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Detecting drift bias and exposure errors in solar and photosynthetically active radiation data

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ABSTRACT

All-black thermopile pyranometers are commonly used to measure solar radiation. Ensuring that the sensors are stable and free of drift is critical to accurately measure small variations in global solar irradiance at the Earth's surface ($K\downarrow$), which is a potential driver of changes in surface temperature. We demonstrate that the decreased responsivities of Eppley PSP pyranometers of $-1.5\%\,\mathrm{y}^{-1}$, or $-0.38\%\,(\mathrm{GJ\,m^{-2}})^{-1}$, were accompanied by a change in its spectral response owing to a discoloration of the sensing element. These observations motivated further work to develop routines to detect probable pyranometer drift in historical time-series. The temporal trends in the following ratios were used to detect pyranometer sensor drift: photosynthetically active radiation (PAR) to $K\downarrow$, $K\downarrow$ to K_{EX} (extraterrestrial radiation at the top of the atmosphere) and PAR to K_{EX}. Data from 8 AmeriFlux sites spanning latitudes from ~32 to 54°N were examined in this analysis. Probable drift in either a pyranometer or PAR sensor was identified at 5 of the 8 sites. The magnitude of the drift represented changes of $0.15\text{–}0.85\%\,\mathrm{y}^{-1}$, which is sufficient to obscure actual trends in $K\downarrow$, although these should be considered conservative low end drift estimates, given that we were not making comparisons to co-located higher grade instruments. Deployment exposure errors caused by sensor shading were also discovered by comparing the daily correlations between (i) $K\downarrow$ and K_{EX} and (ii) PAR and K_{EX}. Sensors drifting at rates similar to our defective PSP over a 5 year period would contribute to an underestimation of available energy of $\sim 70\,\mathrm{W\,m^{-2}}$, which is non-trivial in the context of assessing eddy covariance energy balance closure, employing Penman-Monteith or Bowen ratio methods or calculating albedo radiative forcings. Given that probable drift was identified at multiple AmeriFlux sites, we recommend enhancing network access to calibration services that are traceable to a high quality gold standard.

1. Introduction

Solar radiation, sometimes referred to as shortwave radiation, is the primary input of energy to the climate system. The surface shortwave radiative fluxes – incoming ($K\downarrow$) and outgoing ($K\uparrow$) – are important drivers of available energy (net radiation, R_n), and are of interest in the context of understanding variations in evapotranspiration (ET) and atmospheric circulation. Therefore, $K\downarrow$ is a key forcing variable in global climate and regional weather forecasting models, while R_n is used for assessing energy budget closure for eddy flux QA/QC (Leuning et al., 2012), and as an input for estimating ET by the Penman-Monteith or Bowen ratio methods. In addition, the shortwave spectrum contains the entire photosynthetically active radiation (PAR) band, which is a critical variable controlling gross primary production. Furthermore, there has been growing interest in evaluating the radiative forcings associated with land-use changes that modulate surface albedos and net ecosystem $\mathrm{CO_2}$ exchange (NEE) (Arora and Montenegro, 2011; Betts, 2000; Georgescu et al., 2011). Accurate records of shortwave radiative fluxes at the surface are thus needed to support a wide range of research activities.

The most common sensor deployed to measure hemispherical, broadband solar radiative fluxes is the thermopile pyranometer (Stanhill and Cohen, 2001), which is currently available from a variety of manufacturers. The availability and relative simplicity of these sensors belies the fact that making accurate $K\downarrow$ and $K\uparrow$ solar radiation measurements is a non-trivial exercise. Beyond errors induced by improper deployment and maintenance (e.g.,

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leveling, dome cleaning or clearing and shading from other tower components), known issues with thermopile pyranometers include thermal offsets (Bush et al., 2000; Philipona, 2002) and directional response errors (Myers et al., 2002). Applying corrections (Dutton et al., 2001; Ji, 2007), custom sensor modifications (Bush et al., 2000; Haeffelin et al., 2001; Ji and Tsay, 2010; Ji et al., 2011), conditioning with heated ventilation (Philipona, 2002) or deploying more recently developed pyranometers can effectively control these errors. However, a significant challenge that remains is long-term sensor stability, something that can only be mitigated by regular and frequent calibrations.

The contamination of solar radiation time-series with calibration drift makes it impossible to accurately track long-term trends that have been estimated to be on the order of $-0.5\,\mathrm{W\,m^{-2}}$ per year from the 1960s through the late 1980s (Stanhill and Cohen, 2001), with updated analyses suggesting brightening of a similar magnitude during the 1990s (Wild et al., 2005). Practices are thus needed to prevent sensor drift from contaminating long time-series of radiation data. For the highest measurement accuracy, manufacturers recommend 1–2 year intervals between calibrations, although high quality networks generally require calibration at least once per year if not more. Although calibrations correct responsivity drift, these procedures do not fully account for physical changes to the sensing element. Calibrations are typically performed by matching the response of a field deployed pyranometer to a reference sensor under controlled indoor or ambient outdoor conditions (ISO 9847:1992). Unfortunately, this procedure will be unable to adequately correct for drift that is due to changes in spectral response caused by physical changes to the sensing element, such as fading of the black paint (Riihimaki and Vignola, 2008).

