Limitation of Ground-based Estimates of Solar Irradiance Due to Atmospheric Variations

Guoyong Wen, Robert F. Cahalan, and Brent N. Holben

For submission to *Journal of Geophysical Research*

Popular Summary

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.

Before the satellite era, solar input energy at the top of the atmosphere, or exo-atmospheric solar irradiance, was estimated from ground-based radiometers using the traditional Langley Plot method in clear atmospheric condition. In Langley Plot analysis, one plots out the "path" that light goes through in the atmosphere and solar irradiance (in logarithmic scale) observed at each time step of observation. When the sky is clear and clean, the plot is nearly a straight line. Then one extrapolates the line to zero "path" to estimate exo-atmospheric solar irradiance. Langley Plot method is named after Samuel P. Langley who introduced this method in early 1900s. This method works perfectly well when atmospheric conditions are absolutely stable (i.e., uniform in space and time). Absolute stable atmospheric condition does not happen in the real world. An example of that is star twinkle in a clear and clean night. The Nature fluctuation of the atmosphere makes the star looks a little brighter or darker when there is little bit less or more molecules and aerosols along the path between the surface observer and the star. Therefore exo-atmospheric solar irradiance can only be estimated by extrapolating a best-fit line to zero "path".

Great efforts were made in the first half of the last century to estimate exo-atmospheric solar irradiance from ground-based radiometers. All attempts failed. Without atmospheric effects, satellite observations of the 1980s and 1990s truly reveal the variations of the solar irradiance with time.

It is well known that the variation of the atmospheric conditions has a major impact on the ground-based estimates. But no one has ever quantified such impact. This paper quantitatively describes the relation between uncertainty in the ground-based estimates and the variation of the atmosphere. Then the directly observed solar irradiances from SOLSTICE (Solar Stellar Irradiance Comparison Experiment) on UARS (Upper Atmosphere Research Satellite) are compared with the ground-based estimates from the AERONET site at Mauna Loa for almost two years of data. We conclude the inadequacy of ground-based estimates in monitoring solar variations.

The launch of the SORCE (Solar Radiation and Climate Experiment) in January 2003 starts a new era of Sun – Earth climate research. Since variations of solar energy occur on a time scale of decade (or longer), revealing the influence of solar variation on Earth's climate requires long-term observations from space.

Limitation of Ground-based Estimates of Solar Irradiance Due to Atmospheric Variations

GUOYONG WEN[1 2]
ROBERT F. CAHALAN[2], AND BRENT N. HOLBEN[2]

Joint Center for Earth Systems Technology, Univ. of Maryland Baltimore County
and
Laboratory for Atmospheres, NASA Goddard Space Flight Center

For submission to *Journal of Geophysical Reseach* (*Atmosphere*)

[1] Joint Center for Earth Systems Technology, U. of Maryland Baltimore County, Maryland.
[2] NASA Goddard Space Flight Center, Greenbelt, Maryland

Corresponding author address:
Dr. Guoyong Wen
NASA/GSFC
Climate and Radiation Branch
Greenbelt, MD 20771

Authors - Dr. Guoyong Wen

NASA/Goddard/913

Greenbelt, MD 20771

(301) 614-6220

(301) 614-6307 (fax)

wen@climate.gsfc.nasa.gov

Dr. Robert F. Cahalan

NASA/Goddard/913

Greenbelt, MD 20771

(301) 614-5390

cahalan@climate.gsfc.nasa.gov

Dr. Brent N. Holben

NASA/Goddard/923

Greenbelt, MD 20771

(301) 614-6658

brent@ltpmail.gsfc.nasa.gov

ABSTRACT

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 ($\sim \pm 13\sigma(\delta\tau)$). The estimates of spectral solar irradiance (SSI) in two Cimel sun photometer channels from the Mauna Loa site of AERONET are compared with satellite observations from SOLSTICE (Solar Stellar Irradiance Comparison Experiment) on UARS (Upper Atmospheric Research Satellite) for almost two years of data. The true solar variations related to the 27-day solar rotation cycle observed from SOLSTICE are about 0.15% at the two sun photometer channels. The variability in ground-based estimates is statistically one order of magnitude larger. Even though about 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.

1. Introduction

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.

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 20th 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 [cf. 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.

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].

Solar irradiance as a function of wavelength is referred to as "spectral solar 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 which depends on the wavelength [Lean, 1997; London et al., 1992; Woods et al., 2000].

In the meantime, ground-based radiometers have also undergone great advancement. A worldwide sun photometer network, AERONET, 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 website. 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.

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; Shaw, 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 puzzled pioneer scientists for half a century 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 that from ground-based estimates from Mauna Loa for almost two years of data, we will quantitatively demonstrate the inadequacy of ground-based estimates in monitoring solar variations.

Data sets used in this study are described in Section 2. Sections 3 presents an analytical relationship between ground-based estimates of SSI and physical quantities. Section 4 compares ground-based estimates of exo-atmospheric SSI in two sun photometer channels from the best AERONET site at Mauna Loa with directly measured values from SOLSTICE. Based on 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

We employ daily observations from the SOLSTICE instrument on UARS. 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 [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 determine the SOLSTICE instrument transmission over time, providing relative calibration. A detailed description of the SOLSTICE instrument can be found in 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 accurate daily average SSI between 119 and 420 nm at an increment of 1 nm [Rottman et al., 1994].

