P2.1 SOLSTICE OBSERVED AND CIMEL ESTIMATED EXO-ATMOSPHERIC

ATMOSPHERIC SOLAR IRRADIANCE

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1. Introduction

Solar radiation is the major energy source for the ecosystem. The total solar irradiance (TSI) at the mean sun-earth distance (1 AU) is known as the solar "constant". Variations of solar input may directly influence Earth's climate. Systematic observations of variability of TSI traced back to the Smithsonian Astrophysical Observatory Solar Constant Program established 100 years ago (Hoyt, 1979). Before the satellite era, the solar irradiance was estimated from ground-based radiometers using the traditional Langley Plot method. Both long-term variations of TSI associated with the sunspot cycle (cf. Abbot, 1958), and short term fluctuations over days or weeks (Clayton, 1923) were reported. Because the influence of fluctuation of the atmosphere, variations of the TSI reported were not generally accepted (e.g., Mitchell, 1965).

Unaffected by atmospheric effects, satellite observations truly reveal the variation of TSI associated with magnetic activity of the Sun (Willson, 1984; Willson and Hudson 1991; Lean, 1997). Variations related to the 11-year sunspot cycle, 27-day solar rotation cycle, and daily variability of the solar irradiance were observed from different satellites as summarized by Fröhlich and Lean (1998).

Solar irradiance as a function of wavelength is referred to as "solar spectral irradiance" or SSI. The observations from SOLSTICE (Solar Stellar Irradiance Comparison Experiment) on UARS (Upper Atmospheric Research Satellite) reveal variation of SSI. The amplitude of variation of SSI depends on the wavelength (Lean, 1997; Woods et al., 2000).

In the meantime, ground-based radiometers have also undergone a great advancement. A worldwide sunphotometer network, AERONET, has been established to observe the turbidity of the atmosphere (Holben et al., 1998). Quality assured data sets are available from the AERONET website. The availability of satellite observations and ground-based estimates makes it possible to compare the two directly.

Much research has been devoted to the studying of effects of the variability of atmosphere and other factors on the estimation of solar irradiance from ground-based radiometers (Shaw, 1983; Reagon et al., 1986, Russell et al., 1993). However, determining how the variability of the atmosphere affects the estimates in the Langley plot analysis is not trivial.

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Here we examine the old problem emphasizing the limitation of detection of solar variations from ground-based estimates. An analytical relation between the estimated solar irradiance and aerosol optical properties is presented. Furthermore, the estimated SSI from two Cimel sunphotometers at the Mauna Loa AERONET site are compared with the true SSI from SOLSTICE. The lower and upper bounds of uncertainty in the estimates are presented analytically.

2. Langley Plot method

Given the true exo-atmospheric irradiance F_0, the irradiance F_i at each time step i during observations may be expressed as

$$\ln F_i = \ln F_0 - m_i(\tau_m + \bar{\tau} + \Delta\tau_i) \qquad (1)$$

In Eq. (1) m_i is the airmass, τ_m, $\bar{\tau}$ are molecular optical thickness, and average aerosol optical thickness respectively, $\Delta\tau_i$ is the deviation of aerosol optical thickness from the mean at each time step during the period of observations.

The Langley plot method finds a best fit of linear regression line in airmass and logarithmic solar irradiance of the form

$$\ln F = \ln F_0^{'} - m(\tau_m + \tau) \qquad (2)$$

where $F_0^{'}$ and τ may be determined by minimizing the sum of squared residuals (Eq. (3)).

$$J = \sum_{i=1}^{N}\left[\left(\ln F_0^{'} - m(\tau_m + \tau)\right) - \left(\ln F_0 - m_i(\tau_m + \bar{\tau} + \Delta\tau_i)\right)\right]^2 \qquad (3)$$

