The Danish Meteorological Institute

DMI Report 21-19 Polar Stratospheric Conditions Relevant for Ozone Depletion Studied with Radio Occultation Data

Final scientific report of the 2020 National Centre for Climate Research Work Package 1.1.3, Ozone

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By Hans Gleisner and Helge Jønch-Sørensen

The Danish Meteorological Institute

Colophon

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Author(s)	Hans Gleisner and Helge Jønch-Sørensen
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Content

1 Abstract

Polar Stratospheric Clouds (PSCs) are strongly associated with increased ozone depletion in the polar regions. These clouds form in the stratosphere at altitudes around 15-30 km at sufficiently low temperatures. The occurrence of very cold atmospheric conditions may be affected by climate change. We have investi-gated methods for quantifying PSC volumes from GNSS Radio Occultation (RO) stratospheric temperature and pressure data. We have also studied the long-term variability and potential changes of PSC volumes and stratospheric temperatures conducive to the formation of PSCs. We show that GNSS-RO data can be used to quantify the areas and volumes of PSC formation in the Arctic and Antarctic stratosphere and that this novel method for PSC volume estimation appears to be robust to certain type of algorithmic choices. Using these RO-based estimates we can confirm the statistical relation between ozone depletion and PSC volumes in the polar regions that is described in the scientific literature.

The time series of data are not sufficiently long (in relation to the highly irregular year-to-year variation) to allow firm detection of trends. However, there is a tendency that during parts of the seasons the coldest conditions in the stratosphere tend to slowly become colder. The exact relation to climate change and/or decreasing concentrations of ozone depleting substances, and the extent to which the detected changes are statistically significant, will have to be further investigated.

2 Resumé

Polar stratosfæriske skyer (PSC) er stærkt forbundet med ozonnedbrydningen i stratosfæren over de polare egne. Disse skyer dannes i 15-30 km højde, når temperaturerne bliver tilpas lave. Hændelser med meget lave temperature kan være påvirket af klimaændringer. Vi har undersøgt metoder for at kvantificere PSC volumenet udfra GNSS Radio okkultations (RO) målinger af temperature og tryk op gennem stratosfæren. Vi har også set på variabilliteten og eventuelle ændringer af PSC volumener og temperaturforhold der befordrer dannelse af PSCer. Vi finder, at GNSS-RO data kan bruges til at kvantificere arealer og volumener af PSC dannende områder I stratosfæren over Arktis og Antarktis, samt at den nye metode til at bestemme PSC volumen virker robust i forhold til valg af algoritme. Ud fra disse RO-baserede værdier har vi bekræftet den kendte statistiske relation mellem ozonnedbrydningen i de polare egne og PSC volumen.

Tidslinjen for disse data er ikke lang nok, sammenlignet med de store og irregulære år-til-år variationer, til sikkert at kunne bestemme tendenser, men der ses en tendens mod at det i noget af sæsonen bliver langsomt koldere i stratosfæren. Den præcise sammenhæng mellem dette og klimaændringer og den dalende koncentration af ozonnedbrydende stoffer, samt hvorvidt de observerede ændringe er statistisk signifikante, kræver yderligere studier.

3 Introduction

The Danish National Centre for Climate Research (Nationalt Center for Klimaforskning, NCKF) has completed its first year in 2020. It has been a source of funding for the Danish Meteorological Institute and collaborators for climate change related research during this year. The 18 work packages fall under 4 general themes:

1. Arctic and Antarctic Research
2. Climate change in the near future
3. Use of climate data
4. Support for the IPCC

The present report describes the outcome of work package 1.1.3 Ozone, which is part of the theme on Arctic and Antarctic Research.

3.1 Science background

The stratospheric ozone layer is expected to slowly recover as the concentrations of ozone depleting substances decreases over the present century. However, the recovery is modulated by factors related to climate change. Ozone chemistry in the polar regions is strongly coupled to the presence of polar stratospheric clouds (PSCs) which forms around 15-30 km at sufficiently low temperatures. One of the key factors to understand the impact of climate change on the recovery of the ozone layer is the presence of temperatures low enough for PSCs to form.

Rex et al. (2004, 2006) found a strong correlation between ozone loss and the volume, V_{PSC}, of polar-stratospheric air masses cold enough for PSCs to form. They described a linear relation between ozone loss and V_{PSC} when integrated over the period of seasonal polar vortex existence. This correlation explains much of the inter-annual variation of the Arctic ozone loss (*Harris et al.*, 2010). The existence of such a simple correlation was surprising, given the complexity of the physics involved. It was, however, independently confirmed by *Tilmes et al.* (2004) and has since become a relatively established notion.

The correlation between V_{PSC} and seasonal ozone loss is potentially very useful for understanding the role played by climate change in the recovery of the ozone layer. The volume of cold air in the stratosphere can be monitored observationally and climate model projections of this geophysical variable are readily available, or can be computed from modelled variables. Most observational estimates of V_{PSC} in the scientific literature are based on reanalysis data. Radiosondes provide a very sparse data set that does not cover large parts of the Arctic Ocean. Satellite-based remote sensing data from infrared and microwave instruments are often difficult to interpret at high latitudes for various reasons (e.g., *Anthes et al.*, 2008). GNSS radio occultation (GNSS-RO) data provides an alternative to reanalysis data (*de la Torre Juarez et al.*, 2009). The advantages are high vertical resolution and a high temporal stability. The latter is particularly important for studies of inter-annual variability and long-term trends. The disadvantages of RO data are a relatively sparse data set and a short time series – continuous observations with reasonable data numbers start in mid-2006. A small number of RO data that may be used at a lower spatial and temporal resolution are available from September 2001. In this study we investigate the potential for exploiting GNSS-RO data, which has a strong research base at DMI, to address observational issues related to the role of climate change for the recovery of the ozone layer.

3.2 Purpose of this study

The purpose of this study is a) to investigate methods for quantifying the volume, V_{PSC}, from GNSS-RO stratospheric temperature and pressure data, and b) to investigate the long-term variability and trends of PSC volumes and stratospheric temperatures conducive to the formation of PSCs. The objectives with these investigations are to further our understanding of role played by climate change for the evolution of ozone-depleting conditions in the Arctic, but also to lay the foundations for an operational service at DMI to monitor these conditions as they evolve day by day during the winter-spring seasons in the Arctic and Antarctic.

