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# Representativeness errors of point-scale ground-based solar radiation measurements in the validation of remote sensing products

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ABSTRACT

We usually use ground-based solar radiation measurements to validate satellite-derived solar radiation products from kilometer to grid scales. Questions such as, how large is the representativeness error of surface measurements in the validation and how much of the product-measurement difference can be attributed to their inherent differing spatial scales, cast doubts on the suitability of this direct validation approach. In this paper, we will investigate and quantify the representativeness errors of point-scale ground-based measurements using the surface flux-observation matrix from HiWATER (Li et al., 2013) and the solar radiation data retrieved from geostationary meteorological satellite (Huang, Li, Ma, & Li, 2016). The current study demonstrates that wildly fluctuating representativeness errors exist which are strongly contingent on the time and space scales of remote sensing products, as well as instant atmospheric conditions. For example, for an area of $5 \times 5$ km$^2$ 1.4~8.1% of representativeness errors are found from monthly to "instantaneous" timescales; while for an area of $1° \times 1°$ grid 3.1~8.1% of representativeness errors are seen. Such scale-dependent representativeness errors offer some implications for validations of remote sensing products. On timescales longer than or equal to one day, representativeness errors do not need to be considered for validations of kilometer-level products, but on shorter timescales representativeness errors will affect the validation results to some extent. For instantaneous products with 5 km resolution, our study indicates over 13% of errors can be attributed to the inherent representativeness error, and 30-minute surface measurements are recommended for a routine validation. However, for validations of grid-level products, representativeness errors basically cannot be neglected regardless of timescales. The errors caused by the poor representativeness of surface sites, likely significantly contribute to the large differences between measurements and products.



## 1. Introduction

Monitoring surface radiation budget by remote sensing technique is a very important use of satellite data. Especially for surface solar radiation (SSR), the earliest studies can date back to the 60s of the last century (Fritz, Rao, & Weinstein, 1964). Besides large and continuous spatio-temporal coverage, another main advantage of the satellite remote sensing technique over other approaches (e.g., discrete surface observation or reanalysis modelled products) is that it can accurately capture the spatial distributions and dynamic changes of cloud, which is regarded as a superior modulator of SSR (Forman & Margulis, 2009). Up to now, over decades of rapid development, estimation of SSR based on satellite remote sensing technique has become increasingly mature, and many products have already been produced (Liang, Wang, Zhang, & Wild, 2010; Pinker & Laszlo, 1992; Pinker et al., 2003; Posselt, Mueller, Stockli, & Trentmann, 2012; Zhang, Liang, Zhou, Wu, & Zhao, 2014; Zhang, Rossow, Lacis, Oinas, & Mishchenko, 2004).

Approximately, these products can be separated into two classes: 1) kilometer-level or pixel-level products such as the SSR data (Posselt et al., 2012) from European Satellite Application Facility on Climate Monitoring (CM SAF) and the downward surface shortwave radiation data (Huang et al., 2013; Zhang et al., 2014) from Global Land Surface Satellite (GLASS); 2) grid-level products (it should be noted that "grid" in the paper exclusively refers to larger geographic latitude-longitude grids that are generally ≥0.25°) such as the surface radiation budget data (Pinker & Laszlo, 1992) of Global Energy and Water Cycle Experiment (GEWEX) and the flux data (Zhang et al., 2004) of International Satellite Cloud Climatology Project (ISCCP). The kilometer-level products are typically derived from satellite top-of-atmosphere (TOA) radiance or reflectance directly, and primary high spatial resolution is

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preserved; whereas the grid-level products are usually calculated either using coarse satellite and reanalysis atmospheric data as the model inputs or through simply averaging higher spatial resolution products, and mainly used for the studies of global water cycle and climate change.

In general, the validation of products, whether at the kilometer-level or grid-level, is conducted via a direct comparison of collocated estimates from products with ground-based SSR measurements (Huang et al., 2013; Sanchez-Lorenzo, Wild, & Trentmann, 2013; Yang, Koike, Stackhouse, Mikovitz, & Cox, 2006; Yang et al., 2008). However, the spatial nature of satellite remote sensing products and that of ground-based measurements are totally different. Essentially, what kilometer-level or pixel-level products provide are the areal retrieved values over the footprints of satellite pixels; what grid-level products give are the means within latitude-longitude grids; whereas ground-based measurements are point-specific. They are three distinct spatial samplings on surface radiation fields and embody the space attributes of kilometer-scale, grid-scale, and point-scale, respectively. Such scale diversity poses the following question: how well do surface point measurements represent the larger scale surrounding means characterized by satellite remote sensing products? If the error originating from their unique spatial sampling scales is defined as representativeness error (Li, 2014), how large is it in the routine validation of remote sensing products?

To our knowledge, an in-depth and comprehensive study on this issue has not been performed to this date. Sporadic, related researches mainly focus on discussions of sampling errors between the kilometer-scale and the grid-scale spaces. For example, Li, Cribb, and Chang (2005) used SSR retrieved from Geostationary Operational Environmental Satellite (GOES) to mimic ground measurements and quantify the sampling errors within grid-level surroundings; Hakuba, Folini, Sanchez-Lorenzo, and Wild (2013) calculated the representativeness errors with respect to the standard 1° grid on climatological mean conditions in Europe with the help of the SSR from CM SAF. Therefore, it is necessary to thoroughly investigate and quantify the representativeness errors from the point-scale to the kilometer-scale, to the grid-scale.

