

ESTIMATING DAILY SUNSHINE DURATION OVER THE UK FROM GEOSTATIONARY SATELLITE DATA

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Abstract

The Met Office produces sunshine maps for the UK based on observations from ground-based instruments. These maps have uncertainty owing to the number and distribution of stations that record sunshine. This article describes a method for estimating sunshine duration from geostationary satellite data that provides near-complete spatial coverage. Comparisons with daily ground-based observations from Kipp & Zonen sensors over four months indicate a mean satellite minus station bias and standard deviation of -0.2 and 1.6 hours, respectively. Satellite-station correlation is 0.89. The new data set could be used to improve the interpolation of station observations in the Met Office maps.

INTRODUCTION

Sunshine duration data are relevant for a number of applications, including the calculation of global radiation (Masaki et al, 2009; Revfeim, 1981), vegetation growth and human leisure. As part of its climate monitoring activities, the Met Office produces monthly sunshine maps for the UK (<http://www.metoffice.gov.uk/climate/uk/anomacts/>). These maps are based on interpolated sunshine observations from ground-based instruments that record the number of hours of bright sunshine in a day. Measurements from two types of instruments are used in this data set: (1) the long-established Campbell-Stokes recorder, which is a glass ball that burns a trace on a card, and (2) the more modern Kipp & Zonen CSD1 sunshine duration sensor, which uses photo-diodes to determine when insolation exceeds 120 Wm^{-2} , which is the World Meteorological Organization (WMO) definition of bright sunshine (World Meteorological Organization, 2003). There are currently about 125 stations in the UK that record sunshine duration. Finding suitable locations to deploy sunshine recorders is hindered by common obstructions, such as buildings, hills and trees; vandalism can also be a problem. Owing to the number and distribution of stations, the maps have some uncertainty, particularly in regions where there are no observations (e.g. upland areas). Uncertainty is higher in the provisional version of the maps, produced at the end of each month, which are based on data from approximately 65 stations that report in near-real time.

Scarcity of in-situ sunshine observations is not unique to the UK and some researchers have attempted to derive sunshine duration from satellite data sets, which potentially provide improved spatial coverage and representation (Kandirmaz, 2006; Olseth and Skartveit, 2001). In this article, a new, simple method for estimating daily sunshine duration from geostationary satellite data is presented. The basic principle of the method is to analyse a time-series of cloud observations from satellite data in order to estimate the fraction of daylight hours where bright sunshine occurs. The approach is demonstrated over the UK, where the satellite sunshine duration estimates are validated against independent daily in-situ observations from the UK station network over four months in 2008. The motivation for developing this data set is to provide additional, independent information that could be used to improve the interpolation of station sunshine data in the Met Office sunshine product, rather than to provide a new data set to replace the existing observations.

METHOD: SATELLITE SUNSHINE ESTIMATE

Satellites provide observations of top-of-atmosphere (TOA) radiances, which depend on the underlying surface conditions and atmospheric state. A number of techniques exist for the

identification of cloud in the TOA radiance data, the most common of which involves the use of multi-channel threshold-based tests (e.g. Ackerman et al, 2002; Saunders, 1986; Saunders and Kriebel, 1988). This method compares satellite radiances from one or more channels, sometimes expressed as a ratio or difference, with a pre-determined threshold. If the radiance exceeds the threshold (or falls short, depending on the specific test), the pixel is flagged cloudy. Typically, a number of tests are employed on a pixel-by-pixel basis, where each test is sensitive to a different cloud type. The result is a cloud-classified pixel scene that corresponds exactly to the original TOA radiance observation data set. If the satellite observations originate from a geostationary sensor, these classification data can be used to build up a dynamic picture of cloud evolution throughout the day.

In this study, cloud classification data from the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) are used to infer daily sunshine duration over the UK. SEVIRI is an instrument on board the Meteosat Second Generation (MSG) satellite, which is geostationary above 0° longitude, 0° latitude. The SEVIRI supports a number of visible and infrared channels that are suitable for cloud detection, including channels at 0.6, 3.9, 8.7, 10.8 and 12 μm . Full-disc observations, which include the landmasses of Europe, Africa and South America, are acquired every 15 minutes throughout the diurnal cycle at a resolution of approximately 3 km at the sub-satellite point. Over the UK, the pixel size is slightly larger at approximately 3.3 x 7.3 km, because of the inclined view angle of the instrument away from the sub-satellite point, and the curvature of the earth.

The cloud-type data product used here is that of the Satellite Application Facility to support NoWCasting and very-short-range forecasting (SAFNWC; see SAFNWC (2009) for further information on the cloud type product). The data consist of 21 classifications (Table 1), and are provided at full pixel resolution for each 15-minute observation 'slot'. Figure 1 shows an example of the SAFNWC cloud-type product.

