Observed and modelled record ozone decline over the Arctic during winter/spring 2011

D. Balis,[1] I. S. A. Isaksen,[2] C. Zerefos,[3,4] I. Zyrichidou,[1] K. Eleftheratos,[3] K. Tourpali,[1] R. Bojkov,[1] B. Rognerud,[2] F. Stordal,[2] O. A. Søvde,[5] and Y. Orsolini[6]

Received 10 August 2011; revised 2 November 2011; accepted 6 November 2011; published 1 December 2011.

[1] This work describes observational and modelling results of the ozone depletion which took place during the winter/spring of 2011 in the Arctic stratosphere. Assimilated total ozone data from GOME-2 were used to estimate the integrated ozone mass deficit at polar latitudes and the Oslo CTM2 model calculated low winter/spring ozone values over the Arctic, which compare well with the satellite observations. Model runs with and without chemistry in the Arctic during the winter/spring of 2011 show that the very low Arctic stratospheric air temperatures led to significant chemical ozone loss. The calculated winter/spring ozone mass deficit (O_3MD) reached extreme high values in 2011 (2700 Mt) and the seasonal zonal mean total ozone extreme low values of 333DU. Dynamics have set up the conditions for cold temperatures in the lower stratosphere in winter/spring of 2011. Comparison of ozone columns with the previous 13 years shows record low ozone column values during winter/spring in the Arctic in 2011. A comparison is also given with similar model studies for the overall warmer winter/spring of 2010 which show higher ozone column values and significantly less chemical ozone loss. The interannual variability of column ozone over the northern polar region is, as expected, highly correlated with the corresponding year-to-year variability of the seasonally-averaged temperatures in the lower stratosphere. **Citation:** Balis, D., et al. (2011), Observed and modelled record ozone decline over the Arctic during winter/spring 2011, *Geophys. Res. Lett.*, *38*, L23801, doi:10.1029/2011GL049259.

1. Introduction

[2] Over the high latitudes of the Northern Hemisphere severe chemically-induced ozone losses are observed during the winter/spring season [e.g., *Tilmes et al.*, 2006]. The interannual variability of the polar stratospheric temperatures, result to a corresponding variability in the chemical ozone loss which is confirmed also by modelling studies [e.g., *Tripathi et al.*, 2007]. Planetary waves are the dominant mechanism for the interannual variability, weak wave forcing resulting to very cold polar stratospheric air temperatures, while intense wave activity can result to warming of the lower polar stratosphere [*World Meteorological Organization*, 2010]. Although CFCs have been phased-out and their abundance in the atmosphere falls with time, because of their long lifetimes, their removal from the atmosphere is slow and ozone layer will remain vulnerable for a few more decades [*Zerefos et al.*, 2009]. Moreover, the stratosphere is predicted to cool, in parallel to the warming of the climate at the Earth's surface and the short and long-term processes that determine polar stratospheric temperatures in winter are complex [*Zerefos et al.*, 1994; *Rex et al.*, 2006]. These developments lead to the continuation of the ozone destroying effect of the remaining CFCs. After the PSC season is over, competition between ozone loss and recovery of the activated chlorine species into passive reservoir starts. Under such conditions, significant amounts of ozone are expected to be destroyed while these competing processes occur and the amount of ozone lost during this process depends on the degree of denitrification inside the vortex [*Schulz et al.*, 2000]. This paper describes observational and modelling characteristics of the unprecedented ozone depletion [*Manney et al.*, 2011], which occurred during the winter/spring period of 2011 over high latitudes in the Arctic stratosphere.

