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A technique for quantifying the reduction of solar radiation due to cloud and tree cover.

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Abstract

The micro-climate of a domestic residential landscape can affect both the energy use of the dwelling and the human thermal comfort within that landscape. Radiant energy produced from, or reduced by different landscape elements such as trees, and hard and soft surfaces, directly affects the amount of heat incident on the walls of the residence or on people present in the garden. Quantifying this energy will enable the development of a relative scale of thermal performance for these elements and consequently for the landscape as a whole. This gives a measured consequence for each landscape design, allowing comparisons and hopefully improvements, between and within designs.
Radiant energy is produced from direct or diffuse solar short wave and infrared radiation and longwave radiation from heated landscape elements. This paper presents a technique which has been developed for inexpensively and easily estimating the amount of incident radiation reduced by cloud and by three different tree types. The measurement surfaces of cheap temperature sensors with data logging capabilities (iButtons) were coated with either a white gloss or a matt black paint. White gloss paint has an emissivity of ~0.9 in the longwave spectrum but only ~0.3 in the short wave, whereas matt black paint has an emissivity of ~0.95 for both and can be used to detect both short and long wave radiation. The temperature difference between the two gives a measure of the amount of shortwave radiation or visible light. This enabled measurements of cloud shade and local plant shade, and an estimation of the quantity of that shade when compared with full sky exposed reference iButtons. The iButtons can be mounted concurrently at numerous points around a house envelope or in a landscape, at multiple house locations to determine the quantity of shade provided by different native and introduced plant species.

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Keywords: Micro-climate; thermal radiation; iButtons; landscape design

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Introduction

The microclimate of a residential landscape can have a significant influence on increasing resilience (social, economic and ecological) and reducing emissions ([1], [2]). The landscape has an effect on the emissions produced by the residence through cooling and heating requirements; shade reduces the amount of radiant heat on surfaces thus reducing absorbed, re-radiated and reflected heat; transpiration from vegetation increases cooling; permeable surfaces increase the amount of water available to vegetation, increasing transpiration rates; trees planted together can create wind breaks, moderating hot or cold breezes ([3], [4], [5],[6]). These effects increase the resilience of the homeowner economically through reduced energy costs, and health-wise through a cooler home environment (lower heat stress) both within the landscape and inside the residence ([1]). Ecosystem services provided by gardens go beyond those of thermal services to include aesthetic appeal, improved air quality, biodiversity, water and wind management, food production and many more ([7], [8]). For example, green landscapes are also associated with reduced stress and increased mental health - substantiating the concept of biophilic design ([9], [10], [11]), however the thermal effects are more easily quantified and in this paper will form a starting point for landscape comparisons.

Comprehensive research has been done on the effects of both shade trees and light coloured surfaces in reducing energy use by homeowners and increasing human thermal comfort. The [12] report from fieldwork, that strategically planted trees and shrubs could typically reduce summer air conditioning costs by 15-35% and up to 50% is some situations; other more recent studies based on both computer modelling and fieldwork have found similar results ([13] show a reduction of 20% due to urban trees and high-albedo surfaces; [2] and [14] show tree shade is associated with reduced electricity consumption in summertime depending on tree location; [15] state that trees can contribute 167kWh/tree of electricity savings). [16], [17] and [3] report reduction in energy use and improvement in Human Thermal Comfort due to green infrastructure. [18] found that trees could reduce heat stress from ‘very strong’ to ‘strong’. [19] found air conditioning requirements were reduced by using rooves of higher total solar reflectance, as did [20]. [21] showed tree shade could reduce surface temperatures of buildings by up to 9°C. This body of knowledge would be improved by measuring and modelling the thermal properties of more types of landscape elements and their relative positions within a residential landscape (particularly where tree shade is not possible) to both reduce energy use and improve human thermal comfort.

