Letter

Cloud ‘shrinking’ and ‘optical thinning’ in the ‘dimming’ period and a subsequent recovery in the ‘brightening’ period over China

Su Yang1, Zijing Zhou*, Yu Yu1 and Martin Wild2

1 National Meteorological Information Centre, China Meteorological Administration, Beijing, People’s Republic of China
2 ETH Zurich, Institute for Atmospheric and Climate Science, Zurich, Switzerland

E-mail: yangsu@cma.gov.cn and martin.wild@env.ethz.ch

Keywords: cloud fraction, cloud radiative effect, aerosol radiative effect, interaction between clouds and aerosols

Abstract

There was a dramatic increase in aerosol loading in China after the 1960s due to rapid industrialization, followed by a gradual reduction due to improvements in air quality since the early 2000s. They are deemed to be the main cause of ‘dimming’ and ‘brightening’ in China, respectively. China, therefore, provides an ideal testbed to investigate the multi-decadal evolution of clouds under a background of large variations in the amount of atmospheric aerosols. We used a unique combination of long-term in-situ observational records combined with a radiative transfer model to investigate the changes in clouds and aerosols over the last 60 years (1958–2018) over China. We found during the dimming period, the clouds over China shrunk in area steadily, gradually thinned in terms of optical depth, and thereby blocked less and less solar radiation. This situation reversed during the brightening period. The clouds over China showed a quick expansion in extent and thickening in terms of optical depth, and accordingly the amounts of solar radiation blocked by clouds recovered rapidly. It is observationally demonstrated that high levels of pollution and the associated amount of aerosols cause a suppression of cloud growth and a reduction of optical depth.

1. Introduction

Clouds are crucial in affecting the water cycle and adjusting the radiation balance of the Earth (Mason 2002, IPCC 2014, Radley et al 2014, Hang and L’Ecuyer 2017, Hartmann and Berry 2017, Yin and Porporato 2017, 2018, Södergren et al 2018, Smith and Myers 2018, Walker et al 2018). Low, thick clouds primarily reflect solar radiation and cool the surface of the Earth. High, thin clouds primarily transmit incoming solar radiation; at the same time, they trap some of the outgoing infrared radiation emitted by the Earth and radiate it back downward, thereby warming the surface of the Earth. Deep convective clouds, on average have neither a warming nor a cooling effect because their greenhouse and albedo forcings, although both large, nearly cancel one another. Clouds also cause the largest uncertainties in estimates and interpretations of the Earth’s climate system due to their high spatiotemporal variability (Nitta 1986, Mace and Benson-Troth 2002, Evan et al 2007, Eastman and Warren 2013, Zhai et al 2015) and the complicated aerosol–cloud interactions in multiple ways because the aerosols could act as cloud condensation nuclei and their presence may modify (determined by the component of aerosols) the clouds’ amount (Norris 2001, Koren et al 2004, Ma et al 2009, Perlwitz and Miller 2010, Quaas et al 2010, Georgouliais et al 2015, Adebiyi and Zuidema 2018), droplets size (Andreae et al 2004, Khain et al 2004, Rosenfeld et al 2008), albedo (Twomey et al 1984, Menon et al 2002, Quaas et al 2004, Fan et al 2013, Wang et al 2018), heights (Andreae et al 2004, Khain et al 2004, Koren et al 2005, Alizadeh-Chooobari and Gharaylou 2017, Liu and Yim 2018) and life time (Jiang et al 2006, Christensen et al 2020). In pristine and sufficiently moist environments, the increasing amount of aerosols meets the requirement of cloud condensation nuclei and favors the formation of clouds(Kaufman et al 2005, Rosenfeld et al 2006, Wild 2012), while the excess amount of particles in polluted environments restricts the size of cloud droplets (Bréon et al 2002, Pandithurai et al 2009, Fan et al 2013) and even heats the clouds, especially in the case of strongly absorbing particles such as black carbon (Ackerman et al 2000, Conant et al 2002).
To know where clouds occur, as well as their characteristics and their response to the variations in aerosols, may well be a central key for a better understanding of the energy balance and climate change. There was a dramatic increase in aerosol loads in China after the 1960s due to rapid industrialization, followed by gradual improvements in air quality since the year 2000 (Norris and Wild 2009, Wild 2009a, 2012, Xia 2010, Yang et al 2012, 2019, Wang and Yang 2014, He et al 2018, Schwarz et al 2020). The remarkable changes in aerosol loads in the atmosphere are supposed to be the main cause of a multi-decadal decrease in solar radiation at the Earth’s surface since the 1960s and a subsequent increase since the 2000s over China, which are known as ‘dimming’ and ‘brightening’ periods, respectively (Wang et al 2009, Wild 2009a, Xia 2010, Tang et al 2011, Yang et al 2012, 2019, Allen et al 2013, Román et al 2014, Sanchez-Lorenzo et al 2015, Wang and Wild 2016). China, therefore, provides an ideal testbed to investigate the multi-decadal evolution of clouds under a background of large variations in the amount of atmospheric aerosols.

