GLOBAL TOTAL OZONE CHARACTERISTICS ESTIMATED FROM INDIVIDUAL SATELLITE SENSORS AND MERGED DATA SETS

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Abstract

It is well established that the overall decline of the total ozone (O3) has varied extensively during the last decades in both hemispheres. Using gridded daily satellite measurements of total O3 from Nimbus 7/TOMS, EarthProbe/TOMS, GOME/ERS-2, SCIAMACHY/Envisat, OMI/Aura and GOME-2/MetOp we present a number of objective characteristics of this decline such as the ozone mass deficiency (O3 MD) from the pre-1976 climatological base average and its areal extent with negative deviations equal to ~2σ for the years 1978-2009.

For the time frame of the aforementioned satellite measurements, the corresponding stratospheric temperatures are calculated from NCEP reanalysis data and their role on the O3 decline is investigated. In addition a statistical analysis of the O3 hole characteristics such as duration and size over Antarctica is performed for each individual data, for the cases of regions with O3 values less than 220 DU and the results are compared. Throughout 2009 the OMI observed maximum O3 hole area was greater than 22 million km2 in the end of September over Antarctica compared to more than 27 million km2 that was detected at the same time period of 2006, which is the largest O3 hole so far observed by OMI.

Finally, a gridded merged assimilated dataset spanning from 1978 until 2008 created from 14 distinct satellite data sources, including TOMS, SBUV, GOME, SCIAMACHY, OMI and GOME-2, derived from the Royal Netherlands Meteorological Institute (KNMI), is compared with a corresponding merged level-2 data set, developed by the German Aerospace Center (DLR), which includes from GOME, SCIAMACHY and GOME-2 total O3 estimates.

INTRODUCTION

It has widely been shown that the known total O3 decline has varied extensively during the last decades in both hemispheres. There are several detailed scientific studies discussing the change of the global O3 regime (e.g. Andersen and Knudsen 2002, Balis et al., 2009). These and the International O3 Assessments (World Meteorological Organization, 1994, 1998, 2006 and the references therein) have presented that since the 1970s total O3 has been depleted in middle and polar latitudes of both hemispheres. The basics of the physical and chemical processes creating and sustaining the O3 hole are summarized in Rowland (2006).

Due to the Montreal protocol and its subsequent amendments, the amount of the O3 depleting substances in the stratosphere is now slightly declining (WMO/UNEP 2003; Montzka et al., 2003; World Meteorological Organization, 2006). Many model and satellite studies show a near zero trend and first signs of O3 recovery in the recent 7-year period from 1996 to 2003 (e.g. Newman et al., 2006, Vyushin et al., 2007). As for the future O3 trends, some models predict a slow O3 recovery by 2068 (e.g. Eyring et al., 2007). However, recent studies showed that there will be further delay due to
nitrous oxide (N\textsubscript{2}O) (Chipperfield, 2009). N\textsubscript{2}O is not covered by the Montreal Protocol and has become the most highly emitted ozone depleting substance and is expected to remain so throughout the 21st century.

The main aim of this work is to examine the variability of the total O\textsubscript{3} characteristics using long term O\textsubscript{3} datasets and to study the relationship between the observed O\textsubscript{3} destruction and the lower stratospheric temperatures throughout the last 30 years. Concurrent KNMI and DLR total O\textsubscript{3} merged datasets are compared in our analysis. The present paper demonstrates observational characteristics of the O\textsubscript{3} decline such as the ozone mass deficiency (O\textsubscript{3}MD) and its areal extent during winter spring over both hemispheres by examining the polar regions and the middle latitudes using satellite measurements from 1979 onwards. In addition zonal mean stratospheric temperatures at 100 hPa are used in order to investigate the correlation with the observed O\textsubscript{3}MD. In the next sections the satellite data and methodology used in this study are presented and the results of the statistical analysis are provided and discussed as well. Finally, some tentative conclusions are drawn.

DATA AND METHODOLOGY

The total O\textsubscript{3} columns retrieved by the KNMI algorithm are assimilated and publicly available on a day-by-day basis via ESA’s TEMIS project (http://www.temis.nl). For the assimilation of GOME (Burrows et al., 1999 and references therein), SCIAMACHY (Bovensmann et al., 1999), OMI (Levelt et al., 2006), GOME-2 (Callies et al., 2000) total O\textsubscript{3} the ozone data assimilation model TM3DAM is used. The assimilated KNMI single sensor (Eskes et al., 2003) and merged satellite data (van der A et al., 2010) have a spatial resolution of 1°x1.5° (lat x lon), whereas the resolution of the DLR merged GOME, SCIAMACHY and GOME-2 total O\textsubscript{3} column dataset is 5°x5° (lat x lon). As for the DLR algorithm, the operational GOME and GOME-2 total ozone products (GDP 4.x) are used and the SCIAMACHY total O\textsubscript{3} columns are retrieved using SDOAS, an adaption of the algorithm GDOAS to the SCIAMACHY instrument (Lerot et al. 2009). The 5°x5° monthly measurements are created averaging the daily 0.33°x0.33° measurements using sqrt(cos(lat)) as weighting (Loyola et al., 2009). For the temperature data NCEP Reanalysis dataset was used, provided by NOAA/OAR/ESRL PSD, Boulder, CO, USA, available at http://www.cdc.noaa.gov. The winter-spring averages of the temperature poleward of 60°N (1 January-15 April) and 60°S (1 September-15 December) were calculated from the daily mean temperature at 100hPa.

