Record-low Arctic stratospheric ozone in 2020: MLS observations of chemical processes and comparisons with previous extreme winters

Gloria L Manney[1,2], Nathaniel J Livesey[3], Michelle L Santee[3], Lucien Froidevaux[3], Alyn Lambert[3], Zachary D Lawrence[4,1], Luis F Millán[3], Jessica L Neu[3], William G Read[3], Michael J Schwartz[3], Ryan A Fuller[3]

[1]NorthWest Research Associates, Socorro, NM, USA
[2]New Mexico Institute of Mining and technology, Socorro, NM, USA
[3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
[4]National Oceanic and Atmospheric Administration / Cooperative Institute for Research in Environmental Sciences, Boulder, CO, USA

Key Points:

- MLS trace gas data show that exceptional polar vortex conditions led to record-low ozone in the Arctic lower stratosphere in 2019/2020
- Early and persistent cold conditions led to the longest period with chlorine in ozone-destroying forms in the 16-year MLS data record
- Chemical ozone destruction began earlier than in any Arctic winter in the MLS record and ended later than in any year except 2010/2011

Corresponding author: Gloria L Manney, `manney@nwra.com`

Abstract

Aura Microwave Limb Sounder (MLS) measurements show that chemical processing was critical to the observed record-low Arctic stratospheric ozone in spring 2020. The 16-year MLS record indicates more polar denitrification and dehydration in 2019/2020 than in any Arctic winter except 2015/2016. Chlorine activation and ozone depletion began earlier than in any previously observed winter, with evidence of chemical ozone loss starting in November. Active chlorine then persisted as late into spring as it did in 2011. Empirical estimates suggest maximum chemical ozone losses near 2.8 ppmv by late March in both 2011 and 2020. However, peak chlorine activation, and thus peak ozone loss, occurred at lower altitudes in 2020 than in 2011, leading to the lowest ozone values ever observed at potential temperature levels from ∼400–480 K, with similar ozone values to those in 2011 at higher levels.

Plain Language Summary

Unlike the Antarctic, the Arctic does not usually experience an ozone hole because temperatures are often too high for the chemistry that destroys ozone. In 2019/2020, satellite measurements show record-low stratospheric wintertime temperatures and record-low springtime ozone concentrations in the Arctic lower stratosphere (about 12–20 km altitude). Only one other winter/spring season, 2010/2011, in this 16-year satellite data record comes close. Low temperatures, which result in chlorine being converted from non-reactive forms into forms that destroy ozone, started earlier than in any previous Arctic winter in the record and lingered later than in any year except 2011. The ozone-destroying chemistry in 2019/2020 occurred at lower altitudes (where more of the ozone that filters out harmful ultraviolet radiation resides) than in 2010/2011. Such extensive ozone loss can have important health and biological impacts because it leads to more ultraviolet radiation reaching the Earth's surface. While the success of the Montreal Protocol in limiting human emissions that increase ozone-destroying gases in the stratosphere has resulted in much less Arctic ozone destruction than we would have otherwise had, future temperature changes could lead to other winters with even more chemical ozone depletion than in 2019/2020.

