EGU Sharing Geoscience Online 2020

Impact of electron density values from space-geodetic observation techniques on thermospheric density models

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07 May 2020

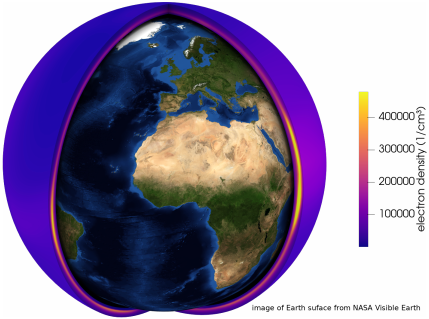
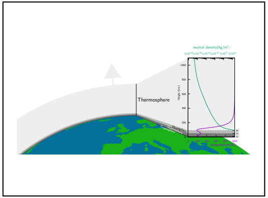


image of Earth suface from NASA Visible Earth

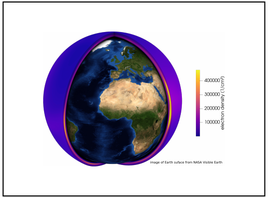
Development of High-precision **T**hermosphere Models for **I**mproving **P**recise **O**rbit **D**etermination of Low-Earth-Orbiting Satellites

Watch this 2.5 minutes video for a quick introduction

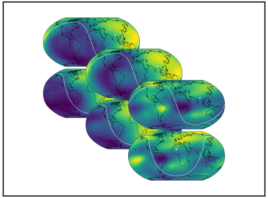
Introduction



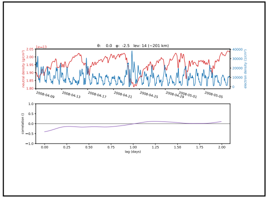
TIE-GCM



Data Assimilation



Correlations



click on an image to jump to the corresponding section

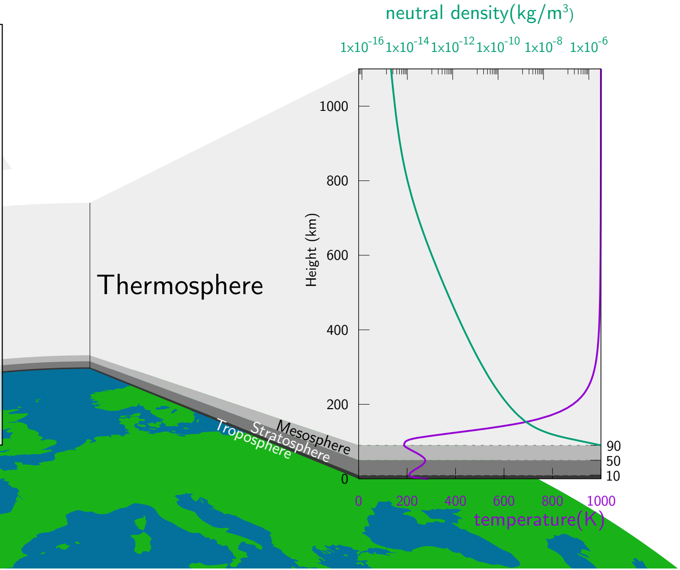
Motivation

Image: ESA/D.Ducros

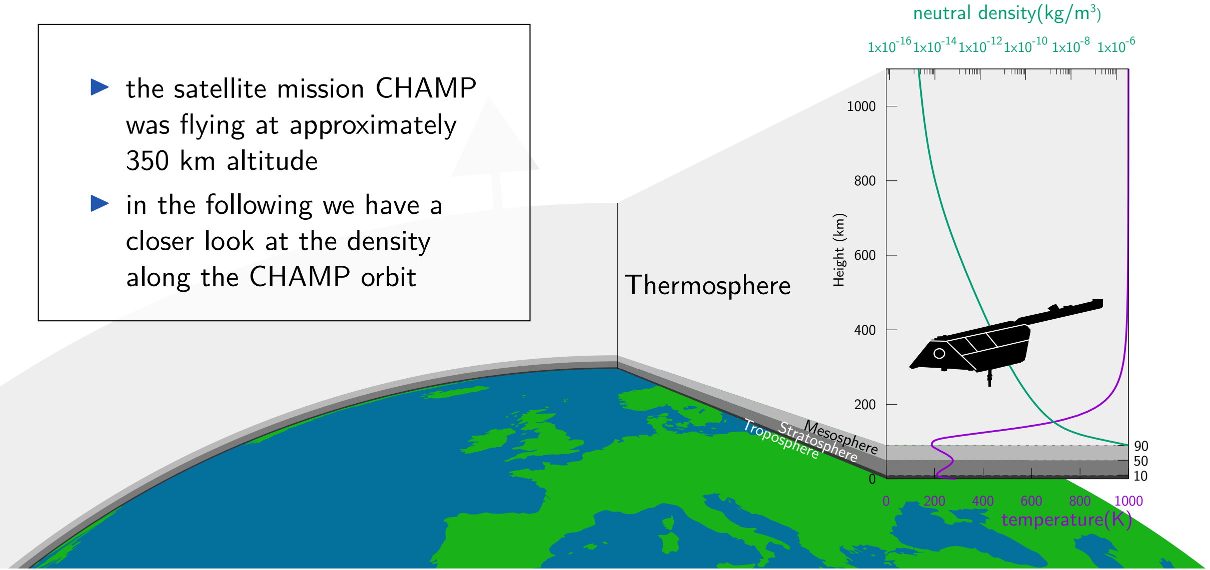
- **atmospheric drag** is largest non gravitational acceleration acting on on LEO satellites
- atmospheric drag depends on **air density** along the orbit
- significant differences between models providing air density
- idea: improve models using **data assimilation**, including electron density observations

