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Annales Geophysicae Discussions

Lower Thermosphere response to solar activity: an EMD analysis of GOCE 2009-2012 data.

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Abstract. Forecasting the Thermosphere (Atmosphere's uppermost layer, from about 90 to 800 km altitude) is crucial to space-related applications, from space mission design, to re-entry operations, space surveillance and more. Thermospheric dynamics is directly linked to the solar dynamics through the solar UV input, which is highly variable, and through the solar wind and plasma fluxes, impacting Earth's magnetosphere. The solar input is non-periodic and non-stationary, with long-term modulations from the solar rotation and the solar cycle, and impulsive components, due to magnetic storms. Proxies of the solar input exist and may be used to forecast the thermosphere, such as the F10.7 radio flux and the MgII EUV flux. They relate to physical processes on the Solar atmosphere. Other indices, such as the A_p geomagnetic index, connect with Earth's geomagnetic environment. We analyse the proxies' time series comparing them with in-situ density data from the ESA/GOCE gravity mission, operational from March 2009 to November 2013, therefore covering the full rising phase of solar cycle XXIV, exposing the entire dynamic range of the solar input. We use Empirical Mode Decomposition (EMD), an analysis technique appropriate to non-periodic, multi-scale signals. Data are taken at an altitude of 260 km, exceptionally low for a LEO satellite, where density variations are the single most important perturbation to satellite dynamics.

We show that the synthesized signal from optimally selected combinations of proxies's basis functions, notably MgII for the solar flux and Ap for the plasma component, show a very good agreement with thermospheric data obtained by GOCE, during low and medium solar activity periods. In periods of maximum solar activity, density enhancements are also well represented. The Mg II index proves to be, in general, a better proxy than the F10.7 one, to model the solar flux, because of its specific response to the UV spectrum, whose variations have the largest impact over thermospheric density.

1 Introduction

Forecasting the Thermosphere is crucial to space mission design, re-entry operations and space surveillance applications. Most low-Earth-Orbit operational satellites fly in a narrow zone between 400 and 800 km, within this layer. Orbital decay rate of Satellites depends on atmospheric drag which is directly affected by the variable solar activity (Masutti et al., 2016). Orbital decay rate at 250km of altitude is very significant, causing re-entry of a satellite in about two weeks. Large uncertainties in the determination of satellite impact location during re-entry, results from the uncertainty in the knowledge of thermospheric density. During de-orbiting of GOCE, for instance, two hours before re-entry, the most probable ground impact area was still extending over the entire descending orbit, across the Pacific and Indian Oceans. (GOCE Flight Control Team, HSO-OEG, 2011). An impact over Europe could be ruled out just 12 hours before satellite disruption.

Various indices and proxies of the solar input are available, and used in monitoring and predicting the status of the Thermosphere. Most atmospheric density models have adopted the solar radio flux at 10.7 cm wavelength (the F10.7 index) as solar flux proxy (Floyd et al., 2005) and the Ap/Kp indices for geomagnetic activity (Omniweb, 2018). F10.7 has been measured daily since 1947 at Pentiction (Canada) at 17, 20 and 23 UTC. The Ap index instead provides 3-hourly averages of geomagnetic data. Other proxies and indices have been defined over time, some of them based on direct in-situ measurements from satellites, others derived from Earth-based obervatories. The Mg II core-to-wing ratio (cwr), has been provided daily since 1978 and is available through NOAA Space Environment Center or by the Institut für Umweltphysik - Universität Bremen (SORCE, 2018; UVSAT, 2018). The Mg II cwr has proved an excellent proxy for the solar Mid-UV. It originates from a chromospheric line emission near 280 nm. In particular, the chromospheric Mg II H and K lines at 279.56 and 280.27 nm, and the weakly varying photospheric wings continuum of the core line emission are observed by a number of on-board satellite instruments. Current semi-empirical models of the thermosphere, such as NRLMSISE-00 (Picone et al., 2002) and JB2008 (Bowman et al., 2008) include satellite drag data, mostly available between 400 and 600km height, and solar proxies. The NRL one includes, for instance, the F10.7 solar flux (present and averaged over the previous 81 days), and the Ap index for the previous 57-hours. These models, though, may prove inaccurate in predicting neutral thermospheric density, depending on the level of solar activity, see e.g. (Lathuillère and Menvielle, 2010; Masutti et al., 2016). During times of high magnetic activity, modeled density may underestimate by a factor two the measured one (Sutton et al., 2005). Moreover, some authors (Pardini et al., 2012) found that below 500 km, many atmospheric models overestimated the average atmospheric density by 7% to 20% because of the assumption of a fixed drag coefficient, independent of altitude. An example of how incorrect calculations from empirical models may dramatically affect satellite control, is again the case of the GOCE satellite which, soon after launch, went to safe mode because of what proved a wrong assumption on density levels. Because of the overestimated drag from model, the satellite attitude was bound to rapidly evolve to a critical tumbling condition, with high risk of loss. Different solar indices may prove more apt than others to reproduce thermospheric density, depending on the status of the solar activity. For instance, comparison of EUV proxies in thermospheric density reconstruction at 800 km altitude, from 1997 to 2010, (Dudok de Wit and Bruinsma, 2011) indicated SOHO EUV data as the most suitable to reproduce thermospheric densities at 800 km, during the analysed period. MgII index was also compared to this proxy, showing good, although not optimal, performance, at that altitude.

In our analysis paper, we shall analyse MgII data available for the 2009-2012 period, thus partly overlapping to that data set, although at a very different height. We shall use the low-altitude GOCE data which have become available since that cited analysis (Bruinsma et al., 2014).

