

How Does the Sun's Spectrum Vary?

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for Submission to Journal of Climate, Expedited Contribution

Draft: September 8, 2011

Abstract

Recent observations made by the Spectral Irradiance Monitor (SIM) on the Solar Radiation and Climate Experiment (SORCE) spacecraft suggest that the Sun's visible and infrared spectral irradiance increased from 2004 to 2008, even as the total solar irradiance measured simultaneously by SORCE's Total Irradiance Monitor (TIM) decreased. As well, solar ultraviolet (UV) irradiance decreased 3 to 10 times more than expected from prior observations and model calculations of the known effects of sunspot and facular solar features. Analysis of the SIM spectral irradiance observations during the solar minimum epoch of 2008, when solar activity was essentially invariant, exposes trends in the SIM observations relative to both total solar irradiance and solar activity that are unlikely solar in origin. We suggest that the SIM's radically different solar variability characterization is a consequence of undetected instrument sensitivity drifts, not true solar spectrum changes. It is thus doubtful that simulations of climate and atmospheric change using SIM measurements are indicative of real behavior in the Earth's climate and atmosphere.

1. Introduction

Since incoming solar radiation supplies the energy that powers Earth's climate and atmosphere, reliable knowledge of the spectral distribution of this radiation and of wavelength-dependent long-term irradiance variations is critical for assessing solar-induced climate and ozone change. Multiple space-based measurements made in the past 30 years show that total solar irradiance (TSI), the radiant energy integrated over all wavelengths, increased $\sim 0.1\%$ at peaks of the Sun's recent 11-year cycles (Kopp and Lean 2011) and middle ultraviolet spectral energy increased by at least an order of magnitude more (Lean and Woods 2010). But only the Solar Irradiance Monitor (SIM) on the Solar

Radiation and Climate Experiment (SORCE) has observed spectral irradiance simultaneously at the ultraviolet, visible and infrared wavelengths that compose the bulk of TSI changes. SIM measured solar spectral irradiance variations at wavelengths between 240 and 1630 nm from the 2004 to 2008, during a portion of the descending phase of solar cycle 23, reporting a 0.3 Wm^{-2} (2%) decrease in UV energy at 250 to 300 nm and a corresponding 0.3 Wm^{-2} (0.2%) increase in visible energy at 600 to 700 (Harder et al. 2005). Figure 1 shows these changes in the context of the spectral irradiance database.

In lieu of direct, continuous solar spectral irradiance observations on climatological time scales, models such as the Naval Research Laboratory Solar Spectral Irradiance (NRLSSI) variability model have been developed to calculate the variations arising from the wavelength-dependent effects of sunspots and faculae, the two primary known sources of solar irradiance variations (e.g., Lean and Woods 2010). NRLSSI reproduces short term spectral irradiance changes (time scale of days) associated with the Sun's nominal 27-day rotation on its axis observed simultaneously throughout the UV, visible and infrared spectrum but suggest much smaller solar cycle changes (time scale of years) than SIM reports, and a solar cycle change in the visible spectrum both smaller in amplitude and in-phase (rather than out-of-phase) with solar activity. Analogous models that utilize bolometric (spectrally weighted and integrated) sunspot and facular parameterizations account for a high fraction (92%) of the total solar irradiance variance that TIM measured simultaneously with SIM's spectral irradiance measurements, on both solar rotation and solar cycle time scales (Kopp and Lean 2010).

A recent simulation of climate and atmospheric responses to solar spectrum changes using the SIM measurements reported that "the effects of solar variability on temperature

throughout the atmosphere may be contrary to current expectations” (Haigh et al. 2010), concluding that higher solar activity cools, rather than warms, the Earth. Specifically, because the solar visible spectral energy is less during high solar activity, according to the SIM measurements, the effect of the solar activity cycle is to cool the Earth’s surface temperature. This statement contradicts numerous empirical analyses that relate increased global surface temperature with higher solar activity (Lean 2010). Indeed, the combination of global surface cooling produced by decreasing solar irradiance from 2002 to 2008 and greenhouse gas-induced warming is an explanation for the minimal upward trend in the University of East Anglia Climate Research Unit (CRU) surface temperature record between 2002 and 2009.

During the 2008 minimum between solar cycles 23 and 24 trends in solar activity and total solar irradiance were negligible. We analyze SIM measurements during this period with the goal of clarifying causes of the severe discrepancies between the spectral irradiance changes that SIM measures and NRLSSI models, and averting misleading inferences from climate model simulations.