Thermosphere

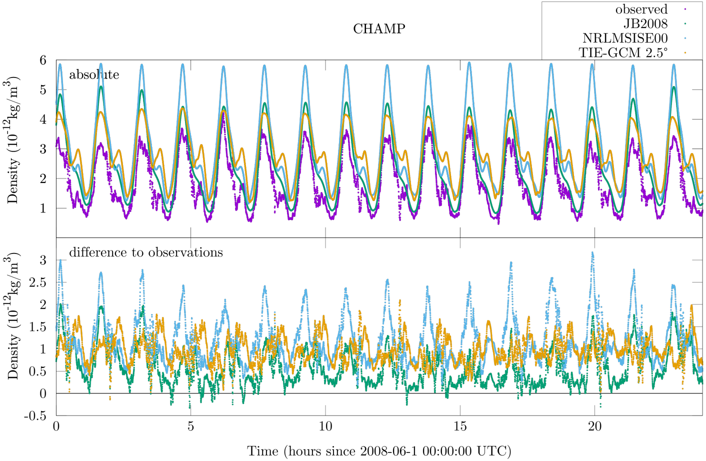
- highest layer of atmosphere when classifying by temperature
- thermosphere approximately begins above **90 km**
- temperature increase due to absorption of **UV radiation**
- asymptotically approaching **exospheric temperature**



- the satellite mission CHAMP was flying at approximately 350 km altitude
- in the following we have a closer look at the density along the CHAMP orbit

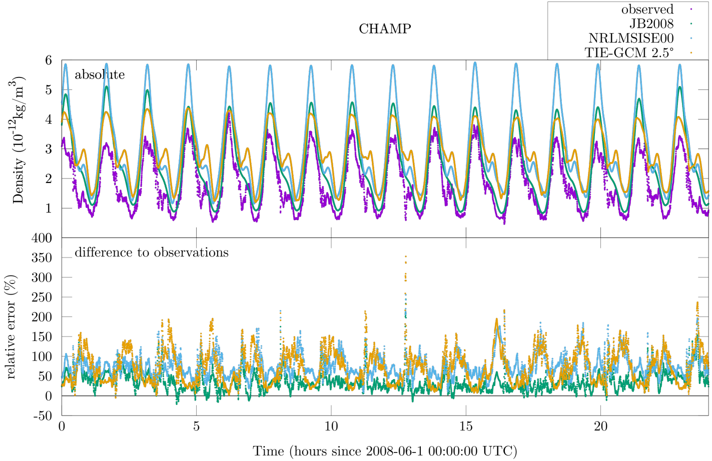


Model fit to density observations



- solar minimum
- no geomagnetic storm
- for more details on observed densities see slide 23

Model fit to density observations



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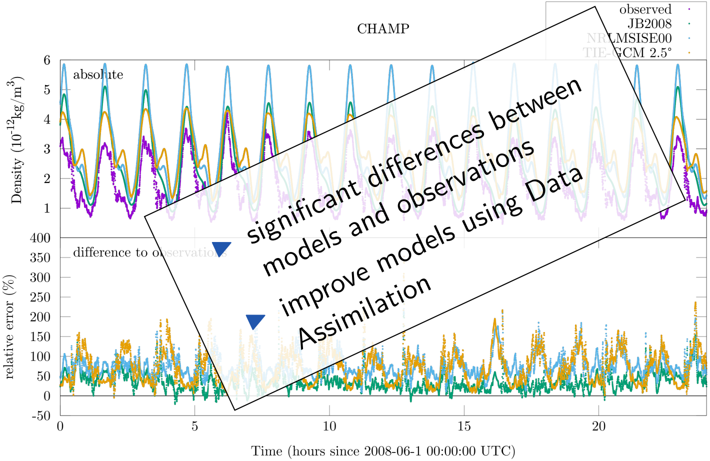

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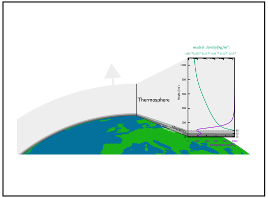
Overview

Introduction



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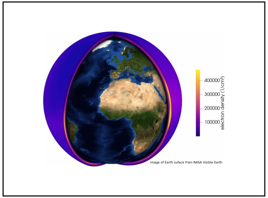

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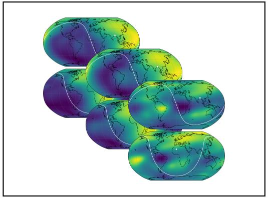