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. A detailed description of the Cimel sun photometer system is given by Holben et al. [1998]. The Cimel sun photometer is estimated to have an absolute accuracy of ~5% and <1% for precision. 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 3397m above sea level in the middle of 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.

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 (airmass > 2) measurements of quality assured Cimel data in this study. To examine whether ground-based estimates could capture exo-atmospheric SSI variation at the time scale of the 27-day solar cycle, every clear day's data is used.

3. Method

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.

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

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

or

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

where F_0 is exo-atmospheric SSI, m_i is the airmass, τ_m and $\overline{\tau}$ 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.

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 $-(\tau_m + \overline{\tau})$ in the plot of airmass versus logarithmic solar irradiance. Atmospheric optical properties fluctuate during the observations, and the airmass 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.

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 airmass m_i, molecular optical thickness τ_m, and aerosol optical thickness $\bar{\tau} + \delta\tau_i$ (cf. Eq. (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 time scale 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.

In the fitting process, both $\ln F_0^{'}$ and τ are determined by minimizing the sum of squared residuals (Eq. 4).

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

After a simple mathematical manipulation, we obtain

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

or

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

where

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

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

$$M_i = \frac{m_i^2}{\overline{m^2}} - \frac{m_i}{\overline{m}} \qquad (6c)$$

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

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

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

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

It is evident from Eq. (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., $\rho(M,\delta\tau) = 0$).

In practice, a reference value of 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 so 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 Eqs. (5a,b) is only acting as a surrogate for the observed irradiance, as determined by Eq. (1), so that the right hand side of Eq. (5) is fully determined by the observed irradiance and airmass.

Expressing the Langley estimate $F_0^{'}$ as in Eqs. (5a,b) 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., airmass 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 the following section.

4. Comparison

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.

SOLSTICE data provide SSI in units of Wm^{-3}, while Langley Plots are in terms of voltage values. Both space borne and ground-based instruments face a time degradation 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 Eq. (5a).

The time series of relative irradiance from SOLSTICE and that 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 Cimel data set, cloud screened and data quality controlled, has gaps during the same time period, with a total of 360 days of data.

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

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 Fig. 1. The large variation in the estimates is primarily due to the variation in atmospheric aerosols as discussed in Section 5.

Scatter plots of SOLSTICE observations and ground-based estimates are presented in Fig. 2. Ground-based estimates are not correlated with the true SSI from satellite as expected from Fig. 1. The correlation coefficients are calculated for the days when both SOLSTICE and ground-based data are available, excluding outliers of ground-based estimated data ($\frac{F_0'}{F_0} \le 0.94$ or $\frac{F_0'}{F_0} \ge 1.06$). 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 nm 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.

It is interesting to examine the distributions of ground-based estimates and satellite observations. The cumulative distribution of the relative irradiance is presented in Fig. 3 for both SOLSTICE observations and ground-based estimates. The two distributions for ground-based estimates are very similar (Fig. 3a,b), as are the two for SOLSTICE (Fig. 3c,d). 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 (Fig. 3a,b). The obvious difference between the two distributions indicates that the mechanisms influencing them are different, as discussed in Section 6.

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 about 17% (i.e., the bottom 10 and top 7 percentiles in Fig. 3c,d). The chance that Cimel estimated SSI deviates <0.3% from the calibration coefficient is about 20% (from 12 to 30 percentiles in Fig 3a,b). Because there are about 300 cloudy days (about half of the total available days in SOLSTICE) excluded in the Level 2.0 Cimel data, approximately 10% of the entire time period occurs when ground-based estimates are less than 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 less than 2% (i.e., 17% x 10%).

5. Limitation due to the atmosphere

The comparison in the previous section 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.

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

From Schwarz' inequality [Feller, 1971], we have

$-\sigma(M)\sigma(\delta\tau) \le Cov(M,\delta\tau) \le \sigma(M)\sigma(\delta\tau)$ or $-1 \le \rho(M,\delta\tau) \le 1$. Eq. (5a) yields

$$-c\ \sigma(\delta\tau) \le \ln(\frac{F_0'}{F_0}) \le c\ \sigma(\delta\tau) \qquad (7a)$$

where $c = \dfrac{\overline{m^2}\ \overline{m}}{\overline{m^2} - \overline{m}^2}\sigma(M)$

Typically $\dfrac{\Delta F_0}{F_0} = \dfrac{F_0' - F_0}{F_0}$ is much less than 1, so that Eq. (7a) can be approximated as

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

Since c may be predetermined from the airmass 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 airmass step in the airmass range concerned.

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 ($\Delta = \ln\frac{F_0}{F_t}$) in Eq. (7b)

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

where $\dfrac{\Delta F_0}{F_t} = \dfrac{F_0' - F_t}{F_t}$, and F_t is the true exo-atmospheric SSI on any given day.

Even though the small correction term ($\Delta = \ln\frac{F_0}{F_t}$) in Eq. (7c) may be estimated from the SOLSTICE data, the relative difference from Eq. (7a) or (7b) is sufficient to demonstrate the effects of the temporal variation of aerosols on the estimates of SSI from ground-based radiometers.

