Reply to Anonymous Referee #1 review of manuscript acp-2023-788

Trends in polar ozone loss since 1989: First signs of recovery in Arctic ozone column

Andrea Pazmino on behalf of all co-authors

We thank Anonymous Referee #1 for the time devoted to evaluate our work. Your valuable comments have helped us to improve our manuscript. Note that the title of the article and the wording used to explain the results related to metric 3 were changed also in response to referee 2 comments. The new title is:

Trends in polar ozone loss since 1989: **Potential sign** of recovery in Arctic ozone column

Please find our answers below (in red)

Clarifying questions and comments.

Line 128. What is the definition of the "overpass" criteria?

Thank you for this question. The overpass values correspond to the averaged amount of the available MSR2 grid values at ±1° of the station coordinates.

The following sentence was modified to clarify the overpass criteria:

"Daily ozone columns at the stations mentioned in Table 1 are retrieved from the global gridded MSR2 assimilated data fields **by averaging the total ozone columns of MSR2 within ±1° of the station coordinat**e".

Line 143. Please provide station and satellite/model matching criteria. The satellite grid is at 0.5 and SLIMCAT model is at 2.8 degrees. Are there additional matching/averaging is done to reduce sampling biases? Also, it might be useful to provide the number of observations for all stations inside of the vortex during the analyzed period.

The SLIMCAT model fields are interpolated linearly in longitude and latitude at each output time during the simulation to obtain profiles at the SAOZ stations. The following sentence in L143 was changed as follows:

"The passive and active ozone columns are sampled above the stations of Table 1 at 12 UT **by performing a bilinear interpolation of the model fields (in longitude and latitude) to the location of the SAOZ stations during the model simulation**."

In order to consider your suggestion about the number of observations inside the vortex, the following text and figure (new Figure 1) was added at the end of the 1st paragraph of the Methodology section:

"**Figure 1 shows the number of merged data inside the vortex for each winter of the considered periods for the SH (blue line) and NH (red line). Between 200 and 400 observations are considered for the Arctic vortex, and about 800 for the Antarctic vortex. The number of the observations in the Arctic vortex displays a large interannual variability while it is much more stable in the Antarctic. These differences are explained by the larger area and the longer persistence of the SH vortex compared to the NH one.**"

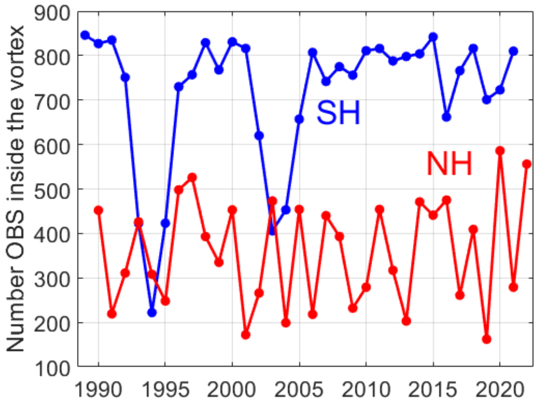

Figure 1. Number of merged data (OBS) inside the vortex for each winter of the SH (blue line) and NH (red line).

Line 149. Please provide additional details of datasets merger, i.e. temporary and special matching, treatment of missing data, weighting of the MSR2 and SAOZ data in the combined record.

A weighting criterionwas not applied to the MSR2 and SAOZ normalized data since the differences between both data series are lower than respective error bars. The only temporary criteria considered in this work was to select data on the same day in UT and average them. The sentence in L163 was modified as follows:

"**In the case of the days when only one measurement is available, the corresponding value is considered.** The amplitude of the mean monthly difference **during the winter** between **normalized SAOZ data and MSR2 or merged data is less than 2% or 1%, respectively,** which is smaller than the SAOZ **precision (Hendrick et al., 2011)**."

Line 163. What is the reason for not selecting March to normalize all years of SAOZ data? This could make normalization consistent through the entire analysed record.

