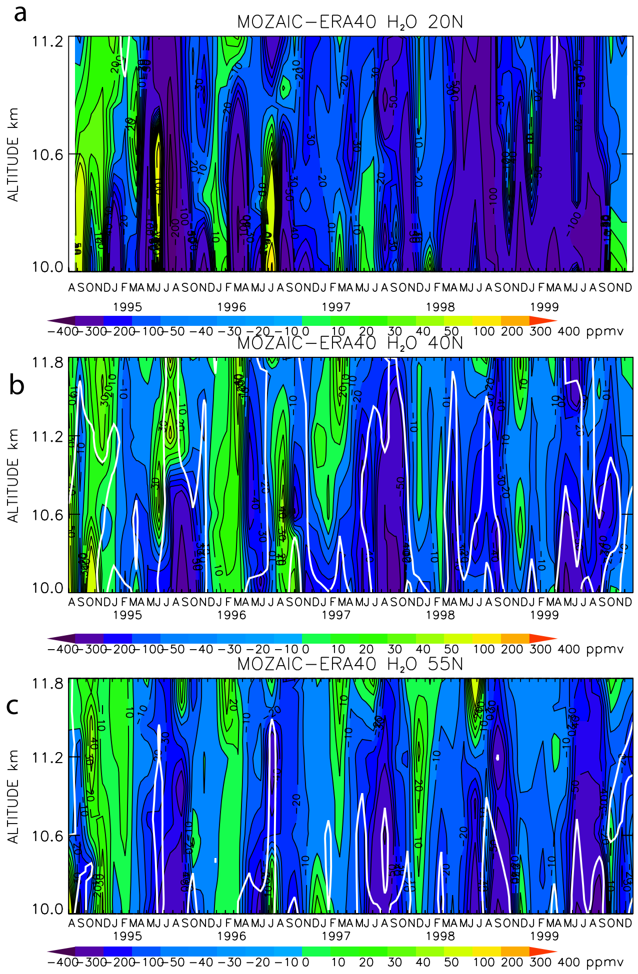

Figure 13. Time series of the vertical variation of the MOZAIC–ERA-40 water vapor differences for the period 1 August 1994 to 31 December 1999 at (a) 20°N, (b) 40°N, and (c) 55°N. The contour range is [−400, 400] ppmv with a 50 ppmv step. PV = 2 pvu (thick white line). White areas represent data gaps. The top cruise level of 11.8 km at 20°N is not considered here because at this level over 20°N the MOZAIC measurements are discontinuous.

sively drier air reaches the tropical middle stratosphere in ERA-40. For example, at 40 hPa and during March ERA-40 is drier than HALOE by 15% in 1992 and by 30% in 1997. In ERA-40 as the 1990s evolves, the ascending dry air masses appear to have longer residence times in the tropical stratosphere before they eventually degrade. For example, over the equatorial stratosphere in 1992 dry air of 3.5 ppmv is encountered at 10 hPa up to July, whereas in 1997 dry air at the same level and of similar water vapor content can be found even in October (Figure 12b). Although ERA-40 is drier than HALOE in the upper and middle stratosphere, in the equatorial LS at levels 70–100 hPa ERA-40 is moister by 30–40% in comparison with HALOE. During 1993 and especially during 1998, ERA-40 reproduces a considerably moister (by 60%) LS compared with HALOE. Moreover, this wet bias in ERA-40 over the tropical LS spreads into the tropical middle stratosphere in 1993, and even into the upper stratosphere in 1998 that results in an exceptionally moist tropical stratosphere for ERA-40 during 1998.

[60] Time series in the UTLS showing seasonal variability of water vapor related to the meridional movement of tropical convective upwelling is well represented by ERA-40. An example is given in Figure 13 where time series of the MOZAIC–ERA-40 water vapor differences are plotted at 20°N, 40°N and 55°N (at 20°N, the highest cruise level of 11.8 km is not considered here since at this altitude the MOZAIC data over the tropics are discontinuous in time). In the tropical UT near 20°N (Figure 13a), ERA-40 tends to be drier than MOZAIC during northern late spring and early summer, but it becomes wetter in late summer and early autumn. The above pattern persists till the end of 1997, when ERA-40 becomes generally moister than MOZAIC, and this wet bias in the reanalysis becomes more pronounced in 1998 and 1999, as can also be seen for these years in the ERA-40 water vapor comparison with HALOE over the tropics (Figure 12c). During northern summer and autumn at 40°N, the MOZAIC aircraft fly mainly in the UT (Figures 10b, 10c, and 13b). During these months at 40°N, ERA-40 tends to be moister by 100 ppmv (30–35%) than MOZAIC throughout the 1990s (Figure 13b). Finally, at 55°N and at the cruise levels between 10.0 and 11.2 km the general wet bias of ERA-40 compared with MOZAIC seems to be most pronounced during northern summer and it is roughly constant in time through the 1990s (Figure 13c). In addition, the dry bias found at the 11.8 km cruise level over high latitudes during the northern winters of 1994, 1995 and 1997 spreads down to 10.6 km (Figure 13c).