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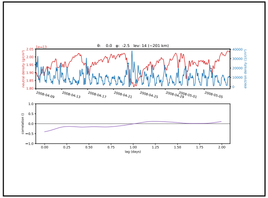
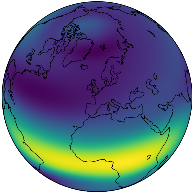


click on an image to jump to the corresponding section

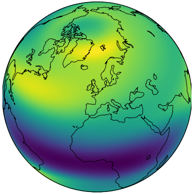
Thermosphere **I**onosphere **E**lectrodynamics **G**eneral **C**irculation **M**odel [3]

- developed by NCAR High Altitude Observatory
- physical model
- written in Fortran 90
- parallelized with MPI

Thermosphere Ionosphere Electrodynamics General Circulation Model [3]

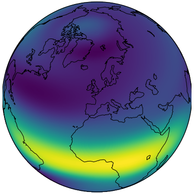


Total Neutral Density



Neutral Temperature

Thermosphere Ionosphere Electrodynamics General Circulation Model [3]



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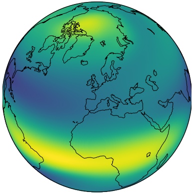
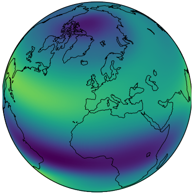


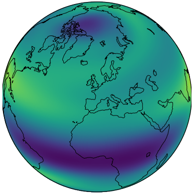
O2

+



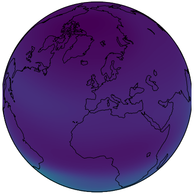
O1

+



N2

+



HE

TIE-GCM

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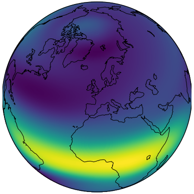
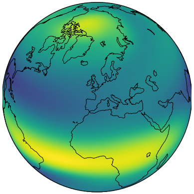
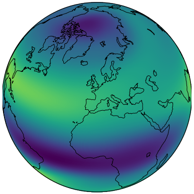
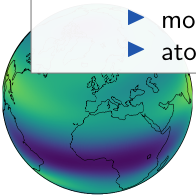
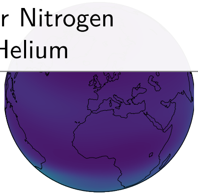


Total Neutral Density

- Total neutral density is derived from 4 individual species:
  - molecular Oxygen
  - atomar Oxygen,
  - molecular Nitrogen
  - atomar Helium

 +  +  + 

O2 O1 N2 HE

TIE-GCM

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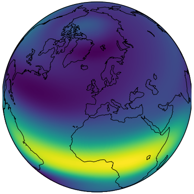
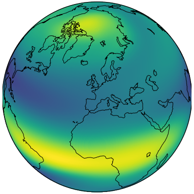
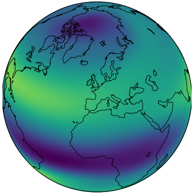


Total Neutral Density



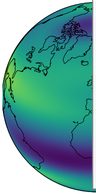
O2

+

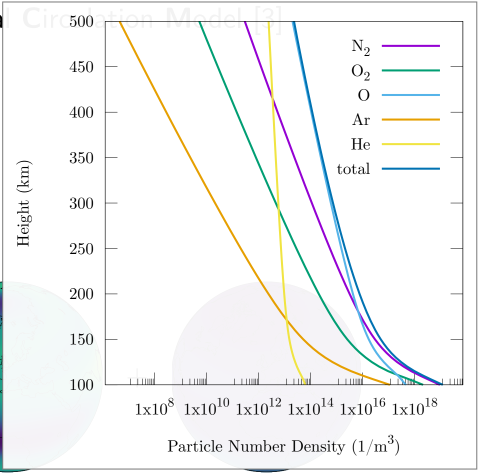


O1

+



N2



HE

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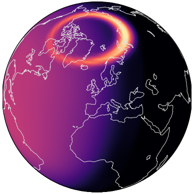
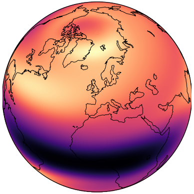
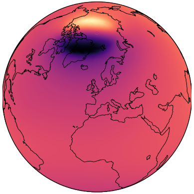


Electron Density

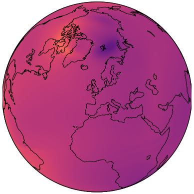


Electron Temperature

Thermosphere **I**onosphere **E**lectrodynamics **G**eneral **C**irculation **M**odel [3]