In the northern hemisphere, normalization of SAOZ data for the four stations equatorward of the polar circle was treated in the same way as the normalization of passive and active tracers of the SLIMCAT model in the different stations. Since the ozone loss is a value relative to that in the beginning of the winter, a good normalization during that period is essential. The additional data available since February-March were considered to improve the sampling within the vortex and a simple normalization in March was used to avoid any large bias. The mean differences in March between merged data (OBS) and SAOZ at the four stations vary between 0.15% to 1.1%, which is lower than the error bars of ozone loss at the end of the winter.

Line 185. Please clarify what you mean by "diurnal differences".

In the sub-section 2.1 the diurnal difference was specified in L115

"The difference between sunset and sunrise NO_2 total columns is calculated at each SAOZ station to follow the amplitude of the NO_2 diurnal cycle"

We have changed the sentence in L185 as follows

"At that time, the diurnal NO_2 difference rapidly increases **(Fig. 3, bottom panel)** and ClO values from SLIMCAT rapidly decrease (not shown)."

And the legend of the Fig. 2 (new Fig. 3)

"Figure **3**. Top panel: time series of observed ozone loss (%) inside the vortex above each SAOZ station for the 2022 NH winter. Bottom panel: Time series of the amplitude of the NO_2 diurnal variation **(NO_2 sunset – NO_2**

sunrise) inside the vortex above SAOZ stations. The 10-day running median and standard error of the median (IP68/2, see the text) are superimposed by the black line on both panels."

Line 215-216. Can you please mention ozone variability in 2019 that was also an anomalous year in the Antarctic ozone depletion? It clearly deviates from other years.

In this part we only mention the atypical years before 2018. The year 2019 is described in particular in the sub-section 4.1 dedicated to recent years.

Line 228. Fig. 4 caption. I would not say that 2002/2011 winters are unusual anymore since we had similar anomalies in recent years. Do you agree?

We cannot agree from a statistical point of view if we consider only 10% of years as atypical within the last two decades. As can be seen in Fig. 8, there are only two "atypical" years in both hemispheres. 2002 and 2019 stand out as the years with lowest ozone loss in the SH while 2011 and 2020 stand out as the years with largest ozone loss in the NH. Only 2 stratospheric warmings occurred in the SH since 1990: in 2002 and 2019. But indeed, the dynamics play a more important role during the last decade favouring extremes winters.

Lines 325-328. Is there a known reason for the offset between observations and the model since 2003?

For the moment, we do not have any explanation to this difference between model and merged data since 2003. It would be interesting to compare with a long-term run of another CTM model. This analysis could be the objective of a specific work on comparing model simulations but is beyond the scope of this work.

Lines 375-377. Please provide uncertainty of the linear and the parabolic fit for the sunlit PSC area and ozone. What does the SLIMCAT data fit show? Do data and a model fit agree? Can you add a plot that shows the change in the sunlit VPSC as function of time? This could provide a reference of climate change over polar regions.

In order to perform a more robust consideration of the relationship between ozone loss and sunlit VPSC, and to then derive a trend, a multi-parameter regression model was applied to the ozone loss dataset considering as proxies the sunlit VPSC (2^{nd} degree polynomial relationship for the SH and linear relationship for the NH) and a linear trend as a function of time.

The multi-parameter regression was also applied to the ozone loss obtained from the SLIMCAT model simulation. A paragraph at the end of sub-section 5.3 compares the trend using simulations from SLIMCAT to the ones using the merged datasets.

For the uncertainties, please see the answer to the next question which, considering also the comment of Reviewer 2 lead to an update of sub-section 5.3.

Lines 396-402. If uncertainty of the ozone/PSC fit is taken into account, would the trend of the residuals be significant?

A multi-parameter fit of the ozone loss and sunlit VPSC data has been performed since 2000 in order to improve the issues of uncertainties in the regressions. In the Arctic, a trend of -2.00 ± 0.97 % dec^{-1} was found, slightly significant at 2σ. This points to a potential recovery of total ozone in the Arctic. The used multi-parameter fit is explained in detail hereafter.

