Projected long-term decline in upper atmosphere density and its impacts on the space debris environment

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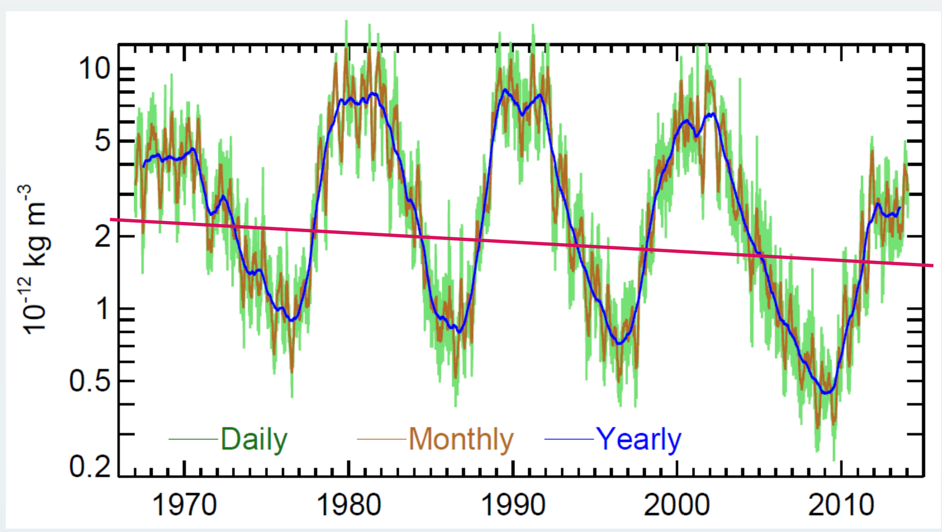
Abstract

Over the past ~50-60 years, a decline in the density of the upper atmosphere has been observed of about 2% per decade at 400 km altitude. This is largely attributed to the increase in atmospheric CO_2 concentration, which causes cooling and contraction across the stratosphere, mesosphere, and thermosphere. The reduction in thermosphere density reduces drag on active satellites and space debris, affecting orbital characteristics and increasing debris lifetimes. To manage the risk of the growing space debris population, predictions of the future climate of the thermosphere are needed. A long transient simulation with the Whole Atmosphere Community Climate Model eXtension (WACCM-X) 2.0 was carried out to provide the first realistic projection of thermosphere density up to 2070. The simulation included all known drivers of long-term change and variation, following Shared Socio-economic Pathway 2–4.5, a moderate emission scenario. Realistic assumptions on main magnetic field changes and variations in solar activity, which also affect the climate of the upper atmosphere, were also included. The predicted global mean cooling in the thermosphere and associated decline in thermosphere density for 2015–2070 is stronger than for the past, due to the more rapid increase in CO_2 concentration. The Realisations of the Engineered and Natural Evolution of the Global Atmosphere and Debris Environment (RENEGADE) model was used to assess the effects of the projected thermosphere density trend on the evolution of the space debris population. Preliminary results suggest that the cumulative number of catastrophic collisions by 2070 is significantly higher due to the expected decline in thermosphere density.

1. Introduction

- Increased greenhouse gas levels cause long-term cooling above the tropopause
- Thermal contraction leads to a decrease in thermosphere mass density at fixed height
- Reduced atmospheric drag increases space debris lifetime

Observed density at 400 km altitude



Emmert (2015)

