Authors response to Anonymous Referee #2

Second review of "Impact of aerosols and clouds on decadal trends in all-sky solar radiation over the Netherlands (1966-2015)," by R. Boers, T, Brandsma, and A. P. Siebesma

General comments:

This paper shows an innovative approach to isolate the sources of dimming and brightening for the Netherlands over a 50-year period. It is of high scientific significance because the trends of dimming then brightening over the period of study are well known global phenomena, but their causes are not universally consonant. Problems in documenting dimming, especially, in the early part of the period of study are hampered by a lack of appropriate data that have been generally available during the recent brightening period. In my opinion, the authors have ably used available sources of data to create credible proxies and correct data appropriately (e.g., cloud fraction over the transition from human observers to ceilometers) to study dimming and brightening over the Netherlands and impressively determined the relative contributions of aerosols and clouds to those phenomena.

We thank the Referee for the comments. Below follow the comments and our answers to them:

The mathematics used is impressive but cumbersome and could be simplified for the reader by including only the final equations in the main text of the paper, with complete descriptions of their components and the details of the derivations placed in an appendix. That is only a suggestion. In addition, more frequent reminders to the reader of the time periods that terms discussed represent would be useful.

Authors response: This point was also brought up by Referee #1. The authors have decided to put the Method sections 2.1, 2.2, 2.3, and 2.4 in an appendix and only write down the end result (including a description of it) of the final equations, namely Eq. (17) and Eq. (21). This is a substantial reduction in the main text which improves the flow of the manuscript.

One major concern is that the primary results presented in Table 2, and summarized in the abstract, are not intuitive and require more explanation. That is, the 50-year trends in clear-sky and cloud-base radiation are both greater than the 50-year trend in all-sky radiation. Intuitively, the former two trends should add to the all-sky trend. However, when examining sub-trends during the periods of dimming and brightening separately, which can be done from the results presented in Table 2, the component trends (i.e, clear- sky and cloud-base) do sum better to the reported all-sky trends for those sub-periods, within the margins of error presented.

Authors response: For the better part of a year the first author shared with Referee #2 the notion that the clear-sky and cloud-base radiation trends should add up to the all-sky trend. This is also what is implicitly stated in many studies on this subject. So we can appreciate Referee #2 's difficulty in understanding the issue at hand. It was only after the third author was able to write down the equations on the separation of clear and cloudy signals that we realized how wrong we were. Intuition is not a good guide in this matter. Perhaps the simplest way to see it is to picture the 'all-sky' as partly 'clear-sky' and partly 'cloudy-sky' . This then must mean that both should be weighted by their sky fraction, and that changing the sky fraction itself should also be of importance in determining the trend. Furthermore, included in the complexity associated with understanding this analysis are the concepts associated with the separation between 'real' data and its 'proxy' counterpart. These points of Referee #2 are quite valid in our opinion and additional statements explained the results should be of assistance in understanding all of these issues, so we included at the end of the discussion of Table 2 on the proxy analysis:

Note that both the trends in all-sky radiation and the trend in all-sky proxy radiation are given in the table. The trend in all-sky radiation is simply inferred from the data whereas the trend in all-sky proxy radiation is computed from Eq. (3). Thus, contrary to common notion the trend in measured all-sky radiation cannot be recovered from the trends in proxy data. It is only the all-sky proxy trend that can be recovered from the clear-sky proxy term and the cloud-base proxy term of Eq. (3) and in addition from the fractional cloudiness term of Eq. (3). Note furthermore that the fractional cloudiness term in Eq. (3) is a scaled version of the trend in fractional cloudiness, whereas the other two are scaled versions of the trend in clear-sky proxy radiation and cloud-base proxy radiation.

Also at the end of the appendix when the trend analysis is explained we included some statements on the counterintuitive aspects of understanding the trends:

The implications of this expression are quite important. Eq. (A22) demonstrates that the trend in all-sky radiation is not a simple summation of trends in clear-sky and cloudy-sky trends, which would perhaps be an intuitive notion when seeking to explain the observed trend in all sky radiation. Eq. (A22) demonstrates that a) the trends in clear-sky and cloud-base radiation need to be weighted by their fractional occurrence in the atmosphere, and that b) there is a third term constituting the trend in fractional cloudiness scaled by the difference in average cloud-base and clear-sky radiation. Furthermore, the additional fourth term, which is shown to be negligible in the current analysis, may not always be small when there are significant cross correlations between the perturbations.

