Observed and modelled neutral densities during the 2015 St. Patrick's Day geomagnetic storm

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Abstract

Countless processes are occurring in Earth's upper atmosphere constantly, many of which are not fully understood. An increase in solar and geomagnetic activity can add to, and even change, these processes, which can exacerbate their effects. The neutral density of the atmosphere is one factor that varies according to these processes and can, in turn, have its own impact on satellites in low Earth orbit. *In situ* measurements of neutral density in the upper atmosphere are scarce, however a small number of satellites have been used for this. Another option is to use upper atmospheric models to estimate neutral density, which has the advantage of predicting on a global scale, but with the drawback of an unknown level of accuracy. To quantify models' neutral density accuracy, validation against satellite data is commonly performed. In this study, Swarm A and Swarm C satellite neutral densities are used to validate outputs from the physical TIE-GCM and the empirical NRLMSISE-00, JB2006, and JB2008 for the 2015 St. Patrick's Day geomagnetic storm. Reliability of Swarm A and C density data is discussed. One result of the analysis is that both satellites measure intense spikes in neutral density over polar regions during the early stages of the storm, which are not reproduced within the models.

Background

- Below ~800 km, atmospheric drag is the largest non-conservative perturbing force [1]
- Drag equation:

$$a_{drag} = \frac{1}{2} C_d \rho \frac{A}{m} v_{rel}^2$$

  - a_{drag} – acceleration due to drag
  - C_d – drag coefficient
  - ρ – mass density
  - A – cross-sectional area
  - m – mass
  - v_{rel}^2 – velocity relative to atmosphere
- During geomagnetic storms, atmospheric density is increased
- Density measurements are difficult to obtain and are scarce; models could help to recreate and predict variations in atmospheric density
- We compare four models to satellite observations for the 5-day period 15-19 March 2015 covering the St. Patrick's Day geomagnetic storm

Data and Empirical Models

Swarm Satellites

- 3-satellite constellation – Alpha (A), Bravo (B), and Charlie (C)
- A and C orbit side-by-side in near-polar orbits at ~462 km altitude and ~87.4° inclination
- Satellites generate thermospheric density measurements based on accelerometer and GPS data [2]
- Densities have been normalised to 467 km using NRLMSISE-00 via [3]

$$\rho_{sat}(467\ km) = \rho_{sat}(h_{sat}) \cdot \frac{\rho_{mod}(467\ km)}{\rho_{mod}(h_{sat})}$$

NRLMSISE-00 (2000 US Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar Extended)

- Empirical upper atmospheric model [4]
- Solar inputs: daily and 81-day centred average F10.7
- Geomagnetic inputs: daily Ap and 3-hourly ap

Figure 1. Swarm constellation (*Credit: ESA – P. Carril, 2013*)

JB2006 (Jacchia-Bowman 2006)

- Empirical upper atmospheric model [5]
- Solar inputs: daily and 81-day centred average F10.7, S10.7, and Mg10.7
- Geomagnetic inputs: 3-hourly ap

JB2008 (Jacchia-Bowman 2008)

- Empirical upper atmospheric model [6]
- Solar inputs: daily and 81-day centred average F10.7, S10.7, MgII, and Y10.7
- Geomagnetic inputs: temperature change computed from Dst

Physical Model

TIE-GCM (Thermosphere-Ionosphere-Electrodynamics General Circulation Model)

- Physical upper atmospheric model [7]
- Spatial resolution: 5° x 5° in latitude and longitude, 2 grid points per scale height
- Temporal resolution: 60 second time step with outputs recorded every 15 minutes
- Solar inputs: daily and 81-day centred F10.7 as a proxy for atmospheric heating
- Geomagnetic inputs: 3-hourly Kp to drive the Heelis high latitude convection pattern

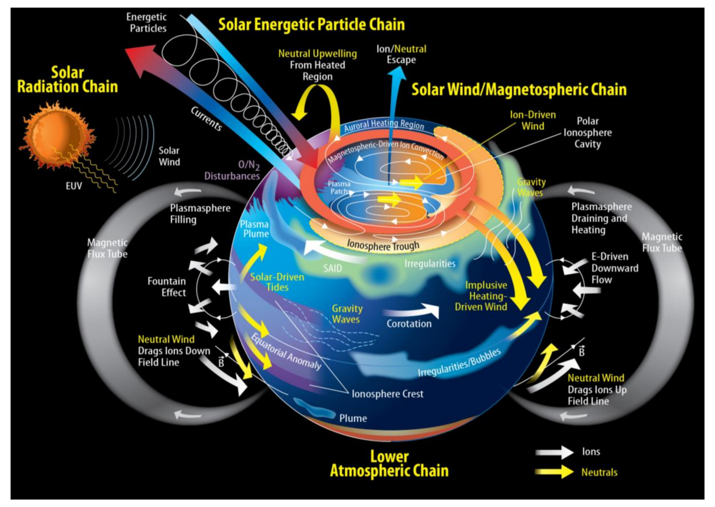

Figure 2. Physical processes in Earth's upper atmosphere (*Credit: NASA's Scientific Visualization Studio*)