2. Models used

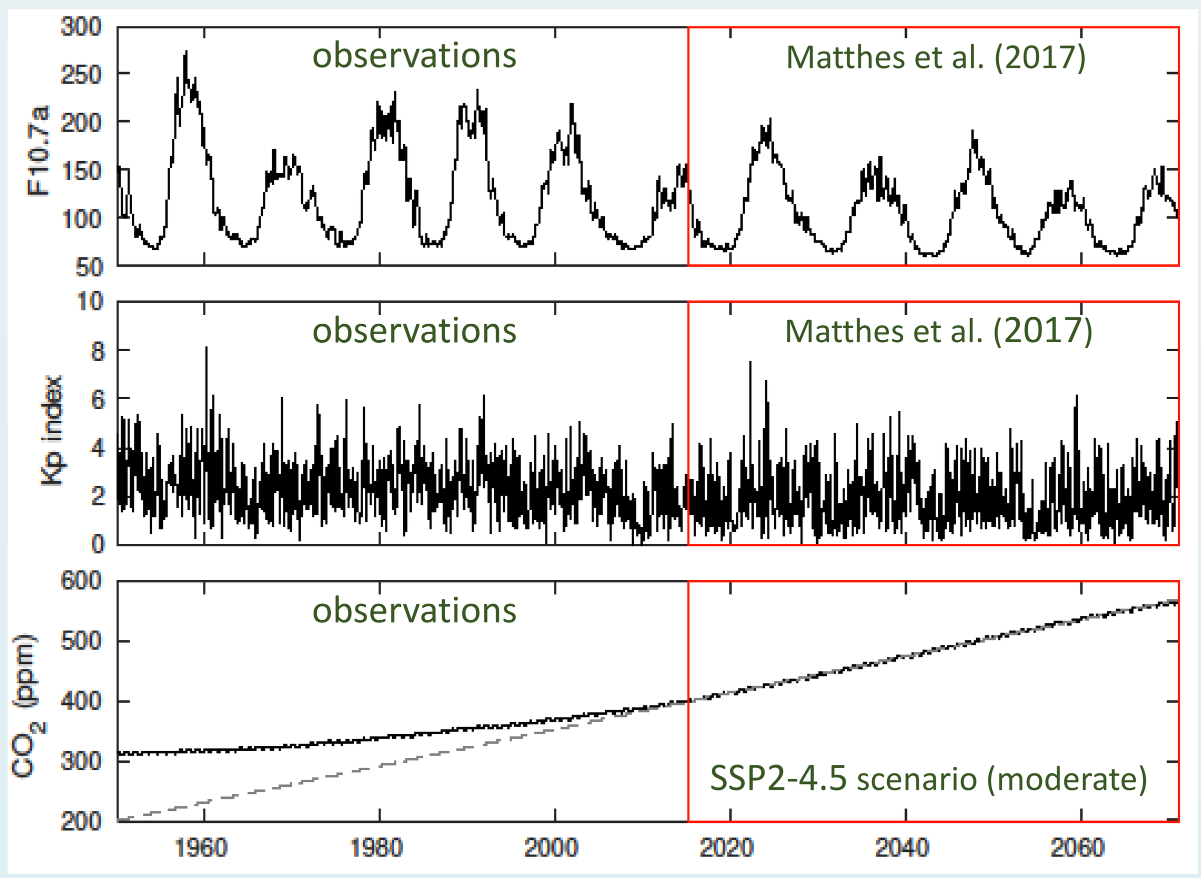
WACCM-X = **W**hole **A**tmosphere **C**ommunity **Cl**imate **M**odel – e**X**tended (physics-based atmosphere model, surface up to 400-700 km)

RENEGADE = **R**ealisations of the **E**ngineered and **N**atural **E**volution of the **G**lobal **A**tmosphere and **D**ebris **E**nvironment (space debris model, 200-2000 km)

MSIS2.0 = **M**ass **S**pectrometer **I**ncoherent **S**catter radar model – version **2.0** (empirical atmosphere model, 0-2000 km)

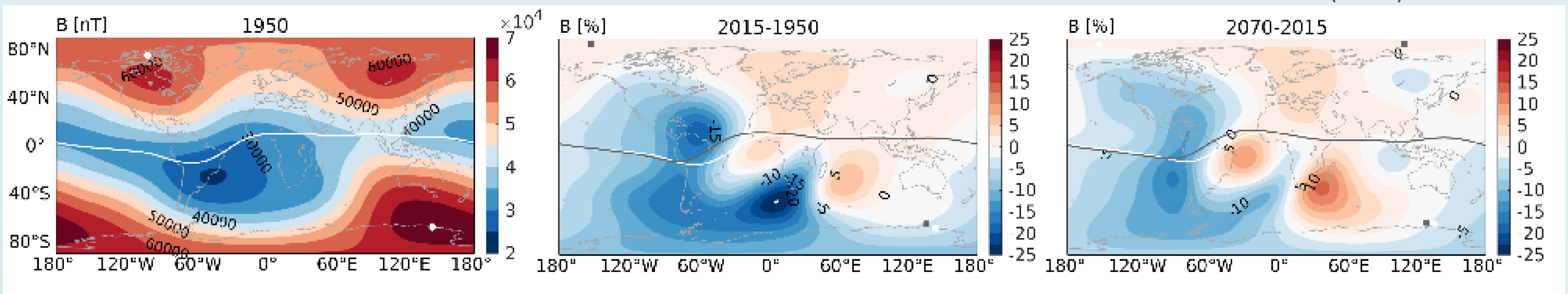
3. Long transient WACCM-X simulation (1950-2070)

- Includes all known drivers of long-term change
  - Solar and geomagnetic activity variations
  - Radiatively active trace gases (CO_2, methane, CFCs, ozone)
  - Main magnetic field changes
- Moderate future emissions scenario (SSP2-4.5)



