SPECIAL PROJECT “GLOBMODEL”
FINAL REPORT

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Researchers: Stefano Migliorini (University of Reading), Andrea Kaiser-Weiss (University of Reading)

Collaborators: Rossana Dragani (ECMWF)

1 Introduction

The aim of the GlobMODEL project is to assimilate Earth Observation (EO) data in the ECMWF operational atmospheric model, with a particular focus on ozone. Operational meteorological centres are interested in improving the quality of their ozone analyses for a number of reasons (e.g. [1]). For example, a more realistic ozone field can provide more accurate estimates of atmospheric radiative heating rates than those derived from an ozone climatology. Another example is in the field of satellite radiance assimilation. To simulate the radiances measured by remote sensing instruments, radiative transfer models require estimates of a number of geophysical parameters, including ozone mixing ratio profiles along the instrument line of sight. Therefore, a better knowledge of the ozone distribution can improve the assimilation of these data and ultimately the performance of numerical weather prediction (NWP) models. Several works in the literature have discussed the results of assimilating ozone retrievals for NWP applications. For example, [2] investigated the assimilation of ozone total columns measured by the Global Ozone Monitoring Experiment (GOME) - on board the Second European Remote Sensing Satellite (ERS-2) - and ozone profiles from the Microwave Limb Sounder (MLS) instrument - on board the Upper Atmosphere Research Satellite (UARS) - within the Met Office data assimilation system. They showed that the synergistic use of both observation types improved the quality of the ozone analyses with respect to assimilating each observation type on its own. Also, [3] experimented with the assimilation of the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) ozone profiles within the European Centre for Medium-Range Weather Forecasts (ECMWF) data assimilation system, showing improvements in the ozone analyses at high latitudes in the winter hemisphere as well as achieving a better characterization of the Antarctic ozone hole. Assimilation of MIPAS ozone profiles also proved to be effective in improving the ozone analyses, particularly in the polar night region and below the ozone maximum [4]. By assimilating MIPAS data in the Met Office system, [5] were able to reproduce accurately the unusual ozone hole split event that occurred in September 2002. Improvements in the stratospheric ozone distribution were found by [6] and [7], who investigated the assimilation of ozone profiles from MLS on board the NASA’s Aura satellite within the Met Office and the ECMWF data assimilation systems, respectively. Their results were confirmed by those found by [8], where OMI total column ozone data were used synergistically with ozone profiles from MLS onboard Aura. In their study, [8] showed that the assimilation of ozone profiles can improve the vertical ozone distribution as well as the tropospheric ozone column analyses.

In this project we made use of the ECMWF operational NWP system to evaluate separately the impact of new EO estimates of total column ozone (TCO) and ozone profiles from the Ozone Monitoring Instrument (OMI) on the quality of forecasts and analyses of stratospheric ozone. The research and operational centres involved in the study discussed here were the Data Assimilation Research Centre (DARC), now part of the National Centre for Earth Observation, and ECMWF. The Royal Netherlands Meteorological Institute (KNMI) had the role of data provider.

2 Description of the experiments

The GlobMODEL project experiments were run with the ECMWF NWP system used operationally from 6 November 2007 up to 2 June 2008 (cycle CY32R3). The experiments were performed at a reduced horizontal resolution with a truncation of T255 instead of the operational T799, on 60 vertical levels, spanning from the surface up to 0.1 hPa. ECMWF uses a 4 Dimensional Variational (4D-Var) Data Assimilation System (DAS) with a 12-hour assimilation window. Ozone is fully integrated in the ECMWF system [9] as a model variable in addition to other meteorological fields (e.g. wind components, temperature and humidity). The ozone chemistry is described by a modified version of the Cariolle and Déqué scheme [10]. In the Cariolle and Déqué parameterization, the continuity equation for the ozone mass mixing ratio at a given grid point 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. In addition, an ozone destruction term is also included to parameterize the heterogeneous chemistry as a function of the equivalent chlorine content for the actual year. The whole parameterization of the ozone chemistry has undergone significant upgrades in recent years (e.g. [11]) thanks to collaboration with Daniel Cariolle (Météo-France).

