# IDENTIFYING THE SOURCES OF THE VARIABILITY IN THERMOSPHERIC MASS DENSITY

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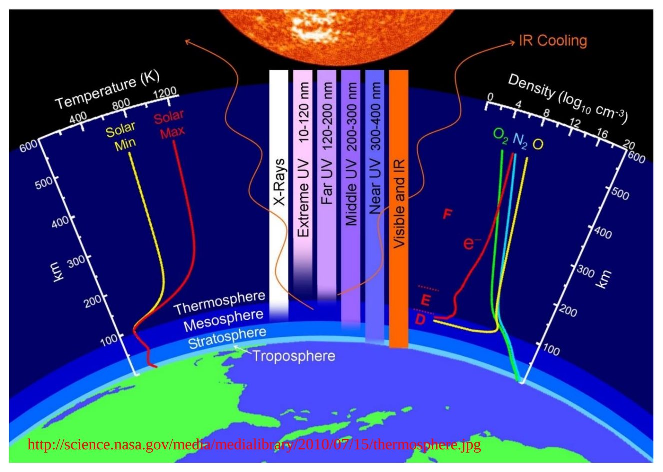
## Abstract

Recent accelerometer observations onboard LEO spacecrafts have revealed considerable amount of variability in thermospheric neutral mass density on various temporal and spatial scales, not only during periods of elevated geomagnetic activity, but also during quiet times. Accurately predicting the atmospheric density in the upper atmosphere is crucial for estimating the trajectory of objects in Low Earth Orbit (LEO), since satellite drag introduces errors in orbit determination solutions for the rapidly increasing number of man-made objects. The overall purpose of our project is to quantify the degree of variability in the neutral mass density in the thermosphere and identify the possible causes, by using a coupled Whole Atmosphere Model and Ionosphere-Plasmasphere-Electrodynamics (WAM-IPE) that is running test-operationally at NOAA/SWPC. In this presentation, we will compare the mass density variations for various geophysical conditions, between the WAM-IPE model and accelerometer satellite observations (e.g., CHAMP and GOCE), as well as the thermosphere, ionosphere, plasmasphere, and electrodynamics (CTIPe) model that has been well established by continuous effort of validation for over a decade.

## Thermosphere

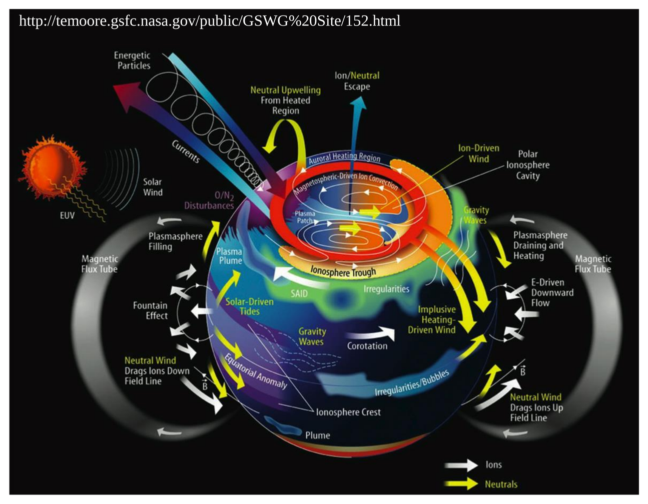


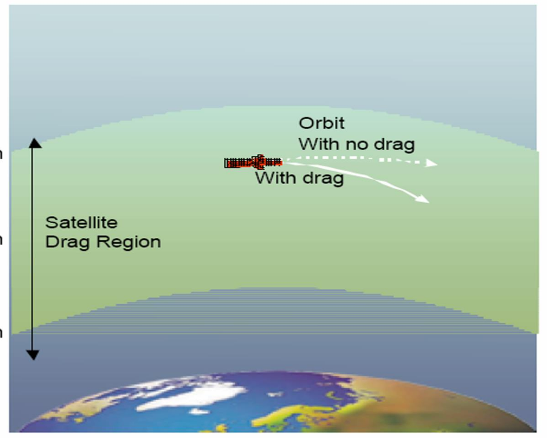
http://science.nasa.gov/media/...