1 Introduction

Arctic chemical ozone loss varies dramatically because of extreme interannual variations in the meteorology of the stratospheric polar vortex (e.g. WMO, 2014). For the past 16 years, the Aura Microwave Limb Sounder (MLS) has been providing a uniquely comprehensive suite of daily global measurements of species involved in lower stratospheric polar chemical processing. The two previous Arctic winters on record with coldest conditions and greatest ozone loss occurred during this period: In 2010/2011, although lower stratospheric minimum temperatures did not consistently set records, the exceptionally prolonged (lasting into April) cold led to unprecedented Arctic chemical ozone loss (Manney et al., 2011; WMO, 2014, and references therein). December 2015–January 2016 Arctic temperatures were the lowest in at least 68 years (Manney & Lawrence, 2016; Matthias et al., 2016), Arctic denitrification and dehydration were the most severe in the MLS record (e.g., Manney & Lawrence, 2016; Khosrawi et al., 2017), and ozone dropped more rapidly than in 2010/2011. Springtime cumulative ozone loss did not match or surpass that in 2011 only because a major final warming in early March 2016 halted chemical processing and dispersed processed air from the vortex (Manney & Lawrence, 2016; Johansson et al., 2019). In 2019/2020, lower stratospheric temperatures were persistently below the threshold for chemical processing on polar stratospheric clouds (PSCs) and other aerosols earlier than in any other year observed by MLS and remained low approximately as late as in 2011 (see Lawrence et al., 2020, for an overview of stratospheric vortex meteorology in 2019/2020).
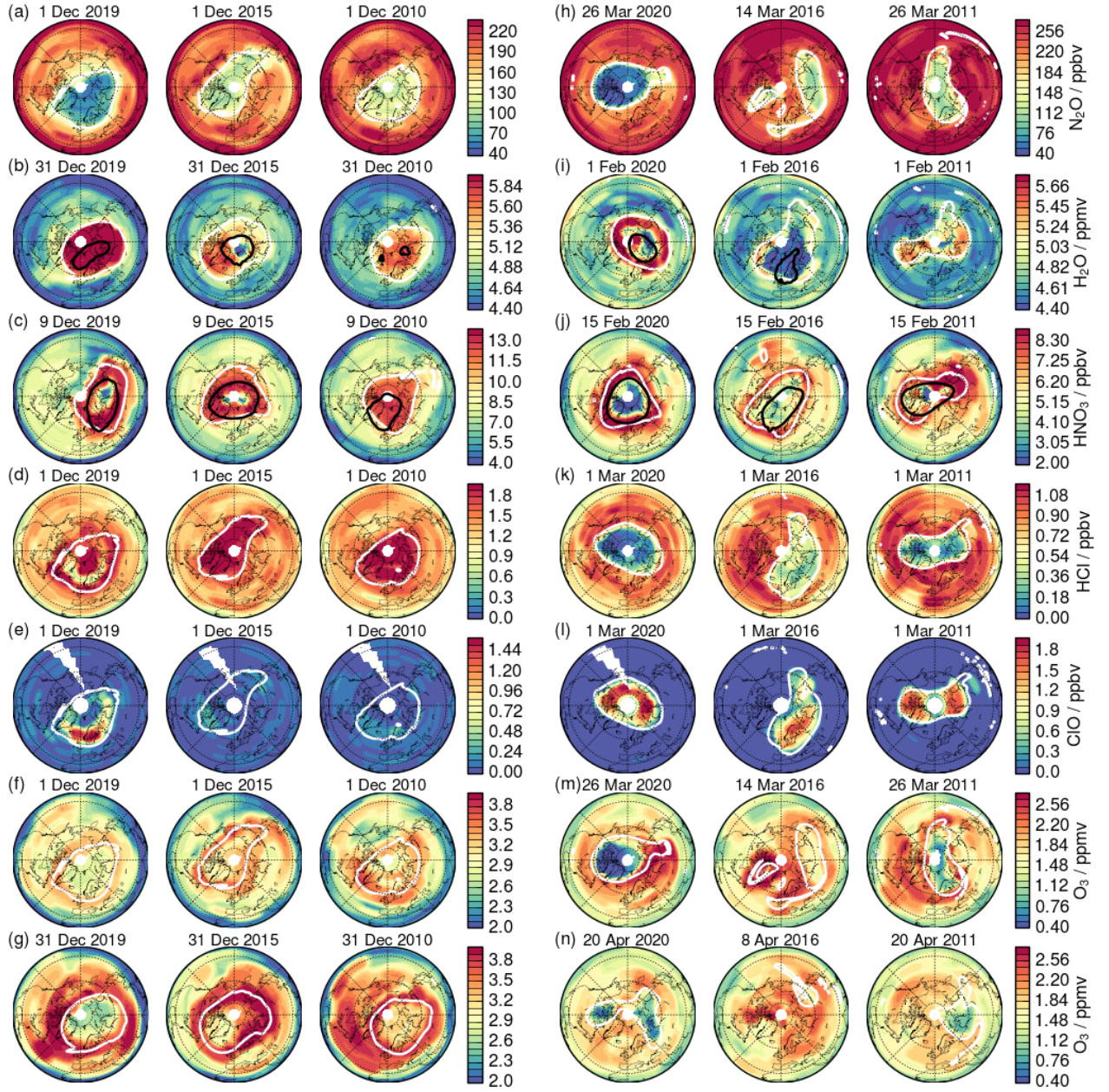
We use the MLS version 4 dataset (Livesey et al., 2020), along with meteorological fields from the Modern Era Retrospective Analysis for Research and Applications Version 2 (MERRA-2) (Gelaro et al., 2017) to show details of lower stratospheric polar processing in the extraordinary 2019/2020 winter/spring Arctic vortex, the resulting record-low ozone values, and comparisons with the previous Arctic winters (2010/2011 and 2015/2016) during which MLS observed largest ozone losses.

2 Results

Figures 1a–g show Northern Hemisphere (NH) MLS $520\,K$ ($\sim 18\,km$) trace gas maps in December 2010, 2015, and 2019. N_2O within the polar vortex was substantially lower (and H_2O higher) by early December 2020 than that in either 2015 or 2010, and its gradients across the vortex edge were steeper, consistent with a stronger signature of confined descent and/or descent of lower values from above. By 9 December, the region of temperatures below the nitric acid trihydrate (NAT) PSC threshold (Hanson & Mauersberger, 1988) was larger and more concentric with the vortex in 2019 and 2015 than in 2010. Temperatures remained consistently below this threshold starting earlier in 2019 (by mid-November) than in either 2010 (which did not become cold particularly early) and 2015 (which did) (see Lawrence et al., 2020, to be submitted). Both 2019 and 2015 showed significant areas of depressed HNO_3 in the vortex by 9 December, but only 2019 showed substantial chlorine activation; in fact, much of the sunlit portion of the vortex was filled with high ClO by 1 December 2019, with a corresponding region of low HCl values. Typically, lower stratospheric ozone (O_3) is higher near the vortex edge than in its core before the onset of chemical loss and increases through late December (as in 2015 and 2010). In 2019, however, O_3 was already lower throughout the vortex (even near the inside edge) than outside by 1 December and continued to decline through the month, while it continued increasing outside the vortex as in other years. Along with the early chlorine activation, this suggests a very early onset of chemical O_3 loss.

Figures 1h–n show $460\,K$ ($\sim 16\,km$) maps on dates when each species is near its most extreme observed values in the polar vortex. By 26 March 2020, N_2O throughout the vortex was even lower compared to other years (and H_2O in the portions unaffected by ice PSCs was higher) than in December, consistent with the signature of confined descent continuing to be unusually strong. The depression in HNO_3 abundances, evident in large portions of the vortex in each winter shown, was more severe in 2020. In contrast, temperatures remained below the ice PSC threshold much longer in 2016 than in any other Arctic winter on record (Manney & Lawrence, 2016; Matthias et al., 2016), leading to unprecedented dehydration (Khosrawi et al., 2017). Through most of the winter (e.g., Fig. 1k), HCl was slightly lower in 2020 than in 2011, and lower in both of those years than in 2016; consistent with this, on the same dates ClO was comparably high in 2020 and 2011, and somewhat lower in 2016. MLS recorded no data from 27 March through 19 April 2011 because of an instrument anomaly (e.g. Manney et al., 2011). By 26 March (Fig. 1m), $460\,K$ O_3 was distinctly lower in 2020 than in 2011 and remained so until late April (Fig. 1n), when values had started to rise in both years as the vortex weakened. Maps of extreme values of trace gases on MLS retrieval levels (see supporting information, hereinafter "SI", Figs. S1 and S2) show consistent results, with lower minimum values in 2020 than in 2011 both before and after the 2011 data gap.