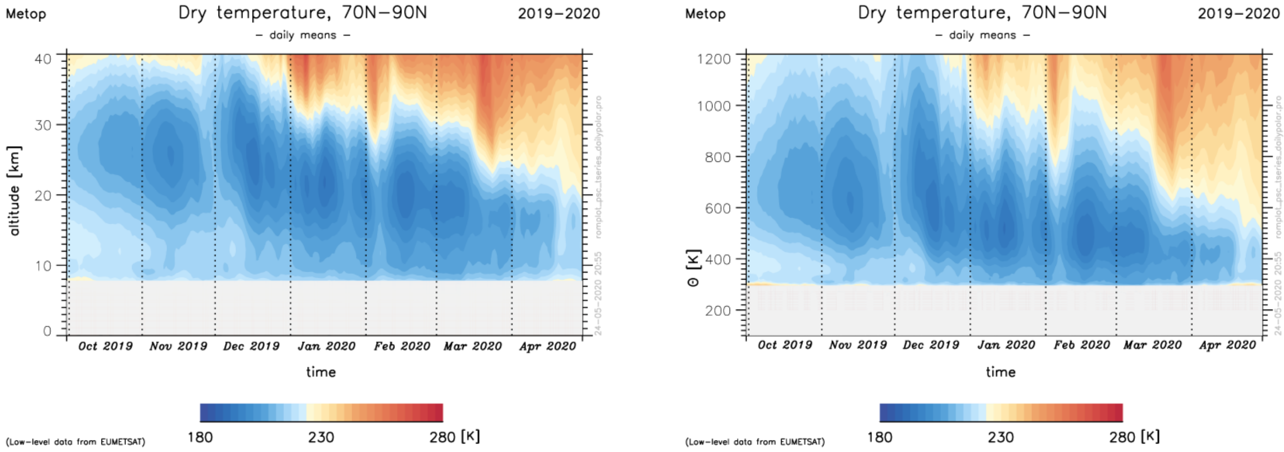

Figure 1. *Daily mean stratospheric temperatures north of 70 degrees latitude during the 2019-2020 winter-spring season. Data are shown as a function of altitude (left panel) and as a function of potential temperature (right panel). The data were obtained from the ROM SAF Metop ICDR data record.*

4 Data and methods

4.1 Ozone monitoring data

The Arctic ozone data presented in this study quantify maximum ozone depletion as measured by the SAOZ network. The ground based SAOZ network consists of around 9-10 instruments at various locations in the Arctic area measuring total column ozone. In years with a stable polar vortex during January-March, the data is supplemented with results from the Match campaign. In the Match campaign the launch of ozone sondes are coordinated with calculated trajectories of air parcels inside the vortex, such that the ozone depletion inside the same volume of air is measured as it travels the Arctic area.

For Antarctica the area of the ozone hole from 1980 to 2020 is presented in Section 5. The ozone hole is defined as the area south of -50° S where the total ozone column is below 220 Dobson Units (DU). Measurements are combined for several satellite missions from NASA, ESA and EUMETSAT. In a future study ozone profiles, and total ozone columns, from EUMETSAT AC SAF will be included.

4.2 Radio occultation data

The ROM SAF Climate Data Record v1.0 (CDR v1) consists of RO data that has been reprocessed by the ROM SAF. The CDR includes data from four RO satellite missions: CHAMP (Sep 2001 – Sep 2008), COSMIC (July 2006 – Dec 2016), Metop (Oct 2006 – Dec 2016) and GRACE (Mar 2007 – Dec 2016). For the CDR based on Metop data there is an associated Interim CDR (ICDR) that extends the CDR time series. In order to include the ozone depletion season over the Antarctica the ROM SAF Near Real Time (NRT) data based on Metop data from August 2020 to November 2020 has been included. The quality of the NRT data is in general comparable to the CDR and ICDR data. The profiles are averaged from the original ~200m altitude resolution to profiles with 1 km altitude steps.

For this study the atmospheric profiles containing dry temperature profiles were extracted from the ROM SAF data. Profiles north of 50°N and south of 50°S were extracted for January–April (north) and August-December (south). The total number of useful profiles for the two areas is 691898 and 875454 respectively,

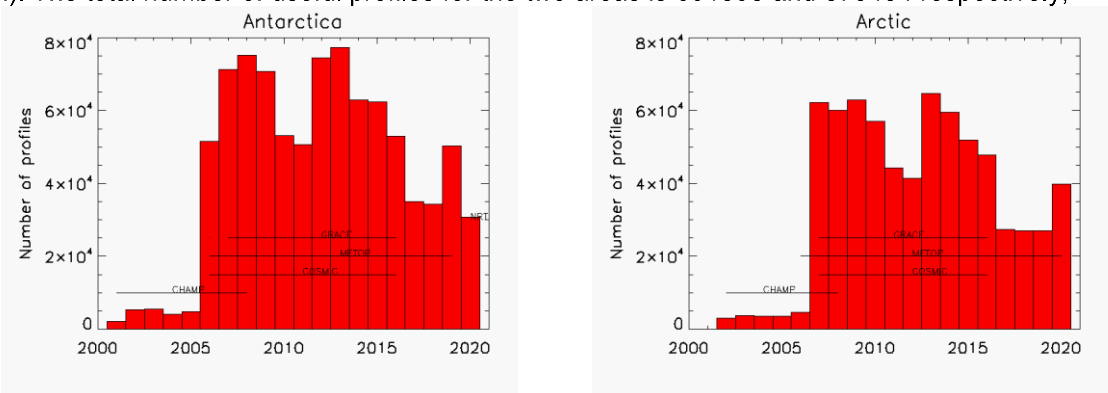

Figure 2. *Left: Total number of profiles per year for Antarctica (South of 50°S, August-December). Right: Total number of profiles per year for Arctic (North of 50°N, January-April).*

which amounts to approximately 175000 profiles per month. From 2001 to 2005 the data is only from the CHAMP mission and the data numbers are rather small (< 5000 per year, Fig.2) compared to the rest of the period (30.000-70.000 profiles per year). The lower statistical weight of the data before 2006 is taken into account in the following.

In addition we used dry temperature and dry pressure data from the Metop CDR and ICDR data records to investigate the feasibility of estimating PSC formation volumes from RO data (Sections 5.4 and 5.5). That data set allows us to study the 14 northern hemisphere winter-spring seasons from 2006-07 to 2019-20.

4.3 Methods for retrieval of PSC volumes from RO data

The volume, V_{PSC}, where the temperatures are low enough for PSCs to form are vertically integrated from the corresponding areas, A_{PSC}. These areas are computed as function of vertical level for latitude-time bins (we assume purely zonal bins). The vertical level may be altitude, h, but is more commonly chosen as potential temperature, θ, defined as

$$\theta = T \cdot \left(\frac{P_0}{P}\right)^{R/c_p} \tag{1}$$

where P_0=1000 hPa and R/c_p = 0.285714. Figure 1 shows daily mean stratospheric temperatures north of 70 degrees latitude during the 2019-2020 northern hemisphere winter-spring season, as a function of altitude (left panel) and as a function of potential temperature (right panel).

The retrieval of V_{PSC} from the RO measurements is based on computing the fraction, q, of temperature observations that fall below a certain threshold, T_{cold}. If the RO data are randomly distributed across the latitude bin, this fraction is proportional to the area where the stratospheric temperatures are lower than T_{cold}. We know the total area of the latitude bins, A_i, and from the fractions q we can compute the areas with temperatures lower than the threshold T_{cold}. The temperature threshold is normally altitude dependent (or rather potential temperature dependent), and the areas where PSCs form can be computed as

$$A_{PSC}(\varphi_i, h_j, n) = q_{ijn} \cdot A_i \tag{2}$$

where φ_i indicates a latitude bin, h_j an altitude bin, and index n denotes a day number.

