Solar Irradiance Anomalies Caused by Clear-Sky Transmission Variations above Mauna Loa: 1958–99

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ABSTRACT

The clear-sky transmission of the atmosphere contributes to determining the amount of solar irradiance that reaches various levels in the atmosphere, which in turn is fundamental to defining the climate of the earth. As of the end of 1999, sustained clear-sky solar transmission over the mid-Pacific, as viewed from Mauna Loa, Hawaii, reached its highest level of clarity since before the eruption of Mount Pinatubo in 1991 and appears to be continuing to increase toward baseline levels established during 1958–62 and not sustained since. This record is used to answer the question as to impact of transmission variations, which can be attributed to either upward scattering or absorption above the station, on the net solar irradiance at 3.4 km, the altitude of the isolated mountain-top observing site. Net solar irradiance at a given level describes the total solar irradiance absorbed below that level. Monthly mean net solar anomalies caused by transmission variations, relative to the 1958–62 baseline, range from −14 to 2 W m^{-2} and averaged −1.45 W m^{-2} (−0.7%) between 1963 and 1999. Because of inherent attributes of this transmission record, the observed fluctuations in the record are of unusually high precision over the entire period of record and are also representative of an extended surrounding region. Irradiance anomalies have a long-term precision of better than 0.1 W m^{-2} (~0.05%) per decade. Any possible linear trend for the entire 42 yr is limited by the data to between about 0.0 and −0.1 W m^{-2} $decade^{-1}$, or any net shift over the 42 yr must be in the range of about 0.0 to −0.35 W m^{-2} (0.0% to −0.15%). The transmission fluctuations are potentially caused by various atmospheric constituents, primarily aerosols, ozone, and water vapor, but the role of a specific constituent cannot be uniquely isolated on the basis of the transmission record alone. Aerosols have the greatest potential influence on the record and in general have the ability to cause both scattering and absorption such that the net radiative heating effect in the entire atmospheric column cannot be determined from the transmission data alone. However, because the largest anomalies in the record are known to be due to volcanic eruptions that produce predominantly conservative scattering aerosols, those large anomalies resulted in net radiative cooling tendencies in the entire associated atmospheric column.

1. Introduction

The transmission of the atmosphere contributes to the determination of radiation quantities within and at the boundaries of the atmosphere. Typical potential irradiance variations that might affect climate change are relatively small, on the order of <1 W m^{-2} $decade^{-1}$ (e.g., Hansen et al. 2000; Houghton et al. 1996). Related changes in transmission would also be relatively small and difficult to detect because associated irradiance measurement accuracies (e.g., Ohmura et al. 1998) do not typically support such detection. Occasional greater but shorter-term (several months to a couple of years) changes in atmospheric transmission that resulted in solar irradiance fluctuations have been previously observed (or inferred) and related to possible short-term changes in climate variables (Hansen et al. 1978; Dutton and Christy 1992; Minnis et al. 1993; Stenchikov et al. 1998). Knowledge of any long-term irradiance variations that may or may not have occurred would be useful in the diagnosis of current and past climate, particularly when compared with similar quantities computed in general circulation models.

Although many atmospheric constituents contribute to the determination of transmission for climate applications, it is useful to consider the cloud-free atmosphere separately as a reference state because water clouds can have such a potentially dominant and highly variable role. The purpose of this paper is to examine the extent to which solar irradiance variations have occurred at a mid-Pacific site because of observed clear-sky transmission variations on timescales of a month to several decades.

