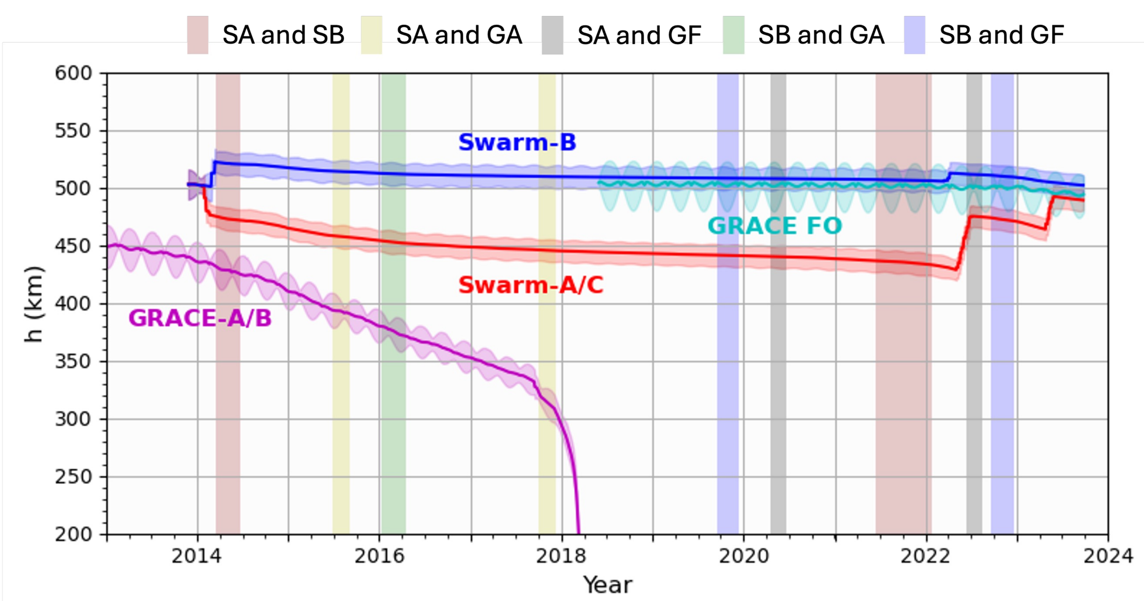
Variations of upper thermospheric scale height based on neutral mass density measurements from coplanar low-Earth-orbit satellites

Heikki Vanhamäki[1], Lei Cai[1], Anita Aikio[1], Marcus Pedersen[1], and Milla Myllymaa[1]
1. Space Physics and Astronomy, University of Oulu, Finland
Contact: lei.cai@oulu.fi

Background

The mass density scale height H_ρ in the upper atmosphere is a measure of the vertical distance over which the neutral mass density ρ decreases by a factor of e (the base of natural logarithms). The change in H_ρ indicates changes in several key parameters of the upper atmosphere, including neutral temperature and composition.

The mass density scale height can be determined by the density measurements from a pair of co-planar satellites, where two satellites with similar inclinations are in the same local time sector but at different altitudes. Since 2014, multiple low-Earth-orbit (LEO) satellite missions have provided neutral mass density measurements, including Swarm, GRACE, and GRACE-FO. Coplanar events have been identified as shown in the figure below.



Neutral mass density data

- Neutral density data products from ESA's Swarm Dissemination Server:
  - DNS-ACC: every 10 s
  - DNS-POD: every 30 s

Satellite	DNS-ACC	DNS-POD
Swarm-A	N/A	X
Swarm-B	N/A	X
Swarm-C	X	X
GRACE-A/B	X	N/A
GRACE-FO1	X	N/A

Theory

Assuming hydrostatic equilibrium for an ideal gas, the neutral mass density scale height is defined as

$$H_\rho = -\frac{\rho}{d\rho/dz} \quad (1)$$

where z is the altitude. Deriving from Eq. (1), we get

$$\ln\frac{\rho_A}{\rho_B} = \int_{z_A}^{z_B} \frac{1}{H_\rho}\, dz \quad (2)$$

where z_A and z_B are the altitudes of satellites A and B, respectively, and ρ_A and ρ_B are the neutral mass densities measured from the two satellites.
Taking the average of the integrand, the height-averaged reciprocal of the density scale height can be expressed as