From the low-temperature areas given by Eq. 2, we can compute the corresponding volumes V_{PSC} by vertical integration of A_{PSC} at each latitude bin and day:

$$V_{PSC}(\varphi_i, n) = \sum_{j=j_{400}}^{j_{550}} \Delta h \cdot A_{PSC}(\varphi_i, h_j, n) \tag{3}$$

This integration is preferably done on the altitude grid, rather than on the potential temperature grid. Irrespective of the type of grid, we can choose to limit the vertical integration to either a fixed altitude interval or a fixed potential temperature interval. In Eq. 3 the vertical integration is done on an altitude grid between potential temperatures 400 K and 550 K, indicated by the indices j_{400} and j_{550}.

The volumes V_{PSC} obtained by the procedure described above depend of several choices: the temperature thresholds used, the horizontal and vertical limits applied, and the method used to determine the fraction q. In this study we have used the nitric acid trihydrate (NAT) equilibrium temperature as the threshold for PSC formation. Table 1 shows the assumptions about the dependence of NAT equilibrium temperature on potential temperature that were used in this study.

We explore two methods for computing the fraction q:

i. based on the detailed count statistics of the RO temperature data within latitude-time bins

ii. based on the means and standard deviations of gridded RO data available from the ROM SAF

The fraction q can be obtained from the temperature observation count statistics. Within a latitude-time bin and at each height we compute the fraction q from the number of temperature observations that falls below a certain temperature threshold T_{cold}. That fraction is used in Eq. 2 to compute the area A_{PSC}, followed by vertical integration into the volume V_{PSC} according to Eq. 3.

The fraction q can alternatively be obtained from gridded RO data means and standard deviations, which are directly available as a part of the ROM SAF gridded data products. We assume that temperatures within a latitude-time bin and at each height have a Gaussian distribution with mean m_T and standard deviation s_T valid for that bin. Using the properties of a Gaussian distribution we compute the fraction, q, of temperatures that fall below a certain threshold T_{cold}. That fraction is used in Eq. 2 to compute the areas A_{PSC}, followed by vertical integration into the volume V_{PSC}.

RO data are quasi-randomly distributed in latitude and longitude for sufficiently small latitude bins. For broader latitude bins there may be deviations from a uniform random distribution in the latitudinal direction, and there may be some deviations from a uniform distribution over the solar day. The magnitude of these deviations from uniformity, and their consequences, should be investigated as they may introduce biases into the estimates of cold temperature areas and volumes.

Similarly, the shape of the temperature distributions, how well they approximate a Gaussian distribution, and their stability in space and time, should be investigated as potential sources of biases. The feasibility of correcting for any deviations should be considered.

Table 1: *Nitric acid trihydrate (NAT) equilibrium temperature as function of potential temperature.*

NAT eq temp [K]	potential temp [K]
200.30	350
198.60	380
197.07	400
195.50	475
192.90	550
190.70	675
186.30	950

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5 Study

5.1 Arctic and Antarctic ozone holes

In the Arctic, the polar vortex builds up during November-December and temperatures low enough for the formation of PSCs are normally reached early. However, the chemical ozone depletion first occurs when the Sun reach the polar region in early February and severe ozone depletion is only found in years where the polar vortex and low temperature areas stay present after the beginning of February. In the Arctic atmosphere the so called Sudden Stratospheric Warming (SSW) events are often seen, with the consequence that the polar vortex dissolves or breakup, ending the ozone depletion. Although a strong polar vortex in special cases may continue into April, the temperatures are too high for the formation of PSCs. The most relevant months for studying the Arctic ozone depletion is thus February and March.

Over the south polar region, the situation is different due to the geographical conditions. The presence of the Antarctic continent stabilizes the atmosphere and SSW events are less frequent and appear mostly much later in the season than in the Arctic. The polar vortex is normally very stable until October-November and the lowest temperatures reached are more than 10 K lower than those is found in the Arctic. Ozone depletion begins in August and results in ozone hole conditions that normally lasts to early November. The maximum size of the ozone hole is reached in September and the slight decrease in size observed since the year 2000 is interpreted in terms of the decreasing concentration of the ozone depleting substances. However a tendency of prolonged ozone hole season has been indicated in recent years. The maximum area in November seems to increase for years with stable vortex conditions. This may be explained by changing temperature conditions in the stratosphere that might be a consequence of the general climate change.

Figure 3 shows the evolution of the Antarctic ozone hole during 23 southern hemisphere winter-spring seasons. The 2020 ozone hole was very spectacular during November and December and underlines the trend that described above, the five largest ozone holes in November all occurred after 2006.

Figure 4 shows the maximum ozone depletion inside the Arctic vortex during January-March from 2002 to 2020. In 2011 then largest ozone depletion occurred and in March 2020 the first real ozone hole over the Artic was observed, with minimum ozone layer thickness below 220 DU for most of the month.

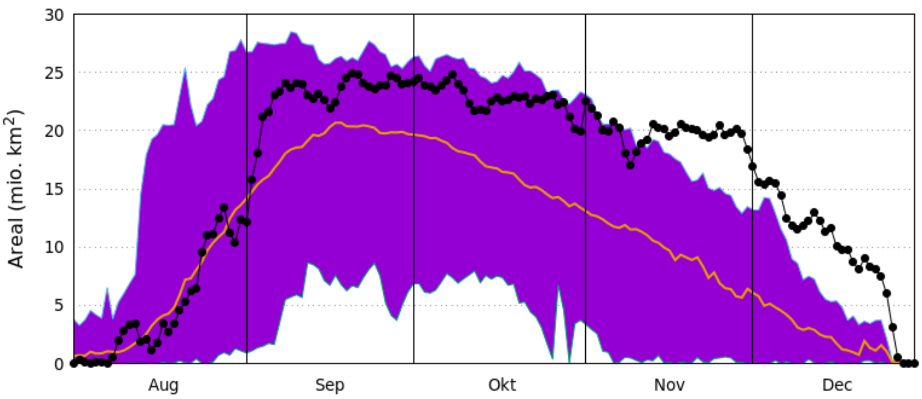

Figure 3*. Statistics of the daily areas of the Antarctic ozone hole.* The yellow *curve shows the mean daily area 1986-2019, while the coloured (purple) area shows the minimum and maximum daily areas 1986-2019. The black curve shows the daily areas in 2020.*