One potential problem I see in your analysis is in your interpretation of eq. 21. As stated on lines 256-257, the over-bars in the equation represent 50-year means and the primed quantities represent <u>yearly</u> deviations from <u>decadal</u> averages. This inconsistency may lead to problems. Another potential problem I see is that the weights applied to the clear-sky term (.32) and the cloud fraction term (.68) represent the fractional periods of clear and cloudy conditions over the entire 50-year period. Since those fractions likely change through the 50-year period, I believe it would be beneficial to analyze eq. 21 over decadal periods, using decadal means, yearly deviations from decadal means, and decadal weights of fractional clear-sky and cloudy periods to compute $S'(y_k)$. Then, the means and deviations used would be internally consistent and the fractional mean periods of clear and cloudy skies would be appropriate to the decade being analyzed.

Authors response: This was an error in the text: it should read: <u>'yearly deviations from an average over 5 decades of the yearly averages'.</u> We regret the confusion caused by this error. Given Referee #2 's interpretation of the erroneous text in the original manuscript the suggestions given are quite logical. However, the two time periods given in the text (1966 – 1984) and (1984 – 2015) are not multiples of a decade which impedes the analysis suggested here (the break point of 1984 would have to be changed). We prefer to leave as is (but of course corrected the error in the text which now appears in the appendix).

Specific comments:

Abstract: As detailed in the general comments, the differences among the three trends listed needs more explanation.

Authors response: Yes, the problem with the abstract is that the aspect of real data versus proxy data were not even addressed, so this point certainly needs to be amplified: We inserted a set of statements in the abstract more fully explaining what we did, which now reads as follows:

A 50-year hourly dataset of global shortwave radiation, cloudiness and visibility over the Netherlands was used to quantify the contribution of aerosols and clouds to the trend in yearly-averaged all-sky radiation (1.81±1.07 Wm^{-2}/decade). Yearly averaged clear-sky and cloud-base radiation data show large year-to-year fluctuations caused by yearly changes in the occurrence of clear and cloudy periods and cannot be used for trend analysis. Therefore, proxy clear-sky and cloud-base radiations were computed. In a proxy analysis hourly radiation data falling within a fractional cloudiness value are fitted by monotonic increasing functions of solar zenith angle and summed over all zenith angles occurring in a single year to produce an average. Stable trends can then be computed from the proxy radiation data A functional expression is derived whereby the trend in (proxy) all-sky radiation is a linear combination of trends in fractional cloudiness, (proxy clear-sky radiation and proxy cloud-base radiation. Trends (per decade) in fractional cloudiness, proxy) clear-sky and (proxy) cloud-base radiation were respectively 0.0097±0.0062, 2.78±0.50 Wm^{-2}, and 3.43±1.17 Wm^{-2}. To add up to the(proxy) all-sky radiation the three trends have weight factors, namely the difference between the mean cloud-base and clear-sky radiation, the clear-sky factor (1-fractional cloudiness) and the fractional cloudiness, respectively. Our analysis clearly demonstrates that all three components contribute significantly to the observed trend in all-sky radiation. Radiative transfer calculations using the aerosol optical thickness derived from visibility observations indicate that Aerosol Radiation Interaction (ARI) is a strong candidate to explain the upward trend in the clear-sky radiation. Aerosol Cloud Interaction (ACI) may have some impact on cloud-base radiation, but it is suggested that decadal changes in cloud thickness and synoptic scale changes in cloud amount also play an important role.

l. 28-30 Brightening in the U.S. from the mid 1990s to ~2011 is attributed primarily to a reduction in cloud cover in Long et al. (2009), Augustine and Dutton (2013), and their results are based on data alone.

Authors response: Long et al is equivocal about it, certainly in comparison to Augustine and Dutton. At this point in the text it is inappropriate to include these references because this paragraph deals with European data. We inserted the references at the end of the next paragraph though where more general comment are made.

Why mention that climate models are not capable of reproducing these trends. Are climate models even capable of resolving the cloud physics necessary to resolve the various cloud types and cloud cover responsible for dimming and brightening? I doubt it.

Authors response: On balance a fair point: The paper hardly discusses models so we remove the reference to Allen.

l. 36-42 Wang et al. (2013) has clearly shown that errors associated with single black detector pyranometer measurements adversely affect trends in solar radiation. In this respect, GEBA data are not of unmistakable quality.

Authors response: we adjusted the sentence to:

GEBA data can be used to good effect because of the fact that many stations have submitted data, but the peculiarities of the radiative signals typical to individual localities are invariably lost in the abundance of data.

l. 73-73 Does your statement that cloud cover data are collected simultaneously with radiation data apply to the Netherlands? That may not be true for most of the radiation stations over the globe.

Authors response: True enough, in that sense the Netherlands may indeed be the exception. The statement was adjusted to:

Also, data on fractional cloudiness needs to be collected simultaneously with radiation data.

l. 105 Define acronyms

Authors response: Done

l. 132-133 How is a representative cosine of the solar zenith angle (SZA) determined for a particular hour? Do you use the cos(SZA) at the midpoint of the hour or do you average the SZAs within the hour period? Averaging SZAs at low sun does not provide a good "representative" SZA for the hour.

