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The Smithsonian solar constant data revisited: no evidence for a strong effect of solar activity in ground-based insolation data

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Abstract. Apparent evidence for a strong signature of solar activity in ground-based insolation data was recently reported. In particular, a strong increase of the irradiance of the direct solar beam with sunspot number as well as a decline of the brightness of the solar aureole and the measured precipitable water content of the atmosphere with solar activity were presented. The latter effect was interpreted as evidence for cosmic-ray-induced aerosol formation. Here I show that these spurious results are due to a failure to correct for seasonal variations and the effects of volcanic eruptions and local pollution in the data. After correcting for these biases, neither the atmospheric water content nor the brightness of the solar aureole show any significant change with solar activity, and the variations of the solar-beam irradiance with sunspot number are in agreement with previous estimates. Hence there is no evidence for the influence of solar activity on the climate being stronger than currently thought.

1 Introduction

Quantifying the effect of solar-activity variations on Earth's climate remains an important, yet somewhat controversial issue. There is now a broad consensus, however, that there is a small, but discernible influence of solar variability on the climate on decadal and longer time scales (see Foukal et al., 2006; Haigh, 2007; Lockwood, 2009; Gray et al., 2010, for recent reviews). The climatic changes associated with solar variability are largely caused by variations of the total solar irradiance (TSI) and the solar spectral irradiance (SSI) with solar activity. Furthermore, it has been speculated that the modulation of cosmic-ray flux with solar activity might influence the climate via formation of cloud condensation nuclei or aerosols (see Kirkby, 2007, for a review). Observational evidence for this hypothesis, however, remains rather limited (Gray et al., 2010).

One important prerequisite for an improved understanding of the relationship between solar activity and Earth's climate is the precise measurement of changes in solar radiation associated with the Sun's variable activity. During the first half of the 20th century, the Smithsonian Astrophysical Observatory (SAO) carried out a large observational campaign to measure solar irradiance from several high mountain sites (Abbot et al., 1932, 1942; Aldrich and Hoover, 1954). Historically, the SAO data are important as the first attempt to measure possible changes of the solar constant (the irradiance above the atmosphere) with solar activity from ground-based data, an effort now superseded by highly accurate space-based measurements taken during the last four decades (Fröhlich and Lean, 2004).

The SAO data were used in a number of studies to investigate changes of solar irradiance with solar activity. Earlier claims regarding an increase of radiation with solar activity in the SAO data (Aldrich and Hoover, 1954) were later shown to be likely due to calibration changes (Allen, 1958) or reflect variations in atmospheric transmission rather than changes of the solar constant (Ångström, 1970). Furthermore, searches for periodic signals on decadal timescales in the solar constant derived from these data yielded no results (Sterne and Dieter, 1958; Hoyt, 1979), and an upper limit of less than 0.17% for any long-term trend of the solar constant over the 30 yr of SAO measurements was established (Sterne and Dieter, 1958). On shorter timescales, variations of the solar constant due to bright faculae and dark sunspots have been detected at a level of below 0.1% (Foukal et al., 1977; Foukal and Vernazza, 1979).

Despite their importance, however, the SAO data are generally considered to be strongly influenced by systematic effects caused by different observers, instrument upgrades, changes in calibration procedures and the effects of local

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pollution and volcanic aerosols (Hoyt, 1979; Roosen and Angione, 1984), requiring an extremely careful analysis before any sound conclusions can be drawn.

Recently, apparent evidence for a strong effect of solar activity on terrestrial insolation based on the SAO data was presented (Weber, 2010, hereafter W10). Specifically, the analysis of the observational data forming the first part of W10 reports a strong increase of the irradiance of the direct solar beam (measured on the ground) with sunspot number as well as a decline of the brightness of the solar aureole with solar activity. Moreover, a relatively strong decline of atmospheric water content with sunspot number was found. In the second part of W10, these results are theoretically interpreted in terms of a signature of cosmic-ray-induced aerosol formation.

Motivated by the findings of W10, this paper re-analyses the SAO dataset for trends associated with solar activity (the first part of W10), focusing not on the solar constant measurements, but on the ground-based data on precipitable water vapour, aureole brightness, and direct solar beam irradiance. It thus investigates whether these results in W10 can withstand critical tests concerning systematic biases and an improved error analysis. Note that this paper will not discuss the theoretical considerations on cosmic-ray-induced aerosol formation comprising the second part of W10; it rather investigates whether the observational basis on which this theory is based is sound.

This paper is organised as follows: Sect. 2 introduces the dataset and potential problems with the analysis in W10. Sections 3, 4 and 5 re-analyse the data for the precipitable water, the brightness of the solar aureole and the irradiance of the direct solar beam for potential trends with solar activity as traced by sunspot number, before the findings are summarised in Sect. 6.

2 Datasets, data analysis and problems

2.1 Datasets

During the first half of the 20th century, the Smithsonian Astrophysical Observatory (SAO) carried out an ambitious campaign to determine the solar constant from ground-based observations at various mountain stations. Here I focus on these SAO data for the years 1923–1954 and the two sites Cerro Montezuma (Chile) and Table Mountain (California)[1]. (The data prior to 1923 are generally considered problematic, and stations other than Cerro Montezuma and Table Mountain were operated only for very brief periods of time.)

