Reply to Anonymous Referee #2

We appreciate your insightful suggestions. With your constructive comments, this manuscript, especially Section 3.2, will be largely improved. And further consideration will be given on cloud effects.

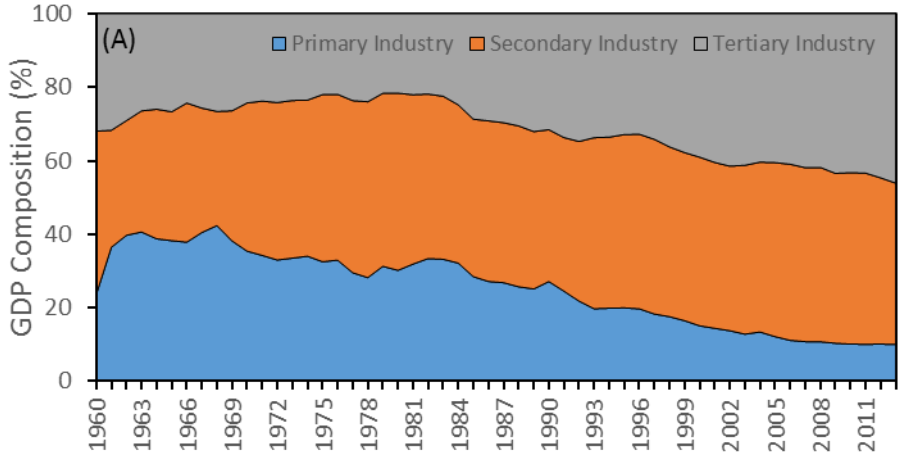
Please find the point-by-point responses to your specific comments in the following context.

Major comments

1. The major finding of this study is that urbanization may play an important role in the dimming period, but not in the brightening period in China. But as suggested by the authors, the urbanization level was low and stable (P6, L5) before 1978, which was accompanied by a significant decreasing trend of sunshine duration. This looks some controversy to the conclusion.

Reply 1: Thanks very much for noticing this issue. The low and stable urbanization level before 1978 might be due to the official calculation method of urban and rural population. In the urban population only the formally registered urban residents were considered, while people who worked in urban areas without a registered urban residence were still counted as rural population. At that time and even now, it is not so easy for the migrant workers to get a registered residence from the cities they work in. This population calculation method was changed from registered to permanent residents during the 1980s. A similar discussion will be added to the 2nd paragraph of Section 3.2, according to your comments. Since the calculation of urbanization level contains such issues, the bold line in Fig. 5 will be deleted, and accordingly Fig. 5 will be combined with Fig. 4 as Fig. 4C.

An increasing urbanization process during the 1960–1978 period can also be inferred from the GDP composition trends shown in the figure reported below. This figure will replace Fig. 6A of the old version and become Fig. 5A in the revised manuscript (since the former Fig. 5 will become the part C of Fig. 4). The secondary sector of the economy increased by 7.6% decade^{-1} during the 1960–1978 period, whereas the primary sector decreased by 3.3% decade^{-1}. This suggests a transfer from primary industry to secondary industry, which is one of the main characteristics of urbanization.



Based on your comments, we will thoroughly modify the second and third paragraph of Section 3.2 as follows:

"In the dimming phase between 1960 and 1989, China experienced a boom in population and industrialization. China's population rapidly increased by an almost linear trend of 166 million persons decade^{-1} (Fig. 4C). The urban population only accounted for a small portion of the total population, and grew slowly during the dimming phase. One possible explanation to this is the calculation method of urban population in China before the 1980s where only the formally registered urban residents were counted in. In this case, people worked in urban areas but without a registered urban residence were still counted as rural population. This standard for calculating population was changed from registered to permanent residents during the 1980s. An increasing urbanization process during the dimming phase can be inferred also from the GDP composition trends (Fig. 5A). The portion of the secondary industry in China's GDP largely increased by 4.2% decade^{-1} during the period of 1960–1989. Meanwhile, the primary sector of the economy decreased by 3.8% decade^{-1}. This suggests a transition from primary industry to secondary industry. The secondary industry, which contributed up to 48% to the total GDP, became the backbone of China's booming economy at this stage. The industrial growth during this pre-reform period was in an extensive way characterized by low efficiency of energy use (Zhang, 2005; Fei et al., 2011). Environmental protection was of seldom concern in this period, and the first law with possible effects on air quality protection was issued only after 1978 in China, which gradually increased to 15 in 1989 (Fig. 5B). This indicates a beginning, even if not so efficient, of pollution control. Therefore, the strongest decline in sunshine duration was observed in this period and a large difference can be noted in urban and rural sunshine duration trends, which declined by 0.20 h d^{-1} decade^{-1} and 0.14 h d^{-1} decade^{-1} respectively for 1960–1989 (Fig. 4A). Meanwhile, urban and rural total cloud cover slightly decreased by 0.41% decade^{-1} and 0.48% decade^{-1} respectively (Fig. 4B), which thus cannot explain the decrease in sunshine duration and the obvious difference in urban and rural dimming."

