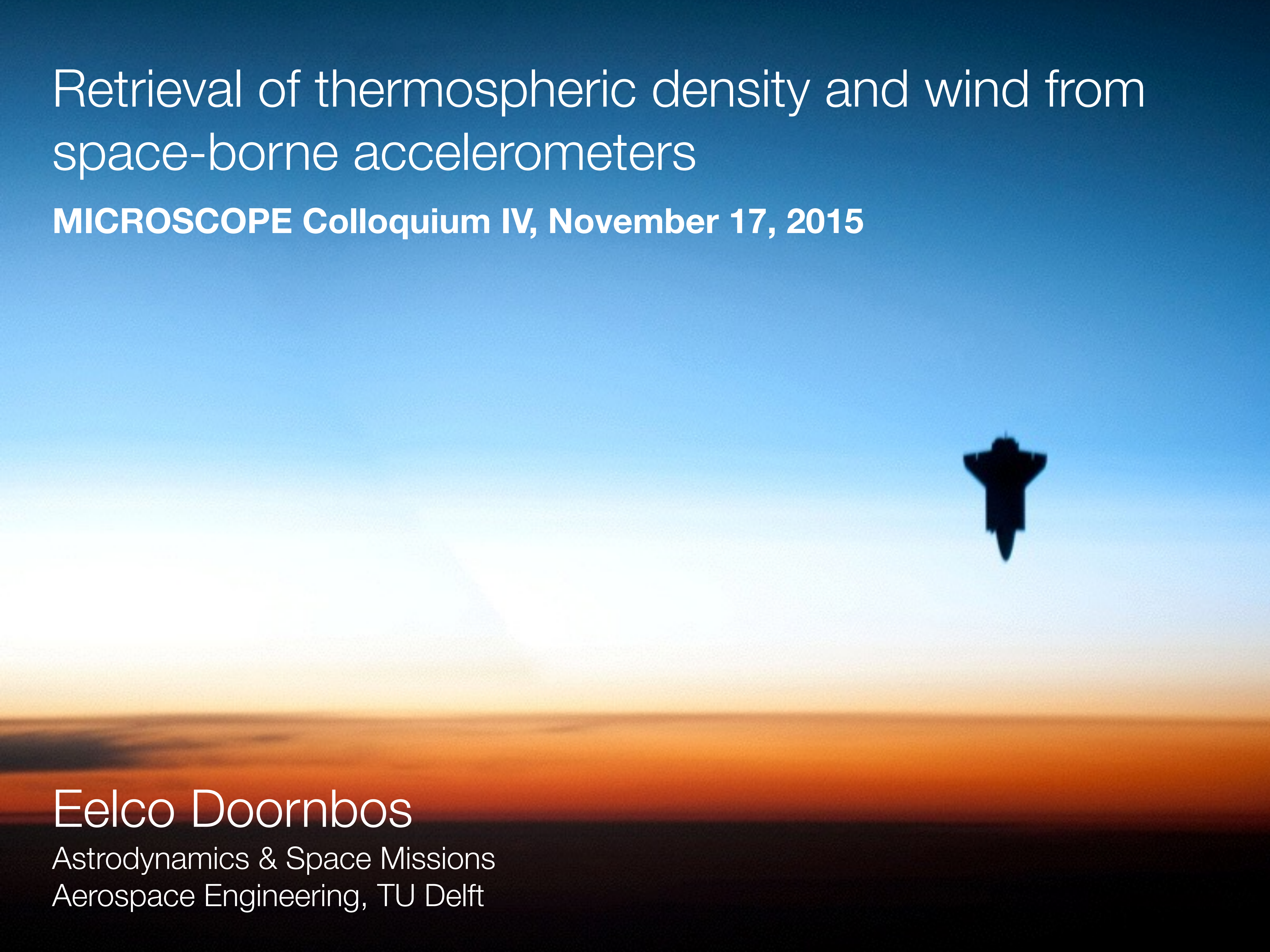


Retrieval of thermospheric density and wind from space-borne accelerometers

MICROSCOPE Colloquium IV, November 17, 2015

Eelco Doornbos

Astrodynamics & Space Missions

Aerospace Engineering, TU Delft

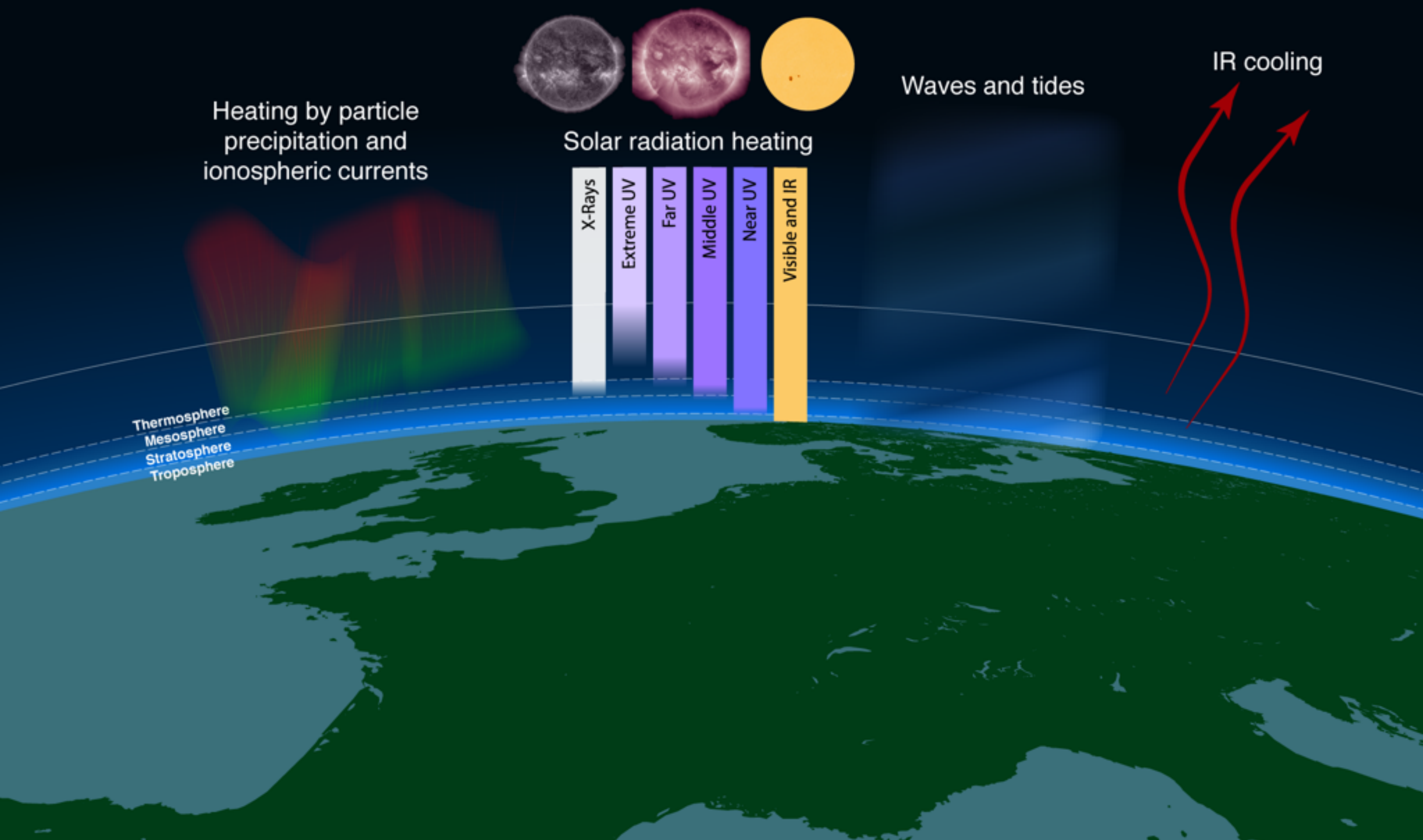
Contents

- Introduction to the thermosphere
- Experience with CHAMP, GRACE, GOCE and Swarm data processing
- Outlook and requirements for MICROSCOPE

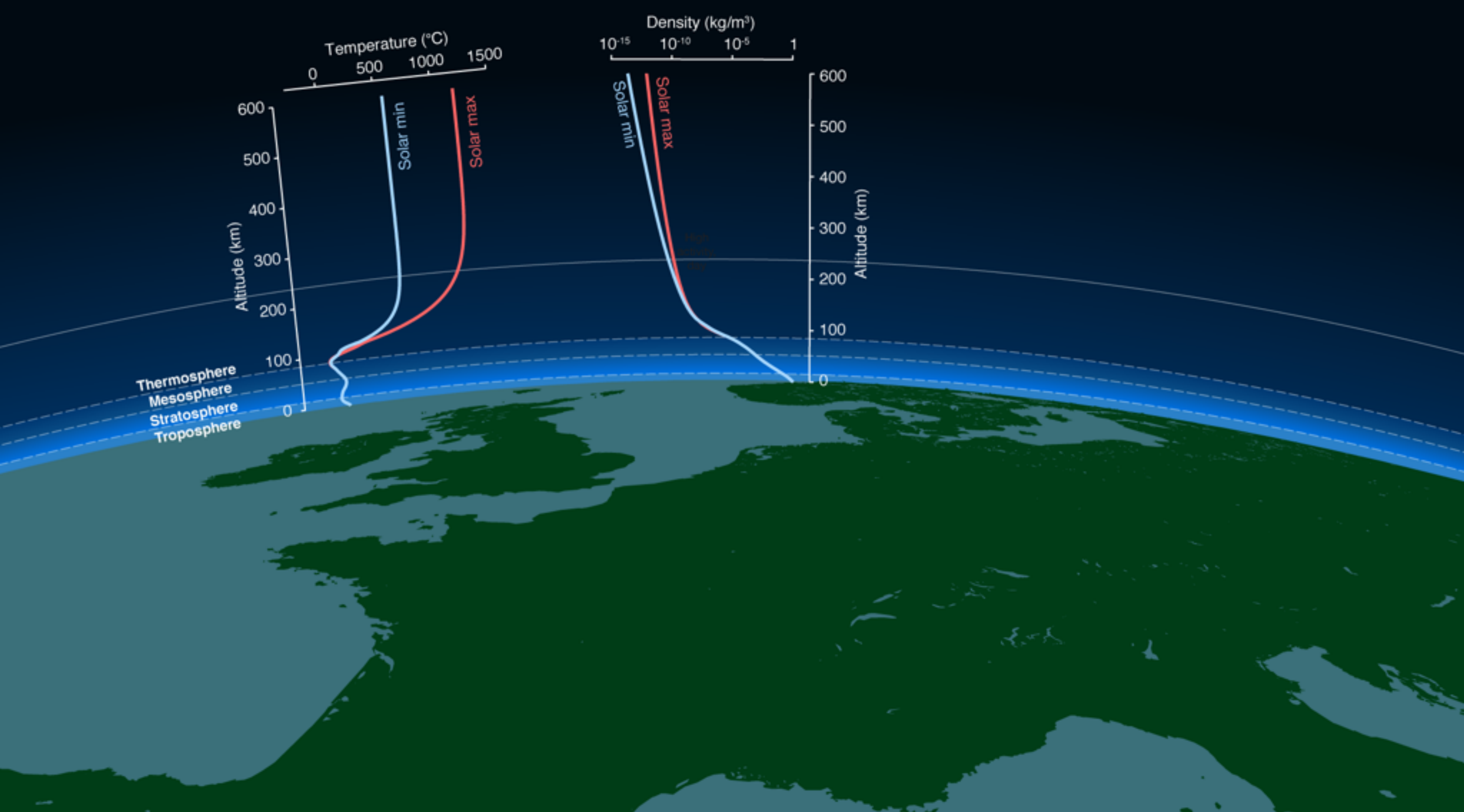
The thermosphere and exosphere

- Upper layers of the Earth's atmosphere, starting at ~90 km.
- Strong coupling of thermosphere dynamics with ionosphere and magnetosphere.
- Large thermospheric variability, driven by solar UV radiation, Joule heating and particle precipitation, taking place in the lower thermosphere.

