

Space Weather Influences on Space Junk Orbit Decay

M. Lockwood¹, M.J. Owens¹, C. Saha¹, L.A. Barnard¹, C.J. Scott¹, J.
O'Donoghue¹

¹Department of Meteorology, University of Reading, Reading, Earley Gate, PO Box 243, Reading, RG6
6ET, UK

Key Points:

- The debris cloud from the high-altitude breakup of Fengyun 1C is proving to be even more persistent than predicted
- Debris raised in apogee during the breakup has acted as a reservoir, giving a reentry rate to date only weakly influenced by cloud depletion
- In addition to debris altitude decay by storms there is another, subtle, geomagnetic effect through the Russell-McPherron mechanism

Corresponding author: Mike Lockwood, e-mail: m.lockwood@reading.ac.uk

Abstract

The effect of space weather on the debris cloud generated by the high-altitude Anti-Satellite (ASAT) test on the Fengyun-1C satellite is studied over the subsequent 18 years. Using the 3532 tracked debris pieces, we show that more of the cloud at sizes above about 10cm has survived than was predicted four years after the ASAT test, despite the average space weather activity being higher than was assumed in making those predictions. We show how debris accelerated by the test into high-apogee orbits has acted as a reservoir, giving a long-lived supply of objects ready to start the reentry spiral. The average rate of descent varies with the solar cycle and with the solar rotation period because of the variation in EUV heating of the thermosphere. It is shown that geomagnetic storms have a short-lived but significant effect on the altitude decay of the debris. A second, more subtle, geomagnetic effect is seen to be present, identified as being driven by the Russell-McPherron effect on solar wind-magnetosphere coupling. The contribution of this mechanism to the semi-annual variation in average debris descent speed is greatest at high altitudes but other thermospheric effects, such as wave and tide dissipation and circulation changes, are more important at lower altitudes. At times of low solar activity the EUV heating is the dominant effect but the total geomagnetic contribution is more significant during disturbed times. We discuss how these results are of importance to controlled de-orbiting of space junk.

Plain Language Summary

A “star wars” anti-satellite (ASAT) missile test at high altitudes generates space junk that will remain a great collision hazard for objects in low-Earth orbit for many decades. We study the debris cloud that was generated by such a test on the defunct Fengyun-1C satellite on 11 January 2007 and show it has decayed even more slowly than was predicted soon after the event. Like many pollution events, this has generated considerable problems but, ironically, tracking the consequences can provide scientific insights. In this case, the problems are associated with our exploitation of near-Earth space, but we can study the variations in, and contributions to, the heating of the upper atmosphere (the thermosphere). This is because thermospheric heating increases the atmospheric density at all heights and hence the drag it exerts on objects in low-Earth orbit. This slows them and causes their altitude to decrease.

1 Introduction

The decline in altitude of all objects in Low-Earth Orbit (LEO) is caused by the frictional drag as they move through the upper atmosphere. This slows the objects, making them drop in altitude. The loss of gravitational potential energy increases the kinetic energy so, counter-intuitively, the drag has the effect of speeding up the objects, but causes their altitude to decay. When objects reach about 120 km., orbit is no longer possible and they “reenter”. This primarily means that they burn up in the atmosphere but some pieces fall all the way to Earth’s surface. Record numbers of satellite and rocket pieces have reentered in recent years and the rate at which they are reaching all the way down to Earth’s surface has risen to more than 3 per day (i.e., more than 1,100 per year) globally. The frictional drag depends on the size of the object and on the density of the thermosphere, which is raised at all altitudes if the thermosphere is heated. The thermosphere is primarily heated by absorption of solar Extreme Ultraviolet (EUV) radiation and by Joule heating caused by ionospheric currents (currents which also give rise to geomagnetic activity). There are also heating contributions from the dissipation of waves and tides propagating upward from below, while changes in atmospheric composition can modify the thermospheric energy balance by affecting both heating and cooling. The wave and tide dissipation heating can be significant, but unlike the EUV and geomagnetic heating, does not vary much over the solar cycle (Neogi et al., 2026),

In a recent paper, Lockwood et al. (2026) detected a contribution of the Russell-McPherron (R-M) effect (Russell & McPherron, 1973) to the well-known semi-annual variation in global mean thermospheric densities (Paetzold & Zschörner, 1961; Emmert, 2015; Jones et al., 2018; Yue et al., 2019). Because thermospheric densities have a controlling influence on the decay of the altitude of objects in Low-Earth Orbit (LEO) (Vallado & Finkleman, 2014; Doornbos, 2012), this raises questions about a possible detectable influence of the R-M effect, and space weather in general, on the evolution of debris clouds and other space junk. In this paper, we use the debris from the 2007 anti-satellite (ASAT) test on the Fengyun-1C satellite. The method used here to detect the R-M effect is that employed by Lockwood et al. (2026) which sorts the data by the dawn-dusk component of the near-Earth Interplanetary Magnetic Field (IMF) in the Geocentric Solar Equatorial (GSEQ) frame of reference.

1.1 The FY-1C ASAT test and consequent debris

On 11 January 2007 the Chinese army conducted an ASAT test by destroying a defunct meteorological satellite, Fengyun-1C (hereafter FY-1C) using a ballistic kill missile. FY-1C was in a near-circular (eccentricity $e = 0.0015$), Sun-synchronous orbit at altitude $h_S = 863 \text{ km}$ with an orbital period of $T_S = 102.1 \text{ min}$. The missile released a kinetic kill vehicle (KKV) which impacted the spacecraft at a relative velocity of 9.36 km s^{-1} . The impact generated a huge debris cloud. Objects of size 5 cm and above were detected on the day of the test by the US Space Surveillance Network (SSN) and of size $> 0.5 \text{ cm}$ from the next day using the Haystack observatory (including HAX, the Haystack Auxiliary Radar) (Johnson et al., 2008). Objects 1 cm to 2 cm were observed from 13 March (debris cloud evolution time, $t_e = 0.17 \text{ yr}$) by the EISCAT Svalbard radar (Markkanen et al., 2009) and observations of $> 3 \text{ cm}$ objects began at the Goldstone bistatic radar in December (Johnson et al., 2008). By the end of 2007 ($t_e = 0.97 \text{ yr}$), SSN had detected, and were tracking, over 2500 debris pieces, a number that subsequently rose to 3532. These tracked pieces are mainly greater than about 10 cm in diameter. It is estimated that, in addition, there were between 35000 and 150000 fragments larger than 1 cm in diameter and several millions of smaller fragments (Liou & Johnson, 2009; Johnson et al., 2008). These figures have been used to inform NASA’s Standard Breakup Model (Cimmino et al., 2021). ESA’s DISCOS database reveals that of the 3532 tracked debris pieces, 1071 had re-entered by 1 April 2025 ($t_e = 18.22 \text{ yr}$) of which 1018 have adequately-complete tracking data available from Space Track (<https://www.space-track.org>). Hence even 18 years after their generation, 2461 debris objects from FY-1C remained in orbit, which is 70% of the total. This ASAT test was the largest single contribution to space junk in history (Lockwood, 2025).

At the time of the test, the FY-1C satellite had a mass of approximately 880 kg , almost all of which will ultimately re-enter and ablate in Earth’s atmosphere. We do not have a precise inventory of its constituent materials, but it likely contained about 250 kg of aluminum, contributing to the anthropogenic input of metals into the middle atmosphere from space activities. To put this into context, Ferreira et al. (2024) estimate that $4.17 \times 10^4 \text{ kg}$ of aluminum entered the atmosphere from all satellite reentries in 2022, about 30% above the natural meteoritic aluminum influx and over 150 times greater than the likely aluminum content of FY-1C. Aluminum is of particular concern because it is oxidized during atmospheric reentry, producing aluminum oxide particles that have the potential to act as catalysts of stratospheric ozone depletion. It is not presently possible to establish whether the FY-1C ASAT event caused more total ozone depletion, integrated over time, than would have occurred had the satellite remained intact. However, the fragmentation converted what would otherwise have been a single eventual reentry into a prolonged source of aluminum and other spacecraft-derived material. The potential implications for stratospheric ozone therefore warrant further investigation. Although fragmentation does not increase the total mass of aluminum ultimately released from the spacecraft, it spreads its injection into the atmosphere over a much longer period and over a

much bigger area. Because the proposed ozone-destroying mechanism involves the catalytic action of fine aluminum-containing particles, which are not themselves consumed in the reaction, it is possible that the prolonged injection from a debris cloud could produce a greater integrated ozone loss than would occur following a single conventional re-entry. We need further studies to quantify the magnitude of this potential effect.

The debris is known to be a hazard for our exploitation of Low-Earth Orbit (LEO). One piece of the debris, cataloged as FY-1C debris fragment 30670, may have destroyed the Russian satellite was BLITS (Ball Lens In The Space), which suddenly changed in orbit and spin on 22 January 2013. Fengyun-1C debris object 30670 was the only known object that was in close proximity to BLITS at the time. The encounter was predicted at about 07:56 UTC, with a relative velocity of about 9.7 km/s. However, a detailed analysis by Kelso et al. (2013) found that the orbit of FY-1C fragment 30670 showed no detectable change at the supposed collision time. Conservation of momentum means that a collision capable of producing the observed change in BLITS should also have measurably perturbed the fragment. The authors therefore ruled out fragment 30670 as the cause of the demise of BLITS. However, the closeness of the conjunction still highlights the potential hazard. In addition, the International Space Station (ISS) has had to perform avoidance maneuvers because of FY-1C fragments (well-documented examples were on 28 January 2012 and 25 November 2024), and we know of 14 collision-avoidance maneuvers by NASA spacecraft that were conducted to avoid FY-1C debris.

In 2011, using the rescaled ballistic coefficients discussed below, Pardini and Anselmo (2011) predicted that less than 49% of the FY-1C debris cloud would remain in orbit by 1 April 2025 (see their Figure 16), compared to the 70% that, in the event, was still in orbit at this date. It might be thought that the smaller-than-predicted fraction that has actually reentered was because the solar activity level was lower than the prediction that they had employed, which was the long-term prediction of F10.7 solar radio flux issued by NASA on 1 March 2010. In fact, the average predicted F10.7 for the interval was 106.1 sfu ($1 \text{ sfu} = 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$), whereas the observed average was 113.8 sfu . Hence the solar activity was slightly higher than used in the prediction and yet considerably fewer of the tracked debris cloud objects re-entered than had been predicted. Hence it is timely to look at how the prevailing space weather has depleted the debris cloud.

A Gabbard plot is a standard way of representing the debris cloud after a fragmentation event. Johnson et al. (2008) showed one for the FY-1C debris cloud for 11 July 2007 (cloud evolution time $t_e = 0.5 \text{ yr}$), by when a total of 2360 objects had been identified and tracked and 13 has reentered, leaving 2347. This is reproduced in Figure 1A. The legend to the figure explains the Gabbard plot format. Shortly after a fragmentation event, a Gabbard plot has a characteristic “open-scissors” form. This is because the debris accelerated forward by the impact have period, T , greater than that of the craft before the impact ($T > T_S$, marked along the plot x-axis in mauve) and have perigee at the altitude of the satellite before impact (h_S) but reach up to higher altitudes, the highest known for the FY-1C fragmentations reaching an apogee of 3921 km . This half of the cloud generally experiences lower drag as each debris piece spends much of their orbit at raised altitude. On the other hand, the half of the debris cloud with $T < T_S$ initially keeps the satellite altitude h_S at apogee but have lowered perigee altitudes and so subsequently experience increased drag and decay faster in altitude (marked along the Gabbard plot x-axis in green).

Figure 1B shows the location of the further 95 reentries that occurred between 11 July 2005 and 19 September 2010 (i.e., at $t_e < 3.69 \text{ yr}$), plotted on the Gabbard plot for 11 June 2007. This date in 2010 is adopted as, by then, most all the trackable debris had been identified. The plot shows that the early reentries came from three distinct sources: (1) very low T objects that were the most strongly decelerated by the ASAT event; (2) objects that kept an orbital period close to T_S but went into a more elliptical orbit, and (3) a few very highly-accelerated objects that went into highly elliptical orbits. Of these,

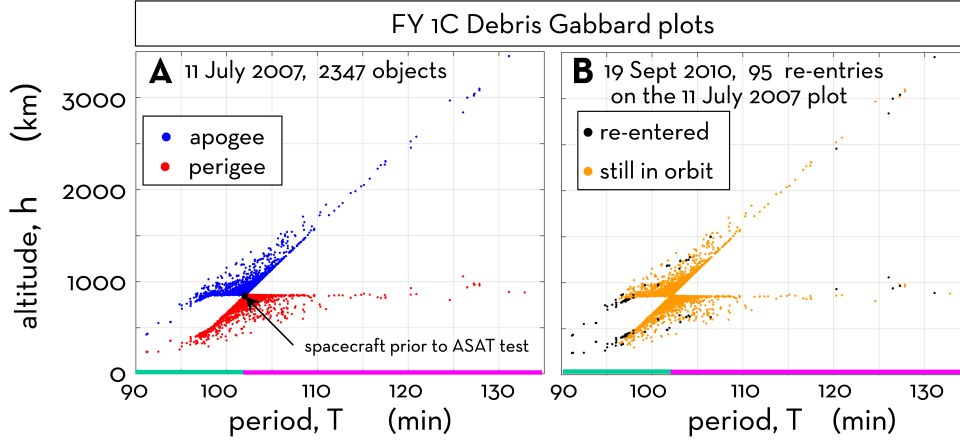


Figure 1. **A**—“Gabbard plot” of height, h (vertical axis) as a function of period, T (horizontal axis), describing the debris cloud generated by the Fengyun 1C ASAT missile test on 11 July 2007, as was presented by Johnson et al. (2008). Thus this plot is for a cloud evolution time after the ASAT test of $t_e = 0.5$ yr. Each of the 2347 pieces of debris tracked generates a pair of dots: a blue dot with a red dot vertically below it, giving its height at apogee and perigee, respectively. The black dot is at the pre-test coordinates of the satellite (T_S, h_S). Debris accelerated forward by the impact was raised to a higher apogee (losing speed and increasing orbit length so the period T rose), but perigee remained at the same altitude as that is the fastest point on each orbit. Debris slowed by the impact falls to a lower perigee (gaining speed so T falls) and in this case apogee stays at the same altitude because that is the slowest point of any orbit. By this time ($t_e = 0.5$ yr), 13 tracked pieces had already re-entered. Part **B** shows the same Gabbard plot as in Part **A** but all objects in the cloud that survived to 19 September 2010 ($t_e = 3.69$ yr) are shown by pairs of orange points and the 95 that had re-entered and burned up in the atmosphere between 11 July 2007 and 19 September 2009 are shown by pairs of black points.

category (1) is by far the dominant one. In addition to the fact that by $t_e = 0.5$ yr 13 objects had re-entered, Figure 1A shows that the processing of the cloud by orbital drag was already detectable by this time as the very lowest T some objects have already lost some height at both perigee and apogee and so were no longer precisely in the fragmentation “open scissors” pattern.