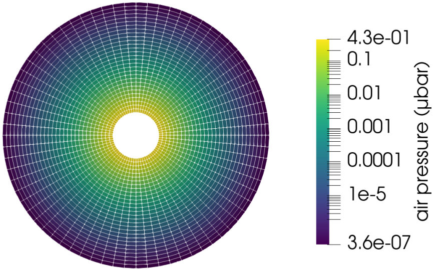
Electric Potential

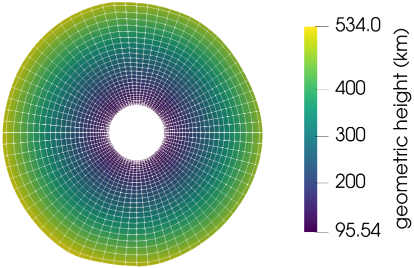


Meridional Ion Drift

Grid Structure

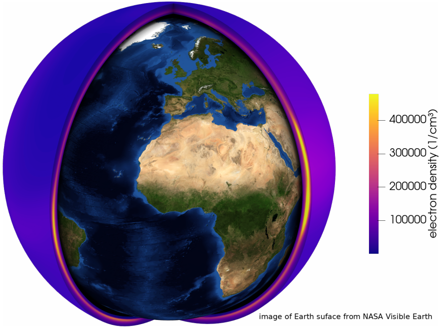
- 4-D regular grid:
  longitude, latitude, **pressure level**, time
- grid has either 5° or 2.5° resolution
- transformation from pressure level to height makes vertical component **irregular** (but structured) and **time dependent**
- transformation necessary for interpolation of satellite orbits in model fields





Why are we using a physical model?

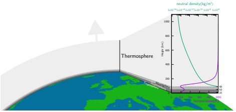
- TIE-GCM requires more computational power than empirical models
- free run does not necessarily perform better than empirical models (fit to observations)
- But, enables us to **assimilate a lot of different data**, especially observations of the **ionosphere**
- there are more geodetic measurement of the ionosphere then thermosphere density measurements



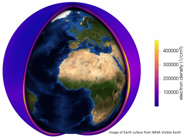
Electron density derived from TIE-GCM on 9 April 2008 12:00 UTC

Overview

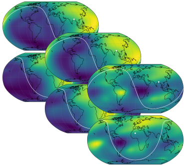
Introduction



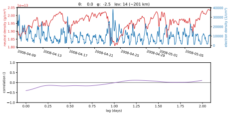
TIE-GCM



Data Assimilation



Correlations



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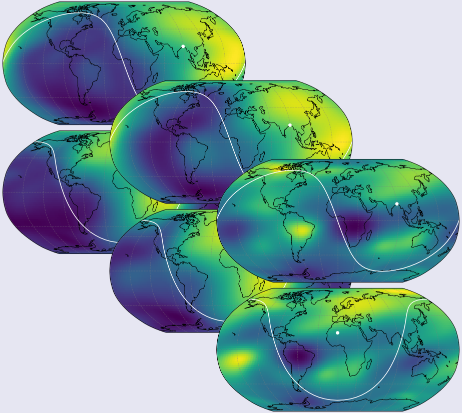
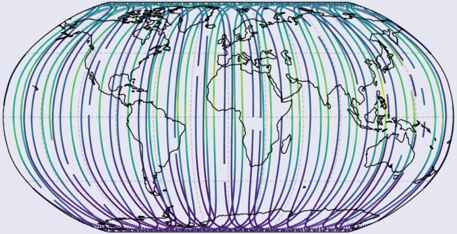
Data Assimilation

Model



Observations



combine a model with observations

Model

Forward Operator

model state

force data

$$\boldsymbol{z}(\boldsymbol{x}, t) = \begin{bmatrix} \boldsymbol{z}'(\boldsymbol{x}, t) \\ \boldsymbol{c} \end{bmatrix} = F\left(\boldsymbol{z}_0(\boldsymbol{x}),\ \boldsymbol{u}(\boldsymbol{x}, t),\ \boldsymbol{b}(\boldsymbol{x}, t),\ t\right)$$

calibration parameters

boundary conditions

initial model state

Model

model state

O_1

O_2

T

...

Forward Operator

TIEGCM

force data

F10.7

Kp

$$\boldsymbol{z}(\boldsymbol{x}, t) = \begin{bmatrix} \boldsymbol{z}'(\boldsymbol{x}, t) \\ \boldsymbol{c} \end{bmatrix} = F\left(\boldsymbol{z}_0(\boldsymbol{x}),\ \boldsymbol{u}(\boldsymbol{x}, t),\ \boldsymbol{b}(\boldsymbol{x}, t),\ t\right)$$

calibration parameters

F10.7

Kp

initial model state

boundary conditions

temperature

meridional wind

zonal wind

Model

$$\boldsymbol{z}(\boldsymbol{x}, t) = \begin{bmatrix} \boldsymbol{z}'(\boldsymbol{x}, t) \\ \boldsymbol{c} \end{bmatrix} = F\left(\boldsymbol{z_0}(\boldsymbol{x}),\ \boldsymbol{u}(\boldsymbol{x}, t),\ \boldsymbol{b}(\boldsymbol{x}, t),\ t\right)$$

computed observation

computed observations at time t_i

$$\boldsymbol{y}_i \ = \ G\left(\boldsymbol{z}(\boldsymbol{x}, t_i)\right) \ = \ G\left(F\left(\boldsymbol{z_0},\ \boldsymbol{u},\ \boldsymbol{b},\ t_i\right)\right) \ = \ H\left(\boldsymbol{z_0},\ \boldsymbol{u},\ \boldsymbol{b},\ t_i\right)$$