2. Measured Spectral Irradiance Variations

Multiple measurements and analyses indicate that high solar activity produces high solar UV irradiance, with shorter UV wavelengths increasing more (Lean and Woods 2010; DeLand and Cebula 2011). The databases of the HI Lyman α emission line at 121.6 nm and the irradiance in a band from 250-300 nm in Figures 1a and 1b illustrate this; during times of recent solar activity maxima (1980, 1990, 2000) the UV irradiance increased ~60% at Lyman α and ~2% in the 250-300 nm band. In the visible and near infrared spectrum,

irradiance changes during the solar cycle are an order of magnitude smaller than in the UV spectrum and, according to the SIM observations shown in Figure 1c, opposite in phase. Figure 2, which shows spectral irradiance changes from April 2004 to December 2008, indicates that SIM's measurements are out of phase with solar activity at all wavelengths longer than 400 nm, and in phase with solar activity at all shorter wavelengths.

The significant differences evident among overlapping measurements in UV irradiance at 250 to 300 nm, such as from 1992 to 1995 in Figure 1b, point to instrumental effects in the database. Because the relative long-term accuracies of the measurements made prior to the SIM are of order 2% (Woods et al. 1997) separating solar cycle changes from instrumental drifts in the middle ultraviolet spectral irradiance database is a challenging task. The much larger cycle amplitudes of far ultraviolet spectral irradiance, as exemplified by the Lyman α data in Figure 1a, are measured with greater certainty and evident in the general agreement among the multiple measurements (allowing for different calibration offsets arising from absolute uncertainties in individual datasets).

Harder et al (2009) report that the ~2% decrease in the 250-300 nm band in Figure 1b and the middle and near UV spectral irradiance changes in Figure 2 characterize real solar variability because the magnitudes of the variations exceed the long-term relative accuracy of the SIM instrument, reported to be 0.5% to 0.1% at wavelengths from 200 to 300 nm and 0.2% to 0.05% at wavelengths from 300 to 400 nm. That the decrease in SIM's UV irradiances occurs during only one third of cycle 23's full dynamic range suggests a solar cycle amplitude two to three times larger than derived from previous observations after careful scrutiny of in-flight instrumental behavior (DeLand and Cebula 2011).

The 0.2% increase in the 600-700 nm band in Figure 1c from 2003 to 2005 and the spectral irradiance changes at visible and infrared wavelengths are likewise claimed to be real solar increases concurrent with the large UV irradiance decreases because the magnitudes of the variations exceed the presumed long-term relative accuracy of the SIM instrument of better than 0.05% at wavelengths from 400 to 1600 nm. Only the increase in irradiance at 900 - 950 nm is acknowledged to be an instrumental artifact.

3. Comparison of Measured and Modeled Spectral Irradiance Variations

The NRLSSI model calculates solar spectral irradiance variations by accounting for the wavelength dependences of sunspot and facular influences. During epochs of high solar activity, the greater number and larger area of both sunspots and facular alter spectral irradiance at all wavelengths, relative to solar minimum levels, because they are respectively darker and brighter than the surrounding background “quiet” Sun. As the Sun rotates on its axis, approximately once every 27 days, active regions appear to pass across the hemisphere of the Sun projected to Earth, producing additional short term spectral irradiance variations. This 27-day rotational modulation of spectral irradiance has larger magnitude during high solar activity than during solar minima, when sunspots and faculae are far less prevalent.

The NRLSSI model closely tracks short-term changes in solar irradiance variations that space-based instruments, including SIM, measure at all wavelengths on time scale of days to weeks; these changes occur on sufficiently short time scales that instrumental effects are relatively small, by comparison. Evident in Figure 3a is the excellent agreement of the Lyman alpha changes measured by SOLSTICE and modeled by NRLSSI during approximately six 27-day solar rotations. The changes are of order 15% and unequivocally

of solar origin. Even though the variability is an order of magnitude smaller at middle UV wavelengths, there is good agreement in Figure 3b between rotational modulation of the 250-300 nm band that SIM measures and NRLSSI models. Aside from an underlying trend in the SIM observations, the measured and modeled irradiance decreases evident in the 600-700 nm band, of order 0.5%, also agree well. This good agreement of the SIM observations and the NRLSSI model of rotationally modulated solar spectral irradiance extends to all wavelengths, during both solar minimum and maximum epochs, and indicates that the sunspot and facular parameterizations in the NRLSSI model are robust.