The EO data used within the GlobMODEL project includes all the conventional and radiance observations that were routinely assimilated at ECMWF in model cycle CY32R3. This set of data corresponds to millions of observations per day derived from different sources (such as radiosondes, aircraft, satellites). Satellite data are by far the most important source of information used to constrain the model fields. About 99% of the data volume received by ECMWF is derived from satellite measurements. Also, only 4.6% of the whole screened data is actively assimilated, and of this 4.6%, over 88% consists of remote sounding data. At the time the GlobMODEL experiments were run, data from about 46 different remote sounders were actively assimilated at ECMWF, either in form of raw radiances or as retrieved products (namely, ozone columns). As far as the ozone assimilation is concerned, data from the SCIAMACHY (ozone total columns) and OMI (ozone total columns and profiles) instruments were also used in the GlobMODEL experiments. Note that, to extract a sufficient signal and better understand possible inter-instrumental biases, the active assimilation of NOAA-16 SBUV/2 data was switched off.

The main aims of the GlobMODEL project were to assess 1) the impact of assimilating separately OMI TCO and OMI ozone profiles on the ECMWF ozone analyses and forecasts, and 2) their synergy with already assimilated and better-known ozone observations. For this reason, three assimilation experiments were run for the two-month period between 1 July and 31 August 2006:

1. CTRL: assimilation of standard meteorological observations and of ozone total columns from SCIAMACHY.

2. OMIT: assimilation of standard meteorological observations and of ozone total column from SCIAMACHY and OMI.

3. OMIP: assimilation of standard meteorological observations along with ozone total columns from SCIAMACHY and ozone partial column profiles from OMI.

The results of the three assimilation experiments (CTRL, OMIT and second iteration of OMIP) are discussed next, including an evaluation of the impact of OMI total columns and profiles on the ozone analyses, as well as of the quality of the analyses.

3 Analysis of assimilation results

This section describes the results of the assimilation experiments. The quality of the experiment outputs, composed of estimates of geophysical fields by using numerical models and observations (hereafter referred to as analyses), is assessed by comparison against independent observations.

3.1 Assimilation of OMI TCO

We first assess the impact of OMI TCO on the ozone analyses by comparing the two sets of analyses from experiments CTRL and OMIT.

The temporal mean total column ozone difference (Figure 1), obtained by subtracting the OMIT TCO analyses from those obtained from the CTRL experiment and then averaged over the two-month period under study, shows that the assimilation of OMI TCO leads to a mean reduction (up to 4 DU) in the total ozone analyses between the equator and 50N, and an increase (up to 12 DU) of the TCO elsewhere, with the largest changes in the polar region in the Southern Hemisphere (SH). Figure 2 shows the difference between the CTRL zonal mean ozone analysis and the corresponding one from the OMIT experiment valid for 12 UTC on 23 August 2006. Note that here we decided to consider an analysis at a given time - close to the end of the assimilation period to minimise the transient effects of the assimilation of new data products on the analyses - rather than a temporal mean to emphasise the small scale features of the difference patterns. By looking at the ozone vertical distribution, the OMI TCO mainly contributes in the lower stratosphere between 10 and 80 hPa. Given that the only ozone source actively assimilated in both experiments is in the form of total column ozone, any vertical variation of the ozone analysis difference plotted in Figure 2 is likely to be determined by the ozone short-range forecast (or “background”) error covariance matrix, which distributes spatially the observation increments.

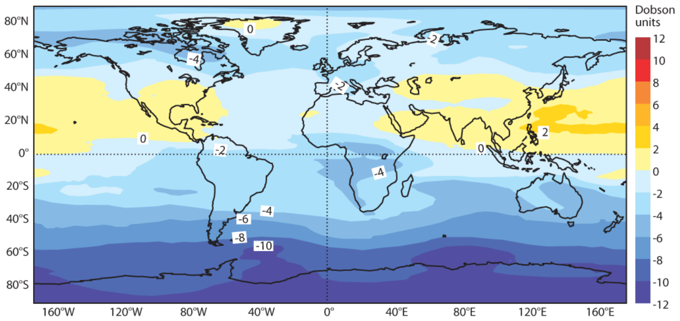

Figure 1 Difference between the CTRL and OMIT total column ozone analyses averaged over the period 1 July - 31 August 2006. Data are in DU. Yellow-red colours correspond to an ozone reduction determined by the OMI TCO assimilation; blue colours correspond to an ozone increase determined by the OMI TCO assimilation.