The relative difference of ground-based estimates of SSI compared to the reference value is presented in Fig. 4 for both 340 nm and 380 nm channels. The open circles represent the deviation of the estimate of SSI from the reference value for each day. The gray triangles are the upper and lower bounds for the deviation of the estimate of each day defined in Eq. (7b). Taking the mean value of c (about 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 about one order of magnitude larger than the temporal variability of aerosol optical thickness during the time period of observations.

It is interesting to note that the atmosphere always varies, as can be seen from the non-zero 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 (Eq. (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 approximately 0.4% and 0.5%, corresponding to the minimum aerosol standard deviation of 0.0003 and 0.0004, for the 340 nm and 380 nm respectively (Fig. (4a,b)).

The error in the estimates does not have a good correlation with the mean aerosol optical thickness as demonstrated in Fig. 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 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-airmass voltages, as demonstrated by Shaw [1983]. Also 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 (ef. Eq. (7a)).

6. Summary and Discussion

An analytical relationship between ground-based estimates of exo-atmospheric SSI and meaningful physical quantities (i.e., airmass and aerosol optical thickness) is derived (Eq. (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 ($\sim \pm 13\sigma(\delta\tau)$) (Eq. 7b). Since there are not any assumptions regarding the wavelength in the derivation, the relations (Eqs. (5,7)) 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.

Ground-based estimates require clear atmospheric conditions. However, having a clear atmosphere is not sufficient. A clear sky implies only as a cloudless atmosphere 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 about 0.4% for the two Cimel channels (340 nm and 380 nm) at perhaps the most favorable ground site at Mauna Loa under the most favorable stable atmospheric condition.

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

Even though there are some occasions when the estimated SSI has very small variation (Fig. 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 Eqs.(5a),(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 time scale 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.

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.goc:8080/). 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 the same 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 (Fig. 1, 3) indicate a systematic behavior of either the atmosphere or instrument or both. However, to exactly characterize the instrument variability and stability requires further research.

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, 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 (cf. Eq. (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.

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.

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.

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 about 30% of all days in

Level 2.0 Cimel data (i.e., 10 to 40 percentile in Fig. 3) ground-based estimates could provide 0.4~0.5% accuracy of zero airmass 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.

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 space-borne 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 EOS (Earth Observing System) program [Woods et al., 2000]. The launch of the SORCE (Solar Radiation and Climate Experiment) satellite early in year 2003 starts a new era of Sun – Earth climate research. Short time scale variations of solar irradiance may have relatively little influence on Earth's climate. Because variations of solar energy occur on a time scale of a decade (or longer), revealing the influence of solar variation on Earth's climate requires long-term observations from space.

Acknowledgements
We thank Barry Knapp for providing the SOLSTICE data, and help of Ilya Slutsker with Cimel data. Wen thanks Tom Elk for useful discussions. This work is supported by the NASA SORCE Project and Earth Observing System (EOS).

References

Abbot, C. G., The constancy of the solar constant, *Smithsonian Contrib. Astrophys.*, **3**, 1958.

Alder, H. L., and E. B. Roessler, *Introduction to probability and statistics*, 313 pp, W. H. Freeman, San Francisco, 1964.

Ångström, A., Apparent solar constant variation and their relation to the variability of atmospheric transmission, *Tellus*, *22*, 205-218, 1970.

Clayton, H. H., World Weather, MacMillan, New York, 1923.

Feller, W., *An introduction to probability theory and its application*, Vol II, 669 pp, John Wiley & Sons, New York, 1971.

Fröhlich, C. and J. Lean, Total solar irradiance variation: The construction of a composite and its comparison with models, *IAU Symposium 185: New Eyes to See Inside the Sun and Stars*, edited by F. L. Deubner, 82-102, Kluwer Academic Publ., Dordrecht, The Netherland, 1998.

Hoyt, D. V., The Smithsonian astrophysical observatory solar constant program, *Rev. Geophy. Space Physics.*, **17**, 427-458, 1979.

Holben, B., N., T. F. Eck, I. Slutsker, D. Tanre, J. P. Buis, A, Setzer, E. Vermote, J. A. Reagon, Y. J. Kaufman, T. Nakajima, F. Lavenu, I. Jankowiak, and A. Smirnov, AERONET- A Federated Instrument Network and Data Archive for Aerosol Characterization, Remote Sens. Environ., 66, 1-16, 1998.

Holben, B., N., D. Tanre, A. Smirnov, T. F. Eck, I. Slutsker, A. Abuhassan, W. W. Newcomb, J. S. Schafer, B. Chatenet, F. Lavenu, Y. J. Kaufman, J. Vande Castle, A. Setzer, B. Markham, D. Clark, R. Frouin, R. Halthore, A. Karneli, N. T. O'Neill, C. Pietras, R. T. Pinker, K. Voss, and G. Zibordi, An emerging ground-based aerosol climatology: Aerosol optical depth from AERONET, *J. Geophy. Res.*, **106**, 12,067-12,097, 2001.

Hudson, H. S., Observed variability of the solar luminosity, *Annu. Rev. Astron. Astrophys.*, ***26***, 473-507, 1988.

Lean, J., The Sun's variable radiation and its relevance for Earth, *Annu. Rev. Astron. Astrophys.*, ***35***, 33-67, 1997.

