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Limitations of ground-based solar irradiance estimates due to atmospheric variations

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[1] The uncertainty in ground-based estimates of solar irradiance is quantitatively related to the temporal variability of the atmosphere's optical thickness. The upper and lower bounds of the accuracy of estimates using the Langley plot technique are proportional to the standard deviation of aerosol optical thickness (approximately $\pm 13\sigma(\delta\tau)$). The estimates of spectral solar irradiance in two Cimel Sun photometer channels at 340 and 380 nm from the Mauna Loa site of the Aerosol Robotic Network are compared with satellite observations from the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) on the Upper Atmospheric Research Satellite for almost 2 years of data. The true solar variations related to the 27-day solar rotation cycle observed from SOLSTICE are ~0.15% at the two Sun photometer channels. The variability in ground-based estimates is statistically 1 order of magnitude larger. Even though ~30% of these estimates from all Level 2.0 Cimel data fall within the 0.4–0.5% variation level, ground-based estimates are not able to capture the 27-day solar variation observed from SOLSTICE. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 0343 Atmospheric Composition and Structure: Planetary atmospheres (5405, 5407, 5409, 5704, 5705, 5707); 1640 Global Change: Remote sensing; 1650 Global Change: Solar variability; *KEYWORDS:* Langley plots, aerosols, AERONET, SORCE, SOLSTICE

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1. Introduction

[2] Solar radiation is the major energy source for Earth's biosphere. Solar radiation directly affects physical, chemical, and biological processes on the Earth. It is the direct forcing for atmospheric and oceanic circulations and climate. Understanding this input energy is crucial for understanding the processes of the Earth-atmosphere system. The total solar irradiance (TSI) at the mean Sun-Earth distance (1 AU) had been known as the solar "constant" until satellite observations of the 1980s and 1990s made its variations evident. Before the satellite era, solar irradiance was estimated from ground-based radiometers using the traditional Langley plot method.

[3] Systematic ground-based observations of variability of TSI trace back to the Smithsonian Astrophysical Observatory Solar Constant Program established 100 years ago [*Hoyt*, 1979]. In the first half of the twentieth century, a great deal of effort was made to estimate the change of TSI from ground-based measurements and its possible effect on Earth's climate. Both long-term variations associated with the sunspot cycle [*Abbot*, 1958], and short-term fluctuations over days or weeks [*Clayton*, 1923] were reported. However, a firm belief that the TSI is invariant was established in some circles [*Mitchell*, 1965]. Efforts were also made to measure the TSI from rocket and high-altitude balloons and aircraft in the 1960s and 1970s as reviewed by *Willson* [1984]. Whether or not TSI is actually constant, or how it might vary, was much debated before satellite observations answered affirmatively.

[4] Unaffected by atmospheric effects, only satellite observations truly reveal the variation of TSI associated with magnetic activity of the Sun [*Hudson*, 1988; *Lean*, 1997; *Willson*, 1984; *Willson and Hudson*, 1991]. Variations related to the 11-year sunspot cycle, 27-day solar rotation cycle, and daily variability of solar irradiance have been observed from a variety of satellites as summarized by *Fröhlich and Lean* [1998].

[5] Solar irradiance as a function of wavelength is referred to as "spectral solar irradiance" (SSI). The observations from the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) on the Upper Atmospheric Research Satellite (UARS) reveal variation of SSI, the amplitude of which depends on the wavelength [*Lean*, 1997; *London et al.*, 1992; *Woods et al.*, 2000].

[6] In the meantime, ground-based radiometers have also undergone great advancement. A worldwide Sun photometer network, the Aerosol Robotic Network (AERONET),

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has been established to observe the turbidity of the atmosphere [*Holben et al.*, 1998]. Quality-assured data sets are available on a daily basis from the AERONET Web site. The availability of daily observations of exo-atmospheric SSI from satellites, and ground-based estimates of SSI (excluding cloudy days), makes it possible to compare the two directly.

[7] The major limitation to the accuracy of ground-based estimates of solar irradiance is the variation of atmospheric optical properties. Much research has been devoted to the study of the effects of the variability of the atmosphere and other factors on the solar irradiance observed by ground-based radiometers [*Ångström*, 1970; *Shaw*, 1976, 1983; *Reagan et al.*, 1986; *Russell et al.*, 1993; *Schmid and Wehrli*, 1995]. However, determining how the variability of atmospheric optical properties affects the estimate of SSI in the Langley plot regression analysis is not trivial. In this paper, we revisit the outstanding problem that for half a century puzzled pioneer scientists focusing on quantifying the impact of atmospheric variations on ground-based estimates of SSI. We will show that the uncertainty in ground-based estimates of SSI is theoretically related to the temporal variation of the atmosphere. By comparing the true SSI from SOLSTICE observations and from ground-based estimates from Mauna Loa for almost 2 years of data, we will quantitatively demonstrate the inadequacy of ground-based estimates in monitoring solar variations.

[8] Data sets used in this study are described in section 2. Section 3 presents an analytical relationship between ground-based estimates of SSI and physical quantities. Section 4 compares directly measured SOLSTICE SSI values with ground-based estimates of exo-atmospheric SSI in two Sun photometer channels from the AERONET site at Mauna Loa, relatively one of the atmospherically "cleanest" sites. On the basis of the analytical relation presented in section 3, section 5 further presents upper and lower bounds of uncertainty in ground-based estimates of SSI as a function of the variability of the atmosphere. The results are summarized and discussed in section 6.