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2 The Solar Input and thermospheric response

The structure and dynamics of Earth's Thermosphere is controlled by the solar input mainly through the highly variable solar EUV radiation, on the day side. Joule dissipation of induced ionospheric currents and kinetic energy deposition from low energy particles in the auroral zones (Sarris, 2019; Knipp et al., 2004; Qian and Solomon, 2012) also contribute. Geomagnetic activity, that is particles deposition and ionospheric/magnetospheric effects, is triggered by the interaction , with Earth's magnetosphere. The solar wind itself is composed by two components, fast and slow, which may interact with each other during their travel in the interplanetary space, originating shocks impacting the Earth's magnetosphere. The EUV flux accounts on average for about about 80% of this energy input, while the geomagnetic input accounts for the remaining 20%. However, during intense geomagnetic activity, geomagnetic contribution may rise up to about 70% of the energy input (Immel et al., 2004; Lu et al., 1998). The EUV flux has itself a large (up to a factor two) spectrum of variability around its base value (Del Zanna and Andretta, 2011). Thus geomagnetic activity is a variable source of energy and has an impulsive component varying on short timescales of hours, during geomagnetic storms, and a more stable background, away from storms. These fast variations in time, may cause local variation of density of a factor of 2 or three with respect to the pre-event average value, see Figure.4 below. Radiative input from the Sun, instead, has a more continuous character. The 27-day solar rotation period induces changes in the solar emission correlated with the motion of active regions across the Earth-facing solar disk. During the course of the 11-years solar cycle, density is seen to vary by a factor of about 6 at low altitudes (250 km). Seasonal and semi-annual variations are induced by the movement of the sub-solar point and the uneven heating of the two hemispheres at solstices; Diurnal variations are also present, which produce an asymmetry in density between the sun-lit and the dark hemispheres. Thermosphere thus responds to this composite input on many different timescales.

3 Data sets: GOCE Thermospheric density and solar and geomagnetic indices

GOCE, the Gravity field & steady-state Ocean Circulation Explorer (Drinkwater et al., 2003), was launched by ESA on March 17, 2009 to map Earth's gravity field. It has had a 5 year lifetime flying at the exceptionally low altitude between 260 and 230 km. No other civilian satellite has ever flown this low within the thermosphere. GOCE was kept in a drag-free orbit in a dawn-dusk 96.7° sun-synchronous orbit at a mean altitude of 260 km from September 2009 through the end of July 2012. Orbit was then further lowered to 229 km, until de-orbiting, in late October 2013. Mission profile is shown in Fig. 1. To keep the satellite in drag-free mode, extremely sensitive accelerometers were coupled to an ion thruster. Data from the accelerometers has been processed to a thermospheric density dataset (Bruinsma et al., 2014) which has been made available by ESA through the GOCE Virtual Archive (ESA). Data are organized in monthly data files starting from November 1st, 2009 00:00:00 and ending October, 20, 2013 04:07:10 . Sampling rate is 10s. We use Release 1.5 of the dataset. Geomagnetic Ap Index and Solar index F10.7 have been retrieved from NASA Goddard Space Flight Center OMNIWeb interface (Omniweb, 2018). Composite Mg II index v5 dataset have been retrieved from UVSAT of Bremen University Institut für Umweltphysik, (UVSAT, 2018). Sunspot number has been retrieved from SILSO data/image portal of Royal Observatory of Belgium, Brussels. Figure 2 shows the GOCE thermospheric density dataset in context with Solar Cycle XXIV. Three sub-periods have been selected for subsequent

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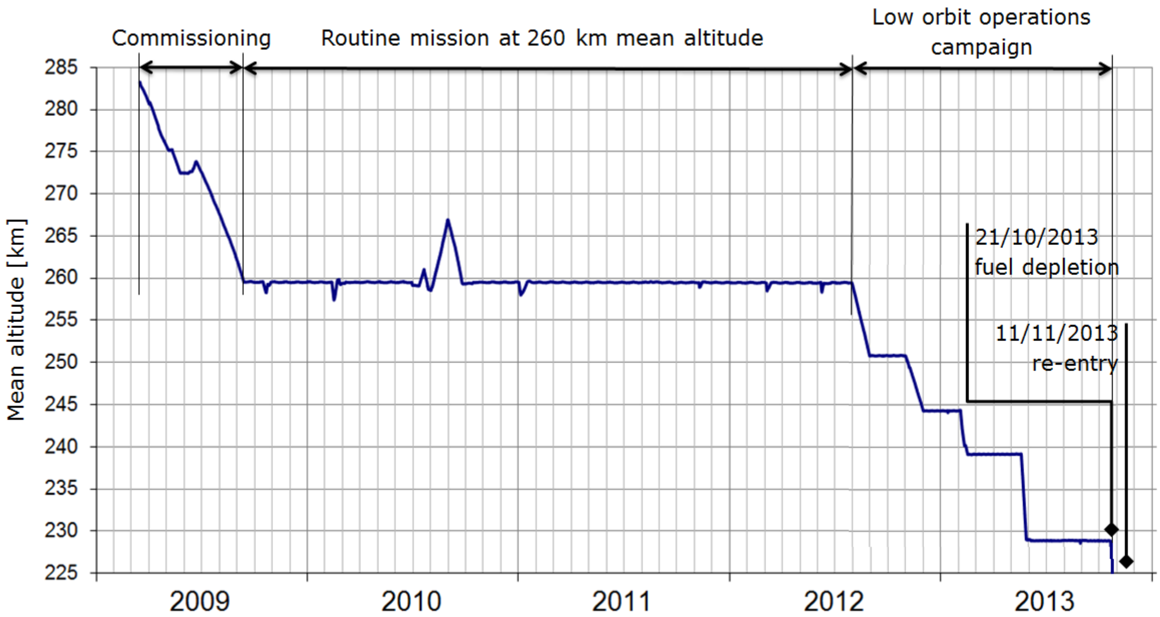

Figure 1. GOCE Mission profile (GOCE Flight Control Team, HSO-OEG, 2011). Low orbit campaign (260-230km height) starts August 2012.

