Satellite Reentries: A Global Analysis of Their Impacts across Earth Systems and the Atmosphere

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ABSTRACT

The increasing frequency of satellite reentries raises concerns about their potential environmental impacts. This study aims to investigate whether reentry events correlate with changes in meteorological and hydrological parameters using data from space-track.org, the GLOBE Program, and the Copernicus Climate Change Service. Statistical analyses, including Student's T-tests, revealed significant changes in temperature interquartile range (IQR; p = 0.04) and dissolved oxygen levels (p = 0.0221) following reentries. However, the mean distance between decay sites and measurement locations was approximately 645 km, making direct attribution uncertain. Additionally, satellite imagery analysis showed no clear observable correlation between reentry locations and large-scale environmental disturbances. These results suggest that while some statistical anomalies exist, they may reflect natural variability rather than direct effects from reentries. Further research with more localized measurements and controlled conditions is necessary to determine whether satellite reentries have a meaningful environmental impact.

Keywords: Satellite reentry, environmental impact, space debris, climate change, statistical analysis.

RESEARCH QUESTION

In order to determine the impact of satellite reentries on earth's systems and weather patterns, it is essential to compare atmospheric conditions before and after these events. This work aims to answer the following research question: **How do satellite reentries impact the atmosphere, specifically in relation to local climate and weather phenomena?** The reentry of satellites into Earth's atmosphere is an alarming situation that has been occurring with more frequency over the years, going hand in hand with the growing space industry and its environmental footprint. Understanding this potential impact requires further comprehensive data collection and analysis to accurately assess whether satellite reentries contribute to shifts in normal environmental and climatic conditions.

INTRODUCTION & REVIEW OF LITERATURE

Different objects such as satellites, telescopes, rockets and different equipment that accompany them have been sent into space over the decades at an increasing non-constant rate with the purpose of completing different missions benefiting humanity. While there is significant awareness of these benefits, and also the negative consequences at launch time, awareness remains limited regarding decommissioned satellites returning to Earth as space debris. This debris remains in orbit until atmospheric reentry, during which it releases metal compounds such as lithium, aluminum, copper, lead, magnesium, and sodium into atmospheric layers (Murphy, et al. 2023) All of these compounds that are released on reentry embody an increasing preoccupation on the environmental impacts of reentries.

Another of the main concerns about space debris is the phenomenon known as the *Kessler Syndrome*, that describes the increasing probability of collisions between space debris as more matter is launched into space. These collisions are expected to break objects up and further increase the probability of future collisions. Pollutants emitted upon descent, can exacerbate climate change and influence different natural phenomena. *"These events inject pollutants and carbon dioxide (CO_2) in all atmospheric layers, affecting climate and stratospheric ozone"* (Barker et al., 2024, p. 1).

An important factor to consider when assessing the potential effects of space debris on weather and climatic conditions is precisely the modelling of these conditions. Earth systems are complex, and dynamical, the atmosphere is no exception. (Donner et al, 2009) Earth's climate and weather dynamics are governed by systems of partial nonlinear differential equations, Systems of this sort heavily depend on their inputs, and even minute changes to these can give rise to exponentially different solutions with time, in other words, they are chaotic. This further validates the importance of analyzing localized perturbations in earth systems, as even small perturbations, such as those from reentry emissions, could amplify phenomena like the El Niño–Southern Oscillation (ENSO) through complex feedback mechanisms (Arfken, 2005, pp. 1079-1108)

METHODOLOGY

A mixed-methods approach combining correlational analysis and geospatial mapping was employed. Satellite reentry data (2004–2024) from Space-Track.org were cross-referenced with GLOBE Program environmental measurements (temperature, humidity, dissolved oxygen) and Copernicus Climate Change Service datasets.

DATA COLLECTION

- **Reentry Events:** Tracking and Impact Prediction (TIP) messages from space-track.org identified decay locations.
- **Environmental Data:** GLOBE measurements were mapped to the nearest reentry sites (mean distance: 646 km).
- **Satellite Imagery:** Copernicus Climate Data Store provided gridded historical temperature data.
- **Orbit trajectory and demise paths**: The Satflare website was used to correlate satellite imagery and demise paths.
- **Geographical data**: NaturalEarth data sets were used to segment reentry data based on proximity to GLOBE measurement sites. When

mapping, the same polygons were used to show land for geographical reference.

