Atmos. Meas. Tech. Discuss., 7, 8927–8943, 2014
www.atmos-meas-tech-discuss.net/7/8927/2014/
doi:10.5194/amtd-7-8927-2014

Atmospheric Measurement Techniques Discussions

Open Access

This discussion paper is/has been under review for the journal Atmospheric Measurement Techniques (AMT). Please refer to the corresponding final paper in AMT if available.

Potential impact of contrails on solar energy gain

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Received: 21 March 2014 – Accepted: 2 August 2014 – Published: 29 August 2014

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

Abstract

We investigated the effect of contrails on global shortwave radiation and on solar energy gain. The study was done for days with a high contrail persistence and looking at situations where the contrails were obstructing the sun. Measurements of cloudiness using a fish eye camera, diffuse and direct shortwave measurements and measurements of the short circuit current of three different types of photovoltaic (PV) modules were performed at the solar observatory Kanzelhöhe (1540 m a.s.l.) during a period of one year with a time resolution of one minute. Our results show that contrails moving between sun and observer/sensor may reduce the global radiation by up to 72 %. A statistic of contrail persistence and influence of contrails on global irradiance and solar energy gain is presented. The losses in solar energy gain that were recorded may even be critical under some circumstances for PV system performance.

1 Introduction

The effect of air traffic on climate has been a topic of research for 50 years. Most investigations were focused on the radiative forcing caused by contrails and by cirrus cloudiness originating from contrails. Most studies have examined this effect by using radiative transfer models and by using satellite information on contrail optical thickness, contrail coverage, man-made cirrus cloudiness etc. The mean annual radiative forcing estimate – e.g. for the specific location Herbstmonceux (Stuber et al., 2006) is 0.75 $\mathrm{W\,m^{-2}}$ in the long wavelength range and $-0.5\,\mathrm{W\,m^{-2}}$ in the short wavelength range which amounts to a total radiative forcing around 0.25 $\mathrm{W\,m^{-2}}$. Minnis et al. (2004) showed that 85 % of the days with persistent contrails are also days with cirrus cloudiness.

Only few studies, however, have investigated the impact of contrails on ground based irradiance by analysing ground based measurements. Wendler et al. (2005) explored this effect within the scope of a case study using ground-based measurements of direct

AMTD
7, 8927–8943, 2014

and diffuse irradiance and fish-eye photographs. They found a maximum decrease in global irradiance of up to 16 % (116 W m^{-2}) when the contrails were moving between sun and observer. Between these obstruction events the diffuse irradiance was enhanced by up to 29 % due to reflexion and scattering of the direct radiation by the surrounding clouds. This increase in radiation, not only includes the reflexion and scattering by contrails but also the effect of cirrus cloudiness. Feister and Shields (2005) investigated the increase in diffuse irradiance solely caused by contrails and found enhancements of 8 %. Pfister et al. (2003) observed short-term enhancements in global irradiance of up to 60 % which were caused by thin clouds but over an hour the average increase would not be larger than 10 %. The analysis of the influence of contrails on the global irradiance of the studies mentioned above was only based on a visual determination of the contrails using the fish eye photographs. The automated all sky imaging systems usually had a field of view of 180° and performed the measurements at at least 1 min intervals.

A preliminary study by Weihs et al. (2013), who analysed 8 months of data from observatory Kanzelhöhe, Austria, found reduction in global irradiance by contrails obstructing the sun by up to 68 %. The number of days with persistent contrails were determined for each months. The winter months showed a higher number of persistent days with around 30 % of the days with persistent contrail occurence in January 2011. In June 2011 persistent contrails were only observed during 10 % of the days. Overall, there are still only a few studies dealing with measurements of the effect of contrails on ground-based diffuse and direct irradiance. To the authors knowledge, no studies have examined possible effects of contrails on solar energy production losses. The present study investigates the effect of contrails on short wave global irradiance and on solar energy production. The innovative aspects of the present publication are not related to innovative measurements techniques but to new results stemming from the data analysis. We first continued the preliminary study by Weihs et al. (2013) by including more days and by performing the analysis for a longer time period of one year. Second, conclusions and estimations as to a possible impact on solar energy gain were made.

