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Improved ozone profile retrievals from GOME data with degradation correction in reflectance

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Abstract

We present a simple method to perform degradation correction to Global Ozone Monitoring Experiment (GOME) reflectance spectra by comparing the average reflectance for 60° N–60° S with that at the beginning of GOME observations after removing the dependences on solar zenith angle and seasonal variation. The results indicate positive degradation of up to ∼15–25% in the wavelength range 289–370 nm during 2000–2002; the degradation also exhibits significant dependence on wavelength and view zenith angle. These results are consistent with previous studies using radiative transfer models and ozone observations or climatology. The degradation causes retrieval biases of up to ∼3% (10 DU, 1 DU=2.69×10^{16} molecules cm^{-2}), 30% (10 DU), 10%, and 40% in total column ozone, tropospheric column ozone, stratospheric ozone and tropospheric ozone, respectively, from our GOME ozone profile retrieval algorithm. The application of this degradation correction generally improves the retrievals relative to Dobson and ozonesonde measurements during 2000–2003 and improves the retrieval consistency during 1996–2003.

1 Introduction

The Global Ozone Monitoring Experiment (GOME), launched on board the European Space Agency's (ESA) second Earth Remote Sensing (ERS-2) satellite in April 1995, measures backscattered light from the Earth's atmosphere and surface in the wavelength range 240–790 nm (ESA, 1995). Observations with spectral resolution of 0.2 nm and high signal to noise ratio in the Hartley and Huggins bands enable retrieval of the vertical distribution of ozone down into the troposphere (Chance et al., 1997; Munro et al., 1998; Hoogen et al., 1999; Hasekamp and Landgraf, 2001; van der A et al., 2002; Müller et al., 2003; Liu et al., 2005).

GOME has degraded over time because of ultraviolet light damage to its optical elements and the build-up of a thin contaminating ice layer on the surface of the scan mirror (Tanzi et al., 2000). Although a degradation correction is applied in the standard GOME Data Processor extraction software, it is assumed that radiance and irradiance spectra degrade in the same way (i.e., no degradation in the reflectance or sun-normalized radiance). However, the scan-mirror degradation due to the etalon effect produced by ice build-up has a strong dependence on the incident angle. Therefore, the degradation differs substantially between the irradiances and backscattered radiances (Tanzi et al., 2000). This scan-angle dependence of the scan-mirror degradation and the degradation in the diffuser plate can cause degradation in the reflectance (Tanzi et al., 2000; van der A et al., 2002). Without degradation correction in the reflectance after 1998, ozone profile retrievals can be significantly affected or even cannot proceed (van der A et al., 2002). Empirical schemes have been developed to correct the reflectance degradation by comparing measured and simulated reflectance spectra, rendering ozone profile retrievals possible after 1998. The simulated reflectance is calculated using ozone profile climatology (van der A et al., 2002) or a combination of climatology and ozonesonde observations (Landgraf et al., 2005) and with retrieved surface albedo from measurements (e.g., 340 nm, 400 nm). However, using surface albedo derived from uncorrected measurements leads to incomplete degradation correction. In addition, because of the inhomogeneous performance of ozonesonde observations, especially in the upper troposphere and lower stratosphere (Liu et al., 2006), and limited ozonesonde observations, the derived correction parameters can vary significantly with latitude or vary from location to location.

In our retrieval algorithm (Liu et al., 2005), we correct part of the degradation by fitting a 2nd-order polynomial in the spectral region 289–307 nm and a wavelength-dependent surface albedo (2nd-order polynomial) in the wavelength region of 326–339 nm. This correction enables ozone profile retrievals to proceed for all measurement periods. However, the quality of the retrievals, especially the tropospheric ozone, has degraded significantly in 2000. A degradation correction is necessary to make the retrieval performance consistent for all periods. This study presents an alternative and simple degradation correction scheme for GOME measurements which does not require the use of radiative transfer models and climatological/observed ozone profiles. We demonstrate that this scheme can greatly improve the consistency of GOME retrievals.

