ERA report series

2 On the quality of the ERA-Interim ozone reanalyses

Part I Comparisons with in situ measurements

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Abstract

This is the first of two companion papers presenting an assessment of the quality of the ERA-Interim ozone reanalyses by comparisons with independent observations, during the period January 1989 to December 2008. Overall, ground-based ozone observations and satellite ozone products were used to validate both the three-dimensional ERA-Interim ozone analyses and the ERA-Interim total column ozone (TCO). This first part focusses on the assessment of the quality of the ERA-Interim ozone analyses against in-situ ozone data. The residuals between the ERA-Interim TCO and the ground-based Dobson TCO showed values within $\pm 10\%$ at high latitudes, and within $\pm 5\%$ elsewhere. The comparisons of the three-dimensional ERA-Interim and ERA-40 ozone analyses with ozone sondes showed a dependence on the season, latitude, as well as on the period accounted for as a consequence of the varying ozone observing system actively used. In particular, the ERA-Interim ozone product benefitted from the assimilation of GOME ozone profiles (January 1996 - December 2002), particularly in the tropics. In the pre-GOME assimilation period, the residuals between the ozone sondes and their corresponding ERA-Interim ozone profiles were within $\pm 10\%$ in the tropics and at midlatitudes at most levels, and within $\pm 20\%$ at high latitudes. From January 1996 onwards, the level of agreement was within $\pm 5\%$ in the tropics and at high latitudes in summertime, and within $\pm 10\%$ at high latitudes in wintertime as well as at midlatitudes throughout the year. The comparisons also showed substantial improvements in ERA-Interim over the ERA-40 equivalent both at stratospheric and troposheric levels throughout the twelve year overlapping period. In particular, the RMS of the sonde-analysis differences were reduced up to 40% in the lower stratosphere, and between 20 and 50% in the troposphere when using ERA-Interim instead of ERA-40.

1 Introduction

In the last two decades, the European Centre for Medium-Range Weather Forecasts (ECMWF) has devoted increasing effort in producing consistent global reanalyses of the state of the atmosphere, land and ocean. Two major reanalysis projects were completed over this period, namely ERA-15 (Gibson *et al.*, 1997) and ERA-40 (Uppala *et al.*, 2005), that covered the periods between December 1978 through February 1994, and mid-1957 to August 2002, respectively. These global fields, generated with stable and invariant versions of the ECMWF data assimilation system, were used in many studies spanning from seasonal prediction to climate, and thanks to the wide range of products offered they allowed the scientific community to progress not only in the more conventional meteorological applications but also in new and diverse fields such as hydrology, air quality, health.

During the same timeframe, the number of reanalysis initiatives and projects worldwide rapidly increased, underlining their importance and value, as well as the fact that they were becoming an indespensable tool to monitor the Earth system as a whole, and to give the best initial conditions to produce realistic prediction of its evolution. On the Numerical Weather Prediction (NWP) side, apart from ECMWF, the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) jointly produced a 40-year long reanalysis at the end of the 1990s (Kalnay *et al.*, 1996), completed just a few years before the ERA-40 Atlas was released. The Data Assimilation Office at the National Aeronautics and Space Administration (NASA/DAO) completed a global reanalysis for the period 1985-1993 (Schubert *et al.*, 1993). More recently, the Japan Meteorological Agency (JMA) conducted a 26-year reanalysis project referred to as the Japanese 25-year Reanalysis (JRA-25) (Onogi *et al.*, 2007). On the observation side, most space agencies have an intense reprocessing programme with the objective of producing long-term series of consistent observations to be used in several fields, like for example climate studies. In this context, the European Space Agency (ESA) has recently launched its Climate Change Initiative (CCI) to capitalize on the European wealth of measurements from past, present, and future missions and meet the need of global observation of climate, as recognized by the United Nations Framework Convention on Climate Change (UNFCCC), as well as by the Global Climate Observing System (GCOS). The long-term high-quality records of the Essential Climate Variables (ECV), that the CCI will deliver, is likely to further henance and improve the future NWP reanalyses.

Alongside its operational activities, ECMWF is currently producing a new global reanalysis, ERA-Interim (Dee and Uppala, 2009), that focusses on the period since January 1989, extending the temporal coverage beyond the ERA-40 availability. The main aims of this latest effort are to improve the exploitation of the enormous amount of data available, particularly from satellite instruments, and to provide an improved baseline for the future reanalysis production by using an up-to-date stable version of the ECMWF operational suite that included several improvements compared with the ERA-40 one. For example, in addition to improvements in the model physics and parameterizations, the ERA-Interim data assimilation system was upgraded to a four-dimensional variational data assimilation scheme (4D-Var), as opposed to the 3D-Var scheme used in ERA-40, and it made use of a variational bias correction scheme (VarBC) for satellite radiances, that automatically detects and corrects for observation biases.

In the present and its companion (Dragani, 2010) papers, we present extensive validation and quality assessment of the ERA-Interim ozone reanalyses against ground-based and satellite measurements during the period January 1989 to December 2008. For completeness, similar comparisons were also produced for the ERA-40 ozone reanalyses in order to highlight the differences between the two projects, and the improvements achieved in the latest reanalysis effort. This study also pointed out a number of deficiencies in the system that still need to be addressed by the next reanalysis project in order to provide more accurate ozone products.

The present paper, that focusses on the validation of the ERA-Interim ozone analyses against in-situ ozone measurements, is structured as follows: section 2 briefly describes the main characteristics of the ozone system used in ERA-Interim, mainly focussing on the differences to that used for the ERA-40 reanalysis. The criterion used to match the ozone analyses and the independent observations is described in section 3, where an account of the diagnostic tools applied later on in the paper is also provided. The results from the validation of the ECMWF ozone reanalyses against in situ data are presented in section 4. Section 5 investigates the possibility of trends in the agreement between the ERA-Interim ozone reanalyses and the independent observations as function of vertical level and latitudinal band. This study aims at identifying specific improvements / degradations related to the changes in the observing system (e.g. when the assimilation of data from a new instrument started), given that the model version and those of the retrieval data actively assimilated were normally stable, that could provide insight on how such a system should be exploited in the next reanalysis project. Finally, conclusions and remarks are given in section 6.

2 The ozone system in ERA-Interim

A discussion on the ERA-Interim assimilation system, including a brief one on ozone, was given in Dee and Uppala (2009). Focusing on the ERA-40 reanalysis project, Dethof and Hólm (2004) already described in detail the main characteristics of the ECMWF ozone system. Most of that discussion still applies to ERA-Interim, although a number of changes and improvements that are worth mentioning were implemented in the latest reanalysis project.

As pointed out by Dethof and Hólm (2004), the ozone first guess used at ECMWF is derived from an updated version of the Cariolle and Déqué (1986) scheme. In this scheme the ozone continuity equation is expressed as a linear relaxation towards a photochemical equilibrium for the local value of the ozone mixing ratio, the temperature, and the overhead ozone column. An additional ozone destruction term is used to parametrize the heterogeneous chemistry as a function of the equivalent chlorine content for the actual year. Since the Dethof and Hólm (2004) paper, this parametrization has undergone significant upgrades thanks to collaboration with Daniel Cariolle (Météo-France) (Cariolle and Teyssendre, 2007).

Compared with the ERA-40 reanalysis the ERA-Interim project made use of a larger dataset of remotely sensed observations, both in the form of radiances and of ozone retrievals. Dee and Uppala (2009) provided a full description of the assimilated datasets used in ERA-Interim, as well as a comprehensive discussion of the difficulties in assimilating such a long, and inhomogeneous set of data. Regarding the ozone data actively assimilated in ERA-Interim, this dataset included both data from instruments already utilized in ERA-40 (with their usage generally extended beyond that of ERA-40 when possible) and new datasets that were not used before, such as the GOME ozone profiles retrieved at the Rutherford Appleton Laboratory (Siddans *et al.*, 2002) and NOAA-14 SBUV partial columns. Figure 1 schematically shows the time coverage for the twenty year period (from January 1989 to December 2008) in ERA-Interim (black lines). The ERA-40 data usage is also marked in grey for the available period (from January 1989 to August 2002). For each instrument, data provider, data version and product type are given in table 1.

