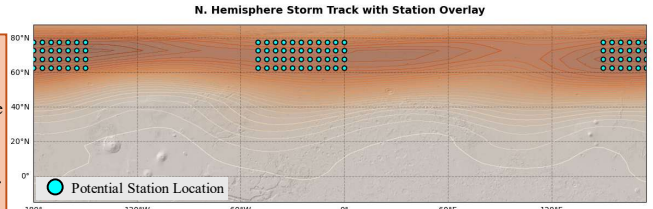
Martian Global Dust Storms: Optimization Study of Climate Stations for Martian Planetary Waves

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Abstract

- Current ground-based climate observational instruments do not have the ability to characterize atmospheric phenomena.
- Set MACDA V2.0 Global Climate Model as the baseline "truth", then use a Monte Carlo down-sampling method to simulate potential ground station networks.
- Generate a global root mean square error (RMSE) as a function of station counts.
- **Preliminary analysis reveals that a 26-station network optimizes the trade off between station count and global error reduction.**



Northern Hemisphere Storm Track: Standard deviation of surface pressure anomalies highlighting peak planetary wave activity. Cyan markers indicate the maximum 96 potential station locations deployed during the Monte Carlo down-sampling simulations

Results

- **Preliminary Network Configuration:** Based on surface pressure anomalies, ***a network of 26 stations is the optimal configuration*** for resolving 2-15 sol period transient planetary waves.
- **Signal Preservation:** 1D and 2D spectral analyses confirm that core planetary wave integrity is preserved for this reduced station count.
- **Next Steps:** Subsequent analysis will assimilate additional atmospheric variables and incorporate Martian topography to refine these network optimization models across terrain.

Motivation

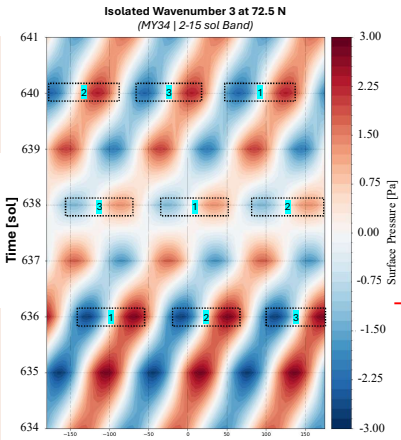
- Global dust storms severely threaten the operational viability of robotic and future crewed missions. [1]
- Fine particulates (1 μm) in the lower atmosphere degrade solar arrays [1, 2] and compromise habitation infrastructure.
- There is a lack of ground-based instruments for accurately measuring the Martian atmosphere.

Terminology

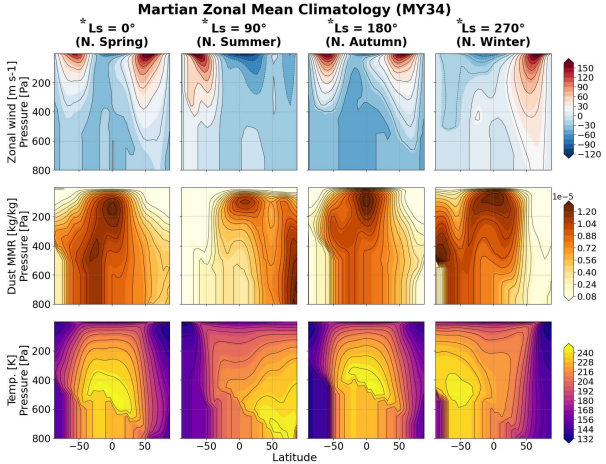
- **Planetary Waves:** Large scale, planet-spanning atmospheric oscillations (pressure, temperature, wind) that act as the primary drivers of Martian climate variability.
- **Wavenumbers:** The number of complete wave cycles along a latitudinal band.
- **Climatology:** The "baseline" behavior of the atmosphere for a specific variable.
- **Anomaly:** Deviations from the climatology. Found by subtracting climatology from the raw data.

Methodology

1. **Baseline Climatology & Anomaly Extraction**: Derived a baseline Martian climatology spanning Mars Years (MY) 29-35, intentionally excluding the anomalous global dust storm of MY 34. Isolated surface pressure anomalies by subtracting this baseline from the raw MACDA V2.0 data.
2. **Spatiotemporal Signal Processing**: Applied a Fast Fourier Transform (FFT) to the pressure anomalies to isolate specific planetary wave signatures, filtering for temporal periods of 2-15 sols and spatial wavenumbers +/- 1, 2, and 3.
3. **Domain Constraint:** Restricted the spatial domain strictly to high northern latitudes (~60°– 80° N) to prevent southern hemisphere interpolation artifacts from skewing error margins.
4. **Monte Carlo Down-Sampling:** Executed a Monte Carlo simulation to model hypothetical ground networks. Randomly assigned station coordinates across discrete density bins (spanning from 6 to 96 stations), running five separate batch iterations per bin.
5. **Interpolation & Error Analysis:** Masked the global dataset to the simulated station locations and linearly interpolated the data. Processed the interpolated data using steps 1 & 2. Evaluated network accuracy by calculating the Root Mean Square Error (RMSE) between the down-sampled interpolation and the baseline "truth" at each station count.



Visualizing Wavenumber 3: Hovmöller diagram tracking eastward wave propagation over time. The labels (1, 2, 3) highlight the three distinct pressure ridges that make up a single wavenumber 3 structure around the planet.