The fundamental differences between the SIM measurements and the NRLSSI model on time scales of months to years, evident in Figures 1b and 1c and Figure 2, must therefore arise from a mechanism that dominates on solar cycle time scales, but differs from, and is of greater strength than, the direct effects of sunspots and faculae. In the absence of solar activity, spectral irradiance is expected to neither increase nor decrease. During the quiescent period from May to December 2008 when sunspots were absent from the disk for extended periods and other indicators of solar activity flux essentially invariant, the NRLSSI model indicates negligible irradiance trends at all wavelengths. Figure 4a shows that during this time the trend in the Lyman α observations was indeed minimal (-0.016 mW m⁻² per year, less than 0.5% of the cycle amplitude) and equal to the NRLSSI model trend (-0.004 mW m⁻² per year) to within the 2% measurement instability (± 0.14 mW m⁻²).

The SIM measurements, however, diverge markedly from the NRLSSI model in 2008, which Figures 4b and 4c illustrate for the UV and visible bands. The most likely explanation for this divergence is not solar variability, which was essentially absent, but uncorrected on-orbit instrument changes. Solar exposure is known to decrease the sensitivity of solar

UV instruments by degrading the performance of the optical elements and to initially increase the sensitivity of bolometric detectors by enhanced cavity blackening. Assuming that trends in the SIM measurements from May to December 2008 are instrumental allows an estimate of uncertainties associated with SIM's measurements. Figure 5 shows the wavelength dependence of SIM measurement uncertainties over the mission duration from April 2004 to December 2008 estimated from the absolute value of the trend during solar minimum, compared with the generally (much) smaller uncertainties that Harder et al (2009) report. Since instrumental changes are typically larger during the beginning of a space mission, the uncertainties in Figure 5 estimated during 2008 (the 6th year of SORCE mission) likely underrepresent the instrumental instabilities in prior years.

The uncertainty in the SIM UV spectral irradiance measurements during the SORCE mission is as large as 2% at some wavelengths, and typically a factor of 2 to 5 larger than Harder et al. (2009) report (but quite typical of uncertainties reported for prior UV irradiance measurements). Because of these larger uncertainties, is not possible to claim that the UV spectral irradiance variations that SIM measures are entirely real solar variations rather than, at least partly, uncorrected instrumental changes.

4. Total Irradiance Constraints on Spectral Irradiance Variations

An immutable constraint on solar spectral irradiance is that the integral over wavelength equals the total solar irradiance. Yet there are notable differences between SIM's summed and scaled (by 1.11) energy from 240 to 1630 nm and the total solar irradiance measured independently by TIM, shown together Figure 6. During solar minimum, from May to December 2008, TIM measured a long-term TSI trend of -0.01 W m^{-2} per year, which is effectively zero because it is less than TIM's 10 ppm per year relative

accuracy. But over the same period, the trend SIM's integrated (scaled) energy is -0.25 Wm^{-2} (183 ppm) per year. Drifts in the integrated SIM energy relative to the TSI are also evident in 2003, and point to with uncorrected instrumental effects in the SIM measurements.

A probable explanation for SIM's anomalous measurements is that during the initial few years of the SORCE mission, instrument sensitivity decreased at UV wavelengths and increased at visible wavelengths with the (fortuitous) result that the net energy change is comparable to that measured in TSI by TIM. By 2007, the instrument sensitivity stabilized at visible wavelengths, after which the visible energy decreased as solar activity decreased, contradicting the inference from the earlier measurements that the visible spectrum varies out-of-phase with solar activity. In fact, Figure 1c shows that the SIM spectral irradiance at 600-700 nm varies quite consistently with the NRLSSI sunspot-facular model during the latter half of the SORCE mission.

Conclusions

SIM's solar spectral irradiance measurements from April 2004 to December 2008 and inferences of their climatic implications are incompatible with the historical solar UV irradiance database, coincident solar proxy data, current understanding of the sources of solar spectral and total irradiance changes, and climate change attribution, but are consistent with known effects of instrument sensitivity drifts, demonstrated to be present in SIM observations during the recent solar minimum period.

In the absence of solar activity in 2008, SIM's ultraviolet irradiance at 240 to 400 nm continued to change and the integrated spectral energy decreased in conflict with the negligible trend in total solar irradiance measured independently by TIM over the same

period. The anomalously large decrease in UV energy is likely a result of uncorrected instrumental changes compensating an anomalously large energy increase in the visible and infrared spectrum, also of instrumental origin. Both the UV and visible anomalies are consistent with known changes in instrument sensitivities. These trends in SIM observations independent of solar activity (in 2008) suggest UV measurement uncertainties larger by a factor of 2 to 5 than Harder et al. (2009) report.