Authors response: We use mid-point of the hour which is now stated in the text. [in the appendix]

l. 199 Change "to suggesting that" to "that suggests"

Authors response: Done

l. 220-221 To get proxy data for Scj(yk) I assume that you plot the data corresponding to the variables in eq. 15 in a way analogous to Langley plots, and then use the resulting relationship to generate the proxy data per okta. Correct? If so, I assume that the scatter, and thus uncertainty, of those plots would be small for clear-sky data and larger for oktas 1 through 8. Those uncertainties would define the error in the various terms of eq. 21. Were those uncertainties incorporated into your analysis? They should at least be presented in some form—if possible. If my interpretation of your proxy data generation is wrong, please better explain your method in the paper.

Authors response:

Yes, thank you for bringing this point to the fore. Scattering and thus uncertainty is larger for higher fractional coverage. We include that in the text (see below). The rest of Ref #2's statement is a rather complicated point though, as for the trend analysis we mix uncertainties in the data points with natural atmospheric variability on a multi-year time scale. The M-K test does not separate these; it simply uses the given data to derive trends. So it will be hard to satisfy Ref #2 's comments completely. We experimented with other types of trend analysis than the M-K including one whereby the trend was calculated by randomly imposing errors of a specified value on the data points and recalculating the trends and thus their uncertainties. We got very similar results as our M-K analysis. As the M-K analysis is a standard test of significance used in this type of study we prefer to keep it in (see for example Long et al, 2009). Nevertheless it may be of use to clarify certain parts of the text. Therefore:

We included in the appendix several extra statement explaining the function B and the errors involved:

The parameters α and β are constants determined by fitting the data. The method expressed in Eq (A18) is equivalent to the Langley method of obtained optical thickness with the only difference the weak dependence of B on sun angle. Such dependence is necessary to include because the diffuse radiation arriving at the surface is weakly dependent upon $\mu_{0,}$

And a little lower in the appendix:

Eq (A19) expresses the dependence of atmospheric optical thickness on μ_0. Regression fits using Eq. (A19) carries uncertainties into the parameter B and through Eq. (A18) into parameter G and into Eq. (A20). For clear-sky the scatter is small but for skies under (partly) cloudy skies the scatter is larger. The standard 1-sigma uncertainty associated with the clear sky proxy computed in Eq. (A20) is 2-3%, increasing to 8-9 % for high okta values.

And in the main text

Tests of trends will be performed using the standard Mann-Kendall (M-K) (Kendall, 1975) non-parametric test often used in this type of analysis (see f.e. Long et al., 2009). after the time series was first decorrelated. The uncertainty value attached to the trend is a test of significance indicating the 95% confidence interval of the calculated slope line. The uncertainties in trend are due to two factors, namely those in yearly-averaged values of S_p as a result of uncertainties in fitting constants in Eq. (A19) (see Appendix for details) and due to natural variability of a multi-year or even decadal origin. Thus the stated uncertainty in output trend is a mix of both factors.

l. 249 This sentence needs to be reworded.

Authors response: 'Is' was changed into 'it' which clarifies it!

l. 270 The 4th term is shown.

Authors response: Point was also noted by Referee #1. It was remnant of a previous version of this manuscript. It is now corrected.

l. 321 "is" should be changed to "in"

Authors response: Yes, done

l. 355 Since you are discussing aerosol optical depth and cloud optical depth in the same sentence, references to each should be specific. In this case, insert "cloud" in front of "optical depth" on this line.

Authors response: Yes, done

l. 366-368 By “cloud fractional coverage at specific cloud cover,” do you mean the transformation of okta observations to fractional cloud cover? If so, please state this more clearly.

Authors response: An imprecise statement on our part. We corrected:

In our analysis, cloud fraction is obtained in a straightforward manner by counting the hourly cloud data so that the hypothesis that changes in aerosol results in changes in cloud cover can be tested.

l. 414 The sentence beginning with “The SNHT was applied …” is difficult to understand. What do you mean by “reduced with?” and how does that apply to the a) and b) permutations?

Authors response: Yes, we agree, it was unclear and we changed it:

In the first test each station series was subtracted by the mean of the four other station time series. In the second test each station series was subtracted by the other four station time series separately.

l. 516 What is ERA?

Authors response: An acronym in an acronym, not common but unfortunately not unheard of either in the atmospheric sciences! We expanded it:

the European Centre for Medium Range Weather Forecast’s Re-Analysis project, ERA

l. 537 “b)” should be changed to “2)”

Authors response: Done

l. 555 The sentence beginning with “Cloud amount is increasing…” is counterintuitive. It would benefit by inserting “in solar radiation at the surface” after “overall trend.”

Authors response: Done

l. 560 The large tick marks represent 10 Wm^{-2}.

Authors response: Done