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Contract Report to the European Space Agency

Monitoring and Assimilation of SCIAMACHY, MIPAS and GOMOS retrievals at ECMWF

January 2012

Rossana Dragani

Annual report for ESA contract 21519/08/I-OL
CCN No. 1: Technical support for global validation of ENVISAT data products

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Abstract

This report discusses the results from the operational validation and monitoring of level 2 data retrieved from the atmospheric instruments on board Envisat performed at ECMWF during 2011 in support to the ESA activities.

The NRT SCIAMACHY total column ozone (TCO) produced at KNMI and distributed via the ESA funded PROMOTE consortium was continuously disseminated during 2011, and therefore assimilated at ECMWF. The quality of the data was generally stable during 2011. The first-guess and analysis departures were normally less than 10DU during the whole year in the tropics and at midlatitudes. Larger departures were found near the end of the illuminated part of the orbits, normally associated with larger observation errors. Comparisons with OMI and GOME-2 TCO showed residuals well within ±15DU.

On 25 November 2011, ECMWF could restart archiving MIPAS retrievals of ozone, temperature and water vapour in the MARS archive, and thereby restart the operational monitoring. The quality of the MIPAS retrievals is generally very high. The level of agreement with the ECMWF fields is better than the observation standard deviation for all parameters. The ozone first-guess and analysis departures from MIPAS retrievals are normally within ±10% at most vertical levels and latitudes. The temperature retrievals are in an agreement with the ECMWF temperature field which is better than 1% in the stratosphere. While the water vapour retrievals are within 20% from their ECMWF model equivalent, showing a dry bias in the UTLS region, and a wet bias in the mid and high stratosphere, as well as in the mesosphere. Assimilation tests using the MIPAS ozone profiles were also run. Results showed that the assimilation of MIPAS ozone data could substantially improve the quality of the ECMWF ozone analyses. Based on those results, ECMWF restarted the assimilation of these data on 8 December 2011.

The GOMOS instrument suffered of a number of anomalies that caused severe data loss and data unavailability from the end of August onwards. Based on the data availability, the NRT GOMOS ozone profiles showed a level of agreement with their model within -10 and +15% in most of the stratosphere (for $p<40$hPa) in the tropics and at midlatitudes, but larger in the lower stratosphere and in the mesosphere. The quality of the GOMOS water vapour profiles was generally poor at all levels, and latitudinal bands, with stratospheric values typically from one to four orders of magnitude larger values than their model equivalent. A new NRT algorithm (version 6.01, hereafter v6.01) was implemented in June 2011 for GOMOS data. The operational monitoring and an ad-hoc study of the comparisons of the GOMOS retrievals with their ECMWF equivalent before and after switching to the v6.01 algorithm showed very little impact on the water vapour, although the data scatter seemed reduced, and a more significant change on the ozone retrievals, which showed a degraded level of agreement with the ECMWF ozone analyses in the region of the ozone maximum, in favour of a better agreement in the UTLS region.

1 Executive summary

The level 2 products retrieved from the atmospheric instruments on board of the ENVISAT satellite have been routinely monitored at ECMWF during 2011. Table 1 provides an executive summaryof the monitoring and assimilation activity performed at ECMWF during this period. Table 1 is composed of three parts: For each instrument (GOMOS, SCIAMACHY, MIPAS), it focuses on 1) the data availability to ECMWF (in terms of timeliness, long period of data unavailability, and their reasons), 2) the period when theobservations were assimilated at ECMWF (if applicable), and 3) the level of agreement (”Poor”, ”Medium”, ”Good”, and ”Excellent”) between each product and their ECMWF equivalent.

It is noted that the operational monitoring of MIPAS L2 products could only be performed from 25 November 2011 onwards. Details and reasons for this are discussed in section 5. Furthermore, it is also pointed out that ECMWF restarted the operational assimilation of the MIPAS ozone profiles.

	GOMOS	SCIAMACHY	MIPAS
Timeliness	93.4%	85.1%	82.4%
Unavailability	24 Oct - onwards	N/A	N/A
Anomalies	Since 26 Aug	N/A	N/A
Actively assimilated	No	Yes	O_3 only (from 8 Dec 2011)
Ozone	Medium	Good	Excellent
Temperature	N/A	N/A	Good
Water Vapour	Poor	N/A	Good

Table 1: Summary of the key points resulting from the 2011 monitoring and assimilation of the Level 2 products retrieved from the ENVISAT atmospheric instruments.

2 Introduction

The present annual report summarises the results from the global validation and monitoring of the ENVISAT atmospheric data products performed at ECMWF under the ESA funded project 21519/08/I-OL CCN No. 1 (“Technical support for global validation of Envisat data products”) during 2011. These products, usually referred to as the Meteo products, are retrieved at ESA and available to ECMWF on their ftp servers in near-real time (NRT) in BUFR format. Formally, the list of products included in the present contract are temperature, ozone and water vapour profiles from MIPAS (MIP_NLE_2P) and from GOMOS (GOM_RR__2P), as well as total column ozone retrievals from SCIAMACHY nadir measurements (SCI_RV__2P). It should be noted that, among these products, the NRT SCIAMACHY nadir TCOs (SCI_RV__2P) have not been available since May 2006 (Dragani, 2006). As agreed during the ESA-ECMWF final progress meeting held at ECMWF on 6 December 2006, the operational monitoring of the ESA retrieved SCIAMACHY TCO was replaced by that of the SCIAMACHY TCO retrieved at KNMI under the ESA funded project PROMOTE. It should also be noted that, no monitoring was performed of the GOMOS temperature as the data currently available in the GOMOS BUFR files are not actual retrievals, but rather the ECMWF 24-hour forecasts[1]. Project 21519/08/I-OL CCN No. 1 runs for a period of two years from January 2011 to December 2012, and continues the activity carried out under a number of previous ESA contracts, namely 14458/00/NL/SF (Dethof, 2003), 17585/03/I-OL (Dethof, 2004; da Costa Bechtold and Dethof, 2005), 17585-CCN-1 (Dragani, 2006, 2008), and 21519/08/I-OL (Dragani, 2009b, 2010b, 2011a). This paper discusses in details the results from the monitoring and assimilation of the available ENVISAT L2 atmospheric data products during the period January to December 2011.

The ECMWF deterministic model is a global spectral model. It benefits from a current horizontal resolution truncation of T1279, which corresponds to about 16 km grid spacing, and 91 vertical levels with the model top at 0.01 hPa (corresponding to an altitude of about 80 km). The model uses a four-dimensional variational (4D-Var) scheme (Rabier et al., 2000) to assimilate observations at 6- and 12-hourly time windows. The ECMWF assimilation system has two main 6-hour 4D-Var (early-delivery) analysis and forecast cycles for 00 and 12 UTC and two 12-hour 4D-Var analysis and first-guess forecast cycles. The 0000 UTC analysis of the 12-hour 4D-Var analysis uses observations in the time window 2101-0900 UTC, while the 1200 UTC analysis uses observations in the time window 0901-2100 UTC. These analyses are run with a delayed-cut-off time of 14 hours (with respect to the nominal analysis times), in order to use the maximum possible number of observations. The 6-hour 4D-Var analyses have a shorter cut-off time (4 hours) and the analysis observation windows are 2101-0300 UTC for the 00 UTC analysis and 0901-1500 UTC for the 12 UTC analysis. All the observation monitoring, ENVISAT data monitoring included, is done in the delayed-cut-off analyses (Dethof, 2004) and (Haseler, 2004).

[1] As agreed during the ESA-ECMWF final meeting held at ESA ESRIN on 25 February 2011

Because ozone is fully integrated into the ECMWF forecast model and analysis system (Dethof and Hólm, 2003) as an additional three-dimensional model and analysis variable, the ECMWF model can be used to monitor ozone retrievals from the ENVISAT instruments in addition to temperature and water vapour. The ozone forecast model uses an updated version of the Cariolle and Déqué (1986) scheme (hereafter CD86). In particular, compared with CD86, the ECMWF ozone parameterization includes an additional term which parameterizes the depletion of ozone in the polar regions by heterogeneous reactions. At present, ozone is included uni-variately in the ECMWF data assimilation system. This means that there are no ozone increments from the analysis of the dynamical fields. In addition, the assimilation of ozone observations cannot modify the wind field in 4D-Var through the adjoint calculations. This treatment was chosen to minimize the effect of ozone on the rest of the analysis system. For the same reason, the model's ozone field is not used in the radiation scheme, where an ozone climatology (Fortuin and Langematz, 1995) is preferred instead.

Ozone data from a number of satellite instruments are currently assimilated in the ECMWF system. At the time of writing, the ozone data either monitored or assimilated in the ECMWF operational system are those listed in table 2.

Instrument	Satellite	Usage	Data Type
SBUV/2	NOAA-16	Passive	Partial columns
SBUV/2	NOAA-17	Active	Partial columns
SBUV/2	NOAA-18	Active	Partial columns
SBUV/2	NOAA-19	Active	Partial columns
SCIAMACHY	ENVISAT	Active	Total columns
GOMOS	ENVISAT	Passive	Profiles
MIPAS	ENVISAT	Active[1]	Profiles
OMI	Aura	Active	Total columns
MLS	Aura	Passive	Profiles
GOME-2	MetOp-A	Passive	Total columns
SEVIRI	Met-9	Passive	Total columns

Table 2: List of all the ozone products actively assimilated or passively monitored in the ECMWF operational system. [1]*The assimilation of MIPAS ozone profiles became operational on 8 December 2011.*

The NRT ozone retrievals from the Solar Backscatter Ultra Violet (SBUV/2) instruments, produced by NOAA and available from NESDIS[2], are retrieved as a 21 level ozone profiles. These data are converted into a six-layer product at ECMWF to reduce the observation error correlation. The NRT SCIAMACHY TCO produced by KNMI[3] and generally referred to as TOSOMI has been assimilated at ECMWF almost continuously since 28 September 2004. The two longest interruptions to the TOSOMI data assimilation, that were recorded since 2004, occurred during the three-year period 2008-2010: 1) from 18 December 2008 to 16 September 2009, and 2) from 22 October to 16 December 2010, as documented by Dragani (2009c) and Dragani (2010a), respectively. NRT OMI total column ozone data have been assimilated since June 2008. The active assimilation of this product was switched off during the period between 27 January and 18 March 2009 due to instrumental anomalies that affected a number of pixels. The assimilation of OMI was then restarted when it was proven that by removing the anomaly-affected pixels the quality of the (remaining) data was still suitable for operational use Dragani (2009a). SBUV/2 and KNMI SCIAMACHY data are not used at solar zenith angles greater than 84°, and OMI data are not used at solar zenith angles greater than 80°. Variational quality control and first-guess checks are carried out for all assimilated data. Temperature retrievals are not assimilated at all in the system, although this field is strongly constrained by the assimilation of radiances. The assimilation of ozone-

[2]See http://orbit-net.nesdis.noaa.gov/crad/sit/ozone/ for more information.

[3]See either http://www.temis.nl/products/o3total.html or http://www.gse-promote.org/ for further information.

sensitive radiances in the infrared (IR) spectral range from three advanced IR sounders, namely the Advanced InfraRed Sounder (AIRS), the Infrared Atmospheric Sounding Interferometer (IASI), and the High-resolution Infrared Radiation Sounder (HIRS), was extensively tested during 2011 and became operational with the implementation of model cycle CY37R3 (15 November 2011). Total column water vapour (TCWV) data from the MERIS instrument aboard ENVISAT have continuously been assimilated since September 2009, with the only exception of the period between 22 October and 16 December 2010 when ENVISAT was commanded to the current orbit Dragani (2010a). A variational bias correction (VarBC) scheme (Dee, 2005) is available for the satellite observations. This scheme became operational in September 2006, when it was first used to correct for biases in the radiance data, and only in September 2009 it was extended to retrieved products and used for ozone (Dragani, 2009c) and TCWV (Bauer, 2009).

During the period January to December 2011, the ECMWF operational model system was upgraded twice to model cycle CY37R2 on 18 May, to model cycle CY37R3 on 15 November 2011. The model cycle CY37R1, which included a number of technical changes, was not operationally implemented. With cycle CY37R2, the ECMWF system was upgraded with several technical and scientific changes. In particular, among the scientific changes the following are worth mentioning: the background error variances were switched to those computed from the ensemble data assimilation system (EDA); the AMSU-A observation errors were reduced; the tangent point drift in GPS radio occultation data were now accounted for; a number of changes to the assimilation of all-sky microwave data and to the cloud scheme were implemented.

Several changes were introduced in cycle CY37R3. Many changes and retuning were introduced in the model physics, e.g. entrainment/detrainment of convection, supersaturation and deposition rate for clouds, and modification of the surface roughness, as well as in the use of data, which including, as mentioned above, the assimilation of infrared radiances sensitive to ozone changes from AIRS, IASI, and HIRS. The assimilation of these ozone-sensitive channels improved the quality of the ozone analyses in the UTLS region.

This report is structured as follows: Section 3 gives an indication of the operability of ESA and KNMI products during 2011, and compares it with that of the past few years. Section 4 summarizes the results of the monitoring and assimilation of SCIAMACHY total column ozone retrievals; section 5 shows results of the assimilation of MIPAS ozone profiles; section 6 shows results of the monitoring of GOMOS data. Conclusions are presented in the last section.

3 Operability of ESA and KNMI products during 2011

This section provides an indication of the operability of both ESA and KNMI product at ECMWF during 2011, in the same way it was produced by previous reports (Dragani, 2008, 2009b, 2010b, 2011a).

To assess the operability of these products then, we have compared the data volume received within the analysis cut-off times with the total amount of data received. As anticipated above, ECMWF has two main 12-hour 4D-Var analysis and forecast cycles for 00 and 12 UTC (referred to as early-delivery) and two 12-hour 4D-Var analysis and first-guess forecast cycles (referred to as delayed-cut-off). The passive monitoring is performed with a delayed cut-off configuration, while the data actively assimilated - depending on their timely availability - are used in both the delayed-cut-off and early delivery suites.

In the delayed-cut-off, the 00 UTC analysis makes use of all the observations available in the Report Data Base (RDB) within the assimilation window between 2101 and 0900 UTC. These data are extracted in two phases. Data between 2101 and 0300 UTC are extracted from RDB at 1345 UTC; while data between 0301 and 0900 UTC are extracted from RDB at 1400 UTC. The 12 UTC analysis makes uses of all the observations available in RDB within the assimilation window between 0901 and 2100 UTC. Data between 0901 and 1500 UTC are extracted from RDB at 0145 UTC; while data between 1501 and 2100 UTC are extracted from RDB at 0200

UTC (Haseler, 2004).

The early delivery analyses make use of only six-hour observation windows. The 00 UTC analyses are obtained by assimilating all data within the assimilation window between 2101 and 0300 UTC that are available in RDB by 0400 UTC. The 12 UTC analyses are obtained by assimilating all data within the assimilation window between 0901 and 1500 UTC that are available in RDB by 1600 UTC. All the observations that fall into a given observation window but are not available in the RDB by the early delivery cut-off times can still be used in the delayed-cut-off analyses. We also note that the information from the data that cannot be actively assimilated in the early delivery system (but arrive in time for the delayed-cut-off) still indirectly affects the (early delivery) analyses as the first guess used in the assimilation are the three-hour forecasts from the delayed-cut-off.

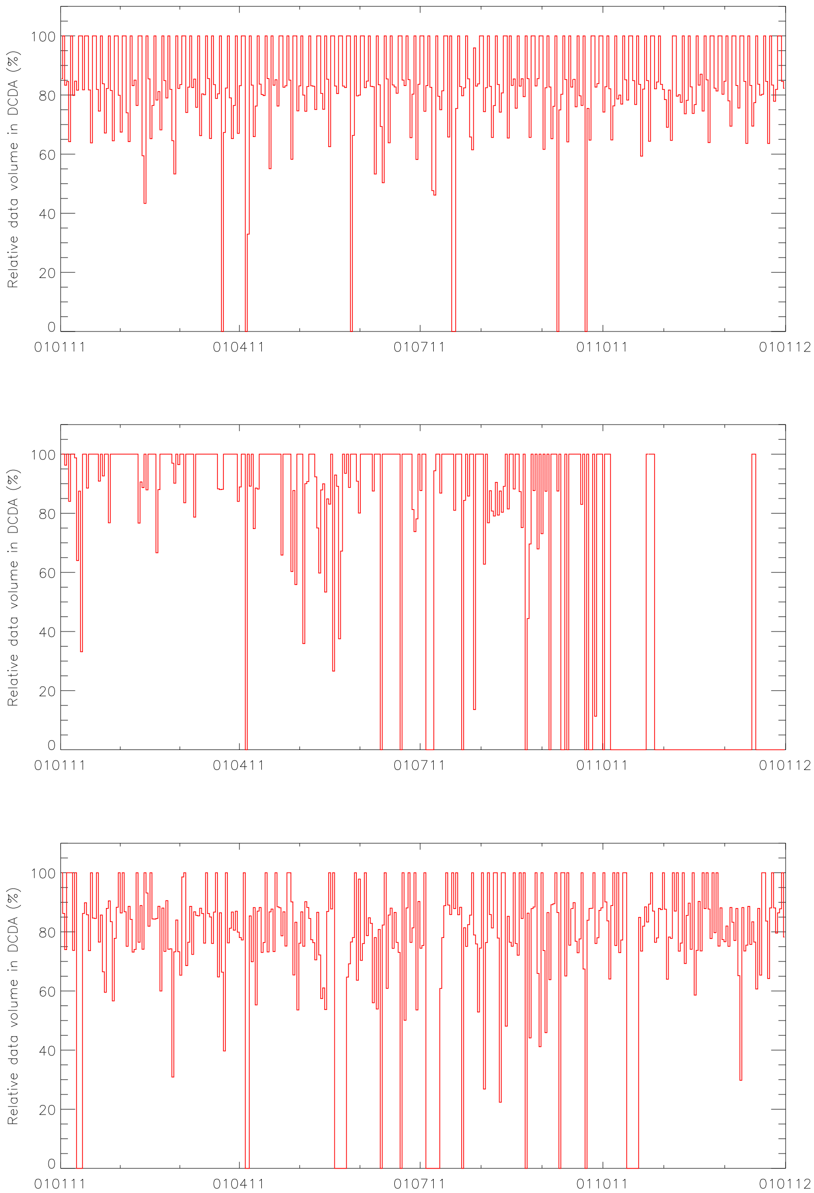


Figure 1: The 2011 time series of the level 2 daily data volume received in time for the delayed-cut-off relative to the total daily data volume received. The top panel refers to TOSOMI; the middle panel refers to GOMOS; the bottom panel shows the results for MIPAS. Values are in %.