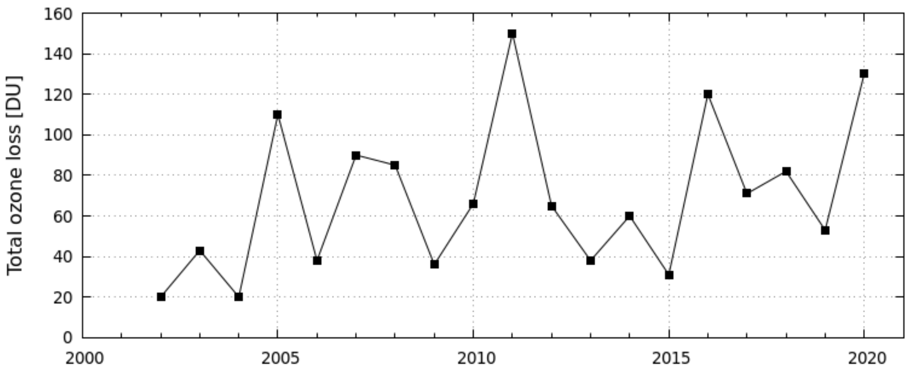

Figure 4. *Maximum ozone depletion during January-March inside the Arctic vortex for 2002-2020.*

5.2 Volumes of PSC formation

5.2.1 Seasonal evolution of PSC forming regions

Using the methods devised in Section 4.3, with the low-temperature fraction *q* determined by the means and standard deviations from the daily gridded RO data, we have computed the areas, A_{PSC}, and volumes, V_{PSC}, of Arctic stratospheric regions cold enough for PSCs to form. Figure 5 shows the total areas with temperatures lower than T_{NAT} north of 60°N during the 2019-20 northern hemisphere winter-spring season. The total areas in Figure 5 are computed as the sum across all 5-degree latitude bins north of 60°N. The panel to the left show the areas as function of altitude and the panel to the right show areas as function of potential temperature. During the winter-spring season there is a slow downward motion of the PSC formation, as a consequence of the slow sinking of the altitudes of the coldest air in the polar vortex. During the 2019-20 winter-spring season there were no stratospheric warming event strong enough to completely disrupt this process, with the consequence that there was an unusually long period of PSC formation and ozone depletion. In fact, the 2019-20 season stands out in the data records, as the ozone depletion started earlier than in any other season on record and continued to a later date than in any year except for 2011 (Manney et al., 2020).

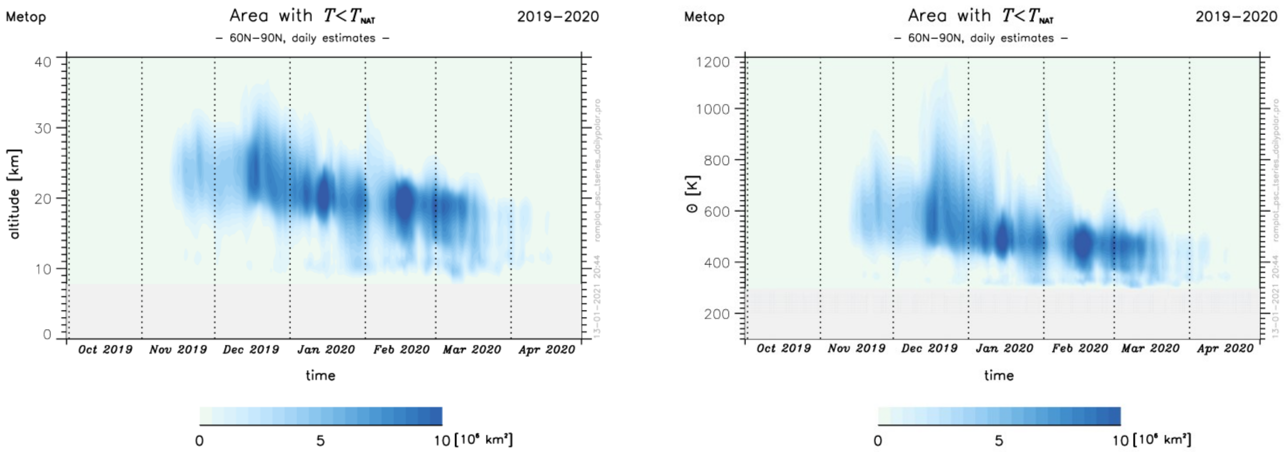

Figure 5. *Daily areas with temperatures low enough for PSC formation in the Arctic stratosphere north of 60 degrees latitude during the 2019-20 northern hemisphere winter-spring season. Data are shown as a function of altitude (left panel) and as a function of potential temperature (right panel). The data were obtained from the ROM SAF Metop ICDR data record.*

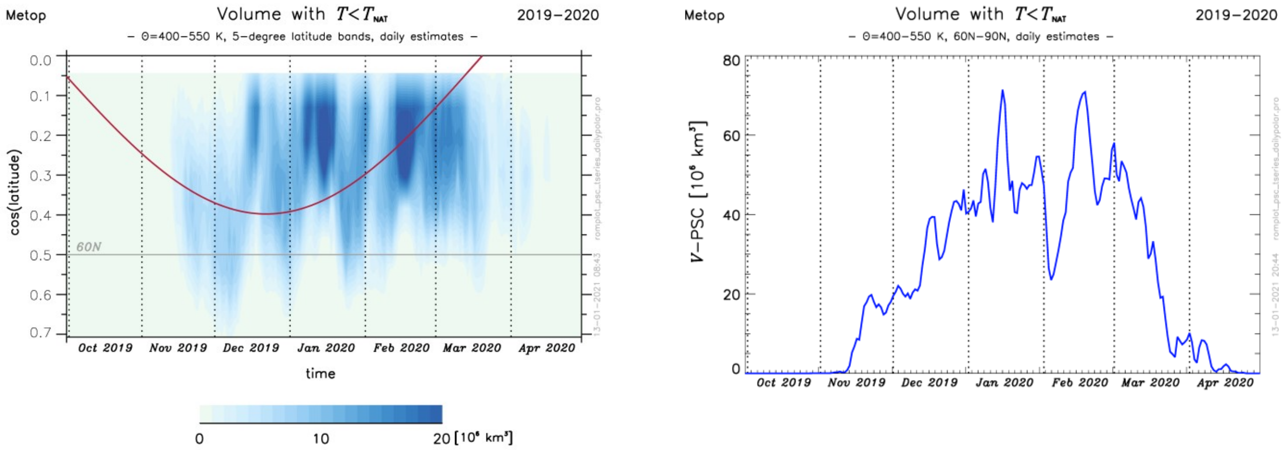

Figure 6. *Daily volumes with temperatures low enough for PSC formation during the 2019-20 northern hemisphere winter-spring season, as a function of latitude (left panel) and summed north of 60°N (right panel). The red line in the left-hand panel indicates where the Sun is just above the horizon. The data were obtained from the ROM SAF ICDR data record.*

In Figure 6, we have computed the PSC volumes by integrating the partial volumes between potential temperatures 400 K and 550 K. The left-hand panel of Figure 6 shows the volumes as function of latitude (or rather the cosine of latitude). It is also indicated where the Sun is above the horizon. The right-hand panel in Figure 6 shows the sum of volumes north of 60°N. This time series can be interpreted as a proxy for the total volume of PSC formation in the Arctic stratosphere.

