A Different View of Solar Cycle Spectral Variations

Modeling Total Energy during Six-Month Intervals

Tom Woods
tom.woods@lasp.colorado.edu

SORCE SOLSTICE V13: Marty Snow
SORCE SIM V21: Jerry Harder
TIMED SEE V11: Frank Eparvier
SFO Proxies: Gary Chapman and Angie Cookson
PART 1

MOTIVATION TO MODEL 6-MONTH INTERVALS
Why model six-month intervals?

- Different analysis technique could shed some light on the debate about the SORCE SIM results of out-of-phase variations for visible and near infrared and larger ultraviolet variations (Harder et al., GRL, 2009)

From Ermolli et al., A.C.P., 2013
Why model six-month intervals?

• Modeling longer term (e.g. 11-year solar cycle) variations can be sensitive to instrument degradation trending.
Why model six-month intervals?

- Modeling short-term (e.g. 27-day solar rotation) needs both positive and negative components for the TSI and NUV-Vis-NIR SSI.
- Short-term UV variability only has positive component.

**Energy** == **Integration of Irradiance above background over time**

**UV Energy**: always positive

**TSI Energy**: positive or negative?
Why model six-month intervals?

• The lifetime of solar active regions is about 6 months.  
  – e.g. Preminger & Walton, *JGR*, 2005
• Woods *et al.* (*Solar Physics*, 2015) explore the energy variability over six-month intervals

**Outburst Behavior for New Active Region**

Ultraviolet (UV) has large peak followed by weaker peaks for about 5 months.  
Total Solar Irradiance (TSI) has dip for new sunspot and then peaks like the UV.

---

**Graphs:**

- **H I 121.6 nm Lyman-alpha**
- **TSI (W/m²)**
PART 2

MODEL PARAMETERS
## Irradiance, Variability, Energy Definitions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equation</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiance</td>
<td>$I$</td>
<td>TSI, Band: W/m² SSI: W/m²/nm</td>
</tr>
<tr>
<td>Variability</td>
<td>$V = I - I_{\text{min}}$</td>
<td>TSI, Band: W/m² SSI: W/m²/nm</td>
</tr>
<tr>
<td>Relative Variability</td>
<td>$V_R = \frac{I}{I_{\text{min}}} = \frac{I}{I_{\text{min}}}$</td>
<td>%</td>
</tr>
<tr>
<td>Energy (outburst, 6 months)</td>
<td>$E = TV dt$</td>
<td>TSI, Band: J/m² SSI: J/m²/nm</td>
</tr>
<tr>
<td>Relative Energy</td>
<td>$E_R = \left( \frac{V_R dt}{t_{\text{days}}} \right)$</td>
<td>%</td>
</tr>
</tbody>
</table>
2-Component Solar Variability Model

\[
\text{Variability} = \frac{\text{Daily/Min}}{1}
\]

\[
\text{Variability} = C_0 + C_E \cdot P_E + C_D \cdot P_D
\]

- **Constant** (ideally zero)
- **Positive Component**
  - facular Excess
- **Negative Component**
  - sunspot Deficit

- **Premise:** spectral variability for one active region (outburst) can be related to longer term (solar cycle) variations that involves many active regions.
  - Decomposition of solar images indicate that active regions are the primary source of irradiance variability

**Important Change from prior studies:** energy variability (\(E, E_R\)) is examined instead of irradiance variability (\(V, V_R\))
San Fernando Observatory (SFO) processes images of the Sun at 672 nm for Sunspot Deficit and at 393.4 nm (Ca II K) for Facular Excess – http://www.csun.edu/sfo/sfosolar.html

Parameters for Energy Variability Model (EVM)

Woods et al., Solar Physics, 2015

- Energy (E) is the irradiance (I) integrated over 6-months.
- Average energy variability is the average of the energy results for each 6-month period every 2-months over the mission.

\[ E = \text{Energy:} \]
\[ E_R = \left( \frac{V_R \, dt}{t_{days}} \right) \quad V_R = \left( \frac{I - I_{min}}{I_{min}} \right) \]