After analyzing several satellite images, the unpredictability of demise patterns became a challenge. This led us to focus our analysis on SpaceX's Starlink satellites, which have much more predictable demise paths, with shorter windows, and thus, more localized and observable effects. In addition, the consistency in Starlink's launch, reentry and operation patterns allows for better calibration and validation of the results which would not be possible if not by limiting the scope of missions, since for many of them the information is sparse, limited or non-existent.

DATA PROCESSING

Computational methods were also used to identify patterns and relationships between atmospheric variables and space debris reentry events, descriptive statistical procedures, namely:

- Median
- Mean
- Standard Deviation
- Range
- Interquartile Range

Correlation analysis and hypothesis testing were used to assess the relationship between atmospheric changes and space debris impact. The analyses were performed using Python code, MatPlotLib and Cartopy for data visualization, Pandas and Numpy for numerical operations and Xarray for parsing Copernicus' NetCDF datasets. APIs used include the GLOBE API, Copernicus Climate Data Store (CDS) API and the Space-Track.org API.

LIMITATIONS

While this study provides valuable insights regarding the comparison of variables, some limitations were encountered and must be acknowledged.

- **Data Management**: The large amount of data significantly increased the time complexity of various processes, including storage, processing, analysis, and debugging. For instance, generating just one map with the CDS API and running the statistical calculations took at least 1m30s, in a batch of more than 300 reentries.

- **Data Consistency**: GLOBE's data was highly inconsistent in various sites, which made it necessary to filter reentries with insufficient data.
- **Limited Granularity**: Especially in GLOBE measurements, it also could have skewed our analysis.

For future research activities, we advise our fellow GLOBE researchers to compare their data with different sources, especially when finding statistical significance in their findings. As data with low resolution (spatial & temporal) can lead to confusion and misleading results.

RESULTS

GLOBE DATA

Using GLOBE data, it was found that, over a window of 72 hours, the following statistically significant impacts on atmospheric conditions could be observed:

- Temperature: IQR before-after difference statistically significant (t: 2.0896, p: 0.04).
- Humidity: No statistical value was found to be significant. Closest to significance was Dew Point IQR before-after difference (t: 1.7317, p: 0.087).
- Dissolved Oxygens: O_2 mg/L mean before-after difference statistically significant (t: -2.3999, p: 0.0221)

It is important to note that these findings depended on significantly sparse data in the spatial dimension; the mean distance from the decay site to the measurement site was 645.88 km for the analyzed sample. Taking this, and the relatively small sample size into consideration, we could interpret that any detected statistical significance might be more indicative of broader atmospheric variability rather than a direct impact from satellite reentries.

SATELLITE IMAGERY

To further understand these findings and their significance, we took the variables that had shown statistical relevance within the GLOBE dataset, to a satellite mapping software with the objective of discerning features that may resemble a demise path. For this purpose we used historical data from the Copernicus Climate Change Service, over a window of 72 hours before and after each reentry. We believe our analyses to be non-conclusive in this regard, as we could not discern any observable features from the analyzed statistical values. Figures 2 et al. show a sample of reentries with different variables being analyzed.

DISCUSSION

As noted by Dr. Alan Barreca (2024) associate professor at the Institute of the Environment and Sustainability, humidity is defined as the amount of water vapor in the air. Humidity has a very important role in temperature regulation, precipitation formation and heat index. Because of this it was considered an important factor of investigation. However, the analysis did not yield any statistically significant results. The closest variable to significance was the before-after difference in Dew Point IQR (t = 1.7317, p = 0.087). We attribute this to the relationship between dew point, temperature, and relative humidity. Given the high variability of humidity across different geographic regions, seasons, and altitudes, these factors likely influenced the results, making it difficult to identify clear patterns or significant correlations. Future research could explore alternative methods or larger datasets to have a better understanding on the role of humidity in climate and the potential connections that might happen with atmospheric variables.

The Dissolved Oxygen (DO) GLOBE Protocol was selected for its superior temporal resolution across multiple sites. As noted by Yao et al.