Thanks to the referees' comments, the sub-section 5.3 was rewritten including now the results obtained by the updated multi-parameter regression model. You will find the new Section 5.3 here below:

"**5.3 Residuals of ozone loss/VPSC relationship**

Climate change can influence the polar ozone loss by changes in temperature within the vortex that directly influence the formation of PSCs. Figure 11 represents the interannual evolution of sunlit VPSC above the Antarctic and Arctic regions (top and bottom panels respectively). Larger sunlit VPSC values are expected in the SH than the NH due to much lower polar temperatures. Low values of sunlit VPSC are found for the years of low ozone loss and inversely as expected (see Fig. 9). Record of values sunlit VPSC are observed in 2020 for both hemispheres. As a consequence, very high ozone loss was found in the NH, and large but not record ozone loss in the SH. A linear trend was computed for VPSC from 2000, yielding an insignificant value in the SH and a positive value in the NH but significant only at 1σ level.

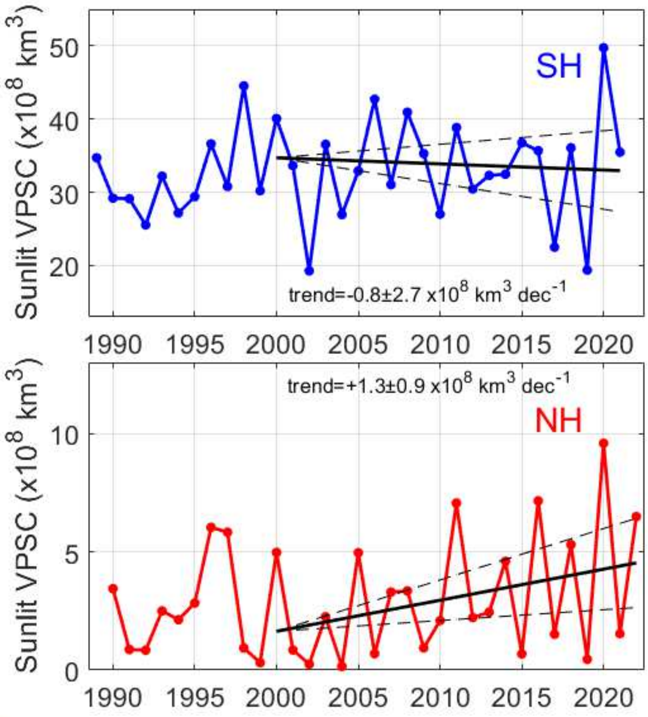

Figure 11. Interannual evolution of sunlit volume of polar stratospheric clouds (VPSC) in the SH (top panel) and NH (bottom panel). The estimated robust trend (thick black line) and uncertainty level values of ±1σ (dashed black lines) since 2000 are added for both regions.

Figure 12 presents the ozone loss value as a function of sunlit VPSC for each winter of the NH (triangles) and SH (inverse triangles). The figure highlights the difference between both hemispheres with much higher sunlit VPSC in the SH and consequently higher ozone loss. The range of sunlit VPSC in the SH varies between 2×10^9 and 5×10^9 km^3, which corresponds to an ozone loss between 36 and 55%. The range of sunlit VPSC in the NH is much smaller ($< 10^9$ km^3) but the dynamical range of ozone loss is slightly higher (4-27%). The figure highlights a quasi-linear relationship between ozone loss and VPSC in the NH (lower-left region in Fig. 12) and a different behaviour for larger ozone loss values due to the saturation of ozone loss in the lower stratosphere in the SH (e.g., Yang et al., 2008).