2. Data Description

[9] We employ daily observations from the SOLSTICE instrument on UARS. The UARS satellite was launched on 12 September 1991 into a near-circular Earth orbit with an inclination angle of 57° to the equator and an altitude near 585 km [*Reber 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. Stellar theory predicts that early-type blue stars are stable in emitting the UV radiation spectrum observed by SOLSTICE. Thus any change observed for a select group of early-type blue stars is interpreted as instrument degradation and determines the SOLSTICE instrument transmission over time, providing relative calibration. A detailed description of the SOLSTICE instrument is given by *Rottman et al.* [1993] and *Woods et al.* [1993]. The observing system is estimated to have an absolute error of <3% and precision of <1%. With correction for the drift in transmission the calibrated SOLSTICE data provide an accurate daily average SSI between 119 and 420 nm at an increment of 1 nm [*Rottman et al.*, 1994].

[10] We consider ground-based SSI estimates from Cimel Sun photometer measurements of AERONET. Started in the early 1990s, AERONET is a federated instrument network and data archive program for aerosol characterization [*Holben et al.*, 1998]. The Cimel Sun photometer 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 the 340-nm channel, 4 nm for the 380-nm channel, and 10 nm for the remaining channels. The Cimel Sun photometer is estimated to have an absolute accuracy of ~5% and precision of <1%. A detailed description of the Cimel Sun photometer system is given by *Holben et al.* [1998]. The automatic robotic AERONET program has grown rapidly to over 100 sites worldwide. In this study we use data from Mauna Loa, Hawaii. At an altitude of 3397 m above sea level in the middle of the Pacific Ocean, the site at Mauna Loa Observatory (19°32′N, 155°34′W) is famous for calibrating radiometer instruments, and is perhaps the "clearest" ground site for inferring exo-atmospheric solar irradiance.

[11] Even at Mauna Loa, atmospheric conditions are not absolutely stable. The marine inversion layer that traps aerosols is often broken through due to upslope winds as a result of mountain surface heating from solar insolation. When upslope winds bring surface aerosols to higher altitude, more variable atmospheric conditions result [*Luria et al.*, 1992; *Ryan*, 1997; *Perry et al.*, 1999; *Shaw*, 1979]. To avoid such variable atmospheric conditions, the Langley plots are applied to early morning (air mass >2) measurements of quality assured Cimel data in this study, where the air mass is the ratio between the slant path and the vertical optical depth [e.g., *Russell et al.*, 1993]. The air mass is approximated by secθ, where solar zenith angle θ may be calculated [e.g., *Michalsky*, 1988]. To reduce the effects of spherical atmosphere, only observations with air mass between 2 and 5 are used in this study. Within that range, air mass appears not sensitive to the curvature effects of the atmosphere [e.g., *Russell et al.*, 1993]. To examine whether ground-based estimates could capture exo-atmospheric SSI variation at the timescale of the 27-day solar cycle, every clear day's data is used.

3. Method

[12] The Langley method works perfectly well when the atmosphere is absolutely stable. In reality, the atmosphere experiences constant changes related to dynamics and chemical processes. Number density fluctuations due to turbulence are expected for aerosols in the path between the Sun photometer and the Sun. These processes cause temporal variations of aerosol optical thickness and consequently affect estimates of solar irradiance based on the Langley plot method described below.

[13] From the Lambert-Beer-Bouguer law, the ground-observed direct solar irradiance F_i at any time step i may be expressed as

$$F_i = F_0 e^{-m_i(\tau_m+\bar{\tau}+\delta\tau_i)} \tag{1}$$

or

$$\ln F_i = \ln F_0 - m_i(\tau_m + \bar{\tau} + \delta\tau_i), \tag{2}$$

where F_0 is exo-atmospheric SSI, m_i is the air mass, τ_m and $\bar{\tau}$ are molecular optical thickness (including scattering and gaseous absorption (e.g., O_3, NO_2)) and average aerosol optical thickness, respectively, during the time period of observations, and $\delta\tau_i$ is the deviation of aerosol optical thickness from the mean. Rayleigh optical thickness is calculated with input of elevation and optical parameters for a standard atmosphere [*Holben et al.*, 1998]. A climatological value is used for O_3 [*London et al.*, 1976]. Because of its negligible impact on inferred aerosol optical thickness, NO_2 absorption is ignored [*Russell et al.*, 1993]. The variability of molecular optical thickness is effectively embedded in $\delta\tau_i$. This is further discussed in section 6.

[14] It is evident that if the atmosphere is absolutely stable ($\delta\tau_i = 0$ for every time step), every point (m_i, $\ln F_i$) lies in a straight line with intercept $\ln F_0$ and slope $-(\tau_m + \bar{\tau})$ in the plot of air mass versus logarithmic solar irradiance. Atmospheric optical properties fluctuate during the observations, and the air mass and the corresponding logarithmic solar irradiance will not strictly follow a straight line. Thus the parameters (i.e., intercept and slope) can only be statistically estimated, with inevitable uncertainties.

[15] The Langley method finds a best fit linear regression line of the form

$$\ln F = \ln F_0' - m(\tau_m + \tau) \tag{3}$$

from a set of N observations of $\ln F_i$ with air mass m_i, molecular optical thickness τ_m, and aerosol optical thickness $\bar{\tau} + \delta\tau_i$ (equation (2)) to estimate the parameters $\ln F_0'$ (the intercept) and τ (the equivalent aerosol optical thickness). This is practically performed in the early morning observations on a timescale of couple of hours. The estimated F_0' usually differs from the true value F_0. Here we demonstrate that the estimate of exo-atmospheric solar irradiance may be expressed as a function of meaningful physical quantities.

