RESPONSE OF THE SPACE DEBRIS ENVIRONMENT TO GREENHOUSE COOLING

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ABSTRACT

Whilst it is well known that an increase in the density of the greenhouse gases carbon dioxide and methane (CO_2, CH_4) and others results in warming of the troposphere, a more significant cooling of the thermosphere is produced in response to rising CO_2 levels. Modelling studies performed in the 1990s concluded that with a doubling of CO_2, the average cooling in the thermosphere is 40 – 50 K. The result of this is a reduction of atmospheric density by more than 40% at a given height and significant changes in chemical composition. Observational studies of the long-term orbital decay of Earth satellites in low Earth orbit (LEO) have now provided considerable evidence for a secular decline in thermospheric density, indicating a decrease in density in this region of approximately 10% during the past 35 years. The consequences of this negative density trend are longer orbital lifetimes for both satellites and space debris.

In this paper, results from a set of studies performed by the University of Southampton's Debris Analysis and Monitoring Architecture for the Geosynchronous Environment (DAMAGE) model are presented. These studies show that a secular decrease in thermospheric density can increase the orbital lifetime of satellites in disposal orbits, which initially follow the 25-year re-entry guideline, by up to 24%. Future projections of the debris environment for objects larger than 1 mm also show an increase in the number of catastrophic and damaging collisions due to decreasing thermospheric density over the next 100 years. The consequences of longer orbital lifetimes and rising collision rates are an increase in the number and spatial density of objects within a critical altitude band (200 – 1,200 km) in low Earth orbit.

1. INTRODUCTION

It is well known that the build-up of 'greenhouse gases' in the troposphere causes global heating, but it is perhaps less well known that the increase of CO_2 in the thermosphere causes cooling. The principal mechanism for this is the excitation of CO_2 molecules due to collisions with atomic oxygen, causing infrared emission at a wavelength of around 15 μm. Consequently the thermosphere is cooled, which in turn impacts its density structure.

The effects of this cooling mechanism on temperature and density of the thermosphere at low Earth orbit (LEO) altitudes was discussed by Roble and Dickinson (1989), and soon afterwards the effects on the ionosphere were assessed by Rishbeth and Roble (1992). More recently, the key role of the collisional excitation of carbon dioxide (CO_2) and nitric oxide (NO) as a cooling mechanism was discussed by Sharma and Roble (2002) in the general context of planetary thermospheres. Building on this evidence, Keating (2000), Emmert *et al.* (2004) and Marcos *et al.* (2005) have used orbit data to derive negative density trends. Emmert *et al.* (2004) examined the orbital evolution of 27 near-Earth space objects in long-term orbits, spanning the period 1966 – 2001. Their study indicated a cooling trend over this period, and also exhibited dependence on orbital altitude and on the level of solar activity. Taking care to evaluate possible sources of error, their study indicated average values for density decrease in the range $-2\,\%$ to $-5\,\%$ per decade.

The Intergovernmental Panel on Climate Change (IPCC) predict that atmospheric CO_2 concentrations will continue to rise over the next 100 years even if the path to stabilize CO_2 emissions is followed (see Figure 1), thus maintaining the mechanism for cooling. Hence, the implication of both the theoretical and observational studies of the thermosphere is that within a century the average density at a given height may be reduced to half of its present value (Emmert *et al.*, 2004).

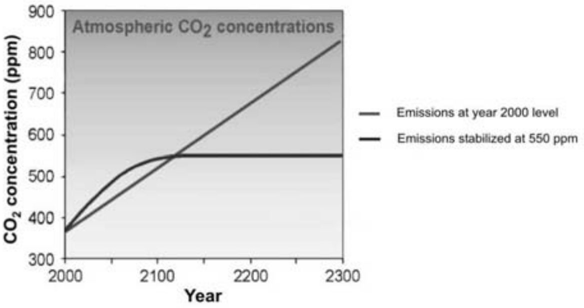

Figure 1. Predicted atmospheric CO_2 trends from IPCC's Climate Change 2001 (IPCC, 2001).

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The following assessment of the consequences of thermospheric cooling on the long-term space debris population is based upon the atmospheric density trends indicated by the work of Emmert *et al* (2004).