The evolution of the FY-1C debris cloud was predicted by Pardini and Anselmo (2009) and Pardini and Anselmo (2011) using the ballistic parameters of the cloud members and assuming that they remained constant (i.e., no further fragmentations). We need to be clear on the definitions used. Pardini and Anselmo (2009) define the ballistic parameter as

$$\beta = C_D \cdot \frac{a}{m} \quad (1)$$

where C_D is the drag coefficient, a is the reference cross-sectional area, and m is the object mass. This definition represents the sensitivity of an object to atmospheric drag, with larger values corresponding to greater drag acceleration for a given atmospheric density and velocity. For the catalogued Fengyun-1C fragments, Pardini and Anselmo did not determine β from independent measurements of fragment mass, area, and aerodynamic properties. Instead, the ballistic parameters were derived from the B^* values contained in the available orbital Two-Line Element (TLE) tracking data. B^* is the drag-related parameter used by the SGP4 orbit propagator, the analytical model used to propagate TLE orbits (Vallado et al., 2012). Within SGP4, atmospheric drag is represented through an empirical perturbation model in which B^* acts as an effective scaling parameter for the drag terms that modify the satellite’s mean orbital elements over time. It is obtained during orbit determination by fitting the predicted orbit to tracking observations, rather than by directly measuring the physical aerodynamic characteristics of the object. Consequently, although B^* is related to the physical drag term $C_D \cdot a/m$, it is not the same. The fitted B^* value will include uncertainties in atmospheric density models, altitude variations, uncertainties in the reference area and mass, and other orbit-determination errors. Pardini and Anselmo (2009) found that ballistic parameters β derived directly from TLE B^* values were inconsistent with the observed orbital decay of FY-1C fragments over the 15 months after the ASAT test. To obtain more realistic drag parameters, they performed a decay analysis in which the ballistic parameter was adjusted until numerical orbit propagation reproduced the measured semi-major axis evolution of a set of representative fragments. The ratio between these fitted values and the original B^* -derived parameters was used as a scaling factor. The resulting corrections were substantial, the mean of the rescaled β values being higher than the that of the unscaled values by a factor of about 40 (see Figure 8 of their paper).

Pardini and Anselmo (2009) then used their re-scaled ballistic parameters to predict the evolution of the FY-1C cloud forward to 2015. Figure 12 of that paper shows a very interesting and valuable result: although the number of debris pieces in the cloud decreased between 2007 and 2015, the distribution remained the same in shape. That means the average of the ballistic parameter $\langle\beta\rangle$ remained approximately constant. In the later paper, these authors further extended their predictions to 2110 (Pardini & Anselmo, 2011).

An advantage of using a debris cloud to study orbit decline is that, unlike satellites that retain some delta-V propulsion, there are no maneuvers to consider - something that is much more common in recent years as active, controlled de-orbiting becomes accepted standard practice (Ailor & Patera, 2007; Rhatigan & Lan, 2020) and semi-automated or remotely controlled collision avoidance is deployed (Parker & Linares, 2024). The other advantage is that there are very large numbers of objects in a debris cloud. The disadvantage is that the pieces are tumbling and so present a continuously changing cross sectional area a and there is a wide spectrum of particle sizes and, more importantly, of ballistic parameters β . However, the result by Pardini and Anselmo (2009) implies that the average value of β remains roughly constant for the surviving debris in the cloud.

1.2 Thermospheric Heating and Orbit Decay

Thermospheric heating causes the atmosphere to expand, increasing the density at a fixed altitude and hence the drag on objects orbiting in LEO. The two main sources of heating in the upper thermosphere are absorption of solar EUV radiation and electrodynamic Joule heating (Forbes et al., 2025). Other mechanisms, including the dissipation of upward-propagating tides and waves, also contribute to heating, particularly in the lower thermosphere. The full formula for Joule heating is

$$H_{Joule} = \vec{J} \cdot (\vec{E} + \vec{V}_n \times \vec{B}) \quad (2)$$

where $\vec{J}$ is the current density, $\vec{E}$ is the ionospheric electric field in the Earth-fixed (inertial) frame, $\vec{V}_n$ is the thermospheric neutral wind velocity and $\vec{B}$ is the geomagnetic field. The quantity $(\vec{E} + \vec{V}_n \times \vec{B})$ is therefore the electric field in the rest frame of the neutral gas. The heat dissipation is by Pedersen currents (for which $\vec{J} \cdot \vec{E} > 0$) and not by the Hall currents (for which $\vec{J} \cdot \vec{E} = 0$). For a horizontally uniform ionosphere only Hall currents generate geomagnetic disturbance on the ground and, in general, Hall currents make the larger contribution to geomagnetic activity. In the partially ionized thermosphere, a major contribution to H_{Joule} arises from momentum transfer between drifting ions and neutral atoms and molecules through ion-neutral collisions, giving rise to ion-neutral frictional heating:

$$H_{in} = \rho_i \nu_{in} |\vec{V}_i - \vec{V}_n|^2 \quad (3)$$

where ρ_i is the ion mass density, ν_{in} the ion-neutral collision frequency for momentum exchange and $\vec{V}_i$ and $\vec{V}_n$ the ion and neutral velocities. Because the neutral atmosphere responds much more slowly to changes in the electric field than the ion population, temporal fluctuations in $\vec{E}$ increase the ion-neutral drift velocity, viz the difference between $\vec{V}_i$ and $\vec{V}_n$. This means that the heating can occur in two ways: there can be a large steady electric field, to which $\vec{V}_n$ can never fully respond, giving large H_{in} which is associated with large $\vec{J}$ (readily detected by ground-based magnetometers) or there can be fluctuations in $\vec{E}$ to which $\vec{V}_n$ responds more slowly than $\vec{V}_i$. In the latter case, the heating can be subtle and not readily detected in the magnetometer data. Note there is also energy input from particle precipitation, but this is generally smaller than H_{Joule} (Lu et al., 1998; W. Xu, 2011; D. J. Knipp et al., 2004; J. Guo et al., 2012).

The heating of the thermosphere by large and/or rapid fluctuation in $\vec{E}$ during geomagnetic storms is a much-studied phenomenon (Smith et al., 2023; Balan et al., 2011; T. Fuller-Rowell et al., 2013). H. Liu and Lühr (2005) make the point that there are many processes active simultaneously, giving variability to the thermospheric response. The heating and enhanced density of the thermosphere following a storm is short-lived, typically lasting a day. The reasons are that the energy input is largely at high latitude and effects are dissipated as they disperse around the globe. Also upwelling of nitric oxide causes enhanced radiative cooling (Bag & Ogawa, 2024; D. Knipp et al., 2017) and vertical winds can also have a cooling effect (Li et al., 2023; Yamazaki et al., 2024). These storm-time heating events have an effect on orbit degradation that is also short-lived (Oliveira & Zesta, 2019), but Chen et al. (2014) find that storms driven by Coronal Mass Ejections (CMEs) have, in general, lower net effect than (recurrent) storms driven by Corotation Interaction Regions (CIRs) because CIR storms tend to last longer, giving the a greater integrated energy input into the thermosphere. This is consistent with the work of Turner et al. (2009) who found CIR-driven storms last a longer and deposit a slightly larger fraction of the energy extracted from the solar wind into the ionosphere-thermosphere system than do CME-driven ones. These conclusions are also supported by Pokhotelov et al. (2009) and N. Wang et al. (2021).

Tourgaidis et al. (2025) note that energy input into the thermosphere is often underestimated. Some of this is likely because fluctuations in the input electric field are smoothed out in lower-resolution data: non-linearity and the effect of the sluggish response of the neutral wind mean the smoothed input causes an under-estimation in the

power deposited. This has interesting consequences: for example, a northward turning of the IMF when the solar wind density is relatively low can lead to the generation of a “space hurricane” in ionospheric convection through lobe reconnection (Zhang et al., 2021). In these events, northward IMF leads to a drop in the rate of energy transfer across the magnetopause (power) but (Xiu et al., 2024) show that the power deposited in the polar thermosphere goes up because the neutral wind cannot respond to the changed ion convection. The importance to heating events of the sluggish neutral wind response to electric field changes was demonstrated by Lockwood et al. (1988). R. Liu et al. (2010) used the magnetopause reconnection rate to estimate power deposited but this neglects the additional heating caused by temporal variations introduced by the substorm cycle and the response time effects after the IMF orientation changes. The heating effect of smaller ionospheric electric field fluctuations was recently studied by (Matsuo et al., 2021) and a number of other studies are showing considerable heating by geomagnetic currents in quiet and non-storm times (Day et al., 2024; Cai et al., 2022).

We note that (X. Wang et al., 2020) find the Dst index is a better indicator of energy deposition in the thermosphere than auroral or mid-latitude geomagnetic indices. We here use the Dcx index (Karinén & Mursula, 2005) which is a “ Dst -like” index but derived from more stations and using a more robust construction algorithm.

To quantify the EUV heating we use the H_{EUV} index derived by Lockwood et al. (2026). This is the integral of the observed EUV irradiance spectrum, convolved with a theoretical thermospheric heating cross section spectrum. Further details are given in the cited paper.

1.3 The Russell-McPherron (R-M) Effect

The R-M effect (Russell & McPherron, 1973) is the effect of the dawn-dusk component of the Interplanetary Magnetic Field (IMF) in the GSEQ (Geocentric Solar Equatorial) frame on the coupling of mass, momentum and energy from the solar wind flow into the magnetosphere. It is caused by the varying tilt of the Earth’s magnetic axis in a solar frame which alters the southward component of the IMF in the GSM (Geocentric Solar Magnetospheric) coordinate system and hence the transfer of mass, energy and momentum from the solar wind into the magnetosphere. Estimates of the fraction of solar wind energy transferred to the magnetosphere that is subsequently deposited in the thermosphere vary between approximately 10% and 40%, depending on geomagnetic activity level and the adopted estimation of solar wind–magnetosphere energy coupling. The majority of this deposition occurs through heating by ionospheric currents, with auroral particle precipitation providing a smaller contribution (Lu et al., 1998; W. Xu, 2011; D. J. Knipp et al., 2004; J. Guo et al., 2012). Although the fraction deposited in thermosphere is not constant, we know that the R-M effect has a controlling effect on currents in the ionosphere from the associated geomagnetic activity detected by magnetometers (Lockwood, Owens, Barnard, Haines, et al., 2020).

The R-M effect occurs because magnetic reconnection in the dayside magnetopause means that southward-pointing IMF in the GSM (Geocentric Solar Magnetospheric) frame has a controlling influence on energy input into the magnetosphere, but the near-Earth IMF, on average, is oriented in the X - Y plane of the GSEQ frame. The GSM and GSEQ frames share the same X axis but the Z axis of the GSM frame precesses around that of the GSEQ frame on an annual basis due the Earth’s annual orbit and the fixed orientation of Earth’s rotational axis relative to the fixed stars and, to a lesser extent, because the Earth’s magnetic axis (that determines the Z axis direction in GSM) precesses around Earth’s rotational axis on a daily basis. This effect of the tilt in Earth’s magnetic axis means that the dominant IMF B_Y component in the GSEQ frame can add or subtract a significant component to the southward IMF in the GSM frame ($[B_Z]_{GSM} < 0$). This happens most effectively around the equinoxes when the tilt in the Z - Y plane is great-

est and so the R-M mechanism generates a semi-annual variation with equinoctial peaks. The R-M mechanism is not the only one proposed to explain the semi-annual variation in geomagnetic activity, but it does make a unique prediction which can be used to identify it: namely that enhancement of the September equinox peak is caused by IMF $[B_Y]_{GSEQ} > 0$ and that of the March peak is caused by $[B_Y]_{GSEQ} < 0$. This unique signature was used to identify and quantify the R-M effect in geomagnetic currents by Zhao and Zong (2012) and Lockwood, Owens, Barnard, Haines, et al. (2020) and in global mean thermospheric densities by Lockwood et al. (2026).

As pointed out by Lockwood et al. (2026), the R-M effect influences the average pattern of power extraction because it is systematic; however, it is only rarely the dominant effect driving large space weather events. Lockwood et al. (2016) and Lockwood, McWilliams, et al. (2020) show that the dominant origin of southward IMF in GSM ($[B_Z]_{GSM} < 0$) during major terrestrial space-weather events is transient events of southward IMF in the solar frame ($[B_Z]_{GSEQ} < 0$) and that in major events, the R-M effect contributes only a very small fraction to the total negative $[B_Z]_{GSM}$, compared to the effect of negative $[B_Z]_{GSEQ}$. Of course, a favorable/unfavorable $[B_Z]_{GSEQ}$ polarity at a given equinox can enhance/reduce the negative $[B_Z]_{GSM}$ because of the R-M effect, taking it above/below a threshold and so the number of storms exceeding a certain threshold magnitude will show a semi-annual variation (Lockwood, Owens, Barnard, Haines, et al., 2020). However, on its own, the R-M effect cannot cause a large storm and the R-M effect predominantly changes average activity levels rather than causing large events. This makes the detection of the R-M effect on thermospheric densities a significant indicator of average thermospheric heating mechanisms, not just of the large storm-time geomagnetic heating.

Hence detection of the R-M effect in thermospheric densities by Lockwood et al. (2026) implies a quiet-time geomagnetic contribution in addition to the well known storm-time one. We note that this finding is consistent with the results of D. Guo et al. (2015) who sorted the thermospheric data by the sector structure rather than the daily values of the IMF $[B_Y]_{GSEQ}$ component. We also note that Cai et al. (2022) have detected effects of the IMF B_Y component on the middle atmosphere and lower thermosphere.

2 Update on the FY-1C debris cloud

The orbital parameters of the tracked debris from the FY-1C ASAT test have been derived from the TLEs obtained from the Space Track website (<https://www.space-track.org>). The reentry dates are taken to be when debris fell below about 120 km and are given by the DISCOS database.

Figure 2A shows the Gabbard plot for 19 September 2010 ($t_e = 3.69yr$). This date is chosen as, by then, identification of trackable debris pieces was almost complete. In addition, some evolution of the Gabbard plot has taken place by this time and a total of 108 tracked debris pieces had re-entered by then (15 and 95, respectively, before and after 11 July 2007). On this date, the $T > T_S$ subset comprised 1015 objects and the $T < T_S$ subset comprised 1044 objects. As 89 of the 108 known re-entered objects initially had $T < T_S$ (and so 19 initially had $T \geq T_S$) we should add these numbers to the total for that subset, yielding that in the ASAT test 47.74% of the debris of trackable size were accelerated, and raised in altitude (the $T \geq T_S$ subset) and 52.26% were decelerated and lowered in altitude ($T < T_S$): however, we should note uncertainties here as there will have been a number of early reentries of undetected objects, nevertheless the initial split seems to have been close to 50% in both categories.

The processing by atmospheric drag of the $T < T_S$ subset by $t_e = 3.69yr$ can be seen in Figure 2A where more objects have lost height at both apogee and perigee. What is noticeable is that this loss in altitude extends mainly up to $T = 98min$ which was the

same in Figure 1A, but more objects now have periods below this period. However there are also a small number that have lost height at $98 \text{ min} < T < T_S$ and the gap between apogee and perigee is closing, so there is tendency for orbits to move to lower ellipticity, e , which is discussed further below.

Parts B and C of Figure 2 show the evolution of the debris cloud over the subsequent 14.25 years by comparing with the situation on 31 December 2024 ($t_e = 17.97 \text{ yr}$). Part B shows the Gabbard plot on this date. It can be seen, that the $T > T_S$ subset is similar in form but the decline in both apogee and perigee means that the gap between the subsets has closed down completely in the $T < T_S$ subset: hence ellipticity e has continued to decline and become zero for many objects (where the red and blue areas touch). However there are still objects with $e > 0$ as both red and blue areas at $T < T_S$ have width in altitude. There were a further 910 known reentries in the interval $3.69 < t_e < 17.97 \text{ yr}$, making 1018 in total by $t_e = 17.97 \text{ yr}$. The black dots in Part C give the position on the Gabbard plot for 19 September 2010 of objects that re-entered before 31 December 2024 (the orange dots underneath are the full Gabbard plot for 19 September 2010). It can be seen that they cluster on the inner edges of the $T < T_S$ subset showing that the more circular orbits tend to re-enter first. Part D shows that 75.1% of all reentries before 1 January 2011 came from the $T < T_S$ subset on 11 July 2007 and only 24.9% came from the $T > T_S$ subset. The most common orbital period (on 11 July 2007) that had resulted in reentry was $T = 101 \text{ min}$. The reentries from the $T > T_S$ subset were mainly from initial periods $T \leq 106 \text{ min}$ and just 5.1% coming from $T > 106 \text{ min}$ and 25.1% coming from $T > 112 \text{ min}$.

