Sunshine duration instrument comparisons in New Zealand

R. Srinivasan[1], G. Macara[1] and B. Liley[1]

[1]National Institute of Water and Atmospheric Research (NIWA), Private Bag 14901, Wellington, New Zealand

Correspondence: Raghav.Srinivasan@niwa.co.nz , +64-4-386-0525

Key words: sunshine, sun hours, radiation

Abstract

Sunshine duration in New Zealand has historically been measured using a Campbell-Stokes sunshine recorder. The contemporary upgrade of climate stations has resulted in the introduction of Kipp & Zonen CSD sunshine recorders. In this study, different sunshine durations have been measured by each instrument operating in parallel at the same climate station location. We aimed to compare the difference between the two measurement methods, to make an informed judgement about 1) which instrument is more suitable for measuring sunshine duration, and 2) whether homogenisation of New Zealand's historic Campbell-Stokes data with subsequent Kipp & Zonen data are achievable. Campbell-Stokes and Kipp & Zonen sunshine duration data from four locations were assessed in this study, and these sunshine durations were validated against radiation-derived sunshine duration data. On average, Kipp & Zonen sunshine durations were higher than Campbell-Stokes sunshine durations at all four sites, with the difference ranging from 2% at Invercargill to 17% at Hokitika. When compared to radiation-derived sunshine duration data, Kipp & Zonen sunshine data were more accurate (mean absolute errors of 0.07-0.09 hours) compared to Campbell-Stokes data (mean absolute errors of 0.22-0.32 hours). We propose that the Kipp & Zonen instrument is more suitable for the measurement of sunshine duration compared to the Campbell-Stokes instrument. Without an understanding of the intra- and inter-site variability of sunshine durations measured by each instrument, the homogenisation of historic Campbell-Stokes data with subsequent Kipp & Zonen data would prove challenging and ultimately unsuitable.

1. Introduction

The duration of bright sunshine is a variable routinely measured at climate stations, and it contributes to our understanding of weather and climate variability at local through to international scales. Several different instruments are available to measure the duration of bright sunshine. These may be broadly categorised as either 'manual' or 'automatic' instruments. Historically, sunshine duration was typically measured using a manual Campbell-Stokes (CS) sunshine recorder. These instruments comprise a glass ball suspended above a semi-circular or rectangular suncard. Bright sunshine passes through the glass ball, and then burns a trace into the suncard. Sunshine duration may then be interpreted by an observer, who measures the length of the burnt trace using a scale and equates this to the corresponding time. In contrast, automatic instruments are electronic,

Submitted: 2 August 2019
Accepted: 1 November 2019

and measure sunshine duration by the length of time incident solar radiation exceeds a pre-defined threshold.

New Zealand has sunshine duration records dating back to the early 1900's, when CS were traditionally used. CS continue to be used in New Zealand, however the contemporary upgrade of New Zealand's climate station network has seen the introduction of automatic weather stations and associated electronic instruments. This has resulted in the installation of electronic Kipp and Zonen CSD (K&Z) sunshine duration sensors, which were first deployed among New Zealand's climate observation network in the early 2000's.

1.1 Definition of bright sunshine

The purpose of both manual and automatic sunshine instruments is to measure the duration of bright sunshine. The sun must be sufficiently bright for a trace to burn in the suncard of a CS; if the sun is obscured by enough cloud then no trace will burn. Painter (1981) found the irradiance threshold required to produce a burn on a suncard varied from 106-285 W m^{-2}, with an average of 170 W m^{-2}. Several factors may contribute to this threshold range. For example, studies have demonstrated that the threshold varies depending on sun angle and time of year (Painter, 1981; Kerr and Tabony, 2004). In addition, high humidity or other sources of moisture can make the suncard damp and increase the solar intensity required to burn a trace (Lockart et al., 2015).

The World Meteorological Organization (WMO) have produced guidance for practitioners that defines 120 W m^{-2} of direct solar irradiance as the threshold value for bright sunshine (WMO, 2010). This guidance is used to inform the threshold of incident solar radiation required for an automatic sunshine instrument to record bright sunshine. No attempt has been made to assess the veracity of this threshold value in the present study, particularly regarding what threshold was required to burn a trace in the suncard.

The K&Z instrument response is fixed by the manufacturer, and there is no reasonable way to apply a calibration factor to the sunshine duration. Nonetheless, the K&Z instruments are regularly compared with a reference K&Z at Lauder, and their threshold is tested against 1-minute measurements with a pyrheliometer calibrated by the Bureau of Meteorology. They are removed from service if the threshold is outside the manufacturer's specified ±10% of the 120 W m^{-2}.

1.2 Study aims

Parallel measurements of bright sunshine duration by manual and automatic instruments are relatively limited in New Zealand. There are four locations where both CS and K&Z instruments are operating in parallel at the same site; Hokitika, Invercargill, Kaitaia and Paraparaumu (Figure 1). There have been no published

Figure 1: Map of New Zealand, showing the four locations with sunshine duration data analysed in this study.

studies undertaken comparing the measurements made by the two instruments in New Zealand to date. Several international studies have compared observations from K&Z instruments with CS instruments. These have demonstrated both positive and negative differences in bright sunshine duration (Matuszko, 2015; Urban & Zajac, 2017; Baumgartner et al., 2018). The purpose of the present study is to compare measurements of bright sunshine by both CS and K&Z at the four available locations. In Section 2, CS data were compared with that obtained from K&Z. To further explore the differences between CS and K&Z, measurements from both instruments were compared with solar radiation data (Section 3). Using these comparisons, we aim to make an informed judgement about 1) which instrument is more suitable for measuring sunshine duration, and 2) whether homogenisation of New Zealand's historic CS sunshine duration data with K&Z data are achievable.

2. Campbell-Stokes compared with Kipp and Zonen

The purpose of this section is to compare the parallel measurements of bright sunshine duration made by CS and K&Z instruments in New Zealand.

2.1 Method

All bright sunshine duration data were extracted from New Zealand's National Climate Database (CliDB), which is maintained by the National Institute of Water and Atmospheric Research (NIWA).

Sunshine data from K&Z instruments were available from the early 2000's, however comparison of these data was limited to dates from July 2012 to September 2019. This start date was chosen as the original CS suncards were available from this date, enabling spot-checks of CS data. All four locations with parallel observations available for sunshine using both CS and K&Z instruments were assessed. These instruments are situated within the same climate station enclosure of 10 m x 10 m dimension. Sun-eye horizon profiles have been taken at each instrument site and show that the instruments share the same exposure to sunlight at each of the study locations.

Only concurrent daily sunshine data from both instrument types were used for analyses at each location. For a daily sunshine total to be obtained, all hourly data must be available for the day. The sunshine data were aggregated into monthly totals and the percentage difference of sunshine hours between the two instruments was calculated, where:

Percentage difference = (sum(K&Z sunshine hours) – sum(CS sunshine hours)) * 100 / sum(CS sunshine hours).