After a simple mathematical manipulation, it can be shown

$$\ln(\frac{F_0^{'}}{F_0}) = \frac{\overline{m^2}\ \overline{m}}{\overline{m^2} - \overline{m}^2} Cov(M, \Delta\tau) \qquad (4)$$

where

$$\overline{m} = \frac{1}{N}\sum_{i=1}^{N} m_i \qquad (5a)$$

$$\overline{m^2} = \frac{1}{N}\sum_{i=1}^{N} m_i^2 \qquad (5b)$$

$$M_i = \frac{m_i^2}{\overline{m^2}} - \frac{m_i}{\overline{m}} \qquad (5c)$$

$$Cov(M, \square\square) = \frac{1}{N}\sum_{i=1}^{N} M_i \square\square_i \qquad (5d)$$

It is evident from Eq. (4) that the estimated exo-atmospheric solar irradiance F_0' will deviate from the true value F_0 unless the atmosphere is absolutely stable (i.e., $\square\square_i = 0$), or M and $\square\square$ are not correlated.

Since aerosol optical thickness at each time step is derived from each irradiance observation, as in Eq. (1), the estimated exo-atmospheric solar irradiance F_0' from Eq. (4) is equivalent to the intercept obtained from the Langley plot.

In practice, a reference value of calibration coefficient is used for F_0 instead of the true solar irradiance. An instrument is typically calibrated every 2~3 months (Holben et al., 2001) giving a new F_0. This is done often enough that F_0 does not change significantly from one calibration to the next. The aerosol optical thickness will therefore differ from the true values due to variations of exo-atmospheric solar irradiance. However, aerosol optical thickness in Eq. (4) is only acting as a surrogate for the observed irradiances,, as determined by Eq. (1), so that the right hand side of Eq. (4) is fully determined by the observed irradiances and airmass. Thus relative variations in F_0' are determined by (4) in units given by F_0, and may be compared with true variation determined from SOLSTICE.

3. Data Set

SSI as observed by SOLSTICE on UARS is used as truth in this study. The UARS satellite was launched on September 12, 1991 into a near-circular Earth orbit with an inclination angle of 57 degrees to the equator and an altitude near 585 km (Rebert et al., 1993). SOLSTICE measures the SSI between 115 and 420 nm with a spectral resolution of 0.1 to 0.2 nm in a daylight orbit. SOLSTICE instrument degradation is tracked by measuring the stellar irradiance from a large number of bright, blue stars (Rottman et al.,1993; Woods et al., 1993). The calibrated SOLSTICE data are provided as daily averages between 119 and 420 nm at an increments of 1 nm.

We apply the Langley plot method (Eq. (4)) to Cimel sunphotometer morning measurements at the Mauna Loa site of AERONET (2< airmass <5). Started in the early 90's, AERONET is a federated instrument network and data archive program for aerosol characterization (Holben et al., 1998). The Cimel sunphotometer of AERONET measures direct transmitted solar irradiance and sky radiance at 340, 380, 440, 500, 675, 870, 940, and 1020 nm with band pass of 2 nm for 340 nm channel, 4 nm for 380 nm channel, and 10 nm for the remaining channels. In this study we use data at the Mauna Loa site at an altitude of 3397m above sea level in the middle of Pacific Ocean. The site at Mauna Loa Observatory ($19^\circ 32' N, 155^\circ 34' W$) in Hawaii is famous for calibrating radiometer instruments, and perhaps the "clearest" ground site to infer the exo-atmospheric solar irradiance. In this study, Cimel sunphotometer channels at 340 and 380 nm are used. Data are used from a period of almost two years.

3. SOLSTICE vs Cimel

The SOLSTICE data set provides calibrated SSI in units of Wm-3, while the Langley method gives uncalibrated voltages values. To make meaningful comparisons, we examine relative irradiance values from these two methods. SOLSTICE data is normalized by the average value of the entire time period. Langley plot estimates are normalized by the reference value as determined in Eq. (4).