Rather than revising current understanding of solar physics and solar variability effects on climate, improved characterization of the SIM observations themselves is needed. Work is in progress to reassess the spectral irradiance variations measured by SORCE SIM and a new, advanced SIM has been designed and is under construction for flight on the Joint Polar Satellite System (P. Pilewskie, private communication, 2011). To prevent future research following a path of unrealistic solar-terrestrial behavior, the SORCE SIM observations should be used with extreme caution in studies of climate and atmospheric change until additional validation and uncertainty estimates of these observations are available.

Acknowledgements

NASA funded this work. Jerry Harder provided the SIM spectral irradiance data. In preparing this article we appreciate the encouragement of Edouard Bard and Gavin Schmidt, and discussions with Peter Pilewskie.

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Figures

1. Assorted space-based observations made of solar spectral irradiance during the past three solar cycles are compared for a) the Ly α emission line at 121.6 nm, b) the middle ultraviolet band from 250 to 300 nm, and c) the visible band from 600 to 700 nm, after making offset-adjustments to account for their different absolute calibration scales. Also shown, as the grey time series, is the NRLSSI model of the irradiance variations in the same wavelength bands, derived by scaling the observed rotational modulation variations to the *Mg* facular proxy and sunspot blocking, using multiple linear regression to determine their relative contributions. Lean and Woods (2010) and DeLand and Cebula (2011) provide additional details about individual measurements and model.

2. Shown are the (monthly average) solar spectral irradiance changes from April 2004 to December 2008 measured by SIM and modeled by NRLSSI at a) 200 to 400 nm, b) 400 to 800 nm, c) 800 to 1200 nm, and d) 1200-1600 nm.

3. Compared are the solar spectral irradiance changes in a) the Ly α emission line at 121.6 nm, b) the middle ultraviolet band from 250 to 300 nm, and c) the visible band from 600 to 700 nm, measured during six solar rotations in 2004, a period of moderately high solar activity, compared with the changes arising from sunspot and facular influences, as modeled by the NLSSI.

4. Compared are the solar spectral irradiance changes in a) the Ly α emission line at 121.6 nm, b) the middle ultraviolet band from 250 to 300 nm, and c) the visible band from 600 to 700 nm,

measured from May to December 2008, a period of quiescent solar activity, compared with the changes arising from sunspot and facular influences, as modeled by the NLSSI. The trends in the measured and modeled irradiances are also given.

5. Uncertainties in the SIM measurements are estimated for the duration of the available dataset (April 2004 to December 2008) at different wavelengths by scaling (with time) the absolute magnitude of the measurement trends during solar minimum from May to December 2008, when solar activity was negligible.

6. Compared in a) is the record of total solar irradiance measured directly by TIM with that obtained by summing and scaling the SIM spectral irradiance observations from 240 to 1630 nm. The differences of the two time series are shown in b) in both energy units and percentages.