AMTD
7, 8927–8943, 2014

2 Methods

The investigations were carried out at the Sun Observatory Kanzelhöhe, Carinthia, Austria which is situated at 1526 m altitude. The Sun Observatory Kanzelhöhe belongs to the University of Graz which performs various meteorological measurements. Typical climatic and synoptic measurements are also being performed by the Austrian Weather Service. The Sun Observatory Kanzelhöhe also hosts an "Aeronet" station. A high quality radiation station (baseline surface radiation network (BSRN) level) is just being installed. Routine measurements of global irradiance using EMS 11 silicon photodetector pyranometers have been performed at 1 min interval since June 2010. At the same time, the short circuit current (current conversion efficiency at short circuit) of three different PV module types (crystalline silicon – c-Si: 220 Watt Peak (W_p) and 1.66 m^2, – amorphous silicon – a-Si: 95 W_p and 1.45 m^2 – and Cadmiumtelluride – CdTe: 75 W_p and 0.72 m^2) were recorded. The PV modules were mounted with a 35° inclination, one of each type oriented towards south, one of each type oriented towards east and towards west (altogether this amounted to 9 PV modules). In addition fish eye photographs of the sky hemisphere with a 180° field of view automatic camera (CMS Schreder) have been performed also using 1 min intervals.

From fish eye photographs, videos were created for each week. Using these videos, days with contrail persistence and the time of day when sun obstructions by contrails occurred were visually identified. For most of the contrails we could see the creation of the contrails by the air planes. If the creation of the contrails could not be seen, the identification of the contrails was made based on their typical linear shape. In case of doubt, when the clear identification between contrails and other wave shaped cirrus clouds (e.g. cirrus fibratus, radiatus or vertrebatus) was not possible, the case was omitted. A contrail was considered to be persistent when the contrail was still detectable after the plane it originated from had disappeared. Within the scope of the present investigation we determined the reduction R_{max} of the global irradiance during a sun

AMTD
7, 8927–8943, 2014

obstruction event by a contrail as:

$$R_{max} = 2 \cdot I_{min} / (I_1 + I_2), \quad (1)$$

where I_1 is the global irradiance before the sun obstruction (no influence by contrails), I_2 is the global irradiance after the sun obstruction (no influence by contrails) and I_{min} is the minimum global irradiance during the sun obstruction by the contrail.

We assume that other clouds in the sky (e.g. sub visual or visual cirrus clouds, or small cumulus clouds) have an impact on global radiation lower than 1 % during the sun obstruction events.

With the strong winds in these altitudes (above at least 8000 m a.s.l.), the contrails move fast. A contrail, created at larger distance from the observer (lower elevation) may move out of sight of the observer within some minutes, may however also remain visible up to 60 min depending on the wind direction. A sun obstruction occurs when the contrail moves between sun and observer. This "obstruction" event is also clearly visible in the global radiation measurements which show a reduction during this obstruction (Fig. 1). Just before and just after this obstruction event (when the sun is fully visible and the contrails very close to the sun), a slight increase in global radiation was observed due to reflexions and scattering of the direct solar radiation towards the pyranometer by the contrails. The duration of an obstruction is determined using the fish eye photographs but also in addition looking at the length of a reduction in global irradiance as compared to the expected interpolated cloudless global irradiance during the obstruction event. The interpolation during the obstruction event was performed using the radiative transfer (RT) model interface uvspec from the LIBRADTRAN (Mayer and Kylling, 2005) package. Calculations were performed using SDISORT with two streams and SBDART molecular absorption approach. To obtain as a reference – for the same time and day – the bell shaped curve of global irradiance (the variation in clear sky global irradiance during this time period) clear sky global radiation calculations were performed using the RT model. In order to compensate for small discrepancies between RT model calculations and measurements of global radiation due

AMTD
7, 8927–8943, 2014

to uncertainties in model input parameter determinations (e.g. sub visual cirrus clouds) or expected systematic errors of ±2 % in the measurement accuracy the model results were fitted to the measured global radiation by introducing a multiplication factor in the order of maximum 1.05 or 0.95 (correction of 5 % of the model values). This is also the accuracy of the absolute values ($\mathrm{W\,m^{-2}}$) in global radiation changes stated in the present study.