5.2.2 Long-term evolution of PSC forming regions

There are reasons to believe that RO data records have better long-term stability than present day reanalysis data sets (*Gleisner et al.*, 2020). The data shown in Figures 5 and 6 were obtained from RO data alone. In Figure 7 we show the observed evolution of seasonally averaged PSC volumes in the Arctic stratosphere from 2006-07 to 2019-20 using the same methods as those in Section 5.2.1. Following the study by *Rex et al.* (2004) the seasonal averages include data from mid-December to end of March.

The data record shown in Figure 7 is too short to make inferences about trends. The 2019-20 Arctic season stands out with very large volumes of PSC formation. That season is preceded by three seasons (2016-17, 2017-18, 2018-19) with low or moderate volumes of very cold air, while the 2015-16 winter-spring season was also characterized by unusually large volumes of PSC formation.

In Figure 8 (left-hand panels) we show the average PSC volumes in the Arctic stratosphere separately for February and March. The PSC volumes were estimated from RO data using the methods devised in Section 4.3, but we here employed a slightly different method with the low-temperature fraction *q* determined directly from the count statistics of RO temperature data (see Section 4.3). Note the high degree of similarity between the time series in Figure 7 and those in the upper left-hand panel of Figure 8. We conclude that the method to estimate PCS volumes from RO data is relatively robust with respect to certain algorithmic choices.

The PSC volumes normally disappear during March. However, 2020 was a quite special year that stands out in the statistics as evidenced from the large PSC volume that remains in March (lower left-hand panel of Figure 8).

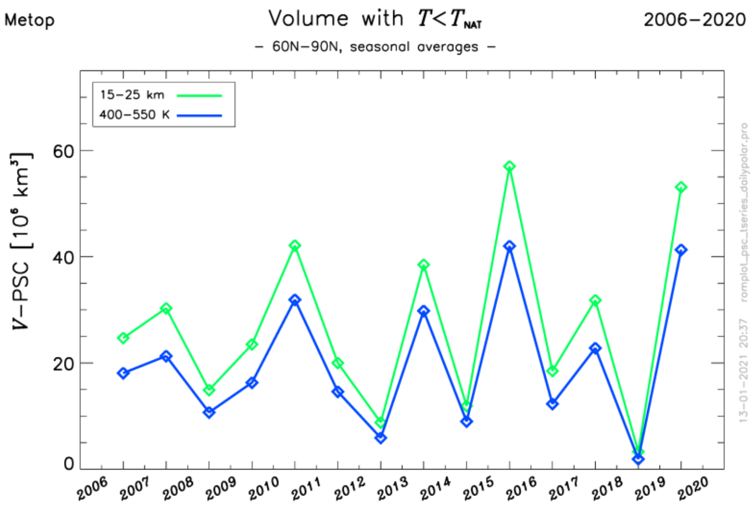

Figure 7: *Seasonally (mid-December to end of March) averaged volumes of PSC formation in the Arctic stratosphere north of 60ºN within the 15-25 km altitude region (green line) and the 400-550 K potential temperature region (blue line). The volumes are estimated from RO data and are presented in units of million km³.*

Figure 8 (right-hand panels) shows the temperatures inside the PSC forming regions in the Arctic. We note that temperatures in the PSC volumes show a decline from 2006 to 2020. In particular, the minimum temperatures seem to be affected. This may be a consequence of the general climate change.

In Figure 9 we show corresponding plots for the Antarctic stratosphere, for the months of September and November. PSC volume for September shows a decreasing trend and the average temperature inside the PSC volume is slightly increasing, while minimum temperatures are stable. It has been found that ozone depletion has cooled the Antarctic stratosphere leading to a delayed breakup of the polar vortex (WMO 2018). Thus the apparent temperature increase may be a consequence of increased levels of ozone as the concentrations of ozone depleting substances are decreasing. For November the PSC volume is highly variable but the when the conditions are right the volume still grows. The temperatures inside the PSC volume show no trend for November.

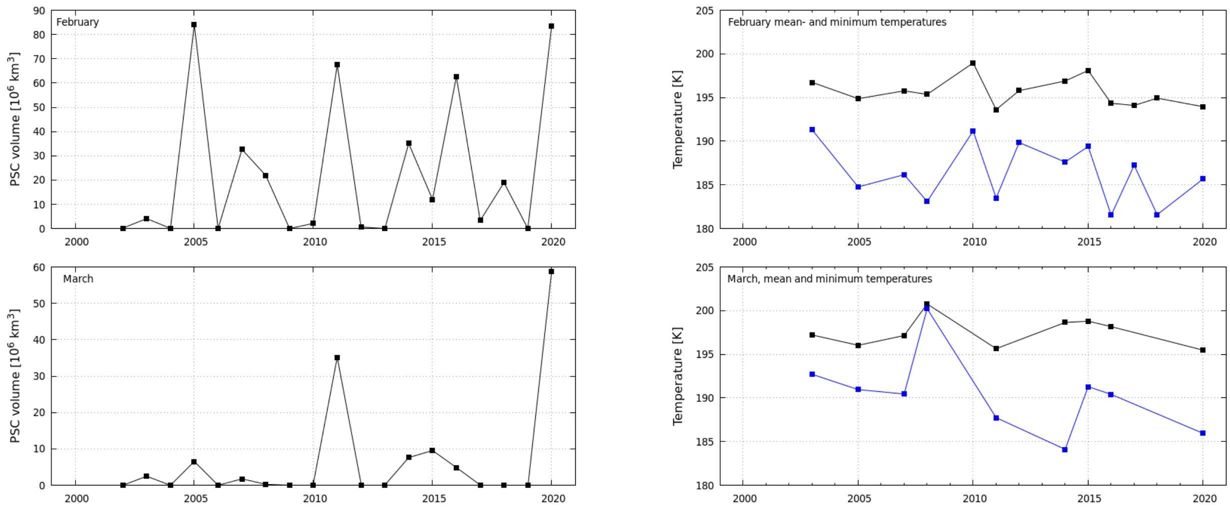

***Figure 8**. Left-hand panel: Average PSC volumes during February and March in the Arctic stratosphere from 2003 to 2020. The volumes are estimated from RO data and are presented in units of million km^3. Right-hand panel: Mean (black) and minimum (blue) temperatures inside the PSC forming regions.*