These data mainly contain three measured quantities: (1) the precipitable water content of the atmosphere determined from the ratio of the intensity in three water-vapour absorption bands to the continuum intensity; (2) the brightness of the solar aureole (a bright glow around the Sun caused by forward scattering of sunlight by atmospheric aerosols which is also known as circumsolar sky radiation or, historically, as pyranometry) measured in a ring around the Sun (viewing angles from 3.5° to 14.5° from the centre of the Sun until the early 1930s, and from 8.5° to 18.5° afterwards); (3) the pyrheliometry, i.e. the irradiance of the direct solar beam corrected for sky brightness as measured by the pyranometer (see also Hoyt, 1979). From these measurements, daily values for the solar constant (the irradiance on top of the atmosphere) were derived which are not considered here.

These SAO observations were combined with data on daily sunspot numbers to allow analysis of trends associated with solar activity[2]. Units in the combined catalogue were converted to SI units, and, following Roosen and Angione (1984), empirical offsets to the pyranometry data (reflecting changes to the instruments due to different viewing angles and the addition of sunshades in the early 1930s) were taken into account. Furthermore, two obvious typos in the number of the year were corrected. No further changes were applied to the data.

In addition to the SAO data used in the following, in Sect. 5 the solar irradiance data from Mauna Loa Observatory (MLO, Price and Pales, 1963) will be briefly considered as they form part of the analysis in W10. These MLO data (Dutton et al., 1994; Dutton and Bodhaine, 2001) were kindly provided by Ellsworth G. Dutton and comprise automatic measurements of solar irradiance from 1958 to 2008 taken at local noon as well as at airmass values of 2, 3, 4 and 5 both during mornings and afternoons. After correcting for a few obvious typos in the data, they were merged with daily sunspot number in much the same way as the SAO data. Low solar irradiance values (either due to bad weather or instrument failure) were filtered out using a cut-off of 80% of the median value.

2.2 Data analysis

As in W10, changes of the solar irradiance on the ground, the brightness of the solar aureole and the atmosphere's water content with sunspot number are investigated in terms of linear regression analysis. A linear dependence on sunspot number is chosen due to its simplicity; this choice is not based on any assumption about the underlying physics. Note that there is some debate in the literature about how well sunspot numbers actually trace solar activity in general and changes in solar irradiance in particular (e.g. Wang et al., 2005); analysing the SAO data with respect to other indicators of solar activity is beyond the scope of this paper, however.

In addition, changes in median values and the variance of the three variables with sunspot number R are analysed.

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[1] Available at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_IRRADIANCE/abbot/, access: 12 November 2010.

[2] Available at http://sidc.oma.be/DATA/dayssn_import.dat, access: 12 November 2010.

Table 1. Dependence of precipitable water content W, aureole brightness A and the irradiance I of the direct solar beam on sunspot number R as measured by the best-fitting linear slopes dW/dR, dA/dR, and dI/dR for the SAO data taken at Cerro Montezuma (M) and Table Mountain (T). The second column lists the values as reported in Table 1 of W10, but with 1σ error bars. In the third column the values from this re-analysis of the data are presented, showing mostly very similar values to the ones in W10, but substantially larger 1σ error bars. Finally, the values in the last column are based on data corrected for seasonal variations and without periods affected by volcanic aerosols or local pollution. After correcting for these effects and with improved error estimates from bootstrapping simulations, the data show no significant trend of the three quantities with sunspot number.

		This work	
Data and station	Weber (2010)	not corrected	corrected
	Trend in precipitable water content dW/dR [mm]		
SAO all	-0.020 ± 0.0033	-0.026 ± 0.0121	$\mathbf{-0.0010\pm0.0139}$
SAO M	-0.042 ± 0.0046	-0.050 ± 0.0113	$\mathbf{-0.0056\pm0.0119}$
SAO T	$+0.017\pm0.0053$	$+0.008\pm0.0134$	$\mathbf{+0.0116\pm0.0193}$
	Trend in the brightness of the solar aureole dA/dR [W m^{-2}]		
SAO all	-0.010 ± 0.0003	-0.012 ± 0.0011	$\mathbf{-0.0014\pm0.0011}$
SAO M	-0.013 ± 0.0004	-0.014 ± 0.0010	$\mathbf{-0.0026\pm0.0010}$
SAO T	-0.006 ± 0.0005	-0.007 ± 0.0013	$\mathbf{+0.0016\pm0.0015}$
	Trend in the irradiance of the solar beam dI/dR [W m^{-2}]		
SAO all	$+0.059\pm0.0051$	$+0.073\pm0.0135$	$\mathbf{+0.0100\pm0.0399}$
SAO M	$+0.084\pm0.0069$	$+0.116\pm0.0131$	$\mathbf{+0.0191\pm0.0362}$
SAO T	$+0.032\pm0.0076$	$+0.024\pm0.0140$	$\mathbf{-0.0049\pm0.0460}$

Median and variance are computed in four intervals of the sunspot number ($0 \leq R < 40$, $40 \leq R < 80$, $80 \leq R < 160$ and $160 \leq R < 320$). The width of these intervals is chosen to increase with sunspot number in order to reduce the imbalance in the number of points within the bins.

Finally, mostly results from the Cerro Montezuma data are shown in this work since they are generally considered to be of the highest quality. The same analysis was also performed for the Table Mountain data, however, with quantitatively very similar results unless explicitly mentioned otherwise. In the following, potential problems with the dataset and the analysis presented in W10 are discussed, beginning with a critical look at the errors for the linear regressions.

2.3 Error of the fit

First, it should be pointed out that the formal errors for the slope of the linear regression reported in W10 appear to be too small. W10 lists 98% confidence level errors for the slope of the linear regression in Table 1 of his paper. These values have been converted to 1σ intervals and are shown in Table 1 in this work. In the re-analysis of the dataset presented here, 1σ errors for the slope of the linear regression were computed following the standard procedure (e.g. Bevington and Robinson, 2002), finding errors for the slope which are typically a factor of 2–2.5 larger than the ones reported in W10 (see the values in column 3 of Table 1).