Table 1: The SAFNWC cloud types. Note: in the current version of the SAFNWC cloud type scheme, there is no separation of cumuliform and stratiform clouds, with all low, medium or high clouds classified as stratiform (SAFNWC, 2009).

Cloud Type No.	Description
0	Non-Processed
1	Cloud-free land
2	Cloud-free sea
3	Land contaminated by snow
4	Sea contaminated by snow/ice
5	Very low cumuliform clouds (not currently used in SAFNWC scheme)
6	Very low stratiform clouds (Include fog, used for all very low clouds)
7	Low cumuliform clouds (not currently used in SAFNWC scheme)
8	Low stratiform clouds (used for all low clouds)
9	Medium level cumuliform clouds (not currently used in SAFNWC scheme)
10	Medium level stratiform clouds (used for all very medium level clouds)
11	High cumuliform clouds (not currently used in SAFNWC scheme)
12	High stratiform clouds (used for all very high opaque clouds)
13	Very high cumuliform clouds (not currently used in SAFNWC scheme)
14	Very high stratiform clouds (used for all very high opaque clouds)
15	High semitransparent very thin cirrus
16	High semitransparent thin cirrus
17	High semitransparent thick clouds
18	High semitransparent cirrus above low or medium clouds
19	Fractional clouds (sub-pixel water clouds, including cloud edges)
20	undefined (has been processed but classification not possible).

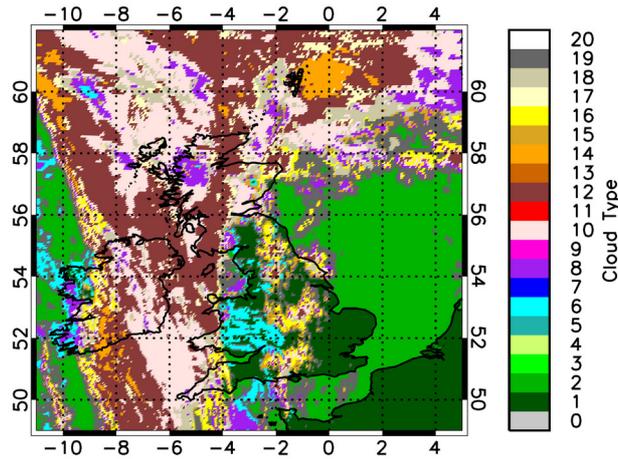


Figure 1: Example of SAFNWC SEVIRI cloud-type data set for 1 July 2008, at 1200 UTC. See Table 1 for description of cloud types.

Either bright sunshine or no bright sunshine is assigned to each SEVIRI pixel observation made during daylight hours, using the SEVIRI cloud-type indicator. Once this assignment has been made, the sunshine duration is calculated for each pixel according to the following process:

1. The total number of available daytime SEVIRI observation slots is counted (O_{total})
2. The total number of available daytime SEVIRI observation slots assigned 'bright sunshine' is counted ($O_{sunshine}$)
3. The number of hours of daylight, $H_{daylight}$, is calculated.
4. The sunshine duration, D , is estimated as:

$$D = \frac{O_{sunshine}}{O_{total}} H_{daylight} \quad (1)$$

In practice, daylight is defined to be where the solar elevation angle (SEA) is greater than 2.5 degrees. This limit is imposed to ensure consistency between the satellite and in-situ data sets, as the latter are unlikely to record any sunshine for smaller SEAs (P. Fishwick, Met Office, Personal Communication). Occasionally, as is common with any satellite data set, the SEVIRI observational record is incomplete, where individual pixels are missing or uninterpretable, or data for an entire time slot are absent. To ensure the SEVIRI observations provide representative coverage during the day, D is only calculated for pixels where a minimum of 90% of all available 15-minute daytime observation slots are valid and available. This process usually provides close to 100% spatial coverage for each day. On this basis, daily grids are typically available for more than 98% of days over the course of a year.

A key aspect of the method is in the assignment of bright sunshine or no sunshine to each SEVIRI pixel observation. The situation is straightforward where no cloud is detected (SAFNWC cloud types 1 and 2); in this case, bright sunshine is always assumed. Similarly, where opaque cloud is observed (SAFNWC cloud types 5-14 and 18), no sunshine is assumed. Less straightforward are the situations where semi-transparent or fractional (sub-pixel) cloud types are detected (SAFNWC cloud types 15-17, and 19). In these cases, it is possible that some bright sunshine may be recorded by the in-situ sensors. Therefore to ensure the satellite estimates are consistent with the station observations it is also necessary to include allowances for some bright sunshine for these cloud types in the satellite data.