2. The authors argued that urbanization might not be able to reflect variation of atmospheric environment sine 1990s because regulations were gradually taken into action. This is somewhat speculative and needs some evidence. Satellite aerosol data such as MODIS AOD products during last 16 years may be used to shed light on this issue, otherwise, the speculation is not acceptable.

Reply 2: Thanks very much for this valuable comment. We will add a discussion based on recent satellite aerosol trends in China in the revised version of the manuscript. Based on your major comments 1 and 2, the fourth paragraph of Section 3.2 will be thoroughly modified as follows:

"In the brightening phase between 1990 and 2013, urban population sharply increased by 196 million persons decade^{-1} and its proportion reached 54% in the end, indicating that urban population exceeded rural population in China (Fig. 4C). Besides, the primary industry only accounted for ~ 10% of total GDP in the year 2013, further indicating a more urbanized status. However, the increasing urbanization process did not result in a stronger decrease in sunshine duration but in contrast in a levelling off by –0.01 h d^{-1} decade^{-1} in both rural and urban areas (Fig. 4A). This suggests an insignificant urbanization effect on sunshine duration in the

brightening phase. Meanwhile, the total cloud cover trend in urban and rural areas significantly recovered by 1.23% decade^{-1} and 1.03% decade^{-1} respectively (Fig. 4B), thus not contributing to the slow-down of the declining trend in sunshine duration. However, effective air pollution regulations after 1990 are indicated in Fig. 5B, in that the number of air pollution-related laws and regulations rapidly increased to 135 in the year of 2013. The investment completed in the treatment of environmental pollution in China in 2013 (952 billion yuan) was 9.4 times of that in 2000 (101 billion yuan) (Fig. 5C). A slow-down in the increasing trend of total population to a rate of 92 million persons decade^{-1} was also noted for the period of 1990–2013 when the one-child policy was implementing in China (Fig. 4C). In addition, the tertiary industry, which contributes less to air pollution than the secondary industry, kept growing in China during 1990–2013 and contributed equally as the secondary industry to the national economy in the end (Fig. 5A). The national pollution control efforts may have helped to offset anthropogenic air pollution induced during the urbanization process in the brightening phase, so that the trend of aerosol optical depth (AOD) simulated by the GOCART global chemical transport model started to decrease after 1996 (Streets et al., 2008). Consistently, a decline in $PM_{2.5}$ and PM_{10} concentrations was noted in the 2000s (Lei et al., 2011; Wang et al., 2012a; Wang et al., 2013). However, using TOMS AOD products (1980–2001) along with MODIS/Terra AOD data (2000–2008), Guo et al. (2011) observed a continuous upward trend in average AOD (550 nm) over eight typical regions across China without any transition in 1990. Nevertheless, a significant increment of aerosol single scattering albedo was reported in China, which could result in less absorption and thus more radiation reaching the Earth's surface (Qian et al., 2007). The difference in the trends between PM concentrations and satellite AOD might be explained by the emission-control policies in China, which target primary aerosols (mainly related to PM) but are less strict for secondary aerosol precursors (e.g., NO_x, NMVOC and NH_3, mainly related to AOD) (Lin et al., 2010). In general, in the dimming phase without effective pollution regulations, the emissions generated during the urbanization process were directly changed into equivalent pollutants. On the other hand in the brightening phase, the increasing emissions were compensated by the clean air policies and investments, thus urbanization no longer simply meant an increase in air pollution and its effect on sunshine duration variations became insignificant."

Please note that according to the comments of Dr. Tanaka, the number of laws and regulations in Fig. 5B will be changed. Only those having possible effects on air quality protection will be picked out in the revised version. After this modification, the general trend of the accumulated number of laws and regulations remains similar to the old version.