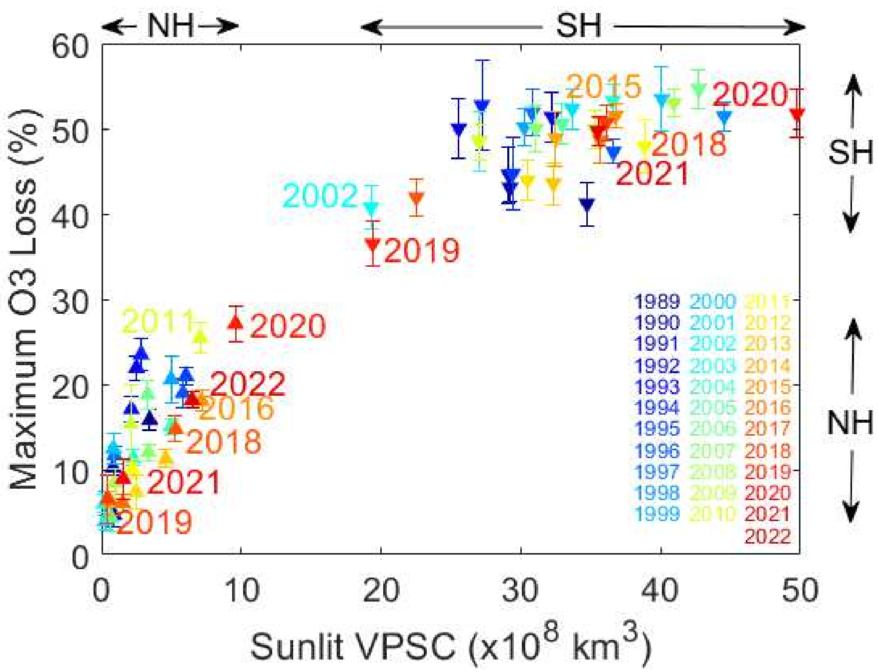

Figure 11. Maximum ozone loss as a function of sunlit VPSC for each winter for the Northern and Southern hemispheres. The 68% inter-percentile range of ozone losses are also represented (see Sect. 3, Methodology). The colour code represents the years.

In order to remove the influence of temperature interannual variability in the estimation of trends since 2000, a multi-parameter model was applied to the ozone loss dataset of each region as presented in Eq. 1:

$$\text{MOLoss}(t) = \text{SunlitVPSC\_contr}(t) + t1 * (\text{year}(t) - 2000) + \in(t) \quad (1)$$

where t is year since 2000, t1 is the time linear trend since 2000, $\in(t)$ is the ozone loss residual and SunlitVPSC_contr corresponds to the contribution of sunlit VPSC considering a linear fit for the NH and a parabolic fit for the SH due to the saturation of ozone loss in the lower stratosphere (Eqs 2 and 3, respectively)

$$\text{Sunlit\_VPSC\_contrNH}(t) = K_{0\_NH} + K_{1\_NH}*\text{SunlitVPSC\_NH}(t) \quad (2)$$

$$\text{Sunlit\_VPSC\_contrSH}(t) = K_{0\_SH} + K_{1\_SH}*\text{SunlitVPSC\_SH}(t) + K_{2\_SH}*\text{SunlitVPSC\_SH}(t)^2 \quad (3)$$

The regression coefficients in Eq. 2 and 3 are significant at 2σ level. The autocorrelation of residuals of ozone loss in Eq. 1 is weak and lower than 0.2, and the determination coefficient (R^2) is of 0.83 for the SH and 0.82 for the NH. Figure 13 (left panels) shows a good agreement between MOloss dataset (colour lines) and the regression model results (black lines) considering estimated sunlit VPSC contribution (black dashed line) and trend.

The difference between the maximum ozone loss and the regressed sunlit VPSC contribution (ROLoss) is calculated for each year of the corresponding hemisphere as follows:

$$\text{ROLoss}(t)=\text{MOLoss}(t)- \text{SunlitVPSC\_contr}(t)= t1 * (\text{year}(t) - 2000) + \in(t) \quad (4)$$

Figure 13 (right panels) shows the ROLoss dataset for the SH (top panel) and NH (bottom panel), respectively. The residuals vary between approximately 0 and -8% for the SH and within ±5 % for the NH. A decrease is observed since 2000 in both hemispheres with a higher interannual variability in the NH. The linear trend estimated by the multi-parameter regression model in both hemispheres (Eq.1) is around 2 % dec^{-1} and significant at 2σ. Unlike the other two metrics, this metric provides a potential detection of a negative trend in the NH at the limit of significance.

