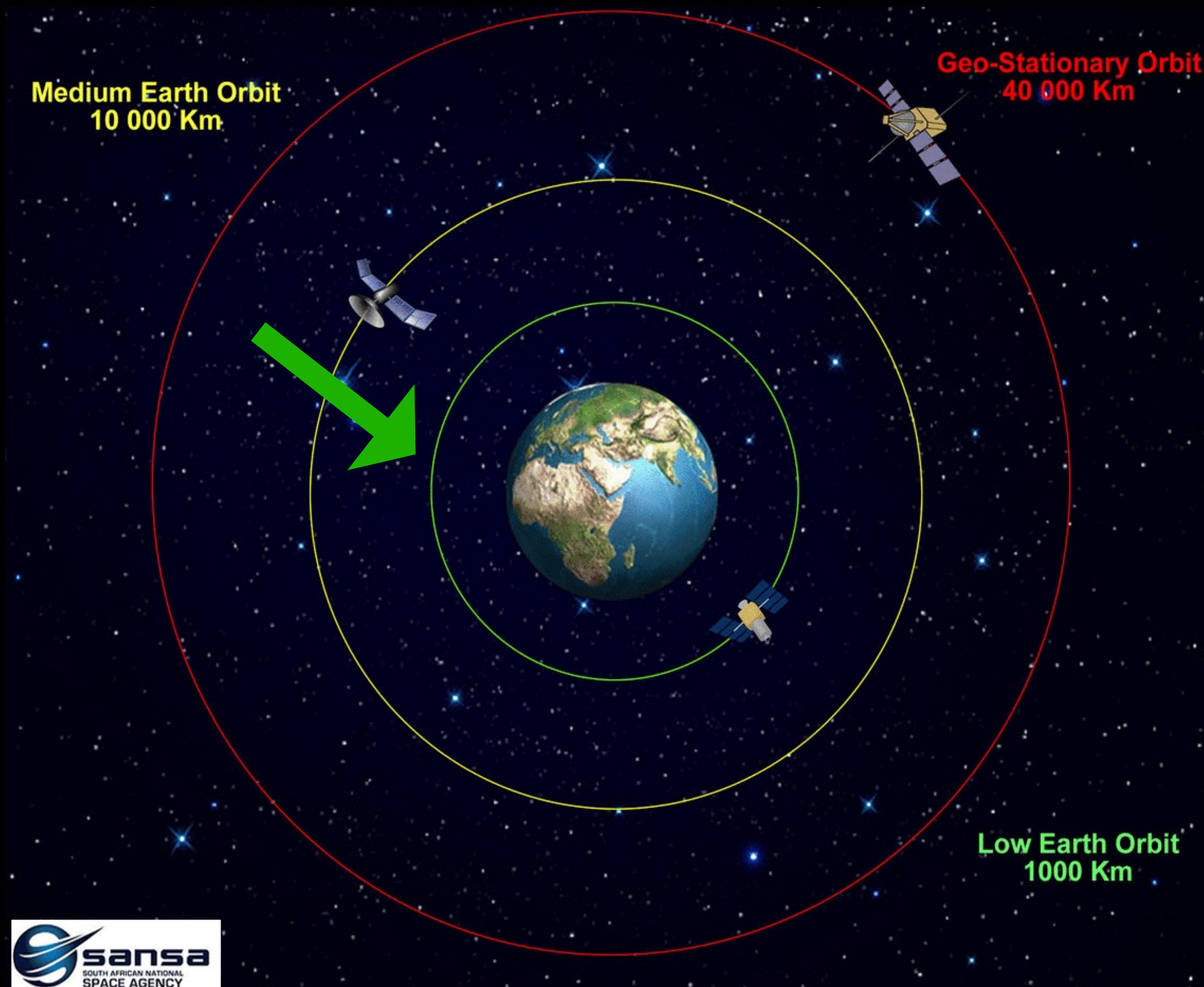
Perspectives on the use of data assimilation for improving thermospheric empirical models: Focus on extreme magnetic storms



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and collaborators

Physical Process: Upwelling of neutral particles

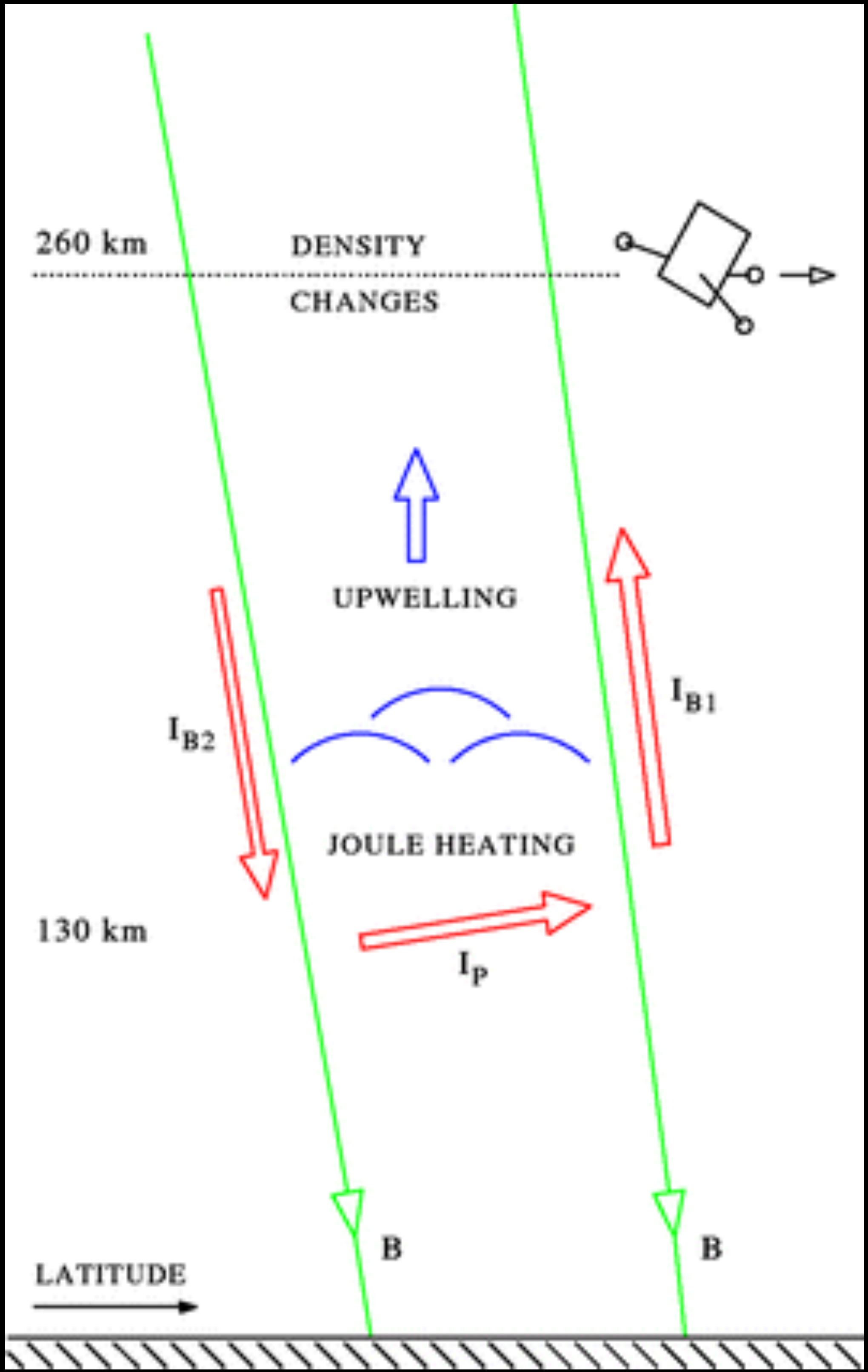
Intensification of field-aligned currents

⬇

Mechanical collisions between plasma and neutrals are enhanced

⬇

Neutral upwelling takes place



Prölss (2011)

First satellite in space: Sputnik (4 October 1957)

Extracted from the NOVA documentary on Sputnik: https://www.youtube.com/watch?v=0MayNS7ZF68

First observations of density perturbations caused by a storm in LEO: Sputnik observations