In the thermosphere, composition changes drastically with altitude such that the heavier species are concentrated lower down, while the light ones dominate at the higher altitudes. Thermospheric temperatures increase with altitude due to absorption of highly energetic solar radiation by the small amount of residual oxygen. The neutral mass density fluctuates based primarily on thermospheric heating.

The thermosphere system is primarily controlled by various external sources of forcing, while various mechanisms convert, transport and redistribute the input energy from the system. External energy inputs include primarily solar energy in the form of EUV radiation, auroral precipitation, and magnetospheric convection at high latitudes. Internal influences include tides, gravity waves, and planetary waves as well as turbulence and convection.

http://temoore.gsfc.nasa.gov/public/GSWG%20Site/152.html



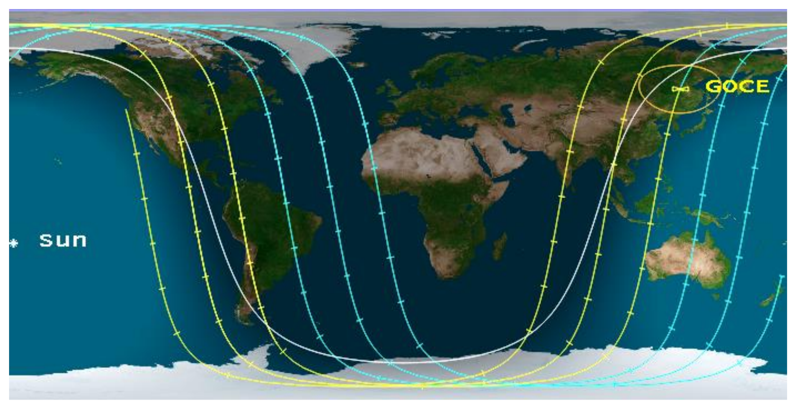



http://lws.gsfc.nasa.gov/documents/mission_requir_ws_2_2000/marcos_020900.pdf

The temperature of the Earth's thermosphere can be substantially increased during geomagnetic storms mainly due to high-latitude Joule heating induced by magnetospheric convection and auroral particle precipitation. Thermospheric heating increases atmospheric density and the drag on LEO satellites. LEO constitutes the region of space below the altitude of 2,000 km.

