Is the lower atmosphere (anywhere below LEO) significant for satellite drag and reentry?

When fundamental research meets applied science

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Inspired during a visit to Sean Bruinsma at CNES, Toulouse, France

In 2023

PART of the COSPAR ISWAT Action Team Activity: G2A Atmosphere

Initial motivation (two years ago)

CEDAR: Coupling, Energetics and Dynamics of Atmospheric Regions Program

Mesosphere and Lower Thermosphere (MLT) couples the lower atmosphere with the ionosphere-thermosphere (CEDAR objective).

NSF requires broad impact .

MLT is too high for weather, climate, ozone hole, too low for LEO and spread F, scintillation etc, except billionaire tourism.

MLT/lower atmosphere impact satellite drag/communication indirectly through wave propagation and other processes.

Strategic Goal 2 — Discover

Create new knowledge about our universe, our world and ourselves.

This goal furthers the first part of NSF's mission, "to promote the progress of science," pursuing the generation of new knowledge so the nation remains a global leader in expanding discovery in science, engineering and learning. By generating new knowledge, NSF-funded researchers provide the nation with the capability to maintain scientific, technological and economic leadership in a competitive world.

Fundamental research is a capital investment for the nation. Basic research leads to new knowledge. It provides scientific capital. It creates the fund from which the practical applications of knowledge must be drawn. New products and new processes do not appear full-grown. They are founded on new principles and new conceptions, which in turn are painstakingly developed by research in the purest realms of science.

NSF 2022-2026 Strategic Plan

Motivations

- Urgent need to understand and predict thermosphere mass density/satellite drag at LEO, collision avoidance
- Not all space objects burn out during reentry
- Satellite reentries around 120 km (ERS-2 as example), the MLT region
- To identify more direct applications for the mesosphere and lower thermosphere researches

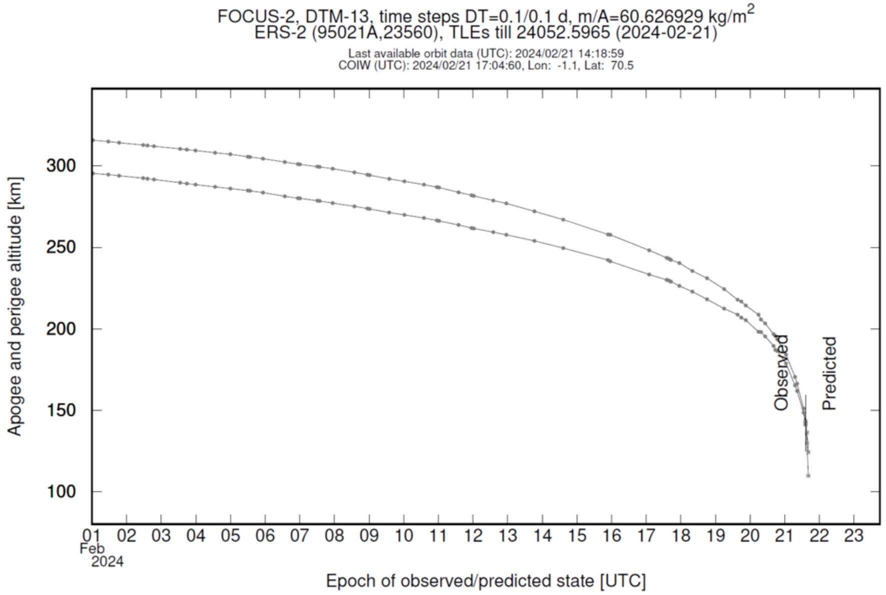
No damage reported after 5,000-pound satellite fell to Earth Wednesday

By Ashley Strickland, CNN
3 minute read · Updated 10:26 AM EST, Thu February 22, 2024
21 comments

CNN World WatchListenLive TV

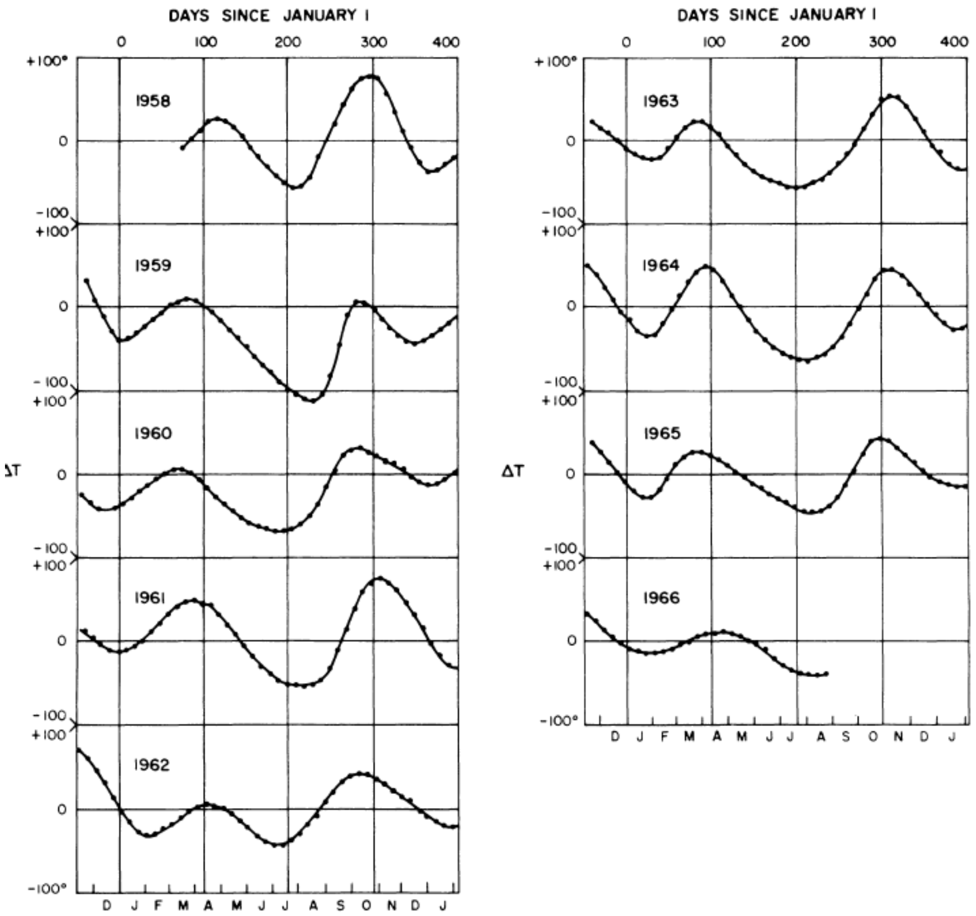
An illustration showing the ERS-2 ESA

ESA ERS-2 Reentry epoch



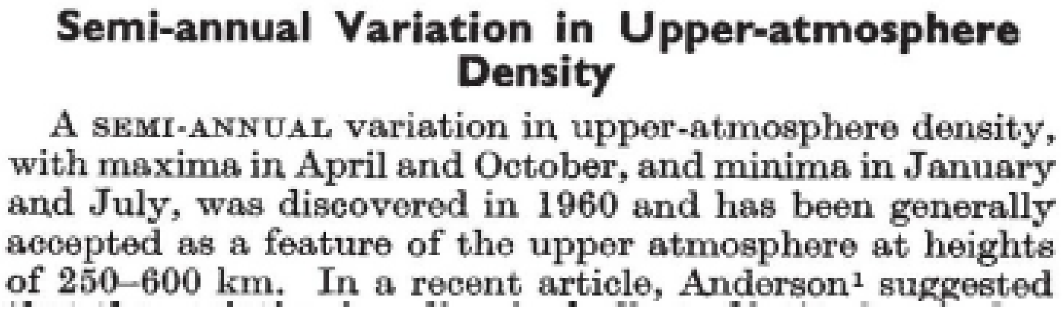
Is the lower atmosphere significant for satellite drag and reentry?

