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Measurement Biases Explain Discrepancies between the Observed and Simulated Decadal Variability of Surface Incident Solar Radiation

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Observations have reported a widespread dimming of surface incident solar radiation (R_s) from the 1950s to the 1980s and a brightening afterwards. However, none of the state-of-the-art earth system models, including those from the Coupled Model Intercomparison Project phase 5 (CMIP5), could successfully reproduce the dimming/brightening rates over China. We find that the decadal variability of observed R_s may have important errors due to instrument sensitivity drifting and instrument replacement. While sunshine duration (SunDu), which is a robust measurement related to R_s, is nearly free from these problems. We estimate R_s from SunDu with a method calibrated by the observed R_s at each station. SunDu-derived R_s declined over China by -2.8 (with a 95% confidence interval of -1.9 to -3.7) W m^{-2} per decade from 1960 to 1989, while the observed R_s declined by -8.5 (with a 95% confidence interval of -7.3 to -9.8) W m^{-2} per decade. The former trend was duplicated by some high-quality CMIP5 models, but none reproduced the latter trend.

Solar radiation is the ultimate energy source of the earth's climate system, which drives weather and climate change and vegetation growth[1]. Due to its importance, surface incident solar radiation (R_s) has been widely measured since the late 1950s. These observations have been archived by the Global Energy Balance Archive (GEBA)[2]. They have suggested a widespread decrease between the 1950s and 1980s ("global dimming")[2] with the subsequent brightening[3,4].

Recent studies[5,6] have compared the Coupled Model Intercomparison Project phase 3 (CMIP3) and phase 5 (CMIP5)[7] decadal variability of simulated R_s with observations collected by GEBA over land for the last half century and have reported large discrepancies. In particular, it was found that all of the 42 models of CMIP5 underestimated the trend of the observed R_s and none of the simulations of the CMIP5 models could reproduce the magnitude of the observed dimming trend over China and India[5]. From these comparisons, it could be inferred that the models are seriously flawed in their determination of the decadal variability of R_s. If this is so, their reported good ability to reproduce twentieth century climate could be called into question because R_s has an important contribution to decadal variability of surface air temperature[8–10].

In this study, we examine the decadal variability of observed R_s in China and find that the observed R_s may have overestimated the dimming rate due to the degradation problem of instruments before 1990 and overestimated the brightening rate due to instrument replacement from 1990 to 1993. When these sources of error are accounted for, the inference that there is serious disagreement between models and observations becomes much weaker.

Results

Here, we evaluate the decadal variability of the observed R_s with an independent measurement of sunshine duration (SunDu). SunDu is a conventional meteorological observation that records the time duration during a day when the direct solar beam is greater than 120 W m^{-2}, which is defined by the world meteorological organization. The light-sensitive paper of a SunDu recorder is burned when the direct solar beam is higher than a threshold, i.e., 120 W m^{-2}. SunDu is measured through reading the length of the burned mark during a day.

R_s can be calculated from SunDu, i.e., with the method (Eq. (1)) proposed by Yang et al.[11], which has been regarded as having the capability of reflecting the impacts of clouds and aerosols on R_s accurately[12–17]. To apply the

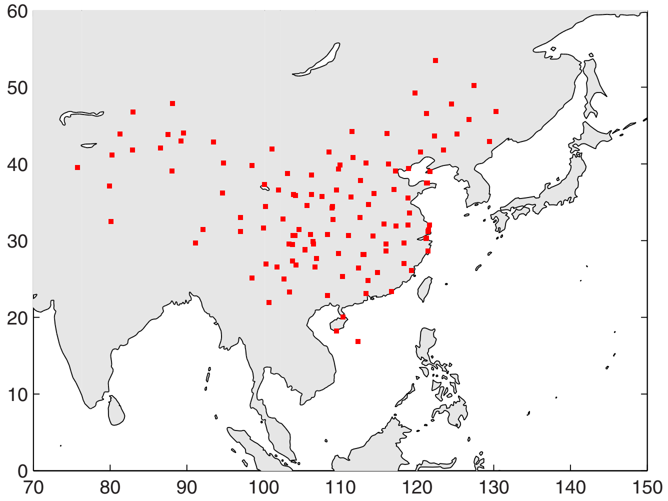

Figure 1 | A map of the stations (red square) where data durations of both surface incident solar radiation (R_s) and Sunshine Duration (SunDu) were longer than 120 months from 1958 to 2012. There are 122 stations in total. The figure was produced using MATLAB.

method globally or regionally, existing studies[12,13] tried to derive a suite of parameters by calibrating the equations with the observed R_s.

However, the burning threshold depends on the types of SunDu recorders and the sitting environment, i.e., its geographical location[16]. To address this issue, we calibrate the Eq. (1) to estimate R_s from SunDu at each station. We find 122 stations where both R_s and SunDu were measured for more than 10 years from 1958 to 2012 (Fig. 1), from which a reliable relationship between R_s and SunDu can be established at each station (Eq. (1) of Method Section). The relationship between R_s and SunDu may vary with geo-location and types of SunDu recorders. However, this relationship is expected to be stable for a station given the same SunDu recorder has been used. Under the assumption that the relationship between R_s and SunDu is stable for a station, the calibrated equation can be used to calculate R_s from SunDu for a longer time period, as SunDu has a longer observation history than R_s[16].

Fig. 2 shows scatterplots of SunDu-derived R_s as a function of the observed R_s at four stations. The biases are near zero because Eq. (1) used to estimate R_s from SunDu was calibrated with the observed R_s at each station. The statistical results of the standard deviation and correlation coefficients of all the stations are shown in Fig. 3, which shows R_s can be accurately estimated from SunDu at daily and monthly time scales. SunDu has difficulty in estimating R_s at time scales shorter than one day, as only daily SunDu was documented.