2. THE DAMAGE ENVIRONMENT MODEL

2.1. General Details

The Debris Analysis and Monitoring Architecture for the Geosynchronous Environment (DAMAGE) is a semi-deterministic debris environment model implemented in C++, running under Microsoft Windows and using OpenGL for graphical support. DAMAGE makes use of support modules in order to evolve the space debris environment. These include:

- **Orbital propagator** – this is a semi-analytical propagator incorporating expressions for perturbations arising from Earth gravity harmonics (J_2, J_3, J_{22}, J_{31} and J_{33}), atmospheric drag for a non-rotating, oblate atmosphere with density values taken from the COSPAR International Reference Atmosphere (CIRA) 1972 model, luni-solar gravity and solar radiation pressure. Future solar activity is described in DAMAGE using one of two flux models. The first uses a constant-duration, constant-amplitude model of the $F_{10.7}$ cm solar flux, (used for this initial investigation into the effects of thermospheric cooling), whilst the second represents a realistic model of solar flux (see Figure 2) based on the model of sunspot activity described by Hathaway, Wilson and Reichmann (1994).
- **Breakup model** – DAMAGE currently employs the Batelle model for low-intensity and high-intensity explosions, and for catastrophic (energy-to-mass ratio > 40 J/g), damaging and low-velocity (relative velocity < 3 km/s) collisions.
- **Collision probability assessment** – collisions are determined using a ‘sampling-in-time’ approach similar to the Cube method employed in the LEO-to-GEO Environment Debris Model (LEGEND; Liou, 2004). Debris spatial densities and fluxes are calculated only when two or more objects are co-located within small volume elements (cubes). Determination of the collision rate is based on the approach developed by Kessler (1981).

The evolution of the space debris environment proceeds in time steps from a reference epoch, using an initial population of objects larger than 1 mm. Launch traffic and fragmentation debris from explosions and collisions, if any, are added to the population at each time-step (only launch and fragmentation sources of debris are currently included within DAMAGE), and objects with perigee altitudes below 120 km are removed.

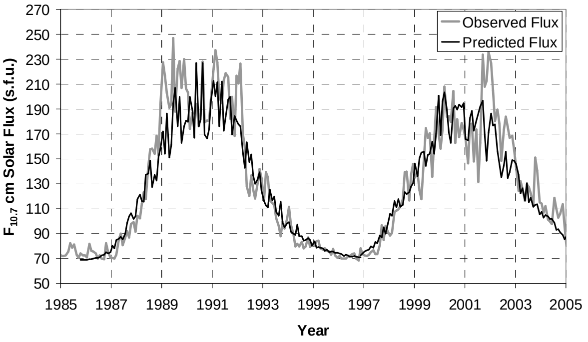

Figure 2. Comparison of historical $F_{10.7}$ cm solar flux with DAMAGE predicted flux.

2.2. Modelling the Cooling Thermosphere

DAMAGE accounts for thermospheric cooling within the CIRA-72 atmospheric model using secular density trends reported by Emmert *et al*. (2004). Their results show that the rate of density decrease is a function of solar flux and altitude, with the trend increasing at solar minima and with altitude. DAMAGE models the secular density trend, $\Delta\rho$, as

$$\Delta\rho = -3.4 + 0.1441(F - 70) - 0.0036(h - 240) \quad (1)$$

percent per decade, where F is the $F_{10.7}$ cm solar flux, in solar flux units (s.f.u.), and h is the height above sea level, in kilometres. This expression was determined using trends derived from orbital elements, presented in Fig. 10 of Emmert *et al*. (2004). A comparison of the secular density trends deduced by Emmert *et al*. and those predicted by DAMAGE is shown in Figure 3 for solar flux values less than 90 s.f.u. and using all data for the period 1966 – 2001. Whilst empirical and theoretical data is limited for altitudes greater than 800 km, it was assumed that the density trend would be maintained above this altitude.