[16] In the fitting process both $\ln F_0'$ and τ are determined by minimizing the sum of squared residuals (equation (4))

$$J = \sum_{i=1}^{N} \left[\left(\ln F_0' - m_i(\tau_m + \tau) \right) - \left(\ln F_0 - m_i(\tau_m + \bar{\tau} + \delta\tau_i) \right) \right]^2 \tag{4}$$

After a simple mathematical manipulation we obtain

$$\ln\left(\frac{F_0'}{F_0}\right) = \frac{\overline{m^2}\,\overline{m}}{\overline{m^2} - \overline{m}^2} Cov(M, \delta\tau) \tag{5a}$$

or

$$\ln\left(\frac{F_0'}{F_0}\right) = \frac{\overline{m^2}\,\overline{m}}{\overline{m^2} - \overline{m}^2} \rho(M, \delta\tau)\sigma(M)\sigma(\delta\tau), \tag{5b}$$

where

$$\overline{m} = \frac{1}{N} \sum_{i=1}^{N} m_i \tag{6a}$$

$$\overline{m^2} = \frac{1}{N} \sum_{i=1}^{N} m_i^2 \tag{6b}$$

$$M_i = \frac{m_i^2}{\overline{m^2}} - \frac{m_i}{\overline{m}}. \tag{6c}$$

$Cov(M, \delta\tau)$ and $\rho(M, \delta\tau)$ are covariance and correlation coefficient of M and $\delta\tau$, and $\sigma(M)$ and $\sigma(\delta\tau)$ are standard deviations of M and $\delta\tau$ as defined below.

$$Cov(M, \delta\tau) = \frac{1}{N} \sum_{i=1}^{N} M_i \delta\tau_i \tag{6d}$$

$$\rho(M, \delta\tau) = \frac{Cov(M, \delta\tau)}{\sigma(M)\sigma(\delta\tau)} \tag{6e}$$

$$\sigma(M) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} M_i^2}\ ; \quad \sigma(\delta\tau) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \delta\tau_i^2}. \tag{6f}$$

[17] It is evident from equation (5b) that the estimated exo-atmospheric SSI F_0' will deviate from the true value F_0 unless the atmosphere is absolutely stable (i.e., $\sigma(\delta\tau) = 0$), or M and $\delta\tau$ are not correlated (i.e., $\rho(M, \delta\tau) = 0$).

[18] In practice, the calibration coefficient (V_0, instrument voltage for direct normal solar flux extrapolated to the top of the atmosphere [*Shaw*, 1983; *Holben et al.*, 1998]) is used for F_0 instead of the true solar irradiance. An instrument is typically calibrated every 2 to 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 value due to variations of exo-atmospheric solar irradiance. However, aerosol optical thickness in equations (5a) and (5b) is only acting as a surrogate for the observed irradiance, as determined by equation (1), so the right hand side of equation (5) is fully determined by the observed irradiance and air mass.

[19] Expressing the Langley estimate F_0' as in equations (5a) and (5b) has two advantages. First, the relative change of exo-atmospheric solar irradiance from the Langley estimate is clearly related to geometric and physical quantities (i.e., air mass and optical thickness). Second, the relative value F_0' can be compared with the SOLSTICE relative value (e.g., relative to the mean) without worrying about absolute calibration, as explained in section 4.

4. Comparison

[20] Even though AERONET started in the early 1990s, only later in the decade did it become sufficiently stable to provide daily measurements at some sites. Starting from 1998, the Mauna Loa site has provided daily measurements. Here data from 1998 to 1999 are compared.

[21] SOLSTICE data provide SSI in units of Wm^{-3}, while Langley plots are in terms of voltage values. Both spaceborne and ground-based instruments face a time deg-

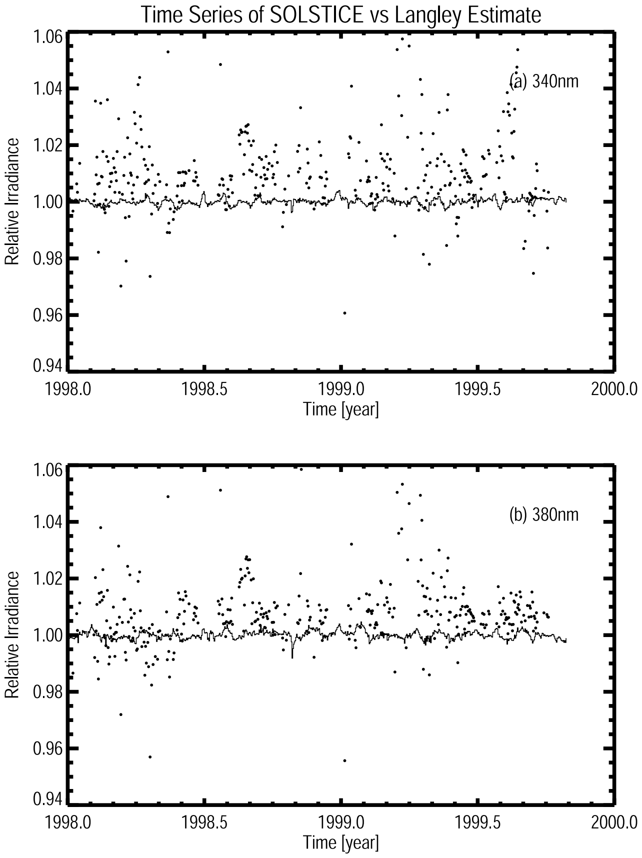

Figure 1. Time series of the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) observed (lines) and ground-based estimated (dots) solar irradiance at (a) 340 nm and (b) 380 nm with total number of days of 666 for SOLSTICE (from 1 January 1998 to 28 October 1999). There are 360 days available in the Level 2.0 Cimel data set to perform the Langley analysis.