Furthermore, it is important to note that even these corrected formal errors of the linear regression parameters underestimate the true error for three reasons. First, any measurement is afflicted by random measurement errors. For the current data, this effect should be small, however, due to the comparatively small measurement errors and the large number of data points. This assumption has been tested and confirmed using Monte Carlo simulations, finding a negligible influence on the error of the slope.

Secondly, one needs to be concerned about the distribution of data points to which the line is approximated: there are very many data for small sunspot numbers, but only very few points for large sunspot numbers. These few points at large sunspot numbers will certainly influence the slope of the line. To assess the effect of this statistical sampling on the error of the fit a set of 10 000 bootstrapping simulations was performed for each measurement variable, station and airmass. In these simulations, the original sample was first duplicated, before half of the sample was selected randomly each time (thus keeping the number of data points used in the linear regression the same), and the linear regression for the potential trend of the variable in question with sunspot number repeated.

The resulting error for the slope of the linear fit is now on average 20% larger than without the bootstrapping, indicating a non-negligible effect of the poor statistics at large sunspot numbers on the slope of the trend. These improved error estimates are used in the following analysis unless otherwise noted.

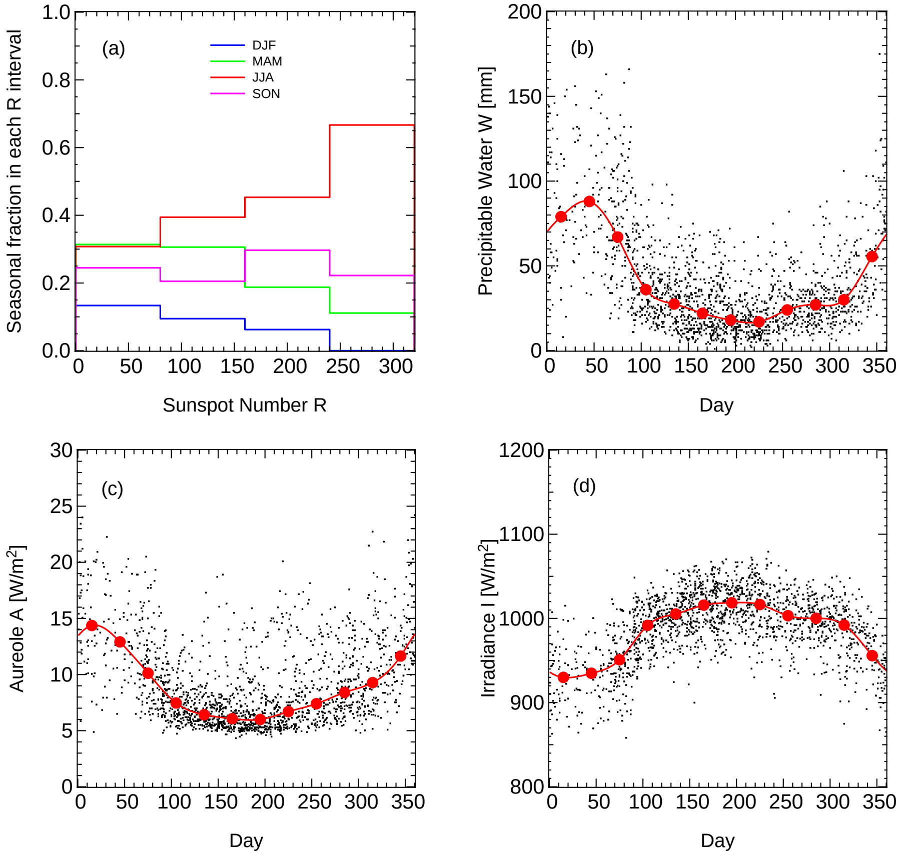

Fig. 1. Illustration of seasonal selection bias for observations at Cerro Montezuma and airmass 2.5. **(a)** Fraction of observations taken in each season as a function of sunspot number R, showing a strong difference in the seasonal distribution between small and large sunspot numbers. **(b)** Annual variation of the measured precipitable water content W (black squares), based on all years in the dataset, but excluding years affected by volcanic aerosols or local pollution (see Sect. 2.5). The red circles are monthly median values, and the red line a third-order spline fitted to these. Note the strong seasonal variation and the large short-term scatter of the values. **(c)** Same as before, but showing the annual cycle of aureole brightness A and **(d)** of the irradiance I of the direct solar beam.

Thirdly, there could be some sort of systematic trends or offsets in the data which are due to the way the measurements were done or analysed. These effects have been reported for the SAO data and include selection effects due to cloudy days or instrument failures combined with the large daily and annual variations, instrument changes, slight differences in readings done by different observers, and calibration issues (Hoyt, 1979; Roosen and Angione, 1984). For example, there is a decrease in pyrheliometry for Cerro Montezuma in 1924 which might be an artefact, and an unexplained increase in Table Mountain pyrheliometry in 1939. Furthermore, systematic errors which are probably due to changes in calibration of the SAO measurements have been reported (Allen, 1958). These effects are difficult to assess and will not be considered further, although it should be kept in mind that this dataset is far from being homogeneous and is certainly not without systematic errors, making any analysis of trends very difficult.

There are two systematic effects, however, which are well known and must be corrected before analysing the dataset. These effects are the annual variation of the data and certain periods heavily affected by volcanic aerosols or local pollution.

