

RESEARCH ARTICLE

10.1029/2018JA025464

Key Points:

- Reanalysis of ionospheric electron content by Emmert et al. (2017) found it lower during the 2008–2009 solar minimum than the 1996 minimum
- Model simulations showed that both ionospheric electron content and thermospheric neutral density were lower during 2008–2009 than in 1996
- Thermosphere and ionosphere reductions during the 2008–2009 solar minimum were consistent in observations and in model simulations

Correspondence to:

S. C. Solomon,
stans@ucar.edu

Citation:

Solomon, S. C., Qian, L., & Mannucci, A. J. (2018). Ionospheric electron content during solar cycle 23. *Journal of Geophysical Research: Space Physics*, 123, 5223–5231. <https://doi.org/10.1029/2018JA025464>

Received 12 MAR 2018

Accepted 17 MAY 2018

Accepted article online 23 MAY 2018

Published online 22 JUN 2018

Ionospheric Electron Content During Solar Cycle 23

Stanley C. Solomon¹ , Liying Qian¹ , and Anthony J. Mannucci² 

¹High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO, USA, ²Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

Abstract The solar minimum period between solar cycles 23 and 24 has generated extensive study, in part because the changes in the upper atmosphere and ionosphere were so dramatic. Thermospheric density during 2008–2009, at the benchmark 400-km altitude, was shown to be approximately 30% lower than the previous solar minimum during 1996, in observations and in model simulations. Ionospheric densities were also estimated to be lower, by 10% to 20%. However, earlier analyses using data from the global network of Global Navigation Satellite System receivers did not find any significant reduction in global mean total electron content. Recent work reexamining those data using a limited set of receivers, but with consistent processing, identified a 19% reduction (Emmert et al., 2017, <https://doi.org/10.1002/2016JA023680>). In this study, we compare model simulations of the thermosphere-ionosphere system during the 2008–2009 solar minimum to its predecessor and estimate a 16% reduction in global mean total electron content. This is consistent with the neutral thermosphere density change seen in model simulations and in satellite drag observations. In the model simulations, the primary driver is a 10% reduction in solar extreme ultraviolet irradiance, with a smaller contribution from lower geomagnetic activity, and a very small decrement due to increase in atmospheric carbon dioxide.

Plain Language Summary The Sun goes through 11-year activity cycles, best known with regard to the number of sunspots. At solar minimum, when sunspots mostly vanish, the extreme ultraviolet region of the solar spectrum also diminishes. This causes lower temperature and density in the ionosphere and upper atmosphere above 100 km, where the extreme ultraviolet radiation is absorbed. Past solar minimum periods have seemed basically similar with regard to extreme ultraviolet radiation, and other manifestations of solar activity. However, the solar minimum during 2008–2009 was longer and had fewer sunspots than its predecessor during 1996, or than any minimum period in the past century. The thermosphere was also lower in density, and the ionosphere also appeared to be lower in density, but there were some contradictory measurements. Recent reanalysis of ionospheric measurements found better agreement with the thermospheric measurements. Modeling studies attempting to explain the changes in the ionosphere and thermosphere have suggested that they were caused by a decrease of about 10% in solar extreme ultraviolet radiation. Here we show that the model results and the ionospheric measurements are now in good agreement. This demonstrates that solar minima are not all the same and may have implications for understanding the Sun during extended periods of very low activity.

1. Introduction

In the gloaming of solar cycle 24, the weakest excuse for a solar cycle in a century, we are finally able to recapitulate its predecessor. Solar cycle 23 seemed ordinary enough, but its long descent into shade included peculiar persistence of periodic, low-grade activity, finally fading into the longest, deepest, and quietest minimum seen during the Space Age. That solar minimum period, during 2008–2009, provoked considerable comment and speculation in the solar physics community, but its effects were first reported in ionospheric observations by Heelis et al. (2009) and in thermospheric neutral density measurements by Emmert et al. (2010). Although the deep solar minimum seemed to be the cause of the low thermosphere and ionosphere densities, significant controversy ensued regarding the quantification of cause and effect, or even if solar variability were the cause at all.

Our previous modeling and data analysis work (Solomon et al., 2010, 2011, 2013) attempted to quantify the thermosphere/ionosphere response, including the known sources of difference between the 1996 and the 2008–2009 solar minimum epochs: solar extreme ultraviolet (EUV) irradiance, geomagnetic activity, and radiative cooling by anthropogenic trace gases. We found that a ~10% reduction in solar EUV, which is

supported by some solar indices and measurements, was the major driver, with a smaller contribution from lower levels of geomagnetic activity, and a very small contribution from increase in carbon dioxide (CO₂) cooling (cf. Solomon et al., 2015, 2018). The results were similar to a thermospheric neutral density reduction of -36% at 400-km altitude, estimated from changes in satellite orbits due to atmospheric drag (Emmert et al., 2010, 2014). They also compared favorably with a variety of ionospheric observations by radars, ionosondes, and satellites, documented by a dozen publications referenced in Solomon et al. (2013). For instance, Chen et al. (2011) showed that the relationship between the solar EUV flux and the $F_{10.7}$ index was different during the 2008–2009 solar minimum than its predecessor, Liu, Chen, et al. (2011) showed that f_0F_2 from most ionosondes and global total electron content (TEC) went to their lowest levels during cycle 23/24 minimum, and Liu et al. (2012) investigated anomalously low ionospheric levels at the Jicamarca station. Since then, there have been several more observational studies also showing ionospheric reduction by various amounts in various locations. Chen et al. (2014) investigated the effect of lower geomagnetic activity on ionospheric electron content, Chaitanya et al. (2016) analyzed $\mathbf{E} \times \mathbf{B}$ drift impacts on the F_2 and F_3 layers, Ji et al. (2016) compared TEC from the JASON-1 satellite to the International Reference Ionosphere model, Perna and Pezzopane (2016) found good correspondence between the Mg II solar proxy and ionosonde data (cf. Perna et al., 2017), and Santos et al. (2017) observed anomalous zonal plasma drift over Jicamarca in 2008.