London, J., Bojkov, R. D., Oltmans, S., and Kelley, J. I., Atlas of the Global Distribution of Total Ozone July 1957 – June 1967, *NCAR Technical Note 133+STR*, National Center for Atmospheric Research, Boulder, CO 276 pp., 1976.

London, J., G. J. Rottman, and T. N. Woods, Variation of solar ultraviolet irradiance derived from SOLSTICE (UARS) observations, *Proc. IRS'92*, Tallinn, Estonia, (Eds., Keevallik and Karner) Deepak Publ., Humpton, VA., 1992.

Luria, M., J.. F. Boatman, J. Harris, J. Ray, T. Straube, J. Chin, R. L. Gunter, G. Herbert, T. M. Gerlach, and C. C. Van Valin, Atmospheric sulfur dioxide at Mauna Loa, Hawaii, *J. Geophys. Res.*, *97*, 6011-6022, 1992.

Mitchell, J. M. Jr., The solar inconstant, in Proceedings Seminar on Possible Response of Weather Phenomena to Variable Extra-Terrestrial Influence, NCAR Tech Note TN-8, 155-174, Natl. Center for Atmospheric Research, Boulder, Colorado, 1965.

Perry, K. D., T. A. Cahill, R. C. Schell, and J. M. Harris, Long-range transport of anthropogenic aerosols to the National Oceanic and Atmospheric Administration baseline station at Mauna Loa Observatory, Hawaii, *J. Geophys. Res.*, ***104***, 18,521-18,533, 1999.

Reagan, J. A., L. W. Thomason, B. M. Herman, and J. M. Palmer, Assessment of atmospheric limitation on the determination of solar spectral constant from ground-based spectrometer measurements, *IEEE Trans. Geosci. Remote Sens.*, ***GE-24***, 258-266, 1986.

Reber, C. A., C. E. Trevathan, R. T. McNeal, and M. R. Luther, The Upper Atmosphere Research Satellite (UARS) Mission, *J. Geophys. Res.*, ***98***, 10,643-10,647, 1993.

Rottman, G. J., T. N. Woods, and T. P. Sparn, Solar-Stellar Irradiance Comparison Experiment 1, 1. Instrument Design and Operation, *J. Geophys. Res.*, ***98***, 10,667-10,677, 1993.

Rottman, G. J., T. N. Woods, O. R. White, and J. London, Irradiance observations from the UARS/SOLSTICE Experiment, *The Sun as a Variable Star: Solar and Stellar Irradiance Variations*, Cambridge Univ. Press, 73-80, 1994.

Russell, P. B., J. M. Livingston, E. G. Dutton, R. F. Pueschel, J. A. Reagan, T. E. DeFoor, M. A. Box, D. Allen, P. Pilewskie, B. M. Herman, S. A. Kinne, and D. J. Hofmann, Pinatubo and pre-Pinatubo optical-depth spectra: Mauna Loa measurements, Comparison, Inferred particle size distribution, radiative effects, and relationship to lidar data, *J. Geophys. Res.*, ***98***, 22,969-22,985, 1993.

Ryan, S., The wind field around Mauna Loa derived from surface and balloon observations, *J. Geophys. Res.*, ***102***, 10,711-10,725, 1997.

Schmid, B., and C. Wehrli, Comparison of Sun photometer calibration by use of the Langley technique and the standard lamp, *Appl. Opt.*, ***34***, 4500-4512, 1995.

Shaw, G., Error analysis of multiwavelength sun photometry, *Pageoph.*, *114*, 1-14, 1976.

Shaw, G. E., Aerosols at Mauna Loa: Optical properties, *J. Atmos. Sci.*, ***36***, 862-869, 1979.

Shaw, G. E., Transport of Asia desert aerosol to Hawaii Islands, *J. Appl. Meteorol.*, ***19***, 1254-1259, 1980.

Shaw, G., Sun photometry, *Bull. Am. Meteorol. Soc.*, ***64***, 4-10, 1983.

Willson, R. C., Measurements of solar total irradiance and its variability, *Space Sci. Rev.*, ***38***, 203-242, 1984.

Willson, R. C., and H. S. Hudson, The sun's luminosity over a complete solar cycle, *Nature*, **351**, 42-44, 1991.

Woods, T., G. Rottman, J. Harder, G. Lawrence, B. McClintock, G. Kopp, and C. Pankratz, Solar Stellar Irradiance Comparison Experiment I, 2 Instrument Calibration, *J. Geophys. Res.*, ***98***, 10,679-10,694, 1993.

Woods, T., G. Rottman, J. Harder, G. Lawrence, B. McClintock, G. Kopp, and C. Pankratz, Overview of the EOS SORCE Mission, *SPIE Proceedings*, **4135**, 192-203, 2000.