2.4 Seasonal bias

To test whether any seasonal selection bias could influence the analysis of trends with solar activity, a histogram of sunspot numbers R for all four seasons, Cerro Montezuma, and airmass 2.5 is shown in Fig. 1a. The fraction of observations in June–August (JJA) increases with R, dominating for high sunspot numbers, while the fractions of data taken in December–February (DJF) and March–May (MAM) decrease with R. At $R > 240$, for example, 67% of all observations were taken during JJA, whereas there are no data from DJF. The precipitable water content of the atmosphere, the aureole brightness, and the irradiance of the direct solar beam

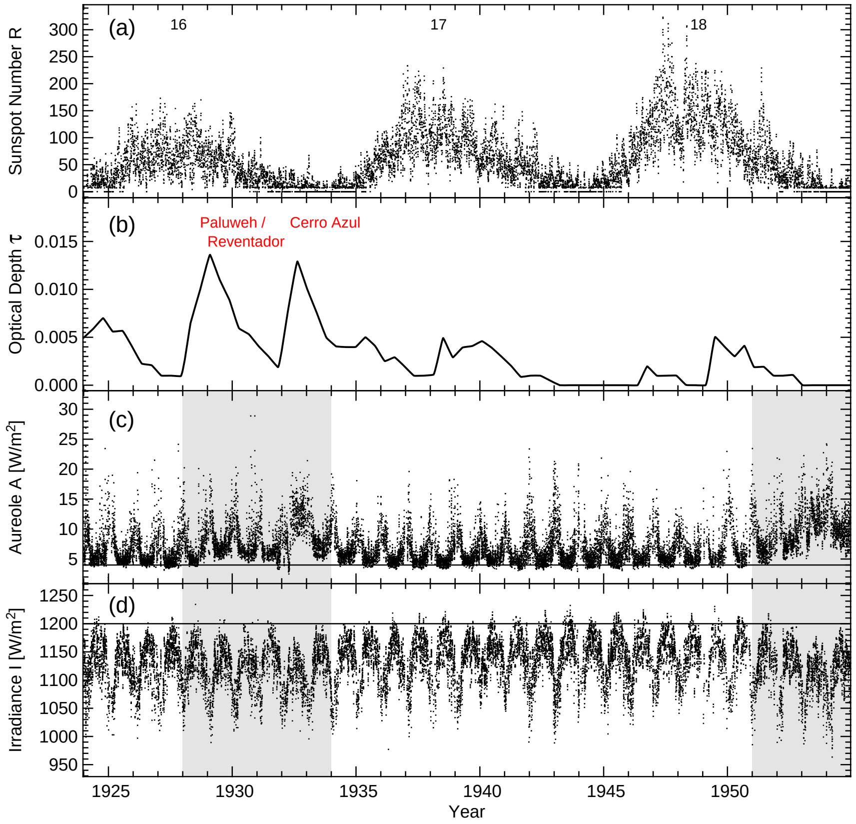

Fig. 2. Time series diagrams for **(a)** the daily sunspot number R for solar cycles 16 to 18, **(b)** the absorption by volcanic aerosols (expressed as the smoothed optical depth τ at 550 nm in the Southern Hemisphere, Sato et al., 1993), **(c)** the brightness A of the solar aureole (pyranometry), and **(d)** the direct solar beam irradiance I (pyrheliometry) for Cerro Montezuma and all airmass values. Years affected by aerosols from volcanic eruptions and/or local pollution (for the years after 1950) according to Hoyt (1979) and Roosen and Angione (1984) are marked by the grey shaded areas in the lower two panels. A baseline at an arbitrary value of $4\,\mathrm{W\,m^{-2}}$ (close to the annual minimum) is shown in **(c)**, making clear that during these times the seasonal minima of the pyranometry values are larger than normally. Similarly, an arbitrary line at $1200\,\mathrm{W\,m^{-2}}$ is shown in **(d)**. For greater clarity, the pyrheliometry values were converted to airmass 1 using an empirically determined extinction coefficient $\kappa = 0.0884$ (see Sect. 5).

vary strongly with the seasons, however (see the other panels of Fig. 1), suggesting that the observed trends with sunspot number are in reality, at least partly, due to a seasonal effect.

The seasonal distribution of observations for other stations and/or other airmass values is not in all cases as skewed as for Cerro Montezuma and airmass 2.5, but it is never free of seasonal bias, an effect which must be accounted for. One way of doing this would be to work with annual averages of the data, thus losing all information on shorter time-scales. Alternatively, one could correct for this seasonal variation by simply subtracting the deviations of the monthly medians from the annual mean for the variables in question, and re-analysing the distribution of these corrected values with sunspot number R. Results of this exercise for the trends of the corrected values of the precipitable water content, the brightness of the solar aureole, and the direct solar beam irradiance with sunspot number are presented in Sects. 3, 4, and 5, respectively.

2.5 Volcanic eruptions and other sources for aerosols

It is highly instructive to look at the time-series diagram of the sunspot number, the brightness of the solar aureole and the solar-beam irradiance shown in Fig. 2. According to Hoyt (1979) and Roosen and Angione (1984), the years 1928–1931 are affected by the eruptions of the volcanoes Paluweh and Reventador, 1932–1933 by volcanic activity at Cerro Azul, 1951–1952 by a number of smaller eruptions, and 1953–1955 by local aerosols at Cerro Montezuma and/or a global stratospheric dust veil of unknown origin.