measurment
operator

Model

$$\boldsymbol{z}(\boldsymbol{x}, t) = \begin{bmatrix} \boldsymbol{z}'(\boldsymbol{x}, t) \\ \boldsymbol{c} \end{bmatrix} = F\left(\boldsymbol{z_0}(\boldsymbol{x}),\ \boldsymbol{u}(\boldsymbol{x}, t),\ \boldsymbol{b}(\boldsymbol{x}, t),\ t\right)$$

computed observation

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Model

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sequential DA

$$\boldsymbol{z}_i = \boldsymbol{z}(t_i) = F(\boldsymbol{z}_{i-1}, t_i)$$

$$\hat{\boldsymbol{z}}_i = \boldsymbol{z}_i + \boldsymbol{K_i}\underbrace{(\ell_i - H(\boldsymbol{z}_i))}$$

Kalman Gain

observed - computed

Model

$$\boldsymbol{z}(\boldsymbol{x},t) = \begin{bmatrix} \boldsymbol{z}'(\boldsymbol{x},t) \\ \boldsymbol{c} \end{bmatrix} = F\left(\boldsymbol{z}_0(\boldsymbol{x}),\ \boldsymbol{u}(\boldsymbol{x},t),\ \boldsymbol{b}(\boldsymbol{x},t),\ t\right)$$

computed observation

$$\boldsymbol{y}_i \ = \ G\left(\boldsymbol{z}(\boldsymbol{x},t_i)\right) \ = \ G\left(F\left(\boldsymbol{z}_0,\ \boldsymbol{u},\ \boldsymbol{b},\ t_i\right)\right) \ = \ H\left(\boldsymbol{z}_0,\ \boldsymbol{u},\ \boldsymbol{b},\ t_i\right)$$

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$$\hat{\boldsymbol{z}}_i = \boldsymbol{z}_i + \boldsymbol{K_i}(\ell_i - H(\boldsymbol{z}_i))$$

Error Subspace Kalman Filters

- Amount of parameters in TIE-GCM is huge.
- with 5° resolution a single field has 75168 cells
- using error subspace Kalman filters (no need to compute full covariance matrix)

Ensemble Filters		Low-rank Filters
EnKF Ensemble KF	**SEIKF** Singular Evolutive Interpolated KF	**SEEKF** Singular Evolutive Extended KF
ETKF Ensemble Transform KF	**ESTKF** Error Subspace Transform KF	

PDAF

PDAF Parallel Data Assimilation Framework

- developed at Alfred Wegener Institute
- implementation of many error subspace filters
- written in Fortran 90
- parallelized with MPI

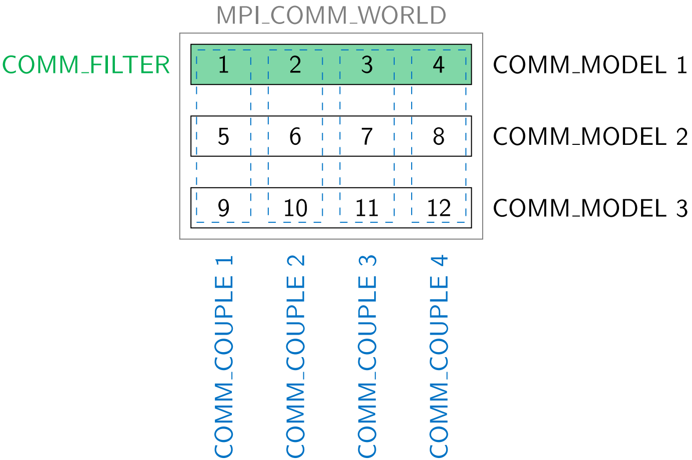
PDAF

PDAF Parallel Data Assimilation Framework

- developed at Alfred Wegener Institute
- implementation of many error subspace filters
- written in Fortran 90
- parallelized with MPI
- 'Online mode': TIE-GCM code is extended by calls to PDAF routines
- no I/O overhead

fully parallel data assimilation with PDAF

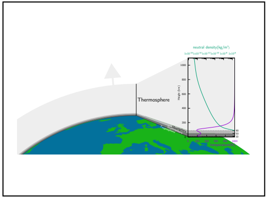
- message passing interface (MPI) is used for fully parallel implementation
- each instance of TIE-GCM (each ensemble member) runs parallel
- several instances of TIE-GCM are computed parallel



PDAF integration status

- Adaptation of the parallelization ✓
- Initialization of PDAF and the ensemble ✓
- Modification of the model code for the ensemble integration ✓
- Implementation of the analysis step
  - observation operator for NRLMSISE-00 observations implemented but not tested
  - observation operator for electron density observations X
  - observation operator for neutral density observations derived form accelerometers X

Introduction



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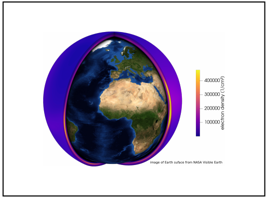

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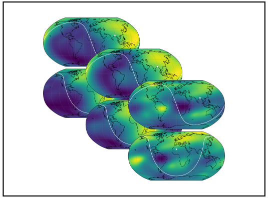

