Quantifying LEO Orbit Perturbations Driven by Thermospheric Density and Wind Variability

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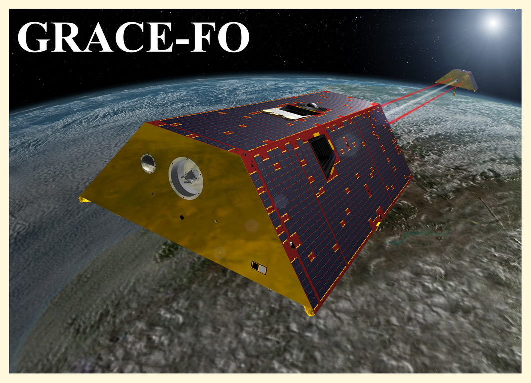
1. Scientific Question and Motivation

- Atmospheric drag is a major uncertainty source for LEO satellite orbit prediction. It depends on neutral density, winds, and satellite velocity.
- The February 2022 Starlink loss event showed the impact of storm-time drag: ~38 satellites were lost, neutral density at Starlink altitudes increased by ~20–30%, with localized enhancements exceeding 60%.
- Geomagnetic storms enhance thermospheric density and can produce stronger orbit perturbations.
- Quiet-time thermospheric tides also create structured density and wind variations along satellite trajectories.
- This study evaluates how both storm-time density enhancements and quiet-time tidal structures affect LEO orbit deviations using WACCM-X, GRACE-FO density, HWM14 winds, and a numerical orbit model.

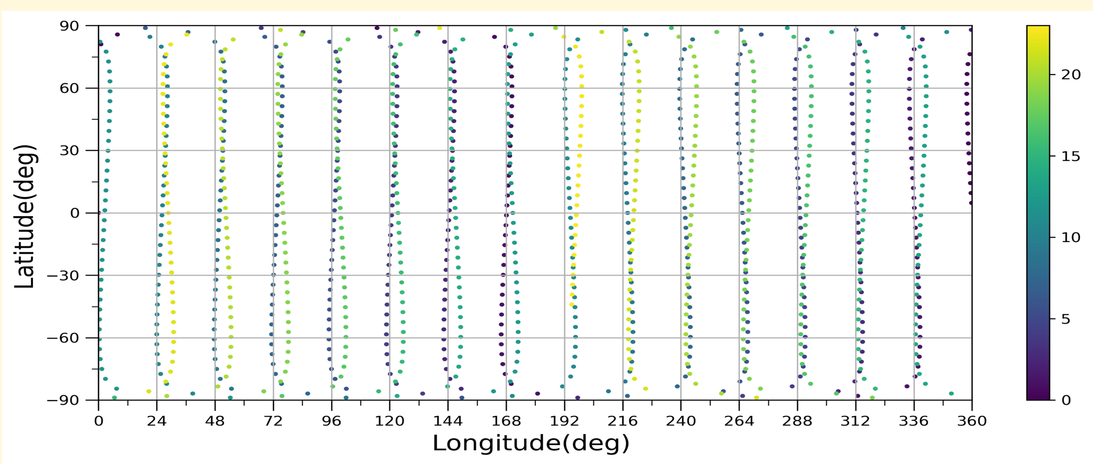
Scientific question: How do neutral density structures perturb LEO satellite orbits through atmospheric drag?

