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Special Section:

The Exceptional Arctic Polar Vortex in 2019/2020: Causes and Consequences

Key Points:

- Local minimum ozone mixing ratios of 0.1–0.2 ppm observed by sondes in Arctic spring 2020 are significantly lower than in any previous year
- Local ozone loss (93%) and low mixing ratios are comparable to typical values in the Antarctic ozone hole (95–99%, 0.01–0.1 ppm)
- The reason for the unprecedented chemical loss was an unusually strong, long-lasting, and record cold polar vortex

Correspondence to:

I. Wohltmann,
ingo.wohltmann@awi.de

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Near-Complete Local Reduction of Arctic Stratospheric Ozone by Severe Chemical Loss in Spring 2020

I. Wohltmann¹ , P. von der Gathen¹ , R. Lehmann¹ , M. Maturilli¹ , H. Deckelmann¹ , G. L. Manney^{2,3} , J. Davies⁴ , D. Tarasick⁴ , N. Jepsen⁵ , R. Kivi⁶ , N. Lyall⁷ , and M. Rex¹ 

¹Alfred Wegener Institute for Polar and Marine Research, Potsdam, Germany, ²NorthWest Research Associates, Socorro, NM, USA, ³New Mexico Institute of Mining and Technology, Socorro, NM, USA, ⁴Air Quality Research Division, Environment and Climate Change Canada, Downsview, Ontario, Canada, ⁵Danish Meteorological Institute, Copenhagen, Denmark, ⁶Space and Earth Observation Centre, Finnish Meteorological Institute, Sodankylä, Finland, ⁷Lerwick Observatory, UK Met Office, Shetland Islands, UK

Abstract In the Antarctic ozone hole, ozone mixing ratios have been decreasing to extremely low values of 0.01–0.1 ppm in nearly all spring seasons since the late 1980s, corresponding to 95–99% local chemical loss. In contrast, Arctic ozone loss has been much more limited and mixing ratios have never before fallen below 0.5 ppm. In Arctic spring 2020, however, ozonesonde measurements in the most depleted parts of the polar vortex show a highly depleted layer, with ozone loss averaged over sondes peaking at 93% at 18 km. Typical minimum mixing ratios of 0.2 ppm were observed, with individual profiles showing values as low as 0.13 ppm (96% loss). The reason for the unprecedented chemical loss was an unusually strong, long-lasting, and cold polar vortex, showing that for individual winters the effect of the slow decline of ozone-depleting substances on ozone depletion may be counteracted by low temperatures.

Plain Language Summary The severe stratospheric chemical ozone loss in the Antarctic ozone hole and its impact on human health and climate have generated widespread public, political, and scientific interest. In contrast, Arctic stratospheric ozone reduction has been much more limited because of higher temperatures and higher transport variability in the Northern Hemisphere (lower temperatures lead to more chemical loss, and more transport can increase ozone values). In the Arctic spring 2020, however, observations of balloon sondes and satellites show that locally, absolute values of ozone (measured in mixing ratios, i.e., molecules of ozone per molecules of air) are significantly lower than in any previous year and are comparable to typical local values in the Antarctic ozone hole, albeit over a much narrower vertical layer. Locally, the chemical loss of ozone peaked at 93% in the Arctic spring of 2020, compared to values of 95–99% in the Antarctic in most winters since the late 1980s. The reason for the unprecedented loss was unusually cold and stable conditions in the Arctic stratosphere.

1. Introduction

The discovery of the Antarctic ozone hole in the 1980s (Farman et al., 1985) and of its impact on human health and climate generated widespread public, political, and scientific interest (e.g., WMO, 2018). Soon, chlorine and bromine released from decomposition of man-made chlorofluorocarbons (CFCs) and other ozone-depleting substances (ODS) in the upper atmosphere were identified as the cause of the ozone hole (Solomon et al., 1986). Chlorine is transformed from inactive reservoir gases to active chlorine species on the surfaces of polar stratospheric clouds, which only form at very low temperatures in polar winter. With the return of sunlight in spring, ozone is depleted by photochemical catalytic cycles. As a consequence of these discoveries, the production of CFCs was phased out by the Montreal protocol and chlorine levels have been slowly declining since about the year 2000 (e.g., WMO, 2018).

Ozone volume mixing ratios have been depleted from 1–3 ppm to extremely low values of 0.01–0.1 ppm in nearly all Antarctic spring seasons since the late 1980s in a wide altitude range from 360–510 K potential temperature (12–20 km; e.g., Kuttippurath et al., 2018; Solomon et al., 2014), corresponding to about 95–99% local chemical ozone loss. In recent decades, Antarctic ozone loss has reached saturation and is not expected to get any more severe (e.g., Kuttippurath et al., 2018). Early signs of a recovery due to the success of the Montreal protocol have been reported (e.g., Kuttippurath et al., 2018; WMO, 2018).

In contrast to the Antarctic, ozone depletion in the Arctic is usually much less pronounced and shows a much higher interannual variability because of the significantly higher stratospheric temperatures and higher dynamical activity in the Northern Hemisphere (e.g., Manney et al., 2011; Solomon, 1999; Solomon et al., 2014; Tegtmeier et al., 2008). In addition to less pronounced chemical depletion, ozone loss is masked by variable amounts of ozone transported in the Northern Hemisphere. On average, the variability of chemistry and transport contributes about equally to the interannual variability in Arctic polar ozone (Tegtmeier et al., 2008; Weber et al., 2011).