2 Degradation correction scheme

The degradation on a certain day and at a particular wavelength is derived from the ratios of reflectance ($I/F\cos\theta_0$, where I is the radiance, F is the irradiance, and θ_0 is the solar zenith angle) averaged over all longitudes between 60° N–60° S to that on 1 July 1995 using additional post-processing described as below. A similar approach was used to perform degradation correction for GOME irradiances (http://wdc.dlr.de/sensors/gome/degradation_files/degradation.html). However, unlike the irradiances, the measured radiances depend strongly on atmospheric conditions (e.g., clouds, aerosols, absorbers, surface albedo) and viewing geometry. To reduce the dependence on atmospheric variability, we average the reflectance over a large region (excluding the South Atlantic Anomaly region). Figure 1a (purple) shows an example of the directly computed ratios at 331 nm for the nadir pixel from 1 July 1995 to 1 June 2003 (using the first and middle day of each month). Data after this period are excluded because the break of the onboard tape recorder for intermediate data storage leads to limited spatial coverage. This curve clearly shows inter-annual variations superimposed over the long-term variation. These interannual variations are primarily caused by the variation of average solar zenith angle (black line), the seasonal variation of atmospheric conditions, and the short-term atmospheric variation. We use a non-linear least squares fit to remove the components related to solar zenith angle and seasonal variation. To further reduce the dependence on atmospheric conditions, we normalize the derived ratios to the average ratio over July–December 1995 and then apply a two-month running mean. The derived curve of reflectance degradation for nadir pixel (light blue) shows little degradation until late 1999 and afterwards a positive bias gradually increases, peaks at 1.18 in May 2001, gradually returns to normal, and

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then changes sign, consistent with the prediction of Tanzi et al. (2000), which is based on physical understanding of how the ice build-up affects the reflectance. Figure 1a also illustrates that degradation varies significantly with scan position, with the peak degradation ranging from 1.07 for the West pixel to 1.25 for the East pixel, which supports the analysis of Tanzi et al. (2000). Figure 1b demonstrates that the degradation behaviors are different at various wavelengths especially after 2000. The “peaks” and “troughs” occur at different times for different wavelengths and second peaks appear in middle 2003 for shorter wavelengths. The main characteristics are consistent with the derived degradation from radiative transfer simulations with a combination of observed and climatological ozone profiles (Landgraf et al., 2005). As shown in Fig. 1c, the degradation also exhibits significant wavelength dependence for different time periods. It should be noted that there is a jump around the channel 1a/1b border (i.e., 307 nm, this border has been switched to 282 nm since June 1998). This jump is mainly caused by inconsistent radiances between these two sub-channels before March 1996.

To apply the degradation correction to our ozone profile retrieval algorithm (Liu et al., 2005), we parameterize the degradation as a function of wavelength (3rd-order polynomial) over the two fitting windows (289–307 nm, 325–339 nm) separately and calculate the average degradation over 368–372 nm, which is used to derive cloud fraction in the subsequent retrievals. The purpose of this parameterization is to remove the high-frequency structures shown in Fig. 1c, which can interfere with ozone retrievals and largely increase fitting residuals. To perform degradation correction in retrievals, we multiply the derived degradation spectra with the corresponding solar spectra before retrievals start.

This degradation scheme is simpler than other approaches (van der A et al., 2002). It does not require the use of radiative transfer models and observed/climatological ozone profiles. In addition, the correction can be performed over non-ozone absorbing wavelength ranges. This method can be used to detect major degradation features in reflectance and to cross-calibrate observations from different instruments. However, because this correction assumes that the globally-average radiation fields do not change over time, retrievals with this derived degradation correction may be inadequate for trend analysis.