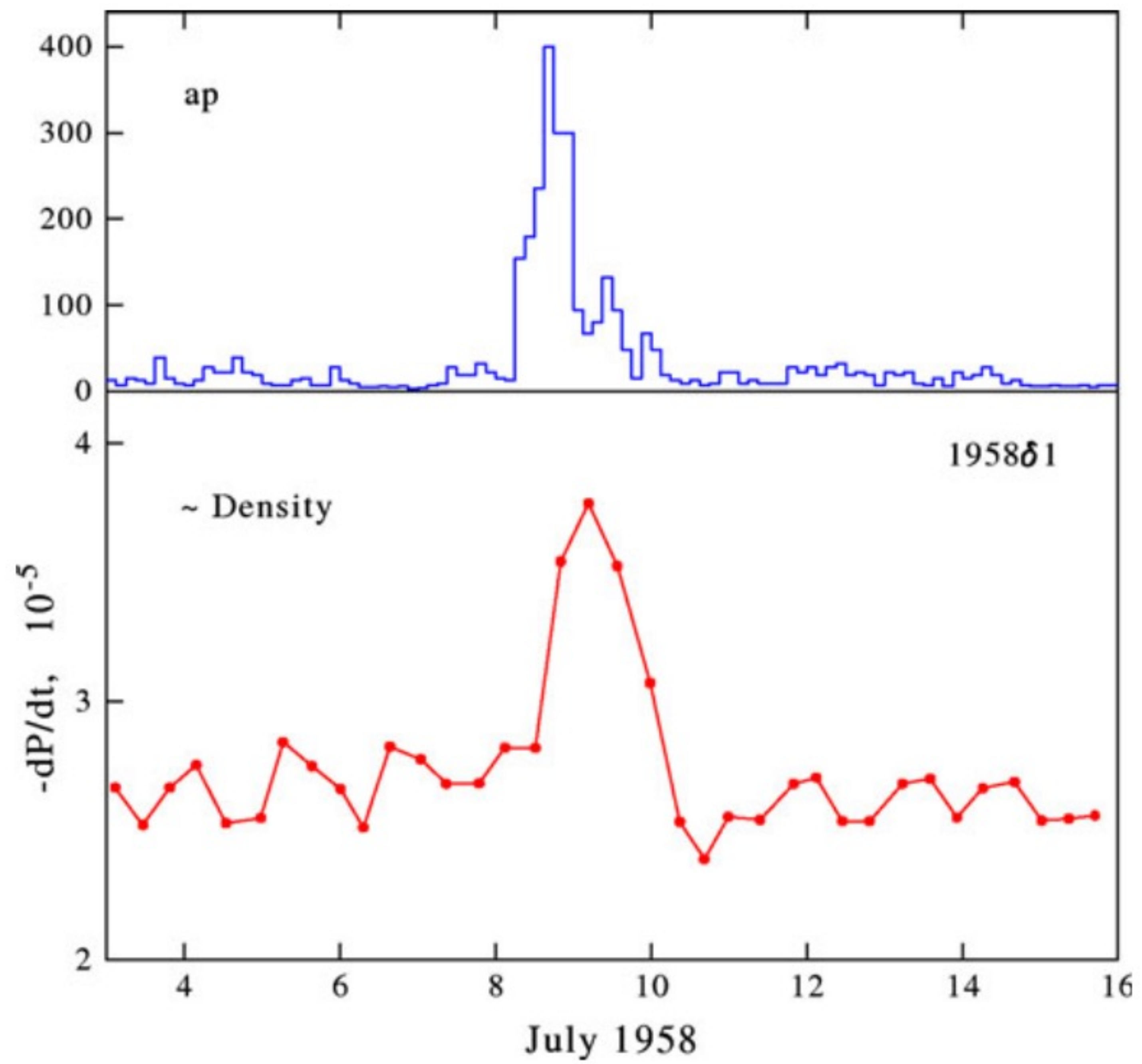


Fig. 3 Secular acceleration of the space object 1958δ1 (SPUTNIK 3 rocket) during the large geomagnetic storm of July 8, 1958. The *upper panel* shows the *ap* index, the *lower* the rate of decrease in the orbital period, $-dP/dt$. This latter quantity is proportional to the atmospheric mass density along the orbit of the space object. (Based on data published by Jacchia 1959)

Figure from Prölss (2011)

Data from Jacchia (1959)

1. The development of many thermospheric empirical models for density determinations such as the Jacchia model series, and the MSIS models by the NRL

2. The launch of satellites equipped with mass spectrometers, such as the EXPLORER series and DE satellites (before 2000)

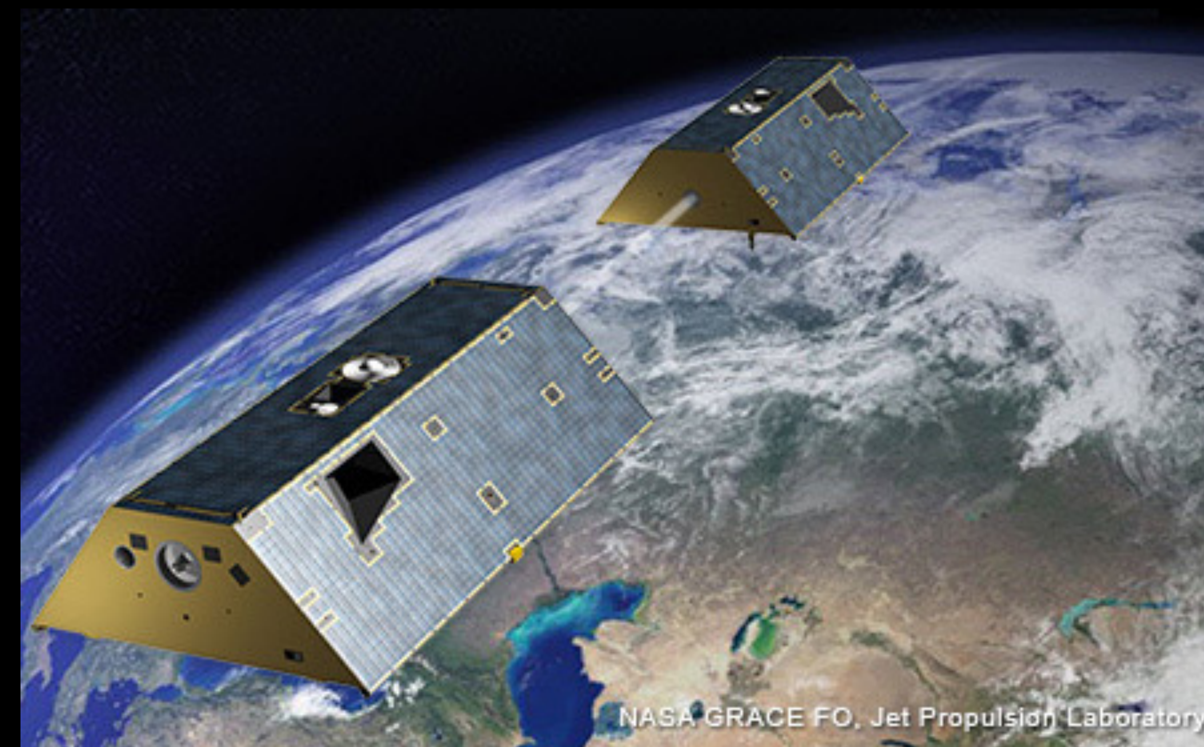
Surv Geophys (2011) 32:101–195
DOI 10.1007/s10712-010-9104-0

Density Perturbations in the Upper Atmosphere Caused by the Dissipation of Solar Wind Energy