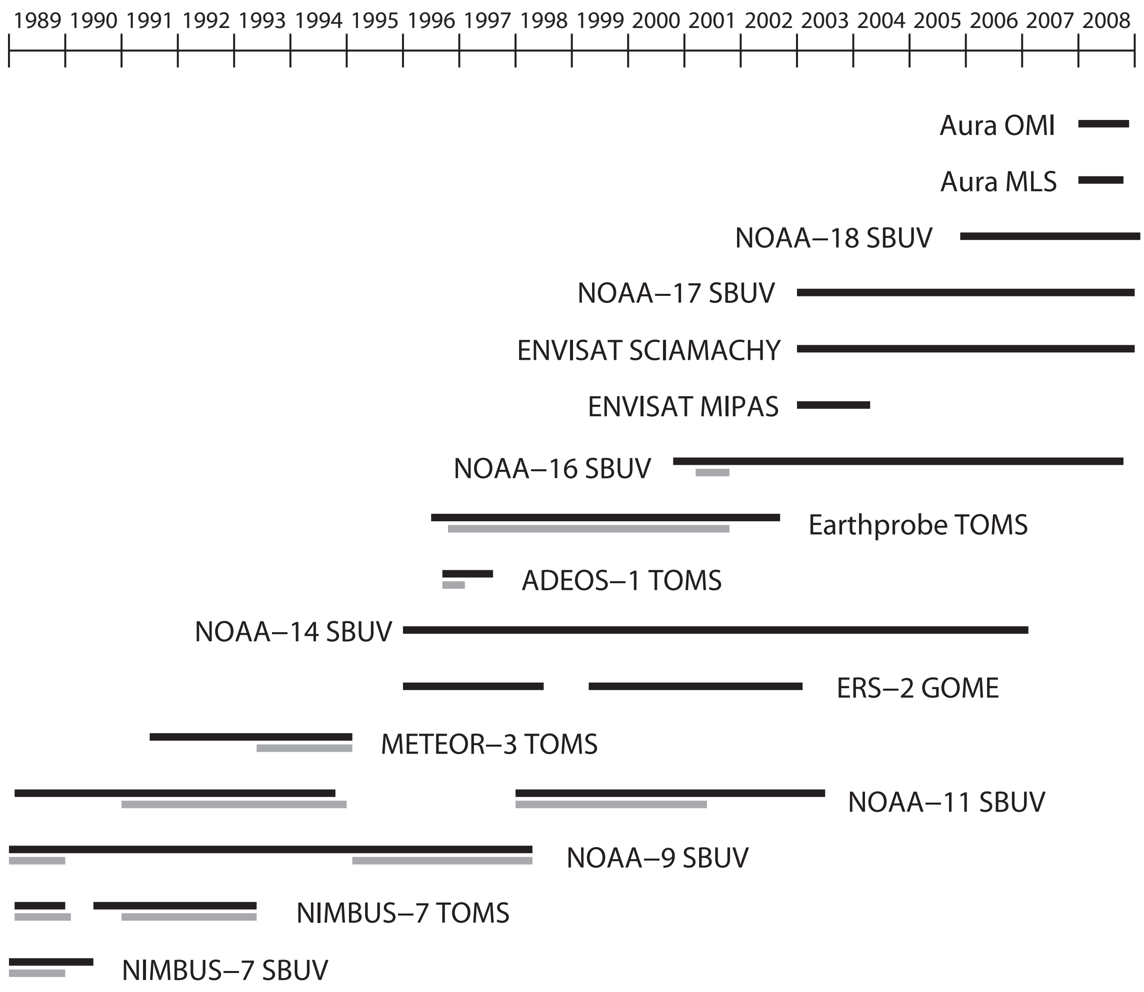

Figure 1: Time coverage of the remotely sounded ozone data actively assimilated in the ECMWF ERA-Interim reanalysis project (black lines). For comparison, the corresponding data usage for ERA-40 is overplotted (grey lines).

Regarding the data assimilation, ERA-Interim made use of a Four-Dimensional Variational data assimilation scheme (4D-Var). However, from 1 February 1996 onwards, the sensitivity of the mass and wind variables to ozone observations during the assimilation minimisation was switched off. Preliminary analysis of the quality of the ERA-Interim products showed that the assimilation of ozone profile data such as those from GOME and SBUV could generate large and unrealistic temperature and wind increments over a deep layer around the stratopause. These large temperature and wind increments arose when 4D-Var attempted to accommodate

Instrument	Provider	Version	Type	Instrument	Provider	Version	Type
NIMBUS-7 SBUV	NOAA	6	PCO	**Ep TOMS**	NOAA	7	TCO
NIMBUS-7 TOMS	NOAA	7	TCO	**NOAA-16 SBUV/2**	NOAA	6 / 8[1]	PCO
NOAA-9 SBUV	NOAA	6	PCO	**MIPAS**	ESA	4.61	Profile
NOAA-11 SBUV	NOAA	6	PCO	**SCIAMACHY**	KNMI	0.43	TCO
METEOR-3 TOMS	NOAA	7	TCO	**NOAA-17 SBUV/2**	NOAA	6 / 8[1]	PCO
ERS-2 GOME	RAL	2.1	Profile	**NOAA-18 SBUV/2**	NOAA	6 / 8[1]	PCO
NOAA-14 SBUV	NOAA	6	PCO	**Aura MLS**	NASA	2.2	Profile
ADEOS-1 TOMS	NOAA	7	TCO	**Aura OMI**	NASA	3	TCO

Table 1: List of data provider, data version and product type per assimilated ozone data set. The acronomys TCO and PCO stand for Total Column Ozone and Partial Column Ozone profile, respectively. [1] *Version 6 SBUV/2 data were used until 20 January 2008. Version 8 SBUV/2 data were used from 21 January 2008 onwards. The OMI product used here is the DOAS (Differential Optical Absorption Spectroscopy) TCO retrievals.*

observed large local changes in ozone concentration by modifying the flow where it was least constrained. The adopted solution of switching off the sensitivity of the mass and wind variables to ozone data completely overcame the problem. However, this has to be regarded as a temporary fix to the problem and more definitive measures are required to address it. Since these unrealistic feedbacks were mainly related to deficiences in the ozone data, an adequate ozone bias correction scheme should, in principle, help in controlling these kind of situations. At the time the ERA-Interim reanalysis project started, this option could not be exploited as a bias correction scheme for retrievals in general and specifically for ozone was not yet available, but it could be employed by future reanalysis projects.

3 Matching criterion and diagnostic tools

The ERA-Interim ozone analyses were extensively validated against independent, unassimilated ozone observations. The comparisons were run for the whole recording period of the independent observations, providing a comprehensive assessment of the ozone reanalyses during the whole ERA-Interim production period spanning from January 1989 till December 2008. In addition to assess the quality of the ozone reanalyses per se, the following discussion will also investigate the relative differences in the fit of ERA-40 and ERA-Interim ozone analyses to the independent data, and attempt to identifying the reasons for those differences. This is hardly an academic discussion. As the name suggests, the ERA-Interim project has to be regarded as a preparation for a future ECMWF reanalysis project, and therefore any insight on these differences could lead to improvements in the follow-up reanalysis.

Data from both remote and ground based instruments, as well as a global mean TCO reference created *ad-hoc* from the NASA's merged satellite dataset were used to assess the quality of the ECMWF ozone reanalyses, both in terms of ozone vertical profiles and integrated columns. A description of the independent satellite observations used in this paper to validate and assess the quality of the ozone reanalyses will be presented in the companion paper (Dragani, 2010). Regarding the ground-based ozone observations used here, these were mainly retrieved from the World Ozone and UV Data Centre (WOUDC) archive. Figure 2 schematically shows their geographical co-locations.