There was a troubling exception to this confluence of cause and effect, which was the analysis by Lean, Emmert, et al. (2011), Lean, Meier, et al. (2011) of global mean TEC (gTEC) derived from the network of dual-frequency Global Navigation Satellite System (GNSS) receivers compiled in the Center for Orbit Determination (CODE) database. This work found, rather than a decrease, a small increase of 0.6 ± 0.3 TEC units (10^{16} electrons m^{-2} , or 10^{12} electrons cm^{-2}). Also, Jee et al. (2014) found negligible global average change in TEC derived from TOPEX/JASON data, although an apparent daytime decrease and nighttime increase. Even if the CODE result were interpreted as essentially no change, it would be difficult to reconcile with the observed thermospheric density reduction (cf. Emmert et al., 2014) or with the many other ionospheric analyses. Several authors have since commented on the methodology: Liu, Le, et al. (2011) pointed out that prior to 1998, the GNSS receivers were sparse and that data consistency needed further validation; Lastovicka (2013) considered the positive TEC trend to be physically implausible, noting that it was not supported by foF_2 trends; Didkovsky and Wieman (2014) found that results for some sectorial harmonics in the CODE data base were quite different from the zero-degree harmonic on which the Lean et al. analysis relied.

Recent work by Emmert et al. (2017) revisited the TEC analysis. They used a subset of the GNSS stations compiled in the Jet Propulsion Laboratory (JPL) database, with temporally consistent processing, to investigate long-term changes in TEC with greater fidelity. They estimated that the change in gTEC between solar minima was $19.3\% \pm 1.0\%$. The reasons for the difference between that result and the Lean, Emmert, et al. (2011) and Lean, Meier, et al. (2011) analysis included changes in processing and interpretation methodology during 2000–2001, and the differences in station cohort. Lastovicka et al. (2017) agreed that the positive TEC trends by Lean et al. were caused by data problems in 1995–2001, and, with the revised analysis, “the trend in TEC is in reasonable agreement with observed trends in other ionospheric parameters as well as with trends expected based on model calculations of trends in ionospheric electron density.” The purpose of this paper is to substantiate this reasonable agreement by direct comparison between the revised TEC data and model simulations.

2. Ionospheric Data

The method for obtaining the column electron density or TEC between a high-altitude (~ 20 Mm) GNSS transmitter and a dual-frequency ground receiving station is well established (e.g., Hernández-Pajares et al., 1999; Lanyi & Roth, 1988; Sardón & Zarraoa, 1997), and the means of converting this to an estimate of the vertical TEC, and then obtaining an area-weighted gTEC using multiple stations, have been extensively documented (e.g., Hernández-Pajares et al., 2009; Mannucci et al., 1998). Similarly, Astafyeva et al. (2008) calculated global electron content, defined as the global integral of vertical TEC. However, using daily average gTEC to establish solar cycle or longer-term variability is complicated by the ever-expanding dual-frequency GNSS receiver network, now numbering thousands of stations, and by occasional changes in processing or analysis

methods. Emmert et al. (2017) found that using a limited set of 35 long-term, well-characterized stations in the JPL database, with consistent processing for all times, yielded a reliable result (with regard to temporal stability) for the period 1994–2014. The daily-mean gTEC values designated “JPL-35” are therefore employed in this study. Emmert et al. found a 19.3% decrease in gTEC from the solar minimum between cycles 22 and 23, in 1996, to the solar minimum between cycles 23 and 24, in 2008–2009.

3. Model Calculations

Model simulations employed the National Center for Atmospheric Research Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) v. 1.94 (Richmond et al., 1992; Roble et al., 1988). The TIE-GCM is a first-principles upper atmospheric general circulation model that solves the continuity, momentum, and energy equations for the thermosphere-ionosphere system. The model configuration used in this study is summarized in Solomon et al. (2013), and references therein. See Solomon et al. (2012) for the methodology concerning high-latitude inputs, and Solomon et al. (2011) for a discussion of model uncertainties. A seasonally varying eddy diffusion coefficient was applied at the lower boundary (Qian et al., 2009, 2013) which increases the semiannual and annual variation in atomic-to-molecular composition, and hence in electron density. For solar EUV irradiance, we used an ad hoc method for employing the 280-nm magnesium ion line core-to-wing ratio (MgII c/w) from Viereck et al. (2004, 2010) to scale solar input to the TIE-GCM. Daily average values of the solar 10.7 cm radio flux $F_{10.7}$ were compared to MgII c/w during 1978–2007, and a linear least squares fit of MgII c/w to $F_{10.7}$ performed, resulting in the virtual index $M_{10.7}$, that is, the MgII c/w scaled to $F_{10.7}$, in units of $10^{-22} \text{ W} \cdot \text{m}^{-2} \cdot \text{Hz}^{-1}$ (see Solomon et al., 2011, for further details). This was then applied to the standard solar EUV irradiance input methodology (Richards et al., 1994; Solomon & Qian, 2005). The annual mean EUV energy flux derived from $M_{10.7}$ was 10% lower in 2008 than in 1996, as compared to only 4% lower if the solar 10.7-cm radio flux ($F_{10.7}$) were used. These inputs generated model results that were in good agreement with thermospheric neutral density observations, with the 2008 annual average density 27% lower than the 1996 annual average, at 400 km, as compared to 30% lower in the Emmert et al. (2010, 2014) data set (on an annual average basis).

Obtaining an estimate of TEC from TIE-GCM output requires some extrapolations and assumptions, because the model extends to 500- to 800-km altitude (depending on solar activity) and does not include the hydrogen ions (H^+) or helium ions (He^+) that dominate the plasmasphere above $\sim 1,000$ km. The quantity that is sometimes called model TEC is actually the integrated column electron density through the model extent. Charge neutrality is assumed, with the main positive ion the atomic oxygen ion (O^+), and a small contribution from molecular ions in the lower ionosphere. To obtain an improved estimate of TEC using these modeled parameters, we extrapolated the topside electron density from the top of the model using a logarithmic slope and integrated the column above the model top by assuming that slope was constant. This obtains a good approximation of “ionospheric” plasma up to an altitude of $\sim 1,000$ km and results in an increase to the model TEC of $\sim 10\%$ (at low solar activity) to $\sim 15\%$ (at high solar activity). Then, in order to make a coarse estimate of the “plasmaspheric” contribution, we adopted the observational results of Shim et al. (2017) who employed measurements from the JASON satellite to estimate plasmaspheric TEC above $\sim 1,000$ km. They found a global average of ~ 4 TEC units with slight dependence on solar activity, about 10–20%, and very little dependence on geomagnetic activity (cf. Cherniak et al., 2012). Therefore, for this study that is focused on solar minimum, we simply added an assumed uniform 4 TEC units to our global average calculations, to estimate the TEC that ground-based GNSS receivers would observe.

