Increase of surface solar irradiance across East China related to changes in aerosol properties during the past decade

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Abstract

Previously, it was widely documented that an overall decrease in surface solar radiation occurred in China at least until 2005, in contrast to the general background of ‘global brightening’. Increased anthropogenic aerosol emissions were speculated to be the source of the reduction. In this study, we extend the trend analysis to the most recent decade from 2005–2015 and find that surface solar radiation has shifted from ‘dimming’ to ‘brightening’ over East China, with the largest increase over the northeast and southeast parts. Meanwhile, satellite and ground observation both indicate a reduction in aerosol optical depth (AOD) during the same period, whereas no significant trends in cloud amount show up. Detailed analysis using co-located radiation and aerosol observation at the XiangHe station in North China suggests that both AOD and single scattering albedo (SSA) changes contribute to the radiation trends. AOD reduction contributes to the increase of direct solar radiation, also decreasing the diffuse radiation, while the increase of SSA serves to increase the diffuse fraction. Simple calculations using a radiative transfer model confirm that the two effects combined explain changes in the global solar radiation and its components effectively. Our results have implications for potential climate effects with the reduction of China’s aerosol emissions, and the necessity to monitor aerosol composition in addition to its loading.

1. Introduction

Surface solar radiation is an important component of the climate system. It directly affects surface temperature, the hydrological cycle and the ecological environment (Ramanathan et al 2001, Roderick and Farquhar 2002, Wild et al 2005). Moreover, because it is highly sensitive to climate perturbations such as those caused by anthropogenic greenhouse gases and aerosols (Ramanathan et al 2001), the change in surface solar radiation has become an indicator of climate change and has been receiving extensive attention. Wild et al (2005) documented that surface solar radiation had shifted from the ‘solar dimming’ period (meaning reduction of global surface solar radiation) between the 1950s–1980s to the ‘solar brightening’ (increase of global surface solar radiation) period of the 1990s. Nonetheless, the trends were not uniform globally. Further regional analysis revealed that the ‘brightening’ was mostly concentrated over developed regions including North America, Europe, Australia, Japan, etc, while developing countries such as China and India still suffered from a radiation reduction in the 1990s (Wild et al 2007). Later, Wild et al (2009) extended the analysis into 2000–2005 and arrived at similar conclusions, albeit with larger spatial variations.

The trends in surface solar radiation over China have been investigated by many previous studies, particularly considering that it is one of the most rapidly developing regions as well as a pollution hotspot. Che et al (2005) analyzed 40 years of surface radiation and sunshine duration measurements in China
and found that global and direct solar radiation has significantly decreased while diffuse radiation increased over the latter half of the 20th century. Qian et al (2007) arrived at the same conclusion and suggested that the largest decrease of global and direct solar radiation occurred between 1961–1983. Although later studies applied stricter quality assurance to the data, the trends appeared unaffected (Shi et al 2008, Tang et al 2011).

Despite various datasets and regions being analyzed, previous studies uniformly considered that the surface solar radiation trends were due to changes in atmospheric composition (cloud, aerosols, water vapor) rather than the incident solar radiation at the top of the atmosphere. In particular, changes of aerosol emission in different regions appear in phase with the solar radiation changes and are thus considered as the primary factor. Norris and Wild (2007, 2009) respectively analyzed the radiation trends over Europe, China and Japan, and concluded that the trends could not be fully explained by cloud variability and that anthropogenic aerosols were the most likely factor. Qian et al (2007) examined aerosol loading, single scattering albedo (SSA) and relative humidity changes in China and found that increase of aerosol loading should be the main factor for the obvious solar radiation reduction before 1983, whereas possible SSA increase might compensate for the reduction afterwards. By considering various climatic factors, Liang and Xia (2005) also indicated that aerosol increase should be the primary factor for the observed radiation decrease in China.

All of these studies arrived at the consistent conclusion that surface solar radiation has decreased in the past century in China, with an increase in aerosol emissions being the most plausible cause. In recent years, China has become more aware of the pollution issue and implemented a series of emission reduction policies for the recent climate changes as well as future climate projection.