In this study, we used a unique combination of long term observational records of surface solar radiation (SSR), cloud fraction (CF), and meteorological visibility measurements combined with a radiative transfer model to investigate the changes in cloud coverage over the last 60 years (1958–2018) and the effects of clouds and aerosols on SSR over China. The data used in this study is described in section 2, and the clear-sky identification, the calculation of the average time series over China as well as the calculations of shortwave radiative effect of clouds, the shortwave cloud extinction efficiency (SWCEE) and the shortwave aerosol radiative effect (SWARE) are also presented in section 3. The results of the effects of clouds and aerosols on SSR over China are shown and discussed in section 4. Finally, the conclusions of this study are presented in section 5.

2. Data

We used homogenized daily SSR data from 99 sites (figure 1) from which any dramatic shifts in the historical records caused by non-climatic causes (e.g. changes in instruments and observation schedules (Tang et al 2010, Hakuba et al 2013, Manara et al 2016, Yang et al 2018)) had been eliminated (Yang et al 2019). The daily SSR data were segregated into clear and all-sky conditions based on CF data available from the same site. A total of 47 of the 99 SSR sites terminated CF observations in 2013 and therefore their CF measurements after 2014 were estimated from nearby sites by the method which has been demonstrated to provide useful results for long-term climate research (Yang et al 2019). The daily visibility, relative humidity, and air temperature data for the period 1958–2018 from the 99 sites were used to retrieve the long-term aerosol optical depth (AOD) over China. Significant inhomogeneity issues in the relative humidity and air temperature data were detected and adjusted by Zhu et al (2015) and Xu et al (2013), respectively. These data were obtained from the China Meteorological Administration (http://data.cma.cn).

3. Methods

3.1. Clear-sky identification and regional average calculation

In this study, the threshold of maximum CF to consider a day as cloud-free is set at 15% which barely reduces the representativeness of clear-sky and provides more samples for this study in comparison with the commonly used level of 10% (Yang
et al 2019). The ideal annual clear-sky series should include each month of the year, but there are fewer clear-sky samples in summer (June–August) than in the other seasons because of the Asian monsoon climate and associated cloudiness (Ding and Chan 2005, Shi and Xu 2006). In order to reduce the impact of the small sample size in the rainy season on the calculation of the annual average values, we first calculated the annual clear-sky indices (CSI, the ratio between the measured SSR and the insolation at the TOA) series based on seasonal series rather than monthly series and then converted the CSI to SSR (Yang et al 2019). The average values over China were the areal average of the gridding values of SSR for each 5°-by-5° grid box. The details of the clear-sky identification and the method of regional average calculation have been introduced by Yang et al (2019).

3.2. The shortwave radiative effect of clouds (SWCRE)

The SWCRE is derived from the difference between the SSR under clear- and all-sky conditions based on homogenized in situ SSR records from 99 sites in China corrected for biases caused by non-climate issues, e.g. changes in instruments and observation schedules (Yang et al 2019). The SSR_{clean-sky} measurements in equation (1) are hardly affected by clouds and are identified by a CF threshold (Qian et al 2007, Manara et al 2016, Yang et al 2019). Details on the justification for the threshold for clear sky conditions can be found in Yang et al (2019). The SSR_{all-sky} measurements in equation (1) represents the measurement of SSR under all-sky conditions.

\[
\text{SWCRE} = \text{SSR}_{\text{clean-sky}} - \text{SSR}_{\text{all-sky}}. \tag{1}
\]

3.3. The shortwave cloud extinction efficiency (SWCEE)

To reveal the radiative/optical characteristics of clouds, the ratio of the SWCRE to the CF seen in equation (2), referred to here as the SWCEE, is calculated. The SWCEE represents the ability of each unit of CF (in terms of percentage fraction of the sky) to block solar radiation reaching the surface and serves as a first-order parameter to quantify the optical characteristics of clouds. It is mainly determined by the optical properties of the clouds and can be considered to be similar to the cloud shortwave optical depth. A high SWCEE signifies a thick cloud in terms of the shortwave optical depth and vice versa.

\[
\text{SWCEE} = \frac{\text{SWCRE}}{\text{CF}}. \tag{2}
\]

3.4. The shortwave aerosol radiative effect (SWARE)

It is not easy to obtain historical information about the evolution of aerosol loadings in China directly. Previous studies have attempted to retrieve the AOD from visibility data (Wang et al 2009, Wu et al 2014, Zhang et al 2020) and have indicated that the aerosol loads in China have been decreasing since the mid-2000s after a continuous increase since the 1960s. Unfortunately, the meteorological visibility observation network in China has gradually been changing its measurement approach from manual observations to nephelometers since 2013, potentially causing inhomogeneities in the retrieved AOD values.