All the comparisons discussed below and in Dragani (2010) made use of the same matching criteria. The 3D ozone analysis (or 2D analysis in the case of TCO) closest in time to the independent measurements was interpolated to the independent observation location. Based on this criterion, a temporal mismatch of up to 3 hours between observation time and analysis valid time should be expected. As for the vertical representation, for each independent dataset, the ozone analyses and the independent ozone profiles were interpolated on the

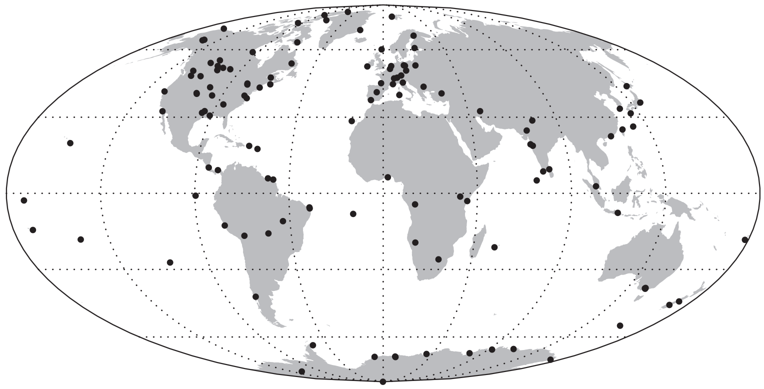

Figure 2: Location of the ozone sondes used in this paper.

coarsest vertical grid to be chosen between that provided by ERA-Interim (60 vertical layers spanning from surface to 0.1hPa) and that of the independent observations. Ideally, one should have compared the observations with the simulated profiles obtained by applying the observation averaging kernel to the ozone analyses (e.g. Rodgers and Connor, 2003; Migliorini *et al.*, 2004) rather than with the ozone analyses directly. Unfortunately, this was not a viable option as the averaging kernel information was not always available for the datasets used in this study. In the comparisons with ozone sondes, the horizontal displacement during the ascending stage - the data during the descending stage were not used - was not accounted for, as generally unknown, and the longitude and latitude at the launch were used as the sonde position. Only the sonde measurements that had a burst pressure level less than 40hPa (i.e. sonde profiles that reached at least a pressure level of 40hPa) were considered in the profile comparisons discussed below.

The results will be presented both in terms of absolute and mean relative residuals computed between the independent ozone observation (O_3^{Obs}) and its reanalysis equivalent (O_3^{ERA}) over the whole period of data availability. The monthly mean relative residuals were calculated as follows:

$$Relative\ \ bias = 100 \times \overline{\frac{O_3^{Obs} - O_3^{ERA}}{\left(O_3^{Obs} + O_3^{ERA}\right)/2}} \qquad (1)$$

In addition, the RMS of the independent observations minus ERA-Interim computed as function of pressure, and latitudinal band was compared with that from the independent observations minus ERA-40 to highlight the regions where the ERA-Interim ozone analyses fitted the independent datasets better than the corresponding ERA-40 reanalyses.

4 Comparisons with in-situ ozone measurements

We now discuss the results from comparing the ERA-40 and ERA-Interim ozone reanalyses with ground-based observations (Logan, 1999), in the form of both total columns and ozone profiles. The ozone sondes used in this paper were obtained from the World Ozone and UV Data Centre (WOUDC) archive and from the ECWMF Meteorological Archive and Retrieval System (MARS) that holds part of the NILU sonde measurements. Both electrochemical concentration cell (ECC), and Brewer Mast (BM) sonde types were used, and without any distinctions in the following plots. Komhyr *et al.* (1995) found that the ECC precision was of the order of $\pm 5\%$ in the range between 200 and 10 hPa. Outside that vertical range, the precision was estimated to be between -14% and +6% above 10hPa and in the range between -7% and +17% below 200 hPa. Higher errors were found in the presence of steep gradients and where the ozone amount is low. The same order of precision was found by Steinbrecht *et al.* (1996) for the BM sondes.

Figure 3 presents the time series of monthly mean total ozone from four ground stations and their ERA-40 and ERA-Interim equivalents. Each plot also shows, in color, the relative biases. The four ground stations were selected for being representative of different latitudinal bands, as well as for providing reliable and long time series data over the twenty years under investigation. At high latitudes in the NH (panel **a**), both reanalyses can reproduce the seasonal variation shown in the ground based measurements, with one exception represented by ERA-40 during 1990 when no ozone data were actively assimilated. The relative differences are typically within -10 and +5%, and occasionally down to -20% in wintertime. At midlatitudes in the NH (panel **b**), the level of agreement between sondes and reanalyses is, with a few exceptions, within ±5%. The seasonal variability is well captured both in terms of total ozone and temporal occurrence. In the tropics (panel **c**), the ERA-Interim reanalysis and sonde residuals are also within ±5%, slightly larger residuals where found in the comparisons with ERA-40. Finally, at Amunden-Scott (panel **d**), the residuals are mostly within ±10% for both reanalyses and only occasionally larger, particularly during spring confirming the known problems in representing the ozone depletion.

Figures 4 to 6 show the comparisons between mean sonde profiles and the corresponding mean ERA-Interim profiles at high latitudes, midlatitudes and in the tropics, respectively. The averages were performed over the months of January-February-March (JFM) and June-July-August (JJA). The results presented in the comparisons with satellite data showed that the assimilation of the GOME ozone profiles was significantly beneficial to the ERA-Interim ozone analyses. For that reason, three groups of years were considered (from top to bottom in the figures): the pre-GOME assimilation period (1989-1995), the GOME assimilation period (1996-2002), and finally the post GOME assimilation and most recent period (2003-2008).

At high latitudes (figure 4), the residuals between the mean ERA-Interim ozone profile and the ozone sondes were typically within ±20% in winter and within -20 to +10% in summer in the upper troposphere and stratosphere during the pre-GOME period. In the SH, the stratospheric ozone amount is too low both in summer and in wintertime. In the NH, the ozone maximum values were well estimated by the reanalysis. However, the peak was generally placed too low, particularly during winter. Larger departures up to 50% were found in the troposphere. The assimilation of GOME ozone profiles (mid panels in figure 4) constrained the ozone analyses well and reduced their bias against the ozone sondes in the UTLS to be within ±5% in summer, and within ±10% in the NH and within -10 to +20% in the SH during winter. The tropospheric bias is also reduced to 30% at most. Particularly noticeable is the representation of the observed ozone structure in the NH summer between 200 and 300hPa (black lines in the middle right panel of figure 4) that seems to be equally captured in ERA-Interim. A similar level of agreement was found in the stratosphere in the post-GOME assimilation period. Here, the lack of constraint given by the GOME ozone profiles during the previous period could have been compensated by that of other data. For example, Dethof (2004) showed that the assimilation of SCIAMACHY TCO could improve the ECMWF ozone analyses and forecasts, in particular the representation of the ozone hole over Antarctica. It should then not be forgotten that, in addition to the direct assimilation of ozone information, any improvements on any other meteorological field, particularly on temperature, reflects on the ozone variable via the ozone continuity equation.

At midlatitudes (figure 5), the ERA-Interim ozone reanalyses compare generally well with ozone sondes with residuals of less than 10% in the stratosphere. However, some points are worth mentioning. The ozone peak is usually underestimated in ERA-Interim during the pre-GOME and post-GOME summer periods, with relative biases of about 20% in the NH and from 10 to 15% in the SH.