2. Data and Methodology

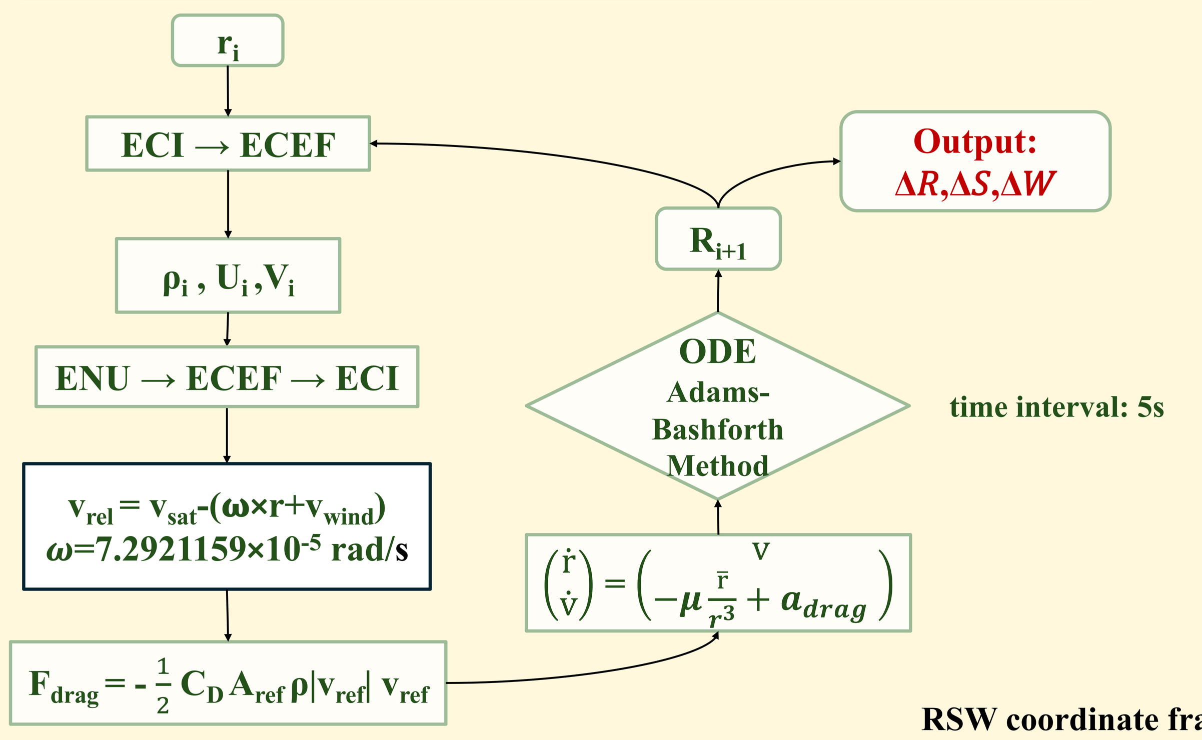


- **Thermospheric Inputs:** WACCM-X neutral density and winds, GRACE-FO density, and HWM14 winds.
- **Case design:**
  - Storm(03/17/2015 St. Patrick's Day) vs. quiet (03/10/2015) WACCM-X;
  - Quiet-time GRACE-FO cases used to examine tidal density variability;
- **Altitude:** ~220km(Starlink), ~500km (GRACE and GRACE-FO)
- **Trajectory sampling:** density and winds are interpolated along the satellite orbit.
- **Relative velocity:** satellite–atmosphere relative velocity includes satellite motion, Earth's co-rotation, and neutral winds.
- **Orbit integration:** satellite motion is integrated using two-body gravity plus atmospheric drag.
- **Comparison strategy:** use the same initial orbit to compare drag vs no-drag, quiet vs storm, and model vs observation cases.
- **Diagnostics:** orbit deviations are evaluated in the RSW frame as radial, along-track, and cross-track differences.

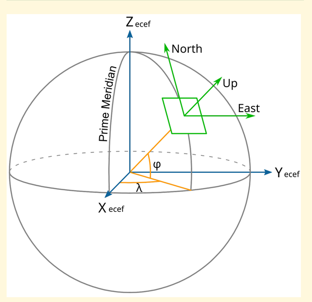
GRACE Ground Track



Orbital Model (Flow Chart)

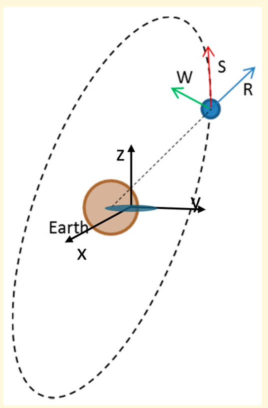


Coordinate frame



ECEF coordinate frame
- x lon=0°;
- y lon=90°;
- z north pole;

ENU coordinate frame
- x East Zonal wind;
- y North Meridional wind;
- z x×y;



RSW coordinate frame
- $R = \frac{r}{|r|}$ radial;
- $W = \frac{r \times v}{|r \times v|}$ cross-track;
- $S = \frac{v}{|v|}$ along-track;

ECI coordinate frame
not rotating
- x Vernal Equinox;
- y z×x;
- z north pole;

3. Result 1: Storm-Time Density Enhancement & Impact

Storm-time density enhancement produces much stronger along-track deviation, especially at lower altitude.