Figure 3 shows the numbers of FY-1C debris objects still in orbit on 31 December 2024 that have undergone a given height loss over the 14.25 years between the dates of the Gabbard plots in Figures 2A and 2B. Parts A, B and C show the histograms for loss in mean height, apogee height and perigee height, respectively. In all three plots the green histogram is for the $T < T_S$ and subset, the mauve for the $T \geq T_S$ subset and the blue for the whole cloud. The figure shows that falls have been smaller for perigee than apogee, indicating a trend towards more circular orbits. This is consistent with analyses of the effects of thermospheric drag, which show that both the mean altitude and the orbital eccentricity decrease with time (G. Xu et al., 2011). Atmospheric drag is greatest during passage through perigee, where both the orbital speed and the thermospheric density are highest. Consequently, orbital energy is removed most efficiently near perigee where the both the object velocity and the thermospheric density are greatest. The specific energy of an orbit ϵ is the sum of the kinetic and potential energies per unit mass. For an elliptical orbit

$$\epsilon = -\frac{\mu}{2a} \quad (4)$$

where a is the semi-major axis of the ellipse and μ is the product $G \times M_E$ where G is the gravitational constant and M_E the Earth's mass. Note ϵ is negative, the maximum value being zero at an infinite distance from the Earth. The atmospheric drag reduces ϵ (makes it more negative) and so reduces a ($\delta a < 0$). The radial distances of perigee and apogee are

$$r_p = a(1 - e) = h_p + R_E \quad (5)$$

$$r_a = a(1 + e) = h_a + R_E \quad (6)$$

where R_E is a mean Earth radius. Differentiating with respect to time we have in unit time

$$\delta r_p = (1 - e)\delta a - a\delta e \quad (7)$$

$$\delta r_a = (1 + e)\delta a + a\delta e \quad (8)$$

If we take equation 7 in the small change limit so $\delta r_p \rightarrow 0$ we have

$$\delta e \approx (1 + e)\frac{\delta a}{a} \quad (9)$$

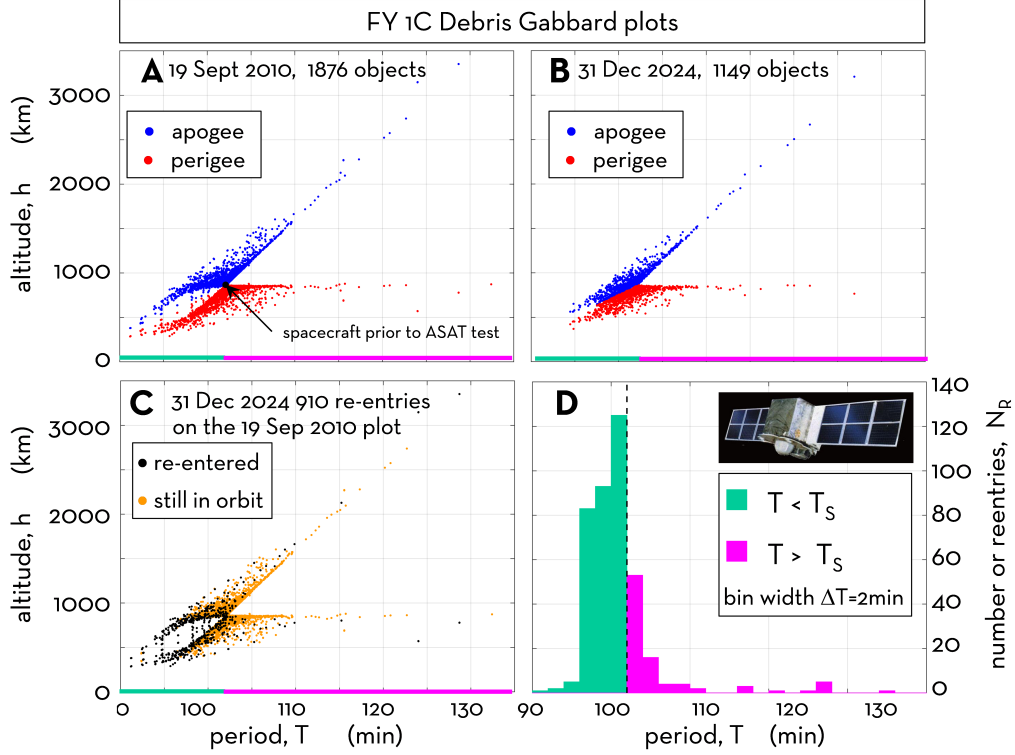


Figure 2. **A.** Gabbard plot describing the FY-1C debris cloud on 19 September 2010 ($t_e = 3.69$ yr). **B** The corresponding Gabbard plot of debris still in orbit on 31 December 2024 ($t_e = 17.97$ yr). **C** is in the same format as Part **B** of Figure 1B but the black points are reentries that occurred in the interval between the two dates shown in Parts **A** and **B** (3.69 yr $< t_e < 17.97$ yr), whereas the orange points are the Gabbard plot for $t_e = 3.69$ yr of the objects that are still in orbit at $t_e = 17.97$ yr. Part **D** shows a histogram of the orbital periods on 11 July 2007 of the 1005 debris pieces that had subsequently re-entered by 31 December 2024 (remember 13 had re-entered before 11 July 2007 so the total by 31 December 2024 was 1018): the mauve part is for $T > T_S$, and so is debris from the raised-apogee part of the cloud, whereas the green part for $T < T_S$ and is from the lowered-perigee part of the cloud.

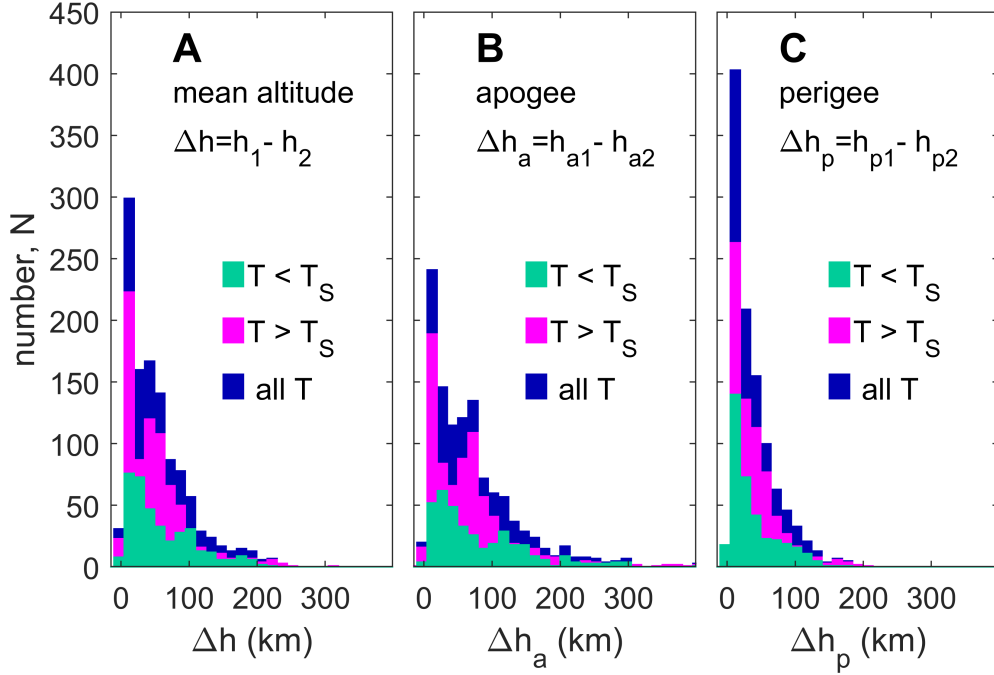


Figure 3. The decay in orbit altitudes over fourteen and a quarter years (height losses Δh , Δh_a and Δh_p) between 19 September 2010 (time 1) and 31 December 2024 (time 2). Histograms of height lost are shown for: **A** average orbit height h ; **B** apogee altitude, h_a and **C** perigee altitude h_p . In each panel the total number is shown by the blue histogram, and the green and mauve areas shown the number from the $T < T_S$ and $T \geq T_S$ subsets, respectively. Height loss bins are 15 km wide.

Hence $a\delta e$ is negative (because in Equation 9 $\delta a/a < 0$ and $(1 + e) > 0$) and the second terms in Equations 7 and 8, are smaller in magnitude than the first (because $|\delta a/a|$ is small). Hence

$$\delta r_a < \delta a < \delta r_p < 0 \quad (10)$$

Hence h_a and h_p both decrease but h_a decreases by more than h_p and so e decreases. Thus fragments approaching reentry are generally in more circular orbits than they were immediately after the ASAT event.

The shapes of the perigee-height-loss distributions in Figure 3 are similar for the $T < T_S$ and $T \geq T_S$ subsets, and consequently for the cloud as a whole. This is not true of the apogee-height-loss distributions, which are bimodal, with a relative minimum between two distinct peaks. As for the perigee-height losses, the primary peak lies close to zero. However, the secondary peak occurs at approximately 72 km for the $T \geq T_S$ subset (objects raised by the ASAT test) and at approximately 132 km for the $T < T_S$ subset (objects lowered by the ASAT test).

Figure 4 shows the orbital decay of the 1018 pieces of FY-1C debris that re-entered before 2025 for which we have reasonably complete tracking data. The mean altitude

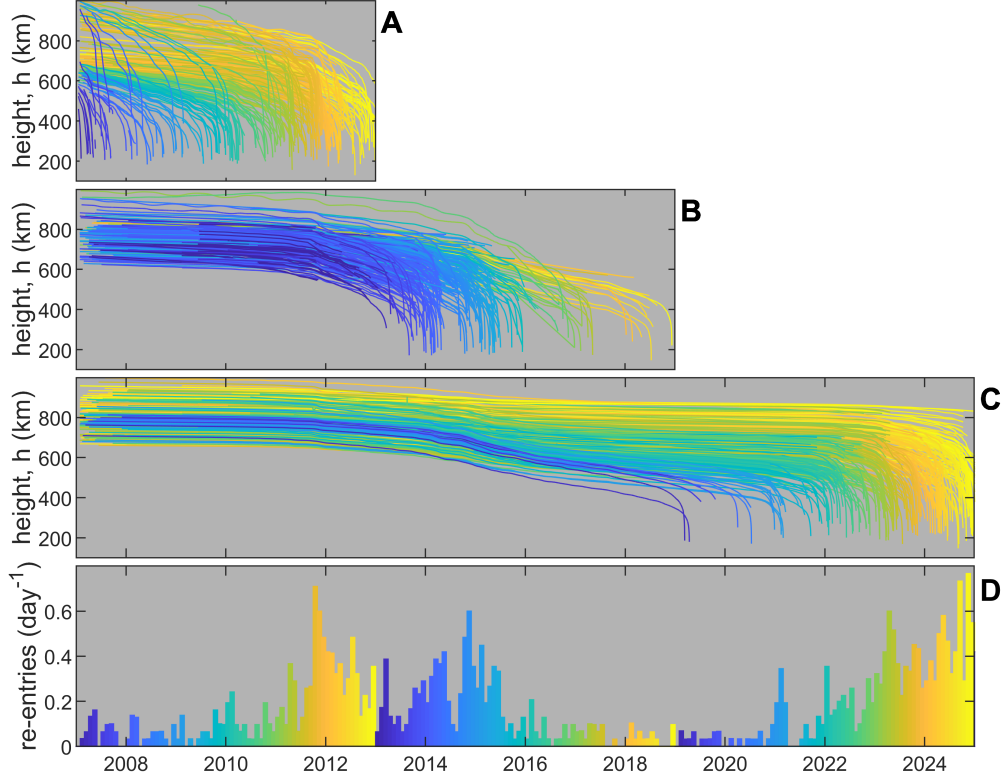


Figure 4. The trajectories of the 1018 FY-1C debris pieces that have re-entered between the ASAT test and 1 January 2025 and for which we have a complete tracking record. Parts **A**, **B**, and **C** are for reentry dates in 2007-2012, 2013-2018 and 2019-2025, respectively. The mean orbital altitude of each piece is plotted using colors that evolve through each interval from dark blue through to yellow. Note that trajectories for later reentries are drawn first and so tend to be over-written by ones for earlier reentries. Part **D** shows the reentry rate r_d for the whole interval in a colored histogram, using the same colors as for the trajectories.

(over a full orbit), h is plotted as a function of time for each piece. To prevent the traces from later reentries completely over-writing earlier ones, we have divided the interval into three 6-year intervals and plotted the full trajectories for debris re-entering in that interval. Within each of the three intervals we have color-coded the trajectories by reentry date (from dark blue to yellow with increasing date) and plotted earlier reentries last so that they are not over-written, and so hidden from view, by later ones. Note the increased rate of descent in panel **C** at h above 500 km between 2011 and 2016 and the increased rate of reentries seen simultaneously at lower h in panels **A** and **B** and quantified in panel **D**. This interval is around the sunspot maximum of solar cycle 24. From the trajectories we compute daily values of the average rate of decent $v = \langle -dh/dt \rangle$ in overlapping altitude bins of width 200 km centered of [400:100:900] km. These average values in descent speed will, in general, vary for two reasons: (1) thermospheric density variations that will be correlated at the different heights and (2) changes in the average β of the cloud which will be altitude-dependent. The work of Pardini and Anselmo (2009) shows that effect (2) is small, at least relatively early in the life of the cloud.

The trajectories of the same objects as shown in Figure 4 in height-time coordinates are plotted on Gabbard plots (height-period coordinates) in Figure 5 and show interesting behavior. A total of 157 objects with initial $T > T_S$ of the accelerated debris

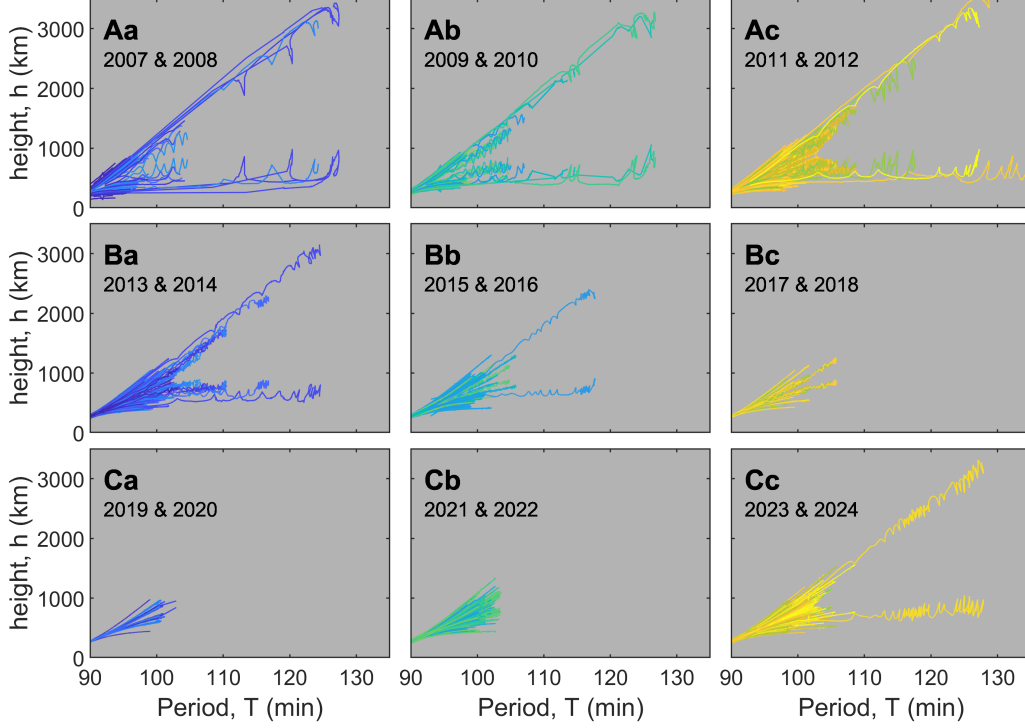


Figure 5. The trajectories of the 1018 FY-1C debris pieces shown in Figure 4 on Gabbard plots. Because these trajectories overlap more in this h - T frame than in Figure 4, Parts **A**, **B**, and **C** of Figure 4 are here split into three 2-year subparts (labelled **a**, **b**, and **c** in each case). The color scheme used is as in Figure 4 and again the first entries are plotted last to minimise overplotting.