Gerd W. Prölss

Density is measured by low-Earth orbit (LEO) satellites

CHAMP

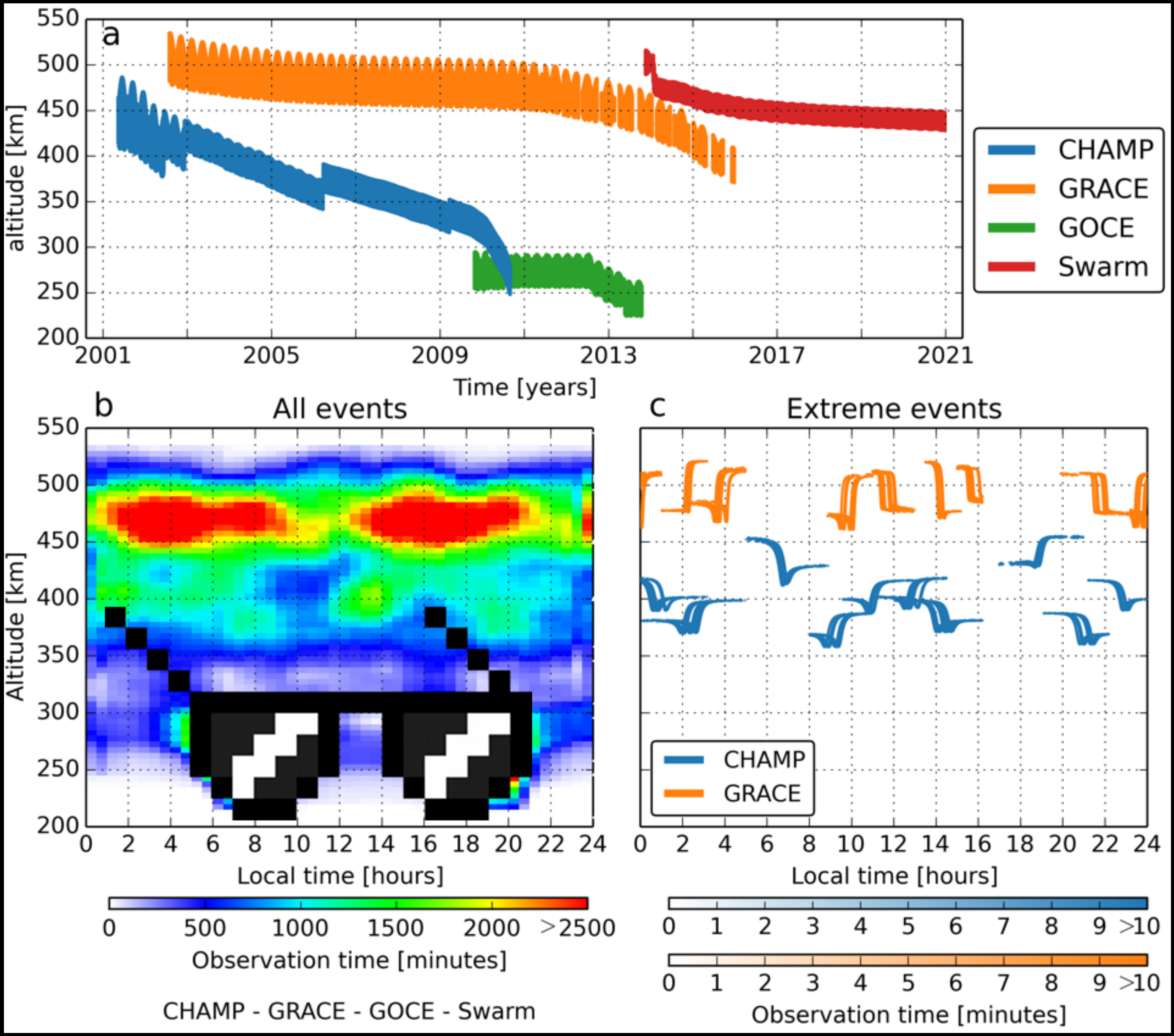


GRACE

High-accuracy accelerometers measure accelerations due to drag forces

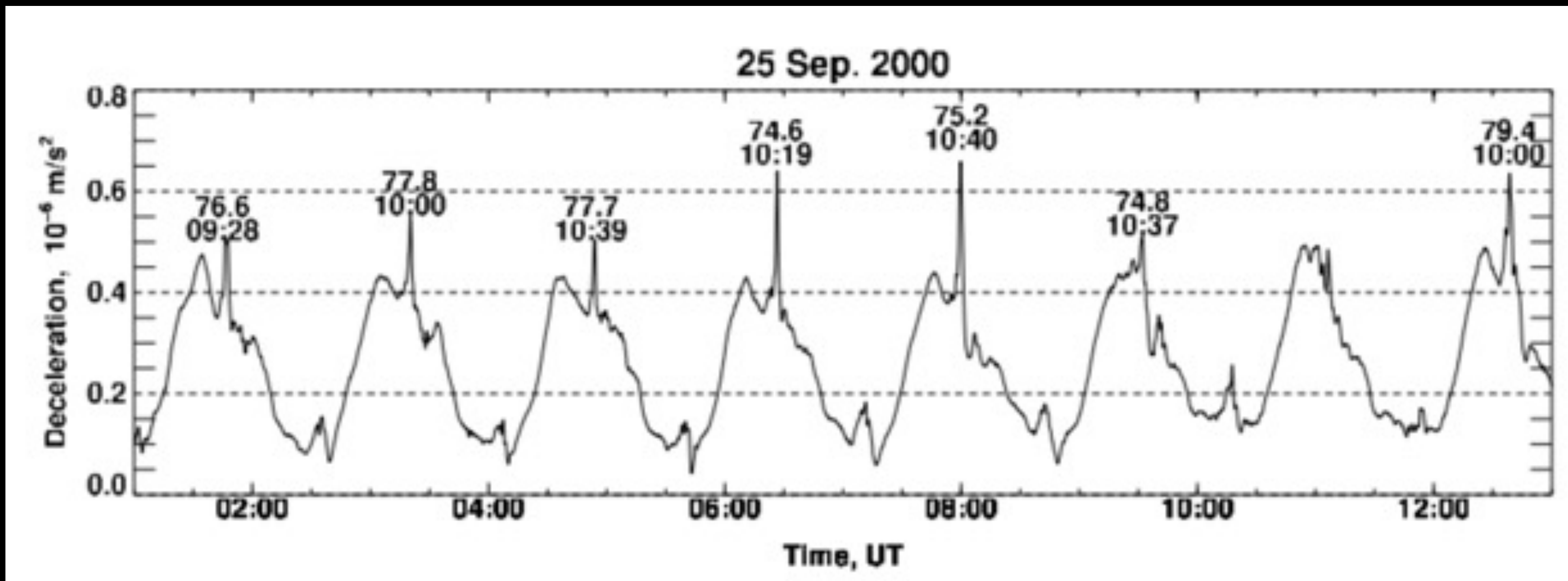
$$a_d = -\frac{1}{2}\rho C_D \frac{S}{m} V^2, \qquad V = |\vec{V}_{s/c} + \vec{V}_{wind}|$$