A unique 42-yr record of clear-sky atmospheric solar transmission has been acquired at the National Oceanic and Atmospheric Administration (NOAA) Climate Monitoring and Diagnostics Laboratory (CMDL) Mauna Loa Observatory (MLO) located at 19.53°N,

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155.58°W, and 3.4 km above sea level on the north slope of the Mauna Loa volcano, which rises from the Pacific floor. This atmospheric transmission record is particularly useful because of its inherent precision and remote representativeness, which derive from the measurement method and location, respectively. The transmission values, as computed for the MLO record, are in dimensionless units that are specific to the measurement geometry (absolute atmospheric path length, or air mass) arbitrarily but consistently used. Apparent transmission is directly and physically related to the true vertical transmission (transmitted irradiance divided by incident irradiance) of the atmosphere above the site. However, over the past several decades, measurements of the atmospheric constituents necessary to accurately compute transmission from radiative transfer formulations have only been made sporadically and sometimes with considerable uncertainty, especially for aerosols. Therefore, the MLO record presents a rare documentation of the radiative state of the clear atmosphere in the region, and is well suited for detecting unusually small as well as large variations that historically could have otherwise gone undetected.

To help to translate the apparent transmission record to more familiar and useful units, we estimate solar irradiance anomalies (departures from the 1958–62 baseline period) from the transmission record by using the observed relationships between apparent transmission and more recently observed (1978–99) solar irradiances at a fixed solar zenith angle (60°). The relationships are stable over more than two decades, and therefore are assumed to be useful over the entire four decades of the record. Total solar irradiance observations at MLO consist of separate direct solar beam and diffuse-sky measurements that are summed to give more accurate total downwelling irradiance measurements as opposed to using a single detector (Ohmura et al. 1998; Michalsky et al. 1999; Bush and Valero 1999). Solar irradiances were scaled to 24-h-mean values and also scaled to net solar irradiance, using a fixed representative underlying reflectance, so that the results are quantitatively similar to the absorbed irradiance anomalies below 3.4 km. These deduced irradiance anomalies are thereby isolated to be those caused only by clear-sky transmission variations above 3.4 km, not by extraterrestrial or underlying reflectance variations.

A summary of the results indicates that the inferred net solar irradiance anomalies over the last 42 yr range from -14 W m^{-2} for a single month, to about -7 W m^{-2} averaged over several seasons following some major volcanic eruptions, to about 1.5 W m^{-2} for the amplitude of an annual cycle, to a maximum possible long-term linear trend of about -0.1 W m^{-2} decade^{-1}. Although no statistically significant long-term linear trend can be shown to exist in the data, the possibility of a linear trend no larger than about -0.1 W m^{-2} decade^{-1}, or overall shift of up to -0.35 W m^{-2} cannot be eliminated based on a comparison of the data at the beginning and end of the smoothed record. However, the current tendency is a return to the same baseline level of about 40 years ago, suggesting a stability in the record, and the atmosphere, of better than about 0.3 W m^{-2} over 40 yr, although a baseline defined as well as in the earliest portion of the record has not yet been reestablished. The deduced solar irradiance anomalies are insufficient in themselves to deduce climate-scale irradiance variations but could be used to help to confirm associated radiation quantities in adequately resolved and initialized physical climate models.

2. Mauna Loa apparent transmission

Ellis and Pueschel (1971) developed a high precision method to compute ‘‘apparent’’ transmission for the purposes of monitoring the solar transmission of the clear-sky atmosphere. They used observational data first acquired at MLO in 1958 from a program that has been subsequently maintained as a research-grade effort. Factors contributing to the quality and representativeness of the MLO transmission record are the frequent clear skies, the remoteness of the site from anthropogenic influences, high elevation above the midoceanic boundary layer, and downslope winds during observation times that virtually assure that the atmosphere over the site is devoid of local contamination. The inherent precision (long-term stability) of the transmission record comes from its lack of dependence on either instrument calibration or magnitude or variability of the extraterrestrial solar irradiance.

The MLO transmission record has been used to determine the limit to possible trends in background aerosols (Ellis and Pueschel 1971), the extent of the influence of certain volcanic eruptions (e.g., Mendonca et al. 1978; Robock 2000), the effects of seasonal aerosol transport from Asia to the mid-Pacific (Bodhaine et al. 1981), the effects of water vapor, ozone, and aerosols on solar apparent transmission (Dutton et al. 1985), the extent of the impact of the quasi-biennial oscillation (QBO) on solar transmission modulation (Dutton 1992), and has been applied with limited success at other locations (e.g., Hoyt 1979a,b).