Figure 2 shows $460\,K$ MLS 2019/2020 fields along with differences from climatology for 2019/2020, 2015/2016, and 2010/2011 as a function of equivalent latitude (the latitude that would encompass the same area between it and the pole as each potential vorticity, PV, contour, Butchart & Remsberg, 1986) and time, giving a vortex-centered view of the seasonal evolution. In 2019/2020, vortex temperatures (Fig. 2a shows MERRA-2 temperatures) were comparable to those in 2010/2011 and much lower than climatological values in late February through March. During late December through January, 2015/2016 temperatures were still the lowest on record, with the longest period below

Figure 1. MLS maps: (a–g) 520 K in December and (h–n) at 460 K on dates illustrating extreme values, for 2019/2020, 2015/2016, 2010/2011. Overlays: vortex boundary scaled potential vorticity (sPV, white; see Lawrence et al., 2018; Lawrence & Manney, 2018); NAT (on HNO$_3$) and ice (on H$_2$O) PSC threshold temperatures (black). 26 March (20 April) (m–n for 2011, 2020) is the day before (day after) the 2011 data gap.

the ice PSC threshold (e.g., Lawrence et al., 2020); however, since low temperatures are more common during these months than later on, the 2015/2016 temperatures were not as anomalous as those later in the season in 2020 and 2011. Temperatures were anomalously low much earlier in the winter in 2019/2020 than in 2010/2011.

Vortex strength (Fig. 2a, MERRA-2 overlays) particularly stands out in 2019/2020 (see also Lawrence et al., 2020), with PV gradient anomalies in late December 2019 comparable to those in mid-January 2011 and much stronger PV gradient anomalies as the season progresses than those in 2011 (the previous record-strong lower stratospheric vortex, e.g., Manney et al., 2011; Lawrence et al., 2020). The scaled PV (sPV) overlays in Figures 2b-g also emphasize these differences and show that the 2019/2020 vortex attained its maximum area earlier and maintained it longer than in other years; furthermore, the 2019/2020 vortex was larger than that in 2010/2011 throughout the winter.

Figure 2b,c shows N_2O and H_2O as the difference from each year's 1 November field to emphasize changes in the confined descent signature through the winter. N_2O decreased more rapidly through February 2020 and developed steeper gradients across the vortex edge, clearly indicating stronger and more confined vortex descent than in previous years. Before temperatures reach ice PSC thresholds, H_2O also showed this signature as a more rapid increase in 2019/2020 than in other years. Work in progress indicates that this signature arises largely from a combination of descent of anomalously low N_2O/high H_2O entrained into the developing mid-stratospheric vortex and stronger vortex confinement in 2019/2020 than in the other years shown.

Consistent with the temperature and vortex evolution, the period of low gas-phase HNO_3 was longest in 2019/2020: While negative HNO_3 anomalies in late December 2015 and January 2016 were more pronounced, and significant low anomalies lingered longer in 2011 than in 2016, in 2020 low anomalies appeared only slightly later than in 2016 and endured as late as those in 2011. Moreover, since HNO_3 was anomalously high before the onset of PSCs in 2019/2020, the net decrease was similar to that in 2016. Significant denitrification occurred in both 2011 and 2016 (e.g., Manney et al., 2011; Khosrawi et al., 2017; Johansson et al., 2019), and similarly low values indicate extensive denitrification in 2020. There were several multi-day periods in 2020 with temperatures below the ice PSC threshold, notably in late January, and a distinct signature of H_2O sequestration in PSCs is seen in early February; this drop (considering higher H_2O values before its onset) is comparable to the initial drop in 2016. Small negative or reduced positive anomalies near the vortex core persisted for a month or so after temperatures rose above the ice PSC threshold in 2020, suggesting some dehydration; however, 2016 (when strong low anomalies lingered throughout the season) remains the only Arctic winter in which MLS observed vortex-wide dehydration.

