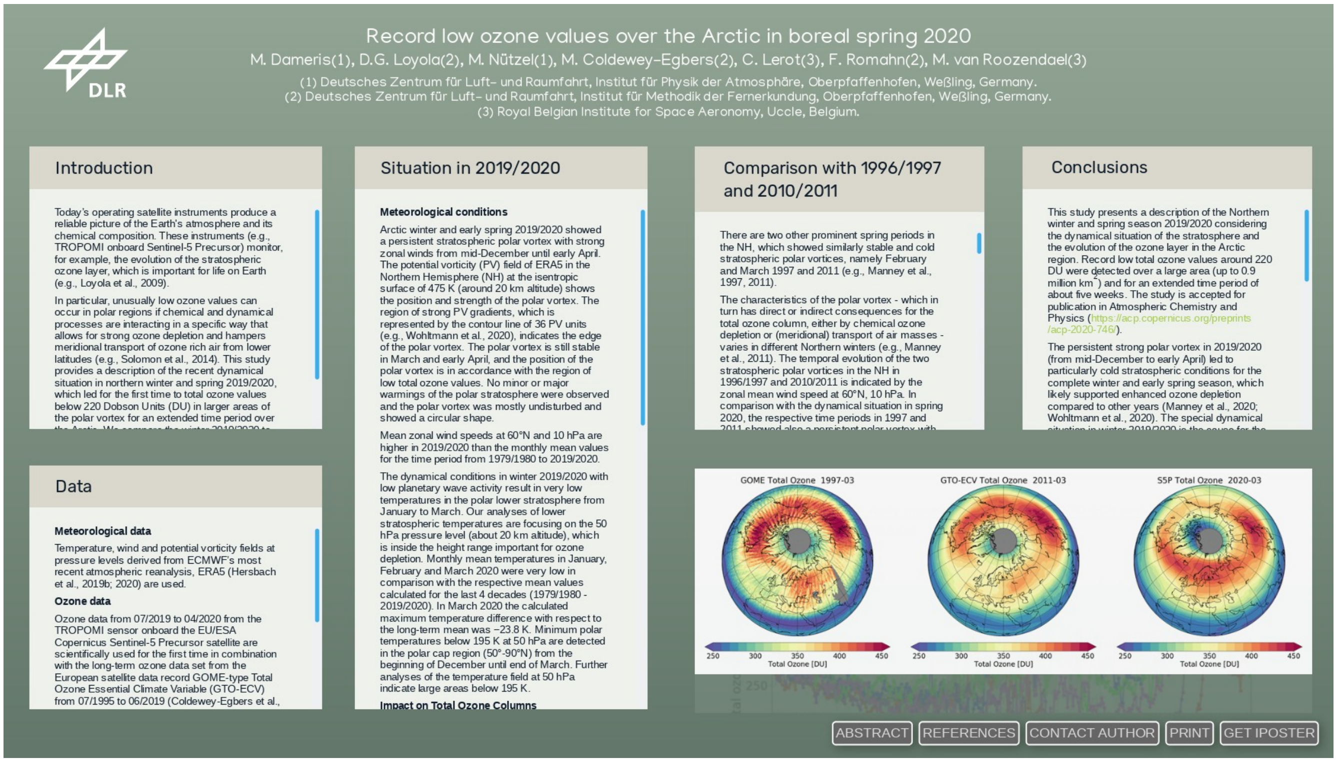


## Introduction

Today’s operating satellite instruments produce a reliable picture of the Earth's atmosphere and its chemical composition. These instruments (e.g., TROPOMI onboard Sentinel-5 Precursor) monitor, for example, the evolution of the stratospheric ozone layer, which is important for life on Earth (e.g., Loyola et al., 2009).

In particular, unusually low ozone values can occur in polar regions if chemical and dynamical processes are interacting in a specific way that allows for strong ozone depletion and hampers meridional transport of ozone rich air from lower latitudes (e.g., Solomon et al., 2014). This study provides a description of the recent dynamical situation in northern winter and spring 2019/2020, which led for the first time to total ozone values below 220 Dobson Units (DU) in larger areas of the polar vortex for an extended time period over the Arctic. We compare the winter 2019/2020 to winters with similar dynamical conditions in northern spring, but which did not show such low total ozone column values below 220 DU.

## Data

### Meteorological data

Temperature, wind and potential vorticity fields at pressure levels derived from ECMWF’s most recent atmospheric reanalysis, ERA5 (Hersbach et al., 2019b; 2020) are used.

### Ozone data

Ozone data from 07/2019 to 04/2020 from the TROPOMI sensor onboard the EU/ESA Copernicus Sentinel-5 Precursor satellite are scientifically used for the first time in combination with the long-term ozone data set from the European satellite data record GOME-type Total Ozone Essential Climate Variable (GTO-ECV) from 07/1995 to 06/2019 (Coldewey-Egbers et al., 2015). GTO-ECV has been developed in the framework of the European Space Agency’s Climate Change Initiative ozone project and is based on observations from the satellite sensors GOME/ERS-2, SCIAMACHY/ENVISAT, OMI/Aura, and GOME-2/MetOp-A and -B. For all satellite sensors incl TROPOMI the retrieval algorithm GODFIT (Lerot et al., 2014) is used to derive total ozone columns.