Apparent transmission is computed from within-the-day ratios of the relative output of broadband direct-beam radiometers, similar to (but distinct from) the Langley method used to determine spectral transmission from monochromatic instruments, and is described in more detail later in this paper and references. Variations in the apparent transmission record are related to variations in total (direct + diffuse) solar irradiance to the extent that the changes in transmission are caused by noncompensating changes in absorption and scattering above the site. Abundant measurements necessary to determine regular routine solar apparent transmission have been made at MLO since 1958. An instantaneous apparent transmission value is the ratio of the output from a normal-incidence pyrheliometer (linearly sen-

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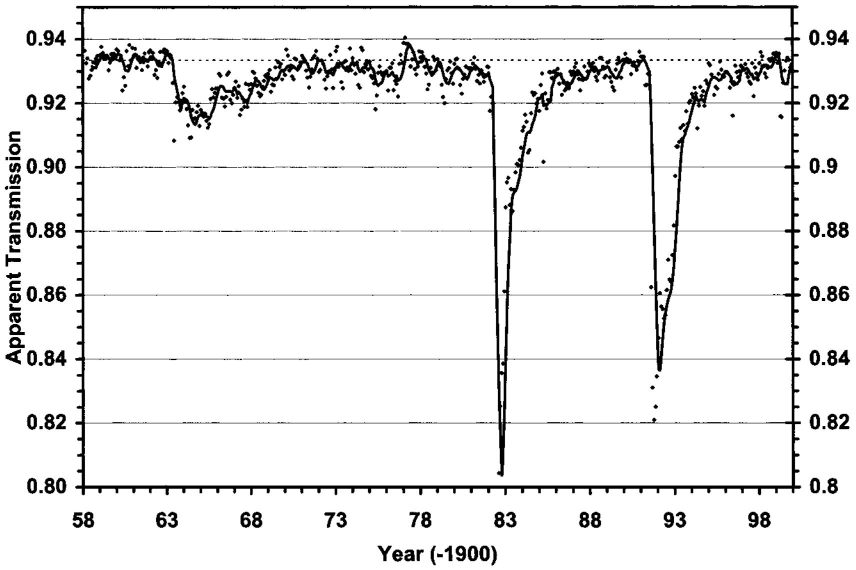

FIG. 1. Monthly average apparent solar transmission for Mauna Loa. The solid line is a 6-month LOWESS smoother, individual points are monthly averages, and the dashed line is the 1958–62 background value of 0.9335. Note that a few points are offscale (low) in 1982.

sitive to the direct solar beam in the 0.3–2.8-μm spectral band) for a specific pair of solar zenith angles corresponding to integer air masses in the morning of a given day. This was first implemented during the early years of the program because the ability to accurately calibrate the instruments (pyrheliometers) did not exist (Ellis and Pueschel 1971). Additionally, instruments frequently failed or were exchanged and the ability to maintain even a consistent relative calibration was lost. Likewise, the value of the extraterrestrial irradiance, which would be required to determine broadband solar transmission directly, was not well known. Although the ability to accurately calibrate pyrheliometers and extraterrestrial irradiance measurements is now greatly improved (Fröhlich 1991), this method remains viable and useful because of its inherent stability and long-term history.

Physically, the apparent transmission for a pair of solar zenith angles is the spectrally and vertically integrated direct transmission for an incident spectrum identical to the extraterrestrial spectrum attenuated by the shorter of the two paths. This physical definition assumes stable horizontal homogeneity between the times of the two observations. If the constituent properties above the site are known or assumed, transmission in the units of the MLO record, as well as associated downward solar irradiances, can be computed using common radiative transfer methods. The daily apparent transmission value routinely calculated for Mauna Loa is described in detail by Dutton et al. (1985) and is the average of three airmass pairs. An abundance of clear skies and the typical absence of local influences during early morning hours because of downslope winds (Mendonca 1969) have resulted in a quasi-daily transmission record with 46% of all mornings between 1958 and 1999 yielding a stable clear-sky result. However, because of the discontinuous nature of the daily record resulting from clouds and because of an interest in longer-duration effects, the transmission data are routinely reduced to monthly averages for further analysis (Fig. 1). The 6-month running mean in Fig. 1 takes out some random variability and emphasizes the persistent annual cycle present in the data. The effects of three major volcanic eruptions (Agung in 1963, El Chichón in 1982, and Mount Pinatubo in 1991) are readily apparent in the record.

