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Ozone layer in a changing climate studied with GNSS radio occultation data

Final scientific report of the 2021 National Centre for Climate Research Work Package 2.4.1, Ozone

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1. Scientific summary

Polar Stratospheric Clouds (PSCs) are strongly associated with increased ozone loss in the polar regions. These clouds form at altitudes around 15-30 km at sufficiently low temperatures. Such conditions are expected to become more common as a result of climate change. In this project we have investigated the variability and trends of polar stratospheric temperatures low enough for PSCs to form, using satellite based GPS radio occultation (RO) measurements. Related to this, we have investigated methods for quantifying PSC volumes from GPS-RO data. Using data records starting in 2002 we show that GPS-RO data can be used to quantify the volume of PSC formation in the Arctic stratosphere, allowing us to confirm the statistical relation between ozone depletion and PSC volumes reported in the scientific literature. Even though the time series of data are not yet sufficiently long (in relation to the highly irregular year-to-year variation) to allow firm detection of temperature trends, we note that during parts of the seasons the coldest conditions in the stratosphere tend to slowly become colder.

General results

- GNSS-RO measurements can be used to quantify the areas, A_{PSC}, and volumes, V_{PSC}, of PSC formation in the Arctic and Antarctic stratosphere.
- Detailed information about the seasonal evolution of PSC forming regions can be obtained, allowing us to better understand ongoing events in the polar stratosphere.
- The previously reported statistical relation between ozone depletion and PSC volumes in the Arctic region is confirmed
- We note a tendency that at some altitudes and during some parts of the season cold conditions seem to become even colder.
- Implementation of an experimental Arctic stratosphere monitoring service (http://psc.dmi.dk/nckf) with daily updates of PSC parameters and historical data.

Future process

Continue to monitor the temperatures in the polar stratosphere to quantify any trends due to climate change that may postpone the recovery of the ozone layer.

The correlation between the PSC volume and ozone column should break in the coming years as a consequence of decreasing concentration of ozone depleting substances. This is of great importance to the ongoing work on monitoring the effect of the Montreal Protocol.

Study the temperatures in the polar vortex with special focus on sudden stratospheric warming events.

2. Scientific reporting

2.1 Scientific 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.

2.2 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 polar regions.

2.3 Data

Temperature profiles are supplied by the EUMETSAT Radio Occultation Meteorological Satellite Application Facility (ROM SAF). The ROM SAF Climate Data Record v1.0 (CDR v1) consist of RO data that has been reprocessed by the ROM SAF. The CDR includes data from four RO satellite missions: CHAMP, COSMIC, Metop, and GRACE. 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 December 2021 has been included. The quality of the NRT data is in general comparable to the CDR and ICDR data.

Ozone depletion starts when the sunlight reach the polar regions in the later winter period and continues during spring until the temperatures in the stratosphere rise above the critical temperature for PSC formation. 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). For the operational web page daily data for the whole year has been extracted since January 2021.

Ozone measurements include mainly total ozone columns combined from several satellite missions from NASA, ESA and EUMETSAT. Monthly averaged ozone values are from the Multi Sensor Re-analysis version 2 (MRS-2; 1970-2020). For the Arctic measurements of total ozone column from the ground based SAOZ network is also included.

2.4 Retrieval of PSC volumes V_{PSC}

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, and the areas where PSCs form can be computed as $A_{PSC} = q_{ijn} \cdot A_i$, where index i indicates a latitude bin, index j an altitude bin, and index n denotes a day number. From the low-temperature areas, A_{PSC}, we can compute the corresponding volumes V_{PSC} by vertical integration of A_{PSC} at each latitude bin and day:

$$V_{PSC}(\varphi_i, n) = \sum_{j=j_{400}}^{j_{550}} \Delta h \cdot A_{PSC}(\varphi_i, h_j, n) \tag{1}$$

In Eq. 1 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}.

2.5 Selection of results

Temperature trends

There is a tendency that at some altitudes and during some parts of the season, cold conditions seem to become even colder. An example is shown in Figure 1 depicting minimum temperatures south of 80S at 22-28 km altitude.