The results of these calculations are shown in Figures 1 and 2. In each figure, we compare the model global mean maximum electron density at the peak of the ionospheric F region ($N_m F_2$), to our derived gTEC. The extrapolation described above was performed on 6-hr model output fields at each latitude-longitude grid point, then global means of $N_m F_2$ and TEC were obtained using cosine (latitude) weighting, and daily means computed from the global means. Results are displayed in Figure 1, with 81-day centered-mean smoothing, in order to remove solar-rotational and geomagnetic variation, but display the semiannual and annual variation. The same results are shown in Figure 2, with 365-day centered-mean smoothing, in order to focus on the solar cycle variation. The model gTEC tracks global mean $N_m F_2$ fairly well, but it is notable that the annual variation is slightly smaller in TEC, while the solar cycle variation is somewhat larger.

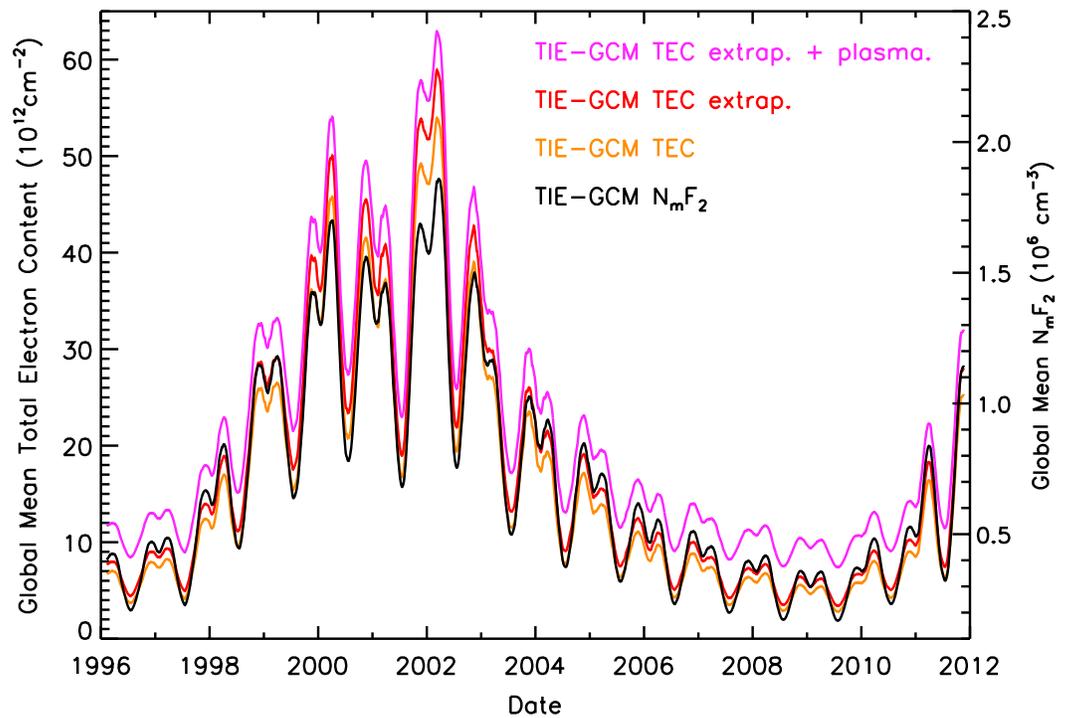


Figure 1. Global mean peak electron density (N_mF_2) and global mean total electron content (gTEC) derived from a 16-year run of the National Center for Atmospheric Research Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM), showing 81-day smoothed values of the daily means. Black: N_mF_2 . Orange: Column integrated gTEC within the model domain. Red: Column integrated gTEC plus logarithmically extrapolated column above the model upper boundary, assuming a constant topside scale height. Magenta: Integrated plus extrapolated gTEC plus an assumed global mean plasmaspheric constant value of 4 TEC units.

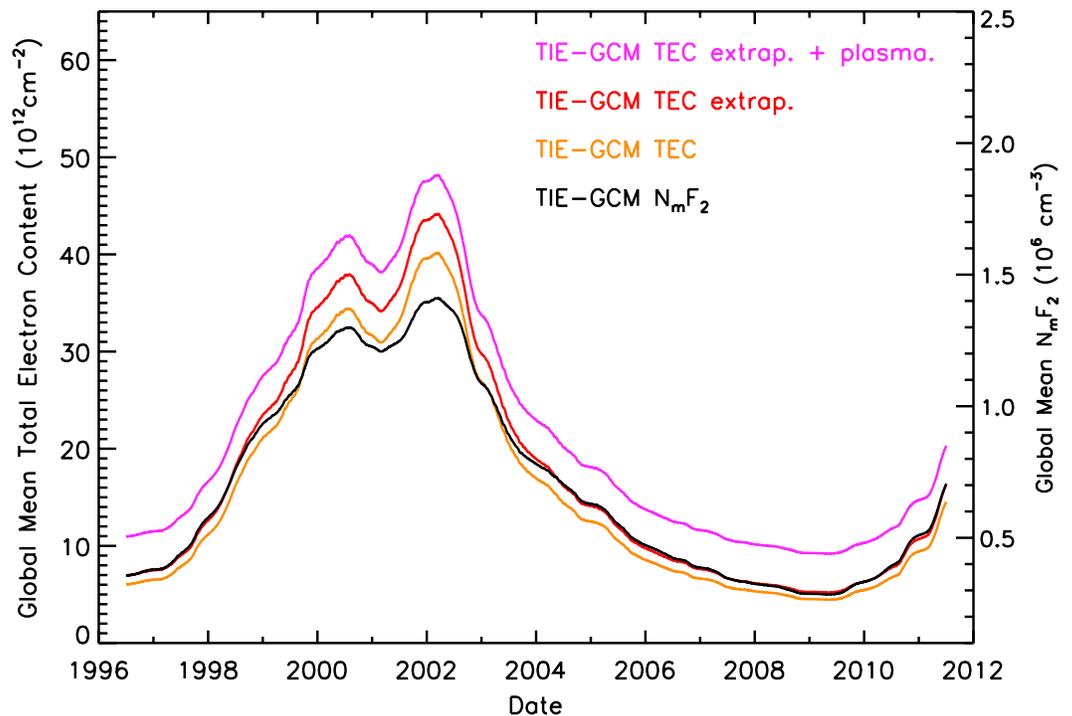


Figure 2. Same as Figure 1 but with 365-day smoothing, to remove the seasonal variation, and exhibit the differences between successive solar minima.