First of all, the average total O\textsubscript{3} columns for the years 1979-1981 were estimated for each 1°x1.5° grid from the Nimbus 7 measurements in order to create a reference base with normal mean total ozone values. Then we use the O\textsubscript{3} values for which the negative deviations from the 1979-1981 averages are smaller than 10% (representing approximately the boundary of ~2\sigma of the O\textsubscript{3} natural variability) because knowing the O\textsubscript{3} values in Dobson units (DU), it is a simple matter to determine the respective O\textsubscript{3} mass for each grid point inside the 10% contour (see for e.g. Bojkov et al., 1998). The daily O\textsubscript{3}MD values were subsequently integrated to arrive at the overall mass deficiency in Megatonnes for a given latitudinal belt and for time-period of interest. A temporal integration of the estimated departures was made over a 105 days period (1 January-15 April in the Northern and 1 September-15 December in the Southern hemisphere) and only within the -10% contours of the O\textsubscript{3} deviations. The O\textsubscript{3}MD and its surface area were also calculated using the limit of 220 DU, the commonly used definition of the O\textsubscript{3} hole, as the boundary of the region representing O\textsubscript{3} loss over Antarctica. The value of 220 Dobson Units is chosen since total ozone values of less than 220 Dobson Units were not found in the historic observations over Antarctica prior to 1979. In the plots showed below we used the baseline value of 220DU in our calculations, except for the plots in which the seasonal averaged stratospheric temperatures over the two polar regions is depicted.

RESULTS AND DISCUSSION

Figures 1 and 2 demonstrate the consistency between KNMI and DLR retrieval algorithms, as far as the O\textsubscript{3} surface area with negative deviations and the O\textsubscript{3}MD are concerned. In Figure 1 the annual mean variability of the area where O\textsubscript{3} deviations of the total O\textsubscript{3} columns from the 1979-1981 averages are negative (in Mkm\textsuperscript{2}) is shown. The black and red lines represent the results of KNMI and DLR long-
term merged data sets for the middle Northern latitudes (35°N-50°N) respectively. The retrievals of the 2 algorithms are in good agreement and show a maximum in 2002 (~41Mkm²) and a minimum in 2003 (~28Mkm²). Figure 2 presents the O₃MD (in Mt) calculated again from KNMI (black line) and DLR (red line) long-term merged data sets for the same latitudinal belt as in Figure 1. The DLR O₃MD results are slightly larger than those of KNMI but both show the same O₃MD year-to-year variability. In both hemispheres, around the polar night, poleward of 50°, there is limited coverage of the DLR merged satellite data, whereas the KNMI assimilated merged measurements provide a global dataset.

![Figure 1](image1.png)

**Figure 1:** Annual variability of the O₃ hole surface area (Mkm²) for the latitudinal belt 35°-50° of the Northern Hemisphere as derived by the KNMI and DLR satellite merged datasets.

![Figure 2](image2.png)

**Figure 2:** Annual variability of the O₃MD (Mt) for the latitudinal belt 35°-50° of the Northern Hemisphere as derived by the KNMI and DLR satellite merged datasets.

Figure 3 depicts the maximum size of the O₃ hole (blue line) and the lowest total O₃ value in the O₃ hole (orange line) using the threshold of O₃<220DU for each year since 1979. Particularly the blue line shows the variability of the annual maximum O₃ hole area. It is shown that the Antarctic O₃ hole reached its greatest size in year 2000. GOME, EPTOMS and MERGED satellite datasets show that that year the O₃ hole covered more than 28 million km². The maximum extent of the O₃ hole area exceeded 10 million km² in the mid-1980s and reached 22 million km² during the 1990s. In the last ten years except 1999, 2002, 2004 and 2007 (when there was an earlier polar vortex breakdown) the maximum observed surface O₃ hole area was >25 million km², while the last six years it seems that it
reached a plateau around 26 million km$^2$, with no tendency to become smaller. The orange line depicts the variability of the annual lowest O$_3$ value. The minimum O$_3$ value was observed in 2006 and was 89DU, almost twenty years after the Montreal Protocol has been implemented. In the last decade the annual minimum O$_3$ value was <108DU. The same stabilising behaviour seems to apply to the minimum O$_3$ value as well for last six years.

Figure 3: Variability of i) the annual maximum O$_3$ hole area (blue line) and ii) the annual minimum total O$_3$ value inside the O$_3$ hole (orange line).

In Figure 4 the observations show the annual variability of the date of the O$_3$ hole disappearance over Antarctica, as derived from 7 different satellite data sets depicted with different coloured line as yearly averages. It is interesting to note that there is a general agreement between the satellite data sets during their overlapping time period and that there is a consistency between the merged data set and that of the individual satellites. Except for the beginning of 1980s and the years 1988, 2002, 2004 the O$_3$ hole disappearance occurs after the middle of November due to the springtime breakdown of the polar stratospheric vortex.