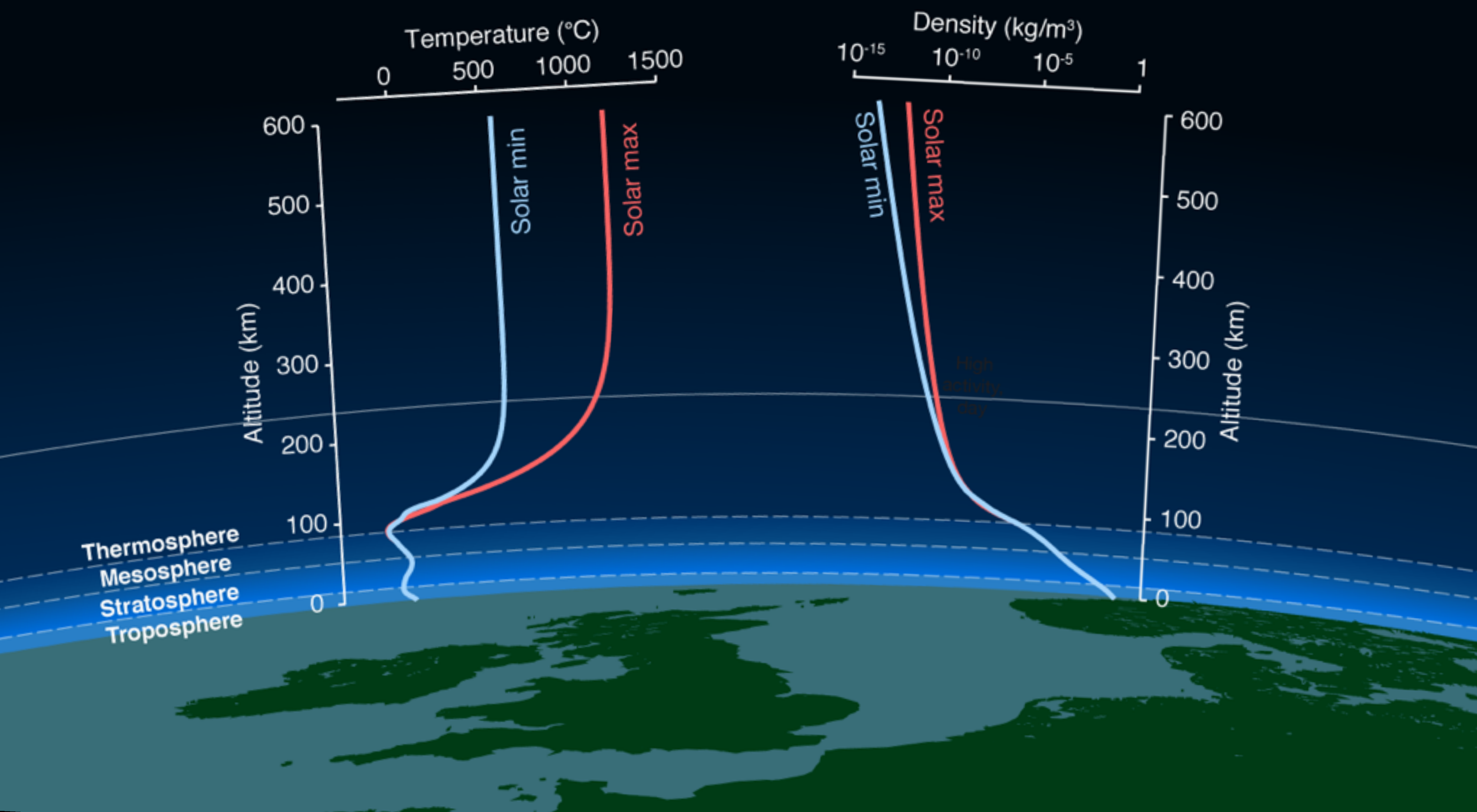
Energy sources

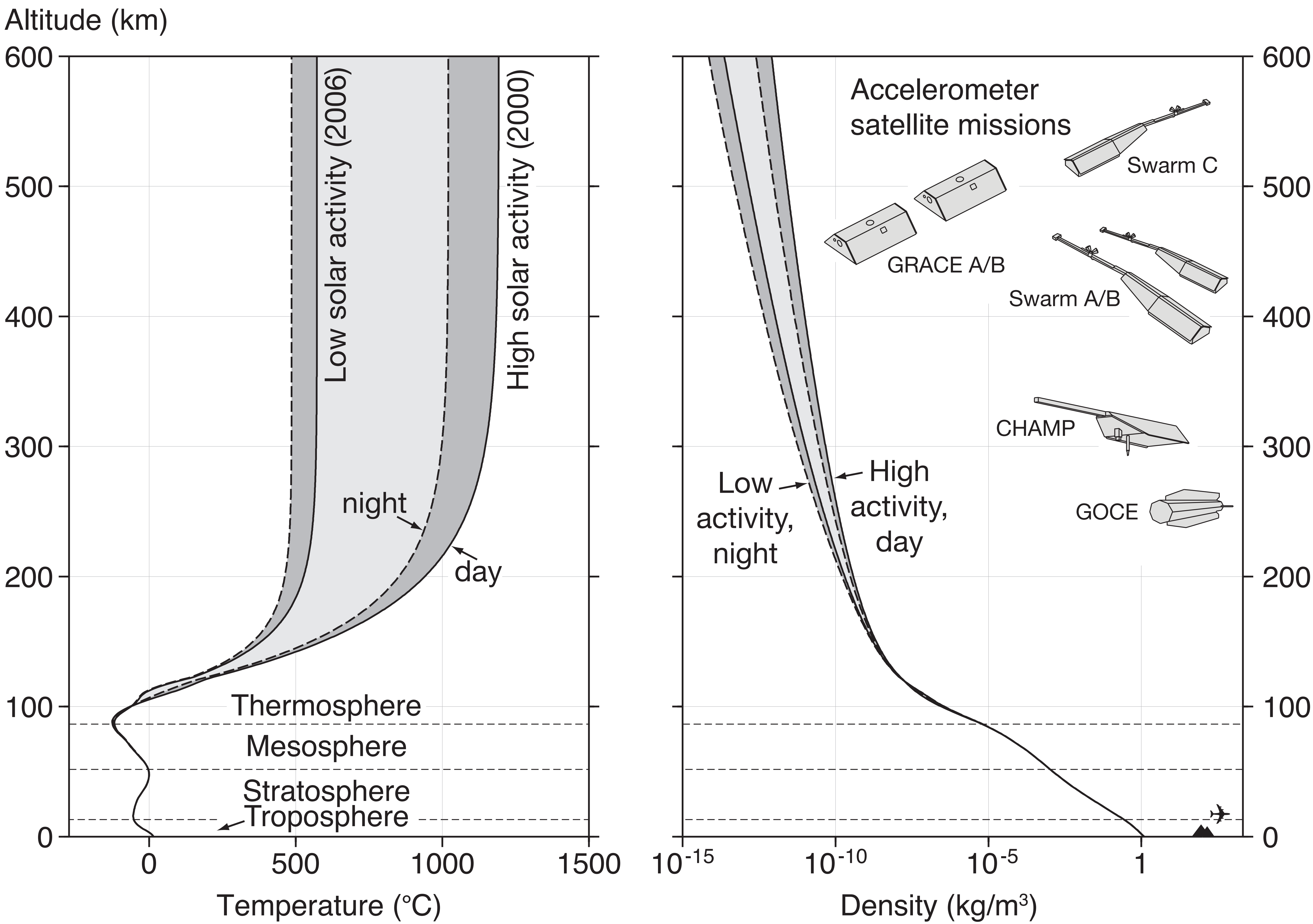


Temperature and density

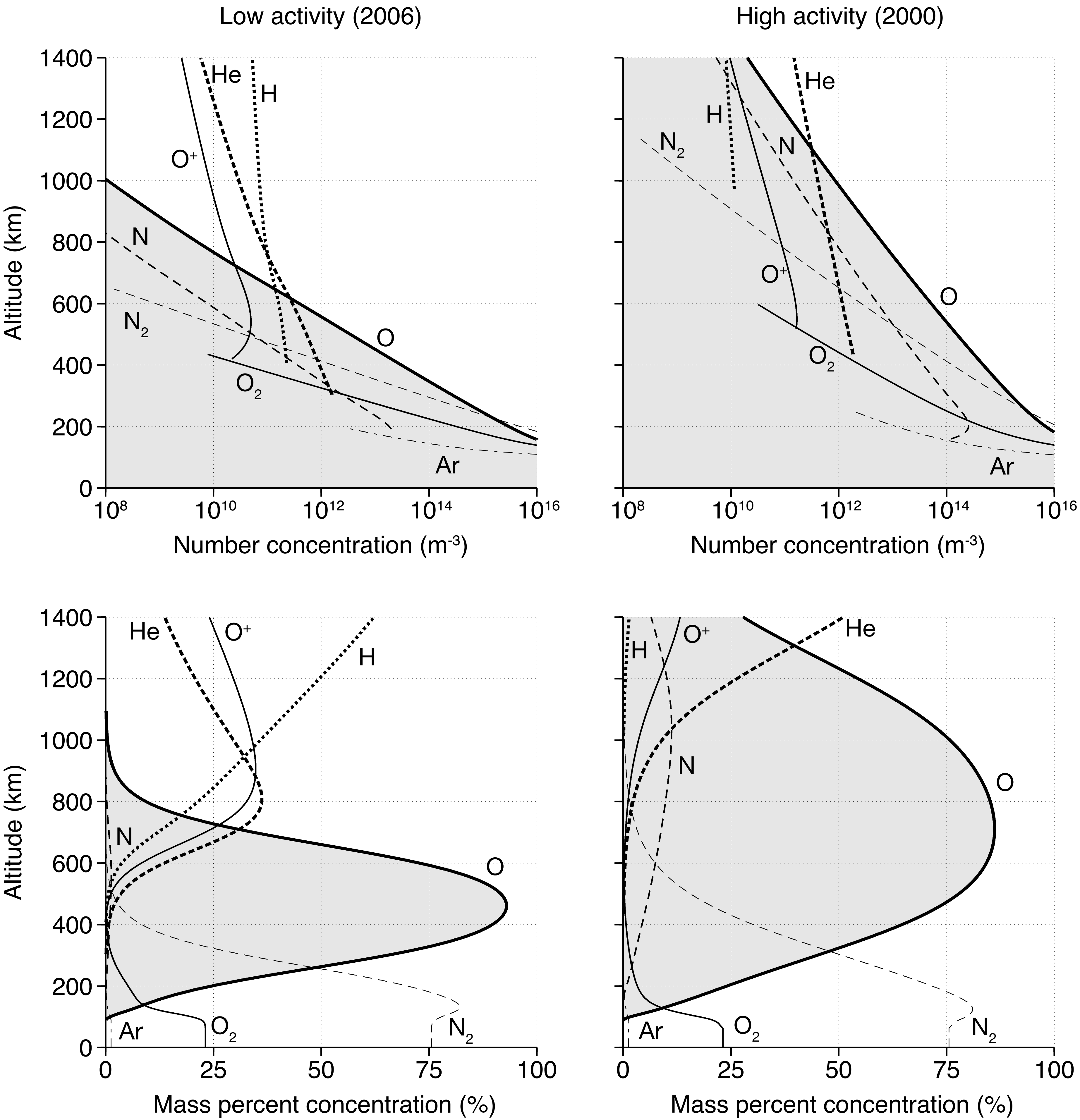


Temperature and density

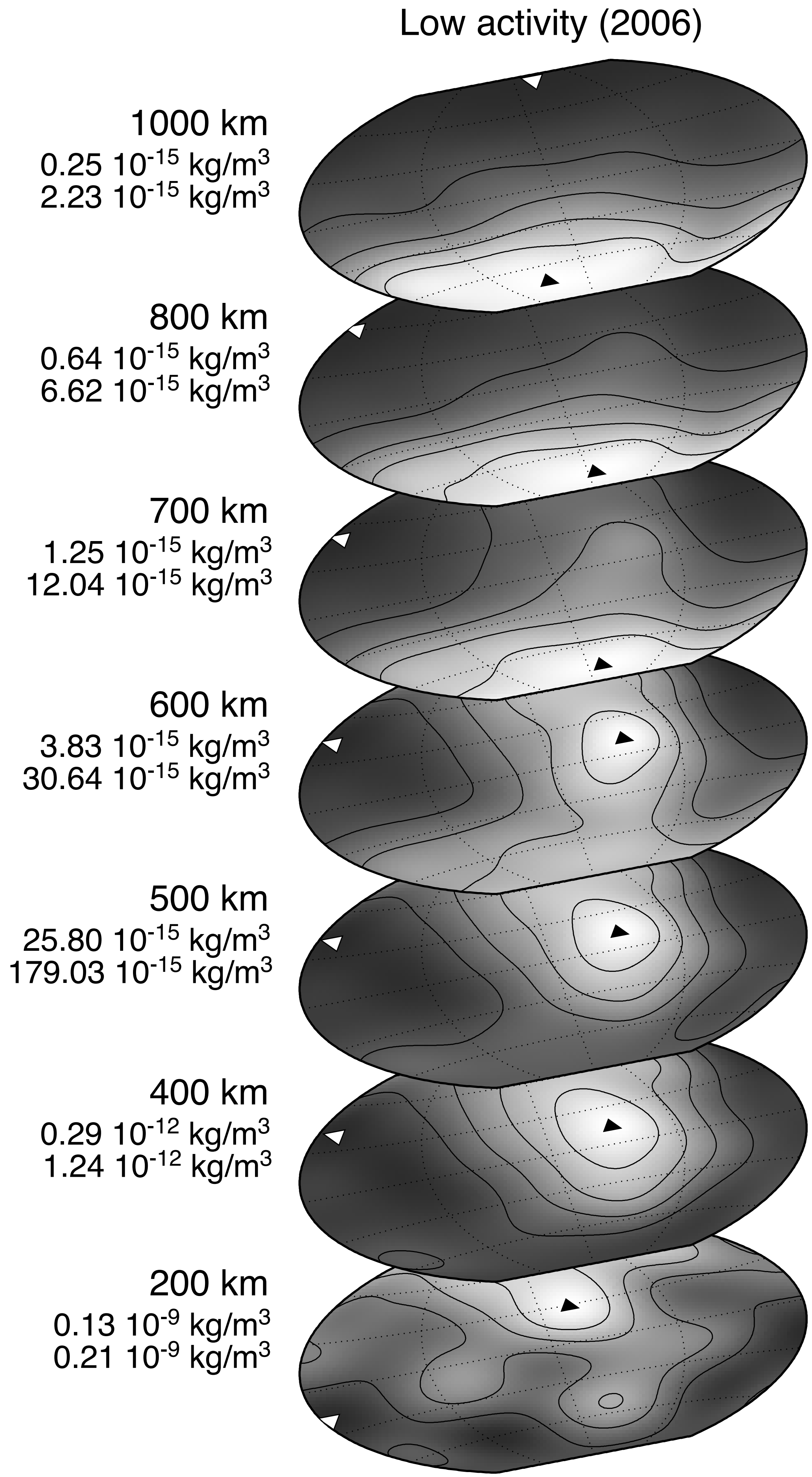




Altitude (km)
600
500
400
300
200
100
0
Low solar activity (2006)
High solar activity (2000)
night
day
Thermosphere
Mesosphere
Stratosphere
Troposphere
0
500
1000
1500
Temperature (°C)
Accelerometer satellite missions
Swarm C
GRACE A/B
Swarm A/B
CHAMP
GOCE
Low activity, night
High activity, day
10^{-15}
10^{-10}
10^{-5}
1
Density (kg/m^3)



Low activity (2006)
High activity (2000)
Altitude (km)
Number concentration (m-3)
Mass percent concentration (%)
He
H
O+
N
N2
O
O2
Ar
1400
1200
1000
800
600
400
200
0
10^8
10^10
10^12
10^14
10^16
25
50
75
100

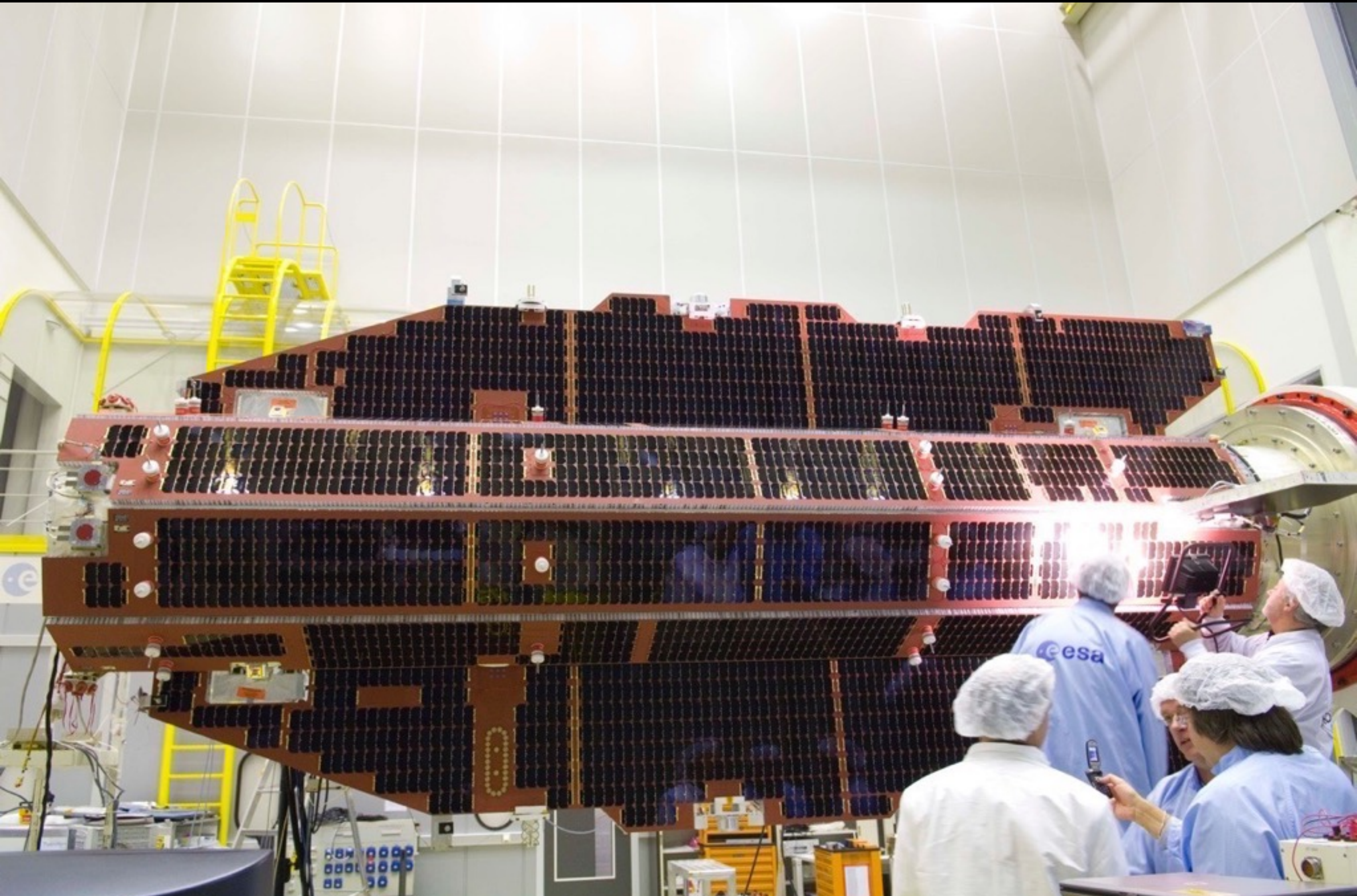


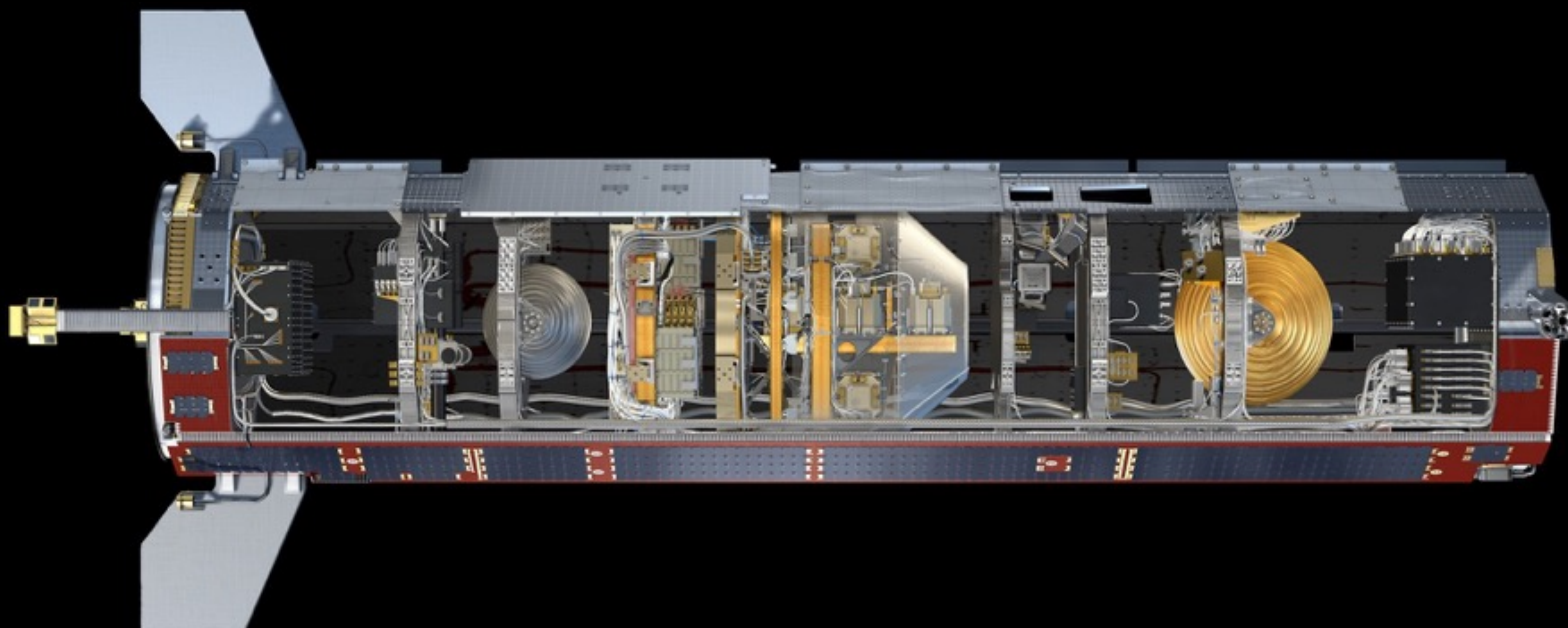
Latitude / local solar time density variation at low solar activity, according to the NRLMSISE-00 model.