As discussed by Bodhaine et al. (1981) and others, ozone, water vapor, and aerosols primarily influence the apparent transmission values, which are screened to remove cloud effects. Cloud screening is accomplished by examining the stability of the continuously recorded solar signal so that thin or even invisible cirrus are identified. The sensitivity of apparent transmission to water vapor is diminished because of spectral saturation of many of the water vapor bands in the shorter path such that little additional absorption occurs in the longer paths. Ozone sensitivity is relatively small in comparison with water vapor and aerosols because of the weakness of ozone absorption over the spectral interval. Dutton et al. (1985) gave the sensitivities of the Mauna Loa apparent transmission to ozone, water vapor, and aerosol optical depth as 0.0005, 0.0017, and 0.007, respectively, for typical annual mean ranges of 50 Dobson units of ozone (15% of the annual mean), 0.2 cm of water vapor (70% of the annual mean), and 0.007 500-nm aerosol optical depth (100% of the annual mean), respectively. The water vapor sensitivity is nonlinear and is somewhat dependent on the spectral shape of aerosol optical depth, and is given for column water amounts between 0.2 and

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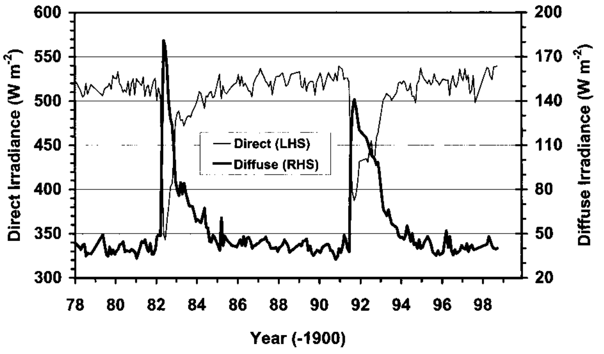

FIG. 2. Monthly average clear-sky direct and diffuse solar irradiance observed at Mauna Loa for a morning solar zenith angle of 60°.

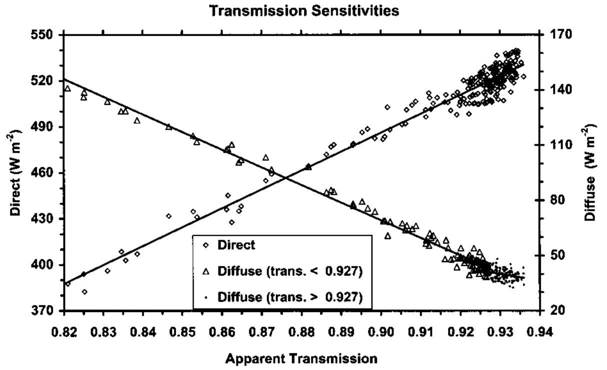

FIG. 3. Clear-sky, monthly average, direct and diffuse irradiance at Mauna Loa for zenith angle of 60° from 1980 to 1998 vs apparent transmission. Plotted lines are least squares fit to the data and give the linear relationship between irradiance and apparent transmission. Note that two different lines were fit to the diffuse data above and below a transmission value of 0.927 at which apparently different scattering phase functions come into existence. Note also that some data points used in the fits are offscale to the left so that an expanded scale can be used to better display the 0.927 transmission transition region but yet show many of the lower transmission points.

about 0.5 cm for spectral aerosol optical depth typical of undisturbed conditions. As a result, most observed variability in the apparent transmission record is due to aerosols, which is particularly evident following the major volcanic eruptions, as emphasized by Mendonca et al. (1978). These sensitivities are used to determine the amount of a particular constituent that could cause a given change in apparent transmission.