Figure 1

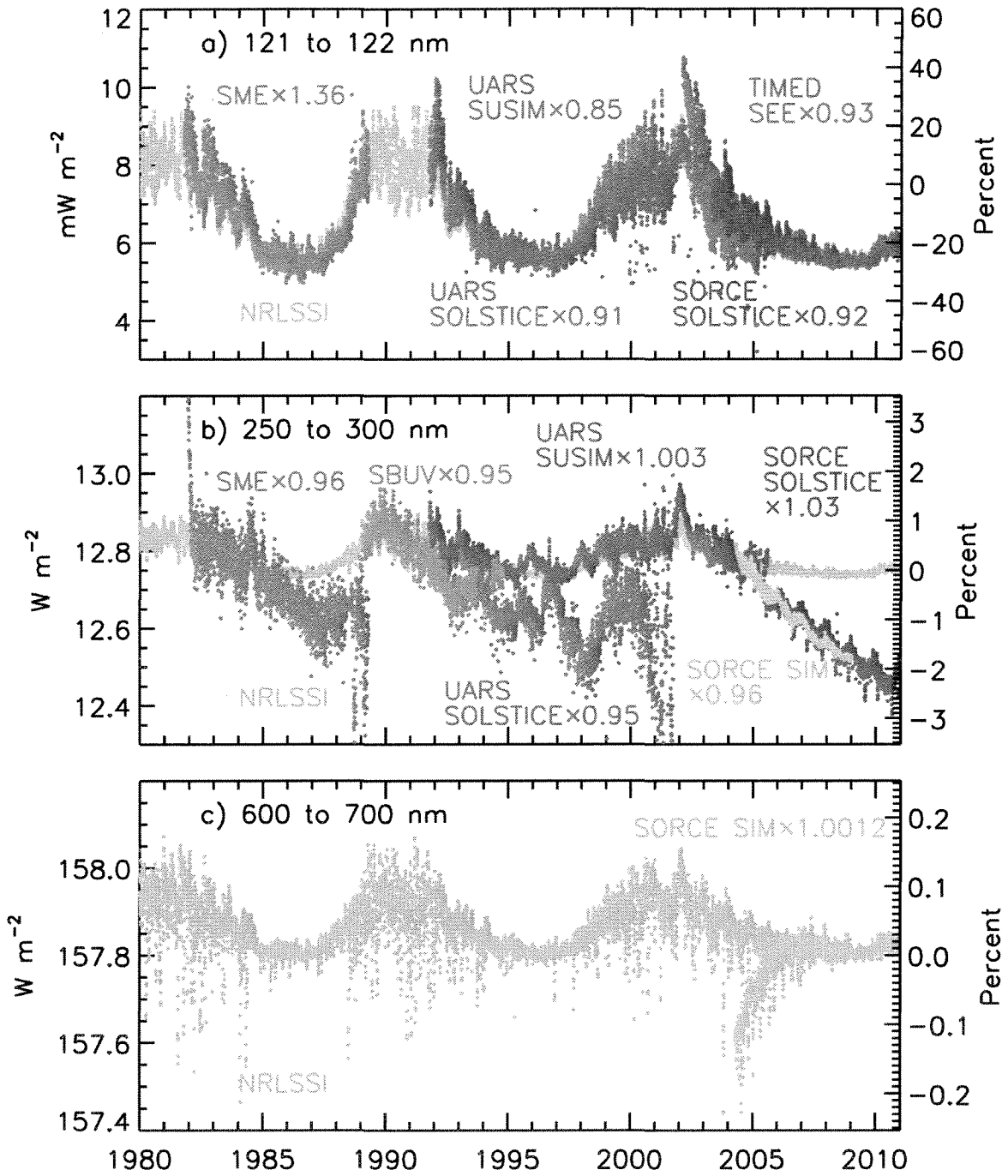


Figure 2