## Thermospheric Neutral Density Observations

https://www.nasaspaceflight.com/2013/10/goce-end-life-destructive-reentry/




https://4gfc.files.wordpress.com/2013/11/3499400_orig.png

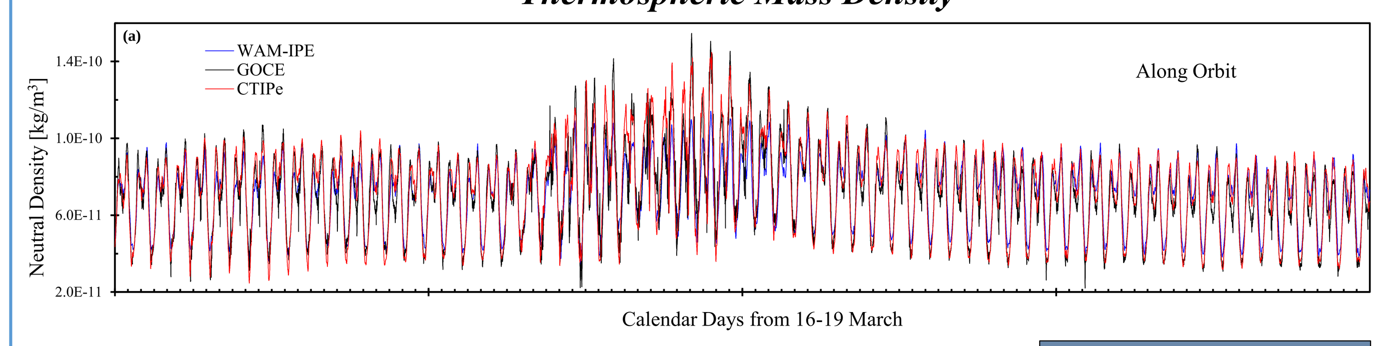
**Orbit path of GOCE**

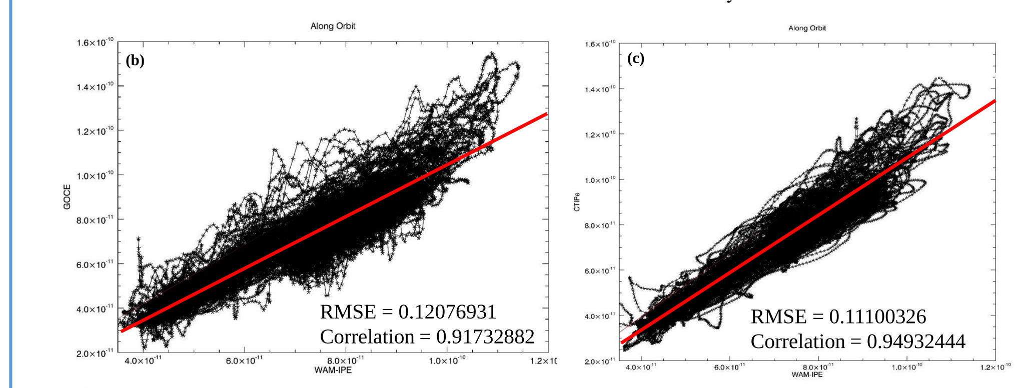
Physics-based models are compared with multiple sources of observations including CHAMP and **GOCE.**

Launched in March 2009 into a Sun-synchronous orbit (96.7° inclination) at 255 km altitude, GOCE's orbital altitude gradually decreased until end of mission in November 2013. Total mass density estimates were derived from the along-track acceleration through the drag using accelerometers with a sampling rate of 10s (Doornbos et al., 2013).

## 2013 St. Patrick's Day Storm GOCE/CTIPe/WAM-IPE Comparisons

### *Thermospheric Mass Density*



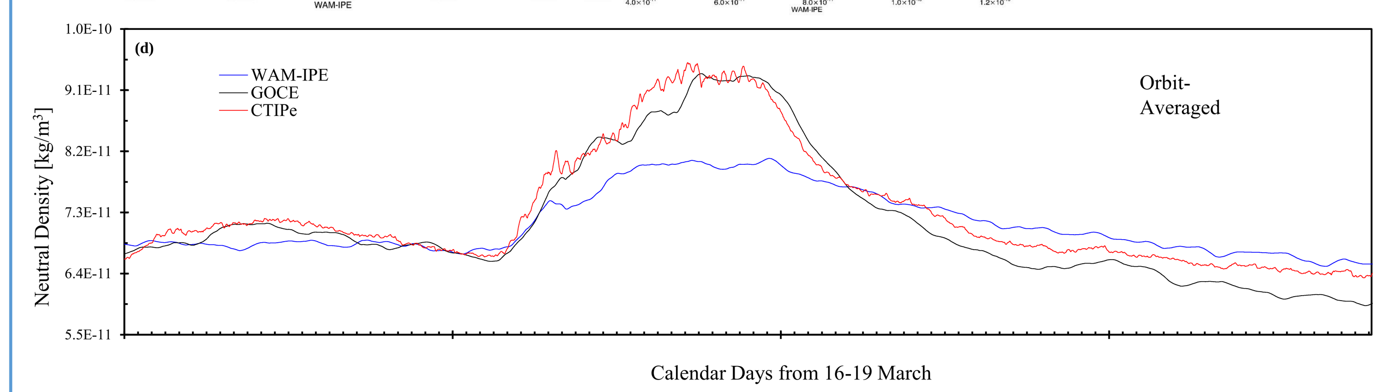

**Metrics (log space)**

$$\mu(m/o) = \exp\left(\frac{1}{N}\sum_{n=1}^{N}\ln\frac{\rho_{m,i}}{\rho_{o,i}}\right)$$

