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On the improved stability of the version 7 MIPAS ozone record

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Abstract. The Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) was an IR limb emission spectrometer on the Envisat platform. From 2002 to 2012, it performed pole-to-pole measurements during day and night, producing more than 1000 profiles/day. The European Space Agency (ESA) has recently released the new version 7 of Level 1 MIPAS spectra, in which a new set of time-dependent correction coefficients for the non-linearity in the detectors' response functions was implemeted. This change is expected to reduce the long-term drift of the MIPAS Level 2 data. We evaluate the long-term stability of ozone level 2 data retrieved from MIPAS V7 Level 1 spectra with the IMK/IAA Scientific Level 2 Processor. We compare it with ozone measurements from the Microwave Limb Sounder (MLS) instrument on NASA's Aura satellite, ozonesondes and ground-based lidar instruments. The ozonesondes and lidars alone do not allow us to conclude with enough significance that the new version is more stable than the previous one, but a clear improvement in long-term stability is observed in the satellite-data based drift analysis. The results of ozonesondes, lidars and satellite drift analysis are consistent: all indicate that the drifts of the new version are less negative / more positive nearly everywhere above 15 km. These results indicate that MIPAS data are now even more suited for trend studies, alone or as part of a merged data record.

1 Introduction

The Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) was an infra-red (IR) limb emission spectrometer on-board the ENVISAT platform. It performed pole-to-pole measurements during day and night, at altitudes from 6 to 70 km (up to 170 km in special modes), providing more than 1000 profiles/day of about 30 species, temperature and cloud composition. In 2002-2004, the instrument operated at full spectral resolution, giving rise to the retrieved ozone product with a vertical resolution of about 3.5 - 6 km; this period of MIPAS operations is referred to as the full resolution (FR) period. Due to a failure of the instrument's mirror slide in 2004, the operations were suspended during almost a year and were resumed in 2005 with reduced spectral, but improved vertical resolution. The corresponding period until the loss of communications with the ENVISAT platform in April 2012, is referred to as the reduced resolution (RR) period of MIPAS operations.

The ESA recently released the new version 7 of Level 1 MIPAS spectra. One of two main improvements of this release is that a full instrument misalignment matrix was implemented in this version, which results in better knowledge of tangent altitudes. This change is of minor relevance to the IMK/IAA data product because tangent altitudes are retrieved from the spectra. Another major improvement is the implementation of a new set of time-dependent correction coefficients for the non-linearity in the detector response functions. In the previous version, the correction coefficients were taken from pre-flight studies and were not time dependent, but the instrument is aging and the detector response is changing (Eckert et al., 2014). This improvement of the level 1 spectra is expected to have a major impact on MIPAS Level 2 data, by reducing the instrument drift. The goal of the present paper is to demonstrate this improvement for the MIPAS IMK/IAA ozone dataset. The MIPAS IMK/IAA dataset versions V7H_O3_40 (2002-2004, for the FR period) and V7R_O3_240 (2005-2012, for the RR period) are part of the new edition of HARMonized dataset of OZone profiles (HARMOZ) database (Sofieva et al., 2013). They are also used in the Long-term Ozone Trends and Uncertainties in the Stratosphere (LOTUS) Stratosphere-troposphere Processes And their Role in Climate (SPARC) Initiative as a parent dataset for two long-term ozone timeseries: the merged SAGE II/MIPAS/OMPS NASA dataset (Laeng et al., 2017) and the merged SAGE II/CCI/OMPS Sask dataset (Sofieva et al., 2017).[1]