The three panels of figure 1 show the data volume received by ECMWF within the analysis delayed-cut-off times given above relative to the total amount of data downloaded for (from top to bottom) TOSOMI, GOMOS, and MIPAS, respectively. Although for technical reasons, the MIPAS observations could not be monitored in the operational system before the implementation of model cycle CY37R3 (15 November 2011), these data were nonetheless received by ECMWF during the entire 2011. Values of 100% in figure 1 correspond to the total amount of data received within the analysis cut-off times. In contrast, 0% values mean that either there was an instrument unavailability or the total data volume was received after the cut-off times. It should be noted that because the information on the uploading times is only available on the remote (ESA and KNMI) servers for a short period (up to one week), it is not possible to cross-compare the uploading and downloading times for long periods. Therefore, delays in the data acquisition (values that are less than 100%) could be related either to delays in the data processing, or to server access problems.

Instrument	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
GOMOS	96.1%	94.7%	96.4%	97.1%	96.3%	93.4%
TOSOMI	89.0%	83.1%	80.7%	81.0%	83.0%	85.1%
MIPAS	N/A	N/A	N/A	N/A	N/A	82.4%

Table 3: Annual mean of the data volume received by ECMWF within the delayed cut-off times relative to the total amount of data delivered. Periods of total data unavailability (such as during instrument unavailability) were not included in the annual mean.

Table 3 gives the annual mean percentage of data volume received in time for the delayed-cut-off analyses since 2006 for GOMOS and TOSOMI, and for MIPAS in 2011. Annual plots for the operability of the available ESA and KNMI products for the years from 2006 to 2010 were presented in previous reports (Dragani, 2008, 2009b, 2010b, 2011a).

The best timeliness was found to be that of GOMOS products, with the 2011 value of 93.4%. The timeliness of the TOSOMI product, although not as high as in 2006 (89%), has been increasing over the last few years, with the 2011 value being the second best since the record began in 2006.

4 Monitoring and assimilation of SCIAMACHY NRT total column ozone retrievals

SCIAMACHY (Burrows et al., 1988) measures sunlight transmitted, reflected and scattered by the Earth's atmosphere or surface in the ultraviolet, visible and near infrared wavelength region (240-2380 nm) at moderate spectral resolution (0.2-1.5 nm). The instrument provides global measurements of various trace gases including ozone in the troposphere and stratosphere, as well as information about aerosols and clouds. SCIAMACHY measurements are performed in three viewing modes: nadir, limb and occultation. Depending on the type of measurement mode, global coverage is achieved within 3 to 6 days, e.g. nadir measurements yield global coverage in about 6 days.

NRT total column ozone retrievals from the nadir measurements in the UV/VIS (SCI_RV__2P) were produced operationally by ESA until 8 May 2006. These retrievals were passively monitored[4] at ECMWF in the operational suite from February 2003 until the dissemination of the L2 TCO from the nadir measurements was stopped. The latest results from the monitoring of ESA SCIAMACHY TCO for the period 1 January to 8 May 2006 were discussed by Dragani (2006). Although the production of the L2 ozone data has recently restarted, the current timeliness is normally too long to be monitored operationally.

[4] Data go into the system, statistics are calculated e.g. statistical analyses of the differences between the model's first-guess or analysed fields and the observations, the so-called departures, but the data is not assimilated into the ECMWF model.

In addition to the NRT ESA TCO, ECMWF has also been receiving NRT total column ozone data retrieved by KNMI from the nadir measurements in the UV/VIS spectral range and distributed via the ESA funded PROMOTE-2 consortium (the so-called TOSOMI product) since March 2004. This product differs from the operational ESA one as the retrieval procedure makes use of the Ozone Monitoring Instrument (OMI) Differential Optical Absorption Spectroscopy (DOAS) algorithm (Veefkind and de Haan, 2002), instead of a GOME Data Processor-like algorithm. Owing to the unavailability of the NRT ESA SCIAMACHY TCO retrievals, it was agreed that the TOSOMI product should be regarded as the operational ESA Level 2 total column ozone retrieval from SCIAMACHY (Minutes of the ENVISAT progress meeting held at ECMWF on 6 December 2006).

The TOSOMI product was passively monitored at ECMWF from March 2004 to 27 September 2004. Based on the positive impact that these data could make on the ECMWF ozone analyses, especially in the Antarctic polar vortex region (Dethof, 2004), the operational assimilation of this product started on 28 September 2004, when the model was updated to cycle CY28R3, and still performed.

The TOSOMI product was assimilated at ECMWF during the whole 2011, without interruptions. Figure 2 shows the timeseries of globally averaged NRT TOSOMI ozone data, its averaged departures, standard deviations, and number of data actively assimilated with respect to the number of available observations for the periods January to June 2011 (l.h.s. panels), and July to December 2011 (r.h.s. panels), respectively.

The 2011 global mean timeseries is presented in figure 2. The uncorrected first-guess and analysis residuals - residuals calculated before applying the bias correction to the data - (blue and red lines in the mid panels) were generally negative and within -10 to 0 DU during most of the 2011, although three sharp changes in the statistics can be detected. The first one occurred on May 9 when ECMWF switched the assimilation from TOSOMI version 0.43 (v0.43) to TOSOMI version 2 (v2) on. The new algorithm implemented at KNMI contained a number of small improvements, the most important being an improved cloud scheme based on a MERIS albedo climatology. To prepare for the transition, KNMI provided ECMWF with test data that were used to run research assimilation experiments (Dragani, 2011b). The results (not shown) consisted in geral neutral impact on the ECMWF ozone field when the v0.43 data were replaced with those retrieved using the v2 algorithm. values were on average about 1DU higher than in the old version. The second change occurred on 15 November when cycle CY37R3 was implemented. This cycle included several modifications, as mentioned in section 2, the most important here was the activation of the assimilation of ozone sensitive channels in the infrared from three advanced sounders, AIRS, IASI, and HIRS. The assimilation of the ozone sensitive channels was found to globally increase the amount of total ozone that improved the level of agreement of the resulting ozone analyses with independent observations. In spite of the improved quality of the ozone analyses, the residuals of the uncorrected ozone analyses and first-guess from SCIAMACHY slightly increased after the activation of the assimilation of the IR ozone channels from about 0 to -3DU, more consistent with the TOSOMI documented bias (Eskes et al., 2005). The last modification that also impacted the 2011 SCIAMACHY statistics was implemented on 8 December, when ECMWF restarted the operational assimilation of MIPAS ozone profiles. The impact of assimilating MIPAS data is discussed below in section 5.

A few episodes characterized by larger first-guess and analysis departures were registered during summer from May through August. In many cases, these large differences are generally associated to episodes of large ozone variations in the data (only partly captured by the first guess) often associated with smaller than average standard deviations. When these situations occur, the 4D-Var assimilation scheme is likely to give a large weight to the observations which can lead to large changes in the analyses.

As also reported in the previous annual reports, the standard deviation of the observations (green line in the third row panels from the top of figure 2) during the second half of the year shows slightly smaller mean values, as well as a smaller variability than that seen during the first six months.

The generally good behaviour of the TOSOMI data can also be seen in the timeseries of the zonal mean first

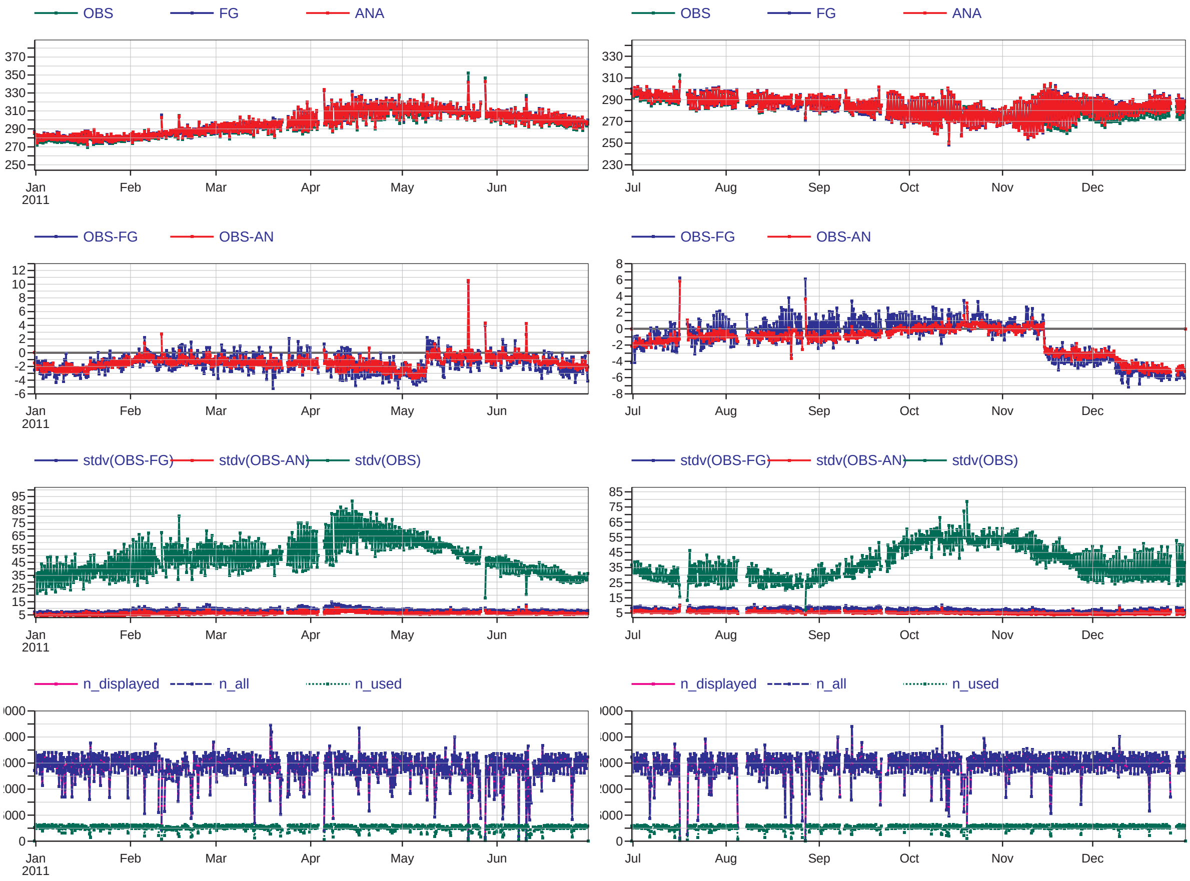


Figure 2: Timeseries of globally averaged data covering the periods 1 January to 30 June (left panel), and 1 July to 31 December 2011 (right panel). The top panels of each figure show TOSOMI SCIAMACHY NRT total ozone observations, first-guess and analysis values, the middle panels first-guess and analysis departures and the bottom panels the standard deviations of SCIAMACHY and of first-guess and analysis departures. All ozone values are in DU.

guess departures shown in figure 3. On average the first-guess departures (top panel in figure 3) are within ±10 Dobson Unit (DU) at most latitudes, that represents about 3% of the global mean total column ozone value. However, a lower level of agreement between the model and the observations can be observed near the end of the illuminated part of the orbits especially in the winter hemisphere, and it is more pronounced in the NH than in the SH. The lower level of agreement at high latitudes reflects in the observation standard deviations (bottom panel in figure 3) which exhibit higher values than average at the same locations in the winter hemisphere. Here, the observation standard deviation can reach values of 50 to 70 DU. In the tropics the observation standard deviation exhibits smaller values, typically of about 5DU or less.

Comparisons with total column ozone data from other UV instruments also show the generally good quality of these observations. Figure 4, in particular, shows the comparison between the time series of the zonal mean SCIAMACHY total column ozone (top panel) and of the zonal mean OMI total column ozone (bottom panel) for the whole 2011. The OMI data used in the comparisons are the NRT total column ozone distributed by NASA. On average, figure 4 shows a good level of agreement between SCIAMACHY and OMI total column ozone, particularly during the first half of 2011. Some differences can be found in the tropics, where SCIAMACHY usually exhibits lower values than OMI throughout the year (differences are normally between -15DU and +5 DU, -5 and +1.5% of the global mean TCO value, respectively), and at high latitudes where the OMI ozone values are normally up to 10% lower than those of SCIAMACHY. It should be noted that UV nadir

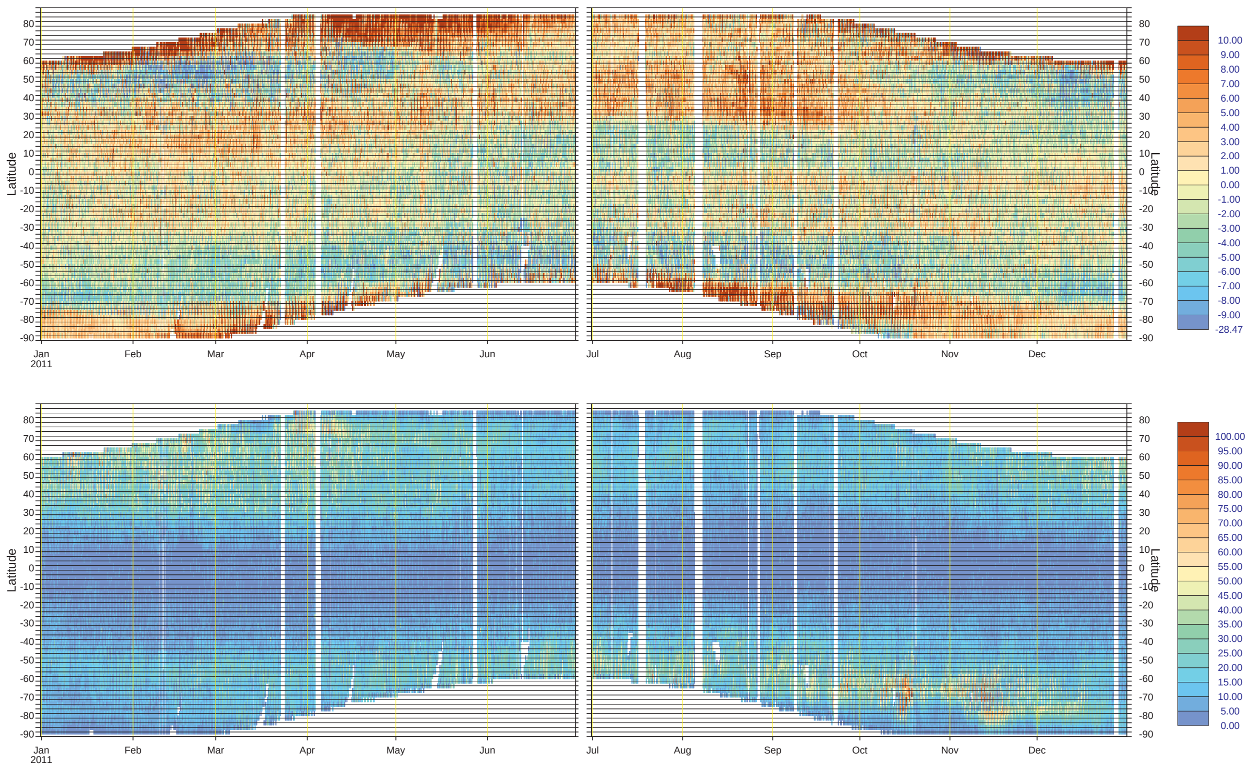


Figure 3: Time series of the zonal mean NRT SCIAMACHY first-guess departures (top panel) and of the zonal mean NRT SCIAMACHY standard deviation (bottom panel) during 2011. All ozone values are in DU.

sensors like OMI and SCIAMACHY[5] are prone to provide less accurate measurements near the end of the illuminated part of the orbits, as noted in the bottom panel of figure 3, and therefore the large differences at these latitudes should be of a less concern provided that the poorer quality of the data reflects in the observation errors (as shown in figure 3).

Figure 5 shows the time series of the zonal mean difference between SCIAMACHY TCO and MetOp-A GOME-2 TCO for 2011. The GOME-2 TCO used here is the operational TCO product provided in NRT by EUMETSAT. In general, the SCIAMACHY minus GOME-2 residuals are generally positive (SCIAMACHY values larger than those of GOME-2) and of about 10-15DU at most latitudes, with the exception of the end of the illuminated part of the orbits in the NH during spring 2011, where the differences were up to 30DU in places.