3 The effect of degradation correction on ozone profile retrievals

To show the effect of degradation on ozone profiles retrieved using our retrieval algorithm (Liu et al., 2005), we compare the retrievals with and without degradation correction from GOME measurements collocated (±1.5° latitude and ±12.5° longitude) at Hohenpeißenberg (12.0° E, 47.8° N) from 1996 through May 2003 and from an orbit of GOME measurements on 15 July 2001 . Figure 2 shows the differences in retrieved total column ozone (TO) and tropospheric column ozone (TCO) around Hohenpeißenberg. The differences are small during 1996–1999 due to insignificant degradation. Negative biases of up to ∼10 DU (∼3% for TO and ∼30% for TCO) occur during 2000–2002, corresponding to the large reflectance degradation during this period. Note that the biases for TO and TCO peak at different times because of the wavelength dependence of the degradation. The retrievals return to normal in early 2002 and then show positive biases. Figure 3 illustrates the mean retrieval biases in ozone profiles for selected months. After 2000, biases of up to ∼10% and 40% occur in the stratosphere and troposphere, respectively. Figure 4 shows the retrieval biases in TO and TCO for an orbit of GOME data in July 2001, when the TCO bias peaks at Hohenpeißenberg. The biases vary significantly with latitude, ranging from ∼−10 DU (∼−3%) to 0 DU in TO and from ∼−15 DU (∼30%) to 0 DU in TCO. The TO and TCO biases near the equator are small due to calibration features implemented in the algorithm. These calibrations are constrained by the derived total ozone from the Huggins bands and the a priori profile used. These constraints are probably stronger in the tropics and thus the on-line degradation correction works better. The profile biases can be up to ∼−10% and −30% in the stratosphere and troposphere, respectively (Fig. 5). It should be noted that the retrieval biases shown above are for our particular algorithm because the radiometric calibrations implemented in our algorithm partly perform the correction and reduce the biases. The biases could be larger for algorithms that do not use such degradation features.

Figures 6 and 7 illustrate the comparison of retrieved TO, TCO, and ozone profiles (with and without degradation) with collocated Dobson and ozonesonde measurements (±1.5° latitude, ±600 km in longitude, and ±8 h) at Hohenpeißenberg (archived at World Ozone and Ultraviolet Radiation Data Centre, ftp://ftp.tor.ec.gc.ca). Ozonesonde measurements are integrated to GOME retrieval grids and convolved with GOME retrieval averaging kernels to the GOME vertical resolution. For TO (Fig. 6a), the improvement with degradation correction is obvious during 2001, the biases was reduced from −5.2±11.2 DU to −0.7±11.3 DU. The bias with correction (2.2±11.6 DU for with correction vs. 0.7±12.0 DU for without correction) during 2000–2003 is more consistent with the 1996–1999 comparison (2.7±12.3 DU). For TCO (Fig. 6b), we can clearly see substantial improvements, especially during 2000–2001. With the degradation correction, the biases are changed from −1.3±5.0 DU (R=0.62, R: correlation coefficient) and −5.2±6.9 DU (R=0.3) to 0.6±4.4 DU (R=0.71) and 0.1±6.3 DU (R=0.51) for these two years, respectively; the bias during 2000–2003 (−0.1±5.2 DU, R=0.64 with correction vs. −0.9±6.2 DU, R=0.53 without correction) also shows better consistency with the 1996–1999 comparison (−0.2±5.6 DU, R=0.60). Figure 7 shows that the profile biases during 2000–2002 were reduced by up to 30% and 10% in the troposphere and stratosphere, respectively, with the degradation correction. One exception occurs in December 2000, where the degradation correction increases the tropospheric biases. This is probably because the degradation offsets other systematic biases; note that retrievals in December 1997 show similar biases.

4 Summary

The degradation in GOME reflectance is derived from the ratio of average reflectance in 60° N–60° S to that on 1 July 1995, with additional procedures to remove the dependence on solar zenith angle and seasonal variation and to reduce the dependence on atmospheric variability. This simple method does not need radiative transfer simulations with ozone observations or climatology and can be applied to the non-ozone absorbing wavelength range. Significant positive degradation of up to ∼15–25% occurs in the wavelength range 289–370 nm during 2000–2002. The degradation varies significantly with wavelength and viewing zenith angle. The major features of the derived degradation are consistent with the physical understanding of how the thickness of a contaminating ice layer on the scan mirror affects the radiances measured at different scan positions (Tanzi et al., 2000) and with derived degradation involving radiative transfer simulations with ozone observations or climatology (Landgraf et al., 2005).