- Outputs are interpolated to satellite positions for each time interval using cubic spline interpolation

Results

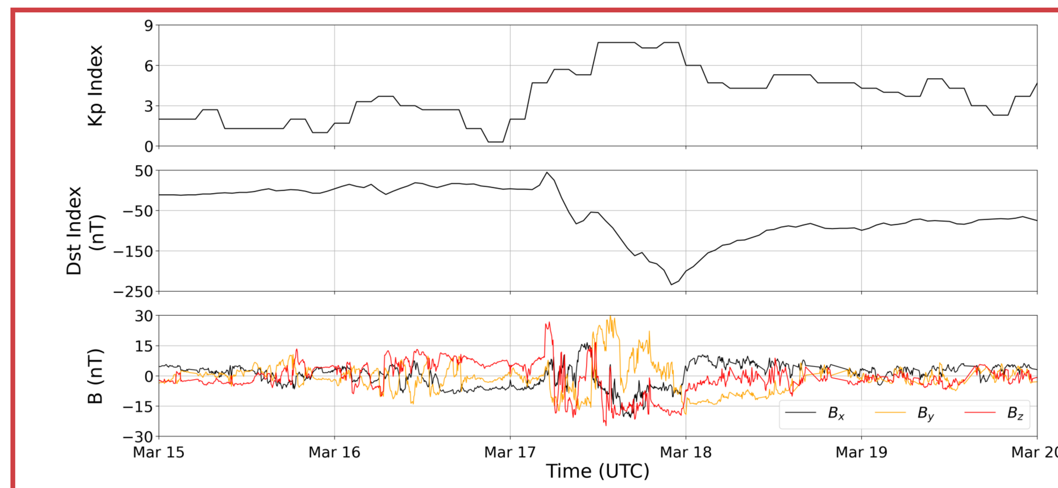

Figure 3. Geomagnetic summary of the 2015 St. Patrick's Day geomagnetic storm. Kp index (top), Dst index (middle), and magnetic field components of solar wind (bottom) from 15-19 March 2015.

- Quiet conditions prior to March 17
- SSC on March 17 at ~4:45 UT
- High Kp, low Dst
- Prolonged negative B_z on March 17 after ~14:00 UT
- Main phase ends on March 17 at ~22:45 UT

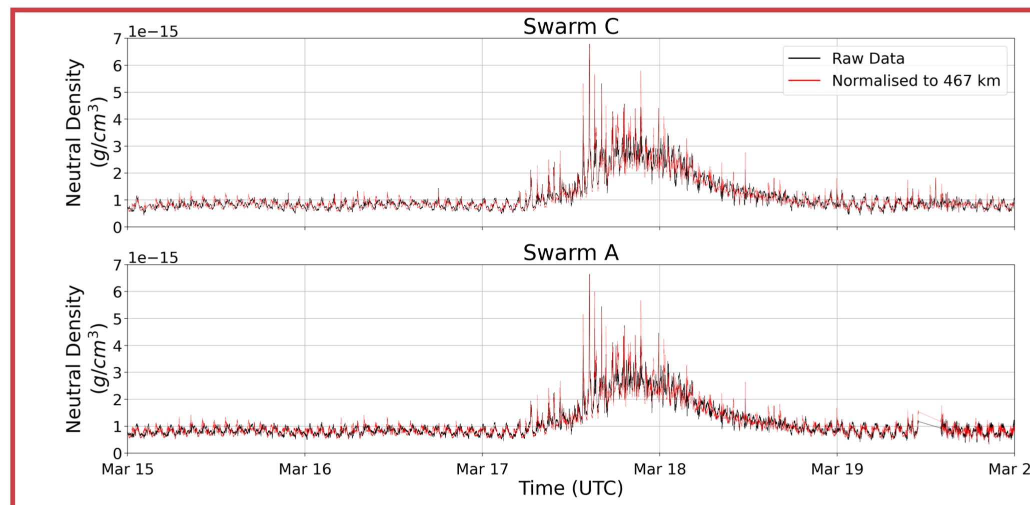

Figure 4. Swarm C (top) and A (bottom) neutral density data from 15-19 March 2015. Raw data are in black, and data normalised to 467 km are in red.