- Indirectly important for Seasonal Variation of neutral density



Jacchia, Slowey, Campbell, 1968

Sputnik 1, 1957



Semi-annual Variation in Upper-atmosphere Density

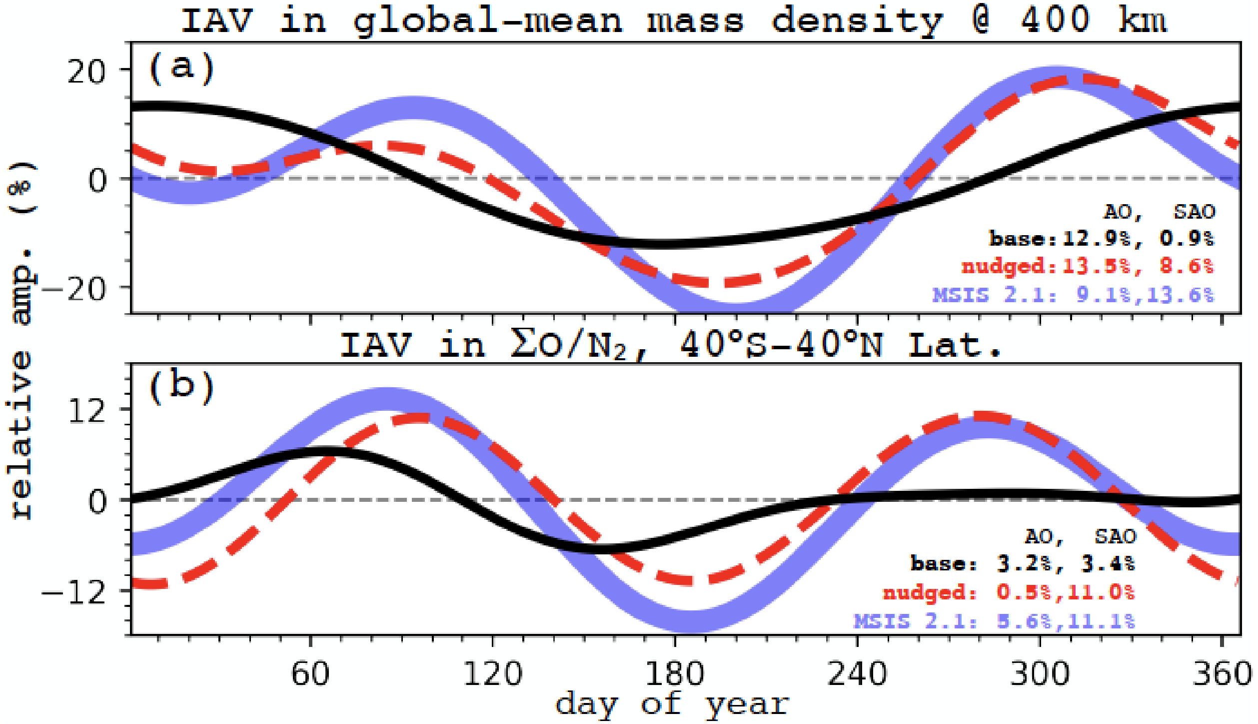
A SEMI-ANNUAL variation in upper-atmosphere density, with maxima in April and October, and minima in January and July, was discovered in 1960 and has been generally accepted as a feature of the upper atmosphere at heights of 250–600 km. In a recent article, Anderson[1] suggested

King-Hele, 1966, Nature

NRLMSIS 2.1 based on observations

TIE-GCM base run: no lower atmosphere information at lower boundary of 98 km

TIE-GCM v3 nudged by WACCM-X, the lower thermosphere controls O abundance for the thermosphere/ionosphere, including gravity waves, tides, planetary waves that are excited by "terrestrial weather" and other processes



Wang et al., 2025, GRL

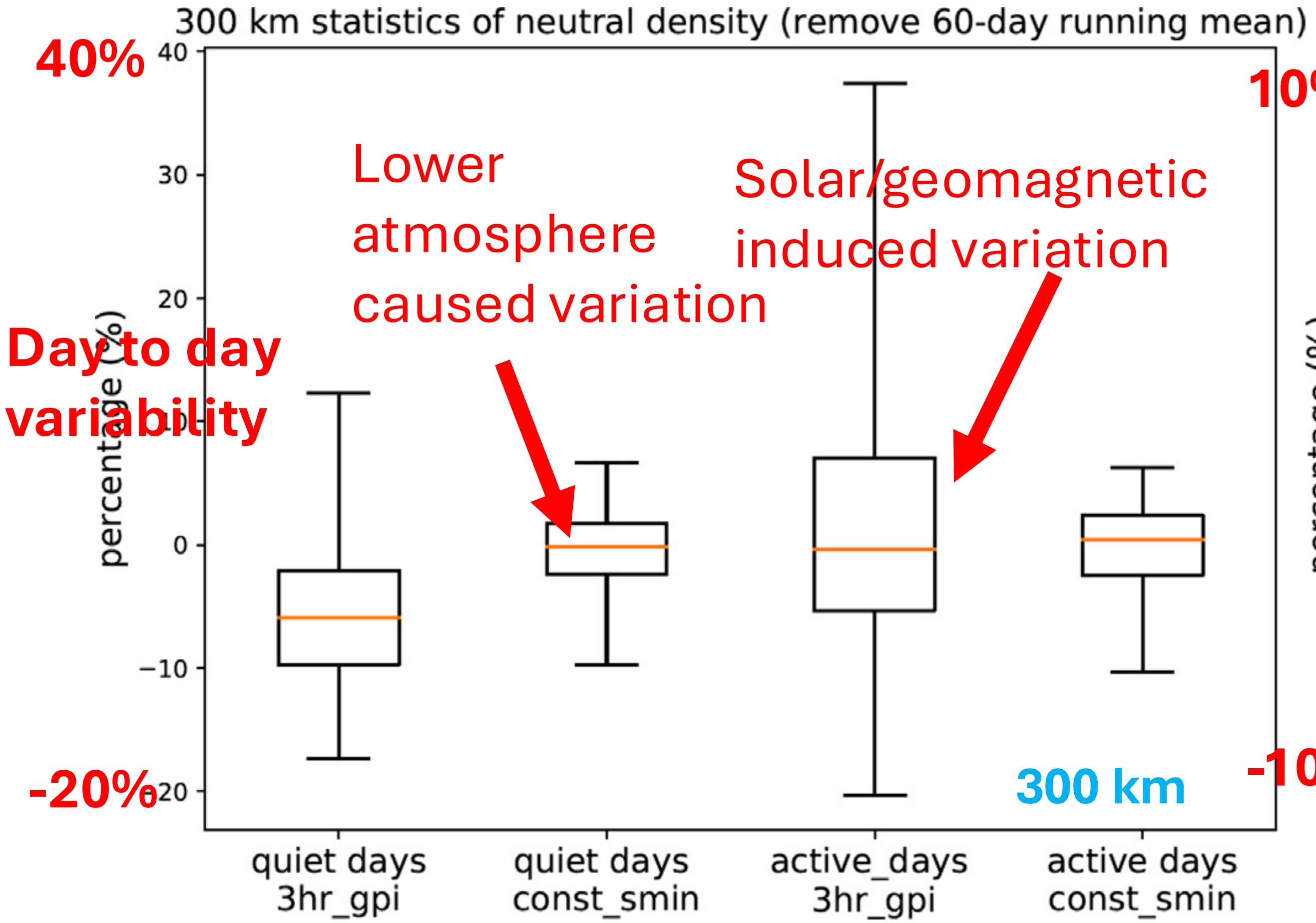
Is the lower atmosphere significant for satellite drag and reentry?