2. Data and Modelling Tools

2.1. Observations

[3] The focus of this study is to understand qualitatively and quantitatively the processes which caused the strong stratospheric ozone decline in the winter 2011 over the Arctic. The Multi Sensor Reanalysis total ozone dataset, briefly MSR [*Van der A et al.*, 2010] has been used throughout this work. This data set is the product of merging all available total ozone columnar data, measured in the near-ultraviolet on board polar orbiting satellites during the past thirty years. Satellites providing data were: TOMS (onboard Nimbus-7 and Earth Probe), SBUV (Nimbus-7, NOAA-9, NOAA-11 and NOAA-16), GOME (ERS-2), SCIAMACHY (Envisat), OMI (EOS-Aura) and GOME-2 (Metop-A). A bias correction scheme has been applied to all satellite observations, based on independent ground-based total ozone data from the World Ozone and Ultraviolet Data Centre of WMO. The correction is a function of the solar zenith angle, the viewing angle, the time (because the trend is also of concern) and stratospheric temperature.

[4] As a next step a data assimilation scheme is applied to create the global dataset of total ozone. The data assimilation method includes a sub-optimal implementation of the Kalman filter technique and it is based on a chemical transport model driven by the meteorological fields provided

[1]Laboratory of Atmospheric Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece.
[2]Department of Geophysics, University of Oslo, Oslo, Norway.
[3]Biomedical Research Foundation, Academy of Athens, Athens, Greece.
[4]Navarino Environmental Observatory, Messinia, Greece.
[5]Center for International Climate and Environmental Research Oslo, Oslo, Norway.
[6]Norwegian Institute for Air Research, Kjeller, Norway.