We also compute the mean global irradiance I_{mean} during the whole time in which the contrail is between the sun and observer. Using Eq. (1) and substituting I_{min} by I_{mean} we may determine the mean reduction R_{mean} during a sun obstruction. For calculations of the influence of contrails on daily energy yield, we remove all changes (reductions and enhancements) in global radiation caused by contrails and interpolate the global radiation for this time interval using the RT model fitted to global radiation before and after this period as described above. The daily sum of the altered global radiation may then be compared to the real daily radiation sum.

3 Case study

We examined two consecutive days (22–23 September 2010). 22 September was almost cloudless without any contrail persistence during the whole day. The diurnal range of global irradiance on this day shows a perfect bell shaped curve (Fig. 1). 23 September was a day with strong contrail persistence. Figure 1 shows all identified sun obstruction events by contrails with arrows. Altogether 49 contrails were observed, 22 of which moved between sun and observer. Reductions in global irradiance of up to 68 % (370 $\mathrm{W\,m^{-2}}$) were observed. Between the sun obstruction events an increase in global irradiance compared to the day before is visible. These radiation enhancements could not be explained by a reduction in aerosol optical depths between 22 and 23 September. On both days similar values were measured by Aeronet. The radiation enhancements of up to 10 % were caused by cirrus clouds and additionaly just before and after the obstruction events also by the contrails contributing to enhancements (by

AMTD
7, 8927–8943, 2014

up to 3 %). The maximum mean enhancement over a period of 30 min was around 8 %. During the course of the day we could observe an increase in cirrus cloudiness which represents a characteristic feature for many days with contrail persistence. The increase in cirrus cloud fraction and optical thickness of the cirrus clouds during the day lead to a reduction in global irradiance during some parts of the afternoon.

4 Statistics

The number of days with contrail persistence during the period, from September 2010 to August 2011 was determined (Fig. 2). A maximum persistence was reached in January 2011 with approximately 35 % of all days showing contrail persistence. Overall contrail persistence is larger during late autumn, winter and early spring.

Besides persistence, R_{max} and R_{mean} were computed for all sun obstruction events caused by contrails and where any interference by cirrus clouds during the events could be omitted. The results for R_{min} and R_{mean} are shown in Fig. 3a and b respectively. The maximum R_{max} is 72 %. This corresponds to a reduction in global irradiance of 390 W m^{-2}. The average of all R_{max} values is equal to 16 %. The average of all R_{mean} values is equal to 8 %. The maximum duration of a sun obstruction event by a contrail is 15 min whereas the mean duration of a contrail remaining between sun and observer is 5 min.

The median of the global radiation reductions as well as minimum, maximum and 25 and 75 % quartile are shown in Fig. 4. The largest reductions in global radiation occur for durations of sun obstructions by contrails of 7 to 8 min. For longer durations the reductions become smaller. This is probably explained by a broadening of the contrails with time, connected with a reduction of their optical thickness.

Other results that were obtained (not shown in figures) show that on average after or before obstruction events the global radiation was enhanced by contrails only by up to 3 % and on average over 30 min by up to 1.5 %. Mixture of contrails and cirrus may however lead to an enhancement in global irradiance of up to 8 % over 30 min. For a whole

AMTD
7, 8927–8943, 2014

day only taking the enhancements/reduction by contrails and cirrus between the sun obstruction events into account we obtain changes in daily radiation sums between −2 and +1.5 %. Under perfect cloudless conditions (no cirrus clouds) and only taking into account sun obstructions by contrails we obtain reductions in daily radiation sums of up to 4.5 %. Cirrus cloudiness therefore on average lower the diminutions in daily radiation sums. Because the origin of the cirrus cloudiness is not clearly identifiable (man made developing from contrails or of natural origin) and may lead to an enhancement as well as to a reduction of the daily radiation sum we take only the effects of contrails into consideration in the following section.