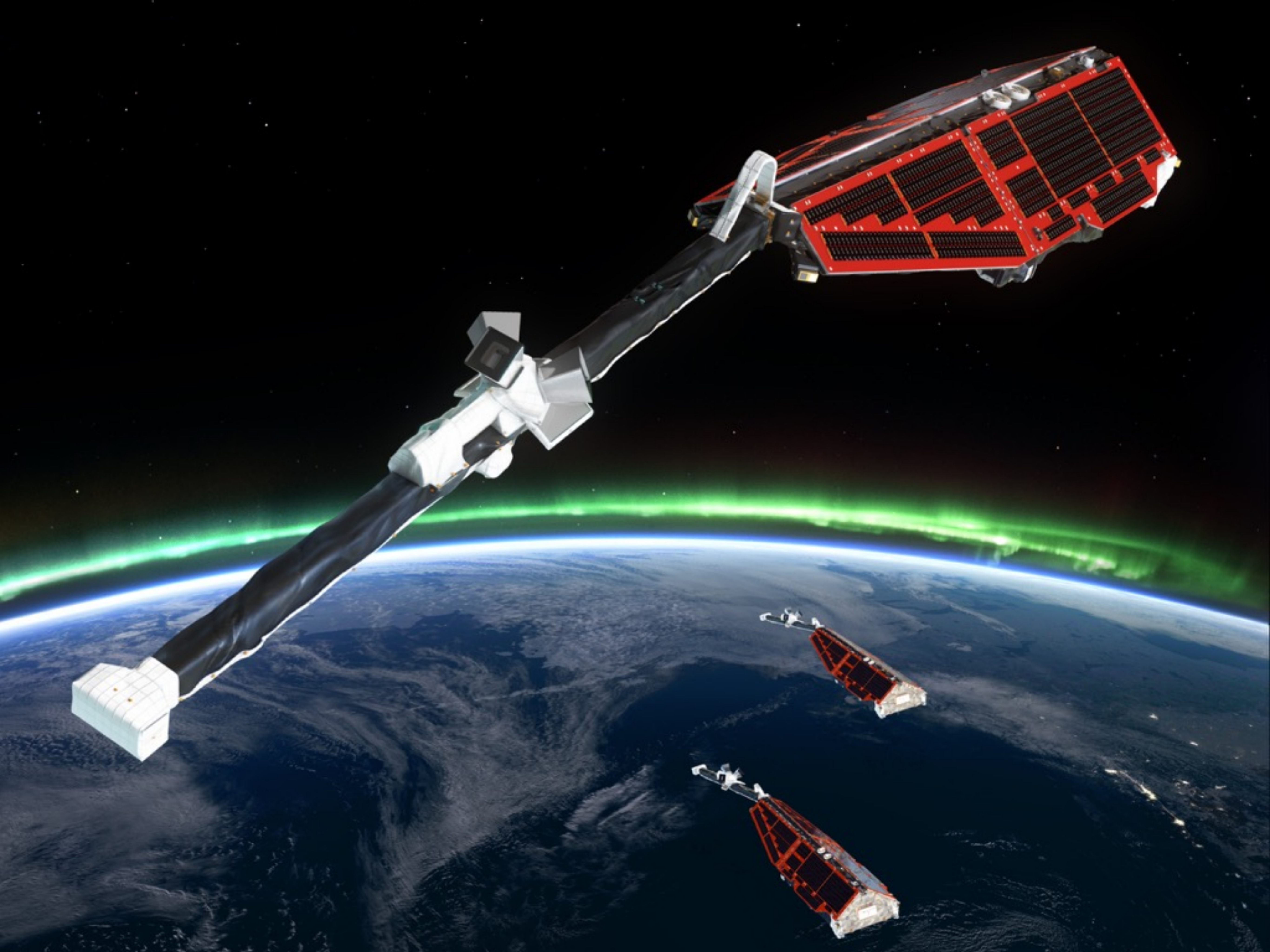
Experience with CHAMP, GRACE, GOCE and Swarm data processing

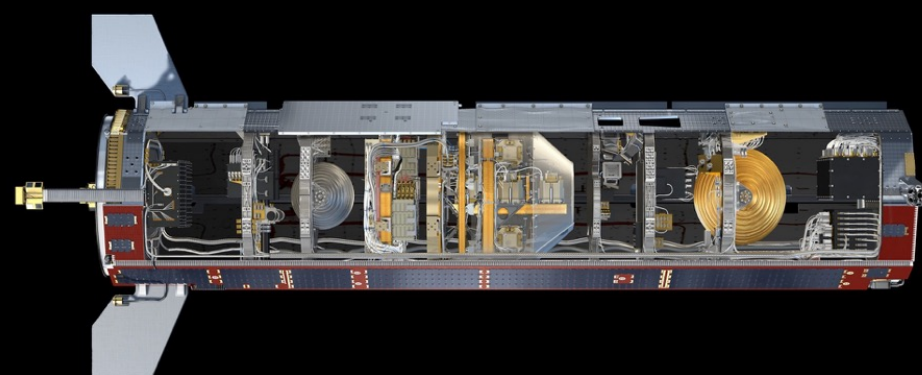
- Goal: create an accurate long-term, high temporal resolution, multi-mission thermosphere data set.
- Application areas:
    - Detailed study of climatology and weather in the thermosphere.
    - Validation of numerical thermosphere-ionosphere models.
    - Input to empirical models for use in space mission planning, operations, re-entry prediction, collision avoidance, etc.


Gmax 1000 daN


esa







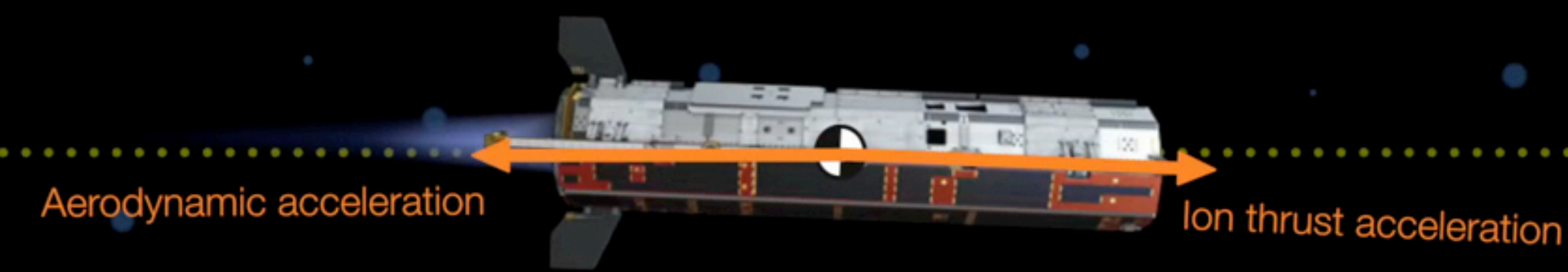
GOCE orbital dynamics:

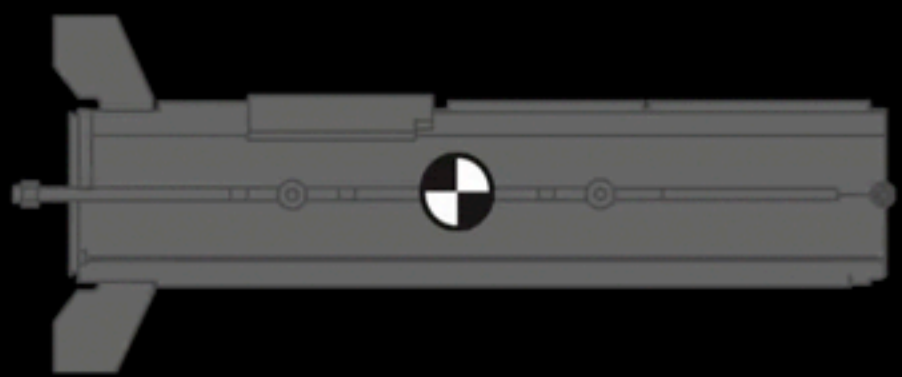
Aerodynamic acceleration

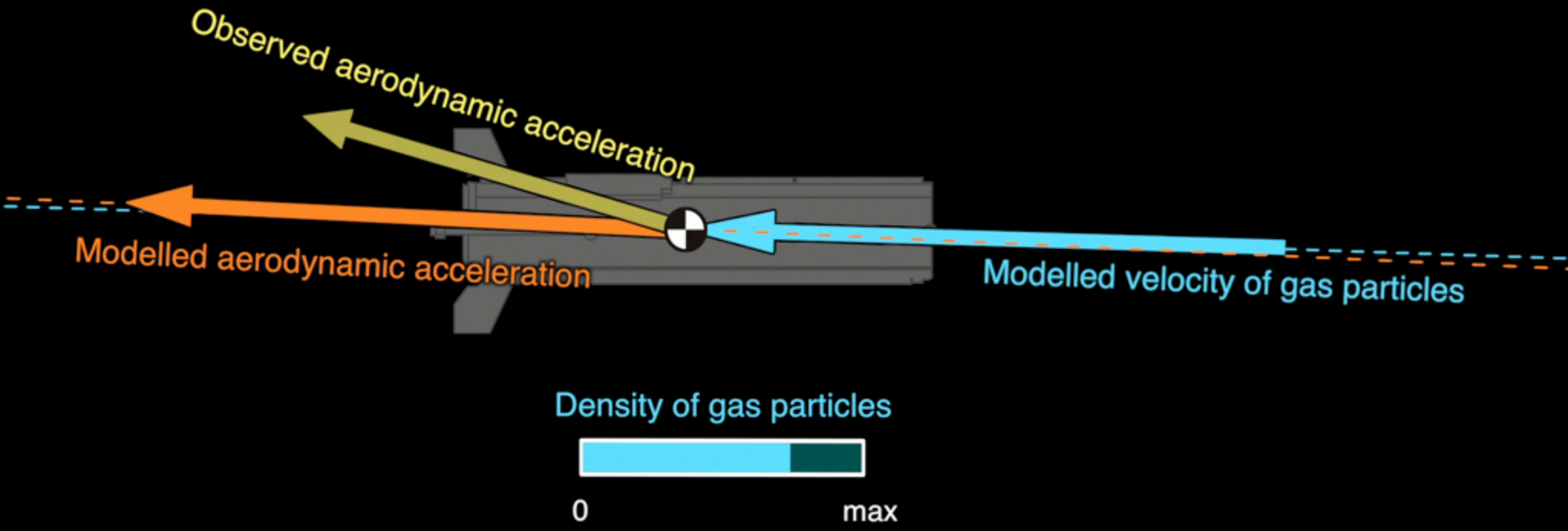
GOCE orbital dynamics:

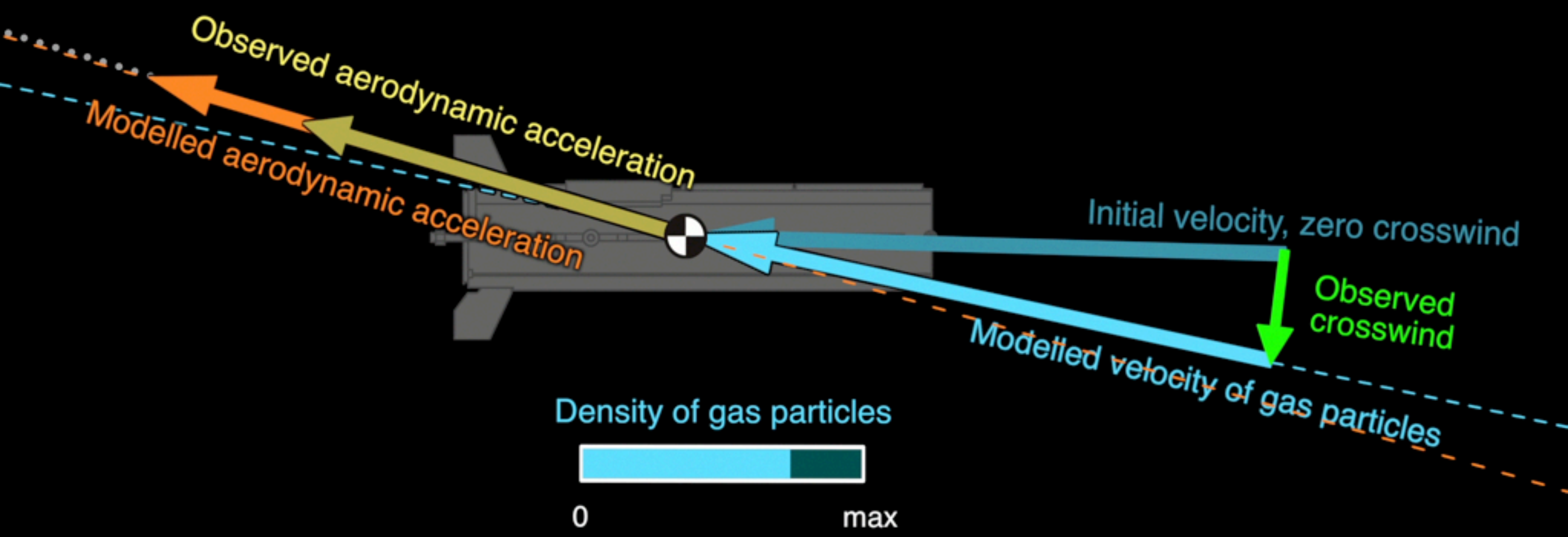
Ion thruster acceleration

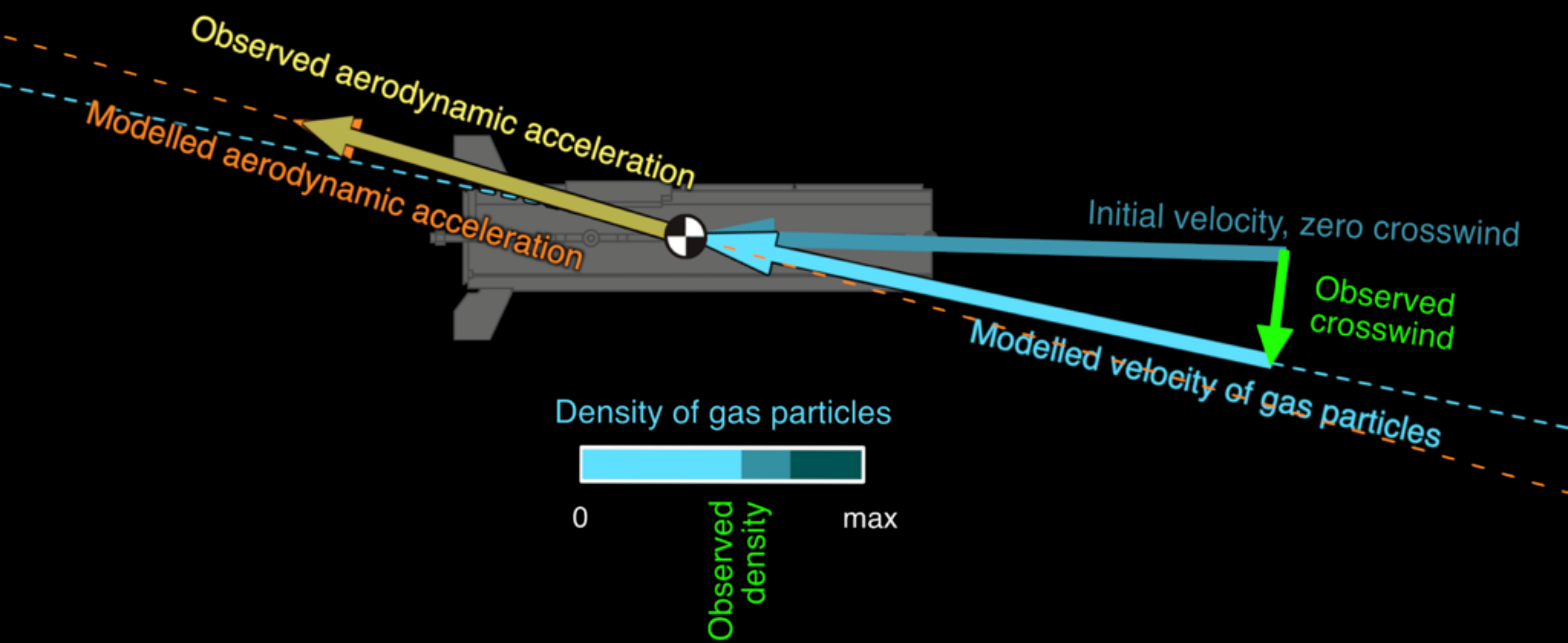
GOCE orbital dynamics:
Radiation pressure acceleration

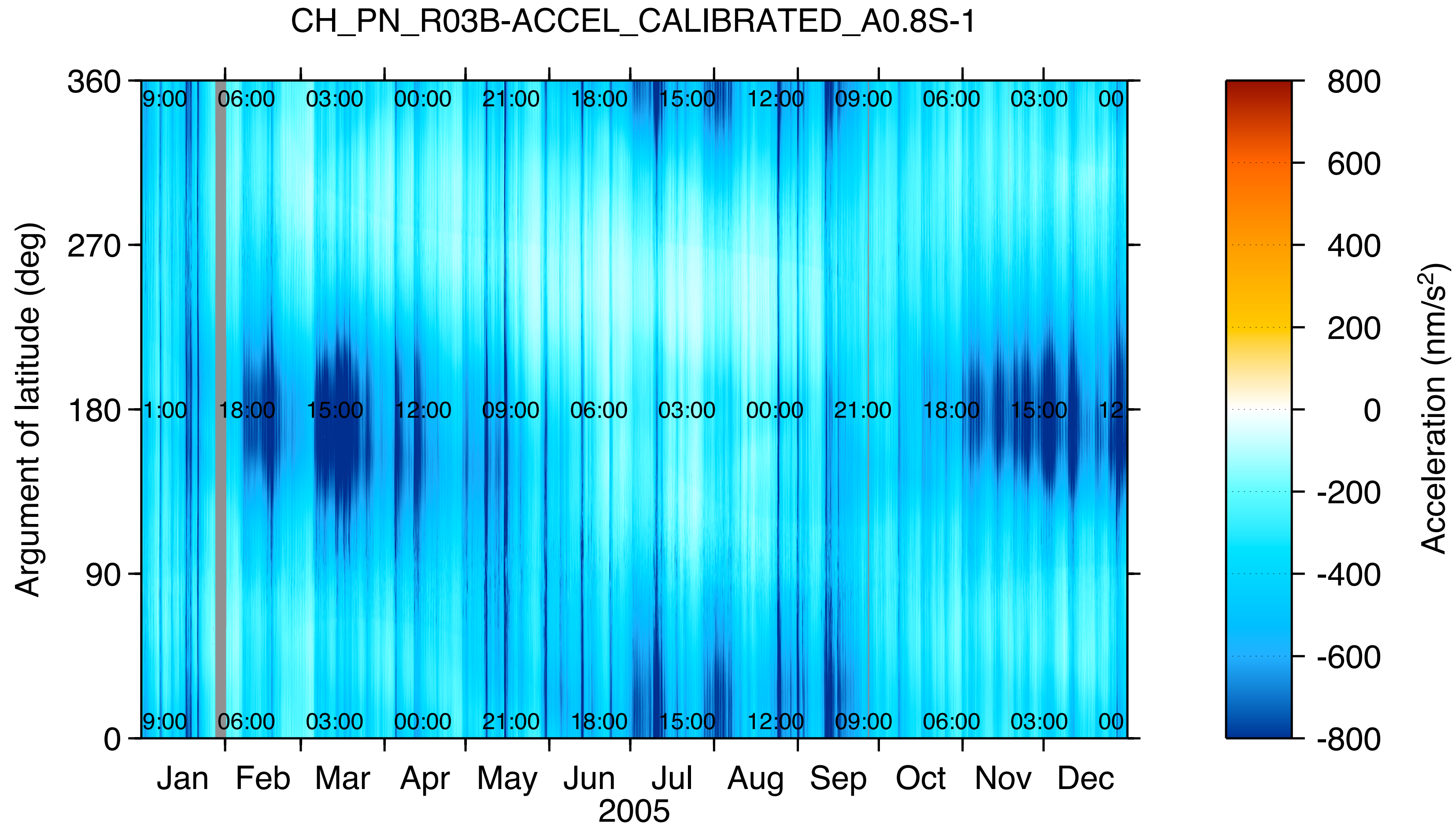


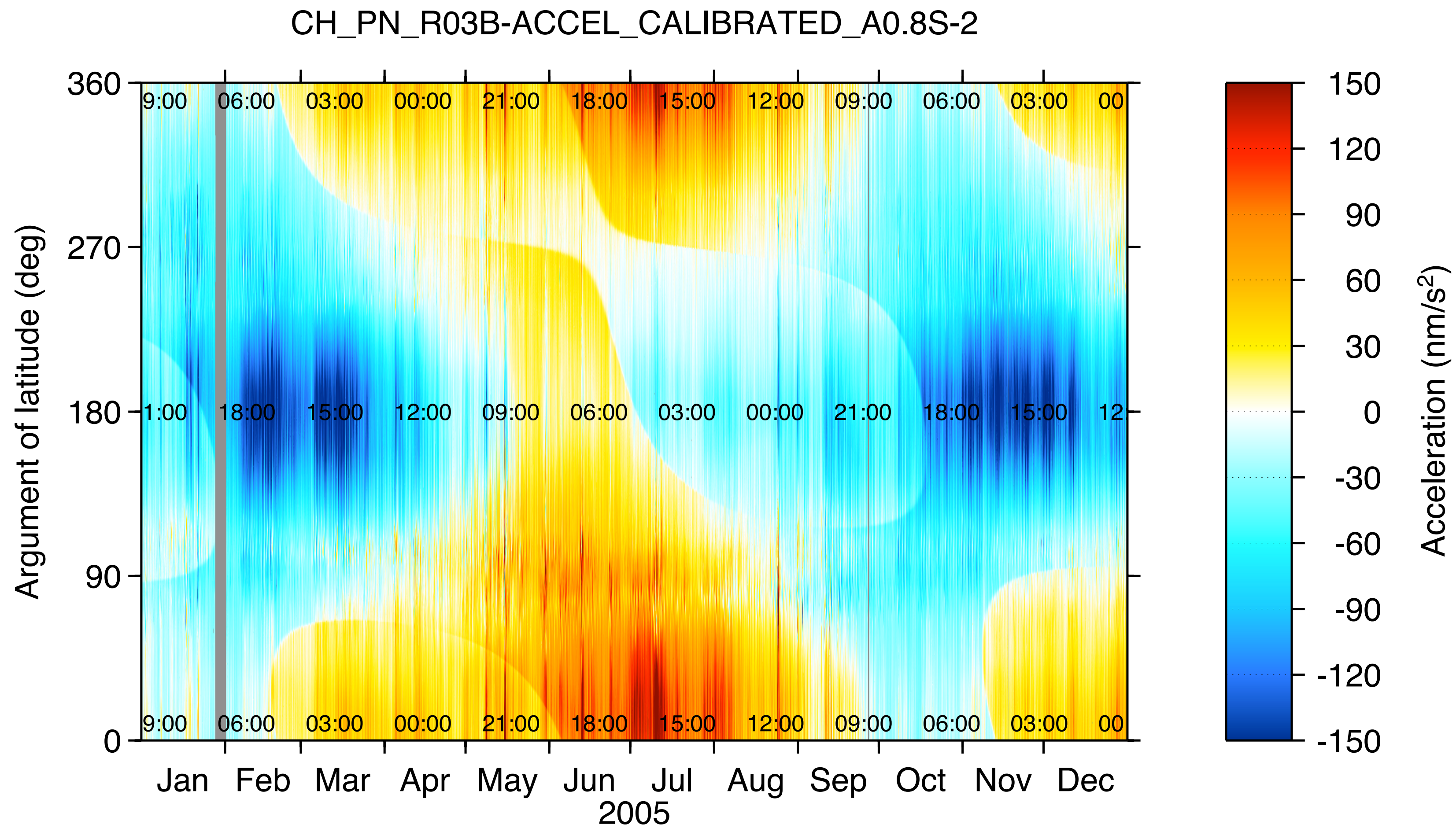


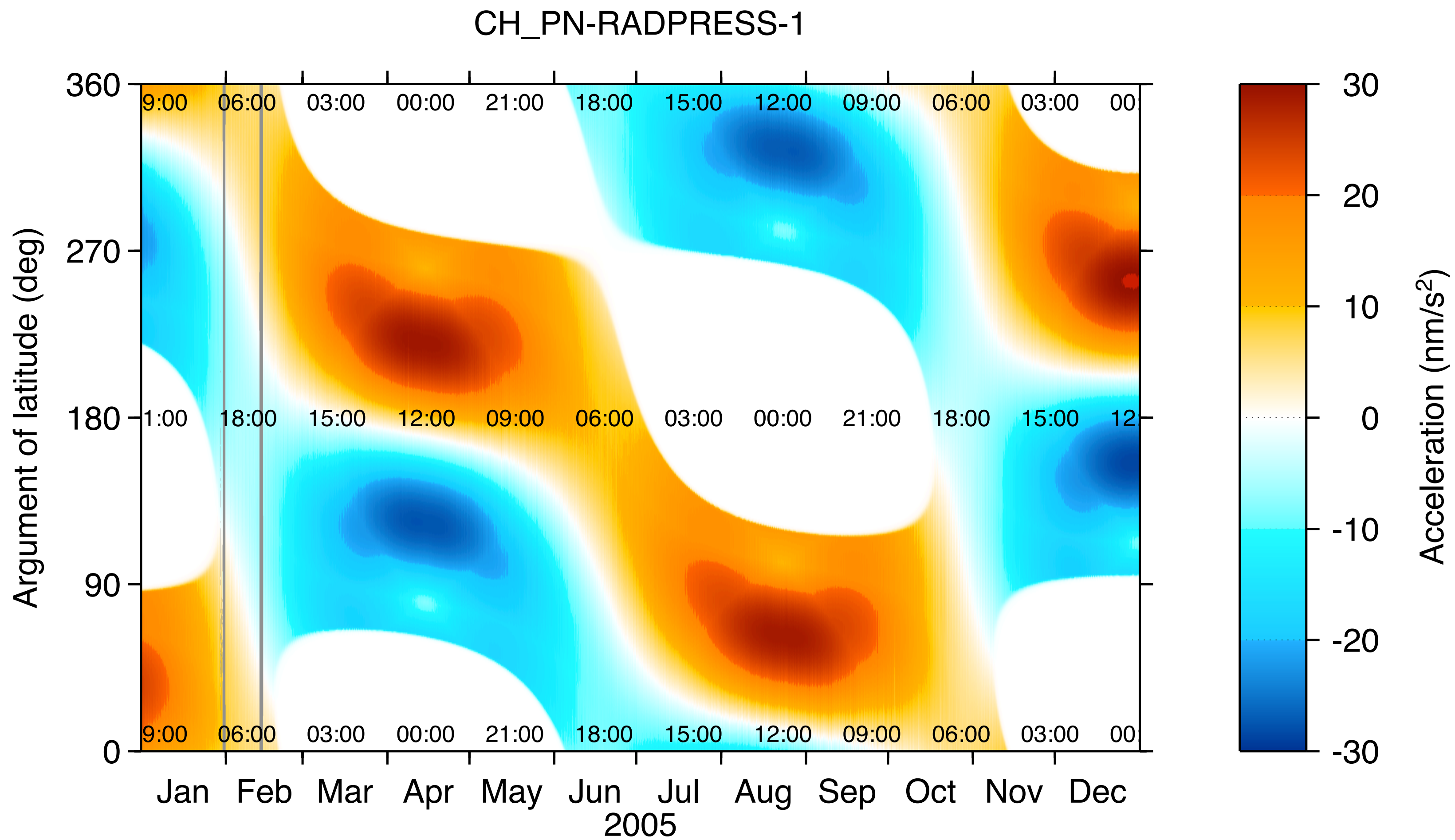

Observed aerodynamic acceleration
Modelled aerodynamic acceleration
Modelled velocity of gas particles
Density of gas particles
0
max