$$\text{RMSe} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\ln\frac{\rho_{m,i}}{\rho_{o,i}}\right)^2}$$

$$\sigma(m/o) = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\ln\frac{\rho_{m,i}}{\rho_{o,i}} - \ln\mu(m/o)\right)^2}$$

$$\text{RMSe}^2 = \ln(\mu(m/o))^2 + \sigma(m/o)^2.$$



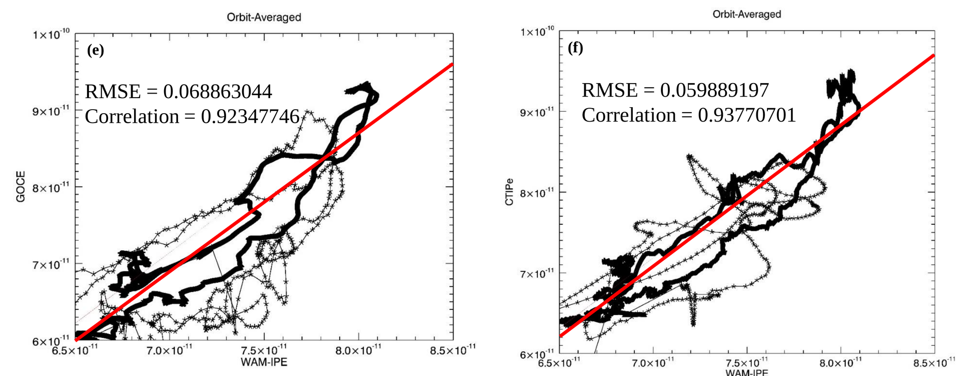
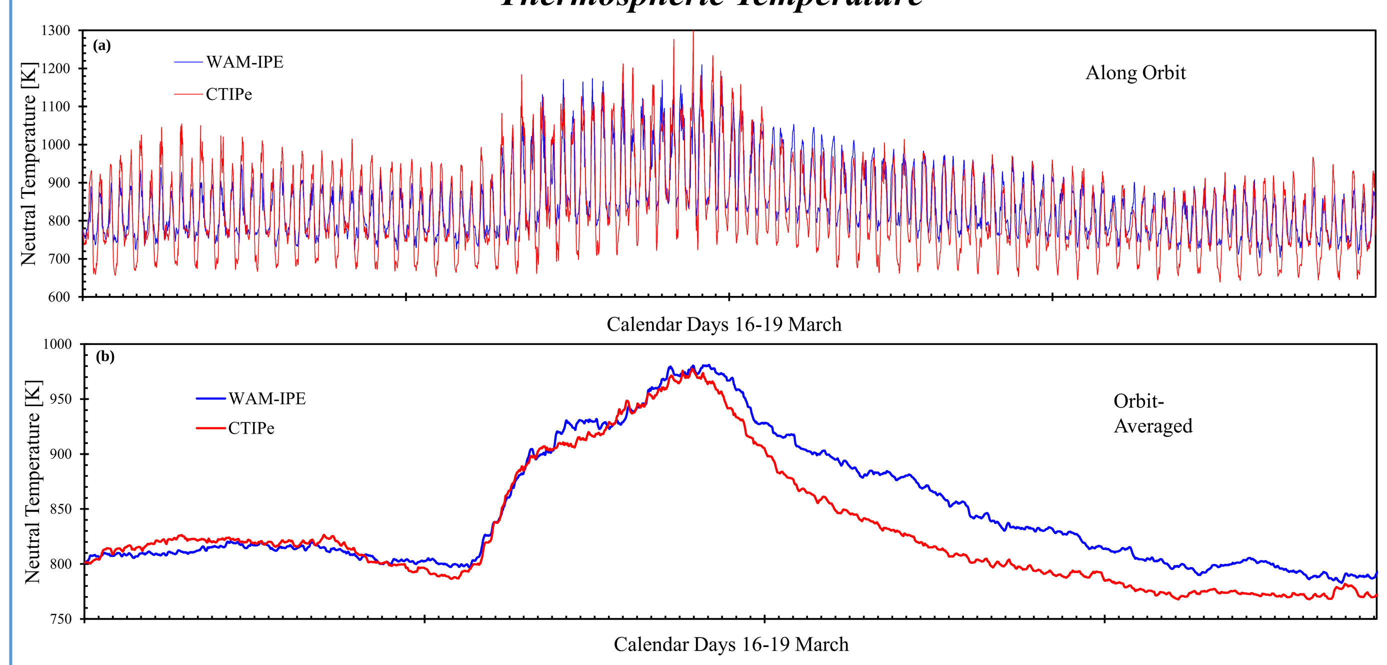