5 Impact of contrails on photovoltaic energy gain

The first impression, namely that the short term irradiance obstructions may have no impact on a daily scale is misleading. On the contrary, the pure reduction of irradiance (direct and diffuse) is of a magnitude and frequency that the energy loss of photovoltaic systems should at least be considered. For this, over the whole investigation period three different PV module types (crystalline silicon – c-Si: 220 Watt Peak (W_p) and 1.66 m^2, – amorphous silicon – a-Si: 95 W_p and 1.45 m^2 – and Cadmiumtelluride – CdTe: 75 W_p and 0.72 m^2) were studied by recording their current conversion efficiency at short circuit and their module temperature. From the current values the linearly temperature-corrected power values (IEC, 2009) were calculated which were added up to the daily energy yield values (Y_d) following the method described in Sect. 2. From 28 days of persistent contrails a medium reduction in daily energy yield calculated on a basis of 23 days of about 0.35 % (a-Si), 0.37 (CdTe) up to 0.44 % (c-Si) was found. At the same time the irradiance enhancement resulting only from contrails was on average between 0.086 % (a-Si) up to 0.119 % (c-Si). The maximum reductions were found in autumn and winter: 2.24 % (c-Si; 23 September 2011 with 22 persistent contrails and 3.33 % (c-Si; 9 January 2011 with 7 persistent contrails). the maximum increase

AMTD
7, 8927–8943, 2014

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂◂ ▸▸
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

in energy yield due to contrails was 1.63 % (c-Si; 9 January 2011; with 7 persistent contrails).

The results were further calculated in terms of daily energy yield in Watt-hour (Wh) per module and also normalized to an ideal photovoltaic model system with a size of 1000 W_p. On average, the loss for c-Si is 4.6 Wh (from daily 1197 Wh), for a-Si 1.7 Wh (from daily 436 Wh) and for Cdte 1.4 Wh (from daily 336 Wh) for the single modules, see Fig. 5. This corresponds to average values of 21 Wh for c-Si (from daily 5444 Wh), 18 Wh for a-Si (from daily 4592 Wh) and 19 Wh for CdTe (from daily 4886 Wh) for an installed nominal capacity of 1 kW_p. All technologies show the maximum loss in energy yield for a duration of the obstruction of approximately 6 min. The results are summarized in Table 1.

The losses seem small compared to the daily energy yields which are gained. Nevertheless, the maximum losses for c-Si were 11, 17 and 36 Wh day^{-1}. For a small island system including one module and 2 × 60 Ah solar batteries the loss then would be up to 3 Ah at a level of 12 V DC. This is up to 2.5 % of the assumed storage capacity.

In total 22 of the 28 days of persistent contrails were found between August and the end of January which is a critical time for solar supply via island systems. Moreover, 3 days were found to show irradiances below 800 Wh m^{-2} from all 28 days. First, this shows that persistent contrails have an impact mainly on days of high irradiances and therefore affect days of most value for solar energy gain. Second it shows that the reduction in energy yield for solar applications may be relevant on days in autumn and winter as well as for systems with bad system balance or after a series of days of low irradiances (Abawi, 2013).

6 Conclusions

Assuming thin cirrus cloudiness from anthropogenic origin and assuming a mean enhancement of 8 % of the global irradiance (which was the mean enhancement over a period of 30 min between the obstruction events by contrails on some of the days),

AMTD
7, 8927–8943, 2014

the following statement may be made: under all conditions met during days with persistent contrails, the sun must be obstructed between 35 and 40 min per hour in order to be sure that a reduction in global irradiance will occur. This corresponds to approximately 7 to 8 contrails moving between the sun and observer. With thickening of the cirrus cloudiness (that may be of anthropogenic origin) we do not observe any enhancement of the radiation anymore but a reduction. Altogether the decrease in global irradiance during a sun obstruction by a contrail is very high compared to the radiation enhancement. If further the air traffic frequency continues to increase, a contrail frequency may be reached where the duration of sun obstruction by contrails reaches a critical threshold following which each additional contrail leads to a reduction in the daily global radiation yield compared to a clear sky reference day. For periods of successive days of bad weather island system layouts may therefore – already under present conditions-come to states of critical performance. Losses in the daily energy yield for critical days then have to be considered.