2 MIPAS IMK/IAA V7H_O3_40 and V7R_O3_240 profiles: the new retrieval setup

The processing scheme of the MIPAS IMK/IAA research processor and its adaptation to the RR spectra of MIPAS are described in von Clarmann et al. (2003) and von Clarmann et al. (2009) respectively. The processor retrieves the stratospheric Ozone Profiles from MIPAS/ENVISAT limb emission spectra. The retrieval strategy is based on constrained inverse modelling of limb radiances. In stratospheric/tropospheric retrievals, local thermodynamic equilibrium (LTE) is assumed. The processor is designed so that the major contributors to the infrared spectrum are the first to be retrieved, before the gases with tiny spectral features. First, the spectral shift of the measurements is determined. Then, temperatures and altitude pointing information (i.e. the elevation angle of the line of sight of the instrument) are jointly retrieved. The sequence of retrieval operations is: H_2O, O_3 and then other trace gases. As a general rule, results of preceding steps are used as input for the subsequent retrieval steps, i.e. the H_2O retrieval uses retrieved temperatures and pointing information, and the subsequent O_3 retrieval uses retrieved H_2O abundances, etc. Beside each target species, microwindow-dependent continuum radiation profiles and microwindow-dependent, but height-independent zero level calibration corrections are jointly fitted. A new dedicated ozone retrieval setup was recently developed for the IMK/IAA Level 2 Scientific processor. The new setup incorporates a major change in the way the temperature is retrieved in a preceding step: the forward calculation now uses two-dimensional temperature fields that are taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) re-analysis. *A priori* information on temperature at altitudes above 60 km, where MIPAS nominal mode measurements contain little information, is derived from the Whole Atmosphere Chemistry Climate Model (WACCM), see Marsh et al. (2013), while before it was taken from MSIS (Hedin, 1991). The CO_2 climatology used is now also based on WACCM. In the new setup, the background continuum

[1] SAGE II: Stratospheric Aerosol and Gas Experiment, CCI: ESA's Climate Change Initiative, OMPS: Ozone Mapping and Profiler Suite, NASA: National Aeronautics and Space Administration

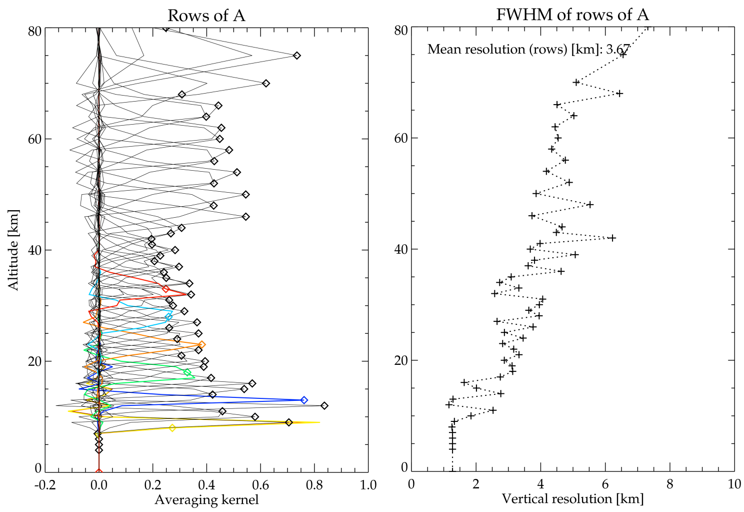

Figure 1. Rows of averaging kernels matrix (left) and vertical resolution of ozone profiles calculated from these rows (right). Rows of the averaging kernels corresponding to 10, 15, 20, 25, 30, and 35 km are highlighted in colors.

radiation is fitted up to 60 km, while before, this fit was only used up to 33 km. These improvements in the temperature retrieval indirectly affect the ozone retrieval, because the retrieved temperatures are used in the latter. To avoid propagation of H_2O a priori uncertainties to the ozone profiles, in the new setup ozone is retrieved jointly with H_2O. For this purpose two H_2O microwindows have been included in order to better fit H_2O in the upper troposphere and lower stratosphere (UTLS). Furthermore, the forward model KOPRA (Stiller, 2000) is now run with higher numerical accuracy.

The left panel of Figure 1 shows the rows of the averaging kernels matrix of a typical MIPAS RR ozone retrieval; they represent the contributions of the true ozone amount at various altitudes to the retrieved ozone amount. The right panel of Figure 1 shows the vertical resolution derived from the full-width at half maximum (FWHM) of these rows. The vertical resolution is determined by the vertical sampling of the instrument, which in case of MIPAS was from 3 to 8 km, and regularization. The vertical resolution varies between 2.5 – 4 km at 10 – 40 km altitude, and 4 – 6 km at 40 km and higher.