0094-8276/11/2011GL049259

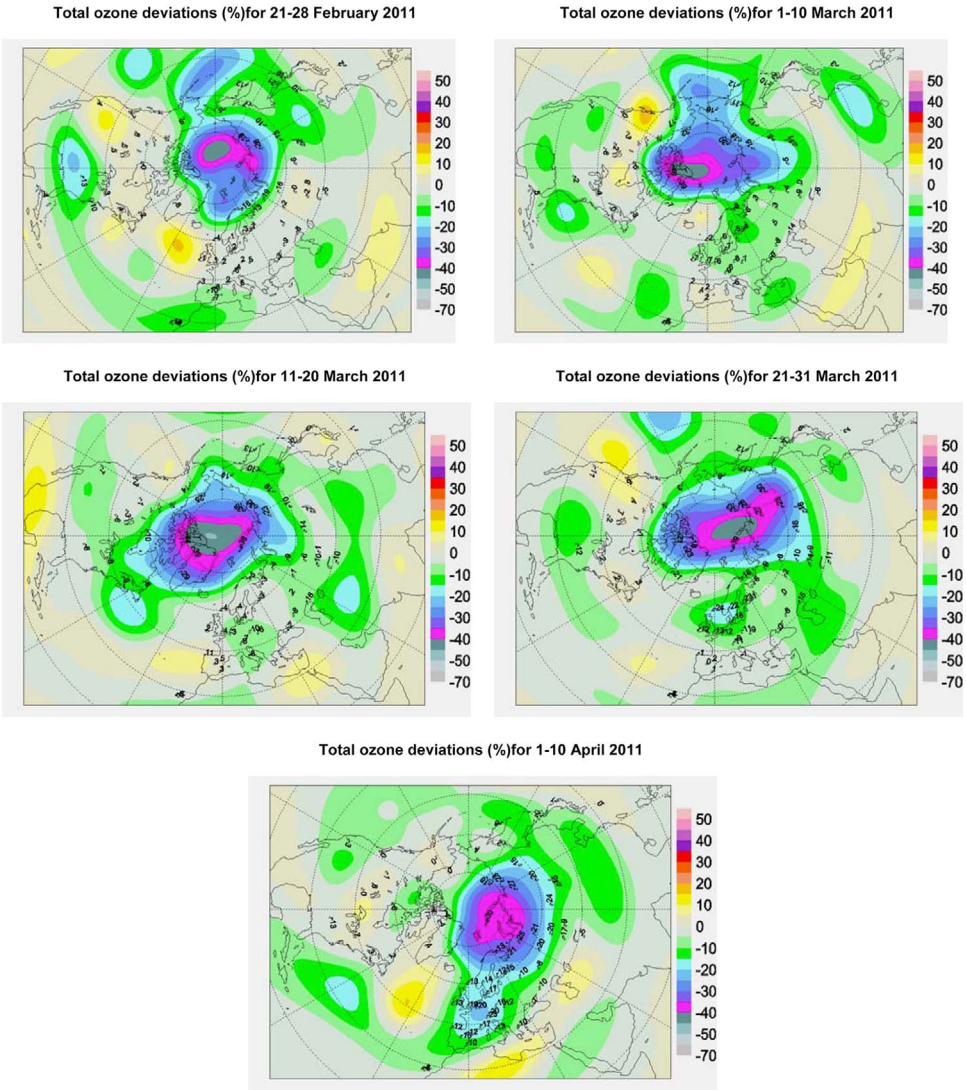

Figure 1. Spatial evolution of the total ozone deviations from the pre-1976 climatological means of the extreme low polar ozone event during winter-spring 2011 based on assimilated GOME-2 data and ground-based observations.

by ECMWF. The MSR total ozone dataset is available on a grid of 1 × 1.5 degrees latitude-longitude, with a sample frequency of 6 h for the time period 1978–2008 [*Van der A et al.*, 2010] (http://www.temis.nl/protocols/O3global.html). For the period after 2008, use was made of the corresponding data from GOME-2 (http://www.temis.nl/protocols/O3global.html). For the temperature data at 100 hPpa, the NCEP reanalysis data set was used, provided by the NOAA/OAR/ESRL PSD, Boulder, USA (http://www.cdc.noaa.gov). For the determination of the surface area of the polar vortex the potential vorticity at 475 K provided by ECMWF was used as an indicator.

[5] A daily Ozone Mass Deficit (O_3MD) was next estimated for the period from 1 January to 15 April 2011, as described by *Bojkov et al.* [1998]. The ozone mass deficit is defined as the product of the negative column ozone deviations at a certain grid point (in kgm^{-2}) from their pre-1976 climatic mean, multiplied by the surface area of the corresponding grid. Only deviations of less than −10% from the pre-1976 climatic means were considered, the −10% representing an approximate 2σ in statistical significance. The calculation of gridded daily climatic means was based on the period 1979–1981 of TOMS/Nimbus7 data, adjusted to 1976 using the existing zonal trends in total ozone in the late 70s as estimated from the ground-based measurements and partially verified by comparison with the first two years of BUV data [*Bojkov and Fioletov*, 1995] These deficits were subsequently added to arrive at an integrated ozone mass deficit (O_3MD), in megatons (Mt) for the given latitudinal belt/area and/or the time period of interest. Seasonal means for given latitude belts and/or areas were calculated subsequently. The O_3MD is an indicator based on the statistical significance of the observed negative deviations and is not directly comparable to the ozone loss.

2.2. Modelling Tools

[6] The Oslo CTM2 chemistry- transport model is used to study long term ozone changes and variations from 1997 to present on a day to day basis, but with focus on the ozone columns north of 60 degree N for the winter months of 2011 (January 1 to April 15). The model is run with 60 vertical sigma-pressure layers extending from the Earth's surface to