References:

Guo, J. P., Zhang, X. Y., Wu, Y. R., Zhaxi, Y. Z., Che, H. Z., La, B., Wang, W., and Li, X. W.: Spatio-temporal variation trends of satellite-based aerosol optical depth in China during 1980–2008, Atmospheric Environment, 45, 6802-6811, 10.1016/j.atmosenv.2011.03.068, 2011.
Lin, J., Nielsen, C. P., Zhao, Y., Lei, Y., Liu, Y., and McElroy, M. B.: Recent changes in particulate air pollution over China observed from space and the ground: Effectiveness of emission control, Environ. Sci. Technol., 44, 7771-7776, 10.1021/es101094t, 2010.

Qian, Y., Wang, W., Leung, L. R., and Kaiser, D. P.: Variability of solar radiation under cloud-free skies in China: The role of aerosols, Geophys. Res. Lett., 34, L12804, doi:10.1029/2006gl028800, 2007.
Streets, D. G., Yu, C., Wu, Y., Chin, M., Zhao, Z., Hayasaka, T., and Shi, G.: Aerosol trends over China, 1980–2000, Atmospheric Research, 88, 174-182, 10.1016/j.atmosres.2007.10.016, 2008.

3. The authors used sunshine duration as a proxy data for surface solar radiation. It should be noted that sunshine duration mainly reflect cloud information. It may be argued that long-term variation of cloud cover did not support that of sunshine duration. However, cloud cover can not reflect all effects of cloud on surface solar radiation, furthermore, long-term trend of cloud cover obtained from surface manual observations is not free of large uncertainty. Therefore, it is suggest to exclude cloud effect on surface solar radiation in the analysis, for example, to perform similar analysis based on sunshine duration measurements in the case of cloud cover of 20%.

Reply 3: We appreciate your suggestion and agree with you that cloud effects on sunshine duration variations are not negligible. However, this study mainly focuses on the difference in sunshine duration variations between urban and rural areas. The selected urban-rural pairs are within 1°×1°. Regional cloud effects should therefore not cause the local difference in sunshine duration variations. This is also indicated in Fig. 4B, since urban and rural cloud trends almost coincide.

Since clouds have insignificant effects on the difference between urban and rural sunshine duration variations, it is conceivable that applying this study under clear-sky conditions will lead to the same conclusions. In the dimming phase, after excluding the effect of slightly decreasing total cloud cover, the decline in both urban and rural sunshine duration might be strengthened, which is also mentioned in previous studies under cloud-free skies (Qian et al., 2006, 2007). This may further verify a significant urbanization effect on sunshine duration in the dimming phase. Since the difference in urban and rural total cloud cover trends is very small (only 0.07% decade^{-1}), the ratio of rural to urban dimming might remain the same after excluding cloud effects. In the brightening phase, after excluding the effect of increasing total cloud cover, even an increasing trend in sunshine duration can be expected. This can be inferred from the stronger brightening trend in solar radiation in China estimated under clear-sky conditions (4 W m^{-2} decade^{-1}, Wang et al., 2014) than under all-sky conditions (2.7 W m^{-2} decade^{-1}, Shi et al., 2008). This would indicate an insignificant urbanization effect on sunshine duration variations in the brightening phase, similar with the conclusion made from all-sky conditions.

We agree with the reviewer that visually observed total cloud cover contains large uncertainties due to subjective eye observations and cannot fully represent all cloud effects. We will add this as a limitation at the end of the last paragraph of Section 3.2 as flows:

“The reason for the recent levelling off in the sunshine duration trend in China is still an open question and needs further discussion. Besides cloud cover, which contains uncertainties due to subjective eye observations, the cloud type as well as physical and radiative properties should also be fully considered. Effects from other potential driving factors, such as surface albedo, water vapor and wind speed, need to be clarified”.

Finally, we would like to highlight that sunshine duration records can contain signals of the effects of aerosols, as reviewed by Sanchez-Romero et al. (2014).