7. Discussion

[61] In this section we discuss some aspects of particular interest concerning how well the reanalysis reproduces the ozone and water vapor fields, as indicated by the comparison with independent data.

7.1. Effect of Changes in the ERA-40 Data Assimilation System

[62] ERA-40 over the tropics consistently underestimates the ozone maximum. Although the time series of the ERA-40 ozone evaluation exhibits no trend in the stratosphere, in the UTLS the reanalysis shows a considerable change after October 1996; this period coincides with changes in the ERA-40 system, when revised background error covariances were introduced in the data assimilation algorithm in order to improve the vertical distribution of ozone increments [*Dethof and Hólm*, 2004]. This new analysis increment was found to be more confined in the vertical, with no correlations between the stratosphere and the troposphere, or between levels at and above the stratospheric ozone maximum [*Dethof and Hólm*, 2002]. The effect of these changes is shown in Figure 8. Post-October 1996, the ERA-40 ozone field in the UTLS has a regular seasonal cycle over middle and high latitudes (not shown), which was less prominent in the 1990s before that date. In addition, post-October 1996 in the UTLS, ERA-40 has more ozone than earlier in the decade over middle and high latitudes, and is in better agreement with MOZAIC observations (not shown). This result implies that trends in actual UTLS

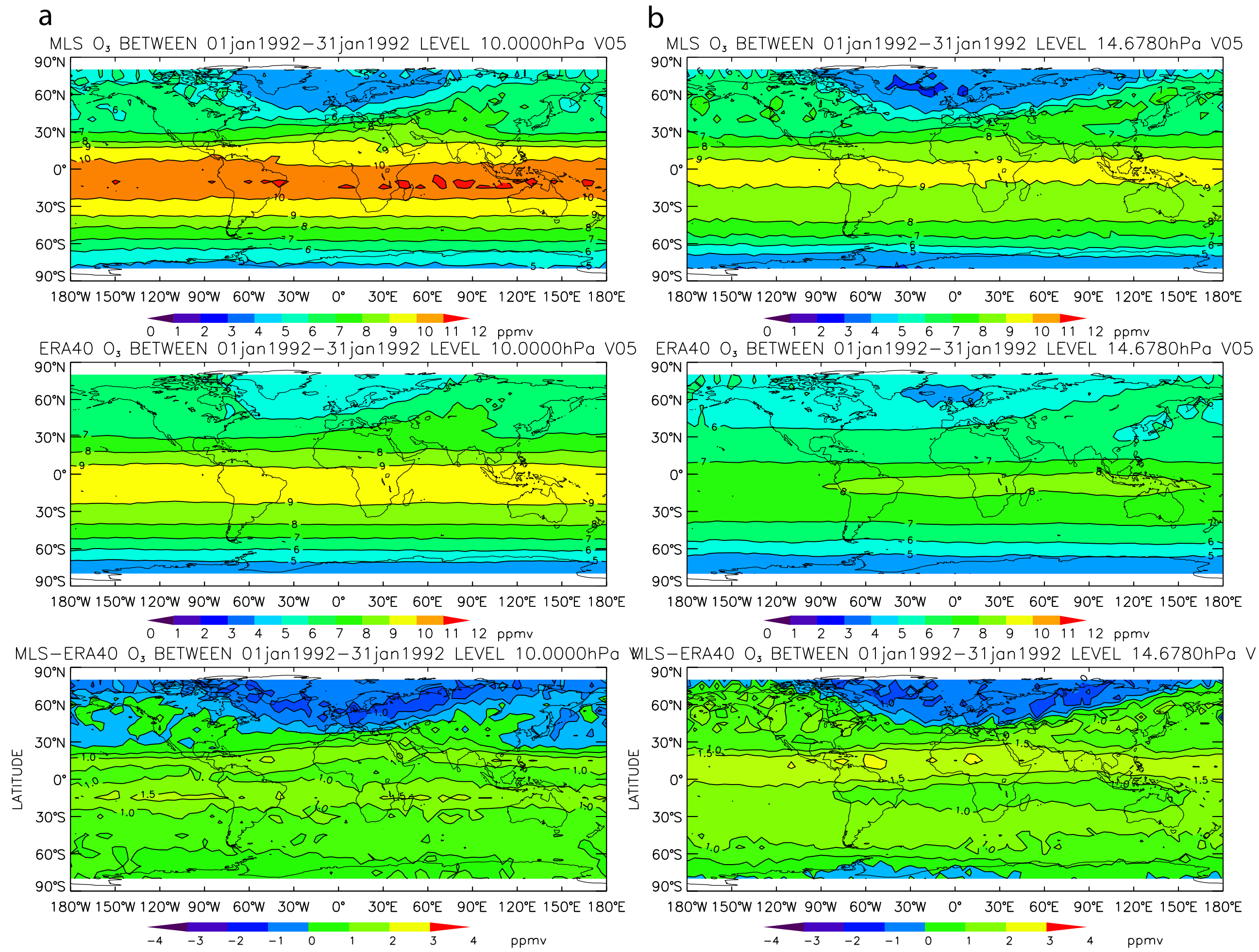

Figure 14. MLS (top panels), ERA-40 (middle panels), and MLS–ERA-40 (bottom panels) ozone zonal means for MLS version 5 measurements during the period 1–31 January 1992 at (a) 10 hPa and (b) 14.678 hPa. The contour range for both MLS and ERA-40 ozone fields is [0, 12] ppmv with a 1 ppmv step. The contour range for the MLS–ERA-40 differences is [−4, 4] ppmv with a 0.5 ppmv step.