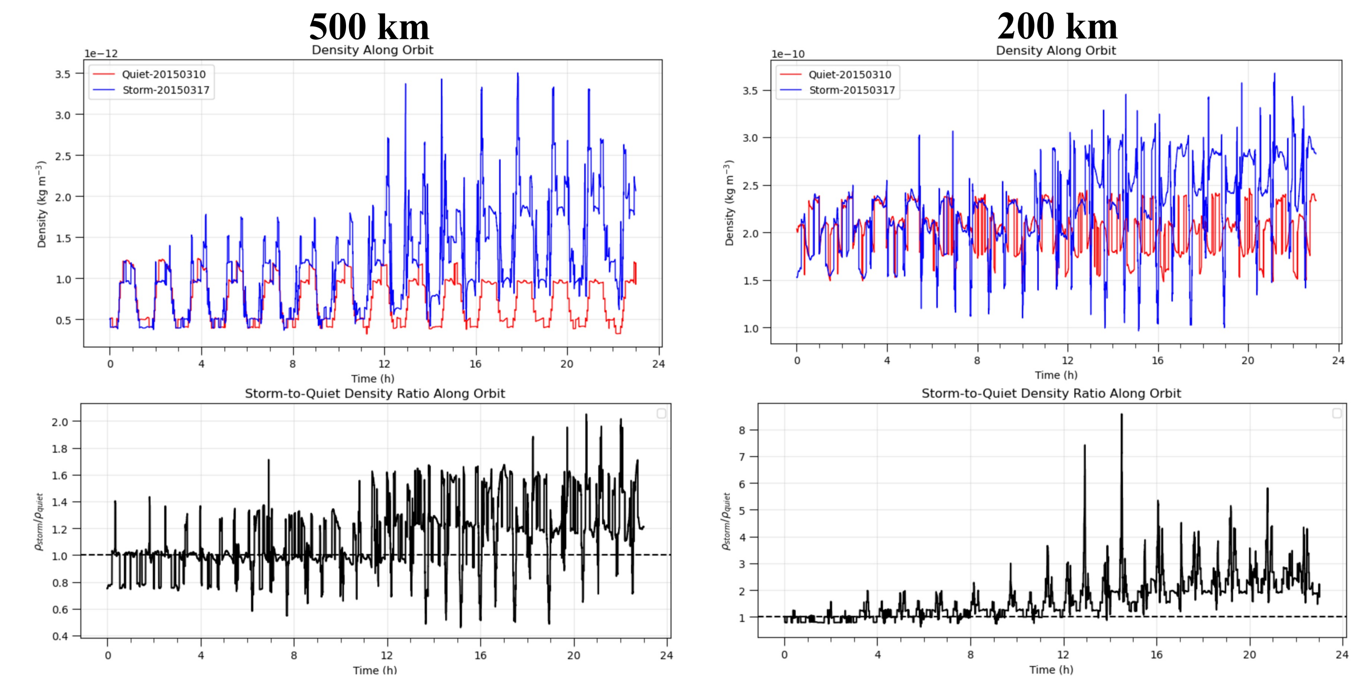


Figure 1. Density sampled along the satellite orbit under quiet and storm conditions at 500 km and 220 km altitude. The lower ones show the storm-to-quiet density ratios.

Key Points: The storm case shows stronger density enhancement and variability, especially at 500 km after 12 UT.

ΔR, ΔS, and ΔW represent radial, along-track, and cross-track deviations.