A negative percentage difference indicated that the automatic K&Z instrument measured lower sunshine duration compared to the manual CS recorder. A positive difference indicated that the K&Z instrument measured higher sunshine duration compared to the CS recorder. It was expected that the K&Z instrument would record higher sunshine duration than the CS instrument, due to the higher sensitivity and sampling frequency of the automatic instrument. This is additionally based on anecdotal comparisons following the introduction of K&Z instruments into New Zealand's climate monitoring network, where sunshine durations obtained from K&Z instruments are frequently anomalously high compared to the historic sunshine duration climatology of a location (which is primarily based on CS data).

A basic linear fit was applied between the monthly sunshine durations of the K&Z and CS instruments. The correlation between the two sunshine instruments was also examined, and these results are presented in Section 2.3.

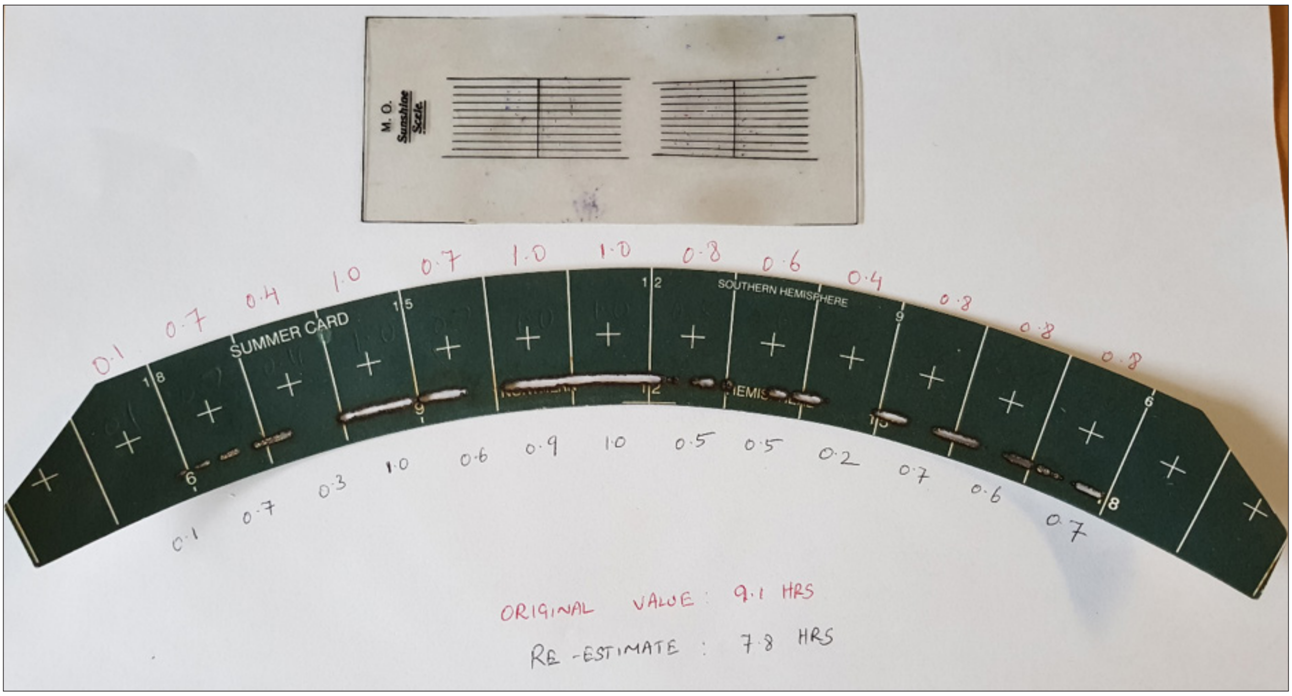

Figure 2: An example suncard, with hourly sunshine durations estimated by two different people. The scale used to assist estimations is included above the suncard.

2.2 Data caveats

Sunshine duration from CS are obtained from suncards, which must be interpreted by manual observers. As a result, a certain level of subjectivity is inherent regarding these data, which can result in dissimilar sunshine duration estimations from different observers (Figure 2). Ideally, all suncards would be interpreted by a single observer applying an objective measure, however this isn't a practical solution. Furthermore, the sheer volume of historic suncards (let alone their availability or lack thereof) means a 'recount' of historic records is impractical. As a result, the CS sunshine duration data used in these analyses were the original data from CliDB without any re-estimation.

2.3 Results and discussion

Figures 3-6 are scatterplots of daily sunshine duration by month recorded by CS compared to K&Z instruments. Scatterplots have been generated for each month at each of the four study sites. Each plot includes a reference red line of x = y; datapoints above the line indicate the K&Z CSD sunshine duration was higher than the corresponding CS sunshine duration. An R-squared value associated with the linear trendline is included for each scatterplot. R-squared values are relatively high, ranging between 0.93-0.97 at Hokitika, 0.89-0.96 at Invercargill, 0.89-0.95 at Kaitaia and 0.90-0.95 at Paraparaumu. Daily sunshine durations tend to cluster about the linear trendline at low and high sunshine durations, with higher dispersion observed for remaining sunshine durations. This may be because on mostly cloudy (low daily sunshine duration) or mostly clear sunny (high daily sunshine duration) days, the K&Z and CS instruments tend to measure similar sunshine durations. In contrast, at middling daily sunshine durations (relative to the time of year), sunshine durations measured by each instrument tend to be more dissimilar. This may be partly attributed to the different measurement method of each instrument. Specifically, the CS instrument will require a certain period of sustained sunshine for a trace to burn through the suncard. In contrast, the K&Z instrument is operated a relatively high sampling frequency of three seconds. Therefore, at times

