Response to comments from Reviewer 2:

We thank the reviewer for the useful comments, analyses and proposed corrections. We humbly apologize for the inconvenience caused by repeated delays in our response since the publication of reviews.

General comments:

The explicit strength of the “original” Heliosat approach (referred to as Heliosat-o in this review) is that the retrieved cloud index (“cloud transmission”) is completely based on observations. No simulations or external data are needed to retrieve the cloud index (cloud transmission) but the observed radiances are used. This includes the retrieval of Xmin (“clear sky reflection”) & Xmax (“calibration”). Heliosat-o and the resulting radiation data are well validated and established (e.g CM SAF, ISE, University of Oldenburg and Bergen, Satellight….) and already close to the accuracy of well maintained ground based stations. Of course, there are some limitations linked with the Xmin retrieval, as listed by the authors (L85). However, some of the mentioned handicaps are already partly resolved (e.g. shadow correction method by University of Oldenburg) or on average of relative small effect (e.g. long lasting clouds occur usually in the North-West during wintertime. This means high COD and low SZA. Hence, low solar irradiance and thus low absolute errors induced by uncertainties in Xmin). In my opinion there is a high likelihood that the simulation of Xmin adds more handicaps and uncertainties than it resolves. Thus, the central question is: Is there an overall benefit, concerning accuracy and precision, if the observational-based Xmin retrieval is replaced by simulations. Why should the simulations lead on average to more accurate results than using observations ? The authors mention “Simulations consider the anisotropy of the reflectances caused by both surface and atmosphere, and are adapted to the spectral sensitivity of the sensor. The anisotropy of ground reflectances is described by a bidirectional reflectance distribution function model and external satellite-derived data”. Simulations might consider it, but to my experience they induce also additional uncertainties, e.g. the uncertainty induced by using 3rd party surface albedo data can easily lead to a bias of several per cent. Further, as for RMIN, clear sky situations are needed to retrieve the surface albedo, thus concerning long lasting clouds the same handicap is shared. The needed BRDF (ADM) functions induce further uncertainties and add complexity. A more complex method providing overall a lower accuracy would be of no significant value. The effect of SAL (surface albedo) and BRDF is already considered by observational-based Xmin for the same sensor and viewing geometry, no need for simulation.

We appreciate your complementary views on Heliosat methods. We agree on the strength (especially the simplicity) of a self-calibrated method like Heliosat-o to produce climate data records like SARAH over several generations of satellite sensors, especially for past sensors like Meteosat First Generation/MVIRI.

To answer the central question “Is there an overall benefit, concerning accuracy and precision, if the observational-based Xmin retrieval is replaced by simulations?”, the method already shows a precision similar to operational products. But developing this new method aims also at investigating on the origin of cloud index uncertainties. Using simulations of TOA reflectances integrating surface, clear atmosphere, and cloud properties provides flexibility for future improvements and sensitivity analyses. We also consider that the development of an alternative method to compute the cloud index with different assumptions is useful to assess, for example, the robustness of DSSI time variations within multi-model comparison exercises.

This work is exploratory, and our publication comes as a first version showing encouraging results. Several significant sources of errors are identified (source of calibration gains, spectral interpolation of MODIS BRDF data, cloud properties used in the ρ_{ovc} Look-Up Table, angular description of the LUT). These errors will be further considered in future works (including on-going works), and their treatment is likely to improve results. Please also note that, as the paper focuses on the computation of the cloud index, the clear-sky index/cloud-index relationship is not investigated, and may also improve the quality of future results.

Concerning surface BRDF, products like MODIS MCD43C1 are useful to consider surface anisotropic reflection and reproduce TOA reflectances in clear-sky conditions. It provides a spectral description that allow us to apply the same method to a wide range of satellite sensors and channels, and a global coverage so we can apply the method to satellites on different orbits with the same inputs. We agree that using external sources of data to describe the surface BRDF introduces sources of errors, linked to data product quality (here MODIS MCD43C1), the BRDF model (RossThick-LiSparse) and their integration into our radiative transfer simulations. Despite all these sources of errors, we observe that our simulations are sufficiently close to clear-sky observations to ensure a good quality of surface irradiance estimates.

Concerning the long-lasting clouds situations, MODIS MCD43 is based on TOA reflectance measurements that passed a detailed cloud masking procedure involving about 22 spectral channels from visible to thermal infrared (Ackerman et al., 2010) and an atmospheric correction. In case of long-lasting clouds, the product relies on back-up information to provide information on BRDF. This is information may be of lower quality, but without cloud contamination.