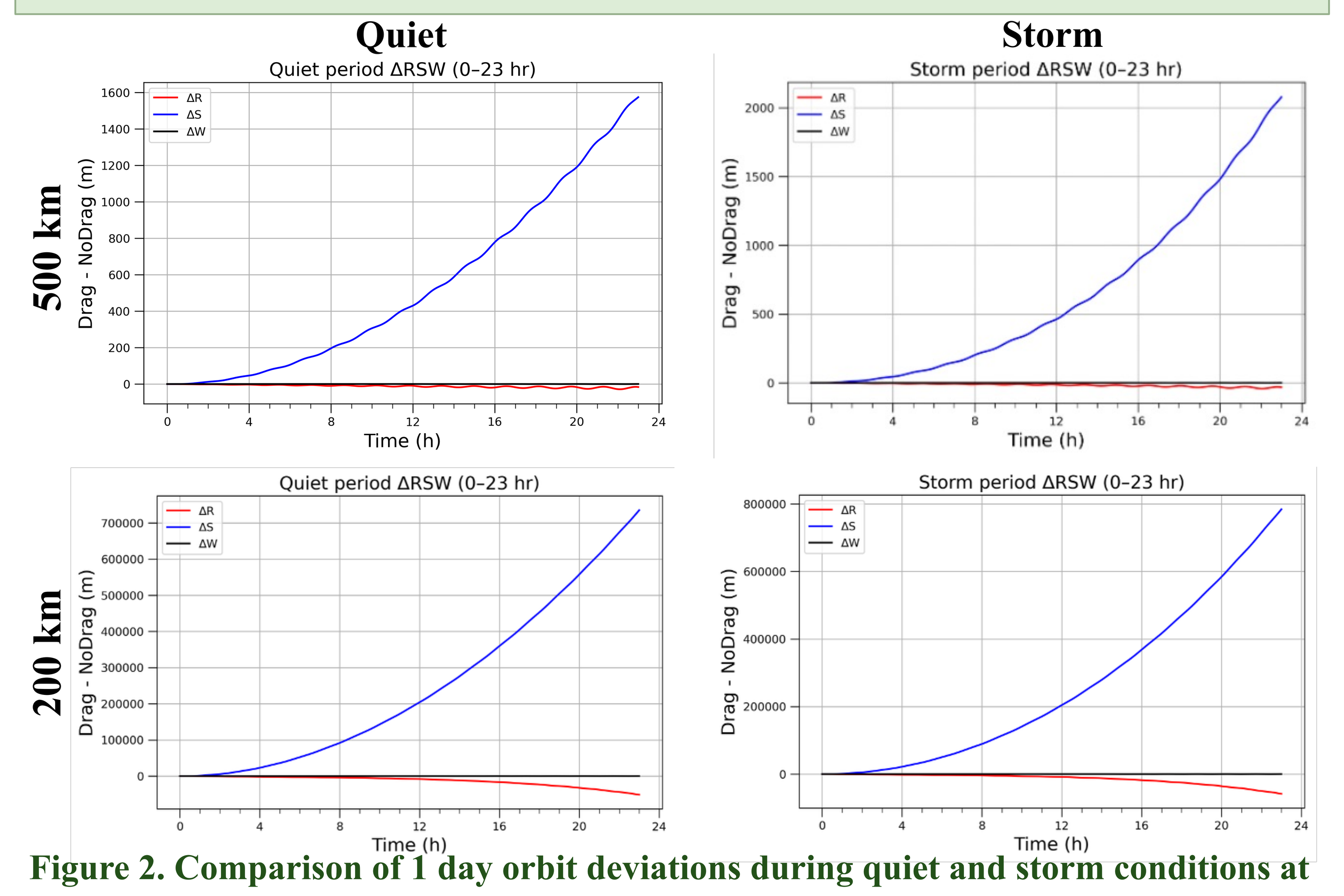


Figure 2. Comparison of 1 day orbit deviations during quiet and storm conditions at 500 km and 200 km altitude.