It can be seen from Fig. 2 that during these periods of time the baseline values of the solar aureole brightness were considerably higher than at other times. Similarly, the atmospheric transmission as measured by the irradiance was markedly lower. Note that these two periods overlap with the minima between solar cycles 16 and 17, and 18 and 19, respectively, suggesting a strong effect of these distorted measurements on trends with sunspot number. It should also be noted that the solar minimum between cycles 17 and 18 is not affected by volcanic aerosols and shows neither an enhanced aureole brightness nor lower irradiance values, which argues against solar activity being the cause of the changes in irradiance and aureole brightness during the other two solar minima.

Due to these effects visible in the data taken between 1928–1933 and 1951–1955 these measurements should not be considered in any search for trends with solar activity. Indeed, they have been excluded from the analysis in Sects. 3, 4, and 5.

On a related note, volcanic aerosols are also behind the apparent wavelength-dependent trends of atmospheric transmissions with sunspot number based on Mount Wilson data taken in the period 1905–1920 and shown in Fig. 2 of W10. A comparison of sunspot numbers and optical depth of stratospheric aerosols in the Northern Hemisphere at $\lambda = 550\,\mathrm{nm}$ (Sato et al., 1993) during this time interval is presented in Fig. 3. The solar minimum between cycles 14 and 15 is heavily affected by volcanic aerosols from the eruption of Katmai (Alaska) in 1912, naturally explaining why solar-minimum transmissions appear to be lower and redder during this time interval.

In any case, the SAO observations prior to 1923 are generally considered to be less reliable, and the short time-span of less than two solar cycles with data for only one solar minimum (heavily affected by volcanic aerosols) makes any investigation of trends with solar activity meaningless. It should also be noted that astronomers regularly measure night-time atmospheric extinction coefficients at optical and near-infrared wavelengths at numerous observatories around the world, and no correlation with solar cycles of the magnitude reported in W10 is known (e.g. Angione and de Vaucouleurs, 1986).

3 Precipitable water content

First the reported decline in precipitable water content with solar activity is investigated. For illustration I focus on the Cerro Montezuma data taken at airmass 2.5 shown in Fig. 1 of W10 (a re-analysis is shown in Fig. 4a in this work). Indeed, the observed trend is largely driven by data from this site (see Table 1 in W10); from this table it is also clear that data from Table Mountain actually show the opposite trend of water content with sunspot number, a fact that should already raise some concern about the general validity of the result.

As described above, I correct for seasonal variations of atmospheric water vapour by subtracting the difference of the monthly medians and the annual average of the precipitable water content before computing the linear regression. Note that there is considerable day-to-day scatter in the precipitable water content, especially in DJF (see Fig. 1b), which will affect the computation of median values, resulting in a non-perfect correction for seasonal variations. Furthermore, I omit data taken during periods affected by volcanic or other aerosols as described in Sect. 2.5.

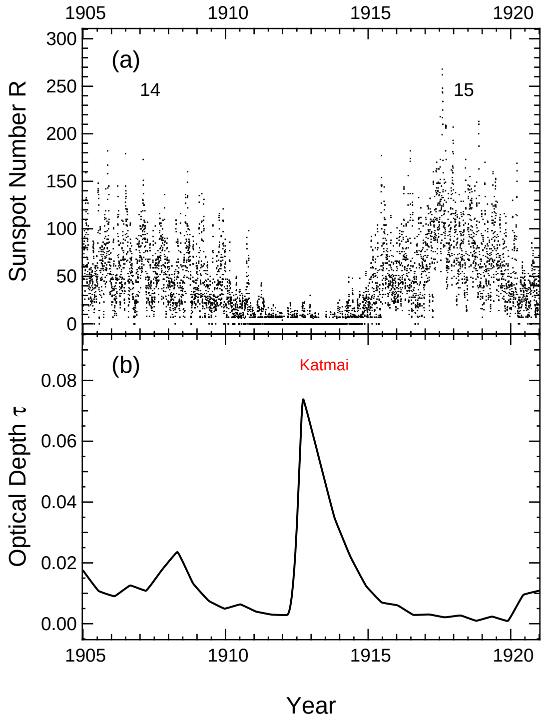

Fig. 3. (a) Time series diagram for the daily sunspot number R for the time period of early SAO observations (1905–1921), spanning solar cycles 14 and 15. **(b)** Absorption by stratospheric aerosols (expressed as the smoothed optical depth τ at 550 nm in the Northern Hemisphere, Sato et al., 1993) during the same period of time, showing that the solar minimum between cycles 14 and 15 coincides with high levels of volcanic aerosols from the eruption of Katmai in 1912. Please note the change in scale for the optical depth as compared to Fig. 2.

The result of this exercise is shown in Fig. 4b. The formal value for the slope of the linear fit is now -0.010 ± 0.014. In other words, there is no significant trend (at the 1σ level) of the observed atmospheric water content with sunspot number. To test its robustness, the seasonal correction was also performed using monthly averages instead of medians, both computed at a given airmass and for all airmass values, as well as with seasonal corrections computed for each day using the spline shown in Fig. 1. The results are very similar for all cases.