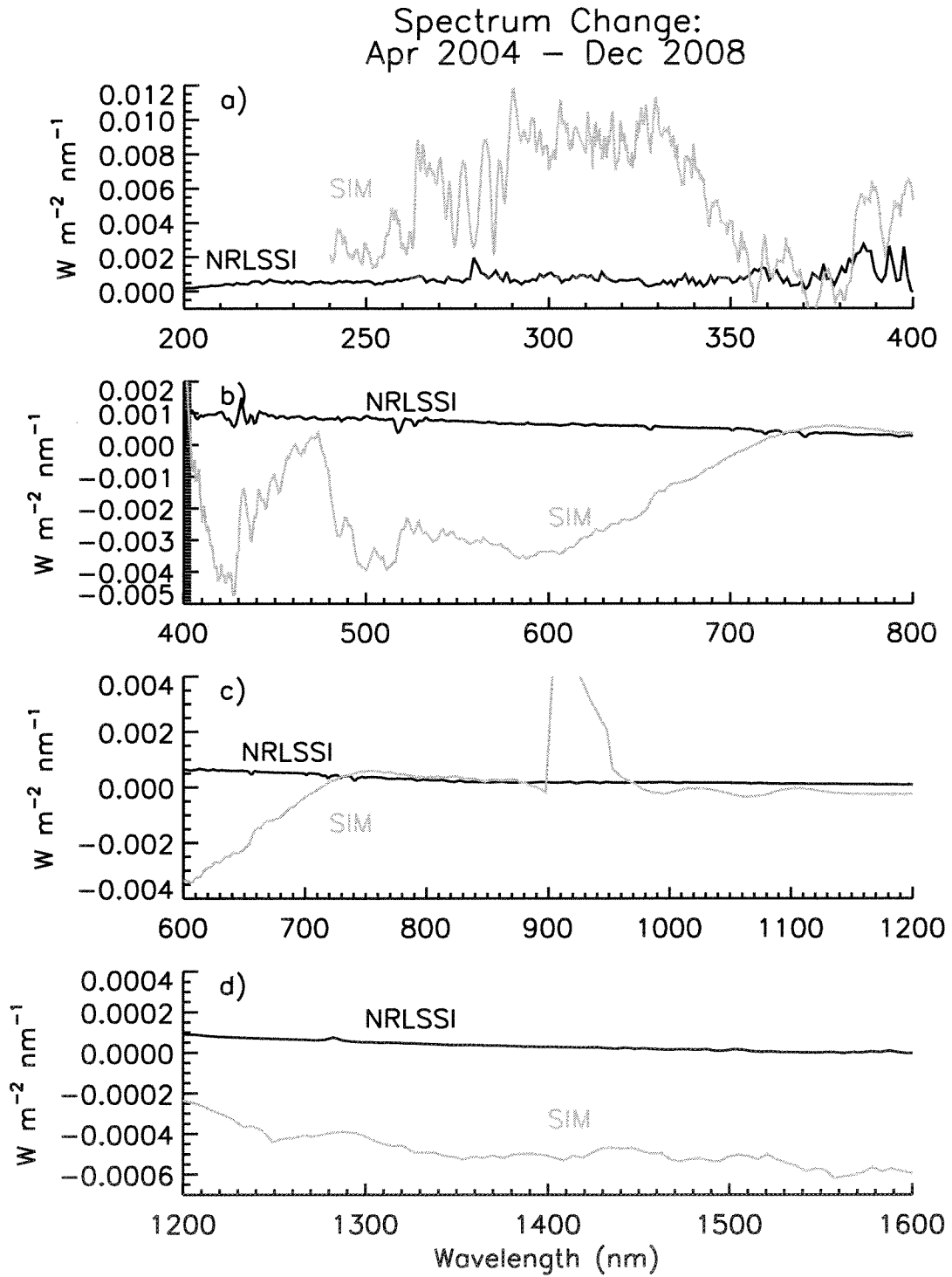


Figure 3

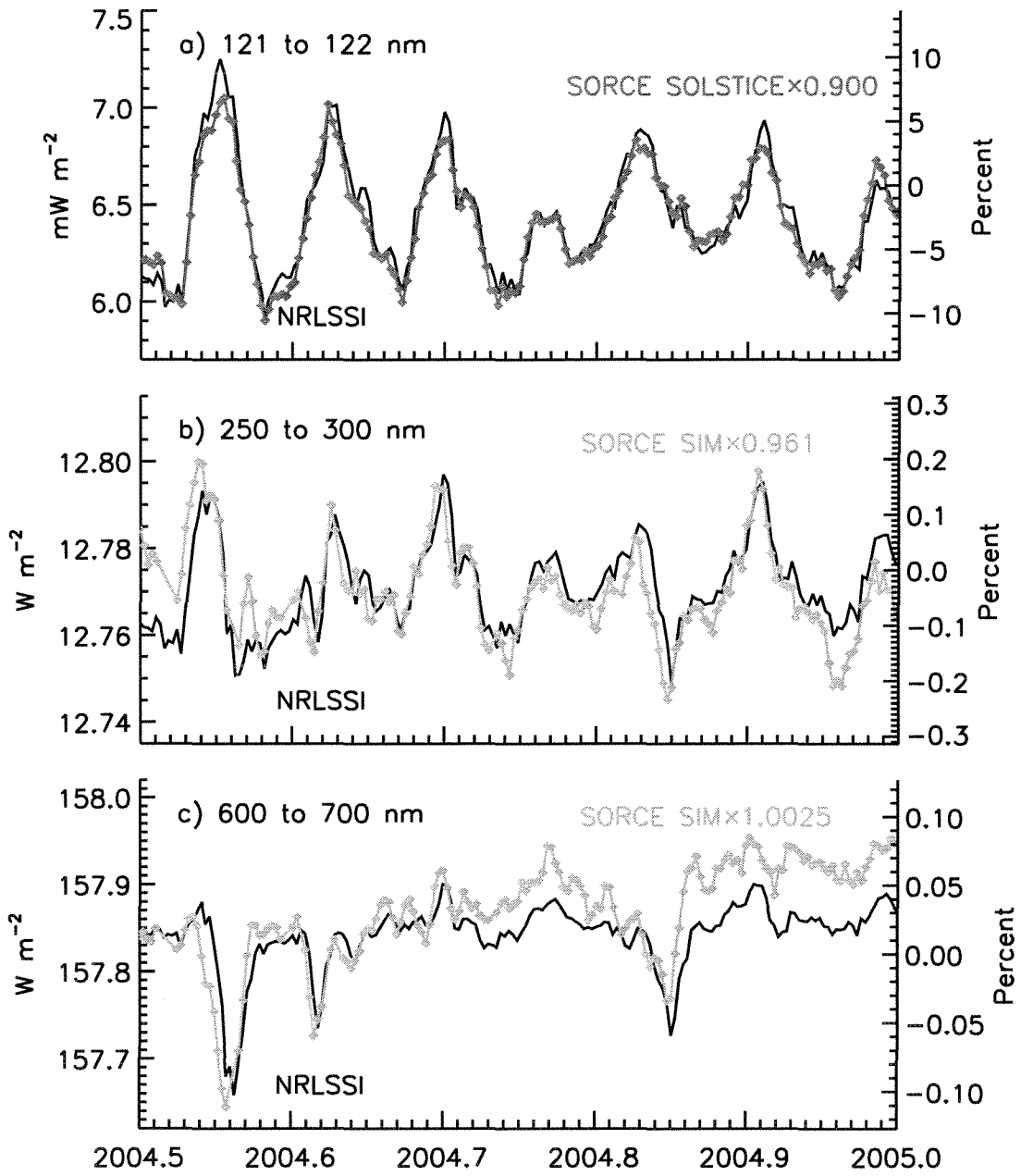