To estimate the aerosol loads covering the whole period of this study (1958–2018), we calculated the SWARE over China derived from equation (3) as the difference between the SSR under clear sky (without clouds) and clean sky (without aerosols and clouds) conditions. SSR under clean sky conditions has been determined using the Simple Model of Atmospheric Radiative Transfer of Sunshine (SMART) (Gueymard 2001). We also calculated the AOD during the period 1958–2018 from the meteorological visibility measurements with the help of SMART (Gueymard 2001). This AOD is treated as a reference to verify the reliability of SWARE in the investigation of the multi-decadal evolution of aerosols in China. Visibility, relative humidity, and surface temperature data and geophysical information are required for the retrieval. Details can be found in the SMART Manual (www.solarconsultingservices.com/smarts.php).

\[
\text{SWARE} = \text{SSR}_{\text{clean-sky}} - \text{SSR}_{\text{clear-sky}}. \tag{3}
\]

4. Results

4.1. Changes in cloud radiative properties and coverage over China from 1958 to 2018

Figure 2(a) shows the area-weighted station-average SWCRE anomaly series over China for the period 1958–2018. The SWCRE shows a long-term gradual decrease of $-1.3 \pm 0.2$ W m$^{-2}$ decade$^{-1}$ before 2000 when dimming occurred, and a subsequent increase of $4.8 \pm 0.9$ W m$^{-2}$ decade$^{-1}$ in the brightening period (after 2000). During the last decade, the SWCRE has almost recovered to its level before the mid-1970s. This reversal of the trend in the SWCRE is more distinct in the nine-points smoothing results.

Changes in CF are thought to be amongst the most important causes of the changes in the SWCRE (Liu et al 2011, Xie et al 2014). Assuming unchanged cloud radiative characteristics (e.g. transmission and reflection in the shortwave), the higher the CF, the lower the probability of insolation reaching the surface. Figure 2(b) shows the area-weighted average CF anomaly series over China for the period 1958–2018 based on CF data from the same sites that also provide the SWCRE. The CF shows almost the same variations as the SWCRE: a slow reduction ($-1.0 \pm 0.1$% decade$^{-1}$) in the dimming period (before 2000) and a rapid enlargement ($4.5 \pm 0.8$% decade$^{-1}$) in the brightening period (after 2000). The correlation coefficient between the time-series of SWCRE and CF reaches 0.92, showing
that the SWCRE varies with the CF. This suggests that changes in cloud coverage play a leading role in the evolution of SWCRE during the last 60 years.

Figure 2(c) shows the area-weighted SWCEE average anomaly series over the 99 observation sites in China, again for the period 1958–2018. A slight transition from a downward trend before 2000 (−0.8 ± 0.2 \(10^{-2}\) W m\(^{-2}\) decade\(^{-1}\)) to a more recent upward trend (1.5 ± 1.0 \(10^{-2}\) W m\(^{-2}\) decade\(^{-1}\)) can be seen, indicating that the cloud optical properties also experienced notable changes in the last 60 years, although less substantial than the variations of CF. The similar transition from a decline in the dimming period to a rise in the brightening period seen in all three parameters SWCEE (figure 2(c)), CF (figure 2(b)) and SWCRE (figure 2(a)) suggests that the shrinkage in cloud coverage has been accompanied with a thinning in terms of optical depth, and this combined effect has caused the decrease in the amount of shortwave solar radiation blocked by
clouds in the dimming period. Conversely, the expansion in cloud coverage along with a thickening in terms of optical depth brought about a recovery of the amount of shortwave solar radiation attenuated by clouds.