Acknowledgements. This work was performed within the scope of KLIEN, Neue Energien 2020 Project Nr. 822053 entitled: Einfluss von Sonnenspektrum und Klima auf die Performance von photovoltaischen Anlagen: Regionale Abschätzung des Sonnenenergiepotentials Österreichs. Data used in this paper can be obtained from the two first authors of this paper.

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AMTD

7, 8927–8943, 2014

Potential impact of contrails on solar energy gain

P. Weihs et al.

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AMTD
7, 8927–8943, 2014

Table 1. Energy yield losses for the given PV-technologies. The mean values in % are statistical values, the mean values in Wh were calculated from the fit in Fig. 4.

	PV-technology		
	Crystalline Si	Amorphous Si	CdTe
Mean loss of daily energy yield			
Single module [% d^{-1}]	0.38	0.39	0.42
Single module [Wh d^{-1}]	4.6	1.7	1.4
System 1 kWp [Wh d^{-1}]	20.9	17.5	18.8
Maximum loss of daily energy yield			
Single module [% d^{-1}]	3.33	2.12	2.23
Maximum increase of daily energy yield			
Single module [% d^{-1}]	1.63	0.94	1.03

AMTD
7, 8927–8943, 2014

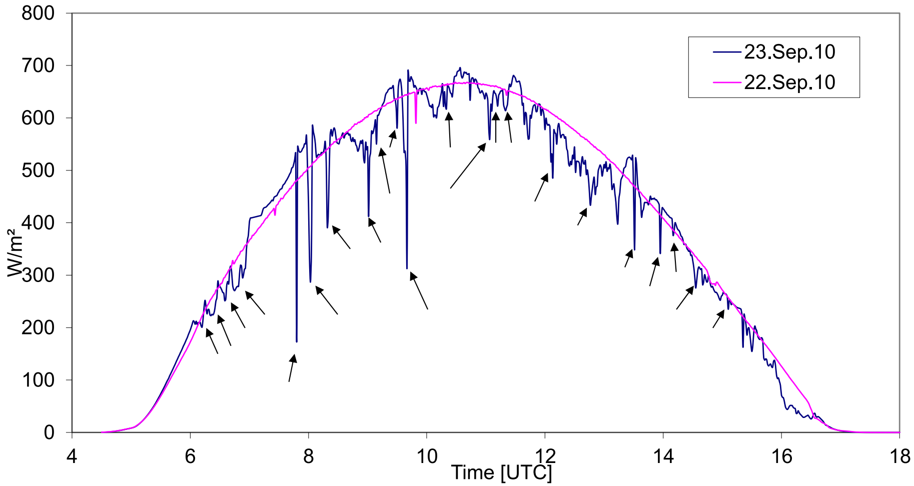

Figure 1. Global irradiance of two consecutive days: 22 and 23 September 2010. 22 September was a clear sky day without contrail persistence whereas on 23 September 2010 a strong contrail persistence (altogether 49 persistent contrails from 06:00 to 16:00 UTC) was observed. The arrows show the decrease in global irradiance due to contrails shading the sun (altogether 22 such events were observed) (Reproduced with permission from Weihs et al. (2013). Copyright (2013), AIP Publishing LLC.).

