Solar activity and Space Weather effects on Earth's upper atmosphere
Analysis of thermosphere density from ESA GOCE mission

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Summary

• What is Space Weather?
• Space Weather scientific background
• Solar activity and thermosphere: an example of operational space weather service
• Analysis of thermosphere density from ESA GOCE mission
• Outcomes

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What is Space Weather?

Although “space weather” is a fairly recent term, there is a rich history of similar terms being used beginning in the middle to late 1800s. “Solar meteorology,” “magnetic weather,” and “cosmic meteorology” all appeared during that time frame.


<table>
<thead>
<tr>
<th>Year</th>
<th>Term</th>
<th>Usage</th>
<th>Originator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1847</td>
<td>Solar meteorology</td>
<td>Sunspots and the conditions of the Sun's atmosphere</td>
<td>John Herschel, Herschel (1847)</td>
</tr>
<tr>
<td>1850</td>
<td>Magnetic weather</td>
<td>Disturbances in the Earth's magnetic field</td>
<td>John Phillips, Phillips (1851)</td>
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<tr>
<td>1872</td>
<td>Cosmic meteorology</td>
<td>Solar-terrestrial interaction</td>
<td>Giovanni Donati, Donati (1872)</td>
</tr>
<tr>
<td>1953</td>
<td>Outer space weather</td>
<td>Fictional aliens, studying the Earth, might ask “would the climate be suitable for us since we are used to outer space weather?”</td>
<td>Fred Hague, Hague (1953)</td>
</tr>
<tr>
<td>1855</td>
<td>Electrical weather</td>
<td>Dynamics of the ionosphere and resulting magnetic disturbances</td>
<td>Ann Ewing, Ewing (1955)</td>
</tr>
<tr>
<td>1956</td>
<td>Interstellar meteorology</td>
<td>Motions and transformations of interstellar clouds</td>
<td>Lyman Spitzer, Spitzer (1956)</td>
</tr>
<tr>
<td>1957</td>
<td>Space “weather”</td>
<td>“The weather of interstellar space, the motions and composition of the vast clouds of matter in the void between stars”</td>
<td>Science News Letter, Society for Science and the Public (1957)</td>
</tr>
<tr>
<td>1959</td>
<td>Space weather</td>
<td>Refers to measurements of the radiation belts by Explorer VI</td>
<td>Science News Letter, Society for Science and the Public (1959)</td>
</tr>
<tr>
<td>1964</td>
<td>Space weather</td>
<td>Scientists are “trying to set up a space weather bureau which could give astronauts advance notice of solar storms.”</td>
<td>Walter Wingo (editor, Science News Letter), Wingo (1964)</td>
</tr>
<tr>
<td>1968</td>
<td>Space weather (first appearance in peer-reviewed literature)</td>
<td>Space weather forecasting as a part of the new Environmental Science Services Administration</td>
<td>Walter Hahn, Hahn (1968)</td>
</tr>
</tbody>
</table>

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Plate II (“Tav. II”) showing the instruments installed in the Collegio Romano Magnetic Observatory (Secchi, 1861)

Father Angelo Secchi (International Conference - THE LEGACY OF ANGELO SECCHI 200 YEARS AFTER HIS BIRTH, Rome, September 3-5, 2018, Biblioteca Casanatense) realized a permanent magnetic observatory in 1858 in Rome in connection with magnetic observatories in Stonyhurst (UK), Manila, Ebro (SP) and Zi-ka-wei (China).
What is Space Weather?

The term space weather generally refers to **conditions on the sun**, in the **solar wind**, and within Earth's magnetosphere, ionosphere and thermosphere that can influence the **performance** and **reliability** of space-borne and ground-based technological systems and can endanger **human** life or **health**.