Without degradation correction, retrieval biases of up to ∼3% (10 DU), 30% (10 DU), 10%, and 40% exist in total column ozone, tropospheric column ozone, stratospheric ozone and tropospheric ozone, respectively, from our GOME ozone profile retrieval algorithm (Liu et al., 2005), which features some on-the-fly radiometric calibrations to reduce the effect of degradation. We apply our new degradation correction to GOME measurements collocated around Hohenpeißenberg and demonstrate that this correction usually improves the retrievals relative to Dobson and ozonesonde measurements during 2000–2003 and improves the retrieval consistency during 1996–2003.

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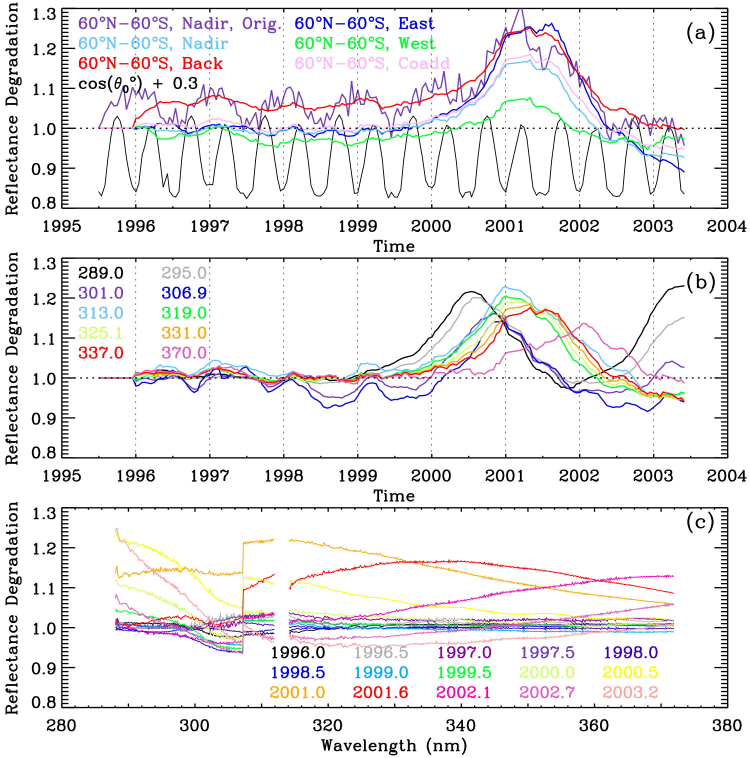

Fig. 1. (a) Derived degradation in reflectance at 331 nm for different scan positions and the average solar zenith angle vs. time. "Orig." means the ratios of average reflectance to that on 1 July 1995 and "coadd" refers to the average degradation of the four scan positions. **(b)** Degradation (coadded) vs. time for different wavelengths. **(c)** Degradation (coadded) vs. wavelength for different times. Note that there is a jump around 307 nm, the channel 1a/1b border before June 1998 (this border is changed to 282 nm afterwards).