AMTD
7, 8927–8943, 2014

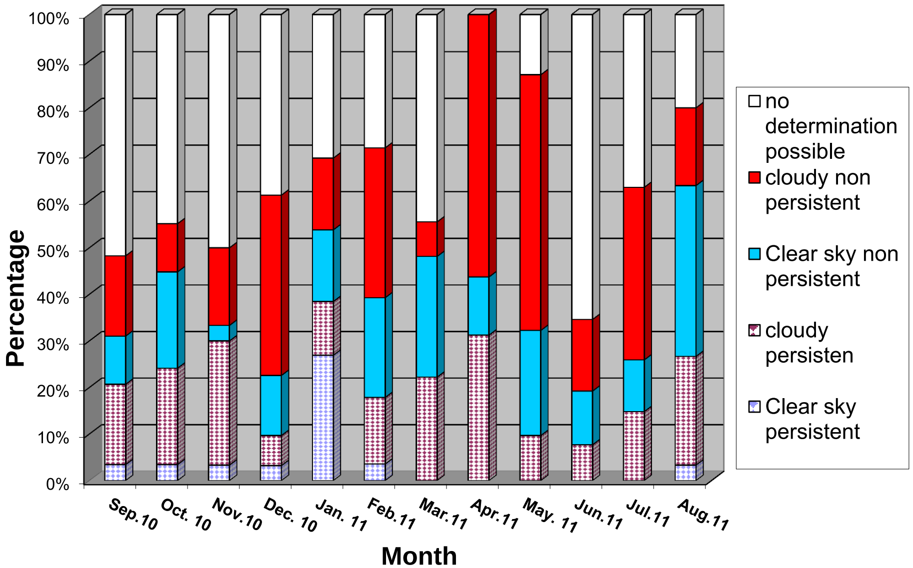

Figure 2. For each month the percentage of days with and without contrail persistence are shown. Many days (upper part of the columns referred as "no determination possible") mostly with full cloud cover do not allow a determination as to the persistence of contrails. The redand blue parts of the columns are cloudy ("cloudy non persistent") and clear sky ("clear sky non persistent") days without contrail persistence whereas the two lowest partitions of the columns show days with contrail persistence under cloudy ("cloudy persistent") and clear sky ("clear sky persistent") conditions.

AMTD
7, 8927–8943, 2014

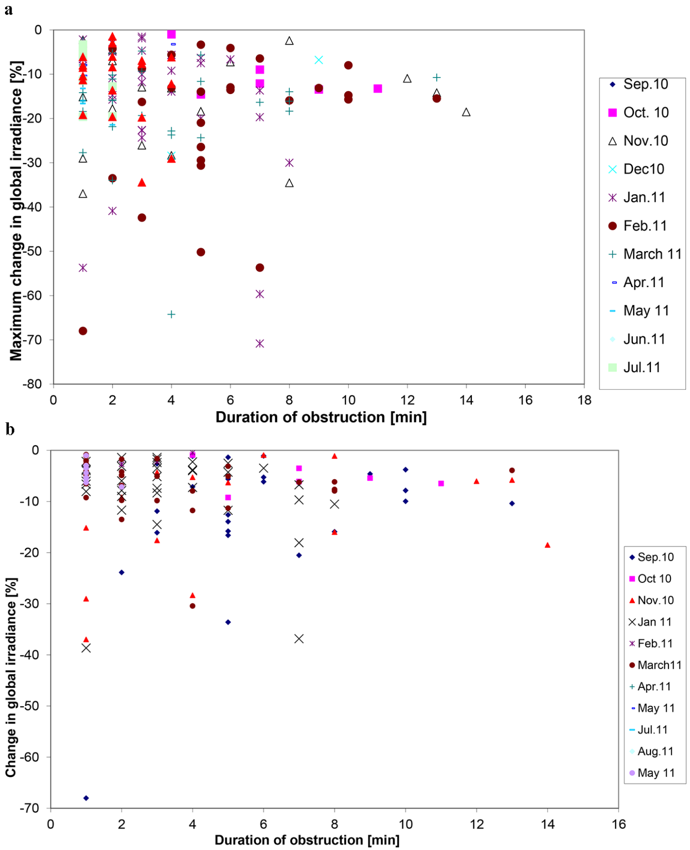

Figure 3. The maximum **(a)** and mean **(b)** reduction in global irradiance (during the shading event) as a function of the duration of the shading event by the contrails is shown for the 12 months that were analysed. For June 2011 no shading event was suited for the analysis because of interfering cloudiness which falsified the global irradiance decrease.