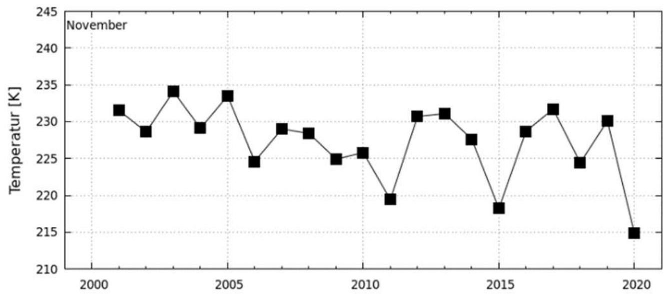

Fig. 1. *Minimum temperatures in the stratosphere south of 80S at 22-28 km altitude.*

PSC volume trends

In Figure 2 we show the calculated PSC-volumes from 2002 to 2021. A tendency of increasing PSC-volumes late in the ozone depletion season (in March at north, November at south) is noticed.

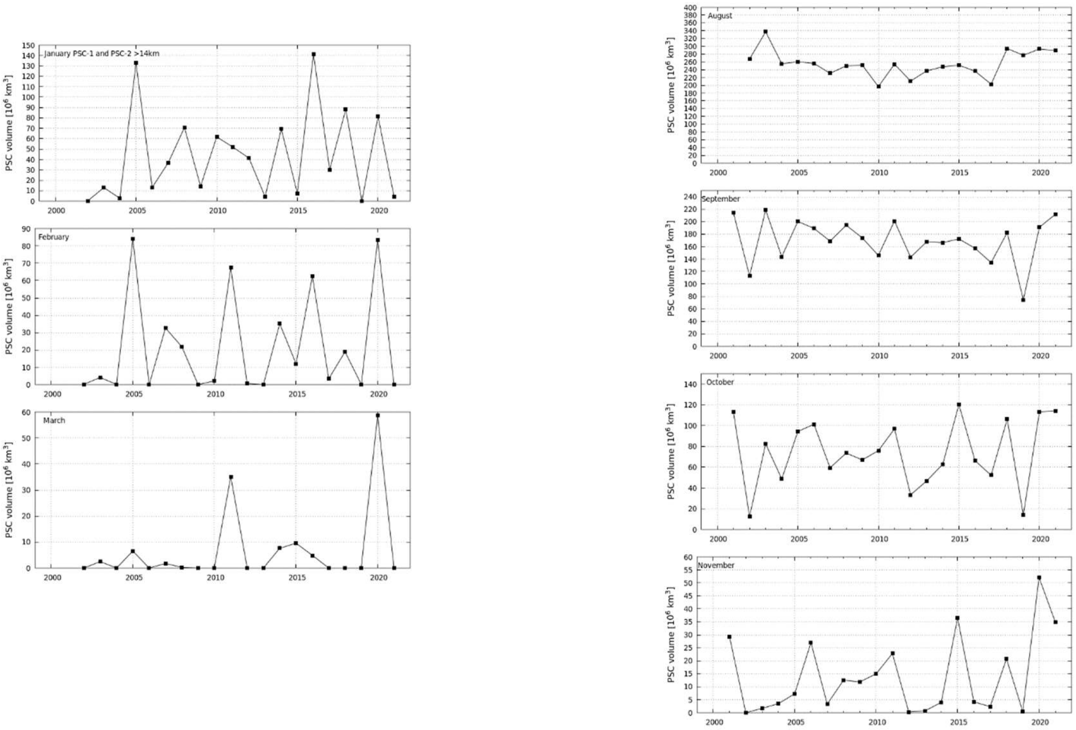

Fig. 2. *Volumes of the PSC forming area over the Arctic (left) and Antarctica (right).*

Vortex temperatures

A strong and stable polar vortex is necessary to keep temperatures low enough for PSC formation during the polar spring time. Using information on the daily position of the polar vortex from ECMWF we have extracted temperature profiles from positions inside the polar vortex and compared with temperatures outside. An example is shown in Figure 3.