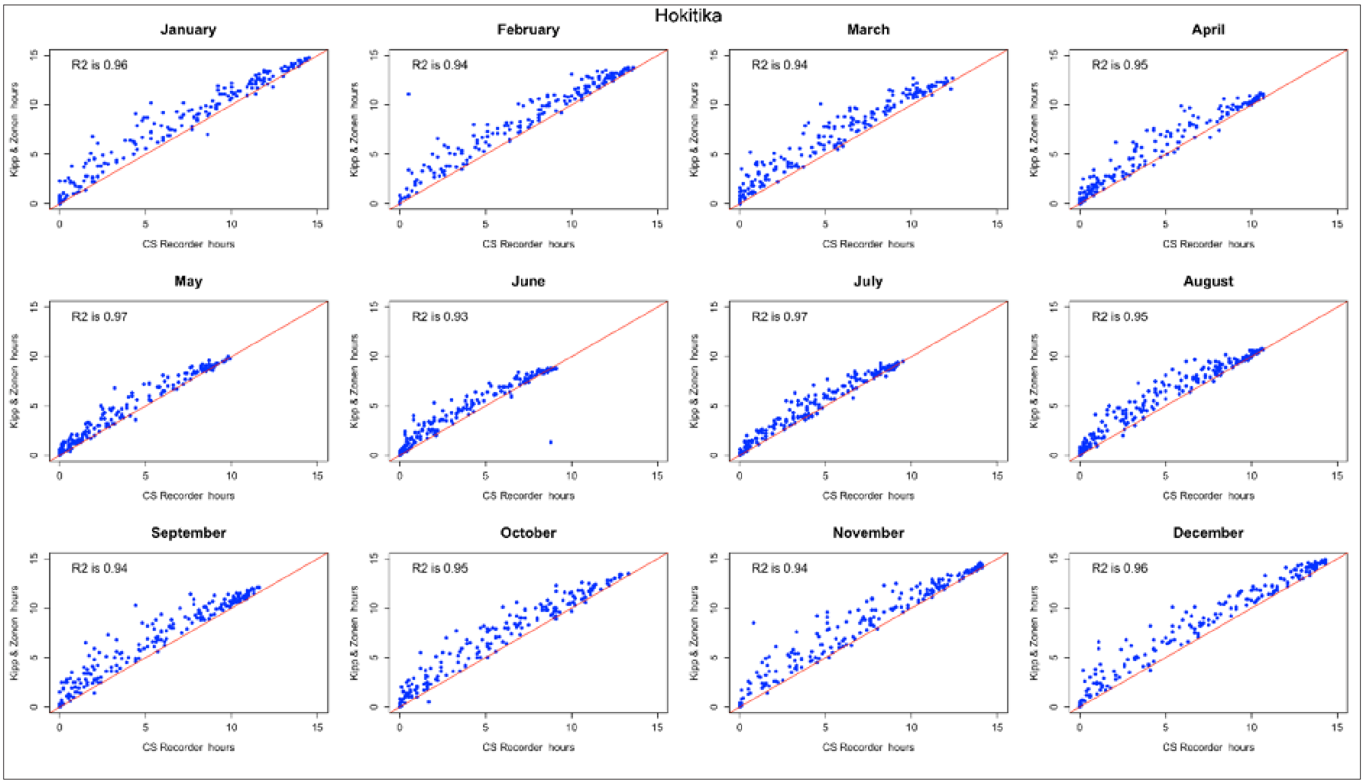

Figure 3: Scatterplots of daily sunshine duration by month in Hokitika. CS measurements are represented on the x-axis and K&Z measurements are represented on the y-axis. The red line is a reference of x = y.

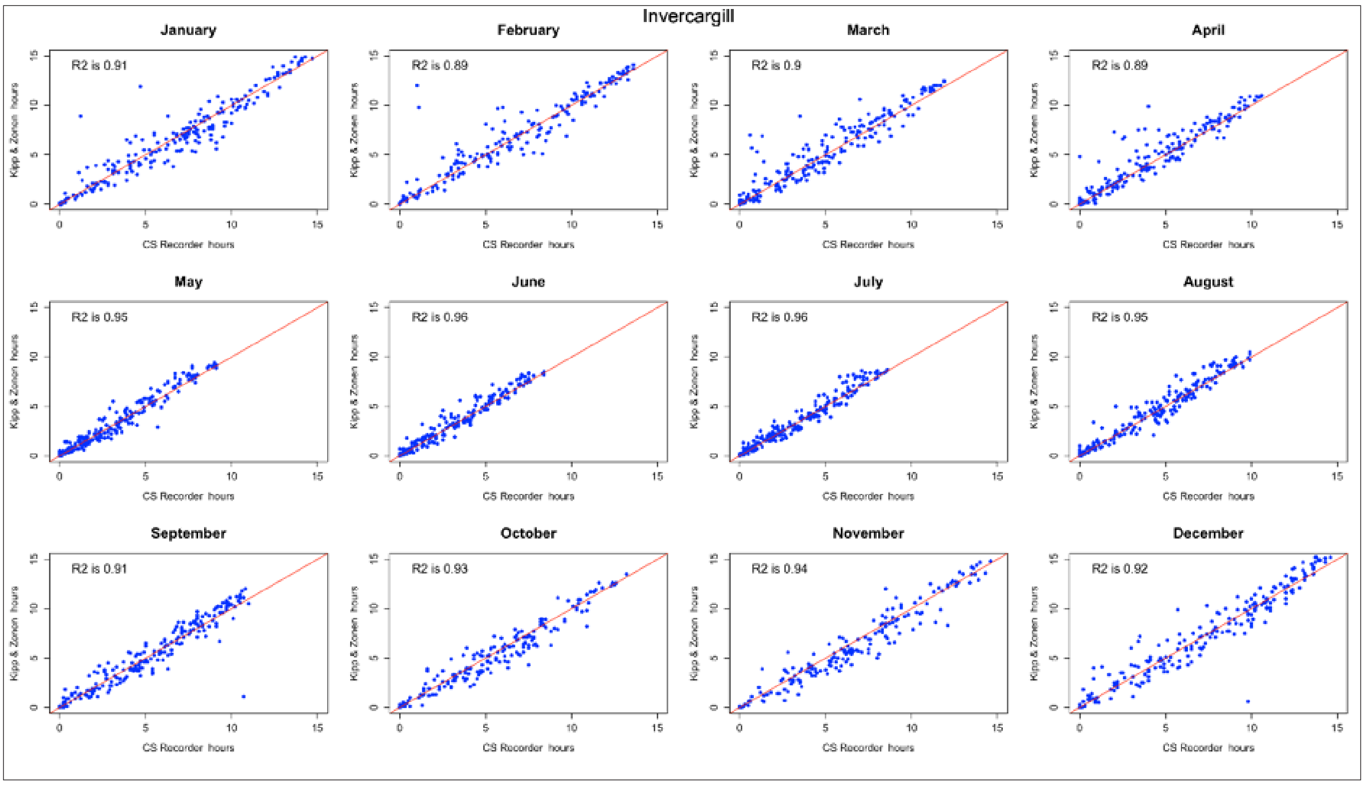

Figure 4: Scatterplots of daily sunshine duration by month in Invercargill. CS measurements are represented on the x-axis and K&Z measurements are represented on the y-axis. The red line is a reference of x = y.