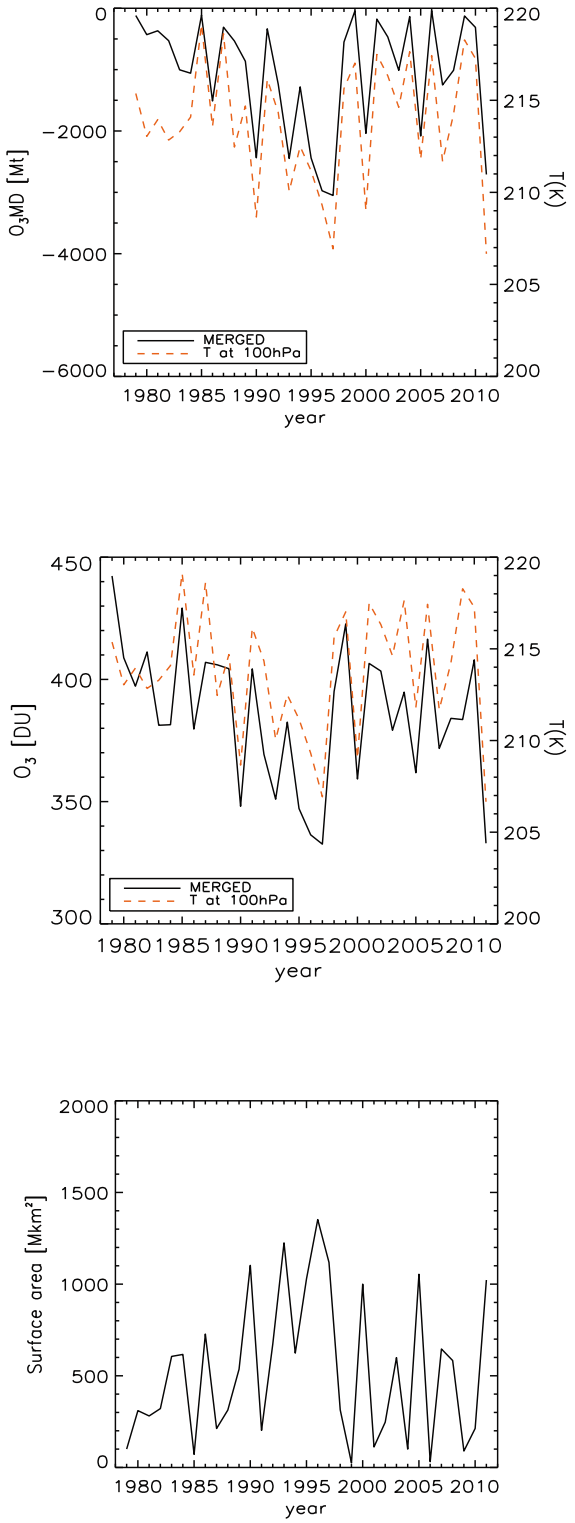

Figure 2. (top) O_3MD from pre-1976 averages, inside the −10% deviation contours, calculated from the merged data set and integrated for 105-days (1 Jan-15 Apr) in Mt inside the polar vortex for the period 1979–2011 together with the corresponding average temperatures at 100 hPa. (middle) Average total ozone for the same period and years as the upper panel, together with the corresponding average temperatures at 100 hPa. (bottom) Integrated area of the −10% ozone deviations contour inside the polar vortex for the same period and years.

0.1 hPa, and with a horizontal resolution of 2.81 degree (T42). The selection of upper boundary at 0.1 hPa, instead of at lower levels as in previous versions has improved stratospheric circulation, important for investigation of ozone variation and changes in the middle and upper stratosphere [*Søvde et al.*, 2008]. The vertical resolution in the tropopause region is typically 0.8 km to 1.2 km.

[7] The model has extensive tropospheric and stratospheric chemistry, including stratospheric particles and PSCs parameterizations, which affect the partitioning of NOy, ClX, BrX, and thereby the stratospheric production and loss of ozone at high latitudes during winter months [*Søvde et al.*, 2007, 2011]. The Oslo CTM2 is a free running CTM, with surface emissions set at the year 2000 (C. Granier et al., POET, a database of surface emissions of ozone precursors, 2005, available at http://www.aero.jussieu.fr/projet/ACCENT/POET.php). Boundary conditions for stratospheric species are set at the surface and at the model top as explained by *Søvde et al.* [2008]. Advective transport is carried out with the low diffusive second order moments scheme [*Prather*, 1986]. For calculation of photo-dissociation coefficients the Fast-J2 method is used [*Wild et al.*, 2000; *Bian and Prather*, 2002]. The model is driven by 3-hourly meteorological forecast data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS) model, which are produced with 12 hours of spin-up starting from an analysis at noon on the previous day. Another technical improvement is the update of the meteorological data driving the Oslo CTM2, which has been updated to ECMWF IFS cycle 36. Several comparisons of modelled ozone and ozone column distributions with observations show that estimated distributions in the troposphere and the stratosphere is well represented in the model [*Isaksen et al.*, 2005; *Sausen et al.*, 2005; *Hoor et al.*, 2009; *Eleftheratos et al.*, 2011; *Søvde et al.*, 2011].