To provide accurate decadal variability of R_s, it is necessary to regularly and properly calibrate the instruments (i.e., the pyranometers) to measure R_s. However, a world-wide radiometric reference for such a calibration was not established until the year 1979[18,19]. Without an accurate and regular calibration, the instruments would lose their sensitivity and introduce a false dimming trend of the observed R_s[3]. SunDu recorders do not have this issue[20] as their recording material, the light-sensitive paper, is replaced every day. Fig. 4 shows that there were obvious instrument degradation problems for the observed R_s at the four stations in the Tibetan Plateau, while the SunDu-derived R_s were more stable and more homogeneous.

These instrument degradation issues were very common for the R_s measurements in China before 1990. Fig. 5 shows that trends of R_s from observations are substantially more negative than those of the SunDu-derived R_s from 1960 to 1989. There are four stations where the observed R_s had a near-zero trend while SunDu-derived R_s had significant positive or negative trends. Fig. 6 shows that this is because the instruments used to measure R_s were inaccurately calibrated at the stations at certain years.

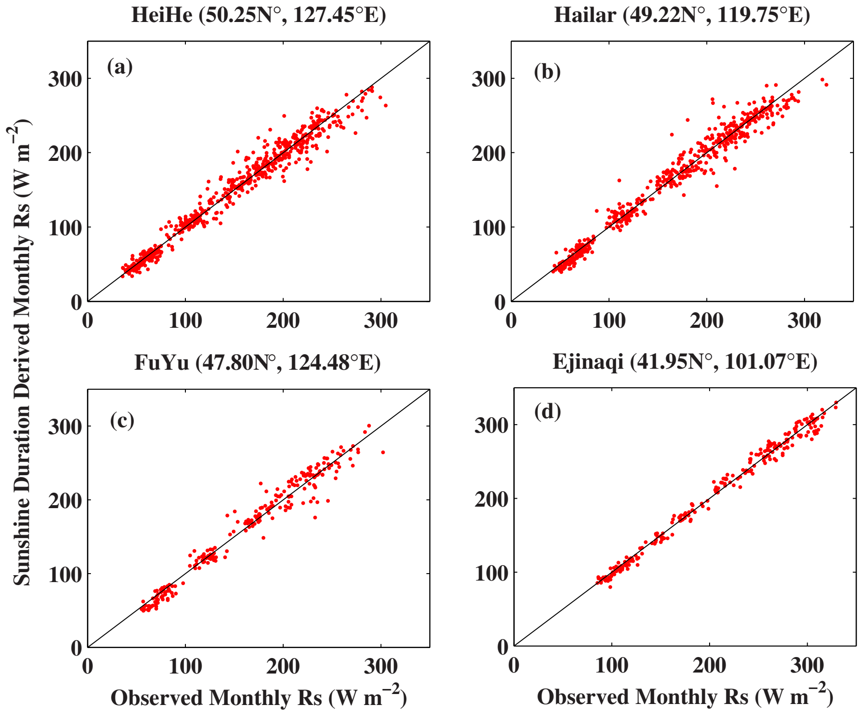

Figure 2 | Scatterplots of monthly averages of Sunshine Duration (SunDu) derived surface incident solar radiation (R_s) as a function of the observed R_s at four stations. The biases, standard deviations, and correlation coefficients of the comparisons between SunDu-derived R_s and observed R_s at the four stations are: (a): −0.3 W m^{-2}, 12.0 W m^{-2}, 0.99, (b) −0.6 W m^{-2}, 12.9 W m^{-2}, 0.98, (c) −0.8 W m^{-2}, 12.5 W m^{-2}, 0.98, and (d) −0.4 W m^{-2}, 7.9 W m^{-2}, 0.99. The biases are near zero because Eq. (1) used to calculate R_s from SunDu was calibrated at each station with the observed R_s. Four examples are shown here and the statistical results of all the stations are shown in Fig. 3. The figure was produced using MATLAB.