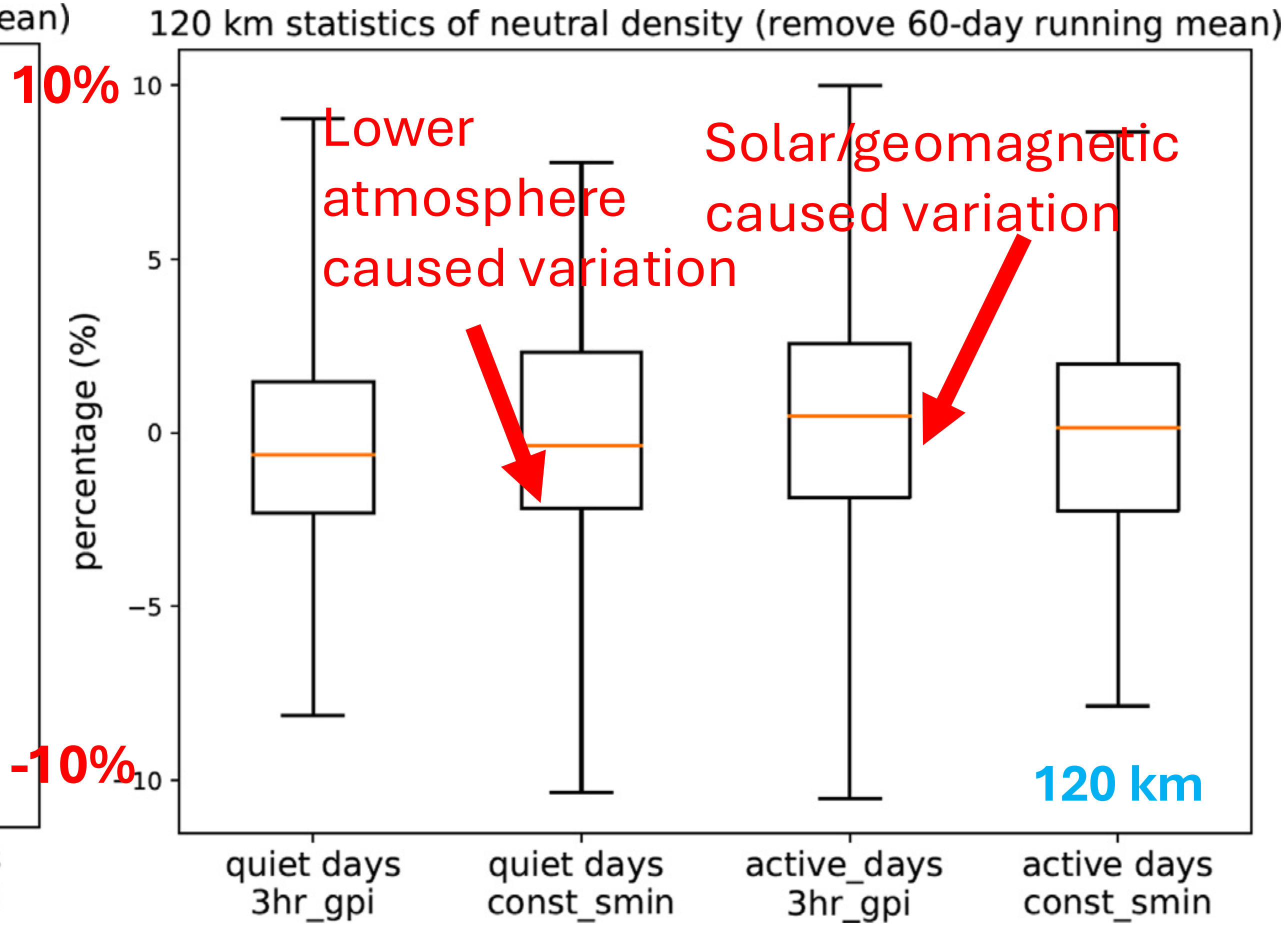
Yes and No for day-to-day variability, depending on altitude, solar cycle, etc.

Numerical experiment (control runs with no variability caused by solar or geomagnetic activities)

- WACCM-X runs during solar minimum with and without varying F10.7 and Kp
- WACCM-X runs by Nick Pedatella: ensemble of 40 Northern Hemisphere Winters by introducing random perturbations to the model temperature fields at the start
- Constant solar flux: 70 SFU, geomagnetic activities: 0+
- MSIS00: F10.7=70, ap= 1
- Sean Bruinsma ran reentry POD (Precise Orbit Determination) program from 200 km to 120 km
- Semi-major axis= 6500 km eccentricity= 0.001 inclination = 89
- Polar orbiting
- Forces in calculation: gravity field, 3d body (Sun, Moon), ocean and solid earth tides, satellite drag

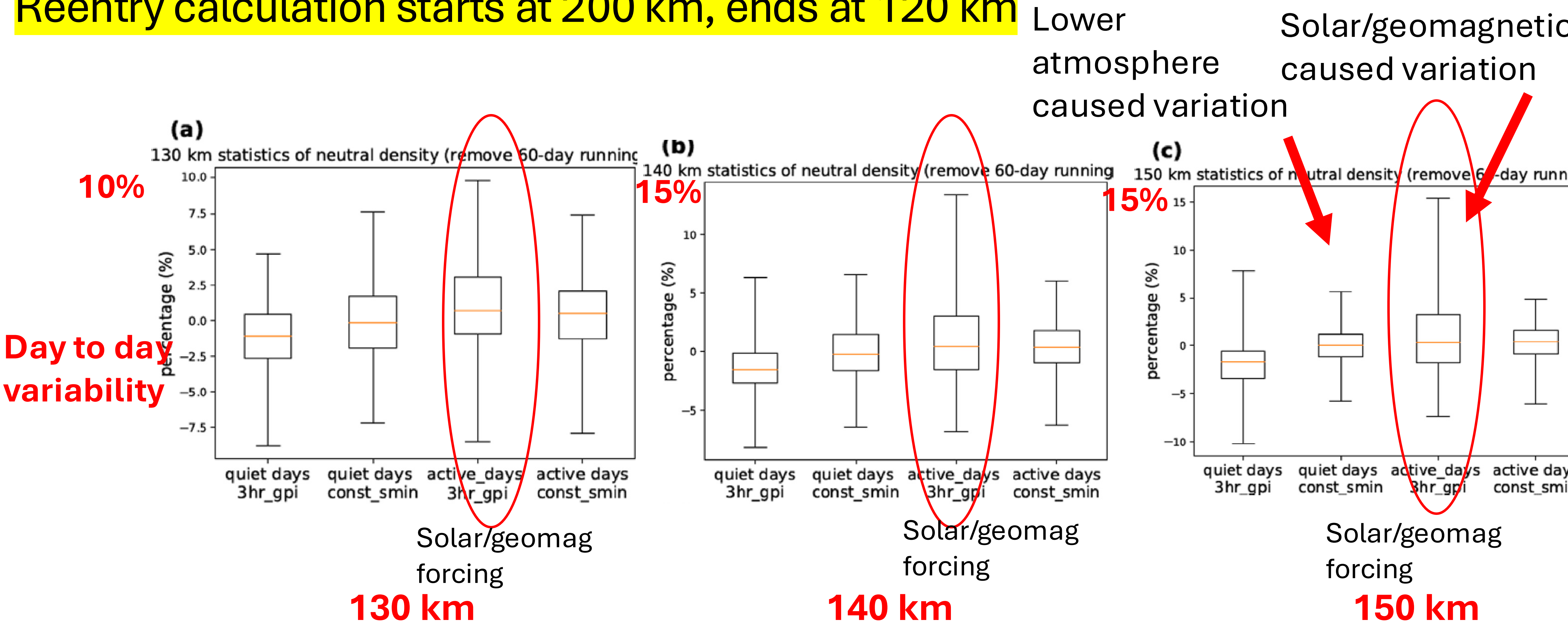
Yue et al. (2022) shows variability of global mean mass density (satellite drag) in WACCM-X is controlled mainly by solar EUV (F10.7) and geomagnetic forcing above 150 km and the lower atmosphere forcing below 120 km during solar minimum.