radation problem. SOLSTICE uses stable blue stars as a reference to resolve the instrument drift. The Cimel Sun photometer uses the Sun as a standard candle to recalibrate every 2 to 3 months. To make a meaningful comparison, we examine their relative values. SOLSTICE data binned to the same band pass of Cimel channels is normalized by the average value of the entire time period. Langley plot estimates are normalized by the calibration voltage as determined in equation (5a).

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

[23] The variation of the SOLSTICE observations, defined as the standard deviation divided by the mean, is 0.12% and 0.14% in the 340 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 an order of magnitude larger than the true solar variation observed by SOLSTICE.

[24] The variation from the mean in SOLSTICE irradiance can reach 0.5% in both channels. This variation is clearly not detected from the ground-based estimates as demonstrated in Figure 1. The large variation in the estimates is primarily due to the variation in atmospheric aerosols as discussed in section 5.

[25] Scatterplots of SOLSTICE observations and ground-based estimates are presented in Figure 2. Ground-based estimates are not correlated with the true SSI from satellite as expected from Figure 1. The correlation coefficients are calculated for the days when both SOLSTICE and ground-based data are available, excluding outliers of ground-based

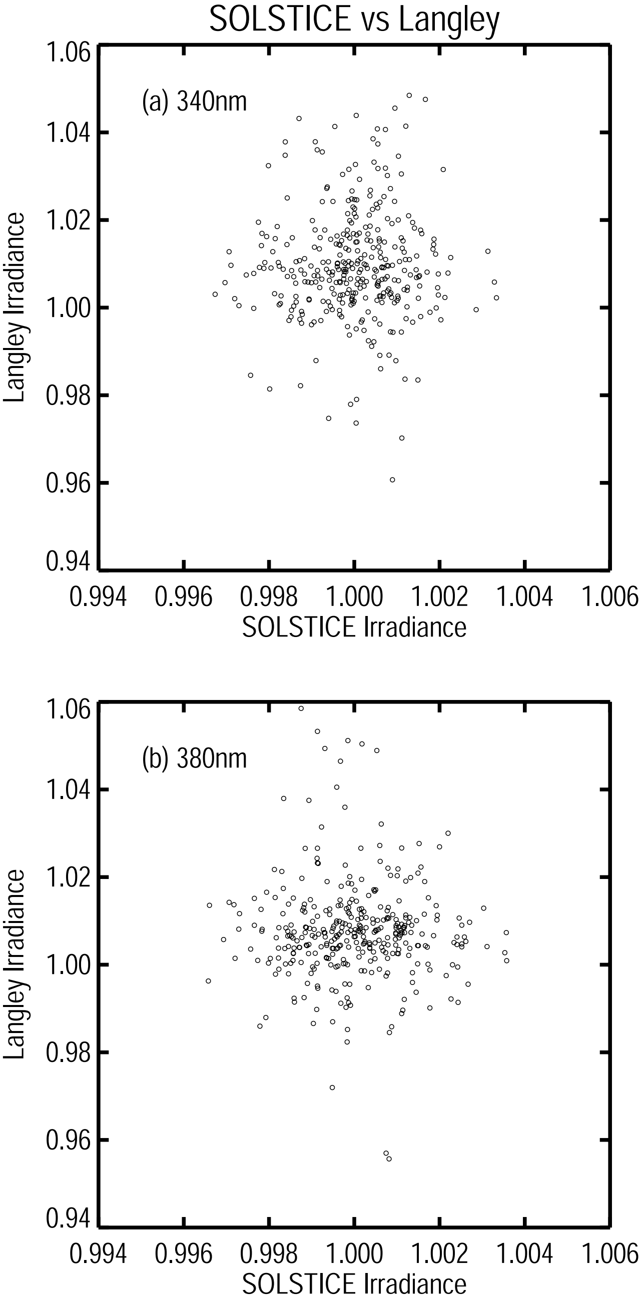

Figure 2. The scatterplot of SOLSTICE-observed and ground-based estimated solar spectral irradiance at (a) 340 nm and (b) 380 nm.

