Introduction to Computing
name last name, date

Abstract

This paper analyzes data about the size of the Antarctic ozone hole and US CFC emissions. Previous data from NOAA and the UNEP show a decreasing trend in the size of the ozone level and CFC emissions. Analysis from this paper agrees with these findings and also includes regression modeling to predict that the size of the ozone hole will decrease and ozone levels are on track to reach pre-1980 levels. Moreover, the paper sought to understand if the Montreal Protocol, an initiative by the United Nations to reduce the emission of ozone-depleting substances (ODS), has been successful, and it was found there was a stark decrease in CFC emissions by the US after the initiative was passed in 1989. Overall, decreasing ozone hole size and CFC emissions are promising signs of ozone remediation.

Background

The ozone layer is a layer with high concentrations of ozone (O_3) located in the Earth's stratosphere and is critical for sustaining life on Earth. The ozone in the ozone layer blocks most of the ultraviolet-B (UVB) radiation from the sun from reaching the surface of the Earth, which has deleterious effects on organisms such as humans causing diseases such as skin cancer, cataracts, and reduced immunity.

In the 1940s, many household refrigerators and air conditioners used refrigerants that were called chlorofluorocarbons – carbon compounds that contain halogens such as chlorine and fluorine. Unbeknownst to scientists at the time was that these chlorofluorocarbons were volatile, could readily change to vapor, and would enter the stratosphere binding to the oxygen molecules in ozone, destroying thousands in the process. In 1985, the Halley Research Station recorded a stark decrease in ozone levels over the South Pole, revealing an ozone hole now known as the Antarctic ozone hole.

The discovery of the Antarctic Ozone prompted discussions on how to solve the problem of ozone depletion. In a worldwide initiative called the Montreal Protocol passed in 1989, 100 ozone-depleting substances (ODS) were discovered and countries were mandated to end the use of these substances for the ozone levels to return to pre-1980 levels.

Ozone depletion is a very pressing issue that can be detrimental to life on Earth, and thus this problem must be remedied.

Data on the size of the ozone hole and the usage of chlorofluorocarbons were taken from the NASA Ozone Watch (2023) and the UN Environment Program (2022) taken from Our World In Data site. In this paper, the maximum size of the Antarctic ozone hole from 1979 to the present year and the total ozone-depleting substance emissions from the US after the enactment of the UN Environment Program Protocol of 1989 will be statistically analyzed and visualized.

Methods

This paper utilized two datasets taken from two different organizations. The first dataset contained data on the area of the Antarctic ozone hole from 1974 to 2023 and was taken from the NASA

Ozone Watch (2023). The second dataset containing data on the total ozone-depleting substance emissions from countries around the world from 1986 to 2022 is taken from the UN Environment Program (2022).

This project utilized the Python3 language and the NumPy, Pandas, and Matplotlib libraries were imported to perform the statistical analysis, linear regression, and data visualization. Both datasets were loaded into the python3 file via the Pandas read_csv() method and stored as DataFrame objects. In the first dataset, the maximum area of the Antarctic ozone hole and the year associated with the value were extracted. For the second dataset, the rows corresponding to the US and the CFC values for each year were extracted. The maximum, mean, and standard deviation were calculated using the pandas max(), mean(), and std() functions on the maximum ozone hole area and the US CFC emissions. The formulas used for the statistical analysis are shown below:

(1) Mean formula: $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$

(2) Standard Deviation formula: $s = \sqrt{\frac{\sum_{i=i}^{n}(x_i - \bar{x})}{n-1}}$

Data visualization and linear regression were performed primarily using the NumPy and Matplotlib libraries. For the first dataset, the year was plotted against the maximum hole area and the polyfit() from NumPy was used to fit the data and make predictions. From the sklearn.metrics module the r2_score() function was imported to calculate the R^2 value between the data and the predicted values from the fitted model. For the second dataset, the US CFC values were plotted against the year and a line was added to the graph to include the year when the Montreal Protocol was enacted.

(3) R^2 value: $R^2 = 1 - \frac{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{N}(\hat{y}_i - y_i)^2}$

(4) Linear Regression model for Maximum Ozone Hole Area:

$$y = \mathrm{a}x^2 + \mathrm{b}x + \mathrm{c}$$

Analysis

Statistical Analysis

The maximum of the ozone hole area was calculated to be 2.99 x 10^7 km^2, which occurred in the year 2000. This is clearly shown in **Figure 1 and Table 1**, where the maximum area of the ozone hole increases from 1979 to 2000 and then has a decreasing trend from 2000 to 2023. This was expected because despite the US CFC emission being very low, CFC emission worldwide was still high contributing to ozone depletion. However, after 2000 ozone depletion severely dropped due to CFC emission dropping significantly as shown in **Figure 2 and Table 2**. The average of the maximum ozone hole area was calculated to be 2.16 * 10^7 km^2 with a standard deviation of 7.01 * 10^7 km^2.

