Stability of solar radiation sensor calibration in the NZ Climate Network

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Abstract

The NIWA Climate Database holds solar radiant energy data for ~150 stations around New Zealand and the southwest Pacific, largely from Licor photodiode sensors but with Eppley PSPs at some sites. There are good multi-year data for about 70 sites, including all major population centres. There are hourly global, diffuse, and direct radiation data from Eppley sensors at Kaitaia, Paraparaumu, and Invercargill since 1988, but the best NZ solar radiation data are from the Baseline Surface Radiation Network (BSRN) station at Lauder, in Central Otago. Meteorological Service of New Zealand Limited (MetService) has regularly calibrated their own and other solar radiation sensors, at Paraparaumu, for the New Zealand Climate Network but since November 2013 NIWA’s instruments have been calibrated at Lauder. Instruments that remain in statistical control are redeployed to the next vacant site, but the practice of using the new calibration directly has led to dubious steps in the data. Records of calibrations and deployments are incomplete, and somewhat error-prone, but they show that dividing out applied calibrations actually reduces the variance in (near-to-) clear-sky values. For more reliable time series for analysis of patterns or trends, regular calibration should be combined with statistical control theory, so that instrument response that can be regarded as constant or slowly trending does not become an additional source of error.

1. Introduction

Global irradiance, the solar energy flux through a horizontal surface, is a critical parameter in Earth’s energy balance, in the energy flux of weather and climate systems, as a driver of the biosphere, and increasingly for renewable energy supply. Detecting changes in global energy balance requires data of very high quality, motivating formation in the 1990s of the global Baseline Surface Radiation Network (Ohmura et al., 1998). For the 48 open and 11 closed BSRN stations, the direct and diffuse components of solar radiation are or were measured with solar tracking pyrheliometers and shaded pyranometers to the highest available accuracy and high time resolution (1 to 3 minutes). The data are widely used in analyses of global energy balance and validation of satellite-derived data and earth system models.

New Zealand’s only BSRN station is at the Lauder site of the National Institute of Water & Atmospheric Research Ltd. (NIWA), with BSRN data since 1999. Direct and diffuse radiation were measured by the NZ
Meteorological Service and subsequent MetService at Kaitaia, Paraparaumu, and Invercargill from the late 1980s with tracking pyrheliometers and a pyranometer with shade band, logged at hourly intervals. From 2000 the instruments were transferred to NIWA data loggers, with both hourly and 10-minute recording. In 2011, trackers were upgraded to EKO systems using a shade ball for diffuse measurements.

The New Zealand National Climate Database (CLIDB), managed by NIWA and accessible at https://cliflo.niwa.co.nz/, holds global irradiance data for over 200 climate stations around New Zealand. Of those stations, 181 are open, and 100 have at least 10 years of data. Most of the stations are operated by NIWA, 48 belong to MetService, and some are owned by other CRIs, Airways Corporation, regional and district councils, universities, and others.

The New Zealand global irradiance data find use in calculating solar heating, evaporation rates, plant growth, and the like. Within NIWA, they have been used to develop maps of solar flux (Tait and Liley 2009), to estimate UV radiation anywhere in the country (Bodeker and McKenzie 1996; Bodeker et al., 2002; Bodeker et al., 2006), and to calculate available solar energy on a panel of arbitrary tilt and bearing allowing for horizon shading (http://solarview.niwa.co.nz). All of these NIWA products use the ratio of measured global irradiance to clear sky values, and that calculation raises a question about the stability of instrument calibration.

MetService operates a calibration facility at Paraparaumu, and all pyranometers in the New Zealand climate network were previously calibrated there. Since November 2013, NIWA sensors have been calibrated at Lauder. Only 17 of the NIWA pyranometers are thermopile radiometers (all Eppley) that measure the 300 nm to 2800 nm integral (e.g., https://s.campbellsci.com/documents/au/manuals/psp.pdf). The manufacturer suggests figures of 2% uncertainty in hourly and 1% in daily integrals (unstated, but presumably both 2σ) for these instruments, while the calibration certificates from the MetService’s Calibration Laboratory give a figure, including reference sensor uncertainty of ±2.8% (2σ), of ±6% (2σ) in hourly data. Most of the other sensors are Licor silicon photodiodes, for which the manufacturer suggests a calibration uncertainty of ±3% within 60° angle of incidence (https://www.licor.com/env/products/light/pyranometer.html). MetService calibration certificates give a figure of ±8% (2σ) for hourly values in field data.