**Figure 1.** Time series of (a & d) scaled WAM-IPE densities (bias corrected for 16 March) compared with CTIPe and GOCE with error and correlations (b, c, e & f) for along orbit and orbit-averaged from 16 to 19 March 2013. WAM-IPE underestimates storm-time and cooling recovery response.

### *Thermospheric Temperature*



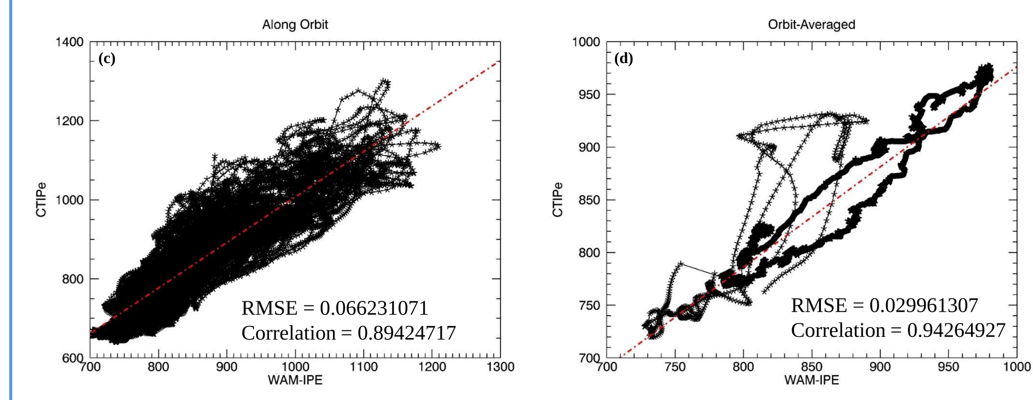




**Figure 2.** Time series of (a & b) scaled WAM-IPE temperatures (bias corrected for 16 March) compared with CTIPe with error and correlations (c & d) for along orbit and orbit-averaged from 16 to 19 March 2013. WAM-IPE underestimates cooling recovery response.