The purpose of this study is therefore to examine the trends of surface solar radiation in the most recent decade from 2005–2015, in conjunction with cloud and aerosol changes, to identify the driver of the trends. Since previous studies still lack co-located analysis of the relationship between radiation and aerosol properties, here we intend to investigate this problem in more detail using data at one North China site where high resolution, simultaneous solar radiation and aerosol measurements are available. It is hoped that our results can contribute to the understanding of recent solar radiation change in China and its associated mechanisms.

2. Data and methods

2.1. Surface solar radiation data

The surface solar radiation data come from three public sources, namely the Baseline Surface Radiation Network (BSRN, Ohmura et al 1998) at the World Radiation Monitoring Center (http://bsrn.awi.de/), the Global Energy Balance Archive (GEBA) at ETH Zurich (Gilgen and Ohmura 1999, www.geba.ethz.ch/), and the World Radiation Data Center (WRDC, http://wrdc.mgo.rssi.ru/wrdc_en_new.htm) at the Voeikov Main Geophysical Observatory. BSRN provides global, direct and diffuse radiation, WRDC reports global radiation and diffuse radiation for most sites, while for GEBA, only global radiation is available for the 2005–2015 period. With respect to BSRN measurements, direct radiation measurement uncertainty is estimated to be 1 W m$^{-2}$, whereas diffuse radiation has ±5 W m$^{-2}$ uncertainty (Ohmura et al 1998). The measurement accuracy of GEBA global radiation was estimated to be on the order of 2% (Gilgen and Ohmura 1999). Moreover, all three datasets have undergone rigorous quality control to ensure both high quality and homogeneity. Over the study period, there is one BSRN station (XiangHe), seven GEBA stations and nine WRDC stations that have more than ten years of continuous data records. Note there is a substantial overlap between GEBA and WRDC stations. The name and location of the stations used are listed in supplementary table S1 available at stacks.iop.org/ERL/13/034006/mmedia.T he BSRN data is reported as 1 min observations, GEBA in monthly means and WRDC in daily sums. Both BSRN and GEBA report solar irradiance in W m$^{-2}$. WRDC collects integrated solar irradiance in J cm$^{-2}$, which has been converted to daily means in W m$^{-2}$ in this study.

2.2. Aerosol and cloud data

We examine the two major factors affecting surface solar radiation—aerosols and clouds, and the data come from both satellites and ground based measurements for more robust analysis. Satellite aerosol products including aerosol optical depth (AOD) from the Moderate Resolution Imaging Spectroradiometer (MODIS, Collection 6, Levy et al 2013, https://ladsweb.modaps.eosdis.nasa.gov) onboard the EOS-Aqua platform, and from the Multi-angle Imaging Spectroradiometer (MISR, Martonchik et al 1998, https://eosweb.larc.nasa.gov/project/misr/misr_table) onboard the EOS-Terra platform. Level 3 gridded monthly means are used. The dataset names are ‘MYD04_M3’ and ‘MIL3MAE’ for MODIS and MISR respectively. The MODIS AOD accuracy over land is ±0.05 + 15% AERONET AOD (Levy et al 2013), and that for MISR AOD is estimated to be better than 0.05 (Kahn et al 2007). Ground based aerosol observations are provided by the Aerosol Robotic Network (AERONET, Holben et al 1998, available at https://aeronet.gsfc.nasa.gov/). This network has
more than 400 stations worldwide, performing routine measurements and retrievals of major aerosol optical properties. In mainland China, only limited sites have a sufficient record for trend analysis and we only use data from the XiangHe site, which is collocated with the BSRN site. This study uses Level 2.0 direct beam AOD retrieval at 440 nm and SSA and asymmetry parameter from the inversion algorithm (Dubovik et al 2000), with accuracy estimates of ±0.02 for AOD (Eck et al 1999) and ±0.03 for SSA (Dubovik et al 2000).

The satellite cloud fraction and microphysics data are from the Aqua-MODIS Level 3 monthly joint atmosphere product (MYD04_M3), https://ladsweb.modaps.eosdis.nasa.gov/search/order/1/MYD08_M3-6. The MODIS cloud detection products have been validated against both ground based and other space-born sensors by Ackerman et al (2008). Ground based, gridded cloud cover observation from the Climate Research Unit (CRU, v4.00, Harris et al 2014, https://crudata.uea.ac.uk/cru/data/hrg/) is also used for corroboration. Comparison with other ground and satellite based datasets indicates reasonable agreement (Harris et al 2014).