The tropospheric residuals are usually larger in the NH than in the SH and, of the three groups of years, the GOME assimilation period is the one that exhibits the smallest tropospheric bias, suggesting a positive impact

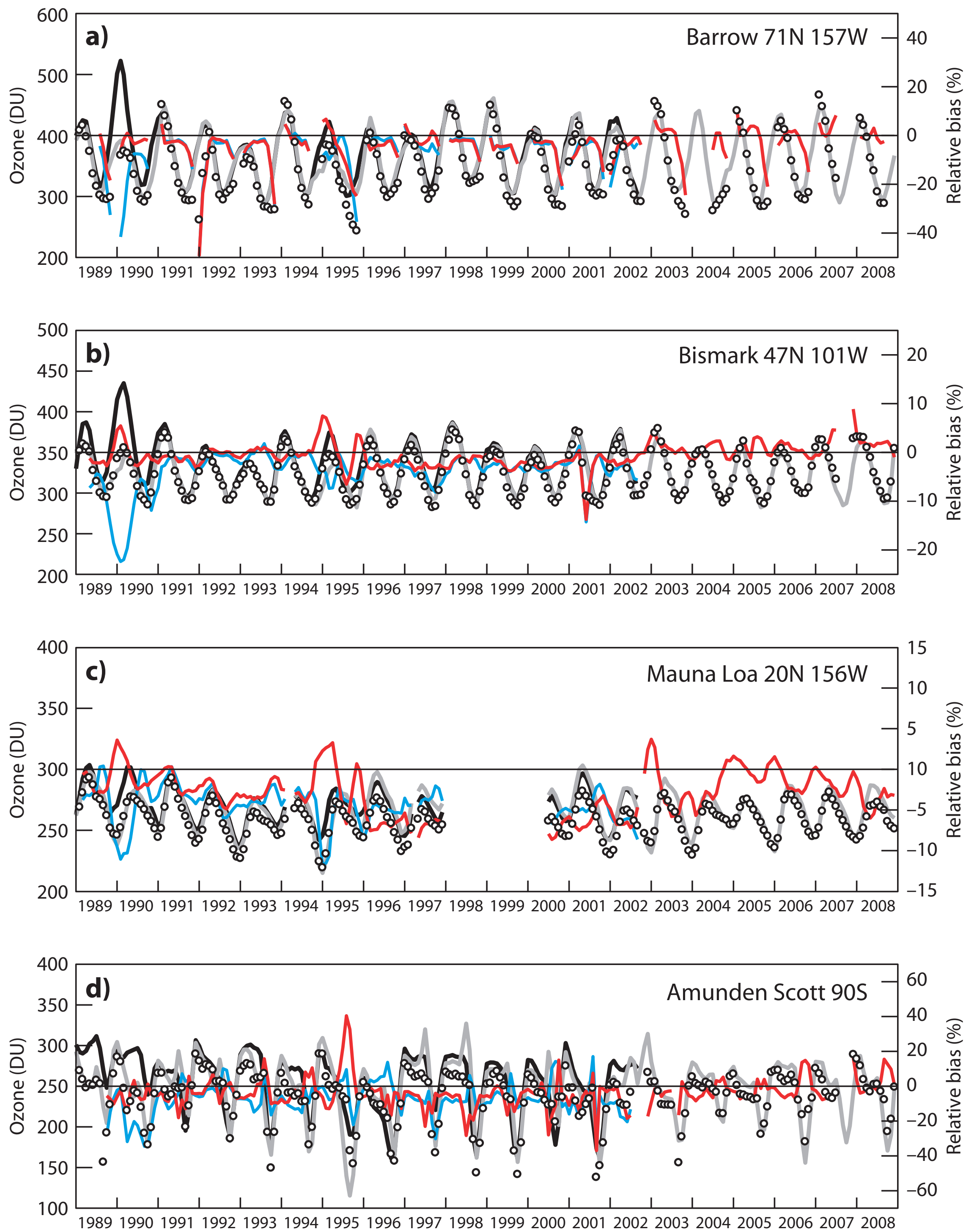

Figure 3: Time series of monthly mean total ozone from ground based observations (open circles), and co-located ERA-40 ozone reanalyses (black lines), and ERA-Interim ozone reanalyses (grey lines). Panel a) refers to the station at Barrow (71°N); panel b) shows the comparisons at Bismark (47°N); panel c) refers to the station at Mauna Loa (20°N); and panel d) shows the comparisons at Amunden-Scott (90°). The red and blue lines refer to the mean relative biases limited within the right vertical axis range and computed for ERA-Interim and ERA-40, respectively.

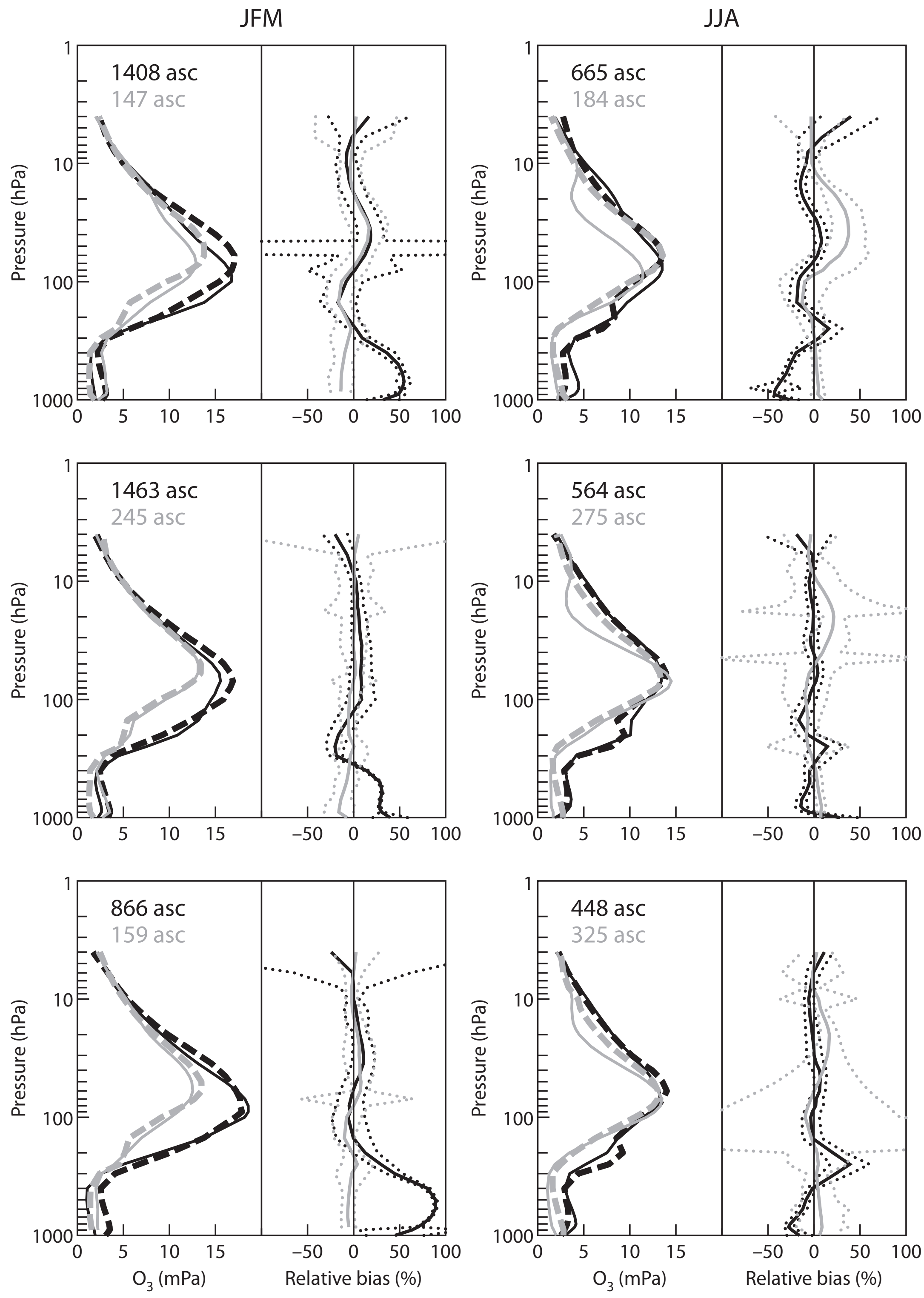

Figure 4: Mean profiles (in mPa) and relative differences (in %) for the comparisons between ozone sonde profiles (thick dashed lines) and the corresponding ERA-Interim reanalyses (thin solid lines) at high latitudes averaged over the months of January, February and March - JFM - (left) and the months of June, July, and August - JJA - (right). In each panel, the black lines refer to the NH, while the grey lines shows the results for the SH. The dotted lines around the mean relative biases represent the uncertainty in the mean (i.e. standard deviation divided by the square root of the number of coincident pairs). The number of ascents included in the average can be found on the top-left corner of each panel (black for the NH and grey for the SH).The top panels show the averages over the years 1989-1995; the mid panels refer to the years 1996-2002; and finally the bottom panels show the results for the years 2003-2008.

of these data also in the troposphere. Also in the tropics (figure 6) the ERA-Interim ozone peak is usually underestimated during the pre-GOME period, with residuals up to 20%, but not afterwards (during the GOME and post-GOME periods) when biases up to 5% were seen in the stratosphere. Residuals larger than 50% were instead found in the lower troposphere. This is because the ozone analyses are only marginally constrained in this region of the atmosphere. UV nadir sounders, that provide most of the available ozone products, have low sensitivity to the troposphere to accurately resolve ozone information at these levels. In addition, they can strongly be affected by clouds that contaminate the data and reduce their accuracy.