Table 1. The numbers of fully tracked debris cloud objects on 19 September 2007 ($t_e = 3.69 \text{ yr}$) and 31 December 2024 ($t_e = 17.97 \text{ yr}$), for which the Gabbard plots are shown in Parts **A** and **B** of Figure 2 and for which the numbers (in various categories) were N_1 and N_2 , respectively. The TLEs for 19 September 2007 are missing f_1 objects which first appear in later TLEs and these have been added in the revised estimates for 19 September 2007 in the $N_1 + f_1$ column. Continuity shows that 392 objects were transferred by orbit decay from the $T \geq T_S$ subset to the $T < T_S$ subset, showing how the descent of the population that was accelerated in the ASAT test partially offsets the loss of the $T < T_S$ subset of the cloud due to reentries.

	number at $t_e = 3.69 \text{ yr}$	found later	revised number	number at $t_e = 17.97 \text{ yr}$	change	reentries	transfer
	N_1	f_1	$N_1 + f_1$	N_2	$\Delta N_{12} = N_1$ $+ f_1 - N_2$	r	$r - \Delta N_{12}$
$T < T_S$	887	157	1044	683	361	753	+392
$T \geq T_S$	989	26	1015	466	549	157	-392
<i>Total</i>	1876	183	2059	1149	910	910	0

that rose in apogee the fall to Earth by $t_e = 17.97 \text{ yr}$ - those falling from very high T can be clearly seen. They all subsequently fell down the crossed lines of the Gabbard plot as T and h_a fall but h_p stays almost constant. Some show a tendency to briefly move away from the apogee and perigee lines but then recover back to them. These are likely to be objects that have some inaccurate tracking data points. Another interesting feature is that this decay of the very high T objects to reentry ceases almost completely in Parts **Bc**, **Ca** and **Cb** (and there are only 3 such objects in Part **Bb**; and those are the intervals when sunspot numbers are low. Figure 2**D** shows that in total there have been just 25 of these rapidly descending objects that fell from $T > 112 \text{ min}$ to re-entry, which is the extreme tail of the pink distribution in Figure 3**B**. Figure 3 also shows that, in addition to these rapid descending objects of the $T \geq T_S$ population (presumably objects with a high β), there is a population that drops in apogee much more slowly. This acts as a supply of debris near $T = T_S$ which then joins the $T < T_S$ (decelerated) population in starting its descent towards the reentry altitude. Hence the population accelerated to $T > T_S$ by the test acts as a reservoir feeding particles into the reentry spiral from the top and very few of the accelerated objects have declined enough in period and apogee to join the decelerated objects in the reentry spiral.

The reservoir action of the accelerated half of the cloud (with $T \geq T_S$) is quantified in Table 1. The table shows that the majority of reentries over the interval 19 September 2007 to 31 December 2024 was from the decelerated part of the cloud ($T < T_S$), the number or reentries, r being 753 and 157 for $T < T_S$ and $T \geq T_S$, respectively. However, the decay of the $T < T_S$ subset was not as great as that for the $T \geq T_S$ subset because 392 objects decayed in period T and altitude h such that they moved out of the $T \geq T_S$ subset and into the $T < T_S$ one.

Part **A** of Figure 6 compares the rate at which FY-1C debris has re-entered with the reentry rate of debris from the collision of the Iridium 33 and Kosmos 2251 satellites which took place on 10 February 2009 at an altitude of 789km. This generated a total of 1603 trackable debris pieces from Kosmos 2251 and 598 from Iridium 33, giving a total of 2201. In both cases, the reentry rates are counted daily in sliding 15-day intervals. Interestingly, despite the different fragmentation altitudes and dates, the reentry from this collision correlates well with that from the FY-1C ASAT test. The correlation coefficient for these two reentry rates is $r = 0.657$ for which the p -value (the prob-

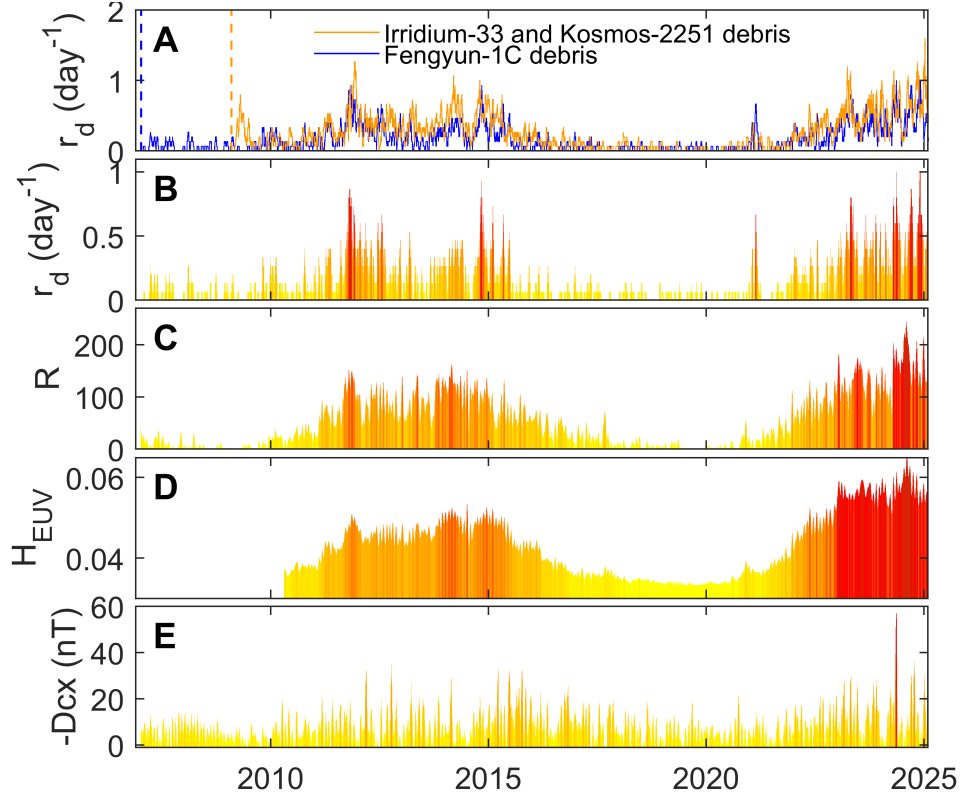


Figure 6. Part **A** shows daily average reentry rate of debris, r_d , in sliding 15-day intervals. The blue line is for debris from the Fengyun 1C (FY-1C) ASAT test on 11 January 2007 and the orange line is for debris from the collision between the Iridium33 and Kosmos2251 satellites on 10 February 2009. The vertical dashed lines mark the dates of those two events. Part **B** repeats the r_d data for FY-1C in a colored-histogram format for comparison with other panels. Parts **C**, **D**, and **E** show daily values of, respectively, the sunspot number R , the thermospheric EUV heating index derived from data from the Solar Dynamics Observatory H_{EUV} and the negative of the Dst geomagnetic index.

ability of obtaining a correlation of this magnitude by chance, assuming no true correlation exists) is essentially zero. (Indeed the very long time series of data used here means that all correlations described in this section have p -values that are indistinguishable from zero.) This implies that there is a sufficient reservoir of objects in both debris clouds that the solar activity variation causes a very similar reentry rate from the two.

The solar cycle effect on the thermospheric densities is apparent in the FY-1C reentry rates r_d shown Figure 6B.. The correlation of FY-1C debris reentry rate r_d with sunspot number, R , is $r_R = 0.717$. In fact, a slightly higher correlation is obtained for the EUV thermospheric heating index H_{EUV} . This is derived from observed spectra from the Extreme Ultraviolet Variability Experiment (EVE) instrument on NASA's Solar Dynamics Observatory (SDO) satellite which is in an inclined geosynchronous orbit around the Earth and which covers the wavelength range from 1 nm to 120 nm. The spectral intensities are multiplied by model heating efficiencies as also deployed in the TIE-GCM thermosphere-ionosphere coupled model. These are linearly interpolated to the EVE wavelengths. The EUV heating index, H_{EUV} is the integral over the EVE wavelength band of the EUV irradiance multiplied by the heating efficiency at each wavelength. Further details are given in Lockwood et al. (2026). The correlation coefficient between r_d and H_{EUV} is $r_H = 0.730$, which is only very slightly higher than r_R . That the correlations for R and H_{EUV} are so similar is not surprising as the correlation between these two solar parameters is $r_{RH} = 0.944$. However the difference between r_H and r_R is statistically significant. Using the Meng-Z test, which allows for r_{RH} (Meng et al., 1992), the p -value for the null hypothesis that r_R and r_H are the same is only $p_{RH} = 9 \times 10^{-6}$. However, we note that there are several simultaneous spikes in r_d and R that are not found in H_{EUV} some of which (but not all) also coincide with spikes in $-Dcx$. These transient events are not, therefore, caused by EUV irradiance.

Lastly there is an correlation between $-Dcx$ and r_d , with a weaker correlation coefficient of $r_{-Dcx} = 0.292$. This is a considerably lower correlation but still statistically significant with a p value that is still indistinguishable from zero.

Figure 7 shows the variations of the numbers of tracked FY-1C debris objects that re-entered before April 2025 in various (overlapping) height ranges. The grey area in Part A shows the number of reentries prior to the date. Note that numbers in all height ranges decline after decimal year 2021.5 because the plot is only for objects that re-entered before 2025.35 (1 April 2025). Before 2021.5 the three height ranges above 600 km (the black, mauve and orange lines) show continuous declines that are most rapid during the enhanced solar activity of solar cycle 24. What is interesting is that the objects lost from above 600 km are well balanced the loss rate from the 500-700 km band (in blue) to lower altitudes. This means that the numbers at this height remain remarkably constant: even a small but rapid loss from this height at the start of increased solar activity in cycle 24 (around 2011.8) is replenished. This appears to be the near constant reservoir of objects ready to decay into reentry invoked in relation to Figure 6A and that explains why the solar cycle variation is so clearly seen in reentry rate (as opposed to that rate reflecting the accumulated solar activity over the objects' lifetime in orbit. At altitudes between 400-600 (cyan line) we see a similar constancy with a very slight rise in numbers over time.

Numbers at 300-500 (in purple) are low and constant on average but with fluctuations. Those are more easily seen in Part B where it is re-plotted on an expanded scale (again in purple).

Also plotted in Figure 7B as a gray filled area is the number of reentries. It can be seen after an initial rise caused by objects first descending to populate the 300-500 height range, the variations match the reentry rate, but not precisely as there is a variable lag. Around 2012 and 2015 there are near simultaneous peaks in the two traces show-

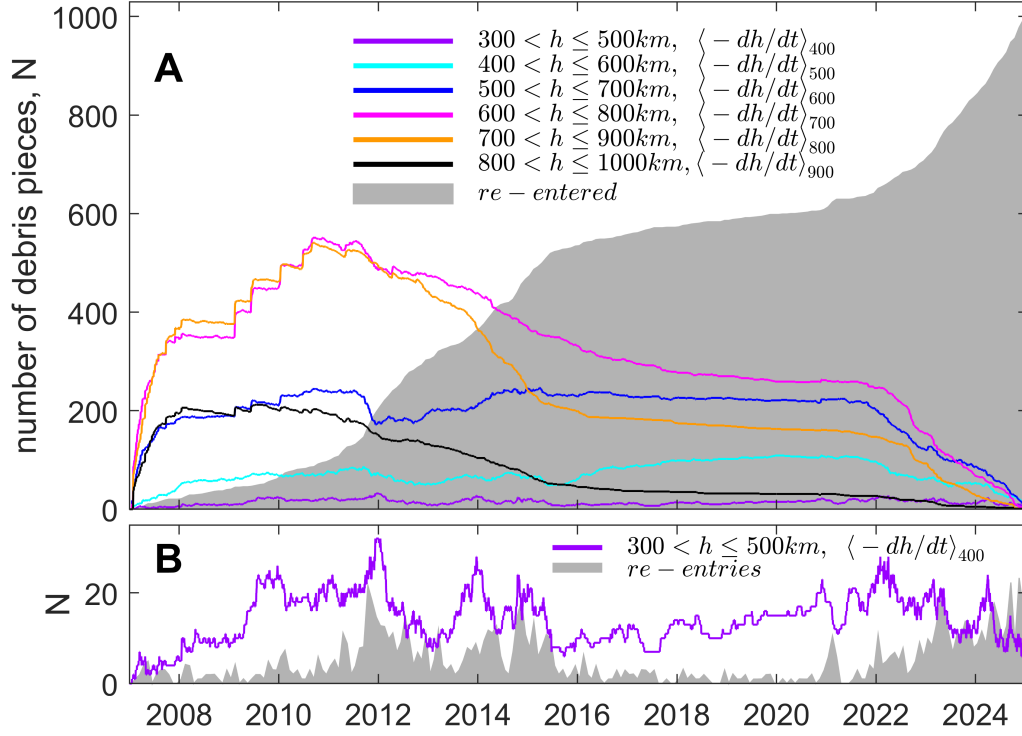


Figure 7. **A.** Time series of the number of the FY-1C debris particles that all re-entered before April 2025, N in overlapping altitude ranges 200 km wide. Note the step increases in numbers before 2011 revealing the efforts to discover, catalog and track debris pieces. The gray histogram gives the total number of them that had re-entered as a function of time. **B** the number in the lowest altitude bin ($300 < h \leq 500$) in purple and the variation in the reentry rate is shown by the gray histogram.

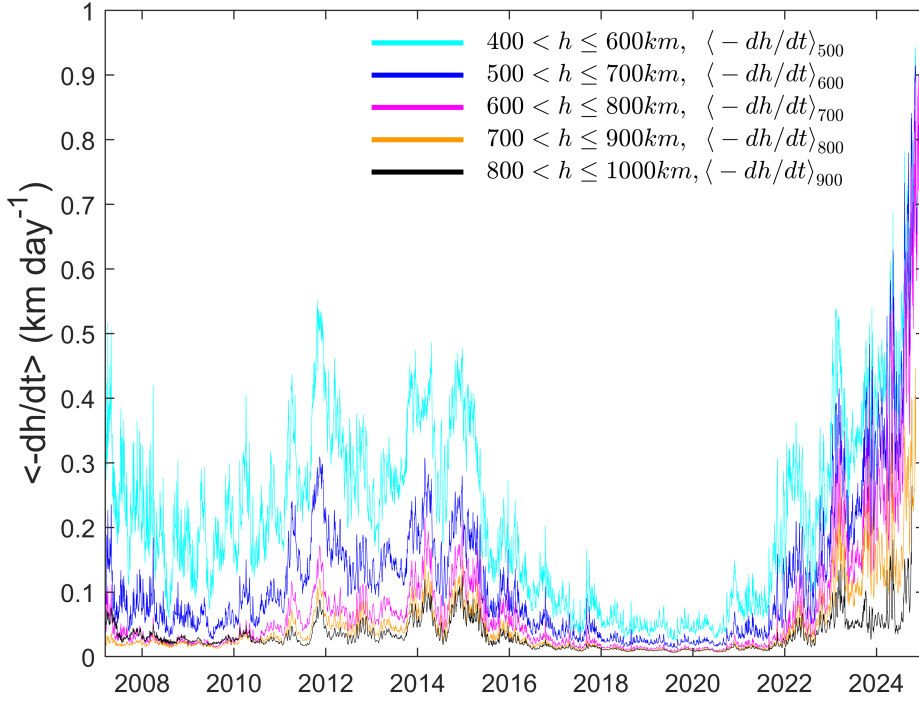


Figure 8. Time series of average rate of daily height loss $\langle -dh/dt \rangle$ for 5 of the 6 height ranges shown in 7. (The lowest altitude bin is omitted as there are insufficient numbers and because the descent of particles is very much more rapid at lower h , and individual reentry events have much large influence on the mean values at these lower h).

ing objects orbit rapidly decaying from above 500 km to reentry. On the other hand, around 2014 and 2015 there is a clear lag in reentries showing a slower orbit decay.