### *Thermospheric Mass Density*

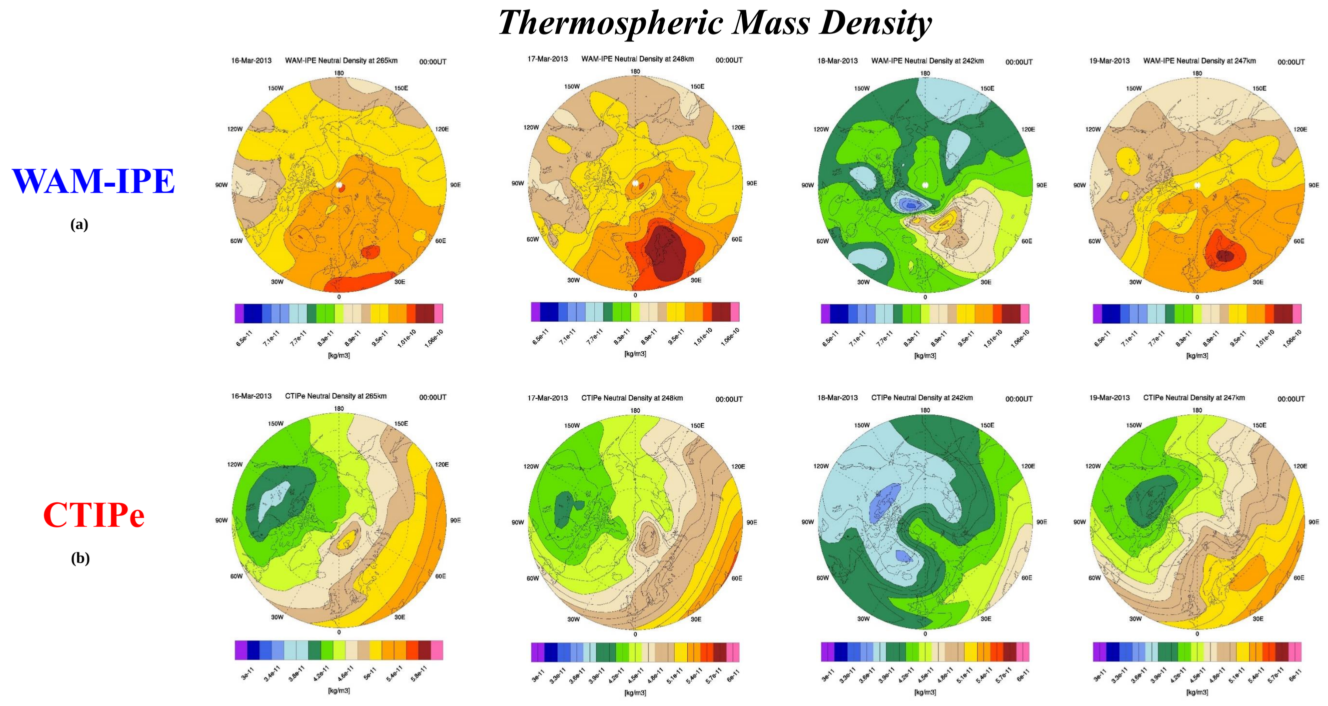



**Figure 3.** Neutral mass density at constant pressure levels at an average altitude 250km through time from WAM-IPE and CTIPe. Neutral mass density decreases as temperature increases during the storm.

## Modeling Thermospheric Mass Density

### Whole Atmosphere Model Ionosphere Plasmasphere Electrodynamics (WAM-IPE)

- Comprehensive, 3D, time-dependent coupled model of the Earth's ionosphere, thermosphere, and lower atmosphere (ground – 600km)
- Radiative heating (UV & EUV) and cooling, ion drag and Joule heating
- Predicts ionospheric parameters such as total electron content, peak ionospheric electron density, and other factors affecting GPS and HF radio communications

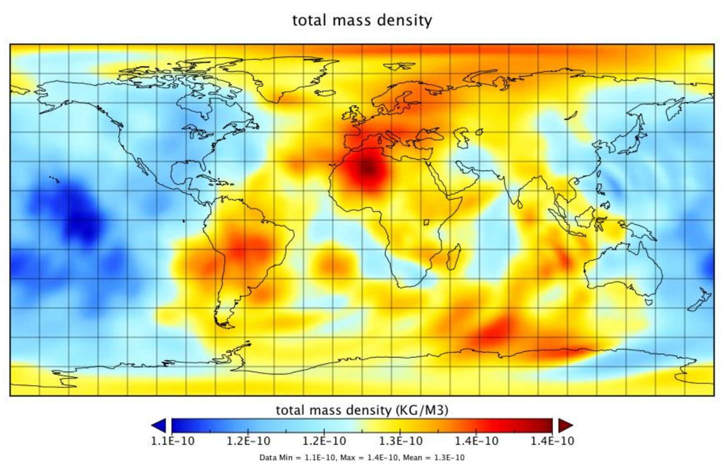



**Figure 4.** Sample neutral mass density taken from WAM-IPE

### Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics Model (CTIPe)