analysis: Low activity, from Mission start to end of September 2010; Rising phase, where activity rises from minimum to maximum levels, until July 2012, and a steady, High Activity phase, until end of Mission, Nov 2013, where activity is almost stationary and close to the levels of Solar Maximum. High activity period also coincides with GOCE low-orbit campaign, bringing the satellite down from 260 to 230 km height. The average value of density is steady rising, in this period, solely due to the altitude lowering. In the subsequent analysis, solar proxies are tested with their capability to reproduce thermospheric density, within these three different dynamical regimes. In Fig.3, the full-Mission thermospheric density dataset is shown. Due to in-flight anomalies, the density dataset is affected by gaps, ranging from tens of seconds to days. The most significant gap starts July 8th 2010 and lasts 67 days. Also to be noted is the expected steady increase in average density due to the orbit lowering after July 2012. Signal from solar and geomagnetic proxies, F10.7, MgII and Ap, have been pre-treated for outliers identification and removal. Spline interpolation have been used to fill in missing or removed data. The Ap signal, which is available on a three-hours interval, has been averaged over 24 hours. Ap has also been shifted by a fixed 9-hours amount. The thermosphere, infact, reacts to the impulsive geomagnetic forcing with a delay. We have determined this delay by maximising the correlation between Ap and ρ signals during geomagnetic events, resulting in a a fixed 9-hours delay which has been applied to the Ap signal. Geomagnetic storms represent the impulsive component of the solar input, lasting from hours to days. They originate from solar plasma ejected during CME events and impacting Earth's magnetosphere, or from shocks forming at the interfaces between fast and slow solar wind. Figure 4 shows four examples of atmospheric response to geomagnetic storms, occurred during Mission lifetime and captured by GOCE. Reconfiguration of the geomagnetic field induces currents

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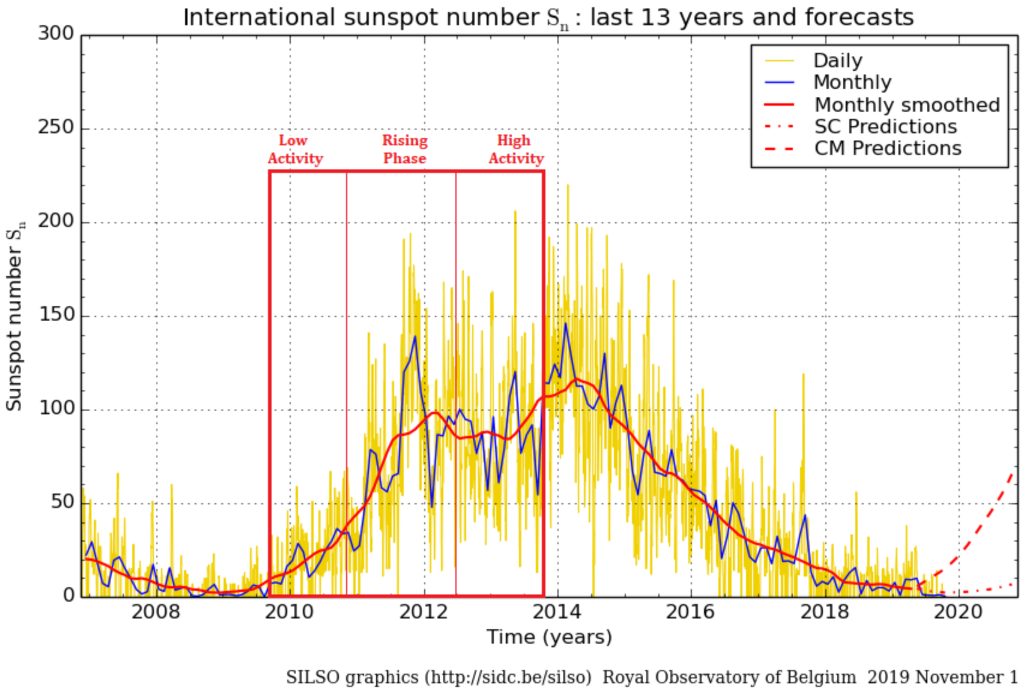

Figure 2. GOCE dataset in context with Solar Cycle 24. The inset shows the data span, further divided into low activity (from Mission start), medium activity (rising phase of cycle 24, from 24/09/2010) and high activity (cycle 24 stationary high-activity phase, from 04/07/2012), which mostly coincides with the altitude lowering phase of the Mission.

in the ionosphere. Remembering that Ap's sample period is 3 hr, thermospheric response to geomagnetic forcing may indeed be between six and twelve hours. Fig. 4 also shows (see e.g. top left panel) how thermospheric response is not only delayed, but relaxes to the quiet state with a finite characteristic time of the order of one day. Thus, a second event happening during relaxation (see e.g. bottom left panel), will add up to the first one, not yet relaxed, resulting in an enhanced value of the thermospheric density (see e.g. panel b). This memory effect is not included in our model which only considers a mean time lag between storms and thermospheric density enhancement. A dynamical model may be constructed, also accounting for relaxation, see e.g. (Dudok de Wit and Bruinsma, 2011), which may better fit multiple impulsive events, more characteristic of high solar activity phases, close to solar Maximum.

Fig.5 shows the evolution of Full-mission Thermospheric density, and that of solar indices Ap, F10.7 and MgII. It is apparent how geomagnetic index Ap does not capture the overall trend due to rising solar cycle, describing only impulsive events. MgII and F10.7, better follow the long-term trend of thermospheric density. Both F10.7 and MgII over-represent modulations due to solar rotation (see e.g. the main modulation during days 800 to 1000) than thermospheric density does. Correlation, though, is apparent. Scatter plot of full-mission density data against the solar indices, see Fig.6, confirms how F10.7 and MgII better correlate with average density values, decorrelating at high density values. As expected, very poor average correlation is shown

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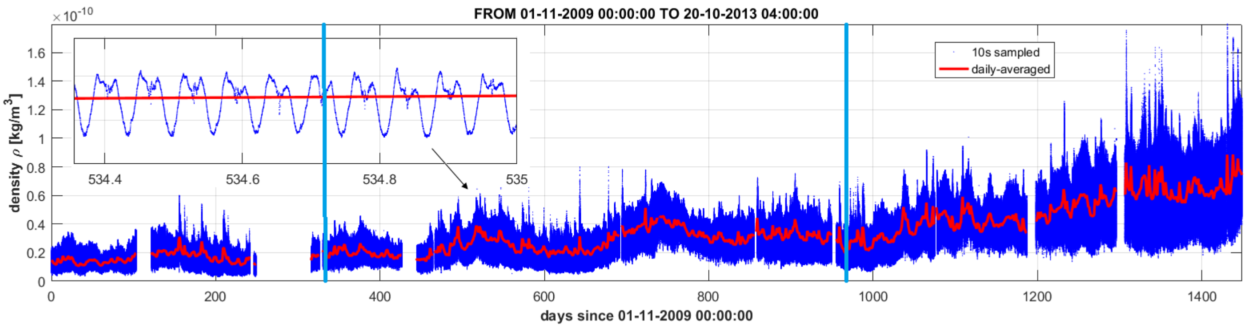