(2023), imbalances in dissolved oxygen can disrupt marine food chains, alter local weather patterns, and even contribute to extreme climate events. Our data indicate a variation in dissolved oxygen (measured in mg/L) following satellite reentry events. Further research in this area should target specific locations where space debris decays over water to better capture these effects. Especially given the fact that satellite imagery cannot be used for this type of measurement. This is an example of how different earth systems interact through latent and complex feedback mechanisms.

GLOBE Protocols related to aerosols, precipitation pH, water temperature, pressure, and clouds, could have provided valuable insights into the impact of space debris reentry on air and water quality, as well as ecosystem health. Unfortunately, our analysis was constrained by inconsistencies in the available data and a limited number of stations reporting these parameters.

Ultimately, our goal was to discern the true impact of satellite reentries on Earth's systems by analyzing various environmental and atmospheric parameters. Although our statistical evidence indicates observable atmospheric changes associated with satellite reentries, qualitative analyses of satellite imagery have raised concerns regarding the overall reliability and admissibility of the GLOBE data in fully capturing these effects.

Discussion 1: GLOBE Data

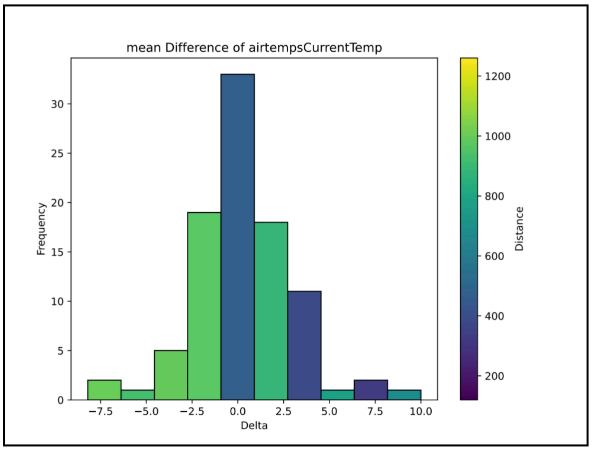

Figure 1.1: Mean Difference of Air Temperature

As seen in Figure 1.1, the mean difference in air temperature shows that there are moderate fluctuations from the zero delta, but no extreme values, suggesting that no significant temperature shifts occurred after the satellite reentries. From this the group could evidence that the satellite reentry events did not show sufficient changes in the regional or global temperature to show an observable impact. Interestingly, measurements taken closer to the reentry site seem to have a positive trend.

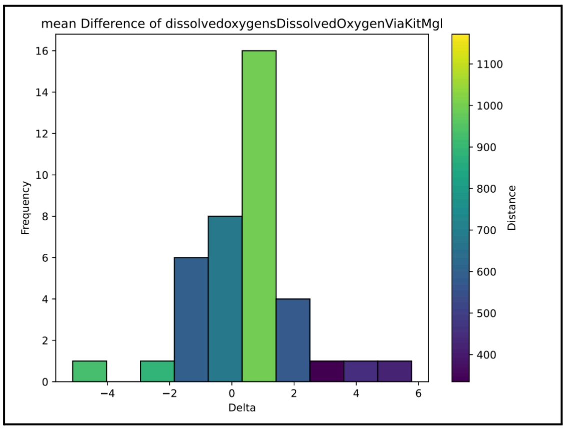

Figure 1.2: Mean Difference of Dissolved Oxygens

In **Figure 1.2**, we can see that data collected closer to the reentry site exhibit more pronounced absolute change after reentry. Water temperature and contamination influence the solubility of oxygens (O_2) in water. The shift in the mean could suggest possible environmental effects from space debris.