ozone concentrations derived from the ERA-40 should be treated with caution, at least during the 1990s. Despite the fact that the changes in the reanalysis system have improved the ERA-40 ozone in the UTLS, they seem to have no particular effect in the way ERA-40 consistently underestimates the tropical ozone maximum in the middle stratosphere throughout the 1990s. *Dethof* [2003] also found that the modified covariances used in ERA-40 from December 1978 to 1989 and then post-October 1996 although they improve the reanalysis ozone profiles in the UTLS, as indicated in the present study, however, the ERA-40 ozone maximum can be reduced too much in situations where the analysis increment is large and negative.

[63] No particular trend in the ozone biases between ERA-40 and UARS is detected during the 1990s in the stratosphere, nor is there an obvious trend in the biases in total column ozone when comparing ERA-40 with ground based observations [*Dethof and Hólm*, 2004].

7.2. ERA-40 Ozone Parametrization Scheme

[64] The ERA-40 ozone evaluation shows that the high latitudes are the second most problematic region in need of further attention (the tropical UTLS being the other region). ERA-40 appears to produce an Antarctic ozone hole that is not deep enough and also extends less into the middle stratosphere near the pole in comparison with the satellite observations (Figures 1c, 2c, and 7). In addition, there exists a strong altitude dependence in the way ERA-40 ozone compares with UARS ozone (Figure 4), as explained in section 5.5. These results suggest that the ERA-40 ozone parameterization scheme may need to be revised, for instance, the temperature threshold of 195 K, implemented to activate parameterized heterogeneous chemistry, is not at present altitude dependent and probably should be. In addition, the parameterization should represent the transport of chlorine-activated air to regions with temperatures above this threshold value.

7.3. Arctic Polar Ozone

[65] There are considerable discrepancies between ERA-40 and UARS when examining the less severe Arctic ozone hole found during northern winter, primarily in January. As an example, Figure 14 shows the ERA-40 ozone comparison with MLS for January 1992, which was one of the four