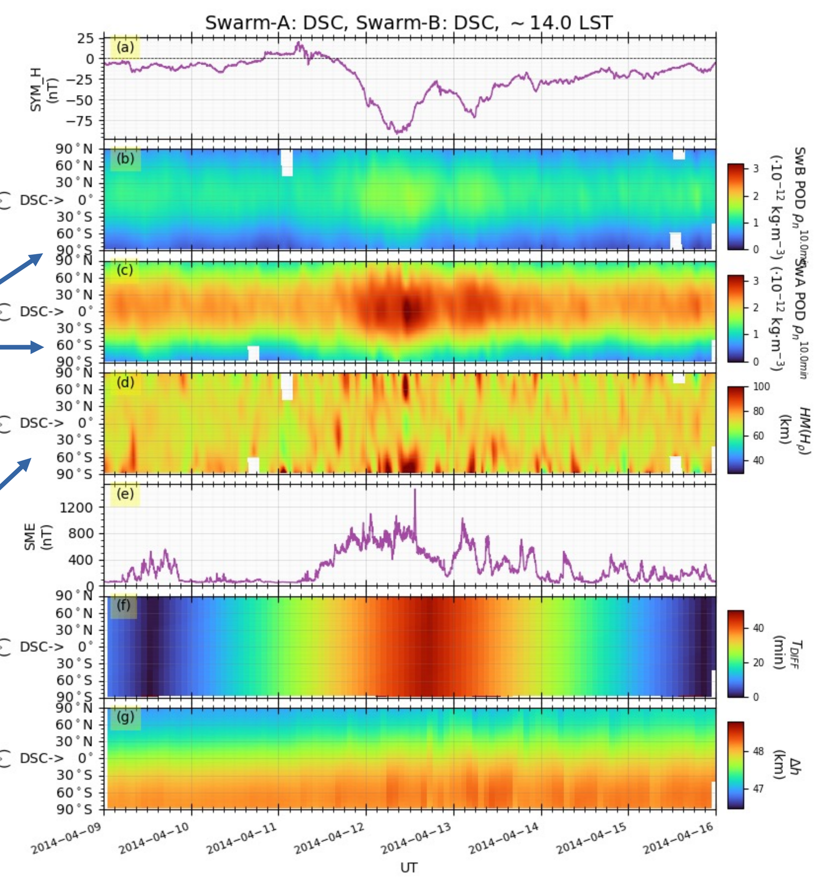
$$\mathrm{HM}(H_\rho) = 1/\left\langle\frac{1}{H_\rho}\right\rangle = \frac{z_B - z_A}{\ln(\rho_A/\rho_B)} \quad (3)$$

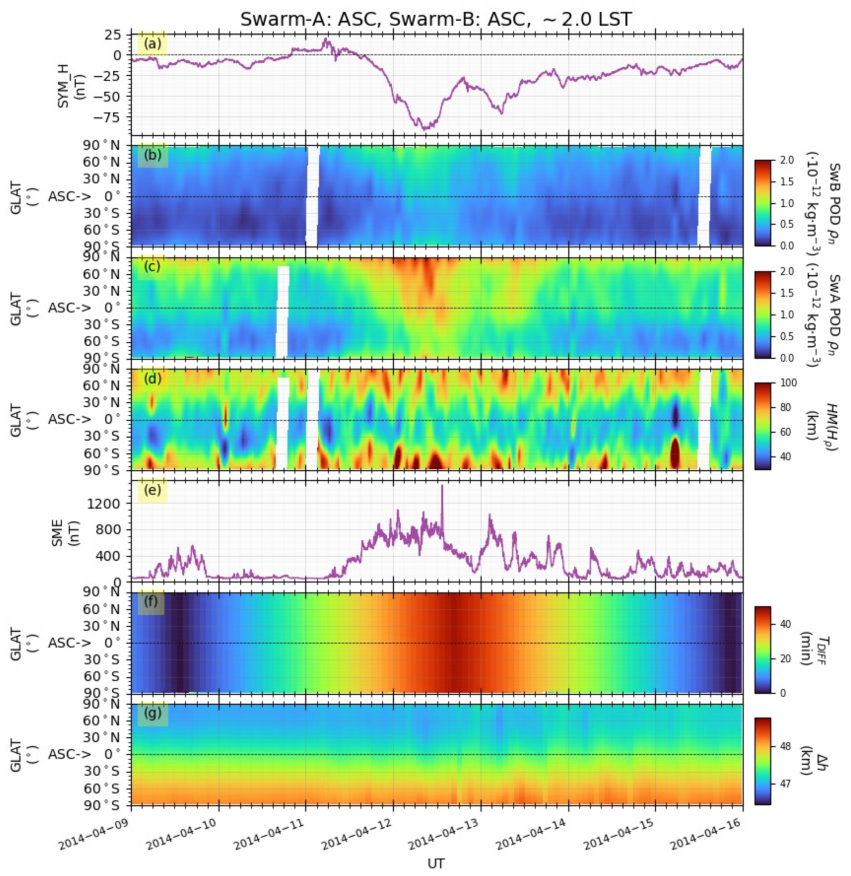
Here HM stands for harmonic mean.

