Atmos. Chem. Phys. Discuss., 11, 2297–2316, 2011
www.atmos-chem-phys-discuss.net/11/2297/2011/
doi:10.5194/acpd-11-2297-2011

Atmospheric Chemistry and Physics Discussions

The Smithsonian solar constant data revisited: no evidence for cosmic-ray induced aerosol formation in terrestrial insolation data

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Received: 7 December 2010 – Accepted: 10 January 2011 – Published: 21 January 2011

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Apparent evidence for a strong signature of solar activity in terrestrial insolation data was recently reported. In particular, a surprisingly strong increase of terrestrial insolation 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 was presented. The latter effect was interpreted as evidence for cosmic-ray induced aerosol formation. Here I show that these spurious result 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, the atmospheric water content, the solar aureole brightness, and the terrestrial insolation show no significant trend with solar activity. Hence there is no evidence for the influence of solar activity on the climate being stronger than currently thought, or a cosmic-ray mechanism linking the two.

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 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, is rather limited (Gray et al., 2010).

Recently, apparent evidence for a strong effect of solar activity on terrestrial insolation based on ground-based measurements (Abbot et al., 1942; Aldrich and Hoover, 1954) carried out by the Smithsonian Astrophysical Observatory (SAO) during the first half of the 20th century was presented (Weber, 2010, hereafter W10). Specifically, a strong increase of terrestrial insolation (measured below the atmosphere) with sunspot number as well as a decline of the brightness of the solar aureole with solar activity was reported. Moreover, a relatively strong decline of atmospheric water content with sunspot number was found and suggested to be a signature of cosmic-ray induced aerosol formation.

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). Earlier claims for an increase of radiation with solar activity in the SAO data (Aldrich and Hoover, 1954), however, 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 periodicities 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 years 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). However, the SAO data are generally considered to be strongly influenced by systematic effects due to different observers, instrument upgrades, changes in calibration procedures and effects of local pollution (Hoyt, 1979; Roosen and Angione, 1984), requiring an extremely careful analysis before any sound conclusions can be drawn.

Motivated by the surprising findings of W10, this paper re-analyses the SAO dataset for trends with solar activity, focusing not on the solar constant measurements, but on the data on precipitable water vapour, aureole brightness, and terrestrial insolation. It thus investigates whether the results in W10 can withstand critical tests concerning systematic biases and an improved error analysis. The 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 intensity 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 Dataset and problems

2.1 Dataset

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 have been operated only for very brief periods of time.)

These data mainly contain three measured quantities: the precipitable water content of the atmosphere determined from the ratio of the intensity in three water-vapour absorption bands to the continuum intensity, the pyranometry (or brightness of the solar aureole) measured in a ring around the Sun, and the pyrheliometry, i.e. the intensity 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 were derived which are not considered here.

These SAO observations were combined with data on daily sunspot numbers to allow analysis of trends with solar activity[2]. Units in the combined catalog were converted to SI units, and, following Roosen and Angione (1984), the empirical offsets to the

[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.

pyranometry data were applied. Furthermore, two obvious typos in the number of the year were corrected. No further manipulation of the data was performed.

In the following, mostly results from the Cerro Montezuma data are shown since they are generally considered to be of highest quality. The same analysis was also performed for the Table Mountain data with qualitatively 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.

2.2 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 with 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 at small sunspot numbers, but only very few points at large sunspot numbers. These few points at large sunspot numbers will certainly strongly 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.

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 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 data set. These effects are the annual variation of the data and certain periods heavily affected by volcanic aerosols or local pollution.

2.3 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 the upper left-hand panel of Fig. 1. Clearly, the majority of measurements at small sunspot numbers ($R<50$) have been taken in DJF or MAM, while for large sunspot numbers ($R>150$) they fall into JJA and SON. The precipitable water content of the atmosphere, the pyranometry, and the pyrheliometry vary strongly with the seasons, however (see the other panels of Fig. 1), making it very likely that the observed trends with sunspot number are in reality at least partly a seasonal effect.

The seasonal distribution of observations for other stations and/or other airmasses is not in all cases as skewed as for Cerro Montezuma and airmass 2.5, but it is, of course, never free of seasonal bias, an effect which must be corrected for. One way to correct for this seasonal variation is to simply subtract monthly medians for the variables in question and re-analyse the distribution of this anomaly with sunspot number R. Results of this exercise for the trends of the anomalies of the precipitable water content, the pyranometry, and the pyrheliometry with sunspot number are presented in Sects. 3, 4, and 5, respectively.