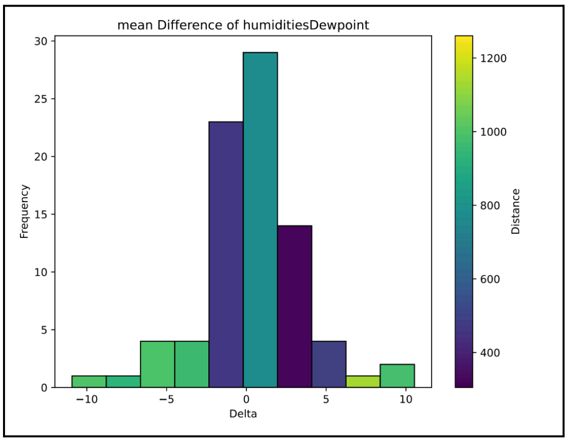

Figure 1.3: Mean Difference of Humidities Dewpoint

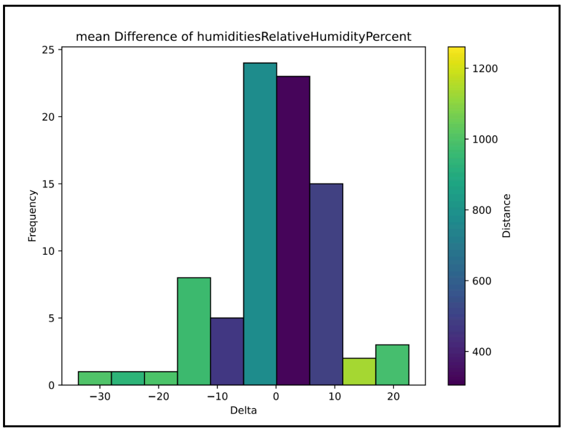

Figure 1.4: Mean Difference of Relative Humidity

As seen in **Figure 1.3** and **Figure 1.4**, the respective means of relative humidity and dew point show that there evidently exists some dispersion but it is not a strong shift in the mean values. This could show that the atmosphere was not greatly impacted by the satellites, at least in a systematic way. In general terms, the data shows that some variations might exist that could be attributed to the effects of reentry, but not enough to show a significant impact.

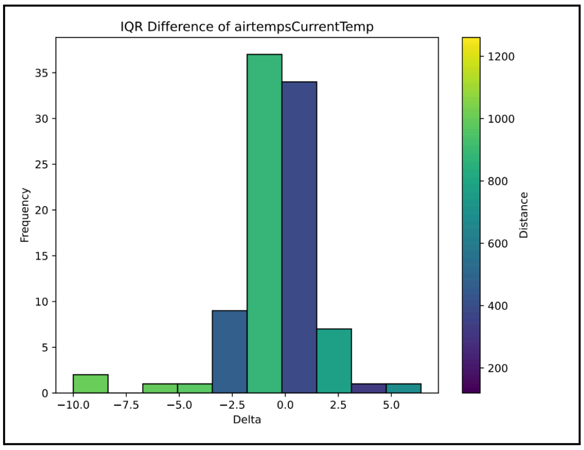

Figure 1.5: IQR Difference of Air Temperature

The histogram represented in **Figure 1.5** showing the IQR difference of air temperature shows moderate variability in the data set, but mostly follows a normal distribution.