- Swarm C and Swarm A neutral densities compare well
- Neutral density begins increasing at storm arrival, decreasing during recovery
- There is large spiking during storm time

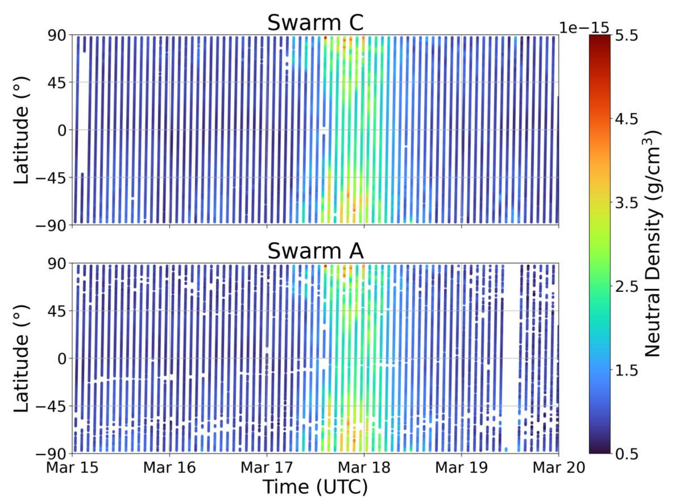

Figure 5. Swarm C (top) and A (bottom) neutral density data over satellite latitude from 15-19 March 2015. Data are for ascending orbits.

- Overall density increase during storm
- Large spiking occurs in polar regions

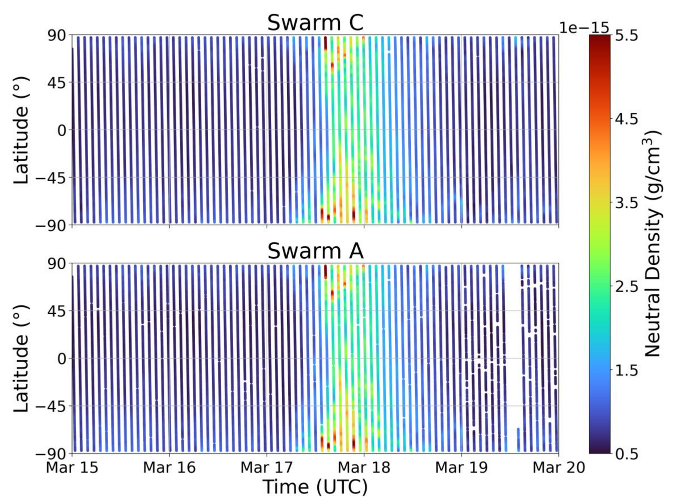

Figure 6. Swarm C (top) and A (bottom) neutral density data over satellite latitude from 15-19 March 2015. Data are for descending orbits.

- Same as for Figure 5
- Both large-scale and short-scale variations

Results

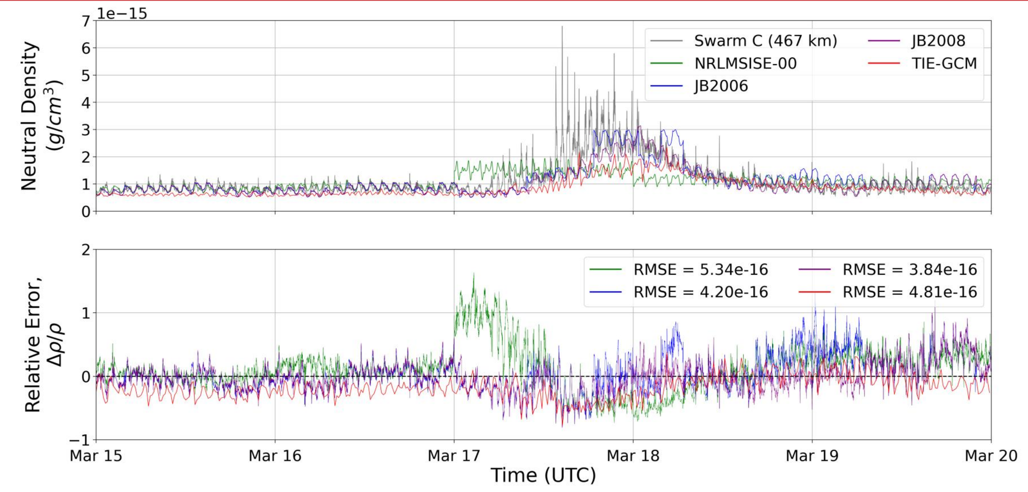

Figure 7. Neutral densities from Swarm C (grey), NRLMSISE-00 (green), JB2006 (blue), JB2008 (purple), and TIE-GCM (red) (top); and relative errors of the models (bottom) from 15-19 March 2015. RMSEs for the full period are listed in the legend.