The multi-parameter model was also applied to ozone loss using only SLIMCAT simulations (not shown). All regression coefficients are significant at 2σ, except the quadratic regression coefficient in the case of the SH. A larger recovery rate is found with the model simulation in the SH with a negative trend of -2.8 ±0.8 % dec^{-1} (1σ).

For the NH, a slightly weaker trend was found compared to the observations with a value of -1.4 ±0.7 % dec^{-1}, also with limited significance at 2σ.

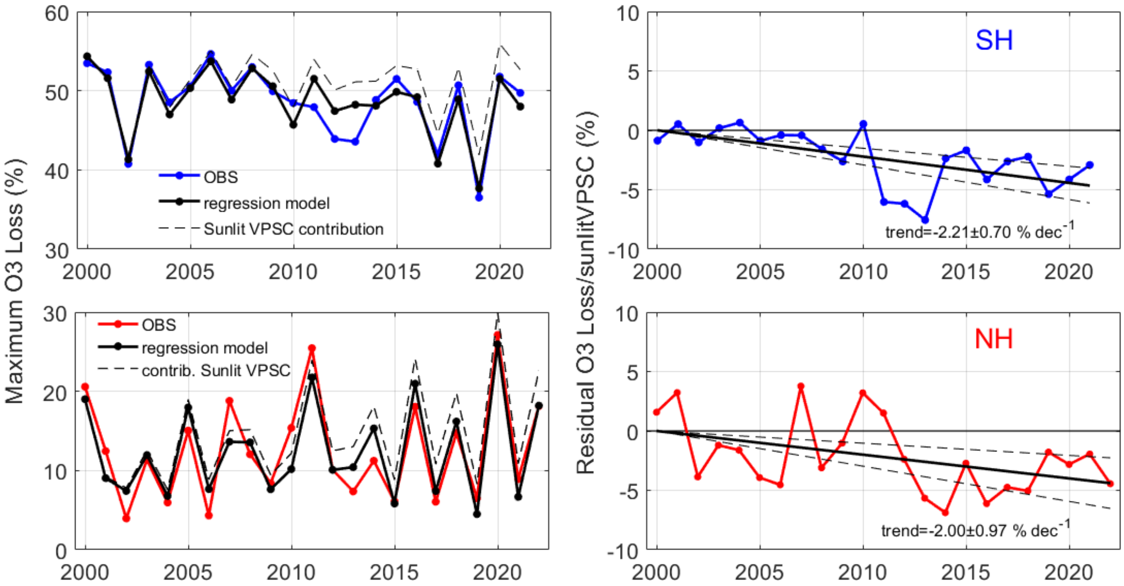

Figure 13. Left panels: Interannual evolution of the maximum ozone loss (colour lines) since 2000 for both hemispheres and regression model (black lines). Sunlit VPSC contribution (see Eq. 2 for NH and 3 for SH) is superimposed by dashed lines. Right panels: Interannual evolution of Residuals of Ozone Loss with respect to regressed ozone loss values computed following Eq. 1 to 4 for the SH (top panel) and NH (bottom panel). The estimated trend (thick black line) and uncertainty level values of ±1σ (dashed black lines) since 2000 are also represented for both hemispheres."

Lines 465, acknowledgements need to be made for the NDACC data

"The data used in this publication were obtained from "NDACC PI name" as part of the Network for the Detection of Atmospheric Composition Change (NDACC) and are available through the NDACC website www.ndacc.org."

The NDACC webpage was already mentioned in Section Data Availability. The sentence was added in the following way:

"The authors thank **the** technical teams operating SAOZ instruments **and NDACC PIs for the consolidated data**"

Line 449. Please provide the link to the ERA5 data.

The following link was added

https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=form