Figure 8 shows the average daily rates of descent in the same height ranges as Figure 7. The purple line is omitted as it is noisy because sample numbers are generally below 30 (as seen in Figure 7). The variations clearly correlate highly with sunspot number R and the EUV heating index H_{EUV} shown in Figure 6. The correlation coefficients r_{dhR} between $\langle -dh/dt \rangle$ and R are 0.764, 0.843, 0.797, 0.805 and 0.726 for $\langle h \rangle$ of 500, 600, 700, 800, and 900km, respectively. For H_{EUV} they are r_{dhH} of 0.880, 0.911, 0.868, 0.879, and 0.846. However scatter plots (see Section 6) shows a clear dependence on H_{EUV}^2 which yields very slightly higher correlations r_{dhH^2} of 0.889, 0.915, 0.874, 0.897 and 0.854. The Meng-Z test shows the correlations are significantly higher for H_{EUV}^2 than for H_{EUV} (and those for R) in every case, even though they are numerically only slightly greater with p -values against the null hypothesis that r_{dhH^2} and r_{dhH} are the same that are indistinguishable from zero except for the h bin centered on 600km, for which $p = 1.641 \times 10^{-4}$.

We also investigated if we could detect an additional contribution of geomagnetic activity using the Dcx index. We experimented with two functional forms:

$$(-dh/dt)_{fit1} = a_1 \cdot H_{EUV}^2 + b_1 \cdot Dcx \quad (11)$$

and

Table 2. Fits to the $\langle -dh/dt \rangle$ values for the data from 2007–2024 (6384 daily samples) that give peak correlation coefficients. The top 2 lines are the fit using H_{EUV}^2 , the next 4 for fit 1 given by Equation 11 and the last 5 for fit 2 using Equation 12. All coefficients are for H_{EUV} in $W m^{-2}$, dh/dt in $km dy^{-1}$, and Dcx in nT. The Meng-Z p-values are against the null hypothesis that the correlations r_1 and r_2 (for fits 1 and 2, respectively) are the same as that for H_{EUV}^2 , r_{dhH2} .

Fit & parameter for $\langle h \rangle$ of:	500 km	600 km	700 km	800 km	900 km
H_{EUV}^2 , correlation r_{dhH2}	0.8890	0.9130	0.8740	0.8970	0.8540
H_{EUV}^2 , p-value	0	0	0	0	0
Fit 1, correlation r_1	0.8890	0.9130	0.8740	0.8970	0.8560
Fit 1, coefficient, a_1	187.3116	142.7837	106.2078	63.6653	29.8254
Fit 1, coefficient, b_1	-0.0012	-0.0011	-0.0010	-0.0006	-0.0004
Fit 1, Meng-Z p-value	0.4742	0.4846	0.4478	0.4858	0.3659
Fit 2, correlation r_2	0.8889	0.9170	0.8857	0.9078	0.8614
Fit 2, coefficient, a_2	187.3116	142.7837	106.2078	63.6653	29.8254
Fit 2, coefficient, b_2	-0.0016	0.0029	0.0040	0.0023	-0.0016
Fit 2, coefficient, c_2	0.2225	-1.7565	-2.2482	-1.3082	-0.4487
Fit 2, Meng-Z p-value	0.4775	0.1154	0.0068	0.0028	0.0939

$$(-dh/dt)_{fit2} = a_2.H_{EUV}^2 + b_2.Dcx + c_2.H_{EUV}^2.Dcx \quad (12)$$

For the full dataset, both these equations gave slightly higher correlations than the r_{dhH2} values at all heights. However, the differences using Equation 11 were not significant according to the Meng-Z test at the 2σ level. On the other hand, using Equation 12 for all height bins except the lowest one, the correlations were significantly higher. The correlations, p -values and coefficients are given in Table 2.

Figure 8 and the correlations demonstrate that the temporal variation of $\langle -dh/dt \rangle$ is very similar at all h but not quite identical. Descent speeds are greater at lower h as expected for orbital decay and so the solar cycle fluctuation amplitudes in descent speed are smaller at greater h . If we take the mean over the height range 400 to 1000 km and correlate it with the time series for each of the 200 km wide bins we find correlations of 0.950, 0.990, 0.946, 0.948 and 0.917 for the height bins centered on h of 500, 600, 700, 800 and 900 km , respectively. (The p values against the null hypothesis of there and all correlations quoted in this section are indistinguishable from zero). Taking means over a year, these correlations become 0.964, 0.983, 0.949, 0.952 and 0.945. Hence long-term trends and short term variations at different heights are both well correlated across the altitude range. For the bin centered on 400 km , the correlations are still highly significant but slightly lower (0.775 for daily data and 0.700 for annual means).

The significance of these high correlations at different heights (both short term and long term) is that they limit how much effect changing debris drag coefficient, $\langle \beta \rangle$ is having. If a large change in $\langle \beta \rangle$ were occurring the effect would propagate downward through the altitude bands. This will eventually occur as the higher β objects decline in number and the correlations between the height ranges would decline. Thus the near constant $\langle \beta \rangle$ found by Pardini and Anselmo (2009) for 2007–2015 appears to have remained approximately valid over the interval studied here. We attribute this to the replenishment effect of the $T \geq T_S$ subset of the cloud which has fed a full spectrum of β value objects into the $T > T_S$ subset and the re-entry spiral.

3 The spectra of variations in the thermospheric densities and in orbit decay

It is instructive to look at the spectra of temporal variations of descent speeds and related parameters. This is done in Figures 9 and 10. In both Figures Part **A** shows autocorrelation functions (a.c.f.s) and Part **B** shows Fourier spectra. The X-axis in both figures is logarithmic and the gray vertical lines mark periodicities at 7 days; a Carrington Rotation period (1 *CR*), and its harmonics 2 *CR* and 3 *CR*; 0.5 *yr* (semiannual); 1 *yr* (annual) and 2 *yr* (biennial).

Figure 9 is for causal factors in altitude decrease such as E_{EUV} , Dcx and the thermospheric densities at 250, 400 and 550 *km* from the NRL empirical model (Emmert et al., 2021) (ρ_{250} , ρ_{400} , and ρ_{5500} , respectively). The E_{EUV} and Dcx data used cover 2007-2025 (the same as the descent speed data $\langle -dh/dt \rangle$ shown in 10. The thermospheric densities show periodicities at all the gray lines (except, obviously, 1 week) and the a.c.f.s actually show a great many higher harmonics of the solar rotation period.

The H_{EUV} index (mauve lines) shows the solar rotation period and harmonics. As would be expected it does not show the semi-annual or biennial periodicities but it does show a knee (rather than a peak) in the a.c.f. at the annual periodicity which is seen as a clear peak in the Fourier spectrum. This variation is expected from the annual variation in Sun-Earth distance r_{SE} which gives a r_{SE}^{-2} variation in EUV irradiance at Earth. The *CR* periodicity (and its harmonics) is generated in H_{EUV} by longitudinal structure in the EUV sources on the Sun.

The Dcx index (black lines) shows all the variations seen in thermospheric densities, including the semi-annual variation, the solar rotation period and its harmonics. In this case the *CR* periodicity and its harmonics is generated by longitudinal structure in the sources of enhanced space weather on the Sun.

Figure 10 is the same as Figure 9, for the variations in the descent speed $\langle -dh/dt \rangle$ shown in Figure 8. The same periodicities can be seen as in Figure 9 but the solar rotation harmonics are stronger and cause some beating with the semi-annual variation. The most consistently strong peaks are the solar rotation and the semi-annual variation. Note that although the former is strong in the EUV heating index H_{EUV} , the semi-annual variation is almost absent in that index. However it is a strong feature of the Dcx geomagnetic index. It is also seen strongly in the NRL empirical model thermospheric densities (which, of course are derived from satellite orbit decay data) and by identifying a partial contribution of the Russell-McPherron effect, Lockwood et al. (2026) have shown that there is a causal mechanism between part of the semi-annual variation in geomagnetic activity and a roughly half of the semi-annual variation in thermospheric densities.

4 A study of the year 2024

The year 2024 is an interesting one to study because of the range of activity levels that were present in the year. At its start, space weather conditions were relatively quiescent despite the rising sunspot number of solar cycle 25. That changed dramatically with the major space weather storm of 10-11 May 2024, which was followed by three more significant storms before the end of the year.

Figure 11 summaries the space weather conditions during 2024 and compares them to the statistical distributions for the same time of calendar year, F . In each panel the gray-shades areas are bounded by the $\pm n\sigma$ contour variations, as a function of the Fraction of the calendar year, F ; with n varying from 1 to 4 with increasingly lighter shades of gray. In each panel the distributions as a function of F are compiled using all available samples of that parameter. Hence 68.27% of all samples are in the darkest gray area, 95.45% in the next darkest, 99.73% in the next and 99.99% in the lightest gray area.

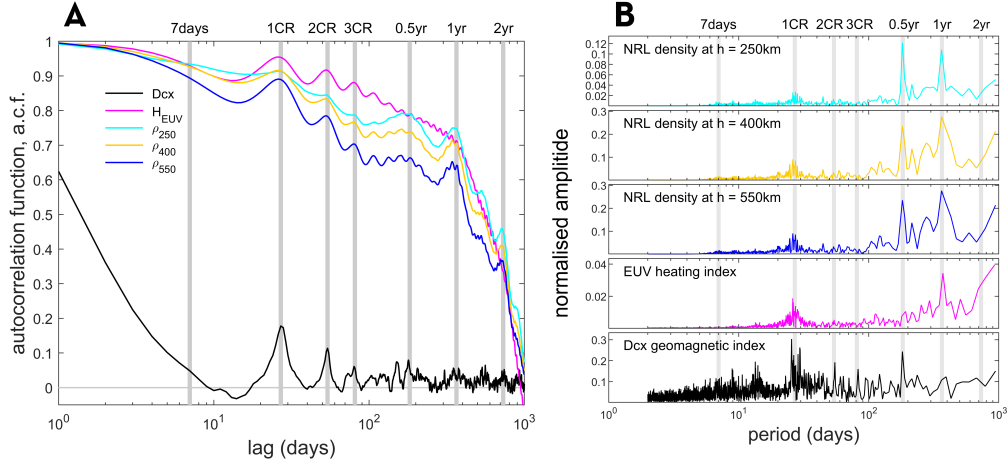


Figure 9. The spectra of variations of parameters relevant to the thermosphere. Part **A** shows the autocorrelation function (a.c.f.) and part **B** the Fourier spectrum (normalized by dividing by the mean value of the parameter). In both cases, the lines are for: (black) the Dcx geomagnetic index, mauve the EUV heating flux H_{EUV} (the integrated EUV spectrum convolved with the thermospheric heating efficiency spectrum); the cyan, orange and blue lines are thermospheric densities from the NRL empirical model (Emmert et al., 2021) at heights h of 250 km, 400 km and 550 km, ρ_{250} , ρ_{250} and ρ_{550} , respectively. The vertical gray lines show the periods of 7days, 27 days (close to the Carrington solar rotation period, 1CR) and its harmonics at 2CR and 3CR, and the semi-annual, annual and biennial periods.

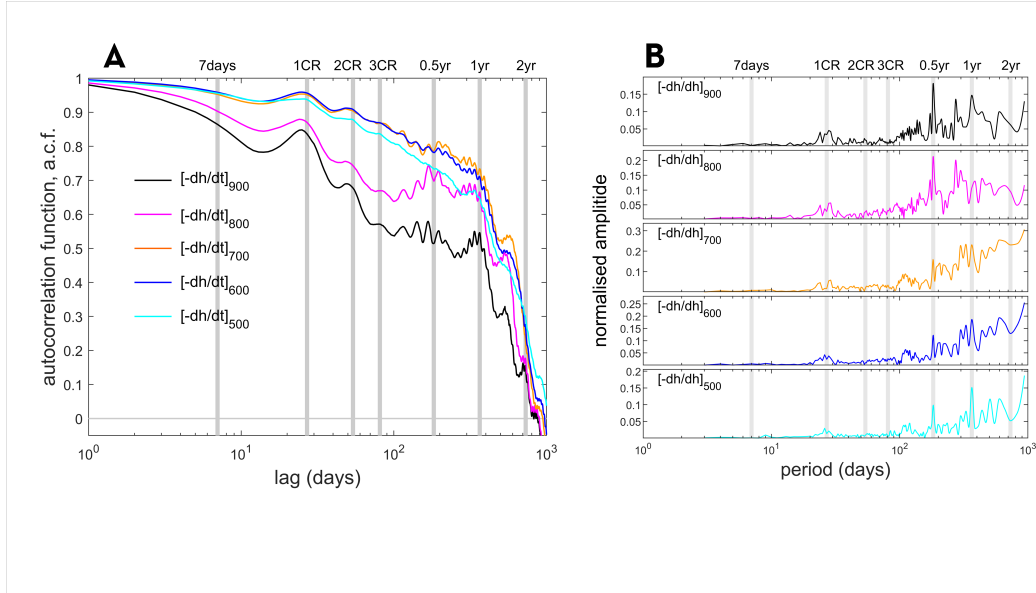


Figure 10. Plot corresponding to Figure 9 for the variations in the daily average rate of descent of FY-1C debris shown in Figure 8. The colors are for the means over the same altitude ranges as used in Figure 8.

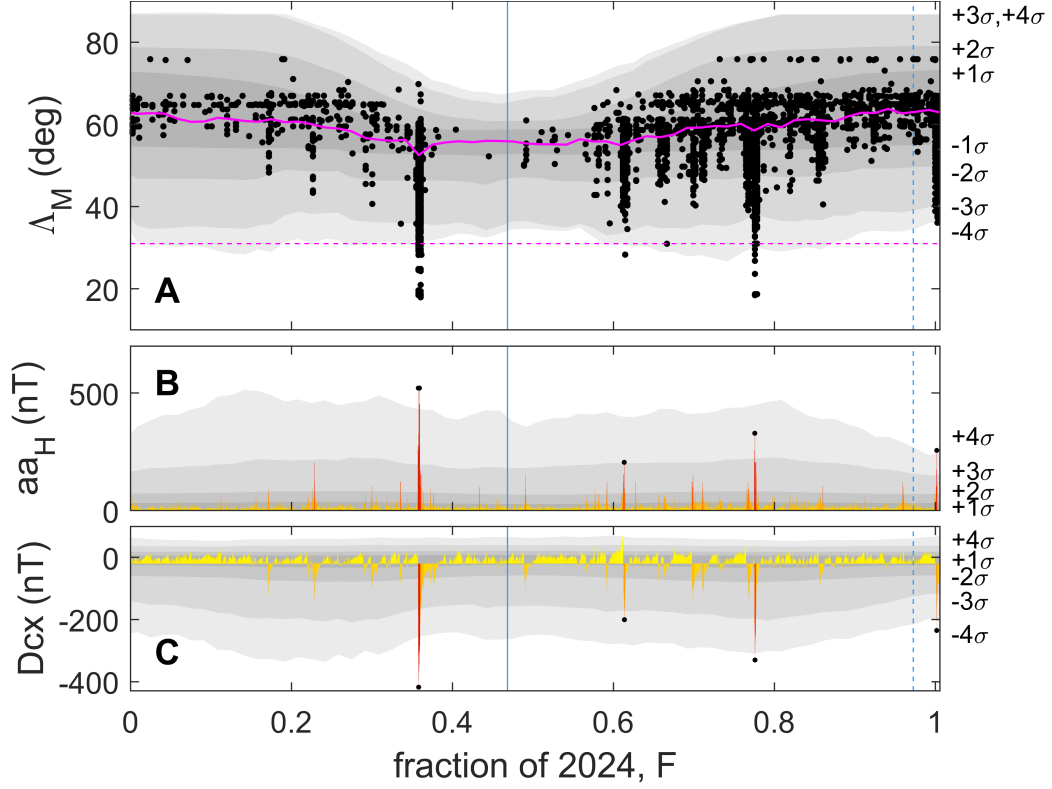


Figure 11. Auroral and geomagnetic activity in 2024. The black dots in panel **A** show daily values of the quasi-dipole geomagnetic latitudes, Δ_M , of observations of aurora in the northern hemisphere. The light-to-dark grey areas are delimited by, respectively, the $\pm 4\sigma$, $\pm 3\sigma$, $\pm 2\sigma$, and $\pm 1\sigma$ points, where σ is the standard deviation, of the distribution of Δ_M for that fraction of a calendar year, F , from over 0.22 million recorded auroral observations between 1650 and 2025 Lockwood et al. (2025): the mauve line shows the variation in the means of the distributions. Panel **B** shows the mid-latitude aa_H geomagnetic index Lockwood, Chambodut, et al. (2018); Lockwood, Finch, et al. (2018) the grey bands again showing the $\pm 4\sigma$, $\pm 3\sigma$, $\pm 2\sigma$, and $\pm 1\sigma$ points of distributions from the 458754 three-hourly observations available for 1868–2025. The corresponding plot for the low-latitude Dcx geomagnetic index Karinen and Mursula (2005) is shown in panel **C**. The Dcx index is available for 1932–2024 and there are 814238 hourly samples. In parts **B** and **C** the peaks of events in which the 3σ level is exceeded are marked with a black dot.