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Space Weather Scientific Background

1. Emergence of magnetic flux from the solar interior in active regions

2. Modification of the coronal magnetic field in response to the emergence of new magnetic field and photospheric advection

3. Eruptive events in the Sun MHD instabilities (flares, CME, SPE, ..)

4. Transport in the interplanetary medium of CME and Solar Wind

5. Magnetic interaction of CME with the Earth’s magnetosphere

6. Impact of Solar Activity on the Ionosphere/Thermosphere

7. GCRs and solar particles in the near-Earth environment

Convective Global Dynamo

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Berrilli et al., *SWERTO: a Regional Space Weather Service*, in Proceedings IAUS No. 335, 2018 in press

Del Moro et al., Forecasting the CME propagation with the P-DBM model, Proceedings IAGA Italia Symposium, 2018 in press

Napoletano et al., A probabilistic approach to the dragbased model, Journal of Space Weather and Space Climate, 8, 25 A11, 2018
Density modeling of the thermosphere for the de-orbiting timeline of satellites and debris (ESA/SSA) is key issue of Space Weather.

Two main topics in the description of the thermosphere density are:

1. the use of appropriate solar inputs (especially solar EUV)
2. the empirical modeling of thermosphere response to solar and to geomagnetic forcings.

This specification is crucial for the tracking of low Earth orbiting satellites.

(e.g., Dudok de Wit and Bruinsma, Geophys. Res. Lett., 38, L19102, 2011)

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Various EUV solar flux proxies can be considered:

1) the F10.7 index from Penticton Observatory, Canada;
2) the MgII index (LASP composite/Bremen Mg II composite);
3) the integrated flux between 26–34 nm from the SEM radiometer onboard SoHO;
4) the s10.7 index, which has been built for orbitography purposes;
5) Lya, the intensity of the bright Lyman-a line (LASP composite);
6) XUV, the baseline of the daily soft X-ray flux in the 0.1–0.8 nm band (GOES).

Geomagnetic activity is represented by the planetary geomagnetic index Ap (the Ap-index is thus a geomagnetic activity index where days with high levels of geomagnetic activity have a higher daily Ap-value).


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From UV to X-Rays, variability increases a lot with decreasing wavelength; however, the bulk of electromagnetic energy at these wavelengths is absorbed very high in the Earth's atmosphere (stratosphere and higher). The UV (120-400nm) accounts for 1% of the TSI, but 14% of its variability.

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Solar UV irradiance at 1 AU (astronomical unit). The red line shows the data from ASTM E-490 while the black line shows the spectral data of Gueymard. These data are representative for average solar activity conditions. L’indice Mg II index is a good describer of solar facular TSI and UV components (Dudok de Wit et al., 2009).

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Launched on 17 March 2009, ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission was the first Earth Explorer mission in orbit.

GOCE mission delivered a wealth of data to bring about a whole new level of understanding of one of Earth's most fundamental forces of nature – the gravity field.

This high-tech gravity satellite embodied many firsts in its design and use of new technology in space to map Earth's gravity field in unprecedented detail.

On-board ultra-sensitive accelerometers used to create dataset of 10s sampled thermospheric density at 260 km altitude available at ESA GOCE Archive (01/11/2009 - 20/10/2013)

https://www.esa.int/Our_Activities/Observing_the_Earth/GOCE/Introducing_GOCE

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a) Atmospheric density vs time (both 10 s sampled and daily averaged) during GOCE mission; b) Geomagnetic index $ap$ and daily-averaged geomagnetic index $Ap$ vs time during GOCE mission; c) and d) F10.7 and Mg II cwr vs time during GOCE mission (signal spikes are removed by interpolation). Mg II index seems “cleaner” and less noisy than F10.7.

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1. Impulsive variations of $ap$ and long-term evolution of F10.7 and Mg II indices are well correlated with thermosphere density variability.

2. The long-term thermosphere density variations are poorly-correlated with geomagnetic index and well-correlated with solar flux indices (especially with Mg II index).

