Attribution of the Arctic ozone column deficit in March 2011

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[1] Arctic column ozone reached record low values (~310 DU) during March of 2011, exposing Arctic ecosystems to enhanced UV-B. We identify the cause of this anomaly using the Oslo CTM2 atmospheric chemistry model driven by ECMWF meteorology to simulate Arctic ozone from 1998 through 2011. CTM2 successfully reproduces the variability in column ozone, from week to week, and from year to year, correctly identifying 2011 as an extreme anomaly over the period. By comparing parallel model simulations, one with all Arctic ozone chemistry turned off on January 1, we find that chemical ozone loss in 2011 is enhanced relative to previous years, but it accounted for only 23% of the anomaly. Weakened transport of ozone from middle latitudes, concurrent with an anomalously strong polar vortex, was the primary cause of the low ozone When the zonal winds relaxed in mid-March 2011, Arctic column ozone quickly recovered. **Citation:** Isaksen, I. S. A., et al. (2012), Attribution of the Arctic ozone column deficit in March 2011, *Geophys. Res. Lett.*, *39*, L24810, doi:10.1029/2012GL053876.

1. Introduction

[2] A large deficit in column ozone relative to the previous 13 years of observations - was observed in the Arctic stratosphere during February- March of 2011. This low ozone resulted in record high UV-B exposure of the Arctic ecosystems in the early spring and thereby environmental damage [*Callaghan et al.*, 2004; *Solheim et al.*, 2006]. Persistent, low values for column ozone, concurrent with colder stratospheric temperatures, were observed in the Arctic (60°N–90°N), with ozone columns 20% or more below their 1998–2010 averages, showing a steep gradient from mid-latitudes to the Arctic. Even in terms of large-scale averages (60°N–90°N, month of March), this 2011 Arctic column ozone was about three standard deviations below the 1997–2011 mean-sigma anomaly. This apparent Arctic ozone hole could be part of a pattern of enhanced halocarbon-driven chemical loss of ozone that arises during particularly cold winters [*Manney et al.*, 2011; *Sinnhuber et al.*, 2011; *Tilmes et al.*, 2006], one that could worsen in the coming decades as a result of greenhouse gases cooling the stratosphere. Here we use a chemistry-transport model that simulates the recent historical record of Arctic column ozone to separate the causative factors and place upper limits on the attribution of the 2011 ozone deficit to halogen-driven ozone depletion. The impact of chemistry and dynamics on stratospheric ozone in the polar regions has been extensively reviewed [*Holton et al.*, 1995; *Solomon*, 1999; *Tripathi et al.*, 2007; *World Meteorological Organization*, 2010]. The meridional transport of heat and ozone from the mid-latitudes into the polar stratosphere is slow in the winter and early spring when the polar wind vortex is strong. Such conditions occur regularly in the Antarctic and less so in the Arctic where the vortex often breaks down in mid-winter. This isolation of the polar stratosphere maintains the cold temperatures that form polar stratospheric clouds (PSCs), activate chlorine and bromine radicals, and rapidly destroy ozone through chemical catalytic cycles. Previous studies have examined the effects of transport and chemistry on interannual variability of ozone in the Arctic. *Chipperfield and Jones* [1999] conclude that ozone variability averaged over the Arctic for the period 1990–1998 was dominated by changes in transport. *Tegtmeier et al.* [2008] examined ozone changes within the polar vortex (rather than over a fixed range of latitudes) and concluded that both transport and chemistry contributed to variability during the period from 1992 to 2004.

[3] In this study the focus is on the very low column ozone values observed in the Arctic stratosphere during late winter of 2011. We separate the role of chemical and dynamical (i.e., transport) processes affecting ozone in the Arctic region from 60°N to 90°N and from January through March. The Arctic stratospheric vortex is constantly moving, tilting, changing shape and size, and mixing with mid-latitude air at its edge. Our focus is on environmental damage associated with extreme low ozone events in the Arctic spring, and thus we diagnose total column ozone averaged monthly over a larger Arctic region (60°N–90°N). For the most part on any day, this region contains the vortex (see discussion in the auxiliary material and Figure S3).[1] Focusing on 60°N to 90°N and March is similar to previous analysis [*Eyring et al.*, 2010a], and parallel analysis for a more restricted region (65°N–90°N) does not change these results. The 2011 observations are placed in perspective by comparing with the previous 13 winters (1998–2010), and our reference climatology includes years 1997–2011 (see Table 1). We compare