The time series of relative irradiance from SOLSTICE and from Cimel Langley Plots are presented in Fig. 1. The time series of the SOLSTICE data is continuous starting from January 1, 1998 and ending on October 28, 1999. The Level 2.0 data set from Mauna Loa, cloud screened and data quality controlled, has some gaps during the same time period, with a total of 360 days of data.

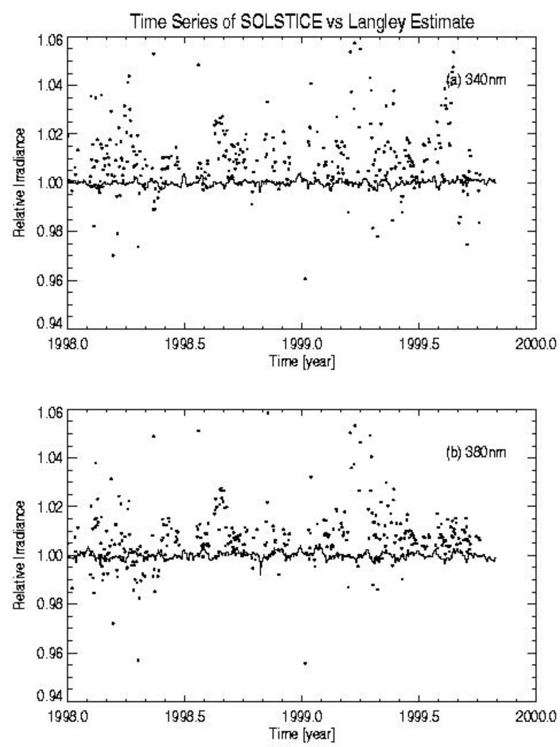

Figure 1. The time series of SOLSTICE observed (lines) and Cimel estimated (dots) solar spectral irradiance at 340nm (a) and 380nm (b) with total 666 days for SOLSTICE (from January 1, 1989 to October 28, 1999).

There are 360 days available in the Level 2.0 Cimel data set to perform the Langley analysis.

The variation of the SOLSTICE observations, defined as the standard deviation divided by the mean, is 0.12% and 0.14% in 340 nm and 380 nm channels respectively. The variation of ground-based estimates in the two Cimel channels is 2.0% and 1.8% respectively, which is 1 order of magnitude larger than the true solar variation observed by SOLSTICE. Furthermore, SOLSTICE observations and Cimel estimates are not significantly correlated. The correlation coefficient is found to be 0.028 (341 pairs of data) and –0.035 (351 pairs of data) at 340 and 380 nm channels respectively.

4. Uncertainty due to atmospheric effects

The estimated SSI from ground-based instruments is influenced by atmospheric effects as demonstrated in Eq. (4). We can further demonstrate that the uncertainty of the estimates is bounded. The upper and lower bounds are proportional to the temporal variation of aerosol optical thickness during the observation period. Applying Schwarz' inequality (Feller, 1971) to Eq. (4), we have

$$-c\,\sigma(\Delta\tau) \le \frac{\Delta F_0}{F_0} \le c\,\sigma(\Delta\tau) \qquad (6)$$

where c is a function of airmass, and $\sigma(\Delta\tau)$ is the standard deviation of aerosol optical thickness.

The uncertainty of SSI ($\Delta F_0 / F_0$), along with its lower bound ($-c\sigma(\Delta\tau)$) and upper bound ($c\sigma(\Delta\tau)$) are presented in Fig. 2. It is clear the estimated SSI is bounded due to the variability of the atmosphere. The average value of c is found to be about 13.5.

5. Summary and Discussion

An analytical expression presented in this work (Eq. (4)), demonstrates the relationship between the ground-based estimates of exo-atmospheric SSI and the variability of the atmosphere during the observation period. Quantitatively, the upper and lower bounds of the uncertainty in the estimate are proportional to the temporal variability of the atmosphere as measured by the standard deviation of aerosol optical thickness ($\sim \pm 13\sigma(\Delta\tau)$) (Eq. (6)).