This is consistent with the fact that the vertical profile of the ozone background error variance used in the assimilation is typically peaked between about 20 and 60 hPa. From Figures 1 and 2 it also appears that OMI exhibits larger TCO values than SCIAMACHY, particularly at high latitudes in the SH.

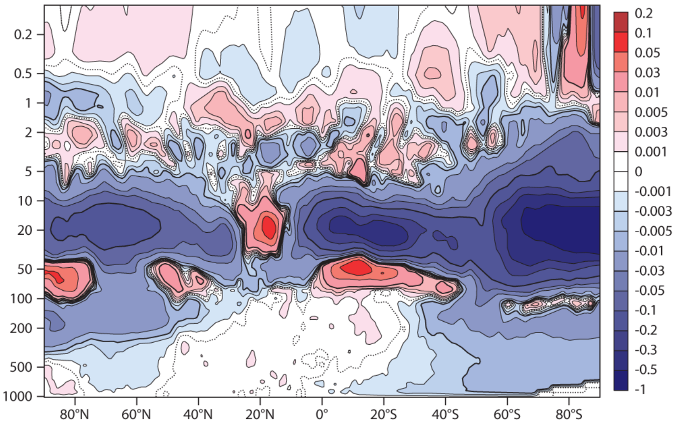

Figure 2 Difference between the CTRL and OMIT zonal mean ozone analyses valid for the 12Z on 23 August 2006. Data are in mass mixing ratio (ppmm). Red-brown colours correspond to an ozone reduction determined by the OMI TCO assimilation; violet-blue colours correspond to an ozone increase determined by the OMI TCO assimilation.

As one would expect from a good data assimilation system, the ozone analyses from the OMIT experiment are in a much better agreement with the OMI TCO observations than those from the CTRL experiment. When OMI TCO is actively assimilated, the standard deviations of the first-guess and analysis departures are also reduced (not shown). Although the differences do not appear to be large in absolute values (about 1 to 2 DU), they still represent a relative reduction of roughly 15%.

To assess whether the changes in the ozone analyses determined by the assimilation of OMI TCO correspond to actual improvements, independent (i.e. unassimilated) observations from both remote sounders and ground stations obtained within 3 hours from analysis time were compared with ozone analyses from both experiments, interpolated at observation locations.

The comparison with a number of ozonesondes shows, in general, negligible differences between the two experiments, with a few exceptions. In these cases, the assimilation of OMI TCO generally leads to a better agreement with the ozonesondes. Two examples are given in Figure 3. They show the comparisons between the monthly-mean sonde profile (red) and the corresponding monthly-mean profile from CTRL (black) and OMIT (blue), over Syowa (high latitudes in the SH) and Nairobi (tropics)

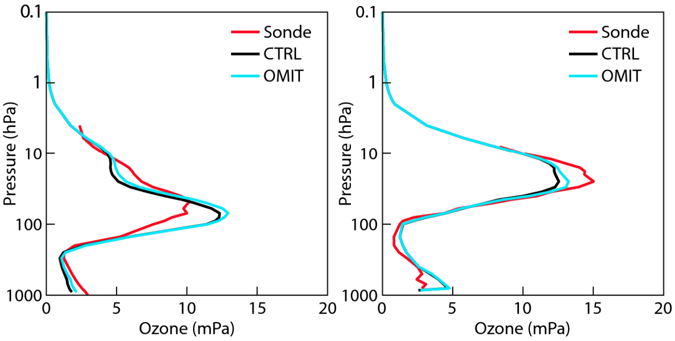

Figure 3 Comparison between the CTRL and OMIT monthly mean ozone analysis profiles at two ground stations and the corresponding ozone sonde profiles. The left panel refers to the Syowa ground station (lat=69°S, lon=39.6°E, eight profiles); the right panel refers to the Nairobi station (lat=1.3°S, lon=36.8°E, four profiles). Data are in partial pressure (mPa).

At high latitudes in the SH (lhs panel in Figure 3), the assimilation of OMI TCO reduces the level of agreement with the sondes in the region between 50 and 100 hPa, while leading to an improved agreement above the ozone maximum (between 10 and 50 hPa,) as well as in the lower troposphere (between 400 and 800 hPa). In the tropics (right panel in Figure 3) both analyses agree well with the mean ozonesonde profile, except in the region of the ozone maximum, where the assimilation of OMI TCO leads to some improvements.