Storm time - quiet time

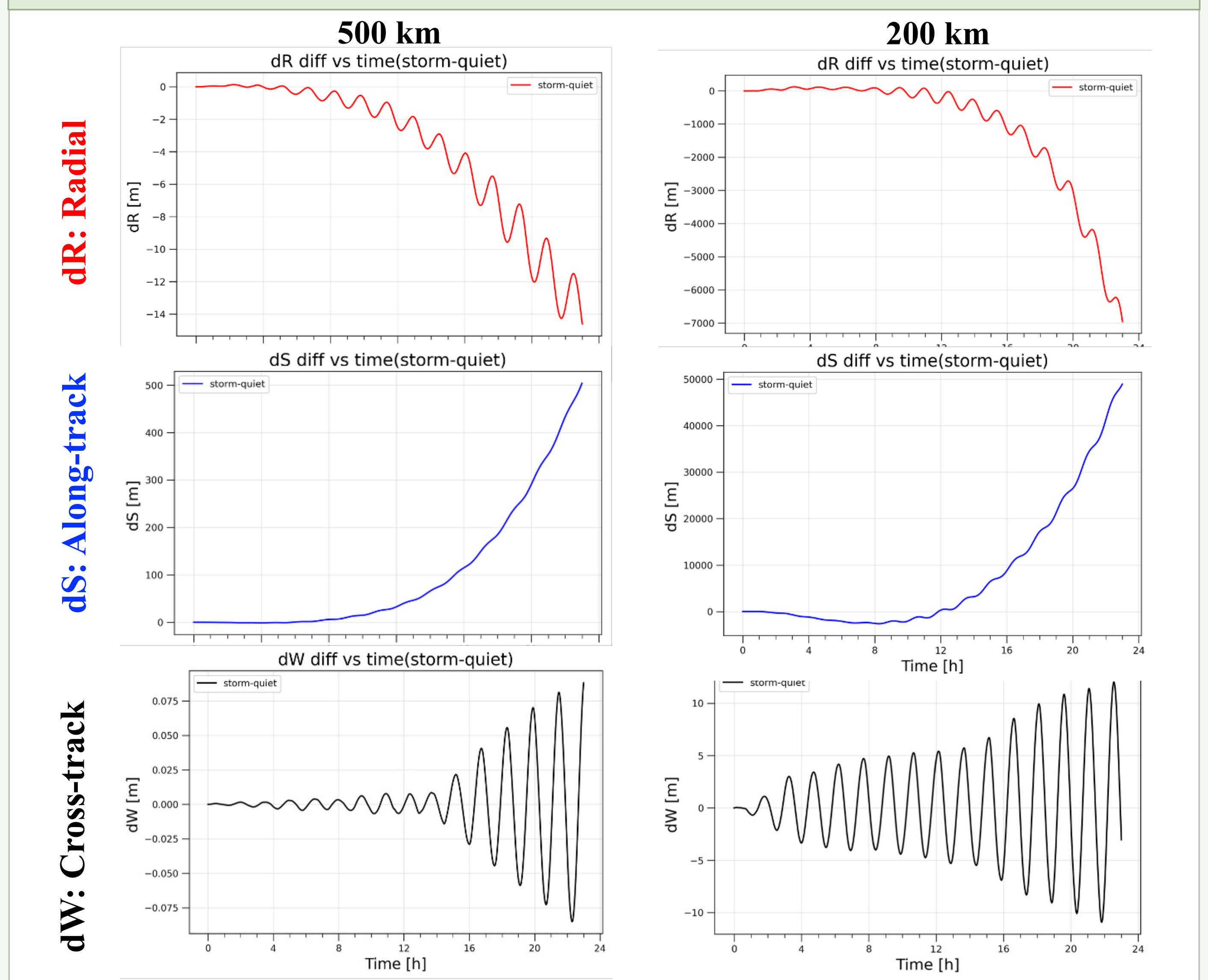
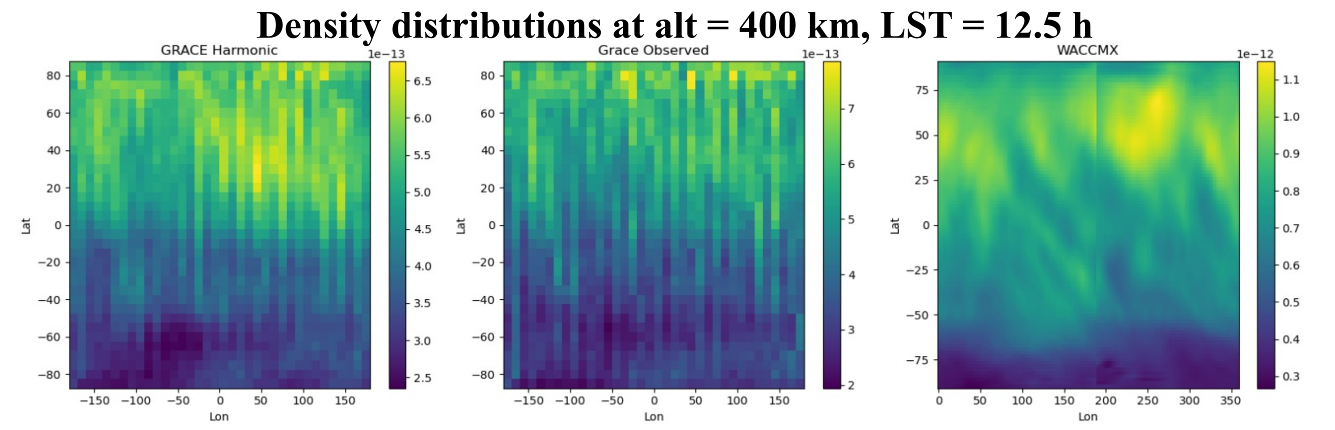