LEO satellite coverage in LEO after 2000

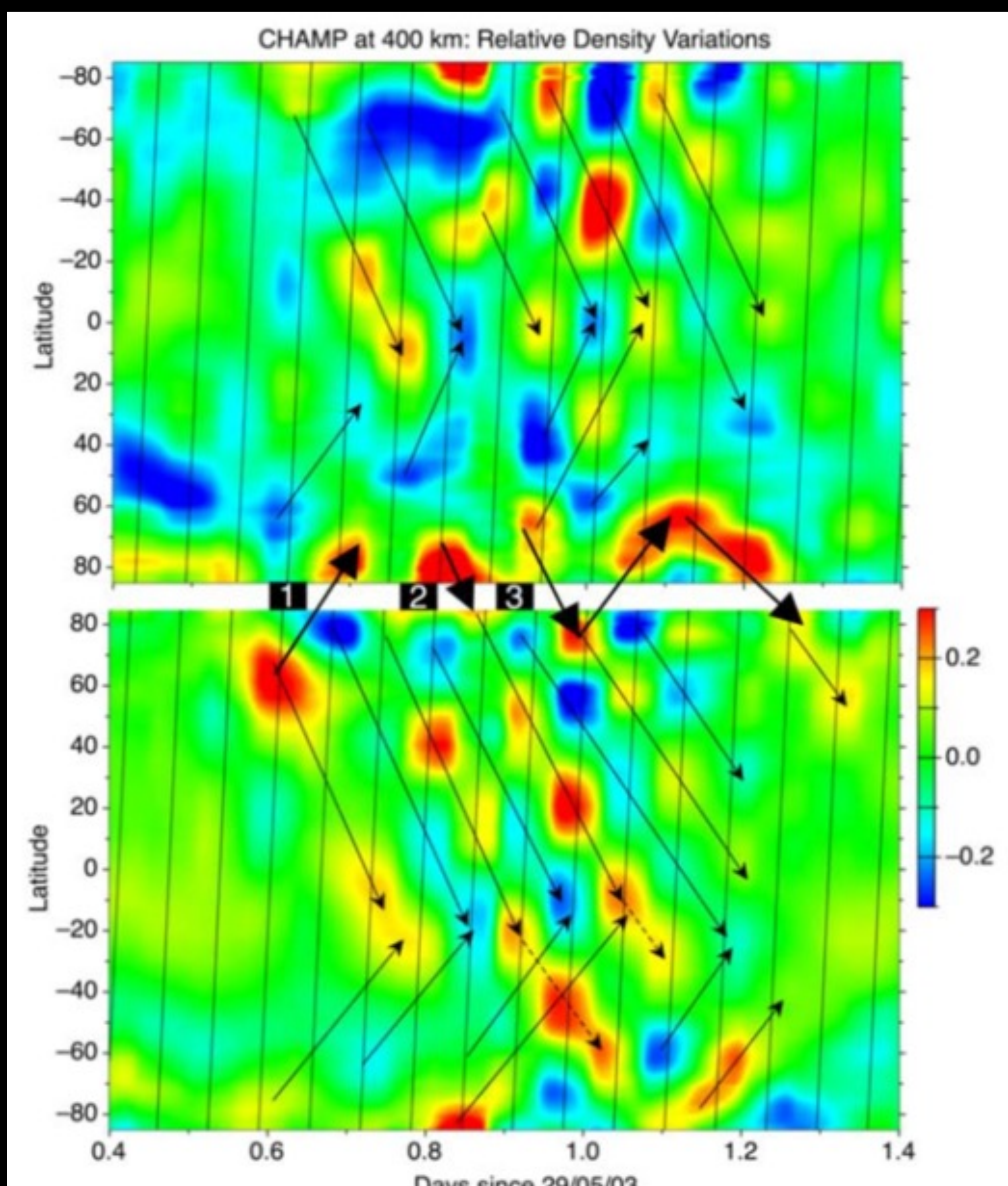


Oliveira et al. (2021), Frontiers

A few discoveries performed with CHAMP and GRACE data

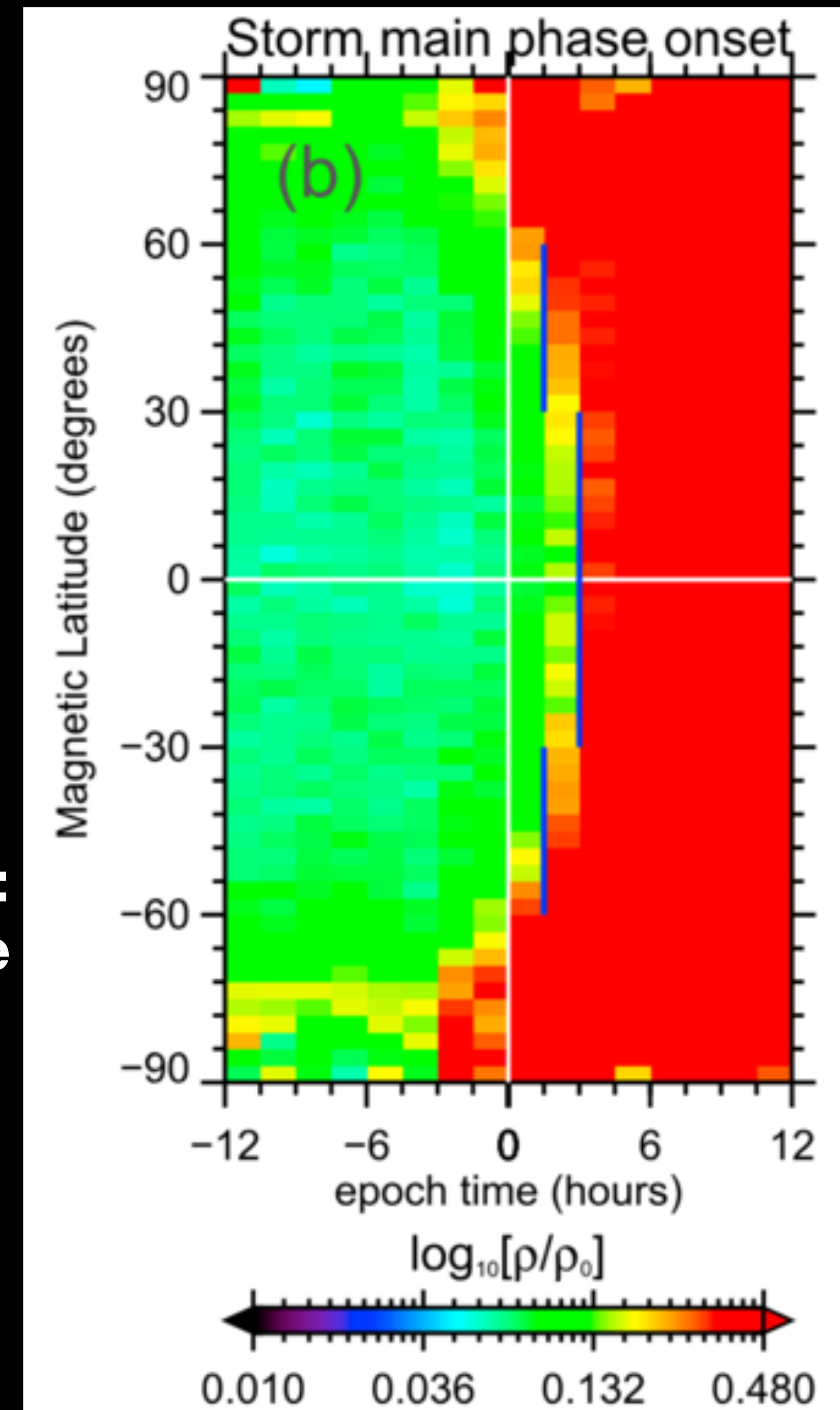


Lühr et al. (2004):
<-- Density enhancements at
The cusp region



Bruinsma & Forbes
🡐 (2007):
TAD propagation

Oliveira et al. (2017):
3-hour average time
For energy →
globaliation



The background density is obtained by the Jacchia-Bowman 2008 model

The JB08 model obtains density from the exospheric temperature T_∞

$$T_\infty = T_\ell(\theta, \delta_\odot, H) + \Delta T_{LST}(H, \theta, z) + T_{UV}(\chi) + T_{GA}(Dst)$$

Quiet density (ρ_0) is obtained when there is no storm contribution, or $T_{GA} = 0$ (Oliveira et al., JGR, 2017)

Following Oliveira and Zesta, SW, 2019:

Orbital decay rate ($\Delta\rho = \rho - \rho_0$)