Figures 7 to 9 show the RMS error between the ozone reanalyses and the ozone sonde profiles, computed for both ERA-Interim and ERA-40, and obtained by averaging over given latitudinal bands and periods of time. Given their sparse coverage, averages of sonde comparisons over given latitudinal bands can often lack statistical significance. However, the number of ground stations and profiles per station used in this study should be large enough to overcome this problem. Five latitudinal bands were, therefore, selected: the tropics covering the equatorial band from 30°S to 30°N; two bands at midlatitudes between 30° and 60°; and finally two bands at high latitudes between 60° and 90°. The temporal averages were computed for three special periods: January-February-March (JFM), June-July-August (JJA), and September-October (SO). For all the selected latitudinal bands and periods, comparisons were produced by averaging over variable numbers of years to identify special behaviours that could otherwise be masked by simply using the whole period ERA-40 and ERA-Interim overlapped. This effort showed that significant differences between the two reanalyses could be found in the tropics by limiting the averages to the pre-GOME (until December 1995) and GOME (from January 1996 to December 2002) assimilation periods. Conversely, the impact at mid and high latitudes was generally modest in the comparisons with sondes so that only the comparisons computed over the 1989-2002 period are shown for these latitudes.

In the tropics (figure 7), the mean ERA-Interim ozone reanalyses generally show a higher level of agreement with ozone sondes than their ERA-40 equivalent during most periods. Despite the general improvement produced in the latest reanalyses, the left panels, that refer to the pre-GOME assimilation years, still highlights some problems in the region of the ozone maximum between 10 and 30hPa during both winter (panel **a**) and summer (panel **c**), as well as in the troposphere during summertime. The assimilation of GOME ozone profiles (right hand side panels) appears to have a beneficial impact on the ERA-Interim tropical ozone reanalyses by reducing their RMSE against ground based measurements in both the lower stratosphere and troposphere and during all periods. The RMSE reduction can be quantified in about 35% in the lower stratosphere, and in about 20% in the tropical troposphere.

As anticipated above, marginal differences were found at mid and high latitudes by varying the number of years used in the mean, therefore the discussion focuses on the whole overlapping period between the two reanalysis projects. Figure 8 shows the RMS fit to ozone sondes in wintertime at mid and high latitudes. In the NH (panels **a** and **b**), the ERA-Interim ozone reanalyses show a reduction of about 30% in the lower stratosphere and between 20 and 75% in the troposphere at midlatitudes; while at high latitudes the RMSE reduction is about 40% in the lower stratosphere and between 20 and 70% in the troposphere. In the SH (panels **c** and **d**), the ERA-Interim ozone reanalyses still show better fit to ozone sondes than their ERA-40 equivalent at midlatitudes where the RMSE reduction ranges from about 20 to 50% both in the lower stratosphere and in the troposphere. Conversely, the SH high latitudes show some degraded fit between the ERA-Interim and the ozone sondes in the region of the atmosphere between 10 and 60 hPa with a RMSE increase between 20 to 50%. The ERA-Interim-sonde comparisons show slightly higher agreement than those between ERA-40 and sondes in the troposphere and in the stratosphere above 10hPa, with differences up to 20%.

Because of its relevance in the context of the SH ozone depletion, the comparisons between the two reanalyses and ozone sonde profiles during spring in the SH are also discussed (figure 9). From these comparisons, it appears that the ERA-Interim ozone reanalyses fit the ozone sondes better than the ERA-40 ozone reanalyses

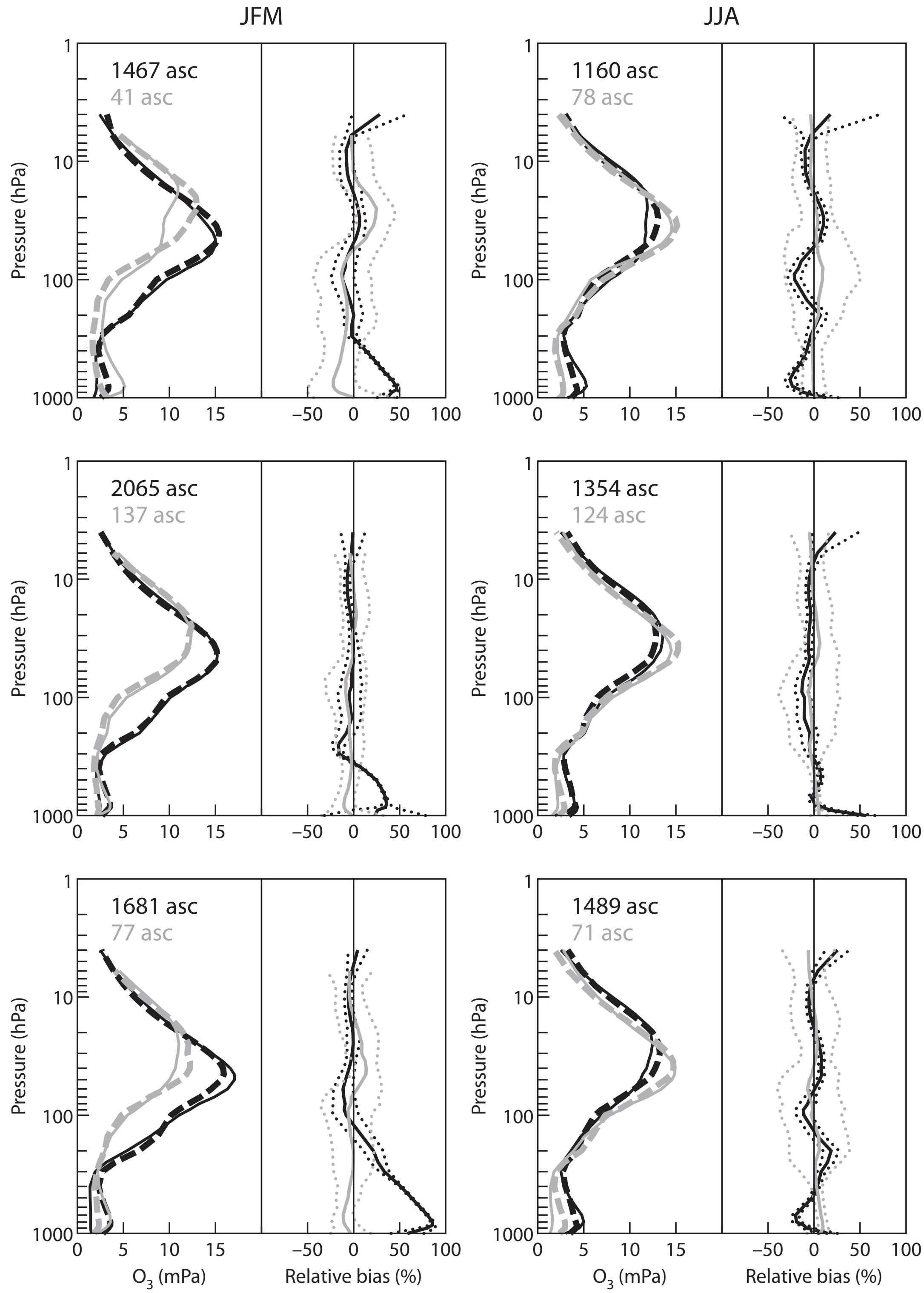

Figure 5: As in figure 4, but for the midlatitudes.