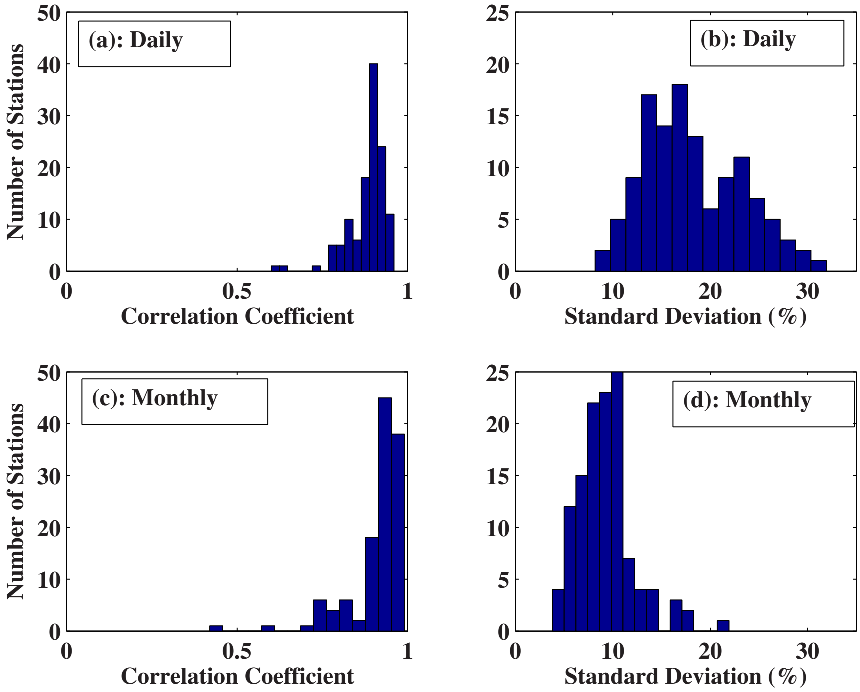

Figure 3 | Histograms of the statistical parameters of the comparisons between daily and monthly observed surface incident solar radiation (R_s) and R_s derived from Sunshine Duration (SunDu). The correlation coefficients and relative standard deviations (normalized by multi-year averages at each station) calculated from daily data are shown in panels (a) and (b), and those calculated from monthly data are shown in panels (c) and (d). As the Eq. (1) used to calculate R_s from SunDu was calibrated at each station, the biases of the comparisons are near zero and are not shown here. The medians of the correlation coefficients and the relative standard deviations between observed and calculated daily R_s are 0.89 and 17.32%, respectively, and the values are 0.94 and 9.11% for monthly R_s. The figure was produced using MATLAB.

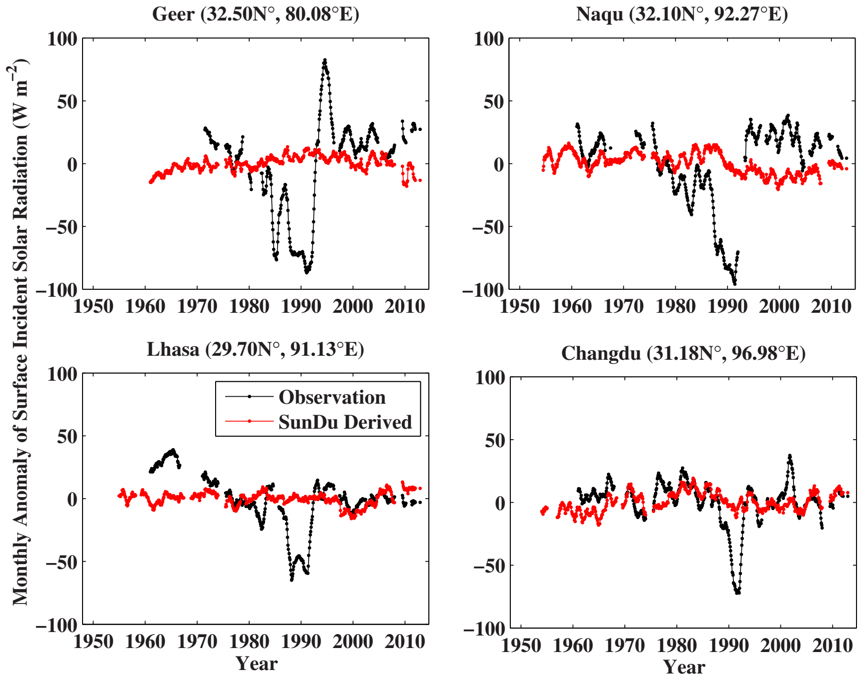

Figure 4 | Time series of 12-month smoothed monthly anomalies of observed surface incident solar radiation (R_s) and R_s calculated from Sunshine Duration (SunDu) at four stations in the Tibetan Plateau. Observations of R_s are impacted by the performance of instruments (pyrheliometer and pyranometers). These instruments should be accurately and regularly calibrated. Otherwise, they would lose their sensitivity and produce a spurious dimming trend of R_s. On the contrary, the measurements of SunDu are much less sensitive to instrument calibration, as its recording material is replaced each day. There is significant evidence that the instruments used to measure R_s at these four stations had important calibration problems before 1992 when the new instruments were deployed. The figure was produced using MATLAB.

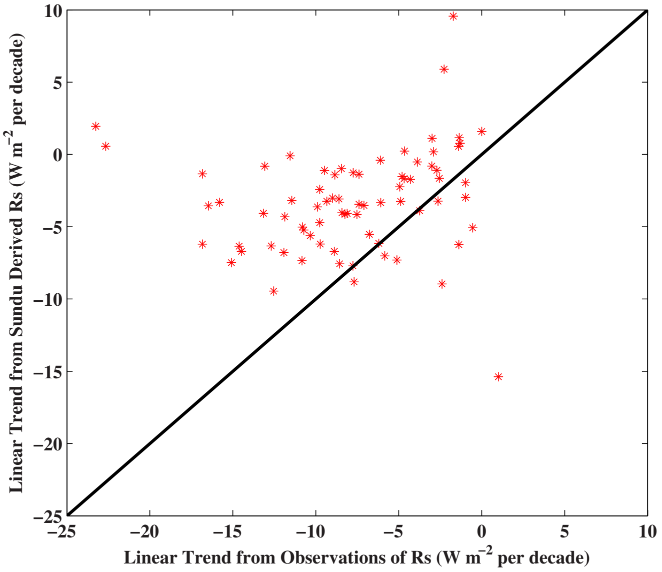

Figure 5 | Scatterplot of the linear trends of observed R_s as a function of trends of SunDu-derived R_s. Each red star represents a station in China where the data duration of both the observed and calculated R_s were longer than 120 months during 1960 to 1989. There are 76 stations in total. Linear trends of observed surface incident solar radiation (R_s) are significantly more negative than those from sunshine duration (SunDu) derived R_s. The figure was produced using MATLAB.

Figs. 4–6 indicate that the lack of calibration or inaccurate calibration made the observed R_s values highly uncertain. Fig. 7 further shows that measurement biases may explain the discrepancies between the observed and simulated decadal variability of R_s. The linear trend of the observed R_s averaged over China from 1960 to 1989 was −8.5 W m^{-2} per decade, with a 95% confidence interval from −9.8 W m^{-2} per decade to −7.3 W m^{-2} per decade. None of the 48 Earth System Models of CMIP5 (CMIP5 ESM)[7,21] reproduced the observed trend (Fig. 7).