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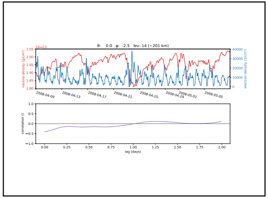

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Correlation Analysis

Hypothesis

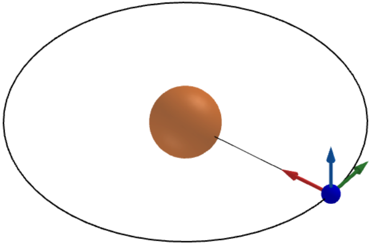
Assimilating electron densities into a physical model of the Thermosphere improves also the neutral density

- Due to Corona disruptions we could not work as much on the density data integration as we would have liked
- But we can show correlations between neutral density and electron density
- Ee investigate:
  - correlations within TIE-GCM (free run)
  - correlations between observations
- These correlations will control the observability of thermosphere density in the EnKF via ionsophere observations

correlations within TIE-GCM: Sun-fixed frame

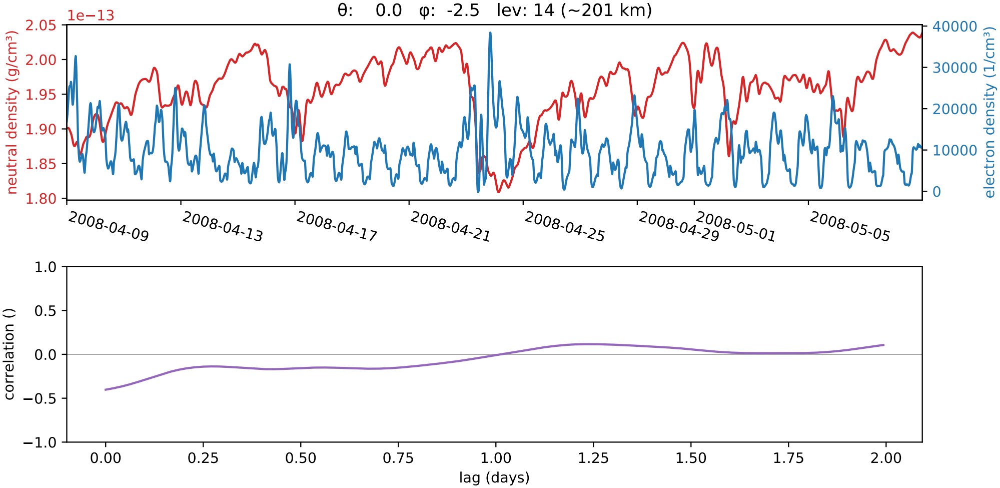
TIE-GCM fields are co-rotating with Earth. For a meaningful correlation analysis we need to compensate the motion of the Sun w.r.t. to the Earth.

- origin in geocenter
- x axis is pointing to the Sun
- z axis is perpendicular to ecliptic
- y axis completes left-handed coordinate system