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Table 1. Artic Ozone Columns and Anomalies (DU) at the End of Winter From Observations and Modeled by Oslo CTM2[a]

	'97	'98	'99	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11
Observed	330	415	451	377	452	417	417	415	409	431	392	424	443	464	327
obs. anomaly	−87	−2	34*	−40	35	0	0	−2	−8	14	−25	7	26	47*	−90
modeled		408	425	367	426	393	391	392	379	406	384	397	402	433	325
model – obs.		−7	−26*	−10	−26*	−24	−26	−23	−30	−25	−8	−27	−41	−31*	−2
model anomaly[A]		13	30	−28	31	−2	−4	−3	−16	11	−11	2	7	38	−70
net chemistry change		−37	−33	−42	−33	−37	−34	−29	−43	−26	−44	−44	−30	−35	−53
chemistry anomaly[B]		0	4	−5	4	0	3	8	−6	11	−7	−7	7	2	−16
transport anomaly[C]		13	26	−23	27	−2	−7	−11	−10	0	−4	9	0	36	−54

[a]Values are averaged over 60°N-90°N and the month of March. Anomalies are defined relative to the 1998–2011 average (observed = 417 ± 34 DU, modeled = 395 ± 26 DU). The two series having correlation R2 = 0.94. The winter of 1997 could not be modeled due to the lack of meteorological fields. Note that anomalously high years (* = 1999, 2001, 2010) are all underestimated by the model. Net chemistry is calculated by the model difference when all ozone chemical tendencies 60°N–90°N are shut off Jan 1. The net chemistry change is −37 ± 7 DU. Transport anomaly is inferred from the difference between model anomaly and chemistry anomaly (C = A – B; round off may prevent some sums from exactly matching).

GOME and GOME-2 ozone observations [*Hoogen et al.*, 1999; *Meijer et al.*, 2006] with hindcasts from the Oslo chemistry-transport model (CTM2) driven with ECMWF meteorology at T42L60 (2.8° × 2.8° × 60-layers) resolution [*Søvde et al.*, 2008, 2011]. Both observations and model results for Arctic column ozone for March 1998–2011 are given in Table 1 along with their anomalies. The model is biased low by about 20 DU out of 420 DU, with most of the bias coming from years with anomalously high column ozone. Observed and modeled anomalies are highly correlated (R^2 = 0.94). The March 2011 Arctic column ozone stands out as an extreme event, being 2.x stdev below the mean in both series.

2. Transport Versus Chemistry in Arctic Ozone

[4] The two consecutive years 2010 and 2011 provide an ideal contrast in terms of the Arctic wintertime stratosphere. Since 1997, the highest end-of-winter ozone was in year 2010, and the lowest, 2011 (see Table 1). The stratospheric zonal winds circumscribing the polar vortex (60°N–70°N) were fragmented and weak in 2010, with a sudden warming occurring at the end of January, followed by a zonal wind reversal [*Dörnbrack et al.*, 2012] (see also auxiliary material and Figure S4). The zonal wind distribution during winter and early spring is a good indication of the isolation of the Arctic vortex and the -strength of the ozone transport to high latitudes. For 2011, winds remained strong (>30 m/s) through the second half of March, and the breakup of the Arctic vortex did not occur until spring. The year 1997 was the most recent year with meteorology similar to 2011 and with Arctic column ozone as low as 2011 (for analysis see *Chipperfield and Jones* [1999] and *Newman et al.* [2001]). All intervening years (1998–2010) had weaker Arctic vortices and much larger column ozone in March. The CTM model simulations for Arctic column ozone are also summarized in Table 1 for years 1998–2011. We could not model earlier years due to the lack of suitably processed meteorological data needed for tracer transport.

[5] The daily variations of Arctic column ozone (60°N–90°N average) from January 1 through April 14 are shown in Figure 1a for year 2011, year 2010 and the range of years 1998 to 2009. Both model and observations are plotted. For years 2010 and 2011, shown individually, the observed overall development of column ozone and its weekly synoptic variability are well captured by the model. In mid-March of 2011, column ozone values fall to a minimum 310 DU in both model and observations. Column ozone increases slowly during the second half of March 2011 and then rapidly during the two first weeks of April. For 2010 the overall development and synoptic ozone variability is also good, although the model underestimates ozone values by up to 30 DU. Too efficient Arctic chemical loss during warmer years is one possible part of the reason for the model's low bias.