3. Results and Discussion

[8] During the period from February to April 2011 over the polar latitudes of the Northern hemisphere, persistent extreme low total ozone values were observed reaching, on a daily basis, values about 40% lower than their pre-1976 climatological mean levels. Figure 1 shows the spatial and temporal evolution of the event, as this is demonstrated in ten-day average total ozone deviation maps based on combined assimilated GOME-2 data and ground based Dobson, Brewer and m-124 observations. These daily maps are operationally produced at the WMO Northern Hemisphere Ozone Mapping Centre at Thessaloniki, Greece. During the last days of February 2011, the vortex was almost circumpolar with small filaments over the North Pacific and with total ozone values about 50% below their climatological mean. During March 2011 the area determined from the −50% deviation contour was enlarged and the vortex was elongated towards Northern Canada and Siberia, resulting there to low ozone levels of almost 40% below the pre-1976 average levels. During the first week of April 2011 the vortex was shifted towards Siberia and Northern Scandinavia with persistent low ozone values (−40%) and polar air was advected over Central Europe resulting to the reduction of column ozone 30% below their pre-1976 values.

[9] To put these low values in perspective, we present in Figure 2 (top) a time series of the ozone mass deficit

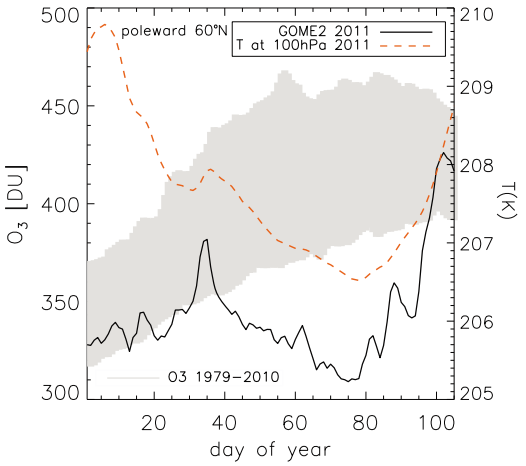

Figure 3. Comparison of the evolution of the mean total ozone and corresponding mean temperatures at 100 hPa north of 60°N during the first 105 days of 2011 based on analysis of GOME-2. The shaded area represents the 2σ envelope of the 1979–2010 mean ozone.

(O_3MD) in Mt. Calculations came from the merged data set and were integrated for the 105-day period (1 Jan.-15 Apr.) and for the area determined by the polar vortex, for each year between 1979 and 2011. These estimates are plotted together with the corresponding average temperatures at 100 hPa. The middle panel shows for comparison, the mean total ozone for the same days of the year, and the average air temperatures at 100 hPa again inside the polar vortex. In the lower panel we present the integrated surface area of the polar vortex over the same 105-day period for each year. As it appears from Figure 2, the seasonal mean total ozone inside the polar vortex reached in 2011 the record low value of 333 DU. The integrated O3MD inside the vortex in 2011 was slightly smaller than the one estimated for 1997 (2708 and 3050 Mt respectively). However, as it is demonstrated in Figure 2 (bottom), the integrated area of the −10% deviation contour inside the polar vortex was much smaller in 2011 than in 1997, indicating that the O_3MD was more dense in 2011. From Figure 2 (bottom) it is evident that the year-to-year variability in ozone highly depends on the corresponding variability of the stratospheric temperatures, which are indicative for the prevailing dynamics over the Arctic.