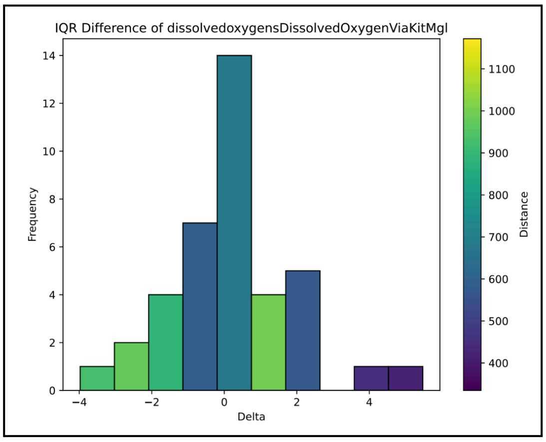

Figure 1.6: IQR Difference of Dissolved Oxygens

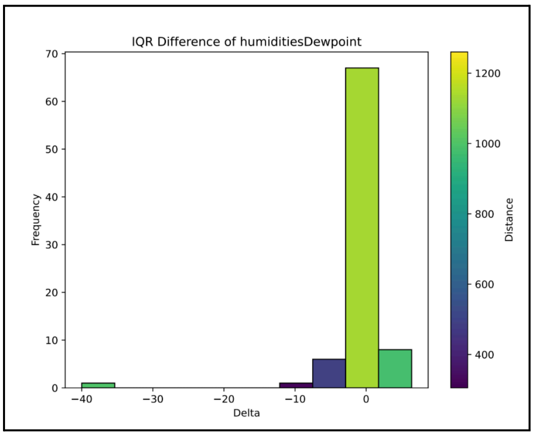

Figure 1.7: IQR Difference of Humidities Dewpoint

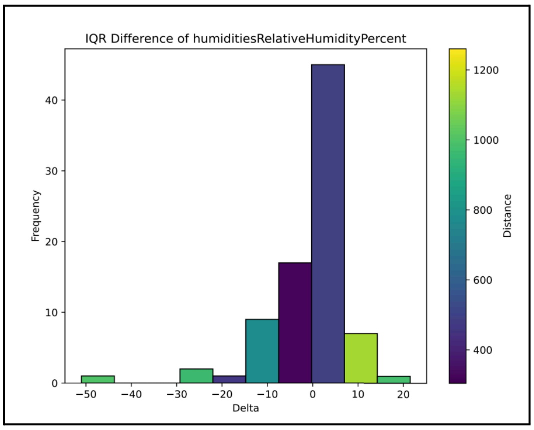

Figure 1.8: IQR Difference of Relative Humidity

The IQR difference in dissolved oxygen as evidenced in **Figure 1.6** seems to not be normally distributed at first sight, but upon further analysis, it seems to be heavily skewed by a few outliers. **Figure 1.7** and **Figure 1.8** exhibit a strong trend to the zero delta value, indicating that there was little to no difference in most measurements.

Discussion 2: Satellite Imagery

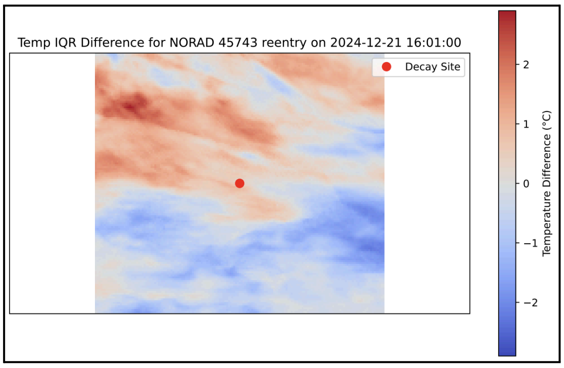

Figure 2.1.1: Temperature (°C) IQR Around NORAD 45743 Reentry Site in the Southern Pacific Ocean (Before and 72h After Reentry).

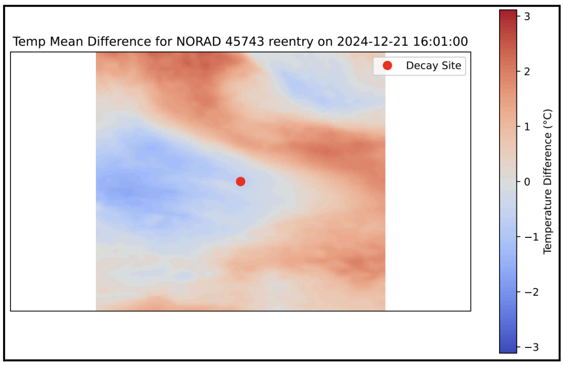

Figure 2.1.2: Mean Temperature (°C) Difference Around NORAD 45743 Reentry Site in the Southern Pacific Ocean (Before and 72h After Reentry).

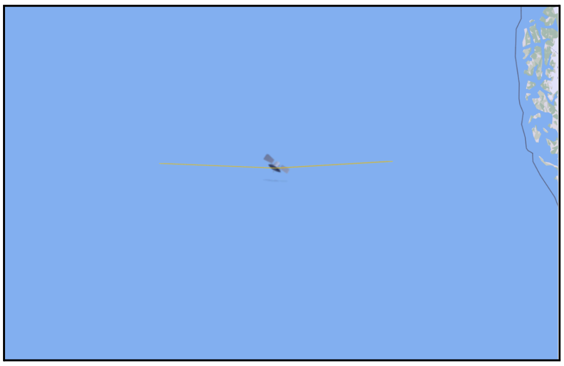

Figure 2.1.3: Tracked Reentry Path of NORAD 45743 in the Southern Pacific Ocean.