The response of silicon sensors drops sharply from 1000 to 1100 nm and beyond, so the calibration against reference thermopile pyranometers is applicable only to the extent that the overall spectrum in field measurement is similar to that at calibration.

For most meteorological and climate parameters, such as temperature, pressure, humidity, or wind speed, the reliability of time series depends on periodic calibration of sensor response against reference sensors or collocated instruments. Drifting instrumental response may be suspected, and detectable in the calibration record, but it cannot usually be inferred just from field data with a single instrument.

With solar radiation data, a further test arises naturally for checking both stability and absolute response when the aerosol optical depth is low. As demonstrated below, fitting the diurnal variation with a suitable model to detect days with clear sky (minimal cloud) provides a ‘field calibration’ or verification method that readily detects any major errors in response or alignment. Here I compare the results of such analysis with the formal calibration record.

2. Data

Radiation data in CLIDB are primarily stored at hourly resolution, and are available free from http://cliflo.niwa.
co.nz, or on request to cliflo@niwa.co.nz for specific datasets. From an error when CLIDB was established, the data were stored at degraded resolution. They were expressed just to one decimal place in units of MJ m$^{-2}$, for which hourly values range up to at most 4.5, and median daytime values are around 1 MJ m$^{-2}$. The mistake was discovered during development of the NIWA UV Atlas (Bodeker and McKenzie 1996), and some earlier data at better resolution were recovered, but mostly only data from 1995 onward are useful for analysis here. An example dataset is shown in Figure 1.

The calibration factors of all the radiation sensors used by NIWA have been maintained in a spreadsheet by NIWA’s Instrument Systems staff (Andrew Harper, personal communication). It records just month and year when each sensor was deployed at a given station, and the month and year when it was calibrated. It might be helpful to have higher precision in those dates, especially of field deployment, but it has little effect on the analysis here.

Data from 90 NIWA Electronic Weather Stations (EWS) and Compact Weather Stations (CWS) were used for the initial analysis. It could readily be extended to the Automatic Weather Stations (AWS) operated by MetService and others, if corresponding calibration records are available.

For detailed study I focus on data from the Lauder EWS site, which allow comparison with data from the BSRN instruments on the Lauder Optics building 200m to the west. The latter data are available from the BSRN website at https://bsrn.awi.de/data/data-retrieval-via-pangaea/. The BSRN instrumentation at Lauder comprises Kipp & Zonen CMP21 pyranometers, a CHP1 pyrheliometer (direct normal incidence pyranometer), and a CAL17 pyrgeometer (global infrared irradiance), with the pyrheliometer and shade disks for the diffuse pyranometer and pyrgeometer mounted on a Middleton Solar tracker (Forgan 2009). The data are processed by the Australian Bureau of Meteorology to the stringent standards of the BSRN (Ohmura et al. 1998), logging data at 1 Hz and recording statistics at 1-minute resolution, with consistency checks.
3. Analysis

The calibration-constancy of global irradiance data is best examined by consideration of clear-sky days, which are readily apparent in plots of diurnal variation. Such days can be detected algorithmically as follows.

For all 90 of the selected NIWA stations, hourly global irradiance data for each day of their respective time-series were fitted with a function of the form

$$ I = I_b \cos(Z)^b $$

where $I$ is the predicted irradiance, $Z$ is solar zenith angle, $b$ is a fitted constant, and $I_b$ is a fitted constant giving the irradiance for overhead sun.

An example is shown in Figure 2, with the lighter grey curve indicating the function for variable exponent $b$.

Although such fitting can be achieved by regression of $\log(I)$ on $\log(\cos Z)$, that is unduly sensitive to small values and requires appropriate weighting. Instead, the non-linear fitting used here assumes constant variance in additive residuals (homoscedasticity). That assumption is imperfect, because there are no negative values, as would be implied by symmetry in the residual error for very low solar elevation.

Figure 2 suggests that the clear days can be selected as those with the largest values of $I_b$, but there is substantial covariance ($r = 0.675$ for $N = 121,520$ site-days in the data used here) between $b$ and $I_b$ (not shown). Using a prescribed value of $b = \beta$ avoids this problem, and it also means that the model can be fitted just with linear regression of $I$ on $(\cos Z)^\beta$. That is sufficiently quick, even for the 394,743 site-days in the full dataset, to permit some exploration of the best value.