Comparisons with observations from the Microwave Limb Sounder (MLS) [12] on Aura were also performed. This instrument, which provides global coverage, was chosen for the validation for two main reasons: 1) it is on the same platform as OMI so that it samples the atmosphere at the same time, over the same region of the globe and 2) it is a limb sounder and therefore with a relatively good vertical resolution, which is important when one wants to assess the quality of the ozone analyses vertical distribution. Figure 4 shows the comparison between the global mean profiles from MLS (black), the CTRL analyses (red), and the OMIT analyses (blue) in panel a), and the mean ozone difference between MLS and the analyses, relative to the analyses in panel b), averaged over the two month period July-August 2006. As noted above, although the difference between the two sets of analyses is small, in the global mean the assimilation of OMI TCO leads to an improved agreement (about 2-3%) with MLS observations in the region of the ozone maximum. When averaged over latitudinal bands, the two sets of analyses mainly differ at mid and high latitudes in the SH. Negligible differences were seen in the tropics and in the Northern Hemisphere (NH).

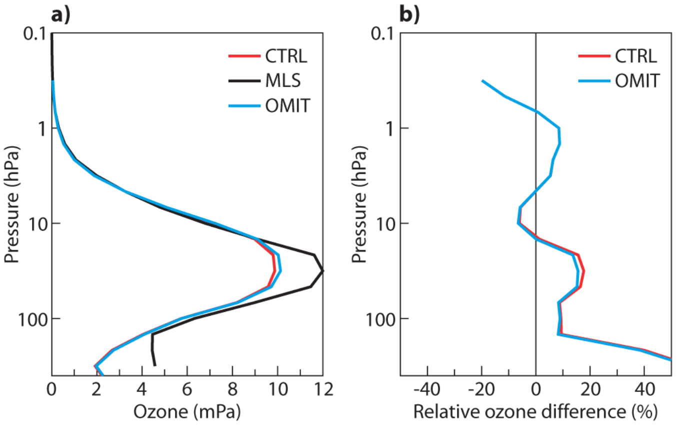

Figure 4 Comparison between the CTRL and OMIT mean ozone analysis profiles and the corresponding MLS ozone profiles (panel a) between 200 and 0.1 hPa. Data are in partial pressure (mPa). Panel (b) shows the relative mean bias computed as 100*(MLS-A)/A, A being the OMIT and CTRL analyses. The mean profiles were computed over the two month period of July and August 2006.

From the results shown in Figures 3 and 4 it is clear that the impact of the OMI TCO on the ECMWF ozone analyses is mainly limited to the region between about 20 and 80 hPa. This is not surprising, given that this region is where the ozone background error variances are largest, as discussed previously. The positive impact determined by the assimilation of OMI TCO at high latitudes in the SH during the winter months is particularly important, as in this region the stratospheric ozone transport and chemistry depletion are generally difficult to model with accuracy. Finally, the beneficial impact of the OMI TCO on the ECMWF ozone analyses was also confirmed by later experiments (not discussed here), where OMI TCO data were assimilated with the full (i.e., including SBUV/2 ozone partial columns) ECMWF operational system.

3.2 Assimilation of OMI Ozone profiles

Here we present the results of the assessment of the impact of OMI ozone profiles on the ECMWF ozone analyses, by comparing first the CTRL and the OMIP assimilation experiments, and then both sets of analyses with independent, unassimilated observations. The mean ozone analysis difference for the two-month period under study, computed as CTRL minus OMIP, shows that the assimilation of OMI profiles leads to changes in TCO that are much less zonally symmetric than those obtained from the OMI TCO assimilation. The main effect (Figure 5) is an increase of TCO (up to 60 DU below 60°S). However, between 0° and 60°N, the TCO shows variations of both signs (between -20 and 20 DU). When the zonally-averaged ozone mass mixing ratio vertical distribution are considered (Figure 6), the assimilated OMI profiles modify the ozone vertical distribution by changing the ozone mixing ratio on six vertical bands, roughly corresponding to the six OMI observation layers.