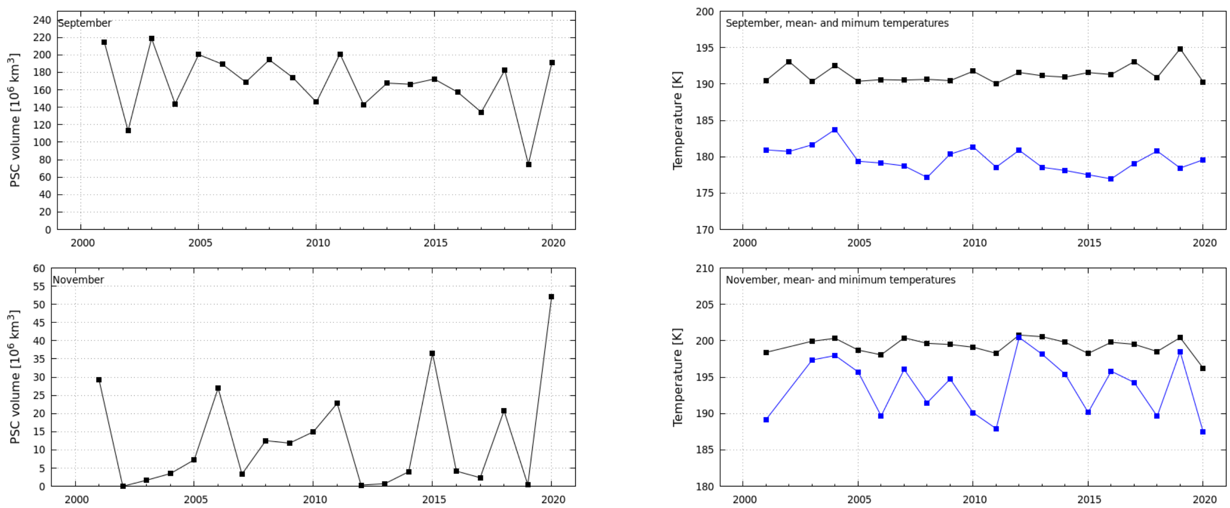

***Figure 9**. Left-hand panel: Average PSC volume during September and November in the Antarctic stratosphere from 2001 to 2020. The volumes are estimated from RO data and are presented in units of million km^3. Right-hand panel: Mean (black) and minimum (blue) temperatures inside the PSC forming regions.*

5.3 Relation between ozone depletion and PSC volumes

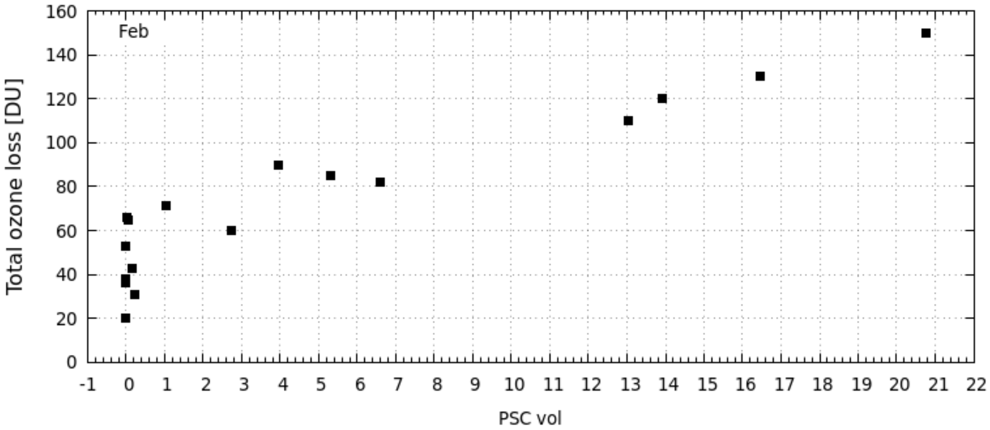

Figure10. *Maximum ozone depletion from January-March inside the Arctic vortex versus the average PSC volume at 20-27 km for February. The volumes are estimated from RO data.*

For Antarctica (Figure 11) the best correlation between PSC volume and area of the ozone hole is found when the whole altitude range (up to 30 km) of the PSC volume is used.

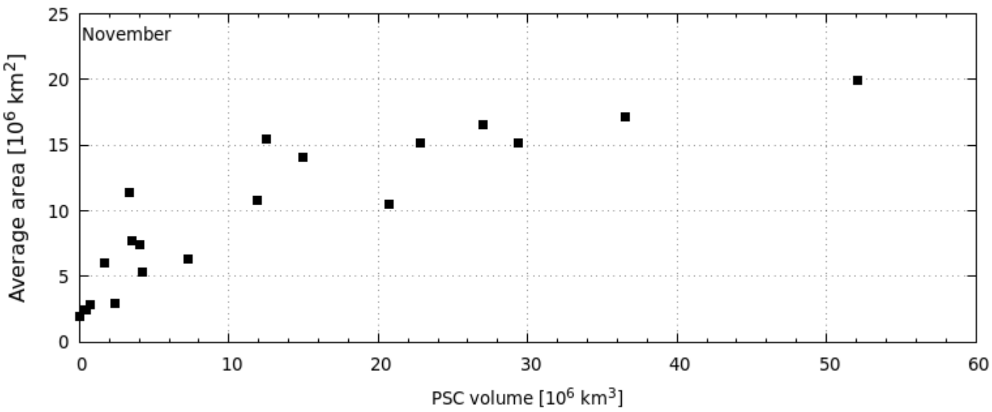

Figure 11*. The average area of the ozone hole in November versus the average PSC volume. The volumes are estimated from RO data.*

5.4 Long-term evolution of stratospheric temperatures

The presence of low stratospheric temperatures governs the volumes of the PSC forming regions where the major part of ozone depletion takes place. Hence, it is important to understand the long-term evolution of the temperature structure in the Arctic and Antarctic stratosphere.

Antarctica:
The ozone depletion starts in August when the sun reaches the area. The ozone hole increase in size during August and culminates in September. Then sometime during October and early November the polar vortex

breaks down, the temperatures in the stratosphere increase, ozone depletion cease to be effective and the ozone hole disappears. The ozone hole area in September has since 2000 shown a decreasing trend due to the reduced concentration of ozone depleting substances, but in recent years a tendency of increasing area in November has been observed. This could be assigned to a change in the atmospheric conditions that favour a long term stabile polar vortex. In Figure 12 and Figure 13 we show examples of temperatures in the ozone layer.

The mean temperature for September 2001-2020 shows no significant trend, but maybe an increase in mean temperature at the upper ozone layer since 2010. Such an increase would be expected from the general increase in ozone as a consequence of less ozone depleting gasses. For November the most significant signature is the very low temperatures in 2020.