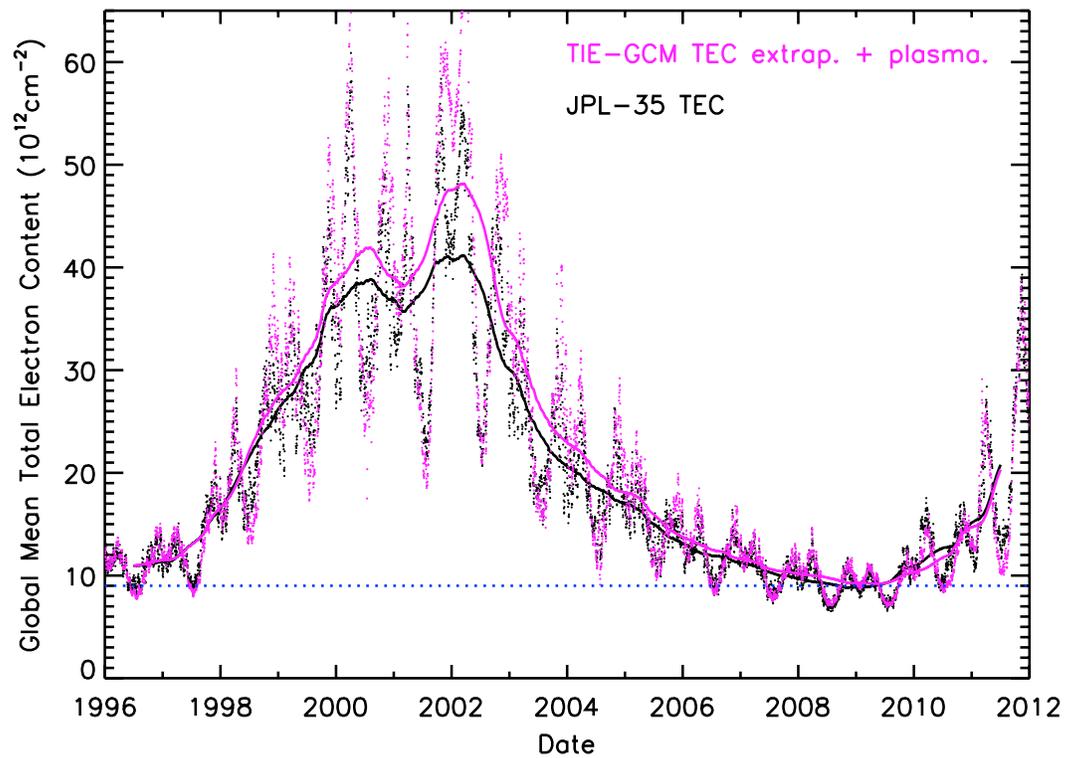


Figure 3. Comparison of measured to modeled global mean total electron content, showing daily mean values (dots) and 365-day smoothed results (lines). Black: Data derived from the JPL-35 analysis by Emmert et al. (2017). Magenta: Model results from the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM), including extrapolation and assumed constant plasmasphere as shown in Figure 1. Blue dotted line: $gTEC = 9$, approximately the minimum of the 365-day smoothed values during 2008–2009, as a guide.

4. Results

Modeled daily mean $gTEC$ is compared to the JPL-35 $gTEC$ data in Figure 3. The extrapolated-plus-plasmasphere model values, described above, are employed. Daily means are plotted as individual dots, and the 365-day smoothed results as solid lines. A blue dotted line at 9 TEC units is included as a guide. The modeled reduction in 365-day smoothed $gTEC$ from mid-1996 to early 2009 was from 11.0 to 9.2, or -16% , which is similar to the -19% change in $gTEC$ from the JPL-35 data reported by Emmert et al. (2017). (The JPL-35 $gTEC$ 365-day smoothed minima were 10.9 in mid-1996 and 8.8 in late 2008.) This result is also similar to the $\sim 15\%$ reduction in global mean annual mean $N_m F_2$ estimated in Solomon et al. (2013). The 365-day smoothed $N_m F_2$ shown in Figure 2 decreased from 3.56×10^5 in mid-1996 to 2.85×10^5 in early 2009, which is -20% .

Uncertainties in the data analysis are discussed in Emmert et al. estimated at just a few percent on a statistical basis (cf. Emmert et al., 2017, Figure 8). Of greater interest are any systematic errors due to changes in processing, sampling, or other instrumental effects, such as the ones that produced the results published by Lean, Emmert, et al. (2011) and Lean, Meier, et al. (2011). Model uncertainties mostly stem from the assumed variation of solar EUV, and in the application of geomagnetic forcing. Since the actual solar EUV change is basically unknown, the model result is in essence a sensitivity study, showing that *if* the solar EUV were reduced by 10%, it would explain most of the resulting $gTEC$ change. The $gTEC$ model estimates are not as robust as the global mean $N_m F_2$ calculation, because of the need for extrapolation, and a plasmasphere assumption. Since the extrapolation only increases $gTEC$ by a factor of ~ 1.1 , even if it were in error by as much as a factor of ± 0.5 , it would only result in an error of a factor of ± 0.05 and that would be almost equally applied at both solar minima. The assumption of a constant global mean annual mean plasmasphere, at solar minimum, is more arbitrary, and in essence could change the minima ratio if that value were changed. But again, even an error of a factor of ± 0.5 in plasmasphere estimation would only change the $gTEC$ reduction by ± 0.03 .

Therefore, we estimate the conversion from $N_m F_2$ to gTEC to result in an RMS uncertainty of ± 0.06 , and so estimate the interminimum change in modeled gTEC to be in the range 10% to 22%.

Solar cycle variation in gTEC is not the focus of this paper, but it is at least similar between the model and measurement. The model estimate is again dependent on solar variability assumptions, and we note that Figure 5 of Solomon et al. (2013) shows excellent comparison with both neutral density and $N_m F_2$ observations under the model assumptions employed. The results shown here are not quite as good for TEC. The observed solar cycle #23 amplitude in TEC is 4.2, whereas the model solar cycle amplitude is 4.8, which is $\sim 15\%$ larger. (The model $N_m F_2$ amplitude is 4.4.) Since $N_m F_2$ and the topside scale height are the dominant parameters controlling TEC, this may tell us something about topside plasma temperature ($(T_e + T_i)/2$) in the model formulation but does not pertain to the solar minimum problem. We note that TEC measurement accuracy can vary during the solar cycle, contributing to this data-model difference (Conte et al., 2011). Emmert et al. (2017) found that the global average TEC difference between the JPL runs with 35 and 100 stations varied with solar cycle. Even accounting for this, Emmert et al. (2017) estimated the JPL35 series accurate to 1% (their Figure 3).