Note that although only MODIS data on the Aqua platform is used, we compared the results with those from Terra and they are quite similar (comparing figure S1 and figures 2 (a) and (c), also see figure S5).

2.3. Trend analysis method

Linear trends of the radiation, aerosol and cloud time series and their significance levels are estimated using Sen’s slope method (Sen 1968) and the Mann–Kendall test (Mann 1945, Kendall 1975) respectively. Sen’s slope trend is calculated as the median of the slope between all data pairs in the time series. The Mann–Kendall test is a non-parametric trend test method. Before calculating the trend, the multi-year averaged seasonal test is a non-parametric trend test method. Therefore only WRDC trends are shown in the maps. From figure 1(a), it is clearly seen that except for the northwest site of Urumqi, almost all East China sites exhibit significant (>90%, P-value < 0.1) increasing trends in global solar irradiance over the past decade. The strongest trends are found over Northeast China (Harbin and Shenyang) and South China (Kunming and Guangzhou), reaching 10 W m⁻²/decade. Trends at XiangHe, Wuhan and Wenzhou are also above 5 W m⁻²/decade. The Shanghai site shows slightly negative but insignificant trends.

For the diffuse radiation (figure 1(b)), the results appear more variable, with sites showing both positive and negative trends. Diffuse radiation is not only affected by the amount of scattering agents, but also by their optical properties such as SSA and phase function. Its changes can be more related to aerosol compositional changes and will be discussed in the next sections.

The trends for each season are also examined and displayed in supplementary figure S4. Overall, the seasonal trends are consistent with annual trends, but some variability can still be seen. For the North China sites (Harbin, Shenyang, XiangHe and Beijing), the largest trends are found during the spring (March, April, May) and summer (June, July, August) seasons, whereas winter (December, January, February) and fall (September, October, November) show weak positive or insignificant trends. For South and central China sites, the seasonal differences are minimal.

2.4. Rapid Radiative Transfer Model (RRTM) model simulation

In order to verify that the changes in surface radiation are associated with changes in aerosol properties, we use the RRTM (Mlawer et al 1997, Clough et al 2005) by Atmospheric and Environmental Research. Only the shortwave component (RRTM_SW) is used. This model calculates shortwave fluxes and heating rates in 14 spectral bands using the correlated k-distribution method and the discrete ordinate radiative transfer integration of the radiative transfer equation (Stamnes et al 1988). The model agrees well with line by line calculations, with 1 W m⁻² accuracy for direct irradiance and 2 W m⁻² for the diffuse. This model has both high efficient and accuracy and has been widely used for aerosol forcing calculations (e.g. Guan et al 2010, Lin et al 2016).

3. Results

3.1. Trends of surface solar irradiance

Maps showing decadal trends of surface global and diffuse solar irradiance are presented in figure 1, and the time series and linear trends for all stations are displayed in supplementary figures S2 and S3. The GEA and WRDC global solar irradiance results are essentially the same (figure not shown) as they come from the same data sources, only with slightly different quality assurance. Therefore only WRDC trends are shown in the maps. From figure 1(a), it is clearly seen that except for the northwest site of Urumqi, almost all East China sites exhibit significant (>90%, P-value < 0.1) increasing trends in global solar irradiance over the past decade. The strongest trends are found over Northeast China (Harbin and Shenyang) and South China (Kunming and Guangzhou), reaching 10 W m⁻²/decade. Trends at XiangHe, Wuhan and Wenzhou are also above 5 W m⁻²/decade. The Shanghai site shows slightly negative but insignificant trends.

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3.2. Trends of clouds and aerosols

Among the various factors influence the solar radiation incident on the Earth’s surface, aerosols and clouds are two important and highly variable components. To help understand the observed radiation trends, we further examine the changes of AOD and cloud amount.