Figure 3. Difference between storm-time and quiet-time orbital deviations at 500 km and 200 km altitude.

- 500 km: about 0.5 km along-track displacement and about 15 m radial deviation in one day.
- 200 km: response reaches about 50 km along-track and about 7 km radial in one day.
- Along-track displacement dominates.

4. Result 2: Quiet-Time Tidal Impact

Quiet-time tidal density structures also produce measurable multi-day orbit effects.



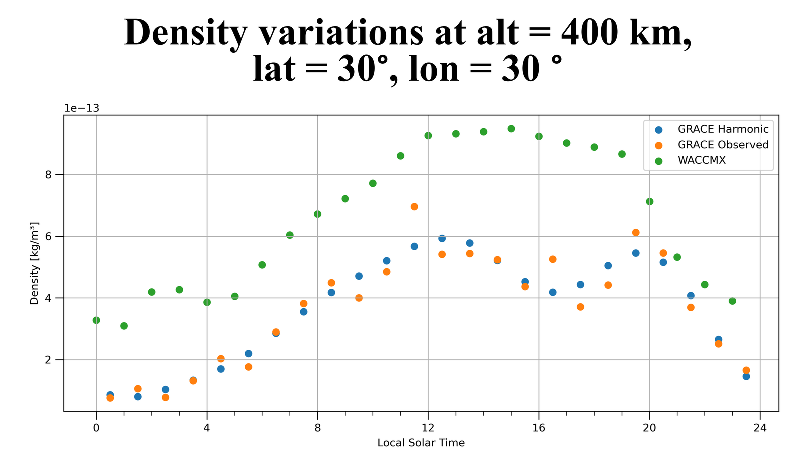
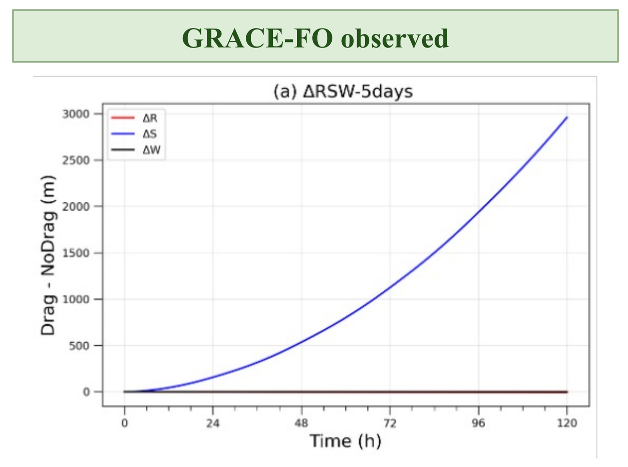
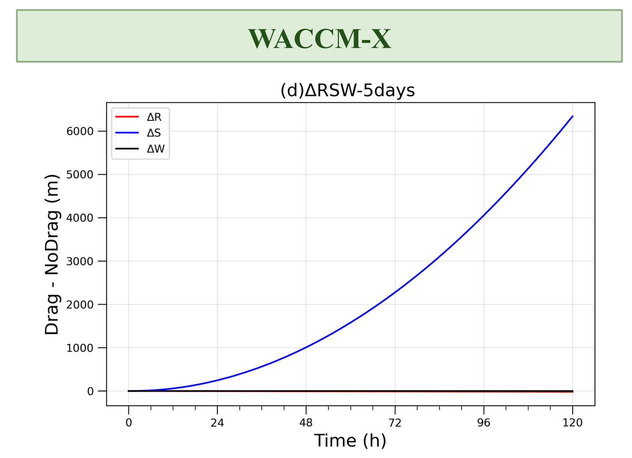
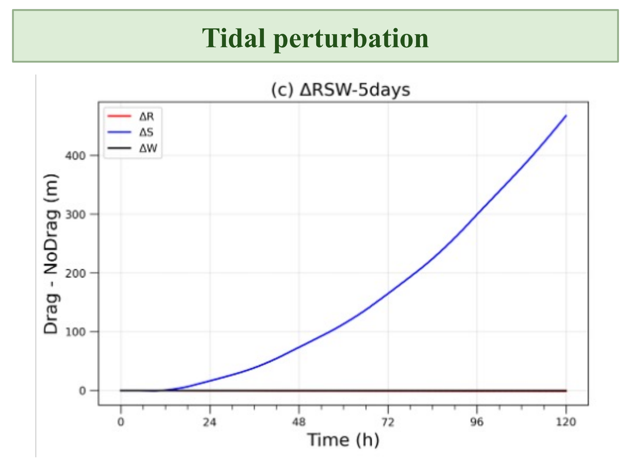


Figure 4. Comparison of neutral density from WACCM-X and GRACE-FO at 400 km on 06/01/2020.

- GRACE-FO harmonic and observed densities are nearly consistent.
- WACCM-X shows a similar spatial and local-time pattern but systematically higher density than GRACE-FO.
- All datasets show enhanced daytime density and lower nighttime/early-morning density.







Final along-track displacement

Observed 2.960 km | WACCM-X 6.337 km | Tidal 0.467 km

Final radial displacement

Observed 8.15 m | WACCM-X 21.32 m | Tidal 1.21 m

- The tidal perturbation contributes ~16% of the GRACE-FO observed along-track displacement after ~2 days.

Figure 5. Comparison of GRACE-FO orbit deviations using different neutral density inputs. The same initial orbit is integrated with density and wind inputs from(a) GRACE-FO grid-observed density, (c) tidal perturbation , and (d)WACCM-X.

5. Conclusions and Next Steps

Conclusions

Deviation \ Alt	500 km	200 km
along-track	0.5 km	50 km
radial	15 m	7 km

- Lower Earth Orbits are much more sensitive to atmosphere density variation.
- Along-track effects dominate orbital perturbations.
- Quiet-time tidal structures produce measurable accumulated effects: the tidal perturbation case reaches ~0.47 km along-track deviation, about 16% of the GRACE-FO observed case after ~2 days.

Future work

- Test higher-cadence thermosphere inputs to reduce temporal-sampling uncertainty.
- Extend simulations toward lower-altitude and reentry-relevant cases.

References

- Dang et al. (2022), Starlink satellite loss during the February 2022 geomagnetic storm.
- Leonard et al. (2012), Impact of tidal density variability on orbital and reentry predictions.
- Yue et al. (2026), Satellite Reentry Predictions During Sudden Stratospheric Warmings.

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Acknowledgements

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