The semiannual and annual variations of the ionosphere are also evident in the model-data comparisons. For these simulations, the model performs quite well. Again, this is subject to the assumptions applied, in this case the variable eddy diffusion at the lower boundary derived by Qian et al. (2009, 2013). This is an ad hoc assumption, meant to account for any and all wave, tidal or subgrid-scale dynamics missing from the model formulation, but it obtains good agreement with both the neutral density data and with the gTEC data.

5. Discussion

The solar origin of reductions in thermosphere and ionosphere density during 2008–2009 is now established, although the quantitative delineation between ultraviolet irradiance effects, and geomagnetic effects driven by solar wind and interplanetary magnetic field variation, remains somewhat uncertain. Since energetic photon and corpuscular radiation are both aspects of solar magnetism, it is expected that these should be linked, as they are throughout the solar cycle.

There was also a small but significant contribution to thermospheric density reduction caused by anthropogenic greenhouse gases, particularly CO_2 , which causes cooling and contraction of the atmosphere above the lower stratosphere (Roble & Dickinson, 1989). Observational studies (Emmert, 2015; Emmert et al., 2004; Keating et al., 2000; Marcos et al., 2005; Saunders et al., 2011) and modeling efforts (Solomon et al., 2015, 2018, and references therein to earlier work) have estimated the rate of density change as between 2% and 7% per decade, at 400-km altitude, as reviewed by Lastovicka et al. (2017). However, for the ionosphere, our model simulations yield only about 1% per decade reduction due to anthropogenic causes, which is difficult to identify in observations. The CO_2 effects are included in the solar cycle simulations shown here. Upper thermosphere density responds significantly to CO_2 cooling because of the compounding effects of small reductions in scale height, but ionosphere density is only slightly affected. By contrast, solar ionizing radiation has a direct effect, although the mechanisms controlling production and loss in the F region are complex. The ionospheric density response in the E region is simpler, but much smaller, going roughly as the square root of ionization rate changes in the molecular-dominated lower thermosphere. In these simulations, a 10% reduction in solar EUV resulted in a $\sim 5\%$ reduction in E region densities.

The solar MgII core-to-wing ratio data we used (Viereck et al., 2004, 2010) to estimate solar ultraviolet change have now superseded by a comprehensive compilation by the Bremen group (Snow et al., 2014; Weber, 2018). In order to be consistent with our previous modeling, we have not yet changed our inputs to this more complete (and ongoing) data set. It shows slightly less change between the 1996 and 2008–2009 minima than the Viereck et al. analysis. If this data set were applied using the same methodology, it would change our estimate of solar EUV reduction from -10% to -8% . We do not know with any certainty if this is the best index for this application. Other, more direct observations of solar EUV are discussed in Solomon et al. (2013). The H Lyman- α compilation (Woods et al., 2000) is in good agreement with the Viereck et al. MgII analysis. In the case of the SOHO/SEM data, it is clear that the earlier releases suffered from some instrumental degradation, but these data have been revised (Wieman et al., 2014) and are now in better alignment with index-based variability.

Heritage indices such as sunspot number and $F_{10.7}$ have the advantage of long-term stability and ground-based continuity but, as indicators of ultraviolet variation, have limitations under low solar activity

conditions. In the case of sunspot number, once it goes to zero, it no longer contains information. In the case of $F_{10.7}$, it reaches a plateau at $\sim 66 \times 10^{-22}$ W/m, as the active region contribution recedes below the background emission. See Tapping and DeTracy (1990), Tapping and Valdés (2011), and Tapping (2013) for description of the sources, measurement, and analysis of this venerable indicator. Since the annual average $F_{10.7}$ values were only $\sim 4\%$ lower during 2008–2009 than during 1996, this has raised some question as to whether solar ultraviolet radiation was lower by a larger amount. But the extensive evidence that solar ultraviolet radiation continues to vary at solar minimum, while $F_{10.7}$ does not, goes all the way back to Solar Mesosphere Explorer observations (Barth et al., 1990).

The strongest conclusion we can draw about actual solar ultraviolet radiation changes between the solar minima is that they are difficult to quantify, but at least all the evidence points in the same direction, and the assumptions used in our modeling studies result in agreement with the thermosphere/ionosphere measurements. The attribution analysis by Emmert et al. (2017) estimates a plausible range of -6% to -13% for the solar EUV irradiance interminimum change, and this work is in agreement with that estimate.

As we approach a new solar minimum, the implication for long-term solar variability is an open question. There has been extensive discussion in the solar physics literature concerning a possible reduction in solar cycle amplitude, perhaps similar to the “Dalton” minimum of 1800–1820, or even the “Maunder” minimum of 1650–1700 (e.g., Clette & Lefevre, 2012). It is also unknown to what extent other parts of the solar spectrum, and the total solar irradiance, might be affected under these conditions. The ultraviolet, and particularly EUV, irradiance is intrinsically linked to solar cycle magnetic variation, and so is the galactic cosmic ray flux, which is again exhibiting record highs, as it did prior to solar cycle #24 (e.g., <http://neutronm.bartol.udel.edu>). Whether this serves as a bellwether for broader solar changes may be discoverable by the ongoing program of comprehensive space-based observations of total and spectral solar irradiance (e.g., Dudok de Wit et al., 2017; Haberreiter et al., 2017; Schmidtke et al., 2015).

6. Conclusion

We compared model simulations of ionospheric global mean electron content during the 2008–2009 solar minimum to the 1996 solar minimum, and estimate that it was $16\% \pm 6\%$ lower, consistent with the neutral thermosphere density changes. In our model simulations, the primary cause is a 10% reduction in solar EUV irradiance, with a smaller contribution from lower geomagnetic activity, and a very small decrease due to increase in atmospheric carbon dioxide.

