# Chlorine and Ozone Depletion are Declining Inside the Antarctic Ozone Hole – MLS Observations and the GMI Chemistry Transport Model Agree

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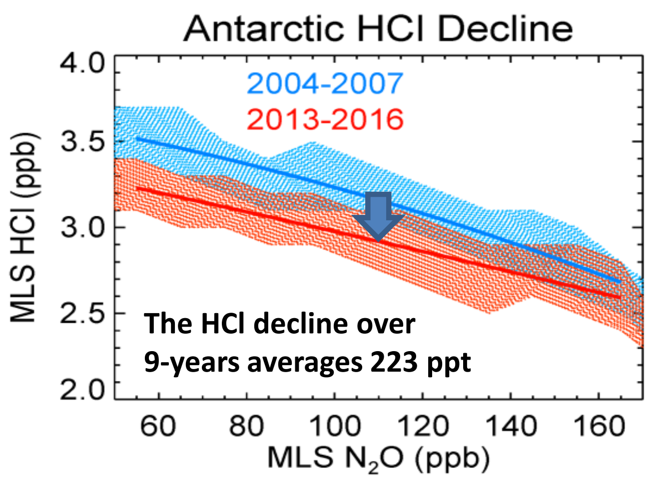
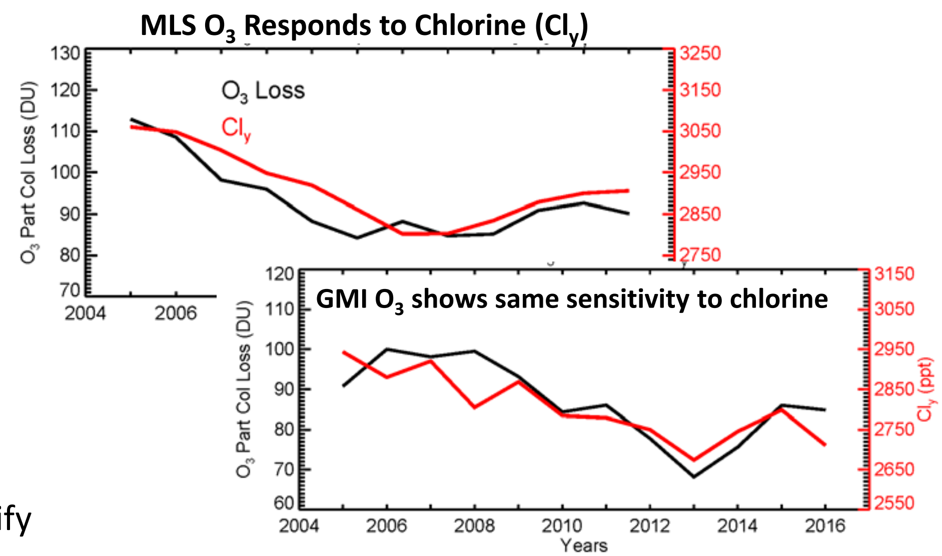



Decreases in HCl for constant $N_2O$ values identify changes in stratospheric chlorine loading that are independent of atmospheric dynamical variability.




The ozone depletion calculated from MLS ozone data varies with changing chlorine levels ($Cl_y$) that were determined from MLS HCl measurements. The GMI simulation shows the same sensitivity of ozone depletion to changing chlorine.

**Summary:** We use Aura Microwave Limb Sounder (MLS) satellite data from 2004-2016 to measure $O_3$ over Antarctica in early July and then compare it to $O_3$ in mid-September. During this period nearly all $O_3$ change is due to depletion. The HCl measurements shown here represent the sum of all ozone-destroying chlorine compounds, $Cl_y$. The HCl change for constant $N_2O$ shows us there is less chlorine now than a decade ago – independent of atmospheric variability. The MLS-calculated $O_3$ depletion responds to changing $Cl_y$ levels, and the model's agreement confirms our understanding of the chemical processes controlling polar ozone . **This is evidence that the Montreal Protocol is working: Antarctic $Cl_y$ is decreasing in the and the ozone destruction is decreasing along with it.**

S.E. Strahan and A.R. Douglass (2017), Decline in Antarctic Ozone Depletion and Lower Stratospheric Chlorine Determined From Aura Microwave Limb Sounder Observations, *Geophys. Res. Lett.*, 44, https://doi.org/10.1002/2017GL074830.

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**References**:

S.E. Strahan and A.R. Douglass (2017), Decline in Antarctic Ozone Depletion and Lower Stratospheric Chlorine Determined From Aura Microwave Limb Sounder Observations, *Geophys. Res. Lett.*, 44, https://doi.org/10.1002/2017GL074830.

**Data Sources**:

NASA Aura Microwave Limb Sounder (MLS) v4.2 Level 2 $O_3$, HCl, and $N_2O$ data, 2004-2016.
The NASA Global Modeling & Assimilation Office (GMAO) Modern Era Retrospective for Research and Applications 2 (MERRA2) reanalysis temperature and potential vorticity products.
The NASA Global Modeling Initiative (GMI) chemistry and transport model integrated with MERRA2 meteorological fields, 2004-2016.

**Technical Description of Figures**:

Chart 1. Co-located MLS $N_2O$ and HCl observations inside the Antarctic ozone hole from 2013-2016 (red) and 2004-2007 (blue). The difference between the means of each distribution (solid lines) is highlighted by the arrow. The shift of the distribution toward lower HCl, represents a decline in Antarctic chlorine.
Chart 2. Time series of $O_3$ depletion and total inorganic chlorine ($Cl_y$) inside the ozone hole, 2005-2016. Depletion is calculated as the change in vortex-averaged 261-12 hPa partial column $O_3$ between early July and mid-September. The $Cl_y$ time series was inferred using lower stratospheric vortex-averaged MLS $N_2O$ (which is strongly anti-correlated with $Cl_y$) combined with the annual mean $Cl_y$ decline of 25 ppt/yr (Chart 1). A 1:2:1 filter was applied to each time series to remove biennial variability in each signal, revealing $O_3$ depletion's response to changing chlorine. (Biennial variability in the depletion comes from temperature variability while in the $Cl_y$ data it comes from composition variability that is unrelated to temperature.)

**Scientific Significance**: One of the challenges in attributing Antarctic ozone recovery to declining chlorine levels is the lack of quantitative measurements of chlorine-containing compounds inside the ozone hole. This study takes advantage of Antarctic chemistry that converts all of the inorganic Cl species into HCl during a brief period each spring. The MLS HCl measurements during this period represent the sum of Cl compounds that can destroy $O_3$. This gives us a way to measure all the chlorine each year from 2004-2016, but without $N_2O$ we can't say *why* it's changing. Using the co-located MLS $N_2O$ measurements along with HCl (Chart 1) provides a fixed dynamical reference point. We see that for constant values of $N_2O$, HCl is really declining, and that can only happen because stratospheric chlorine loading is declining.

**Scientific significance, societal relevance, and relationships to future missions:** Identifying recovery of the Antarctic ozone hole is challenging because year to year changes in the hole are primarily controlled by temperature. Stratospheric chlorine levels are expected to decline because of the Montreal Protocol (MP) and its subsequent amendments. The decline is slow because the atmospheric lifetimes of ozone depleting substances are long. This study is important because it shows the MP is working: it identifies both a decline in chlorine levels inside the ozone hole attributable to the MP and a decline in ozone depletion in response to chlorine changes. The value of $N_2O$ and HCl measurements for interpreting $O_3$ changes supports the need for these measurements in the future as we continue to measure ozone.