The maximum CFC emission by the US was 317,544 tons in 1989. This was expected because this was the year when the UNEP Montreal Protocol was enacted meaning that the US was still utilizing CFCs by this point and had not issued a ban on ODS by then, showing that before the Montreal Protocol the US was a significant contributor to CFC emissions; after its enactment, CFC emissions significantly reduced as shown in **Figure 2 and Table 2**. The average CFC emissions from the US was 40,368.31 tons with a standard deviation of 86,814.10 tons indicating there is a high level of variance in the dataset.

Graphs/Models Analysis

Figure 1 shows a scatterplot of how the maximum ozone hole area (in 10^7 km^2) varies with time from 1979 to 2023 (shown in red). The fitted model, reported in black) is a polynomial with degree 2 ($y = -3.0642 + 1.229 - 1.232 * 10^{-11}$) with $R^2 = 0.77$, indicating a good fit, and was shown on the figure as a blue curve. The data shows an upward trend in the size of the ozone hole with a maximum in the year 2000 and in subsequent years a downward trend. The predicted values from 2023 to 2030 calculated using the model are shown in green, and in 2030 the maximum size of the ozone hole is expected to be $9.51 * 10^6$ km^2, which is about the size of the ozone hole in 1982, thereby showing signs of ozone layer remediation.

Figure 1: Maximum Antarctic Ozone Hole area from 1979 - 2022. The quadratic model is

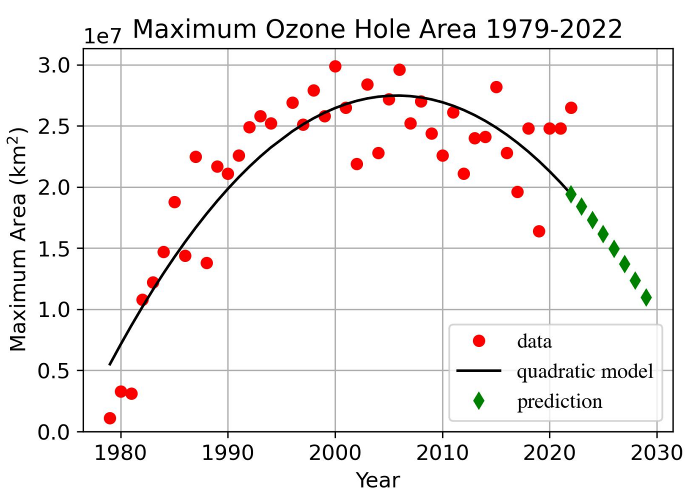

Figure 2 shows a line graph of US CFC emissions as a function of time from 1986 to 2023 (shown in red). The data shows a slight increase in CFC emissions from the US till the year 1989, and later a sharp decrease; the CFC emissions from 2007-2022 become negative and remain relatively constant at this point. Moreover, the enactment of the 1989 Montreal Protocol was included in the graph as a blue-dashed line, indicating that CFC emissions sharply decreased after the passing of the Montreal Protocol.

Figure 2: United States CFC emissions from 1986 - 2021

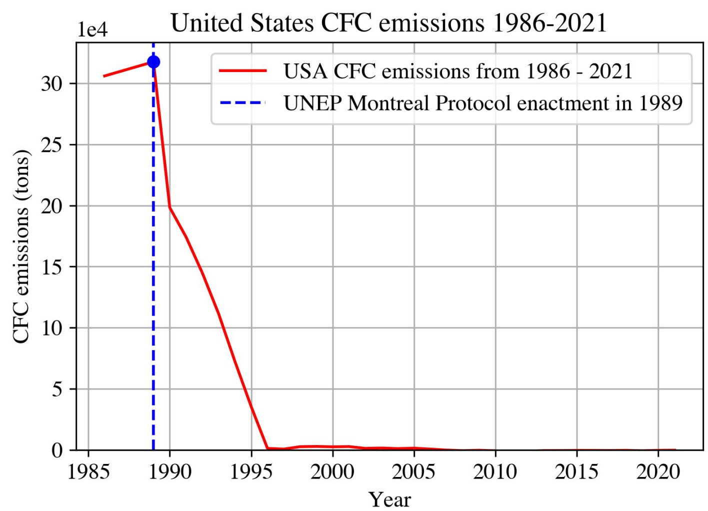

Table 1: Table containing values of Maximum ozone hole area

Year	Maximum ozone hole area
1979	1100000
1980	3300000
1981	3100000
1982	10800000
1983	12200000
1984	14700000
1985	18800000
1986	14400000
1987	22500000
1988	13800000
1989	21700000
1990	21100000
1991	22600000
1992	24900000
1993	25800000
1994	25200000
1996	26900000
1997	25100000
1998	27900000
1999	25800000
2000	29900000
2001	26500000
2002	21900000
2003	28400000
2004	22800000
2005	27200000
2006	29600000
2007	25200000
2008	27000000
2009	24400000
2010	22600000
2011	26100000
2012	21100000
2013	24000000
2014	24100000
2015	28200000
2016	22800000
2017	19600000
2018	24800000
2019	16400000
2020	24800000
2021	24800000
2022	26500000