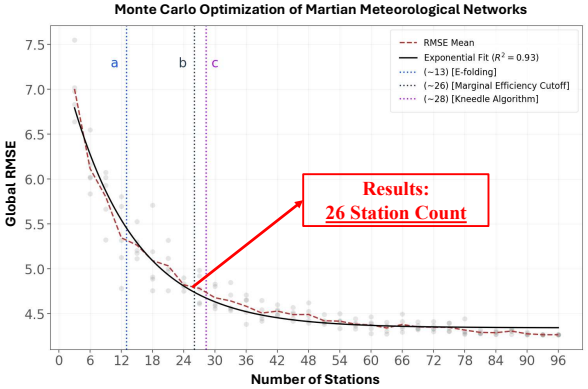


Seasonal zonal mean climatology of the Martian atmosphere (MY 34): Latitude-pressure cross-sections display the east-west (zonal) wind component (top), dust mass mixing ratio (middle), and temperature (bottom) across the four cardinal seasons. Each seasonal profile is temporally averaged over a 30° window (±15° L_s) centered at L_s 0°, 90°, 180°, and 270°.

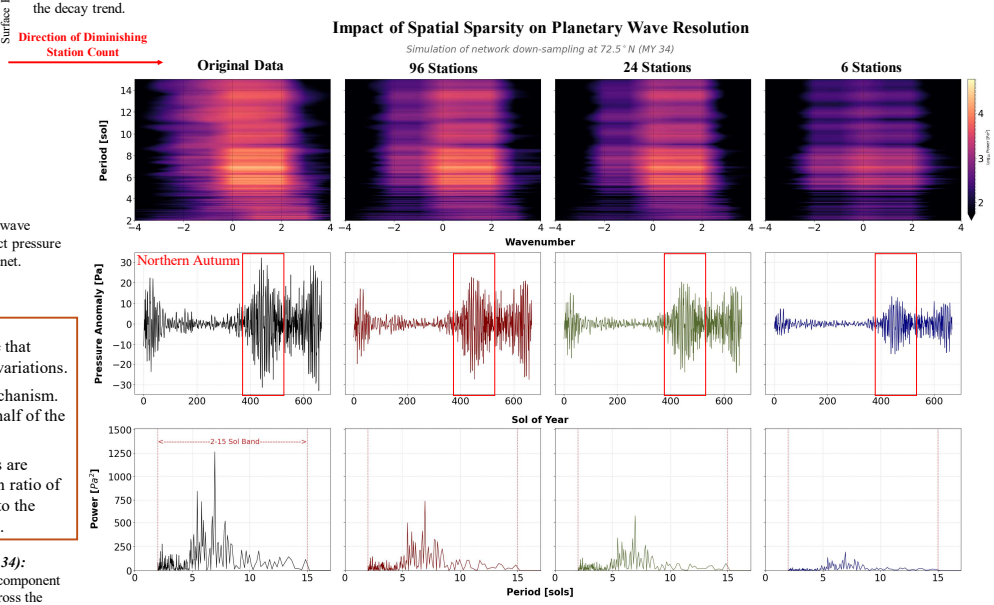
Solar Longitude (L_s): angle of current position in orbit.

The Martian Climate

- **Thin Atmosphere:** Mars possesses a thin atmosphere that undergoes extreme diurnal and seasonal temperature variations.
- **The Dust Cycle:** Dust acts as an energy transport mechanism. Martian dust storms are more prominent in the latter half of the year.
- **Seasonal Shifts:** Seasonal dust and temperature shifts are correlated, while zonal winds are anti-correlated. High ratio of dust is also present consistently over the equator due to the poleward rotating circulation in the upper atmosphere.



Triangulating Optimal Network Density: Global RMSE decay across simulated station counts. **(a)** The *e*-folding threshold, marking where the initial rapid error decay slows by a factor of *e*. **(b)** The Marginal Efficiency Cutoff representing the optimal density where adding a station improves error by <1%, but removing one degrades it by >1%. This optimal point is adjacent to **(c)** the Kneedle Algorithm [3], which mathematically identifies the point of maximum curvature (the "knee") in the decay trend.



Signal Degradation Across Station Densities: **(Row 1)** 2D Wheeler-Kiladis spectra displaying the concentration of surface pressure anomaly power. **(Row 2)** The filtered time-series signal isolating the 2 to 15-sol band (wavenumbers ±3). **(Row 3)** 1D spectral power, demonstrating how core planetary wave energy is preserved despite spatial down-sampling..

References

[1] Guzewich, S.D. et al. (2019) Mars Science Laboratory Observations of the 2018/Mars Year 34 Global Dust Storm. Geophysical Research Letters 46, 71–79. https://doi.org/10.1029/2018GL080839

[2] Guzewich, S. D. et al. (2014), *The vertical distribution of Martian aerosol particle size*, *J. Geophys. Res. Planets*, 119, 2694–2708, doi:10.1002/2014JE004704.

[3] Satopaa, V et al. (2011). Finding a "Kneedle" in a haystack: Detecting knee points in system behavior. *31st International Conference on Distributed Computing Systems Workshops*, 166–171. https://doi.org/10.1109/ICDCSW.2011.20

Acknowledgements

I would like to thank the entire research team for their invaluable guidance and support throughout this project. This research was made possible by the Research Experience for Veteran Undergraduates (REVU) program and hosted at Yale University.