Results

Event 1: SwA-SwB in Apr 2014

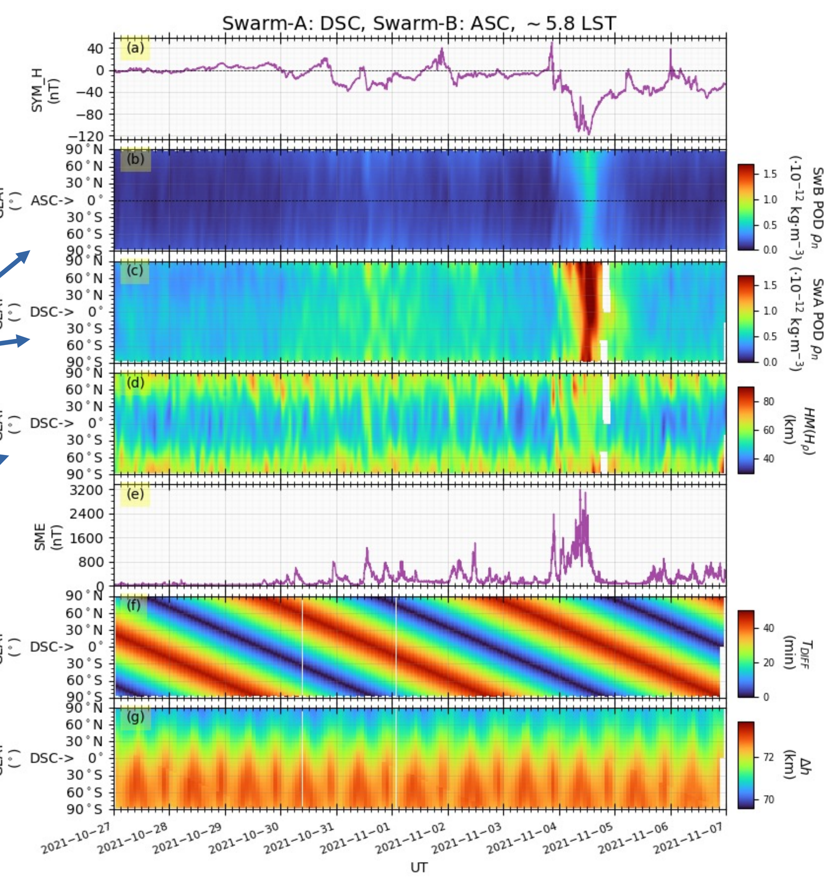
- SwA-SwB coplanar orbits
  - In the afternoon-morning sectors.
  - In the same direction.
  - With a moderate geomagnetic storm.
- Neutral mass densities
  - Maximized close to the equator in the afternoon.
  - Higher density at Northern high latitudes in the morning sector.
  - During the storm, the densities increased significantly.
- Neutral mass scale Height
  - Higher in the afternoon than in the morning.
  - Increases during the storm.
  - Increases with higher altitudes in the morning.