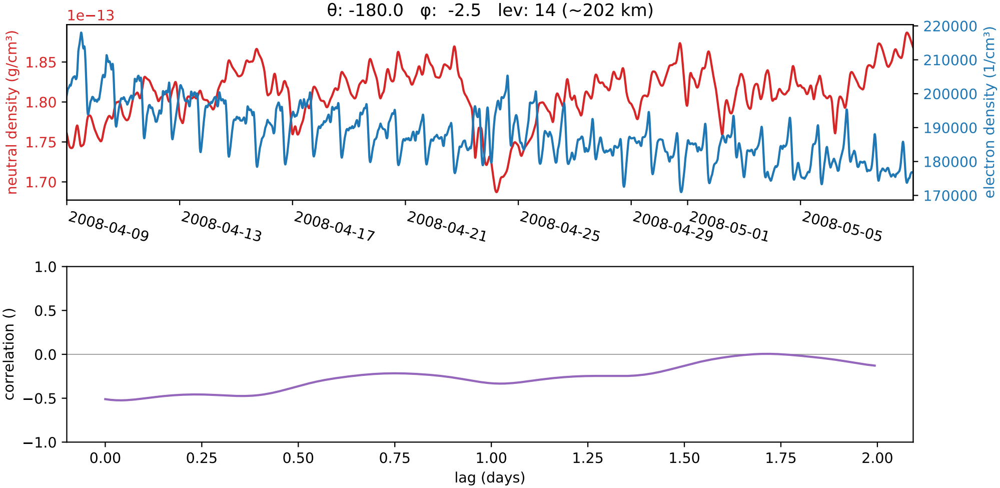
correlations within TIE-GCM

day side



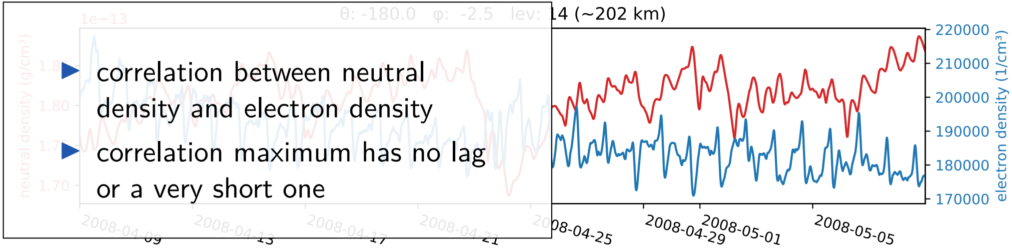
correlations within TIE-GCM

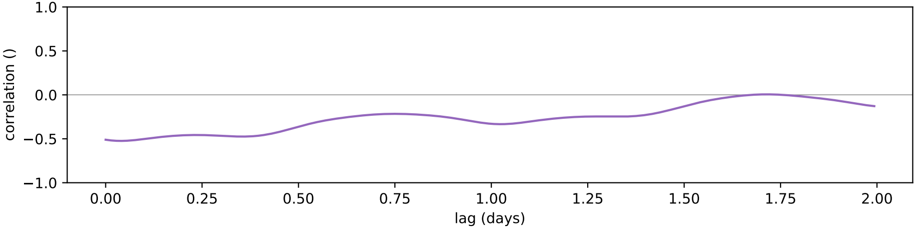
night side



night side

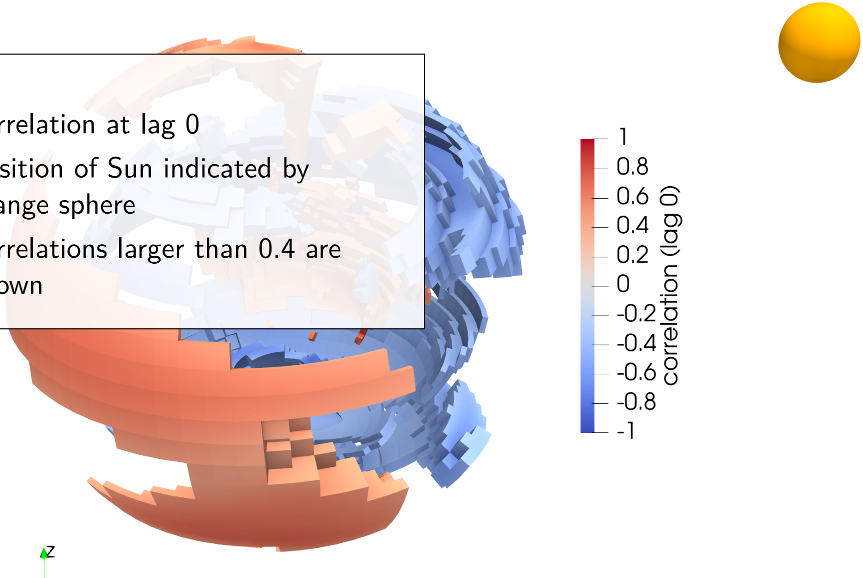
- correlation between neutral density and electron density
- correlation maximum has no lag or a very short one