References:

Qian, Y., Kaiser, D. P., Leung, L. R., and Xu, M.: More frequent cloud-free sky and less surface solar radiation in China from 1955 to 2000, Geophys. Res. Lett., 33, L01812, doi:10.1029/2005gl024586, 2006.
Qian, Y., Wang, W., Leung, L. R., and Kaiser, D. P.: Variability of solar radiation under cloud-free skies in China: The role of aerosols, Geophys. Res. Lett., 34, L12804, doi:10.1029/2006gl028800, 2007.
Shi, G., Hayasaka, T., Ohmura, A., Chen, Z., Wang, B., Zhao, J., Che, H., and Xu, L.: Data quality assessment and the long-term trend of ground solar radiation in China, Anglais, 47, 1006-1016, 2008.
Sanchez-Romero, A., Sanchez-Lorenzo, A., Calbó, J., González, J. A., and Azorin-Molina, C.: The signal of aerosol-induced changes in sunshine duration records: A review of the evidence, J. Geophys. Res.-Atmos., 119, 2013JD021393, doi:10.1002/2013JD021393, 2014.
Wang, Y., Yang, Y., Zhou, X., Zhao, N., and Zhang, J.: Air pollution is pushing wind speed into a regulator of surface solar irradiance in China, Environmental Research Letters, 9, 054004, 2014.
Wang, Y. W., Yang, Y. H., Han, S. M., Wang, Q. X., and Zhang, J. H.: Sunshine dimming and brightening in Chinese cities (1955-2011) was driven by air pollution rather than clouds, Climate Research, 56, 11-20, doi:10.3354/cr01139, 2013.

4. There are some stations showing long-term trend of sunshine duration quite different from that obtained in the majority of stations (Figure 2), some discussion on this issue is required. This might be related to cloud variation since the general tendency in the urbanization in China should be not quite different.

Reply 4: Good suggestion! We will add a discussion on the exceptional regions after line 7, Page 5 (1st paragraph of Section 3.1) as follows:

"The main regions that deviate from the dimming trend in both urban and rural areas are the Qinghai-Tibetan Plateau and Northeastern China (Fig. 2A and 2B), where water vapor and deep cloud cover were identified as critical regulators (Wang et al., 2011; Yang et al., 2012)."

References:

Wang, C. H., Zhang, Z. F., and Tian, W. S.: Factors affecting the surface radiation trends over China between 1960 and 2000, Atmos. Environ., 45, 2379-2385, doi:10.1016/j.atmosenv.2011.02.028, 2011.
Yang, K., Ding, B., Qin, J., Tang, W., Lu, N., and Lin, C.: Can aerosol loading explain the solar dimming over the Tibetan Plateau?, Geophys. Res. Lett., 39, L20710, doi:10.1029/2012GL053733, 2012.

5. The manuscript should be polished in language.

Reply 5: We will make a great effort to improve the English writing of this paper. The language issues mentioned in your minor comments will be carefully revised.

Minor comments

1. Abstract, this ratio should be defined.

Reply 1: We will add the definition as "The ratio of rural to urban dimming" in line 19, Page 1.

2. Why the urbanization effect on dimming diminished when urbanization level exceeds 50%. I wonder whether there are regions where the urbanization level reached to this level in the eastern China before 1990s.

Reply 2: Sorry for this confusing statement. The urbanization indices of *ULE*, *UP* and *PD* were calculated based on the data for 2013, to reflect the general condition of each province for the past decades for comparisons. We will correct the sentence in lines 19-21, Page 1 as follows:

"The ratio of rural to urban dimming generally increases from a minimum of 0.39 to a maximum of 0.87 with increasing indices of urbanization calculated based on the year of 2013, reaching saturation when the urbanization level exceeds 50%, or the urban population exceeds 20 million persons, or the population density becomes higher than 250 person km^{-2}."

Accordingly, the statement in the Conclusion section on line 1, Page 9 will be modified as:

"The ratio overall changes from the minimum of 0.39 to the maximum of 0.87 under different conditions of urbanization calculated based on the data for 2013."

3. P2, L24, delete due to the nature of their composition.

Reply 3: We will delete it.

4. P2, L35, delete furthermore

Reply 4: We will delete it.

5.P3, L3, since sunshine duration is related to cloudiness, why is it excluded in the analysis

Reply 5: Please refer to the reply to your major comment 3.

6. P3, L10, urbanization also occurs in the rural regions?

Reply 6: We will modify the last paragraph of the Introduction section into:

“This study will then make a first attempt to examine the urbanization effect on sunshine duration variations in China. The wide temporal and spatial coverage of sunshine duration observations in China provides a unique opportunity to fully understand the differences of the dimming and brightening phenomenon between rural and urban areas. The value of urbanization as an indicator of pollution level will be evaluated for the dimming and brightening phases, respectively. In conclusion, the effect of urbanization on sunshine duration variations will be quantified.”