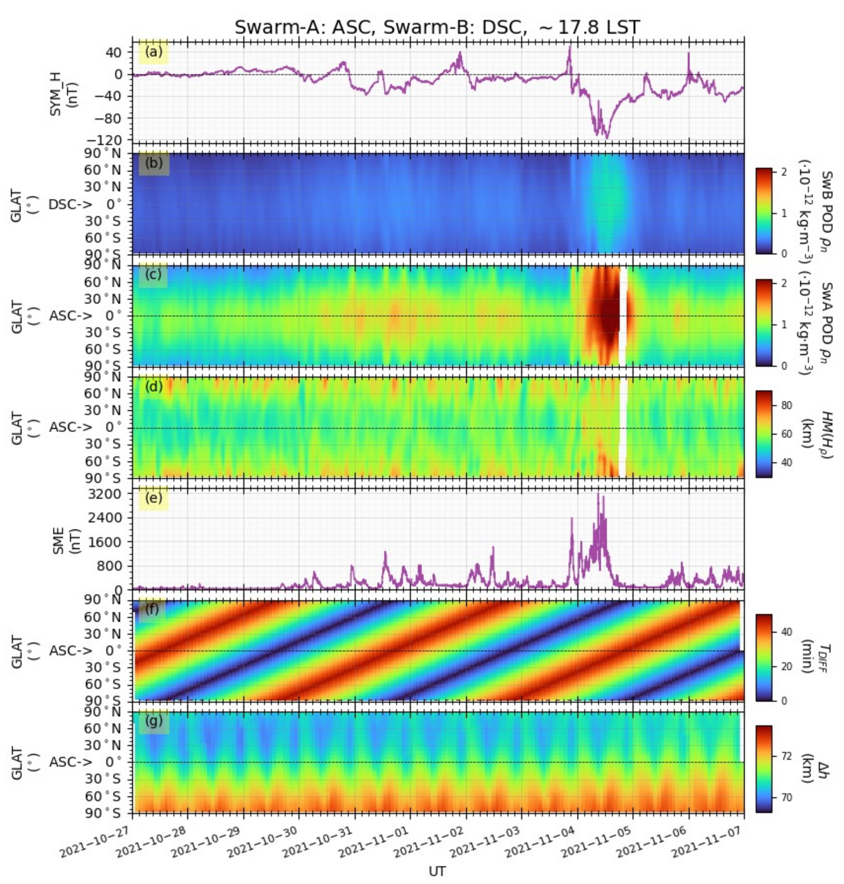




Event 2: SwA-SwB in Oct-Nov 2021

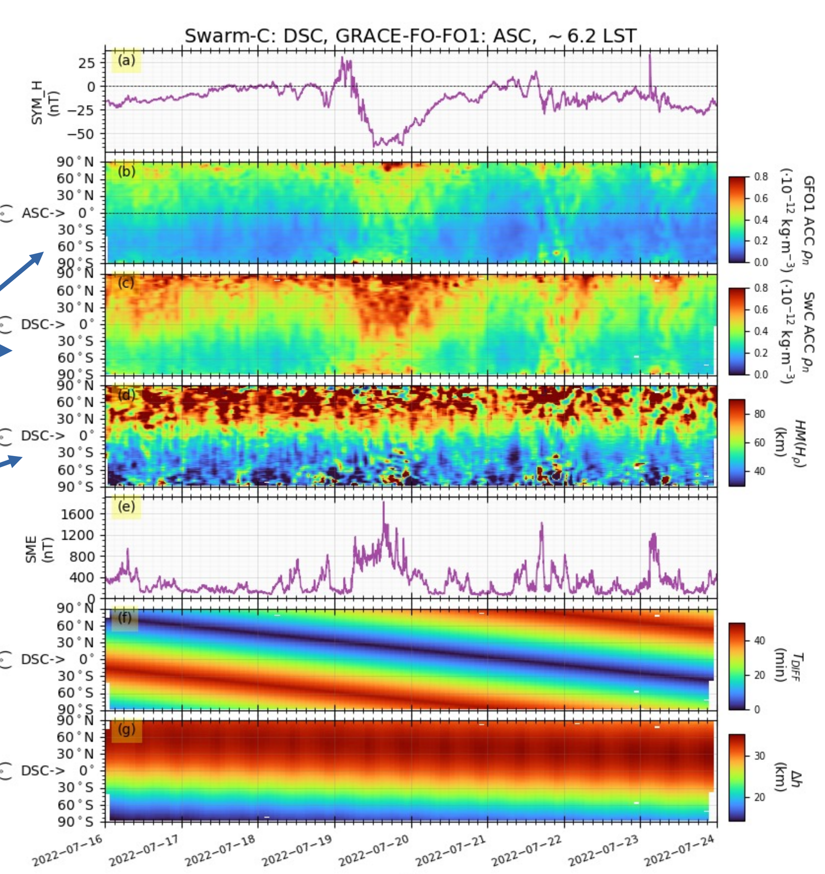
- SwA-SwB coplanar orbits
  - In the dawn-dusk sectors.
  - In the opposite direction.
  - With a strong geomagnetic storm.
- Neutral mass densities
  - Increase with increased geomagnetic activities (storms and substorms)
- Neutral mass scale Height
  - Higher in the dusk than in the dawn sector
  - Increases during the storm
  - Higher values at higher latitudes.