Figure 3 shows the geographical distribution of the SWCRE, CF, and SWCEE trends during the dimming (before 2000) and brightening (after 2000) periods. Figures 3(a) and (b) show the apparent transformation from a slow decrease to a rapid increase in the SWCRE over China (apart from the southwest region south of 35° N and west of 105° E), particularly evident in the Tibetan Plateau. All regions of China experienced shrinkage in cloud coverage in the dimming period (figure 3(c)) and an expansion of cloud coverage in the brightening period (figure 3(d)). The clouds to the north of 35° N expanded more rapidly than those south of 35° N (figure 3(d)). The downward trends in the SWCEE (figure 3(e)) are not as remarkable as the ones of the SWCRE and CF in the dimming period. A total of 56.4% and 43.6% of the sites show a slight decrease and increase in the SWCEE, respectively, suggesting that the SWCRE (the numerator) and the CF (the denominator) changes at similar rate. Strong trends and distinct spatial variations in SWCEE emerged after 2000 (figure 3(f)). The eastern region (east of 105° E) showed a remarkable increase in the SWCEE, with 74.5% of the sites showing an upward trend, in particular in the southeast region (south of 35° N and west of 105° E), where the clouds thickened (increasing SWCEE) at 92.0% of the sites. By contrast, 65.4% of the sites in the western region (east of 105° E) showed downward trends in the SWCEE, suggesting that the clouds were still thinning in the western regions of China after 2000. In comparison with CF, the SWCEE shows
a lower spatial coherence in terms of its long-term changes. Local factors, e.g. the terrain, the amounts and types of fuel consumption, or the climate features, seem to have more significant effects on the cloud optical properties than on the cloud coverage. In southwest China covering the Tibetan Plateau, the SWCRE and CF showed downward and upward trends, respectively that differ from other regions where both SWCRE and CF show increasing trends. The special underlying surface and climate characteristics in this region, e.g. water vapor transport (Jain and Kar 2017, Xu et al 2020) are probably the main cause of the diversity.

4.2. Potential role of aerosols in the changes in clouds

Figure 4 shows the area-weighted average anomaly series of aerosols over the 99 observation sites, expressed by the independent estimates of SWARE on the one hand and AOD on the other hand, the latter retrieved by visibility measurements over China for the period 1958–2018 (see section 3). There is a high correspondence between the SWARE and the AOD time-series, with a correlation coefficient of 0.96. Both SWARE and AOD evidence the rapid deterioration in air quality from the 1960s to the early 2000s and a distinct improvement thereafter, in agreement with previous studies (Wang et al 2009, Wu et al 2014, Zhang et al 2020). The SWARE can therefore adequately represent the evolution of aerosols over China in addition to the AOD. The SWARE indicates that the current aerosol load has reduced to the level before about 1980 when China began to open up to the outside world and to expand its economy.

Figure 5 shows how clouds have evolved with changing aerosol loadings over China during the past six decades. Figures 5(a)–(c) display the relationships between the SWCRE and the SWARE, the CF and the SWARE, and the SWCEE and the SWCRE, respectively, in terms of area-weighted annual anomalies over China for the period 1958–2018. The circles represent the annual observational data point and the gray dashed lines are the quadratic fit results. The root mean squared error between the estimated values (gray lines) and the annual mean observational quantities given as circles are 2.3 W m\(^{-2}\) (SWCRE), 1.5\% (CF) and 2.0 \(10^{-2}\) W m\(^{-2}\) (SWCEE), respectively.

In general, there is a transition from a slight upward trend to a rapid downward trend in each panel of figure 5, with a turning point around −2.5 to 2.5 W m\(^{-2}\) in terms of the SWARE. The sustained increase in aerosols before the early 2000s in China (figure 4) substantially reduced the SSR, which is the main source of energy for evaporation and convection, stabilized the atmosphere, and may have reduced the amount of moisture transferred to the upper atmosphere (Teuling et al 2009, Wild 2009a, 2012, Wild and Liepert 2010, Gedney et al 2014). Interestingly, the clouds showed a slight strengthening (positive correlation) of radiative effect, coverage and optical thickness with the increases in SWARE before 1980 (orange circles in figures 5(a)–(c), respectively) rather than a continuing suppression and then turned into a quick decline (green circles in these panels). This denotes that the aerosols not only strengthen but also weaken the growth of clouds with respect to their coverage and optical thickness, depending on the levels of pollution and the associated amounts of aerosols as postulated in a conceptual framework (Wild 2009a, 2012, Yang et al 2012). After a quick increase in aerosol loadings in China for about 20 years’ (1958–1980), the sign of the impact of aerosols on clouds reversed in the following two decades (1980–2005) while the aerosol amounts were continuing to rise. This could be interpreted as a signal of the change from a pristine regime to a polluted regime in China in terms of the
Figure 5. Comparison of the area-weighted average anomaly series over China for the period 1958–2018 between (a) the SWCRE and the SWARE, (b) the CF and the SWARE, and (c) the SWCEE and the SWARE. The orange, green, and blue circles stand for the annual observations in the periods 1958–1980, 1981–2005, and 2006–2018, respectively. The year of each annual mean measurement is labeled in the circle. The gray dashed lines are the quadratic fit results. The reference period for the determination of the anomalies is 1961–1990. The SWCRE, CF, and SWCEE change from a slight increase to a rapid decrease with increasing SWARE, suggesting that aerosols (as expressed by the SWARE) may not only trigger but also suppress cloud growth in terms of cloud coverage and optical thickness, depending on the level of aerosol concentration.
impact of aerosols on clouds (Ackerman et al 2000, Bréon et al 2002, Conant et al 2002, Kaufman et al 2005, Rosenfeld et al 2006, Pandithurai et al 2009, Wild 2012, Fan et al 2013).