[10] Figure 3 shows the evolution of the mean total ozone north of 60°N during winter/spring 2011, based on GOME-2 and the corresponding mean temperatures at 100 hPa. In addition the 2σ envelope of the 1979–2010 mean ozone is shown based on the merged ozone data set. There is a minor midwinter warming observed in late January, but then between days 40 and 80, the stratospheric temperatures reached very low zonal mean values below 207 K, which as shown in the following, resulted to lowering the zonal mean ozone values to reach extreme values as low as 310 DU, residing outside the 1979–2010 range. The temperature increase induced by changes in the dynamics led after that day to a relative fast recovery of ozone reaching values greater than 400 DU.

[11] The observed ozone columns were compared to model estimates (Figure 4) for 2011 for the same latitudes. Figure 4 shows that on a day by day basis, the model calculations are in good agreement with the observed ozone variability during most of the period under study when chemistry is included. Only in the last few days of the period under study (beginning of April), the observed ozone columns are higher than modelled. An additional calculation where ozone chemical loss in the Arctic is omitted during the period demonstrates clearly that interaction with the gas phase chemistry contributed significantly to the reductions in the ozone column. The day by day range of modelled ozone column for the time period 1998 to 2010 is also shown in Figure 4. Figure 4 demonstrates clearly that the ozone column is lower than the previous 13 years during February and March. A similar presentation is also given for 2010 showing that ozone columns are on the high side during winter/spring in 2010. Table 1 shows the estimated ozone column reduction due to Arctic winter/spring chemistry at the end of March. A comparison is made with similar modelling studies for the same region during the winter months of 2010, when the ozone columnar levels during February and March were significantly higher than in 2011

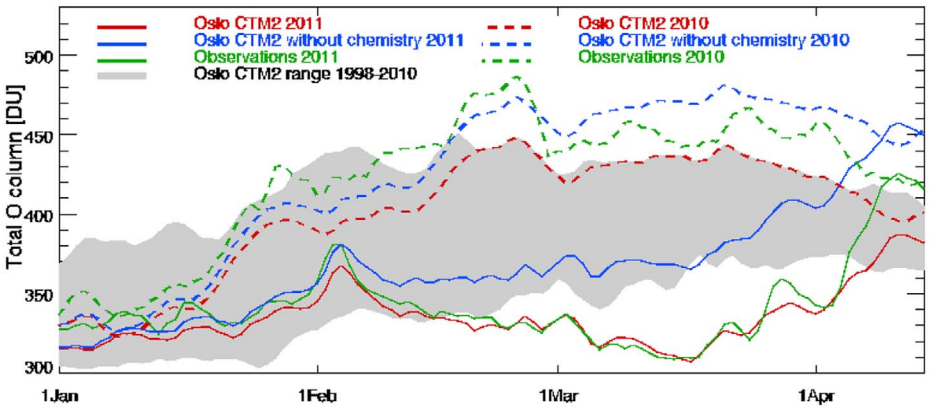

Figure 4. Observed and modeled day to day variation in ozone columns in the Arctic (north of 60 degree N) for the first 105 days of 2010 (dashed lines) and 2011(full lines). Observed values (green) are data from satellite observations (GOME-2) and model values, are with atmospheric chemistry (green). In addition a model run without ozone chemistry north of 60 degree N is included (blue). The shaded area gives the day by day range in Arctic winter/spring ozone column for the years 1998–2010.

Table 1. Comparisons of Chemical Ozone Loss During 2011 and 2010 and Ozone Column Differences Between Observations and Model Results

	Reduction From Chemistry End of March	Difference Between Observations and Model End of March
2011	65.0 DU 20.3%	7.1 DU 2.1%
2010	40.0 DU 9.4%	25 DU 5.9%

(450 DU compared to 330 DU). We see from Table 1 that the chemical loss in the Arctic winter was significantly larger during 2011 than in 2010. The chemical loss by the end of March is approximately twice as large (in %) in 2011 as in 2010. Included are also the differences from the observed ozone column for the two months under study. The match between observations and modelling is excellent during February and March in 2011, when substantial chemical destruction of ozone is expected to occur.