[6] To separate the roles of changing chemistry from changing dynamics, we make additional idealized model simulations with all Arctic chemistry shut off. We eliminate both gas phase and heterogeneous ozone chemistry north of 60°N beginning January 1 and follow the evolution of Arctic ozone into April. In these no-chemistry CTM2 simulations (Figures 1b–1d), ozone is a passive tracer north of 60°N, but chemistry occurring south of 60°N still influences our Arctic region through transport across 60°N. The no-chemistry model shuts off all ozone photochemistry, including for example both production by O_2 photolysis and destruction by reactions involving the ClO dimer. Thus the absolute difference between the standard and no-chemistry simulations does not directly measure the total impact of anthropogenic, halogen-driven ozone depletion. A more complex set of model simulations with pre-industrial and current abundances of the source gases (CFCs, N_2O, etc.) would be needed to fully assess the anthropogenic role here. Much of the middle and upper stratospheric ozone chemistry (e.g., O_2 photolysis) does not have large year-to-year differences due to the vortex differences, but PSC-mediated ozone depletion in the lower stratosphere is highly temperature sensitive, and thus most of the year-to-year variability reflects changes in the latter. Our relatively simple no-chemistry model allows us, therefore, to assess this year-to-year variations in PSC-driven ozone loss. The no-chemistry simulations are initialized each January 1 from the continuous, 14-year, standard model run with full chemistry.

[7] The no-chemistry model results are summarized in Figure 1b showing absolute column ozone from Jan 1 to Apr 14 for different years. Without chemistry, transport of mid-latitude ozone into the Arctic leads to regularly increasing column ozone in all years. With the strong, persistent vortex in 2011, ozone increases the least over this period. Differencing 2011 with all other years (Figure 1c) shows that for early January all years are similar and show almost no increase in Arctic column ozone (Figure 1b also). Starting in mid-January, year 2011 clearly separates itself from year 2010 and most other years, allowing for only a