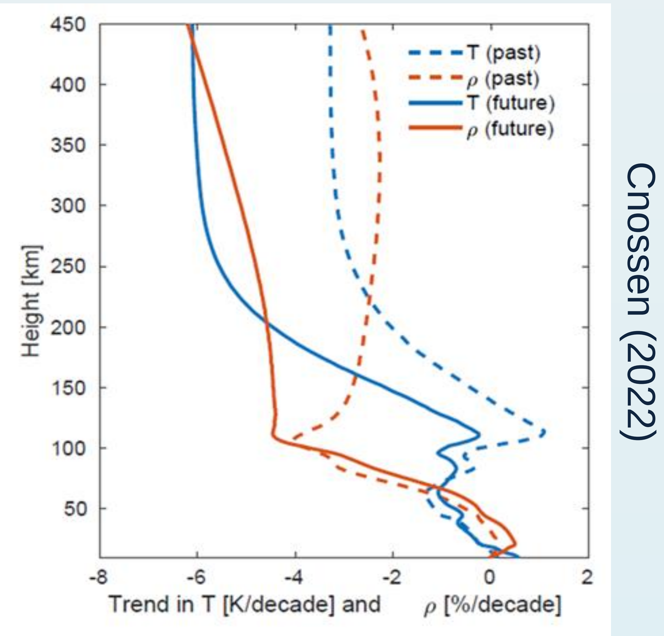
Cnossen (2020, 2022)

observations Aubert (2015)



4. Projected upper atmosphere climate change

- Predicted global mean upper atmosphere trends for 2015-2070 are ~twice as large as for the past (1950-2015)
- Mostly due to more rapid projected increase in CO_2 concentration (SSP2-4.5)

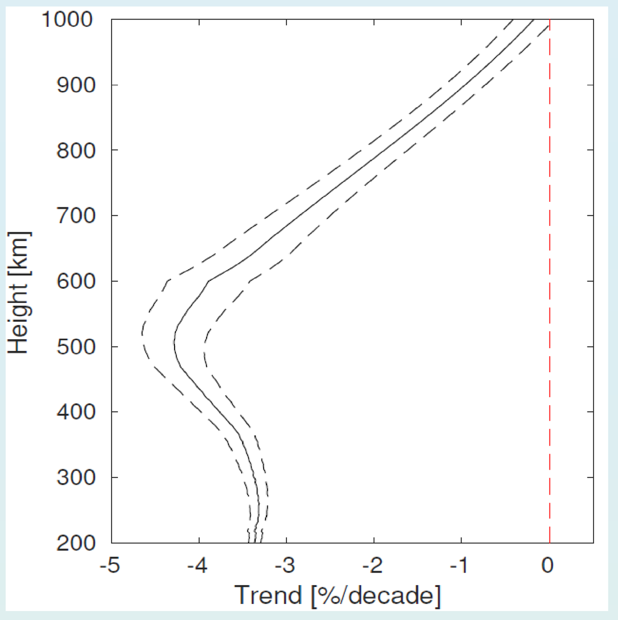


Cnossen (2022)

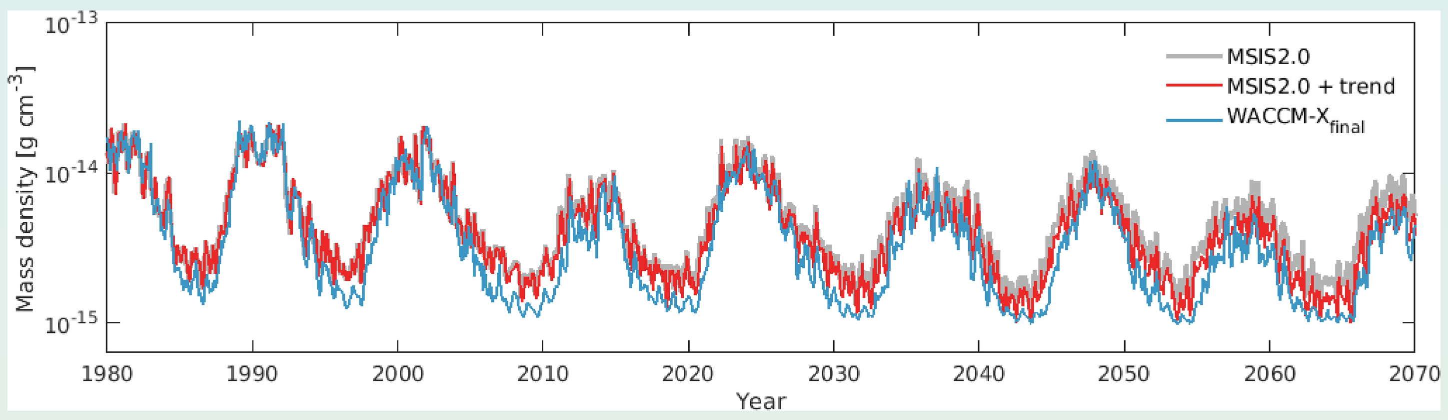
5. RENEGADE simulations (2018-2070)