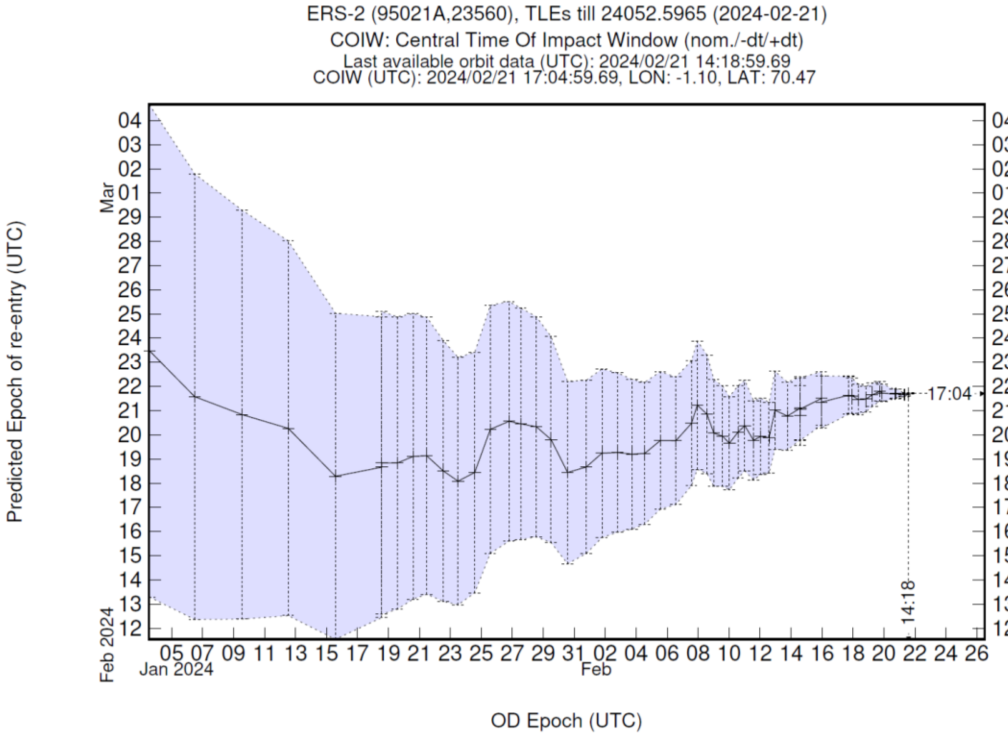


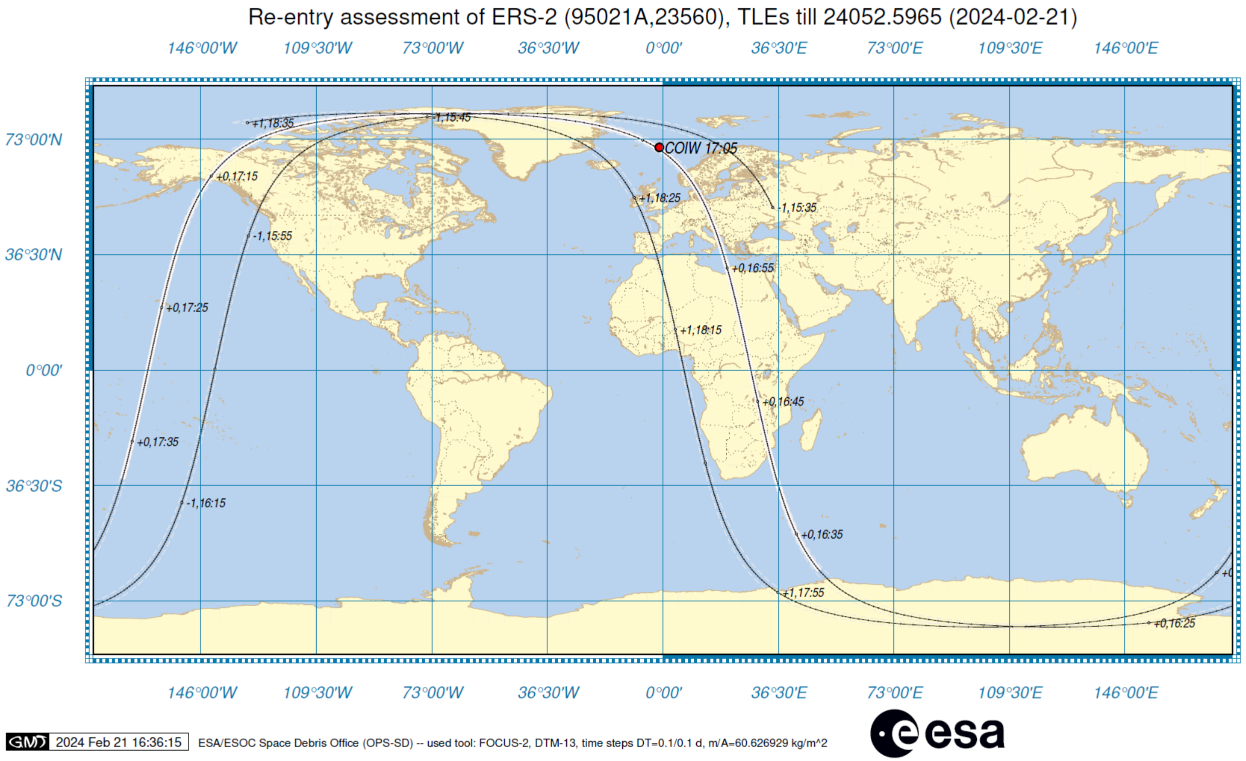
120 km to 150 km is the transition region from lower atmosphere dominant to solar/geomagnetic forcing controlled

Reentry calculation starts at 200 km, ends at 120 km



- Reentry uncertainty is largely the result of how difficult it is to forecast the density of the air through which the satellite is passing. Atmospheric density determines the strength of the drag that causes ERS-2's orbit to decay, but our ability to predict it is limited by how well we can model our very complex atmosphere and by current space weather conditions. (ESA Space Debris Office). How well can we predict F10.7 and Kp for next month?