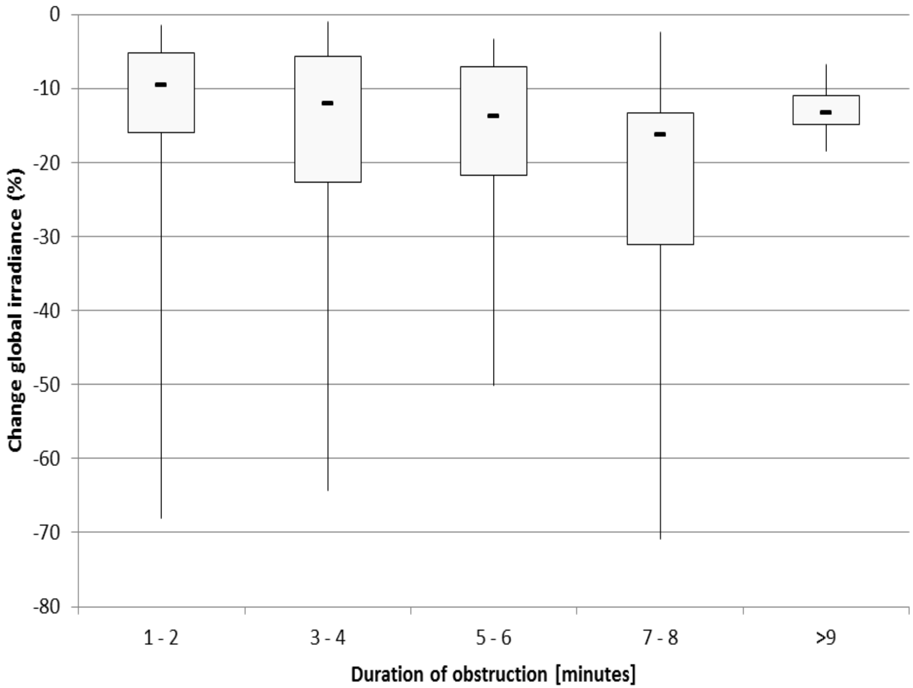

Figure 4. Box and whisker plots of the change in global irradiance as a function of the duration of the sun obstruction by contrails. The high-low lines show minimum and maximum values. The box shows the 25 and 75 quartile and the dash shows the median. Because of a low number of cases at larger durations of obstruction the change in global irradiance is shown as a function of 2 min intervals instead of 1 min intervals.

AMTD
7, 8927–8943, 2014

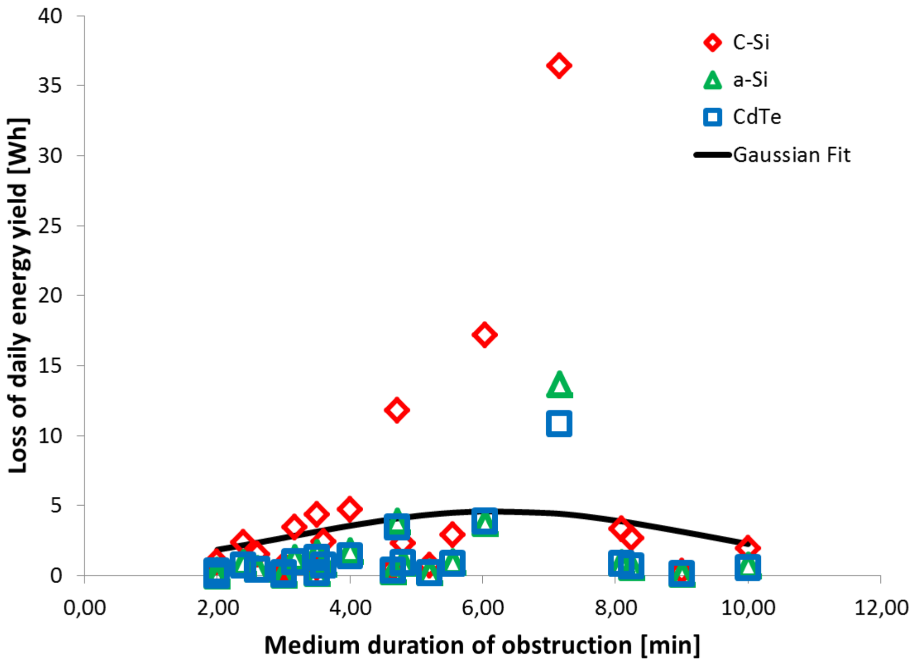

Figure 5. Loss of daily energy yield for the three modules types c-Si (τ), a-Si (Δ) and CdTe (o) as a function of the medium duration of all the obstructions on a day with persistent contrails with on average 4.4 obstructions of the sun by contrails. The medium loss was estimated via a Gaussian fit, see solid line for the fit of the c-Si data.

AMTD
7, 8927–8943, 2014

Potential impact of contrails on solar energy gain

P. Weihs et al.