3. Solar irradiance observations at MLO

Reliable direct and diffuse solar irradiance measurements have been made at MLO since 1978 (Fig. 2). Total solar irradiance is determined from the sum of the direct and diffuse irradiances, a method adopted and widely promoted by the Baseline Surface Radiation Network of the World Climate Research Program (Ohmura et al. 1998) and is used to obtain optimum operational total solar irradiance measurements (Michalsky et al. 1999; Bush and Valero 1999). The measurement accuracy of the component-sum method is further enhanced when the measurements are properly related to absolute calibration scales (Ohmura et al. 1998; Michalsky et al. 1999). Romero et al. (1991, 1995) have shown that the absolute accuracy of the direct-beam cavity radiometer, to which the measurements are now referenced, could be better than 0.01% when scaled to the World Radiation Reference. However, routine pyrheliometer (direct beam) measurements used here are only considered to be accurate to within about 0.5%. The accuracy of the diffuse measurement is more difficult to establish. Comparisons with theoretical Rayleigh diffuse calculations under conditions of very low aerosol at Mauna Loa suggest that the diffuse measurements are correct to about 3–4 W m^{-2} (Kato et al. 1999). Since relative changes in irradiance measurements are used here to establish the relationships with apparent transmission, the dependence of the results on the absolute accuracy of irradiance measurements is further reduced.

4. Derivation of solar irradiance anomalies from apparent transmission

Relative changes in total solar irradiance at Mauna Loa since 1958 are inferred from relationships between the available direct and diffuse solar irradiance measurements and the observed apparent transmission. These relationships between irradiances at solar zenith angles of 60° and the corresponding transmission are shown in Fig. 3, and linear fits are summarized in Table 1 for 1978–99. Significantly different linear slopes are noted for the diffuse relationship for transmission values above and below 0.927. No significant similar differences were found for the direct irradiances. The relationship between diffuse irradiance and transmission is a function of directional scatter and absorption above the site and reflection below the site. The transition at 0.927 could be due to more forward scattering because of the larger volcanic aerosols that dominate the lower transmission values in the record rather than changes in underlying reflection that would not be a function of transmission.

TABLE 1. Slopes from linear regression fits between Mauna Loa apparent transmission and direct and diffuse irradiance. Two ranges of transmission (Trans.) values are given for the diffuse sensitivities as discussed in the text. Units of slope are watts per square meter per unit transmission.

	Direct	Trans. > 0.927 Diffuse	Trans. < 0.927 Diffuse
Slope	1221	−350	−958
Std dev*	17	122	10
DF**	213	111	100

* Std dev of the slope.
** DF is the degrees of freedom of the fit.

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The temporal stabilities of the relationships between transmission and both diffuse and direct irradiance were investigated by performing linear regression on three subsets of minimally volcanically influenced data during the late 1970s, the mid-1980s, and late 1990s. All regression results showed no statistical differences between the three time periods. This suggests that either there are no detectable changes in near-background aerosol directional scattering, absorption, or underlying reflection, or there are compensating differences occurring among the three. The surface characteristics surrounding the observing site have not likely changed over the period. Also, only morning observations are used when typically downslope winds are occurring, so any contribution to reflection from cloudiness below the station is minimized. It is, of course, not possible to check the relationship between transmission and diffuse irradiance during the earliest portion of the record.

The derived 42-yr record of the change in total downwelling solar irradiance at MLO was computed from the relationships given in Table 1 applied to the entire transmission record in the following manner. First a baseline transmission value was computed from the first 5 yr of the record where it appears most stationary. Using the first 5 yr of the record as a baseline is a fortuitous convenience afforded by the fact that the record indicates relatively stable conditions during that time before a series of volcanic eruptions. Transmission anomalies were then obtained by subtracting the baseline value of 0.9355. Irradiance anomalies are computed from the sum of the direct and diffuse sensitivities (slopes in Table 1) times the transmission anomalies. No new features emerge in this irradiance anomaly record when compared with those in the transmission record in Fig. 1 other than that now an irradiance scale may be attached to the variations. The precision of the inferred irradiance variations is thereby tied to the inherently precise transmission record over the entire 42 yr assuming a constant relationship with diffuse irradiance. The different diffuse sensitivities in Table 1 do not impact long-term analysis of near-background conditions since all relevant transmission values are above 0.927.