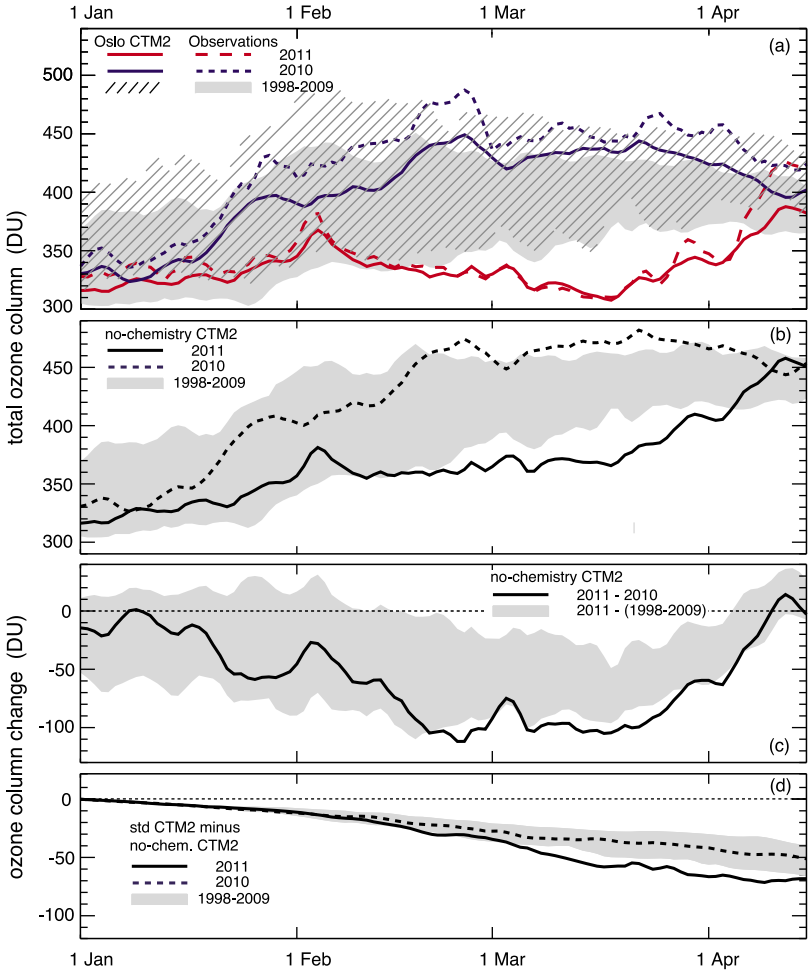

Figure 1. Observed and modeled column ozone (DU) in the extended Arctic region (60°N–90°N) over the period January 1 to April 14. (a) Results are shown for the years 2010 (blue lines) and 2011 (red lines), and range of years 1998–2009 (hatched or shaded). The standard Oslo CTM is shown with solid lines and hatched area; the observations are given with dashed lines and shaded area. (b) Results from the Oslo CTM2 when all Arctic ozone chemistry is shut off on Jan 1 (no-chemistry) are shown for 2011 (solid line) for 2010 (dashed) and the range of 1998–2009 (shaded area). (c) For the no-chemistry results, the relative change in column ozone (DU) for year 2011 minus year 2010 (solid line) and year 2011 minus all other years 1998–2009 (shaded area). (d) Arctic chemistry contribution to the column ozone change (DU), calculated as standard CTM2 minus no-chemistry CTM2 for year 2011 (solid line), year 2010 (dashed) and the range of years 1998–2009 (shaded area).

small increase. By mid-February, year 2011 stands out as unique, maintaining almost constant column ozone. This difference in the no-chemistry (i.e., transport-only) model simulations reached about −100 DU compared to year 2010 and averages about −50 DU for years 1998–2009. The weakening of the zonal winds in late March 2011 (Figure S4) coincides with the influx of mid-latitude ozone and the increase in column ozone. Figure 1d shows the differences, standard minus no-chemistry model, effectively documenting the monotonic, net chemical destruction of Arctic ozone through the winter. This measure of ozone chemical loss accelerates in late winter for all years as sunlight returns to the Arctic, but is particularly strong in 2011 due to the cold temperatures and persistence of PSCs. Note that chemical loss in 2010 is typical of all years, but that 2011 is extreme, far outside the range of all previous 13 years [*Manney et al.*, 2011; *Sinnhuber et al.*, 2011].

[8] A summary of these model results for the March average Arctic column ozone for years 1998–2011 is given in Table 1. For comparison the first two rows show the observed column ozone and its anomaly, where anomalies in this table are always defined relative to the 1998–2011 average. The modeled column ozone and anomalies are shown in rows 3–5. For 1998–2011, the observed column average and standard deviation is 417 ± 34 DU, and that of the model, 395 ± 26 DU. The year-to-year variability March column ozone is very well matched by the model with $R^2 = 0.94$ (see Figure 1a for weekly variability), but the model is biased low by about 20 DU as noted earlier. Given the standard deviation for this 14-year period, both observed and modeled anomalies in 2011 are three-sigma events. The modeled-observed differences (row 4) are largest for years with largest absolute column ozone values (1999, 2001, 2010). The modeled net chemistry change (row 6) is the March average of the results in Figure 1d. The transport anomaly (row 8, SD = 22 DU) for each year is calculated as the model anomaly (row 5, SD = 26 DU) minus the chemistry anomaly (row 7, SD = 7 DU). Thus anomalous transport is the primary cause of variability

in Arctic column ozone, in broad agreement with a study of earlier years, 1990–1998 [*Chipperfield and Jones*, 1999]. For year 2011 the anomalously low column ozone can be thus split into chemistry (−17 DU) and transport (54 DU). Nevertheless, both chemistry and transport anomalies for 2011 stand out as extreme, greater than two-sigma events, while the total anomaly is nearly three-sigma.