Ozone loss in the Arctic has ranged from almost no ozone loss in warm winters (e.g., 1998/1999 and 2018/2019) to the most severe depletion observed so far in the winter 2010/2011. Local minimum volume mixing ratios of about 0.5 ppm were observed in the winter 2010/2011 (Hommel et al., 2014; Manney et al., 2011; Solomon et al., 2014). Values reported for the ozone loss in 2010/2011 range from 2.3–2.6 ppm for the maximum loss in the vortex mean profile, corresponding to 60–80% relative loss and 84–120 DU for the column loss (e.g., Hommel et al., 2014; Kuttippurath et al., 2012; Manney et al., 2011; Pommereau et al., 2013; Sinnhuber et al., 2011; Solomon et al., 2014; Strahan et al., 2013). The wide range of values highlights the inherent uncertainty in calculating ozone loss caused by using different methods, data sets, vortex edge definitions, or altitude ranges (Griffin et al., 2019; Livesey et al., 2015). Here, we show that local ozone reduction in the winter 2019/2020 considerably exceeded the values reached in 2010/2011. Extremely low absolute values of ozone of 0.1–0.2 ppm were reached in some parts of the vortex for the first time.

2. Results

2.1. Temperatures

The reason for the unprecedented loss was an unusually strong, long-lasting, and record cold polar vortex (see Lawrence et al. (2020), this issue, e.g., Figures 10 and 11). The vortex lasted until early to mid-May and showed temperatures below the formation temperature of polar stratospheric clouds from mid-November to late March through early April (depending on altitude). The only winters previously observed in which low temperatures lasted until the end of March were 1996/1997 and 2010/2011 (Manney et al., 2011). Only the winters 1996/1997, 2004/2005, and 2010/2011 showed long periods below the formation temperature of polar stratospheric clouds comparable to 2019/2020 (e.g., Manney et al., 2011). The total volume of air exposed to low temperatures was larger in 2019/2020 than in any previous winter.

A useful metric for the temperatures in the polar vortex is the volume V_{PSC} of air below the threshold temperature for the formation of polar stratospheric clouds composed of nitric acid trihydrate (e.g., Harris et al., 2010; Manney et al., 2011; Rex et al., 2004, 2006; Tilmes et al., 2006). This threshold temperature is also comparable to the temperature below which chemical processing of chlorine reservoir gases on the other important cloud type (supercooled ternary $\text{H}_2\text{SO}_4/\text{HNO}_3/\text{H}_2\text{O}$ solutions) becomes important (e.g., Spang et al., 2018). Empirically, there is a high correlation between V_{PSC} integrated over the Arctic winter and the overall ozone loss integrated over the winter (e.g., Harris et al., 2010; Pommereau et al., 2018; Rex et al., 2004, 2006; Tilmes et al., 2006), and attempts have been made to explain this correlation (Harris et al., 2010). A related quantity is $V_{\text{PSC}}/V_{\text{vortex}}$, which takes into account the volume of the vortex V_{vortex} (e.g., Manney et al., 2011; Tilmes et al., 2006, 2008; von der Gathen et al., 2020). It is expected to correlate better with vortex-averaged ozone loss. It is also more directly comparable between the Arctic and the Antarctic (e.g., Tilmes et al., 2006).

The Arctic stratospheric winter 2019/2020 was the coldest winter on record in the last 41 years in terms of $V_{\text{PSC}}/V_{\text{vortex}}$ integrated over the winter. Figure 1a shows the time series of Arctic $V_{\text{PSC}}/V_{\text{vortex}}$ integrated over November–April for 1979/1980–2019/2020 based on meteorological data from the European Centre for Medium-range Weather Forecasts (ECMWF) ERA5 reanalysis with 0.28125° horizontal resolution and 6 hr temporal resolution (Hersbach et al., 2020). See Lawrence et al. (2020), this issue, for similar calculations for the MERRA-2 reanalysis.

Here and in the following, the vortex edge was assumed at 36 PVU potential vorticity at 475 K, extended to other altitudes by the method used in Rex et al. (1999). The fraction of the vortex volume below the formation temperature of polar stratospheric clouds composed of nitric acid trihydrate was calculated as in Hanson and Mauersberger (1988). A volume mixing ratio of 4.6 ppm was assumed for H_2O . The mixing ratio profile of