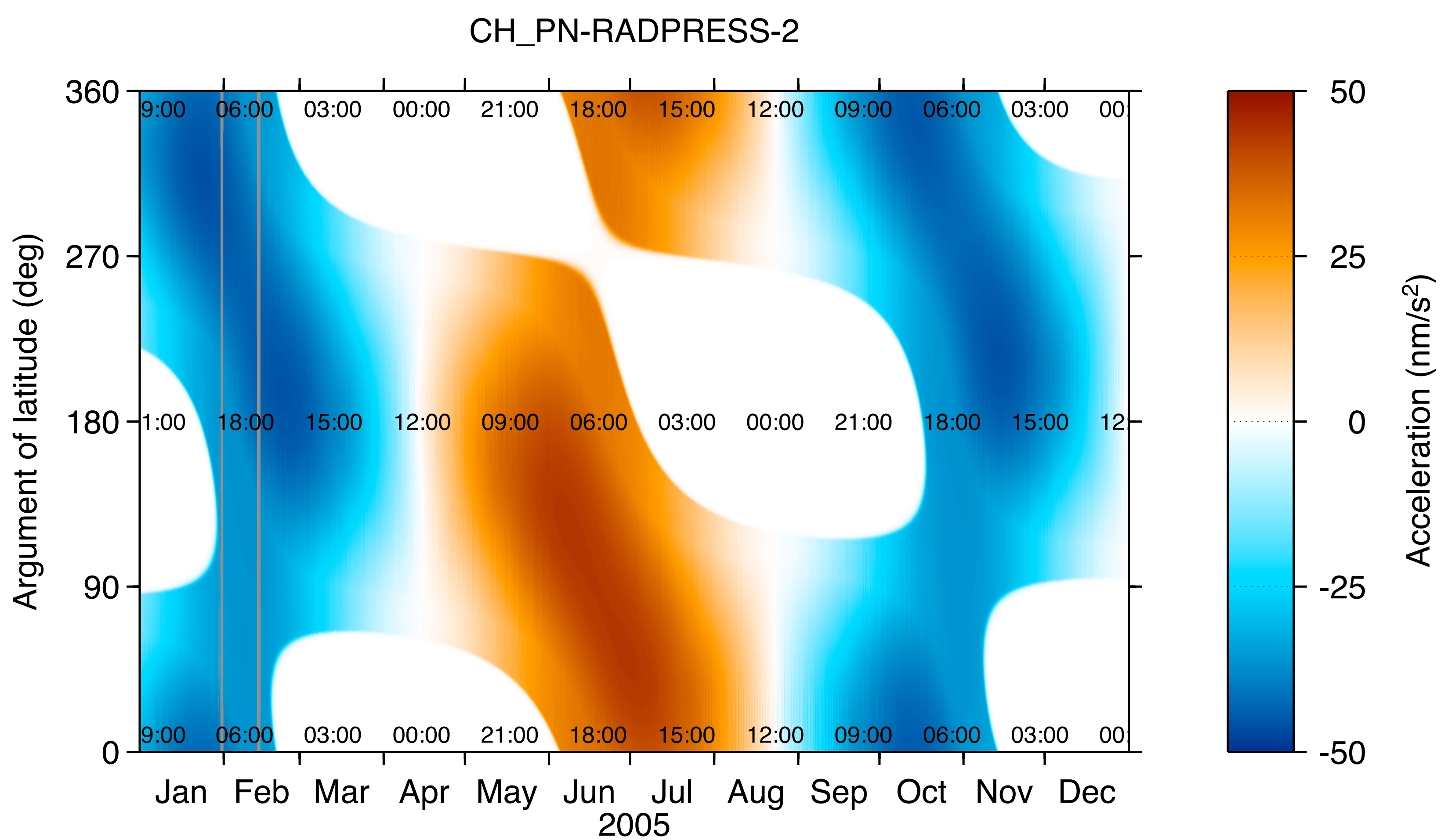

Observed aerodynamic acceleration
Modelled aerodynamic acceleration
Initial velocity, zero crosswind
Observed
crosswind
Modelled velocity of gas particles
Density of gas particles
0
max

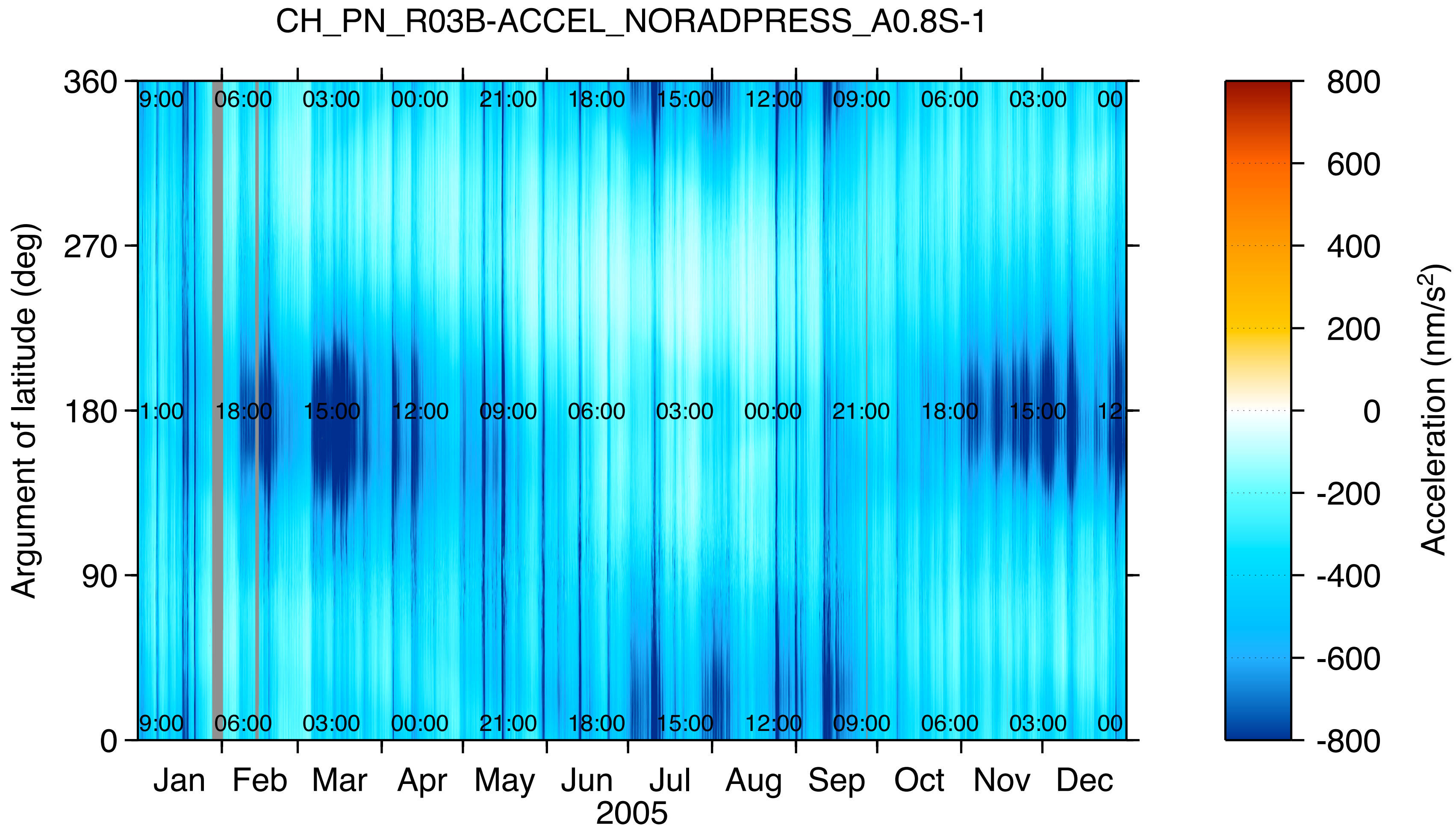

Observed aerodynamic acceleration
Modelled aerodynamic acceleration
Initial velocity, zero crosswind
Observed crosswind
Modelled velocity of gas particles
Density of gas particles
0
Observed density
max

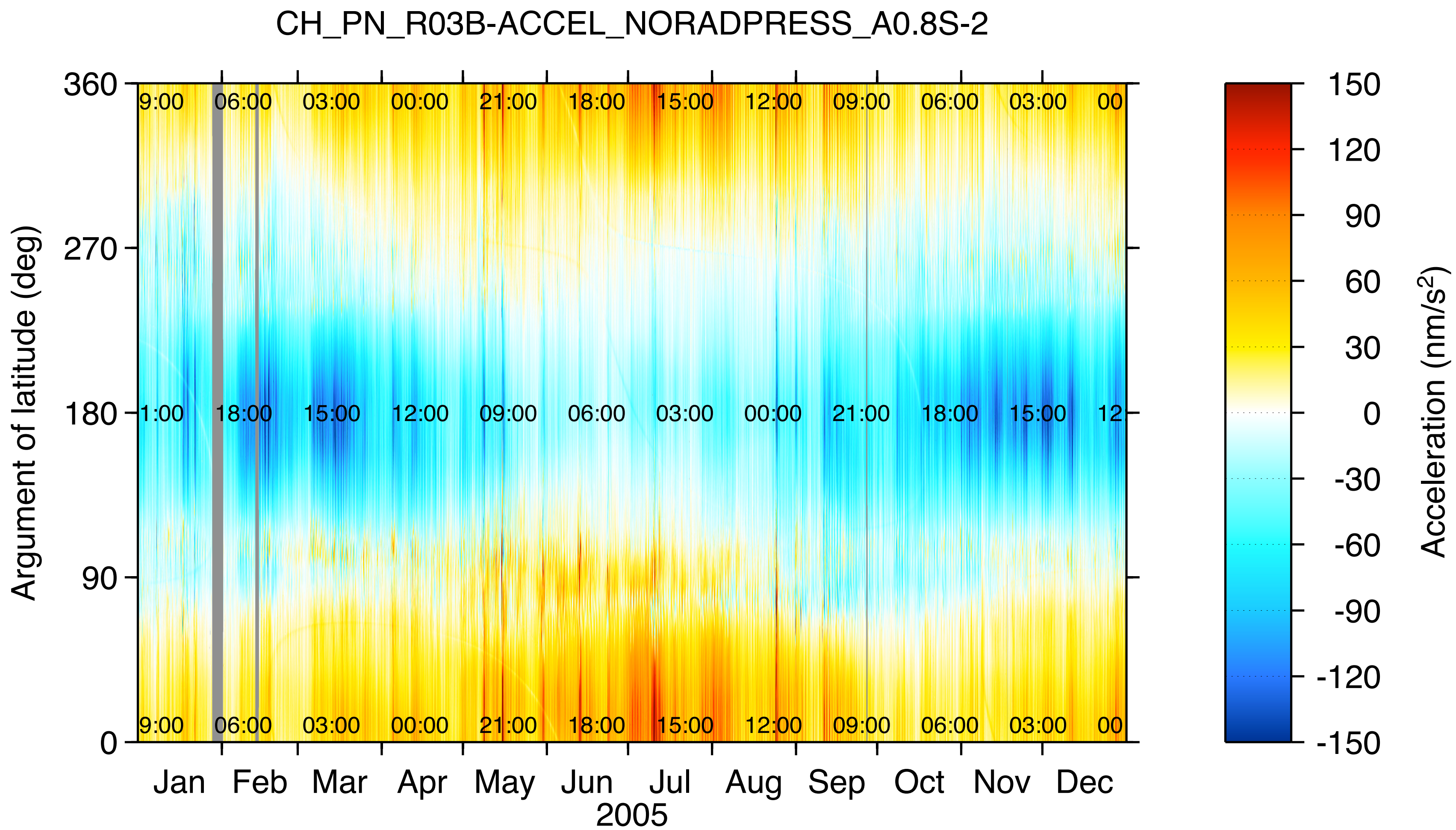

CH_PN_R03B-ACCEL_CALIBRATED_A0.8S-1
Argument of latitude (deg)
360
270
180
90
0
9:00 06:00 03:00 00:00 21:00 18:00 15:00 12:00 09:00 06:00 03:00 00
1:00 18:00 15:00 12:00 09:00 06:00 03:00 00:00 21:00 18:00 15:00 12
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2005
800
600
400
200
0
-200
-400
-600
-800
Acceleration (nm/s2)

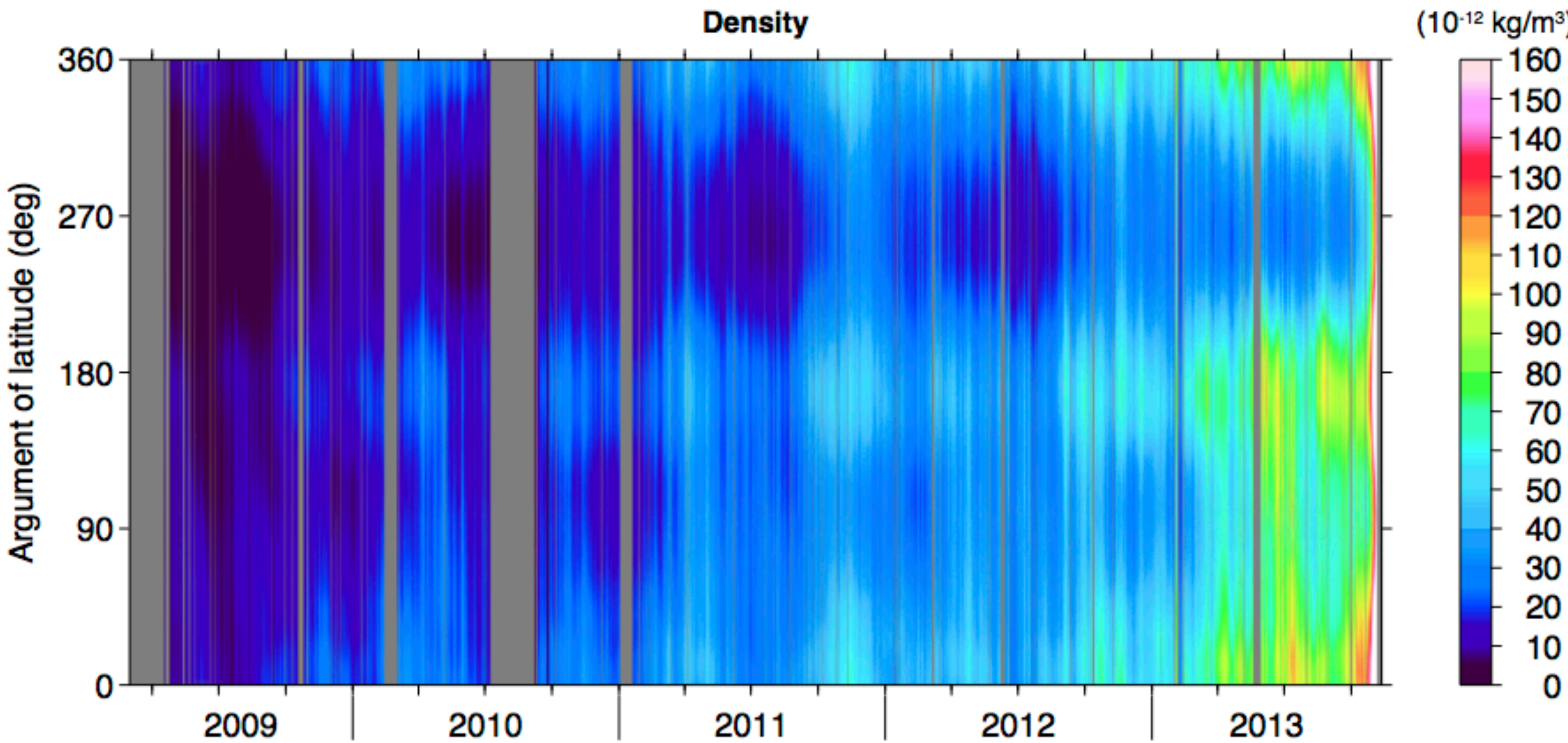

CH_PN_R03B-ACCEL_CALIBRATED_A0.8S-2
Argument of latitude (deg)
360
270
180
90
0
9:00 06:00 03:00 00:00 21:00 18:00 15:00 12:00 09:00 06:00 03:00 00
1:00 18:00 15:00 12:00 09:00 06:00 03:00 00:00 21:00 18:00 15:00 12
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2005
150
120
90
60
30
0
-30
-60
-90
-120
-150
Acceleration (nm/s2)