- **Figure 2.1.1, and Figure 2.2.1:**

1. Positive (red) areas indicate an increase in temperature variability after reentry (larger range of temperature values).
2. Negative (blue) areas indicate a decrease in temperature variability after reentry (more stable temperatures).

- **Figure 2.1.2, and Figure 2.2.2:**

1. Positive (red) areas indicate that the region became warmer after reentry.
2. Negative (blue) areas indicate that the region became cooler after reentry.

- **Figure 2.1.3, and Figure 2.2.3**

1. Yellow line indicates the re-entry path of the decayed object, indicating the trajectory it followed as it re-entered Earth's atmosphere before burning up or impacting the surface.

Deducting from **Figure 2.1.1** the research group identified regions of both increased and decreased temperature (°C) variability in different areas surrounding the satellite decay site without following a constant pattern or an evident correlation with the tracked pass of NORAD 45743 (Starlink-1483) demonstrated in **Figure 2.1.3.** The scattered and seemingly random zones suggest that natural weather fluctuations are likely responsible for temperature variability in this reentry capture.

Concerning **Figure 2.1.2** the research group found that the temperature changes do not follow patterns that could be associated with the demise path of NORAD 45743 (Starlink-1483) demonstrated in Figure **2.1.3,** thus indicating that ocean currents, cloud cover, or wind patterns might have influenced the difference instead of the wide spreading heating effect from the satellite reentry. Additionally, the research group noticed an irrelevant and contradictory effect of reentry, as the surrounding areas demonstrate a cooling effect, rather than the expected warming effect which occurs as an outcome of the pollutants and carbon dioxide (CO_2) injected in the atmosphere upon reentry.

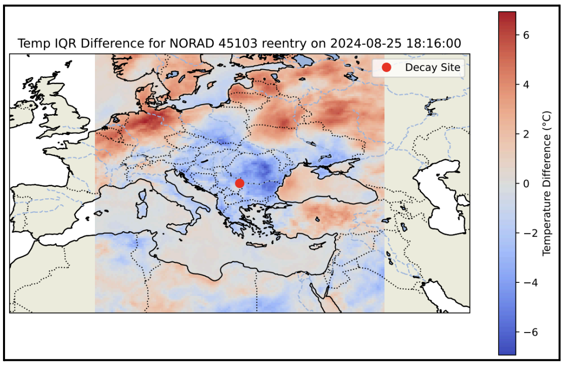

Figure 2.2.1: Temperature (°C) IQR Around NORAD 45103 Reentry Site in Europe (Before and 72h After Reentry)

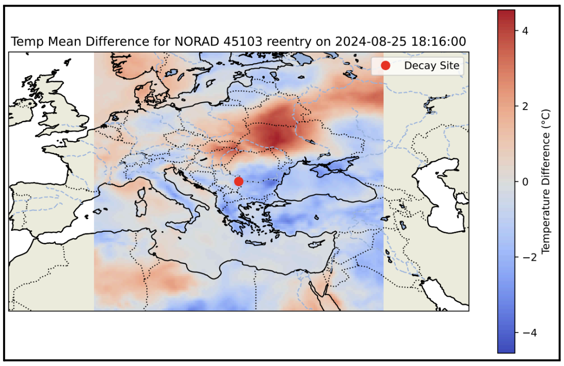

Figure 2.2.2: Mean Temperature (°C) Difference Around NORAD 45103 Reentry Site in Europe (Before and 72h After Reentry)

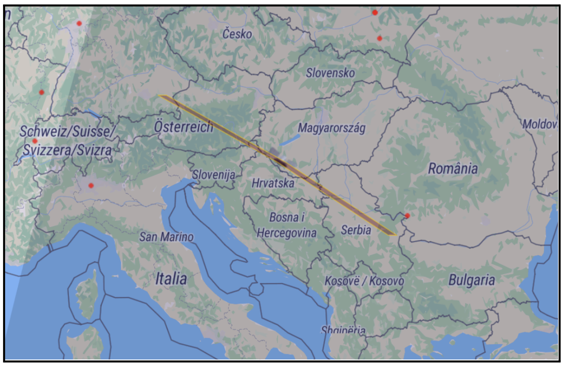

Figure 2.2.3: Tracked Reentry Path of NORAD 45103 in Europe

In **Figure 2.2.1** we can notice that near the satellite reentry there was a reduction in temperature variability, which contradicts the expected effect. Instead the increase in temperature variability took place in upper Western and Central Europe, which suggests little to no correlation with the NORAD 45103

(Starlink-1196) demise path demonstrated in **Figure 2.2.3**.