2.4 Volcanic eruptions and other sources for aerosols

It is highly instructive to look at the time-series diagram of the sunspot number, the pyranometry (the brightness of the solar aureole), and the pyrheliometry shown in Fig. 2. According to Hoyt (1979) and Roosen and Angione (1984), the years 1928–1931, 1932–1933, 1951–1952, and 1953–1955 are affected by a series of volcanic eruptions and, for the last three years, by a global stratospheric dust veil of unknown origin.

It is obvious from Fig. 2 that during these periods of time the baseline pyranometry values were considerably higher than at other times. Similarly, the atmospheric transmission as measured by the pyrheliometry was clearly lower. Note that these two periods overlap with the minima between solar cycles 16 and 17 as well as 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 and shows no enhanced pyranometry or decreased pyrheliometry values. This makes a solar-activity origin of the changes during these

times highly unlikely.

Due to these effects clearly 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 in all likelihood 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 λ=550 nm (Sato et al., 1993) during this time interval is presented in Fig. 3. It is obvious that 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 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 we focus on the Cerro Montezuma data taken at airmass 2.5 shown in Fig. 1 of W10. 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, we correct for seasonal variations of atmospheric water vapour by subtracting monthly medians 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 the upper right-hand panel of Fig. 1, which will affect the computation of median values, resulting in a non-perfect correction for seasonal variations. Furthermore, we omit data taken during periods affected by volcanic or other aerosols as described in Sect. 2.4.

This exercise is shown in Fig. 4. The formal value for the slope of the linear fit is now -0.009 ± 0.014. In other words, there is no significant trend 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.

Although only results for Cerro Montezuma and airmass 2.5 have been shown, it should be emphasized that the results for other stations and other airmass values are very similar. Average fit values for both Cerro Montezuma and Table Mountain are summarised in Table 1. It is obvious that after correction of the seasonal selection bias and without data from years strongly affeced 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. 2.2.

4 Pyranometry

Next we consider the pyranometry (or the brightness of the solar aureole measured in a ring around the Sun) for which W10 found a strong decrease with sunspot number (see the left-hand panel of Fig. 5 for the case of the Cerro Montezuma data at airmass

1.5, the example shown in Fig. 1 of W10). It is obvious from Fig. 1 that – similar to the atmospheric water content – the pyranometry 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 pyranometry data for certain years are strongly affected by aerosols from volcanic eruptions (and local pollution, see the discussion in Sect. 2.4), 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 right-hand panel of Fig. 5). Other stations and airmass values exhibit a similar behaviour, see the summary in Table 1. Hence the trend reported in W10 is again due to systematic effects and not a result of atmospheric changes caused by solar activity.

5 Pyrheliometry

Finally the apparent increase of the intensity 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 left-hand panel of Fig. 6), while the data corrected for seasonal variation (see Sect. 2.3) and without the times affected by volcanic or other aerosols (see Sect. 2.4) again exhibit no statistically significant trend with solar activity. The results for other stations and airmasses are very similar, see the summary in Table 1. 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, 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 Table 1 corresponds to a variation of 0.1% between $R=0$ and $R=100$, which is the order of magnitude for the variation of the total solar irradiance derived from satellite measurements (e.g. Fröhlich and Lean, 2004). Hence there seems to be no evidence for any strong enhancement of solar radiation changes due to feedbacks in the atmosphere.

6 Conclusions

W10 presented surprising evidence for a strong increase of the intensity of the direct solar beam below the atmosphere with sunspot number, and for strong declines of atmospheric water content and solar aureole brightness with solar activity. A careful 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-year solar activity cycle, for example, has been shown to result in global temperature changes of $\simeq 0.1\,^\circ$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 $\simeq 0.5\,^\circ$C, which is less than the warming of $\simeq 0.7\,^\circ$C observed over the 20th century. Even a future Maunder-like solar-activity minimum would diminish global temperatures by $\simeq 0.3\,^\circ$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 with 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.

Acknowledgements. It is a pleasure to thank Claus Fröhlich and Stefan Rahmstorf for helpful comments. This research has made use of NASA's Astrophysics Data System.

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Table 1. Dependence of precipitable water content W, aureole brightness A and the intensity of the direct solar beam I on sunspot number R as measured by the average 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.