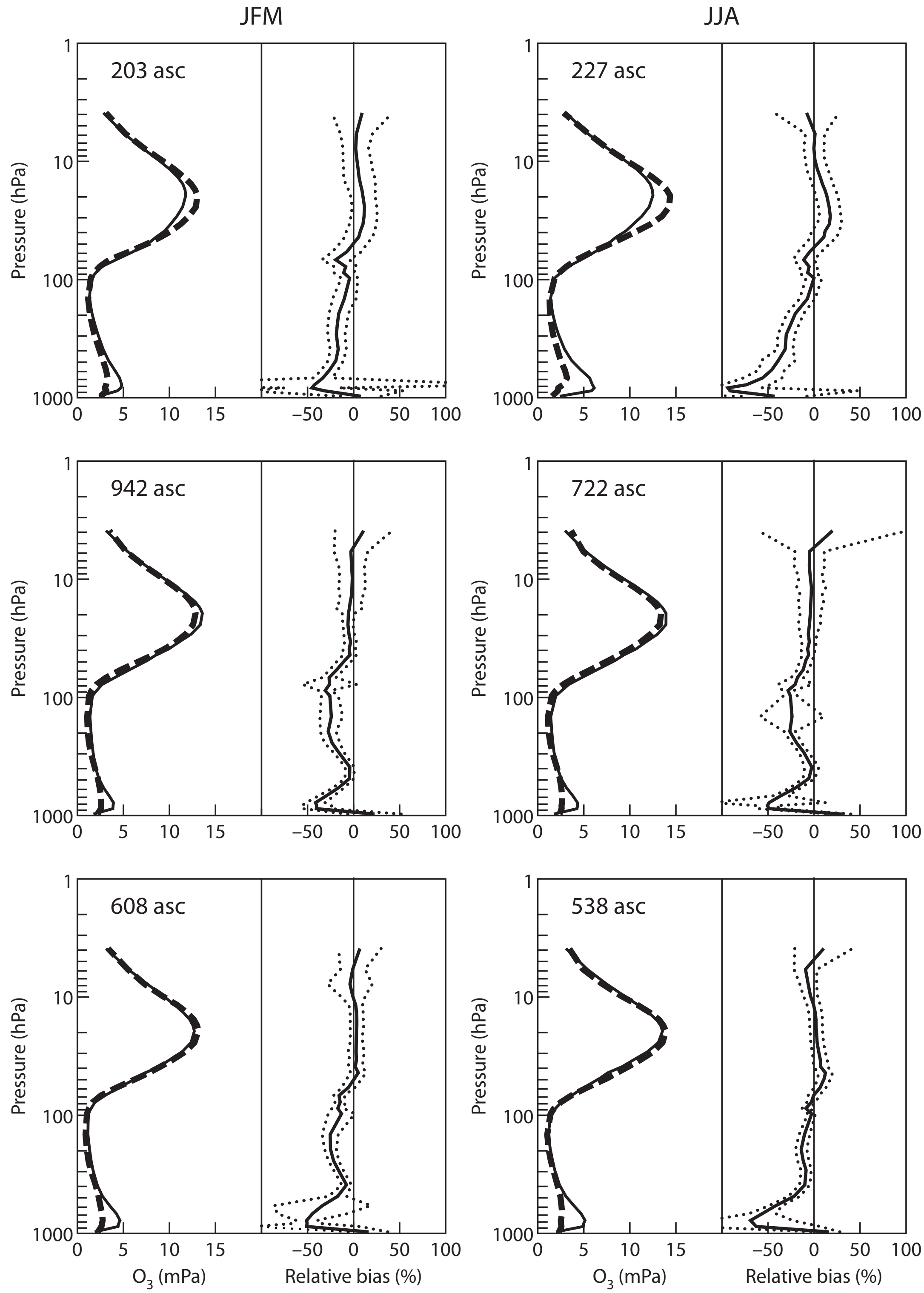

Figure 6: As in figure 4, but for the tropics.

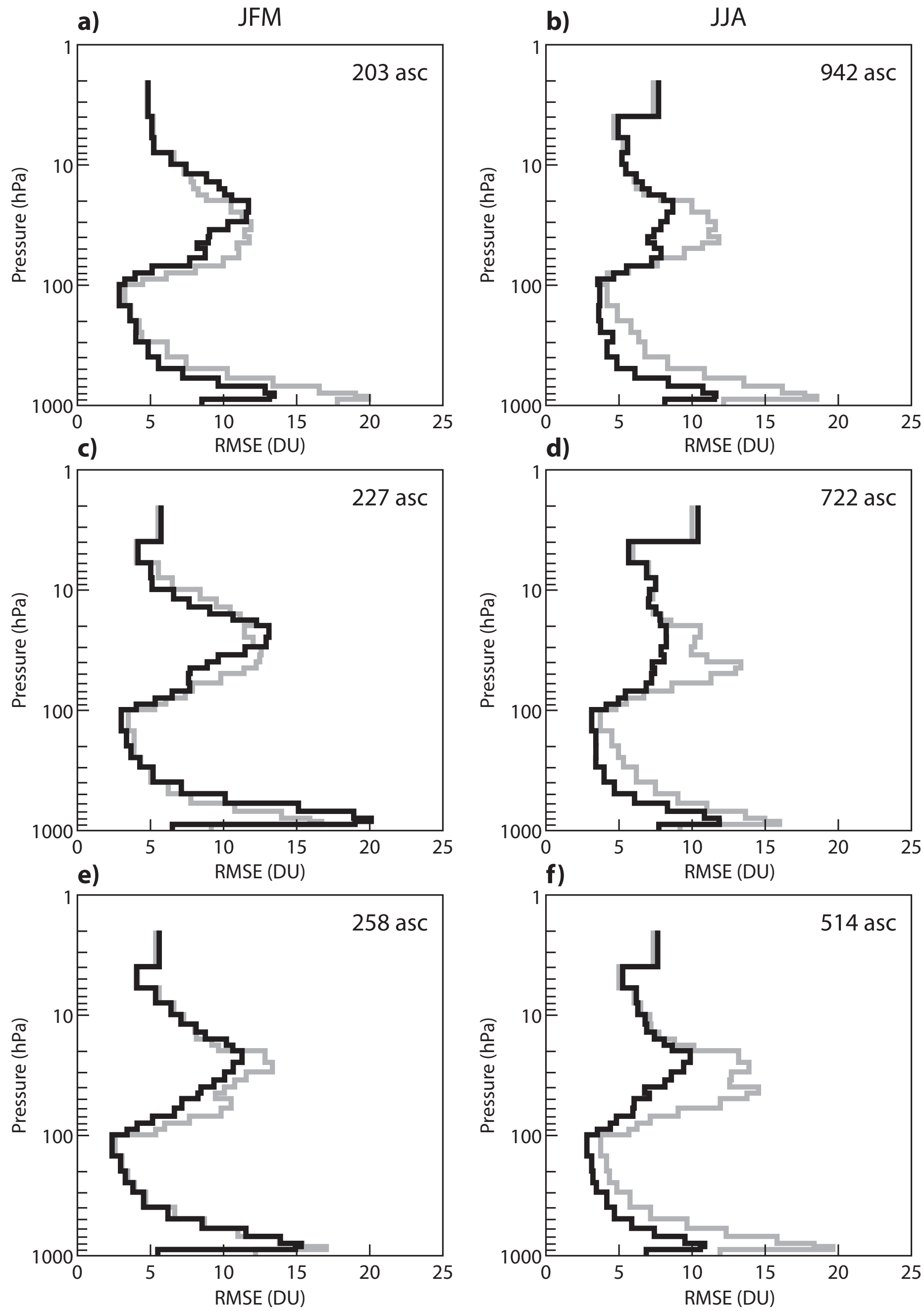

Figure 7: RMS fit of the ERA-40 (grey lines) and ERA-Interim (black lines) mean ozone analyses and ozone sondes averaged over the equatorial band limited by the tropics (30S-30N) during the months of January-February-March (top panels), June-July-August (mid panels), and September-October (bottom panels). The left panels refer to the years from 1989 to 1995 (before GOME assimilation); the right panels refer to the period during which GOME ozone profiles were actively assimilated, that is the period 1996-2002 for panels **b** *and* **d***, and the period 1996-2001 for panels* **f** *as the ERA-40 production ended in August 2002. The number of ascents included in the average can be found on the top-right corner of each panel. Data are in DU.*