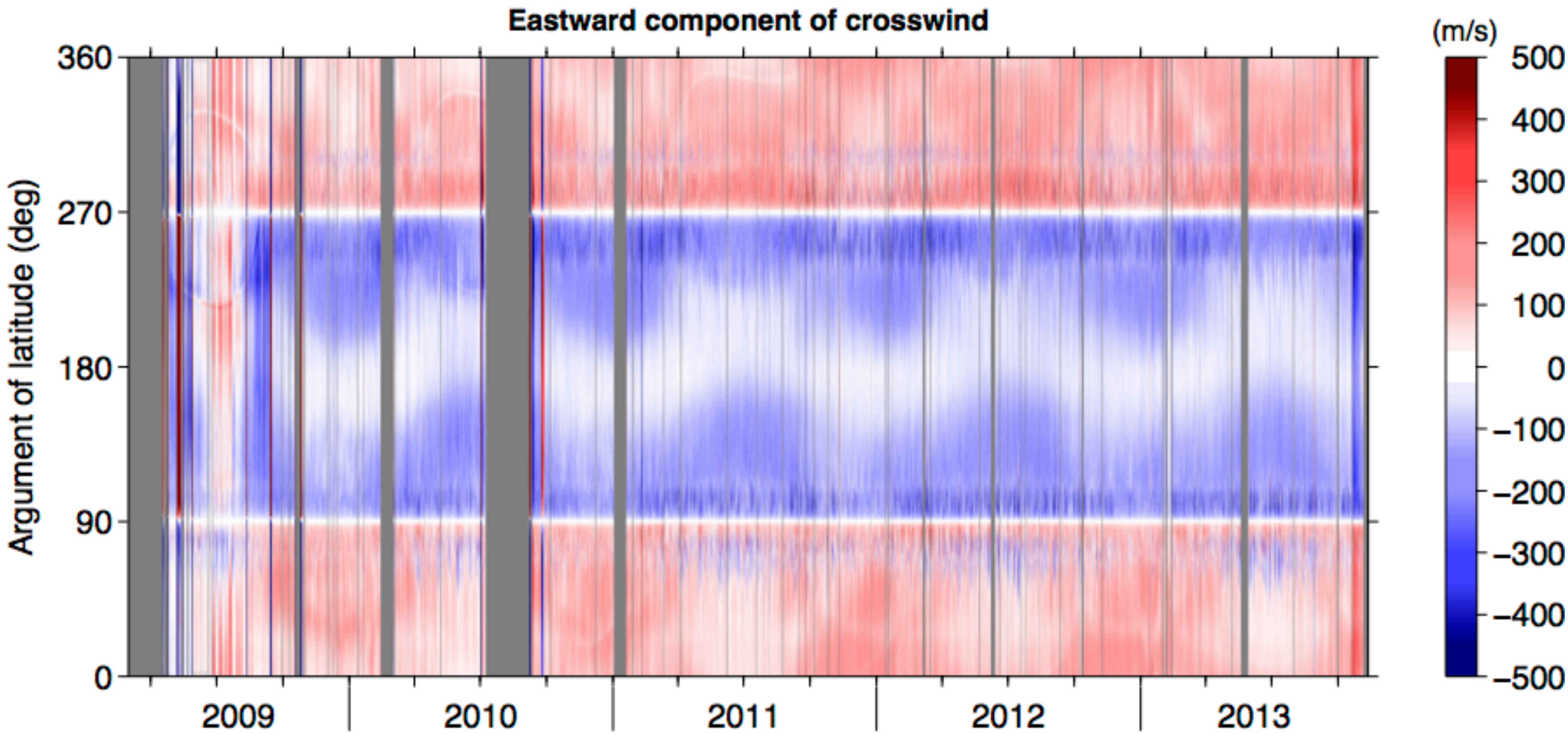

CH_PN-RADPRESS-1
Argument of latitude (deg)
360
270
180
90
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2005
9:00 06:00 03:00 00:00 21:00 18:00 15:00 12:00 09:00 06:00 03:00 00
1:00 18:00 15:00 12:00 09:00 06:00 03:00 00:00 21:00 18:00 15:00 12
Acceleration (nm/s²)
30
20
10
0
-10
-20
-30


CH_PN-RADPRESS-2
Argument of latitude (deg)
360
270
180
90
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2005
9:00 06:00 03:00 00:00 21:00 18:00 15:00 12:00 09:00 06:00 03:00 00
1:00 18:00 15:00 12:00 09:00 06:00 03:00 00:00 21:00 18:00 15:00 12
Acceleration (nm/s²)
50
25
0
-25
-50

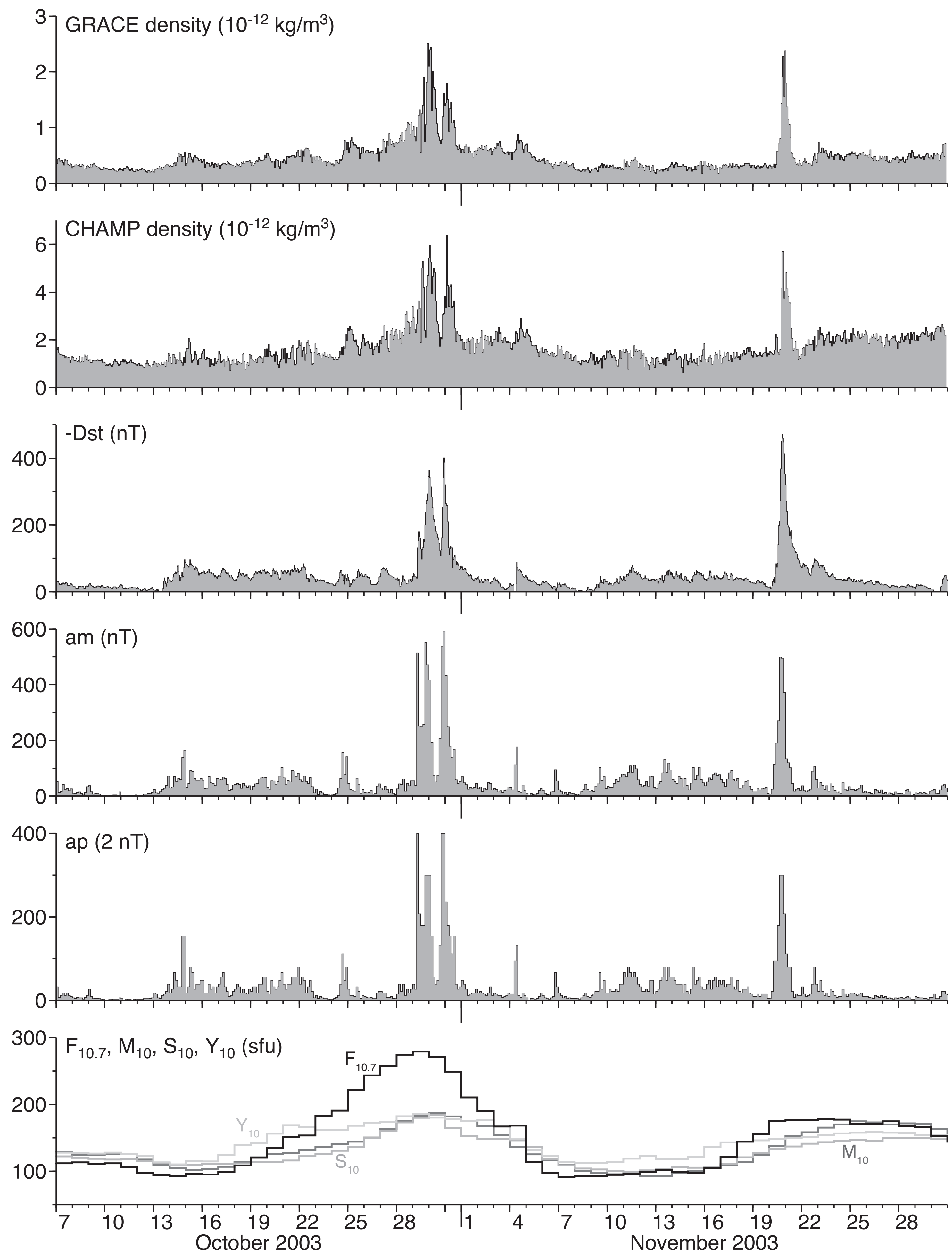

CH_PN_R03B-ACCEL_NORADPRESS_A0.8S-1
Argument of latitude (deg)
360
270
180
90
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2005
9:00 06:00 03:00 00:00 21:00 18:00 15:00 12:00 09:00 06:00 03:00 00
1:00 18:00 15:00 12:00 09:00 06:00 03:00 00:00 21:00 18:00 15:00 12
Acceleration (nm/s^2)
800
600
400
200
0
-200
-400
-600
-800


CH_PN_R03B-ACCEL_NORADPRESS_A0.8S-2
Argument of latitude (deg)
360
270
180
90
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2005
9:00 06:00 03:00 00:00 21:00 18:00 15:00 12:00 09:00 06:00 03:00 00
1:00 18:00 15:00 12:00 09:00 06:00 03:00 00:00 21:00 18:00 15:00 12
Acceleration (nm/s^2)
150
120
90
60
30
0
-30
-60
-90
-120
-150

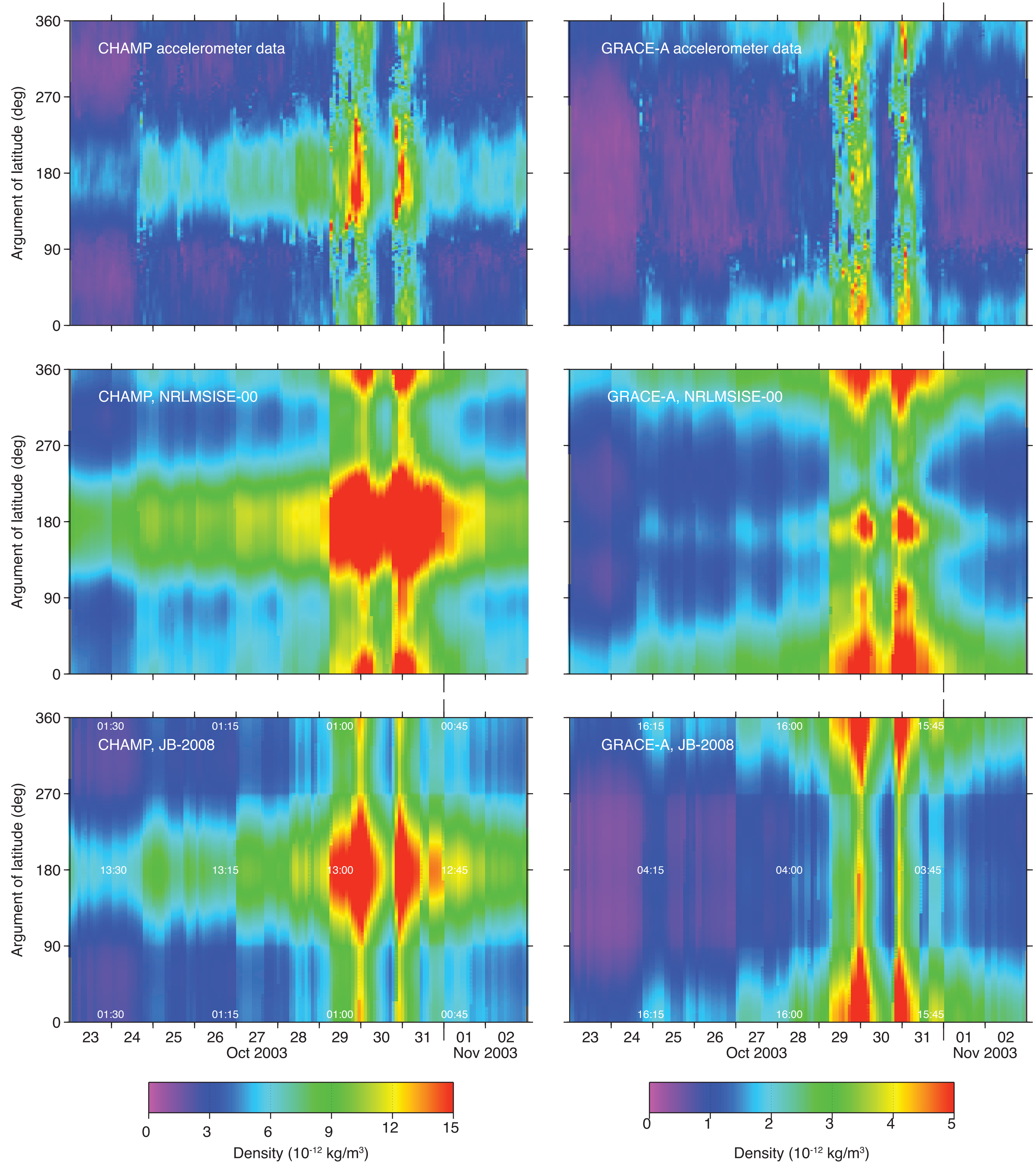

Density
(10-12 kg/m3)
360
270
180
90
0
Argument of latitude (deg)
2009
2010
2011
2012
2013
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0



Eastward component of crosswind
(m/s)
500
400
300
200
100
0
−100
−200
−300
−400
−500
360
270
180
90
0
Argument of latitude (deg)
2009
2010
2011
2012
2013



GRACE density (10^{-12} kg/m^3)
CHAMP density (10^{-12} kg/m^3)
-Dst (nT)
am (nT)
ap (2 nT)
$F_{10.7}$, M_{10}, S_{10}, Y_{10} (sfu)
$F_{10.7}$
Y_{10}
S_{10}
M_{10}
7 10 13 16 19 22 25 28 1 4 7 10 13 16 19 22 25 28
October 2003
November 2003



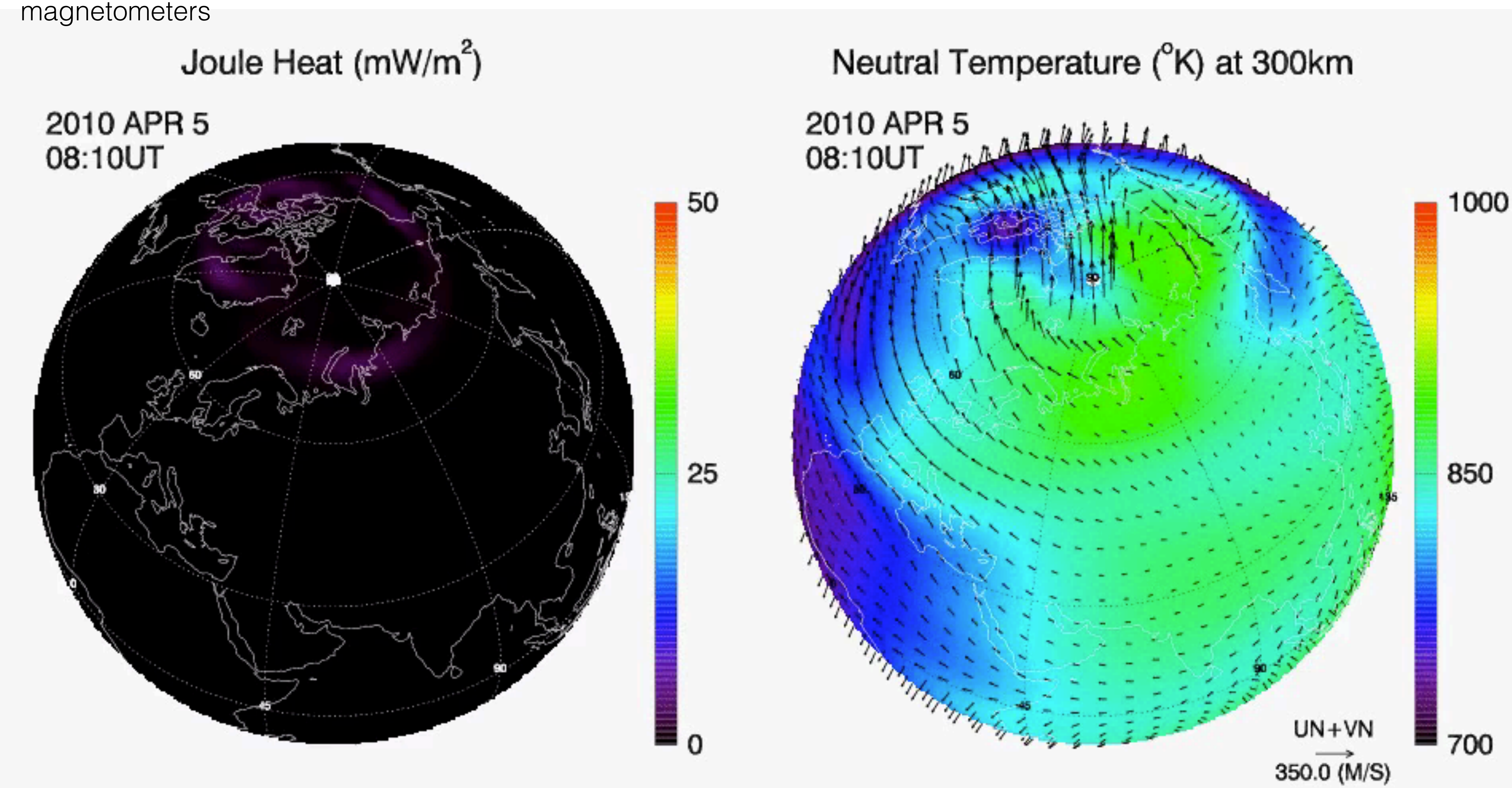
CHAMP accelerometer data
GRACE-A accelerometer data
CHAMP, NRLMSISE-00
GRACE-A, NRLMSISE-00
CHAMP, JB-2008
GRACE-A, JB-2008
Argument of latitude (deg)
360
270
180
90
0
01:30
01:15
01:00
00:45
13:30
13:15
13:00
12:45
16:15
16:00
15:45
04:15
04:00
03:45
23 24 25 26 27 28 29 30 31 01 02
Oct 2003
Nov 2003
0 3 6 9 12 15
Density (10^{-12} kg/m^3)
0 1 2 3 4 5
Density (10^{-12} kg/m^3)