However, many high-quality CMIP5 ESMs reproduced the trend of SunDu-derived R_s very well. The linear trend of the SunDu-derived R_s averaged over China during the same period was −2.8 W m^{-2} per decade, with a 95% confidence interval from −3.7 W m^{-2} per decade to −1.9 W m^{-2} per decade (Fig. 7). The R_s from NASA Goddard Institute for Space Studies (GISS) models show the best agreement with the SunDu-derived values. The four versions of GISS ESM simulated an average trend of R_s by −2.8 W m^{-2} per decade. Other CMIP5 ESMs, including the Centre National de Recherches Meteorologiques Climate Model 5 (CNRM-CM5-2, −2.9 W m^{-2} per decade) and National Center for Atmospheric Research (NCAR) Community Earth System Models (CESM1-CAM5-1-FV2, −2.4 W m^{-2} per decade and CESM1-CAM5, −2.0 W m^{-2} per decade), also had consistent simulations of R_s trend with SunDu-derived R_s. However, the interannual variability of R_s of CMIP5 is much less than those from the observed R_s and SunDu derived R_s because the models have difficulty in simulating variability of clouds[22].

It has been shown that aerosol is the dominating factor for the dimming of R_s in China from 1960 to 1990[23,24] although cloud has been believed to be the key factor for the decadal variability of R_s in the U.S.[25,26] and India[27] during recent decades. A recent study has shown that the CMIP5 models perform significantly different in simulating atmospheric aerosols over India[28]. This is because the atmospheric aerosol loading was interactively calculated by each individual model[10], although the same emission inventory[29–32] was

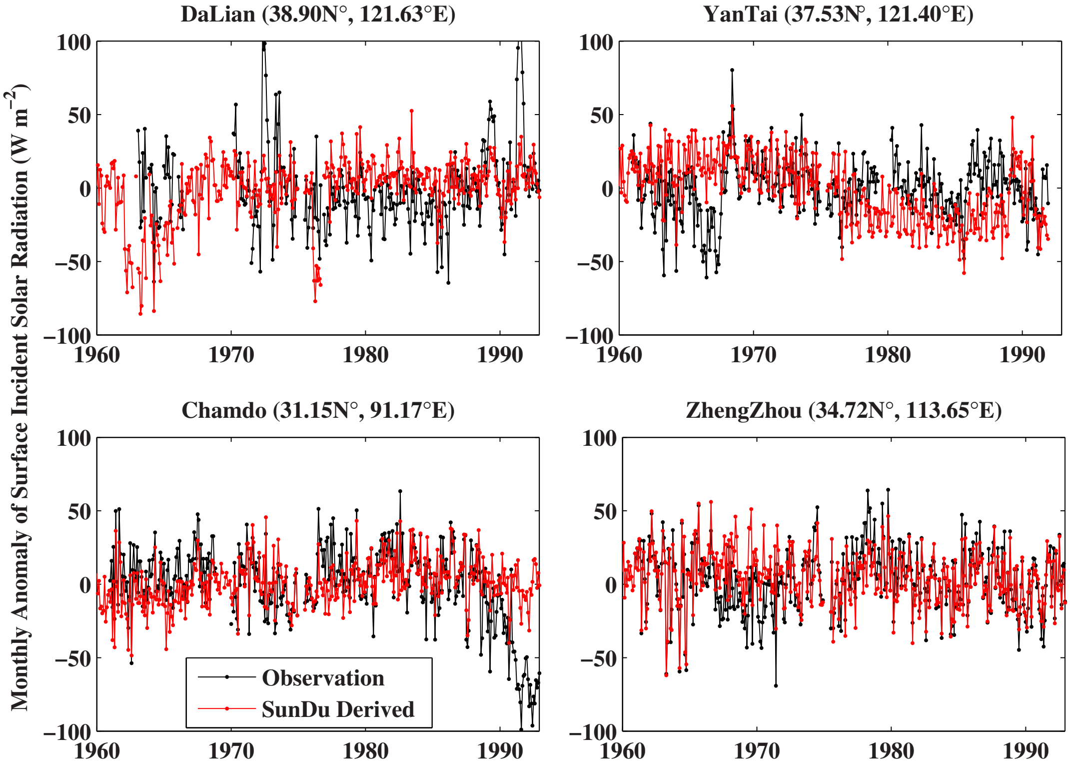

Figure 6 | Time series of observed surface incident solar radiation (R_s) and R_s calculated from Sunshine Duration (SunDu) at four stations where the observed R_s showed a near-zero trend while SunDu-derived R_s had significant positive or negative trends (see Fig. 5). It is obvious that the instruments used to measure R_s were inaccurately calibrated at the DaLian station in the early 1970s and the early 1990s, YanTai station in the late 1960s, and ChamDo station in the late 1980s to the early 1990s. At these stations, the trends of SunDu-derived R_s are more reliable than those of observed R_s. The figure was produced using MATLAB.