4.1 Summary of the NRT SCIAMACHY monitoring and assimilation

The NRT SCIAMACHY ozone columns produced by KNMI (TOSOMI) were available and assimilated during the whole 2011. A change in the version of the TOSOMI retrieval scheme was implemented on 9 May. The changes in the new algorithm had negligible impact on the ECMWF ozone analyses and first-guess. Two more changes in the assimilated observing system were implemented at ECMWF that slightly impacted the statistics for these observations. The first one implemented on 15 November concerned the assimilation of the IR ozone sensitive channels from AIRS, IASI, and HIRS.

[5] The SCIAMACHY TCO used are those retrieved from the nadir measurements only.

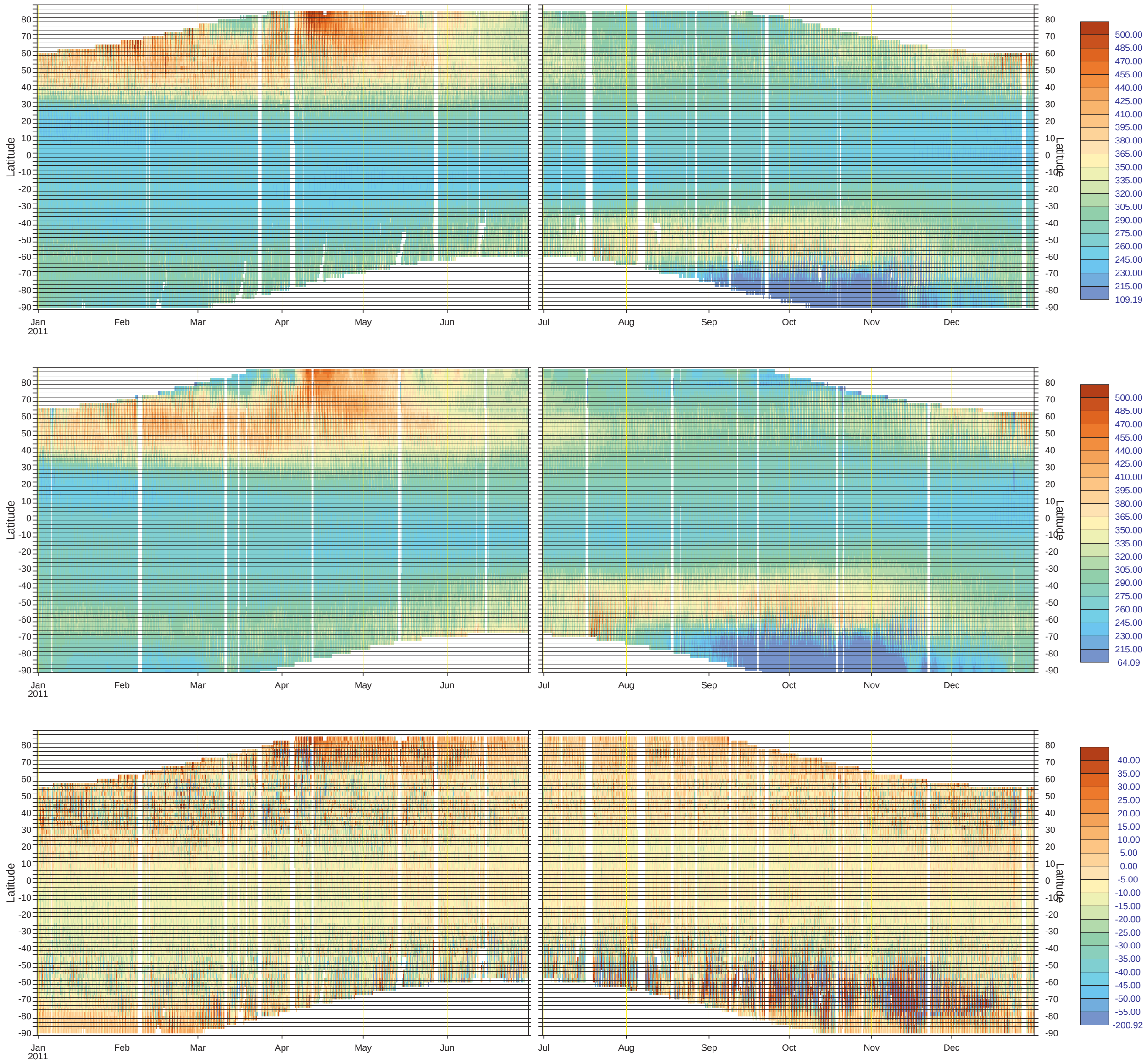


Figure 4: Time series of the zonal mean NRT SCIAMACHY ozone (top panel), OMI total column ozone (middle panel), and their difference (bottom panel) for 2011. All ozone values are in DU.

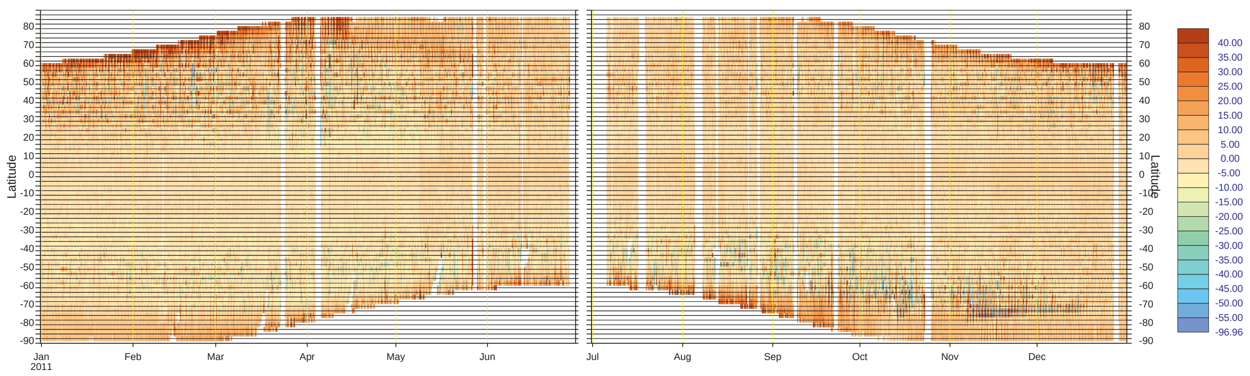


Figure 5: Time series of the zonal mean difference between SCIAMACHY TCO and GOME-2 TCO for 2011. Values are in DU.

The second change implemented on 8 December regarded the assimilation of MIPAS ozone profiles.

Comparisons of the TOSOMI data with the Aura OMI and the MetOp-A GOME-2 total column ozone showed that the level of agreement between these three products was within 5% of the mean observation value.

5 Monitoring and assimilation of MIPAS NRT ozone retrievals

MIPAS is a Fourier transform spectrometer for the detection of limb emission spectra in the middle and upper atmosphere. Because it observes a wide spectral interval throughout the mid infrared (from 4.15 μm to 14.6 μm) at high spectral resolution, MIPAS can detect and spectrally resolve a large number of emission features of atmospheric minor constituents, thus playing a major role in atmospheric chemistry. MIPAS was one of the first ENVISAT instruments to be fully operational after the launch, providing very high quality observations, and NRT MIPAS ozone profiles (MIP_NLE_2P) were actively assimilated at ECMWF from October 2003 until the end of March 2004 (Dethof, 2004). Instrumental problems occurred early on in the mission, so that MIPAS had to be switched off in March 2004. Operations could only be resumed in January 2005 when the original high spectral resolution was reduced from 0.025 cm-1 to 0.0625 cm-1. The reduction in the spectral resolution led to a proportional reduction in the measurement time from 4.5 seconds to 1.8 seconds, that was exploited to increase the number of measured spectra in each scan in order to have a finer vertical limb grid in the upper troposphere and lower stratosphere (UTLS), and an altitude range coverage from 6 to 70 km. The reduction in the measurement time coming from the use of a lower spectral resolution also resulted in a reduced horizontal spacing between two contiguous limb scan measurements. Originally, operations were also restricted to operate MIPAS with a reduced duty cycle (<50%, then relaxed to 60%). Based upon the instrument reliability, ESA decided to restart the MIPAS operations at 100% duty cycle in December 2007. However, because of completely independent issues, the production of the Level 2 data was further delayed, and fully resumed only at the beginning of 2011. As the new product has a slightly different format from the one received at the beginning of the ENVISAT mission, the operational monitoring and assimilation could not be restarted immediately in cycle CY37R2, but they had to be postponed until after the implementation of cycle CY37R3, which became operational on 15 November 2011. Immediately after cycle CY37R3 became operational, ECMWF restarted to archive the MIPAS Level 2 products into the Meteorological Archival and Retrieval System (MARS), where all data monitored and assimilated by the operational suite are stored. On 8 December 2011, based on the positive results from a number of assimilation experiments, ECMWF restarted the operational assimilation of MIPAS ozone profiles. We discuss those results in sections 5.2 to 5.4.

5.1 Monitoring of MIPAS retrievals

This section briefly shows the level of agreement between the MIPAS retrievals (ozone, temperature and water vapour) and their model equivalent. The mean profiles were computed for the period December 2011 for the operational suite.

Figure 6 shows the comparisons between the MIPAS mean ozone profile and its model equivalent at high latitudes in the NH and SH (top and bottom panels, respectively), and in the tropics (middle panel). The difference between the ECMWF first-guess and analysis profiles and the mean MIPAS ozone profile is normally less than the observation standard deviation. The level of agreement between the MIPAS retrievals and the ECMWF ozone first-guess and analyses are generally better than 10% at most latitudes, and vertical layers. The only exceptions are represented by the upper stratospheric layers where the first-guess and analysis departures from MIPAS data are on average up to +15% at high latitudes in the NH, and up to +25% at high latitudes in the SH. The standard deviation of the first-guess and analysis departures are normally larger than 10% at all levels and latitudinal bands.

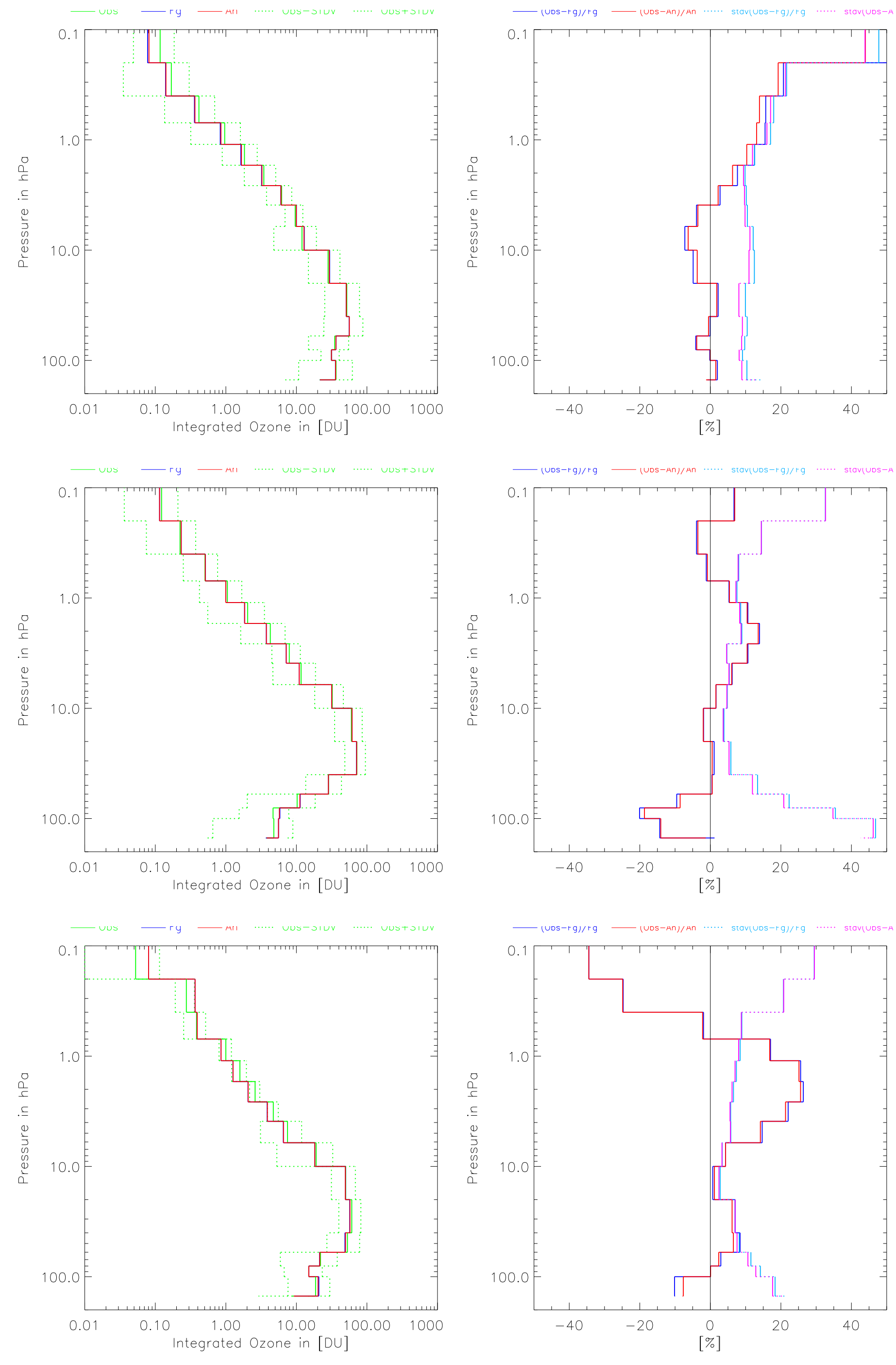


Figure 6: Comparisons between the area averaged MIPAS ozone profiles and the area averaged ECMWF ozone first-guess and analysis (left panels) and their relative departure (right panels) for December 2011. The plots were obtained by averaging the data over the high latitudinal band in the NH ([60°-90°]N) (top panels), the tropics [30°N-30°S] (middle panels), and the high latitudes in the SH ([60°-90°]S) (bottom panels). Ozone values are in DU.

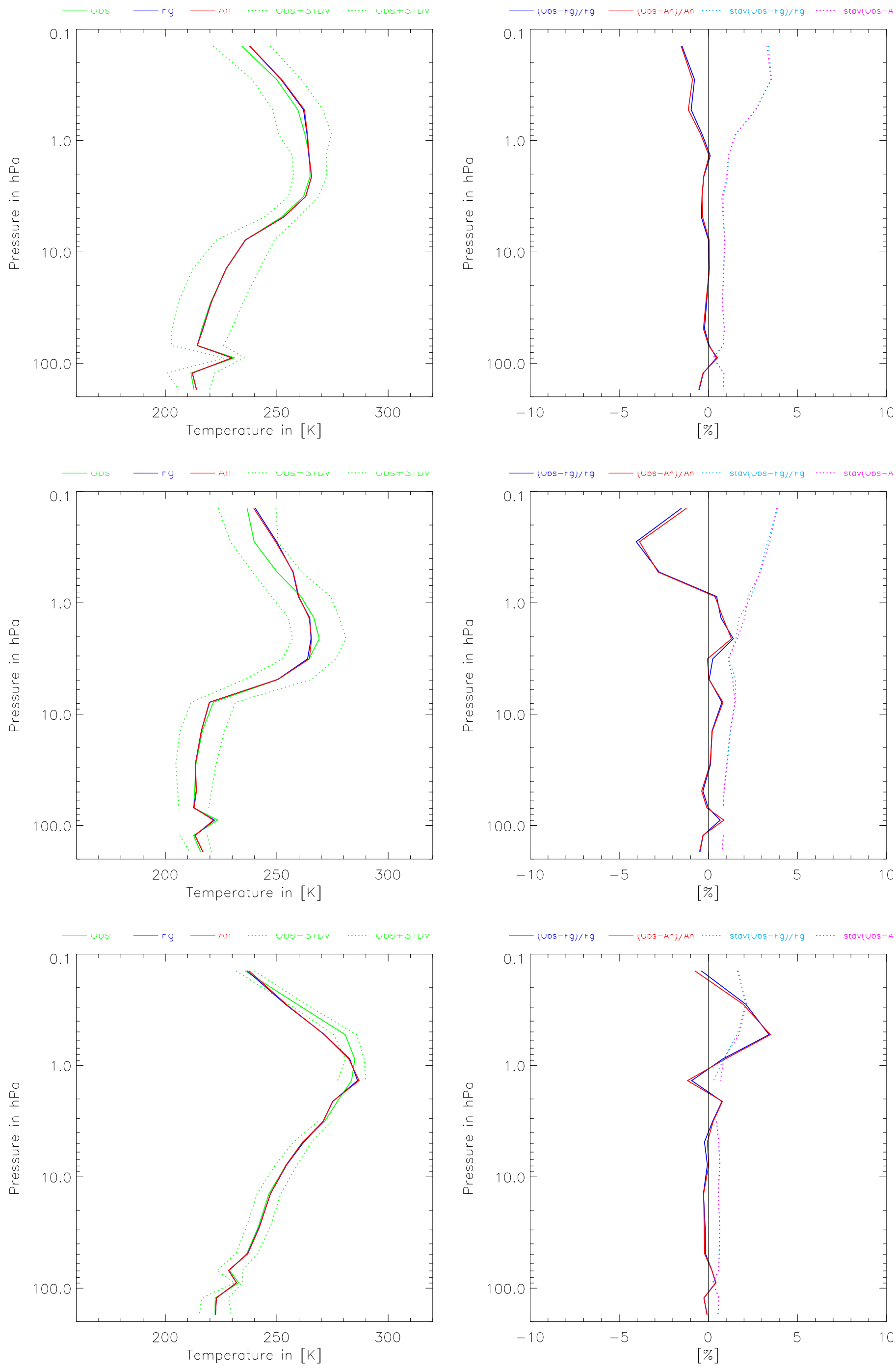


Figure 7: Like in figure 6, but for the temperature. Temperature values are in K.