In turn, owing to the distinct decrease in aerosol loads in recent decades, the SWARE turned to the level before 1980 (figure 4) indicating the air recovered to more ‘pristine’ conditions and the SSR under clear-sky conditions in China reverted to the level in the 1980s (Yang et al 2019) implying an enhanced flux of moisture to the atmosphere. This may have favored cloud formation and induced a quick recovery in radiative effect, coverage and optical thickness after 2005 (blue cycles in figures 5(a)–(c), respectively).

5. Conclusions

This study provides a view of the changes in cloud coverage and cloud radiative/optical properties in China over the past 60 years and the decadal relationship between clouds and aerosols. During the dimming period (before 2000), the clouds over China shrank in area steadily, gradually thinned in terms of optical depth, and thereby blocked less and less solar radiation. This situation reversed during the brightening period. The clouds over China showed a quick expansion in extent and thickening in terms of optical/radiative depth, and accordingly the amounts of solar radiation blocked by clouds recovered rapidly (seen in figures 2 and 3). It is observationally demonstrated that high levels of pollution and the associated amount of aerosols (seen in figure 4) cause suppression of cloud growth (seen in figures 5(a) and (b)) and a reduction in the optical depth (seen in figure 5(c)).

Theses observation-based, quantitative estimates of the decadal-scale changes in the cloud and aerosol components presented here may also be useful for further analysis and may improve the representation of aerosol–cloud interactions in climate models (Wild 2009b).

China has been developing rapidly for nearly 40 years. The amounts and types of fuels consumed have undergone massive changes (www.stats.gov.cn/tjssj/), leading to changes in the composition of aerosols in addition to an increase in the aerosol load (Pu et al 2017, Tao et al 2017). In a future study, it would be interesting to identify the contribution of aerosol composition to the evolution of clouds and SWARE based on the sulfur dioxide (Hoesly et al 2018) and black carbon (Wang et al 2014) emissions estimated from fuel consumption records and aerosol components retrieved from satellite- and ground-based measurements (Li et al 2019).

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: http://data.cma.cn/.

Acknowledgments

This study was funded by the National Natural Science Foundation of China (Grant No. 41805128), National Key R&D Program of China (2017YFA0603502) and National Natural Science Foundation of China (42090033). Global dimming and brightening research at ETH Zurich is funded by a sequence of Swiss National Science Foundation Grants (Grant Nos. 200021_135395, 200020_159938, 200020_188601) and by funding from the Federal Office of Meteorology and Climatology MeteoSwiss within the framework of GCOS Switzerland. The in-situ data used in this study can be accessed from the China Meteorological Administration at http://data.cma.cn/. We thank all the people who were involved in collecting, processing and storing the data.

ORCID iDs

Su Yang https://orcid.org/0000-0001-5609-7815
Martin Wild https://orcid.org/0000-0002-3619-7568

References

Ackerman A S S, Toon O B B, Stevens D E E, Heymsfield A J J, Ramanathan V and Welton E J J 2000 Reduction of tropical cloudiness by soot Science 288 1042–7

Adébíyi A A and Zuidema P 2018 Low cloud cover sensitivity to biomass-burning aerosols and meteorology over the Southeast Atlantic J. Clim. 31 4329–46

Alizadeh-Choobari O and Gharayrou M 2017 Aerosol impacts on radiative and microphysical properties of clouds and precipitation formation Atmos. Res. 185 53–64

Allen R J, Norris J R and Wild M 2013 Evaluation of multidecadal variability in CMIP5 surface solar radiation and inferred underestimation of aerosol direct effects over Europe, China, India, and Japan J. Geophys. Res. 118 6311–36