In a related context concerning ephemeral reduction of solar radiation, Rishbeth (1968) wrote: “The ionospheric physicist might wish that the Sun could be regarded as a constant, uniform source of ionizing radiation; but investigations of the Sun show that it is not. The solar physicist would like to regard the ionosphere as a detector for ionizing radiation. But the ionosphere does not meet the basic requirements of a good detector: straightforward operation, reproducibility, and a linear or other convenient type of response.” Nevertheless, this sensor has some desirable features: durability, orbit/attitude predictability, and large aperture. For the effort to understand solar variability, our challenge on the thermosphere/ionosphere side is to improve the characterization of the detector system.

Space-based instruments designed to track solar irradiance variation, especially in the ultraviolet, degrade with time and must be periodically recalibrated with on-board sources, stars, or suborbital flights. The various proxy indices for solar activity may have better long-term stability but have numerous flaws, particularly at the extrema of the solar cycle. So we return to the thermosphere/ionosphere, utilizing it as a large ionization chamber, in order to detect ionizing radiation by observation of its eponymous ability to remove electrons from atoms and molecules.

Since our planetary-scale detector is being contaminated by CO_2 and other seemingly innocuous emissions, disentanglement of the anthropogenic and solar-driven changes remains a daunting task. Measuring the effects of human activity on the upper atmosphere appears intractable without a stable source of illumination, or at least a cyclical one. If there is to be a solution to this conundrum, comprehensive global numerical models will be a critical element. Although such models are still imperfect, solar cycle #23 has provided an opportunity to demonstrate that even in a possibly anomalous situation, we can describe the broad features of Earth’s response to its star.

Acknowledgments

The authors thank Panagiotis Vergados for contributing to the analysis of the ionospheric data used in this work, which are available in the supporting information of Emmert et al. (2017). Model output data are archived on the NCAR High Performance Storage System (HPSS). The TIE-GCM is an open-source community model available from the HAO/NCAR web site. This research was supported by NASA grants NNX14AH54G and NNX16AB82G to the National Center for Atmospheric Research. NCAR is supported by the National Science Foundation.

References

Astafyeva, E. I., Afraimovich, E. L., Oinats, A. V., Yasukevich, Y. V., & Zhivetiev, I. V. (2008). Dynamics of global electron content in 1998–2005 derived from global GPS data and IRI modeling. *Advances in Space Research*, 42(4), 763–769. <https://doi.org/10.1016/j.asr.2007.11.007>

Barth, C. A., Tobiska, W. K., Rottman, G. J., & White, O. R. (1990). Comparison of 10.7 cm radio flux with SME solar Lyman alpha flux. *Geophysical Research Letters*, 17(5), 571–574. <https://doi.org/10.1029/GL017i005p00571>

Chaitanya, P. P., Patra, A. K., Balan, N., & Rao, S. V. B. (2016). Unusual behavior of the low-latitude ionosphere in the Indian sector during the deep solar minimum in 2009. *Journal of Geophysical Research: Space Physics*, 121, 6830–6843. <https://doi.org/10.1002/2015JA022061>

Chen, Y., Liu, L., Le, H., & Wan, W. (2014). Geomagnetic activity effect on the global ionosphere during 2007–2009 deep solar minimum. *Journal of Geophysical Research: Space Physics*, 119, 3747–3754. <https://doi.org/10.1002/2013JA019692>

Chen, Y., Liu, L., & Wan, W. (2011). Does the $F_{10.7}$ index correctly describe solar EUV flux during the deep solar minimum of 2007–2009? *Journal of Geophysical Research*, 116, A04304. <https://doi.org/10.1029/2010JA016301>

Cherniak, I. V., Zakharenkova, I. E., Krankowski, A., & Shagimuratov, I. I. (2012). Plasmaspheric electron content derived from GPS TEC and FORMOSAT-3/COSMIC measurements: Solar minimum condition. *Advances in Space Research*, 50(4), 427–440. <https://doi.org/10.1016/j.asr.2012.04.002>

Clette, F., & Lefevre, L. (2012). Are the sunspots really vanishing? Anomalies in solar cycle 23 and implications for long-term models and proxies. *Journal of Space Weather and Space Climate*, 2, A06. <https://doi.org/10.1051/swsc/2012007>

Conte, J. F., Azpilicueta, F., & Brunini, C. (2011). Accuracy assessment of the GPS-TEC calibration constants by means of a simulation technique. *Journal of Geodesy*, 85(10), 707–714. <https://doi.org/10.1007/s00190-011-0477-8>

Didkovsky, L., & Wieman, S. (2014). Ionospheric total electron contents (TECs) as indicators of solar EUV changes during the last two solar minima. *Journal of Geophysical Research: Space Physics*, 119, 4175–4184. <https://doi.org/10.1002/2014JA019977>

Dudok de Wit, T., Kopp, G., Fröhlich, C., & Schöll, M. (2017). Methodology to create a new total solar irradiance record: Making a composite out of multiple data records. *Geophysical Research Letters*, 44, 1196–1203. <https://doi.org/10.1002/2016GL071866>

Emmert, J. T. (2015). Altitude and solar activity dependence of 1967–2005 thermospheric density trends derived from orbital drag. *Journal of Geophysical Research: Space Physics*, 120, 2940–2950. <https://doi.org/10.1002/2015JA021047>

Emmert, J. T., Lean, J. L., & Picone, J. M. (2010). Record-low thermospheric density during the 2008 solar minimum. *Geophysical Research Letters*, 37, L12102. <https://doi.org/10.1029/2010GL043671>

Emmert, J. T., Mannucci, A. J., McDonald, S. E., & Vergados, P. (2017). Attribution of interminimum changes in global and hemispheric total electron content. *Journal of Geophysical Research: Space Physics*, 122, 2424–2439. <https://doi.org/10.1002/2016JA023680>

Emmert, J. T., McDonald, S. E., Drob, D. P., Meier, R. R., Lean, J. L., & Picone, J. M. (2014). Attribution of interminimum changes in the global thermosphere and ionosphere. *Journal of Geophysical Research: Space Physics*, 119, 6657–6688. <https://doi.org/10.1002/2013JA019484>

Emmert, J. T., Picone, J. M., Lean, J. L., & Knowles, S. H. (2004). Global change in the thermosphere: Compelling evidence of a secular decrease in density. *Journal of Geophysical Research*, 109, A02301. <https://doi.org/10.1029/2003JA010176>

Haberreiter, M., Schöll, M., Dudok de Wit, T., Kretzschmar, M., Misios, S., Tourpali, K., & Schmutz, W. (2017). A new observational solar irradiance composite. *Journal of Geophysical Research: Space Physics*, 122, 5910–5930. <https://doi.org/10.1002/2016JA023492>