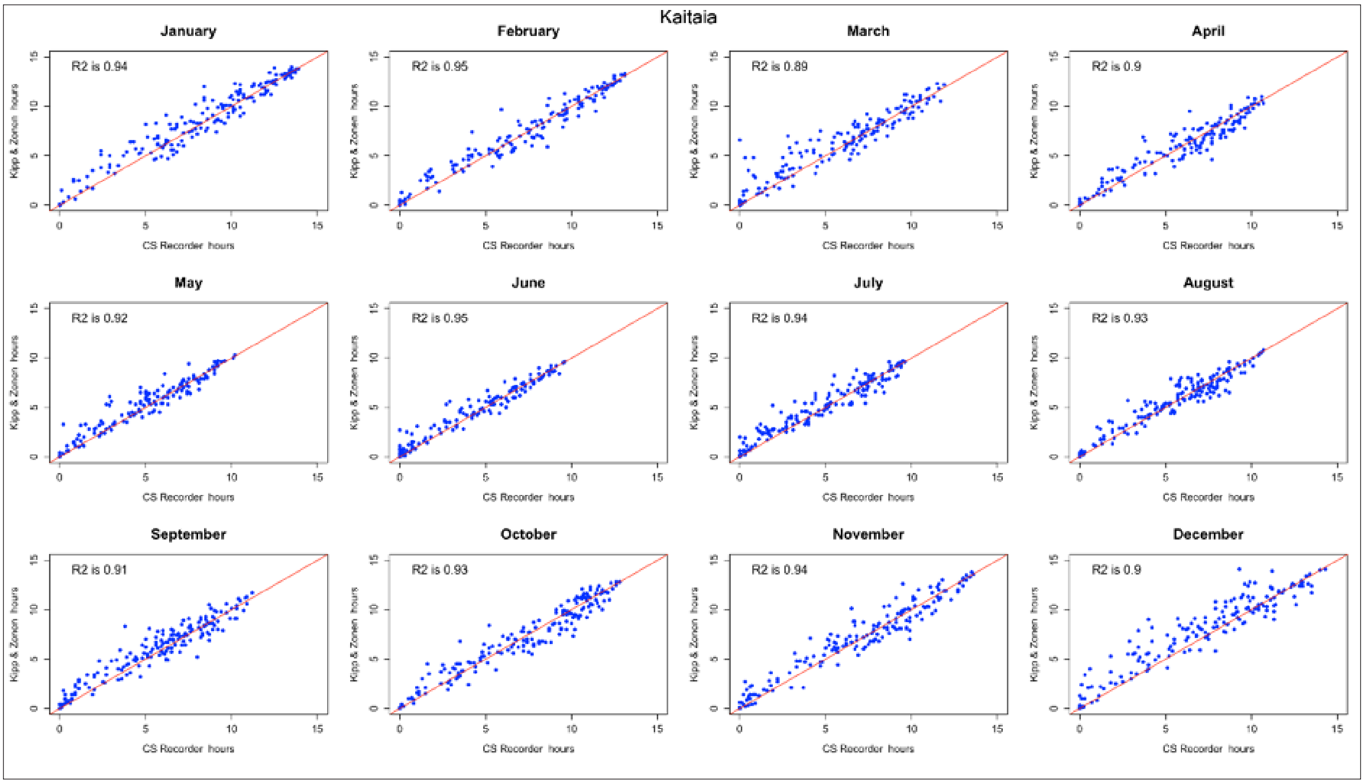

Figure 5: Scatterplots of daily sunshine duration by month in Kaitaia. CS measurements are represented on the x-axis and K&Z measurements are represented on the y-axis. The red line is a reference of x = y.

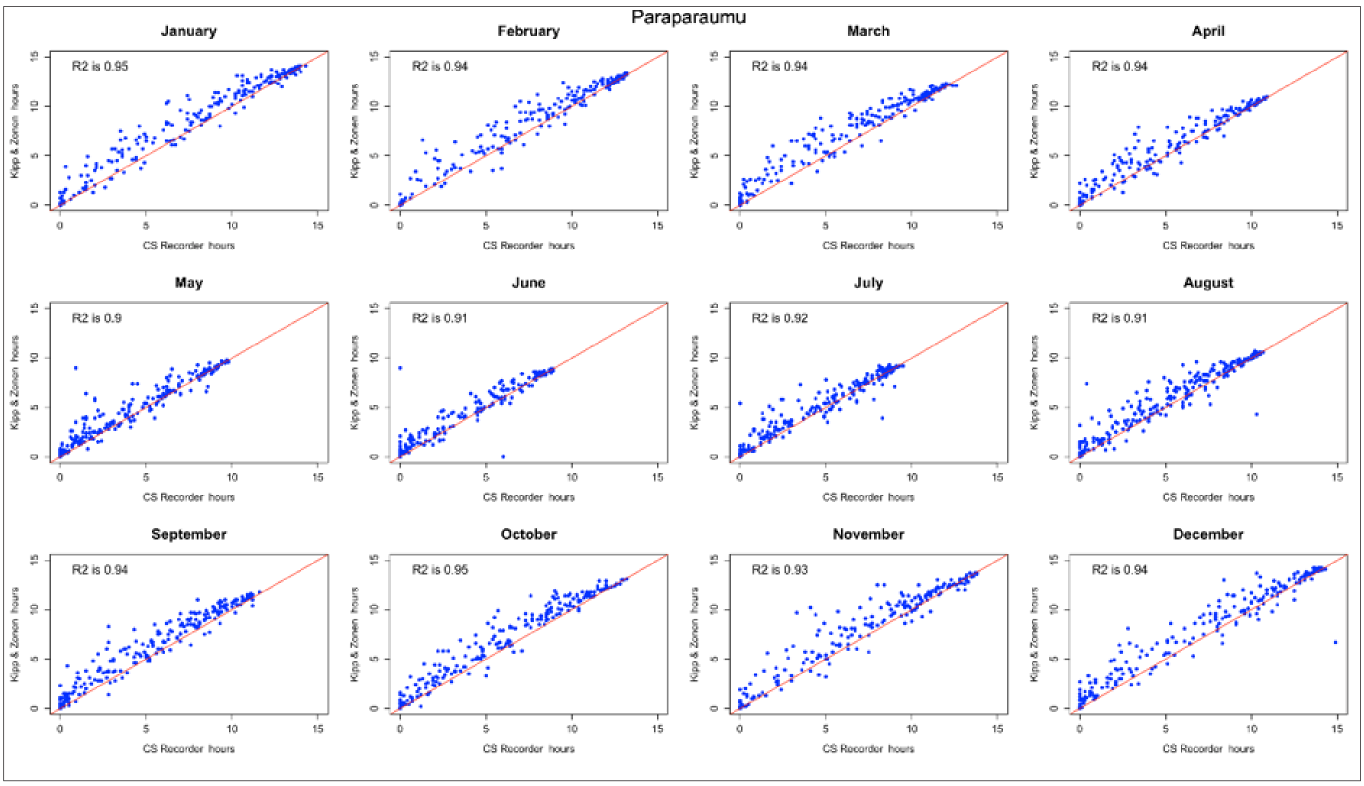

Figure 6: Scatterplots of daily sunshine duration by month in Paraparaumu. CS measurements are represented on the x-axis and K&Z measurements are represented on the y-axis. The red line is a reference of x = y.

