Past and Future Climate of Thermospheric Density: Solar and Anthropogenic Influences

- Thermosphere energy balance
- Thermosphere climate from satellite drag
- Attribution of 2008 solar minimum behavior
- Scenarios for next 200 years
- Possible changes in the orbital debris population

John Emmert, Judith Lean
Space Science Division, Naval Research Lab

Hugh Lewis
Faculty of Engineering and the Environment, University of Southampton

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Electric Currents and Energetic Particles

Temperature (K)

Solar Min
Solar Max

Thermosphere
Mesosphere
Stratosphere

X-Rays
Extreme UV 10-120 nm
Far UV 120-200 nm
Middle UV 200-300 nm
Near UV 300-400 nm
Visible and IR

Cooling Rates

Roble, Geophys. Mon. 87, 1995
Solar EUV Irradiance Variations

Thermospheric Density Response

\[ \ln \rho \]

Density Change

SDO/AIA 30.4 nm

0-103 nm Irradiance (TIMED/SEE)

mW/m²

Day of Year, 2013

Altitude (km)

Latitude

\[ \rho / \rho(t_0) \]
Thermospheric Composition and Mass Density

Number Density (NRLMSISE-00)

O₂, N₂, O, N, He, H

Diffusive Separation
\[ \ln n_s = \ln n_{s0} + \ln \frac{T_0}{T} - \frac{m_s}{k_B} \int_{z_0}^{z} \frac{g(z')}{T(z')} \, dz' \]

Total Mass Density (NRLMSISE-00)

Solar Maximum, Solar Minimum

Hydrostatic Equilibrium
\[ \ln \rho = \ln \rho_0 + \ln \left( \frac{T_0}{T} \frac{\bar{M}}{\bar{M}_0} \right) - \frac{1}{k_B} \int_{z_0}^{z} \frac{\bar{M}(z') g(z')}{T(z')} \, dz' \]
CO₂ Cooling: A major driver of upper atmospheric changes

CO₂ is increasing in the TROPOSPHERE and THERMOSPHERE.

Emmert et al., Nature Geoscience, 2012

Yue et al., GRL, 2015
Changes in Temperature and Density

Modeled 1996-2008 Temperature Change

Qian et al., JGR, 2013

Summary of Modeled and Observed Density Trends

- Akmaev et al. (2006)
- Cnossen (2009)
- Qian and Solomon (2011)
- Saunders et al. (2011)
- Emmert et al. (2004)
- Emmert and Picone (2011)
- Marcos et al. (2005)
- Keating et al. (2000)

Cnossen, 2011

Modeled 1996-2008 Density Change

Qian et al., JGR, 2013

Density
# Orbit-derived Thermospheric Density Data

<table>
<thead>
<tr>
<th>Description</th>
<th>Global average mass density altitude profiles, 200-600 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Derived from</td>
<td>Orbital drag on ~5000 objects</td>
</tr>
<tr>
<td>Time covered</td>
<td>1967-2013</td>
</tr>
<tr>
<td>Temp. Resolution</td>
<td>3-6 days</td>
</tr>
<tr>
<td>Absolute Accuracy</td>
<td>~10%</td>
</tr>
<tr>
<td>Relative Accuracy</td>
<td>~2%</td>
</tr>
<tr>
<td>Reference</td>
<td>Emmert, JGR, 2015</td>
</tr>
</tbody>
</table>

The rate of decay of an orbit is directly proportional to mass density:

$$\frac{da}{dt} = -\frac{a^2 \rho B v^3 F}{\mu}$$

Rate of decay at 400 km: 0.16 m/s^2

![Graph showing time series data for 400 km altitude](image)

![Image of Earth with orbit data](image)
Climate of Global Average Density (400 km)

Solar EUV Irradiance

Geomagnetic Activity

Intra-annual Oscillations

Tropospheric CO₂

Emmert et al., JGR, 2014
Attribution of record-low thermospheric Densities

In 2008 and 2009, lowest observed densities since beginning of space age

Solar Activity
Annual Variation
Geomagnetic Activity
CO₂

Emmert et al., JGR, 2014
Implicit Trends at Solar Minimum

GAMDM2.1 IMPLICIT TRENDS AT SOLAR MINIMUM (400 km)

- $F_{10.7}$
- $K_p$
- Tropospheric $CO_2$

Emmert, JGR, 2015


$F_{10.7}$: 74, 72, 70, 68
$K_p$: 2.5, 2.0, 1.5, 1.0
Tropospheric $CO_2$: 400, 375, 350, 325