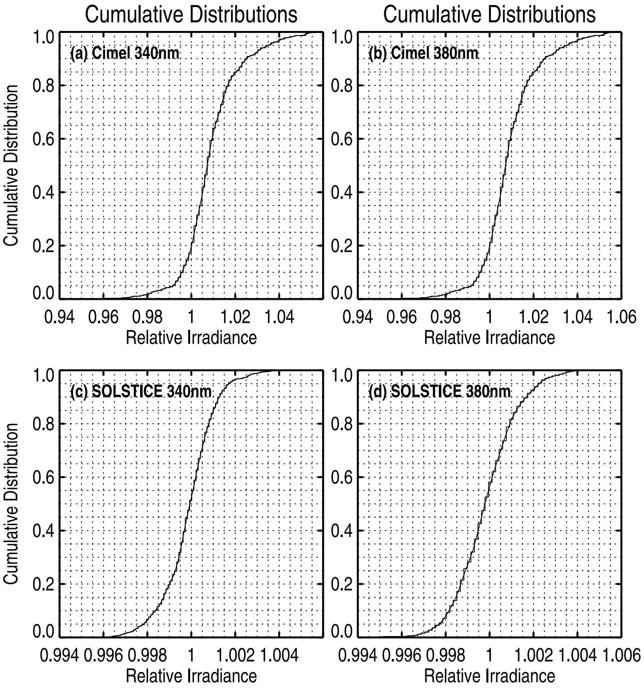

Figure 3. The cumulative distribution of (a, b) ground-based estimated and (c, d) SOLSTICE-observed solar spectral irradiance at 340 nm and 380 nm.

estimated data ($F_0'/F_0 \le 0.94$ or $F_0'/F_0 \ge 1.06$). The cutoff value of ±6% is somewhat arbitrary to exclude only extreme values. The correlation coefficient is found to be 0.028 with 341 pairs of samples, and −0.036 with 351 pairs of samples, for the 340 and 380 nm channels, respectively. It can be shown that the correlation coefficients are too small to be significant [*Alder and Roessler*, 1964]. Thus the ground-based estimates and the true SSI are not correlated. Ground-based estimates cannot statistically capture the signature of true variations of SSI.

[26] It is interesting to examine the distributions of ground-based estimates and satellite observations. The cumulative distribution of the relative irradiance is presented in Figure 3 for both SOLSTICE observations and ground-based estimates. The two distributions for ground-based estimates are very similar (Figures 3a and 3b), as are the two for SOLSTICE (Figures 3c and 3d). The SOLSTICE data are almost symmetrically distributed, with the median close to the mean. In contrast, the Cimel estimated data are evidently asymmetrically distributed with 80 and 20% of data points above and below the reference calibration voltage, respectively, for both channels (Figures 3a and 3b). The obvious difference between the two distributions indicates that the mechanisms influencing them are different, as discussed in section 6.

[27] To evaluate the possibility that ground-based estimates are good enough to capture the evident variation of exo-atmospheric SSI, we need to examine the probabilities of both events occurring. The probability that SOLSTICE irradiance anomalies exceed the typical variability of ~0.15% up to ~0.3% is ~17% (i.e., the bottom 10 and top 7 percentiles in Figures 3c and 3d). The chance that Cimel estimated SSI deviates <0.3% from the calibration coefficient is ~20% (from 12 to 30 percentiles in Figures 3a and 3b). Because there are ~300 cloudy days (about half of the total available days in SOLSTICE) excluded in the Level 2.0 Cimel data, ~10% of the entire time period occurs when ground-based estimates are <0.3% deviation from the reference. Because the variation of true solar irradiance is not correlated with ground-based estimates, the likelihood that the ground-based estimate captures all solar irradiance variations is <2% (i.e., 17 × 10%).

5. Limitation Due to the Atmosphere

[28] The comparison in section 4 demonstrates that variations in SSI are unlikely to be detectable from ground-based estimates. This section presents the physical reasons for the limitation of ground-based estimates of variations of SSI.

[29] As mentioned earlier, if the atmosphere is absolutely stable, then SSI can be obtained accurately. This is clearly shown in equations (5a) and (5b). It is interesting to consider to what extent variations of the atmosphere could affect the estimation of SSI.

[30] From Schwarz's inequality [*Feller*, 1971] we have $\sigma(M)\sigma(\delta\tau) \le Cov(M, \delta\tau) \le \sigma(M)\sigma(\delta\tau)$ or $-1 \le \rho(M, \delta\tau) \le 1$. Equation (5a) yields

$$-c\ \sigma(\delta\tau) \le \ln\left(\frac{F_0'}{F_0}\right) \le c\ \sigma(\delta\tau), \tag{7a}$$

where

$$c = \frac{\overline{m^2}\,\overline{m}}{\overline{m^2} - \overline{m}^2}\sigma(M).$$

Typically $\frac{\Delta F_0}{F_0} = \frac{F_0' - F_0}{F_0}$ is $\ll 1$, so that equation (7a) can be approximated as

$$-c\ \sigma(\delta\tau) \le \frac{\Delta F_0}{F_0} \le c\ \sigma(\delta\tau). \tag{7b}$$

[31] Since c may be predetermined from the air mass at each time step, the error in estimates of SSI is bounded by c times the temporal standard deviation of aerosol optical thickness. Note that c is not sensitive to the resolution of either time step or air mass step in the air mass range concerned.