Data and station	Weber (2010)	This work uncorrected	This work corrected
	Trend in precipitable water content dW/dR [mm]		
SAO all	*−0.020±0.0033*	−0.026±0.0121	**−0.0008±0.0139**
SAO M	*−0.042±0.0046*	−0.050±0.0113	**−0.0055±0.0119**
SAO T	*+0.017±0.0053*	+0.008±0.0134	**+0.0117±0.0192**
	Trend in brightness of solar aureole dA/dR [W m^{-2}]		
SAO all	*−0.010±0.0003*	−0.012±0.0011	**−0.0014±0.0011**
SAO M	*−0.013±0.0004*	−0.014±0.0010	**−0.0026±0.0010**
SAO T	*−0.006±0.0005*	−0.007±0.0013	**+0.0016±0.0015**
	Trend in intensity of solar beam dI/dR [W m^{-2}]		
SAO all	*+0.059±0.0051*	+0.073±0.0135	**+0.0090±0.0400**
SAO M	*+0.084±0.0069*	+0.116±0.0131	**+0.0177±0.0363**
SAO T	*+0.032±0.0076*	+0.024±0.0140	**−0.0050±0.0459**

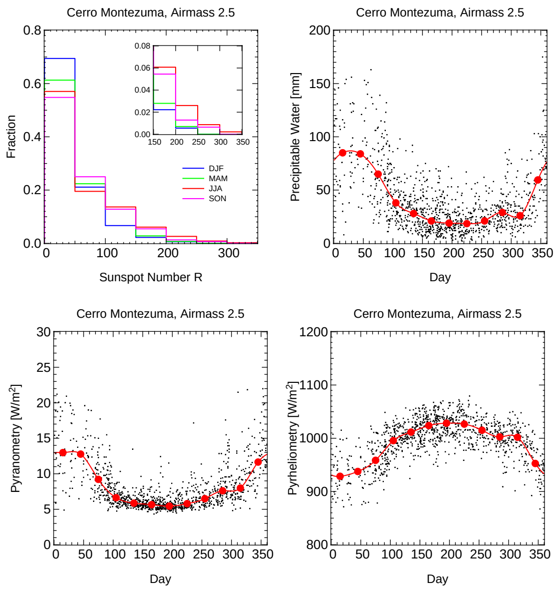

Fig. 1. Illustration of seasonal selection bias for observations at Cerro Montezuma and airmass 2.5. Upper left-hand panel: Normalised distribution of daily sunspot numbers for the four seasons. Data at small sunspot numbers $R<50$ are predominantly taken in December–February (DJF) or March–May (MAM), while observations at higher sunspot numbers $R>150$ happen to occur more often in June–August (JJA) or September–November (SON). Upper right-hand panel: Annual variation of the measured precipitable water content (black squares). 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. Lower panels: Same as before, but for pyranometry (left-hand panel) and pyrheliometry (right-hand panel).

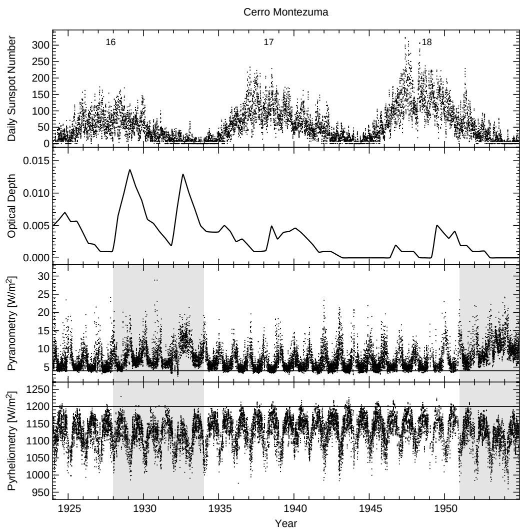

Fig. 2. Time series plot for the daily sunspot number for solar cycles 16 to 18 (first panel), the absorption by volcanic aerosols (expressed as the optical depth at 550 nm in the Southern Hemisphere, Sato et al., 1993, second panel), the brightness of the solar aureole or pyranometry (third panel), and the pyrheliometry (fourth panel) 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 the third panel, 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 the fourth panel. For greater clarity, the pyrheliometry values were converted to airmass 1 using an empirically determined extinction coefficient $\kappa=-0.085$.

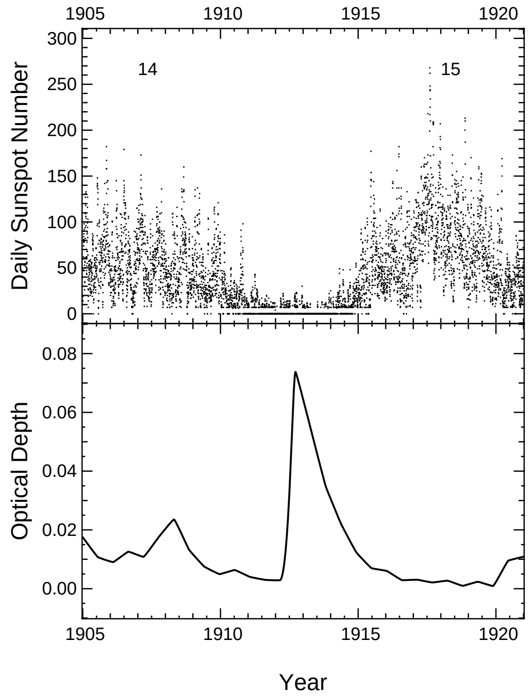

Fig. 3. Upper panel: Time series plot for the daily sunspot number for the time period of early SAO observations (1905–1921), spanning solar cycles 14 and 15. Lower panel: Absorption by stratospheric aerosols (expressed as the optical depth at 550 nm in the Southern Hemisphere, Sato et al., 1993) during 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.