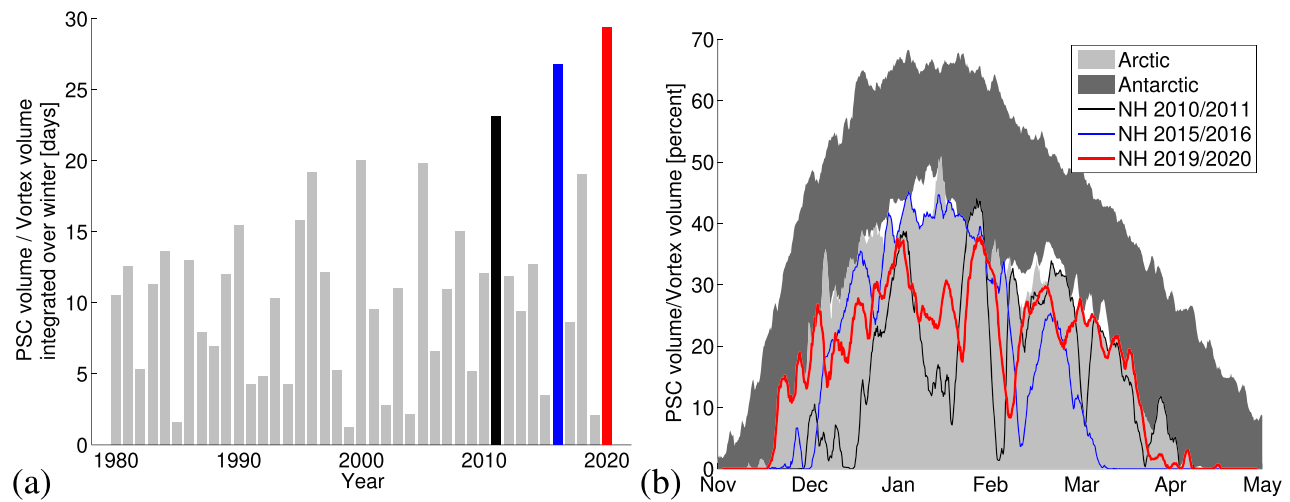


Figure 1. (a) Fraction of Arctic polar vortex volume below the formation temperature of polar stratospheric clouds (V_{PSC}/V_{vortex}) integrated over the winter (November–April) for different years. The three coldest winters by this metric are marked in black (2010/2011), blue (2015/2016), and red (2019/2020). (b) Fraction of polar vortex volume below the formation temperature of polar stratospheric clouds as a function of season. The red line shows Arctic values for 2019/2020, and the thin lines show values for the years 2010/2011 (black) and 2015/2016 (blue), using the same colors as Figure 1a. Light and dark shading shows range of Arctic and Antarctic values for 1979–2020. Antarctic values are shifted by half a year. Results are based on ECMWF ERA5 reanalysis data.

HNO_3 , which varies as a function of pressure, is based on measurements acquired in the Arctic during January 1979 by the Limb Infrared Monitor of the Stratosphere (LIMS) on board Nimbus 7 (Remsberg et al., 2010). Results are comparable to those based on other HNO_3 profiles (e.g., Lawrence et al., 2018). The altitude range for the vertical integration is 400–700 K. For Figure 1a, instantaneous values of V_{PSC}/V_{vortex} (dimensionless) were integrated from November to April, yielding a value in units of time.

From Figure 1a, it appears that the coldest Arctic winters have become colder in recent decades. The record for the coldest winter has been broken typically every 5 years and an increase by a factor of 3 of the V_{PSC}/V_{vortex} metric from 1979/1980 to 2019/2020 is observed in these winters (von der Gathen et al., 2020).

The three coldest Arctic stratospheric winters with respect to integrated V_{PSC}/V_{vortex} all occurred in the last 10 years: 2010/2011, 2015/2016, and 2019/2020. Figure 1b shows the seasonal evolution of these three winters in terms of daily values of V_{PSC}/V_{vortex} , compared to the range of Arctic and Antarctic values. The former record year for the coldest winter (2010/2011) showed the largest Arctic ozone loss so far (e.g., Hommel et al., 2014; Manney et al., 2011; Sinnhuber et al., 2011). The winter 2015/2016 showed greater values of V_{PSC} (and lower temperatures) until February but less ozone loss due to an early warming of the polar vortex (Khosrawi et al., 2017; Manney & Lawrence, 2016). While low temperatures at the end of March lasted for a few days longer in the winter 2010/2011 compared to 2019/2020, this was offset by larger V_{PSC}/V_{vortex} in 2019/2020 than in 2010/2011 in early winter (December and January). In early winter, 2015/2016 and 2019/2020 had similar temperatures.

2.2. Ozone

Figure 2 shows all 52 ozonesonde profiles measured inside the polar vortex from 17 March to 17 April 2020 (light gray and colored lines). We selected a set of 12 ozonesonde measurements from this time period to represent the air masses most depleted in ozone inside the polar vortex (colored lines). This set is intended to exemplify the maximum ozone loss in spring 2020. As a selection criterion, we chose all profiles with a minimum mixing ratio less than 0.2 ppm anywhere in an altitude range of 370–550 K. These sonde measurements were performed at Alert (82.5°N, 62.3°W; 27 March, 2 April, and 8 April), Eureka (80.0°N, 85.9°W; 24 March and 10 April), Ny-Ålesund (78.9°N, 11.9°E; 27 March and 28 March), Ittoqqortoormiit (Scoresbysund) (70.5°N, 22.0°W; 1 and 4 April), Resolute (74.7°N, 94.9°W; 30 March), and Sodankylä (67.4°N, 26.6°E; 2 April) (WOUDC, 2020). One of the profiles was measured above Polarstern (Knust, 2017) in the Arctic Ocean (86.2°N, 15.8°E; 23 March) during the MOSAiC expedition (von der Gathen & Maturilli, 2020).