3 Bias estimation

The two MIPAS datasets from the FR and RR periods must be treated as independent datasets, because of differences in the processing schemes and different vertical resolutions coming from different tangent altitude patterns. The present study was performed using MIPAS RR (2005–2012) ozone data measured in the nominal mode. We work with two versions of the data: the version V5R_O3_224, which we refer to as "the old version", and the version V7R_O3_240, which we refer to as "the new version". The ozone profiles from the two versions were compared to ozonesonde profiles launched from two stations: mid-latitudinal Boulder at 39.99°N and sub-tropical Hilo at 19.72°N. A more extensive ground-based comparison of V7R_O3_240 will be presented in the upcoming paper of Hubert et al. (2017). The collocation criteria are 1000 km and 24 hours. In order

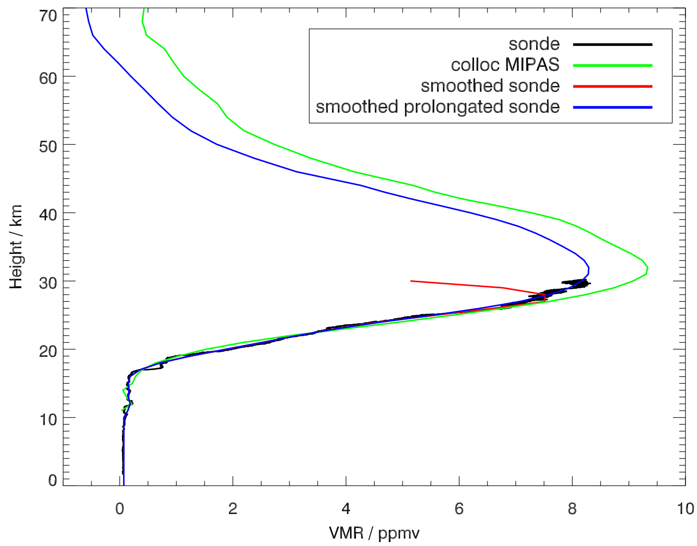

Figure 2. Application of MIPAS AK to the ozonesonde profiles: original ozonesonde profile, collocated MIPAS profile at geolocation 20100630T164035Z, and interpolated, smoothed and prolongated ozonesonde profiles .

to take into account the differences in vertical resolutions between ozonesondes and MIPAS profiles, the ozonesonde profiles were smoothed with the MIPAS averaging kernels. When applying the averaging kernels to ozonesonde profiles, the boundary effects are important. To reduce this, each ozonesonde profile was extended at heights over 30 km by a shifted collocated profile from MIPAS, see Figure 2.

The results of this intercomparison are shown in Figure 3. The percentage relative bias with respect to the reference instrument REF, 100×(MIPAS-REF)/REF of the old MIPAS version is shown in pink, and the new version in green. The results from both stations look fairly consistent, indicating an agreement within ± 5% at 20-30 km height, with the new version having a slightly larger (up to 1%) bias with respect to ozonesonde profiles compared to the old version in this height range. A clear improvement can be observed at 12-14 km, with the bias reduced by 5% for Boulder and by up to 10% reduction at Hilo. Moreover, for the Hilo station, a bias reduction from 15% to 5% from 12 to 20 km can be observed. All these biases are significant at the 2σ level.