Figure Caption

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

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

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

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

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

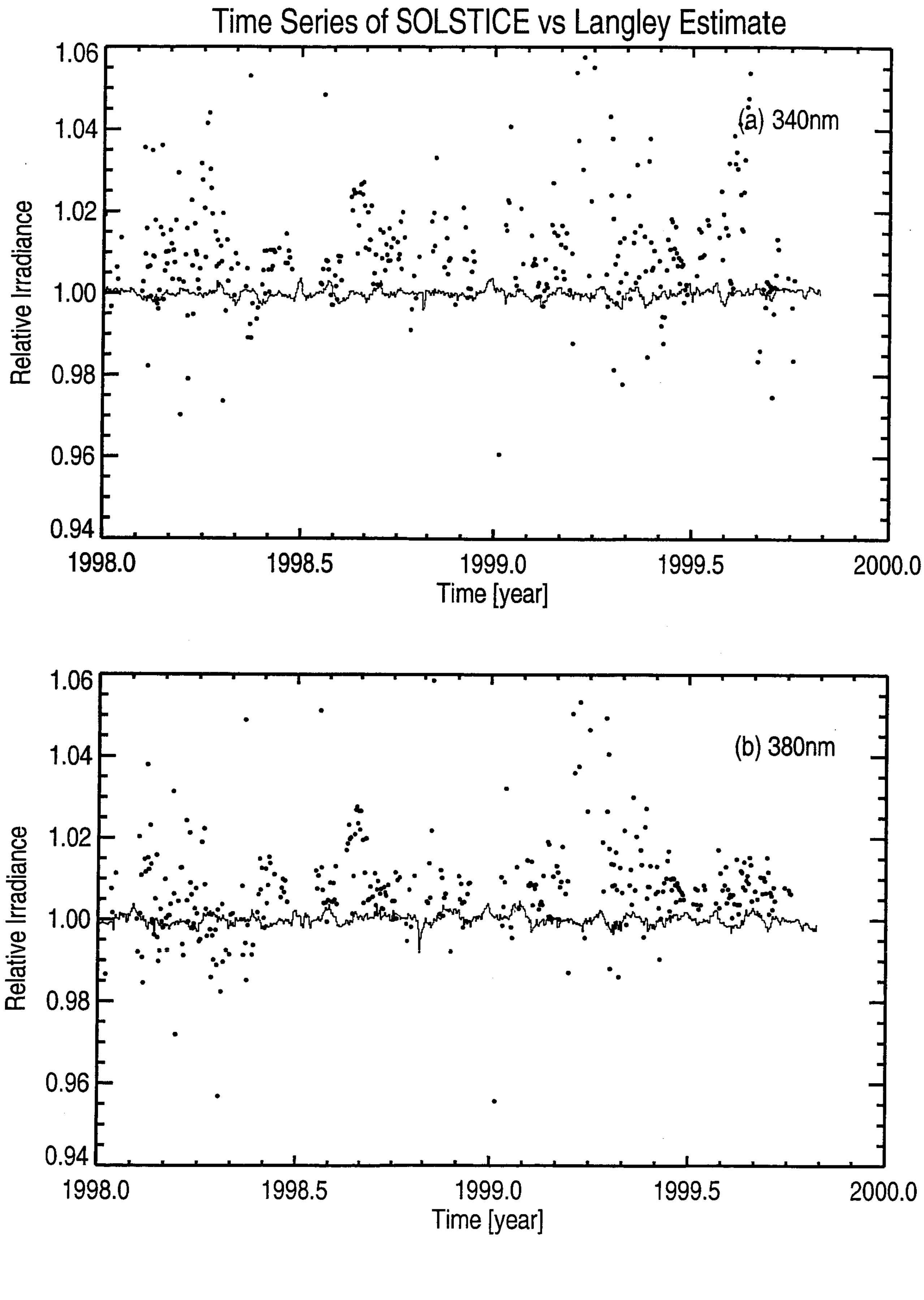
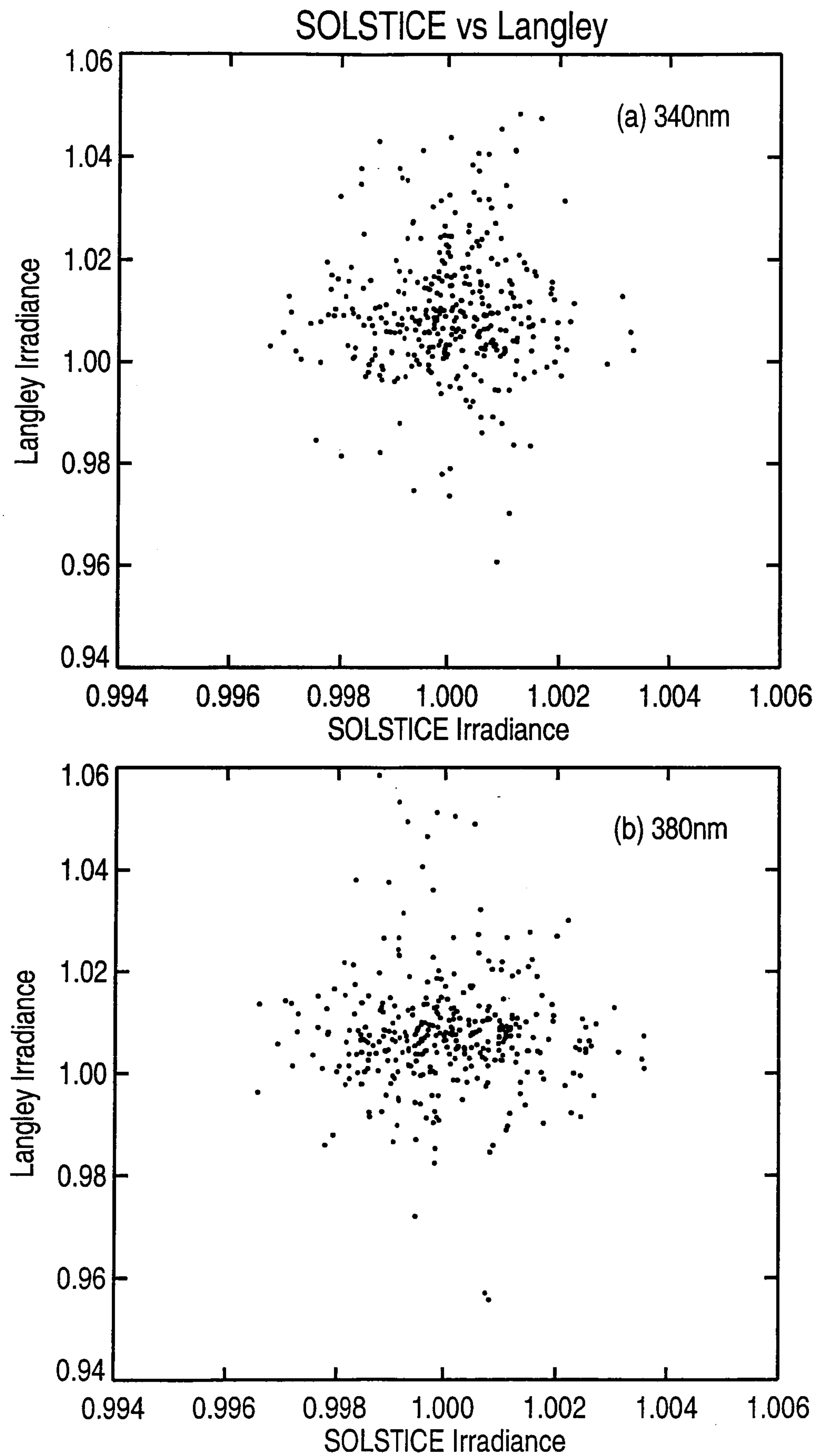