4. Conclusions

[12] In this study the characteristics of the Arctic ozone depletion during the winter/spring period of 2011 have been analyzed, using assimilated (GOME-2) and modelled (Oslo CTM2) calculations. Observations over the polar latitudes of the Northern Hemisphere showed that during the period from February to April 2011, persistent extreme low total ozone values occurred, reaching regionally on a daily basis values even lower than 50% from their climatological mean levels. The calculated winter/spring ozone mass deficit (O_3MD) reached extreme high values in 2011 (2700 Mt) and the seasonal zonal mean total ozone extreme low values of 333 DU.

[13] Calculations with the Oslo CTM2 reproduced well the winter/spring time low ozone values in the Arctic when both chemistry and transport were included. Comparison of model runs with and without chemistry in the Arctic for the 105-day period of study (1 Jan.-15 Apr.) in 2011, showed that the very low Arctic stratospheric temperatures set up the scenario for a significant chemical ozone depletion in the cold areas of the Arctic stratosphere.

[14] **Acknowledgments.** This work was partially supported by the Mariolopoulos-Kanaginis Foundation for the Environmental Sciences, the Navarino Environmental Observatory (N.E.O), Greece, the EU funded project SCOUT-O3 (505390-GOCE-CT-2004) and the Norwegian Research Council (Project 188134/E10). The merged ozone data were made available through TEMIS.

[15] The Editor thanks M. von Hobe and an anonymous reviewer for their assistance in evaluating this paper.

References

Bian, H. S., and M. J. Prather (2002), Fast-J2: Accurate simulation of stratospheric photolysis in global chemical models, *J. Atmos. Chem.*, *41*(3), 281–296, doi:10.1023/A:1014980619462.

Bojkov, R. D., and V. E. Fioletov (1995), Estimating the global ozone characteristics during the last 30 years, *J. Geophys. Res.*, *100*, 16,537–16,551, doi:10.1029/95JD00692.

Bojkov, R. D., D. S. Balis, and C. S. Zerefos (1998), Characteristics of the northern polar and mid latitude ozone decline, *Meteorol. Atmos. Phys.*, *69*, 119–135, doi:10.1007/BF01025187.

Eleftheratos, K., C. S. Zerefos, E. Gerasopoulos, I. S. A. Isaksen, B. Rognerud, S. Dalsoren, and C. Varotsos (2011), A note on the comparison between total ozone from Oslo CTM2 and SBUV satellite data, *Int. J. Remote Sens.*, *32*(9), 2535–2545, doi:10.1080/01431161003698401.

Hoor, P., et al. (2009), The impact of traffic emissions on atmospheric ozone and OH: Results from QUANTIFY, *Atmos. Chem. Phys.*, *9*, 3113–3136, doi:10.5194/acp-9-3113-2009.

Isaksen, I. S. A., C. Zerefos, K. Kourtidis, C. Meleti, S. B. Dalsøren, J. K. Sundet, A. Grini, P. Zanis, and D. Balis (2005), Tropospheric ozone changes at unpolluted and semipolluted regions by stratospheric ozone changes, *J. Geophys. Res.*, *110*, D02302, doi:10.1029/2004JD004618.

Manney, G. L., et al. (2011), Unprecedented Arctic ozone loss in 2011, *Nature*, *478*, 469–475, doi:10.1038/nature10556.

Prather, M. J. (1986), Numerical advection by conservation of second-order moments, *J. Geophys. Res.*, *91*, 6671–6681, doi:10.1029/JD091iD06p06671.

Rex, M., et al. (2006), Arctic winter 2005: Implications for stratospheric ozone loss and climate change, *Geophys. Res. Lett.*, *33*, L23808, doi:10.1029/2006GL026731.