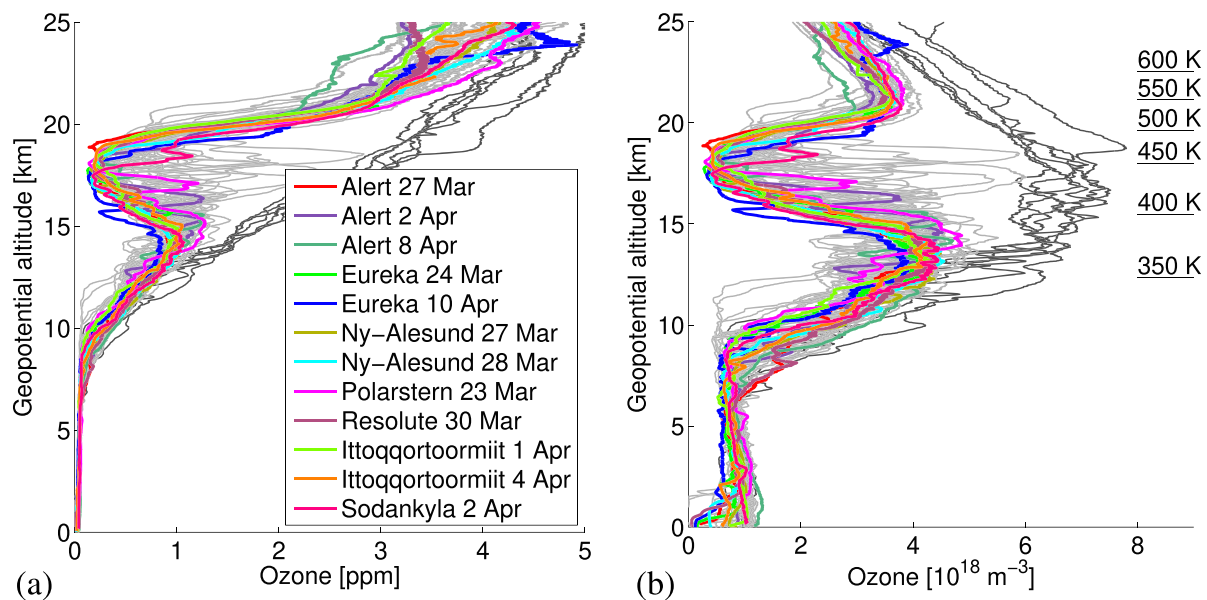


Figure 2. Ozonesonde profiles inside the polar vortex from 17 March to 17 April 2020 as a function of altitude ((a) volume mixing ratios, (b) ozone number concentrations). A set of 12 sondes was chosen from all measurements to represent the air masses most depleted in ozone (colored lines). All other profiles from 2019/2020 are shown in light gray. For comparison, profiles inside the polar vortex from the warm winter 2014/2015 (24 March to 9 April) are shown in dark gray. Approximate potential temperature levels corresponding to the altitudes are indicated.

In addition, we use satellite observations of ozone mixing ratio from the Microwave Limb Sounder (MLS) instrument to confirm the findings from the sondes. While sonde measurements have a higher vertical resolution and higher accuracy and precision than the MLS instrument, the temporal and spatial measurement coverage is much better for MLS: There are several hundred profile measurements in the vortex from MLS every day but typically only 5–10 ozone soundings per week. The estimated precision and accuracy of the MLS instrument in the considered altitude range are 0.04–0.06 and 0.1–0.2 ppm (Livesey et al., 2020), which are in the same order of magnitude as the lowest values measured by the sondes in spring 2020. The precision of the ozonesondes is $\pm(3\text{--}5)\%$, and the accuracy is $\pm(5\text{--}10)\%$ (Smit et al., 2007). In the minimum region, the background current of the sonde and its subtraction handling become important. An assumed 20% uncertainty in the background subtraction in the minimum region converts to a range of 0.002 ppm (Eureka, 10 April) to 0.02 ppm (Ittoqqortoormiit, 4 April), which is usually in the range of $\pm(5\text{--}10)\%$ and below.

A simple estimate of the fraction of the vortex area subject to the largest depletion, found by taking the 12 soundings of 52 to be representative, is 23%. The corresponding estimate calculated from MLS observations inside the vortex that were below 0.2 ppm at 450 K is 12%, averaged between 26 March and 10 April.

All sonde profiles consistently show a pronounced depleted layer between 425 and 485 K (17–19 km). The lowest values are observed around 450 K (18 km). Most profiles show minimum volume mixing ratios of about 0.15–0.2 ppm. The lowest mixing ratio in an individual sonde (0.13 ppm) was observed in a profile measured in Eureka on 24 March. The minimum values are observed near the altitudes that typically show the maximum ozone number concentrations in warm winters with low ozone depletion (about 400 K). For comparison, Figure 2 shows profiles inside the polar vortex from the warm winter 2014/2015 (24 March to 9 April) in dark gray.