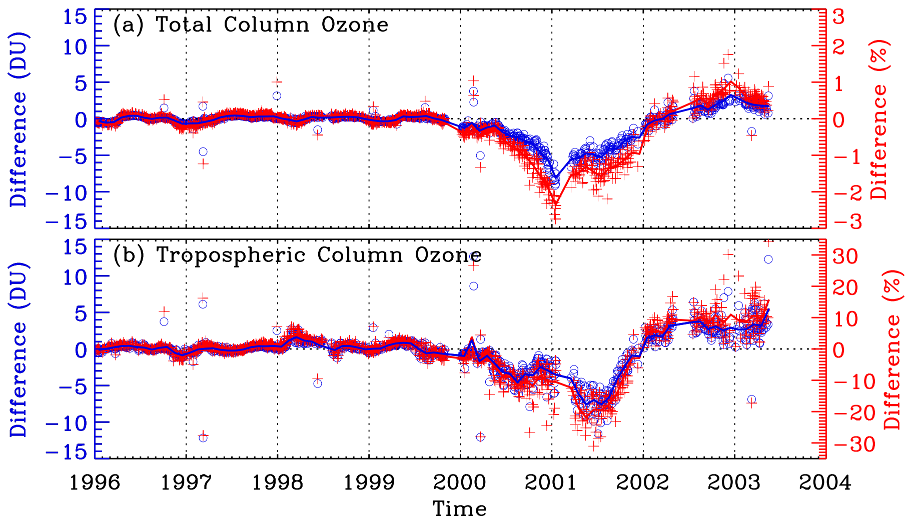

Fig. 2. Absolute (blue) and percent (red) differences in retrieved **(a)** total column ozone and **(b)** tropospheric column ozone ("without degradation correction" minus "with degradation correction") around Hohenpeißenberg (12.0° E, 47.8° N) from 1996 through May 2003. The symbols indicate individual comparison and the lines indicate the monthly mean differences.

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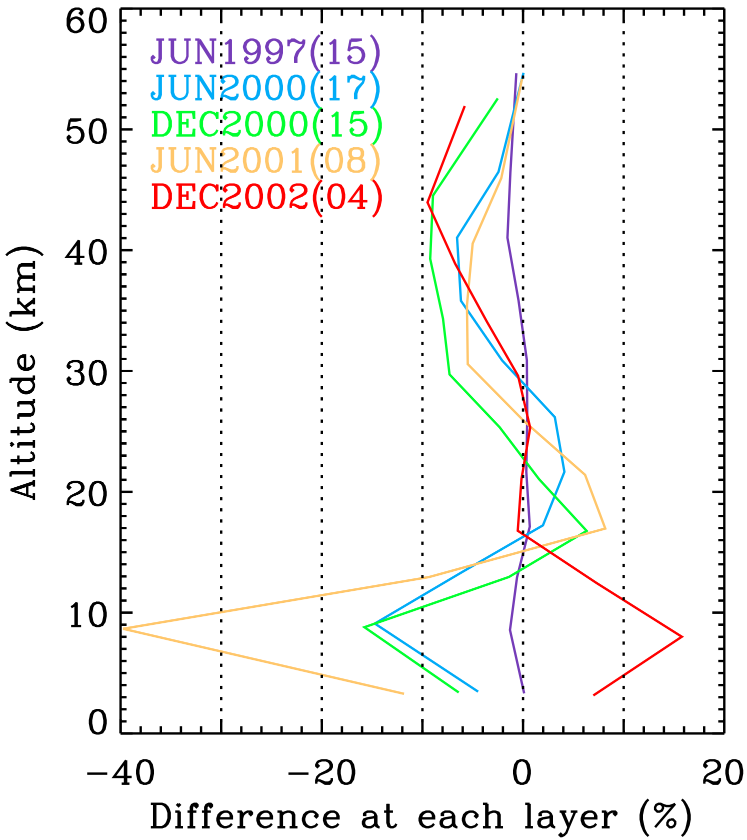

Fig. 3. Monthly mean percent differences in retrieved profiles ("without degradation correction" minus "with degradation correction") for selected months shown in Fig. 2. The numbers in the brackets show the number of profiles within a month.