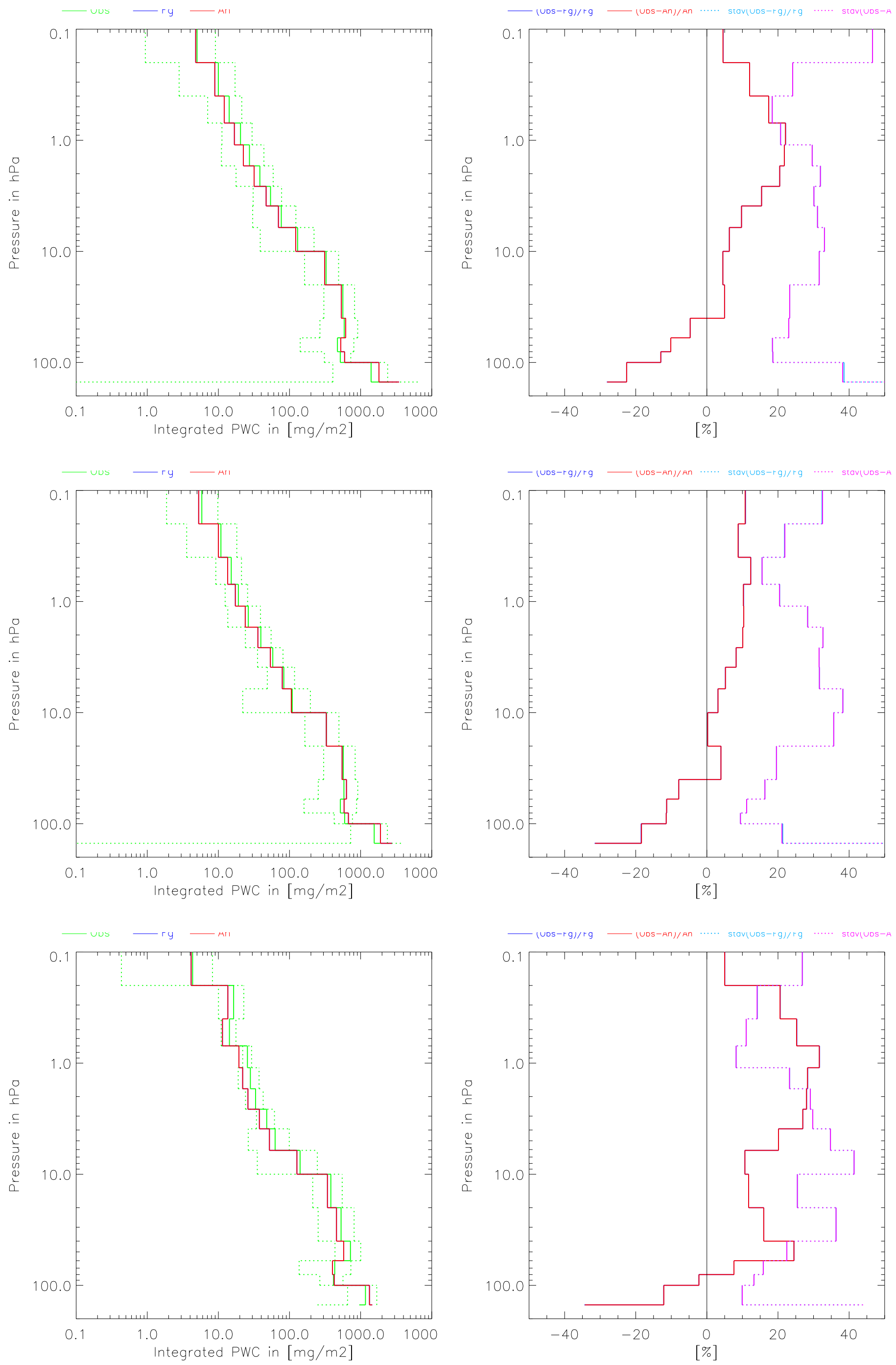


Figure 8: Like in figure 6, but for the water vapour. Water vapour values are in mg/m^2.

The comparisons between the MIPAS temperature retrievals and the ECMWF temperature first-guess and analysis profiles are given in figure 7. Like in the case of ozone, also the level of agreement in the temperature profiles is better than the observation standard deviation at all levels and latitudinal bands. The stratospheric temperature first-guess and analyses are typically less than 1% (< 2 K). Larger departures are normally found in the mesosphere with values up to 4% (about 8K). It should be noted that the quality of the mesospheric temperature first-guess and analyses is not as high as those in the stratosphere. The standard deviation of the first-guess and analysis departures are normally larger than 1% (2K) at all levels and latitudes.

Figure 8 presents the comparisons between the MIPAS water vapour retrievals and their model equivalent. The data show good agreement with the ECMWF water vapour first-guess and analyses, that is normally better than the observation standard deviation. The first-guess and analysis departures from the MIPAS water vapour retrievals are typically within ±20% at most vertical levels and latitudes. The only exception seems to be the upper stratosphere at high latitudes in the SH (bottom panels of figure 8), where the first-guess and analysis departures are closer to +30%. In general, MIPAS has a dry bias in the UTLS region and a wet bias in the mid and high stratosphere, as well as in the mesosphere. The standard deviation of the first-guess and analysis departures are usually larger than 10%.

5.2 Assimilation experiment set-up

Two sets of assimilation experiments (labelled as A and B) were run over two periods February-March, and August-September 2011. The main characteristics of these experiments and their settings are given in tables 4 and 5. All experiments were run using the standard 91 vertical levels from surface up to 0.01hPa.

Set of experiments labelled as A (table 4) included a total of four runs which made use of two model resolutions, namely T255 and T799. This was done to quantify a misrepresentation error made when assimilating MIPAS retrievals in a high resolution data assimilation system without accounting for the horizontal smoothing of the data. This horizontal smoothing of the data is related to the horizontal variations of the real atmospheric state. The MIPAS profiles are instead retrieved under the hypothesis of local horizontal homogeneity of the atmosphere. This means that vertical profiles of atmospheric state variables are retrieved under the assumption that the atmosphere seen during a given limb scan has no horizontal variations (e.g. Raspollini et al., 2006; Ridolfi et al., 2000). As this assumption is not generally met, it introduces the so-called smoothing error (Rodgers, 2000). The way this horizontal smoothing can be accounted for in data assimilation is by using the horizontal averaging kernels (HAK, Ridolfi et al. (2009)). This is particularly important when the model grid is significantly finer than the horizontal resolution of the measurement. For MIPAS retrievals, the horizontal smearing of a MIPAS retrieval can vary typically between about 200 and 350 km for most species, altitudes and atmospheric conditions. In the specific case of ozone, the range where 95% of the information used to retrieve each profile can originate varies over a large distance (up to 300 km in the direction towards the satellite and away from it) from the retrieval nominal geo-location defined as the location of the 30km tangent point (von Clarmann et al., 2009).

The two control experiments of set A (C255 and C799) were run using all the operational data, which include level 2 ozone data from three SBUV/2 instruments (on board of NOAA-17, NOAA-18, and NOAA-19) in the form of partial columns over six vertical layers, and total column ozone retrieved from SCIAMACHY and OMI. The two perturbations (M255 and M799) were run adding MIPAS ozone profiles on top of the observing system used in their corresponding control experiments.

A second set of experiments (labelled as B) was run to assess the potential synergy between MIPAS ozone profiles and the ozone-sensitive channels in the infrared spectral range. These ozone channels have been assimilated operationally at ECMWF from cycle CY37R3 (15 November 2011). These experiments were run at a model resolution of T511. The set-up of the ozone-sensitive IR channels was the same tested in the CY37R3

Set A				
	Control	**Perturbation**	**Control**	**Perturbation**
Period	Feb-Mar	Feb-Mar	Feb-Mar	Feb-Mar
Model cycle	CY36R4	CY36R4	CY36R4	CY36R4
Model resolution	T255	T255	T799	T799
Assimilated data	Ops	Ops+MIPAS	Ops	Ops+MIPAS
O3-sensitive IR channels	No	No	No	No
VarBC anchor	SBUV/2	SBUV/2	SBUV/2	SBUV/2
Initial conditions	Ops suite	Ops suite	Ops suite	Ops suite
Label	C255	M255	C799	M799

Table 4: Summary of the main characteristics of the experiments denoted as **Set A** *that were run to assess the impact of MIPAS ozone profiles. All experiments were run over the standard 91 vertical levels from surface up to 0.01hPa.*

experimental suite, and includes 19 AIRS channels, 16 IASI channels and one HIRS channel, that were assimilated in both control and perturbation experiments. Two of these channels, one from AIRS and one from IASI (each regarded as the most sensitive channel to ozone variations) were used to anchor the ozone bias correction, together with the SBUV/2 partial ozone columns (experiments labelled as CTRL and MIP_Cor in table 5). An additional perturbation experiment (labelled as MIP_Uncor) was run with the same set-up of MIP_Cor except that it made use of MIPAS retrievals as a further level 2 anchor to the ozone VarBC, in addition to the NOAA SBUV/2 data.

Set B			
	Control	**Perturbation**	**Perturbation**
Period	Aug-Sep	Aug-Sep	Aug-Sep
Model cycle	CY37R1	CY37R1	CY37R1
Model resolution	T511	T511	T511
Assimilated data	Ops	Ops+MIPAS	Ops+MIPAS
O3-sensitive IR channels	Yes	Yes	Yes
VarBC anchor	SBUV/2+AIRS+ IASI	SBUV/2+AIRS+ IASI	SBUV/2+AIRS+ IASI+MIPAS
Initial conditions	Exp suite	Exp suite	Exp suite
Label	CTRL	MIP_Cor	MIP_Uncor

Table 5: As in table 4, but for experiments denoted as **Set B***.*

5.3 Analysis of the results from Set A: the model resolution

As MIPAS measures a wide spectral range, and thus it is sensitive to a deep atmospheric layer, it was expected that the assimilation of its ozone profiles could constrain the ozone analyses in the middle and lower stratosphere as well as in the upper troposphere. Figure 9 shows the zonal mean difference in the ozone mixing ratio (MR) between the control and perturbation experiments (at T799) averaged during the two month period February-March 2011. Figure 9 confirms that the assimilation of MIPAS ozone profiles creates ozone increments not just to the region of the ozone MR maximum around 10hPa, but also in the upper troposphere and lower stratosphere (UTLS), particularly at mid and high latitudes in the winter hemisphere.

The impact in the UTLS region (between 40 and 300hPa) in the winter hemisphere is particularly important, as most of the available ozone products (and this is certainly the case of the ECMWF ozone observing system) are retrieved from nadir Backscatter Ultra-Violet (BUV) sensors that can only make measurements in day light

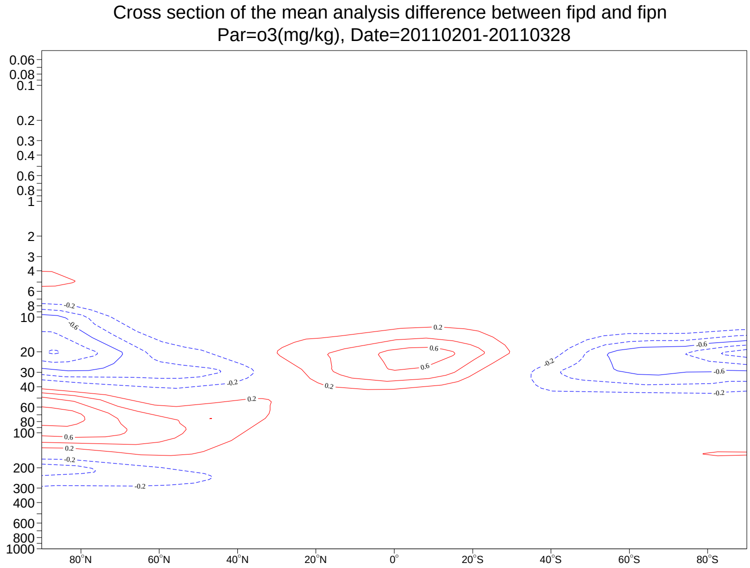


Figure 9: Cross section of the zonal mean ozone analysis difference (C799-M799) averaged over the period Feb-Mar 2011. Data are in ppmm (mg/kg). Positive values (red contours) mean that the assimilation of MIPAS retrievals reduces the ozone analyses; negative values (blue contours) mean that the assimilation of MIPAS retrievals increases the ozone analyse. Contour interval is 0.2 ppmm, data range from -1 to 0.8 ppmm.

and are mostly sensitive to the region of the ozone maximum. Figure 10 shows the fit of the ozone analyses from set A to a number of ozone sondes in terms of RMS difference between the ozone sondes and their co-located ozone analyses. As there were negligible differences between the ozone analyses from the two control experiments only the high resolution case was plotted (simply labelled as CTRL).

Figure 10 shows that at all available latitudes and regardless of the model resolution, the assimilation of MIPAS ozone profiles is beneficial both in the stratosphere and troposphere, as it improves the fit of the ozone analyses to sonde measurements. Particularly noticeable is the large improvements in the fit to sondes launched at midlatitudes in the northern hemisphere (top panel), especially in the region of the atmosphere between 40 and 300hPa. These improvements can be detected both in the M255 and M799 experiments. When the agreement of the M255 and M799 ozone analyses to ozone sondes differs, the indication is that the lower is the model resolution the better is the fit to ozone sonde. The differences between the M255 and M799 quantify the misrepresentation error resulting from not accounting for the data horizontal smoothing, and not using the MIPAS HAK. The exception is represented by the comparisons in the tropics, where at many level the M799 analyses show an higher level of agreement to sondes than their T255 equivalent. However, it should be noted that the number of available profiles in the tropics during the two month period is particularly low, so these results should be regarded as a mere indication rather than a statistically significant result. Another consideration is that this misrepresentation error is more important in regions of the atmosphere and at latitudes dominated by strong ozone gradients (e.g. near the polar vortex edge or across an ozone filament in the surf zone).

Figure 11 shows the zonal mean difference between MLS reprocessed ozone profiles (version 2.2) and co-located ozone analyses from the high resolution control experiment (i.e. C799) and the two perturbations averaged over the two month period Feb-Mar 2011. As MLS ozone profiles are not assimilated, this comparison also provides an independent validation of the impact of MIPAS assimilation. Also in this case, the two perturbations compare better than the control with MLS ozone retrievals, both in the region of the ozone MR maximum and in the UTLS region, particularly in the winter hemisphere. Particularly noticeable is the reduc-

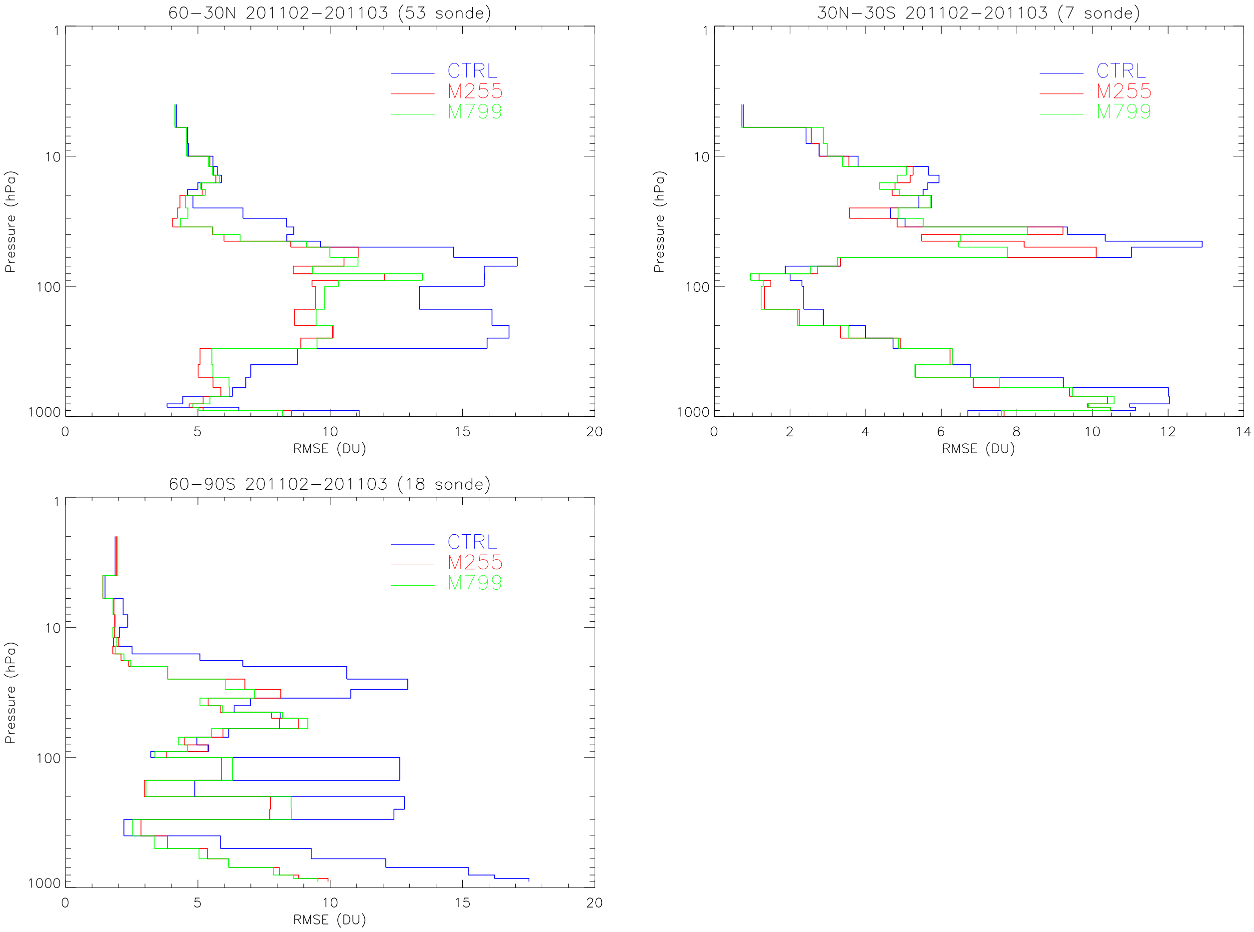


Figure 10: Fit of the ozone analyses to ozone sonde profiles in terms of their RMSE. Negligible differences were found in the two control experiments at T255 and T799 model resolution, so for simplicity only one (namely C799) was plotted. Ozone sondes at latitudes northern than 60N, and between 30S and 60S were unavailable over the considered period. The number of profiles used to compute the mean differences is provided in the title of each panel. Data are in DU.

tion of the negative bias (model exhibiting larger values than MLS) in the tropics about 20hPa, and the positive bias at the same vertical level in the SH.