The observed minimum values are far lower than any minimum values observed so far by sondes or the MLS instrument in the Arctic polar vortex. These minima did not fall below 0.5 ppm even in 2010/2011 (e.g., Solomon et al., 2014). Figures 3a and 3b show the daily minimum mixing ratios observed by sondes in the altitude range 420–480 K in the Arctic polar vortex in 1991/1992–2010/2011, 2015/2016, and 2019/2020 and in the Antarctic polar vortex in 1985–2019 (in linear and logarithmic scale). Antarctic data are from two stations: Georg Forster (70.8°S, 11.9° E) and Neumayer (70.7°S, 8.3°W). The altitude range

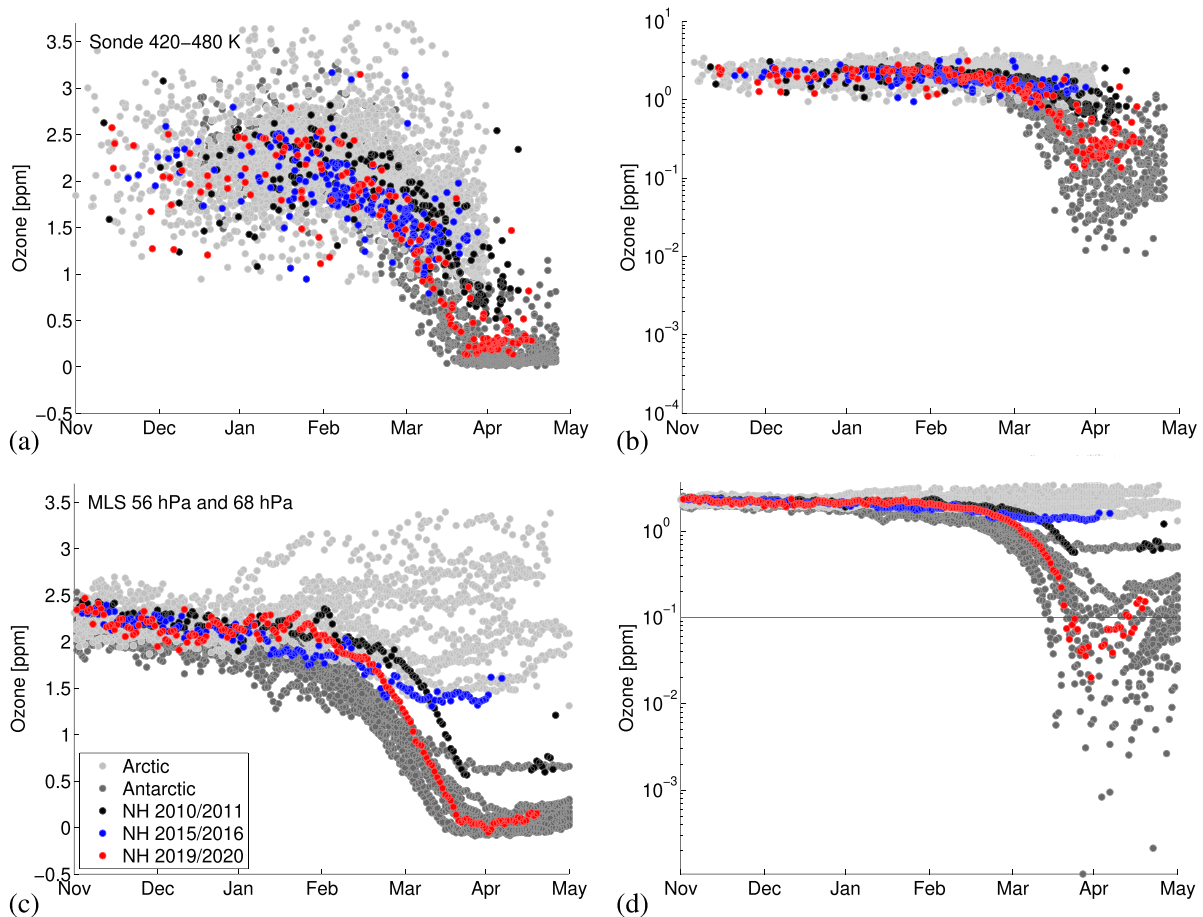


Figure 3. (a) Daily minimum ozone mixing ratios observed by sondes in the polar vortex in the altitude range 420–480 K. The Arctic winters 2010/2011, 2015/2016, and 2019/2020 are highlighted using the same colors as Figure 1. The light and dark gray points show the range of Arctic values (1991/1992–2010/2011) and Antarctic values (1985–2019). Antarctic values are shifted by half a year. (b) Same plot in logarithmic coordinates. (c) Daily mean mixing ratios of the lowest 10% of measurements of the MLS satellite instrument in the polar vortex at 56 or 68 hPa for the winters 2004/2005–2019/2020, shown in the same manner as in (a). The lowest 10% of measurements are used instead of the daily minimum to reduce the influence of measurement noise on the measured minima. (d) Same plot in logarithmic coordinates. The line shows the approximate combined precision and accuracy of the MLS measurements.

has been chosen since it always contains the ozone minimum in the cold Arctic winters 2010/2011 and 2019/2020. The Arctic winters 2010/2011 (black), 2015/2016 (blue), and 2019/2020 (red) are highlighted.