Time Series of SOLSTICE vs Langley Estimate
(a) 340nm
Relative Irradiance
Time [year]
1.06
1.04
1.02
1.00
0.98
0.96
0.94
1998.0
1998.5
1999.0
1999.5
2000.0
(b) 380nm
Relative Irradiance
Time [year]

Fig 1



SOLSTICE vs Langley
(a) 340nm
Langley Irradiance
SOLSTICE Irradiance
1.06
1.04
1.02
1.00
0.98
0.96
0.94
0.994
0.996
0.998
1.000
1.002
1.004
1.006
(b) 380nm
Langley Irradiance
SOLSTICE Irradiance

Fig 2

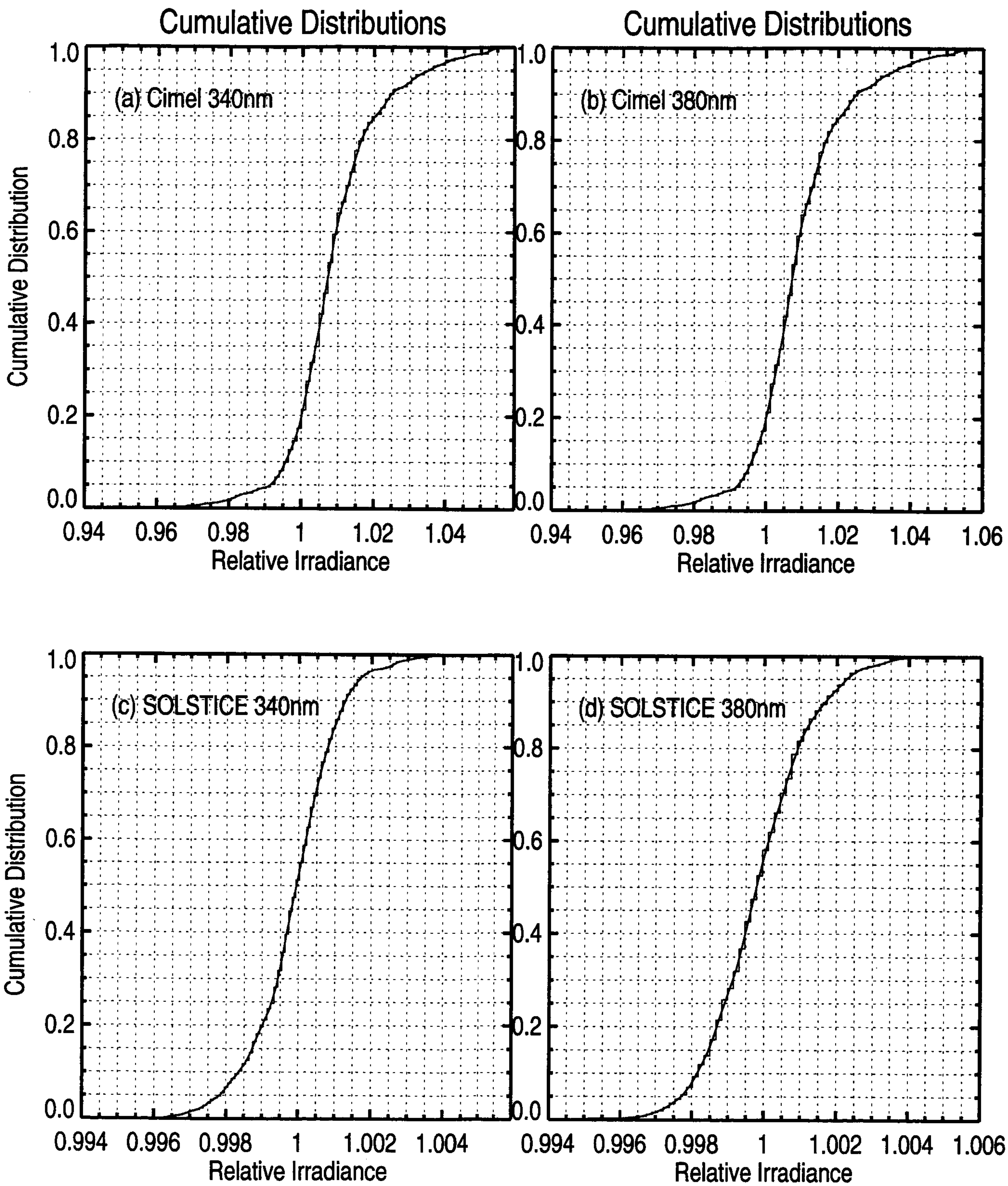

Cumulative Distributions
(a) Cimel 340nm
Cumulative Distribution
Relative Irradiance
1.0
0.8
0.6
0.4
0.2
0.0
0.94
0.96
0.98
1
1.02
1.04
Cumulative Distributions
(b) Cimel 380nm
Relative Irradiance
0.94
0.96
0.98
1
1.02
1.04
1.06
(c) SOLSTICE 340nm
Cumulative Distribution
Relative Irradiance
0.994
0.996
0.998
1
1.002
1.004
(d) SOLSTICE 380nm
Relative Irradiance
0.994
0.996
0.998
1
1.002
1.004
1.006