Conversely to the comparisons with ozone sondes, the impact of the model resolution appears to be generally negligible in this case. Although, in spite of the expectations, it could be argued that the positive bias about 50hPa (particularly at midlatitudes in the SH) is slightly reduced in the comparisons with MLS when the M799 (bottom left panel) analyses are used instead of the M255 (top right panel) ones.

The assimilation of MIPAS ozone profiles also slightly improves the fit to the MetOp-A GOME-2 total column ozone (TCO). Figure 12 shows the distribution of the first-guess and analysis departures from GOME-2 TCO for the control and perturbation experiments at T799 computed for the tropics and the SH and NH extra-tropics. Although, the differences between the control and perturbation departures are small, the statistics indicate improvements in the mean, standard deviation and RMS at all latitudinal bands when MIPAS ozone profiles are assimilated. Similar results were found in the statistics for the T255 experiments that suggest a limited to negligible impact of the model resolution. The fit to used data is negligible, certainly in the case of non-ozone related observations. Some very small, positive improvements were found in the fit to the Aura OMI total column ozone produced by the assimilation of MIPAS ozone profiles (not shown). The impact on the forecasts scores (not shown) is neutral at all tropospheric levels.

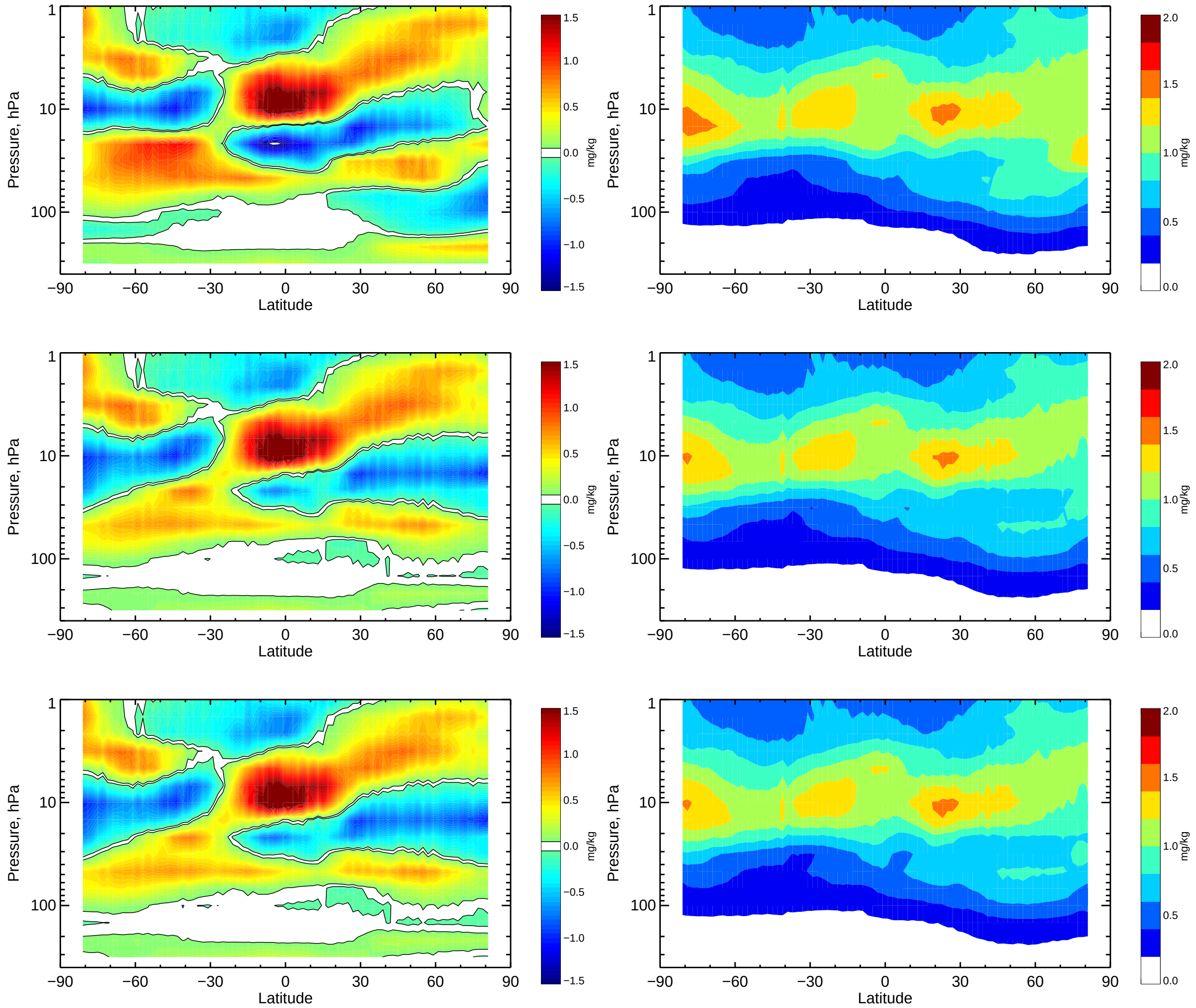


Figure 11: Fit of the ozone analyses to ozone sonde profiles in terms of their residuals (left panels) and their standard deviations (right panels). The statistics were computed for C799 (top panels), M255 (middle panels),and M799 (bottom panels). Data are in mass mixing ratio (ppmm).

5.4 Analysis of the results from Set B: synergy with the ozone sensitive radiances and VarBC set-up

This section discusses the impact of assimilating MIPAS ozone profiles in a system in which both level 2 ozone products and O_3-sensitive IR radiances from AIRS, IASI, and HIRS were assimilated as baseline. As anticipated in section 5.2 (also see table 5), two assimilation experiments were run with MIPAS L2 data to test the possible set-up of the ozone bias correction. A number of research experiments that were run to assess the impact of assimilating the O_3-sensitive IR radiances showed that the bias correction for these channels requires several months to stabilise. For that reason, the three experiments in Set B were all initialised from the CY37R3 experimental suite (e-suite) for which the bias correction was fully spun-up.

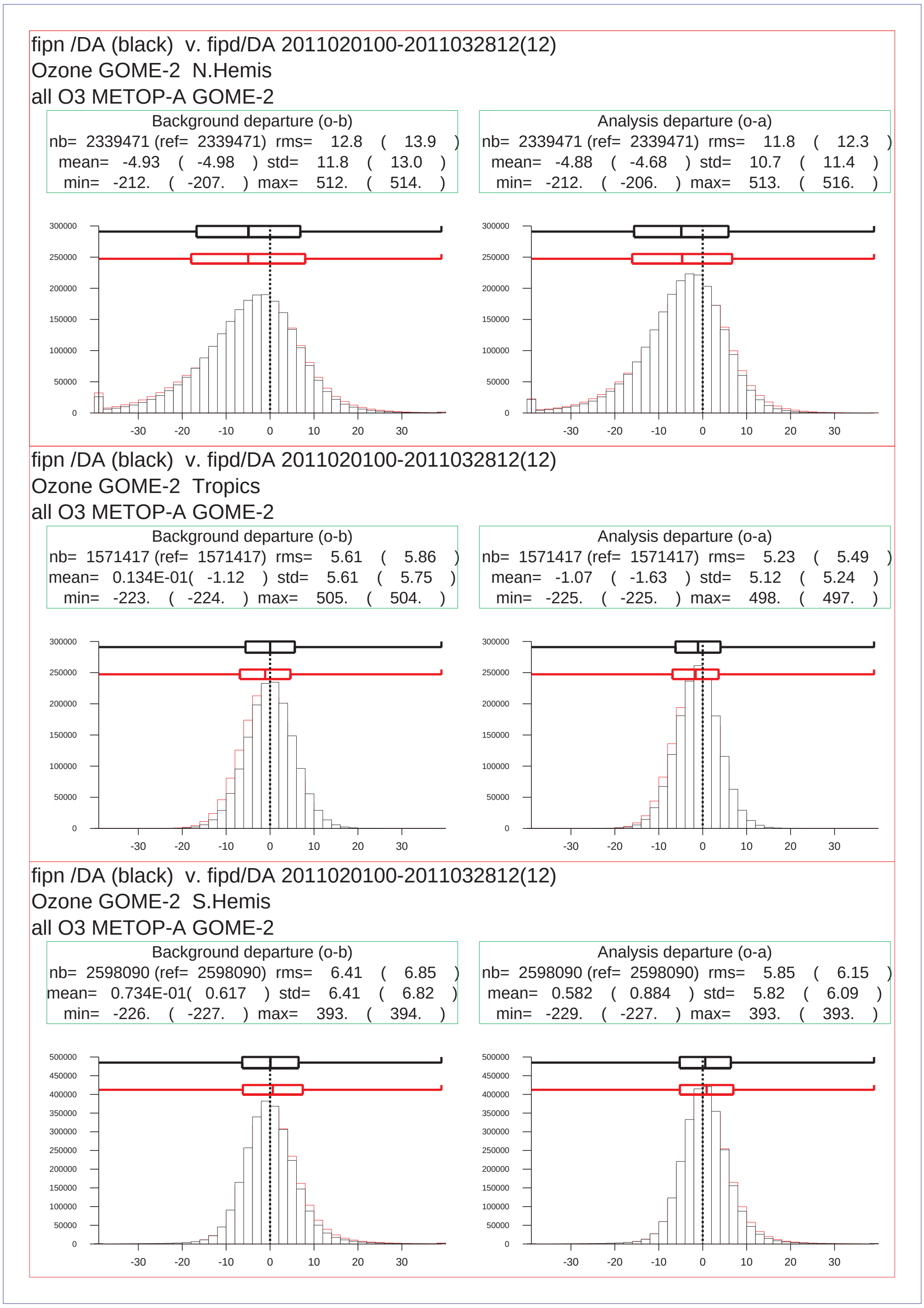


Figure 12: Histograms of the first-guess (left panels) and analysis (right panels) departures for GOME-2 total column ozone computed for the T799 experiments. The black lines refer to M799 (experiment fipn); the red lines refer to the control, C799 (experiment fipd). Statistics are computed over the period Feb-Mar 2011, and refer to the extra-tropics in the northern hemisphere (top panels), tropics (middle panels), and the extra-tropics in the SH (bottom panels). Data are in Dobson Unit (DU).

Figure 13 shows the comparisons of the ozone analyses with MLS ozone profiles in terms of their zonal mean differences averaged over the August-September months (left panels) and their standard deviations (right panels). The top, middle, and bottom panels refer to the Set B CTRL, MIP_Cor, and MIP_Uncor experiments, respectively.

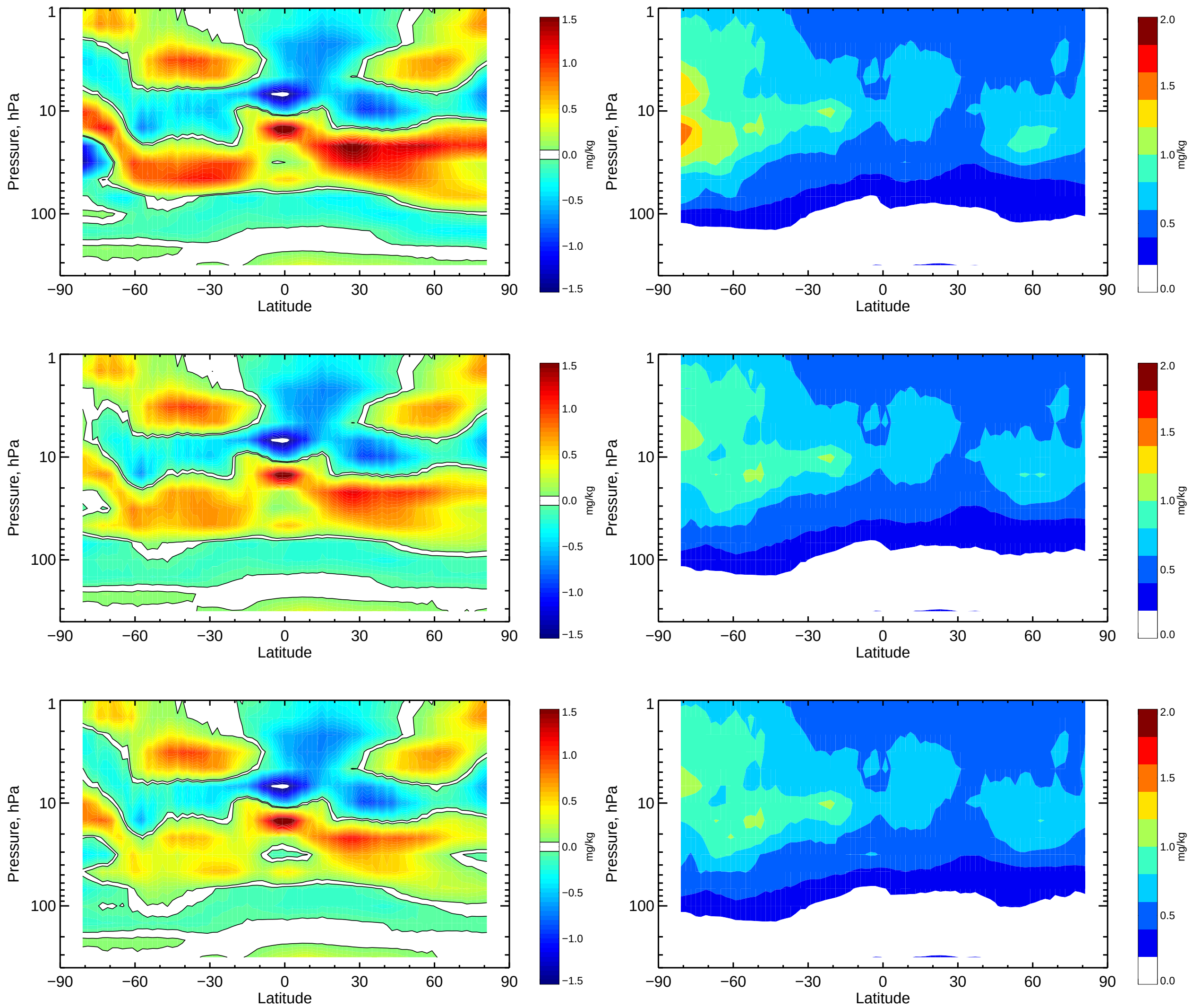


Figure 13: Like in figure 11, but for Set B CTRL (top panels), MIP_Cor (middle panels), and MIP_Uncor (bottom panels).

MIPAS with its high vertical resolution provides useful information able to constrain the vertical distribution of the ozone analyses. Figure 13 presents the comparisons of the ozone analyses obtained from the Set B experiments with the MLS ozone profiles. Figure 13 clearly shows that the assimilation of MIPAS L2 ozone profiles can substantially reduce the large positive differences between MLS retrievals and the ECMWF ozone analyses in the middle stratosphere, particularly if these observations are also used as an anchor to the ozone bias correction, O_3 VarBC (bottom left panel) of figure 13), in addition to the SBUV/2 partial columns. Furthermore, whether the MIPAS ozone profiles are used or not to anchor the O_3 VarBC, the assimilation of these data also slightly reduces the standard deviation of the MLS minus ozone analysis residuals, particularly around the ozone MR maximum at high latitudes in the SH (right panels).

It is also important to notice that the assimilation of MIPAS ozone profiles in either VarBC configuration did not produce changes to the bias correction of the IR O_3-sensitive channels assimilated in all the Set B experiments (not shown). The benefits of assimilating the MIPAS ozone profiles, particularly when these data are used as VarBC anchor, are also confirmed by the comparisons with ozone sondes averaged over different latitudinal bands (figure 14). Negligible impact was produced in both the fit to other assimilation data and the forecasts scores.