The strong decline of the values in 2019/2020 to minimum values around 0.2 ppm is remarkably similar to the typical evolution of the values in Antarctic winters (dark gray), although smaller values down to 0.01 ppm are commonly reached in the Antarctic. Past minimum values in the Arctic in 2010/2011 (0.5 ppm) and 2015/2016 (1.25 ppm) were significantly higher. To confirm the results from the sondes, Figures 3c and 3d show the daily mean mixing ratios of the lowest 10% of measurements observed in the polar vortex by MLS at 56 and 68 hPa in the winters 2004/2005 to 2019/2020 (see also complementary Figures S1–S3 in Manney et al. (2020), this issue, for map and profile views). The MLS retrieval levels 56 and 68 hPa have been chosen since they always contain the measured minimum values in the cold winters 2010/2011 and 2019/2020. Differences between Figures 3a and 3c can be explained by the different vertical resolutions of the instruments, different coverage of the vortex, and the use of minimum values versus averages over the lowest 10% of measurements.

Values measured by MLS even fall to near zero or below due to measurement noise. The lowest 10% of measurements are used instead of a single daily minimum value to reduce the influence of measurement noise on the minima, since the noise is in the same order of magnitude as the lowest values of 0.2 ppm measured by sondes. Taking observed minimum values will always underestimate the true minima of a noisy

measurement, but the degree of underestimation will be dependent on the measurement noise and the unknown distribution of the true measurement values. Hence, we cannot deduce the measured minimum from MLS with certainty, but it seems likely that the measurements are consistent with the lowest values of 0.2 ppm observed by the sondes.

2.3. Ozone Loss

Figures 4a, 4c, and 4e show the ozone loss observed by sondes in the most depleted part of the vortex as a function of altitude, averaged over all 12 profiles. Ozone loss is calculated as the difference between a passive ozone tracer from the global Lagrangian ATLAS Chemistry and Transport Model (Wohltmann & Rex, 2009) and the observed sonde profile. Transport and mixing in the model were driven by winds and temperatures from ECMWF ERA5 meteorological reanalysis data (1.125° horizontal resolution, 3 hr temporal resolution). The model uses a hybrid vertical coordinate, which is to a good approximation a potential temperature coordinate in the stratosphere. Diabatic heating rates from ERA5 were used to calculate vertical motion. The vertical range of the model domain is 350–1900 K. The passive ozone tracer was initialized on 1 December 2019 with ozone observations of MLS. The satellite measurements were interpolated to the location of the model air parcels, and the air parcels were then advected with ozone as a conserved tracer with the ozone chemistry of the model switched off. The passive ozone tracer is then interpolated to the location of each of the sondes.

Reliable values for the ozone loss can be deduced with this method only from 370–550 K for several reasons: (1) For air masses that entered the model domain after 1 December through the lower or upper boundary, neither the initial position nor the mixing ratio on 1 December is known. A passive potential temperature tracer indicates that values of the passive ozone tracer above 550 K are not reliable because of descent in the polar vortex. At the lower boundary, we excluded all values in the lowermost stratosphere below 370 K, where horizontal transport between the troposphere and stratosphere is possible along isentropes. (2) Above 550 K, NO_x chemistry becomes important. (3) With increasing altitude, ozone becomes more short lived and approaches equilibrium, which is not compatible with the idea of a passive ozone tracer.

The shape of the loss profile resembles the shape of the minimum of the ozonesonde profiles and shows values of enhanced ozone loss in a layer from 425–485 K with a maximum loss at 450 K. The minimum in ozone concentrations and mixing ratios at 450 K corresponds to a maximum chemical loss of about 2.8 ppm or 93%, averaged over all sondes. The maximum loss in an individual profile is 96%. The partial ozone column averaged over the sondes between 370 and 550 K is 59 ± 11 DU, and the ozone loss in the partial column is 124 ± 11 DU.

The ozone loss in the most depleted parts of the vortex has to be clearly distinguished from the polar vortex mean loss, which is necessarily less pronounced. Figures 4b, 4d, and 4f show the vortex-averaged ozone loss for the winters 2010/2011 and 2019/2020 obtained by subtracting MLS measurements of ozone from the passive ozone tracer of the ATLAS model in the altitude range 370–550 K inside the polar vortex. The passive ozone tracer was initialized on 1 December again.

The maximum ozone loss in the vortex mean profile in 2019/2020 was about 2.2 ppm at 450 K shortly before the breakup of the vortex (17 April 2020). The corresponding maximum loss for 2010/2011 was 2.5 ppm at 490 K (26 March 2011). The passive profile shows larger values in 2011, so that a reason for the larger loss could be that more ozone was available for depletion. The percentage of loss was generally higher in 2019/2020 and peaks at 73% at 450 K, compared to a value of 63% at 470 K in 2010/2011. The winter 2019/2020 shows considerably lower vortex mean mixing ratios than the winter 2010/2011 below 475 K (e.g., 0.8 vs. 1.4 ppm at 450 K), and ozone loss peaked at lower altitudes in 2019/2020 than in 2010/2011. This explains the higher percentage loss but lower absolute loss. Within the uncertainties in empirical ozone loss estimates, these results are consistent with those of Manney et al. (2020), this issue, using different methods. The vortex-averaged column loss between 370 and 550 K was 133 DU in 2010/2011 and 126 DU in 2019/2020.