Figure 3. Thermospheric Density from GOCE data. Density profile, provided at 10s sampling rate (blue line), is averaged over one day (red line). In the inset, 10 orbits are plotted, showing the high-frequency fluctuations of density due to satellite orbit, lasting around 90 minutes. Day 0 is start of Operations (01/11/2009). Blue vertical lines at day 327 (24/09/2010) and 976 (04/07/2012) indicate the three sub-dataset of low, rising and high solar activity, see also Figure2. Low-orbit campaign starts at day 1004 (01/08/2012). The RSS error in density (not shown) is also provided in the dataset, setting at a level two orders of magnitudes lower than density.

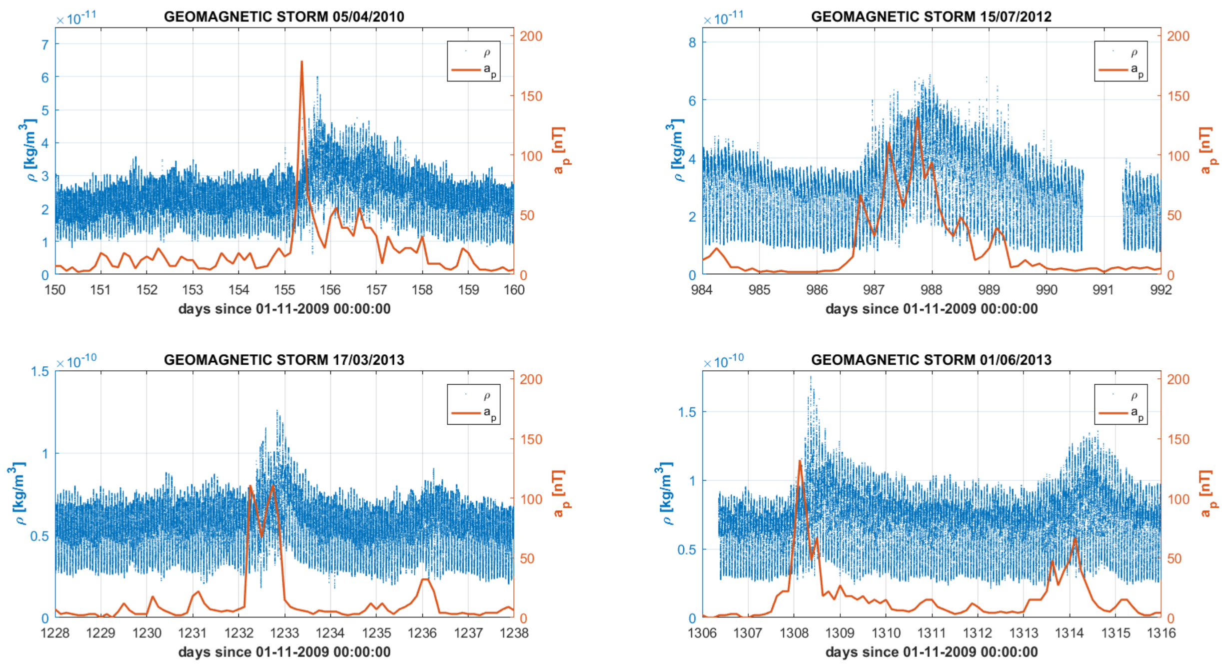

Figure 4. Thermospheric density ρ and a_p index during four geomagnetic storms occurred in the course of the GOCE mission. From Top-Left to Bottom-Right: a) 05/04/2010 [day 155]; b) 14/07/2012 [day 986]; c) 13/03/2013 [day 1232]; e) 01 and 07/06/2013 [days 1308 and 1314]

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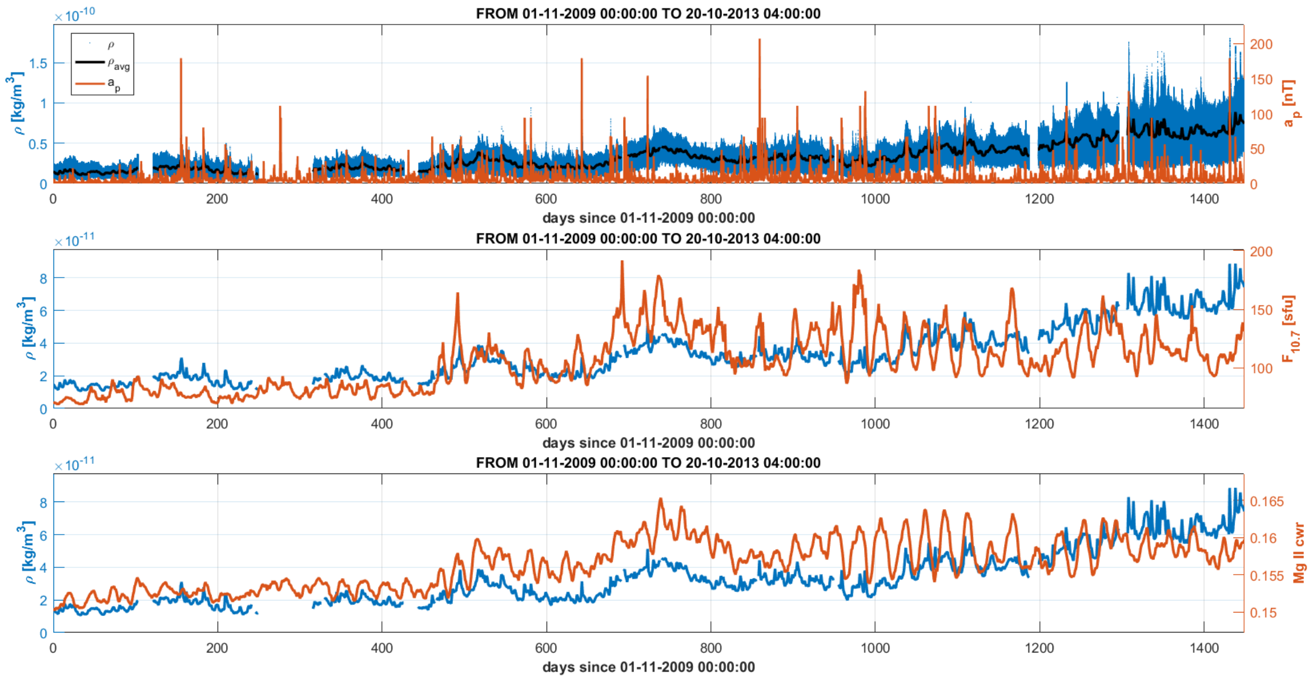