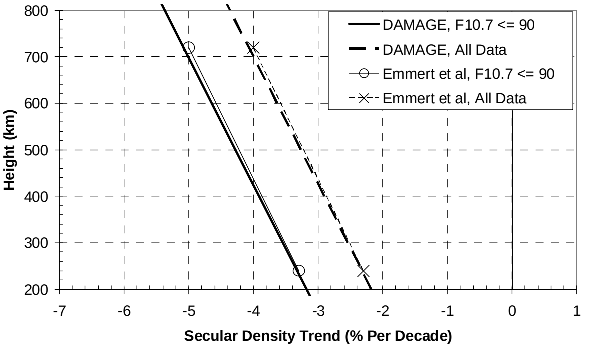

Figure 3. Comparison of the secular density trends derived from orbital elements (Emmert et al., 2004) with those predicted by the modified CIRA-72 atmospheric model in DAMAGE.

Levels of tropospheric CO_2 have been rising since the CIRA-72 atmosphere was introduced. Therefore, the modified CIRA-72 atmospheric model in DAMAGE applies the secular density trend in (1) with effect from 1 January 1973. From (1) it can be seen that the per-decade secular density trend at 800 km will vary from -5.4% at solar minimum (70 s.f.u.) to -3.6% at solar maximum (180 s.f.u.). Table 1 shows the cumulative effect of these trends on atmospheric density over a 100 year period.

Table 1. Predicted changes in atmospheric density over 100 years at 800 km due to thermospheric cooling.

Years from epoch	**Atmospheric Density (% of value at 1 Jan 1973)**	
	-3.6% per decade	**-5.4% per decade**
20	92.9	89.5
40	86.4	80.1
60	80.3	71.7
80	74.6	64.1
100	69.3	57.4

At the higher rate of change, the atmospheric density in the modified CIRA-72 model will be halved at this altitude within the next 100 years, which is in accord with predictions made by Emmert *et al.* (2004).

3. EFFECT OF THERMOSPHERIC COOLING ON ORBITAL LIFETIMES

The drag acceleration, a_D, on a satellite is a linear function of the atmospheric density, ρ,

$$a_D = \frac{1}{2B}\rho v_r^2 , \tag{2}$$

where B is the ballistic coefficient (kg/m^2) and v_r is the velocity of the satellite relative to the atmosphere (m/s). Thus, a decrease in atmospheric density would produce a corresponding decrease in the drag acceleration on a satellite, leading to an increase in the orbital lifetime. For example, the orbital lifetime of a satellite in a disposal orbit with semi-major axis 7,178 km, eccentricity 0.041, and mass-to-area ratio of 75 kg/m^2 in the unmodified CIRA-72 atmosphere is predicted by DAMAGE to be approximately 25 years (disposal epoch 1 January 1973). When a secular decrease in density is introduced to the atmospheric model using (1) the predicted lifetime is extended to approximately 26.5 years (see Figure 4).

In further simulations using DAMAGE it was found that the extension in lifetime was dependent on the disposal epoch and subsequent solar activity. In the worst case, the orbital lifetime of the satellite above was extended by 6 years.

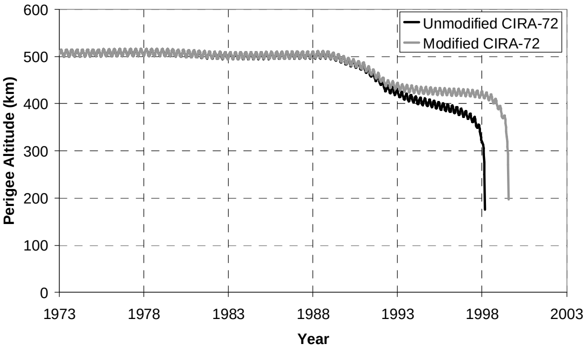

Figure 4. Perigee altitudes and orbital lifetimes predicted using the unmodified and modified CIRA-72 models, for a satellite in a disposal orbit.

Based on the simulations of individual satellite orbits, it was expected that a secular decrease in atmospheric density, applied from 1 January 1973, would also have an impact on predictions of the contemporary debris environment (circa 1 May 2001). Consequently, DAMAGE was used to perform two historical evolutions of the space debris environment in LEO, with a secular density trend applied in the second simulation. Analysis of the spatial density of objects > 1 cm and > 10 cm indicated only a small enhancement at altitudes between 300 and 900 km on 1 May 2001.

Whilst only a small effect of decreasing atmospheric density was found in predictions of the contemporary space debris environment, it was anticipated that the effect would become clearer in long-term, future projections of the environment.