Taking into account the uncertainties in calculating ozone loss, the vortex mean loss in the winters 2010/2011 and 2019/2020 is rather similar, notwithstanding some morphological differences. To highlight the range of the uncertainties, we note here that using different meteorological data sets (ECMWF operational data, ERA5, and ERA Interim) will vary the loss estimates in 2010/2011 between 2.2 and 2.5 ppm.

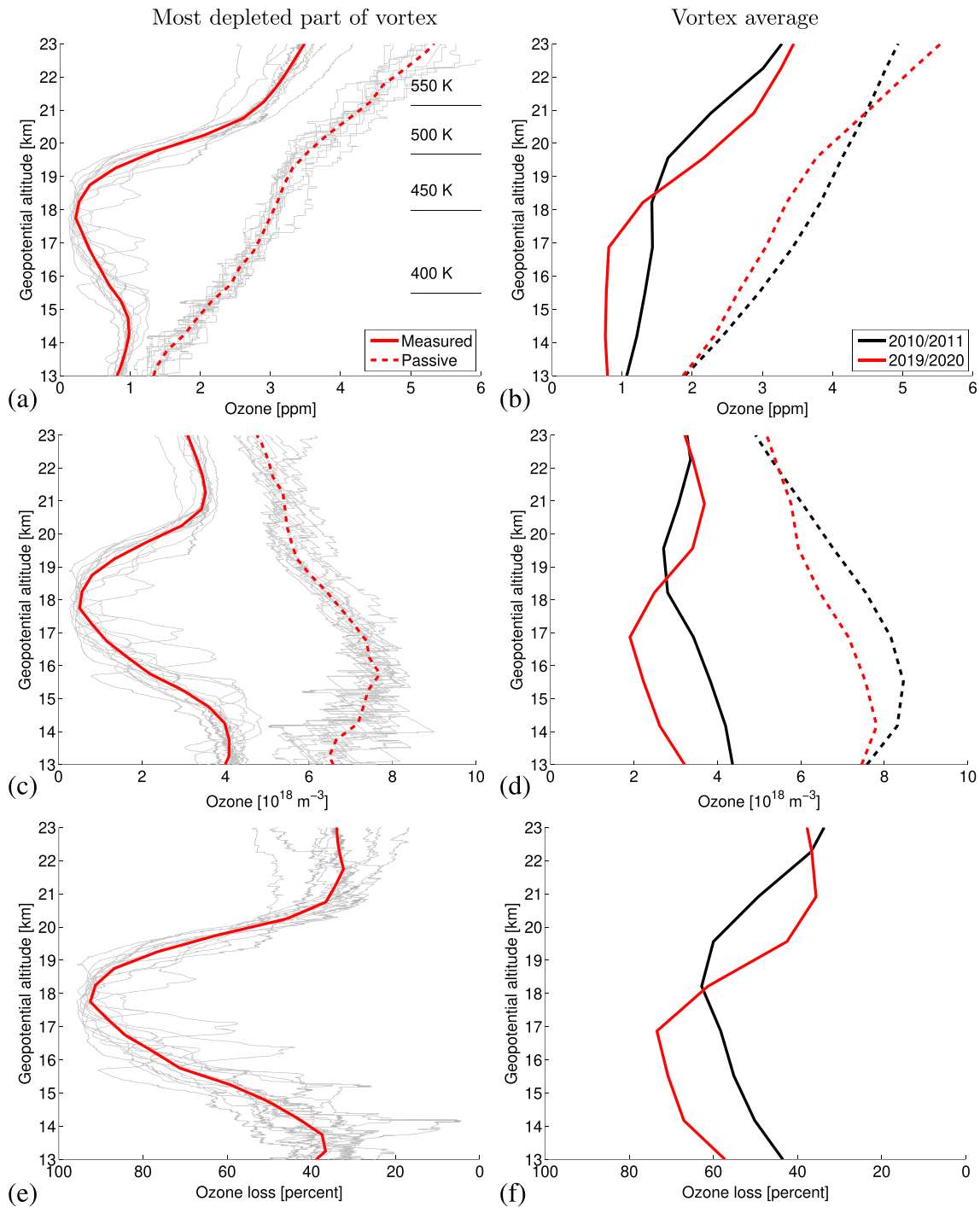


Figure 4. Measured ozone volume mixing ratio (a, b), corresponding ozone number concentrations (c, d), and ozone loss in percent (e, f) calculated by using a passive tracer from the Chemistry and Transport Model ATLAS. Panels (a), (c), and (e) show averages over the 12 selected ozonesondes in the most depleted part of the vortex. Panels (b), (d), and (f) show vortex averages calculated using MLS satellite data. The dashed lines in (a)–(d) show the passive ozone tracer from ATLAS used to calculate the ozone loss in (e) and (f). Red lines show averages for 2019/2020, black lines averages for 2010/2011, and gray lines show individual measurements or passive tracer values, respectively.