Fig 3

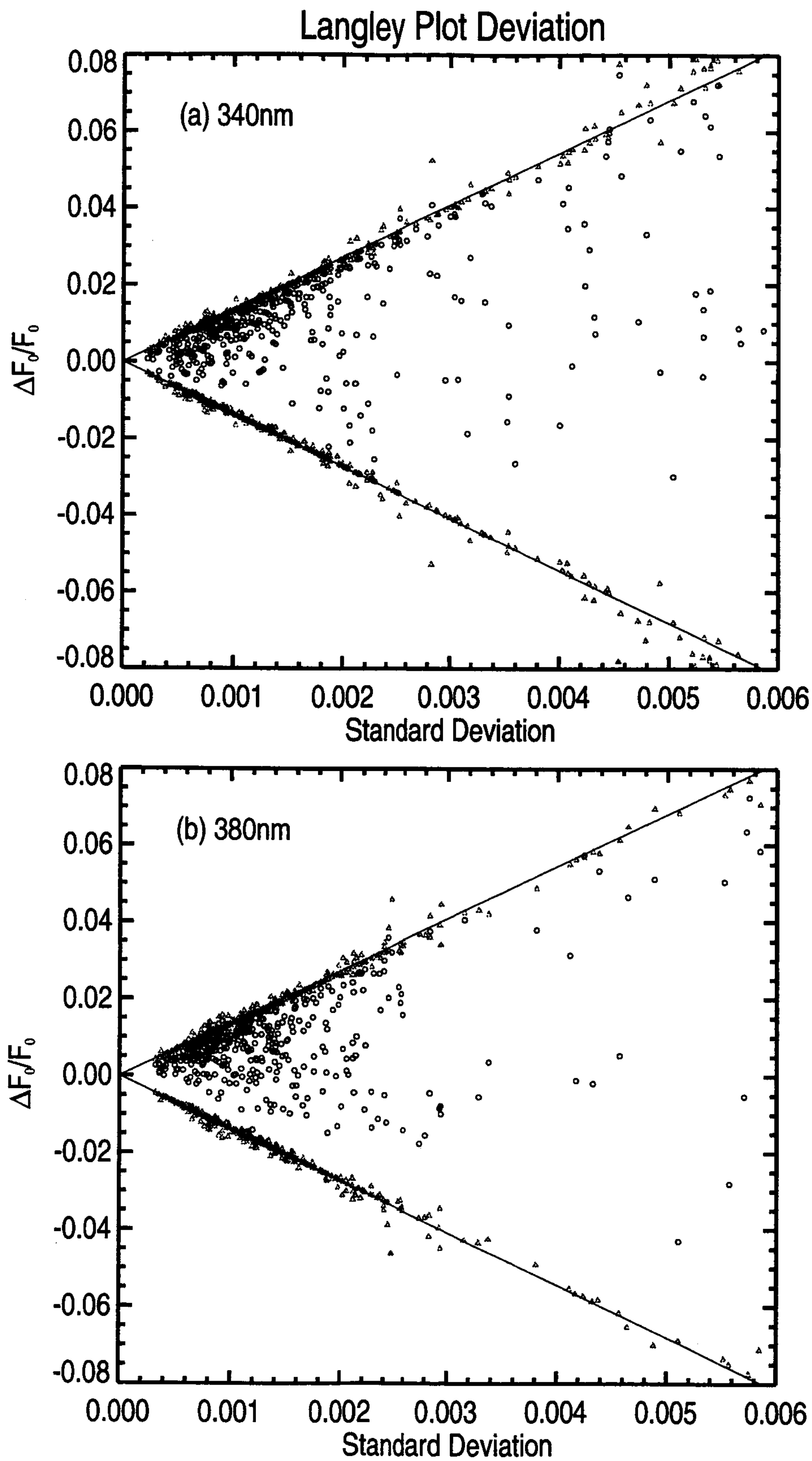
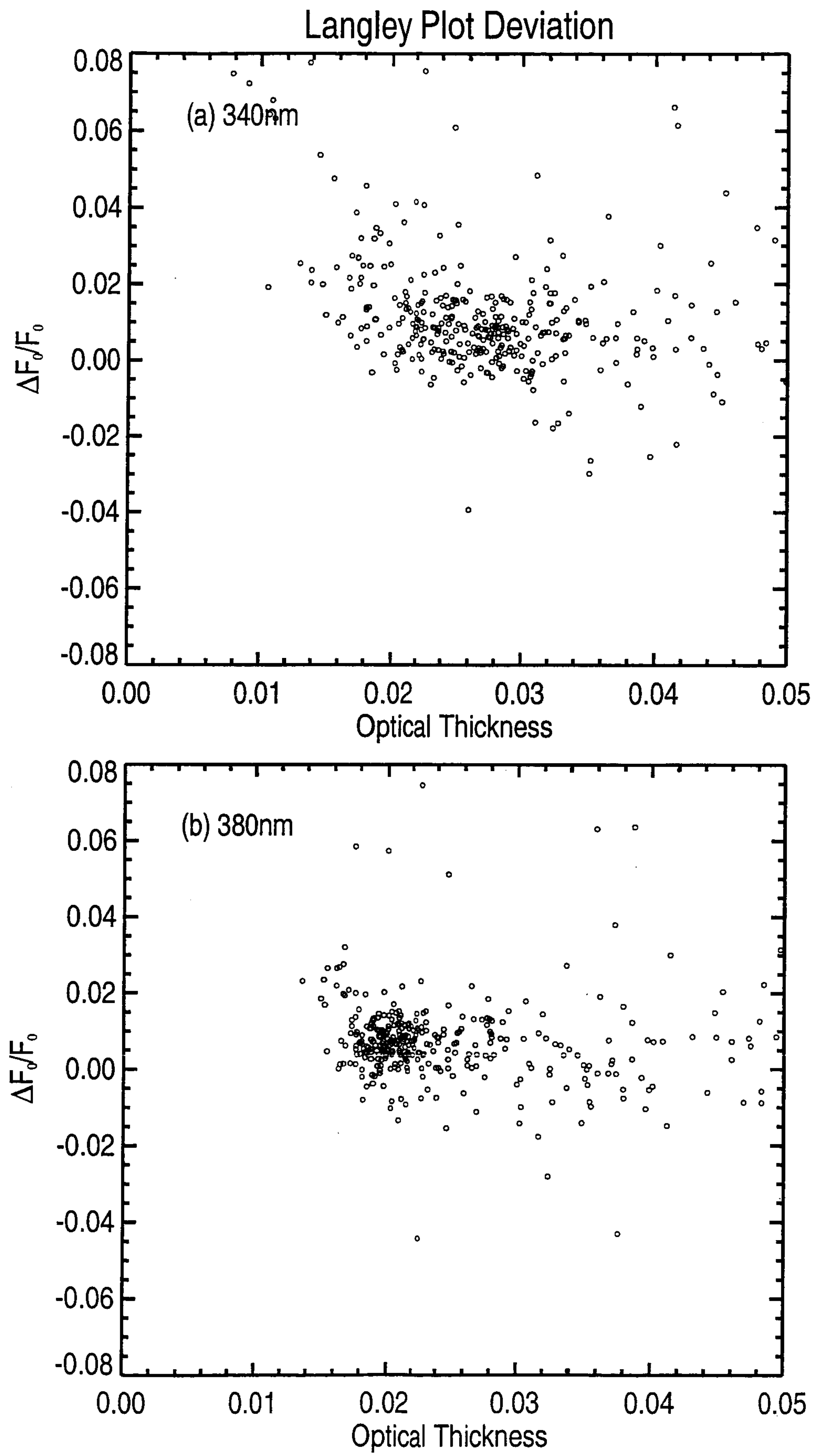

Langley Plot Deviation
(a) 340nm
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
ΔF0/F0
0.000
0.001
0.002
0.003
0.004
0.005
0.006
Standard Deviation
(b) 380nm
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
ΔF0/F0
0.000
0.001
0.002
0.003
0.004
0.005
0.006
Standard Deviation

Fig 4



Langley Plot Deviation
(a) 340nm
$\Delta F_0/F_0$
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
0.00
0.01
0.02
0.03
0.04
0.05
Optical Thickness
(b) 380nm
$\Delta F_0/F_0$
Optical Thickness

Fig 5