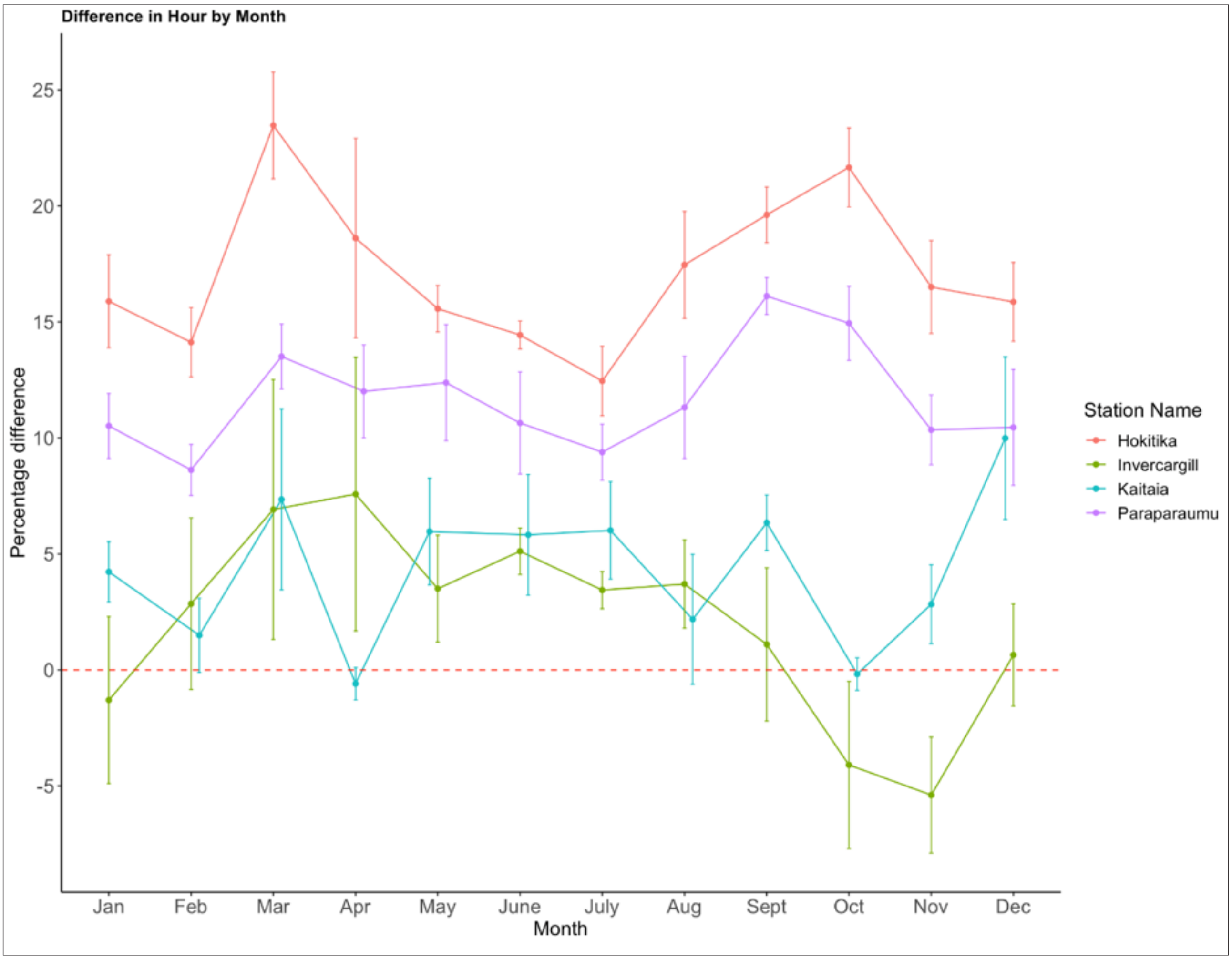

Figure 7: Percentage difference in hourly sunshine duration measured by K&Z and CS instruments, by month, for each of the four study locations. Positive values indicate the K&Z measured higher sunshine duration than the CS, whereas negative values indicate the K&Z measured lower sunshine duration than the CS. Error bars indicate the sampling error calculated using interannual variability of each month. Note that some data have been offset relative to the x axis, to avoid overlapping error bars.

of frequently passing clouds the electronic sensor may be able to accrue periods of short sunshine duration, when those periods aren't sufficiently long to burn a trace in the CS suncard.

Several outliers are also present in the scatterplots (see for example August and December at Paraparaumu; Figure 6). There are several potential sources of error regarding CS measurements, which primarily relate to the manual handling of these data. For example, the trace burned into a suncard may be inaccurately interpreted by the observer, or the daily sunshine duration total may be entered into the climate database incorrectly. In addition, K&Z instruments could be a source of error if there are issues with calibration.

Figure 7 shows the percentage difference between the K&Z and CS instruments for each month of the year, at each of the four study locations. Note that a positive percentage difference indicates the K&Z instrument measured higher sunshine duration than the CS instrument. Overall, the percentage difference is typically positive. The positive difference observed was highest at Hokitika for all months of the year. The highest positive difference of approximately 23% was observed at Hokitika in March. A negative difference was observed in Invercargill from September to November, as well as January. A slight negative difference was observed in Kaitaia in April. When combining the monthly data for the year overall, the average percentage differences at each site were approximately: Hokitika +17%, Paraparaumu +12%, Kaitaia +4%, and Invercargill +2%. Sampling error bars have also been included in Figure 7, showing the monthly interannual variability as defined by the standard error of the mean monthly percentage difference. Interannual variability is relatively high for Invercargill in the months of March, April, September and October. Relatively low interannual variability is observed for Hokitika and Paraparaumu overall, except for Hokitika in the month of April.

It is unclear what factors have caused the observed differences in K&Z and CS sunshine durations. One contributing factor could be the extension of the suncard burn trace during strong and intermittent sunshine, which can result in the overestimation of sunshine duration (Painter, 1981). Furthermore, cloud types have an important role to play. Matuszko (2012) found that under an overcast sky, higher sunshine durations were observed if the cloud type was Cirrus and Cirrostratus (i.e. relatively thin and high cloud) compared to Stratocumulus and Stratus (i.e. relatively thick and low cloud). Some cloud data are available in New Zealand's National Climate Database. However, information pertaining to cloud amount and type is insufficient both spatially and temporally to further explore the effect of cloud on sunshine durations observed in New Zealand.