Heelis, R. A., Coley, W. R., Burrell, A. G., Hairston, M. R., Earle, G. D., Perdue, M. D., et al. (2009). Behavior of the O^+/H^+ transition height during the extreme solar minimum of 2008. *Geophysical Research Letters*, 36, L00C03. <https://doi.org/10.1029/2009GL038652>

Hernández-Pajares, M., Juan, J. M., & Sanz, J. (1999). New approaches in global ionospheric determination using ground GPS data. *Journal of Atmospheric and Solar-Terrestrial Physics*, 61(16), 1237–1247. [https://doi.org/10.1016/S1364-6826\(99\)00054-1](https://doi.org/10.1016/S1364-6826(99)00054-1)

Hernández-Pajares, M., Juan, J. M., Sanz, J., Orus, R., Garcia-Rigo, A., Feltns, J., et al. (2009). The IGS VTEC maps: A reliable source of ionospheric information since 1998. *Journal of Geodesy*, 83(3–4), 263–275. <https://doi.org/10.1007/s00190-008-0266-1>

Jee, G., Lee, H.-B., & Solomon, S. C. (2014). Global ionospheric total electron contents (TECs) during the last two solar minimum periods. *Journal of Geophysical Research: Space Physics*, 119, 2090–2100. <https://doi.org/10.1002/2013JA019407>

Ji, E.-Y., Jee, G., & Lee, C. (2016). Comparison of IRI-2012 with JASON-1 TEC and incoherent scatter radar observations during the 2008–2009 solar minimum period. *Journal of Atmospheric and Space Physics*, 146. <https://doi.org/10.1016/j.jastp.2016.05.010>

Keating, G. M., Tolson, R. H., & Bradford, M. S. (2000). Evidence of long-term global decline in the Earth’s thermospheric densities apparently related to anthropogenic effects. *Geophysical Research Letters*, 27(10), 1523–1526. <https://doi.org/10.1029/2000GL003771>

Lanyi, G. E., & Roth, T. (1988). A comparison of mapped and measured total ionospheric electron content using global positioning system and beacon satellite observations. *Radio Science*, 23(4), 483–492. <https://doi.org/10.1029/RS023i004p00483>

Lastovicka, J. (2013). Trends in the upper atmosphere and ionosphere: Recent progress. *Journal of Geophysical Research: Space Physics*, 118, 3924–3935. <https://doi.org/10.1002/jgra.50341>

Lastovicka, J., Urbar, J., & Kozubek, M. (2017). Long-term trends in the total electron content. *Geophysical Research Letters*, 44, 8168–8172. <https://doi.org/10.1002/2017GL075063>

Lean, J. L., Emmert, J. T., Picone, J. M., & Meier, R. R. (2011). Global and regional trends in ionospheric total electron content. *Journal of Geophysical Research*, 116, A00H04. <https://doi.org/10.1029/2010JA016378>

Lean, J. L., Meier, R. R., Picone, J. M., & Emmert, J. T. (2011). Ionospheric total electron content: Global and hemispheric climatology. *Journal of Geophysical Research*, 116, A10318. <https://doi.org/10.1029/2011JA016567>

Liu, L., Chen, Y., Le, H., Kurkin, V. I., Polekh, N. M., & Lee, C.-C. (2011). The ionosphere under extremely prolonged low solar activity. *Journal of Geophysical Research*, 116, A04320. <https://doi.org/10.1029/2010JA016296>

Liu, L., Le, H., Chen, Y., He, M., Wan, W., & Yue, X. (2011). Features of the middle- and low-latitude ionosphere during solar minimum as revealed from COSMIC radio occultation measurements. *Journal of Geophysical Research*, 116, A09307. <https://doi.org/10.1029/2011JA016691>

Liu, L., Yang, J., Le, H., Chen, Y., Wan, W., & Lee, C.-C. (2012). Comparative study of the equatorial ionosphere over Jicamarca during recent two solar minima. *Journal of Geophysical Research*, 117, A01315. <https://doi.org/10.1029/2011JA017215>

Mannucci, A. J., Wilson, B. D., Yuan, D. N., Ho, C. H., Lindqwister, U. J., & Runge, T. F. (1998). A global mapping technique for GPS-derived ionospheric total electron content measurements. *Radio Science*, 33(3), 565–582. <https://doi.org/10.1029/97RS02707>

Marcos, F. A., Wise, J. O., Kendra, M. J., Grossbard, N. J., & Bowman, B. R. (2005). Detection of a long-term decrease in thermospheric neutral density. *Geophysical Research Letters*, 32, L04103. <https://doi.org/10.1029/2004GL021269>

Perna, L., & Pezzopane, M. (2016). foF2 vs solar indices for the Rome station: Looking for the best general relation which is able to describe the anomalous minimum between cycles 23 and 24. *Journal of Atmospheric and Space Physics*, 146, 13–21. <https://doi.org/10.1016/j.jastp.2016.08.003>