Up to this point, the solar irradiance anomalies are for the total downwelling component at a solar zenith angle of 60°. For many climate considerations, net solar radiation anomalies would be more useful, being representative of changes in the solar energy retained (absorbed) below the altitude of the observations. It is also useful to express solar irradiance values as daily means, which removes much of the zenith angle dependence and makes the resulting anomalies more comparable to radiative quantities in climate models. To estimate the daily mean value, one-half of the irradiance value at a zenith angle of 60° is used. This derives from the fact that the average solar zenith angle for the instantaneously sunlit hemisphere is 60°; therefore one-half the corresponding surface irradiance value is a reasonable estimate of a 24-h average in tropical regions in the absence of continuous measurements.

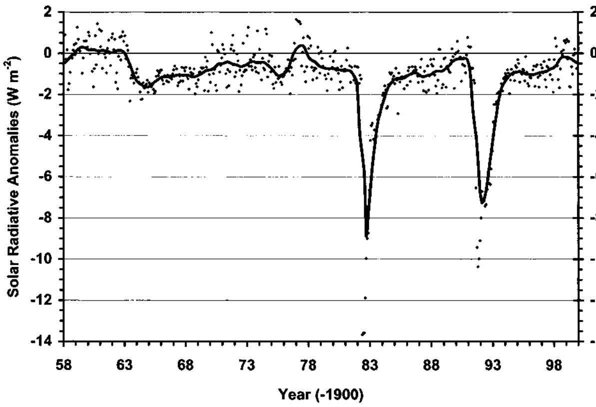

FIG. 4. Smoothed monthly mean net solar radiative forcing at Mauna Loa as derived from daily transmission and irradiance measurements described in the text. The dark solid line is the LOWESS smoother. Individual points are monthly averages.

Net solar irradiance is estimated from the MLO record by multiplying the downwelling irradiance by $(1 - A)$, where A is a representative constant underlying albedo. An albedo of 0.25 was chosen and is intended to approximate a regional mean above broken boundary layer clouds away from the influence of the island. The results are insensitive to the exact choice of albedo because it only changes the estimated irradiance by a fixed fraction such that the irradiance variations are more representative of net irradiance than total irradiance changes. Note that any changes in actual albedo below the site will cause changes in actual net solar irradiance but these are not the variations caused by the transmission variations that are being investigated (likewise for extraterrestrial variations in solar irradiance). The monthly means of the estimated daily mean net solar anomalies are given in Fig. 4. The anomalies in Fig. 4 can also be interpreted as percentage variations by taking the 22-yr-mean total solar irradiance at a zenith angle of 60° (548.7 W m^{-2}) and can also be converted to a comparable daily average net irradiance value (205.8 W m^{-2}) using the same method as used for the time series. The magnitude of the irradiance anomalies serves as a basis for further discussion because these are the quantities that are computed by physical models used in diagnosing climate variations.

5. Discussion

One of the desired applications of the MLO record is to detect and quantify a long-term trend that might be significant relative to a climatic perturbation. The work of Ellis and Pueschel (1971) refuted claims by Peterson and Bryson (1968) and others that there was a significant transmission trend due to increased anthropogenic aerosol loading. With nearly 30 additional years of observations the current dataset should be more

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capable than before to address the question of any possible long-term trends or shifts from what was considered background at the beginning of the record. Unfortunately, after the 1970s, the record continued to be sporadically affected by volcanic eruptions and background conditions were not reestablished with the result that trend analysis using standard stationary times series analysis is not possible. It is apparent that the maximum long-term trend that could exist is about -0.1 W m^{-2} decade^{-1}, based on the current multiyear mean apparent transmission being within about -0.4 W m^{-2} of the beginning years of the record.