3. Discussion and Conclusions

[9] Analysis of the apparent Arctic ozone hole of March 2011, using both observations and the Oslo CTM2 model, places that extreme event in perspective as a 2- to 3-sigma anomaly. Model simulations of column ozone are in good agreement with the daily columns observed by satellite (GOME-2) as well as the Arctic-averaged column ozone for March over the 14-year period, 1998 through 2011. In terms of March average for the 14 years column ozone, model bias is small (−5%) and the correlation is high (R^2 = 0.94). In 2011, the Arctic ozone deficit first appears in late January and reaches a maximum in the middle of March, before a breakdown of the vortex and mixing with mid-latitude air masses. The year 1997, which experienced meteorological conditions similar to those in 2011, also had low Arctic column ozone [*Chipperfield and Jones*, 1999]. Year 2011 represents a record low in late winter Arctic column ozone that was accompanied by increased ozone outside the Arctic region [*Balis et al.*, 2011], a result shown by the Oslo CTM2. Such a pattern is consistent with reduced ozone transport into the Arctic and enhanced descent just outside the vortex.

[10] Using the model to separate the causes of the 2011 ozone deficit for the Arctic region, we infer that chemical loss during March 2011 was extreme, about −17 DU relative to the previous 13 years. The model simulations with and without Arctic chemistry show that year 2011 also had anomalously low transport of ozone into the Arctic region, about −59 DU relative to the other years. We conclude that the major part (78%) of the 2011 Arctic ozone deficit compared to the previous 13 years was caused by changes in the dynamics, with reduced transport of ozone from mid-latitudes.

[11] This analysis applies to an extended Arctic region (60°N–90°N, 13% of the NH area), which includes stratospheric ozone both inside and outside the shifting vortex. It is difficult to diagnose column ozone loss only within the polar vortex because the vortex air mass is not conserved and is not vertically aligned. If we take a more restrictive boundary for the vortex, such as the 70°N–90°N equivalent potential-vorticity latitude on the 475 K potential temperature surface (6% of the NH) and then apply the same boundary to all levels, then we diagnose greater chemical loss, about −95 DU at the end of March 2011. This more closely matches the chemical attribution of *Sinnhuber et al.* [2011] and is comparable to the −112 DU obtained by [*Kuttippurath et al.*, 2012] . Similarly, the modeled chemical loss within the vortex would be higher for all years. Our analysis of the extended Arctic region has effectively spread this loss over twice the area, but provides more reliable statistics for integrating chemical loss over the entire vortex. In terms of the apportionment of loss and the statistics of different years, this does not change our conclusions.

[12] The 2011 Arctic ozone deficit differs in nature from the Antarctic ozone hole because it was caused primarily by the prolonged presence of the stratospheric vortex and a consequent delay of transport from lower latitudes to the Arctic, rather than primarily by chemical ozone destruction. Year 2011 in the Arctic has some analogies with the pre-chlorine Antarctic ozone climatology [*Dobson*, 1966], beginning with the International Geophysical Year before chlorofluorocarbon levels were large enough to produce the Antarctic ozone hole [*Farman et al.*, 1985].

[13] Early springtime deficits of 100 DU averaged over the Arctic, even if occurring only every 14 years, will expose Arctic ecosystems to significantly greater UV-B. What can we expect through this century as stratospheric levels of chlorine and bromine decline and as CO_2 and other greenhouse gases drive climate change? On average, Arctic March column ozone has decreased about 30 DU from 1960 to 2010, but is projected to more than reverse that loss, increasing by ∼60 DU by 2100 [*Eyring et al.*, 2010a]. Thus a 2011-like ozone minimum in year 2100 might be only 390 DU compared with typical March averages of about 480 DU. The *Rex et al.* [2004] analysis developed an empirical model for Arctic ozone depletion that effectively assumed extreme winters like 1997 could be attributed to halogen-driven loss. Thus, the chance of a 100 DU ozone deficit would decrease in the next few decades as chlorine levels decline. This conclusion is clearly not right because 75% of the deficit in winters like 2011 is due to reduced transport into the persistent, strong Arctic vortex. The ability of the CTM to match the year-to-year variability (R^2 = 0.94) supports this conclusion. While there is clearly a correlation between a cold Arctic, PSC area and chemical ozone loss, there is also a correlation with an isolated vortex. Thus, given the dynamical conditions and late final warming as in 1997 and 2011 [*Black and McDaniel*, 2007], ozone deficits of 100 DU over the entire Arctic region could readily occur into the middle of the next century. Whether climate change will alter the frequency of these late final warmings is uncertain, and the recent CCMVal2 finds no significant trend in the timing of the final warming over the 21st century from the multi-model assessment [*Eyring et al.*, 2010b].

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