The SAFNWC cloud product includes three types of semi-transparent cirrus cloud ('very thin', 'thin' and 'thick') and one type of fractional cloud (Table 1). For pixels classified as the latter, a contribution of 0.5 to the value of $O_{sunshine}$ for that slot is assumed (as opposed to a value of 1.0 for other bright sunshine assignments). For pixels classified as one of the three cirrus clouds the SEA is also taken into account when assigning either bright or no sunshine. This is because the optical path of the

sunshine through the cloud increases as the SEA decreases, which has the effect of attenuating more solar radiation than if the sun were directly overhead ($SEA = 90^\circ$). For each of the three cirrus classifications, a unique SEA threshold has been estimated. Where the SEA is above this threshold, bright sunshine is assumed. For SEA below this threshold, the observation is assigned 'no sunshine'. This type of approach is not adopted for fractional cloud as this cloud classification includes both scattered or broken cloud, and cloud edges, with unknown cloud amount. Without knowing the true nature of the cloud and its sky fraction, such effects would be impossible to correct for and so are not addressed further in this work. Fortunately, the distribution of cloud amount is U-shaped, with fractional cloud occurring much less often than either complete cloud or clear-sky conditions (Rossow et al., 1993). The U-shape of the distribution becomes more pronounced with increasing spatial resolution. Figure 2 shows the occurrence of each SAFNWC cloud type during daylight hours for January, April, July and October 2008, confirming that this type of relationship also exists in the SEVIRI data. For these four months, fractional cloud is found to account for between 9 and 17% of all observations, resulting in a relatively small impact on the satellite sunshine duration estimate, compared with completely cloudy or clear-sky conditions.