Figure 5. Comparison of Full-mission Thermospheric density (blue line and black line), and solar indices Ap , F10.7 and MgII.

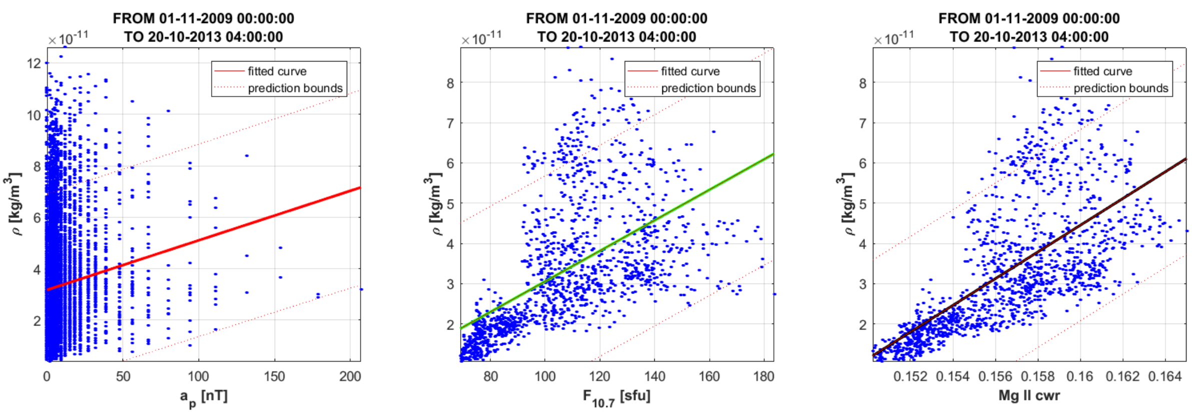

Figure 6. Scatter plot of full-mission thermospheric density vs solar fluxes and geomagnetic index. Straight lines represent the best-fit linear interpolation. Ap samples are shifted by 9 hours. Solar proxies are daily-averaged.

by ρ and Ap , due to the intermittent nature of the geomagnetic input. Correlation between ρ and solar fluxes is instead clear, being higher in times of low solar activity, that's for low values of F10.7 and Mg II. In times of high solar activity (high values of F10.7 and Mg II), correlation with solar fluxes gets worse. MgII tends to be better correlated than F10.7 at average values

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of thermospheric density, confirming the role of UV flus in coupling with the thermosphere. A Correlation coefficient

$$R_{xy} = \frac{\sigma_{xy}}{\sigma_x \sigma_y} \tag{1}$$

may be calculated between the variables $\rho; F10.7$ and $\rho; MgII$, resulting in a value of $R_{\rho,F10.7} = 0.57$ and $R_{\rho,MgII} = 0.67$, respectively, indicating a better overall correlation between thermospheric density and MgII index, with respect to F10.7 EMD analysis below will further clarify the interplay of the various indices to reproduce the density fluctuations.

4 Data analysis and density synthesis from proxies

Time series from the solar proxies have been analyzed into modes, using Empirical Mode Decomposition (EMD). GOCE thermospheric signal has then been reconstructed from an optimal combination of a small set of modes from the solar indices. EMD decomposes a signal into fundamental components called Intrinsic Mode Functions (IMF), and a residual trend. Compared to other methods of spectral decomposition, like Fourier Transform or Wavelet Decomposition, EMD is a efficient in analysing time series which are non-linear and non-stationary. IMF's are all global functions. Each IMF represents an elementary mode which may have a time-variable amplitude and frequency, adapting to local oscillatory features. Lowest modes are associated with the highest variability. The highest mode is the global trend. IMFs are given in the time-domain and are defined in the full time domain as the original dataset. The algorithm defining the IMF consists in a series of steps (called sifting) whereby all local extrema (minima and maxima) of a signal x(t) are identified; local minima are then interpolated by cubic spline to get a lower envelope $e_{min}(t)$. A similar procedure on maxima defines an upper envelope $e_{max}(t)$. A mean envelope $m(t) = [e_{min}(t) + e_{max}(t)]/2$ is then calculated, returning the low-frequency part of the original signal x(t). This process is iterated, starting from a new signal obtained by removing the mean envelope m(t) from the original signal $h(t) = x(t) - m(t)$. In this way, a set of IMF's containing the highest frequency features is obtained first. Iteration is than carried on, defining more IMP's, until the residual between signal and the IMF, becomes a monotonic function from which no furhter IMF can be extracted.

5 Results

Figures 8-10 show the EMD decomposition for solar proxies' time series. Lowest order IMF's are associated with the most rapidly varying components of the signal while the residual captures the overall trend. The number of IMF's is not fixed a-priori and depends on the convergence criterion chosen for stopping the EMD algorithm.