With few exceptions, chlorine was activated through at least late January in the Arctic winters observed by MLS. HCl (Fig. 2e) dropped to anomalously low values as soon as the vortex was well-defined in 2019/2020 and 2015/2016, whereas chlorine activation in 2010/2011 was near average until late January. ClO values (Fig. 2f) before March depend strongly on vortex size and position since much of the vortex may be in darkness; nevertheless, anomalously high ClO during most of December 2019 (compared with near-climatological values until late December in the other years) highlights early chlorine activation in 2019/2020. ClO anomalies in March were similarly high in 2020 and 2011. Arctic chlorine deactivation normally proceeds though the reformation of $ClONO_2$ (e.g., Douglass et al., 1995). In all three years highlighted here, however, low-HNO_3, low-ozone, and low-temperature conditions shifted deactivation towards a more Antarctic-like pathway, with rapid HCl reformation. While we do not know the exact timing of deactivation in 2011 because of the instrument anomaly, the common periods MLS observed show similar patterns in 2020 and 2011.
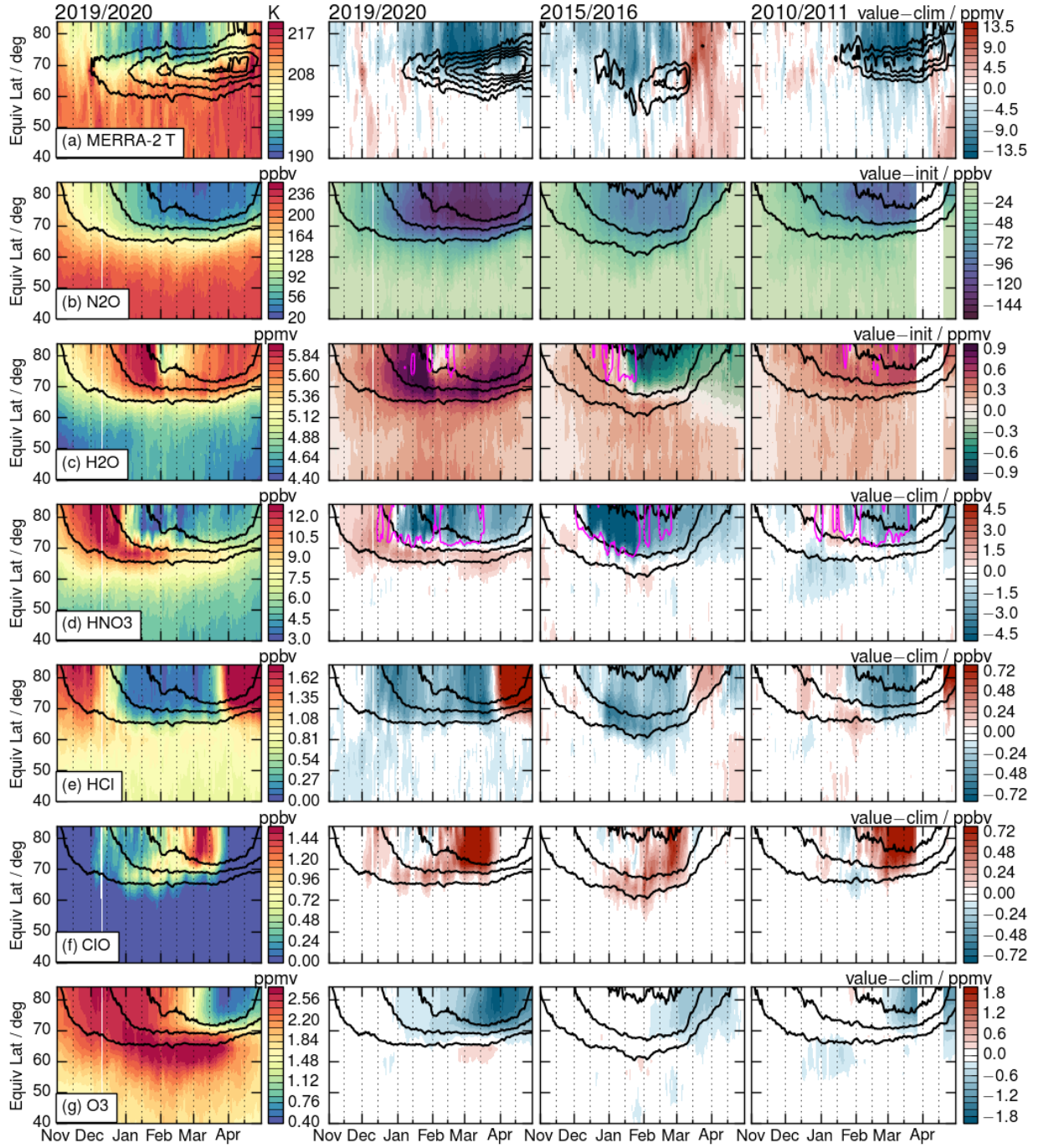
The end result of the more prolonged polar processing in 2019/2020 is apparent in O_3, with substantial low anomalies beginning in early January. Since we would expect O_3 to increase via descent in the strong 2019/2020 vortex, this pattern suggests appreciable chemical loss beginning by late November 2019. Strong low O_3 anomalies are apparent after early February 2016 and after early March 2011. The lowest O_3 observed in 2020 was much lower than that in 2011 at this altitude, and the larger vortex means that these low values covered a greater area. Although O_3 may have continued to decrease during the data gap in 2011, it is clear that the area of very low O_3 was never comparable to that in 2020 (consistent with area of lowest values shown in Fig. 1 and lowest minimum values Figs. S1 and S2).

Vortex averages of MLS data are provided in "Level 3" products that have recently been made public (Livesey et al., 2020, see SI for further description). Vortex-averaged cross-sections (Figure 3) show the vertical structure of the changes shown in Fig. 2. We focus on comparison of 2020 and 2011, since the extreme aspects of 2016 were previously discussed and those conditions did not result in springtime O_3 loss comparable to that in 2020 and 2011. Strong confined descent is apparent in the N_2O and H_2O anomaly fields and in the greater convergence of the overlaid contours of the values that were at 540 and 620 K on 1 November in 2020 than in 2011. The increased N_2O at the top of the 2020 plot indicates the beginning of the vortex breakup at higher levels in April.

In 2019/2020, the area of potential PSC formation shifted steadily down through the winter, with largest areas below PSC thresholds near 520–540 K in early winter and near 460–480 K in late winter/spring; in 2010/2011, this area shifted from ∼520 K in early winter to ∼500 K in spring. The area of anomalously low HNO_3 follows this vertical progression. In 2019/2020, increasing high HNO_3 anomalies in late December and January below the cold region suggest renitrification as PSCs sedimented from above evaporated; a similar pattern was seen in January 2011, albeit with smaller anomalies. High H_2O anomalies throughout most of 2019/2020, consistent with the strong confined descent signature in N_2O discussed previously, are related to initially low/high mid-stratospheric N_2O/H_2O; the abrupt shift from strong high anomalies to no significant anomalies in late January to early February reflects a period with substantial ice PSC activity. H_2O anomalies were weak in 2011 as ice PSCs were infrequent.