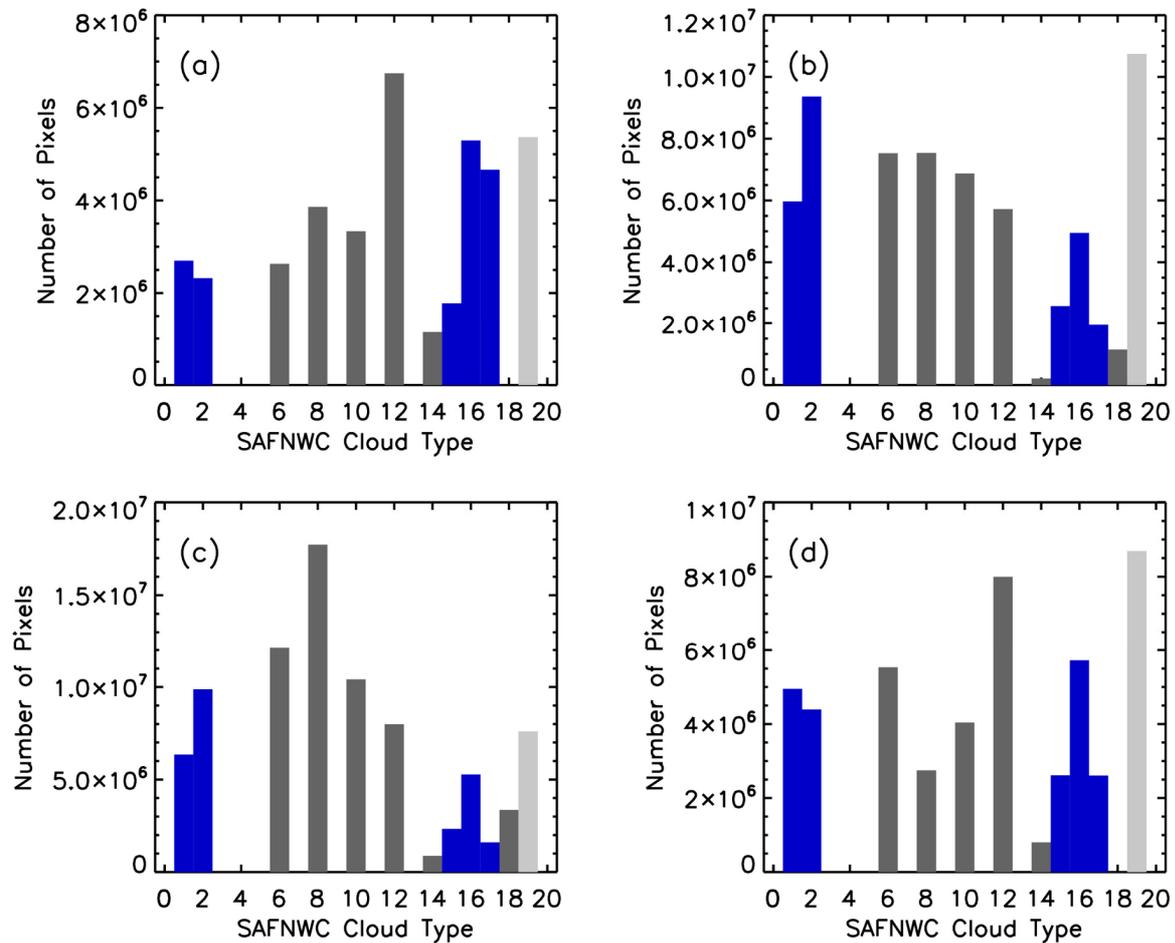


Figure 2: Histogram showing occurrences of each SAFNWC cloud type over the geographical region 49 to 62 °N and 11 °W to 5 °E in 2008 for (a) January, (b) April, (c) July and (d) October. The shading in the bars indicates cloud types associated with bright sunshine (blue), no sunshine (dark grey) and part sunshine (light grey) for the satellite estimates of sunshine duration. See Table 1 for description of cloud types.

The cirrus SEA thresholds have been determined using the Fu-Liou radiation code (Fu and Liou, 1992, 1993; Rose and Charlock, 2002; also available online at <http://snowdog.larc.nasa.gov/cgi-bin/rose/flp200503/flp200503.cgi>). Calculations were performed for both mid-latitude summer and winter atmosphere options available in the code, and for a single cloud layer between 300 and 250 hPa. Other conditions assumed for all simulations included continental aerosol with optical thickness (OT) of 0.2 at 4 km height, CO₂ loading of 360 ppmv and a surface albedo corresponding to the

International Geosphere-Biosphere Programme (IGBP) land-use classification of ‘crops’ for the UK. Simulations were performed for cirrus OTs of 1, 2, 3 and 4, which correspond to the range of typical values for cirrus cloud reported in the literature (e.g. Chen et al., 2000). Assuming an OT of 1 or less for very thin cirrus, 1-2 for thin cirrus and 2-4 for thick cirrus cloud types in the SAFNWC product, SEA thresholds of 12.0° , 13.8° and 15.3° were derived. In reality, of course, the exact SEA threshold will depend on factors such as the atmospheric conditions at the time of the observation and the OT of the cloud. Ideally, these effects would be taken into account here, but this would require sourcing additional data sets and performing situation-specific radiative transfer calculations. This has not been pursued in this study as the objective is to present a method that is simple to implement and does not rely on multiple data sets.

An example of the resulting daily satellite sunshine duration data set is shown in Fig. 3. Overall, the calculated values appear reasonable and have a realistic spatial pattern. Unsurprisingly, the data correspond closely to the patterns in the cloud type data (Fig. 1).

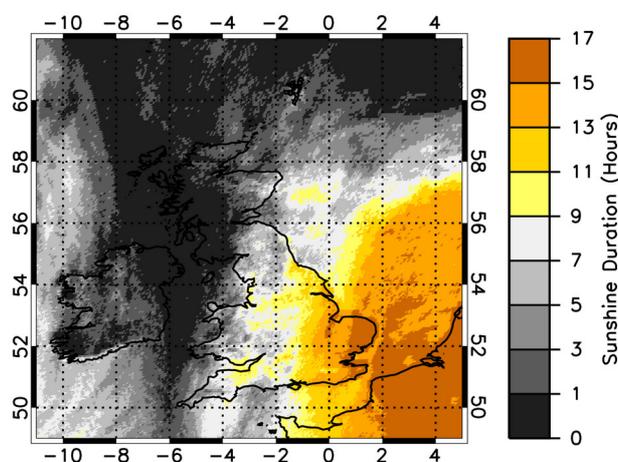


Figure 3: Example of sunshine duration estimated from SEVIRI for 1 July 2008.

EVALUATION WITH IN-SITU DATA

The accuracy and precision of the SEVIRI-derived sunshine duration estimates have been assessed by comparing the daily pixel-based estimates with collocated daily station totals obtained over four months in 2008. The scope for differences in observations from Campbell-Stokes and Kipp & Zonen instruments is well known, and is discussed elsewhere (e.g. Kerr and Tabony, 2004). For this reason, evaluation of the satellite sunshine-duration estimates is presented separately for each type of instrument. The station data used here correspond to those used in the Met Office gridded sunshine maps. Currently, this consists of approximately 90 Campbell-Stokes and 35 Kipp & Zonen CSD1 instruments across the UK.