Figure 4

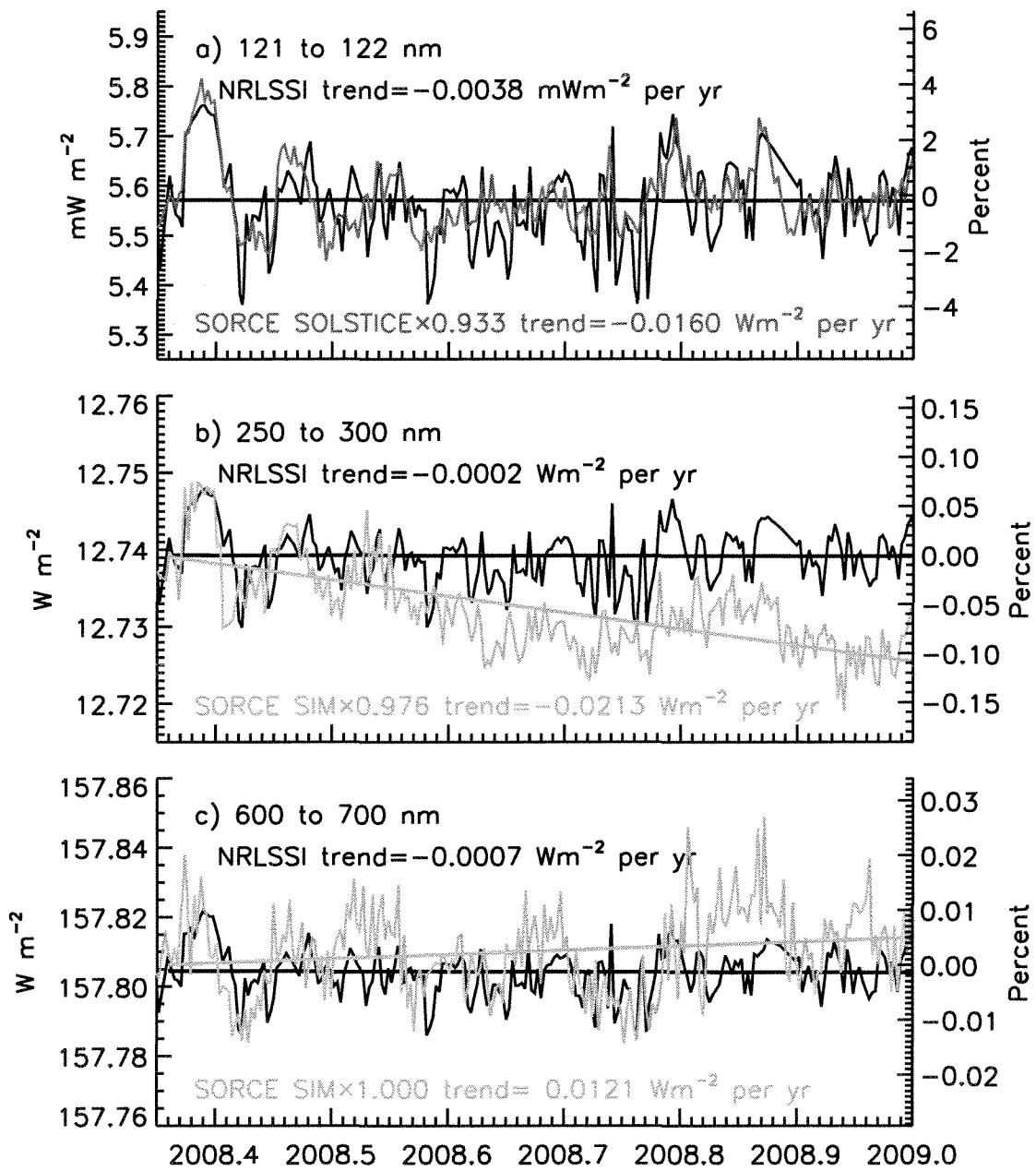