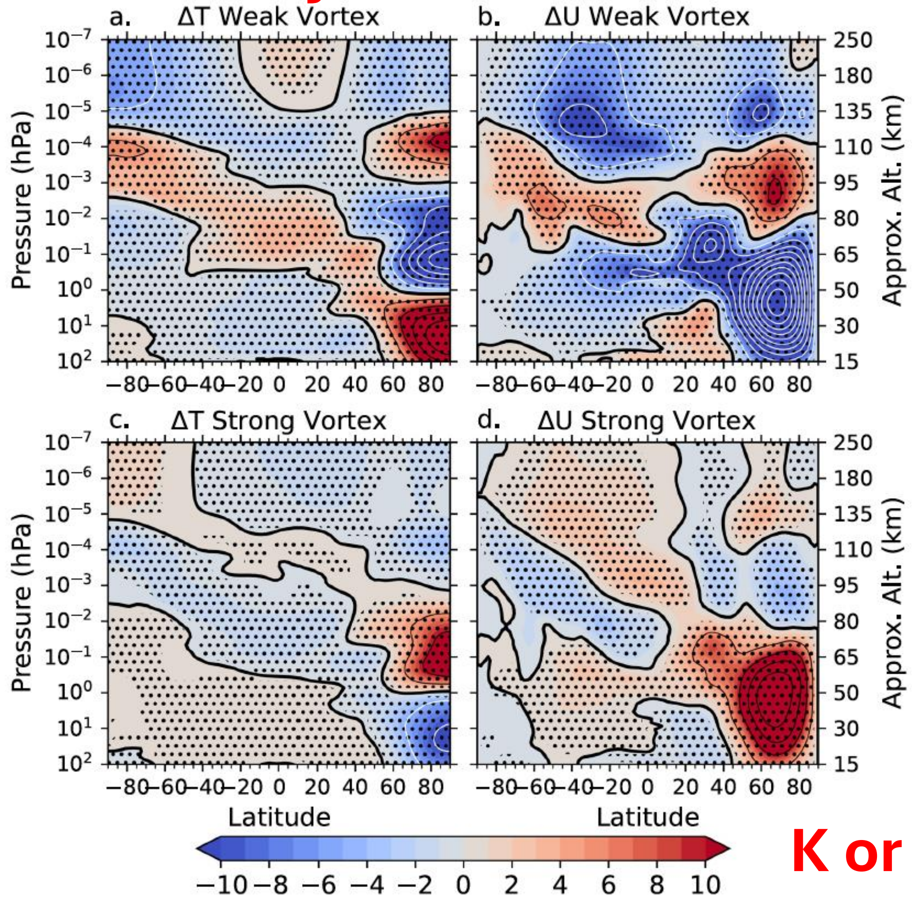


Sudden Stratospheric Warming (SSW) is one of the strongest lower atmosphere perturbations to cause day-to-day variability in the mesosphere, ionosphere and thermosphere (Pedatella, 2023)

Temperature anomaly **Zonal wind anomaly**

SSW

Opposite of SSW

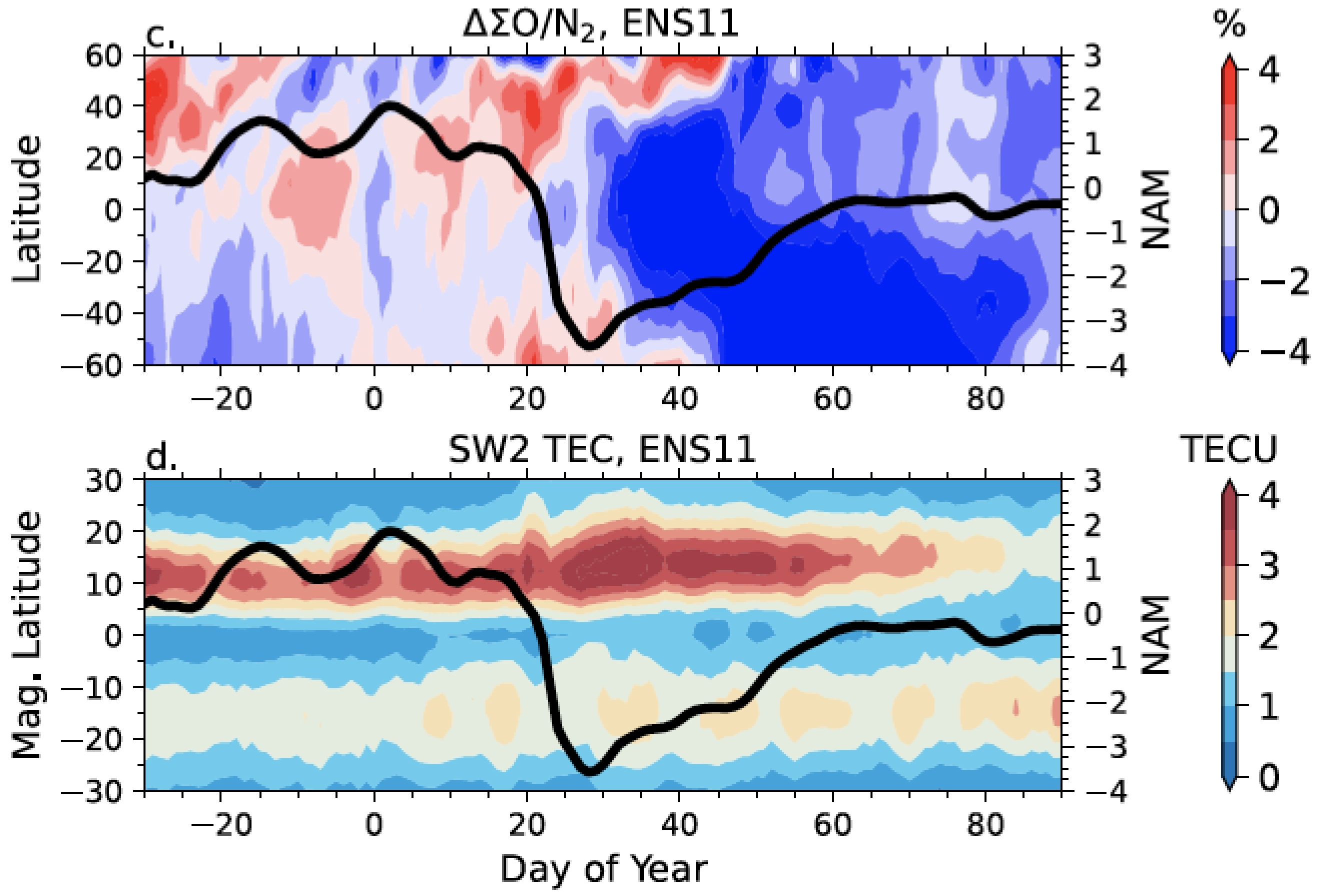


K or m/s

Changes in temperature (and density)

Naturally or naively we speculated if SSW could impact satellite reentry time by changing the thermosphere density

(Pedatella, 2023)



NAM: Northern Annular Mode

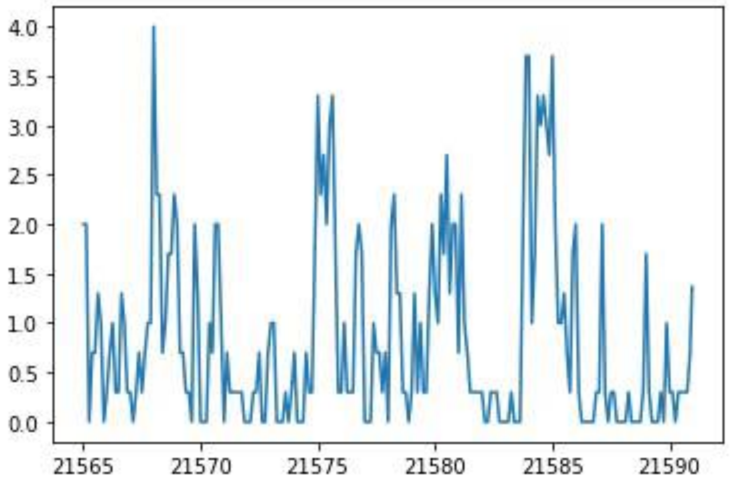
Ensemble SSW WACCM-X runs comparing to MSIS00 (no variability caused by the lower atmosphere)

- Ensemble #6: strongest polar vortex (opposite to SSW)
- Ensemble #11:strong SSW, starting Jan 28+3
- Ensemble #18: neutral conditions
- Density Scaled ~0.7 to NRLMSIS00
- Lower atmosphere forcing causes 1-2 hours or 1-2 orbit uncertainty in reentry time or 2%