- Perna, L., Pezzopane, M., Ezquer, R., Cabrera, M., & Baskaradas, J. A. (2017). NmF2 trends at low and mid latitudes for the recent solar minima and comparison with IRI-2012 model. *Advances in Space Research*, *60*, 363–374. <https://doi.org/10.1016/j.asr.2016.09.025>
- Qian, L., Burns, A. G., Solomon, S. C., & Wang, W. (2013). Annual/semiannual variation of the ionosphere. *Geophysical Research Letters*, *40*, 1928–1933. <https://doi.org/10.1002/grl.50448>
- Qian, L., Solomon, S. C., & Kane, T. J. (2009). Seasonal variation of thermospheric density and composition. *Journal of Geophysical Research*, *114*, A01312. <https://doi.org/10.1029/2008JA013643>
- Richards, P. G., Fennelly, J. A., & Torr, D. G. (1994). EUVAC: A solar EUV flux model for aeronomic calculations. *Journal of Geophysical Research*, *99*(A5), 8981. <https://doi.org/10.1029/94JA00518>
- Richmond, A. D., Ridley, E. C., & Roble, R. G. (1992). A thermosphere/ionosphere general circulation model with coupled electrodynamics. *Geophysical Research Letters*, *19*(6), 601–604. <https://doi.org/10.1029/92GL00401>
- Rishbeth, H. (1968). Solar eclipses and ionospheric theory. *Space Science Reviews*, *8*(4), 543–554. <https://doi.org/10.1007/BF00175006>
- Roble, R. G., & Dickinson, R. E. (1989). How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere? *Geophysical Research Letters*, *16*(12), 1441–1444. <https://doi.org/10.1029/GL016i012p01441>
- Roble, R. G., Ridley, E. C., Richmond, A. D., & Dickinson, R. E. (1988). A coupled thermosphere/ionosphere general circulation model. *Geophysical Research Letters*, *15*(12), 1325–1328. <https://doi.org/10.1029/GL015i012p01325>
- Santos, A. M., Abdu, M. A., Souza, J. R., Batista, I. S., & Sobral, J. H. A. (2017). Unusual behavior of quiet-time zonal and vertical plasma drift velocities over Jicamarca during the recent extended solar minimum of 2008. *Annales Geophysicae*, *35*(6), 1219–1229. <https://doi.org/10.5194/angeo-35-1219-2017>
- Sardón, E., & Zarraoa, N. (1997). Estimation of total electron content using GPS data: How stable are the differential satellite and receiver instrumental biases? *Radio Science*, *32*(5), 1899–1910. <https://doi.org/10.1029/97RS01457>
- Saunders, A., Lewis, H., & Swinerd, G. (2011). Further evidence of long-term thermospheric density change using a new method of satellite ballistic coefficient estimation. *Journal of Geophysical Research*, *116*, A00H10. <https://doi.org/10.1029/2010JA016358>
- Schmidtke, G., Avakyan, S. V., Berdermann, J., Bothmer, V., Cessateur, G., Ciraolo, L., et al. (2015). Where goes the Thermospheric Ionospheric Geospace Research (TIGER) program? *Advances in Space Research*, *56*(8), 1547–1577. <https://doi.org/10.1016/j.asr.2015.07.043>
- Shim, J. S., Jee, G., & Scherliess, L. (2017). Climatology of plasmaspheric total electron content obtained from Jason 1 satellite. *Journal of Geophysical Research: Space Physics*, *122*, 1611–1623. <https://doi.org/10.1002/2016JA023444>
- Snow, M., Weber, M., Machol, J., Viereck, R. A., & Richard, E. (2014). Comparison of magnesium II core-to-wing ratio observations during solar minimum 23/24. *Journal of Space Weather and Space Climate*, *4*. <https://doi.org/10.1051/swsc/2014001>
- Solomon, S. C., Burns, A. G., Emery, B. A., Mlynyczak, M. G., Qian, L., Wang, W., et al. (2012). Modeling studies of the impact of high-speed streams and co-rotating interaction regions on the thermosphere-ionosphere. *Journal of Geophysical Research*, *117*, A00L11. <https://doi.org/10.1029/2011JA017417>
- Solomon, S. C., Liu, H.-L., Marsh, D. R., McInerney, J. M., Qian, L., & Vitt, F. M. (2018). Whole atmosphere simulation of anthropogenic climate change. *Geophysical Research Letters*, *45*(3), 1567–1576. <https://doi.org/10.1002/2017GL076950>
- Solomon, S. C., & Qian, L. (2005). Solar extreme-ultraviolet irradiance for general circulation models. *Journal of Geophysical Research*, *110*, A10306. <https://doi.org/10.1029/2005JA011160>
- Solomon, S. C., Qian, L., & Burns, A. G. (2013). The anomalous ionosphere between solar cycles 23 and 24. *Journal of Geophysical Research: Space Physics*, *118*, 6524–6535. <https://doi.org/10.1002/jgra.50561>
- Solomon, S. C., Qian, L., Didkovsky, L. V., Viereck, R. A., & Woods, T. N. (2011). Causes of low thermospheric density during the 2007–2009 solar minimum. *Journal of Geophysical Research*, *116*, A00H07. <https://doi.org/10.1029/2011JA016508>
- Solomon, S. C., Qian, L., & Roble, R. G. (2015). New 3D simulations of climate change in the thermosphere. *Journal of Geophysical Research: Space Physics*, *120*, 2183–2193. <https://doi.org/10.1002/2014JA020886>
- Solomon, S. C., Woods, T. N., Didkovsky, L. V., Emmert, J. T., & Qian, L. (2010). Anomalously low solar extreme-ultraviolet irradiance and thermospheric density during solar minimum. *Geophysical Research Letters*, *37*, L16103. <https://doi.org/10.1029/2010GL044468>
- Tapping, K. F. (2013). The 10.7 cm solar radio flux ($F_{10.7}$). *Space Weather*, *11*, 394–406. <https://doi.org/10.1002/swe.20064>
- Tapping, K. F., & DeTracy, B. (1990). The origin of the 10.7 cm flux. *Solar Physics*, *127*(2), 321–332. <https://doi.org/10.1007/BF00152171>
- Tapping, K. F., & Valdés, J. J. (2011). Did the Sun change its behavior during the decline of cycle 23 and into cycle 24? *Solar Physics*, *272*(2), 337–350. <https://doi.org/10.1007/s11207-011-9827-1>
- Viereck, R. A., Floyd, L. E., Crane, P. C., Woods, T. N., Knapp, B. G., Rottman, G. J., et al. (2004). A composite Mg II index spanning from 1978 to 2003. *Space Weather*, *2*, S10005. <https://doi.org/10.1029/2004SW000084>
- Viereck, R. A., Snow, M., DeLand, M. T., Weber, M., Puga, L., & Bouwer, D. (2010). Trends in solar UV and EUV irradiance: An update to the MgII Index. Abstract GC21B-0877 presented at 2010 Fall Meeting, AGU, San Francisco, CA, 13–17 December.
- Weber, M. (2018). Retrieved from <http://www.iup.uni-bremen.de/gome/gomemgii.html>
- Wieman, S. R., Didkovsky, L. V., & Judge, D. L. (2014). Resolving differences in absolute irradiance measurements between the SOHO/CELIAS/SEM and the SDO/EVE. *Solar Physics*, *289*, 2907–2925. <https://doi.org/10.1007/s11207-014-0519-5>
- Woods, T. N., Tobiska, W. K., Rottman, G. J., & Worden, J. R. (2000). Improved solar Lyman- α irradiance modeling from 1947 through 1999 based on UARS observations. *Journal of Geophysical Research*, *105*, 27,195–27,215. <https://doi.org/10.1029/2000JA000051>