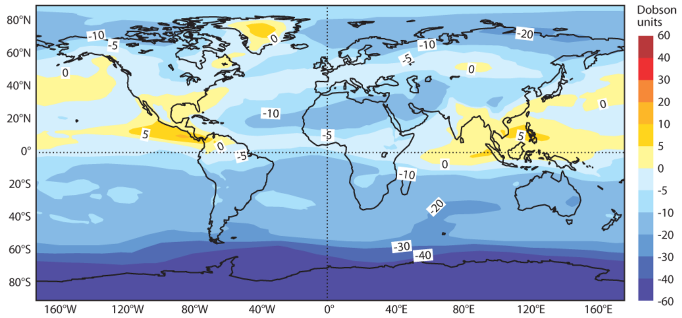

Figure 5 As in Figure 1, but for CTRL minus OMIP.

The effect of OMI profiles on the ozone vertical distribution is, not surprisingly, much more pronounced than when OMI TCO is assimilated: there are variations between -15 and 15 ppmm (15 times more than in the OMIT case).

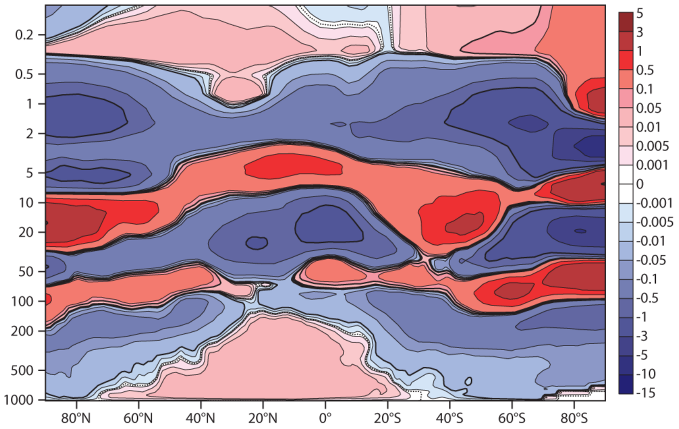

Figure 6 As in Figure 4, but for CTRL minus OMIP.

Both Figures 5 and 6 show a much larger impact of the OMI ozone profiles assimilation on the ozone analyses than that found in the TCO experiments. We believe that the reasons for this are twofold: 1) the impact on the ozone analysis of the prior information - which may not be representative of the period under study - embedded in the OMI ozone profiles over the layers where the instrument is less sensitive to changes in the ozone field, and 2) the interplay between the model background profiles, the model background error covariance as well as the observation profiles in determining the vertical distribution of the ozone analyses.

The OMIP and CTRL ozone analyses were also compared to electrochemical concentration cell (ECC) ozonesondes retrieved from World Ozone and Ultraviolet Radiation Data Centre (WOUDC), for the period of July to August 2006. Only sonde profiles with at least 300 measurements up to at least 20 hPa were used, a total of 215 soundings. Our data set consists of 2 high-latitude (> 60°N) stations in the NH (Ny Alesund, Eureka) with 16 individual measurements; 10 between 30°N and 60°N (Barajas, Bratts Lake, Churchill, Egbert, Goose Bay, Kelowna, Legionowo, Payerne, Wallops Island and Yarmouth) with 148 individual measurements; 7 tropical-latitude (30°S to 30°N) stations (Heredia, La Reunion Island, Maxaranguape, Nairobi, Samoa, San Cristobal, Sepang Airport) with 44 individual measurements; 1 high-latitude (< 60°S) station in the SH (Neumayer) with 7 individual measurements. Note that our dataset does not include any stations between 30°S and 60°S.

Figure 7 shows the results of the comparison as an average over four latitudinal bands and over the whole globe, between 200 and 20 hPa.