Figure 4: Annual variability of the disappearance date of the O$_3$ hole over the Antarctic region.
Figure 5 depicts the seasonal variability of the O$_3$ hole surface area over Antarctica for each day over the last three 10-year periods from the KNMI merged dataset. The maximum observed O$_3$ hole area was 11.3, 22.7, 24.2 Mkm$^2$ during 1979-1988, 1989-1998 and 1999-2008 respectively. It is shown that as the years pass the increase in the maximum observed O$_3$ hole surface area is lower and the date of appearance of this maximum is shifted to earlier dates in the winter spring period of Southern Hemisphere due to the earlier breakdown of the polar stratospheric vortex.

![Figure 5: Seasonal variability of the O$_3$ hole surface area per decade over Antarctica as derived from the merged KNMI dataset.](image)

The seasonal variability of the O$_3$ hole surface area over Antarctica for each day over the last 3 years, as observed by GOME2 instrument, is presented in Figure 6. It is shown that there are not many differences between the O$_3$ hole surface area variability in the last 3 years and the values are comparable with the mean values of the O3 hole area in the last decade (black line).

![Figure 6: Seasonal variability of the O$_3$ hole surface area per decade over Antarctica as derived from the GOME-2 satellite instrument.](image)

It is known that the main O$_3$ decline is observed in the lower stratosphere and the O$_3$ loss over both hemispheres is very sensitive to the year-to-year variability of stratospheric temperatures which depend on atmospheric motions (e.g. Balis et al., 2009) The year-to-year variability of the O$_3$MD, inside the -10% deviation contours, in the northern and southern polar region is highly correlated with the corresponding year-to-year variability of the seasonal averaged temperatures in the lower
stratosphere as indicated in Figures 7 and 8. Colder temperatures result in more polar stratospheric clouds which intensify O\textsubscript{3} destruction. The latter is obvious in Figure 7 where we can see that the winters of 1993, 1996 and 1997 were really cold in the Northern Hemisphere, with stratospheric temperatures lower than 210K, and the corresponding O\textsubscript{3}MD remarkably large (more than 4500Mt). Rapid destruction of ozone in the early spring is associated with polar stratospheric clouds accompanying very cold temperatures near the South Pole, which are associated with a strong polar vortex (Weare, 2009, Harris et al., 2010). The disappearance of the O\textsubscript{3} hole in 1988 and 2002 over Antarctica, discussed above, is also demonstrated in Figure 8 with small O\textsubscript{3} mass deficiency values combined with relatively high stratospheric temperatures.

In the last two Figures it is apparent that the O\textsubscript{3}MD in regions poleward of 60°N was almost similar with that over Antarctica in late 1980s and early 1990s. However, a plateau around 2000Mt is observed for the last ten years over the Northern Hemisphere, whereas at the same time the O\textsubscript{3}MD presents a positive trend (i.e. increasing O\textsubscript{3}MD) over Antarctica. We should note at this point that the individual satellite datasets provide a similar picture as the one shown for the merged dataset as far as the year-to-year O\textsubscript{3}MD variability over both hemispheres is concerned and as such, is not shown here.

**Figure 7:** Annual variability of the O\textsubscript{3}MD and the seasonal averaged stratospheric temperatures over Arctic.

**Figure 8:** Annual variability of the O\textsubscript{3}MD and the seasonal averaged stratospheric temperatures over Antarctica.
CONCLUSIONS

Satellite instruments have made significant contributions to the study of stratospheric ozone depletion. The O₃ hole characteristics presented in this paper are based on observations derived by seven different satellite data sets, Nimbus 7/TOMS, EarthProbe/TOMS, GOME/ERS-2, SCIAMACHY/Envisat, OMI/Aura and GOME-2/MetOp which provide consistent results on a yearly basis during their common time periods. The KNMI total ozone merged dataset used in our analysis show good agreement with the DLR merged dataset when the O₃ areal extent with negative deviations and the O₃MD inside the latitudinal belt 35°N-50°N are calculated. The O₃ hole characteristics demonstrate that the Antarctic spring ozone decline increased rapidly toward the end of the 1980s, continued unabated through the 1990s and reached the highest values so far in the 1998, 2000 and 2006 ozone hole seasons, with no signs of becoming smaller. It has also been shown that over the last ten years seasonally integrated O₃MD over Antarctic reached a record low in 2006 about 8000 Mt, while the maximum observed size of the ozone hole was more than 28 million km² in year 2000. Furthermore, the O₃MD in region poleward of 60°N was almost similar with that over Antarctica in late 1980s and early 1990s and in the last ten years it reached a plateau around 2000 Mt. The temporal and spatial patterns of changes in O₃ and lower stratospheric temperature indicate a strong correlation and are associated with the year-to-year variability of the dynamic processes.

Acknowledgments: We would like to thank the KNMI and DLR scientific team for providing the satellite data.

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