When observing the percentage differences presented in Figure 7, there is an apparent separation in the differences of Hokitika and Paraparaumu (percentage difference typically between 10% to 20%) compared to those of Invercargill and Kaitaia (percentage difference typically between -1% to 7%). This likely can't be accounted for by a latitudinal difference, as Invercargill and Kaitaia are at the extreme high and low latitudinal range of the four study locations. One geographical feature of Hokitika and Paraparaumu is they each are situated on the western side of a mountain range. Given the prevailing westerly flow of weather systems in New Zealand (Macara, 2018), these two locations may observe differences in variables such as the prevailing cloud type and relative humidity compared to Invercargill and Kaitaia. Although not within the scope of the present study, these factors may be worthy of subsequent analyses.

The mean percentage differences should not be interpreted as any sort of correction factor. As is apparent in Figures 3 – 6, both instruments agree well at the ends of range, for overcast or clear skies. Rather, the differences occur for broken or scattered cloud, and a more detailed understanding of instrument responses would be required to reconcile the measurements.

3. Comparison with radiation data

As demonstrated in Section 2, differences in daily sunshine duration measurements from K&Z and CS instruments were common. To assess which measurement is closer to the WMO definition of bright sunshine, the data from each pair of collocated instruments were compared with a measure of sunshine duration inferred from radiation data. This enables a form of validation of the sunshine duration data, where radiation data provide a standardised measure to which both the automatic and manual sunshine duration data can be compared. It is anticipated that the sunshine duration instrument sensor most closely resembling the radiation data will be performing most accurately with respect to sunshine duration measurements.

3.1 Method

A pyranometer is used for measuring 'global' solar

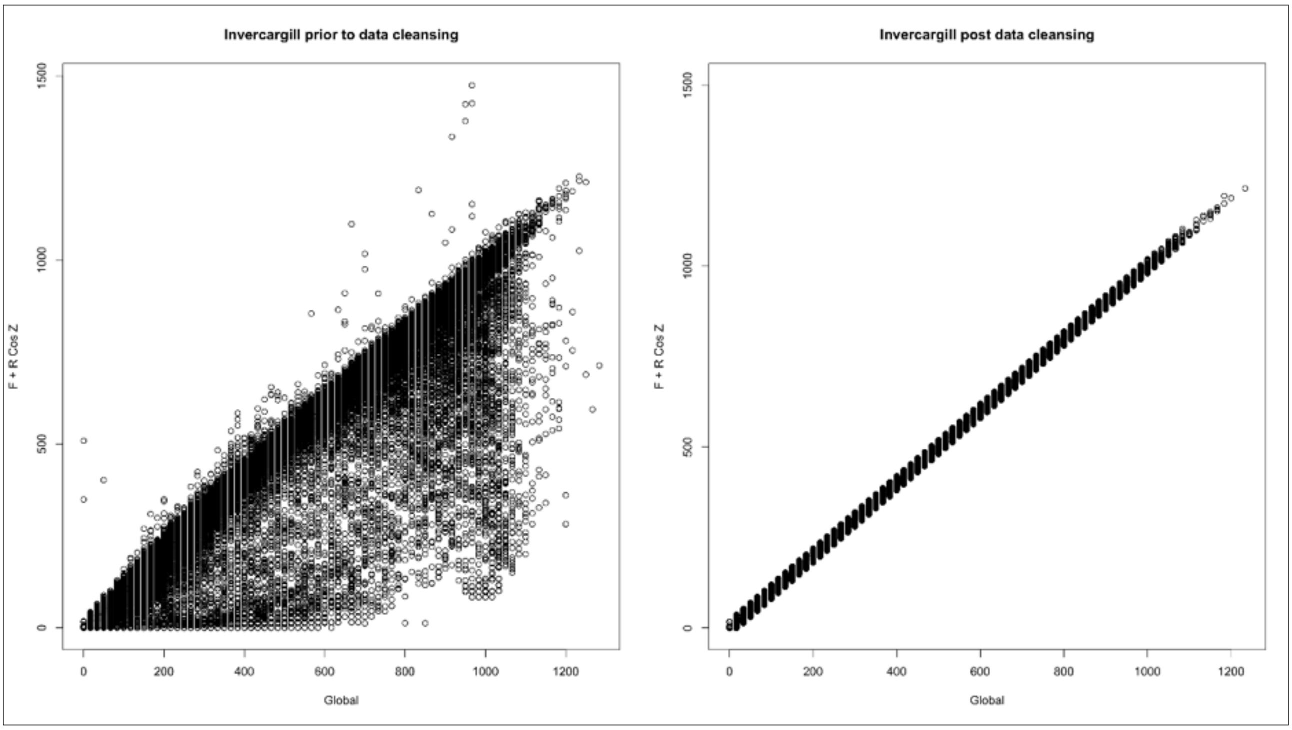

Figure 8: Scatterplot of measured (x-axis) and derived (y-axis) radiation data for Invercargill, showing pre- (left plot) and post-processed (right plot) data.

irradiance on a planar surface. Instruments of this type were operating in parallel with the sunshine instruments at all four of the study locations; indeed, they are deployed at over 100 sites in the New Zealand climate network, mostly recording at hourly timesteps. At three of the sites – Invercargill, Kaitaia and Paraparaumu – data are available from CliDB as 10-minute averages, from the start date of the sunshine duration analyses presented in Section 2 (July 2012). The WMO definition of sunshine duration, as in Section 1.1, is based on direct normal irradiance, from a sun-tracking pyrheliometer. Such instruments are installed at these same three sites, alongside shaded pyranometers that measure diffuse horizontal irradiance. It is usual to measure all three components, though global is a composite of the other two, because it provides for consistency checks as below.

Although 10-minute mean radiation data are available (10-minute average of 3-second sampling frequency), the highest sunshine duration recording frequency in CliDB is hourly. Sunshine duration is recorded for CliDB to tenths of an hour (6-minute intervals), but that does not show when in the hour the sun was unobscured. This difference required aggregation of the 10-minute radiation data to hourly values, to enable comparison of radiation and sunshine duration data.

Before deriving the sunshine duration from radiation data, a series of quality checks were performed, and erroneous observations were removed from the 10-minute radiation data. Radiation data are often beset with errors, from a variety of causes including dirt, rain or frost on detectors; and misalignment of the pyrheliometer, the shade disk, or both. We calculated the corresponding solar zenith angle (Z) based on latitude, longitude and time of observation, and tested the expected relationship of measured Global radiation (G) to the 'component sum' of Diffuse (F) and Direct (R) radiation, which should satisfy:

$$G = F + R\cos Z$$

If all three components are measured with instruments of the highest quality, the 'component sum' is the more accurate measure of *G*, but here it was just used as a consistency check because it was *R* values that were needed.