$$\frac{da}{dt} = -C_D \frac{S}{m} \sqrt{GM \langle a \rangle} \Delta\rho$$

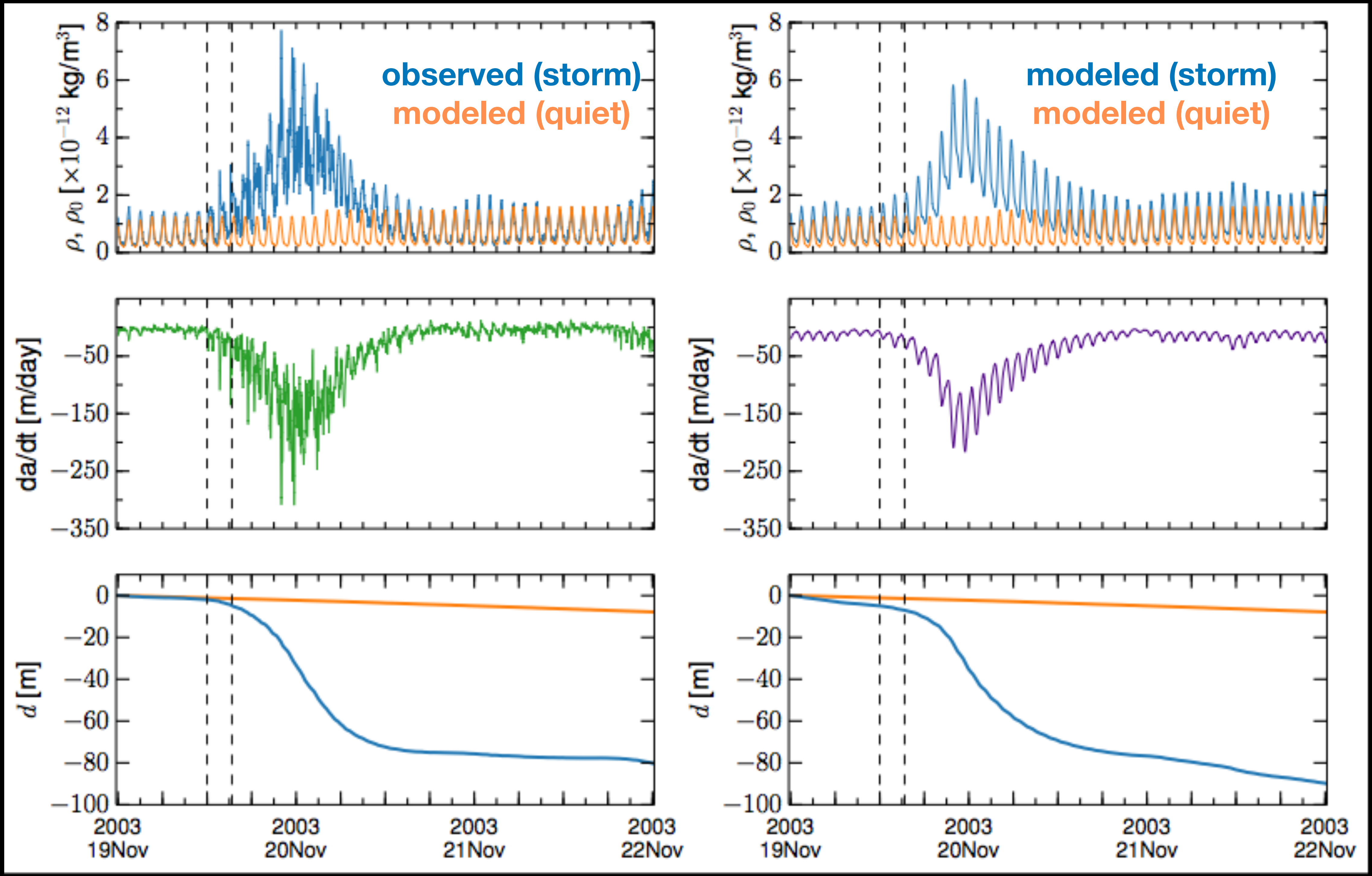
Total orbital decay

$$d(t) = \int_{t1}^{t2} a^{'}(t)\mathrm{d}t$$

20 November 2003 storm [GRACE: h = 480 km]

Oliveira & Zesta, Space Weather, (2019)

Data **Empirical model (JB08)**



Jacchia-Bowman 2008 (JB2008) empirical model

→ solar indices and geomagnetic indices as input data

→ used as a forecasting/prediction model

Bowman et al. (2008)

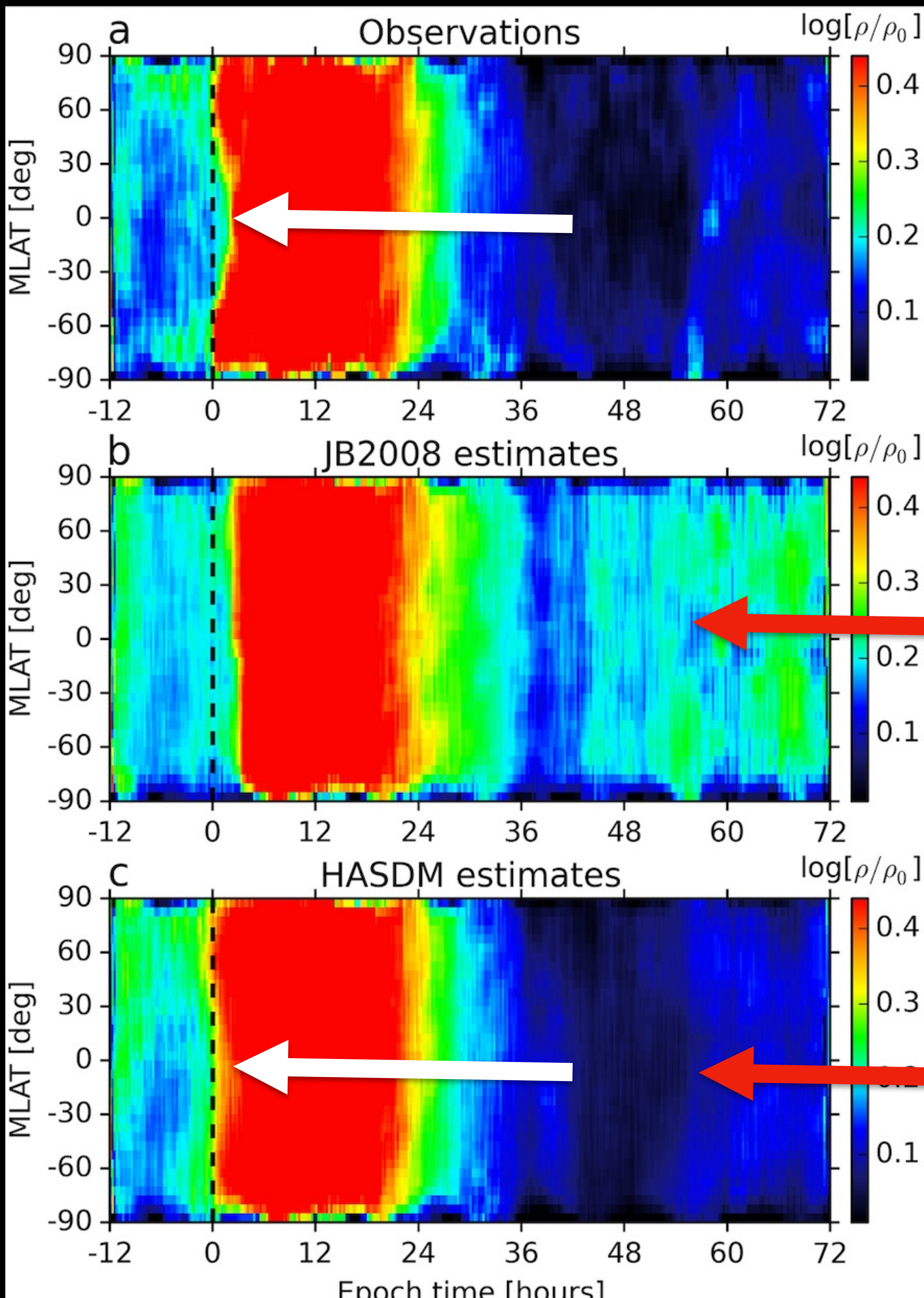
High Accuracy Satellite Drag Model (HASDM)

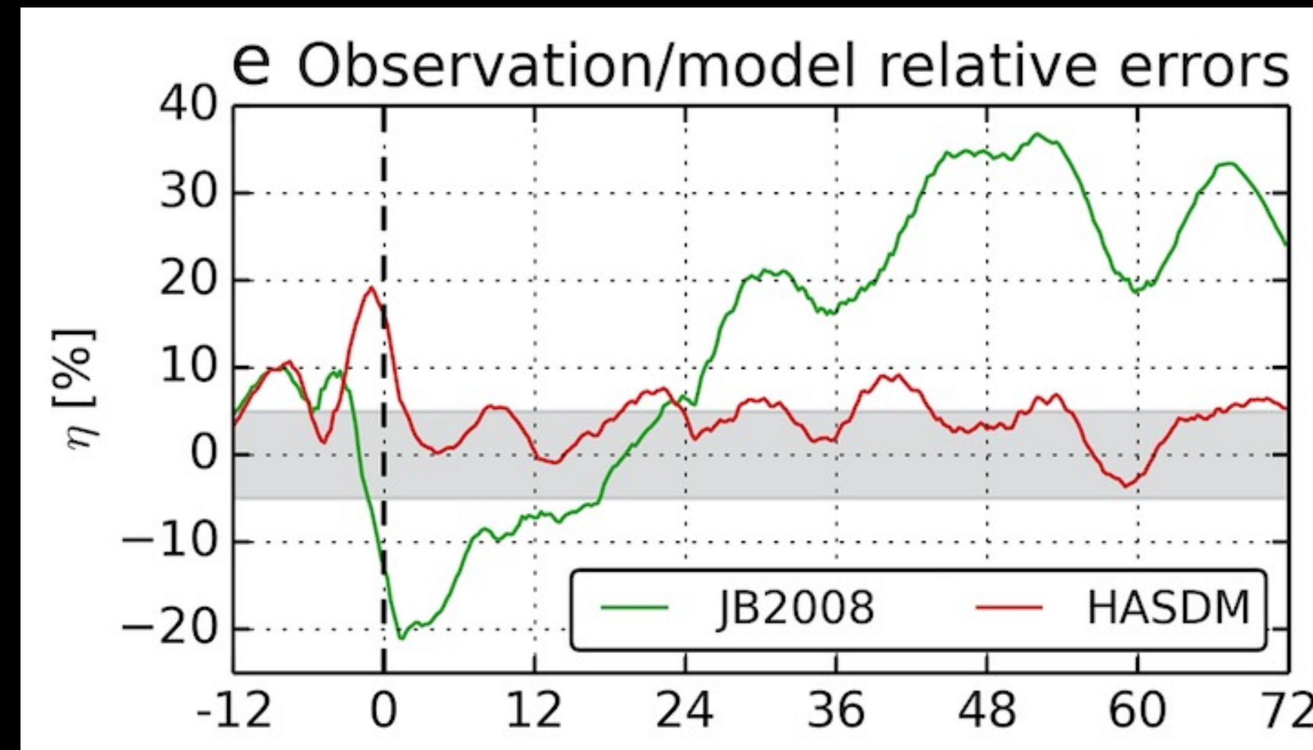
→ the model, property of the U.S. Space Force, is classified, but its outputs have been recently released to the public