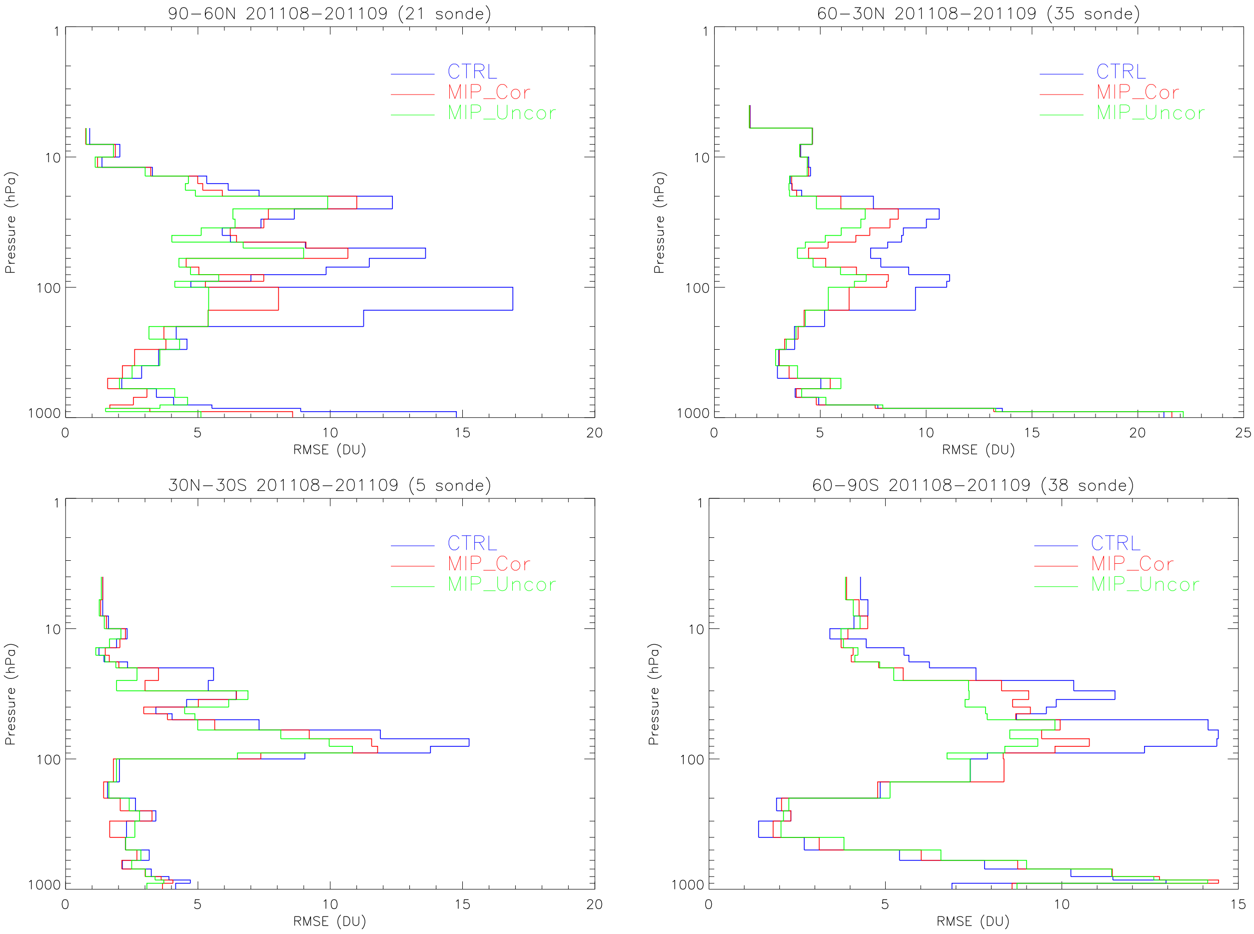


Figure 14: Like in figure 10, but for the Set B experiments.

5.5 Conclusions on the assimilation of MIPAS ozone profiles

Several experiments were conducted to assess the impact of assimilating MIPAS ozone profiles on the ECMWF products. The results clearly showed that after almost a decade in space MIPAS is still able to provide high quality observations that can substantially improve the distribution of the stratospheric ozone analyses. Two sets of experiments were performed. In the first set, MIPAS ozone profiles were assimilated in the ECMWF data assimilation system run at two different resolution (T255 and T799) to assess the impact of the model resolution and indirectly the misrepresentation error that comes from not accounting for the observation horizontal smoothing. The results showed that although the model resolution is an important factor (the higher the model resolution the worse the agreement of the ozone analyses with independent observations), the improvements to the vertical distribution of ozone produced by the MIPAS assimilation are by far more important and substantial. The second set of experiments was performed 1) to assess the potential synergy of MIPAS ozone profiles with ozone-sensitive radiances in the IR spectral range, and 2) to identify the set-up for the ozone bias correction. It was shown that the improvements produced by the IR ozone channels were retained in the experiments in which MIPAS observations were also assimilated. In addition, it was also noted that the high vertical resolution of MIPAS in the stratosphere could provide a very useful constraint on the ozone analyses. It was also shown that the level of agreement of the ozone analyses with independent ozone data is improved when MIPAS ozone profiles are also used to anchor the ozone bias correction. The analysis of both sets of experiments neither showed negative impact on the fit to other observations and bias corrections, nor a degradation on the ECMWF forecasts scores. Based on these results, the assimilation of MIPAS ozone profiles was restarted on 8 December 2011.

6 Monitoring of GOMOS data

GOMOS makes use of the occultation measurement principle by tracking stars as they set behind the atmosphere. GOMOS has an ultraviolet-visible and a near-infrared spectrometer, covering the wavelength region between 250 and 950 nm. It allows the retrieval of atmospheric trace gas profiles in the altitude range 100-15 km, with an altitude resolution better than 1.7 km. GOMOS gives day- and night-time measurements with about 600 profiles per day. The primary GOMOS target species are O_3, NO_2, NO_3, OClO, H_2O and temperature (fixed to the ECMWF temperature forecasts in v5.00).

A subset of these retrieved products that is available in NRT (GOM_RR__2P) is routinely and passively monitored at ECMWF. This subset includes temperature, water vapour and ozone profiles.

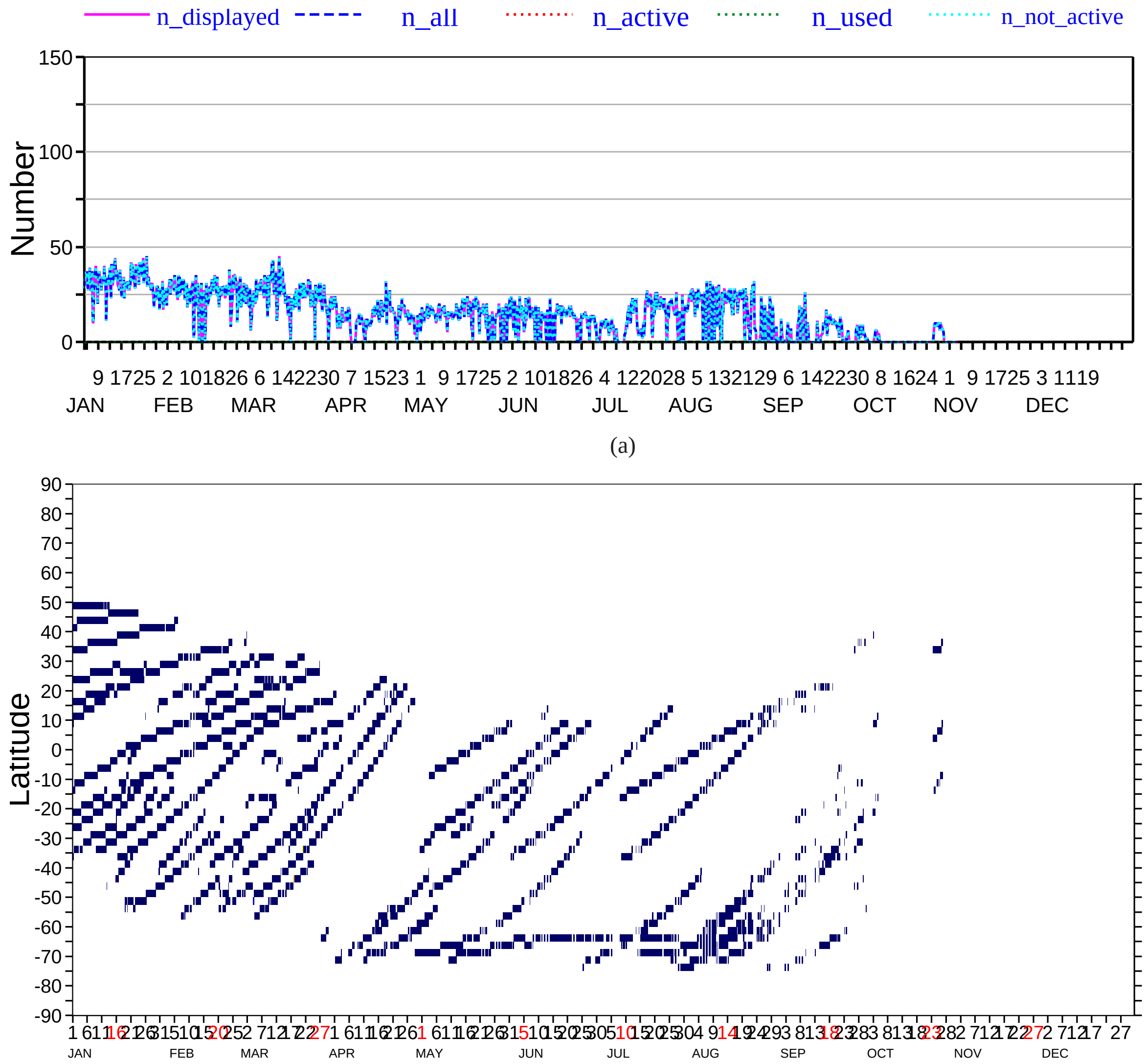
The GOMOS data were generally available during the first half of 2011. However, the GOMOS instrument experienced difficulties in performing nominal operations from 24 August 2011 onwards. These problems resulted in a loss in observation coverage and in a number of instrument measurement interruptions from the end of August till the end of year. The anomaly is triggered by an electronical and mechanical aging of the instrument, impacting the mirror movement (information published at http://earth.esa.int/object/index.cfm?fobjectid=8170 on 23 November 2011). During the intense period of anomaly investigation and testing, only a small number of nominal occultation were successfully performed. In the frame of the anomaly investigation, GOMOS was also switched from the so called ”redundant side B”, in which it is operating since July 2003 to its original ”side A” configuration on 21/11/2011.

Figure 15 shows the time series of the global number of GOMOS ozone observations (top) and of the zonal mean GOMOS temperature (bottom) during 2011, respectively. The plots refer to a mesospheric layer and they are intended to provide a general indication of the daily amount of available data (panel **a**) and their geographical coverage (panel **b**) during 2011. The daily amount, that counted about 40 observations per day during the first three months of 2011, decreased to about 20 profiles per day until the end of August, when the first instrument anomalies started. The decrease from 40 to about 20 profiles per day is normal, it has been observed during past years as well (e.g. Dragani, 2011a), and coincides with the period when the GOMOS orbit is shifted to cover most of the southern hemisphere. From the end of August, the amount of GOMOS measurements further decreased during September, and only occasional observations were available afterwards.

The following sections 6.1 and 6.2 focus on the monitoring of GOMOS ozone and water vapour profiles, respectively.

6.1 Monitoring of GOMOS ozone data

This section discusses the results from the monitoring of the NRT GOMOS Level 2 ozone profiles in 2011.



(b)

Figure 15: Time series of the global number of GOMOS observations (panel a) and their latitudinal distribution (panel b) during 2010. The plots refer to the mesospheric level between 2.6 and 3.9 hPa.

Figure 16 shows the 2011 global mean time series of the observations and their model equivalent (top panel), of the first-guess and analysis departures (middle panel), and of their standard deviations (bottom panel) for the vertical layer between 20 and 40 hPa, which corresponds roughly to the layer where ozone mixing ratio peaks. From figure 16, the GOMOS ozone observations exhibit lower ozone values than the ECMWF ozone analyses of about 6DU over the layer until 7 June when the new Near Real Time (NRT) processing (version 6.01) was activated. With the new algorithm, the observation minus analysis departures became slightly larger and ranged within -8 to -10 DU for the 20-40 hPa layer.

The degradation seen in the layer between 20 and 40 hPa after the implementation of the v6.01 NRT processing has to be seen in the context of the changes over the whole depth of the atmosphere. An early assessment of the quality of the ozone and water vapour profiles retrieved from the GOMOS measurements after implementing the new Near Real Time (NRT) processing (version 6.01) on 7 June 2011 was performed by ECMWF. This assessment covered the one-month period from 23 May to 21 June 2001, thus the period consisting in the two weeks prior the change and the two weeks after. This choice was also made to avoid possible spin-up and sharp changes in the ECMWF system due to the implementation of model cycle CY37R2 (on 18 May) and

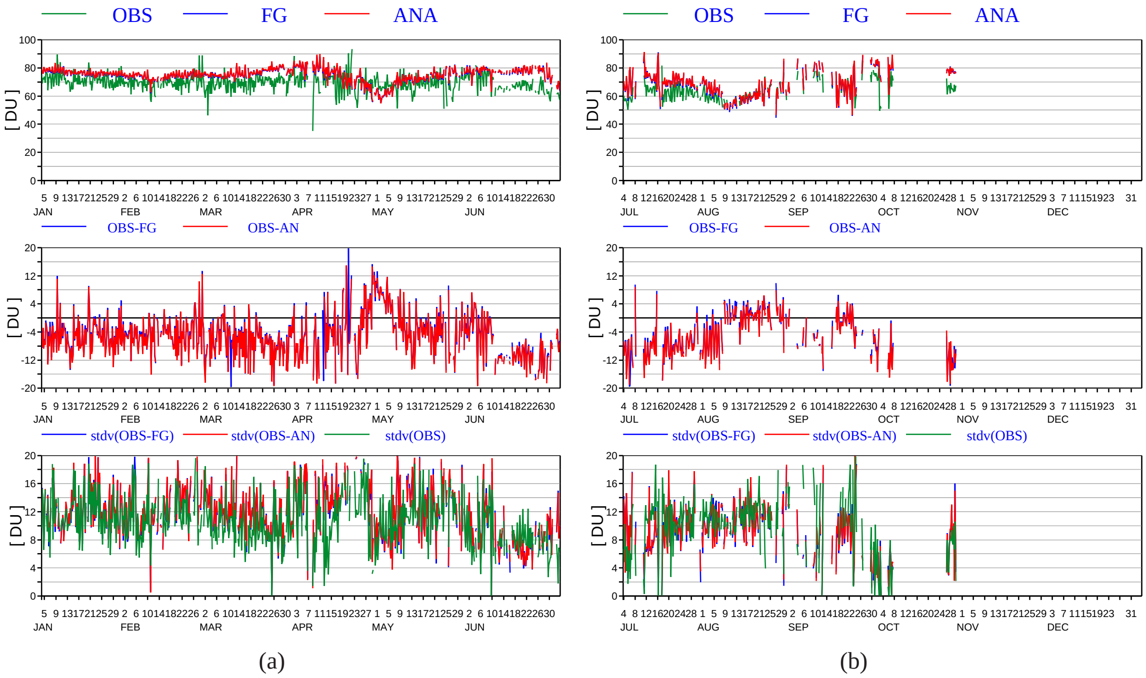


Figure 16: Timeseries of globally averaged data covering the periods (a) 1 January to 30 June, and (b) 1 July to 31 December 2011 at 20-40 hPa. The top panels of each figure show GOMOS NRT partial column ozone, first-guess and analysis values, the middle panels first-guess and analysis departures and the bottom panels the standard deviations of GOMOS ozone data and of first-guess and analysis departures. All ozone values are in DU.

the activation of the assimilation of NOAA-19 SBUV/2 ozone data (on 22 June). Figure 17 shows the profile comparisons between the GOMOS mean ozone retrieval and its model equivalent before (left) and immediately after (right) the implementation of the v6.01 NRT processing.

Figure 17 show that, altough the level of agreement between the GOMOS ozone retrievals and the ECMWF ozone first-guess and analyses was slightly degraded in the mid stratosphere (between 4-40 hPa), confirming the result presented in figure 16, it was improved in the UTLS region (40-140 hPa).

When averaging over latitudinal bands, the level of agreement just discussed is usually confirmed. Figures 18 and 19 show the area averaged GOMOS ozone profiles (left hand side panels) and GOMOS departures (right hand side panels) for the three available latitudinal bands and averaged over two periods of two months each, April-May, and June-July 2011, respectively. The discussion is limited to the first half of 2011 due to the extended anomalies and data loss that affected GOMOS in the second half of 2011. This discussion confirms the results of the early assessment of the impact of the v6.01 NRT processing activation, and can be regarded as an extension to that study. In both figures, the top panels refer to the tropics (30°N-30°S), the middle panels refer to the midlatitudes in the SH (30°-60°S), and the bottom panels refer to the high latitudes in the SH (60°-90°S). There were no data available at latitudes northern than 30°N.