[32] The exo-atmospheric SSI also varies with time as mentioned earlier, and this introduces uncertainty in the estimates. This uncertainty may be accounted for by adding a small correction term $\Delta = \ln(F_0/F_t)$ in equation (7b)

$$-c\ \sigma(\delta\tau) + \Delta \le \frac{\Delta F_0}{F_t} \le c\ \sigma(\delta\tau) + \Delta, \tag{7c}$$

where

$$\frac{\Delta F_0}{F_t} = \frac{F_0' - F_t}{F_t},$$

and F_t is the true exo-atmospheric SSI on any given day. Even though the small correction term $\Delta = \ln(F_0/F_t)$ in equation (7c) may be estimated from the SOLSTICE data,

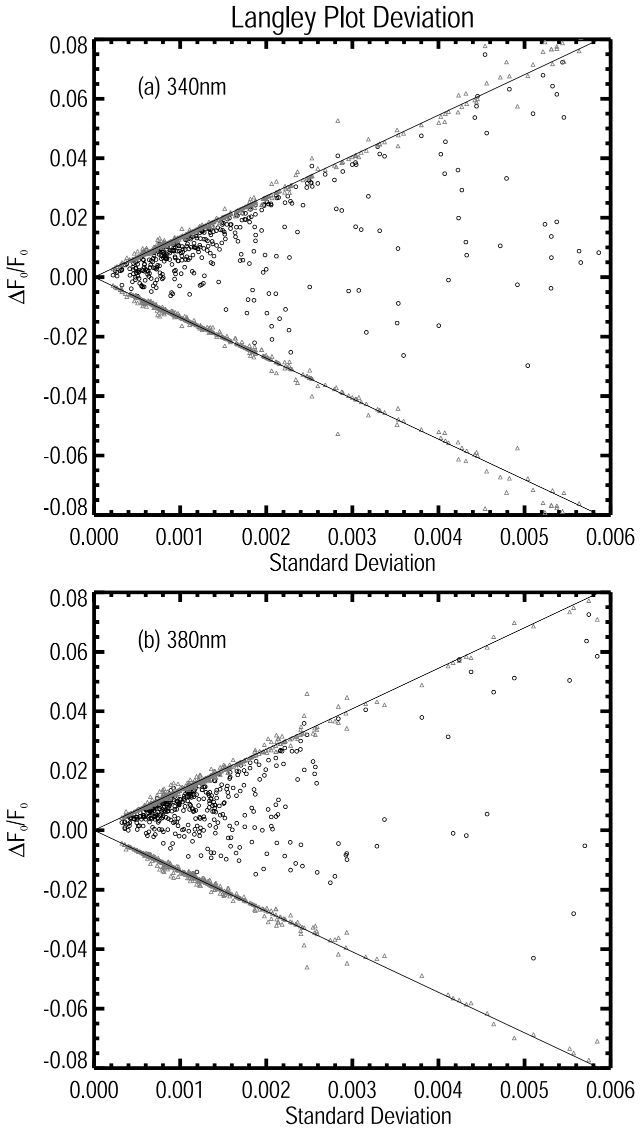

Figure 4. The deviation of solar spectral irradiance estimated from Langley plots as a function of standard deviation of aerosol optical thickness at (a) 340 nm and (b) 380 nm.

the relative difference from equations (7a) or (7b) is sufficient to demonstrate the effects of the temporal variation of aerosols on the estimates of SSI from ground-based radiometers.

[33] The relative difference of ground-based estimates of SSI compared to the reference value is presented in Figure 4 for both 340- and 380-nm channels. The open circles in Figure 4 represent the deviation of the estimate of SSI from the reference value for each day. The shaded triangles in Figure 4 are the upper and lower bounds for the deviation of the estimate of each day defined in equation (7b). Taking the mean value of c ($\sim$13.5) as the slope (positive and negative), two lines passing though the origin give the upper and lower bound of the deviations. Thus the relative error in SSI is $\sim$1 order of magnitude larger than the temporal variability of aerosol optical thickness during the time period of observations.

[34] It is interesting to note that the atmosphere always varies, as can be seen from the nonzero standard deviation of aerosol optical thickness. Hence the associated uncertainty of estimates of SSI is always present. By chance M and $\delta\tau$ may be nearly uncorrelated on some occasions, resulting in a small deviation of the estimates (equation (5b)). Such situations may not be relied on because it is unlikely that M and $\delta\tau$ will be nearly uncorrelated every day throughout a given 27-day solar rotation period. Therefore the accuracy of the best estimate is $\sim$0.4 and 0.5%, corresponding to the minimum aerosol standard deviation of 0.0003 and 0.0004, for the 340- and 380-nm channels, respectively (Figures 4a and 4b).

[35] The error in the estimates does not have a good correlation with the mean aerosol optical thickness as demonstrated in Figure 5. Even if the aerosol loading is relatively large, the Langley technique can give accurate estimates of solar irradiance as long as the atmosphere is