Frequent sensor calibration remains the best practice to ensure that high quality data are collected, and is the standard operating procedure in radiation monitoring networks such as SURFRAD (Surface Radiation Network; (Augustine et al., 2005)) or BSRN (Baseline Surface Radiation Network; (Ohmura et al., 1998)). The challenge is that sites belonging to the highest quality radiation monitoring networks remain sparsely distributed in space. For example, there are currently seven sites distributed across the conterminous United States in the SURFRAD network (http://www.esrl.noaa.gov/gmd/grad/surfrad/sitepage.html) and 51 sites providing global coverage in BSRN (http://bsrn.awi.de/stations/maps.html). In order to improve spatial coverage for regional or ecosystem scale studies, researchers may therefore, be forced to use data from stations where the calibration history is either not known, or it is known that the calibration frequency is less than ideal.

Developing approaches that researchers can use to screen shortwave radiation data to detect probable calibration drift is thus warranted from the standpoint of increasing spatial data coverage while attempting to minimize sacrifices in accuracy. This tool would be of value from the perspective of maintaining sensors at active sites, as well as for post-hoc screening of long-term datasets when performing site syntheses. We hypothesize that drift and step changes in responsivity will be more easily detectable in time-series of the ratios of different radiative fluxes than in the raw time-series of the individual sensors.

Here, we highlight the decay in responsivities of all-black thermopile pyranometers from observations where we have co-located stable measurements. We show that this decay was accompanied by a change in the spectral response of the sensing element, and discuss implications for long-term monitoring campaigns. A method to detect calibration drift and step changes in $K{\downarrow}$ time-series based on examining the ratios of: (i) $K{\downarrow}$ to K_{EX}, (extraterrestrial radiation at the top of the atmosphere), (ii) photosynthetically active radiation (PAR) to $K{\downarrow}$, and (iii) PAR to K_{EX} will be presented and evaluated.

2. Materials and methods

2.1. Calibration drift due to radiation exposure

This analysis uses historical data collected at Rosemount MN, USA, as well as results from a sensor inter-comparison performed where four all-black thermopile pyranometers (model PSP, The Eppley Lab Inc., Newport RI) that were initially deployed in 2002 were evaluated. Two had been deployed facing upwards to measure $K{\downarrow}$ and the other two facing downwards to measure $K{\uparrow}$. Systematic differences of ~10% between the two upward facing PSPs had been observed in the past, which was unexpected because the sensors were deployed within 1 km of one another. Therefore, an inter-comparison was initiated to evaluate the performance of the PSPs. In autumn 2013, the four PSPs were co-located with one black and white (BW) pyranometer (model 8-48, The Eppley Lab Inc.) that had not been field-deployed and was thus presumed to be free of radiation exposure induced calibration drift.

The pyranometers were deployed from September 20 through September 30 on a flat surface at a height of 1.5 m. Measurements were taken every 30 s, and half-hourly averages recorded using a datalogger (model 21X, Campbell Scientific Inc., Logan, UT). In order to better understand the findings from the inter-comparison, historical data from 2006 to 2010 were revisited. In presenting and discussing the results, we differentiate between the PSPs based on their deployment history – G21 or I10 refers to the most recent fields in which sensors were located, while 'upwards' or 'downwards' describes the orientation of the pyranometers during historical deployment, and not the orientation during the inter-comparison, for which they were all facing up.

2.1.1. Data processing

To minimize the effects of cosine response errors, solar radiation data were discarded when the solar zenith angle was >70°. When checking the sensors one morning, we noticed that condensation had formed on the outer surface of the domes on all pyranometers. This problem can be minimized with heating or ventilation (Phillipona, 2002), which we routinely employ for upward-facing instruments. In this case, there were not enough ventilators for all instruments. Therefore, more stringent filtering was implemented, whereby all data with timestamps of 1100 h (LST) and earlier were discarded. Data obtained during rainfall events were also discarded to prevent artifacts associated with variable condensation on the domes from affecting the comparison. All regression analyses were performed using the robustfit.m algorithm in MATLAB (The Mathworks Inc., Natick, MA), using the default 'bisquares' weighting function. In most cases two linear models were considered, one forced through the origin while the other included an intercept term. From a sensor physics perspective, the model forced through the origin is more appropriate because the response of a pyranometer in the absence of incident radiation should be $0\,\mathrm{W\,m^{-2}}$. Thermal offset errors are, however, known to affect PSPs (Bush et al., 2000; Philipona, 2002) which could result in a non-zero intercept. Therefore, considering a model that includes an intercept term is warranted to extract as much information as possible. Parameter estimates were compared using two-tailed *t*-tests.

2.2. Detecting drift in historical data

We developed an approach to identify drift by examining the temporal trends in the three ratios: (i) $\mathrm{PAR}/K{\downarrow}$, (ii) $K{\downarrow}/K_{\mathrm{EX}}$, and (iii) $\mathrm{PAR}/K_{\mathrm{EX}}$. We recognize that atmospheric optical depth can vary in response to anthropogenic and natural factors (Ramanathan and Feng, 2009), which makes detecting sensor drift a challenge. We therefore, took steps to minimize the effect that real trends in the observed radiation variables would have on sensor drift detection.