4. FUTURE ENVIRONMENT PROJECTIONS

The DAMAGE model was used to evolve the space debris population in LEO from 1 May 2001 over 100 years in a ‘Business As Usual’ (BAU) scenario, using the unmodified and modified CIRA-72 atmospheric models. For each atmospheric model 20 Monte-Carlo runs were performed with common launch, explosion and solar activity data. The initial population at 1 May 2001 was derived using DAMAGE from the historical evolution with the unmodified CIRA-72 atmosphere. Future launches and explosions were modelled on events from the period 1992 – 1998. A time-step of 8 days was employed with collision probability being assessed at the same rate using the sampling-in-time approach with cube sizes of 20 km. Future projections were performed using four PCs (2.4 GHz – 3.4 GHz processors) with an average run-time of 5 hours.

4.1. Results and Discussion

The expectation was for the number of objects in all size ranges to show an enhancement due to decreasing atmospheric density. The results from the future projections support this hypothesis. Figure 5 shows the average number of objects > 1 cm and > 10 cm on 1 May 2101 predicted using the unmodified and modified CIRA-72 atmospheric models.

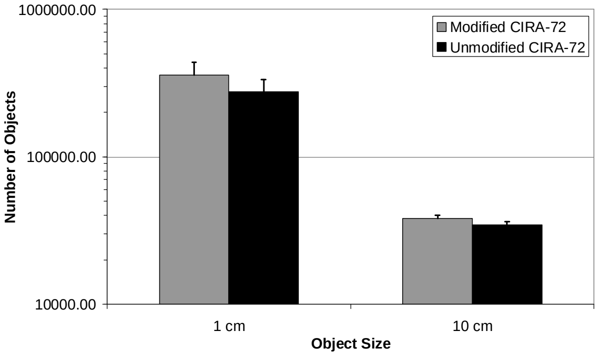

Figure 5. Average number of objects in LEO predicted using the unmodified and modified CIRA-72 models (epoch 1 May 2101). 1-sigma standard deviations are shown.

The number of objects > 1 cm increased by 30.8% and the number of objects > 10 m increased by 9.9% in response to the secular decrease in atmospheric density. Analysis of the number of objects as a function of time indicated that the enhancement of this "lethal" population began at the start of the projection period, 1 May 2001, but with the greatest divergence occurring during the period 2065 – 2101. The augmentation of the populations of objects > 1 cm and > 10 cm is clearly a function of time, as illustrated by Figure 6, but initial investigations do not point to a particular mechanism that would explain these findings.

Figure 6. Percentage difference in number of objects in LEO > 1 cm and > 10 cm due to a secular decrease in atmospheric density.

The distribution of debris spatial density with altitude for objects > 1 cm and > 10 cm (Figure 7) indicates that the enhancement of these populations occurs primarily below 1,200 km. Above this altitude atmospheric density remains too low for the effect of a secular density trend to be discerned.

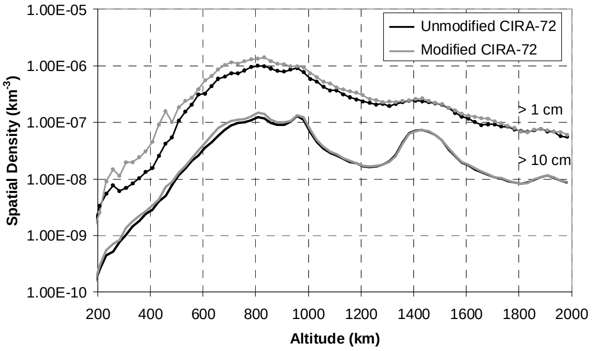

Figure 7. Spatial density versus altitude of objects in LEO > 1 cm and > 10 cm predicted using the unmodified and modified CIRA-72 models.

Orbital lifetimes of small objects (1 – 10 cm) with relatively high area-to-mass ratios are increased in response to declining atmospheric density, contributing to the significant rise in spatial density at low altitudes (250 – 500 km) seen in Figure 8. At an altitude of 450 km, for example, the spatial density of objects > 1 cm is increased by 272%. This is in contrast to an increase in the spatial density of objects > 10 cm by 42% at the same altitude. However, in spite of the decreasing density, the atmosphere remains sufficiently dense at low altitudes for objects to be short-lived. Nonetheless, these results show that the secular atmospheric density trend would exacerbate the spatial density growth at low altitudes caused by debris mitigation strategies employing disposal orbits with lifetimes of < 50 years.