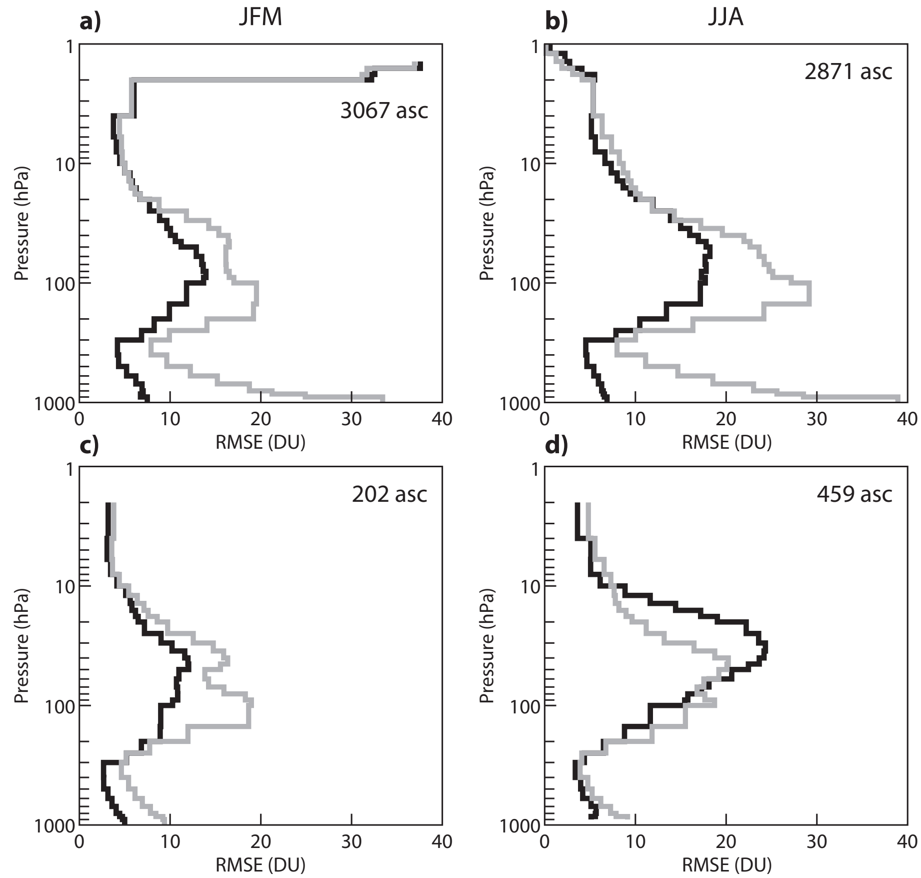

*Figure 8: As in figure 7, but for the winter hemisphere averaged over the years 1989 and 2002. The top panels refer to the NH during January-February-March; the bottom panels refer to the SH during June-July-August. The left panels (**a** and **c**) show the plots at midlatitudes; the right panels (**b** and **d**) refer to the high latitudes.*

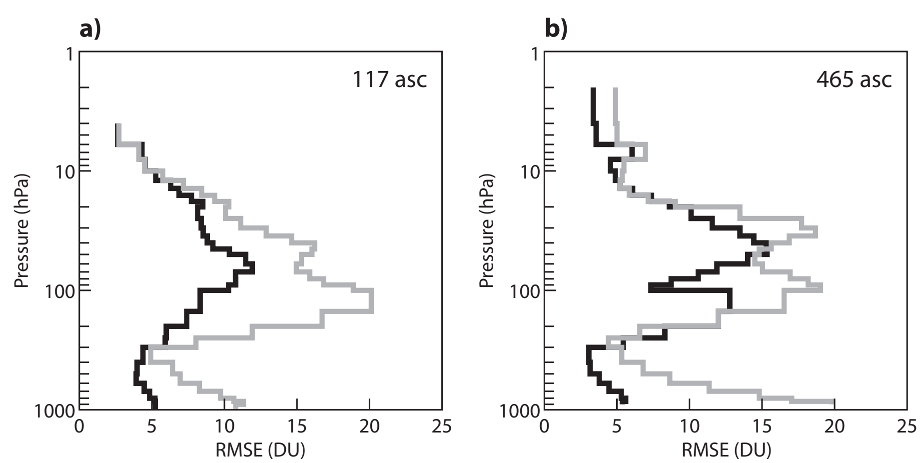

*Figure 9: As in figure 7, but for the mid and high latitudes in the SH during spring (September-October). The plots were obtained by averaging all the available profiles during the years 1989 and 2001. The panel **a** shows the plot at midlatitudes; the panel (**b** refers to the high latitudes.*

at all levels and both at mid (panel **a**) and high (panel **b**) latitudes. At midlatitudes, the RMSE reduction varies from 10 to 50% across the troposphere and the stratosphere.

At high latitudes, the ERA-Interim RMSE generally shows smaller values than their ERA-40 equivalent, with reduction from 5 to 75%. The only exception is the region of the atmosphere between 200 and 300hPa where the ERA-Interim RMSE is about 20% larger than that with ERA-40.

5 Analysis of the trends

In this section, we investigate the existence of possible trends in the residuals between the independent observations used in the validation study and the ERA-Interim ozone reanalyses, as a function of pressure. A weighted least squares fit to the monthly mean departures was used to derive the annual variations at different vertical levels, and to identify statistically significant changes. Because neither the ECMWF system (e.g. model version and various parameterizations) nor the version of the assimilated and independent data changed during the period of the ERA-Interim production considered here, any temporal dependence of the residuals can only be associated to changes in the actual amount of data and data type actively assimilated in the system. It should be noted that the periods considered to estimate the temporal trends were the entire data availability period of the ground stations, and this may lead to differences in the results. Nonetheless, the trends in the residuals at different ground stations in the same latitudinal band often show some degree of agreement.

Figure 10 shows the slope profile of the time series of the ERA-Interim residuals from the ozone sonde observations measured at various ground stations and divided in five latitudinal bands. The variations are typically within $\pm$0.5%/year at all vertical levels and latitudinal bands. In the stratosphere, there are negligible trends in the agreement between the ozone sondes and their ERA-Interim equivalent at mid and high latitudes (with the only exception of the results for Sodankyla). In the tropics, negligible trends were found in the lower stratosphere at Naha, Irene and Ascension Island. In contrast, La Reunion and San Cristobal ground stations showed a generally positive trend in the lower stratosphere up to +0.5%/year at 60hPa. The observation minus ERA-Interim residuals corresponding to the positive trend for a layer around 60hPa at La Reunion and San Cristobal ground stations are plotted in panel **f)** of figure 10. In both cases, the positive trend is associated with a change in sign (from negative to positive) of the observation minus analysis residuals occurring towards the end of 2002 / beginning of 2003 onwards. These two ground stations operated with ECC instruments. An instrumental model upgrade was applied at La Reunion station in summer 2002. However, there is no indication of a direct impact of this change in the ozone comparisons, and the fact that a similar change was also observed in the comparisons at San Cristobal (where no instrumental upgrades were applied at that time) leads to the conclusion that this trend was most likely a consequence of changes in the assimilated ozone products in the ERA-Interim reanalysis. The assimilation of MIPAS ozone profiles and SCIAMACHY TCO started in January 2003. Eskes *et al.* (2005) showed that the TOSOMI retrieval from SCIAMACHY was on average 1.7% lower than ground based data, and it could explain this change. This result is also consistent with the comparisons of the Dobson TCO data with their co-located TCO analyses discussed in section 4.

In the troposphere, the trends are generally positive and up to 0.3%/year regardless of the sonde location. The analysis of the tropospheric time series for several sondes (not shown) revealed improvements in their agreement with their ERA-Interim tropospheric equivalent in some cases and degradation in others to make the results inconclusive. As mentioned in section 4, the tropospheric ozone analyses are in general only marginally constrained as a consequence of the combination of limited vertical resolution of most of the available sensors to resolve accurately the tropospheric ozone distribution and the potential cloud contamination of the data.