→ JB2008 assimilates data from ~75 specification satellites to correct for densities

Tobiska et al. (2021)

Observation/model comparisons for the 7 extreme storms



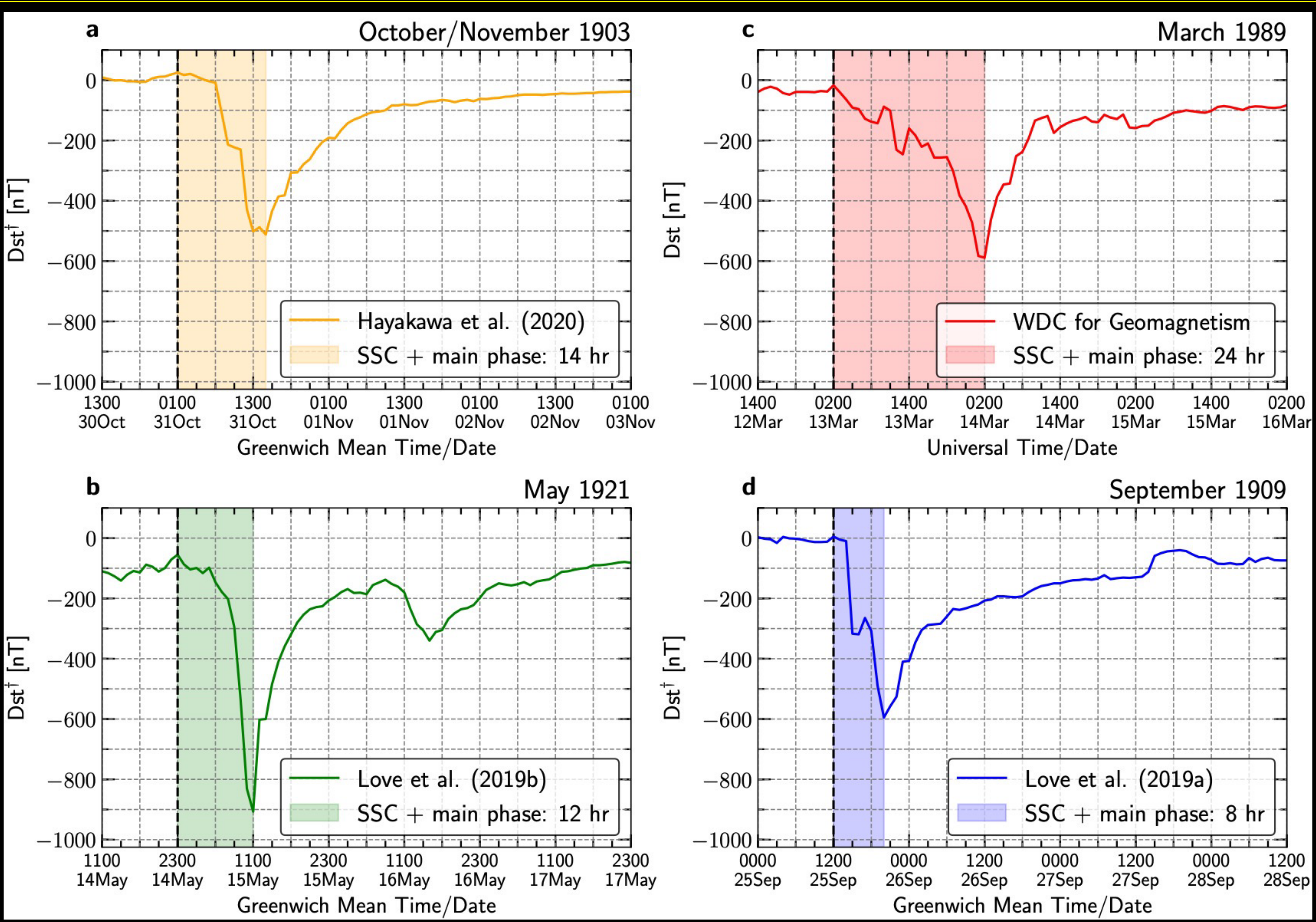


The empirical model overestimates density during storm recovery

Oliveira et al. (2021), Frontiers

The assimilation model (with ~75 specification satellites) perform better

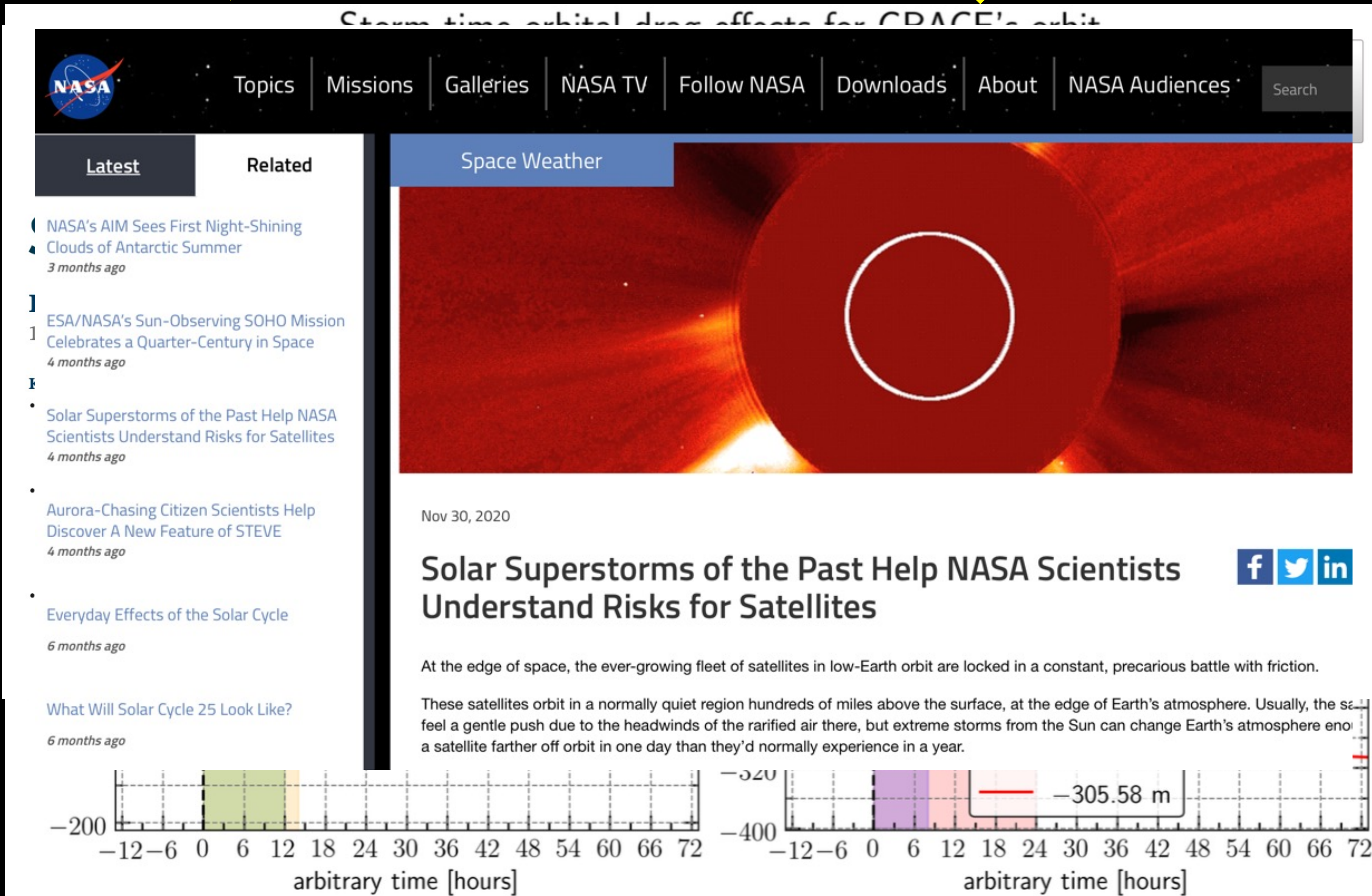
Four historical superstorms with different intensities and durations