Andreae M O, Rosenfeld D, Artaxo P, Costa A A, Frank G P, Longo K M and Silva-Dias M A F 2004 Smoking rain clouds over the Amazon Science 303 1357–42

Bréon F M, Tanné D and Generoso S 2002 Aerosol effect on cloud droplet size monitored from satellite Science 295 834–8

Christensen M W, Jones W K and Stier P 2020 Aerosols enhance cloud lifetime and brightness along the stratus-to-cumulus transition Proc. Natl Acad. Sci. USA 117 17591–8

Conant W C, Nenes A and Seinfeld J H 2002 Black carbon radiative heating effects on cloud microphysics and implications for the aerosol indirect effect. 1. Extended Köhler theory J. Geophys. Res. 107 1–9

Ding Y and Chan J C L 2005 The East Asian summer monsoon: an overview Meteorol. Atmos. Phys. 89 117–42

Eastman R and Warren S G 2013 A 39-year survey of cloud changes from land stations worldwide 1971–2009: long-term trends, relation to aerosols, and expansion of the tropical belt J. Clim. 26 1286–303

Evan A T, Heidinger A K and Vimon D J 2007 Arguments against a physical long-term trend in global ISCCP cloud amounts Geophys. Res. Lett. 34 L04701

Fan J, Leung L R, Rosenfeld D, Chen Q, Li Z, Zhang J and Yan H 2013 Microphysical effects determine macrophysical response for aerosol impacts on deep convective clouds Proc. Natl Acad. Sci. USA 110 E4581
Gedney N, Huntingford C, Weedon G P, Bellouin N, Boucher O and Cox P M 2014 Detection of solar dimming and brightening effects on Northern Hemisphere river flow Nat. Geosci. 7 796–800

Georgoulas A K, Kourtidis K A, Alexandri G, Rapsomanikis S and Sanchez-Lorezo A 2015 Common summertime total cloud cover and aerosol optical depth weekly variabilities over Europe: sign of the aerosol indirect effects! Atmos. Res. 153 59–73

Gueymard C A C A 2001 Parameterized transmittance model for direct beam and circumsolar spectral irradiance Sol. Energy 71 325–46

Hakuba M Z, Sanchez-Lorezo A, Folini D and Wild M 2013 Testing the homogeneity of short-term surface solar radiation series in Europe AIP Conf. Proc. 1531 700

Hang A and L’Ecreux T 2017 Reassessing the effect of cloud type on Earth’s energy balance American Geophysical Union, Fall Meeting 2017, Abstract A4121H-2246 (available at: http://adsabs.harvard.edu/abs/2017AGUFM.A21H2246H)

Hartmann D L and Berry S E 2017 The balanced radiative effect of tropical anvil clouds J. Geophys. Res. 122 5003–20

He Y, Wang K, Zhou C and Wild M 2018 A revisit of global dimming and brightening based on the sunshine duration Geophys. Res. Lett. 45 4281–9

Hoesly R M et al 2018 Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS) Geosci. Model Dev. 11 369–408

IPCC 2014 Climate Change 2013—The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge: Cambridge University Press) (https://doi.org/10.1017/CBO9781107415324)

Jain S and Kar S C 2017 Transport of water vapour over the Tibetan Plateau as inferred from the model simulations J. Atmos. Sol. Terr. Phys. 161 64–75

Jiang H, Xue H, Teller A, Feingold G and Levin Z 2006 Aerosol effects on the lifetime of shallow cumulus Geophys. Res. Lett. 33 1–4

Kaufman Y J, Koren I, Remer L A, Rosenfeld D and Rudich Y 2005 The effect of smoke, dust, and pollution aerosol on shallow cloud development over the Atlantic Ocean Science 302 11207–12

Khain A, Pokrovsky A, Pinský M, Seifert A and Phillips V 2004 Simulation of effects of atmospheric aerosol on deep turbulent convective clouds using a spectral microphysics mixed-phase cumulus cloud model. Part I: model description and possible applications J. Atmos. Sci. 61 2963–82

Koren I, Kaufman Y J, Remer L A and Martins J V 2004 Measurement of the effect of Amazon smoke on inhibition of cloud formation Science 303 1342–5

Koren I, Kaufman Y J, Rosenfeld D, Remer L A and Rudich Y 2005 Aerosol invigoration and restructuring of Atlantic convective clouds Geophys. Res. Lett. 32 1–4

Li L et al 2019 Retrieval of aerosol components directly from satellite and ground-based measurements Atmos. Chem. Phys. 19 13409–43