Sausen, R., et al. (2005), Aviation radiative forcing in 2000: An update on IPCC (1999), *Meteorol. Z.*, *14*, 555–561, doi:10.1127/0941-2948/2005/0049.

Schulz, A., et al. (2000), Match observations in the Arctic winter 1996/97: High stratospheric ozone loss rates correlate with low temperatures deep inside the polar vortex, *Geophys. Res. Lett.*, *27*, 205–208, doi:10.1029/1999GL010811.

Søvde, O. A., M. Gauss, I. S. A. Isaksen, G. Pitari, and C. Marizy (2007), Aircraft pollution—A futuristic view, *Atmos. Chem. Phys.*, *7*, 3621–3632, doi:10.5194/acp-7-3621-2007.

Søvde, O. A., M. Gauss, S. P. Smyshlyaev, and I. S. A. Isaksen (2008), Evaluation of the chemical transport model Oslo CTM2 with focus on arctic winter ozone depletion, *J. Geophys. Res.*, *113*, D09304, doi:10.1029/2007JD009240.

Søvde, O. A., Y. J. Orsolini, D. R. Jackson, F. Stordal, I. S. A. Isaksen, and B. Rognerud (2011), Estimation of Arctic O_3 loss during winter 2006/2007 using data assimilation and comparison with a chemical transport model, *Q. J. R. Meteorol. Soc.*, *137*, 118–128, doi:10.1002/qj.740.

Tilmes, S., R. Müller, A. Engel, M. Rex, and J. M. Russell III (2006), Chemical ozone loss in the Arctic and Antarctic stratosphere between 1992 and 2005, *Geophys. Res. Lett.*, *33*, L20812, doi:10.1029/2006GL026925.

Tripathi, O. P., et al. (2007), Comparison of polar ozone loss rates simulated by one-dimensional and three-dimensional models with Match observations in recent Antarctic and Arctic winters, *J. Geophys. Res.*, *112*, D12307, doi:10.1029/2006JD008370.

Van der A, R. J., M. A. F. Allaart, and H. Eskes (2010), Multi sensor reanalysis of total ozone, *Atmos. Chem. Phys.*, *10*, 11,277–11,294, doi:10.5194/acp-10-11277-2010.

Wild, O., X. Zhu, and M. J. Prather (2000), Fast-J: Accurate simulation of in- and below-cloud photolysis in tropospheric chemical models, *J. Atmos. Chem.*, *37*(3), 245–282, 644, doi:10.1023/A:1006415919030.

World Meteorological Organization (2010), Scientific assessment of ozone depletion 2010, *Ozone Res. Monit. Proj. Rep. 50*, Geneva, Switzerland.

Zerefos, C. S., K. Tourpali, and A. F. Bais (1994), Further studies on possible volcanic signal to the ozone layer, *J. Geophys. Res.*, *99*, 25,741–25,746, doi:10.1029/94JD02142.

Zerefos, C. S., G. Skalkeas, and G. Contopoulos (Eds.) (2009), *Twenty Years of Ozone Decline*, Springer, Dordrecht, Netherlands, doi:10.1007/978-90-481-2469-5.

D. Balis, R. Bojkov, K. Tourpali, and I. Zyrichidou, Laboratory of Atmospheric Physics, Aristotle University of Thessaloniki, Campus Box 149, GR-54124 Thessaloniki, Greece. (balis@auth.gr)

K. Eleftheratos and C. Zerefos, Biomedical Research Foundation, Academy of Athens, 4 Soranou Ephessiou, GR-11527 Athens, Greece.

I. S. A. Isaksen, B. Rognerud, and F. Stordal, Department of Geophysics, University of Oslo, PO Box 1022 Blindern, N-0315 Oslo, Norway.

Y. Orsolini, Norwegian Institute for Air Research, PO Box 100, N-2027 Kjeller, Norway.

O. A. Søvde, Center for International Climate and Environmental Research - Oslo, PO Box 1129 Blindern, N-0318 Oslo, Norway.