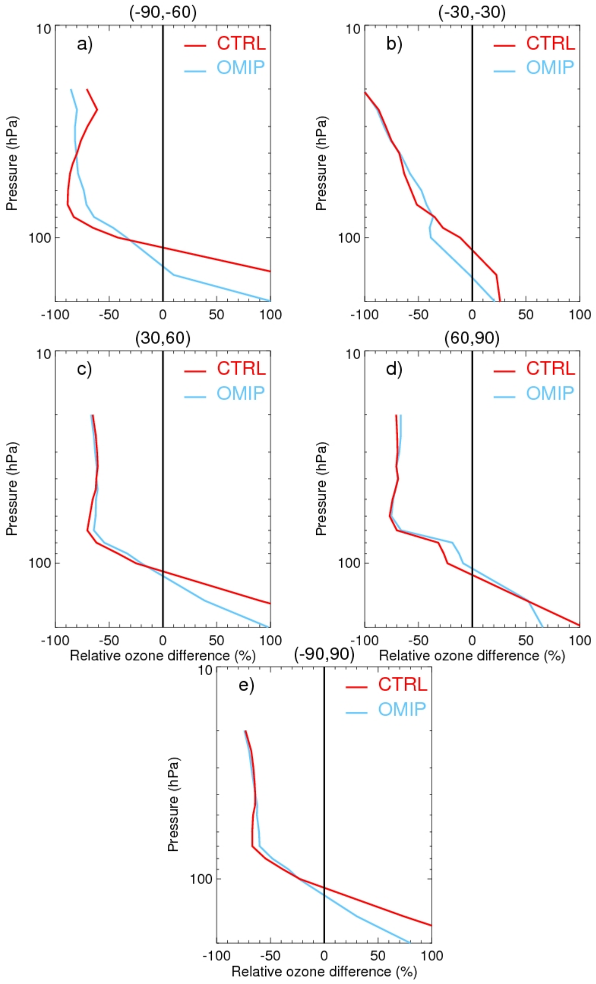

Figure 7 Relative ozone difference computed as relative difference (in %) between ozonesondes profiles and the CTRL (red lines) and OMIP (blue lines) mean ozone analysis profiles for various latitude bands (panels a to d) and (panel e) globally.

We do not discuss the results below 200 hPa because the relative differences between the sonde and the analysis ozone values become greater than 100% for both the CTRL and the OMIP experiments. Between 40 and 20 hPa the differences between CTRL and OMIP are negligible, with the exception of the SH high latitudes where OMIP analyses are closer to the sondes. However, only 7 soundings from only one station are included in our data set for this latitude band. At all latitude bands, OMIP ozone values are closer to the ozonesondes measurements between 80 and 40 hPa. At about 100 hPa the CTRL experiment is in better agreement with the sondes. In the NH midlatitudes and in the SH high latitudes, the assimilation of OMI profiles improves the agreement of the ozone analysis with the ozonesondes between 200 and just below 100 hPa. Although some improvements can be found in the stratosphere, the assimilation of OMI ozone profiles is mainly beneficial in the upper troposphere, between about 200 and 100 hPa.

4 Conclusions

This project focuses on the scientific results from the assimilation of OMI total ozone columns and OMI ozone profiles, and discusses the impact of the ozone data from OMI on the ozone analyses constrained by SCIAMACHY total ozone columns. An improvement of up to 5% was demonstrated in the analyzed ozone field by assimilating total column ozone measurements from OMI when compared against independent, unassimilated observations. In particular, about 3% improvement was seen in the global mean comparison with MLS ozone retrievals. When averaging over different latitudinal bands, a small impact of OMI TCO was found in the tropics and in the NH compared with that found at mid and high latitudes in the SH. Here the ozone analysis fit to MLS retrievals improves up to 5% when OMI TCO is assimilated. These improvements were mainly located in the stratosphere between 20 and 80 hPa. This is the region of the atmosphere where ozone background error variances, contributing to the spreading of total column observations information, are largest.

The assimilation of OMI ozone profile data, on the other hand, did not always lead to the hoped for enhancement in the operational products. A reason for this shortcoming is likely to be due to vertical resolution limitation typical of nadir sounders like OMI. When the prior information embedded in retrievals is not representative of the period under study, it may introduce a bias in the analyses. This could explain the poor level of agreement between the ozone analyses obtained from the OMI ozone profiles assimilation and independent data. Furthermore, when assimilating OMI profile data, the overall quality of the ozone analyses is also likely to be affected by discrepancies between the OMI averaging kernels and the observation operators currently used at ECMWF for assimilating satellite retrieval profiles. Some improvements were found in the lower stratosphere and upper troposphere. A better agreement with ozonesonde measurements was seen both in the global mean and in the mean over selected latitudinal bands, especially in the region of the atmosphere between 80 and 40 hPa. Improvements were also found at midlatitudes in the NH and at high latitudes in the SH between 200 and 100 hPa.

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