Quality checks applied to the radiation data:

1. Where all three components were present, global radiation as 'component sum' was derived as above and checked to ensure it was within 20 W m^{-2} of observed global radiation. The observations (all three components) that did not match these criteria were discarded (Figure 8). Both 30 and 40 W m^{-2} were tested as thresholds, which did reduce the number of discarded observations, but not by a considerable margin. Therefore, we chose 20 W m^{-2} for a higher threshold of accuracy. This resulted in a rejection rate of ~55%.

2. If direct radiation was not present, it was derived from diffuse and global radiation for solar zenith angles below 85° subject to check 3 below.

3. Global clear sky irradiance G_c was estimated for each observation using the equation

$$G_c = G_0(\cos Z)^g$$

The constants G_0 = 1122 W m^{-2} and g = 1.15 were derived for Baseline Surface Radiation Network (BSRN) data at Lauder, as used and described in Liley (2018). The derived global clear sky value multiplied by a factor of 0.5 should be greater than observed diffuse radiation for the observations with Z < 85°.

After applying these quality checks, the 10-minute observations were converted into equivalent sunshine duration totals. If the average direct radiation of a 10-minute observation exceeded 120 W m^{-2}, then this was assigned an equivalent sunshine duration of 10 minutes. If the average direct radiation was less than or equal to 120 W m^{-2} for the 10-minute period, then a sunshine duration of 0 minutes was assigned. These 10-minute equivalent sunshine durations were aggregated to hourly totals, then compared with the corresponding hourly sunshine observations obtained from the K&Z and CS instruments. All six 10-minute radiation data were required for the corresponding hourly equivalent sunshine duration to be calculated.

For analyses, the hourly K&Z and CS sunshine duration data were subtracted from the corresponding radiation-derived data. This enabled quantification of the difference in hourly sunshine duration measurements of each sunshine instrument compared to the radiation sensor. For each hour, a tally was generated of the number of occasions where the sunshine duration from the K&Z instrument was closer to the radiation-derived data than the CS duration, and vice versa. Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) were also derived, to assess the variation of the sunshine observations of each instrument from the radiation-derived sunshine duration data.

3.2 Results and discussion

A summary of results comparing K&Z and CS sunshine duration data with radiation-derived data is shown in Table 1. At each of the three study locations, there were considerably more occasions where the K&Z instrument measured a sunshine duration total closer to radiation-derived data than did the CS instrument. For example, in Invercargill there were 3204 occasions where K&Z data matched more closely to radiation-derived data than CS data. This compares to just 565 occasions where CS data were a better match than K&Z data. This comparison may be expressed as a ratio for Invercargill; for each occasion the CS sunshine duration was closer to radiation-derived data, there were 5.7 occasions where the K&Z sunshine duration was closer. In Kaitaia and Paraparaumu, the ratios were both 1:2.4.

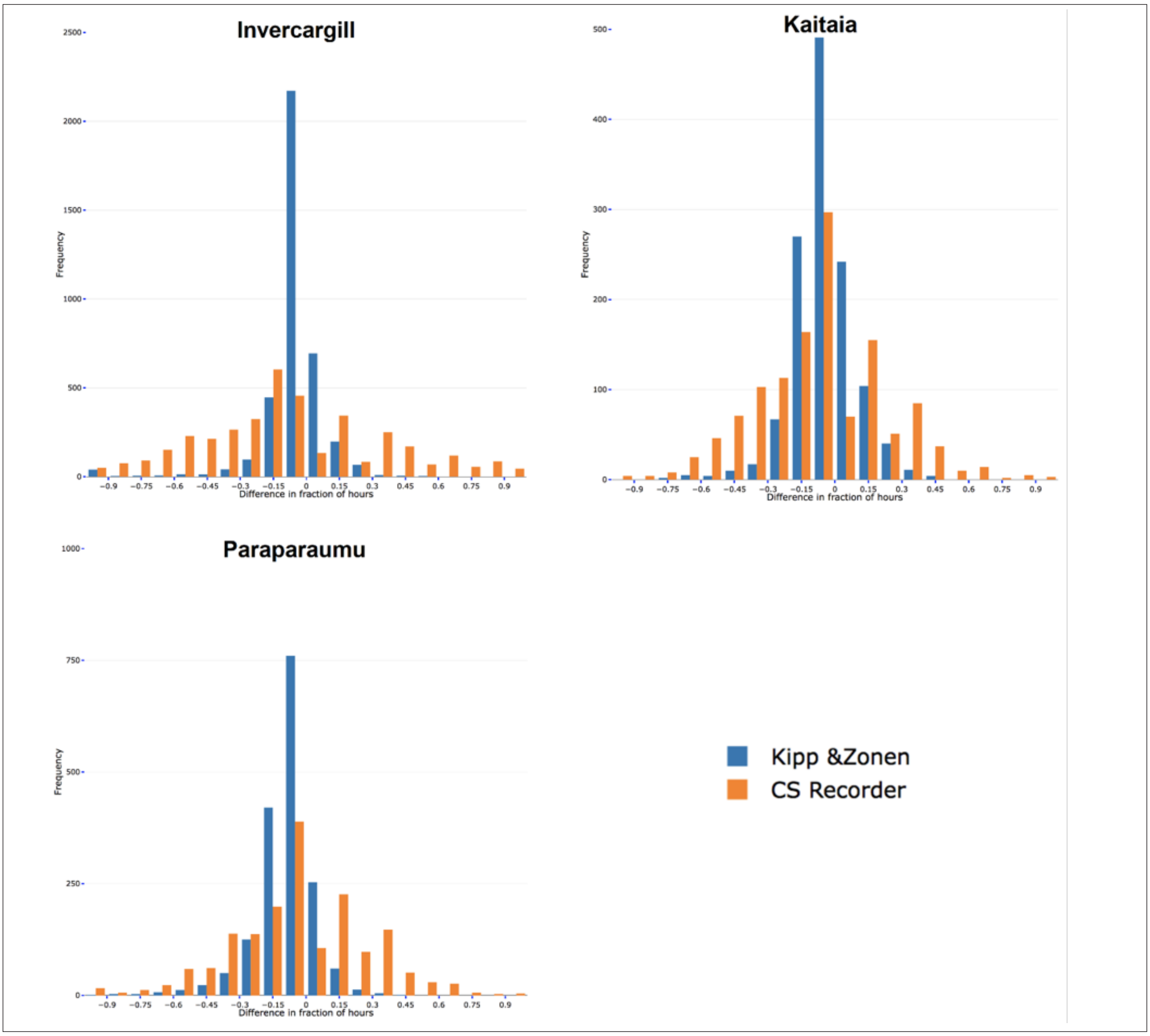

Figure 9: Distribution of hourly differences between CS and K&Z sunshine duration data and radiation-derived sunshine duration data.