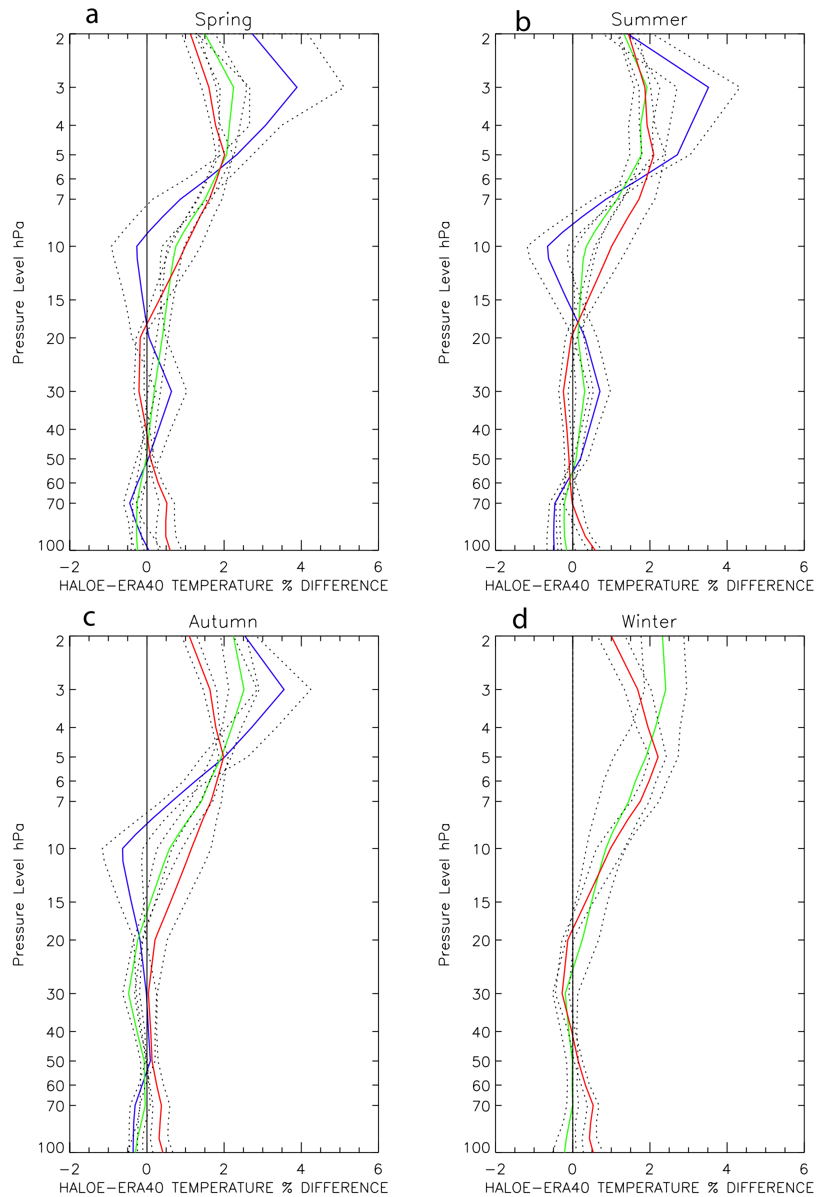

Figure 15. (a–d) HALOE–ERA-40 temperature seasonal zonal mean differences expressed as percentage of the original HALOE observations for HALOE V19 sunrise and sunset measurements for the period 11 October 1991 to 31 December 99. The definition of seasons and geographical areas is the same as in Figure 4.

coldest winters in the NH during the 1990s [*Manney et al.*, 1997, 2003]. MLS captures low ozone centered over Greenland, though ERA-40 significantly overestimates the ozone concentration over the Arctic by 2–3 ppmv (40–50%) in the middle stratosphere near 10 hPa, which is one of the highest MLS–ERA-40 ozone differences. This tendency of ERA-40 to have higher ozone values over the northern high latitudes in the middle stratosphere during winter has also been pointed out by other studies [*Dethof and Hólm*, 2002], and it is believed to be due to a too strong Brewer-Dobson circulation in ERA-40, possibly resulting from differences in temperature biases between the model and the observations. The overall indication that the Brewer-Dobson circulation in ERA-40 is considerably too strong is also suggested by *Noije et al.* [2004]. In order to tackle these drawbacks encountered in the ERA-40 ozone field, ECMWF is currently working to improve the background error covariances in the assimilation scheme, as well as assimilating ENVISAT satellite ozone data into the ECMWF system. ECMWF is also seeking to reduce the excessive Brewer-Dobson circulation through work on model/observation biases in temperature/radiances. Figure 14b also indicates a high MLS–ERA-40 ozone positive anomaly, the highest values of this anomaly being confined between the equator and 30°N, for reasons that are not understood. As explained in section 5.1, ERA-40 has lower values of ozone than UARS around the tropical ozone maximum in the middle stratosphere (i.e., around 10 hPa). At these levels, maximum deviations of the ERA-40 ozone from the UARS data are found to the north of the equator