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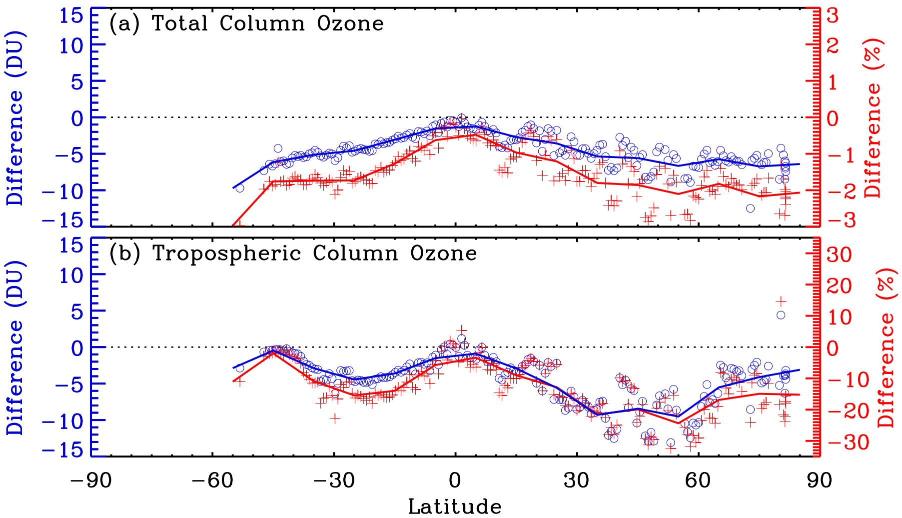

Fig. 4. As for Fig. 2, but for an orbit of GOME measurements on 15 July 2001 (orbit 10715173) as a function of latitude. The lines indicate the mean difference at every 10°-latitude band.

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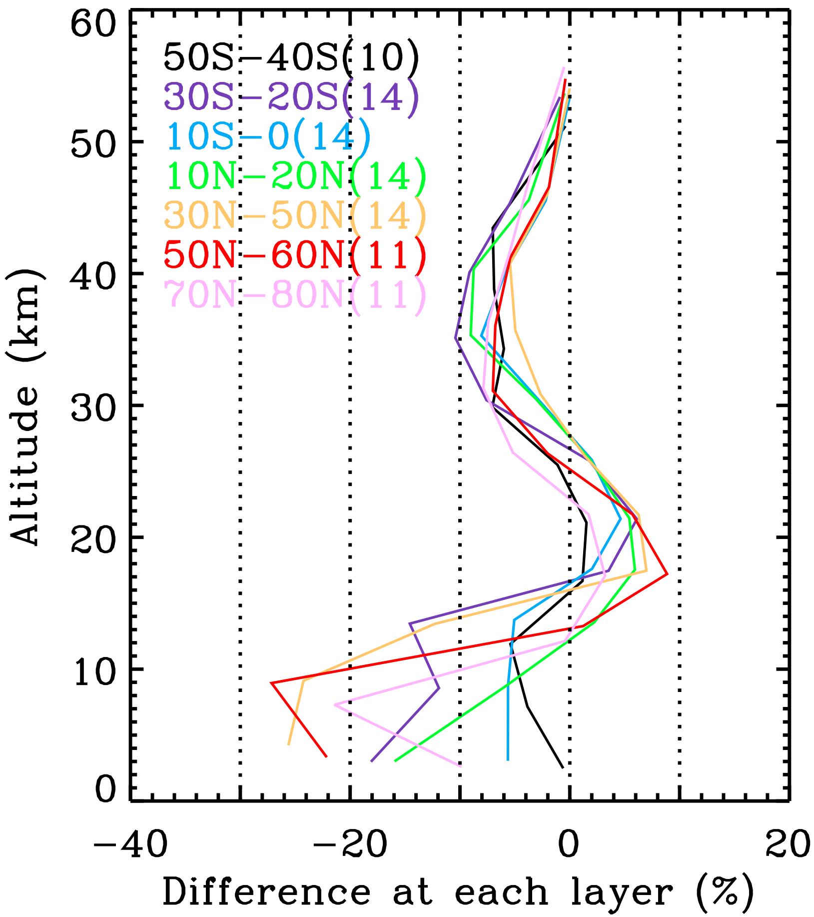

Fig. 5. As for Fig. 3, but for selected latitude ranges shown in Fig. 4.