The black dots in panel **A** show daily values of the quasi-dipole geomagnetic latitudes, Λ_M , of observations of aurora in the northern hemisphere. The $\pm n\sigma$ contours are determined from over 220k recorded auroral observations between 1650 and 2025 Lockwood et al. (2025) and the mauve line shows the variation in the mean of the distributions. Note that the contours poleward of the mean are more to the south around mid-summer because of the effect of daylight on the visibility of aurora. There are four events in the second half of 2024 in which aurora was seen at Λ_M below the distribution -4σ values, the first being the major geomagnetic storm on 10-11 May 2024.

Panel **B** of Figure 11 shows the plot for the three-hourly values of the mid-latitude aa_H geomagnetic index (Lockwood, Chambodut, et al., 2018; Lockwood, Finch, et al., 2018) the gray bands again showing the $\pm n\sigma$ points of distributions which are from the 458754 three-hourly observations of aa_H available for 1868–2025. The aa_H data for 2024 are shown as a colored histogram. For the 10-11 May event aa_H exceed its $+4\sigma$ value as did the storm on New-Years eve. The other two 4σ auroral events exceeded the $+3\sigma$ level.

Panel **C** of Figure 11 shows the corresponding plot for hourly values of the low-latitude Dcx geomagnetic index The Dcx index is available for 1932–2024 and there are 814,238 hourly samples from which the distributions as a function of F are constructed. Again large disturbances (large negative values) are seen during the 4 major events, with Dcx falling to or below the -4σ point in 3 of them and the -3σ point in the other.

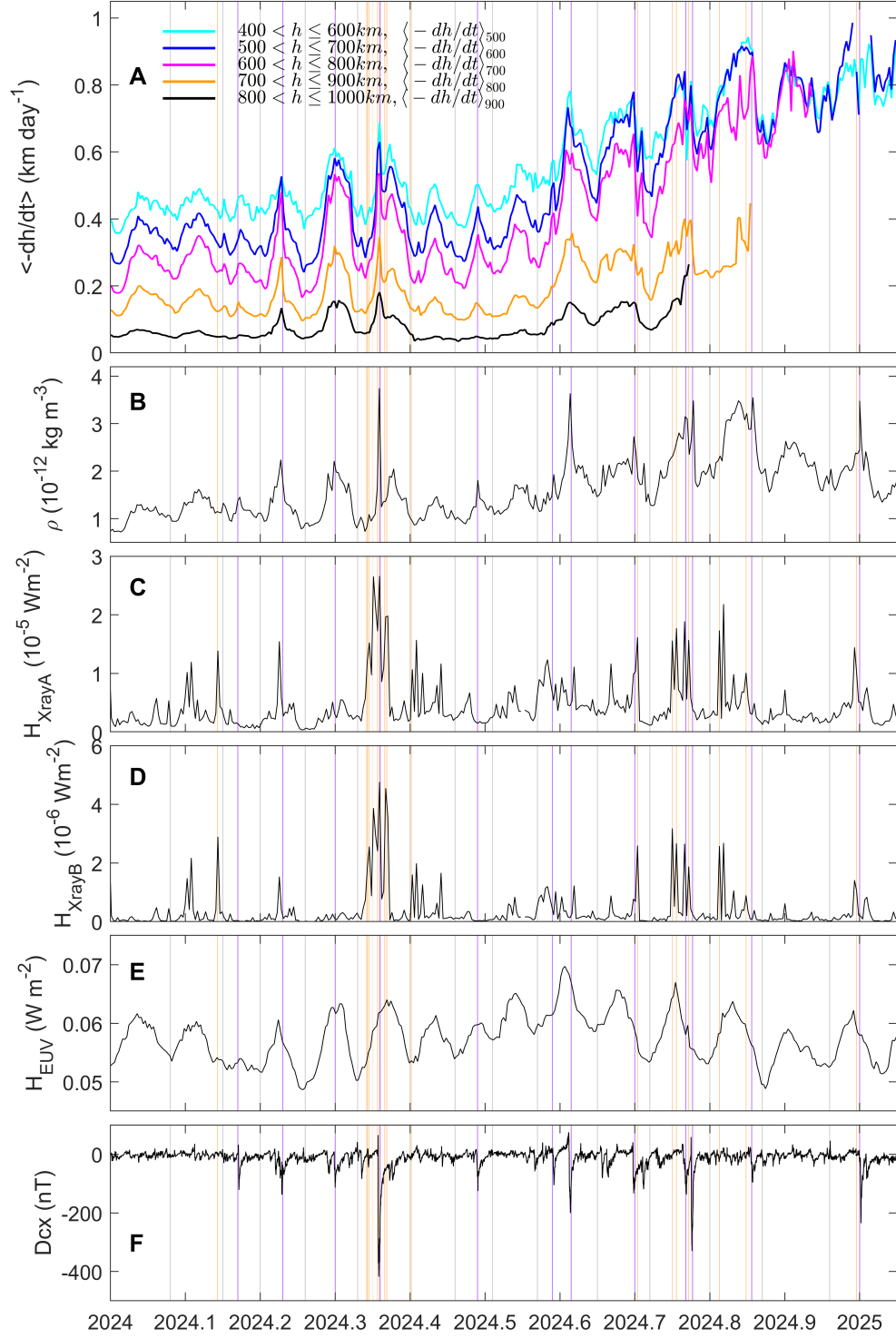


Figure 12. (See legend in text box on next page)

Figure 11 legend. The variation of various parameters relevant to orbit decay during 2024. Panel **A** shows detail of Figure 8, giving the average rates of descent of sets of FY-1C debris in the 5 overlapping 200 *km*-wide altitude ranges. Panel **B** shows the thermospheric density, ρ , at 465*km* altitude, derived from the SWARM-A satellite data, as described by (Doornbos, 2012) and (Siemes et al., 2016), data processed and made available by T.U. Delft in the Netherlands. Panels **C** and **D** show integrated whole-solar-disc X-ray fluxes from the Extreme Ultraviolet and X-ray Irradiance Sensors (EXIS) suite on the NOAA GOES-R series satellites Woods et al. (2024); Machol et al. (2026): Panel **C** shows the daily means from the XRS-A sensor that covers the wavelength range 0.05–0.4*nm* and Panel **D** the results from XRS-B (0.1–0.8*nm*) which extends to lower energies and is widely used in flare classification. **E** The EUV thermospheric heating index, H_{EUV} , as derived by (Lockwood et al., 2026) from spectra observed by the Extreme Ultraviolet Variability Experiment (EVE) instrument on NASA’s Solar Dynamics Observatory (SDO) satellite, convolved with the estimated spectrum of thermospheric heating efficiency. **F** Daily means of the Dcx geomagnetic index (Karinen & Mursula, 2005). In all panels the faint and thin vertical lines allow the reader to see associated features in the various panels: the gray lines are minima in solar rotation oscillation in H_{EUV} caused by longitudinal structure in solar activity regions; the pale orange lines are the times of X- and M-class solar flares as listed in the NOAA GOES X-ray flare catalog, provided by NOAA’s National Centers for Environmental Information (NCEI); the pale mauve lines are geomagnetic storms defined by hourly $Dcx < -100nT$.

Figure 12 shows the variation of parameters related to orbit decay during 2024. Panel **A** is detail of Figure 8 showing the 2024 segment. Note that for the higher altitudes plots cease towards the end of the year because Figure 8 is for objects that re-entered before April 2025 and so numbers of objects at higher altitudes falls below the 20, which is the limit set to ensure a value of $\langle -dh/dt \rangle$ is reliable. The lower panels give variations of relevant influences on $\langle -dh/dt \rangle$. Panel **B** shows the thermospheric density, ρ , at 465 km, derived from the SWARM-A satellite orbital data as described by (Doornbos, 2012) and (Siemes et al., 2016). Panels **C** and **D** show bursts of X-rays from solar flares which have been proposed as contributors to orbit decay (Sutton et al., 2006; Le et al., 2012; Oliveira et al., 2020). Panel **E** shows the EUV heating index H_{EUV} and Panel **F** the Dcx geomagnetic index. The faint and thin vertical lines connect associated features in various panels: the gray lines are minima in solar rotation oscillation in H_{EUV} caused by longitudinal structure in solar activity regions; the pale orange lines are the times of X- and M- class solar flares as listed in the NOAA GOES X-ray flare catalog, provided by NOAA's National Centers for Environmental Information (NCEI) and the pale mauve lines are geomagnetic storms defined by $Dcx < -100nT$.

Some features are immediately apparent in Figure 12. For example, although there were a number of flares associated with the 10-11 May storm, the large spike in ρ and $\langle -dh/dt \rangle$ at all h is associated with the large spike in $-Dcx$ which was shown above to be a 4σ event. Figure 12 also shows a strong solar rotation effect in ρ and $\langle -dh/dt \rangle$ at all h associated with EUV heating that is quantified by H_{EUV} .

A rather different picture emerges from the study of the year 2024 than was described earlier from the whole data period 2007-2024 (inclusive). The role of the EUV heating is still quite clear and introduces a 27-day oscillation into the ρ and $\langle -dh/dt \rangle$ data. However, Figure 12**E** shows that H_{EUV} peaks around decimal year 2024.6 but subsequently declined until the end of 2024. However, Panel **B** shows that the thermospheric density at 465 km, ρ , continued to rise until 2024.85 and Panel **A** shows that $\langle -dh/dt \rangle$ also peaked at this time at all altitudes (but then plateaued or rose slightly rather than falling again, as ρ did). We note that different behavior in $\langle -dh/dt \rangle$ and ρ could reflect temporal changes in the average ballistic parameter, $\langle \beta \rangle$ descending to a given height, but the general similarity of the behavior in different height bins argues against this possibility.

We have repeated the correlation study that was carried out for the whole interval for 2024 alone and, as expected from the above, the results are importantly different. Table 3 is the same as Table 2, but is only for the data from 2024.

Comparison of Table 3 with Table 2 shows that H_{EUV}^2 correlates consistently less well for 2024 than it did for the whole dataset. The correlation coefficient r_{dhH2} is still highly significant, although p -values against the null hypothesis are greater (partly because r_{dhH2} is lower but also because sample numbers are much lower) but still very small. Both Fit 1 and Fit 2 provide correlation coefficients that are higher than r_{dhH2} and the Meng-Z tests shows that the differences are statistically highly significant in both cases.

Fit 2 is still superior to fit 1 but the differences are small. That means to first order approximation we can view the fits to be a simple weighted addition of terms in H_{EUV}^2 and Dcx . However, there is small multiplicative term that is not included in Fit 1.

5 Semiannual Variations in orbit decay

The spectra shown in Figures 9 and 10 show strong annual and semiannual variations. The annual variation is present in H_{EUV} but the semi-annual is not, but it is strongly present in geomagnetic activity because of the Russell-McPherron effect (Lockwood, Owens, Barnard, Haines, et al., 2020).

Table 3. The same as Table 2 for data from 2024 (366 daily samples).

Fit & parameter for $\langle h \rangle$ of:	500 km	600 km	700 km	800 km	900 km
H_{EUV}^2 , correlation r_{dhH2}	0.6830	0.6911	0.7044	0.6826	0.5763
H_{EUV}^2 , p-value	5×10^{-35}	3×10^{-40}	2×10^{-42}	6×10^{-39}	1×10^{-25}
Fit 1, correlation r_1	0.7464	0.7628	0.7778	0.7545	0.7435
Fit 1, coefficient, a_1	181.2135	227.0625	228.1359	119.9880	54.5096
Fit 1, coefficient, b_1	-0.0026	-0.0034	-0.0035	-0.0018	-0.0013
Fit 1, Meng-Z p-value	0.0883	0.0334	0.0243	0.0384	0.0003
Fit 2, correlation r_2	0.7611	0.7690	0.7834	0.7558	0.7462
Fit 2, coefficient, a_2	229.7159	266.4687	265.0545	129.5381	61.5901
Fit 2, coefficient, b_2	-0.0182	-0.0161	-0.0153	-0.0049	-0.0036
Fit 2, coefficient, c_2	4.4402	3.6075	3.3798	0.8743	0.6482
Fit 2, Meng-Z p-value	0.0254	0.0215	0.0160	0.0353	0.0002

The annual variation ultimately arises from the r^{-2} variation in the solar EUV radiance, due to the annual variation in the Sun-Earth distance r . This variation has an amplitude of just 3.45% of the mean value but its effect on thermospheric mass density increases with altitude because of the accumulating effect of the changes in neutral temperature and scale height in the vertical direction (Ma et al., 2015). Even by $h = 400$ km, the amplitude of the annual variation is about 40% of its mean value (Lei et al., 2012).