In addition, Fig. 4b also presents the changes of the values of the median and the variance of the atmospheric water content W with sunspot number R in four R intervals. There is no significant change in the medians, which also demonstrates that a linear model is a reasonable approximation to the data. The slight decrease of the variance with sunspot

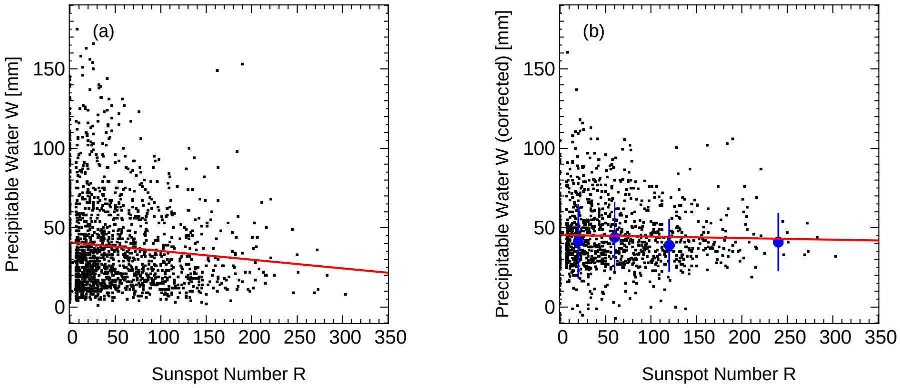

Fig. 4. **(a)** Precipitable water content W versus sunspot number for Cerro Montezuma and airmass 2.5, showing a very similar trend to the one presented in Fig. 1 of W10. The linear slope has a value of -0.055 ± 0.014. **(b)** Same as before, but for the corrected values of the precipitable water contient, i.e. with the deviation of the monthly medians from the annual average subtracted to correct for seasonal variations, and without the data from years affected by volcanic aerosols or local pollution. The red line indicates a linear regression to the data, showing no statistically significant trend with sunspot number (slope -0.010 ± 0.014). The blue circles and their error bars illustrate median values and the variance in four sunspot-number intervals.

number is very likely caused by the larger scatter of W during the months DJF, which comprise a higher fraction of observations for small sunspot numbers than for high sunspot numbers (see Sect. 2.4).

Although only results for Cerro Montezuma and airmass 2.5 have been shown, it should be emphasised that the results for other stations and other airmass values are very similar. Best-fitting values for both Cerro Montezuma and Table Mountain are summarised in Table 1. After correction of the seasonal selection bias and without data from years strongly affected by aerosols the SAO data show no statistically significant trend of the precipitable water content with sunspot number. Note that any small residual trend, if at all present, may be due to the necessarily imperfect correction for seasonal variations or some other systematic bias of the data like calibration changes described in Sect. 2.3.

4 Brightness of the solar aureole

Next the brightness of the solar aureole measured in a ring around the Sun (also called the pyranometry) is considered for which W10 found a strong decrease with sunspot number (see Fig. 5a in this work for the case of the Cerro Montezuma data at airmass 1.5, the example shown in Fig. 1 of W10). It can be seen from Fig. 1c that – similar to the atmospheric water content – the aureole brightness exhibits a clear annual cycle which has to be subtracted to ensure that the trend with sunspot number is not due to seasonal variations.

Furthermore, the aureole data for certain years are strongly affected by aerosols from volcanic eruptions (and local pollution, see the discussion in Sect. 2.5), as is evident from the time series shown in Fig. 2. Repeating the linear regression for the data corrected for the seasonal cycle and without data from the years affected by aerosol contamination yields a much smaller and barely significant value for the slope of the suggested trend with sunspot number (see Fig. 5b). Furthermore, there is insignificant change of median values and the variance with sunspot number.

Other stations and airmass values exhibit a similar behaviour, summarised in Table 1. Hence the trend of solar-aureole brightness with sunspot number reported in W10 is again due to systematic effects and not a result of atmospheric changes caused by solar activity.

5 Solar irradiance

Finally the apparent increase of the irradiance of the direct solar beam (the pyrheliometry measurements in the SAO data) with sunspot number W10 is revisited. The uncorrected data for Cerro Montezuma and airmass 1.5 (one of the examples shown in Fig. 1 of W10) indeed show a positive trend (see Fig. 6a in this work), while the data corrected for seasonal variation (see Sect. 2.4) and without the times affected by volcanic or other aerosols (see Sect. 2.5) again exhibit no statistically significant trend with solar activity (Fig. 6b). As for the other two variables there is no significant change in the median values or variances with sunspot number.

The results for other stations and airmass values are similar (see the summary in Table 1), although the combined SAO data show a non-significant trend of $dI/dR = 0.01 \pm 0.04$. This result is in agreement with a previous study which found no apparent evidence for a solar signal in the SAO pyrheliometry data (Hoyt, 1979).

Note that, although statistically not significant in the SAO data, the change of the intensity I of the direct solar beam with sunspot number R of $dI/dR = 0.01\,\mathrm{W\,m^{-2}}$ indicated in

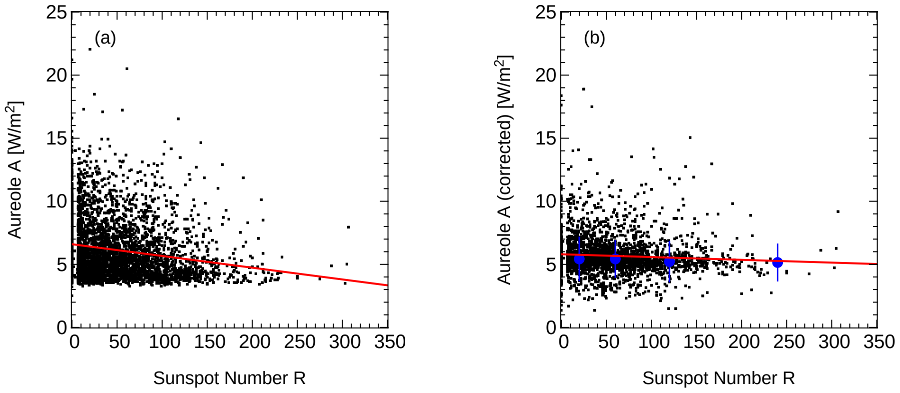

Fig. 5. (a) The brightness A of the solar aureole (pyranometry) versus sunspot number for Cerro Montezuma and airmass 1.5, showing a very similar trend to the one presented in Fig. 1 of W10. The linear slope has a value of -0.0093 ± 0.0010. **(b)** Same as before, but for the corrected values of the pyranometry, i.e. with the deviation of the monthly medians from the annual average subtracted to correct for seasonal variations, and without the data from years affected by volcanic aerosols or local pollution. The red line indicates a linear regression to the data, showing no statistically significant trend with sunspot number (slope -0.0022 ± 0.0008). The blue circles and their error bars illustrate median values and the variance in four sunspot-number intervals.