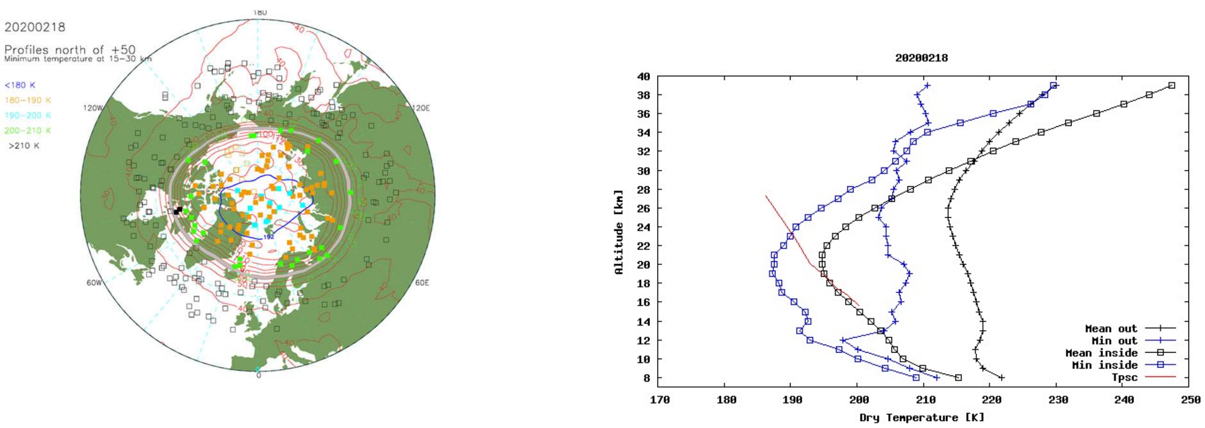

Fig. 3. *Left: Position of the polar vortex (ECMWF) as grey contour, location of "PSC temperatures" (ECMWF) as blue contour. Symbols are RO temperature profiles color coded accordingly to minimum temperatures. Right: Mean- and minimum temperature profiles inside and outside the polar vortex for the same date.*

PSC volume versus ozone depletion

The correlation between the PSC volume and ozone depletion is seen below in Figure 4, where the monthly averaged V_{psc} is plotted against the monthly average total ozone column for the years 2002-2020. The correlation is about the same for both northern and southern polar region, but much less pronounced in the Arctic. For Antarctica the ozone depletion is not strongly correlated with V_{psc} because much of the area are not illuminated by the sun light that is required for the depletion process to proceed. In September and October the light is there and the ozone depletion is ongoing in the areas where temperatures are low enough. The rather tight correlation for these months show that there still are an ample amount of ozone depleting substances present in the stratosphere.

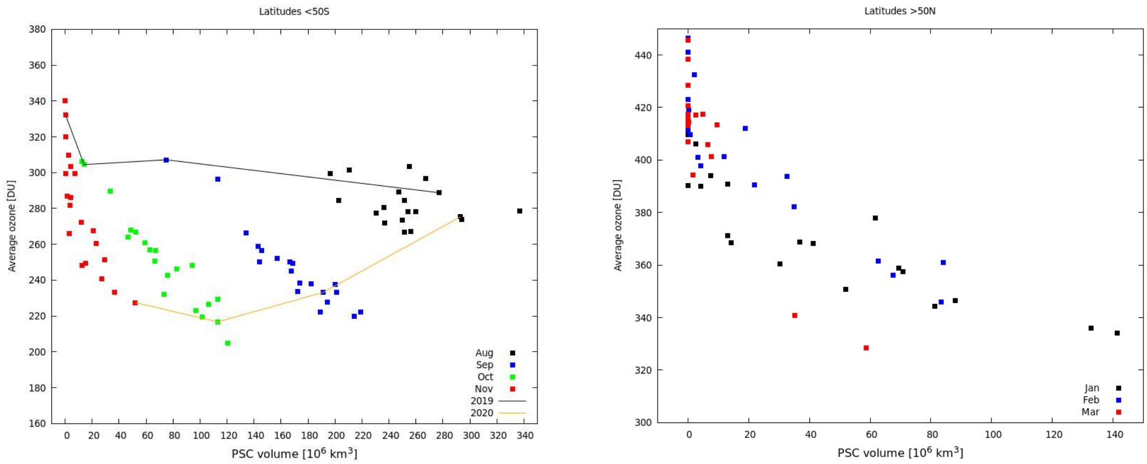

Fig. 4. *Monthly averages of V_{psc} against total ozone column. Left: Antarctica (August to November). Right: Arctic (January to March). As an illustration two years have been marked for Antarctica. The black line connects the point for 2019, where a sudden warming event appeared in September and effectively stopped the ozone depletion. The orange line connects the points for 2020 where a strong polar vortex, and thus low stratospheric temperatures persisted until mid-December***.**

2.6 Conclusions and future perspectives

We have shown that the GNSS-RO measurements can be used for many aspects of research in the polar stratosphere. A continued monitoring of the temperatures and PSC volumes will provide a simple method for tracking the expected decline in the amount of ozone depleting substances and hence follow the subsequent healing of the ozone layer.

As indicated by this study GNSS-RO measurements may also be applied to a general study of the polar vortex and the occasionally events of sudden stratospheric warming.

The impact of climate change on the expected healing of the ozone layer is still not well understood. A continuing monitoring and modeling of both the meteorological conditions in the stratosphere and the concentration of ozone depleting substances is required. The operational monitoring of temperatures in the ozone layer initiated during this study will continue and extend the baseline for future studies.