Thermospheric density signal is then reconstructed from a linear superposition of the set of IMF's from the solar proxies:

$$\bar{\rho} = N[A^{A_p} \cdot \sum_i c_i^{Ap} IMF_i^{A_p} + A^{F_10.7} \cdot \sum_i c_i^{F10.7} IMF_i^{F_10.7} + A^{MgII} \cdot \sum_i c_i^{MgII} IMF_i^{MgII}] \tag{2}$$

where the coefficients c_i may be zero or one, thereby selecting only a subset of the IMF components function resulting from the signal analysis. We have determined the optimal combination of IMF's, capable of reproducing the signal, based on the

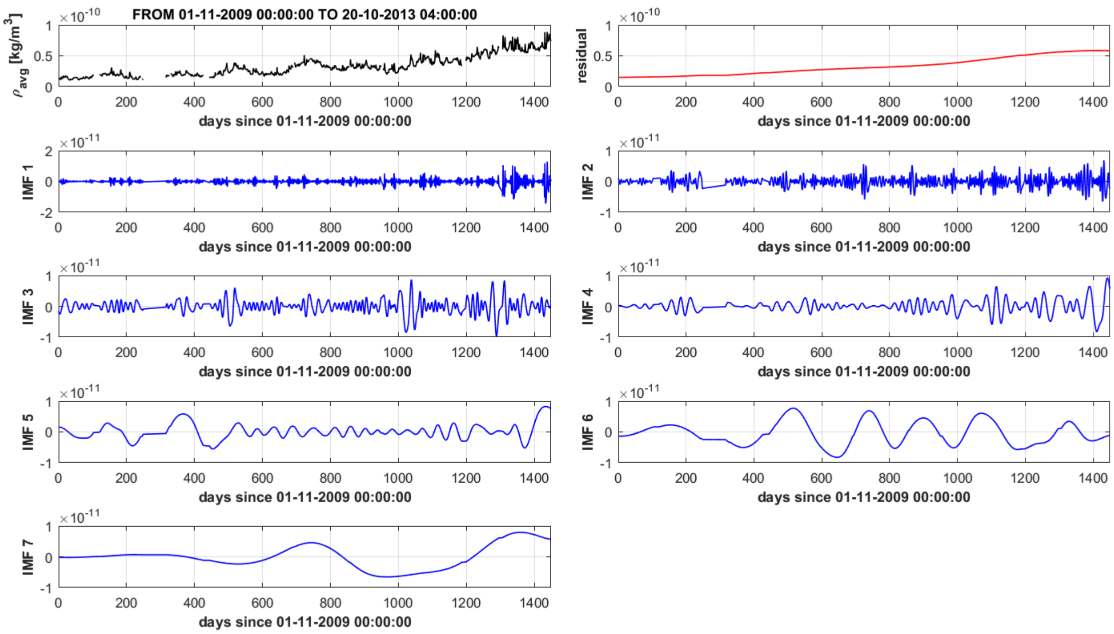

Figure 7. EMD decomposition for the thermospheric density signal from GOCE data, 2009-2013