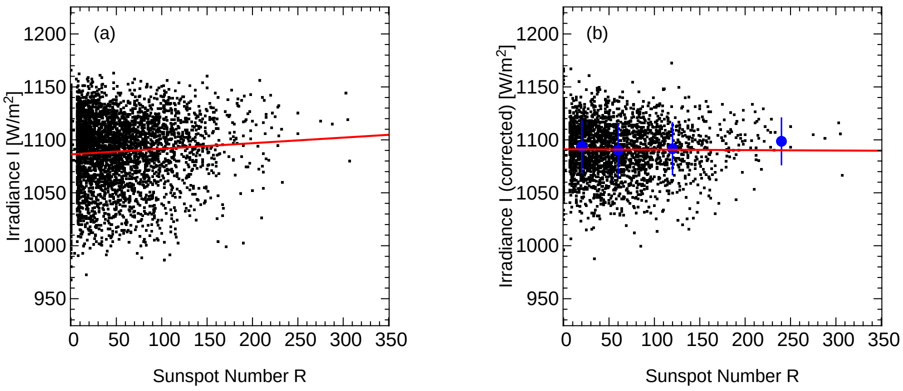

Fig. 6. (a) Irradiance I of the solar beam (pyrheliometry) versus sunspot number for Cerro Montezuma and airmass 1.5, showing a very similar trend to the one presented in Fig. 1 of W10. The linear slope has a value of $+0.053 \pm 0.030$. **(b)** Same as before, but for the corrected values of the pyrheliometry, i.e. with the deviation of the monthly medians from the annual average subtracted to correct for seasonal variations, and without the data from years affected by volcanic aerosols or local pollution. The red line indicates a linear regression to the data, showing no statistically significant trend with sunspot number (slope -0.0039 ± 0.0340). The blue circles and their error bars illustrate median values and the variance in four sunspot-number intervals.

Table 1 corresponds to a variation of 0.13% between $R = 0$ and $R = 150$, which is the order of magnitude for the variation of the total solar irradiance at the top of the atmosphere derived from satellite measurements between solar maxima and minima (e.g. Fröhlich and Lean, 2004).

Due to the importance of the solar irradiance I on the ground, its variation with sunspot number R maybe deserves more attention, and one can try to derive a best estimate for dI/dR from the SAO data. To construct this best estimate, the following steps are taken:

- Only Cerro Montezuma data are considered, since they are generally thought to be of the highest quality.
- Only measurements during JJA are taken into account because of their lower scatter (see Fig. 1d).
- Periods of time with enhanced volcanic and local aerosols are excluded, and seasonal variations are corrected as described above.
- To improve statistics, measurements of I at different airmass values X are combined. The differences in atmospheric extinction are corrected by converting all data to $X = 1$ using a standard extinction law of the form $I(X) = I_0 \exp(-\kappa X)$, with an empirically determined extinction coefficient $\kappa = 0.0884 \pm 0.0009$, see Fig. 7a.

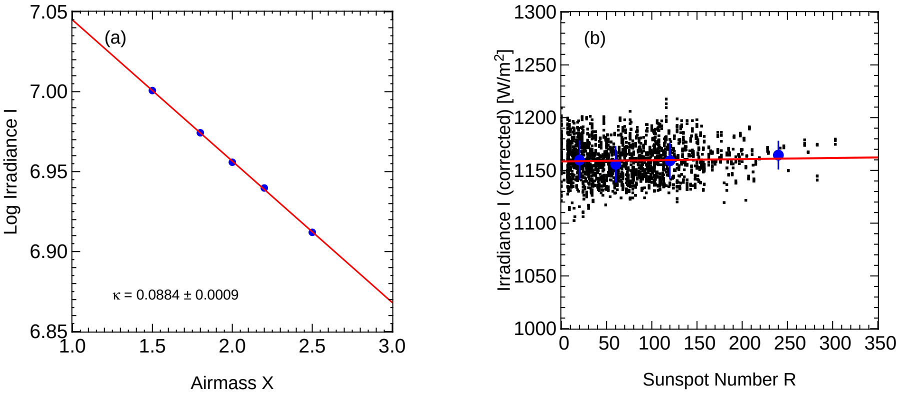

Fig. 7. **(a)** Estimate of the extinction coefficient κ defined by $I(X) = I_0 \exp(-\kappa X)$ from a linear regression *(red line)* to the medians *(blue circles)* of the solar irradiance I at different airmass values X for all data taken at Cerro Montezuma. **(b)** Best estimate of the variation of solar irradiance I with sunspot number R for the Cerro Montezuma data during months JJA at all airmass values and for days with low water content and low aureole brightness, showing an increase of I with R of the order of 0.1% between solar maxima and minima. The values of the median and the variance in four R intervals are shown *(blue circles with error bars)*, as is the result of a linear fit to the data *(red line)*.