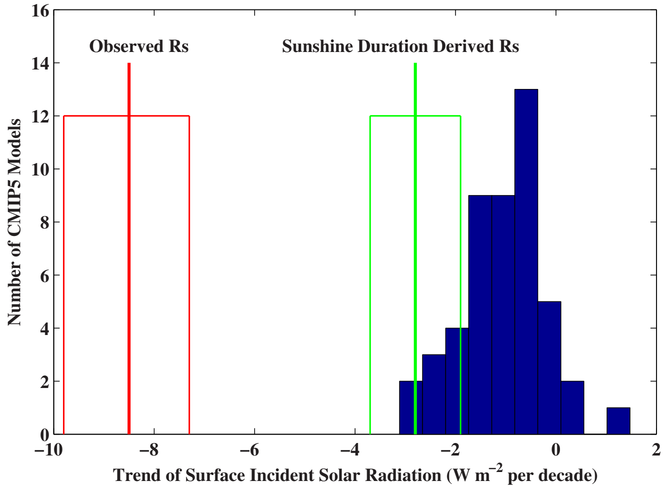

Figure 7 | Histogram of the linear trends of surface incident solar radiation (R_s, blue bars) over China from 1960 to 1989 simulated by 48 CMIP5 models (see Ma et al.[21] for details of these models). None of the models reproduced the observed trend of −8.5 W m^{-2} per decade (thick red line, with the red box showing its 95% confidence interval) based on the raw data of R_s observations. However, some CMIP5 models, including NASA Goddard Institute for Space Studies (GISS) models, National Center for Atmospheric Research (NCAR) Community Earth System Models (CESM-CAM5), and Centre National de Recherches Meteorologiques Climate Model 5 (CNRM-CM5), reproduced our new estimates of the trend based on Sunshine Duration (SunDu) derived R_s, −2.8 W m^{-2} per decade (thick green line, with the green box showing its 95% confidence interval). The figure was produced using MATLAB.

used for all of the CMIP5 models[7]. Our results show that the GISS models perform best, which is partly because the GISS model team has made great effort in simulating aerosols[33–36].

Fig. 8 shows that the agreement of the long-term trends between SunDu-derived R_s and CMIP5 simulations is significantly better than those between observations and CMIP5 simulations over China from 1960 to 1989. The brightening rate of the measured R_s was impaired by instrument replacement between 1990 and 1993[13], as shown in Fig. 4. The observations of diurnal temperature range[8,37] confirmed that the observed brightening from 1990 to 1993 was not real. The observed increase in R_s is inconsistent with the observed increase in stratospheric aerosols because of Pinatubo volcano eruption in 1991[38] either. After 1995, variability of the three estimates of R_s from the observations, the SunDu and the CMIP5 model simulations agreed well because issues of the instruments used to measure R_s had been eliminated. During this period, the impact of increased aerosols on R_s[39] has been offset by the decreasing cloud cover fraction[13], and in turn R_s kept near constant.

Discussion

The overestimation of the dimming trend of the observed R_s over China has been corroborated by independent studies on clouds and aerosols. Observed R_s was reported to have decreased by 21 W m^{-2} in eastern China from 1961 to 1990[40], with changes in aerosols regarded as the primary reason for this dimming trend[13,41]. Changes in cloud cover showed a decreasing trend[41], implying an increasing trend of R_s. The aerosol optical depth (AOD, vertical integration of optical extinction) over the same region during the same time has increased by 0.16[42]. Analyses have shown that R_s under clear sky conditions decreases by 8 Wm^{-2} in the winter seasons or 9 Wm^{-2} in the summer seasons for an AOD increase of 0.1 over China[43]. The change in AOD can explain at most a reduction of $1.6 \times 9 = 14.4$ Wm^{-2} of R_s, which is approximately two-thirds of the observed value, but probably considerably less because of masking by clouds. This is confirmed by the SunDu-derived R_s, which showed a decrease of 8.4 W m^{-2} during the period.

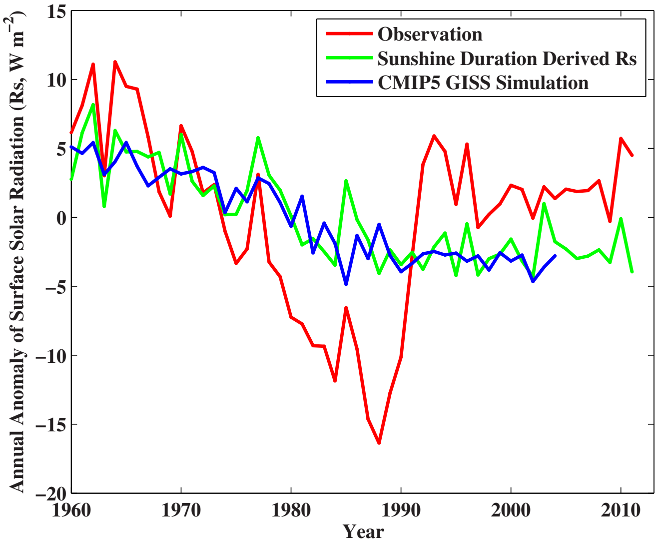

Figure 8 | Time series of observed surface incident solar radiation (R_s, in red), R_s calculated from Sunshine Duration (SunDu, in green) and R_s simulated by CMIP5 GISS (in blue) averaged over China. The observed R_s overestimated the dimming trend from 1960 to 1989. The instrument replacement in China from 1990 to 1993 resulted in an abrupt increase to the observed R_s. The agreement of the long-term trends of R_s between sunshine duration (SunDu) derived R_s and CMIP5 NASA Goddard Institute for Space Studies (GISS) model simulations (averaged from four different model versions) is much better than those between observations and CMIP5 simulations. After 1995, variability of the three estimates of R_s from the observations, the SunDu and the CMIP5 model simulations agreed well because issues of the instruments used to measure R_s had been eliminated. The figure was produced using MATLAB.

Globally distributed *DTR* observations show that since 1985, brightening was only significant over Europe and there was a lack of brightening over other continents[8]. Furthermore, AOD derived from visibility observations has increased globally since 1973 except for Europe[39]. This explains why the CMIP5 ESM could only reproduce the observed brightening over Europe[5].