To assess the bias of the new MIPAS dataset with respect to satellite reference retrievals, the previous and the new version of MIPAS are compared to the ACE-FTS and MLS datasets. For consistency, both the old and the new versions were compared to the same version of reference instruments, the version 3.5/3.6 of ACE-FTS and the version 3.3 of MLS. The version 3.3 of MLS data was used instead of the version 4.2 in order to keep consistency with the analysis of Eckert et al. (2014). To avoid any sampling effects, comparisons used exactly the same coincidences between the reference data set and the old and new MIPAS data. Figure 4 shows the results of these comparisons. The coincidence criteria were chosen to be 500 km and 5

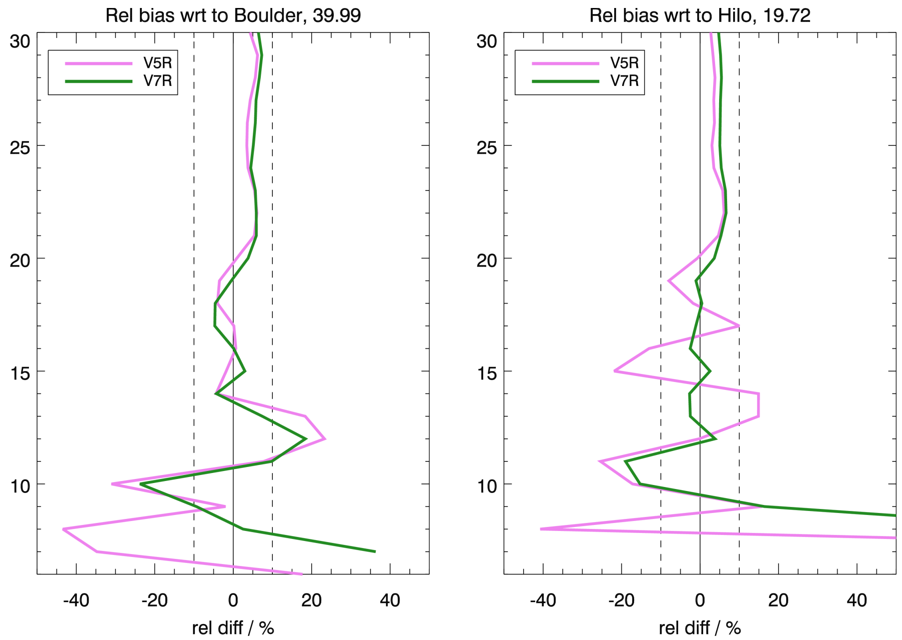

Figure 3. Biases with respect to Boulder (39.99N) and Hilo (19.72N) ozonesondes for the old (V5R) and new (V7R) MIPAS data versions.

hours for ACE-FTS, and 250 km and 4 hours for MLS. Also here, we applied the averaging kernels of MIPAS to both satellite reference datasets; the effect of this operation is, however, negligible, due to the small contrast in vertical resolutions of the three datasets. With respect to ACE-FTS, the new version of MIPAS ozone dataset results in a reduction of the bias by about 2% at 10-20 km, 1 to 4% at 30-52 km, and by about 6-8% at 60 km and higher. With respect to MLS, a reduction of the bias by 1 to 12 % can be observed in the lower mesosphere (52 km and higher), while at other heights the bias is slightly increased by 1 to 4%. Historically, around the ozone vmr peak, MIPAS ozone measurements tended to have a high bias (Laeng et al., 2015), which is attributed to the use of the microwindows in the MIPAS AB spectral band (1020 - 1170 cm^{-1}) at these heights. In this height region, around 35 km, the new version demonstrates an improvement with respect to ACE-FTS where the bias is reduced from 2% to almost 0%. With respect to MLS, the bias has increased slightly from 3% for the previous version to 5% for the new version. In the UTLS, the comparison with ACE-FTS still demonstrates a clear improvement, and MLS compares better with the new version at 10-12 km and 14-16 km.