- Covers global thermosphere (80 – 500 km)
- Solves momentum, energy, composition, etc. balances along many closed flux tubes. Coupled with the Weimer ionosphere electrodynamics model to calculate neutral wind vector, temperature, and mean molecular mass
- Forcing: Solar UV and EUV, Weimer electric filed, TIROS/NOAA auroral precipitation, and tidal forcing

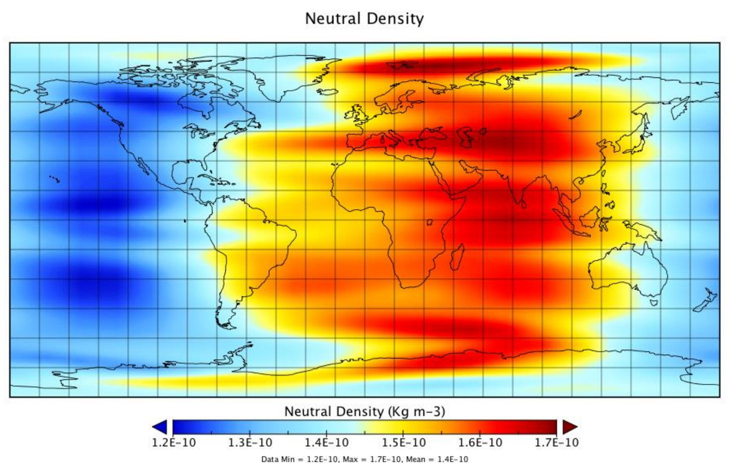



**Figure 5.** Sample neutral mass density taken from CTIPe

## Energy Partitioning during a Geomagnetic Storm

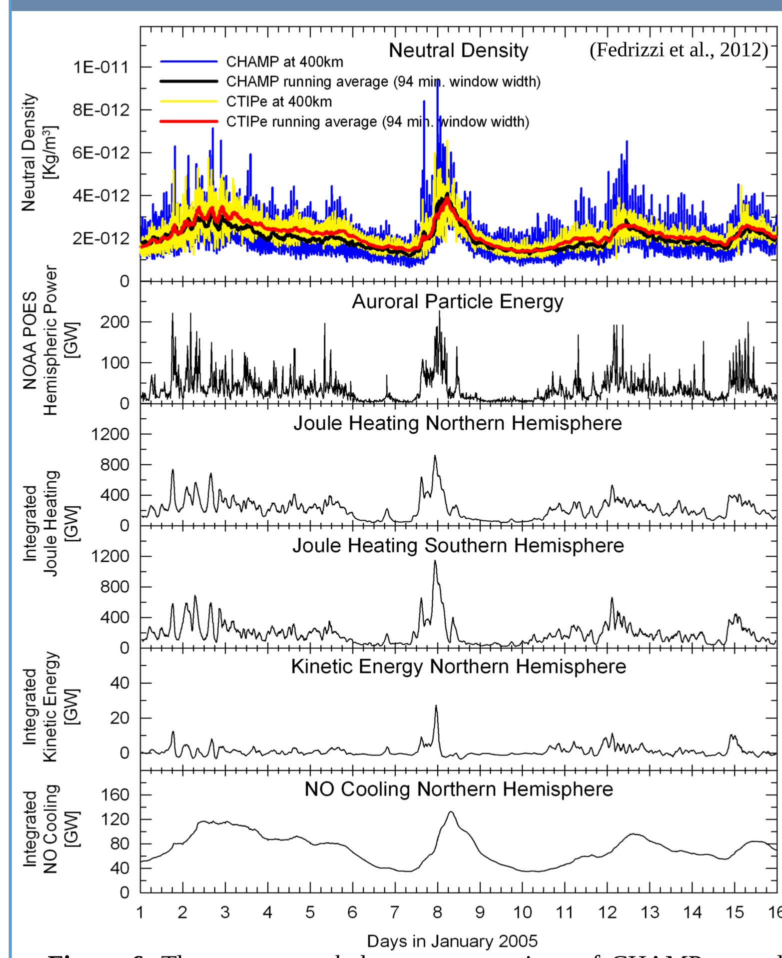
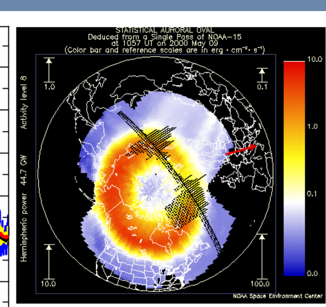
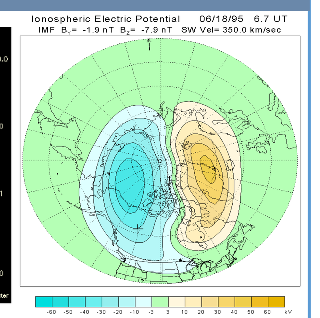