Figure 2 shows the decadal trends of cloud fraction from MODIS (figure 2(a)) and CRU datasets (figure 2(b)). Although there are some regional signals and differences, both datasets indicate insignificant trends over East China where solar radiation appears to have significant changes. Additionally, cloud effective radius and cloud optical depth also show mostly insignificant trends (figure S5). These results indicate that clouds should not be the main reason for the surface solar radiation anomalies over East China.
The trends for aerosols, however, appear different and more promising. The linear decadal trends from both MODIS and MISR AOD are estimated in figures 2(c) and (d). These two instruments have differences in terms of viewing geometry, sampling frequency and retrieving algorithms, which would inevitably result in differences in the magnitudes and the trends. Nonetheless, they consistently indicate a downward trend over most of East China, with stronger decreases over the southern parts. Because aerosols reduce incoming solar radiation, its reduction will then result in an increase of surface solar radiation, which agrees well with the radiation trends observed in the section 3.1. The radiation and AOD trends are most coherent over South China. Over the very northeast region (i.e. Heilongjiang province), the MODIS and MISR trends are inconsistent. This region is typically covered by snow for ~5 months per year, which results in fewer sampling and higher AOD retrieval uncertainty due to the high surface albedo. However, Li et al (2016) indicated a decline of surface extinction there deduced from visibility, which appears consistent with the radiation trends. Moreover, seasonal AOD trends (supplementary figure S6) indicate the strongest negative trends during the spring and summer over North China, and weaker or even positive trends during the fall and winter, both in line with the seasonal solar radiation trends.

3.3. Detailed analysis for the XiangHe site

While surface solar radiation and AOD show largely coherent trends, there is still a need to examine simultaneous radiation and aerosol measurements in order to clarify this effect. Unfortunately, there is only one site—the XiangHe site—where collocated, high temporal resolution radiation and aerosol measurements are available in China. This site has 1 min global, direct and diffuse solar radiation (by BSRN) as well as routine aerosol optical property retrievals (by AERONET). Situated in a suburb of the highly polluted city of Beijing, the aerosol properties at the site were shown to be representative of the North China Plain (Fan et al 2015).

Compared to GEBA and WRDC which only include monthly or daily data, the one-minute BSRN data allows the separation of clear from cloudy skies and the isolation of aerosol effects. For this purpose we follow the procedure introduced by Xia et al (2007). Briefly, the clear sky global surface radiation can be modeled by a power law function of the cosine of the solar zenith angle. Then the observed global surface radiation is compared with the modeled value and cloud conditions are screened using a two-step process: (1) if the absolute relative deviation between observation and model calculation is greater than 20%; (2) if the difference of the running standard deviation during each 30 min period between normalized observation and model is greater than 0.02. Figure 3 shows the surface global irradiance for all sky (figure 3(a)), clear sky (figure 3(b)) and cloudy sky (figure 3(c)). All sky and clear sky irradiances both show significant positive trends, with the clear sky trend being stronger. In contrast, cloudy sky shows a negative trend. This is a clear indication that clear sky trends are the driver of all sky trends and that aerosols are likely the primary factor.

We then match BSRN and AERONET observations to further examine the aerosol effect. Because the effect of aerosols on surface radiation highly depends on the solar zenith angle that varies significantly during the course of a day, it is not fair to average over all collocated observations since AERONET only samples under certain conditions, i.e. the sampling for different sun angles may be different and results in a bias in the averaged result. We therefore respectively calculate the decadal trends for each hour of the day to roughly overcome this sun angle dependency. Although this is not a precise solution, the interannual variability of solar zenith angles during the study period is found to be within 0.08°. Figure 4 shows the trends for global (a), direct (b) and diffuse (c) irradiances for each hour during 8:00 am to 6:00 pm local time. We can see that overall global radiation shows an upward trend for all hours, with an average increase of ~25 W m⁻²/decade. Similarly, direct radiation exhibits a slightly stronger positive trend, with a ~29 W m⁻²/decade increase on average. By contrast, the trends for diffuse radiation are all negative and the average change is only ~6 W m⁻²/decade. This appears somewhat inconsistent with what would be expected if AOD were the only changing quantity, as a decrease of AOD would substantially decrease diffuse radiation. Therefore, we also examine another two parameters, namely SSA and asymmetry parameter, which also affect downward solar radiation (Yang et al 2016a, 2016b). A higher SSA means more radiation can be scattered thus increasing diffuse radiation, and a larger asymmetry parameter indicates more forward scattering which also increases solar radiation reaching the surface. It can be seen (figure 5) that while AOD has been decreasing over the past ten years, SSA has been increasing, whereas no significant trend shows up in the asymmetry parameter. In total AOD decreased by ~0.2 and SSA increased by ~0.02 during 2005–2015. This SSA increase will to some extent compensate for the reduction of diffuse radiation caused by the AOD decrease. We use the RRTM_SW radiative transfer model for a simple calculation of this effect. The model setting and environmental parameters are explained in supplementary section 2, in which the initial AODs and SSAs are taken as the AERONET January and July means of 2005 and the final values are the initial minus the linear trend. Results from tables S2–S5 indicate that decreasing AOD by ~0.2 alone would result in a ~23 W m⁻² (January and July mean) increase of the global irradiation and ~11 W m⁻² decrease of diffuse radiation. However, simultaneously increasing SSA by ~0.02 results in only a ~5 W m⁻² decrease of the diffuse radiation. Although the
Figure 3. Time series and linear trends of all sky (a), clear sky (b) and cloudy sky (c) global solar irradiances at XiangHe. Only statistically significant trends (>90%, $P$-value < 0.1) are shown.