Liu Y, Wu W, Jensen M P and Toto T 2011 Relationship between cloud radiative forcing, cloud fraction and cloud albedo, and new surface-based approach for determining cloud albedo Atmos. Chem. Phys. 11 7155–70

Liu Z. and Yim S H L 2018 The impact of the aerosol direct radiative forcing on deep convection and air quality in the Pearl River Delta Region 45 4110–8

Ma Y, Gong W, Zhu Z, Zhang L and Li P 2009 Cloud amount and aerosol characteristic research in the atmosphere over Hubei province, China 2009 IEEE Int. Geoscience and Remote Sensing Symp. pp [I–I] 631–4

Mace G G and Benson-Troth S 2002 Cloud-layer overlap characteristics derived from long-term cloud radar data J. Clim. 15 2505–15

Manara V, Brunetti M, Celozzi A, Maugeri M, Sanchez-Lorezo A and Wild M 2016 Detection of dimming/brightening in Italy from homogenized all-sky and clear-sky surface solar radiation records and underlying causes (1959–2013) Atmos. Chem. Phys. 16 11145–61

Mason B J 2002 The role of clouds in the radiative balance of the atmosphere and their effects on climate Contemp. Phys. 43 1–11

Menon S, Del Genio A D, Koch D and Tielioudis G 2002 GCM simulations of the aerosol indirect effect: sensitivity to cloud parameterization and aerosol Burden J. Atmos. Sci. 59 692–713

Nitta T 1986 Long-term variations of cloud amount in the Western Pacific Region J. Meteorol. Soc. Japan 64 373–90

Norris J R 2001 Has Northern Indian Ocean cloud cover changed due to increasing anthropogenic aerosol? Geophys. Res. Lett. 28 3271–4

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 1–13

Pandithurai G, Takamura T, Yamaguchi J, Miyaaki K, Takano T, Ishizaka Y, Dipp S and Shininzu A 2009 Aerosol effect on cloud droplet size as monitored from surface-based remote sensing over East China Sea region Geophys. Res. Lett. 36 1–13

Perlwitz J and Miller R L 2010 Cloud cover increase with increasing aerosol absorptivity: a counterpart to the conventional semidirect aerosol effect J. Geophys. Res. 115 8203

Pu W, Quan W, Ma Z, Shi X, Zhao X, Zhang L, Wang Z and Wang W 2017 Long-term trend of chemical composition of atmospheric precipitation at a regional background station in Northern China Sci. Total Environ. 580 1340–50

Qian Y, Wang W, Leung L R and Kaiser D P 2007 Variability of solar radiation under cloud-free skies in China: the role of aerosols Geophys. Res. Lett. 34 1–5

Quaas J, Boucher O and Béron F-M 2004 Aerosol indirect effects in POLDER satellite data and the Laboratoire de Météorologie Dynamique-Zoom (LMDZ) general circulation model J. Geophys. Res. D 109 D08205

Quaas J, Stevens B, Stier P and Lohmann U 2010 Interpreting the cloud cover—aerosol optical depth relationship found in satellite data using a general circulation model Atmos. Chem. Phys. 10 6129–35

Radley C, Fueglister S, Donner L, Radley C, Fueglister S and Donner L 2014 Cloud and radiative balance changes in response to ENSO in observations and models J. Clim. 27 3100–13

Román R, Bilbao J and de Miguel A 2014 Reconstruction of six decades of daily total solar shortwave irradiation in the Iberian Peninsula using sunshine duration records Atmos. Environ. 99 41–50

Rosenfeld D, Kaufman Y J and Koren I 2006 Switching cloud cover and dynamical regimes from open to closed Benard cells in response to the suppression of precipitation by aerosols Atmos. Chem. Phys. 6 2503–11

Rosenfeld D, Lohmann U, Raga G B, O’Dowd C D, Kulmala M, Fuzzi S, Reissell A and Andreae M O 2008 Aerosol optical depth and aerosol optical depth over China and Japan inferred from observed cloud cover, solar ‘dimming,’ and solar ‘brightening’ J. Geophys. Res. 114 1–13

Sanchez-Lorezo A, Wild M, Brunetti M, Guijarro J A, Hakuba M Z, Calbó J, Mystakidis S and Bartok B 2015 Reassessment and update of long-term trends in downward surface shortwave radiation over Europe (1939–2012) J. Geophys. Res. 120 9535–69

Schwarz M, Folini D, Yang S, Allan R P and Wild M 2020 Changes in atmospheric shortwave absorption as important driver of dimming and brightening Nat. Geosci. 13 110–5