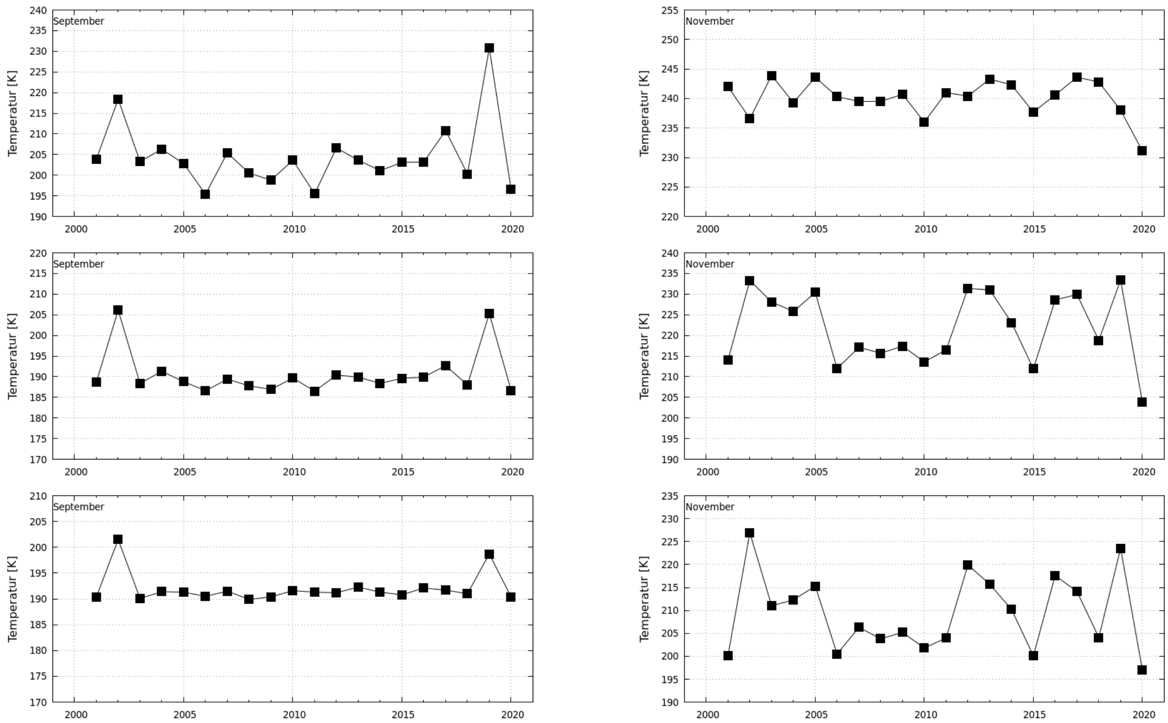

***Figure 12**: Mean stratospheric temperatures in the Antarctic in three altitude intervals, 22-28 km (top), 16-22 km (middle), and 12-16 km (bottom) for September (left) and November (right).*

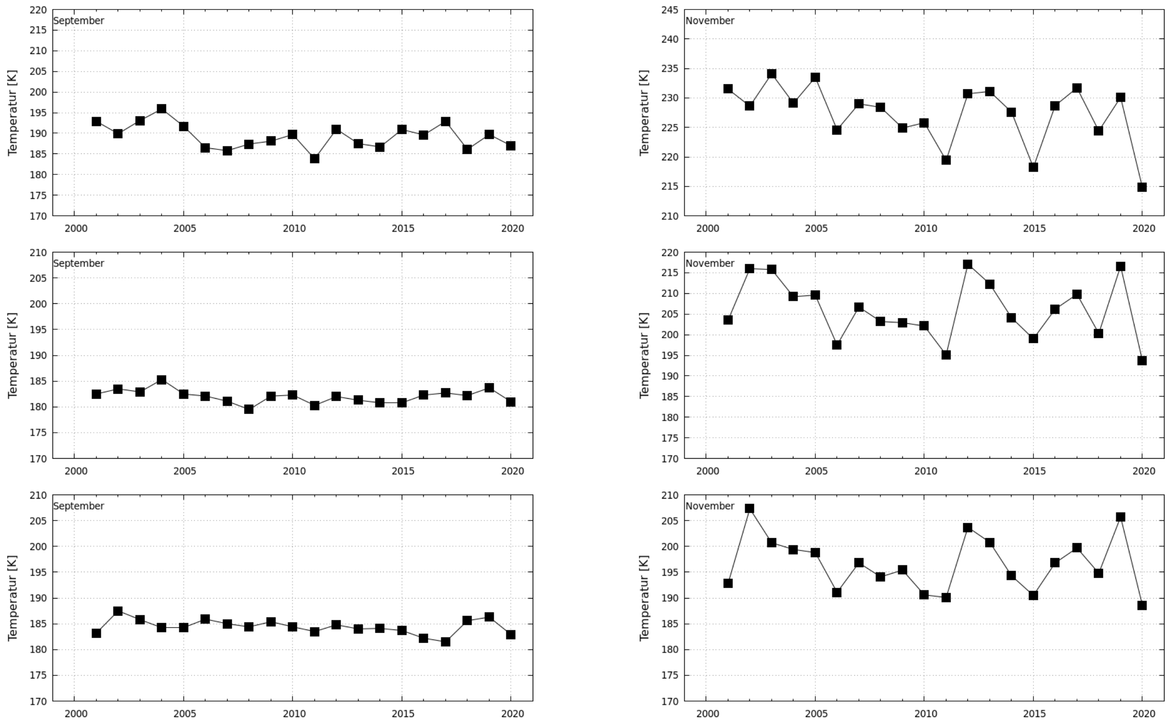

Figure 13*: Minimum stratospheric temperatures in the Antarctic in three altitude intervals, 22-28 km (top), 16-22 km (middle), and 12-16 km (bottom) for September (left) and November (right).*

The minimum temperatures in September (Figure 13) are very stable with no significant trends, whereas the minimum temperatures at the top of the PSC area show rather large variations and a tendency of more extreme values on the cold side.

In the Arctic the mean and minimum temperatures for February and March are shown in Figure 14 and Figure 15 respectively. The year to year variations are rather large for both months and all altitude intervals. The minimum temperatures at the top level show a trend towards lower values in February and the same is found in the lower levels for March.