A number of external sources and internal mechanisms have been proposed to explain the well-known semiannual variation in global mean thermospheric densities seen in Figures 9 and 10 and this has been the subject of much debate. The picture has changed quite substantially in the last few years. For many years the accepted explanation was the thermospheric “spoon” mechanism proposed by T. J. Fuller-Rowell (1998), in which solstitial, interhemispheric circulation mixes the major species and alters the O/N_2 ratio and mean molecular mass, producing lower densities at the equinoxes relative to the solstices. However, more recent modelling work has increasingly pointed to an important dynamical contribution from below: using TIME-GCM (the National Center for Atmospheric Research Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model), Jones et al. (2018) found that the semiannual oscillation in thermospheric atomic oxygen can also originate in the upper mesosphere through seasonally varying advection, tides and diffusion. Qian et al. (2009) needed to add seasonally-varying eddy diffusion, representing contributions from the lower atmospheric forcing, at the lower boundary (at about 97 km) of the model to bring the simulated mass density into good agreement with satellite drag data. Geomagnetic forcing has been generally thought to be a small contributor to the thermospheric semi-annual variation (Detman, 1996) despite it having a very strong semi-annual variation because of the R-M effect (Lockwood, Owens, Barnard, Haines, et al., 2020). Emmert and Picone (2010) presented a climatological analysis of daily globally averaged density data, at heights between 200 and 600 km for the interval 1967–2007. They found that the amplitudes of annual and semiannual variations of thermospheric density only slightly increased with increased solar activity: the argues against a major geomagnetic influence which would have a strong solar-cycle dependence. On the other hand, Bowman et al. (2008) showed that the thermospheric semiannual variation varied in amplitude from year to year, with peak variability at around 800 km altitude and that the solar activity dependence of the amplitude variability to be weak around 400 km, but the amplitude increased with solar activity at greater altitudes. The recent study by Lockwood et al. (2026) presents evidence that the geomagnetic driver of the thermospheric semi-annual effect may be a larger factor than previously thought. How-

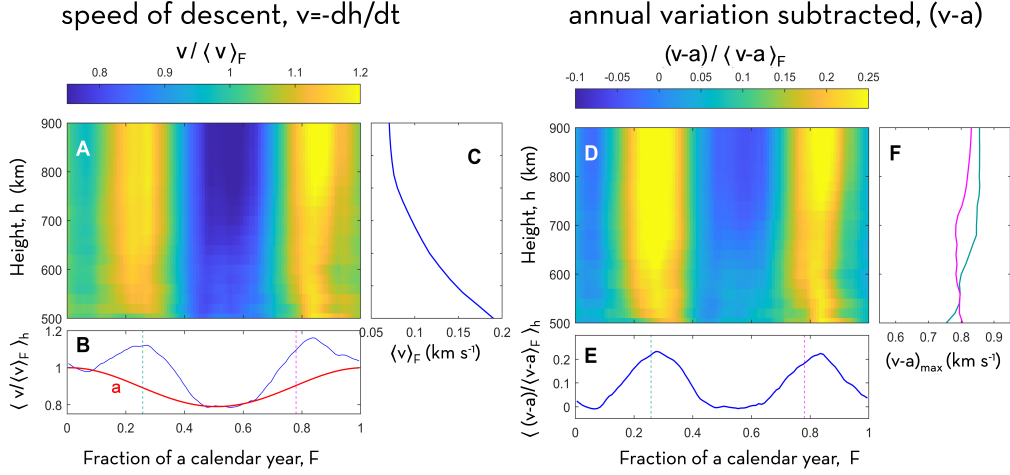


Figure 13. The removal of the annual variation. The left-hand set of 3 panels (**A**, **B** and **C**) are for before the removal of the annual variation $a(h)$ and the right-hand panels (**D**, **E** and **F**) are for after its subtraction. To simplify the labeling of axes we here introduce the notation that the average speed of descent in a time-altitude bin is $v = \langle -dh/dt \rangle$, Part **A** shows values of v , normalized by the mean value at that height, $v / \langle v \rangle_h$ as a function of time of calendar year, F , and altitude, h . Means of v are evaluated in bins $\Delta F = 0.01$ yr wide and $\Delta h = 20$ km wide for all data between 2007 and 2024 (inclusive). The blue line in Part **B** shows the averages of these normalized values over all h below 1000 km as a function of F . At each height h we compute variation of $a = \alpha + \beta/r^2$ due to the annual variation in the Sun-Earth distance, r , where the coefficients α and β are derived to fit the summer and winter solstice values. The red line shows the average of a over all h between 500 km and 1000 km. In Parts **D**, **E** and **F**, $a(h)$ has been subtracted from the v values to remove the annual variation and reveal the semi-annual variation. Part **F** shows the March (in green) and September (in mauve) peaks of the semi-annual variation of $(v - a)$ as a function of altitude h . The times of those peaks predicted by the R-M mechanism are shown by the vertical dashed lines in Part **B**.

ever this paper studied data from a single altitude and the balance of the various mechanisms is likely to be strongly height-dependent. Studying the descent of the FY-1C debris in the present paper gives us the opportunity to look at the variations with altitude,

The study by Lockwood et al. (2026) used the polarity of the Y -component (dawn to dusk) of the Interplanetary Magnetic Field (IMF) in the Geocentric Solar Equatorial (GSEQ) frame to identify a contribution of the Russell-McPherron (R-M) effect on solar wind-to-magnetosphere energy coupling. Their results showed that about half the semi-annual variation in thermospheric densities could be attributed to the R-M mechanism which deposits energy through low-level geomagnetic currents rather than storms. In this section, we study the FY-1C debris decent data as that should show a similar dependence. As shown by Lockwood et al. (2026), we first have to remove the annual variation to see the true amplitudes and timing of the equinox peaks of the semiannual variation. This is demonstrated by Figure 13.

Figure 13A shows $v / \langle v \rangle_h$, where $v = \langle -dh/dt \rangle$ and $\langle v \rangle_h$ is its mean value at that height, as a function of time of year, F (horizontal axis) and altitude h (vertical axis). The blue line in Part **B** is the mean over all heights between 400 km and 1000 km as

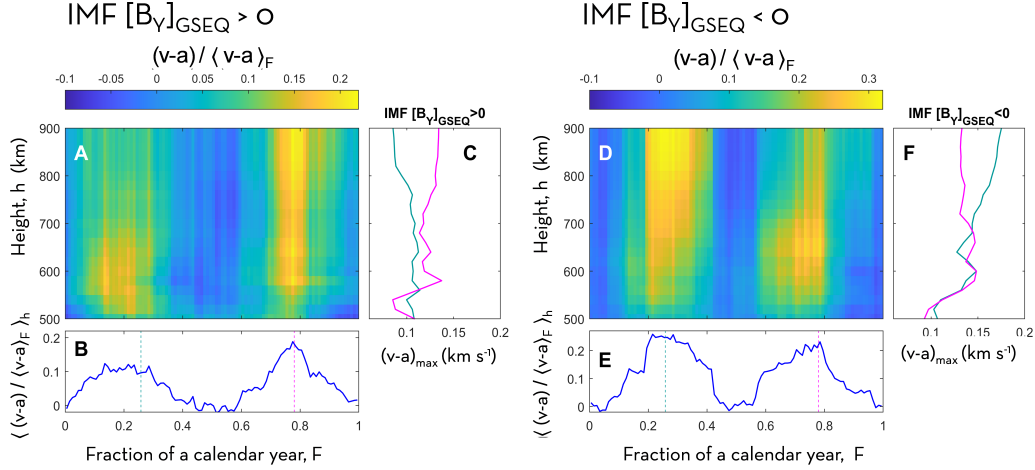


Figure 14. Variations with annual means subtracted, as shown in parts **D**, **E** and **F** of Figure 11, for the two polarities of IMF $[B_Y]_{GSEQ}$. Data for days with dominant IMF $[B_Y]_{GSEQ} > 0$ are shown on the left (parts **A**, **B** and **C**) and days with dominant IMF $[B_Y]_{GSEQ} < 0$ are shown on the right (parts **D**, **E** and **F**).

a function of F and part **C** shows the altitude profile of the mean values, $\langle v \rangle_h$. The red line in **B** is the annual variation fitted to the mean values. This is the variation with F given by the variation of r^{-2} , where r is the Earth-Sun distance, fitted to the values at the times of maximum and minimum r . This procedure is repeated for each altitude bin separately giving annual variations $a(F, h)$. The values of v with the annual variation subtracted, $(v - a)$, are shown in **C**, again normalized to the mean values for that height. Panel **E** shows the means taken over all heights. The vertical green and mauve dashed lines are at the predicted F of the peaks for the R-M effect. Panel **F** shows the height profiles of the normalized $(v - a)$ (i.e., $(v - a)_h / \langle v - a \rangle_h$) at the F of the R-M peaks, with green again for the March peak and mauve for the September peak. These peak value profiles are quite similar in this plot. Comparison of Parts **B** and **E** shows that removing the annual variation a has brought the equinox peaks closer to the F predicted by the R-M mechanism.

Figure 14 applies the critical test for the R-M effect by dividing the data by the dominant polarity of the IMF $[B_Y]_{GSEQ}$ component. The left (Panels **A**, **B**, **C**) and right hand (Panels **D**, **E**, **F**) parts of the figure are the same as Panels **D**, **E**, **F** of Figure 13 (i.e., for the descent speed with the annual variation subtracted) but are for dominant IMF $[B_Y]_{GSEQ}$ of each day that is, respectively, positive and negative.

To define the dominant IMF $[B_Y]_{GSEQ}$ polarity of a day we require the mean IMF $\langle [B_Y]_{GSEQ} \rangle_{1day}$ for the dominant polarity to exceed that of the minority polarity by $3nT$. This is a less stringent criterion than was used by (Lockwood et al., 2026) but is necessary here as we have a shorter dataset and need to keep the sample numbers in the two subsets high. This definition is sufficient to reveal a clear R-M effect at high altitudes, with the September peak favored by $[B_Y]_{GSEQ} > 0$ and the March $[B_Y]_{GSEQ} < 0$. Panels **C** and **F** show at the lower heights the two equinox peaks are roughly equal in magnitude and so evidence for the R-M effect is not found. However, note it may still be present to a lower degree because of periods of the minority $[B_Y]_{GSEQ}$ will enhance the unfavored equinox. Nevertheless it appears that the semiannual variation at the lower altitudes is dominated by mechanisms such as the spoon effect and the effects of waves and

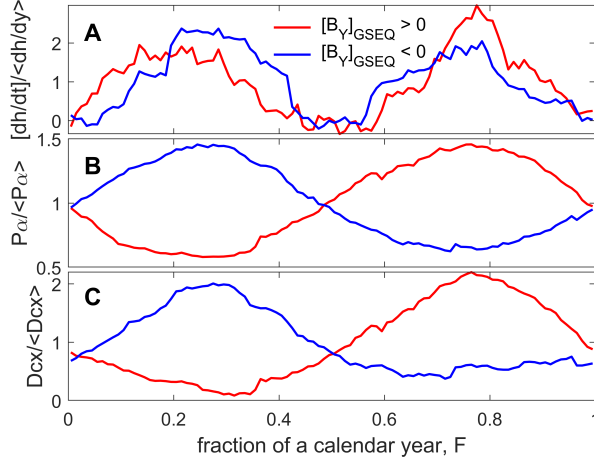


Figure 15. Line plots showing the R-M effect in three parameters: **A** the average descent speed of FY-1C debris pieces $-dh/dt$ for $400 < h \leq 1000$ km, (after subtraction of the annual variation, a). **B** The same plot for the solar wind power input to the magnetosphere, P_α , estimated from near-Earth interplanetary data using the coupling function devised by Vasyliunas et al. (1982) and tested and used by Finch and Lockwood (2007) and Lockwood (2019, 2022). **C** The same plot for the geomagnetic Dcx index. In all three plots, the red/blue lines are for days of predominantly positive/negative IMF $[B_Y]_{GSEQ}$, respectively. The same data interval is used in all three plots and the same classification of the dominant polarity of the IMF Y-component. The variations in Part **A** are those shown in parts **B** and **E** of Figure 14.

tides from below whereas the semi-annual variation in the upper thermosphere is dominated by the R-M effect.

Figure 15A compares the variations, averaged over all heights, shown in Parts B and E of Figure 14. Red is for days of dominant $[B_Y]_{GSEQ} > 0$ and blue for days of dominant $[B_Y]_{GSEQ} < 0$. Figures 15B and Figure 15C show the same plots for parameters relevant to geomagnetic activity for which the R-M is a full explanation of the semi-annual variation (Lockwood, Owens, Barnard, Haines, et al., 2020; Lockwood, McWilliams, et al., 2020; Lockwood, Owens, Barnard, Watt, et al., 2020; Lockwood et al., 2021), sorted using the same threshold to define the dominant IMF polarity. Part B shows the corresponding variations in the power input to the magnetosphere, P_α , estimated from interplanetary parameters. This formulation was derived by Vasyliunas et al. (1982) and is based on correct theory (unlike the much-used ϵ parameter) and was shown by Finch and Lockwood (2007) to perform as well or better than other proposed coupling functions on timescales between 1 day and 1 year.

Part C is the same plot for the Dcx geomagnetic index. Parts B and C of Figure 15 show that the effect of periods of minority polarity $[B_Y]_{GSEQ}$ cannot be seen in either P_α or Dcx (there is no peak at the equinox that is not favored by the R-M effect). Hence we can discount a major effect of minority IMF $[B_Y]_{GSEQ}$ polarity in the debris descent speeds.

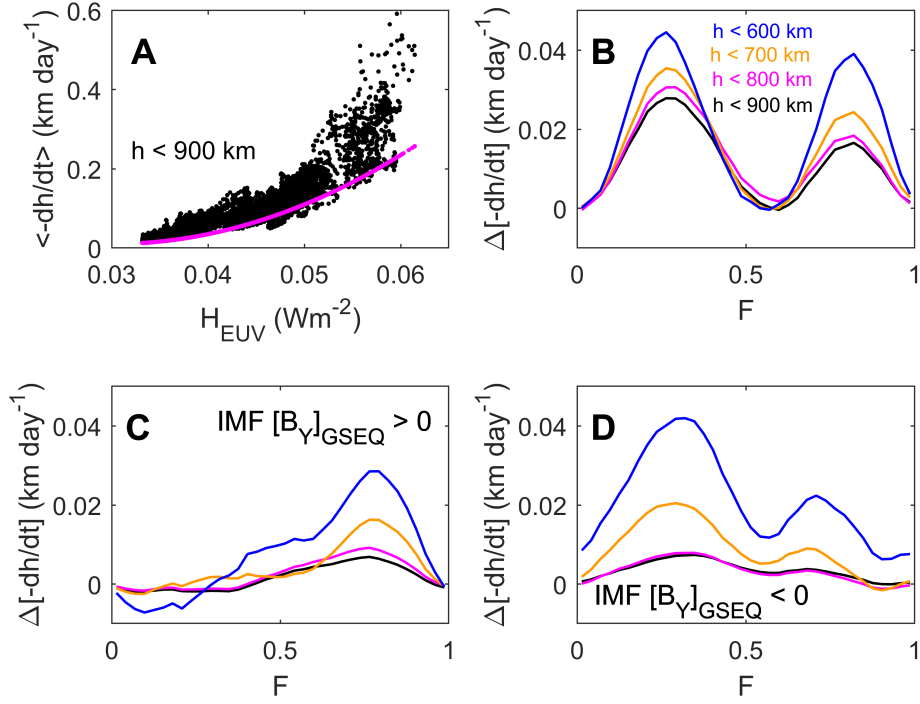


Figure 16. Analysis of the causes of variations in the mean descent speed of FY-1C debris, $v = -dh/dt$. **A** A scatter plot of v as a function of the EUV heating index, H_{EUV} . The mauve line is a fit to the lower edge of the scatter, given by $v_{fit} = c(H_{EUV} - d)^2$ where $c = 235$ and $d = 0.03$ (for v in $km\ s^{-1}$ and H_{EUV} in $W\ m^{-2}$). **B** the variations with the fraction of year F of the residuals $\delta[-dh/dt] = v - v_{fit}$ for all data at: (black) $h < 900\ km$; (mauve) $h < 800\ km$; (orange) $h < 700\ km$ and (blue) $h < 600\ km$. The fit residual variations with F for days of predominantly positive and negative IMF $[B_Y]_{GSEQ}$ are shown in Parts **C** and **D**, respectively.

6 Separation of solar EUV and geomagnetic activity effects on orbit decay

Analysis of the active year 2024 in Section 4 and the presence of the R-M effect seen in Section 5 both indicate that both the currents that drive geomagnetic activity and EUV radiation contribute to the decay of the orbits of FY-1C debris. However, it should be noted that Dcx is an hourly index and so may not capture more rapid variations in the currents. These may be significant for ion-neutral frictional heating because, as discussed in Section 1.2, rapid variations (on sub-hour timescales) can cause significant heating because the neutral velocity cannot respond to changes in the ion velocity and the heating varies as the square of the difference of the two velocities (Equation 3). This means that geomagnetic indices such as Dcx may not capture all of the geomagnetic heating effect. In this section we make an initial attempt to separate the effects of R-M induced currents from the EUV heating effect.