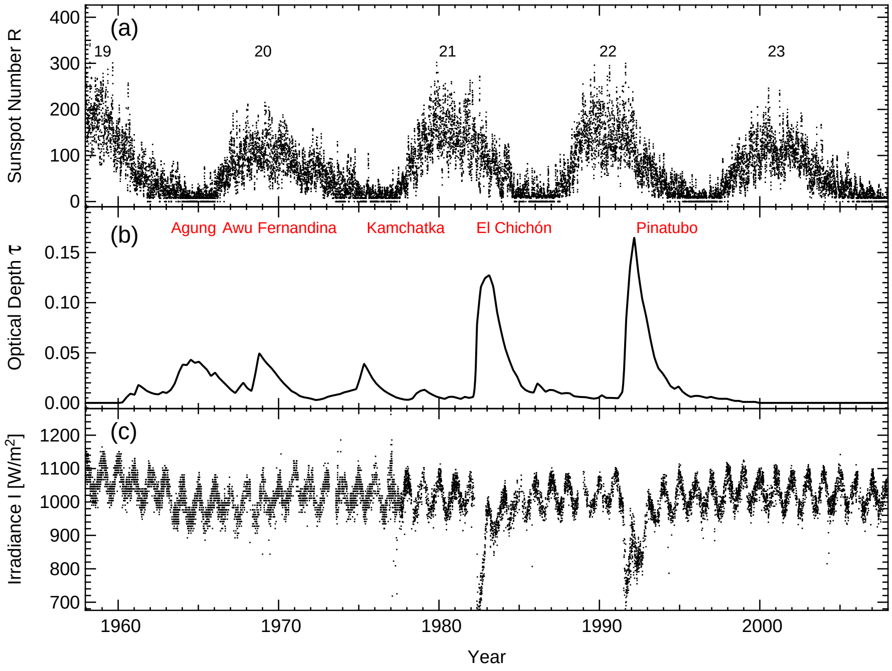

Fig. 8. Time series diagrams for **(a)** the daily sunspot number R for solar cycles 19 to 23, **(b)** the absorption by volcanic aerosols (expressed as the smoothed optical depth τ at 550 nm in the Northern Hemisphere, Sato et al., 1993), **(c)** the direct solar beam irradiance I (pyrheliometry) as measured from Mauna Loa at airmass 2. Note that the maximum values of the optical depth are more than a factor of ten larger than for the SAO data shown in Fig. 2. Prominent volcanic eruptions are labeled.

– Finally upper limits in the brightness of the solar aureole $A < 6\,\mathrm{W\,m^{-2}}$ and in atmospheric water content $W < 30\,\mathrm{mm}$ are applied.

This best estimate of the variation of solar irradiance with solar activity in the SAO data is shown in Fig. 7 and yields a linear trend of $dI/dR = 0.01 \pm 0.03$, in agreement with (and slightly better constrained than) the estimates given in Table 1. Again, this is of the same order of magnitude as the variation of the total solar irradiance determined by measurements from space. Hence there seems to be no evidence for any strong enhancement of solar radiation changes due to unknown feedbacks in Earth's atmosphere.

Finally, it might be interesting to have a brief look at the solar irradiance data from Mauna Loa observatory also considered in W10. Similar to the SAO data, a time-series diagram of these MLO data is shown in Fig. 8. Two things are immediately apparent. First, the MLO data are punctuated by frequent volcanic eruptions. While the El Chichón and Pinatubo events stand out due to their magnitude, a number of sizable eruptions occurred during the first half of the record. In fact, in the SAO data volcanic periods corresponding to aerosol optical depths of about $\tau > 0.005$ had to be excluded from the analysis presented in this paper. Applying a similar cut to the MLO data would leave very little of this data record for investigation. Secondly, there appears to be a steady linear decline in solar irradiance which is most likely caused by aerosols (Dutton and Bodhaine, 2001). For these reasons I would argue that an analysis of solar irradiance changes with solar activity in the MLO data is extremely difficult since it will prove rather challenging to disentangle these changes from the effects described above.

6 Conclusions

W10 presented evidence for a strong increase of the irradiance of the direct solar beam (measured on the ground) with sunspot number, and for strong declines of atmospheric water content and solar aureole brightness with solar activity. In W10, these results were interpreted in terms of modulation of cosmic-ray-induced aerosol formation over the 11-yr solar cycle.

A re-analysis of the data on which these claims are based shows that these trends are due to the effects of volcanic eruptions (and other sources of aerosols) and due to seasonal variations. None of the three quantities shows any significant trend with sunspot number once these effects are taken into account (see the summary in Table 1). This illustrates, once more, that extreme care must be taken to understand any systematic bias of a dataset when investigating possible trends.

Solar activity has an influence on Earth's climate, but it is comparatively small. The 11-yr solar activity cycle, for example, has been shown to result in global temperature changes of $\simeq$0.1 °C between solar maxima and minima (Lean and Rind, 2008). Grand minima of solar activity like the Maunder minimum (Eddy, 1976) in the 17th century lowered global temperatures by $\simeq$0.5 °C, which is less than the warming of $\simeq$0.7 °C observed over the 20th century. Even a future Maunder-like solar-activity minimum would diminish global temperatures by $\simeq$0.3 °C at most, about a factor of ten smaller than the expected warming due to anthropogenic greenhouse-gas emissions (Feulner and Rahmstorf, 2010). Furthermore, these changes can be explained by the variations of the total and spectral solar irradiance, without any need to invoke hypothetical mechanisms involving cosmic rays for which there continues to be little supporting evidence.

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