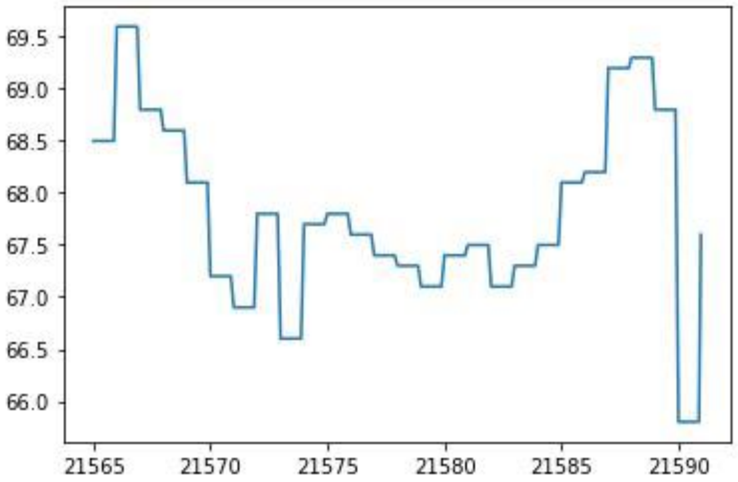
Model (ensemble number)	Reentry time from 200 km (in days)
MSIS00	5.3
WACCM #6	5.053
WACCM #11 SSW	4.993
WACCM #18	5.145

Realistic SD-WACCMX-DART SSW run in Jan 2009 with F10.7 and Kp
comparing to MSIS00
Geomagnetic quiet time and solar minimum
References: Pedatella et al., 2018; Harvey et al., 2022

Kp



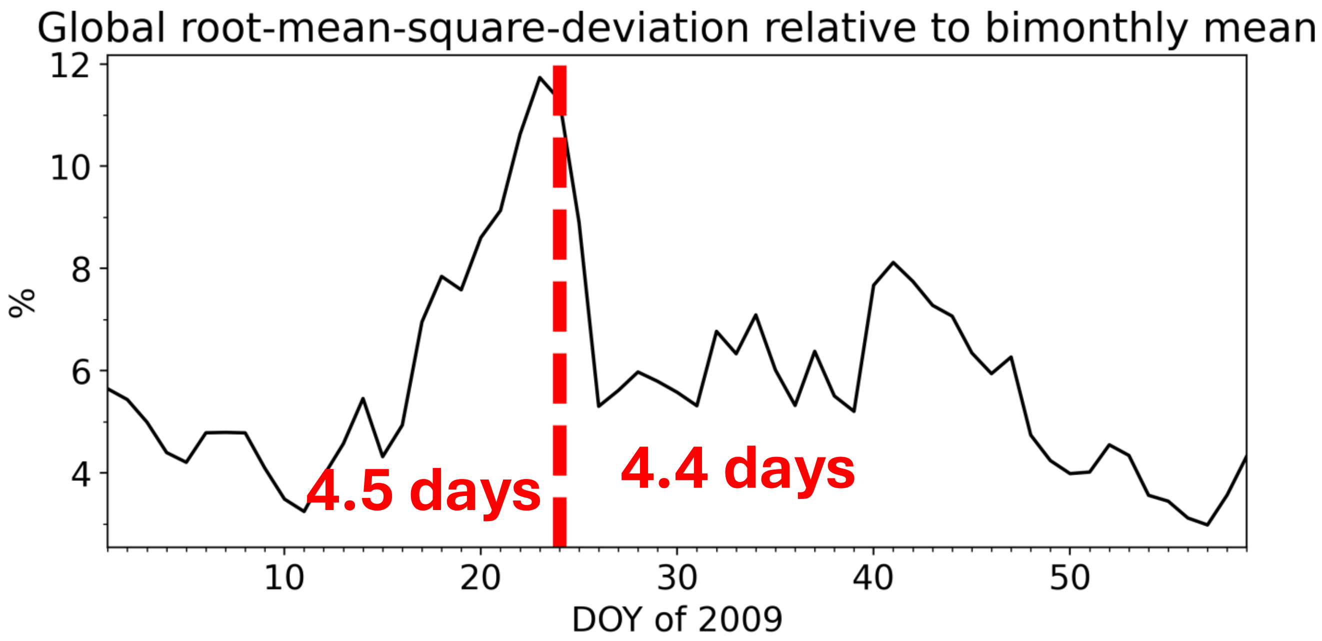
F10.7



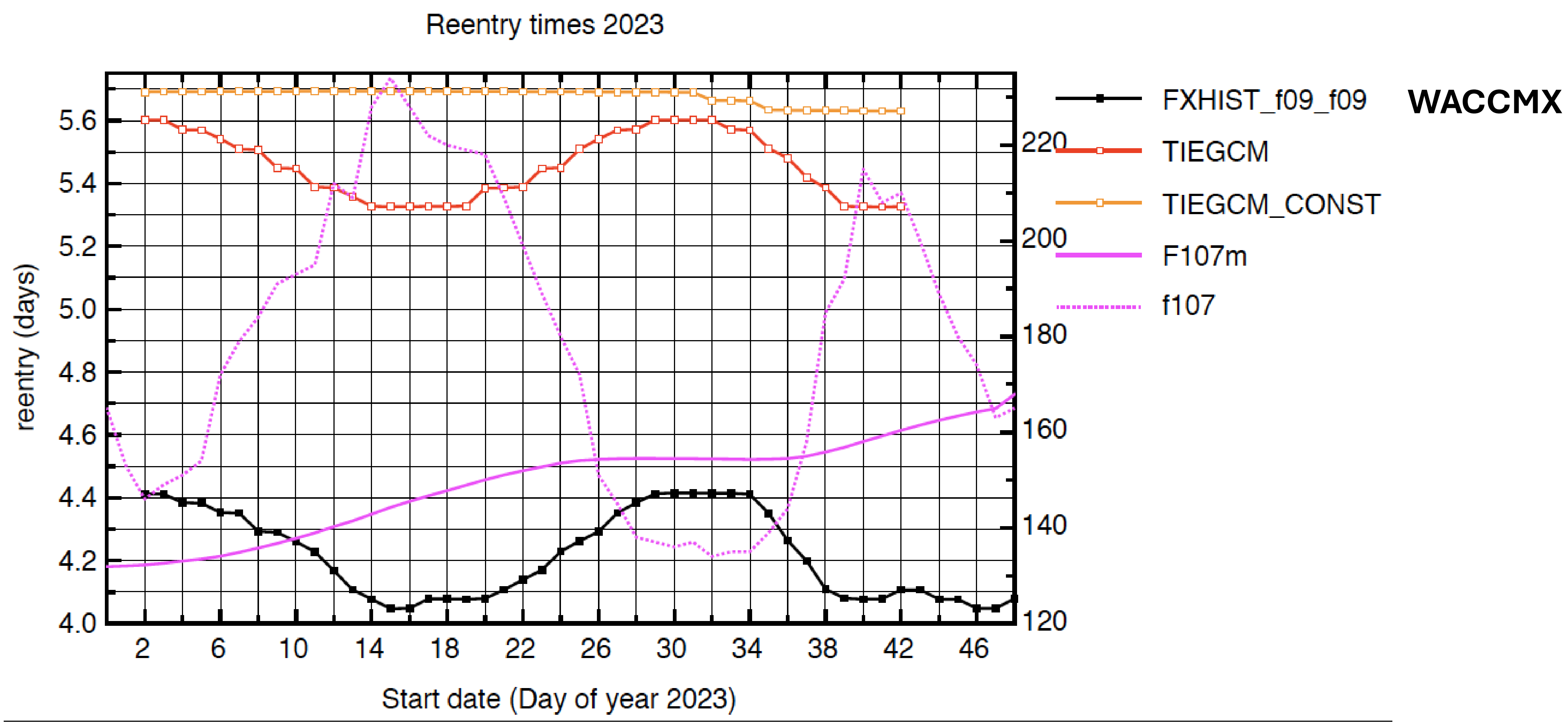
2009/1/16

Reentry time from SD-WACCMX-DART reduced from 4.5 days to 4.4 days during the onset of SSW while MSIS00 shows no change