The patterns of chlorine activation seen in HCl and ClO are consistent with the evidence of PSC activity in temperatures and HNO_3, with the region of most depleted HCl at lower altitudes in winter/spring 2019/2020 than in 2010/2011 – minimum HCl values in spring 2020 end up at ∼480 K versus ∼520 K in 2011. During the period when ClO is highest, maximum values were near 460 K throughout March 2020 and moved from ∼520 K in early March to ∼480 K in late March in 2011. Anomalously high ClO in December 2019 and early January 2020 was consistent with HCl, but varied depending on how much of the vortex experienced sunlight; in contrast, HCl in December 2010 was slightly higher than climatology, indicating a relatively late start to chlorine activation.

Ozone contours (Fig. 3f) show a strong downward tilt through November, consistent with the strong descent signature seen in N_2O and H_2O. Since N_2O and H_2O contours continue to indicate strong descent through December, the flattening of O_3 contours and appearance of negative O_3 anomalies suggest that chemical O_3 loss began by late November and overwhelmed replenishment by descent by early December. In 2011, strong negative O_3 anomalies first appeared in February. Although the MLS record in 2011 is incomplete, no evidence suggests that O_3 reached values as low as those in 2020. Further, minimum vortex-averaged O_3 occurred near 440–460 K in 2020 but 480–500 K in 2011; thus even when values dipped as low in 2011, they were at smaller pressures and consequently affected the total column less. Record-low column ozone and associated record-high surface ultraviolet will be discussed in papers in this special collection (e.g., Bernhard et al., 2020, in preparation).

Figure 2. (a) 460 K EqL/time plots of MERRA-2 temperature for 2019/2020 (left), and difference from climatology for (following columns) 2019/2020, 2015/2016, and 2010/2011; overlays: sPV gradients (left) and positive sPV gradient differences from 2004/2005–2019/2020 climatology (remaining columns). (b–c) EqL/time plots of 460 K MLS N_2O and H_2O for 2019/2020 (left), and differences from the 1 November values (remaining columns). (d–g) As in (b–c), but for other MLS trace gases and differences from 2004/2005–2019/2020 climatology; overlays: vortex edge sPV (black), temperature (magenta; 197 K on HNO_3, 192 K on H_2O).

Vortex-averaged profiles on individual days (Fig. 3, left column) quantify differences between 2020 and 2011. There was a stronger confined descent signature and evidence of more PSC activity in 2020 than in 2011. Chlorine activation was similar at lower altitudes in both years but stronger at higher altitudes in 2011. O_3 abundances were smaller below about $500\,K$ in 2020 than in 2011. Supplementary Fig. S3 shows raw MLS profiles indicating that, though vortex averages were only slightly lower in 2020 than in 2011, localized minimum values were near zero in late March 2020, compared to $\sim 0.5\,ppmv$ in 2011, and occurred at lower altitude. Comparisons of minima from ozonesondes and MLS data (Ingo Wohltmann, personal communication) show consistent results.

Figure 3g shows chemical estimates of O_3 loss using the "MLS Match" method (Livesey et al., 2015, see SI for further information). The computed cumulative chemical change in 2019/2020 indicates some early chemical loss above $520\,K$, but largest loss between about 400 and $470\,K$. Similar loss rates were computed for 2020 and 2011 through late March, with maximum losses near $2.8\,ppmv$. However, consistent with observed chlorine activation, maximum losses were at lower altitude in 2020 than in 2011.
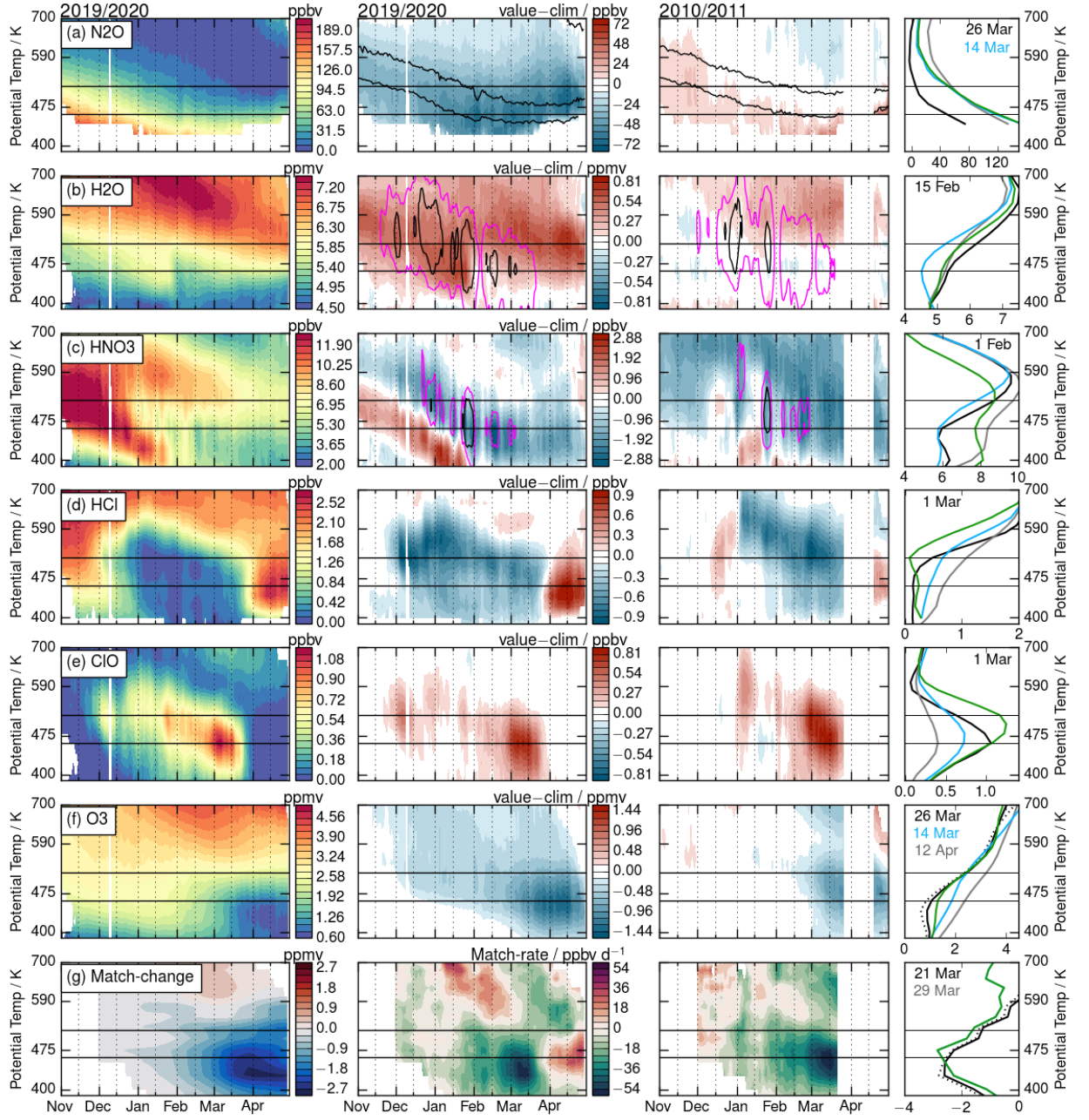
3 Summary and Conclusions