4 Drift estimation

4.1 Level 1 analysis: improvement in detectors' non-linearity characterisation

The MIPAS instrument recorded interferograms in the five spectral bands, A: 685 - 970 cm^{-1}, AB: 1020 - 1170 cm^{-1}, B: 1215 - 1500 cm^{-1}, C: 1570 - 1750 cm^{-1}, and D: 1820 - 2410 cm^{-1}, using 8 infra-red detectors called A1/A2, B1/B2, C1/C2,

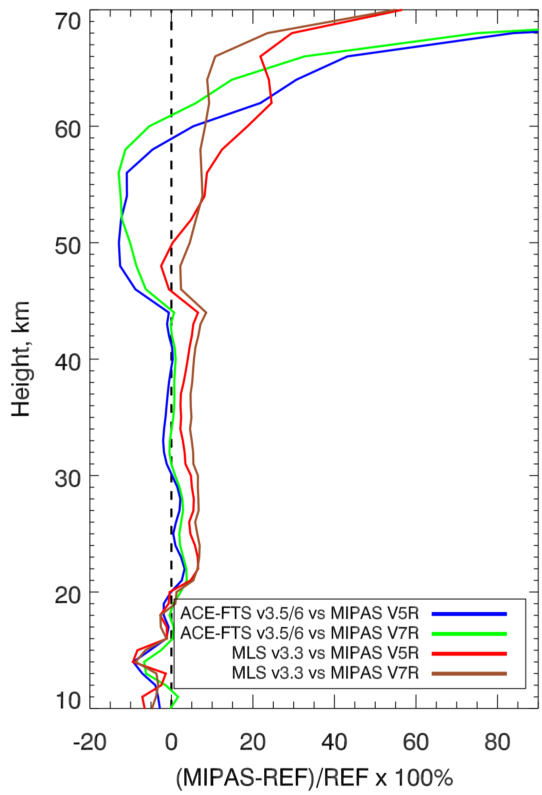

Figure 4. Bias between MIPAS and the ACE-FTS and MLS.

and D1/D2. The spectral signal in each spectral band is composed of the combined information from the different detectors as follows: the A1/A2 detectors contribute to the MIPAS spectral band A, A2/B1 to AB, B2 to B, C1/C2 to C, and D1/D2 to D. Four detectors, namely A1/A2 and B1/B2, show a non-linear response to photon flux which has to be corrected to get the appropriate interferogram. The detectors exhibited ageing; essentially the sensitivity degraded slowly over time and the response became more linear. Hence, for the spectral bands A, AB, and B, precisely those relevant for the ozone retrieval, an impact of the detector ageing on the measurements has to be expected. There was just one pre-flight characterization measurement for the detector non-linearity (NL). This characterization was used throughout the mission (2002-2012) to correct for non-linearity in detectors' responses. This deficient radiometric calibration caused a drift of the instrument (Kleinert et al., 2007; Kiefer et al., 2013; Eckert et al., 2014), making MIPAS data not suitable for trend studies without preliminary drift removal. Wagner and Birk (2005) proposed a new method to characterize the detector non-linearity from in-flight measurements in raw data mode. This correction was incorporated in version 7 of MIPAS Level 1 Spectra. Plotting MIPAS Level 1 spectra with new non-linearity coefficients (NLC) against spectra with old NLC allows to fit two regression parameters: slope and offset, with ideal values to be close, respectively, to 1 and 0. These slopes and offsets, for both directions of the mirror movement, forward and backward, are shown at the Figure 5 for altitudes 16 km (left panel) and 51 km (right panel).