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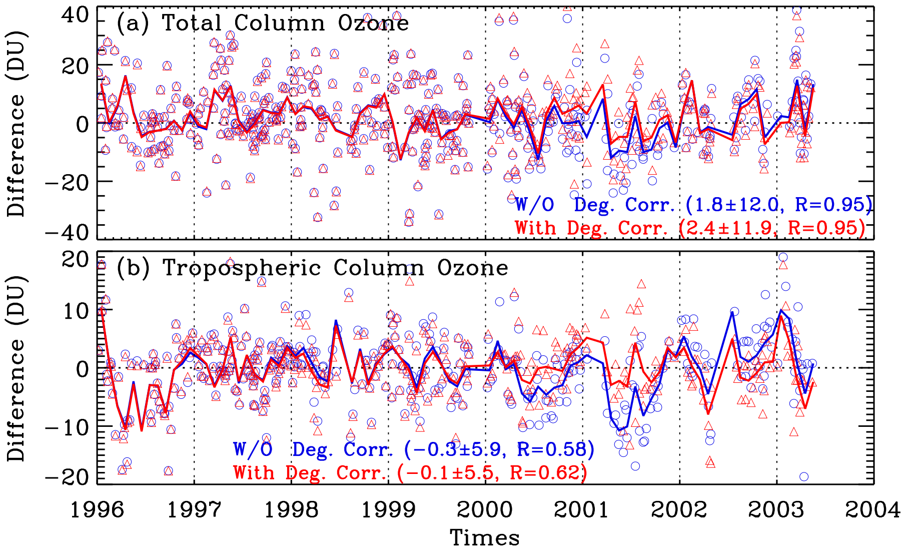

Fig. 6. **(a)** Differences between retrieved (blue/red: without/with degradation correction) and Dobson total column ozone at Hohenpeßenberg during 1996–May 2003. **(b)** Same as (a) but for comparisons with ozonesonde tropospheric column ozone. The mean biases, standard deviations, and correlation coefficients relative to Dobson/ozonesonde observations over the whole period are indicated.

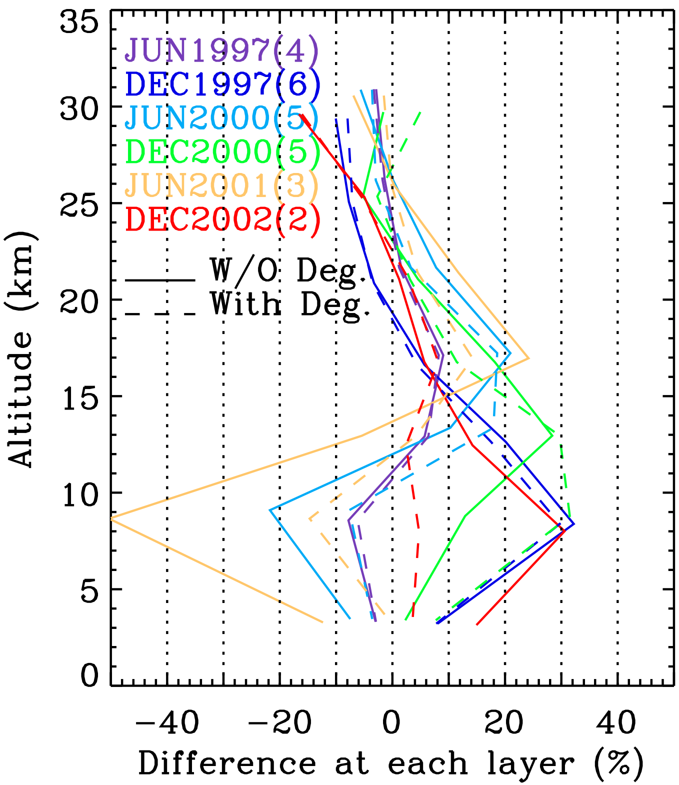

Fig. 7. Mean differences between retrieved (solid/dashed lines: without/with degradation correction) and ozonesonde ozone profiles at Hohenpeißenberg for selected months shown in Fig. 6. The numbers in the brackets show the number of averaged profiles.

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