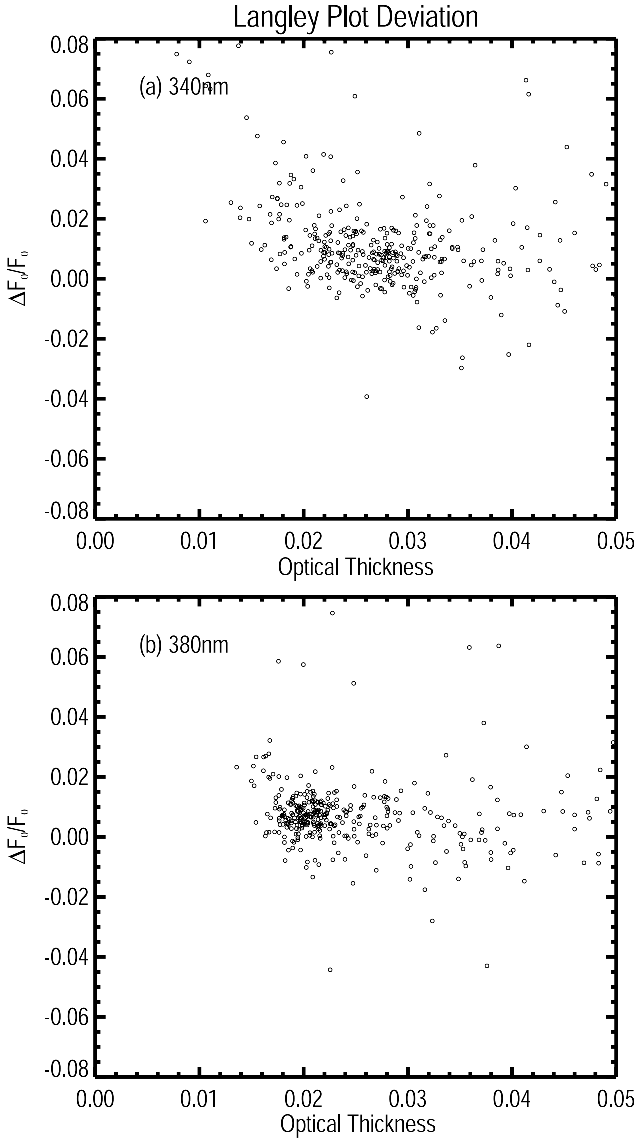

Figure 5. The deviation of solar spectral irradiance estimated from Langley plots as a function of aerosol optical thickness at (a) 340 nm and (b) 380 nm.

stable. Small aerosol loading is not a sufficient condition for obtaining a reliable ground-based estimate. A systematic trend in aerosol optical thickness may provide a nearly linear Langley plot but still result in wrong zero-air-mass voltages, as demonstrated by *Shaw* [1983]. Note that average aerosol loading over Mauna Loa is generally small. Within a small range of average aerosol optical thickness the standard deviation is expected not to have a strong correlation with the average value. Even for large aerosol optical thickness, a slightly higher or lower average loading does not necessarily correspond to a larger or smaller standard deviation. In rural regions, where the range of average aerosol optical thickness is preferentially large, so is the variability. In that case, a different relation is expected. Nevertheless, even here it is the variation of the atmosphere that truly constrains the accuracy of the estimates (equation (7a)).

6. Summary and Discussion

[36] An analytical relationship between ground-based estimates of exo-atmospheric SSI and meaningful physical quantities (i.e., air mass and aerosol optical thickness) is derived (equation (5a)). 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 (approximately $\pm 13\sigma(\delta\tau)$) (equation 7b). Since there are no assumptions regarding the wavelength in the derivation, the relations (equations (5) and (7)) may be applied to narrow or broad band. Not just for aerosols, the relations may also be use to analyze the effects of any other scattering and absorbing constituents.

[37] Ground-based estimates require clear atmospheric conditions. However, having a clear atmosphere is not sufficient. ‘‘clear sky’’ refers to a cloudless atmospheric condition. The factor that truly constrains the accuracy of ground-based estimates of SSI is the variability of the clear atmosphere. The constantly changing atmosphere due to physical, chemical, and dynamical processes imposes a limitation of ground-based estimates of SSI. The accuracy of estimates achievable is ~0.4% for the two Cimel channels (340 and 380 nm) at perhaps the most favorable ground site at Mauna Loa under the most favorable stable atmospheric condition.

[38] Estimates of SSI from Cimel Sun photometers at the Mauna Loa site are compared with the true values from SOLSTICE observations for almost 2 years of data. Standard deviations of SOLSTICE SSI values are ~0.15% for both the 340- and the 380-nm channels. The variability of ground-based counterparts is statistically 1 order of magnitude larger. The SOLSTICE and ground-based values are not statistically correlated.

[39] Even though there are some occasions when the estimated SSI has very small variation (Figure 1), the ground-based estimates fail to capture the 27-day cycle-related solar variation. There are several factors that contribute to the reason why it is so difficult to monitor the variation of exo-atmospheric SSI from the ground. First, the signal itself (i.e., the variation in exo-atmospheric SSI) is very small (~0.15%) [e.g., *Lean*, 1997]. Second, the exo-atmospheric SSI variation has a 27-day cycle related to solar rotation with variable amplitude [e.g., *Lean*, 1997]. Third, the atmospheric variation inevitably imposes an uncertainty in the ground-based estimates as expressed in equations (5a) and (7a). Fourth, the variability of atmospheric properties is due to dynamics, chemical, and physical processes in the Earth-atmosphere system, which are physically independent of the 27-day solar variation. The Langley plot technique applies to early morning time periods with a scale of a couple of hours (no later mornings or afternoons, cloudy days, or nighttime). Unless the favorable atmospheric condition happens to occur at the peak or valley of the 27-day solar variation, or to persist throughout the 27-day cycle, the solar variation in this timescale is unlikely to be captured from ground-based estimates. Since the likelihood to detect all solar irradiance variations is so small (<2%) as discussed in section 4, even combining several potential favorable ground sites together will not significantly improve the ability to detect the solar variation.