2 Components:
\[ V_R = C_O + C_E \, P_E + C_D \, P_D \]
\[ E_R = \left( \frac{C_E \, P_E \, dt + C_D \, P_D \, dt}{t_{days}} \right) \]

- San Fernando Observatory (SFO) facular excess and sunspot deficit proxies are the \( P_E \) and \( P_D \) in the model.
  - TSI Excess (TSI – Sunspot Deficit) is used for 300-1600 nm instead of \( \text{Ca II K} \) facular excess.

\[ \text{SFO Excess x1.4} \quad \text{TSI Excess} \]

\[ \text{SFO Deficit} \]

Excess (ppm TSI)

Time (year)
Example Modeling of the 2005 Outburst

- UV variations, such as $\text{H I Lyman-}\alpha$, only need the Facular Excess
- NUV-Visible-NIR and TSI need both Sunspot Deficit and Facular Excess

$\text{Green is Model Fit}$

\[
\text{Variability} = \frac{\text{Daily}}{\text{Min}}
\]

\[
\text{Variability} = C_0 + C_E \cdot P_E + C_D \cdot P_D
\]

**Lyman-\(\alpha\) SC Variability is large (60%)**

**TSI SC Variability is small (0.07%)**

BOTH are in-phase with solar activity.
PART 3

VARIABILITY RESULTS
Excess (positive) Component Dominates in UV

- The Excess (positive, in-phase) component is the only component needed for wavelengths < 250 nm.
- The Deficit (negative, out-of-phase) component is **zero** for 0-250 nm.

Total Variability = Excess + Deficit

Figure 4a in Woods *et al.* (*Solar Phys*, 2015)
Deficit Component Starts to Show at 290 nm

- The Excess (positive, in-phase) component still dominates up to 400 nm.
  - Excess contributions are shown for NOAA SBUV, UARS SUSIM, SORCE SOLSTICE, and SORCE SIM
- The Deficit (negative, out-of-phase) component appears > 290 nm.
  - Only the SIM deficit contribution is shown for clarity. The deficit is small contribution.

Figure 7b in Woods et al. (Solar Phys, 2015)
UARS SUSIM provides validation for 145-235 nm

- Day-to-day noise in the SUSIM is too high for precise model fits, except in the 145-235 nm range.
Deficit (negative) is very important in Vis-NIR

- Panel A shows the total energy variation
  - Excess dominates when total is positive (in-phase with solar cycle)
  - Deficit dominates when total is negative (out-of-phase with solar cycle)
- Panel B shows the two components (excess and deficit). Add these two together for the total shown in Panel A.

Comparison of Energy Variability Model Results
Woods et al., Solar Physics, 2015

- The out-of-phase (negative) variability is only for 1400-1600 nm for the energy variability model.
- There are factors of 2 differences in variability between the NRLSSI-2 and SATIRE-S models.
- Energy Model and average of solar cycle (SC) 23 & 24 variability are similar but do not have as much out-of-phase variability as Harder et al. [GRL, 2009].
- All three agree with TSI variability.
Energy Model Comparison to TSI

- Energy Model TSI = SSI integrated 0-1600 nm + 154.6 W/m² offset
- Standard deviation between Energy Model TSI and PMOD is 116 ppm
- Energy Model TSI suggests larger decrease from 1996 to 2008 than the decrease in the PMOD composite TSI
Energy Model 1996 to 2008

<table>
<thead>
<tr>
<th>Band</th>
<th>Energy Model</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEM 26-34 nm</td>
<td>8.4% ± 2%</td>
<td>6-15%</td>
</tr>
<tr>
<td>H I Lyman-α 121.6 nm</td>
<td>2.9% ± 1%</td>
<td>3-6%</td>
</tr>
<tr>
<td>Mg II C/W 280 nm</td>
<td>0.45% ± 0.2%</td>
<td>0.05-0.4%</td>
</tr>
<tr>
<td>TSI</td>
<td>136 ppm ± 110 ppm</td>
<td>-50 to 100 ppm</td>
</tr>
</tbody>
</table>

Planck delta Temp = 0.02 K
Conclusions

• The energy variability model results indicate very similar spectral variability from three different solar cycles and from different instruments.

• The deficit contribution is most important for the Vis-NIR (400-1600 nm).