Global ionospheric and thermospheric response to the 5 April 2010 geomagnetic storm: An integrated data-model investigation

G. Lu[1], M. E. Hagan[1], K. Häusler[1], E. Doornbos[2], S. Bruinsma[3], B. J. Anderson[4], and H. Korth[4]

Model input from AMPERE, DMSP, SuperDARN & ground magnetometers

Model output



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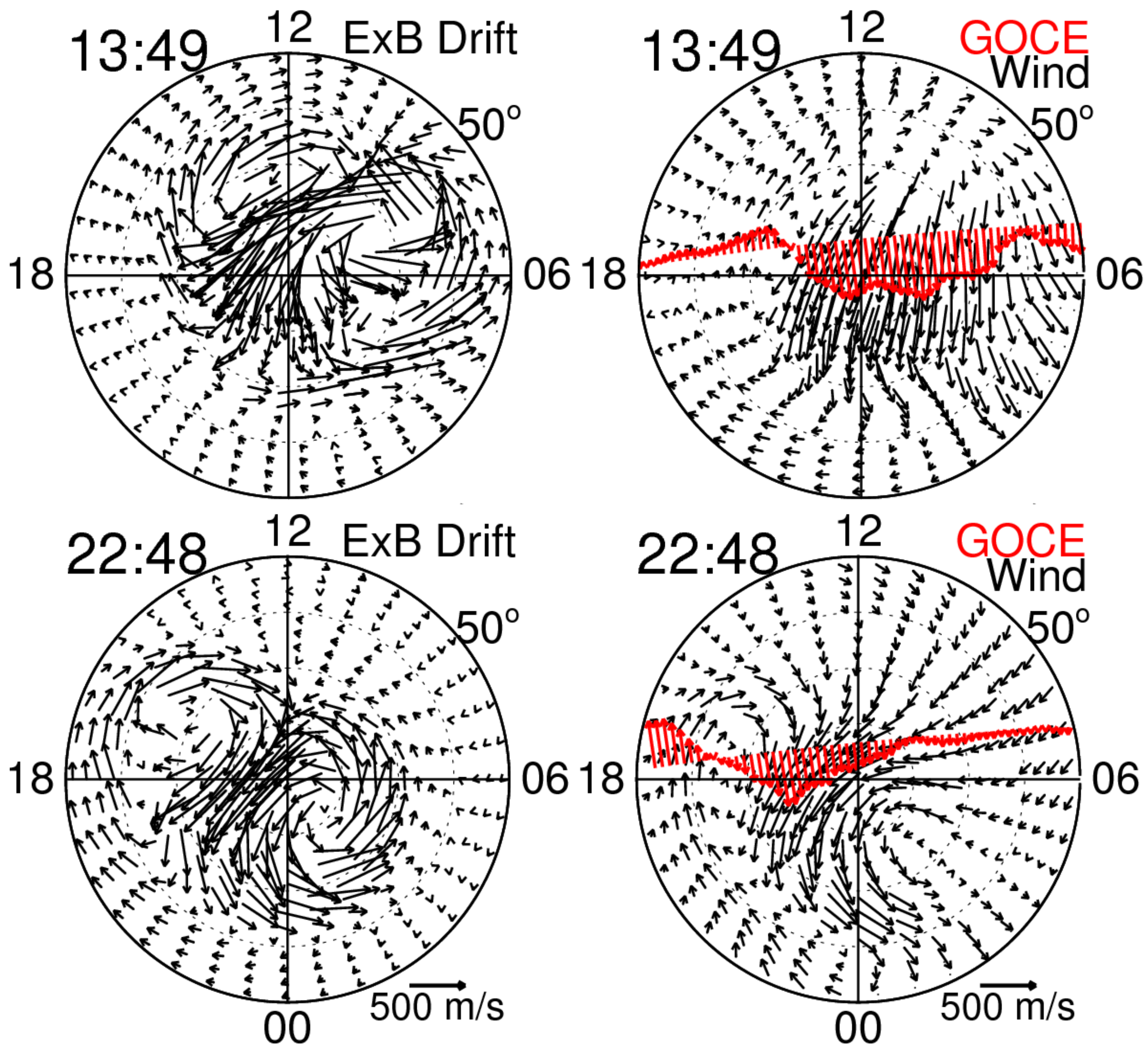
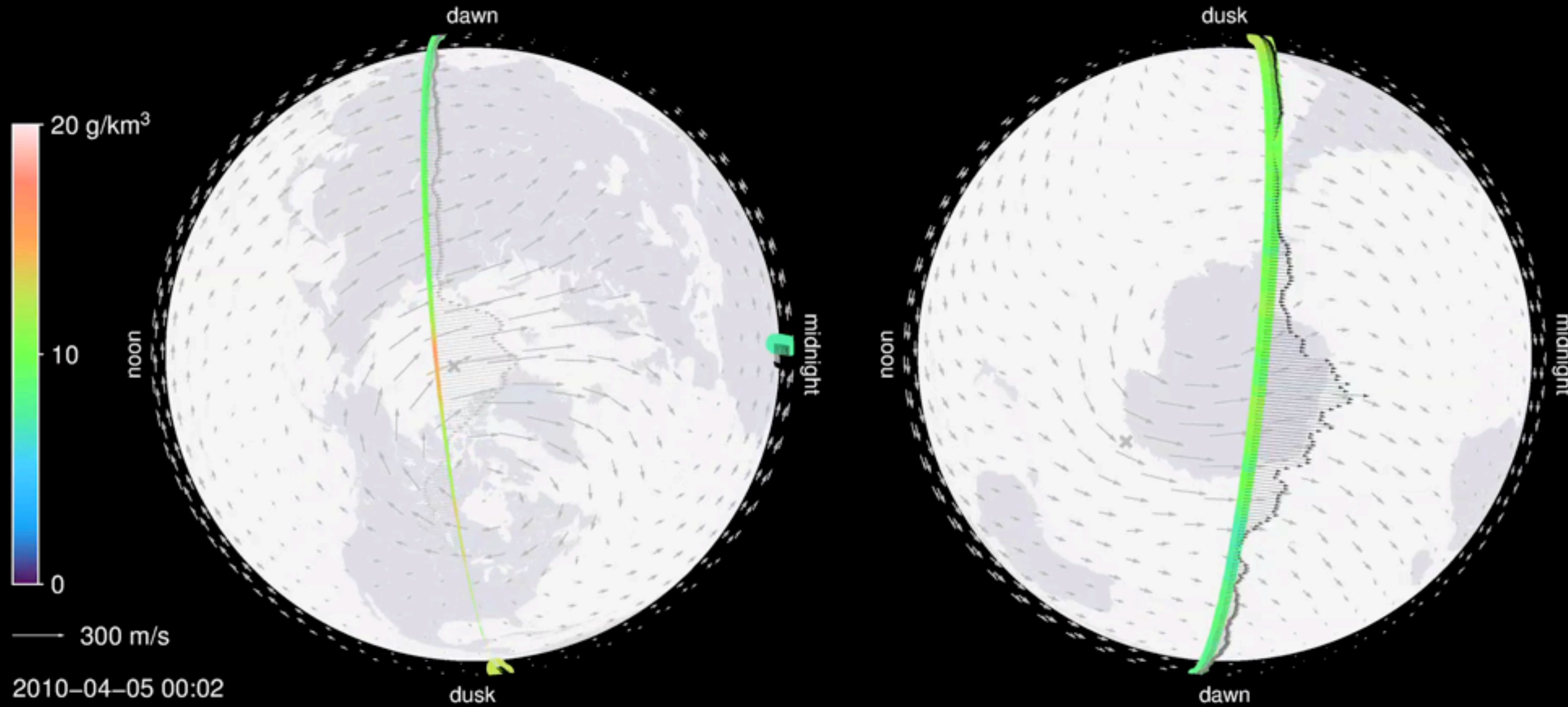


Figure 4. Maps of **E×B** drifts (left column) and neutral winds (right column) from the TIMEGCM at 250 km in the northern hemisphere plotted in geographic latitude versus local time. The marked UT in each panel corresponds to the time when the GOCE spacecraft was closest to the north pole. The GOCE cross-track winds are plotted in red arrows.

Thermospheric density and wind in the polar regions



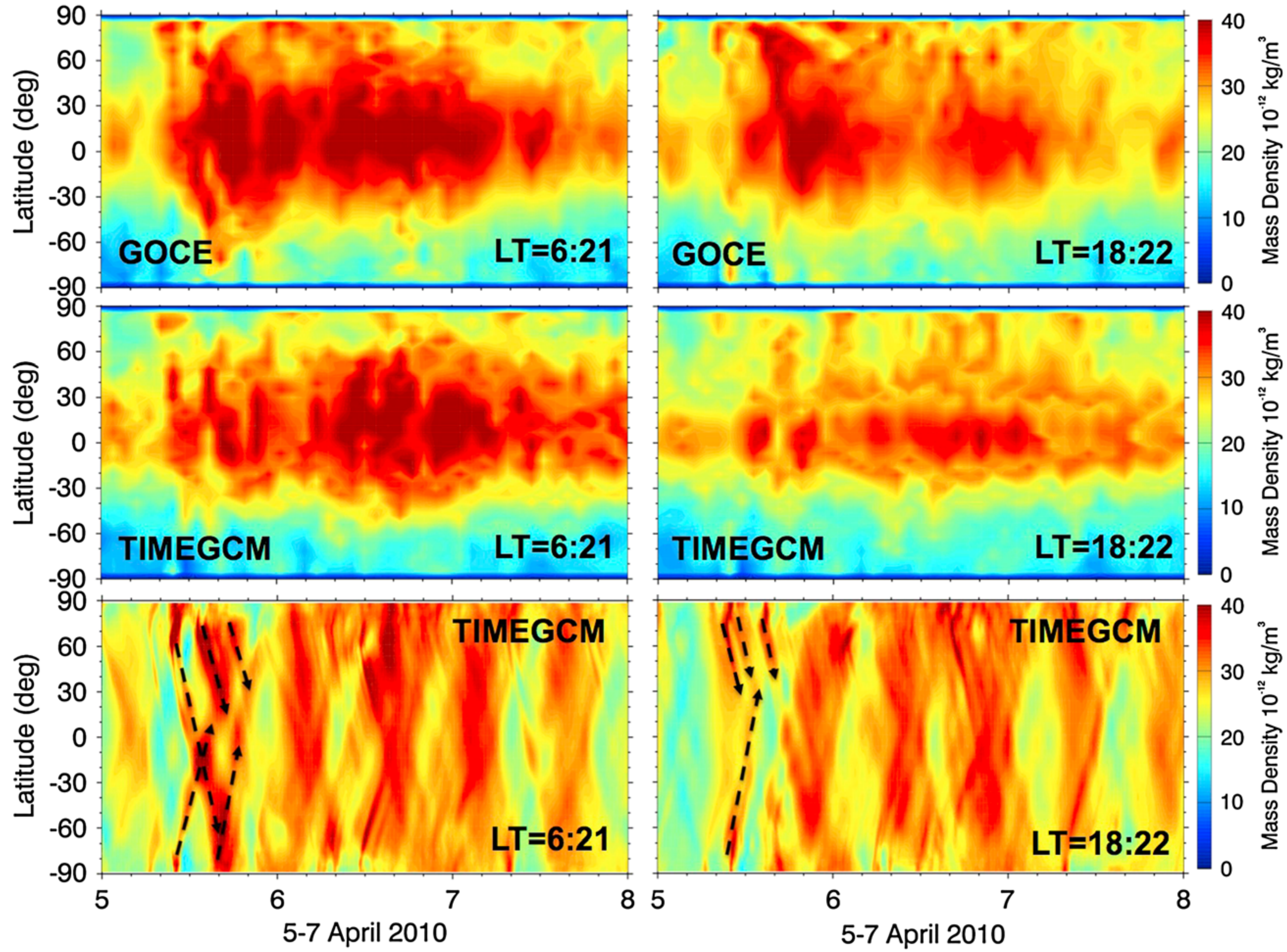
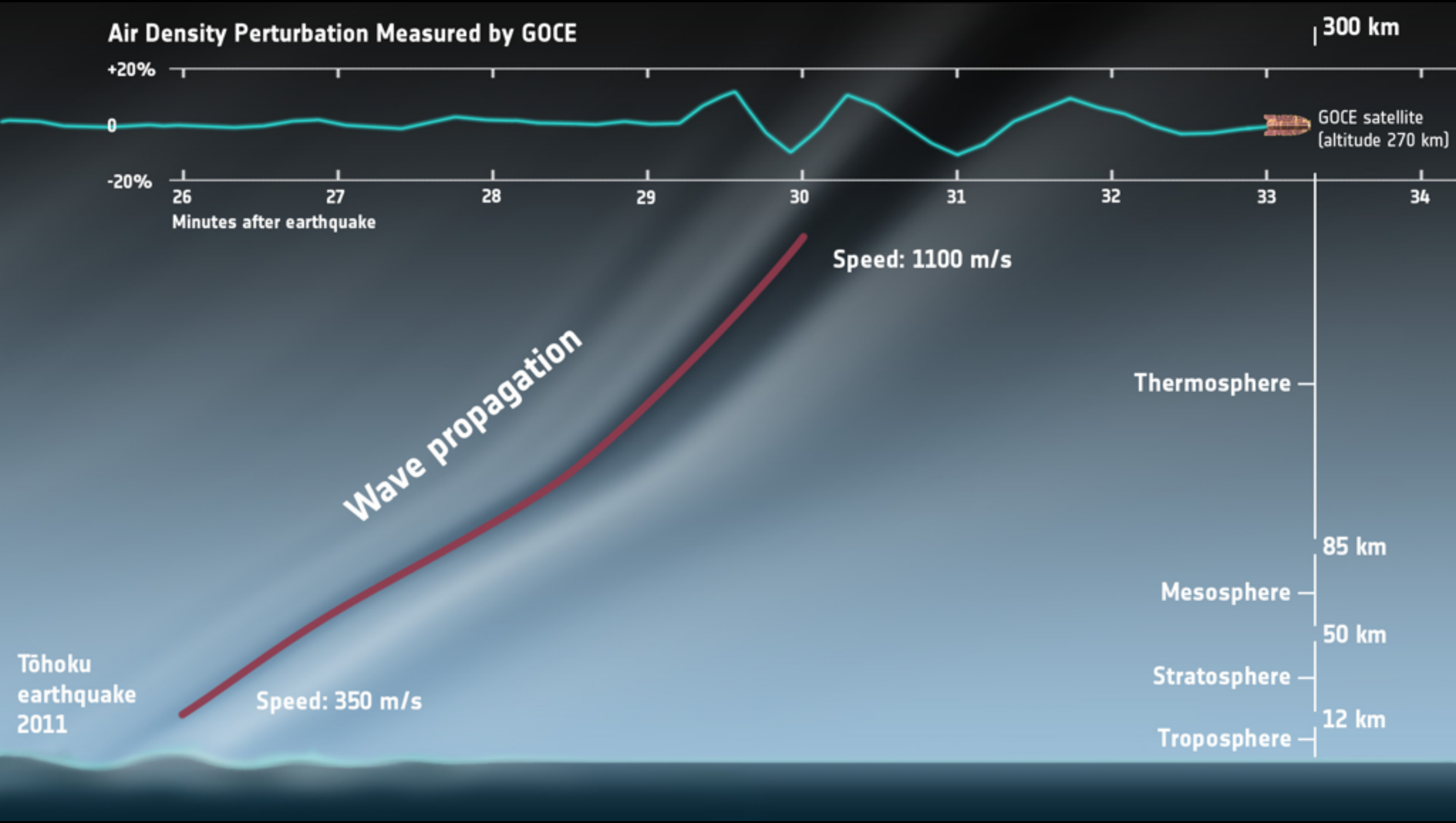


Figure 5. (top row) GOCE neutral mass density measured at (left column) dawn and (right column) dusk. (middle row) Modeled neutral density extracted along the satellite track. (bottom row) Modeled neutral density at fixed local times and a fixed altitude of 266 km. The vertical axis is in geographic latitude. The dashed lines in Figure 5 (bottom row) highlight the main TADs on 5 April with the arrows indicating the TAD propagation directions. The apparent hemispheric difference in Figure 5 (top and middle rows) is due to GOCE's slightly elliptical orbit, which had an average altitude of 266 km in the Northern Hemisphere and 274 km in the Southern Hemisphere.