Figure 4a shows the comparison between the SEVIRI and Kipp & Zonen sunshine data on 1 July 2008. The overall agreement is good, demonstrating only a very small bias (0.1 hours) and quite low standard deviation (1.4 hours). Notably, the agreement between the two data sets where the cirrus and/or fractional cloud occurrence during the day is above 10% is also good, giving confidence in the approach used to account for bright sunshine for these cloud types. For comparison, the equivalent plot where these cloud types are assumed to correspond to no bright sunshine is shown in Fig. 4b: in this case, the overall agreement is much worse (bias -1.8 hours, standard deviation 2.2 hours), particularly for those data points that are significantly affected by cirrus and/or fractional cloud.

Figures 5 and 6 summarise the daily evaluation for each of the four test months: January, April, July and October 2008. For the Kipp & Zonen comparisons (Fig. 5), the correlation between the satellite and in-situ data sets is generally above 0.8, with only a small bias and variance. Considering the daily results for all stations over the four months, the mean bias (satellite minus station) and standard deviation are -0.2 and 1.6 hours, respectively, with a correlation of 0.89. The agreement between the

satellite and Campbell-Stokes data is worse, with much higher variance. In this case, the overall mean bias and standard deviation are -0.6 and 2.2 hours, respectively, with a correlation of 0.82. Notably, it is the months of April and July where the results for the two sets of comparisons differ most markedly. For both the Kipp & Zonen and Campbell-Stokes comparisons, the satellite-minus-station bias is negative for these months, but the magnitude of the latter is approximately twice that of the former (-1.2 to 1.3 hours compared with -0.5 to -0.6 hours). The standard deviation for the Campbell-Stokes is also considerably larger than for the Kipp & Zonen comparisons during April and July (2.3 to 2.4 hours compared with 1.7 to 1.8 hours). Part of the reason may be that the Campbell-Stokes tend to suffer from over-burning, particularly during periods of strong and intermittent sunshine. However, since there are only a handful of sites that have both types of instruments, geographical (e.g. topographic) effects on the accuracy of either the satellite or in-situ data cannot be ruled out.

Despite these differences, both sets of comparisons suggest that the satellite estimates are more accurate in January and October than in April and July. In January and October, the satellite estimates tend to be slightly higher than the in-situ data, while in April and July, they tend to be lower. This may be a result of the way in which cirrus and fractional cloud types are treated in the satellite sunshine data, coupled with natural seasonal variation in the types of cloud that occur over the UK. For example the SEA thresholds are calculated without allowing for seasonal variation in aerosol OT or land surface albedo. Alternatively the accuracy of SAFNWC cloud-type product used in the production of the satellite sunshine duration estimates may have some seasonal dependence.

Figure 7 shows the mean bias for each station in July 2008. While there is no clear geographical pattern in the biases, the satellite estimates tend to be higher-biased at many of the coastal stations. This may be due to a number of reasons. Firstly, there may be errors in the satellite cloud-type data where pixels include both sea and land, since these surface types are dealt with in different ways in the SAFNWC product. Secondly, the presence of coastal mist, which may prevent sunshine being recorded on the ground, could be classified as clear skies in the SEVIRI cloud-type data leading to an over-estimation of sunshine duration in the satellite data set. Lastly, the displacement effects between cloud position, satellite view angle and sun geometry may be more pronounced in coastal regions where there can be striking differences between the cloud cover over adjacent land and ocean. Over the UK, the SEVIRI views the earth from the south at an angle of around 57-67° from the vertical. This means that clouds seen by SEVIRI may occur further south in reality than they appear in the data. For clouds below about 4 km, this displacement will be less than one SEVIRI pixel. For clouds above this, the clouds may appear offset by up to three or four pixels to the north from their true position. A similar displacement effect may occur as a result of the position of the sun, which is always at a SEA of less than 90° over the UK. In this case, we may have sunshine recorded on the ground when there are clouds directly overhead, or the opposite situation, when sunshine is not recorded on the ground but the sky is clear directly overhead. Even at midday during the UK summer (SEA ≈ 60°), this displacement effect could be as much as 8 km for very high clouds. In winter, this displacement could amount to several tens of km. The net result of these displacement effects is likely to cause an overall increase in noise (variance) in the satellite sunshine estimates, compared with the in-situ data, since it depends on a complex interaction between the position of the sun and clouds in relation to the direction of the satellite observations.