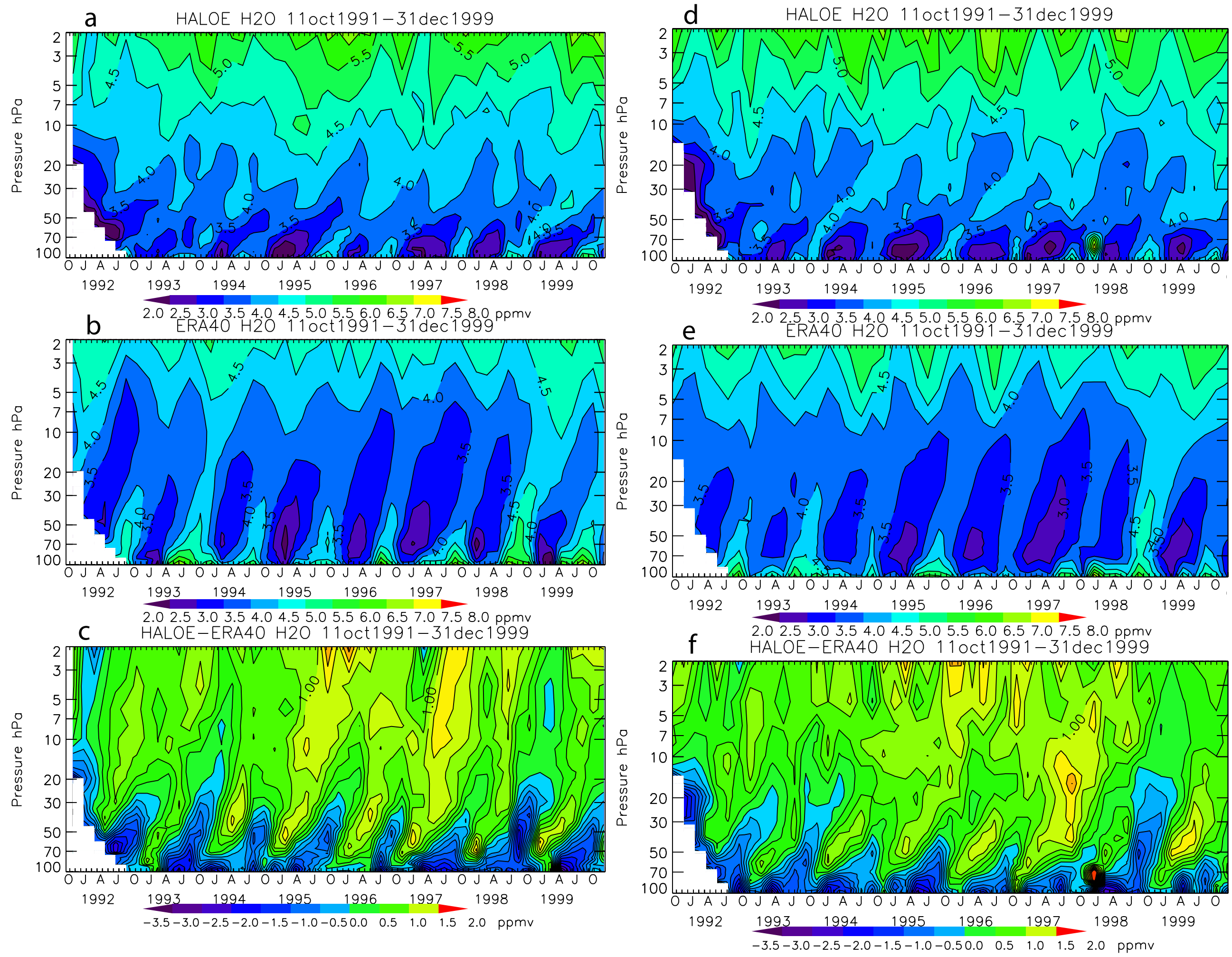

Figure 16. Time series of the HALOE versus ERA-40 water vapor comparison between for HALOE V19 sunrise and sunset measurements during the period 11 October 1991 to 31 December 1999 and (a–c) between 10° and 14°N and (d–f) between 10° and 14°S. HALOE water vapor (top panels), ERA-40 water vapor interpolated to the time and location of the HALOE observations (middle panels), and the HALOE–ERA-40 difference (bottom panels). The contour range for both HALOE and ERA-40 water vapor fields is [2, 8] ppmv with a 1 ppmv step. The contour range for the HALOE–ERA-40 differences is [−2, 2] ppmv with a 0.25 ppmv step.

during DJF (as seen for January 1992 in Figure 14b) and to the south of the equator for JJA.