Emmert, JGR, 2015
Solar Scenarios for Next 200 Years

Scenario 1: Perpetual Grand Maximum (Cycle 18)

Scenario 2: Gleissberg Minimum (Cycle 14)

Scenario 3: Dalton Grand Minimum (Cycle 6)

Scenario 4: Maunder + Gleissberg Minima
Solar Scenarios for Next 200 Years

Tropospheric CO$_2$ (RCP 6.0)

Solar Irradiance ($F_{10.7}$)

Density at 400 km
CO₂ Scenarios for Next 200 Years

Scenarios for Next 200 Years

Tropospheric CO₂

Solar Irradiance (Scenario 2)

Roble & Dickinson, 1989 CO₂ Doubling

Density at 400 km

Roble & Dickinson, 1989

Density (10⁻¹² kg m⁻³)

Altitude (km)

Δρ (%)
The Orbital Debris Population

- NASA Debris Model, > 1 cm (~110,000)
- NASA Debris Model, > 10 cm (~7,500)
- Air Force Catalog (~11,500)
- Operational Satellites (~500)

The Hazard:

18 cm

1.2 cm
The Orbital Debris Population

The graph shows the increase in the number of objects > 10 cm in orbit from 1957 to 2012. Key events marked on the graph include the Iridium/Cosmos Collision and the China Anti-satellite Test.

- **Total Objects**: The number of total objects has significantly increased over the years, with a notable spike in 2007 due to the Iridium/Cosmos Collision.
- **Fragmentation Debris**: Shows a significant increase in the early 2000s, particularly after the China Anti-satellite Test.
- **Spacecraft** and **Mission-related Debris**: These categories display a steady increase over the years, with minor fluctuations.
- **Rocket Bodies**: The number of rocket bodies has increased gradually, with a slight dip around 2000.

The data is sourced from the NRC Debris Study, 2011.
Top “10” worst fragmentations

- **Nimbus 4 Rocket Body**
- **SPOT 1 Rocket Body**
- **OV 2-1/LCS 2 Rocket Body**
- **CBERS Rocket Body**
- **Fengyun-1C**
- **Iridium 33 Cosmos 2251**
- **Cosmos 2421**

**Number of Debris**
- 100
- 500
- 1000
- 2000
- 3000

**Year**
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010

**Altitude (km)**
- 400
- 600
- 800
- 1000
- 1200

**Explosion**
- Catalogued Debris *
- Decayed Debris

**Collision**

- * As of 1 January 2011
UN Space Debris Mitigation Guidelines...

• Limit debris released during normal operations.
• Minimize the potential for break-ups during operational phases.
• Limit the probability of accidental collision in orbit.
• Avoid intentional destruction and other harmful activities.
• Minimize potential for post-mission break-ups resulting from stored energy.
• Limit the long-term presence of spacecraft and launch vehicle orbital stages in the low Earth orbit (LEO) region after the end of their mission.

...are not enough to prevent debris growth:

• Atmospheric drag is currently the only way debris objects are removed from orbit.
• Active debris removal strategies are being researched.
• About 50 removals needed to prevent one collision.
• $1 – $3 billion per year.
Debris Population Projections
(No density trend)

Average Evolution of 10 cm population

30% compliance w/mitigation guidelines
90% compliance
90% compliance with
5 removals p.a.

Ensemble Variance, 30% compliance
Debris Population Projections (90% Compliance with Mitigation Guidelines)

No Density Trend

With Density Trend
Summary

- Solar EUV irradiance is the dominant driver of thermospheric density variations on decadal and shorter time scales.
- Due to its dominant role as a cooling agent in upper atmospheric energy balance, CO$_2$ is a major driver of long-term change in the upper atmosphere.
- Satellite drag derived from orbital tracking data provides a long-term record of global thermospheric climate. Density at 400 km altitude is decreasing at a rate of ~2% per decade, in quantitative agreement with model predictions of enhanced CO$_2$ cooling.
- Attribution of low density during the 2008 minimum is complicated by the fact that the major drivers (solar flux, geomagnetic activity, and CO2) all acted to produce negative inter-minima density trends.
- Long-term variations in solar output (e.g., Grand Maxima vs. Grand Minima), together with CO2 increases, would significantly alter thermospheric density, satellite drag, and the orbital debris population.
- Possible future states of the Sun and thermosphere should therefore be considered in planning debris remediation strategies.