3. The thermosphere response to impulsive changes of $ap$ index is within 6-9 hours.
In order to investigate the different contributions to variations in $\rho$, the empirical mode decomposition (EMD) of thermosphere density and solar and geomagnetic indices (quasi-periodic and non-stationary) during GOCE mission has been performed.

Generally speaking, the sifting process (to separating out components of a signal one at a time) produces a set of IMFs that represent the original data vector broken down into frequency components from highest to lowest frequency.

If all of the IMFs for a given signal are added together, the resulting “summation” signal is a near perfect match for the original signal (i.e., with little or no leftover), yielding a high level of confidence in the EMD results.

(from Hassan & Peirce, 2008)
EMD of daily-averaged thermosphere density $\rho$

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10 IMFs for $\text{Ap}$ have been identified (+ residual trend)

- the first IMFs are relevant for the impulsive $\text{Ap}$ index;
- the residual shows a monotonic profile (geomagnetic activity ↑ when solar cycle ↑);
- the amplitude of the oscillations ↑ during magnetic storms.

8 IMFs for $\text{MgII}$ have been identified (+ residual trend)

- IMF3 (and 2) are associated to 27-day solar rotation;
- the residual trend shows that $\text{MgII}$ index ↑ when solar cycle ↑ because chromosphere/photosphere ratio ↑;
- IMF2 and IMF4 are particularly important during the of high solar activity period.

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The approach used to reconstruct the GOCE mission thermosphere density signal is schematized in the following steps:

1. **Input data loading**: the daily-averaged thermosphere density \( \bar{\rho} \), the daily-averaged geomagnetic index \( A_p \) and the solar flux indices \( F_{10.7} \) and \( Mg \ II \) are considered.

2. **Solar and geomagnetic indices time shifting**: A 9h time delay is assumed for \( A_p \), no time delay for solar indices. A cubic spline interpolation is used for \( A_p \) (1d sampling).

3. **EMD sifting process**: applied to GOCE density and activity indices to extract the corresponding IMFs \( IMF_{i Ap}, IMF_{i F10.7}, IMF_{i MgII} \) and trends \( res^{Ap}, res^{F10.7}, res^{MgII} \).

4. **Thermosphere Density Model(s)**: Iterative data analysis for \( A_p \) and solar indices a weighting factor and a sub-set of IMFs (including the residual trends) are selected (Monte Carlo approach and exhaustive analysis).

Density signals are reconstruction for the whole period and for different solar activity levels.

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Merit function

\[ \bar{\rho}_{\text{norm}} = \text{norm}(0,1) \left[ A^p \cdot \text{IMF}_{\text{norm}}^A + A^{F_{10.7}} \cdot \text{IMF}_{\text{norm}}^{F_{10.7}} + A^{Mg II} \cdot \text{IMF}_{\text{norm}}^{Mg II} \right] \]

\[ \sigma_{\text{RMS}} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} \left( \bar{\rho}_{\text{norm}}(n) - \bar{\rho}_{\text{norm}}^{\text{sim}}(n) \right)^2} \]

Best-solutions for the analyzed periods.

✓ indicates that the corresponding IMF, labeled from 1 to 10, or the residual trend res is used.

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Normalized daily-averaged real and simulated density signal vs time

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Conclusions

• **Low and medium solar activity:** the best reconstruction combine IMFs from Ap, $F_{10.7}$ and $Mg\, II$ solar flux indices. For medium activity the use of only $Mg\, II$ does not lead to significant worsening and can be preferred for simplicity. Density can be reproduced with a RMS error of 2.6% and 7.4% for low and medium activity, respectively.

• **High solar activity:** the best reconstruction combines IMFs from Ap and $Mg\, II$ indices. The RMS error is below 14%. Peaks are well-reproduced.

• **Whole mission:** the best reconstruction combines IMFs from Ap and $Mg\, II$ indices. The reconstruction presents period of over/under-estimation. The RMS error is about 11%.

• Secular trends in the thermosphere density can be derived using historical records of MgII, $F_{10.7}$ and Ap.

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