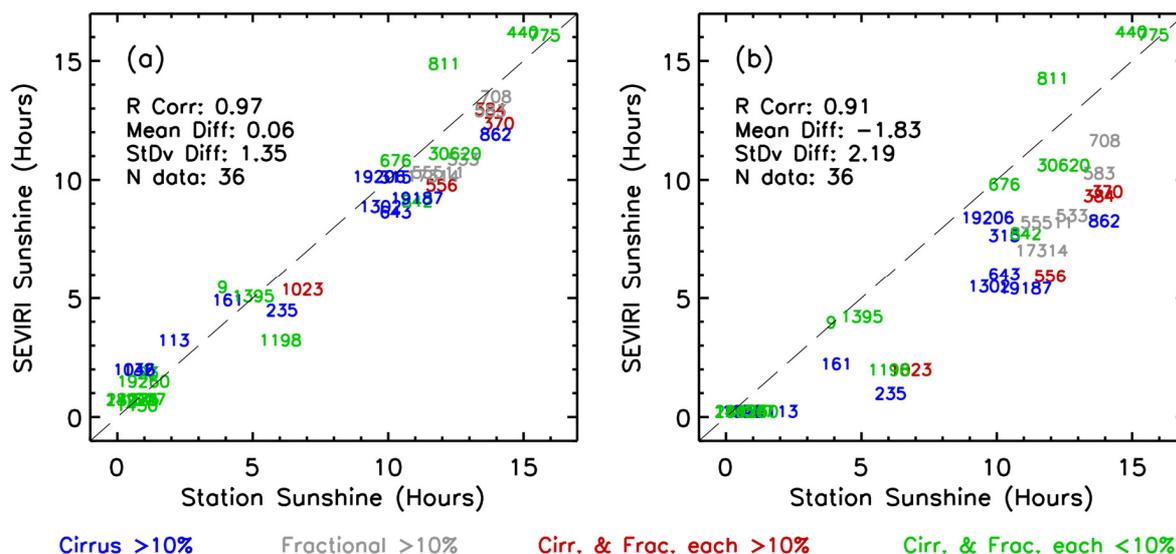


Figure 4: Comparison between SEVIRI and Kipp & Zonen sunshine duration on 1 July 2008 (a) accounting for some bright sunshine for cirrus and fractional cloud types and (b) assuming all cloud types correspond to no bright sunshine. The numbers on the plot represent UK station identification numbers. Blue data points correspond to where the number of SEVIRI slots with cirrus cloud classification is more than 10%, grey data points to where the number of slots with fractional cloud is more than 10%, and red to where both cirrus and fractional cloud are each above 10%. Data points coloured green are where cirrus and fractional cloud are each below 10%. Also shown in each panel are the correlation between the data sets (R Corr), SEVIRI minus station mean difference (Mean Diff) and standard deviation (StDv diff), and the number of data points (N data).