- NRLMSISE-00 – no smooth curve, largest RE range, largest RMSE
- JB2006 – captures overall trend
- JB2008 – captures overall trend, slightly smoother than JB2006, lowest RMSE
- TIE-GCM – captures overall trend, lowest RE range mostly below zero

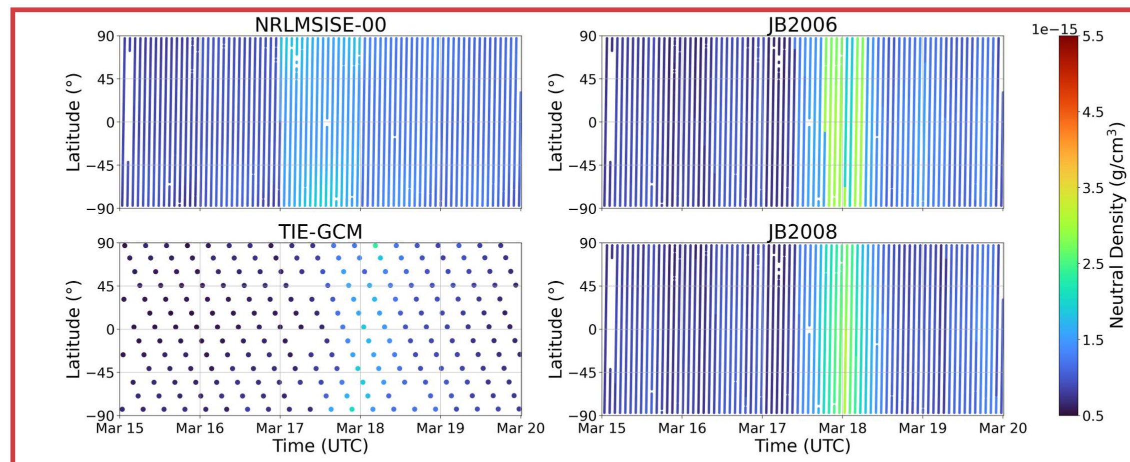

Figure 8. NRLMSISE-00 (top left), JB2006 (top right), TIE-GCM (bottom left), and JB2008 (bottom right) neutral density data over latitude from 15-19 March 2015. Data are for corresponding Swarm C ascending orbits.

- Times for JB2006, JB2008, TIE-GCM density increases align with Figure 5
- Intensity of JB2006, JB2008 density increases align best with Figure 5
- Short-scale variations over polar regions are not seen

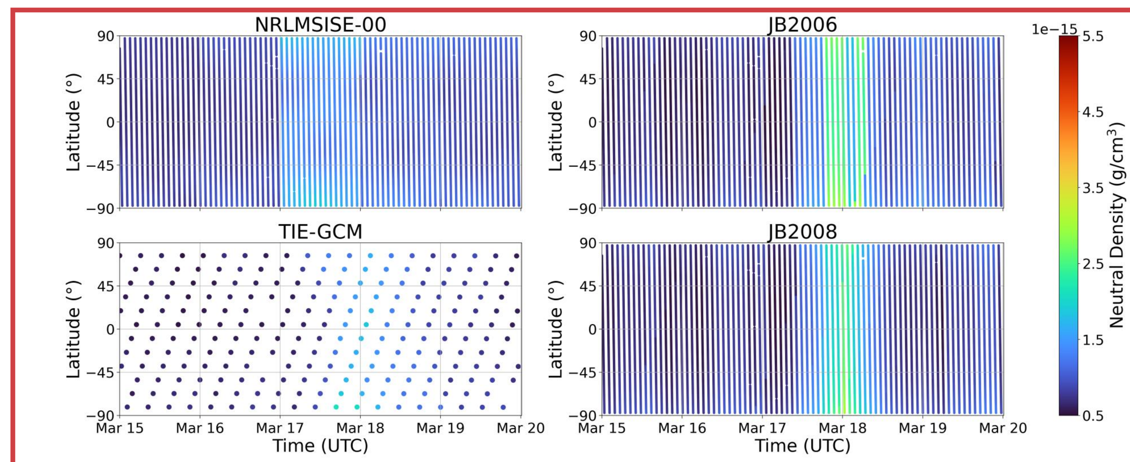

Figure 9. NRLMSISE-00 (top left), JB2006 (top right), TIE-GCM (bottom left), and JB2008 (bottom right) neutral density data over latitude from 15-19 March 2015. Data are for corresponding Swarm C descending orbits.

- Same as for Figure 8 when comparing with Figure 6
- Models only show large-scale variations

Conclusions

- Observed and modelled neutral densities have been presented and compared across the 2015 St. Patrick's Day geomagnetic storm
- Swarm C and A showed that the 2015 St. Patrick's Day storm caused an increase in atmospheric density, with large density spikes over polar regions
- In quiet conditions, empirical models perform similarly, while TIE-GCM consistently underestimates
- In storm conditions and recovery, NRLMSISE-00 had the poorest performance, while JB2008 had the best; however, TIE-GCM was the most precise, suggesting bias within the model that could be corrected for improved results
- No models recreated the observed short-scale variations in neutral density over polar regions

References

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