absolute numbers are different from observation due to model assumptions, the results qualitatively explain the weak diffuse reduction. They also suggest that surface solar irradiation is very sensitive to SSA, which is related to aerosol composition (Xia et al. 2016).

4. Conclusions and discussion

In this study, we continue the ongoing surface solar radiation trend analysis beyond 2005 for China, one of the world’s most polluted countries. Different from the previously documented ‘global dimming’ found here, we show that solar radiation actually starts to recover for the most recent decade, especially over the northeast and south parts. Analysis of AOD trends during the same period indicates that reduced aerosol loading is the likely cause for this upward radiation trend. Detailed examination of collocated radiation and aerosol parameter measurements also suggests that surface solar radiation can also be highly sensitive to the SSA parameter, which is related to the composition of aerosols.

The AOD trends found are mostly consistent with Li et al. (2010) and de Foy et al. (2016), who suggest that China’s SO$_2$ and NO$_2$ emissions have been decreasing in the past few years, and with Li et al. (2016) who reported that surface aerosol extinction has decreased over several East China regions using visibility data. These results combined imply that aerosol forcing, together with its associated climate effects such as temperature and precipitation extremes, has likely changed considerably in the past few years in China. Cloud properties may also change due to the semi-direct and indirect effects, although no significant trends are found in total cloud amount. These topics deserve further study using more sophisticated model simulations.

The increase of SSA is also important in that it suggests that absorbing aerosols might have decreased more than scattering aerosols. This is consistent with China’s control of coal burning as a measure to reduce haze pollution (Zhang et al. 2015). Novakov et al. (2003) also projected an increase of SSA based on black carbon and sulfate emission estimates. However, there is still a lack of long-term SSA observation at the majority of the sites, making it difficult to fully assess the compositional change and its associated impact on solar radiation. Considering that diffuse radiation is very sensitive to this parameter, there is an urgent need to monitor SSA globally, by increasing the ground network density or improving satellite algorithms.
Figure 4. AERONET collocated global, direct and diffuse solar irradiances decade trends calculated for each hour at the XiangHe site. Solid dots indicate that the trend is significant above 90% level.

Figure 5. AERONET AOD, SSA and asymmetry parameter time series and trends at XiangHe. AOD is from Level 2 direct beam measurements while SSA and asymmetry parameter are from Level 2 inversion products. Only statistically significant trends (>90%) are shown.
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The BSRN radiation data is available at http://bsrn.awi.de/. GEBa data is available at www.geba.ethz.ch/. WRDC data is available at http://wrdc.mgo.rssi.ru/wrde_en_new.htm. MODIS AOD and cloud fraction data was downloaded from https://ladsweb.modaps.eosdis.nasa.gov/. MISR AOD data was downloaded from https://eosweb.larc.nasa.gov/project/misr/misr_table. AERONET data is available at https://aeronet.gsfc.nasa.gov/. CRU cloud cover data is available at https://crudata.uea.ac.uk/cru/data/hrg/. Maintenance of BSRN and AERONET instruments at XianqinHe by Nan Weidong, Wu Qinghong, Li Wei, Li Rui and Cheng Qun is greatly appreciated. We also thank the Atmospheric & Environmental Research (AER) Radiative Transfer Working Group for providing the RRTM_SW radiative transfer model. This study is funded by the National Natural Science Foundation of China (NSFC Nos. 41575018, 41530423, 41475138), the Young One-thousand Talent Program and the Young Elite Scientists Sponsorship (YESS) Program by CAST (No. 2016QNRC001).