7. P4, L20-25, what’s difference between county and county-level cities

Reply 7: Most county-level cites in China were created during the 1980s-1990s by replacing counties. Compared to counties, county-level cities have less rural population, more developed economy, and better equipped public infrastructure. Counties are mainly governed by prefecture-level divisions, while county-level cities are usually governed by province-level divisions.

8. P4, L3-5, i do not understand why three big cities were excluded in the analysis since they may be use good examples for showing urbanization effect on surface solar radiation. This, certainly, is related to the method, I do not understand why the analysis were performed in each province.

Reply 8: We understand your concern. That was not an easy decision for us to exclude these three municipalities. But unfortunately, there were no available or suitable rural stations nearby to compare with the three municipalities. We applied two standards to choose the urban-rural pairs. The first is depending on the administrative divisions. There was no available rural station with long-term records directly under the jurisdiction of the three municipalities. The second is the location within 1° × 1° and of similar elevation. This second request seemed feasible also for the three municipalities. But in the other cases, the selected rural-urban pairs were in the same province and so were characterized by a similar background of urbanization process and economic development. By contrast, selecting a rural station for the three municipalities requires to find one in their neighboring provinces. Using a rural station in Hebei province (the neighboring province of Beijing, with the urbanization level of 48% in 2013) to compare with the urban station in Beijing (urbanization level of 86% in 2013) is not suitable. Taking into account these limitations, excluding the three municipalities was in our opinion the best choice.

Besides the reasons mentioned above, another reason for performing the analysis on provincial scale is because the official statistics on urbanization in China were based on this administrative unit.

9. P4, L7-8, not understood.

Reply 9: Sorry for the confusing statement. We will correct the sentence as “Records from 19 of the selected stations (~5.5% of total) were completed based upon their collocated stations with similar climatic and administrative conditions.”

10. Annual ULE, PD, USP data?

Reply 10: The reviewer is right. We will replace “urbanization level, population density, and urbanization speed” with “annual *ULE*, *PD*, and *USP*” in the revised version of the manuscript.

11. Why the trends derived in rural and urban stations did not overlap in 14% pairs.

Reply 11: The urbanization impact has two aspects: (1) it describes the general increase in air pollution emissions which leads to a decrease in sunshine duration in both urban and rural areas, and (2) may lead to a difference between rural and urban sunshine duration trends. The difference in 14% of the pairs confirms that there are differences in the trend observed in urban and rural stations without negating the finding of a nationwide dimming.

12. P5, L 16-20, Since sunshine duration remains to decrease slightly in China, it seems not suitable to say brightening.

Reply 12: Based on your suggestion, the 2nd paragraph of Section 3.1 will be modified into:

“Unlike in the dimming phase where the decline in sunshine duration is almost nationwide distributed, China’s sunshine duration trends in the brightening phase depict a more complex spatial pattern. From Fig. 2C and 2D it can be inferred that in the brightening phase, an increase in sunshine duration occurs in about half of China, especially in the regions of southern, northwestern and northeastern China, while dimming continues in the other half, especially in the North China Plain, where haze pollution is being reported (Wang et al., 2014c). This spatial pattern of sunshine duration trends is obtained in both rural and urban areas, suggesting a regional rather than local phenomenon. About 84% of the rural and urban sunshine duration changing rates overlap in the brightening phase (Fig. 3B). Averaged over the whole China, the sunshine duration trend in both urban and rural stations levels off to –0.01 h d^{-1} decade^{-1} for 1990–2013 (Fig. 4A).”

13. P6, L3-5, total cloud cover stabilized or decreased?

Reply 13: Sorry for causing this misunderstanding. We will correct this sentence in the revised manuscript as follows:

“Meanwhile, urban and rural total cloud cover slightly decreased by 0.41% decade^{-1} and 0.48% decade^{-1} respectively (Fig. 4B), which thus cannot explain the decrease in sunshine duration and the obvious difference in urban and rural dimming.”

14. P6, L26-30, it should be cloud cover effect, not cloud effect. I do not agree with this discussion on cloud effect.

Reply 14: Thanks for the correction. Sorry for the limitation of this study, which will be stated in the revised version. We still deem that clouds should not be the main cause of the local difference in sunshine duration trends in China. Please refer to the reply to your major comment 3.

15. P7, L5-10, It seems in the Wang et al. study, rural-urban pairs are discussed in the 5*5 degree grid.

Reply 15: Thank you for raising this point. This information was not mentioned in their paper. Since the number of urban and rural stations in their study were not equal and evenly spread, it's also difficult to make an estimation from their Fig. 1.