The inhomogeneity of observed R_s caused by inaccurate instrument calibration also impacted the observed R_s over Europe before 1990. A homogeneity test was applied to R_s measurements at 56 stations over Europe where at least 30 years of data of R_s were available at each station[44]. Sixteen of the 56 series (28.6% of the total) were found to be inhomogeneous[44]. After these datasets were appropriately adjusted, the dimming trend over Europe from 1961 to 1984 became −2.0 W m^{-2} per decade, substantially less than the −3.1 W m^{-2} per decade derived from raw data of the observed R_s[45].

Methods

Sunshine Duration (SunDu) records the time during a day that the direct solar beam irradiance exceeds 120 Wm^{-2}. It was initiated 150 years ago and is one of the oldest and most robust measurements related to radiation[3]. Measurement of SunDu is insensitive to instrument calibration as its recording material is replaced each day.

SunDu has long been used to estimate R_s, and the earliest and most popular methods are those developed by Ångström[46] and subsequently modified by Prescott[47], which assumed a linear relationship between relative R_s and SunDu. Yang et al. proposed a revised Ångström-Prescott to estimate daily mean R_s from SunDu[11]:

$$R_s/R_c = a_0 + a_1 \cdot n/N + a_2 \cdot (n/N)^2 \tag{1}$$

where n is the measured SunDu; N is the theoretical values of SunDu, and R_c is the daily solar radiation at the surface under clear-sky conditions:

$$R_c = R_{cb} + R_{cd} = \int I_0 \cdot \overline{\tau_b} \cdot \sin(h) \cdot dt + \int I_0 \cdot \overline{\tau_d} \cdot \sin(h) \cdot dt \tag{2}$$

where R_{cb} is the daily mean direct solar radiation at the surface, R_{cd} is the daily mean diffuse solar radiation at the surface, I_0 is the solar radiation at the extraterrestrial level, $\overline{\tau_b}$ is the atmospheric transmittance for direct solar radiation, $\overline{\tau_d}$ is the atmospheric transmittance for diffuse solar radiation, h(rad) is the altitude angle of sun, and t(s) is the time. The atmospheric transmittances $\overline{\tau_b}$ and $\overline{\tau_d}$ depend on Rayleigh scattering, aerosol extinction, ozone absorption, water vapor absorption and permanent gas absorption. Rayleigh scattering and water vapor absorption can be calculated from surface meteorological observations, and ozone and permanent gas absorption can be calculated using their climatological values. In the calculation of aerosol extinction, winter- and summer-averaged aerosols based on Hess et al.[48] were included but the inter-annual variation of aerosols was not incorporated. Please refer to reference 11 for detailed information of the calculations.

The calculation of R_c does not include time varying aerosols because SunDu is impacted by changes in both clouds and aerosols. Direct solar radiation is generally lower than 120 W m^{-2} for scattered clouds (cumulus, stratocumulus)[20]. High and thin cirrus, as well as aerosols can reduce SunDu at low solar elevations, i.e., at times when the incident clear sky solar radiation is not much larger than 120 W m^{-2}. Recent studies confirmed such an inference and have shown that SunDu can accurately reflect the impact of change of aerosols and clouds on R_s[12–17] at time scales ranging from daily to decadal.

The parameters of Eq. (1), namely a_0, a_1, and a_2, can be obtained by tuning this equation with measurements of R_s and SunDu. In the existing studies, a suite of parameters are derived by calibrating Eq. (1) and then the method is applied regionally or globally[12,13]. This may limit the accuracy of the R_s estimates. In contrast, in this study, we calibrate Eq. (1) at each station in China where both R_s and SunDu observations were available at more than 10 years. We then apply Eq. (1) to calculate R_s from 1958 to 2012 at each station when observations of SunDu were available. Figs. 2–3 show that R_s can be calculated accurately from SunDu data at daily and monthly time scales. These two estimates of R_s allow us to investigate the homogeneity of these two estimates, which are shown in Figs. 4–8. In this study, we show that the R_s decreased at a rate of -2.8 W m^{-2} per decade from 1960 to 1989 over the 76 stations where both the observed R_s and SunDu were available at more than 120 months during the study period. In a previous study, Tang et al.[12] calculated R_s from SunDu with a suite of parameters of Eq. (1) for 716 weather stations in China and estimated an averaged trend of -2.3 W m^{-2} per decade from 1961 to 2000, which is a little weaker than our current estimate because R_s stopped decreasing after 1990 (Fig. 8).

In this study, we propose to combine the advantages of the observations of R_s and SunDu. The observed R_s can accurately quantify the variation of R_s in higher temporal resolution, i.e., hourly, and daily. However, it is impaired by the sensitivity drift of its measurement instruments. This limits its usage in climatic study. The SunDu is nearly free from the sensitivity drift problem. We use the observed R_s to calibrate Eq. (1) used to estimate R_s from SunDu at each station. This makes up the disadvantages of SunDu: (1) SunDu does not directly provide an estimate of R_s, (2) threshold of a SunDu recorder changes with recorder types and their sitting environment. In this paper, we show that the SunDu-derived R_s has an advantage of long-term stability and can be used to climatic studies, i.e., to evaluate climate model simulations, which only require estimates of R_s at coarse time resolution (monthly or annually). However, SunDu has difficulty in estimating R_s at time scales shorter than daily.