Cloud-free atmosphere is a necessary but not sufficient condition for ground-based estimates. What really constains the uncertainty in the estimates is the variability of the cloud-free atmosphere. If the atmosphere were absolutely stable, the Langley method would work perfectly well. The continuous variability of the atmosphere due to physical, chemical, dynamical processes imposes a limitation of the ground-based estimates of SSI. The best accuracy of irradiance estimates achievable is about 0.4% for the two channels at perhaps the most favorable ground site at Mauna Loa. By chance M and $\Delta\tau$ may be uncorrelated on some occasions providing small deviation of the estimates (Fig. 2). Such situations may not be relied on because it is unlikely that M and $\Delta\tau$ will be uncorrelated everyday though a 27-day solar rotation period.

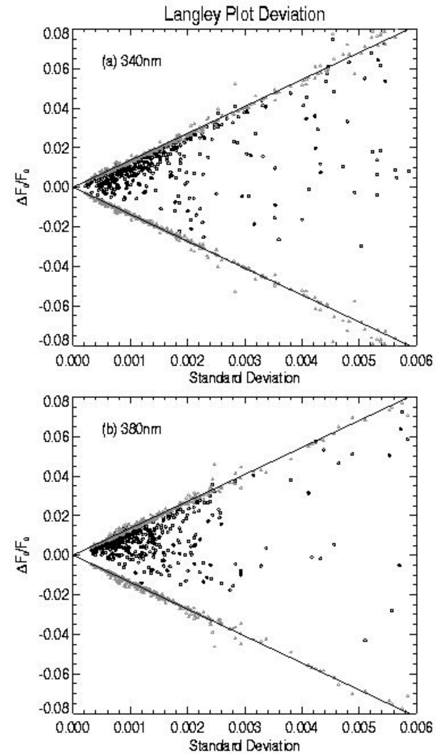

Figure 2. The relative difference between the estimated SSI and the reference vs variability of aerosols at 340 nm (a) and 380 nm (b) (circles), with the lower and upper bounds of the uncertainty (gray triangles). With the average (c ~13.5) in Eq. (6), two straight lines provide the limitation of ground-based estimates due to the fluctuation of atmospheric optical property.

Ground-based estimates of SSI from the Mauna Loa site are compared with "true" values from SOLSTICE observations for almost two years worth of data of two Cimel channels. The true variations of SSI derived from the SOLSTICE are about 0.15% for both 340 nm and 380 nm channels. The variability of the Cimel counterparts is one order of magnitude larger. The true variation and that in the estimate are not statistically correlated. Since the average deviation of ground-based estimated SSI from the reference value is one order of magnitude larger than the true variability of SSI from SOLSTICE, such ground-based estimates are unlikely to capture true solar variations on the order of 0.15%.

The results presented here are only for two Cimel UV channels. Most solar energy is in visible and near-IR spectral bands. The method in this study can be used to understand the difficulties in estimating visible, near-IR, or broadband solar irradiance. Since there are not any assumptions on wavelength dependence, Eqs. (4), (6) may be applied to any wavelength. It appears that the SSI varies even less in visible than UV (Woods et al., 2000). Besides aerosols, water vapor also contributes to the variability of the atmosphere. The detection of variations in visible, near-IR, and total solar irradiance from ground-based radiometers will not be easier than that of the 2 Cimel channels.

It is evident from this research that the amplitude of variation in solar irradiance is unlikely to be captured from ground-based estimates. Nonetheless, how the solar variability can influence the Earth's climate remains still challenging. Continued monitoring of TSI and SSI is one of the major objectives of the EOS (Earth Observing System) program (Woods et al., 2000). The launch of the SORCE (Solar Radiation and Climate Experiment) satellite late this year starts a new era of Sun–Earth climate research. State-of-the-art instruments on SORCE will provide precise TSI, ultraviolet SSI, and visible and near infrared SSI measurements that have never been made before. Data from SORCE will help us to understand and predict the effects of solar radiation on Earth's atmosphere and climate.

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