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References

Ackerman S A, Holz R E, Frey R, Eloranta E W, Maddux B C and Mccull M 2008 Cloud detection with MODIS. Part II: validation J. Atmos. Oceanic Tech. 25 1073–86
Che H Z, Shi G Y, Zhang X Y, Arimoto R, Zhao J Q, Xu L, Wang B and Chen Z H 2005 Analysis of 40 years of solar radiation data from China 1961–2000 Geophys. Res. Lett. 32 L06803
Clough S A, Shephard M W, Mlawer E J, Delamere J S, Iacono M J, Cady-Pereira K, Boukabara S and Brown P D 2005 Atmospheric radiative transfer modeling: a summary of the AER codes J. Quant. Spectrosc. Radiat. Transfer 91 233–44
Dubovik O, Smirnov A, Holben B N, King M D, Kaufman Y J, Eck T F and Slutsker I 2000 Accuracy assessments of aerosol optical properties retrieved from aerosol robotic network (AERONET) sun and sky radiance measurements J. Geophys. Res. 105 9791–806
De Foy B, Lu Z and Streets D G 2016 Satellite NO2 retrievals suggest China has exceeded its NO2 reduction goals from the twelfth five-year plan Sci. Rep 6 35912
Eck T F, Holben B N, Reid J S, Dubovik O, Smirnov A, O’Neill N T, Slutsker I, Kinne S 1999 Wavelength dependence of the optical depth of biomass burning, urban, and desert dust aerosols J. Geophys. Res. 104 31333–49
Fan X, Xia X and Chen H 2015 Comparison of column-integrated aerosol optical and physical properties in an urban and suburban site on the North China Plain Adv. Atmos. Sci. 32 477–86
Gilgen H and Ohmura A 1999 The global energy balance archive Bull. Am. Meteorol. 80 831–50
Guo H, Chmida B, Bucholtz A and Bergstrom R 2010 Sensitivity of shortwave radiative flux density, forcing, and heating rate to the aerosol vertical profile J. Geophys. Res. 115 D06209
Harris I P T, J Jones P D, Osborn T J and Lister D H 2014 Updated high-resolution grids of monthly climatic observations—the CRU TS3. 10 dataset Int. J. Climatol. 34 623–42
Holben B N et al 1998 AERONET—a federated instrument network and data archive for aerosol characterization Remote Sens. Environ. 66 1–16
Kahn R A, Garay M J, Nelson D L, Yao K K, Bull M A, Gaitley B J, Martonchik J V and Levy R C 2007 Satellite-derived aerosol optical depth over dark water from MISR and MODIS: comparisons with AERONET and implications for climatological studies J. Geophys. Res. 112 D18205
Kendall M G 1975 Rank Correlation Methods (London: Griffin)
Krotkov N A et al 2016 Aura OMI observations of regional SO2 and NO2 pollution changes from 2005–2015 Atmos. Chem. Phys. 16 6605–29
Levy R C, Mattoo S, Munchak L A, Remer L A, Sayer A M, Patadia F and Hsu N C 2013 The collection 6 MODIS aerosol products over land and ocean Atmos. Meas. Tech. 6 2899–3034
Li C, Zhang Q, Krotkov N A, Streets D G, He K, Tsay S-C and Gleason J F 2010 Recent large reduction in sulfur dioxide emissions from Chinese plants observed by the ozone monitoring instrument Geophys. Res. Lett. 37 L08807
Li J, Carlson B E, Dubovik O and Lains A C 2014 Recent trends in aerosol optical properties derived from AERONET measurements Atmos. Chem. Phys. 14 12271–89
Li J, Li C, Zhao C and Su F 2016 Changes in surface aerosol extinction trends over China during 1980–2013 inferred from quality-controlled visibility data Geophys. Res. Lett. 43 8713–9
Liang F and Xia X A 2005 Long-term trends in solar radiation and the associated climatic factors over China for 1961–2000 Ann. Geophys. 23 2425–32
Lin J et al 2016 Global climate forcing of aerosols embodied in international trade Nat. Geosci. 9 790–4
Mlawer E J, Taubman S J, Brown P D and Clough S A 1997 RRTM, a validated correlated-k model for the longwave J. Geophys. Res. 102 6663–82