[66] ERA-40 fails to capture accurately the ozone concentration inside the core of both the Arctic and Antarctic ozone holes. This finding raises the question of whether ERA-40 over the high latitudes has errors because of shortcomings in the temperature analysis, or because of a poor representation of heterogeneous chemistry on polar stratospheric clouds. Although it is beyond the scope of the present work to analyze the ERA-40 temperature fields, Figure 15 shows the seasonal variation of the HALOE–ERA-40 temperature percentage differences. ERA-40 reproduces the temperature field with a less than ±0.5% deviation from the HALOE measurements throughout all seasons and latitudes at the levels of 7 hPa and below. The greatest discrepancies occur in the upper stratosphere, where ERA-40 is consistently cooler than HALOE, particularly over the high latitudes where the ERA-40 temperature field deviates its most from the HALOE observations by 2–3% during summer and autumn in both hemispheres (Figures 15b and 15c). *Randel et al.* [2004] have also found a cold bias of ~5 K in the ERA-40 temperature field in the upper stratosphere.

7.4. UTLS Ozone

[67] Despite the problems mentioned above, the reanalysis shows an ability to reproduce the ozone climatology and atmospheric processes in the UTLS where data are far scarcer than in the stratosphere. ERA-40 performs particularly well in the UTLS over midlatitudes, but it is in the tropical UTLS where the largest discrepancies are found. ERA-40 in the UTLS also successfully indicates some ozone variation between coastal zone areas and the oceans (e.g., Figure 10d, south of 35°S). Such ozone variations have already been reported by the MOZAIC team [*Thouret et al.*, 1998]. They are believed to result from zonal variations of the polar front and the position of ridge and

trough systems, as well as from possible differences in the production of ozone between the oceans and the industrial continental areas. Moreover, ERA-40 is capable of reproducing relatively high average ozone values over midlatitudes in the Northern Hemisphere, which are particularly pronounced over the Eastern Mediterranean [*Oikonomou et al.*, 2004]. These high concentrations have been considered so far as an indication of cutoff systems and small-scale filaments, not necessarily associated with potential vorticity filaments, which may erode faster than features in the ozone field [*Morgenstern and Marenco*, 2000].

7.5. Tape Recorder Signal in Water Vapor

[68] The annual variations in the water vapor concentrations in the tropical lower and middle stratosphere, exhibiting large-scale upward advection, was originally reported by *Mote et al.* [1996], a phenomenon referred to as the tape recorder. ERA-40 is able to reproduce the tape recorder signal (Figure 12), as was also found when analyzing operational data from the ECMWF model [*Simmons et al.*, 1999], though with some considerable differences.

[69] In qualitative agreement with HALOE, the amplitude of the tape recorder signal in water vapor in ERA-40 is greater to the north of the equator than it is to the south (Figure 16), though this difference is more pronounced for ERA-40 than for HALOE. During the dry period of the signal, from October to April, low values of water vapor in ERA-40 reach the middle stratosphere apparently faster to the north of the equator than to the south, a feature which is again more pronounced for ERA-40 than for HALOE. ERA-40 mean ascent rates over the tropics are estimated from the water vapor concentrations to be typically of 0.5×10^{-3} m/s, with no significant difference between northern winter and the rest of the year, though these ascent rates may vary with height. This result is in contrast with the HALOE data for which the mean ascent rates were calculated to be slower ($0.2–0.4 \times 10^{-3}$ m/s) and with a seasonal variability [*Mote et al.*, 1996]. Similar results apply for all ERA-40 reanalysis periods (not shown here), including sample runs for the years 1958–1960 and for 1973–1975. The above results suggest once more that the Brewer-Dobson circulation produced by the ECMWF assimilation system is too strong [*Noije et al.*, 2004]. When examining the entire ERA-40 water vapor archive, considerable variations in time are seen in the tape recorder signal over the tropics: the mid stratosphere is less dry in the 1960s, the mid 1970s, and the early 1980s; and the introduction of comparatively dry air into the stratosphere in northern winter reaches 10 hPa later in the season in the 1960s than it does in the 1990s (A. Simmons, personal communication, 2003).