Mean absolute errors of the sunshine duration instruments compared to radiation-derived data were considerably different. For the CS, mean absolute error ranged from 0.22-0.32 hours between the three study sites. In contrast, the K&Z mean absolute errors ranged from 0.07-0.09 hours. Similarly, the K&Z root mean squared errors were lower compared to those derived from CS data.

Figure 9 includes a series of histograms for each of Invercargill, Kaitaia and Paraparaumu. These histograms illustrate the distribution of hourly differences between the sunshine duration measured by each sunshine recorder and the radiation-derived sunshine duration. The K&Z data have a unimodal and skewed-left distribution. In addition, there is a high concentration of observations just below zero. For CS, data have a unimodal and symmetric distribution. The highest concentration of observations also falls just below zero.

For both the K&Z and CS, the centre of data is less than

Table 1: Statistics derived from comparing hourly CS and K&Z sunshine duration to radiation-derived sunshine duration

Site name	Campbell-Stokes			Kipp and Zonen		
	Tally of closest observations	Mean Absolute Error	Root Mean Squared Error	Tally of closest observations	Mean Absolute Error	Root Mean Squared Error
Invercargill	565	0.32	0.41	3204	0.07	0.15
Kaitaia	372	0.22	0.29	895	0.09	0.14
Paraparaumu	506	0.23	0.30	1205	0.09	0.14

zero (i.e. negative bias). This suggests that, on average, the sunshine instruments recorded higher sunshine duration compared to radiation-derived data. However, it is important to note that the radiation-derived sunshine duration was only available at 10-minute resolution. As such, hourly radiation-derived sunshine duration totals could only be either 0, 0.17, 0.33, 0.50, 0.67, 0.83 or 1 hour. In contrast, sunshine duration data from the sunshine instruments were available at a resolution of 0.1 hours (6-minute resolution).

It might be expected that duration values derived from 10-minute means would lead to positive bias in the difference from K&Z or CS, as direct irradiance of 800 W m^{-2} ($Z \approx 70°$) for just 90 seconds of the 10 minutes would ensure a mean value above 120 W m^{-2}. This difference may also contribute to the negative bias observed in Figure 9. Data of higher time resolution are not available for sites with simultaneous CS and K&Z data. At Lauder there are K&Z measurements alongside BSRN data for G, F, and R at 1-minute resolution, and these would support further study of any bias from time-aggregation, but that may not help to reconcile the recent K&Z data with past Campbell-Stokes records.

4. Conclusion

K&Z and CS instruments frequently measure different daily sunshine durations during all months of the year. The difference in sunshine duration measured by each instrument appear smaller on mostly sunny or cloudy days; whereas the differences appear higher on days of periodic cloudy weather. Further investigation is required to verify this apparent relationship. Overall, all four study sites demonstrated a positive percentage difference in average monthly sunshine duration when comparing K&Z and CS data, which indicates that the K&Z instrument recorded higher sunshine durations. Percentage differences between the four study sites ranged from an annual average of +2% at Invercargill to +17% at Hokitika. However, Invercargill observed four months where the average percentage difference was negative, and Kaitaia observed one such month. Homogenisation of CS sunshine duration data with K&Z data would be a beneficial goal, to allow better comparison of contemporary sunshine duration data to New Zealand's historic sunshine duration data (e.g., Liley, 2009). However, both the intra- and inter-site variability of concurrent sunshine duration measurements made by these instruments mean such homogenisation would prove challenging and ultimately unsuitable.

Hourly sunshine durations were derived from radiation data, with 120 W m^{-2} applied as the sunshine occurrence threshold. This provided a standardised reference for comparison with sunshine instrument data. By taking radiation-derived data as reference, K&Z sunshine duration data were more frequently closest matching compared to CS data. In addition, mean absolute errors and root mean squared errors were considerably lower for K&Z sunshine duration data. Based on these results, the K&Z instrument is more suitable than the CS instrument for the measurement of sunshine duration. This is pertinent given the WMO's definition of bright sunshine as 120 W m^{-2} of direct solar irradiance, as it is important for climate observations to follow contemporary and internationally accepted best practice.

Future work could include investigation of the CS and K&Z observing higher sunshine duration compared to the radiation-derived sunshine durations. In addition, further examination may provide insight regarding the relatively high percentage differences between K&Z and CS instruments at Hokitika and Paraparaumu compared to Invercargill and Kaitaia. At present, radiation data stored in CliDB are of 10-minute resolution and K&Z data are stored at hourly resolution. However, these instruments sample at a frequency of three seconds. Obtaining data of higher temporal resolution could be beneficial to future investigations. It is desirable to maintain the current network of CS sunshine recorders for as long as possible. This will enable continued ability to compare contemporary sunshine duration observations from manual instruments with New Zealand's most historic observations.

Acknowledgements

The authors would like to thank Andrew Harper and Alan Porteous for their support of this work.

References

Baumgartner, D. J., Potzi, W., Freislich, H., Strutzmann, H., Veronig, A. M., Foelsche, U. and Reider, H. E., 2018. A comparison of long-term parallel measurements of sunshine duration obtained with a Campbell-Stokes sunshine recorder and two automated sunshine sensors. Theoretical and Applied Climatology, 133, pp. 263-275.

Kerr, A. and Tabony, R., 2004. Comparison of sunshine recorded by Campbell-Stokes and automatic sensors. Weather, 59, pp. 90-95.

Liley, J. B., 2009. New Zealand dimming and brightening. J. Geophys. Res., 114, D00D10.

Liley, J. B., 2018. Stability of solar radiation sensor calibration in the NZ Climate Network. Weather and Climate, 38, pp. 26-35.

Lockart, N., Kavetski, D. and Franks, S. W., 2015. A new stochastic model for simulating daily solar radiation from sunshine hours. International Journal of Climatology, 35, pp. 1090-1106.

Macara, G. R., 2018. The climate and weather of New Zealand. NIWA Science and Technology Series Number 74. ISSN 1173-0382. 50p.

Matuszko, D., 2012. Influence of cloudiness on sunshine duration. International Journal of Climatology, 32, pp. 1527-1536.

Matuszko, D., 2015. A comparison of sunshine duration records from the Campbell-Stokes sunshine recorder and CSD3 sunshine duration sensor. Theoretical and Applied Climatology, 119, pp. 401-406.

Painter, H. E., 1981. The performance of a Campbell-Stokes sunshine recorder compared with a simultaneous record of the normal incidence irradiance. Meteorological Magazine, 110, pp. 102-109.

Urban, G. and Zajac, I., 2017. Comparison of sunshine duration measurements from Campbell-Stokes sunshine recorder and CSD1 sensor. Theoretical and Applied Climatology, 129, pp. 77-87.

World Meteorological Organization, 2010. Manual on the Global Observing System (WMO-No. 544), Volume I. Geneva.