In both periods, the ECMWF ozone first-guess and analyses were within the observation one-standard deviation at all levels and available latitudes. At all available latitudinal bands, the mean difference between the GOMOS observations and their model equivalent typically showed large values (larger than 50% in places) in the lower stratosphere (pressure values larger than 40hPa), while they showed a dependence on the latitudinal band in the mid and upper stratosphere as well as in the mesosphere. The GOMOS mean tropical ozone profile normally exhibits larger values than its model equivalent in the upper stratosphere (pressure values lower than 10hPa) and mesosphere, and smaller in the lower stratosphere, with relative residuals typically within $\pm$10% for pressure values lower than 40hPa. At midlatitudes in the SH, the mean observation minus first-guess / analysis residuals

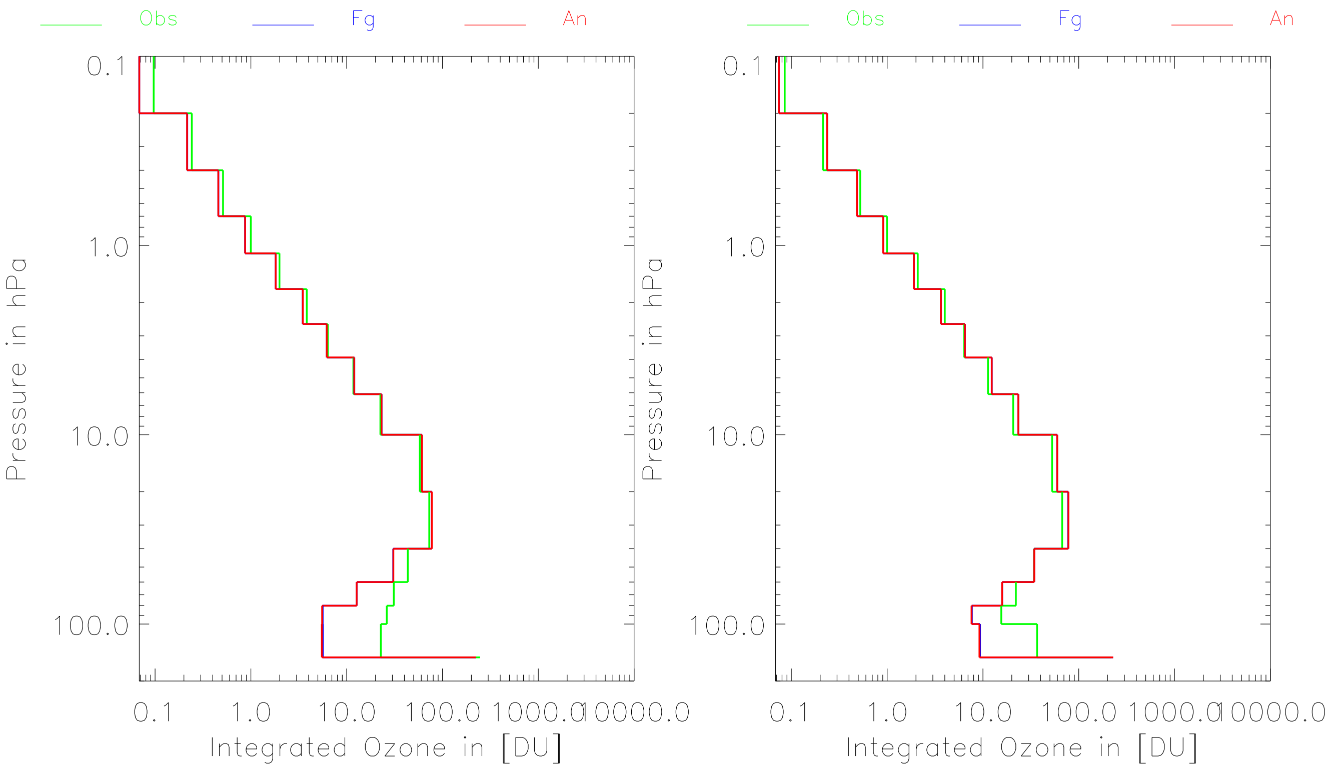


Figure 17: Comparisons between the global mean GOMOS ozone profiles and the area averaged ECMWF ozone first-guess and analysis. The left panel refers to the period 23 May - 6 June; the right panel refers to the comparisons for the period 7 - 21 Jun 2011. Ozone values are in DU.

were usually within ±5% in the vertical range between 4 and 40 hPa, but larger differences (larger than 50%) were found elsewhere. At high latitudes in the SH, the ozone residuals were usually within ±15% in the mid and upper stratosphere (between 1 and 40 hPa), but larger departures were found at mesospheric and lower stratospheric levels. The standard deviations of the departures were larger than 10% at all levels and available latitudinal bands for both periods.

Figure 20 shows the scatter plots of GOMOS ozone data (left panels) and its first-guess departures (right panels) for the layer 20-40 hPa (ozone maximum layer) as function of the latitude. The top panels (a) refer to the period April-May; the bottom panels (b) refer to the period June-July 2011, and thus the retrievals made use of the v6.01 NRT processing algorithm. In both periods, the ozone retrievals show a rather large scatter around their mean that also reflects in a large scatter of the first-guess departures. The comparison between the right panels (first-guess departures versus latitude) confirms that with the 6.01 algorithm the residuals between observations and their model equivalent was increased. It should also be noted that the observation scatter was instead reduced when the v6.01 scheme was adopted.

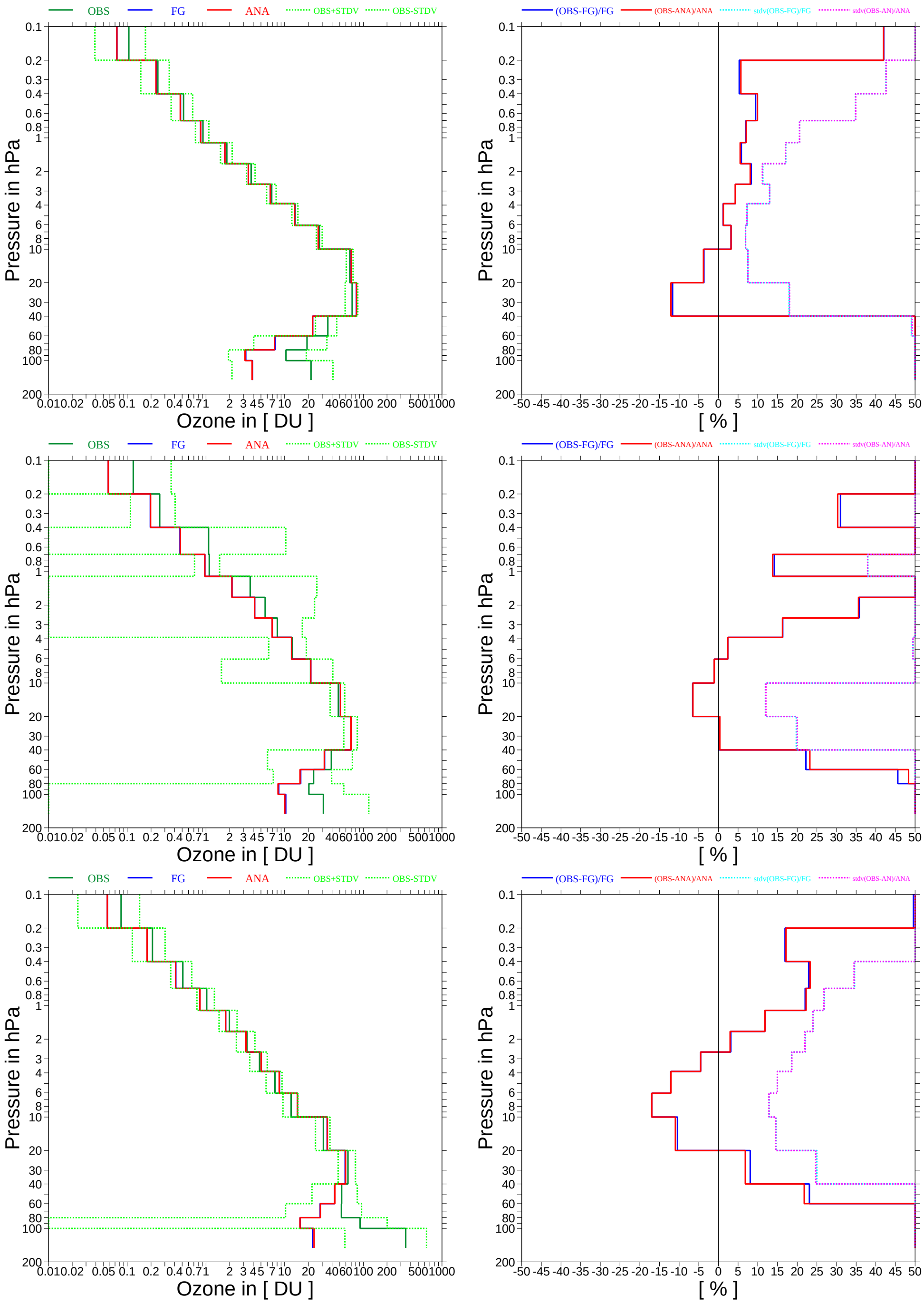


Figure 18: Comparisons between the area averaged GOMOS ozone retrievals and the area averaged ECMWF temperature first-guess and analysis. Right panels refer to the profile comparisons, left panels show the relative first-guess and analysis departures. The averaging period is between April and May 2011. The top panels refer to the tropical band 30°N-30°S, the middle panels refer to the midlatitudes in the SH (30°-60°S), and the bottom panels refers to the high latitudes in the SH (60°-90°S). Ozone values are in DU, departures are in %.

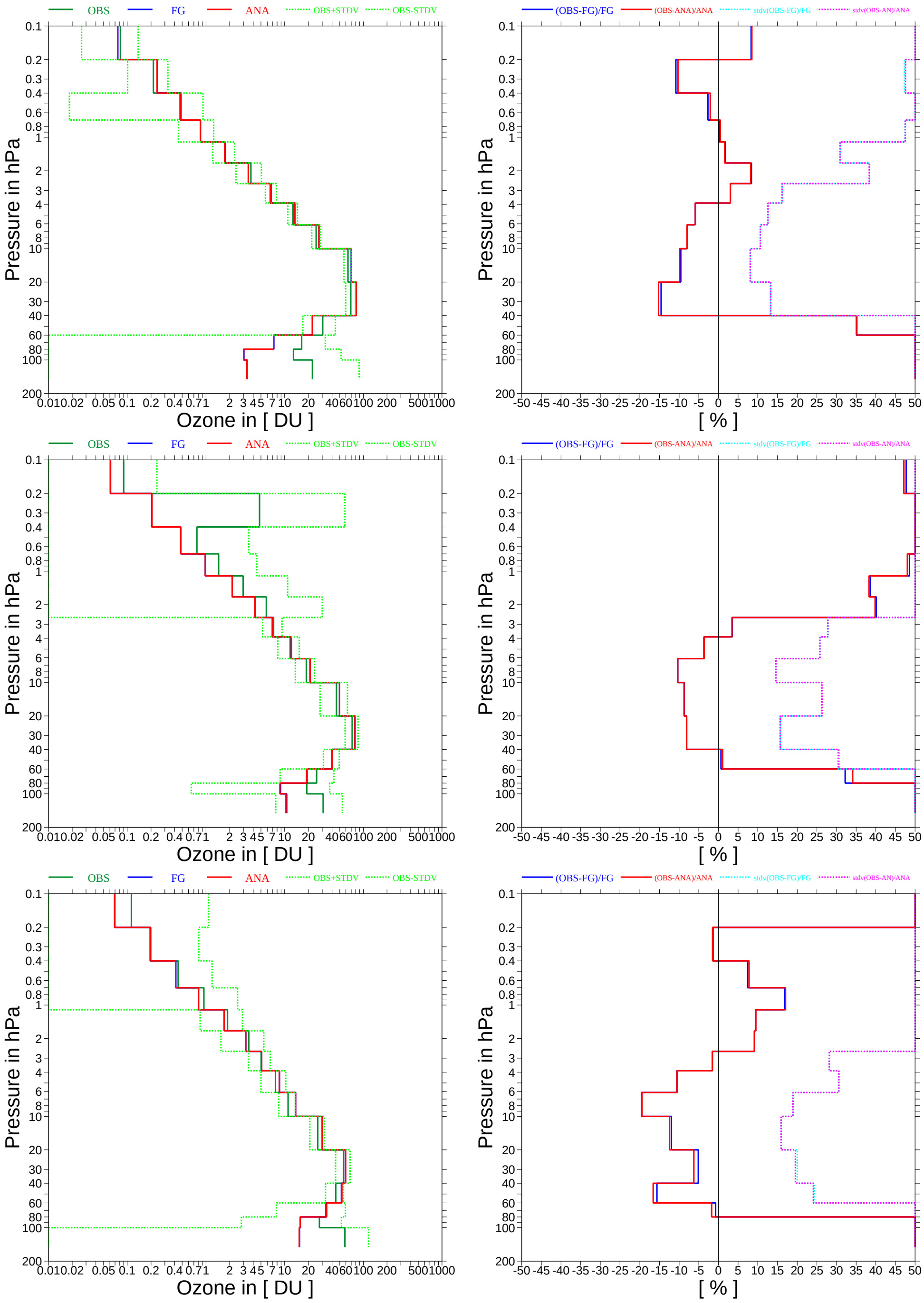


Figure 19: Like in figure 18, but for the period June-July 2011.

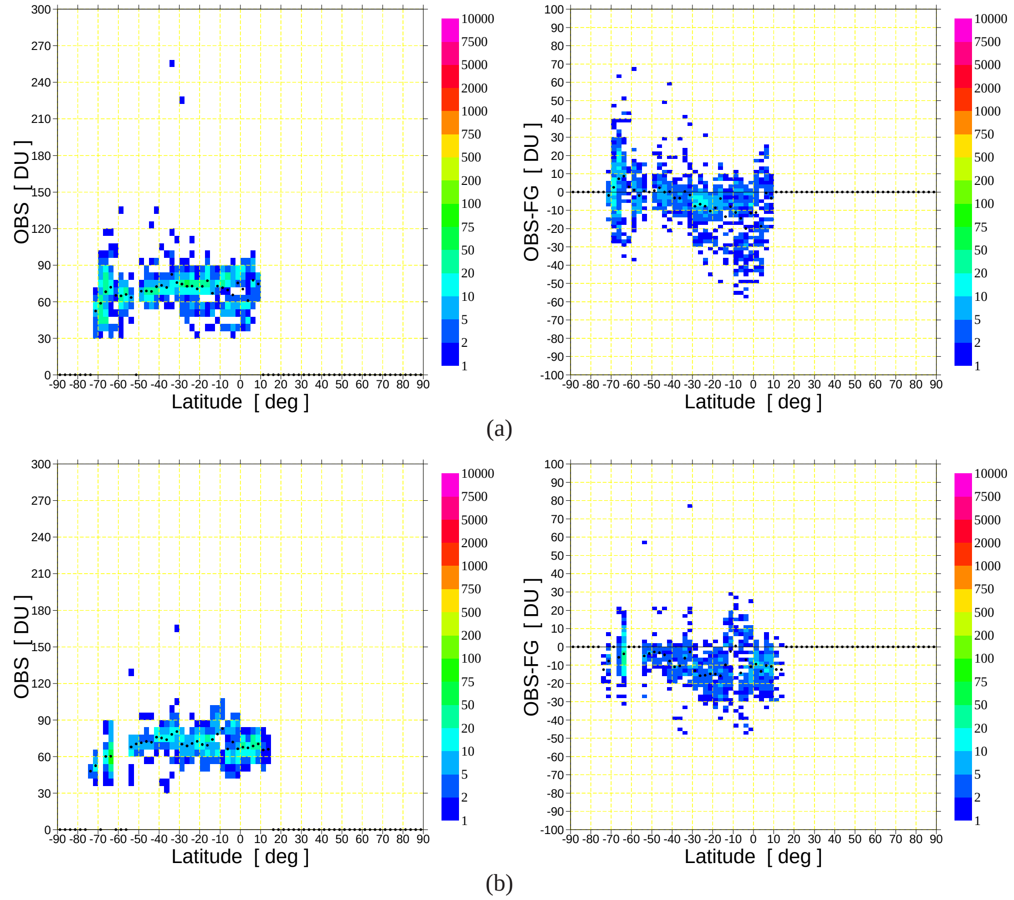


Figure 20: Scatter plots of NRT GOMOS ozone (left) and of NRT GOMOS ozone first-guess departures (right) in the layer 20-40 hPa plotted against latitude, for the periods April-May 2011 (panels [a]) and June-July 2011 (panels [b]). The colours give the number of observations per bin, and the black dots the mean per bin. All ozone values are in DU.

6.2 Monitoring of GOMOS water vapour data

The NRT GOMOS water vapour data were also monitored during 2011, although the above mentioned anomalies significantly reduced the amount of data to just a few profiles in some cases.

The quality of the water vapour data, evaluated as the level of agreement with their ECMWF model equivalent, was still poor in 2011 and comparable with that reported in previous annual reports.

Figure 21 shows the comparisons between the monthly mean area averaged GOMOS water vapour profiles (the green lines) with their model equivalent at three latitudinal bands averaged over the periods April-May (l.h.s. panels) and June-July (r.h.s. panels) 2011 (see captions for details). As done for the ozone comparisons, two periods of two months each were considered, April-May and June-July, so that the impact of the v6.01 algorithm could also be assessed with respect to the water vapour retrievals. The months were the GOMOS instrument was affected by anomalies were not considered.

The profile plots in figure 21 show that the GOMOS water vapour values were from one to four orders of magnitude larger than those given by the model at all stratospheric levels. The largest differences were found in the upper stratosphere, where not only did the GOMOS observations exhibit on average values of four order of magnitudes larger than their model equivalent, they also were larger than the mean GOMOS tropospheric observation.