Another example of data that disproves our hypothesis exists in **Figure 2.2.2**, the research group identified that after 72 hours from the reentry of the satellite, the temperature decreased, instead of demonstrating a concentrated warming of the areas as expected, just as it occurred much above the decay site without showing any overlap with the tracked pass of NORAD 45103 (Starlink-1196) as observed in **Figure 2.2.3**. The mixed warming and cooling differences suggest that the observed temperature changes must be driven by broader atmospheric conditions instead of the reentry.

Future research could dive into the training of Interpretable Machine Learning models with reentry data, with the objective of generating a classification network. Interpretability would play a very important role in this avenue of research, as classifying reentry sites is arguably less vital than understanding the impact of reentry.

CONCLUSION

It is important to note that the research initially was directed towards only GLOBE data, but given the analysis that stemmed from it yielded uncertain results, using satellite data became imperative. The usage of this data allowed us to elucidate and reflect on the real significance of our original dataset and analysis.

Concerning the maps created from this historical data from Copernicus Climate Change Service, both the IQR variability difference and the mean difference in air temperature in NORAD 45743 (Starlink-1483) and NORAD 45103 (Starlink-1196) demonstrated a pattern not consistent with the decay site nor the satellite reentry trajectory. The discrepancy between the measure of central tendency (mean) and the measure of dispersion

(IQR) on and surrounding the decay site suggests that satellite reentry effects on regional temperature are minimal and even negligible (since the decay sites do not show sharp extreme changes, indicating that the reentry did not introduce notable atmospheric disturbances), or possibly hidden by broader atmospheric conditions such as normal meteorological variations or even environmental phenomena just as El Niño–Southern Oscillation (ENSO) or La Niña.

Notwithstanding the results obtained from our analyses, the lack of information as a result of the inconsistency in GLOBE data affected the accuracy and depth of the analysis when identifying any correlation among satellite reentry and weather variables. Measurements could have possibly skewed our analysis, this highlights the importance of diversifying GLOBE-like initiatives around the globe and incentivizing their implementation across borders and in cities and rural areas alike. With a more consistent data set, the interpretation and analysis of the results would have been more rigorous and accurate (as they would follow a more reliable assessment of the meteorological conditions during the satellite's reentry window), and thus, would enable the finding of adequate strategies that mitigate satellite reentry footprint.

The reentry of satellites (as stated previously) does generate some slight changes in the tracked atmospheric variables; however, the research group considers that the concentration of various satellite reentries at the same place could exacerbate imperceptible atmospheric changes, which would then pose a threat to the environment due to the concentration of these emissions. Aiming to mitigate these effects, the group proposes spreading satellite reentry sites as much as possible throughout the planet (in places far from civilization and where the risk of impact to the environment is at a minimum). This measure would reduce the concentration of emissions over a single area and thus avoid the risk of exacerbating adverse climate phenomena. Additionally, we propose that material sciences should be applied to optimize the materials used in satellites to reduce chemical reactions during reentry that give way to harmful compounds, such as CO_2 or aluminum oxides. This solution employed in unison with the previous proposal could potentially reduce medium- and long-term harmful effects of satellite reentry.

DATA AND CODE

Data and code used in order to obtain the results of this project are available at the following public Github repository: https://github.com/pisanvs/GLOBE-spacedebris

ACKNOWLEDGEMENTS

We extend our sincere gratitude to our mentors, María del Pilar Tunarroza, Matthew Reis, Geoffrey Bland Ph.D., Nicolás Cabrera, John Zafra and Brian Saltzer Ph.D., for their invaluable guidance and unwavering support throughout the development of our project. Their expertise and mentorship were instrumental in refining our research focus and navigating the publication process.