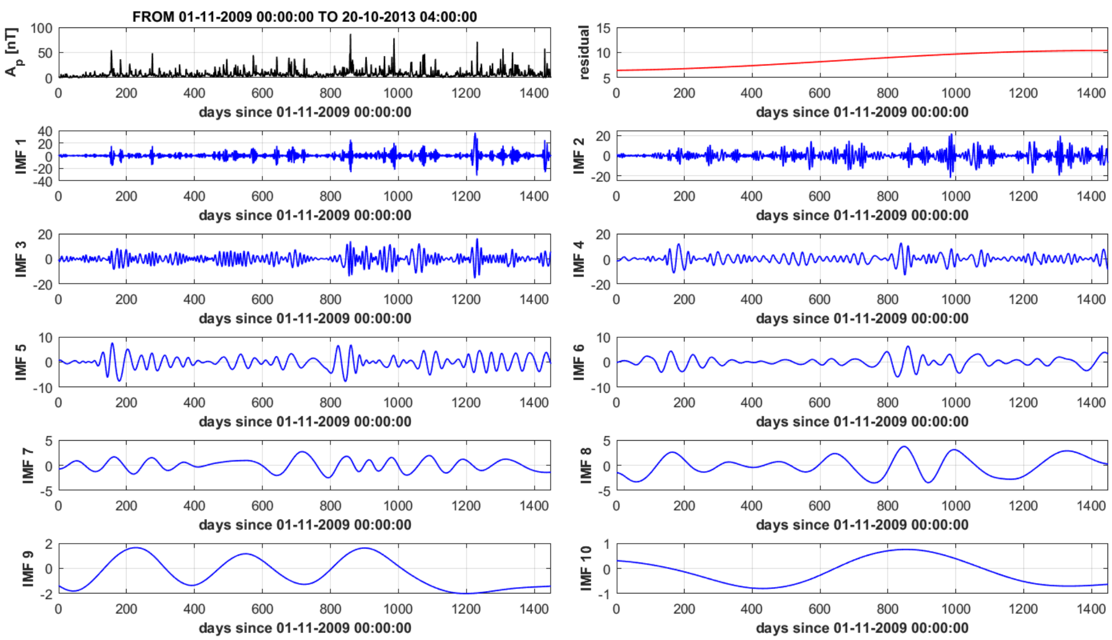

Figure 8. EMD decomposition for the geomagnetic index Ap

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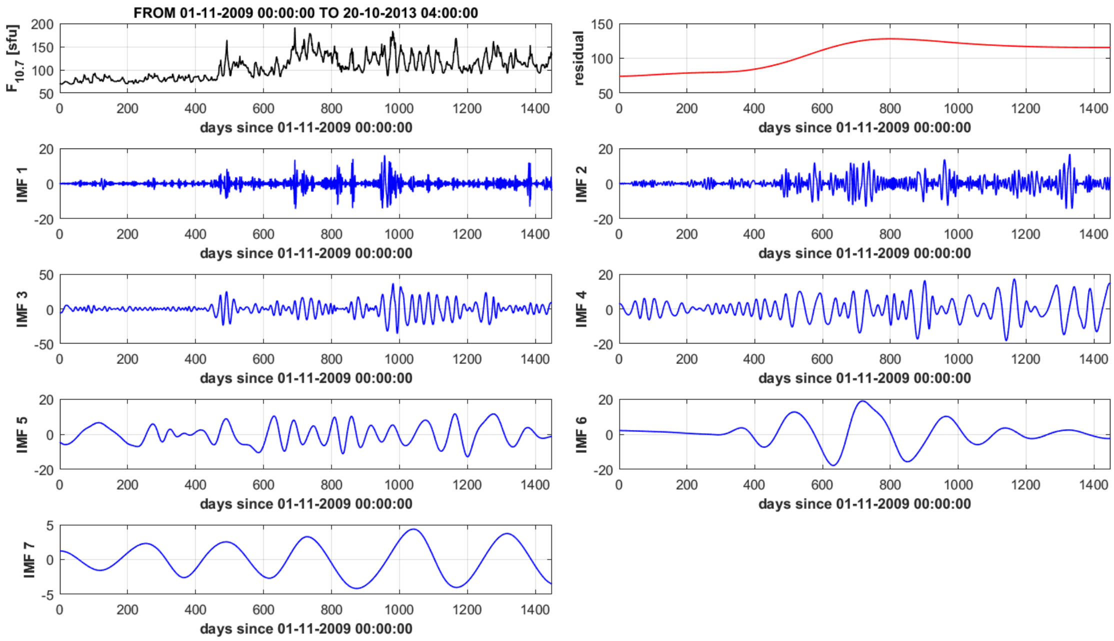

Figure 9. EMD decomposition for the F10.7 solar radio flux

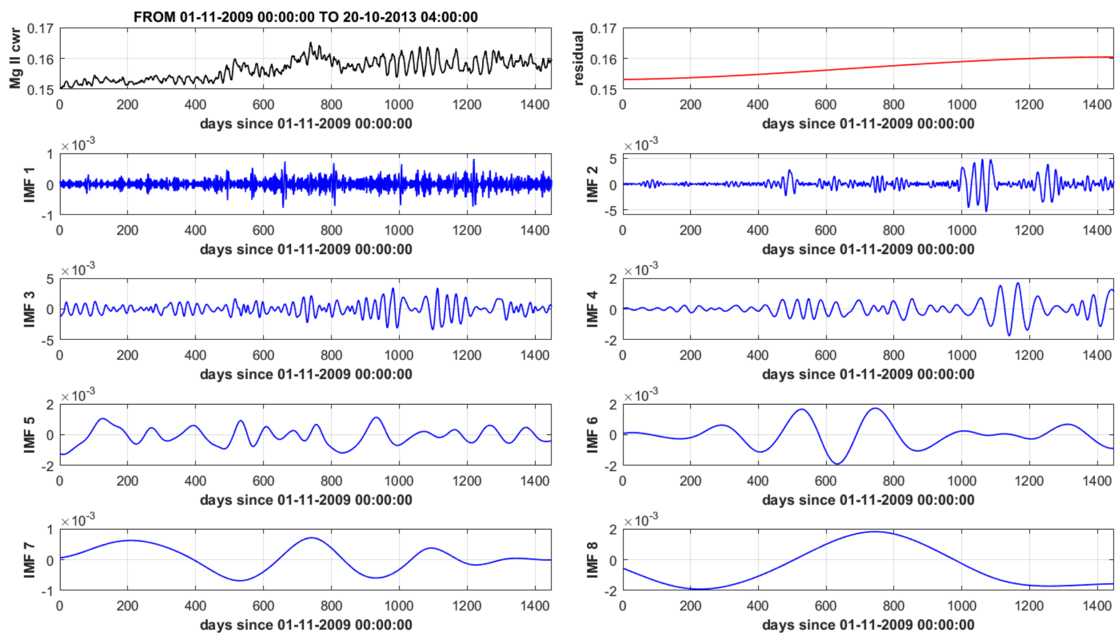

Figure 10. EMD decomposition for the MgII solar UV flux proxy

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Table 1. Components of optimal synthesized signal, for the case of full mission, low, rising and high solar activity during Cycle 24. RMS error σ_{RMS} (normalized to the mean value) and component amplitudes, A.

Dataset	$\sigma_{RMS}[\%]$	Index	1	2	3	4	5	6	7	8	9	10	Residual	A
		A_p	x	x	x	x	x	x		x	x		x	1
Whole Mission	11	$MgII$	x			x		x	x				x	6.7
		A_p	x	x	x	x	x	x	x	x	x	x	x	1
Low Solar Activity	2.6	$F10.7$		x				x					x	11
		$MgII$					x	x		x			x	12
		A_p	x	x	x	x	x	x	x				x	1
Rising Solar Activity	7.4	$F10.7$	x	x									x	0.35
		$MgII$	x			x		x	x				x	5.1
		A_p	x	x	x	x	x	x	x	x		x		1
Max Solar Activity	14	$MgII$							x				x	7

minimization of the RMS error:

$$\sigma_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\rho-\bar{\rho})^2}$$

Fig.11 shows the best synthesised signal from a combination of the Full-Mission IMF modes from Ap , MgII and F10.7 Fig. 12 shows instead the best synthesised signals from the different sets of IMF's determined for the three separate subsets, during low solar activity, rising phase and high solar activity. Table 1 shows, for all cases, the individual components of the optimal synthesized signal. Table 2 compares the optimal solution with two cases where either F10.7 or MgII is selected as solar UV proxy. A number of consideration may be drawn from the analysis. Firstly, all syntheses require the A_p signal to be taken into account, although during low solar activity its relative contribution to the overall signal is small. This confirms the relevance of the state of the interplanetary medium on the short-term dynamics of the thermosphere. The A_p signal is intermittent and all IMF components are always needed to reconstruct the signal. This is not the case for the solar flux proxies, F10.7 and MgII, whose long-wavelength components appear most in the decomposition. Solar input is therefore basically captured by the short-time-scale variations given by A_p, and the longer timescales trends capturedd by the solar flux proxies. Secondly, $MgII$ performs better then $F10.7$. In fact, the sole combination of A_p and $MgII$ is performing very similarly to the full three-indices combination. The only exception being low solar activity periods, where inclusion of $F10.7$, somewhat improves signal reconstruction.