A 24-month smoother is plotted in Fig. 4 and is used to emphasize a specific feature in the record. Smoothing over 24 months reduces the influence of annual and QBO in the record and emphasizes the magnitude of more sustained anomalies. The ''locally weighted polynomial regression and scatterplot smoothing (LOWESS)'' smoother (Cleveland 1979) is a robust running smoother that properly indicates relative maximums and minimums but has end point effects whereby future data will change the tail of the current curve. Since one of the features of interest is the most current level of the record, another view of the end data points is warranted. The anomaly average over the last 24 months is -0.30 W m^{-2}. Also, it is seen that the recent data tend to show a continued recovery toward the baseline value (0.0). The record resolves month-to-month changes of <0.05 W m^{-2}, and current values of the running average are seen to be returning toward the 1958–62 baseline at the rate of about 0.15 W m^{-2} yr^{-1}. At the present tendency to close the difference with the original baseline, it will take about 7 or 8 relatively undisturbed years to reestablish and confirm a stable baseline similar to that seen in the late 1950s. A return to the earlier baseline would indicate the lack of any long-term change and would help to verify the stability and credibility of the intervening transmission and irradiance anomaly values.

The LOWESS smoother in Fig. 4 clearly shows that since 1963 there has been a net loss of solar irradiance at the Mauna Loa site relative to the baseline period of 1958–62. Except for a brief time in 1978, the running mean has not returned to the baseline value. This loss averages about -0.8 W m^{-2} for times other than immediately following major volcanic events where values are as great as -6 W m^{-2}. The indicated anomaly following the Pinatubo eruption in 1991 is consistent with the larger-scale estimates of Minnis et al. (1993), Hansen et al. (1993), Dutton (1997), and Stenchikov et al. (1998) for a conservative scattering aerosol. The overall average irradiance anomaly for the last 37 years is -1.45 W m^{-2}, which is comparable in magnitude (but not physical extent) to the often-cited climate radiative forcing irradiance anomalies (e.g., Houghton et al. 1995). However, this quantity can be taken as a contribution to the radiation absorbed (or in the case of negative values, radiation that was not absorbed) below 3.4 km in this region, as compared with baseline conditions. This could be considered a local radiative forcing due to transmission variations in the upper troposphere and stratosphere.

a. Possible effects of various constituents

According to the transmission sensitivities for various constituents given earlier, an incremental aerosol optical depth of only 0.0022 would account for the entire current 24-month average departure from the baseline, whereas an increase of 0.25 cm of water vapor would be required to solely account for the transmission difference. Although it is not possible to determine which constituent or combinations of constituents are responsible for this small but statistically possible change, some speculation is warranted. The required water vapor change is nearly equal to the annual mean for clear skies over Mauna Loa, and that change is unrealistic. An analysis of 6 yr of Mauna Loa photometric water vapor data (1978–83) did not show a tendency toward a trend (Dutton et al. 1985). The 5% decrease in ozone that has likely occurred over Mauna Loa since the late 1950s (S. Oltmans 2000, personal communication), would only cause an increase in apparent transmission of 0.0001, and can therefore not be responsible for any of the noted or potentially significant variations in the transmission record. Therefore, aerosols would be the most likely candidate for the source of the maximum possible long-term trend that cannot be eliminated by the current data.