Figure 4 summarizes chemical processing and ozone loss at 460 and $520\,K$ in 2019/2020 in comparison to the other winters observed by Aura MLS. Descent of unusually low N_2O from the mid-stratosphere together with a well-isolated vortex resulted in smaller N_2O abundances in the lower stratosphere in 2020 than in any previous winter observed by MLS. Depressed HNO_3 shows the onset of sequestration in PSCs in December; although the timing varied with altitude, the magnitude of the decrease was larger in 2019/2020. An abrupt drop in H_2O in late January 2020 indicates sequestration of H_2O in ice PSCs, but temperatures rose above the ice PSC threshold again too soon to produce vortex-wide dehydration of similar magnitude to that in 2016. Although H_2O decreased over a small altitude range in 2020, at $460\,K$ the drop during the coldest period was comparable to that in 2016.

Chlorine activation began slightly earlier in 2019 than in 2015 at $460\,K$ and earlier than in 2010 at all levels. Previously, earliest strong Arctic chlorine activation was observed in 2012/2013, and the vortex was sufficiently exposed to sunlight for ClO to be elevated in late December (Manney et al., 2015). The timing of the HCl drop in 2019 was similar to that in 2012 at $460\,K$, but about ten days earlier at $520\,K$; at both levels highly elevated ClO was seen nearly two weeks earlier in 2019 than in 2012.

In 2011, chlorine deactivation occurred much later and followed a more Antarctic-like pattern than previously observed in the Arctic (e.g., Manney et al., 2011). The timing and pathway of chlorine deactivation in 2020 were even more similar to those in the Antarctic. Not only did ClO remain enhanced at $460\,K$ as late as in 2011, but also HCl recovered much faster than usual and reached considerably higher values by mid-April than in 2011. In a typical Arctic spring, deactivation initially proceeds through reformation of $ClONO_2$; however, several factors can shift Arctic chlorine partitioning toward HCl as in the Antarctic (e.g., Douglass et al., 1995; Santee et al., 2008). First, denitrification limits the availability of NO_2, inhibiting combination with ClO to form $ClONO_2$. In addition, low ozone and low temperatures together lead to preferential reformation of HCl (e.g., Douglass & Kawa, 1999). Thus HCl production was highly favored inside the persistently cold, strongly denitrified, and ozone-depleted Arctic vortex in spring 2020.

These conditions resulted in record-low Arctic O_3 values in spring 2020 at levels below $\sim 500\,K$. Match estimates suggest more chemical loss in December 2019 through April 2020 than in 2010/2011 below $\sim 460\,K$; peak losses were near $2.8\,ppmv$ in each of these winters, but at lower altitude in 2020 than in 2011. While empirical O_3 loss estimates have large uncertainties (e.,g., Griffin et al., 2019, also see SI), vortex-averaged

Figure 3. (a–f) Potential temperature/time sections of vortex averaged MLS species for 2019/2020 (left), and differences from 2004/2005–2019/2020 climatology for (center two columns) 2019/2020 and 2010/2011; right column: 2011 (green), 2016 (blue), and 2020 (black) profiles on extreme dates, and climatology (grey; for 2020 dates where those differ from other years). Black overlays in (a) show contours of N_2O values that were at 540 and 620 K on 1 November. Overlays in (c) and (d) show area with MERRA-2 temperatures below NAT (magenta 3%, black 5%, of NH) and ice (magenta 1%, black 2%, of NH) PSC thresholds, respectively. (g) (left) Cumulative chemical O_3 change in 2020 from Match (see text and SI), (center two columns) Match rate of O_3 change in 2020 and 2011, and (right) profiles of cumulative O_3 change on 21 March 2020 (black) and 2011 (green), and 29 March 2020 (dotted line). Horizontal lines mark 520 and 460 K.