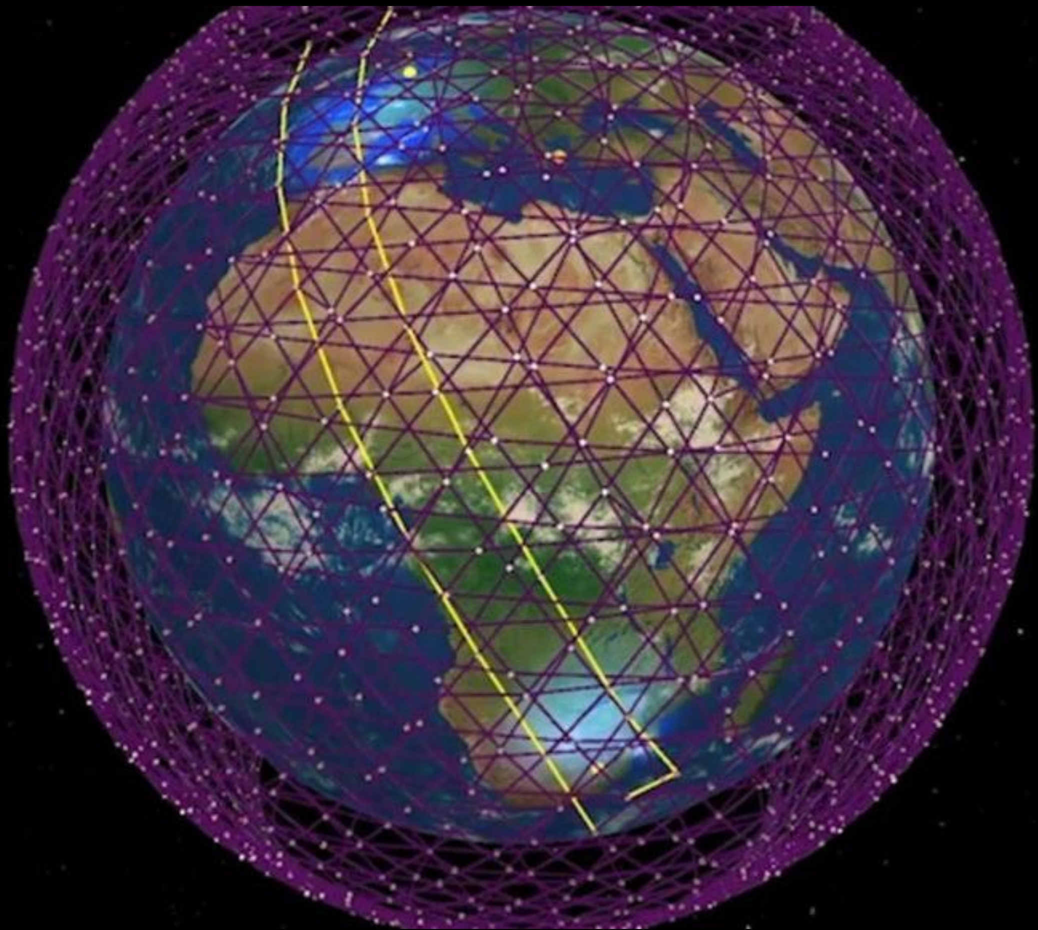
Oliveira et al., Space Weather, (2020)

~ The same storm time, different Dst min

Different storm time, ~ the same Dst min



Future LEO satellite megaconstellations for internet service



Hundreds and thousands satellites

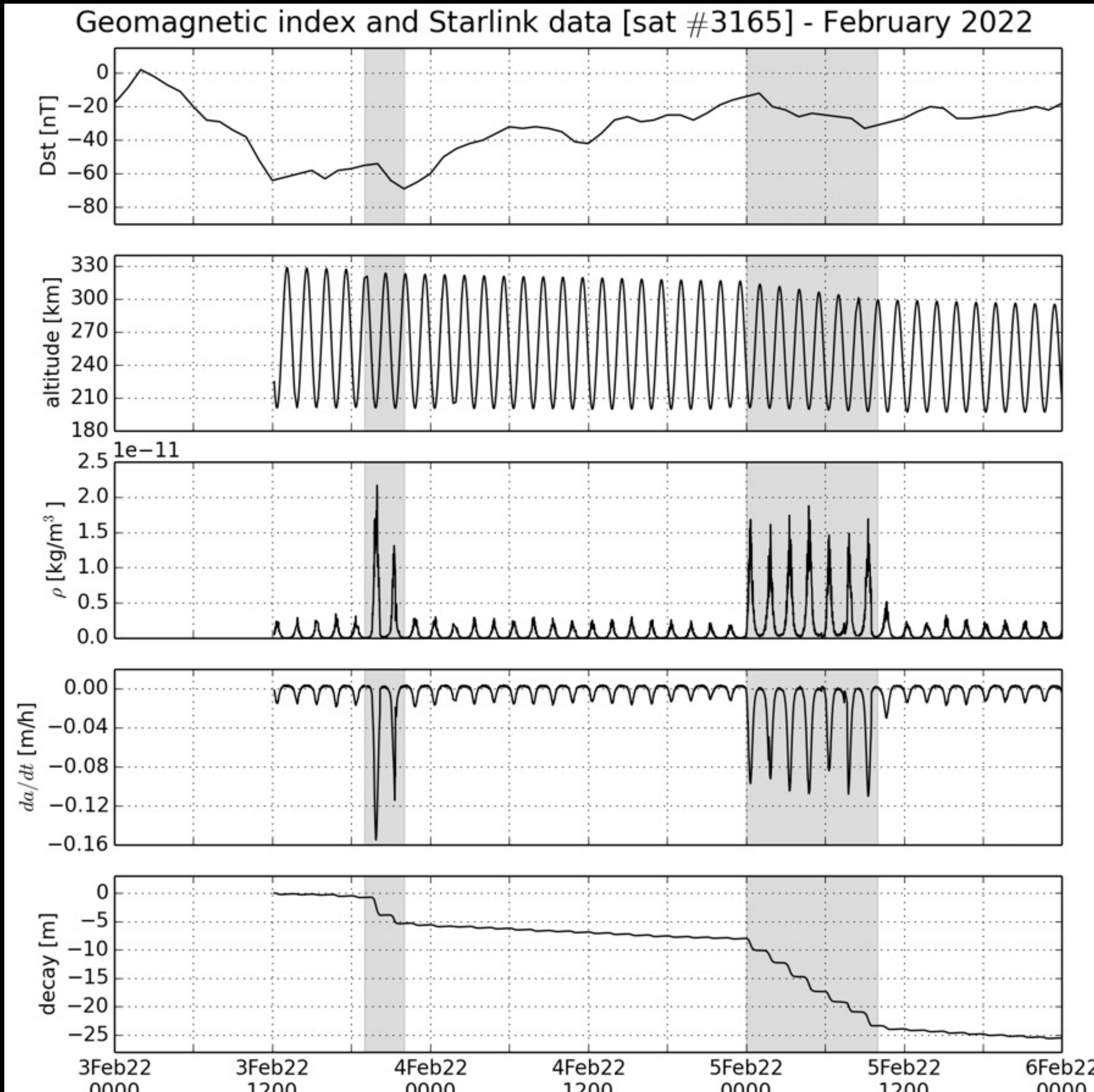
Starlink (by SpaceX)