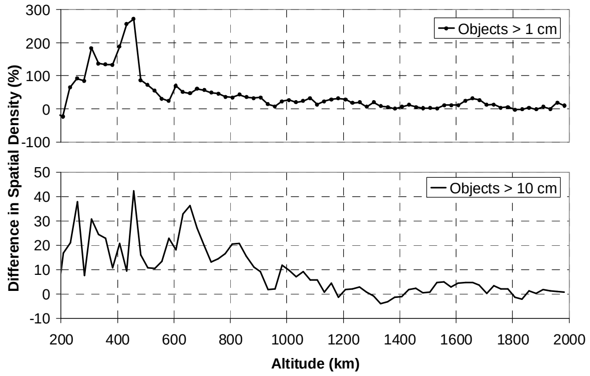

Figure 8. Percentage difference in spatial density of objects in LEO > 1 cm and > 10 cm due to a secular decrease in atmospheric density.

The growth in the spatial density of objects > 1 cm and > 10 cm suggests an increasing probability of collision arising from a secular atmospheric density trend. Indeed, the analysis of the number of objects > 1 cm revealed that whilst the number of intact objects and explosion fragments still in orbit on 1 May 2101 had increased by 5.2% and 8.5% respectively using the modified CIRA-72 atmospheric model, the number of collision fragments was raised by more than 40% (Figure 9). This result is evidence of an increase in the number of collisions that produce fragments > 1 cm in future projections with the modified CIRA-72 model.

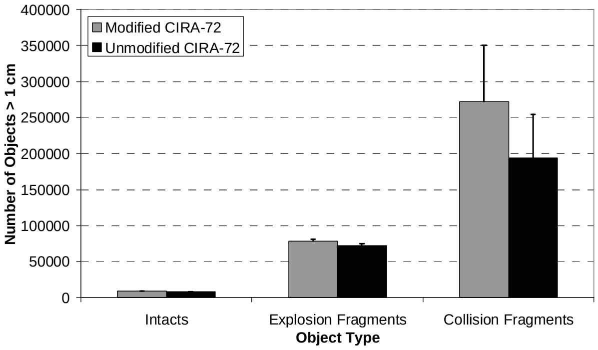

Figure 9. Average number of intact objects, explosion and collision fragments > 1 cm in LEO predicted using the unmodified and modified CIRA-72 models (epoch 1 May 2101). The 1-sigma standard deviations are shown.

The average number of collisions predicted during the period 2001 - 2101, recorded by collision-type, is shown in Figure 10. Four types of collision are identified by DAMAGE; *catastrophic collisions* resulting in the complete break-up of the target and impacting objects (projectile energy to target mass in excess of 40 J/g), *low velocity collisions* occurring for impact velocities < 3 km/s, *damaging collisions* (projectile energy to target mass < 40 J/g), and *critical collisions*. Critical collisions include all catastrophic collisions and the subset of damaging collisions that produce fragments > 10 cm.

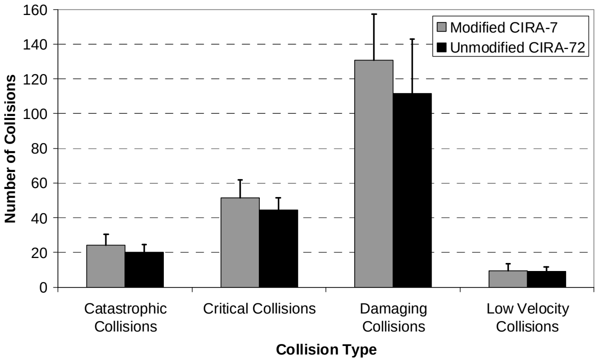

Figure 10. Average number of collisions (catastrophic, critical, damaging and low-velocity) predicted using the unmodified and modified CIRA-72 atmospheric models. The 1-sigma standard deviations are shown.