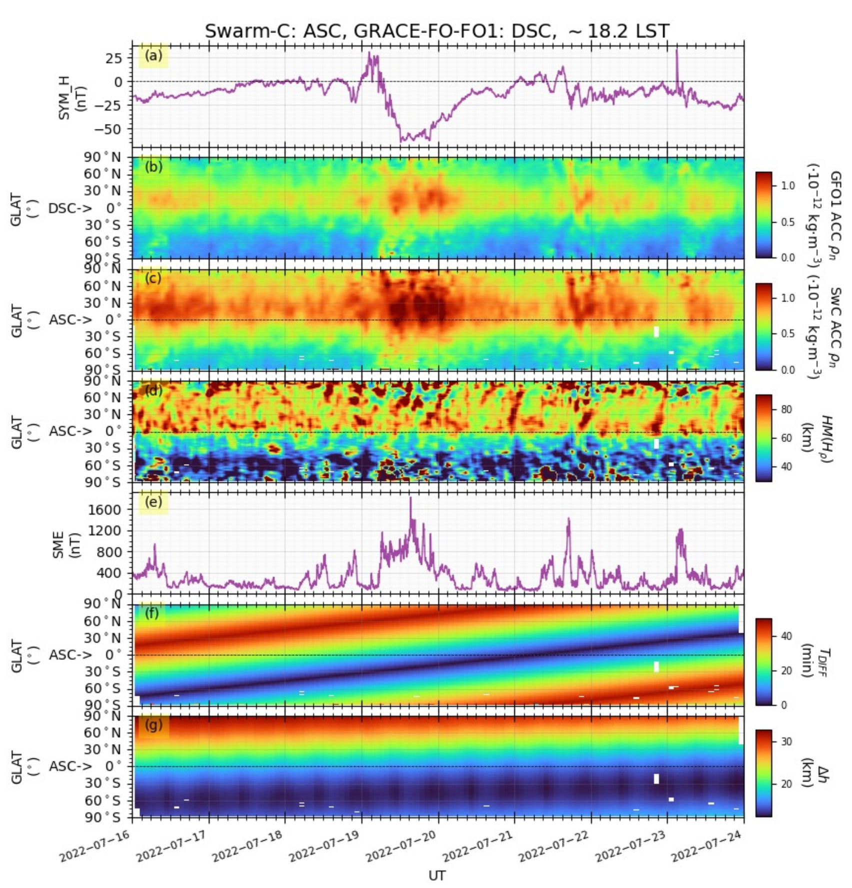




Event 3: SwC-GFO in Jul 2022

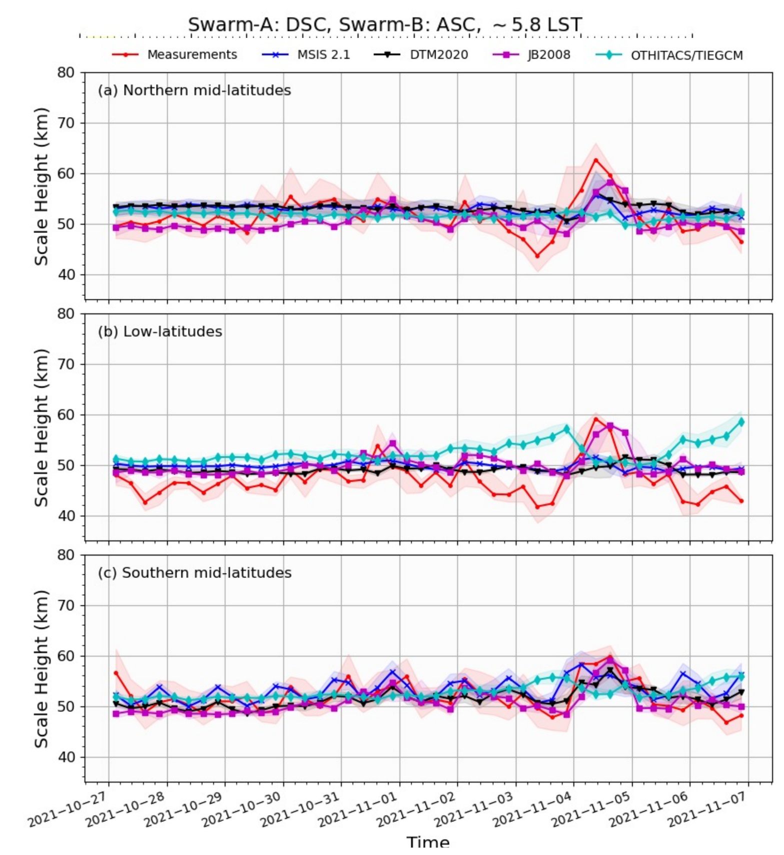
- SwA/C-GFO coplanar orbits
  - In the dawn-dusk sectors.
  - In the opposite direction.
  - With a moderate geomagnetic storm.
- Neutral mass densities
  - Hemispheric asymmetry.
  - Increase with increased geomagnetic activities (storms and substorms)
- Neutral mass scale Height
  - Higher values in the Northern hemisphere than in the Southern hemisphere.