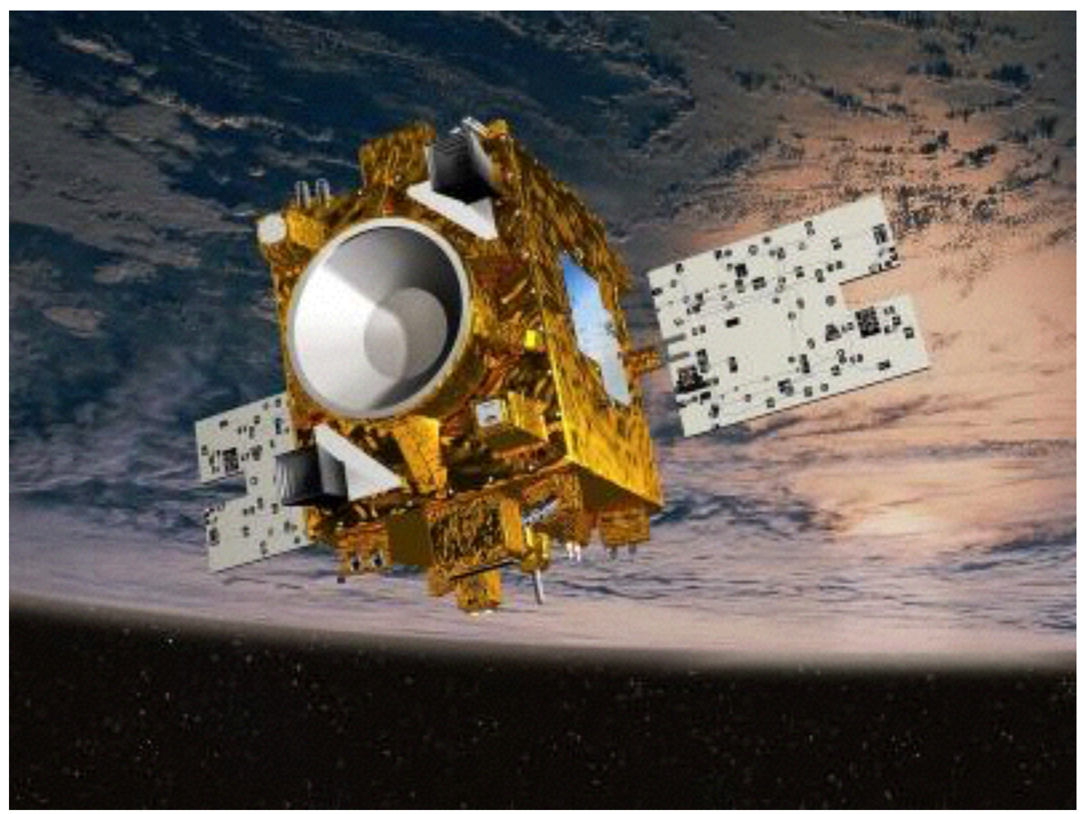


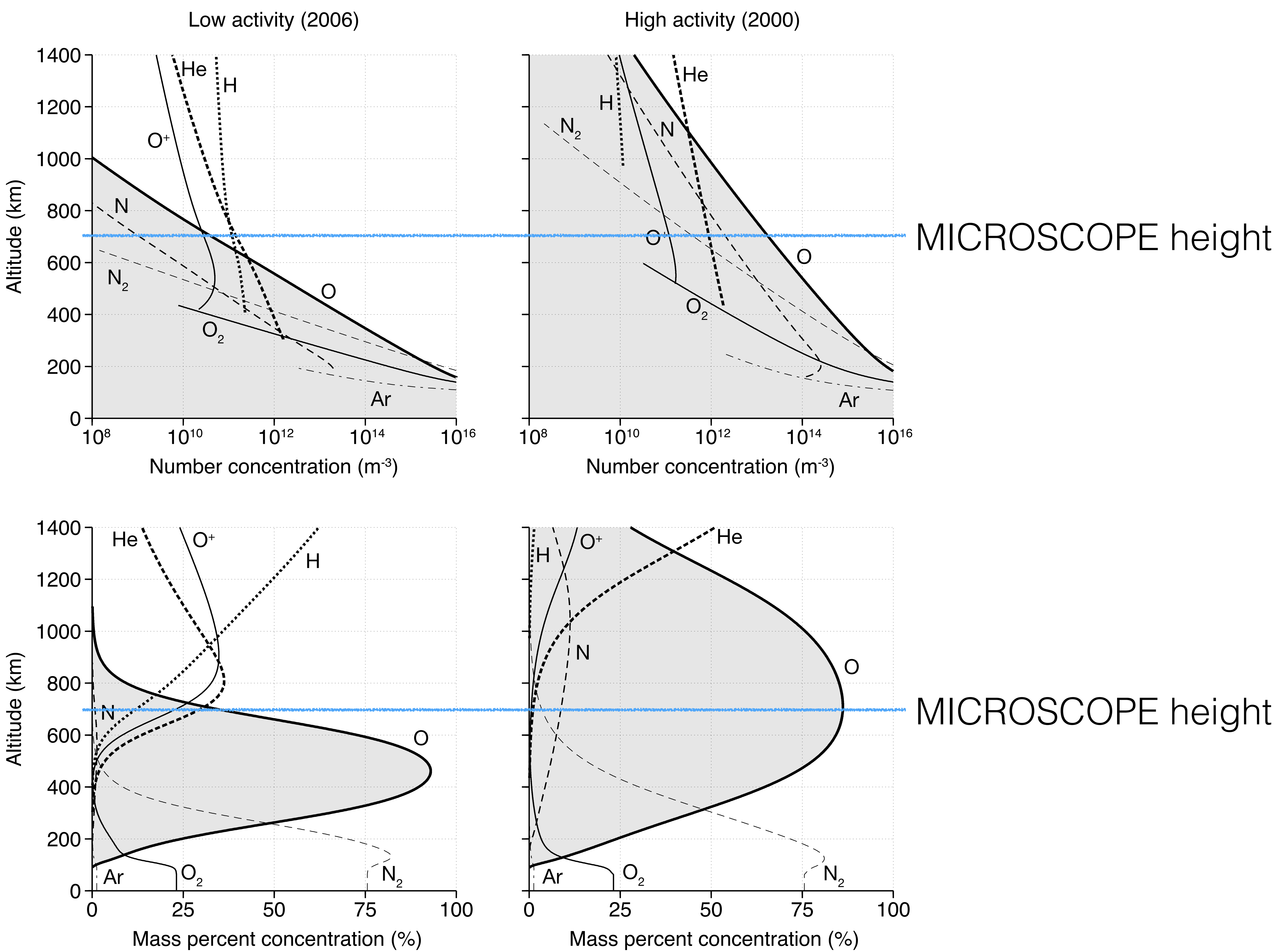
Planetary Visions

Ongoing activities

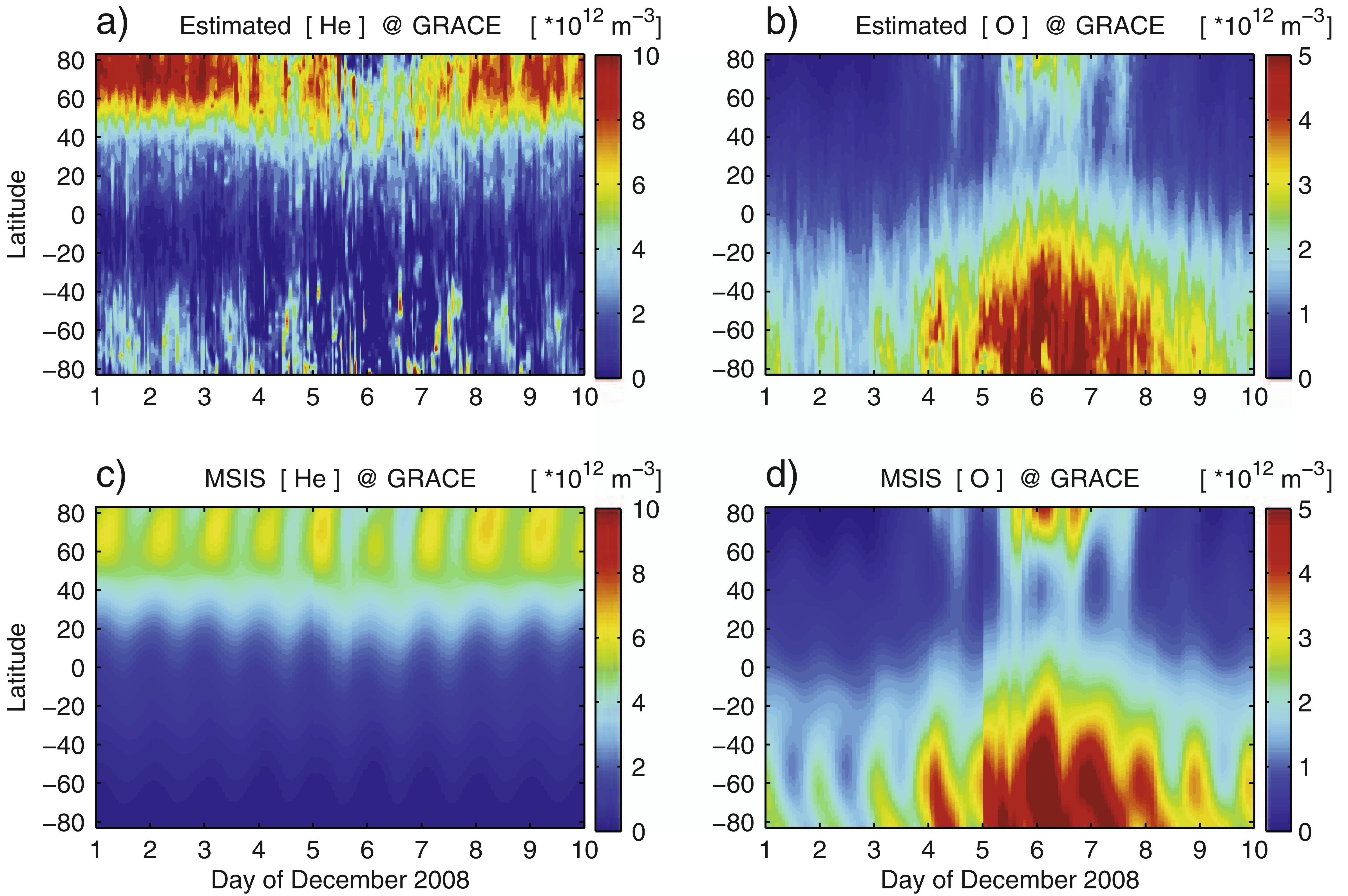
- Characterization of on-board temperature variations on accelerometer signal.
- Elimination of uncertainties in satellite geometry and satellite aerodynamics parameters.
- Use of angular acceleration measurements, analysis of aerodynamic torques using GOCE data.
- Analysis of very low altitude GOCE data at end of life.

Outlook and requirements for MICROSCOPE





Low activity (2006)
High activity (2000)
MICROSCOPE height
MICROSCOPE height
Altitude (km)
Number concentration (m-3)
Mass percent concentration (%)
He
H
O+
N
N2
O
O2
Ar



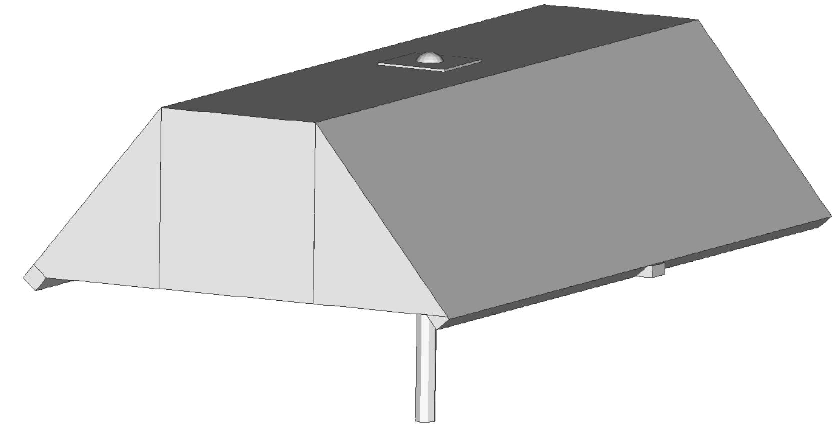
a) Estimated [He] @ GRACE [*10^12 m^-3]
b) Estimated [O] @ GRACE [*10^12 m^-3]
c) MSIS [He] @ GRACE [*10^12 m^-3]
d) MSIS [O] @ GRACE [*10^12 m^-3]
Latitude
Day of December 2008
80
60
40
20
0
−20
−40
−60
−80
1
2
3
4
5
6
7
8
9
10

Characteristics of GOCE and Microscope

GOCE	Microscope
Operations: 2009-2013	Launch: 2016
Sun-synchronous 230-270 km	Sun-synchronous 707 km
Accelerometers: 10^{-12} m/s^2	Accelerometers: 10^{-12} m/s^2
Drag free in X (flight) direction using ion engine	Drag free in all directions using micro-thrusters

Requested data

- Accelerations in SI units, if possible uncalibrated & calibrated
  - From accelerometer
  - From AACS (thrust levels)
- GPS tracking data, e.g. in RINEX format
- For non-gravitational force modelling:
  - Variations of spacecraft mass over time due to fuel consumption
  - Detailed model of geometry of satellite outer surfaces
  - Description of optical properties of satellite outer surfaces



I.5.3.5 GRACE Macro Model: Surface Properties

The surface properties are summarized in the following table. For each surface, the area, the components of its unit normal in the Satellite Frame, the material, as well as its emissivity and absorptivity/reflectivity coefficients are provided.

Panel	Area (m^2)	Unit Normal			Material	Emiss (IR)	Absorp (Vis)	Refl (Vis)		Refl (IR)	
		X	Y	Z				Geom	Diff	Geom	Diff
Front	0.9551567	+1.0	0.0	0.0	SiOx/Kapton	0.62	0.34	0.40	0.26	0.23	0.15
Rear	0.9551567	-1.0	0.0	0.0	SiOx/Kapton	0.62	0.34	0.40	0.26	0.23	0.15
Starboard (outer)	3.1554792	0.0	+0.766044	-0.642787	Si Glass Solar Array	0.81	0.65/0.72 (note 2)	0.05	0.30	0.03	0.16
Starboard (inner)	0.2282913	0.0	-0.766044	+0.642787	SiOx/Kapton	0.62	0.34	0.40	0.26	0.23	0.15
Port (outer)	3.1554792	0.0	-0.766044	-0.642787	Si Glass Solar Array	0.81	0.65/0.72 (note 2)	0.05	0.30	0.03	0.16
Port (inner)	0.2282913	0.0	+0.766044	+0.642787	SiOx/Kapton	0.62	0.34	0.40	0.26	0.23	0.15
Nadir	6.0711120	0.0	0.0	+1.0	Teflon (note 1)	0.75	0.12	0.68	0.20	0.19	0.06
Zenith	2.1673620	0.0	0.0	-1.0	Si Glass Solar Array	0.81	0.65/0.72	0.05	0.30	0.03	0.16
Boom	0.0461901 (note 4)	--	--	--	SiOx/Kapton (note 3)	0.62	0.34	0.40	0.26	0.23	0.15

(1) fluoro ethylene propylene
(2) 0.65 for operating solar array (i.e. power being drawn); 0.72 for non-operating array
(3) S-Band antenna on the boom is protected by a carbon radome (emiss = 0.85; absorp = 0.95), neglected here.
(4) Planar projection area of the cylindrical Boom, along any direction in the Satellite Frame (X-Y) plane.

Challenges of using MICROSCOPE data for thermosphere studies

- Relatively low aerodynamic acceleration signal.
  - Need to very accurately model radiation pressure.
- Attitude not necessarily kept aligned with flight direction.
  - Need to have good calibration for all accelerometer axes.
- Continuous microthruster operation.
  - Need to characterize the

Benefits of Microscope for thermosphere studies

- Compact satellite shape, easier to model satellite aerodynamics.
- Data at altitude close to the most critical altitude range for spacecraft conjunction assessment and collision avoidance
- High-resolution data on the winter Helium bulge, and its response to the various drivers of the thermosphere.