descent calculations using MLS N_2O (overlaid lines/symbols in Fig. 4f,l) and using trajectory-based descent rates (overlaid symbols in Fig. 4) (see SI for description of calculations) give consistent results. They suggest that chemical loss between December and March was very similar in the two winters, but that significant chemical loss occurred in November only in 2019. (As explained in the SI, the vortex-averaged descent methods give slightly lower estimates than Match because they may be more affected by dilution of the chemical loss signature near the vortex edge.) Record-low springtime O_3 at lower altitudes in 2020 than in 2011 is consistent with evidence of record-low column O_3 and anomalously high ultraviolet in 2020 (e.g., Bernhard et al., 2020). Large interannual variability in meteorological conditions in the Arctic stratosphere (which led to the exceptionally strong and long-lived polar vortex in 2019/2020) may yet result in more extreme Arctic O_3 loss in future years while stratospheric chlorine loading remains high: For instance, 2015/2016 still stands out as the coldest Arctic winter with most denitrification and dehydration – if conditions such as those commenced as early in some future year and lasted as late as in 2019/2020, and the vortex remained well-isolated, then greater O_3 depletion could occur. This variability, coupled with likely effects of climate change, makes comprehensive monitoring of polar processes such as that provided by Aura MLS (currently in the 16th year of a 5-year mission) an important priority moving forward.
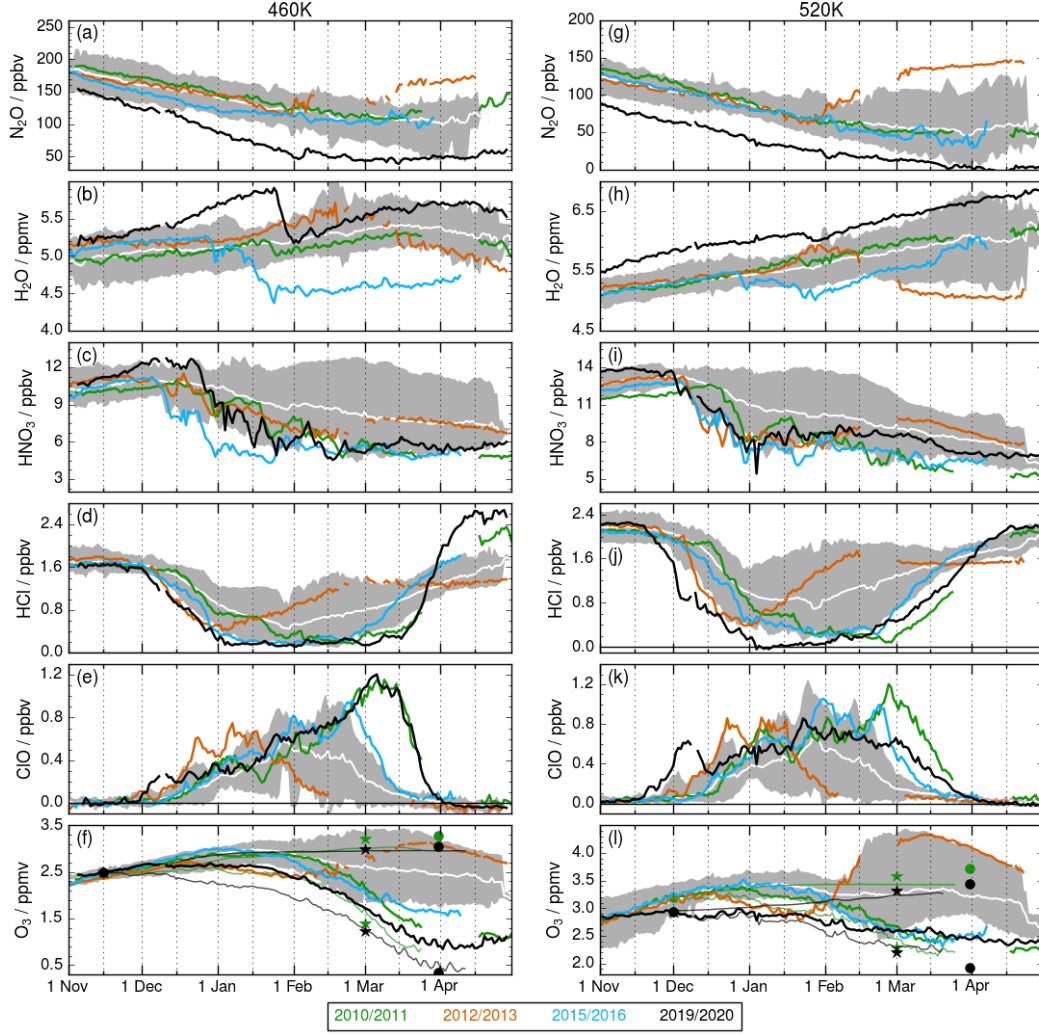
References

Bernhard, G. H., Fioletov, V. E., Grooß, J.-U., Ialongo, I., Johnsen, B., Lakkala, K., ... Svenby, T. (2020). *Record-breaking increases in Arctic solar ultraviolet radiation caused by exceptionally large ozone depletion in 2020.* (to be submitted to GRL for this special collection)

Butchart, N., & Remsberg, E. E. (1986). The area of the stratospheric polar vortex as a diagnostic for tracer transport on an isentropic surface. *J. Atmos. Sci.*, *43*, 1319–1339.

Douglass, A. R., & Kawa, S. R. (1999). Contrast between 1992 and 1997 high-latitude spring Halogen Occultation Experiment observations of lower stratospheric HCl. *J. Geophys. Res.*, *104*(D15), 18,739–18,754.

Douglass, A. R., Schoeberl, M. R., Stolarski, R. S., Waters, J. W., III, J. M. R., Roche, A. E., & Massie, S. T. (1995). Interhemispheric differences in springtime production of HCl and ClONO$_2$ in the polar vortices. *J. Geophys. Res.*, *100*, 13,967–13,978.