Figure 5

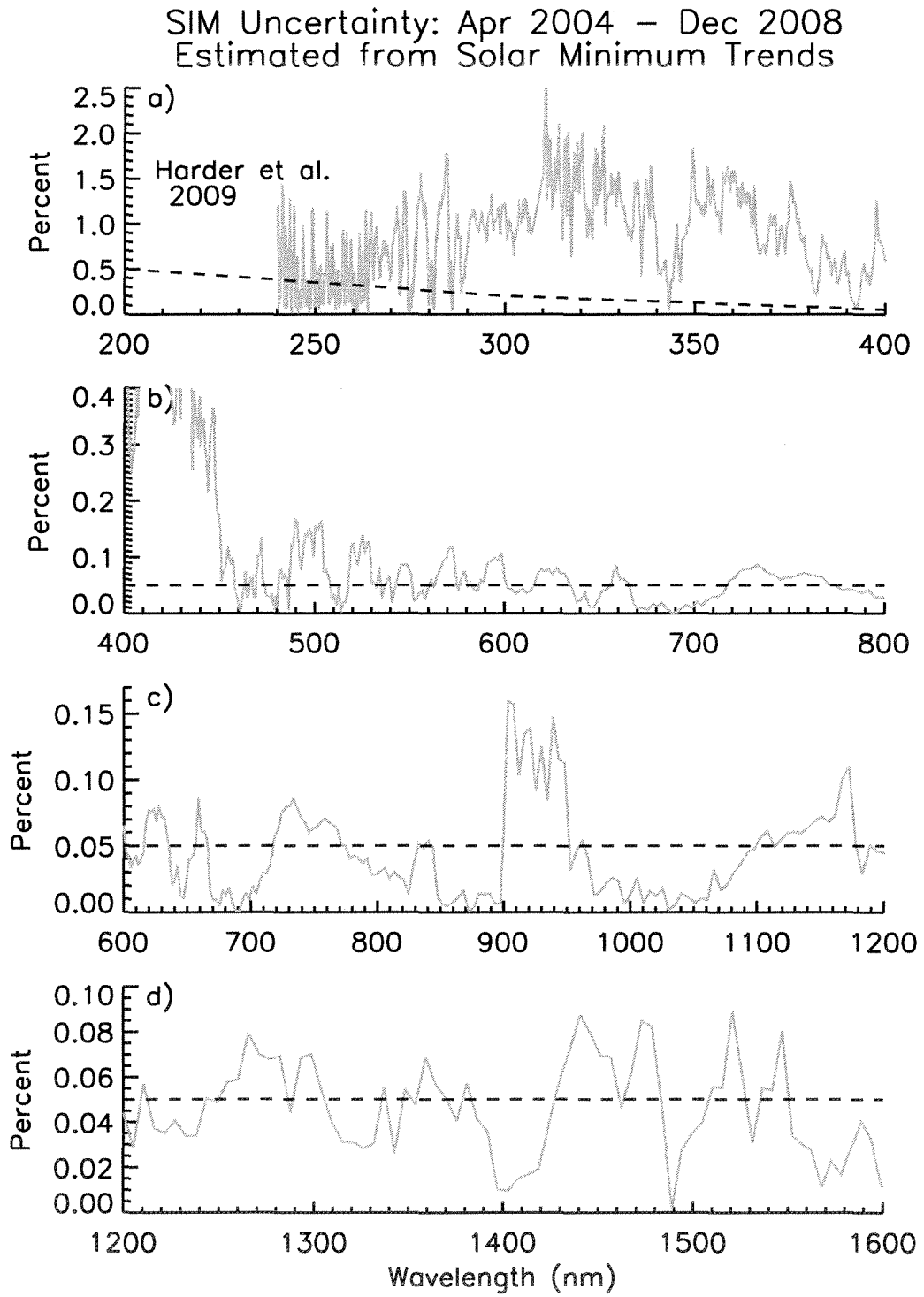


Figure 6