## Situation in 2019/2020

### Meteorological conditions

Arctic winter and early spring 2019/2020 showed a persistent stratospheric polar vortex with strong zonal winds from mid-December until early April. The potential vorticity (PV) field of ERA5 in the Northern Hemisphere (NH) at the isentropic surface of 475 K (around 20 km altitude) shows the position and strength of the polar vortex. The region of strong PV gradients, which is represented by the contour line of 36 PV units (e.g., Wohltmann et al., 2020), indicates the edge of the polar vortex. The polar vortex is still stable in March and early April, and the position of the polar vortex is in accordance with the region of low total ozone values. No minor or major warmings of the polar stratosphere were observed and the polar vortex was mostly undisturbed and showed a circular shape.

Mean zonal wind speeds at 60°N and 10 hPa are higher in 2019/2020 than the monthly mean values for the time period from 1979/1980 to 2019/2020.

The dynamical conditions in winter 2019/2020 with low planetary wave activity result in very low temperatures in the polar lower stratosphere from January to March. Our analyses of lower stratospheric temperatures are focusing on the 50 hPa pressure level (about 20 km altitude), which is inside the height range important for ozone depletion. Monthly mean temperatures in January, February and March 2020 were very low in comparison with the respective mean values calculated for the last 4 decades (1979/1980 - 2019/2020). In March 2020 the calculated maximum temperature difference with respect to the long-term mean was −23.8 K. Minimum polar temperatures below 195 K at 50 hPa are detected in the polar cap region (50°-90°N) from the beginning of December until end of March. Further analyses of the temperature field at 50 hPa indicate large areas below 195 K.

### Impact on Total Ozone Columns

When the sun rises in spring, sunlight delivers the energy required for starting a chemical depletion process of ozone (e.g., Solomon, 1999). In spring 2020 record low Arctic total ozone values below 220 DU developed within the boundaries of the stable polar vortex for eight continuous days from March 12 to 19. A region of significantly reduced ozone values inside the polar vortex was observed over the polar cap from the beginning of March until early April 2020. In winter 2019/2020 ozone values were most of the time slightly below mean conditions until the end of February with respect to mean minimum total ozone values. However, there were several short-term deviations towards even lower total ozone columns, during so-called ozone mini-hole events (e.g., Millán and Manney, 2017) which are primarily resulting from dynamical processes. The most noteworthy examples occurred on 3 and 4 December 2019, 4 and 5 January 2020 and January 7 and 8, respectively, and from 25 to 27 January. Ozone mini-holes are synoptic-scale features with a high-pressure system in the troposphere below the stratospheric polar vortex (i.e. a low-pressure area) leading to significantly reduced total ozone columns.

Remarkable deviations from normal Arctic conditions can be found starting in early March 2020 until early April, when low ozone values in the North polar region were detected. Values below 220 DU were detected for the first time on March 2, and continued with similarly low columns – including a period of 8 consecutive days with minimum values below 220 DU – until April 7. For the first time total ozone values near or below 220 DU were observed for a period of about 5 weeks corresponding to new record low values for this time of the year. The maximum area with ozone columns below 220 DU was 0.9 million km2 on March 12. In comparison with corresponding values of a typical ozone hole in the Antarctic the area of low total ozone is much smaller and the minimum value is clearly higher. The Antarctic ozone hole in spring 2016 showed minimum total ozone columns clearly below 150 DU and ozone columns values below 220 DU were found for a period of about 4 months. The maximum area of the ozone hole was in the order of 20 million km2.

## Comparison with 1996/1997 and 2010/2011

There are two other prominent spring periods in the NH, which showed similarly stable and cold stratospheric polar vortices, namely February and March 1997 and 2011 (e.g., Manney et al., 1997, 2011).

The characteristics of the polar vortex - which in turn has direct or indirect consequences for the total ozone column, either by chemical ozone depletion or (meridional) transport of air masses - varies in different Northern winters (e.g., Manney et al., 2011). The temporal evolution of the two stratospheric polar vortices in the NH in 1996/1997 and 2010/2011 is indicated by the zonal mean wind speed at 60°N, 10 hPa. In comparison with the dynamical situation in spring 2020, the respective time periods in 1997 and 2011 showed also a persistent polar vortex with high zonal wind speeds (>50 ms-1). These values are higher than the long-term mean values. While the temporal evolution of the dynamical situation in Arctic spring 2011 was very similar to the one in 2020 with a persistent polar vortex and high zonal wind speeds until mid-March, the period of strong zonal winds in 1997 continued until April. The polar vortex in December 1996 was weak and therefore polar temperatures were relatively high (>195 K). The evolution of the winter vortices in December 2010 and 2019 are similar, reaching zonal wind speeds of about 40 ms-1 in mid-December. In 2011 the meridional transport was weak at the edge of the polar vortex (i.e. a strong barrier) throughout the winter (Manney et al., 2011). Less ozone was  transported from lower to higher latitudes. The meridional transport was enhanced in 1997 because the polar vortex was weaker in December and January (Manney et al., 2011).