7.6. UTLS Water Vapor

[70] MOZAIC flights provide good coverage over two of the tropical monsoon systems, namely the African monsoon over central Africa and the South American monsoon over the Amazon. The ERA-40 water vapor comparison with independent data in the UTLS indicates overall the ability of the reanalysis to represent these monsoon systems. Since there are no MOZAIC flights over the Indian and Pacific Oceans, the Austral-Asian monsoon system over the maritime continent (including the Intertropical Convergence Zone) and their representation by ERA-40 could not be examined here. Evaluation of the previous ECMWF reanalysis data, ERA-15, also found that the reanalysis in the ITCZ over the Atlantic and eastern Pacific at 215 hPa (equivalent to the 11.2 km MOZAIC cruise altitude) is moister by typically 20–30 ppmv than satellite data, and it was concluded that the ECMWF reanalysis underestimates the dryness of the descending branch in the Hadley circulation [*Clark and Harwood*, 2003]. This finding agrees with the present ERA-40 comparison over the tropics, though our results imply that, in the UT over the tropical oceanic areas, ERA-40 may be even moister than ERA-15.

[71] There is evidence of dehydration processes occurring in the tropical tropopause layer (TTL) and of a strong seasonal cycle in water vapor in the air rising out of the TTL into the stratosphere, with minimum water vapor values in January to April and maximum values during August–November [*SPARC*, 2000]. Furthermore, it is also generally agreed that both stratospheric and tropospheric effects, such as deep convection, radiation, the Brewer-Dobson circulation and the tropospheric effect on the temperature around the tropopause, can play a role in the processes by which air is dehydrated in the TTL. Despite the proposal of potential hypotheses, these processes by which air is dehydrated in the TTL are still inadequately understood [*Read et al.*, 2004b]. The aforementioned seasonal cycle is shown by both HALOE and ERA-40 data (Figure 9) where the HALOE measurements indicate a minimum in the water vapor concentration of 2.5–3.0 ppmv from March to May (Figure 9a) and a maximum of 4.0–4.5 ppmv from September to November (Figure 9c). Since only in the tropics are tropopause temperatures low enough to dehydrate air to these low water vapor mixing ratios observed in the stratosphere, the above seasonal cycle is believed to be temperature sensitive; we find that throughout the validation period ERA-40 remains consistently colder by 0.5% than the HALOE observations in the tropical LS (Figure 15). This cold (warm) bias in ERA-40 over the tropical LS (middle stratosphere) may be connected to the consistent and significant wet (dry) bias found in ERA-40 water vapor over the tropical LS (middle to upper stratosphere). This result is consistent with the previously mentioned evidence for a too strong Brewer-Dobson circulation in ERA-40 if the assimilated observations do not fully compensate for the excess cooling caused by too strong ascent.

7.7. Effect of Validating Against Different Versions of Data

[72] The results of the present study raise two additional points of interest: the variations in differences that can be obtained when comparing with different sensors (e.g., between MLS and HALOE), as well as the discrepancies found for different data versions of the same sensors (e.g., for MLS V4 and V5). Even though, broadly speaking, the ERA-40 ozone comparisons with both UARS instruments agree with each other throughout most of the stratosphere, there are cases where they differ significantly, especially over the tropics. For example, at the tropical 70 hPa level ERA-40 underestimates the ozone content in comparison to MLS V5 by 40%, but only by 20% in comparison to HALOE (Tables 1 and 2). Within the core and the upper levels of the Antarctic ozone hole (i.e., 50–70 hPa) in the

annual-mean, ERA-40 underestimates the ozone content by typically 9% when compared to MLS, and overestimates it by 8% in comparison with HALOE (Tables 1 and 2), recalling though that MLS provides a more continuous coverage over the high latitudes than does HALOE. Differences are also encountered in the evaluation of the water vapor field, particularly at and above the tropical tropopause levels (50–100 hPa), where ERA-40 compares considerably better with MLS V7 than with HALOE (Figure 11).

[73] We have also found that the ozone field in the reanalysis compares better with MLS V5 than with V4: (1) at and below the 46 hPa level at all latitudes; (2) below the tropical ozone maximum and throughout the entire year, especially during northern winter; and (3) at the time and location of the Antarctic ozone hole. Little difference (1 to 2%) is found elsewhere in the comparison of ERA-40 with MLS V4 or V5. Over the tropics and at the level of the tropical ozone maximum, ERA-40 compares better with MLS V5 than V4: throughout the year the MLS–ERA-40 differences for V5 are consistently 0.3 ppmv lower than for V4 (Figure 5). This value compares very well with the overall difference between MLS V5 and V4 at the tropical 10 hPa, as found by the MLS science team (see Table 9 of *Livesey et al.* [2003]).