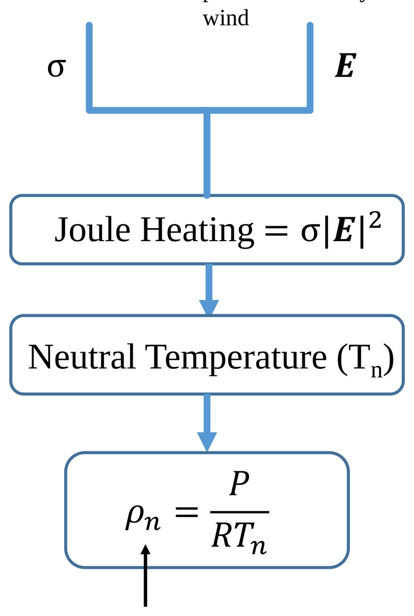

**Figure 6.** The *upper panel* shows a comparison of CHAMP neutral density measurements at 400 km altitude with a numerical simulation for a storm period in January 2005. The *lower panels* show, from top to bottom, estimates of global auroral power, Joule heating in the Northern and Southern hemispheres, kinetic energy deposition, and nitric oxide infrared cooling rates.



**TIROS/NOAA auroral precipitation:** patterns driven by power index



**Weimer 2005:** electric field patterns driven by solar wind




## Conclusions and Future Work

- The results of this study suggest that WAM-IPE can capture the storm-time response and recovery and is comparable to CTIPe and GOCE. With appropriate physical conditions in place, the results yield reasonable agreement across the neutral mass density and temperature comparisons. Energy input forces the neutral atmosphere to expand, thus increasing the neutral mass density.
- It is observed that WAM-IPE underestimates storm-time and cooling recovery response when CTIPe and WAM-IPE are normalized prior to the storm. WAM-IPE captures lower atmosphere effects from the wiggles shown in mass density polar plots (**Figure 3**) when compared with CTIPe.
- For future work, the neutral composition will be validated to improve the storm-time and recovery responses as shown in figures **1d** and **2b**. Furthermore, seasonal dependence of heating and cooling of the WAM-IPE model will be validated. Sensitivity analysis will be carried out to quantify the neutral mass density variability toward improved predictions of satellite orbit errors.

## Acknowledgements

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•E. Doornbos , S. Bruinsma , B. Fritsche , P. Visser , J. Van Den IJssel , J. Teixeira Encarnacˌaoˉ , and M. Kern, Air density and wind retrieval using GOCE data. *ESA Living Planet Symposium 2013*, ESA SP-722, 9-13, September 2013.