[40] In addition to atmospheric variations, instrument variability and stability also inevitably contribute to the uncertainties in the ground estimates. Entangling with uncertainties due to atmospheric variations, instrument variability, and stability make additional difficulties for the ground estimates. There may not be a simple way to characterize this type of uncertainty. Even if the instrument technology is much advanced, data analysis must be carefully performed to reduce the instrumental effects. A great deal of effort (data quality checks, stability checks, cloud screening, etc.) was made to provide the quality assured Level 2.0 Cimel data used in this research (http://aeronet.gsfc.nasa.gov/). There is no doubt that the uncertainty in the instrument calibration coefficient (V_0 or F_0 in section 3), instrument variability, and instrument stability affect the derivation of true aerosol optical thickness and its variation. To minimize the impact of instrument-related uncertainty, we analyze the ratios for both data sets. The time series of the ratios allows us to examine the relative variation of both ground-based estimates and satellite-observed exo-atmospheric solar irradiance. The Cimel instrument is just one example of current instrument capability for this kind of work. Other instruments’ performances could vary and may be used to improve the analysis. However, for a long time series, the statistics should not differ too much, because any instruments face similar time degradation problem. The analysis of the ratio may not remove instruments effects entirely. As a matter of fact, the asymmetric distributions in the estimated SSI in the two Cimel channels (Figures 1 and 3) indicate systematic behavior of either the atmosphere or the instrument, or both. However, to exactly characterize the instrument variability and stability requires further research.

[41] In Sun photometry a constant molecular optical thickness is assumed in deriving aerosol optical thickness. In the real world the molecular optical thickness for both scattering and absorption (e.g., O_3 and NO_2) is also subject to temporal variation. Since the Sun photometer channels are carefully chosen to avoid strong gaseous absorption, the variability of molecular optical thickness is expected to be much smaller than that of aerosols. Efforts could be made to correct for molecular optical thickness variation, such as Rayleigh scattering. There are two situations we need to consider: First, the atmospheric conditions are steady with time, with surface pressure that only differs by a constant from the climatology. Second, the atmospheric conditions

change with time during Langley plot observations, such as a weather system passing though or turbulence fluctuations. For the first situation the Rayleigh optical thickness may be corrected by adding a term computed from surface pressure measurements. Adding this correction term for Rayleigh optical thickness is equivalent to taking away the same amount optical thickness from the average aerosol optical thickness. This does not contribute to the variation of the atmosphere (equation (1)) and does not affect the Langley plot estimates. Thus the correction is not necessary. For the second situation the correction for the Rayleigh optical thickness requires observations along the path between the instrument and the Sun at each time step and may not be easily achieved. This is true for any other gaseous absorption and aerosol extinction. In this situation we may even find that vertical profiles of aerosol and other constituents observed by lidar are not very helpful to determine variations along the trajectory between the instrument and the Sun. For simplicity and generality we consider all time-dependent variations of molecular scattering and gaseous absorption to be intrinsically embedded in the standard deviation of aerosol optical thickness to describe the variability of the atmosphere.

[42] Detection of the 11-year cycle in wavelengths longer than 300 nm from SOLSTICE is limited by insufficient long-term precision of the instrument (~1%) [*Lean*, 1997]. Ground-based instruments also degrade and require calibration every 2 to 3 months [*Holben et al.*, 2001]. If the detection of short-term variations of SSI is unlikely, the monitoring of long-term variability is even more difficult from ground-based estimates.

[43] Because of the larger influence on shorter wavelengths of the Rayleigh scattering, and the characteristic wavelength dependence of aerosol optical properties, the two UV channels of Cimel are expected to have the largest atmospheric effects. Even though Rayleigh and aerosol optical thickness vary less in longer wavelengths, large variability in water vapor increases the impact of atmospheric optical property variations on broadband solar radiation, making additional uncertainties in estimates of the TSI.

[44] We emphasize that the inability to detect solar variations from ground-based radiometers is not due to any unusual pollution in Mauna Loa atmospheric conditions. The problem is that the clean and stable atmospheric conditions required to detect small exo-atmospheric SSI variations do not persist through a 27-day solar rotation cycle even at the relatively pristine Mauna Loa site. This does not detract from selected Mauna Loa Langley plot calibrations for Sun photometry. Indeed during ~30% of all days in Level 2.0 Cimel data (i.e., 10 to 40 percentile in Figure 3) ground-based estimates could provide 0.4–0.5% accuracy of zero-air mass voltages as required for determining optical thickness from Cimel Sun photometers [*Holben et al.*, 2001]. We also need to point out the potential use of ground-based estimates. For example, the ground-based estimates in very clean and stable atmospheric conditions might be used to investigate solar variations from one minimum to another when the Sun is relatively inactive for the interest of monitoring long term change. Knowing the 27-day solar rotation, one may select days to avoid the expected large 27-day variation in TSI and/or SSI.

[45] One hundred years have passed since the Smithsonian Astrophysical Observatory Solar Constant Program started in 1902 [*Hoyt*, 1979]. Even though the program itself failed to measure the variation of TSI, it has stimulated the development of Sun-Earth's climate science discipline. It has lead to spaceborne observation of TSI and SSI and, consequently, the discovery of inconstancy of solar energy. Motivated by this challenging problem, this research has provided the theoretical basis of uncertainty limitations due to atmosphere variations. Nonetheless, the influence of solar variability on the Earth's climate remains a challenge. Continued monitoring of the TSI and SSI is a primary requirement of the Earth Observing System program [*Woods et al.*, 2000]. The launch of the Solar Radiation and Climate Experiment satellite early in 2003 starts a new era of Sun-Earth climate research. Short timescale variations of solar irradiance may have relatively little influence on Earth's climate. Because variations of solar energy occur on a timescale of a decade (or longer), revealing the influence of solar variation on Earth's climate requires long-term observations from space.

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