The selected value of $b = 1.15$ has previously been found to fit very well with 1-minute data for the clearest days in the BSRN dataset, and it remains a good fit as they are aggregated to hourly values like the CliDB data. It is below the mean (1.33) of the fitted $b$ values for days selected as reasonably clear (see below), but within one standard deviation (0.22). It lies between the 15th and
50th percentiles, as calculated weekly throughout the year (Figure 3).

Using the fixed function with $b = 1.15$ fitted to the full dataset, criteria of

\[ I_{1.15} > 850 \text{ W m}^{-2} \]  \hspace{1cm} (2)

\[ X^2 < 0.01 \cdot I_{1.15}^2 \]  \hspace{1cm} (3)

retain about 30% of the data (121 520 site-days) as similar to clear skies. This is a considerably higher proportion than the typical 5-10% of days that are cloud-free even in locations with a high prevalence of such conditions. Further restriction is available at any stage of the subsequent analysis, but doing so for some sites with frequent scattered cloud reduces coverage markedly, especially in winter months when shorter days and lower sun angles cause more variability in $I_{1.15}$ values. Because of the wider acceptance criteria, only the higher values of $I_{1.15}$ correspond to genuinely clear days in the following plots. Note that $I_{1.15}$ is the fitted model irradiance for overhead sun, in which sense it is independent of latitude. Lower average values of $I_{1.15}$ could occur for a site with greater aerosol optical depth, especially of absorbing aerosol.

The overall time series of fitted $I_{1.15}$ since 1996 is shown in Figure 4, together with five percentiles (5,15,50,85,95) for each year. The distribution is stable until perhaps 2008, but then increases to 2012, and the change is actually monotonic from 2005. Such changes may be possible for a single site or even a region, but they are surprising for the country as a whole. Much has been written about ‘Global Dimming and Brightening’, whereby global (meaning hemispheric, rather than world-wide) irradiance decreased from the 1960s to around 1990 (Stanhill and Cohen 2001), then levelled off or increased after that (Wild et al., 2005). The pattern also appears in New Zealand data (Liley 2009), but mostly as an effect of diminished cloud rather than increasing clear-sky irradiance. The latter is very improbable for New Zealand as it would require reduction in absorbing aerosol by an amount much greater than the observed total aerosol burden over New Zealand prior to the increase (Liley and Forgan 2009).

To reliably quantify any such change, it is necessary to check instrument calibrations. Instruments in the NIWA...
network are deployed for up to two years, then returned for recalibration with another sensor installed. From the spreadsheet record of pyranometer calibrations and deployments, it is possible to trace which sensor was in use at any time, as illustrated in Figure 5 for Wallaceville EWS.

Figure 5 does suggest a step change of around 60 W m$^{-2}$ in irradiance at zenith, or 5.5% in measured irradiance, occurred with the change from PSP 17857 to PSP 13996 in early 2008. Another more improbable change, with zenith values to 1250 W m$^{-2}$, occurred with PSP 21249 in 2014, but the #13996 values are reasonably consistent with those from #13994, #35090, and #13995 to the end of 2013.

To explore the relationship further, other reference data are needed, as available at the Lauder EWS site.
There, the BSRN instrumentation includes separate measurements of global (G), diffuse (F), and direct (R) radiation at 1 Hz, reported as 1-minute observations with statistics. In accordance with BSRN practice, the primary measurement of global irradiance is not G but the sum $F + R \cos Z$, which is more stable against measurement artefacts.

With 1-minute time resolution, fitting of the clear-sky model (1) is more precise, as is the fit with $b = 1.15$, allowing more stringent criteria for clear-sky days. Restricting from equation (3) to

$$X^2 < 0.001 I_{1.15}^2$$

(4)

retains only 12% of the clearest days. Fitting the 1-minute data gives slightly higher values of $I_{1.15}$, so for comparison with the CliFlo data the BSRN were aggregated into hourly data for re-fitting, with results as shown in Figure 6.

As noted earlier, it is only the higher values of $I_{1.15}$ from the Lauder EWS data that should match the BSRN values, but it is clear from Figure 6 that the changing peak intensities in the former dataset are at odds with the latter.

Both Figure 5 and Figure 6 suggest that peak values are consistently higher or lower within the period of deployment of particular sensors, calling into doubt the calibration factors use to scale sensor signals. From the periods where the Lauder sensor is identified in the spreadsheet of calibrations, we can divide out the applied calibration factor, and replace it with the average value for that sensor. The result is shown in Figure 7.