Concerning the use of radiative transfer simulations to compute the cloud index and as previously discussed, modeling clear-sky and overcast reflectances with knowledge on surface, clear-sky atmosphere and clouds is a way to identify and quantify sources of errors in cloud-index methods. An example of potential interest is for overcast conditions: Heliosat-2 considers it as only depending on solar zenith angle (Rigollier et al., 2004). For heliosat-o as described in Mueller et al. 2012 & 2015, the X_{max} value corresponds to a percentile on an archive of measurements for a given region and does not appear to depend on the sun-satellite geometry. This is mentioned in SARAH-2's ATBD as a potential source of error. A method like ours could be used to assess the uncertainty caused by the assumption of a Lambertian cloud. Another example is that methods using the cloud-index approach have difficulties to isolate the irradiance attenuation due to aerosols: aerosols loads generally increase the top-of-atmosphere reflectance and thus can be erroneously detected as clouds in the cloud-index computation. In the meantime, they lead to decrease the modeled clear-sky surface irradiance, having aerosol information in input (Mueller et al. (2015)). In Heliosat-V scheme, the variability of aerosols is used both in simulation of clear-sky TOA reflectance and in the clear-sky surface irradiance model e.g. McClear. It should limit this source of error, even if we still have to explore it.

Major concerns:

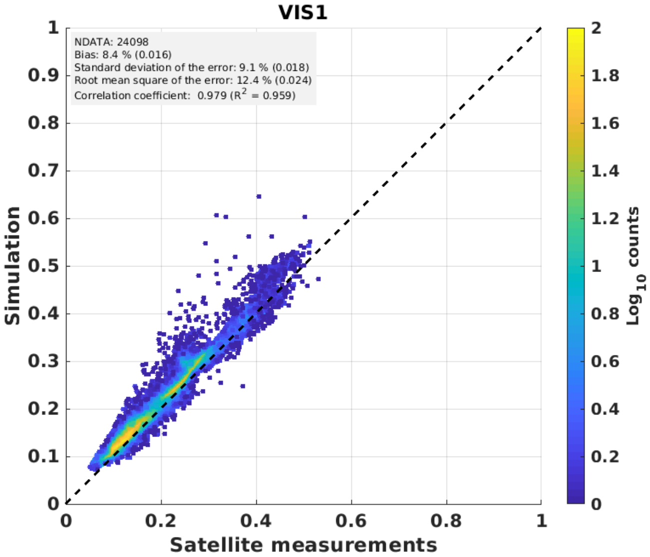
In my opinion the authors fail to show the advantage of combining the Heliosat relation (equation) with simulations of the radiances in order to get Xmin ("clear sky reflection”). If radiances (reflectances) are simulated than why not simply using one of the several RTM based LUT approaches or ECMWF. By the way, using BRDFs simulations to estimate radiances observed by satellite is already applied since decades in RTM based LUT approaches, thus this Is not a new idea. Where is the benefit to use the Heliosat relation (equation 1) when the special strength of Heliosat is disminished by using simulations ? These questions are not appropriately addressed in the manuscript. The authors mention that a motivation for the approach is the use of polar orbiting satellites, but again what is the advantage compared to RTM based LUT approaches (using COD&reff or TOA Albedo).

The interest for a cloud-index method using radiative transfer simulations is addressed above, and we will add more discussion to address this point. To summarize, we consider that this method is also of interest to explore possibilities, being different from previous cloud-index methods and full RTM based LUT approaches, and flexible for sensitivity analyses. Heliosat-o is very useful as a full measurement approach, but we consider also of interest exploring a new cloud-index method able to improve e.g., the description of aerosols and of cloud anisotropy, and even to be applied to non-geostationary sensors.

The introduction has been reorganized and completed to address these concerns.

In summary, a more thorough discussion and description of the pros and cons of the presented method compared to established methods should be added (Heliosat-o and RTM LUT approaches). Uncertainties of BRDF and SAL should be discussed, more information on SAL source should be added.