GLOBE BADGES

I am an Earth System Scientist:

The project analyses the impact of the satellites reentry in the atmosphere in climate, utilizing GLOBE program databases and other scientific resources. The group has examined variables such as temperature, humidity, and dissolved oxygen, which span not only the atmosphere but the hydrosphere and (especially dissolved oxygen) interacts with the biosphere, generating longer term changes. This demonstrates integral understanding of earth systems.

This study focuses on the potential atmospheric and environmental impacts of satellite reentries, the group analyzed real-world data from space-track.org, the GLOBE program, and the Copernicus

Climate Change Service. This research embodied the principles of Earth system Science by investigating the connections between human activities in space and the environmental changes on earth. The study just does not observe data, it explores the effects on atmospheric and hydric conditions.

By comparing environmental variables before and after reentries, the group looked for different patterns across variables, proving their interest in finding correlations to help reduce environmental footprints.

This work highlights the importance of continuous monitoring of earth's systems, recommending better measurement of data, an improved observation method, and future research into long term environmental impacts.

I am a Data Scientist :

This research stands out because it does not rely on assumptions or artificial models, it draws conclusions from real world environmental data. The group analyzed atmospheric and hydrological conditions using statistical tools and methods that allowed them to identify important trends and assess anomalies that might occur due to satellite reentries.

Instead of just gathering numbers in a CSV format, the group questioned the reliability of their sources, recognizing that there are some data gaps, and showed some limitations, showing that their conclusions were based on scientific reasoning rather than speculation. By using different techniques, the group shows how critical thinking, problem solving, and a deep understanding of how data can reveal powerful information about earth's changing environment.

Furthermore, the group demonstrated understanding of the methods employed in the analysis, and communicated the results in a clear and detailed manner.

I am a Collaborator:

The success of this research is in great measure due to the fact that it is built on strong teamwork, where each participant took different roles that complemented one another. Instead of working by themselves, in an isolated manner, students collaborated across different schools, and even countries to bring a diverse analysis to the data, environmental science, and geospatial mapping. All based on their own previous knowledge, helping with what they know how to do well, rounding other members with an integral way of learning.

This collaboration also extended beyond only a student group, as different mentors and scientific advisors also provided guidance, which ensured that the study followed rigorous research methodologies. This ability to integrate multiple perspectives, divide tasks efficiently, and combine the knowledge of different people demonstrates why this research shows effective collaboration in a scientific process.

The following roles were assumed by each team member:

- Emiliano Abello: Data Interpretation and Conclusions
- Diego Sierra: Literature review and research.
- Maximiliano Morel: Coding and data collection

The team worked collaboratively on the writing of the paper, revising the work of each other iteratively.

I make an Impact:

The study shows the importance of diversification of data collection, and proposed strategies to mitigate effects of important matters such as the reentry of satellites.

The research also goes beyond only identifying environmental changes, it also provides an innovative solution to address them. Instead of simply suggesting that satellites should re-enter in different locations where they would directly affect humans, the team proposes a complete proposal related to how satellites should be built up to minimize their impact on Earth systems.

By redesigning materials, using intelligent coats, and integrating combustion systems, the project provides a strategy that could change how space missions are planned.

This project contributes to the conversation related to space sustainability, ensuring that technological and human advancements don't come with high environmental costs. The group is committed to finding solutions, rather than just identifying problems, which makes this research really impactful.

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APPENDIX

Google Drive Folder including all data used for analysis.

https://drive.google.com/drive/folders/1IKecQzvmtS9mF58l9TV0F5O3wpolkHEH?usp=drive_link

Google Drive Folder including all data output from the analysis.

https://drive.google.com/drive/folders/1O71bbtTHzct7xg9ZAGmtmaymRYlcZGqV?usp=drive_link

Individualized comparison tables for each reentry (unfiltered)

https://drive.google.com/file/d/1lGNHxgz9GGMicMQryX2_FC_QrXJxFCXN/view?usp=drive_link

GLOBE Data collected from the API within the decay window

https://drive.google.com/file/d/1Sp5jYdaJcSv15opTfcIntV15Y9Hnac7Q/view?usp=drive_link

(Note: this is a big file. Traditional editors may crash)