3. Discussion

The minimum ozone mixing ratios of 0.1–0.2 ppm observed in Arctic spring 2020 are significantly lower than observed in any previous year (with the lowest values of 0.5 ppm in 2011). They are comparable to typical

mixing ratios in the Antarctic ozone hole. In the vortex-averaged total column, Arctic chemical loss was similar in 2010/2011 and 2019/2020. One of the reasons for the observed low mixing ratios in 2020 may have been that the dynamical supply of ozone was smaller in the winter 2019/2020, as indicated by the lower values of the passive ozone tracer compared to 2010/2011 and consistent with a weaker residual circulation in cold winters (e.g., Tegtmeier et al., 2008). A weaker residual circulation means less downwelling and less transport of ozone-rich air from above. Interestingly, MLS measurements show lower N₂O and higher H₂O mixing ratios compared to other winters (Manney et al., 2020, this issue), which at first glance could also be caused by *more* downwelling; however, evidence in this case suggests that it is caused primarily by descent of N₂O values that already were anomalously low in fall (and anomalously high in case of H₂O) and a more isolated vortex (Manney et al., 2020, this issue).

Several authors noted that the ozone loss in 2011 might arguably be called an Arctic ozone hole (e.g., Manney et al., 2011; Sinnhuber et al., 2011), although this is highly controversial (e.g., Solomon et al., 2014). We avoid calling the ozone depletion in 2010/2011 and 2019/2020 an Arctic ozone hole for several reasons. The common definition of the Antarctic ozone hole is the area below 220 DU (e.g., WMO, 2018). The area below 220 DU in the Arctic winter 2019/2020 is at maximum 0.9×10^6 km², which is less than 5% of the typical area of the Antarctic ozone hole (Dameris et al., 2020). Both the vertical extent and the temporal extent of the lowest ozone values (smaller than 0.2 ppm) are considerably smaller in the Arctic winter 2019/2020 than those of typical Antarctic winters (425–485 K versus approximately 350–510 K and at most 5 weeks versus several months). In addition, the common definition of the Antarctic ozone hole is problematic in the more dynamically active Northern Hemisphere, since column values below 220 DU can be reached for purely dynamical reasons without any chemical depletion.

The very cold winter 2019/2020 is consistent with a tendency of the coldest Arctic winters to become colder in recent decades, which has been suggested by several studies (Rex et al., 2004, 2006; Sinnhuber et al., 2011; Tilmes et al., 2006; von der Gathen et al., 2020). This suggestion has been controversial, with other studies using different metrics, meteorological data sets (Lawrence et al., 2018), or statistical methods finding the trend to be limited to certain months (Ivy et al., 2014) or not significant (Manney et al., 2011; Rieder & Polvani, 2013). Nevertheless, this tendency is found for the temperature metric used in this study. A tendency for Arctic winters to become colder leads to increasing ozone loss in the cold winters (Harris et al., 2010; Rex et al., 2004, 2006; Tilmes et al., 2006; von der Gathen et al., 2020).

Large interannual variability in temperatures and the occurrence of cold winters are expected to extend into the future (Bednarz et al., 2016; Langematz et al., 2014; von der Gathen et al., 2020). While the slow decline in ODS will lead to a complete recovery of the ozone layer in a few decades, this large variability can counteract those effects in individual winters (Dhomse et al., 2018; Eyring et al., 2010; WMO, 2018). There is, however, considerable uncertainty in the future trend of Arctic stratospheric temperatures in both cold and more dynamically active warm winters (Butchart et al., 2010; Eyring et al., 2010; Langematz et al., 2014). These changes are determined by a complex interplay of increases in radiative cooling induced by the growth in greenhouse gases and by dynamical changes, such as changes in the strength of the adiabatic warming induced by changes in the polar downwelling of the Brewer-Dobson circulation (Butchart et al., 2010; Eyring et al., 2010; Langematz et al., 2014).

While it is estimated that stratospheric ozone levels will eventually return to pre-1980 conditions around 2035 in the Arctic and 2060 in the Antarctic (Dhomse et al., 2018; WMO, 2018), it is expected that even around 2060, cold winters could still lead to substantial ozone depletion and show values as much as 100 DU lower than the future average (Bednarz et al., 2016). The winter 2019/2020 is a prime example of such a winter. For the first time, almost complete ozone depletion was observed in a limited region and altitude range in the Arctic vortex and the vortex-averaged loss was among the largest ever observed in the Arctic, even though stratospheric levels of ODS have declined by about 10% since their peak levels around the year 2000.

Data Availability Statement

Some ozonesonde data used in this manuscript were produced as part of the international Multidisciplinary drifting Observatory for the Study of the Arctic Climate (MOSAIC) with the tag MOSAIC20192020 (project id AWI_PS122_00). We thank ECMWF for providing ERA5 reanalysis

data, generated using Copernicus Climate Change Service Information 2020. Neither the European Commission nor the ECMWF is responsible for any use that may be made of the Copernicus Information or Data it contain. Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS), 2017–2020. Ozone data are available on request from the authors and will be available from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) at <https://woudc.org> and the Network for the Detection of Atmospheric Composition Change (NDACC; <https://www.ndacc.org>). MLS data are available online (<https://disc.gsfc.nasa.gov/datasets?page=1&keywords=AURA%20MLS>). ECMWF ERA5 data are available at <https://cds.climate.copernicus.eu/cdsapp#!/home> website. ATLAS model runs are available at <https://doi.org/10.7910/DVN/DWSSOX> website.

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