• These results provide additional evidence for negative (out-of-phase) variability in the NIR 1400-1600 nm.

  – Out-of-phase behavior is when Deficit is larger than Excess

• Assuming most of the variability is from active region evolution, then these 6-month energy variability results could be indicator for solar cycle variability.

• Primary Reference: Woods et al., Solar Physics, 2015
BACKUP SLIDES
Outburst → Impulse Response Function

• **Outburst** is referred to as the *Energy* of the irradiance variation from a *single active region*

• Preminger and Walton (2005) modeled TSI variations with impulse response function (IRF)

![Graph showing impulse response function over time](image)
Model Constant could indicate that a 3\textsuperscript{rd} variability component is needed and/or instrument trend

- Average Energy Variability = average excluding solar cycle minimum

![Graphs showing variability trends over time](image1.png)

SEE 121.5 nm

Likely instrument trend

No Trend
Model Constant could indicate that a 3rd variability component is needed and/or instrument trend

- Example model Constant time series for SORCE SOLSTICE and SORCE SIM

![Graphs showing solar cycle and instrument trends for SOLSTICE and SIM at different wavelengths.](Image)
More Out-of-Phase Variations is possible at different times during solar cycle

- 2-sigma low Excess contribution combined with 2-sigma high Deficit contribution would indicate out-of-phase (negative) variability near 400 nm and for 1000-1600 nm

Figure 9c in Woods et al. (Solar Phys, 2015)
Energy Variability Model Uncertainty

• Variability uncertainty is about 30%
  – e.g., If solar cycle variability is 10%, then uncertainty is 30% * 10% = 3%
• SIM noise in 300-400 nm and in NIR ranges limit model uncertainty

Figure 13 in Woods et al. (Solar Phys, 2015)
Energy Variability compares well to Solar Cycle Variability in the UV range

- 180-day averages used for solar cycle variability

SC-24 variability is factor of about two lower than SC-23

Figure 4c in Woods et al. (Solar Phys, 2015)
Comparison of Energy Variability Model

- 180-day averages used for solar cycle variability using SORCE and NOAA-11 SBUV data
- Good agreement of solar cycle variability for < 290 nm, but larger differences in 290-400 nm range
  - SIM differences are smaller than the NOAA differences

Figure 8d in Woods et al. (Solar Phys, 2015)
Comparison of Energy Variability Model

- 180-day averages used for solar cycle variability using SORCE SIM data
- Large differences in Vis-NIR 500-1600 nm range

Figure 10d in Woods et al. (Solar Phys, 2015)
MDI Magnetic Field Synoptic Images

2008 Outburst

- TSI dips for first rotation
- TSI is bright for the other rotations

Ideal situation with active regions on one side of Sun

3 new Active Regions near disk center

3 decayed Active Regions on disk

WHI 2008 Period

View from Earth
MDI Magnetic Field Synoptic Images

Decayed active regions are on both sides of Sun

New Active Region at disk center

2005 Outburst

- TSI dips for first three rotations
- TSI is bright for the last rotation

5 decayed Active Regions on disk

View from Earth
Fontenla’s Model prediction for SIM Variability

- Solar Radiation Physical Model (SRPM) has prediction for negative (out-of-phase) variation if brightness temperature is $>5770$ K [lower photosphere] (Harder et al., GRL, 2009)

SFO Model Results

- Deficit Larger
  - 1400-1600 nm

- Excess Larger
  - 0-1400 nm

Wavelengths in SRPM that have negative (out-of-phase) SC variation.
SFO Model – SEE Correlation Results

- SEE’s low signal in 170-190 nm range causes for poorer correlation
SFO Model – SORCE Correlation Results

- SORCE SIM’s low signal in 300-400 nm range causes poorer correlation.
- Deficit contribution is not important for shorter than 290 nm.

- SORCE SIM’s diode gain correction with temperature affects the 800-1000 nm range the most.
- Deficit contribution is important over full 400-1600 nm range.
SFO Model – SUSIM Correlation Results

- UARS SUSIM has high day-to-day noise in 115-145 nm and 235-410 nm ranges, thus poorer correlation in those ranges.