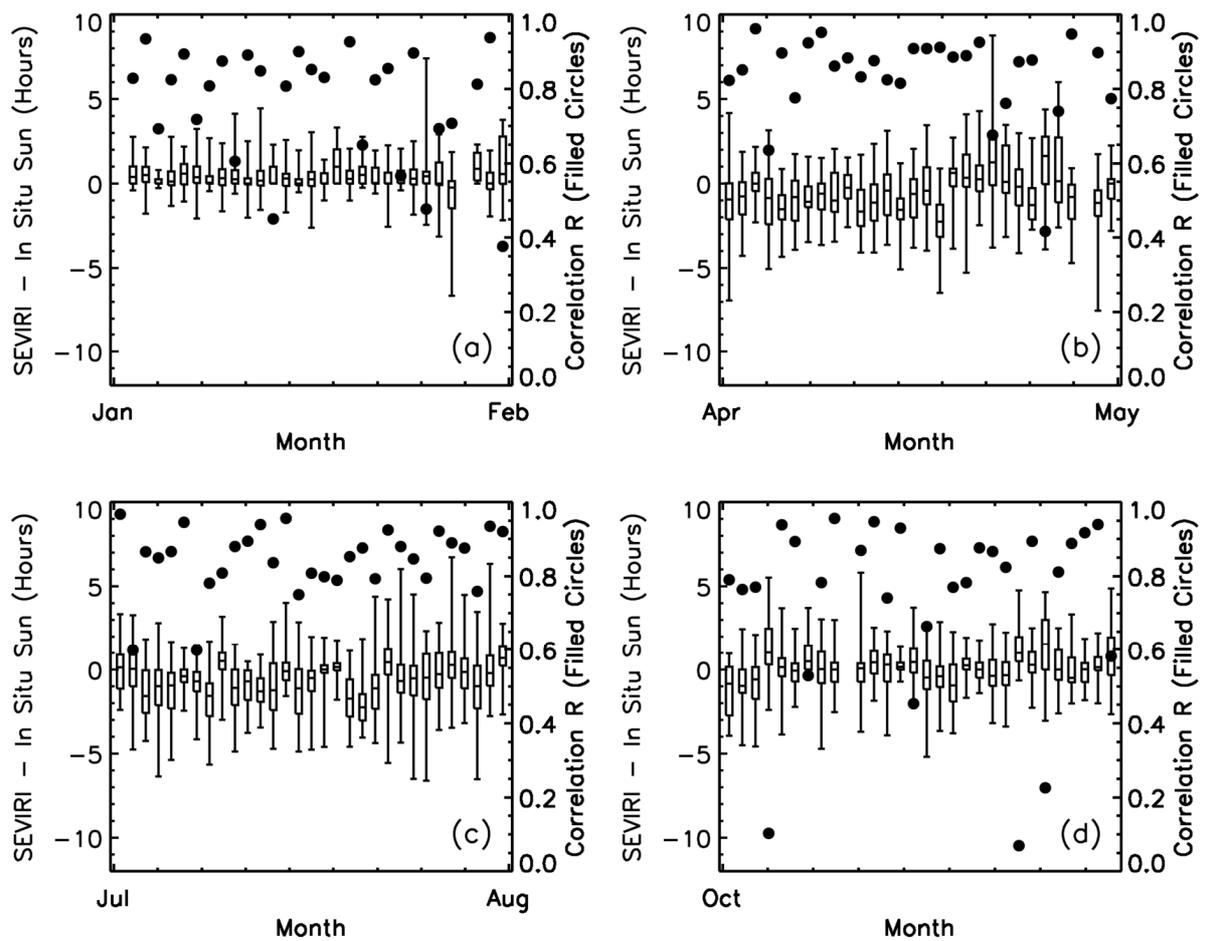


Figure 5: Box-and-whisker plots showing daily SEVIRI minus Kipp & Zonen sunshine duration differences in 2008 for (a) January, (b) April, (c) July and (d) October. The boxes indicate the inter-quartile range for data from all available stations over the UK for each day, the central lines indicate the 50th percentile, and the whiskers show the maximum and minimum values. The filled circles show the correlation between the satellite and in-situ data (right-hand axis).