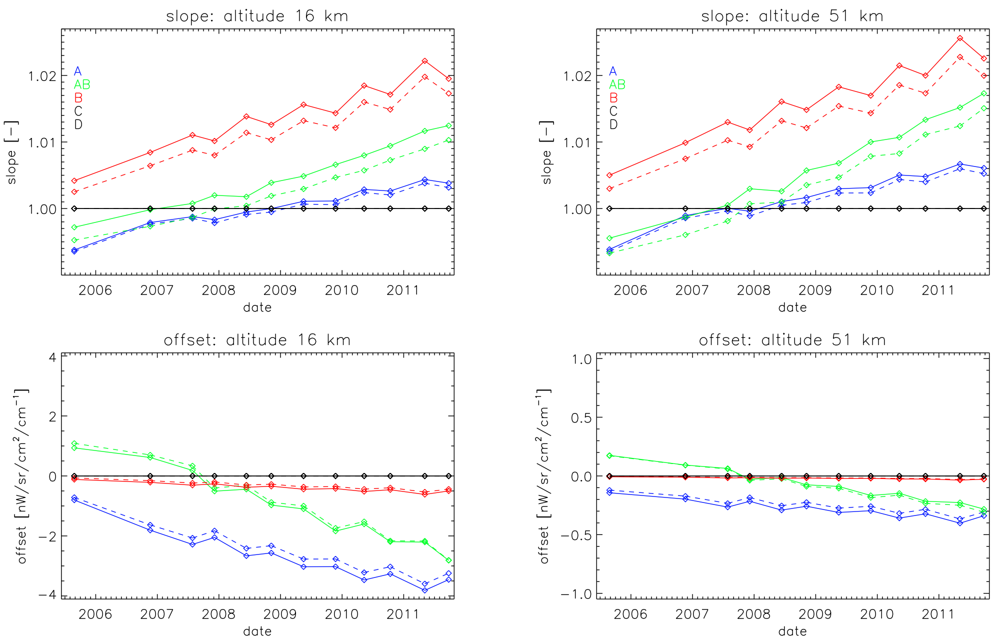

Figure 5. Slope and offset of the linear fit of MIPAS RR Level 1 Spectra with the old set of NL coefficient versus spectra with new set of NL coefficients at 16 km (left) and 51 km (right). Solid lines correspond to forward mirror movement, and dashed lines correspond to reverse mirror movement.

Figure 5 demonstrates that for Level 1b MIPAS spectra in bands A, AB, and B, both slope and offset change over time, i.e. the spectra with the old NLC and the new NLC slowly drift apart (up to 2%). This is the reason why an improvement in long-term stability of MIPAS Level 2 data is expected.

4.2 Level 2 analysis

In our definition, drifts are long-term variations of the bias between two instruments. The drifts appear as artificial trends of a signal due to imperfect instrument stability. To assess the long-term stability of the MIPAS ozone dataset, we compared it to a network of data including ozonesondes and ground-based lidars using the method from (Hubert et al., 2016), and with Aura MLS (Froidevaux et al., 2008), using the method described by Eckert et al. (2014).

4.2.1 Drift with respect to ground-based instruments

We calculated the network-averaged drift of the old and new MIPAS data versions versus co-located lidar and ozonesonde ozone profiles using the regression and averaging procedure described in Hubert et al. (2016). The averaging reduces the uncertainty from spatial and temporal inhomogeneities present in the ground-based data sets, see Hubert et al. (2017) for details. The results are presented in Figure 6. Ozonesonde and lidar results are fairly consistent. The MIPAS drift relative to