Mann H B 1945 Nonparametric tests against trend Econometrica 13 245–59
Martonchik J V, Diner D J, Kahn R A, Ackerman T P, Verstraete M M, Pinty B and Gordon H R 1998 Techniques for the retrieval of aerosol properties over land and ocean using multivariate imaging IEEE Trans. Geosci. Remote Sens. 36 1212–27
Norris J R and Wild M 2007 Trends in aerosol radiative effects over Europe inferred from observed cloud cover, solar dimming, and solar brightening J. Geophys. Res. 112 D08214
Norris J R and Wild M 2009 Trends in aerosol radiative effects over China and Japan inferred from observed cloud cover, solar dimming, and solar brightening J. Geophys. Res. 114 D00115
Novakov T, Ramanathan V, Hansen J E, Kirshstetter T W, Sato M, Sinton I J and Sathaye J A 2003 Large historical changes of fossil-fuel black carbon aerosols Geophys. Res. Lett. 30 1324
Ohmura A et al 1998 Baseline surface radiation network (BSRN/WRCP): new precision radiometry for climate research Bull. Am. Meteorol. Soc. 79 2115–36
Qian Y, Wang W, Leung I R and Kaiser D P 2007 Variability of solar radiation under cloud-free skies in China: the role of aerosols Geophys. Res. Lett. 34 L12804
Ramanathan V C P J, Crutzen P J, Kiehl J T and Rosenfeld D 2001 Aerosols climate the hydrological cycle Science 294 2119–24
Roderick M L and Farquhar G D 2002 The cause of decreased pan evaporation over the past 50 years Science 298 1410–1
Sen P K 1968 Estimates of the regression coefficient based on Kendall’s tau J. Am. Stat. Assoc. 63 1379–89
Shi G, Hayasaka T, Ohmura A, Chen Z, Wang B, Zhao J, Che H and Xu L 2008 Data quality assessment and the long-term trend of ground solar radiation in China J. Appl. Meteorol. Climatol. 47 1096–16
Stamnes K, Tsay S C, Wiscombe W and Jayaweera K 1988 A radiative transfer model for the solar and thermal infrared absorption and emission of aerosols and clouds by scattering and emitting layered media Appl. Opt. 27 2502–9
Tang W J, Yang K, Qin J, Cheng C C K and He J 2011 Solar radiation trend across China in recent decades: a revisit with quality-controlled data Atmos. Chem. Phys. 11 393–406
Wild M, Gilgen H, Roesch A, Ohmura A, Long C N, Dutton E G, Forgan B, Kallis A, Russak V and Tsvetkov A 2005 From dimming to brightening: decadal changes in solar radiation at Earth’s surface Science 308 847–50
Wild M, Ohmura A and Makowski K 2007 Impact of global dimming and brightening on global warming Geophys. Res. Lett. 34 L04702
Wild M, Trüssel B, Ohmura A, Long C N, König-Langlo G, Dutton E G and Tsvetkov A 2009 Global dimming and brightening: an update beyond 2000 J. Geophys. Res. 114 D00D13
Xia X, Li Z, Wang P, Chen H and Cribb M 2007 Estimation of aerosol effects on surface irradiance based on measurements and radiative transfer model simulations in northern China J. Geophys. Res. 112 D22S10
Xia X et al 2016 Ground-based remote sensing of aerosol climatology in China: aerosol optical properties, direct radiative effect and its parameterization Atmos. Environ. 124 243–51
Yang X, Zhao C, Zhou L, Wang Y and Liu X 2016a Distinct impact of different types of aerosols on surface solar radiation in China J. Geophys. Res. Atmos. 121 6459–71
Yang X, Li Z, Liu L, Zhou L, Cribb M and Zhang F 2016b Distinct weekly cycles of thunderstorms and a potential connection with aerosol type in China Geophys. Res. Lett. 43 8760–8
Yue S, Pilon P, Phinney B and Cavadias G 2002 The influence of autocorrelation on the ability to detect trend in hydrological series Hydrol. Process. 16 1807–29
Zhang H, Zhang B and Bi J 2013 More efforts, more benefits: air pollutant control of coal-fired power plants in China Energy 80 1–9