Table 2: Table containing values of US CFC emissions

Entity	Code	Year	CFCs
United States	USA	1986	305963.6
United States	USA	1989	317543
United States	USA	1990	198308.2
United States	USA	1991	174261.8
United States	USA	1992	144855.8
United States	USA	1993	111458.8
United States	USA	1994	72534.4
United States	USA	1995	35529.6
United States	USA	1996	1331
United States	USA	1997	745.7
United States	USA	1998	2709.2
United States	USA	1999	2903.8
United States	USA	2000	2614.6
United States	USA	2001	2806.8
United States	USA	2002	1357.2
United States	USA	2003	1605.2
United States	USA	2004	1153.6
United States	USA	2005	1496.6
United States	USA	2006	752.7
United States	USA	2007	-68.6
United States	USA	2008	-569.2
United States	USA	2009	-223.6
United States	USA	2010	-661.8
United States	USA	2011	-1374.6
United States	USA	2012	-1050.3
United States	USA	2013	-498.6
United States	USA	2014	-459.9
United States	USA	2015	-328.2
United States	USA	2016	-353.9
United States	USA	2017	-418.5
United States	USA	2018	-292.5
United States	USA	2019	-647.8
United States	USA	2020	-300.1
United States	USA	2021	-161.6

Discussion

The analysis in this paper shows key insights into the future of our ozone layer and its remediation. The Antarctic ozone hole data was modeled by a quadratic fit with $R^2 = 0.77$. The fit demonstrated that initially, the size of the ozone layer had an upward trend as referenced by the years 1979-2000 due to the usage of CFCs. However, after the enactment of the Montreal Protocol in 1989, as shown in US CFC emissions data, after the year 2000, there has been an ongoing decreasing trend in ozone hole size. The slight increase in 2020-2023 was due to changing meteorological conditions causing ozone depletion, however, the general trend is decreasing. Based on the model, it is projected that by 2030, ozone levels will return to 1982 levels. It can be corroborated that the current practices and initiatives that are in place have been successful in the remediation of the ozone layer, and thus such policies should be maintained and enforced for ozone levels to reach pre-1980s levels.

In an August 2022 report, NOAA, another body responsible for monitoring ozone levels, concluded that the ozone hole had recovered greatly. Agreeing with the findings of the study, the report concluded that ODS levels have been on a continual decline and that ozone levels in the stratosphere are 50% over the 1980s level, showing great progress. Data from the UNEP further substantiates the conclusions made in this paper, that ozone levels will return to 1980 levels by 2040, even stating that if recovery follows the same trend it can reduce global warming up to 0.5℃.

Though the ozone layer is showing signs of recovery, the threat of ODS remains in the form of methyl bromides and hydrofluorocarbons (HFCs). In 2016, the UNEP amended the existing Montreal Protocol through the Kigali amendment by slowing down the production and consumption of HFCs. Methyl bromides are still in use as a fumigant that is used on airplanes with no real alternative as of yet, making this ODS a real threat to ozone holes. Therefore, it is imperative that governments cooperate with the new guidelines set by the Kigali amendment, as done with the Montreal Protocol, and more research is conducted to find safer alternatives to ODS like methyl bromides. If done, ozone depletion may no longer be a global crisis.

Conclusion

The analysis performed in the paper was in agreement with the primary research on the size of the ozone hole and CFC emissions. In the case of the ozone hole data, the maximum ozone hole area and the year, the continuous downward trend in the size of the ozone hole after 2000 as shown by the model were in agreement with the data from analyses by NOAA in 2022. In the case of CFC emissions by the US, the data agrees with the conclusions of the UNEP 2023 report that there was a sharp decrease in CFC emissions.

Since this study was limited to analyzing and visualizing CFC emissions in the US, future studies can expand the scope of analyzing CFC emissions globally and include more ODS in their analysis.

The paper concludes that the ozone hole is showing signs of recovery due to the positive impact of decreased CFC emissions as set by the 1989 Montreal Protocol.

References

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Additional Notes on Datasets

Ozone Hole area dataset: Data source: NASA Ozone Watch (2023)

ODS dataset: Data source: UN Environment Programme (2023) Note: In some years, gases can have negative consumption values. This occurs when countries destroy or export gases that were produced in previous years (i.e. stockpiles)