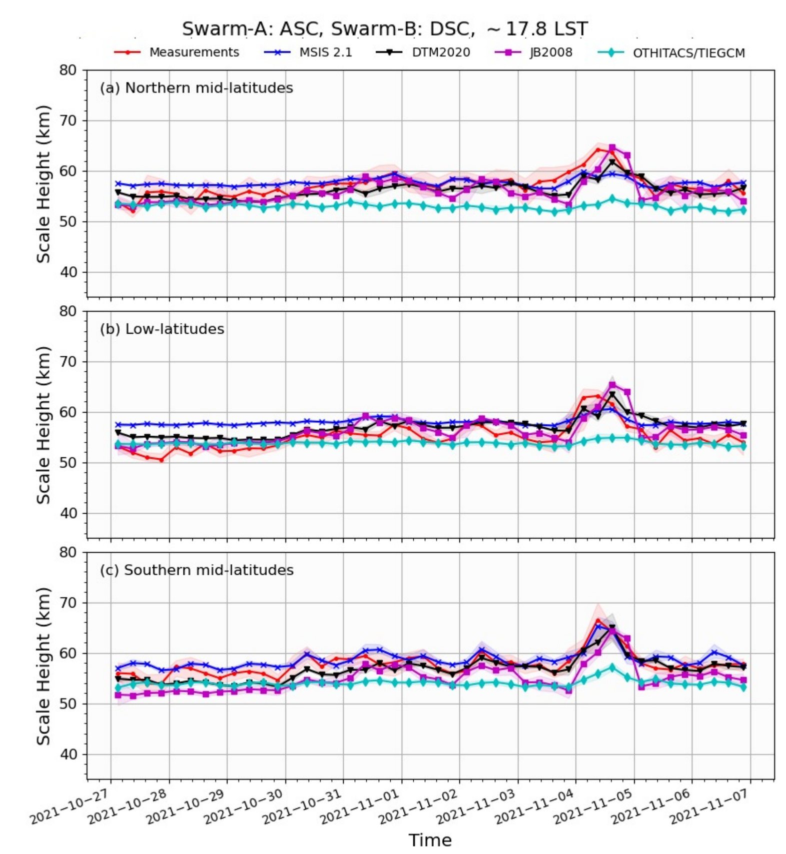




Comparison with models

- Comparison with different empirical and simulation models.
  - NRLMSIS 2.1
  - DTM2020
  - JB2008
  - OTHITACS/TIEGCM
- Example: Event 2 in Oct-Nov 2021
  - Divided into three latitudinal sectors.
  - Averaged with a 6-h time window.
- Dawn sector
  - Smaller values at low latitudes from the measurements.
  - Prestorm increases associated with substorms.
  - JB2000 reproduces better the Increases and decreases during storms.
  - OTHITACS/TIEGCM gives a different trend from measurements and models.
- Dusk sector
  - Higher values than in the dawn sector.
  - JB2000 gives a better performance.
  - OTHITACS/TIEGCM gives smaller values than others.





Discussion and conclusions

- Neutral mass density scale height is estimated using the measurements from coplanar LEO satellites.
- The scale height depends on latitude, local time, season, and geomagnetic storm activity.
- Comparison with different models.
  - JB2008 shows a similar storm dependence as measurements.
  - The scale heights from MSIS and DTM-2020 also show a dependence on storms, but the variations are less significant than those seen in JB2008.
  - None of the tested models can extract small-scale structures comparable to the measured results.
- The role of the neutral temperature and composition changes in the observed scale height variations needs to be further investigated.

Acknowledgements

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JOIN Project
GeospaceLAB