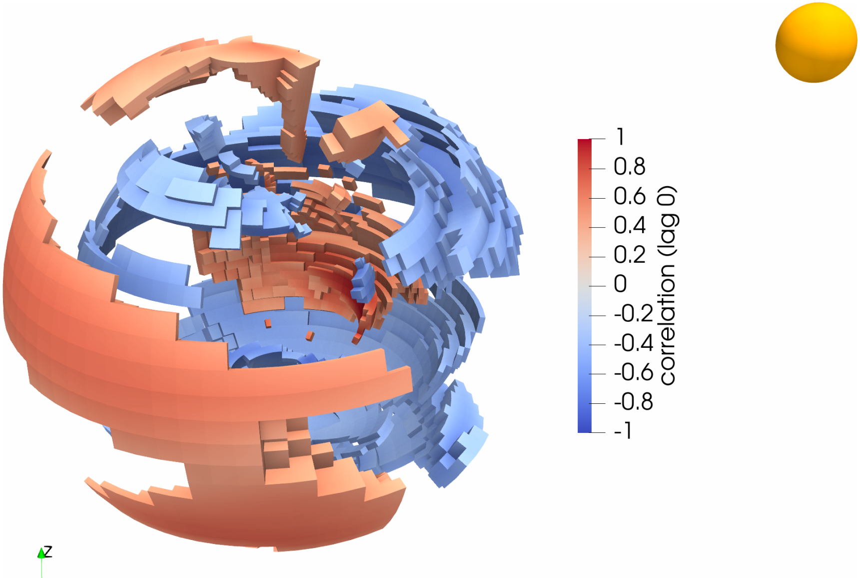


correlation for all cells

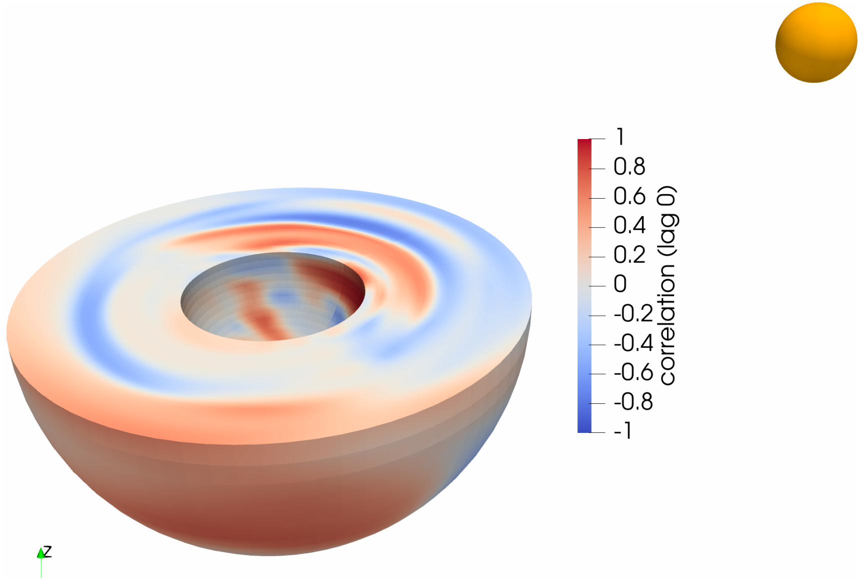
- correlation at lag 0
- position of Sun indicated by orange sphere
- correlations larger than 0.4 are shown



correlation for all cells



correlation for all cells



correlations between observations

neutral density

derived from **calibrated accelerometer data** [4] considering accelerations due to

- Earth radiation pressure [5]
- Sun radiation pressure [5]

electron density

4D electron density model based on GNSS and satellite altimetry observations as well as radio occultation measurements [1]

correlations between observations

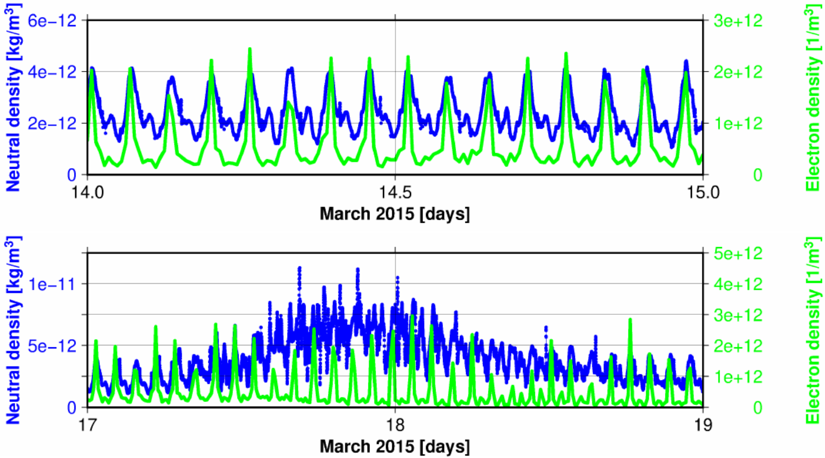
- Neutral density: from GRACE accelerometer data (altitude 410 km)
- Electron density: from 4D-model interpolated to 10 seconds

Quite time

Correlation: 86.1%

Storm time

Correlation: 34.3%

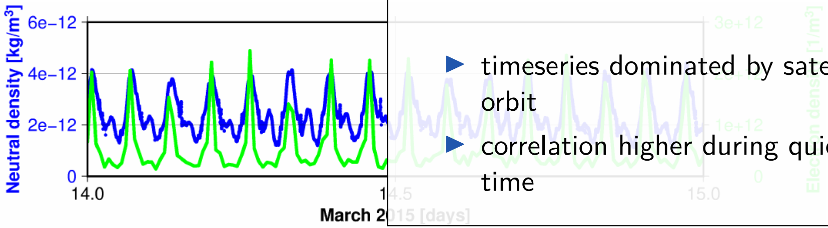


correlations between observations

- Neutral density: from GRACE accelerometer data (altitude 410 km)
- Electron density: from 4D-model interpolated to 10 seconds

Quite time

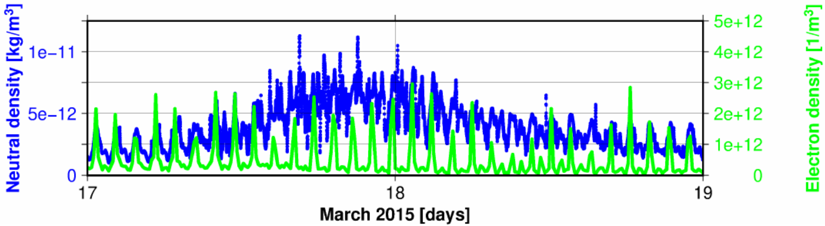
Correlation: 86.1%



- timeseries dominated by satellite orbit
- correlation higher during quiet time

Storm time

Correlation: 34.3%



Conclusions

- Correlations within the model indicate that the **electron density has direct (no lag) impact on neutral density**.
- We also see high correlations between observed neutral densities and electron densities.
- Thus, we are confident that the assimilation of electron densities is likely to improve neutral density.

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[5] Kristin Vielberg and Jürgen Kusche. Extended forward and inverse modeling of radiation pressure accelerations for leo satellites. *Journal of Geodesy*, 94(4):1–21, 2020.