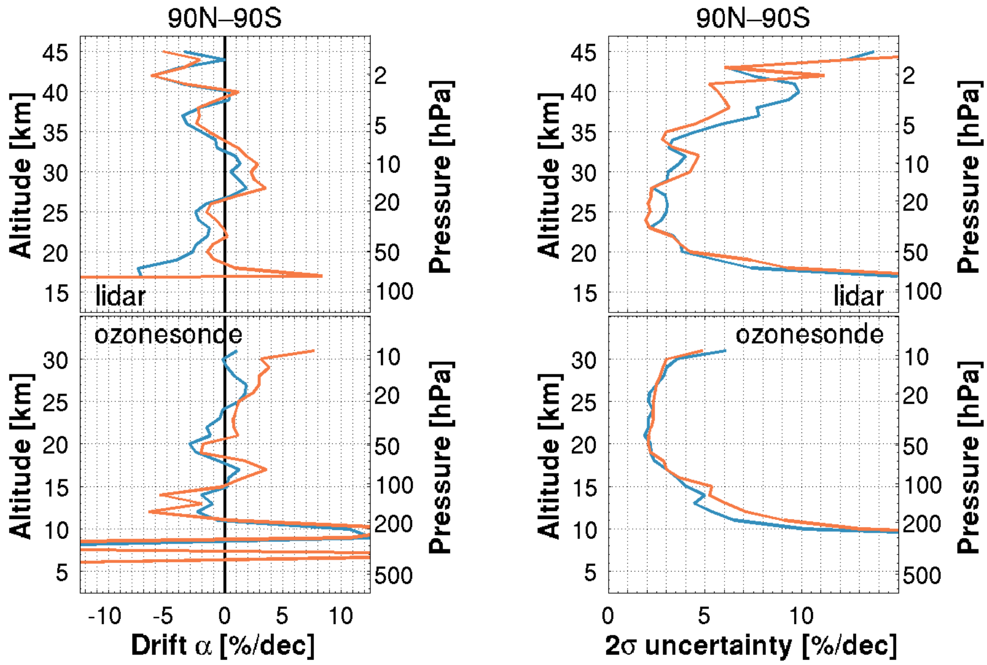

Figure 6. Left panel: network-averaged drift of the old (blue) and the new (orange) MIPAS ozone versus lidar (top) and ozonesonde (bottom) measurements for 2005-2012 period profiles. Right panel : 2σ uncertainty of estimated drifts.

ground-based instruments is not significant for either version. Over the altitude range of 15-37 km, the drift of the old version is 1% per decade (2% at the most) more negative / less positive (depending on altitude) than the drift of the new version. The difference in the drifts between the old and the new version is not significant because the estimated 2σ uncertainty in the drift is at best 2%/decade between 20-25 km, and larger elsewhere. Hence, the ozonesonde and lidar analyses alone do not allow us to conclude with certainty which data version is more stable.

4.2.2 Drift with respect to satellite instrument

For calculating drifts with respect to satellite instruments, we have chosen the Aura MLS data. The reason is that MLS is a dense sampler, in a relative sense, at some heights, MIPAS time series do track the MLS time series more closely, and it is known to be stable (Hubert et al., 2016). The MIPAS drift estimation with respect to MLS uses profiles matched to 250 km and 6 hours, in the period 2005–2012. The differences between the MIPAS and MLS measurements were taken at every valid altitude grid point of each profile pair; then monthly zonal means of these differences were calculated in 10-degrees latitude bins. The multi-linear regression model, described in Eckert et al. (2014); von Clarmann et al. (2010), was then applied to the timeseries. The resulting drifts are shown in the right panel of Figure 7 as a function of altitude and latitude band. The left panel of Figure 7 shows the same drift estimates for the previous version of MIPAS data. Hatching indicates domains with less than 2σ significance.

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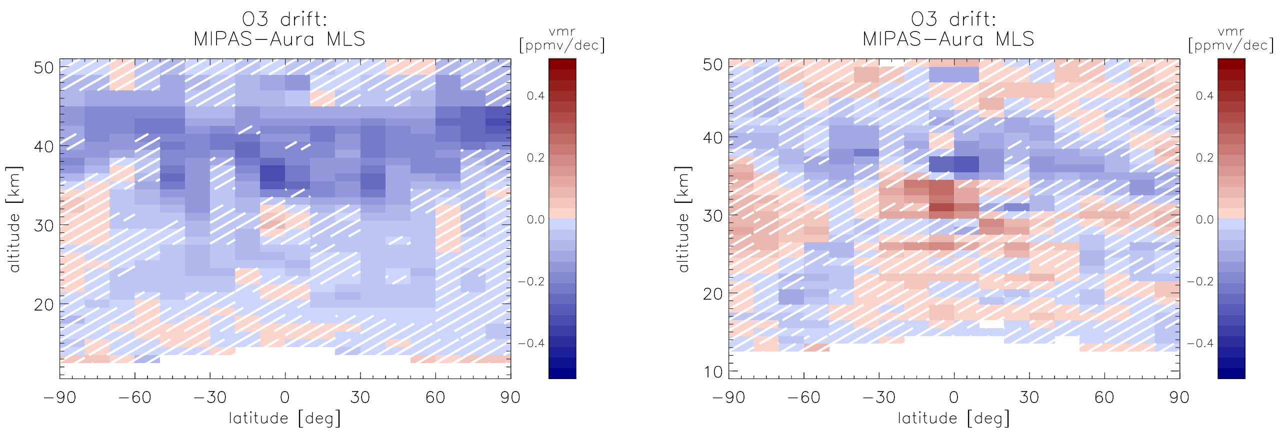

Figure 7. Altitude-latitude cross-section of absolute drifts of MIPAS V5R (left) and V7R (right) vs. Aura MLS ozone measurements. Hatched areas mean that the significance is less than 2 sigma.