1. Mercado, L. M. *et al.* Impact of changes in diffuse radiation on the global land carbon sink. *Nature* **458**, 1014–U1087, doi:10.1038/nature07949 (2009).
2. Gilgen, H., Wild, M. & Ohmura, A. Means and trends of shortwave irradiance at the surface estimated from global energy balance archive data. *J. Clim.* **11**, 2042–2061, doi:10.1175/1520-0442-11.8.2042 (1998).
3. Wild, M. Global dimming and brightening: A review. *J. Geophys. Res.* **114**, D00D16, doi:10.1029/2008JD011470 (2009).
4. Wild, M. *et al.* From dimming to brightening: Decadal changes in solar radiation at Earth's surface. *Science* **308**, 847–850, doi:10.1126/science.1103215 (2005).
5. Allen, R. J., Norris, J. R. & Wild, M. Evaluation of multidecadal variability in CMIP5 surface solar radiation and inferred underestimation of aerosol direct effects over Europe, China, Japan and India. *J. Geophy. Res.* **118**, 6311–6336, doi:10.1002/jgrd.50426 (2013).
6. Wild, M. & Schmucki, E. Assessment of global dimming and brightening in IPCC-AR4/CMIP3 models and ERA40. *Clim. Dyn.* **37**, 1671–1688, doi:10.1007/s00382-010-0939-3 (2011).
7. Taylor, K. E., Stouffer, R. J. & Meehl, G. A. An overview of CMIP5 and the experiment design. *Bull. Amer. Meteorol. Soc.* **93**, 485–498, doi:10.1175/bams-d-11-00094.1 (2012).
8. Wang, K. C. & Dickinson, R. E. Contribution of solar radiation to decadal temperature variability over land. *Proc Natl Acad Sci USA* **110**, 14877–14882, doi:10.1073/pnas.1311433110 (2013).
9. Padma Kumari, B., Londhe, A. L., Daniel, S. & Jadhav, D. B. Observational evidence of solar dimming: Offsetting surface warming over India. *Geophys. Res. Lett.* **34**, L21810, doi:10.1029/2007gl031133 (2007).
10. Ghan, S. J. & Schwartz, S. E. Aerosol properties and processes: a path from field and laboratory measurements to global climate models. *Bull. Amer. Meteorol. Soc.* **88**, 1059–1083, doi:10.1175/bams-88-7-1059 (2007).
11. Yang, K., Koike, T. & Ye, B. S. Improving estimation of hourly, daily, and monthly solar radiation by importing global data sets. *Agric. For. Meteorol.* **137**, 43–55, doi:10.1016/j.agrformet.2006.02.001 (2006).
12. Tang, W. J., Yang, K., Qin, J., Cheng, C. C. K. & He, J. Solar radiation trend across China in recent decades: a revisit with quality-controlled data. *Atmos. Chem. Phys.* **11**, 393–406, doi:10.5194/acp-11-393-2011 (2011).
13. Wang, K. C., Dickinson, R. E., Wild, M. & Liang, S. Atmospheric impacts on climatic variability of surface incident solar radiation. *Atmos. Chem. Phys.* **12**, 9581–9592, doi:10.5194/acp-12-9581-2012 (2012).
14. Sanchez-Lorenzo, A., Calb, J., Brunetti, M. & Deser, C. Dimming/brightening over the Iberian Peninsula: Trends in sunshine duration and cloud cover and their relations with atmospheric circulation. *J. Geophys. Res.* **114**, D00D09, doi:10.1029/2008JD011394 (2009).
15. Sanchez-Lorenzo, A. & Wild, M. Decadal variations in estimated surface solar radiation over Switzerland since the late 19th century. *Atmos. Chem. Phys.* **12**, 8635–8644, doi:10.5194/acp-12-8635-2012 (2012).
16. Sanchez-Romero, A., Sanchez-Lorenzo, A., Calbó, J., González, J. A. & Azorin-Molina, C. The signal of aerosol-induced changes in sunshine duration records: A review of the evidence. *J. Geophy. Res.* **119**, 2013JD021393, doi:10.1002/2013jd021393 (2014).
17. Soni, V. K., Pandithurai, G. & Pai, D. S. Evaluation of long-term changes of solar radiation in India. *Int. J. Climatol.* **32**, 540–551, doi:10.1002/joc.2294 (2012).
18. Gueymard, C. A. & Myers, D. R. [Solar radiation measurement: progress in radiometry for improved modeling solar radiation at the Earth's surface] *Modeling Solar Radiation at the Earth Surface* [Badescu, V. (ed.)] [1–28] (Springer-Verlag Berlin Heidelberg, 2008).
19. Fröhlich, C. in *WMO/CIMO Final Report, WMO No. 490, 97–110.* (PMOD/WRC intern: 545a, 1977).
20. Stanhill, G. & Cohen, S. Solar radiation changes in the United States during the Twentieth Century: Evidence from sunshine measurements. *J. Clim.* **18**, 1503–1512, doi:http://dx.doi.org/10.1175/JCLI3354.1 (2005).
21. Ma, Q., Wang, K. C. & Wild, M. Evaluations of atmospheric downward longwave radiation from 44 coupled general circulation models of CMIP5. *J. Geophy. Res.* **119**, 4486–4497, doi:10.1002/2013JD021427 (2014).
22. Zhang, M. H. *et al.* Comparing clouds and their seasonal variations in 10 atmospheric general circulation models with satellite measurements. *J. Geophys. Res.* **110**, D15s02, doi:10.1029/2004jd005021 (2005).
23. Qian, Y., Wang, W. G., Leung, L. R. & Kaiser, D. P. Variability of solar radiation under cloud-free skies in China: The role of aerosols. *Geophys. Res. Lett.* **34**, doi:10.1029/2006GL028800 (2007).
24. Xia, X. A closer looking at dimming and brightening in China during 1961–2005. *Ann. Geophys.* **28**, 1121–1132, doi:10.5194/angeo-28-1121-2010 (2010).
25. Augustine, J. A. & Dutton, E. G. Variability of the surface radiation budget over the United States from 1996 through 2011 from high-quality measurements. *J. Geophy. Res.* **118**, 43–53, doi:10.1029/2012jd018551 (2013).
26. Long, C. N. *et al.* Significant decadal brightening of downwelling shortwave in the continental United States. *J. Geophys. Res.* **114**, D00D06, doi:10.1029/2008JD011263 (2009).
27. Padma Kumari, B. & Goswami, B. N. Seminal role of clouds on solar dimming over the Indian monsoon region. *Geophys. Res. Lett* **37**, L06703, doi:10.1029/2009gl042133 (2010).
28. Sanap, S. D., Ayantika, D. C., Pandithurai, G. & Niranjan, K. Assessment of the aerosol distribution over Indian subcontinent in CMIP5 models. *Atmos. Environ.* **87**, 123–137, doi:http://dx.doi.org/10.1016/j.atmosenv.2014.01.017 (2014).
29. Lamarque, J. F. *et al.* Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. *Atmos. Chem. Phys.* **10**, 7017–7039, doi:10.5194/acp-10-7017-2010 (2010).
30. Smith, S. J. *et al.* Anthropogenic sulfur dioxide emissions: 1850–2005. *Atmos. Chem. Phys.* **11**, 1101–1116, doi:10.5194/acp-11-1101-2011 (2011).
31. Bond, T. C. *et al.* Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850–2000. *Global Biogeochem. Cycles* **21**, GB2018, doi:10.1029/2006gb002840 (2007).
32. Junker, C. & Liousse, C. A global emission inventory of carbonaceous aerosol from historic records of fossil fuel and biofuel consumption for the period 1860–1997. *Atmos. Chem. Phys.* **8**, 1195–1207, doi:10.5194/acp-8-1195-2008 (2008).
33. de Boer, G., Bauer, S. E., Toto, T., Menon, S. & Vogelmann, A. M. Evaluation of aerosol-cloud interaction in the GISS ModelE using ARM observations. *J. Geophy. Res.* **118**, 6383–6395, doi:10.1002/jgrd.50460 (2013).
34. Lee, Y. H. & Adams, P. J. Evaluation of aerosol distributions in the GISS-TOMAS global aerosol microphysics model with remote sensing observations. *Atmos. Chem. Phys.* **10**, 2129–2144, doi:10.5194/acp-10-2129-2010 (2010).
35. Li, J., Liu, L., Lacis, A. A. & Carlson, B. E. An optimal fitting approach to improve the GISS ModelE aerosol optical property parameterization using AERONET data. *J. Geophy. Res.* **115**, D16211, doi:10.1029/2010jd013909 (2010).
36. Menon, S. *et al.* Analyzing signatures of aerosol-cloud interactions from satellite retrievals and the GISS GCM to constrain the aerosol indirect effect. *J. Geophy. Res.* **113**, D14S22, doi:10.1029/2007jd009442 (2008).
37. Wang, K., Ye, H., Chen, F., Xiong, Y. & Wang, C. Urbanization effect on the diurnal temperature range: different roles under solar dimming and brightening. *J. Clim.* **25**, 1022–1027, doi:10.1175/jcli-d-10-05030.1 (2012).
38. Stevermer, A. J., Petropavlovskikh, I. V., Rosen, J. M. & DeLuisi, J. J. Development of a global stratospheric aerosol climatology: Optical properties and applications for UV. *J. Geophys. Res.* **105**, 22763–22776, doi:10.1029/2000jd900368 (2000).