Because the variations are so well correlated at heights between 400 and 900 km , we here average all observations of descent speed in this height range, giving one average value of $v = -dh/dt$ per day. Part **A** of Figure 16 shows a scatter plot as a function of H_{EUV} : the squared form seen in the correlation results is apparent but the scatter

gets greater at larger H_{EUV} . The mauve line is simple least squares square-law fit v_{fit} to the lower envelope of the scatter and shows at the highest H_{EUV} this underestimates even the lower envelope of observed descent speeds. The other panels in Figure 16 investigate the possibility that the scatter and deviation from the mauve line is a geomagnetic effect, as suggested by the correlation study given in Table 3 for an active geomagnetic year (2024). However in this case, we use the R-M effect to try to identify a geomagnetic source. We term the residual, after subtraction of v_{fit} , $\Delta[-dh/dt]$. Figure 16A is for all heights below 900km. The same pattern was seen if we lowered the upper height limit used but the value of the coefficient a in v_{fit} , needed adjustment: the c required was 360, 300, 250 and 235 for $h < 600$ km, $h < 700$ km, $h < 800$ km and $h < 900$ km.

The colored lines in Figure 16B show the variation with fraction of a calendar year F of $\Delta[-dh/dt]$ for the various upper limits of h of [600 : 100 : 900]. All show a clear semi-annual variation. However what is surprising is shown in Parts C and D. These show the $\Delta[-dh/dt]$ variations for dominant IMF $[B_Y]_{GSEQ}$ that is, respectively, positive and negative. The dominant peak is at the equinox favored by the R-M effect and although there is a weak peak at the unfavored equinox (September) for $[B_Y]_{GSEQ} < 0$ there is no unfavored peak at all (in March) for $[B_Y]_{GSEQ} > 0$. It is not clear why the behavior is slightly different for the two IMF polarities. Note that the solstice minima in Figure 16B are close to zero although no annual variation has been subtracted: hence the annual variation and any background level is inherent in v_{fit} .

This implies that the annual variation and much of the non-geomagnetic semi-annual variation has been removed by subtracting v_{fit} . It is not true to say that because there is no semi-annual variation in H_{EUV} there is not one in v_{fit} because the amplitude of the non-geomagnetic semi-annual variation caused by internal mechanisms (such as tides, waves or the spoon circulation effect) will be enhanced by the enhanced densities caused by increased H_{EUV} . The implication is that the geomagnetic R-M effect is a major contributor to the scatter with H_{EUV} (of which Figure 16A is the example for $h < 900$ km).

7 Discussion

From the perspective of the sustainability of our use of near-Earth space (Lockwood, 2025) the debris formed by the FY-1C ASAT test is a major problem and will remain so for decades to come. However, there is scientific information about the thermosphere and how space weather removes space debris inherent in the tracked orbits and that has been explored in this paper.

Eventually, the nature of the FY-1C debris cloud will change as the drag effect preferentially removes the higher- β components. However up until the time of writing, even 14 years after the ASAT test, we have seen no evidence of this effect and the rate at which objects have re-entered and burned up from the cloud has been set by the space weather conditions. From the Gabbard plots, we see the reason for this is that objects that were accelerated by the impact and raised in apogee form a reservoir with a full spectrum of β values and the slow decay in altitude of these objects has been an effectively constant source of objects of all β at the altitude of the original FY-1C craft, h_S . Only when this reservoir starts to be depleted will the effects of a change in the spectrum of β of the objects falling to lower values be seen. This means in the interval studied, the variations in average descent speed of the FY-1C debris were dominated by the variations in thermospheric density and not strongly modulated by the decay of the source.

Like thermospheric densities (Lockwood et al., 2026), the descent speeds show a clear Russell-McPherron (R-M) effect showing there is a contribution to orbit decay from moderate/quiet-time geomagnetic activity in addition to the effect of geomagnetic storms. There are clear drops in altitude associated with geomagnetic storms and although the R-M effect modulates the occurrence of storms to some degree, this is not a major cause

Table 4. Analyses of the fraction of altitude lost in geomagnetic storms during 2007-2024, inclusive. Σ is the total height lost by all objects tracked in this paper, summed over all days (so the fraction of the Dst distribution considered is $f = 1$). d is the integrated height lost on days when the Dcx index was below its lower decile (i.e., geomagnetic activity is in its upper decile, so $f = 0.10$, and s is the integrated altitude lots on days when Dcx is below the lower 2σ point of its distribution ($f = 0.21$). As well as giving the integrated altitudes lost, d and s , in km , the table gives them as a percentage of the total loss, $100.d/\Sigma$ and $100.s/\Sigma$. Values are given for bins of altitude $200\ km$ wide, centered on altitudes of $400, 500, 600, 700, 800$, and $900\ km$.

f_{Dcx}	$\langle h \rangle$ (km)	400	500	600	700	800	900
1	Σ (km)	2503.6	1399.5	741.6	436.3	284.6	206.5
0.1	d (km)	308.0	189.8	120.9	81.6	51.9	30.5
0.1	$100d/\Sigma$	12.30	13.56	16.30	18.70	18.23	14.75
0.021	s (km)	70.4	46.3	31.8	22.9	14.0	7.7
0.021	$100s/\Sigma$	2.81	3.31	4.29	5.25	4.93	3.75

of orbit decay of the FY-1C debris. The enhanced thermospheric temperatures typically last only 1-2 days after a storm (see Section 1.2) and Figure 12 shows that even the great storm of 10-11 May 2020 only lowered debris by, on average, by about $0.07\ km$ at altitudes around $900\ km$ rising to about $0.15\ km$ at around $500\ km$. There was no marked rise in the numbers of debris objects that re-entered after this event but objects at altitudes below $300\ km$ did experience drops of order $10\ km$ and did generally re-enter within a couple of weeks, a period that will have been shortened by the storm. This is despite this storm being the 3^{rd} greatest known in terms of auroral extent and the 7^{th} greatest by the minimum Dst index generated since the start of that geomagnetic index in 1956 (Hajra et al., 2025).

Table 4 shows that days in the top 10% of geomagnetic activity level, as quantified by Dcx , contribute about 12% of the total altitude loss at h around $400\ km$, rising to a peak of about 19% at $h \approx 700\ km$. In addition, those in the top 2.1% contribute about 2.8% at $h \approx 400\ km$, rising to a peak of 5.25% at $h \approx 700\ km$. Thus storms do contribute to altitude decay, but not to a dominant extent.

The R-M effect does modulate the occurrence of great storms but its main effect is largely a modulation in mean values rather than extreme events (Lockwood et al., 2016, 2026). Hence the discovery of an R-M effect on debris altitude decay rates shows a geomagnetic effect of mean values rather than due to large storms.

The results presented here give us a better understanding of how space weather influences orbit decay. As well as being useful in the prediction of the longevity of the debris from fragmentation events, this work has other potential applications. There are some very large space junk objects in LEO that will require active de-orbiting if we are to avoid the potential consequences of uncontrolled re-entry. Examples include the defunct ENVISAT craft and the International Space Centre at its end of life. ENVISAT is the largest piece of space junk in LEO at the present time. It was launched on 1 March 2002 and its mission ended when control of the craft was lost on 8 April 2012. At launch, its mass was $8211\ kg$ and its estimated end-of-life mass is $7828\ kg$. It orbits at an altitude near $790\ km$ at an inclination of 98.55° with a period of $100.6\ min$. It has in-orbit dimensions of about $26\ m$ by $10\ m$ by $5\ m$ and a cross-sectional area used in modelling of $63\ m^2$. Observations from the TIRA radar (the Tracking and Imaging Radar operated by the Fraunhofer Institute for High-Frequency Physics and Radar Techniques near Bonn, Ger-

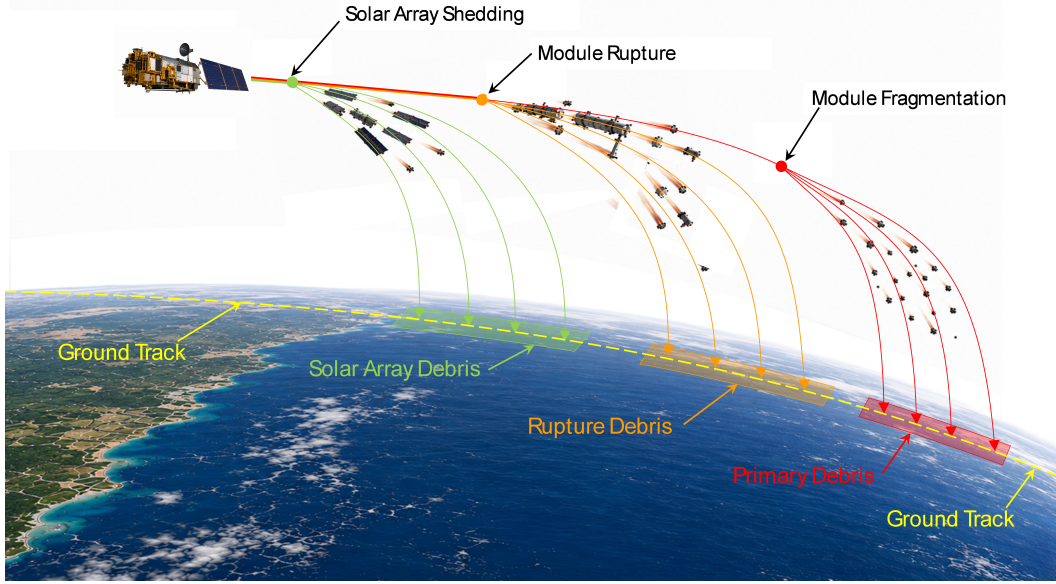


Figure 17. Schematic of the extended debris trail that will form when the defunct ENVISAT satellite re-enters.

many) over 2011–2017 showed that ENVISAT is in a tumbling motion: it has non-principal-axis rotation with the rotation axis describing a nutation cone of about 80° and the spin has slowed reaching a rotation period of 3.77 min by March 2017.

Figure 17 is a schematic of ENVISAT's impending re-entry, showing how it will form an extended debris trail as it breaks up in stages. A reasonable order-of-magnitude estimate for a potential debris-deposition length over which objects could potentially reach the ground is 10^4 km which is about a quarter of an orbit length at the reentry altitude ($h \approx 120 \text{ km}$). ENVISAT's inclination of 98.55° means reentry can occur at all latitudes between $\pm 81.5^\circ$.

Because it is sun-synchronous, the orbital plane has a fixed relationship to the Sun, but the Earth rotates underneath that plane. ENVISAT's orbital period is currently 100.1 min , and will have fallen to 86.9 min when it reaches the near reentry altitude of $h = 120 \text{ km}$, giving about 16.6 orbits per day. Because it is in a Sun-synchronous orbit, successive ground tracks will be shifted westward in longitude by about 21.7° . The longitude of a particular reentry opportunity therefore depends strongly on the precise time of re-entry.

After losing control, ENVISAT wasted all the remaining propulsion delta-V that was planned to use for a controlled reentry which would allow the debris trail to be placed in a known and remote part of the globe. This makes it a good candidate for a de-orbiting clean-up mission. Such a craft would capture ENVISAT (not easy for a tumbling object but still possible) and with applications of considerable delta-V to slow it before releasing it at a time that places the debris train in the required part of the globe. This will require good knowledge of the state of the thermosphere and forecasts that predict no major space weather event that could alter that state the thermosphere, principally EUV and geomagnetic variations.

The other area where the present study has implications is in understanding metal ablation and its effects on the stratosphere. This is an area where much work is urgently needed and as metal particle size distribution and the rate of reentry may well have considerable effect in the catalytic destruction of ozone.

Open Research Section

The data used in this paper are all publicly available. The TLEs used to characterize orbits are available from Space Track at <https://www.space-track.org>. The reentry database used is from the European Space Agency’s DISCOS (Database and Information System Characterising Objects in Space), available from DISCOweb <https://discosweb.esoc.esa.int/>. General background data on spacecraft was obtained from Jonanthan McDowell’s Space Home Page <https://www.planet4589.org/space/>. The SWARM thermospheric densities are published by the Technical University Delft, The Netherlands at <http://thermosphere.tudelft.nl/>. The NRL thermospheric density dataset is published by the Naval Research Laboratory, Washington, DC, USA at https://map.nrl.navy.mil/map/pub/nrl/orbit_derived_density/v2.0_1967-2019/orbit-density-ds03-density-values.txt. The interplanetary magnetic field data are available from the Omniweb web pages maintained by NASA’s Space Physics Data Facility at Goddard Space Flight Center, Maryland, USA at <https://omniweb.gsfc.nasa.gov/>. The Solar Dynamics Observatory EUV Irradiance is made available by EVE Science Processing and Operations Center (SPOC) of the Laboratory for Atmospheric and Space Physics (LASP), University of Colorado Boulder, at <https://lasp.colorado.edu/eve/>. The definitive *Dcx* index (at the time of writing, up to the end of 2016) is available from Oulu University, Finland at <http://dcx.oulu.fi/?link=queryDefinite> and provisional *Dcx* from <http://dcx.oulu.fi/?link=queryProvisional>. The geomagnetic *am* index is available from the International Service of Geomagnetic Indices (ISGI) in Strasbourg at https://isgi.unistra.fr/data_download.php. The sunspot number data used were generated by WDC-SILSO/SIDAC, Royal Observatory of Belgium, Brussels and are available from <https://www.sidc.be/SILSO/datafiles>. AI was employed in some aspects this work. It was mainly used to augment the literature search (Consensus <https://consensus.app> and Connected papers <https://www.connectedpapers.com/>), but any papers revealed that way were then read carefully to check that they did indeed contain the cited information. In addition, AI (Copilot, ChatGPT) was used to generate some Matlab modules for the extraction of some of the data from the internet sources listed in the open data section. These codes were always checked by regenerating various plots of the same data that are already in the literature. AI was not used in any other aspects of the work

Inclusion in Global Research Statement

Our analysis uses space-object data from the U.S. Space Surveillance Network (SSN), accessed through Space-Track, and the European Space Agency (ESA) DISCOS database. These resources are supported by international and inter-agency cooperation and data-sharing arrangements among national space agencies, including coordination through the Inter-Agency Space Debris Coordination Committee (IADC).

Conflict of Interest disclosure

The authors declare there are no conflicts of interest for this manuscript.

Acknowledgments

The authors are grateful to the many scientists and engineers who contributed to the various datasets that were exploited in this study. We also thank the staff and funding bodies of the several data centers that give access to these data. In particular, we wish to give thanks to: Space Track and ESA’s DISCOweb for the debris tracking data; the Technical University Delft, The Netherlands for the SWARM thermospheric densities, The Naval Research Laboratory, Washington, DC, USA for the NRL thermospheric density dataset; NASA’s Space Physics Data Facility at Goddard Space Flight Center, Maryland, USA for the Omniweb one-minute interplanetary magnetic field data; the EVE Sci-

ence Processing and Operations Center (SPOC) of the Laboratory for Atmospheric and Space Physics (LASP), University of Colorado Boulder for the solar EUV irradiance data; Oulu University, Finland for the *D_{cx}* geomagnetic index; the International Service of Geomagnetic Indices (ISGI) in Strasbourg for the geomagnetic *am* index; and WDC-SILSO/SIDAC, Royal Observatory of Belgium, Brussels for the sunspot number data. We thank Jonathan McDowell for his excellent and comprehensive Space Report webpage. The authors also thank a variety of funding sources: ML, CS, JoD, CJS and MJO are part-funded (in the case of CS fully funded) by the UK Science and Technology Facilities Council (STFC) Grant UKRI1207 and MJO is also part funded by the UK Natural Environment Research Council (NERC) Grant NE/Y001052/1. CJS is part funded by the NERC Drivers and Impacts of Ionospheric Variability with EISCAT-3D (DRIIVE) project, UKRI grant NE/W003384/1. LAB is supported by UK Research and Innovation (UKRI) Future Leaders Fellowship MR/Y021207/1.

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