Future projections using the original CIRA-72 atmospheric model predicted an average of 140.6 collisions, including 44.7 critical collisions. By reducing the atmospheric density in the modified CIRA-72 model, the average number of collisions increased to 164.2 (a 16.7% rise), with 51.5 critical collisions (15.2% rise). Figure 11 shows that the cumulative number of critical collisions predicted using both CIRA-72 models begins to diverge circa 2065.

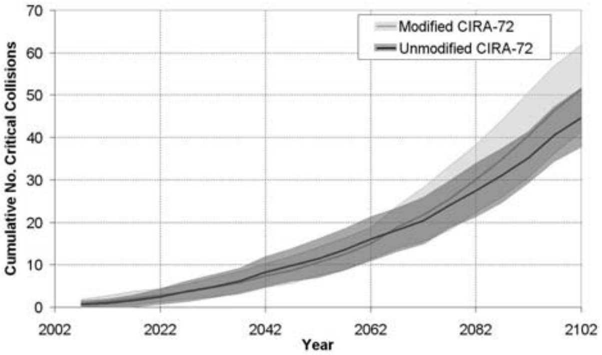

Figure 11. Cumulative number of critical collisions (producing fragments > 10 cm) predicted using the unmodified and modified CIRA-72 atmospheric models. Shaded areas represent the 1-sigma standard deviations.

Figure 11 shows that even with the original CIRA-72 atmospheric model DAMAGE predicted that the number of collisions increases exponentially with time. However, when the *difference* in the number of collisions is studied (Figure 12) it becomes apparent that the *increase* in the number of collisions from 2065 onwards is itself an exponential function of time. This has possible implications for methods of debris mitigation that have been shown to stabilise the future orbital debris population.

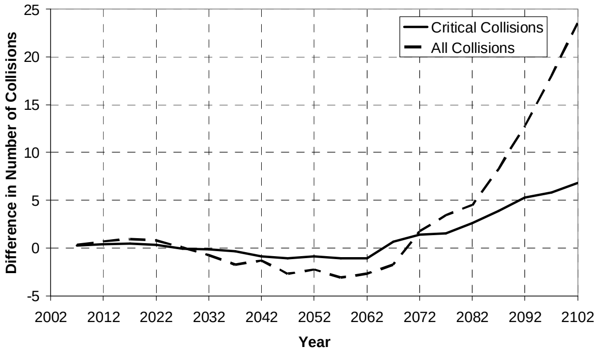

Figure 12. Difference in the number of collisions due to a secular decrease in atmospheric density.

5. CONCLUSIONS

There is growing evidence of a secular decrease in thermospheric density arising from increasing levels of the greenhouse gases CO_2 and NO in the atmosphere. The implications of this density trend are increased orbital lifetimes for satellites and orbital debris.

Simulations using the DAMAGE debris environment model with a modified CIRA-72 atmospheric model show that there may be *two* key effects of a secular density trend on the orbital debris population. Firstly and as expected, objects remain in orbit longer. Propagator studies suggest that orbital lifetimes can be extended by up to 24%, depending on the altitude and prevailing solar activity. Increased lifetimes account for only a small rise in the number of objects, however. For example, the number of intact objects and explosion fragments (two debris sources that remain constant in the future projections presented here) increased by less than 9%. The second, and perhaps more serious, effect of the secular density trend predicted by DAMAGE is an exponential increase in the number of collisions. Simulations using the modified CIRA-72 atmospheric model produced a rise of 16.7% in the collision rate, and a corresponding increase of 40.2% in the number of collision fragments > 1 cm still in orbit on 1 May 2101. The combination of these two effects was an average 30% increase in the number of objects > 1 cm and a 10% increase in the number of objects > 10 cm.

The analysis of spatial density versus altitude indicated that the debris population is enhanced by these effects primarily at heights between 250 km and 1,200 km. A significant increase in the spatial density of objects > 1 cm was observed below 500 km and this may have implications for proposed mitigation practices in low Earth orbit.

This article represents the first investigation of the long-term impact of a secular decrease in thermospheric density on the orbital debris population in LEO. Further work is required to quantify the secular trend in density and to model this dynamic of the thermosphere, and then to investigate the response of the space debris environment. In particular, the implications for debris mitigation practices (post-mission disposal, passivation, etc.) should be investigated.

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