Global mean density anomaly from monthly mean at 120 km

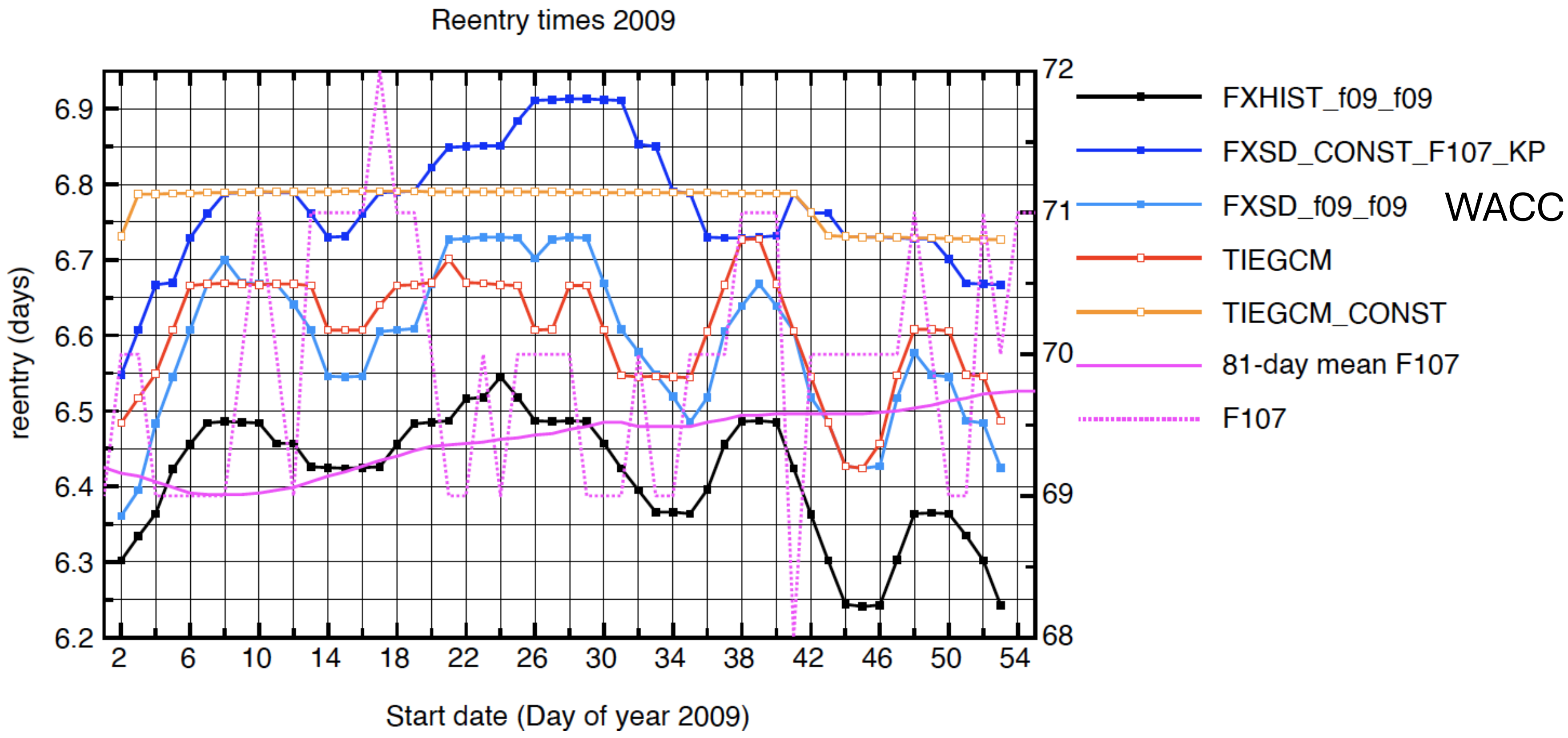


During Solar maximum year, reentry time is well correlated with F10.7 27 oscillation, larger solar heating = higher density = shorter reentry time
Discrepancy between models are larger than drivers



During Solar minimum and geomagnetic quiet time, reentry time variation driven by the lower atmosphere forcing is comparable to solar/geomagnetic drivers

Model discrepancies are large



WACCM-X with no solar/mag

WACCM-X with solar/mag

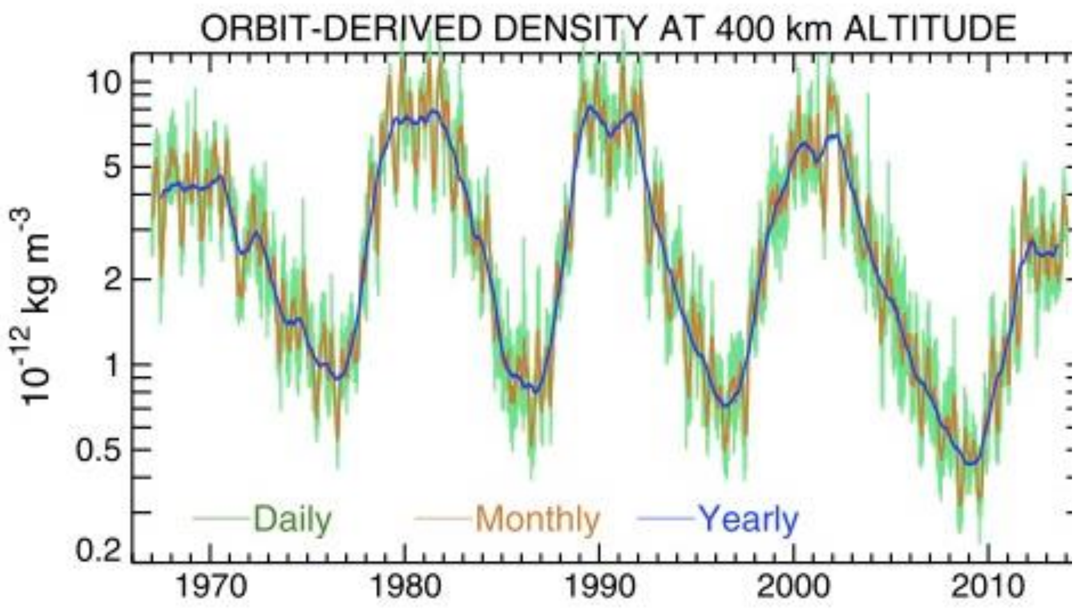
Conclusions

- This study was a result of collaboration between MLT dynamics and geodesy
- Lower atmosphere is driving the seasonal changes (AO, SAO) of thermosphere density and satellite drag in addition to solar EUV.
- 120-150 km is the transition region from the lower atmosphere dynamically controlled MLT to solar EUV/magnetosphere controlled VLEO
- SSW causes 1-2 hours or 1-2 orbit uncertainty in reentry time or 2% of total time from 200 km altitude
- 2009 SSW caused reentry time uncertainty is comparable to solar and geomagnetic drivers during solar minimum (half of satellite lifetimes)
- During solar maximum, solar radiation is well correlated with reentry time
- Reentry time differences due to model discrepancies are larger than the drivers

Thank you and Questions?