- 100 Monte Carlo simulations per case
- Launch scenario: repeat 8 years prior to Feb 2018
- Assume widespread adoption of standard debris mitigation guidelines, no explosions
- MSIS2.0 used >1000 km
- Density inputs <1000 km
  - MSIS2.0 (no trend)
  - MSIS2.0 + trend
  - WACCM-X (extrapolated and corrected based on MSIS2.0)

Trend applied to MSIS2.0

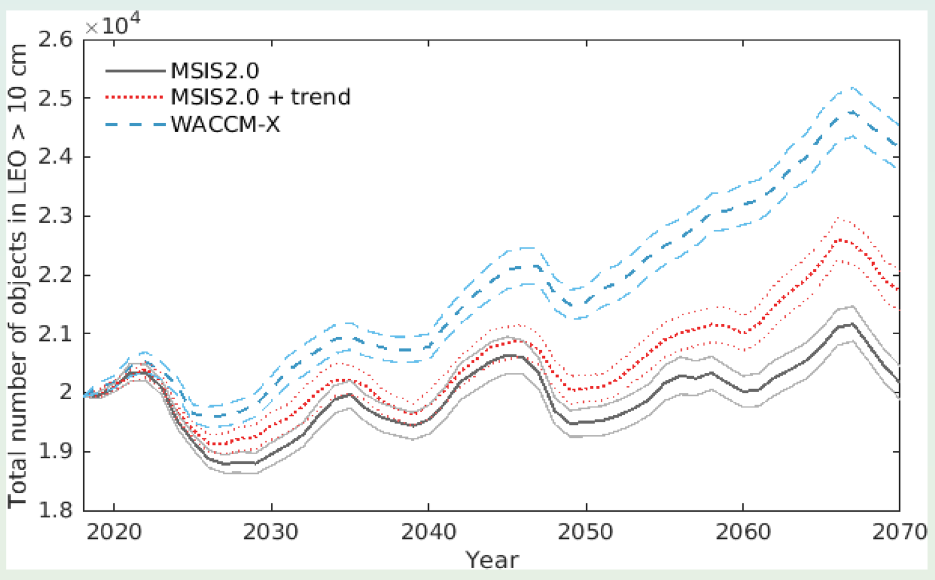


Density inputs at 350 km



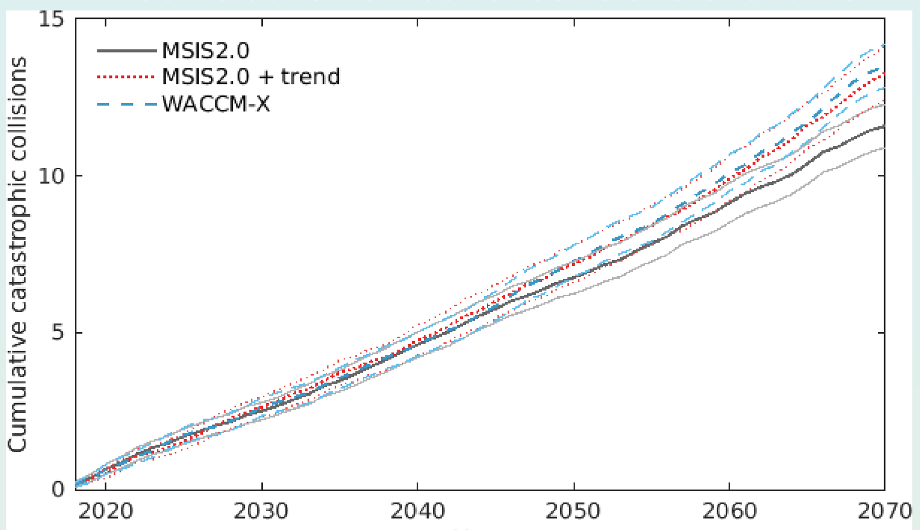
6. Impacts on evolution of space debris population and risk of collisions

- ~8% more objects >10 cm in Low Earth Orbit (LEO) by 2070 for MSIS2.0 + trend versus baseline case without trend
- Even larger increase (~20%) for WACCM-X



Evolution of space debris population in LEO for 3 different density scenarios

Cumulative number of collisions over time



- Catastrophic collisions increase from 11.6±0.7 for MSIS2.0 without trend to 13.3±0.8 for MSIS2.0 with trend and 13.5±0.7 for WACCM-X
- Catastrophic collision rate increases from 0.22±0.01 per year for MSIS2.0 without trend to 0.25±0.01 for MSIS2.0 with trend and WACCM-X

7. Conclusion

Projected reductions in thermosphere mass density due to increased greenhouse gas concentrations are expected to cause a significant increase in the space debris population, leading to a significantly higher risk of collisions by 2070. Numbers provided are for a “best-case” scenario for debris generation and a moderate CO_2 emissions scenario.

References

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