6 Conclusions

We have performed an analysis of three of the most commonly used solar flux and geomagnetic proxies, F10.7, MgII and A_p in relation to the time evolution of thermospheric density measured in-situ grom 260 to 230 km altitude, using the GOCE

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Table 2. Comparison of normalised RMS errors (in %) for different optimal combinations of proxies

Solar activity level	$A_p + MgII + F10.7$	$A_p + MgII$	$A_p + F10.7$
Whole Mission	11	11	14
Low	2.6	3.1	3.3
Rising	7.4	7.4	8.3
Max	14	14	16

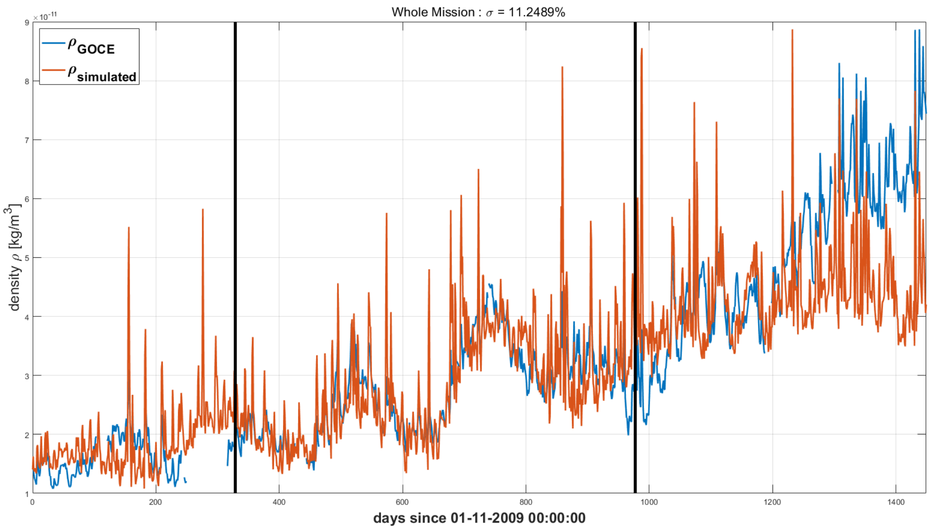

Figure 11. Thermospheric density synthesized (red line) from optimal compbination of A_p , MgII and F10.7. Whole Mission. Blue line shows thermospheric density data. The rising trend in density the last third of the Mission time is due to orbit lowering and is therefore not showing in the reconstructed signal.

thermospheric density dataset, which spans most of the rising phase of Solar cycle 24, from minimum to maximum, covering the full dynamical spectrum of the solar input ot the thermosphere. Thermospheric density signal, for the whole Mission and form three sub-intervals of low, rising and high solar activity, has been analysed through Empirical Mode Decomposition. Once the basis functions have been determined, they have been optimally recombined to reconstruct the density signal. Analysis shows how that during low solar activity, the low-frequency components from the solar flux proxies contribute most to the signal, while during both the rising phase and the high solar activity period, the geomagnetic proxy A_p is needed to capture the impulsive geomagnetic events connected to the evolution of the interplanetary medium. During low and medium solar activity, thermospheric signal can be reconstructed with an RMS errors of about 2.6% and 7.4%, respectively. Semi-empirical atmospheric models (NRLMSISE-00 and Jacchia-family models above all) are usually credited to fall in the 10% error range. During high solar activity, error increases to over 10%, although this figure is affected by the trand due to orbit lowering and

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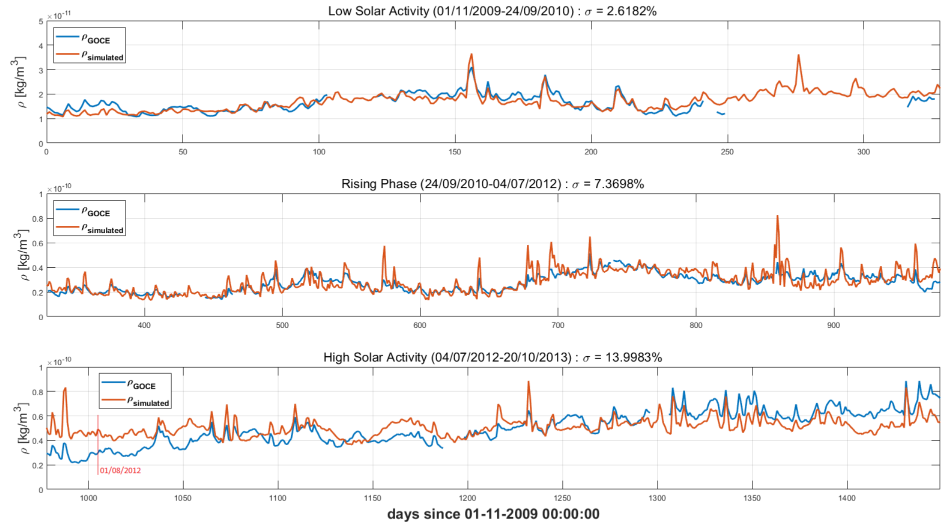

Figure 12. Optimal synthesized Thermospheric density from A_p , MgII and F10.7. Three different EMD sets for the full Mission extent, each covering one of the three selected dynamical activity regimes for Solar Cycle XXIV, low, rising and high. The trend in density apparent in panel three, representing the high solar activity phase, is due to orbit lowering and is therefore not showing in the reconstructed signal.

is therefore over-estimated. MgII, finally, proves to be a better proxy than $F_10.7$ in capturing the long-term trends of the solar input during the solar cycle and is therefore to be preferred when only the long-term trend is of interest. Combining Ap (shifted by 6 hours to take into account thermosphere's dynamical response to the solar input), and the slowest varying EMD modes from the MgII, returns a good representation of the thermospheric density signal at low thermospheric altitudes.

Data availability. All datasets have been referenced into the main text

Code and data availability. Processing software is based on standard Matlab routines

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190 *Author contributions.* AB:Conceptualization, Writing – Original draft; CC: Data analysis, Software; FB: Methodology, Supervision, Writing – review and editing;

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