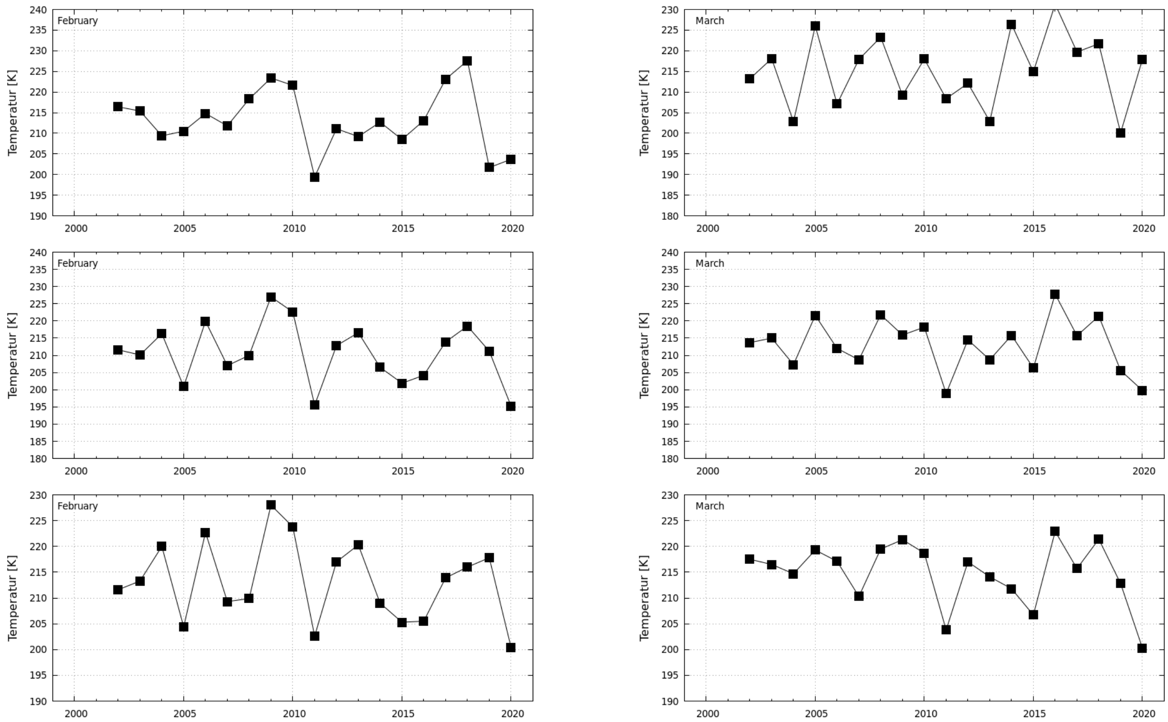

Figure 14. *Mean stratospheric temperatures in the Arctic in three altitude intervals, 22-28 km (top), 16-22 km (middle), and 12-16 km (bottom) for February (left) and March (right).*

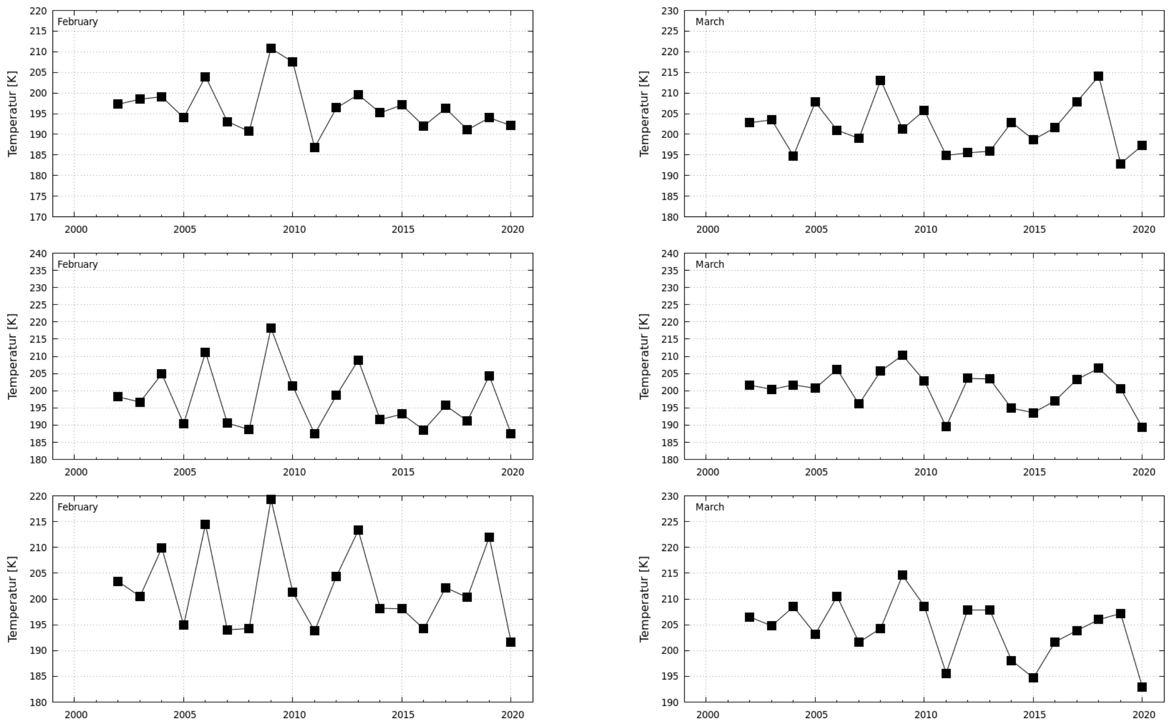

Figure 15. *Minimum stratospheric temperatures in the Arctic in three altitude intervals, 22-28 km (top), 16-22 km (middle), and 12-16 km (bottom) for February (left) and March (right).*

6 Conclusions

The purpose of this study is a) to investigate methods for quantifying the volume, V_{PSC}, from GNSS-RO stratospheric temperature and pressure data, and b) to investigate the long-term variability and trends of PSC volumes and stratospheric temperatures conducive to the formation of PSCs. The objectives with these investigations are to further our understanding of role played by climate change for the evolution of ozone-depleting conditions in the Arctic, but also to lay the foundations for an operational service at DMI to monitor these conditions as they evolve day by day during the winter-spring seasons in the Arctic and Antarctic.

Based on the still rather preliminary results shown in Section 5 we conclude that:

a) We can use GNSS-RO measurements to quantify the areas, A_{PSC}, and volumes, V_{PSC}, of PSC formation in the Arctic and Antarctic stratosphere. This novel method for estimation of PSC volumes appears to be robust to certain type of algorithmic choices (the exact definition of the fraction q of low temperature observations and the particular binning used across the polar region). We have shown that detailed information about the seasonal evolution of PSC forming regions can be obtained, allowing us to better understand ongoing events in the polar stratosphere.

b) From this follows that we can quite easily implement an operational service at DMI to monitor the stratospheric conditions as they evolve day by day during the winter-spring seasons in both the Arctic and Antarctic. RO data are readily available at DMI through the operational services provided by the ROM SAF project as a part of the EUMETSAT activities. Similarly, near real time total ozone data are available at DMI though the EUMETSAT AC SAF project. A preliminary web page for the development of the operational service has been created at: psc.dmi.dk/NCKF/

c) The temperatures within the PSC forming volumes in the Arctic show a decline from 2006 to 2020. In particular, the minimum temperatures seem to undergo a long-term evolution. The corresponding long-term temperature changes in the Antarctic are somewhat different. Here, we find that the average temperature inside the PSC volume during September is marginally increasing, while minimum temperatures appear to be stable. These changes may partly be a consequence of the general climate change, in particular those in the Arctic, while the long-term changes in the Antarctic may in addition be affected by increased levels of ozone as the concentrations of ozone depleting gasses are decreasing.

d) We can confirm the statistical relation between ozone depletion and PSC volumes in the Arctic region that is described in the scientific literature. We are also able to show that a similar relation exists for the Antarctic region. The relation varies depending on altitude and time period during the season.

e) Due to the direct impact of low temperatures on the PSC volumes and, hence, on the ozone depletion, it is important to understand the long-term evolution of the temperature structure in the Arctic and Antarctic stratosphere. We note a tendency that at some altitudes and during some parts of the season cold conditions seem to become even colder. This is the case for November in the Antarctic in the upper part of the ozone layer (22-28 km) and also the case for March in the Arctic in the lower part of the ozone layer (12-16 km). The exact relation to climate change and/or decreasing concentrations of ozone depleting substances, and the extent to which the detected changes are statistically significant, will have to be further investigated.

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