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

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## WHAT IS THE PROJECT ABOUT?

- **Objective:**
  - This study investigates the potential atmospheric and environmental impacts of satellite reentries, focusing on temperature, humidity, and dissolved oxygen changes. By combining GLOBE Program data with satellite reentry records and Copernicus Climate Change Service datasets, we aim to determine whether space debris reentry has measurable effects on Earth's systems.
- **Research question:**
  - How do satellite reentries impact the atmosphere, specifically in relation to local climate and weather phenomena?

## REVIEW OF LITERATURE

- **Space Debris & Atmospheric Reentry:**
  - Satellites, telescopes, rockets, and equipment have been launched into space at an increasing, non-constant rate for various missions.
  - Reentry releases metal compounds (lithium, aluminum, copper, lead, magnesium, sodium) into atmospheric layers [PNAS, 2024].
  - Environmental concerns regarding these compounds are growing, yet awareness remains limited.
- **Kessler Syndrome & Climate Impact:**
  - The Kessler Syndrome describes how space debris collisions increase future collision probability, further fragmenting objects in orbit.
  - Pollutants released upon reentry (including $CO_2$) impact climate and stratospheric ozone [Barker et al., 2024].
- **Atmospheric Modeling & Sensitivity to Perturbations:**
  - Earth's climate and weather are governed by nonlinear differential equations, making them chaotic systems [EPJST, 2009].
  - Small perturbations, such as those from reentry emissions, could amplify natural phenomena like El Niño–Southern Oscillation (ENSO) through complex feedback mechanisms [Arfken, 6th ed.].

## DATA PROCESSING

- **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.

Analyzing satellite images revealed unpredictable demise patterns, so we focused on SpaceX's Starlink satellites due to their predictable, localized reentry paths. Their consistent launch and operation patterns enable better calibration and validation, which would be challenging with missions lacking sufficient data.

## METHODOLOGY

- **Approach & Data Sources**
  - A mixed-methods approach combining correlational analysis and geospatial mapping was used.
  - Satellite reentry data (2004–2024) from Space-Track.orgwas cross-referenced with:
  - GLOBE Program environmental data (temperature, humidity, dissolved oxygen).
  - Copernicus Climate Change Service datasets (historical temperature data).
  - NaturalEarth geographical data for spatial segmentation.
- **Data Collection**
  - Reentry Events: Space-Track.org's Tracking and Impact Prediction (TIP) messages 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 & Demise Paths: Satflare data was used to correlate satellite imagery with demise paths.
  - Geographical Mapping: The same polygon-based land references were used for spatial consistency.
  - Focus on Starlink Satellites: Due to their predictable demise patterns and localized effects, improving calibration and validation.-
- **Data Processing & Analysis**
  - Computational methods identified patterns between atmospheric variables and reentry events.
  - Descriptive statistics applied:
  - Median, Mean, Standard Deviation, Range, Interquartile Range.
  - Correlation analysis & hypothesis testing assessed atmospheric impacts.
  - Software & Tools Used:
  - Python libraries: Matplotlib & Cartopy (visualization), Pandas & NumPy (numerical operations), Xarray (NetCDF data parsing).
  - APIs: GLOBE API, Copernicus Climate Data Store (CDS) API, Space-Track.org API.
- **Limitations**
  - Data Management: Large datasets increased processing time (1m30s per map, 300+ reentries).
  - Data Consistency: GLOBE data varied across sites, requiring filtering.
  - Limited Granularity: GLOBE's low spatial & temporal resolution could affect accuracy.-

To access the full research study, please scan the QR code.

To access the Python code used for the project development, please scan the QR code.

## RESULTS

GLOBE DATA

- **Temperature:**
  - Interquartile Range (IQR) before-after difference was statistically significant ($t = 2.0896$, $p = 0.04$).
- **Humidity:**
  - No statistically significant values were found.
  - The closest to significance was Dew Point IQR before-after difference ($t = 1.7317$, $p = 0.087$).
- **Dissolved Oxygen:**
  - Mean $O_2$ mg/L before-after difference was statistically significant ($t = -2.3999$, $p = 0.0221$).

SATELLITE IMAGERY:

- **Temperature**
  - Air temperature with statistical relevance from GLOBE data was mapped using Copernicus Climate Change Service historical data (72-hour window before & after reentries).

## LIMITATIONS

- **GLOBE Data Limitations:**
  - Data Challenges: Large datasets increased processing time (e.g., 1m30s per map for 300+ reentries).
  - Inconsistencies and limited station reporting constrained analysis. Other protocols (aerosols, precipitation pH, water temp.) could provide further insights.

## DISCUSSION

GLOBE DATA

- **Humidity Analysis:**
  - No statistically significant changes were observed. Dew Point IQR ($t = 1.7317$, $p = 0.087$) was the closest to significance, likely due to high regional and seasonal variability. Larger datasets could improve future assessments.
- **Dissolved Oxygen (DO) Analysis:**
  - Significant variations ($t = -2.3999$, $p = 0.0221$) suggest potential environmental effects, but further research should focus on water-based reentries for better data capture.

SATELLITE IMAGERY:

- **Temperature Analysis:**
  - Observed temperature fluctuations did not correlate with reentry paths. Unexpected cooling effects suggest natural atmospheric variability rather than direct reentry impact.
- **Future Research**
  - Machine learning models could help classify and analyze reentry impacts, focusing on interpretability over classification to enhance understanding.

## CONCLUSIONS

- **Expanding Beyond GLOBE Data:**
  - Initial analysis relied solely on GLOBE data, but uncertain results made it necessary to incorporate satellite data for validation.
- **Satellite Reentry & Atmospheric Impact:**
  - No clear link between reentry sites and temperature variations
  - The lack of sharp changes in central tendency (mean) and dispersion (IQR) suggests minimal or negligible atmospheric impact.
  - Broader meteorological phenomena (e.g., ENSO, La Niña) could obscure reentry effects.
- **Data Limitations & Future Improvements:**
  - GLOBE data inconsistencies reduced the accuracy and depth of the analysis.
  - Expanding citizen science initiatives worldwide could improve data reliability and enhance future assessments.
- **Mitigating Satellite Reentry Impact:**
  - Spread reentry sites globally, focusing on remote and uninhabited areas to reduce human and environmental impact.
  - Prevent the accumulation of emissions in a single location, minimizing localized atmospheric disturbances.
  - Develop materials that burn up cleanly in the atmosphere, reducing harmful emissions like CO2 and aluminum oxides.
  - Use heat-resistant and low-toxicity materials to minimize chemical reactions that contribute to air pollution.

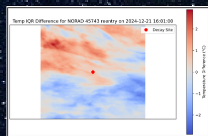


**Figure 2.1.1:** Temperature (°C) IQR Around NORAD 45743 Reentry Site in the Southern Pacific Ocean (Before and 72h After Reentry).

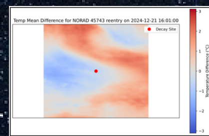


**Figure 2.1.2:** Mean Temperature (°C) Difference Around NORAD 45743 Reentry Site in the Southern Pacific Ocean (Before and 72h After Reentry).

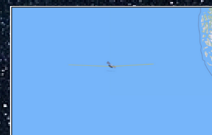

**Figure 2.1.3:** Tracked Reentry Path of NORAD 45743 in the Southern Pacific Ocean