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., ... Zhao, B. (2017). The Modern-Era Retrospective Analysis for Research and Applications, Version-2 (MERRA-2). *J. Clim.*, *30*, 5419–5454. doi: doi:10.1175/JCLI-D-16-0758.1

Figure 4. Vortex-averaged MLS trace gases for 2019/2020 (black), 2015/2016 (blue), 2012/2013 (orange), and 2010/2011 (green), at (a–f) 460 K and (g–l) 520 K. Grey envelope shows range of values for 2004/2005 through 2018/2019, excluding the highlighted years; white line shows mean for those years. Thin green and black lines in (f) and (l) show passive ozone (increasing lines) and calculated chemical loss in ozone estimated from MLS N_2O gradients (see SI) for 2011 and 2020, respectively; overlaid symbols shown passive ozone and chemical loss estimates (higher and lower values, respectively, on end dates) using trajectory-based descent estimates (see SI) with initial and final days shown as pairs of like symbols.

Griffin, D., Walker, K. A., Wohltmann, I., Dhomse, S. S., Rex, M., Chipperfield, M. P., . . . Tarasick, D. (2019). Stratospheric ozone loss in the Arctic winters between 2005 and 2013 derived with ACE-FTS measurements. *Atmos. Chem. Phys.*, *19*(1), 577–601. Retrieved from `https://www.atmos-chem-phys.net/19/577/2019/` doi: 10.5194/acp-19-577-2019

Hanson, D., & Mauersberger, K. (1988). Laboratory studies of the nitric acid trihydrate: Implications for the south polar stratosphere. *Geophys. Res. Lett.*, *15*, 855–858.

Johansson, S., Santee, M. L., Grooß, J.-U., Höpfner, M., Braun, M., Friedl-Vallon, F., . . . Woiwode, W. (2019). Unusual chlorine partitioning in the 2015/16 Arctic winter lowermost stratosphere: observations and simulations. *Atmos. Chem. Phys.*, *19*(12), 8311–8338. Retrieved from `https://www.atmos-chem-phys.net/19/8311/2019/` doi: 10.5194/acp-19-8311-2019

Khosrawi, F., Kirner, O., Sinnhuber, B.-M., Johansson, S., Höpfner, M., Santee, M. L., . . . Braesicke, P. (2017). Denitrification, dehydration and ozone loss during the 2015/2016 Arctic winter. *Atmos. Chem. Phys.*, *17*(21), 12893–12910. Retrieved from `https://www.atmos-chem-phys.net/17/12893/2017/` doi: 10.5194/acp-17-12893-2017

Lawrence, Z. D., & Manney, G. L. (2018). Characterizing stratospheric polar vortex variability with computer vision techniques. *Journal of Geophysical Research: Atmospheres*, *123*(3), 1510–1535. Retrieved from `http://dx.doi.org/10.1002/2017JD027556` (2017JD027556) doi: 10.1002/2017JD027556

Lawrence, Z. D., Manney, G. L., & Wargan, K. (2018). Reanalysis intercomparisons of stratospheric polar processing diagnostics. *Atmos. Chem. Phys.*, *18*, 13547–13579. doi: 10.5194/acp-18-13547-2018

Lawrence, Z. D., et al. (2020). *The remarkably strong Arctic stratospheric polar vortex of winter 2020: Ties to record-breaking Arctic oscillation and ozone loss.* (to be submitted to JGR for this special collection)

Livesey, N. J., Read, W. G., Wagner, P. A., Froidevaux, L., Lambert, A., Manney, G. L., . . . Lay, R. R. (2020). *EOS MLS version 4.2x level 2 and 3 data quality and description document* (Tech. Rep.). JPL. (Available from http://mls.jpl.nasa.gov/)

Livesey, N. J., Santee, M. L., & Manney, G. L. (2015). A Match-based approach to the estimation of polar stratospheric ozone loss using Aura Microwave Limb Sounder observations,. *Atmos. Chem. Phys.*, *15*, 9945–9963.

Manney, G. L., & Lawrence, Z. D. (2016). The major stratospheric final warming in 2016: Dispersal of vortex air and termination of Arctic chemical ozone loss. *Atmos. Chem. Phys. Disc.*, *16*. Retrieved from `http://www.atmos-chem-phys-discuss.net/acp-2016-633/` doi: 10.5194/acp-2016-633

Manney, G. L., Lawrence, Z. D., Santee, M. L., Livesey, N. J., Lambert, A., & Pitts, M. C. (2015). Polar processing in a split vortex: Arctic ozone loss in early winter 2012/2013. *Atmos. Chem. Phys.*, *15*, 4973–5029.

Manney, G. L., Santee, M. L., Rex, M., Livesey, N. J., Pitts, M. C., Veefkind, P., . . . Zinoviev, N. S. (2011). Unprecedented Arctic ozone loss in 2011. *Nature*, *478*, 469–475.

Matthias, V., Dörnbrack, A., & Stober, G. (2016). The extraordinarily strong and cold polar vortex in the early northern winter 2015/2016. *Geophys. Res. Lett.*, *43*(23), 12,287–12,294. Retrieved from `http://dx.doi.org/10.1002/2016GL071676` (2016GL071676) doi: 10.1002/2016GL071676

Santee, M. L., MacKenzie, I. A., Manney, G. L., Chipperfield, M. P., Bernath, P. F., Walker, K. A., . . . Waters, J. W. (2008). A study of stratospheric chlorine partitioning based on new satellite measurements and modeling. *J. Geophys. Res.*, *113*. doi: 10.1029/2007JD009057

WMO. (2014). *Scientific assessment of ozone depletion: 2014.* Geneva, Switzerland: Global Ozone Res. and Monit. Proj. Rep. 55.