We add a figure in appendix showing improved results comparing clear-sky measurements of reflectance and simulations made using only the BRDF with the best quality (figure reproduced below)



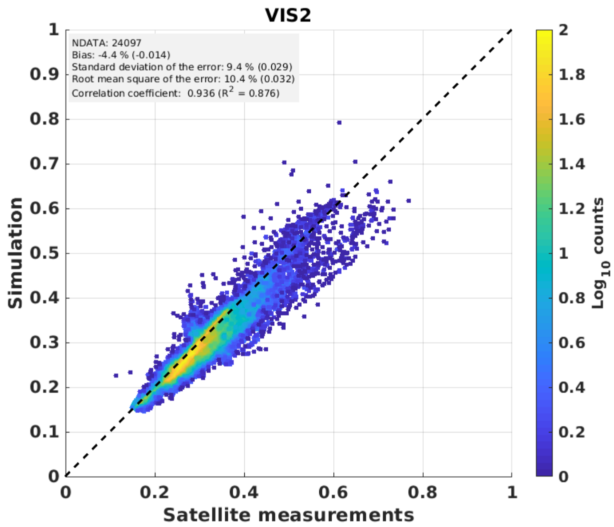


Figure B2. Simulation of clear-sky reflectances at the top of the atmosphere (ρ_{clear}) for MSG 0.6 μm (left panel) and 0.8 μm (right panel) spectral channels compared with actual satellite measurements. The comparison is done for all 11 locations, for the year 2011. Only instants with BRDF data of best quality are used (quality flag 0 of MCD43C1, "Best quality, 100% with full inversion")

Also the solar zenith angle dependency of SAL in relation to BRDF should be discussed in more detail.

We add the following description in the Results section: “On Figure 8, we compare ρ_{clear} values with the surface reflectance $\rho_{surface}$, computed with the RossThick-LiSparse model applied to BRDF parameters derived from MODIS 646 nm channel, and using viewing and solar geometries considered. Firstly, we see that ρ_{clear} values are significantly higher than $\rho_{surface}$ with a different diurnal pattern. This shows the importance of considering the atmosphere anisotropic reflectance to reproduce TOA reflectances. We also can see the contribution from the surface anisotropy in the ρ_{clear} simulations. This appears in particular close to the backscattering direction where surface reflectance is enhanced: around noon in Camborne and the morning in São Martinho da Serra.” This comes with the following figure:

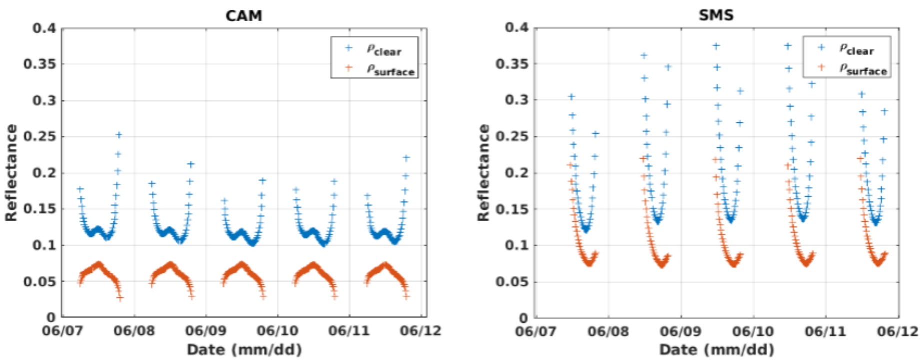


Figure 8. Comparison between simulations of clear-sky reflectances at the top of the atmosphere for MSG 0.6 μm channel (ρ_{clear}, blue plus signs) and corresponding surface reflectances computed with the RossThick-LiSparse model applied to MODIS MCD43C1v6 BRDF parameters for the channel 646 nm ($\rho_{surface}$, red plus signs) for five days in June 2011. Left panel: Camborne station (CAM) ; right panel: São Martinho da Serra station (SMS).

Further, the potential improvements should be proven and discussed thoroughly by comparison with established high quality data sets, which are using the original observational-based Heliosat-o approach and with other data sets from external sources, e.g. ECMWF. Please note, comparison with Helioclim might be not a real benchmark for improvements, see e.g. Posselt et al, Remote Sensing of Environment Vol 118, 2012, pp, 186–198.

We use data from HelioClim3 and CAMS-RAD for comparisons. Posselt 2012 consider HelioClim1 which is no longer produced. The quality of HelioClim3 is similar to other operational products (e.g. Ineichen 2015 for intercomparisons of satellite-based DSSI products). CAMS-RAD is an open database of DSSI operationally provided in CAMS and all validation data used in this article will be provided as supplementary information to the article.