39. Wang, K. C., Dickinson, R. E. & Liang, S. Clear sky visibility has decreased over land globally from 1973 to 2007. *Science* **323**, 1468–1470, doi:10.1126/science.1167549 (2009).
40. Li, X., Li, W. & Zhou, X. Analysis of the solar radiation variation of the China in recent 30 years. *Quart. J. Appl. Meteorol.* **9**, 24–31 (1998).
41. Xia, X. Significant decreasing cloud cover during 1954–2005 due to more clear-sky days and less overcast days in China and its relation to aerosol. *Ann. Geophys.* **30**, 573–582, doi:10.5194/angeo-30-573-2012 (2012).
42. Luo, Y., Lu, D., Zhou, X., Li, W. & He, Q. Characteristics of the spatial distribution and yearly variation of aerosol optical depth over China in last 30 years. *J. Geophy. Res.* **106**, 14501–14513, doi:10.1029/2001jd900030 (2001).
43. Xia, X. *et al.* A compilation of aerosol optical properties and calculation of direct radiative forcing over an urban region in northern China. *J. Geophy. Res.* **112**, D12203, doi:10.1029/2006jd008119 (2007).
44. Sanchez-Lorenzo, A., Wild, M. & Trentmann, J. Validation and stability assessment of the monthly mean CM SAF surface solar radiation dataset over Europe against a homogenized surface dataset (1983–2005). *Remote Sens. Environ.* **134**, 355–366, doi:http://dx.doi.org/10.1016/j.rse.2013.03.012 (2013).
45. Norris, J. R. & Wild, M. Trends in aerosol radiative effects over Europe inferred from observed cloud cover, solar "dimming" and solar "brightening" *J. Geophys. Res.* **112**, D08214, doi:10.1029/2006JD007794 (2007).
46. Angström, A. Solar and terrestrial radiation. Report to the international commission for solar research on actinometric investigations of solar and atmospheric radiation. *Q. J. R. Meteorol. Soc.* **50**, 121–126, doi:10.1002/qj.49705021008 (1924).
47. Prescott, J. A. Evaporation from water surface in relation to solar radiation. *Trans R Soc Sci Austr* **64**, 114–118 (1940).
48. Hess, M., Koepke, P. & Schult, I. Optical properties of aerosols and clouds: The software package OPAC. *Bull. Amer. Meteorol. Soc.* **79**, 831–844, doi:10.1175/1520-0477(1998)0790831:opoaac>2.0.co;2 (1998).

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