The observed quasi-steady recovery rates in the decades following both El Chichón and Mount Pinatubo eruptions suggest that there may be some residual volcanic component persisting to the current time. However, Mauna Loa lidar data (Barnes and Hofmann 1997) show a return to late 1970s aerosol background in the stratosphere over Mauna Loa by the mid-1990s. However, it is seen that in the late 1970s the transmission data were still below the 1958–63 background level. If there is additional aerosol over Mauna Loa as compared with the late 1950s, it is not clear whether it is in the stratosphere or upper (above 3.4 km) troposphere.

b. Annual cycle

A feature of the Mauna Loa transmission record that has long been recognized is the annual variation that has been attributed to seasonal transport of aerosol from Asia in the upper troposphere (e.g., Shaw 1980; Bodhaine et al. 1981; Holmes and Zoller 1996; Perry et al. 1999). This annual cycle is evident in the 6-month-running smoothed data in Fig. 1. The mean annual cycle in monthly average transmission has an amplitude of 0.05 with a statistically significant minimum in April and a maximum in December. Close examination of the daily transmission values (not shown) indicates that the lower springtime monthly means result from sporadic episodes of low transmission for from one to several

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days. The springtime months contribute significantly to the scatter in Figs. 1 and 4. An analysis of the smoothed annual cycle indicates no significant trend in its amplitude. Using the conversion to the solar anomaly developed earlier, the mean annual cycle results in a mean seasonal solar (daily average, net) variation of nearly 1.8 W m^{-2} (0.9%). Individual years have shown deeper depressions in the March–May period (larger annual cycle), such as in the largest of the record in 1999 corresponding to an individual annual variation of 2.5 W m^{-2} (1.2%). The amplitude has been previously shown to have a high coherence with the stratospheric QBO (Dutton 1992). Given that the aerosols responsible for this oscillation originate about 10 000 km away over Asia, larger aerosol loadings and radiative effects are experienced over the ocean to the west of Hawaii but where there are few observations.

6. Conclusions

The magnitude of solar irradiance variations over several recent decades caused by transmission variations above the boundary layer in the background conditions of the mid-Pacific were identified. A 42-yr record of atmospheric transmission and a shorter record of direct and diffuse solar irradiance observations were combined to infer the associated net solar irradiance anomalies for the entire 42-yr period. The accuracy of the derived irradiance anomalies is based primarily on the long-term stability of the apparent transmission technique that is independent of instrument calibration or extraterrestrial irradiance variations. The magnitudes of the largest irradiance anomalies following major volcanic eruptions are in agreement with other studies. The baseline level established in 1958–62 has not been comparably reestablished, with the mean solar irradiance anomaly between volcanic eruptions being about -0.8 W m^{-2} and the current annual mean values being -0.3 W m^{-2} (0.15%). The most recent values have apparently not stabilized and appear to be continuing to return toward the 1958–62 baseline level. Seven or more years of observations without a major disturbance may be required to reach and confirm the reestablishment of the previous or possibly a new baseline level.

The estimated net irradiance under clear skies at MLO shows a small deficit of 1.45 W m^{-2} (0.7%), averaged over the past 37 yr relative to 1958–62. The credibility of the accuracy of this value is enhanced by the fact that most recent values appear to be returning to near the 1958–62 levels. These results should be representative of an extended geographical region because the observations were made under conditions representative of the mid-oceanic free troposphere, and therefore these anomaly results should be replicated in, or constrain, appropriate numerical climate models. However, total column radiative heating could not be deduced because potential aerosol attenuation cannot be partitioned between scattering and absorption, based on the observations.

The question as to the specific cause of the current prolonged, slightly diminished, but apparently recovering, atmospheric transmission that results in a net solar irradiance anomaly (-0.3 W m^{-2}) 9 yr after the last significant volcanic eruption can be raised but cannot be conclusively answered with available information. However, aerosols are the most likely candidate to be responsible for the current deficit. If the cause of the current negative anomaly is stratospheric residual aerosol, then the radiative effects would be widespread globally, at least zonally, and would suggest a net loss of radiant energy in the total atmospheric column because volcanic aerosols are nonabsorbing at solar wavelengths. If the cause of the negative values is due to some episodic or protracted increase in tropospheric aerosols, more information on the absorption properties would be required to determine net radiative effects. Continued monitoring in the absence of additional significant volcanic activity will be required to determine if earlier baseline conditions become reestablished or to what extent a longer-term shortwave deficit or excess exists in this mid-Pacific region due to clear-sky transmission above 3.4 km.

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