8. Conclusions

[74] Broadly speaking, ERA-40 reproduces realistic ozone and water vapor fields in comparison with UARS and MOZAIC measurements with the greatest discrepancies occurring primarily over the tropics and the high latitudes. For water vapor, ERA-40 is drier than HALOE in the upper and middle stratosphere by 10–15%. This discrepancy is now well understood by ECMWF to be due to inadequacies in the methane oxidation scheme used in the reanalysis and ECMWF have changed this scheme in their operational system. Phenomena such as the Antarctic (Figure 7) and Artic (Figure 14) ozone holes, the tropical stratospheric ozone maximum (Figures 1 and 2), the tropical LS water vapor minimum (Figure 9), and the tape recorder signal (Figures 12 and 16) are reproduced by the reanalysis. Nevertheless, there are some quantitative problems in each of these phenomena, such as the lower than UARS altitude of the tropical ozone maximum from May to August and the wet bias found in the tropical UTLS in comparison with MOZAIC.

[75] In the upper stratosphere ERA-40 overestimates the ozone concentrations by typically up to 10% over the tropics and the midlatitudes, and by 10–20% over the high latitudes, with a strong seasonal dependence in the way ERA-40 captures the actual value of the tropical ozone maximum at around 10 hPa. In the middle and lower stratosphere, ERA-40 seems to underestimate ozone by typically 5%, a tendency that persists over the tropics throughout the year, but is highly variable with season, and may even change sign over the middle and high latitudes (Figure 4). In general, ERA-40 underestimates the ozone concentration within the core of the Antarctic ozone hole by 10–20%, though this situation may be the opposite for same years during the 1990s, but ERA-40 consistently overestimates ozone values by 10% at levels above the Antarctic ozone hole. By contrast, ERA-40 seems to significantly overestimate ozone during Arctic ozone hole events (primarily in January), and especially during the coldest winters throughout the 1990s. In the UTLS ERA-40 tends to consistently underestimate ozone in the LS over the high latitudes, and overestimate it in the tropical UT. In the UTLS over the midlatitudes, the ERA-40 ozone performance has a strong seasonal variation (Figure 4). Because of an improvement in the data assimilation system introduced in October 1996, after this date ERA-40 ozone is subsequently closer to MOZAIC data in the UTLS over the middle and high latitudes (though not much difference was seen in the tropics). In view of these results, care should be taken when calculating ERA-40 ozone trends in the UTLS during the 1990s over the middle and high latitudes.

[76] The water vapor cycle in ERA-40 appears to be problematic, and issues are being addressed as part of ECMWF's continuing program of research and development. The water vapor evaluation presented here indicates that the reanalysis is not necessarily in balance with the model's own water vapor climate. More specifically, ERA-40 is too dry by about 10–20% above about 70 hPa (Figure 11). Although within the core of the Antarctic vortex, ERA-40 is wetter than HALOE in the LS by a few percent, above about 50 hPa ERA-40 is significantly drier within the vortex (Figure 9c). This ERA-40 dry bias in the upper and middle stratosphere is not confined to the region of the Antarctic polar vortex but is essentially global. This dry bias seems to increase with time during the 1990s (Figure 12). In the upper stratosphere, ERA-40 does not capture realistically the seasonal cycle in water vapor as observed by HALOE. At tropopause levels and into the UT, ERA-40 values are wetter than those of MOZAIC, typically by about 20% (Figure 10 and Table 6). Finally, the largest discrepancies from the MOZAIC observations occur in the LS over the high latitudes, where the ERA-40 water vapor performance has a strong seasonal and altitude variation, and the reanalysis is >60% wetter than MOZAIC at and below cruise altitudes of 11.2 km (223–215 hPa).

[77] At the time of writing, MLS temperature, ozone and water vapor data are being prepared for assimilation into the ECMWF system by groups at the Universities of Edinburgh and Reading (UK), initially for the period 1992 to 1994. This enhancement of the data assimilation should correct, at least for some years, some of the errors with the current version of the ERA-40 reanalysis noted here.

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