Other companies:

OneWeb
Amazon
Telesat

Data assimilation and Machine Learning

Starlink satellite #3165 survived the Feb 2022 magnetic storm

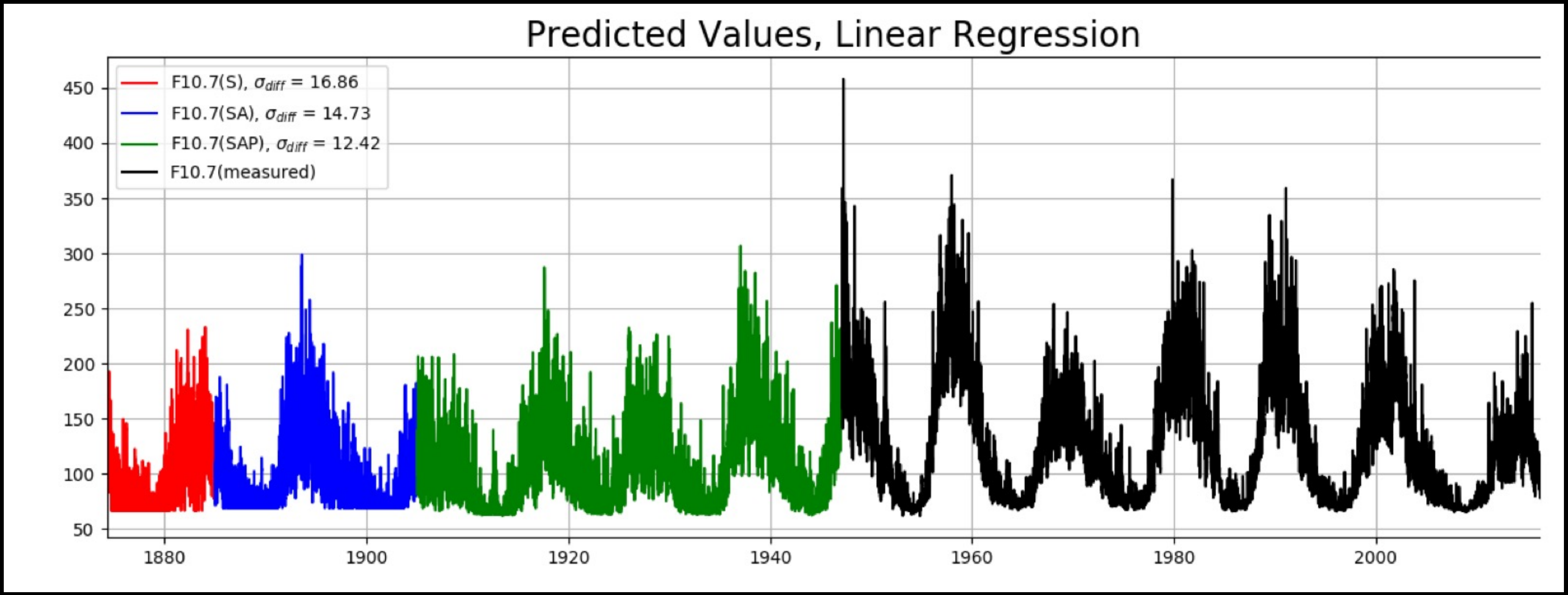


Lesson learned by SpaceX:

A weak magnetic storm can knock down a satellite from LEO. In fact, it brought down 38 out 49 satellites launched on 3 Feb 2022!

Starlink data kindly provided by David Goldy from SpaceX

Predicting solar indices in the past using ML techniques



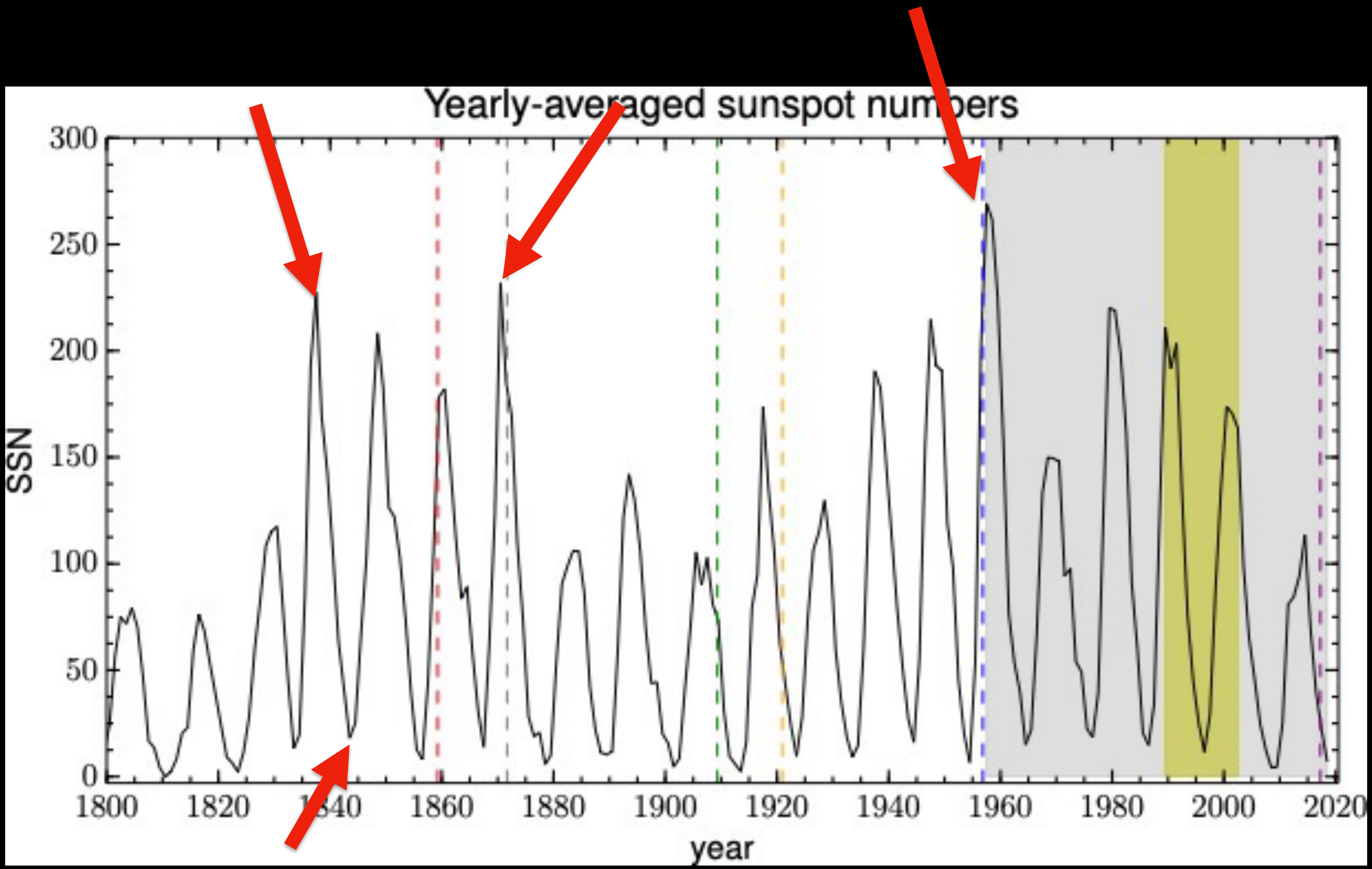
Black: observations

Red: only SSN

Blue: SSN + area

Green: SSN + area + solar plage

The Gleissberg cycle will play a role



Gleissberg, Solar Physics, (1967)

Conclusions

1. A new method to extract background density effects during storm times has been developed

2. Historical archives can be used to assess thermosphere and drag response induced by past extreme storms and superstorms

3. In the future, there will be many megaconstellations of LEO satellites and most likely increased solar activity

4. These large-scale datasets can be assimilated with ML techniques, and increased solar activity will provide more extreme storms to help improve our empirical models

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Bruce Bowman
(Feb 4, 1945 - Dec 31, 2020)

U.S. Air Force Command Scientist and developer of the JB08 empirical model