Shi X and Xu X 2006 The spacial characteristics of decadally climatic turnover pattern in winter and summer over China Chin. Sci. Bull. 51 2075–84
Smith M R and Myers S S 2018 Impact of anthropogenic CO2 emissions on global human nutrition Nat. Clim. Change 8 834–9
Södergren A H, McDonald A J and Bodeker G E 2018 An energy balance model exploration of the impacts of interactions between surface albedo, cloud cover and water vapor on polar amplification Clim. Dyn. 51 1639–58
Tang W J, Yang K, Qin J, Cheng C C K 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
Tang W, Yang K, He J and Qin J 2010 Quality control and estimation of global solar radiation in China Sol. Energy 84 466–75
Tao J, Zhang L, Cao J and Zhang R 2017 A review of current knowledge concerning PM2.5 chemical composition, aerosol optical properties and their relationships across China Atmos. Chem. Phys. 17 9485–518
Teuling A J et al 2009 A regional perspective on trends in continental evaporation Geophys. Res. Lett. 36 1–5
Twomey S A, Piepgrass M and Wolfe T L 1984 An assessment of the impact of pollution on global cloud albedo Tellus B 36 356–66
Walker T W N, Kaiser C, Strasser F, Herbold C W, Leblans N I W, Teuling A J, Tsimpidi A, Herold C W, Leblans N I W, Twomey S A, Piepgrass M and Wolfe T L 1984 An assessment of the impact of pollution on global cloud albedo Tellus B 36 356–66
Wang Y and Wild M 2016 A new look at solar dimming and brightening in China Geophys. Res. Lett. 43 11777–85
Wild M 2009a Global dimming and brightening: a review J. Geophys. Res. 114 D00D16
Wild M 2009b How well do IPCC-AR4/CMIP3 climate models simulate global dimming/brightening and twentieth-century daytime and nighttime warming? J. Geophys. Res. 114 1–10
Wild M 2012 Enlightening global dimming and brightening Bull. Am. Meteorol. Soc. 93 27–37
Wild M and Liepert B 2010 The Earth radiation balance as driver of the global hydrological cycle Environ. Res. Lett. 5 025020
Wu J, Luo J, Zhang L, Xia L, Zhao D and Tang J 2014 Improvement of aerosol optical depth retrieval using visibility data in China during the past 50 years J. Geophys. Res. 119 13570–87
Xia X 2010 A closer looking at dimming and brightening in China during 1961–2005 Ann. Geophys. 28 1121–32
Xie Y, Liu Y, Long C N and Qilong M 2014 Retrievals of cloud fraction and cloud albedo from surface-based shortwave radiation measurements: a comparison of 16year measurements J. Geophys. Res. 119 6196–206
Xu K, Zhong L, Ma Y, Zou M and Huang Z 2020 A study on the water vapor transport trend and water vapor source of the Tibetan Plateau Theor. Appl. Climatol. 140 1031–42
Xu W, Li Q, Wang X L, Yang S, Cao L and Feng Y 2013 Homogenization of Chinese daily surface air temperatures and analysis of trends in the extreme temperature indices J. Geophys. Res. 118 9708–20
Yang K, Ding B, Qin J, Tang W, Lu N and Lin C 2012 Can aerosol loading explain the solar dimming over the Tibetan Plateau? Geophys. Res. Lett. 39 L20710
Yang S, Wang X L and Wild M 2018 Homogenization and trend analysis of the 1958–2016 in situ surface solar radiation records in China J. Clim. 31 4529–41
Yang S, Wang X L and Wild M 2019 Causes of dimming and brightening in China inferred from homogenized daily clear-sky and all-sky in situ surface solar radiation records (1958–2016) J. Clim. 32 5901–13
Yin J and Porporato A M 2017 Radiative effects of the diurnal cycle of clouds and their response to climate change American Geophysical Union, Fall Meeting 2017, Abstract #A33C-2366 (available at: http://adsabs.harvard.edu/abs/2017AGUFM.A33C-2366Y)
Yin J and Porporato A 2018 Radiative effects of daily cloud cycle: general methodology and application to cloud fraction (https://doi.org/10.1007/s00382-019-05077-5)
Zhai C, Jiang J H and Su H 2013 Long-term cloud change imprinted in seasonal cloud variation: more evidence of high climate sensitivity Geophys. Res. Lett. 40 10 25203
Zhang S, Wu J, Fan W, Yang Q and Zhao D 2020 Review of aerosol optical depth retrieval using visibility data Earth Sci. Rev. 200 102986
Zhu Y, Cao L, Tang G and Zhou Z 2015 Homogenization of surface relative humidity over China Clim. Change Res. 11 379–86