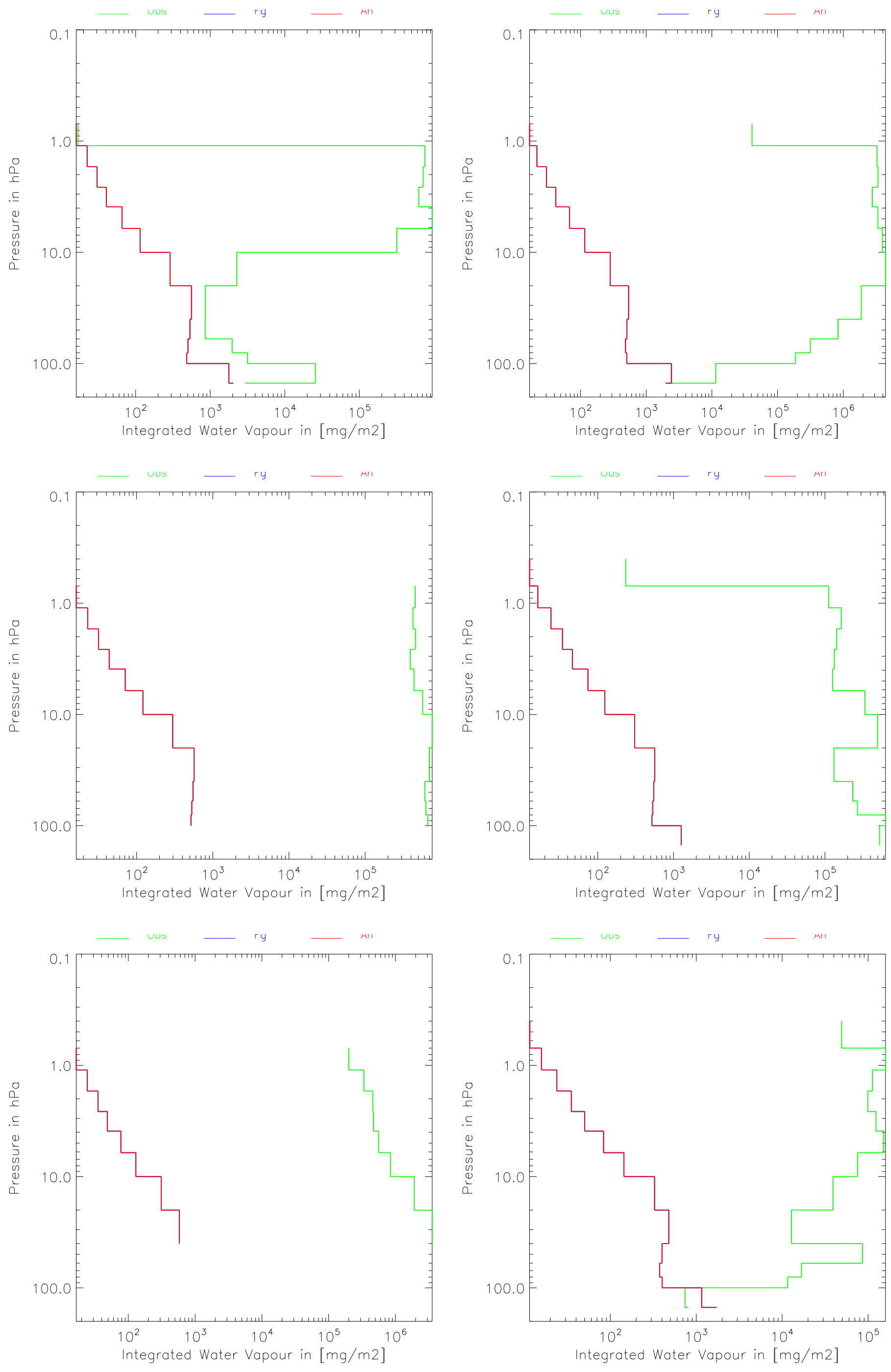


Figure 21: Comparisons between the area averaged GOMOS water vapour profiles and the area averaged ECMWF water vapour first-guess and analysis for April-May (l.h.s. panels) and June-July 2011 (r.h.s. panels). The plots were obtained by averaging the data over the tropical band [30°N-30°S] (top panels), the [30°-60°]S band (middle panels), and the [60°-90°]S latitudinal band (bottom panels), respectively. Water vapour values are in mg/m^2.

The poor level of agreement between the GOMOS water vapour profiles and their model equivalent is also shown in the scatter plots presented in figure 22 for the integrated layer between 1 and 100 hPa. The two panels show the scatter plot for April-May (l.h.s. panel) and June-July (r.h.s. panel) 2011, respectively. Both the profile plots and the scatter plots seem to indicate that the quality of the GOMOS water vapour retrievals was not much affected by the implementation of the v6.01 NRT algorithm.

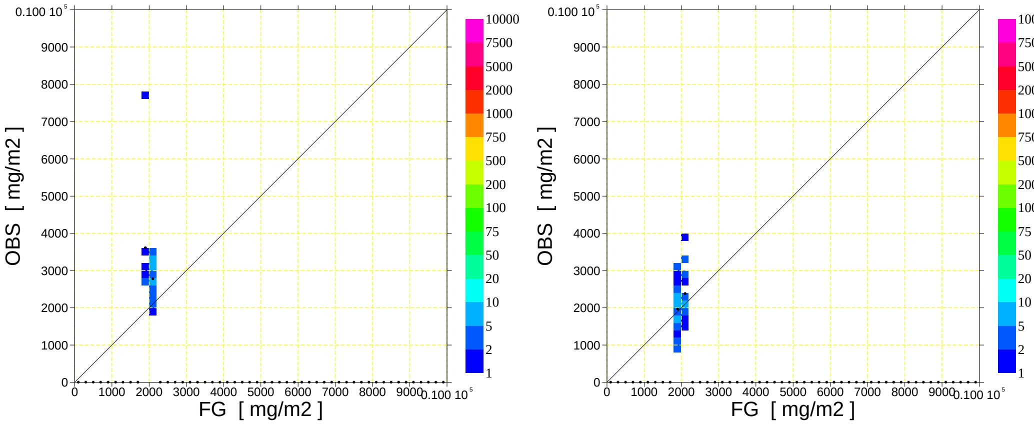


Figure 22: Scatter plots of NRT GOMOS water vapour content against the ECMWF first-guess in the integrated layer 1-100 hPa for the periods April-May (left), and June-July 2011 (right). The colours give the number of observations per bin, and the black dots the mean per bin. Values are in mg/m^2.

7 Conclusions

The ECMWF technical support to ESA for the validation of ozone, temperature and water vapour products retrieved from the three atmospheric instruments on ENVISAT (ESA contract 21519/08/I-OL CCN No. 1: Technical support for global validation of Envisat data products) continued, upon data availability, during 2011. The monitoring of the NRT SCIAMACHY (SCI_RV__2P) product could not be performed after May 2006 also due to data unavailability. The TOSOMI product retrieved at KNMI from SCIAMACHY measurements and distributed via the ESA funded PROMOTE consortium is now regarded as the official ESA Level 2 total column ozone retrieved from SCIAMACHY (Minute of the ESA contract progress meeting held at ECMWF on 6 December 2006). This product was available during the entire 2011. The NRT GOMOS products (GOM_RR__2P) were available during the first half of 2011, serious anomalies affected the instrument from the end of August till onwards that caused severe data loss and interruptions in the nominal operations. In some cases, the amount af data available after August was too low to make the results statistically significant, particularly in the case of the water vapour. At the beginning of 2011, the normal dissemination of MIPAS level 2 products also restarted, although the operational monitoring could only be resumed after November 2011, due to changes that were required in the IFS system to account for the new data farmat.

Based on the data availability, an indication of the operability of the ENVISAT products to ECMWF during 2011 was provided by assessing their timeliness. The timeliness of the TOSOMI products as downloaded by KNMI was 85.1% as annual average in 2011, that of the GOMOS products was 93.4%, and 82.4% for MIPAS.

The TOSOMI product was received and operationally assimilated during the whole 2011. The data generally showed stable quality. A change in the retrieved scheme was implemented at KNMI in spring. This new algorithm included a number of small improvements, the most important probably being the upgrade of the cloud detection scheme which now makes use of an albedo climatology computed from MERIS data. An assessment of one-week worth of test data retrieved with the new algorithm was performed at ECMWF prior the switch to the new data version was performed. The study confirmed that the quality of the total column ozone was generally comparable if not slightly better than that retrieved with the at that time operational scheme. ECMWF switched to the new TOSOMI data on 9 May 2011.

As mentioned above, although ECMWF restarted receiving the MIPAS data at the beginning of 2011, the operational monitoring of these data could not be performed before the operational implementation of model cycle CY37R3 (15 Novemeber 2011). Even before the operational monitoring could be resumed, a number of assimilation experiments were run in research mode aiming at assessing the quality of the data and the possibility of resuming the operational assimilation of the ozone profiles. The results from all the assimilation experiments clearly showed that MIPAS is still providing high quality observations that can substantially improve the distribution of the stratospheric ozone analyses. Two sets of experiments were performed. In the first set, MIPAS ozone profiles were assimilated in the ECMWF data assimilation system run at two different resolution (T255 and T799) to assess the impact of the model resolution and indirectly the misrepresentation error that comes from not accounting for the observation horizontal smoothing. The results showed that although the model resolution is an important factor (the higher the model resolution the worse the agreement of the ozone analyses with independent observations), the improvements to the vertical distribution of the ozone analyses produced by the MIPAS assimilation were by far more important and substantial. The second set of experiments was performed 1) to assess the potential synergy of MIPAS ozone profiles with ozone-sensitive radiances in the IR spectral range (that started operationally with cycle CY37R3 on 15 Novemebr 2011), and 2) to identify the set-up for the ozone bias correction. The results showed a very good synergy between the IR ozone channels, MIPAS and the UV ozone products. The analysis of both sets of experiments neither showed negative impact on the fit to other observations and their bias corrections, nor a degradation on the ECMWF forecasts scores. Based on these results, the assimilation of MIPAS ozone profiles was restarted on 8 December 2011.

The GOMOS ozone monitoring statistics showed that the ECMWF ozone first-guess and analyses were within the observation one-standard deviation at all levels and available latitudes. Two periods were discussed in details: April-May and June-July 2011. These two periods were chosen within the period before the instrumental anomalies started, and in a way that the impact of a new NRT algorithm (version 6.01), implemented on 7 June, could be assessed. The monitoring statistics showed that in general the GOMOS ozone profiles were within $\pm$15% in the mid and upper stratosphere at all available latitudes, but larger departures could be found in the lower stratosphere (typically for pressure values larger than 40hPa) and in the mesosphere. The new algorithm implemented on 7 June seems to have slightly degraded the agreement of the ozone retrievals with their model equivalent in the region of the ozone maximum (20-40 hPa). In contrast, that level of agreement was improved in the UTLS region. Also the scatter of the observations around their mean was reduced when the new scheme was adopted. The standard deviations of the departures were larger than 10% at all levels and available latitudinal bands.

The quality of the water vapour data was still generally poor during 2011 and based on the data availability consistent with that reported in the last annual reports. The monitoring statistics showed that the GOMOS water vapour values were typically from one to four orders of magnitude larger than those given by the model at all stratospheric levels and latitudinal bands. The largest differences were found in the upper stratosphere, where not only did the GOMOS observations exhibit values of four order of magnitudes larger than their model equivalent on average, they also were larger than the mean GOMOS tropospheric water vapour value. The implementation of the v6.01 algorithm did not seem to have produced an impact on the quality of the water vapour retrievals.

8 Acknowledgements

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References

Bauer, P. (2009). 4D-Var Assimilation of MERIS Total Column Water Vapour retrievals over land. *Q. J. Roy. Meteorol. Soc. 135*, 1852–1862.

Burrows, J. P., K. Chance, H. van Dop, J. Fishman, J. Fredereicks, J. Geary, T. Johnson, G. Harris, I. Isaksen, G. Moortgat, C. Muller, D. Perner, U. Platt, J. Pommereau, E. Roeckner, W. Schneider, P. Simon, H. Sunquist, and J. Vercheval (1988). SCIAMACHY: A European proposal for atmospheric remote sensing from the ESA Polar Platform. Technical report, Max-Planck-Institut für Chemie, Mainz Germany.

Cariolle, D. and M. Déqué (1986). Southern hemisphere medium-scale waves and total ozone disturbances in a spectral general circulation model. *J. Geophys. Res. 91*, 10825–10846.

da Costa Bechtold, V. and A. Dethof (2005). Monitoring and assimilation of SCIAMACHY, GOMOS and MIPAS retrievals at ECMWF. Final report for ESA contract 17585/03/I-OL: Technical support for global validation of ENVISAT data products (ENVISAT II). Technical report, ECMWF.

Dee, D. (2005). Bias and data assimilation. *Q. J. R. Meteorol. Soc. 131*, 3323–3343.

Dethof, A. (2003). Monitoring of retrievals from the MIPAS and SCIAMACHY instruments on board ENVISAT. Final report for ESA contract 14458/00/NL/SF: Technical support for global validation of ENVISAT data products. Technical report, ECMWF.

Dethof, A. (2004). Monitoring and assimilation of MIPAS, SCIAMACHY and GOMOS retrievals at ECMWF. Annual report for ESA contract 17585/03/I-OL: Technical support for global validation of ENVISAT data products (ENVISAT II). Technical report, ECMWF.

Dethof, A. and E. V. Hólm (2003). Representation of ozone in the ECMWF model. In *ECMWF/SPARC Workshop on Modelling and Assimilation for the Stratosphere and Tropopause*.

Dragani, R. (2006). Monitoring and assimilation of SCIAMACHY, GOMOS and MIPAS retrievals at ECMWF. Annual report for ESA contract 17585-CCN-1: Technical support for global validation of ENVISAT data products. Technical report, ECMWF.

Dragani, R. (2008). Monitoring and assimilation of SCIAMACHY, GOMOS and MIPAS retrievals at ECMWF. Final report for ESA contract 17585-CCN-1: Technical support for global validation of ENVISAT data products. Technical report, ECMWF.

Dragani, R. (2009a). Assimilation of filtered OMI TCO Technical report R43.8/RD/0907. Technical report, ECMWF. Available from R. Dragani (rossana.dragani@ecmwf.int).

Dragani, R. (2009b). Monitoring and assimilation of SCIAMACHY, GOMOS and MIPAS retrievals at ECMWF. Annual report for ESA contract 21519/08/I-OL: Technical support for global validation of ENVISAT data products. Technical report, ECMWF.

Dragani, R. (2009c). Variational bias correction of satellite ozone data. Technical report R43.8/RD/0934. Technical report, ECMWF. Available from R. Dragani (rossana.dragani@ecmwf.int).

Dragani, R. (2010a). Assimilation of SCIAMACHY TCO and MERIS TCWV after the ENVISAT orbit change. Technical report R43.8/RD/10123. Technical report, ECMWF. Available from R. Dragani (rossana.dragani@ecmwf.int).

Dragani, R. (2010b). Monitoring and assimilation of SCIAMACHY, GOMOS and MIPAS retrievals at ECMWF. Annual report for ESA contract 21519/08/I-OL: Technical support for global validation of ENVISAT data products. Technical report, ECMWF.

Dragani, R. (2011a). Monitoring and assimilation of SCIAMACHY, GOMOS and MIPAS retrievals at ECMWF. Final report for ESA contract 21519/08/I-OL: Technical support for global validation of ENVISAT data products. Technical report, ECMWF.

Dragani, R. (2011b). New SCIAMACHY data from KNMI. Technical report R43.8/RD/1157. Technical report, ECMWF. Available from R. Dragani (rossana.dragani@ecmwf.int).

Eskes, H. J., R. J. van der A, E. J. Brinksma, J. P. Veefkind, J. F. de Haan, and P. J. M. Valks (2005). Retrieval and validation of ozone columns derived from measurements of sciamachy on envisat. *Atmos. Chem. Phys. Discuss. 5*, 4429–4475.

Fortuin, J. and U. Langematz (1995). An update on the global ozone climatology and on concurrent ozone and temperature trends. In R. Santer (Ed.), *Atmospheric Sensing and Modelling*, Volume 2311 of *SPIE Proceedings*, pp. 207–216.

Haseler, J. (2004). Early-delivery suite. ECMWF Newsletter no. 101.

Rabier, F., H. Järvinen, E. Klinker, J.-F. Mahfouf, and A. Simmons (2000). The ECMWF operational implementation of four-dimensional variational assimilation. Part I: Experimental results with simplified physics. *Q. J. R. Meteorol. Soc.* (126), 1143–1170.

Raspollini, P., C. Belotti, A. Burgess, B. Carli, M. Carlotti, S. Ceccherini, B. M. Dinelli, A. Dudhia, J.-M. Flaud, B. Funke, M. Höpfner, M. López-Puertas, V. Payne, C. Piccolo, J. J. Remedios, M. Ridolfi, , and R. Spang (2006). MIPAS level 2 operational analysis. *Atmos. Chem. Phys. 6*, 5605–5630.

Ridolfi, M., B. Carli, M. Carlotti, T. von Clarmann, B. M. Dinelli, A. Dudhia, J.-M. Flaud, M. Hoepfner, P. Morris, P. Raspollini, G. Stiller, and R. J. Wells (2000). Optimized forward model and retrieval scheme for MIPAS near-real-time data processing. *Appl. Opt. 39*, 1323–1340.

Ridolfi, M., B. M. Dinelli, and T. von Clarmann (2009). The Horizontal Averaging Kernels of ESA MIPAS Level 2 Profiles. Technical Report 1, ESA. Available from http://www2.fci.unibo.it/ ridolfi/hak/tn horak 1.pdf.

Rodgers, C. D. (2000). *Inverse Methods for Atmospheric Sounding. Theory and Practice*. Atmospheric, Oceanic and Planetary Physics. PO Box 128, Farrer Road, Singapore 912805: World Scientific Publishing and Co. Pte. Ltd.

Veefkind, J. P. and J. F. de Haan (2002). DOAS Total O3 Algorithm. Algorithm Theoretical Baseline Document: OMI Ozone Products, P. K. Bhartia (Ed.), vol. II, ATBD-OMI-02, version 2.0. Technical report, KNMI.

von Clarmann, T., C. De Clercq, M. Ridolfi, M. Hpfner, and J.-C. Lambert (2009). The horizontal resolution of mipas. *Atmospheric Measurement Techniques 2*(1), 47–54.