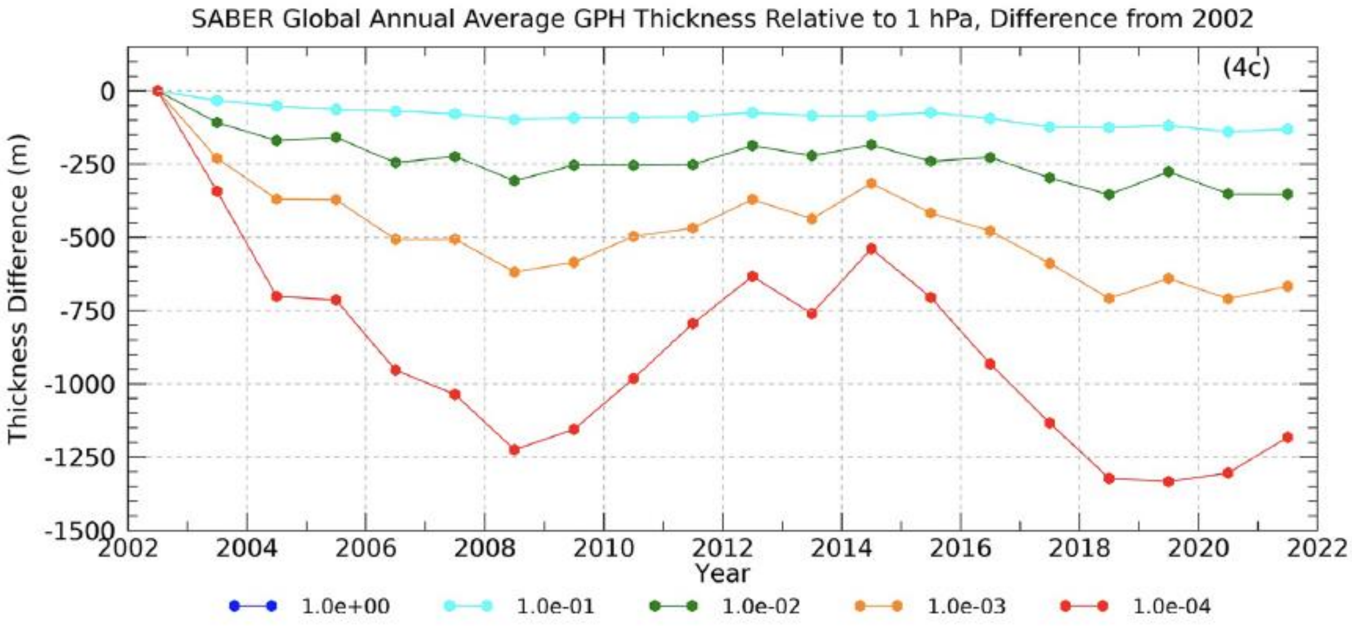
Is the lower atmosphere significant for satellite drag and reentry?

- Yes indirectly, decadal orbit changes due to anthropogenic CO_2 cooling



400 km density, Emmert, 2015

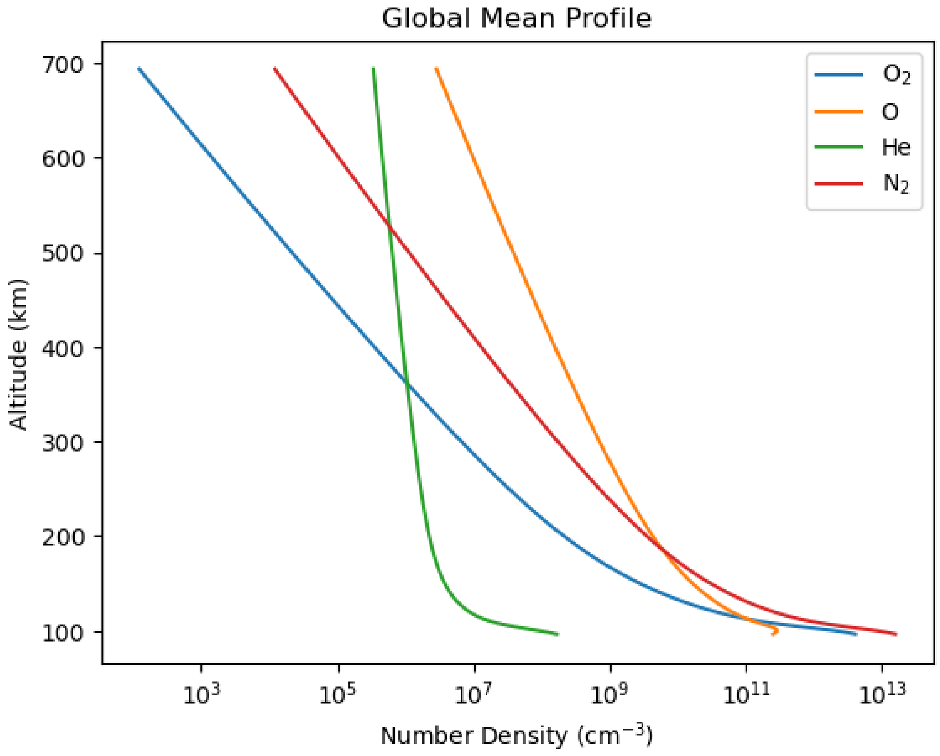
Thickness of the atmosphere



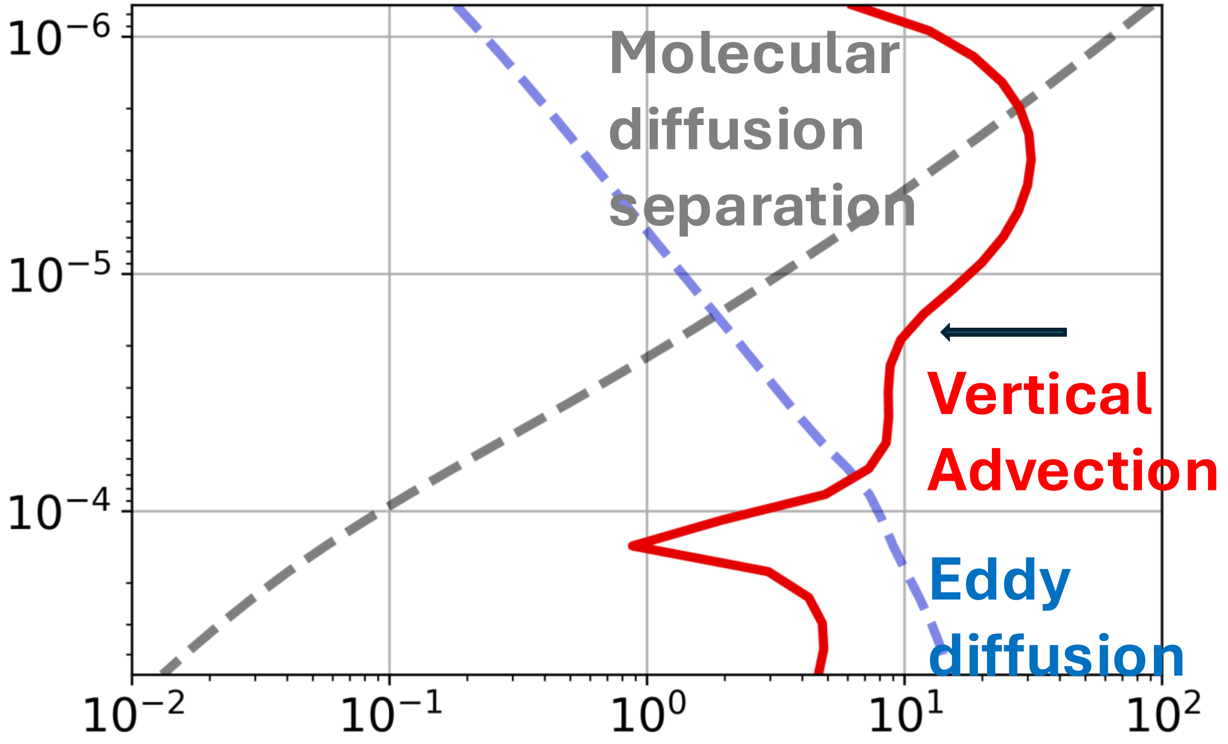
Mlynczak et al., 2022

Is the lower atmosphere significant for satellite drag and reentry?

- Yes, Even seasonal variations of neutral density is largely controlled by lower atmosphere forcing, in addition to imbalanced EUV heating, pressure gradient, magnetosphere energy input, etc.



"Valve" of thermosphere O and ionosphere O+



Dynamics in the MLT determines how much O is "available" for the thermosphere and ionosphere

Wang et al., 2022