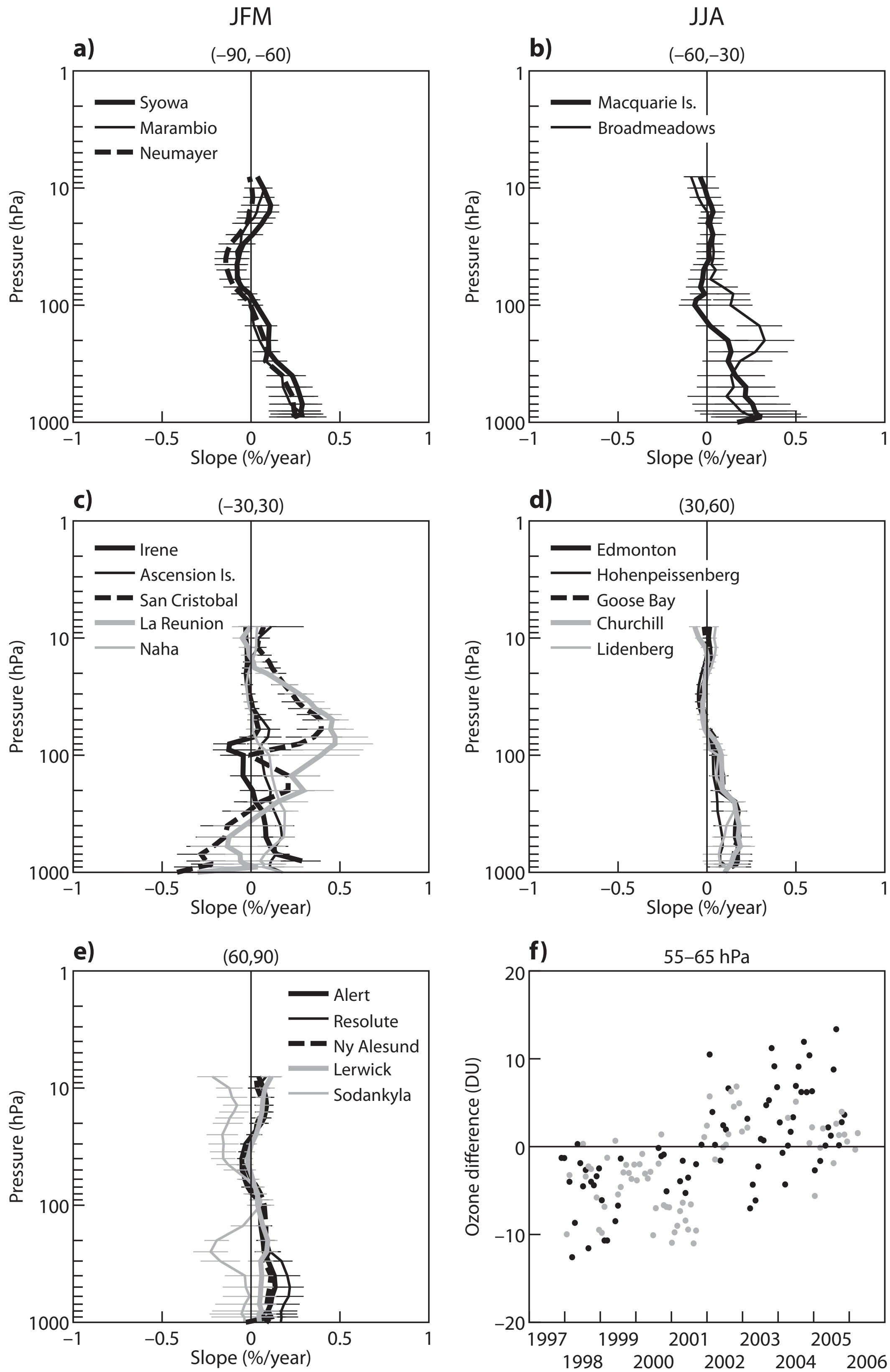

Figure 10: Slopes of time series differences between a set of individual ozone sondes and their co-located ERA-Interim ozone analyses as function of pressure and over five latitudinal bands as reported in each panel title. The error bars refer to twice the error in the slope estimate. Panel **f)** *shows the time series of the Observation minus ERA-Interim residuals (in DU) computed for the layer between 55 and 65hPa at La Reunion (black circles) and at San Cristobal (grey circles).*

6 Summary and conclusions

We presented a validation study of the quality of the ECMWF ERA-Interim ozone analyses for the period January 1989 through December 2008 by comparisons with ground-based independent ozone observations. Total column ozone from Dobson sondes at different locations were used to assess the quality of the ozone column analyses; ozone profiles from ozone sondes mainly retrieved from the WOUDC archive were used to validate the ozone analysis vertical distribution.

In terms of total column ozone, twenty-year long comparisons of the ERA-Interim TCO analyses was performed with ground-based Dobson measurements and four examples, representing different latitudinal situations, were discussed. For completeness, similar comparisons were also repeated for the ERA-40 ozone analyses. In all cases, a good level of agreement between observations and their model equivalent was shown. The residuals were typically negative before January 2003 with values typically down to -10% at high latitudes in both hemispheres, within 0 and -5% at midlatitudes in the NH, and in the tropics. An improved level of agreement was found at all latitudes from January 2003, when the SCIAMACHY TCO assimilation started, onwards. In this case, the residuals were distributed around the zero value with fluctuations within ±5% at midlatitudes in the NH and in the tropics, and within -8 and +10% at high latitudes.

The comparisons of the three-dimensional ERA-Interim and ERA-40 ozone analyses with ECC and BM ozone sondes showed a dependence on the season, latitude, as well as on the period accounted for as a consequence of the varying ozone observing system actively used, particularly in the tropical region. The element that led to the largest differences, and indeed improvements in most cases, was the active assimilation of GOME ozone profiles. Three periods were identified accordingly: 1) the pre-GOME assimilation period (January 1989 - December 1995); 2) the GOME assimilation period (January 1996 - December 2002); and 3) the post-GOME assimilation period (January 2003 - December 2008). For each period, mean profiles over the months of January-February-March (JFM), June-July-August (JJA), and September-October (SO) were produced from the set of all available ozone sondes and co-located ERA-Interim and ERA-40 ozone analyses. In the pre-GOME assimilation period, the residuals between the ozone sondes and their corresponding ERA-Interim ozone profiles were within ±10% in the tropics and at midlatitudes at most levels, and within ±20% at high latitudes. In the GOME and post-GOME assimilation periods, the level of agreement was within ±5% in the tropics and at high latitudes in summertime, and within ±10% at high latitudes in wintertime as well as at midlatitudes throughout the year.

Throughout this paper, we also discussed the quality of the ERA-Interim ozone analyses with respect to those produced in ERA-40. The comparisons with ozone sondes showed the higher quality of the ERA-Interim ozone analyses than that of the corresponding ERA-40 ones. In this case at mid and high latitudes, substantial improvements were seen both at stratospheric and troposheric levels, even at high latitudes in the SH during spring, throughout the twenty year period under investigation with little sensitivity to the assimilation of GOME ozone profiles. Conversely, the assimilation of the GOME ozone profiles was particularly beneficial and produced a non negligible impact in the tropics. Here, the RMS of the difference between the ozone sondes and the co-located ozone reanalyses was reduced up to 40% in the lower stratosphere, and between 20 and 50% in the troposphere when using ERA-Interim instead of ERA-40.

Finally, the analysis of the trends in the observation minus analysis residuals plotted for several stations as function of pressure exhibited small, and often not statistically significant changes both in the stratosphere and in the troposphere, with a few exceptions as in the cases of San Cristobal and La Reunion ground stations that were discussed in section 5.

The results discussed in this paper demonstrated the quality of the ERA-Interim ozone analyses compared with the ERA-40 ozone reanalyses. The present study pointed out where these improvements mainly occurred, but also showed that a number of issues require further attention and will need to be addressed by future projects, e.g. the high latitudes at the beginning of spring, particularly in the SH. It was also shown that the assimilation of accurate ozone information, especially in the form of a profile, can lead to substantial improvements, within the specific instrumental limitations. Here, for example, it was mentioned several times the impact on the quality of the ERA-Interim ozone analyses produced by the assimilation of GOME ozone profiles. The assimilation of ozone products retrieved from instruments sounding different region of the solar spectrum (other than UV) could also be beneficial, particularly under the polar night conditions, and this will be further investigate in the context of the next reanalysis project.

The present paper did not discuss the quality of ERA-Interim (and ERA-40) ozone analyses against satellite ozone retrievals. This discussion will be presented in a companion paper (Dragani, 2010).

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