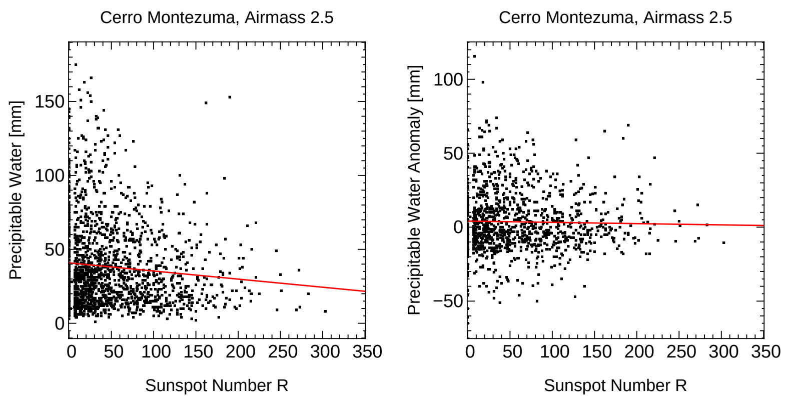

Fig. 4. Left-hand panel: Precipitable water content versus sunspot number for Cerro Montezuma and airmass 2.5, showing a very similar trend to the one presented in Fig. 1 of W10. The linear slope has a value of −0.055±0.016. Right-hand panel: Same as before, but for the anomaly of the precipitable water contient, i.e. with the monthly median value 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 −0.009±0.014).

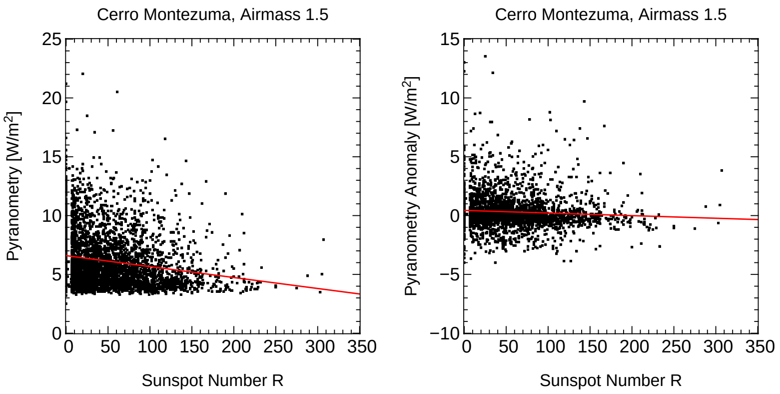

Fig. 5. Left-hand panel: Pyranometry (brightness of the solar aureole) versus sunspot number for Cerro Montezuma and airmass 1.5, showing a very similar trend to the one presented in Fig. 1 of W10. The linear slope has a value of -0.0093 ± 0.0010. Right-hand panel: Same as before, but for the anomaly of the pyranometry, i.e. with the monthly median value 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).

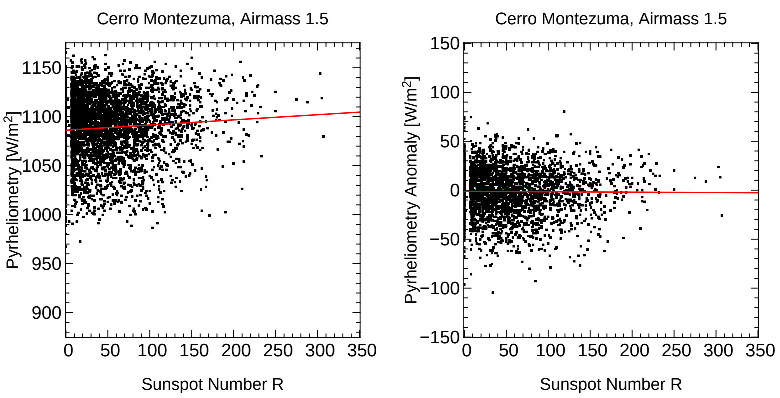

Fig. 6. Left-hand panel: Pyrheliometry versus sunspot number for Cerro Montezuma and airmass 1.5, showing a very similar trend to the one presented in Fig. 1 of W10. The linear slope has a value of $+0.18\pm0.04$. Right-hand panel: Same as before, but for the anomaly of the pyrheliometry, i.e. with the monthly median value 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).