In all three years the dynamical conditions led to low stratospheric temperatures in the polar cap region (50°N-90°N). The daily minimum temperatures were below the threshold temperature for the formation of NAT-PSC (195 K) in February and March. Minimum temperatures at 50 hPa in December 2019 and January 2020 were most of the time slightly lower than the minimum temperatures in 2010/2011. In turn, the minimum temperatures in these two months are clearly higher in 1996/1997 than in 2010/2011 and 2019/2020, respectively. Severe chemical ozone loss  was observed in spring 2011 (Manney et al., 2011). In spring 1997 the chemical ozone loss was only moderate (Manney et al., 1997). The most important reason was the late development of the polar vortex and the late drop of temperatures below PSC thresholds in winter 1996/1997. Total ozone column values were lower in 2020 because chemical loss started earlier and because of less horizontal mixing due to a permanent stable vortex. The daily areas with temperatures below 195 K at the 50 hPa pressure level are larger in 2019/2020 than in 1996/1997 and in 2010/2011. The cumulative areas are markedly different: whereas in 2019/2020 the cumulative area was about 920·1012 m2, in 1996/1997 it was about 370·1012 m2 and in 2010/2011 it was about 650·1012 m2. Furthermore, in the last week of January 2020 the temperatures at 50 hPa fall below 188 K, the typical ice PSC threshold. The maximum daily area with temperatures below 188 K was 2.8·1012 m2 on January 30, and the cumulated area reached its maximum of 18·1012 m2 on March 2, 2020. While the threshold for ice PSCs was not reached in 1996/1997, in 2010/2011 the cumulative area with temperatures below 188 K was estimated with 4.3·1012 m2.

To summarize, in all three years the temperatures in the lower stratosphere in February and March were in a similar range,
showing colder conditions than the long-term mean. The winter 2019/2020 showed a larger area below the formation temperature of PSCs than the other two Northern winters for an extended period. Permanent presence of PSCs over about four months enabled efficient chlorine activation. In addition, PSCs supported strong denitrification of the lower stratosphere by irreversible removal of total reactive nitrogen (NOy), in particular HNO 3, by uptake of NOy on the surface of PSCs followed by sedimentation of PSC particles (Fahey et al., 1990). This ultimately enabled a period of chemical ozone depletion that was longer than usual (e.g., Pommereau et al., 2018).

The seasonal evolution of minimum ozone values north of 50°N between July 1996 and June 1997 between July 2010 and June 2011 indicates normal or slightly enhanced ozone values until February with respect to the long-term mean value based on satellite observations from 1995 to 2019. Typical features of a strong polar vortex can be observed in February 1997 and February 2011 with low total ozone values in the polar vortex and relatively high values in the collar region of the polar vortex. Around the beginning of March 1997 and March 2011 the total ozone values were declining and low values were detected in both years until early April. In spring 1997 the dynamical conditions led to frequent ozone mini-holes (Coy et al., 1997) and to a higher tropopause that contributed to lower total ozone values via dynamical processes (Manney et al., 2011).

The total ozone monthly means for March 1997, 2011, and 2020 indicate low values over the polar cap. The monthly mean minimum total ozone column value for March 2020 (221 DU) is much lower compared to the monthly mean minimum values for March 1997 (267 DU) and for March 2011 (252 DU), respectively.

**Conclusions**

This study presents a description of the Northern winter and spring season 2019/2020 considering the dynamical situation of the stratosphere and the evolution of the ozone layer in the Arctic region. Record low total ozone values around 220 DU were detected over a large area (up to 0.9 million km2) and for an extended time period of about five weeks. The study is accepted for publication in Atmospheric Chemistry and Physics (https://acp.copernicus.org/preprints/acp-2020-746/).

The persistent strong polar vortex in 2019/2020 (from mid-December to early April) led to particularly cold stratospheric conditions for the complete winter and early spring season, which likely supported enhanced ozone depletion compared to other years (Manney et al., 2020; Wohltmann et al., 2020). The special dynamical situation in winter 2019/2020 is the cause for the significant reduction of the total ozone column.

However, the detected Arctic area of record low total ozone values are much smaller compared to a typical Antarctic ozone hole, which is on the order of about 20 to 25 million km2 from early September until mid-October showing total ozone values below 220 DU for up to about 4 months.

If the regulations of the Montreal Protocol regarding the prohibition of CFCs are implemented strictly one can expect a full recovery of the ozone layer including the polar regions by the middle of this century (WMO, 2018). In recent years, first signs of ozone recovery were already detected (e.g., Weber et al., 2018). However, in winters with a cold and stable polar stratospheric vortex, a persistent region of low ozone columns might also develop in the NH in the future again. The recovery of the ozone layer and its interactions with climate change must be monitored carefully, as discussed for instance by Dameris and Loyola (2011). Continued monitoring of ozone with a suite of instruments will be key to understand the future development of Arctic ozone. This capability is crucial to allow an evaluation of specific events in the light of the Montreal Protocol.

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