A surface flux-observation matrix from the Multi-Scale Observation Experiment on Evapotranspiration over heterogeneous land surface of Heihe Watershed Allied Telemetry Experimental Research (HiWATER-MUSOEXE) provided an opportunity for us to study and address this issue (Li et al., 2013). HiWATER is a comprehensive ecohydrological experiment within the framework of the Heihe Plan, which was launched by the National Natural Science Foundation of China (NSFC) in 2010. MUSOEXE is the first thematic experiment launched by HiWATER, and the flux-observation matrix in the middle reach of the Heihe river basin is the major content of MUSOEXE. Although this observation matrix was initially designed to monitor the spatio-temporal variation of evapotranspiration, dense multi-point radiation measurements can also be used to derive representativeness errors of point-scale measurements with respect to their kilometer-level surroundings. Similarly, sampling errors from kilometer to grid scales can be obtained by means of high resolution SSR satellite products (Hakuba et al., 2013; Li et al., 2005). Furthermore, based on the above two types of errors, representativeness errors of point-scale measurements within grid-level domains can be quantified. By analyzing representativeness errors of point-scale ground-based SSR measurements with respect to different levels of areas (kilometer-level or grid-level), implications for the routine validation of remote sensing products are drawn and presented finally.

## 2. Data

### 2.1. Ground-based observations

As mentioned earlier, surface observation data in this study are only provided by the surface flux-observation matrix from HiWATER-MUSOEXE (Li et al., 2013). This observation matrix includes 17 sets of eddy covariance (EC) system and automatic meteorological station and 4 pairs of large aperture scintillometer (LAS) systems, and covers approximately $5 \times 5$ km$^2$ spatial area located in the midstream area of Heihe river basin, northwest China. The experiment was carried out from June to September 2012, and its purpose was to capture the variability of evapotranspiration over heterogeneous land surfaces (Liu et al., 2011).

Solar radiation in HiWATER-MUSOEXE was observed with routine meteorological parameters. The detailed distribution of meteorological sites equipped with radiometers is presented in Fig. 1. In a ~$5 \times 5$ km$^2$ spatial area, 17 radiometers were installed and formed a dense radiation observation matrix. Most of them were CNR1 and CNR4 manufactured by Kipp & Zonen (Netherlands) except Sites 3, 15 and 16 (see Table 1 for details). At Sites 3 and 15 NR01 radiometer (Hukseflux, Netherlands) and PSP/PIR radiometer (Eppley, U.S.) were equipped respectively, and at Site 16 the instrument is Q7 produced by REBS (U.S.). Because only net radiation was output by Q7 radiometer, Site 16 was excluded. Among these radiometers, the pyranometer of PSP/PIR belongs to the 1st class of the World Meteorological Organization (WMO) classification, and the others can only be qualified as the 2nd class of WMO classification. In order to identify and reduce the calibration error among instruments, an instrumental intercomparison test was conducted over the Gobi desert between May 16 and 22, 2012 (Xu et al., 2013) before the matrix experiment. This test indicates some pyranometers have relatively significant calibration error up to ~3%. Hence, with the PSP/PIR pyranometer as the reference, a series of linear regression fits were performed to reduce the calibration error, and the resulting regression equations in Table 1 would be used into the practical field calibrations. After corrections, the discrepancy among instruments is trivial, and the root mean squared deviation (RMSD) all are <8 W/m$^2$ at 10-min timescale.

During the matrix experiment, all measurements were carried out carefully with continuous supervision. Spirit levels and glass domes of the 17 radiometers were checked weekly to guard against any perceptible instrument tilting and possible soiling of the sensors. In spite of this, compared to other routine meteorological parameters, the measurements of surface radiation components are more prone to all kinds of errors (Moradi, 2009). Before further work was proceeded with, a series of error corrections need to be done firstly. Following the study of Vuilleumier et al. (2014), a thermal offset correction, a calibration correction, a leveling correction and a correction on soiling error were initially devised to perform in order. Adopting the method suggested by Dutton et al. (2001) the thermal offset error was first analyzed and corrected for each radiometer separately. Next, the correction on calibration error was conducted by using the linear regressions tabulated in Table 1. By checking azimuth-wise irradiance in some typical clear days (Menyhart, Anda, & Nagy, 2015), we found that most of the sites were well-leveled and horizontal except Site 9. Site 9 may have very slight tilt because the peak of interpolated azimuth-wise irradiance appeared at the azimuth of 182° but not 180°. However, due to the limitation of our observed data (direct beam radiation and diffuse radiation were not measured independently in the experiment), it is very difficult to find a valid approach to correct the leveling-induced error. As for the soiling error, in view of our cautious maintenance, this kind of error should be able to be avoided. That is, latter two kinds of corrections in practice were not performed. The recording cycle of raw SSR was 10 min, and data gaps nearly did not exist during the experiment. The corrected data at the 16 sites would be utilized for the following analyses.

### 2.2. Satellite retrievals

Previous SSR satellite products (Huang et al., 2016) over Heihe river basin in northwest China are used in the current study. The products were based on the look-up table algorithm of Huang, Ma, Liang, Liu,