Respective open data sets are available for inter-comparison. Concerning polar orbiting satellites, results should be compared to the ECWMF radiation data set.

The investigation on non-geostationary sensors is on-going and will be treated in a future paper. ERA5 hourly values of DSSI are part of the data used for this extended validation.

I think that simulations of Rmin has been already used for the so called “Heliosat-2” version. Thus, the novel aspects of the approach should be reflected in more detail relative to “Heliosat-2” as well.

Heliosat-2 approach is almost fully measurement based. It applies an atmospheric correction to estimate X_{min} from an archive of imagery. For Xmax, it is an empirical model based on Nimbus-7 ERB observations. The Heliosat-V approach is therefore not so similar to Heliosat-2.

By the way, calling a method with Rmin simulation still Heliosat is quite confusing. Rmin simulation breaks with the basic idea of Heliosat, thus using the name Helioat should be avoided in order to avoid misleading interpretations.

The Heliosat name only refers to the use of satellite data to estimate solar irradiance and to its link to Mines ParisTech, which has been involved in all Heliosat projects since 1980s. The Heliosat-4 method, used to produce the CAMS Radiation Service and McClear products, is based on radiative transfer simulations, information about aerosol, water vapor and ozone from CAMS and satellite-based products of cloud physical properties.

Overall the discussion should be modified to be more balanced and reflected , lessons learnt in other projects and communities should be considered.

We modify and complete the discussions. To facilitate the reading, the content of the discussion section is integrated to the “Results” different subsections dedicated to simulated and measured reflectances and to comparison of GHI estimates with external datasets.

Specific comments.

- Please change the title, improved is not prooven, see general comments.

  We modify the title for “An alternative cloud index for estimating downwelling surface solar irradiance from various satellite imagers in the framework of a Heliosat-V method”

- 70 „raw satellite numerical counts (Pfeifroth et al., 2017; Perez et al., 2002)“;

Here and throughout oft he manuscript. Misleading citations. Raw satellite counts has been used already decades before within the Heliosat community. Please modify accordingly. In general ATBD, PUMs are grey literature. Please check the citations and replace them with peer reviewed articles where possible.

  We change the reference Pfeifroth et al. 2017 for Müller et al. 2015, and add the reference Cano et al. 1986.

- 80 “In this paper, we aim at finding an alternative to the need for archives of satellite imagery.”

  We complete this sentence with previously mentioned arguments:

This is misleading, as long as radiances are needed using actual and/or 30 day is not a serious problem and not worth mentioning.

- 140 “Kc = 1−n introduced by Darnell et al. (1988)”

I think it is a well known and established that a modification for higher n is needed and respective modifications are published, please refer them.

  The paragraph has been slightly modified to consider the comment. We do not use one of those modification because they are generally based on observed non-linearity between clear-sky index and cloud index that may be partly caused to the treatment of X_{max} in these methods. The new method partly resolved some of them, notably by considering the anisotropy of overcast reflectances with LUT.

- 190 “Cloud-index methods in the literature use various ways to estimate the TOA reflectances in overcast conditions (Perez et al., 2002; Lefèvre et al., 2007; Pfeifroth et al., 2017).”

Pfeifroth et al. 2017, again misleading citation. Please refer to the original peer-reviewed publications . In general ATBD, PUMs are grey literature. Please check the citations and replace them with peer reviewed articles where possible.

We replace Pfeifroth et al. (2017) by Mueller et al. (2015)

- 65 Xmin is ued later on rho_clear please unify.

In equation (1), we use X for the variables, because depending on the study, the cloud index can be computed from TOA reflectances, albedos, raw numerical counts, bottom-of-atmosphere reflectances/albedos. We keep the rho notation for reflectances. We add around line 65 “We name these variables X as they can be of slightly different nature from one work to another (reflectance, albedo, radiance, digital count, etc.).”

Citation: https://doi.org/10.5194/amt-2020-480-RC2

Ackerman et al. 2010, DISCRIMINATING CLEAR-SKY FROM CLOUD WITH MODIS ALGORITHM THEORETICAL BASIS DOCUMENT (MOD35)

Ineichen, Pierre & Office fédéral de l’énergie OFEN, 2015 : Solar Resource Assessment and Forecasting, IEA SHC Task 46