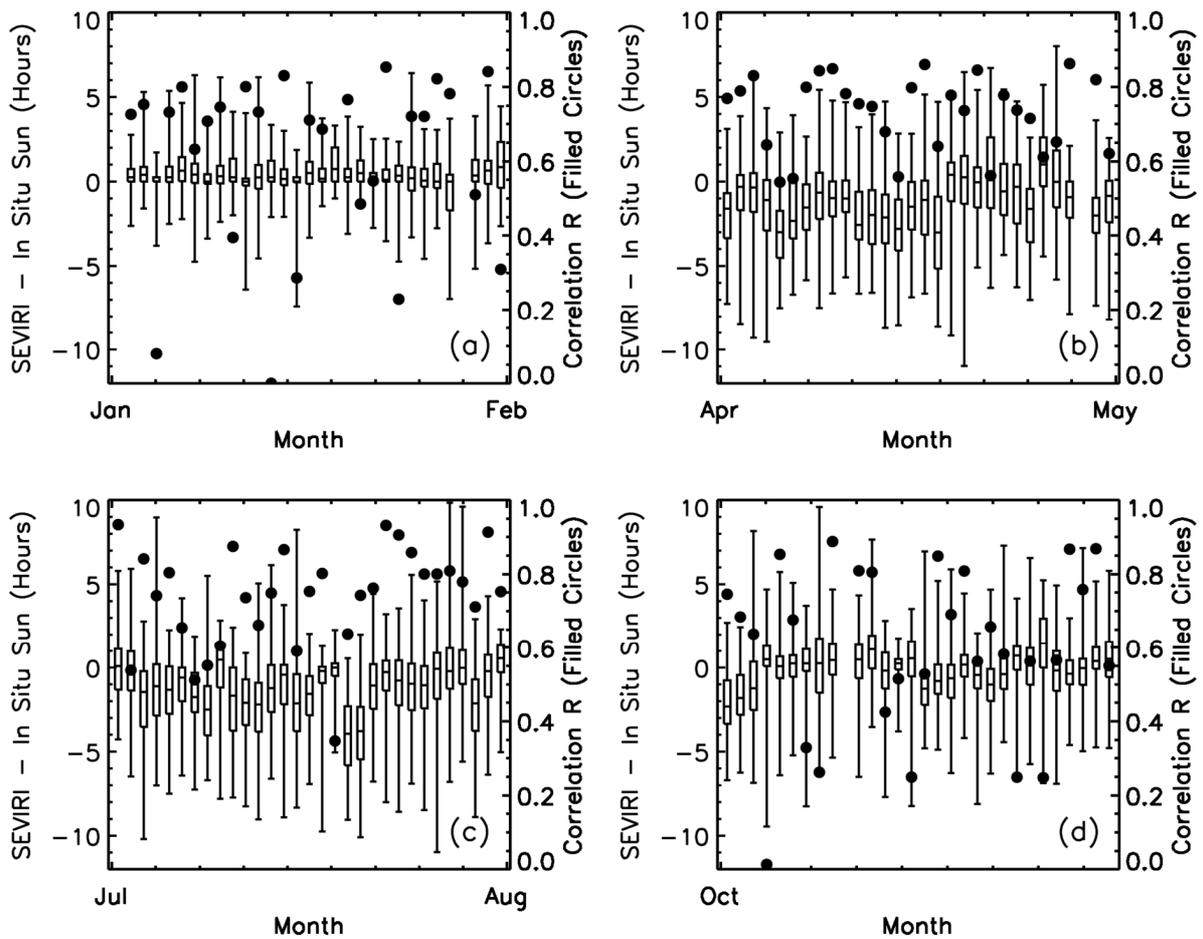


Figure 6: As for Fig. 5 but using Campbell-Stokes sunshine duration.

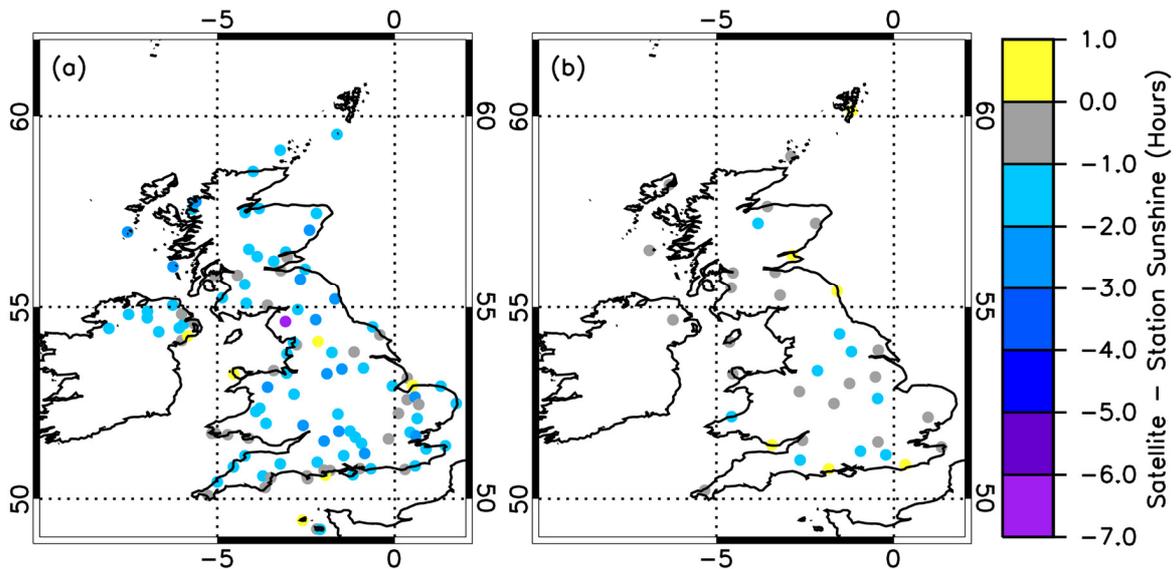


Figure 7: Mean daily SEVIRI minus station bias for each station during July 2008 for (a) Campbell-Stokes and (b) Kipp & Zonen sensors.

CONCLUSIONS

A simple method for estimating sunshine duration over the UK from time-series of cloud type data from geostationary satellite data has been presented. The method provides a daily gridded data set with near-complete spatial and temporal coverage.

The daily satellite sunshine duration estimates have been compared with independent, spatially and temporally collocated in-situ data over four months during 2008, for more than 100 stations. Evaluation has been carried out separately for the two different types of in-situ sunshine sensors deployed in the UK. Results are notably better for the Kipp & Zonen compared with the traditional Campbell-Stokes instruments. For the Kipp & Zonen comparisons, the mean satellite-minus-station bias and standard deviation are -0.2 and 1.6 hours, respectively, with a correlation of 0.89 between the satellite and station observations. For the Campbell-Stokes comparisons, the bias and standard deviation are -0.6 and 2.2 hours, respectively, with a correlation of 0.82. For both analyses, the agreement is better in January and October compared with April and July. In January/October, the satellite data tend to slightly overestimate the in-situ measured sunshine duration, but they underestimate it in April/July, with increased error variance in these months compared with January/October. Nevertheless, overall agreement between the satellite and in-situ data is quite good. In particular, the high correlation of the satellite sunshine data with the station observations suggests that the spatial pattern of sunshine duration is captured well by the satellite data. This suggests that the satellite observations provide a viable source of additional sunshine duration estimates that could be used to supplement existing in-situ data sets.

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