This 'recalibration' removes much of the trend in the Lauder EWS data (with identifiable sensors), and agreement with the BSRN data is somewhat improved. On the 461 days in common from the best 12% of BSRN and 30% of EWS days, the difference between fitted irradiance at zenith has a mean of 57 W m$^{-2}$ and s.d. of 51 W m$^{-2}$ in the unadjusted data. Adjustment as above reduces both figures to 53 and 49 respectively. Such improvement is minor but useful, and it may be improved with higher time resolution to give better clear-sky fits.

The possible implication that the data might be more consistent without regular sensor calibration is
disconcerting, and warrants further exploration. Figure 8 shows the calibration factors for all NIWA PSP sensors. The response of most instruments shows a gradual decline over time, as expected, with random variation that is within the 3.5% (2σ) uncertainty. That uncertainty is illustrated for two instruments (#15639 and #21250) that showed marked decline in response, necessitating their removal from use. Those instruments illustrate why regular calibration checks are necessary.

What should perhaps be reviewed is how the calibration factors are applied, but that presents some difficulty. At first deployment, only one factor is available; usually the manufacturer’s calibration. After the first recalibration, there is a new figure, but any difference within the uncertainty of calibration might be random, or it might
Liley: Stability of NZ radiation sensors

have some component of secular change. At present, just the new value is used to process subsequent data. Repeating this process over time for an unchanging instrument, the variance of calibrations adds to the variance of field measurements.

From statistical control theory, a better approach might be to change the applied calibration factor only when it moves outside the confidence limits of calibration, but then gradual drift would result in step changes.

There are other alternatives, such as treating the mean of all calibrations as the correct factor, or fitting a linear trend for each instrument as would be suggested by Figure 8, and revising past values. Both of these might require regular revision of past data with new calibrations, greatly confusing any analyses and quickly rendering them out of date. Another approach would be to just store voltages, and serve data along with calibration factors for users to apply. This would be awkward and confusing for many users, and it only transfers the problem of maintaining consistency with past values.

Confronted with the same issues, the satellite data community and others maintain different versions of derived data, based on retrospective recalibration or other revisions of data processing. In the context of CLIDB irradiance data, which are just scaled from sensor signals without any offset, the revision necessary for past data would be as simple as applying a factor to all measurements over a series of intervals.

Subsequent to the analysis herein, a reviewer of this paper provided a 2009 report from MetService to NIWA that appears to explain the anomalous change between 2008 and 2012. From around 1990, one of the then internationally-recommended practices implemented by NZ Meteorological Service for calibrating their Working Standards yielded factors that led to field measurements being 3-5% low; a difference of 30-50 W m\(^{-2}\) as in Figure 4. A change in the internationally-recommended practices was implemented by MetService in 2008, thereafter progressively affecting the calibration of all network sensors, and therefore the network data collected from 2009 to 2012.

This change had a larger effect than most of the intrinsic variability of recalibration, and it affected all sensors in a similar way, introducing bias rather than just additional variance. Nonetheless, it provides a further argument for the need to support possible revision of historical irradiance data, whether for an overall correction or for applying a smoothed description of instrumental response.

What is needed is a new CLIDB metadata record type giving instrument type and serial number, deployment dates, and calibration factors as applied to the stored data. The same record type, with version, could be used for any suggested revision.

The analysis here was for Eppley PSPs, as the instruments deployed at Lauder for the period of BSRN data. Other sites may provide a similar opportunity for comparison: Paraparaumu with (corrected) data from MetService Working Standards; Kaitaia, Paraparaumu, and Invercargill with direct and diffuse data; and other sites where different agencies, especially NIWA and MetService, have sensors near to each other. They might support a comparison of Licor measurements, but the larger uncertainty in Licor data will probably reduce the statistical significance of any differences.

4. Conclusions

Fitting pyranometer data with a simple function of solar zenith angle can be used to find clear-sky days. For New Zealand’s generally clean (low aerosol) atmosphere, fixing the dependence on solar zenith angles still provides a good fit, and also gives a reasonably consistent measure
of pyranometer response that can be related to calibration factors.

Applying this process across all NIWA pyranometer data suggests that some of the measured variation is spurious, probably resulting from uncertainty in the calibration procedure.

Of possible improvements to procedures to give more accurate data, the simplest will be to derive a set of suggested adjustments to be applied retrospectively. For any strategy, the one critical component is maintaining complete and accurate records of both calibrations and deployments.

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References