The comparison of the old (left) and the new (right) version in Figure 7 reveals the following features. In the new version, there are a lot fewer areas with significant drift. Combined with the fact that drift uncertainties are of similar size for the old and new version, we interpret this reduction of significant areas as an improvement: the drifts became smaller in absolute values. As pointed out by Eckert et al. (2014), the old version exhibited mostly negative drifts, going down to -0.33 ppmv/decade and becoming more negative with altitudes up to $\sim$ 40 km. This clear pattern of significant negative drifts was extending over all latitudes at altitudes over 30 km, and going down to 20 km at mid-latitudes. In the new version, this pattern has disappeared and there is no clear systematic drift pattern; some areas with small positive drifts are neighboring areas with small negative drifts, with the majority of both areas being non-significant. This can be attributed to the small absolute values of the drifts. The appearence of some pixels with significant positive drifts is tentatively attributed to an over-correction in non-linearity coefficients in Level 1b spectra. The version 8 of Level 1b MIPAS spectra, which at the time of this writing is in a testing phase, is expected to correct for this undesirable effect.

Let us point out that the ground-based and MLS-based results are consistent. Both indicate that the drifts of the new version are less negative / more positive nearly everywhere above 15 km.

5 Conclusions

We have assessed the bias and long-term stability of the new MIPAS ozone dataset retrieved with KIT IMK/IAA Scientific Level 2 MIPAS Processor from the new version 7 Level 1b MIPAS spectra. The biases with respect to the ozonesondes from Hilo and Boulder stations are consistent, with an agreement within ±5% at 20-30 km. At 12-14 km, the bias against Boulder is reduced by 5%. For the Hilo station, the bias is reduced from 15% to 5% from 12 to 20 km.

The old and new MIPAS datasets were compared with ACE-FTS and MLS satellite instruments. With respect to ACE-FTS, the new version of the MIPAS ozone dataset shows a bias reduction by about 2% at 10-20 km, a bias reduction by about 1 to 4% at 30-52 km, and a bias reduction by about 6-8% at 60 km and higher. With respect to MLS, a bias reduction by 1 to 12 % is observed in the lower mesosphere (52 km and higher), while at other heights the bias is slightly increased by 1 to 4%. Around 35 km, the new version demonstrates an improvement with respect to ACE-FTS where the bias is reduced from 2% to almost 0%, and a degradation with respect to MLS, where the bias increases from 3% for the previous version to 5% for the new version. In the UTLS, the comparison with ACE-FTS still demonstrates a clear improvement, while MLS agrees better with the old version at 12-14 km altitudes, and better with the new version at 10-12 km and 14-16 km altitudes.

For drift estimation, a network of ozonesonde and lidar stations was used. Obtained MIPAS drifts relative to the ground-based network are not significant for either version. The network analysis alone does not allow to conclude whether the old or new version is the more stable.

For drift estimation with respect to satellite instruments, the Aura MLS dataset was chosen for comparison. The pattern of significant negative drifts at heights over 30 km and going down to 20 km at mid-latitudes, which was observed in the old version, has completely disappeared in the new version. The appearence of some pixels with significant positive drift in the new version is tentatively attributed to the over-correction in non-linearity coefficients in Level 1b spectra, which is expected to be corrected in the upcoming version 8 of Level 1b MIPAS spectra. The results of network and satellite drift analysis are consistent: both indicate that the drifts of the new version are less negative / more positive nearly everywhere above 15 km.

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