[6] studied the effect of using vines to shade the walls of houses. He used thermocouples attached to sheets (10x15cm) of aluminium backed with styrofoam as the “walls” behind the vines and recorded data using a data logger over a period of several years. The aluminium was painted either dark brown or white to simulate dark or light wall colours. In much the same way, this study uses self-logging temperature sensors painted either black or white to examine the incident radiation under conditions of full sun, tree shade and cloud shade. Although instrumentation is commercially available to measure both long and short wave radiation (pyrgeometers; pyranometers), and to measure quality of tree shade (LAI-2200 [22]; hemispherical photography), they are relatively expensive which limits the amount of measurements which can be done concurrently. By designing a cheaper alternative, multiple landscapes can be monitored over different seasons, providing a much larger data set for analysis.

Nomenclature

JH	Josh Byrnes’ House
SR	solar radiation, includes direct and diffuse
LWR	longwave radiation, 3 - 100μm
SWR	shortwave radiation, 0.1-3μm
T_B	Temperature of the black painted iButton
T_W	Temperature of the white painted iButton

1. Methods

1.1. Calibration Methods

The company Maxim Integrated produces a product called an iButton. This a computer chip enclosed in a 16mm diameter stainless steel can. The Thermochron is an iButton which can measure temperature and logs this data over time with parameters being user controlled through computer connection of a 1-Wire interface. The small size, reliability, accuracy and durability of the iButton makes it eminently suitable for scientific fieldwork.

The top surface of one iButton was painted black using a matt black PVC paint (estimated solar absorptivity 0.95, emissivity 0.95). This iButton absorbed almost all the incident radiation, regardless of wavelength. One other iButton was painted with a white gloss PVC paint (estimated solar absorptivity 0.3, emissivity 0.90). This iButton absorbed almost all the incident LWR and reflected approximately 70% of the SWR or visible light. The temperature difference between these iButtons gives an estimation of the amount of incident SWR or visible light.

The iButtons were mounted in individual polystyrene block of dimensions ~40 x 40 x 20mm and were slightly recessed within this block by about 1mm. Each block was then covered with Gladwrap leaving a small air gap to the surface of the iButton. Gladwrap was used to prevent convective losses and is a suitable plastic (Polyethylene) to use, being a very good transmitter of both LWR and SWR [23].

The back of each polystyrene block was attached to a wooden mounting block using Velcro. The iButtons were attached with their surface horizontally facing skywards. Measurements were done at JH. The wooden block was fixed approximately 3m above ground level at the north-west side of the house to give a clear sky view throughout the day. Monitoring was done over a period of 12 days with a 10min sampling rate. Concurrent readings were taken from JH pyranometer (SolData 80spc, range 0.3 – 1.15 μm)[24, 25].

1.2. Tree shade methods

Four iButtons were painted black and four painted white. One set of iButtons consisted of one black and one white iButton recessed in their polystyrene blocks, covered with Gladwrap and mounted on a wooden block with their surfaces horizontally facing upwards. One set was placed about 2m high and such that it would have a clear sky view for the whole day. This was the reference set which enabled cloud shade if any, to be determined. The second set was placed ~2m to the south of a peach tree such that it would receive shade from this for the middle part of the day. This tree had lost its leaves and was classified as providing light shade. A third set was placed similarly to the second set ~2m to the south of a very young acacia saligna (Western Australian golden wattle). This tree provided moderate shade. A fourth set was placed directly under an adenanthos cunninghamii (prostrate woollybush) and was under heavy shade for most of the day. Monitoring was done for a period of 4 days at a sampling rate of 10 mins. A GoPro was set up to take visual images of the second set of iButtons to establish the times of tree shading. This test was repeated on another day for comparison, with the iButtons located in approximately the same locations (Fig. 1).

Fig. 1. Images of the reference iButtons, iButtons under heavy, medium and light shade respectively.

2. Results

2.1. Estimating the amount of cloud shade

2.1.1. Calibration curve

Graphs of solar radiation and the temperature difference between the black and the white iButtons ($T_B - T_W$) versus time of day were examined visually for their similarities. From these it was apparent that when the cloud passes over the sun, the pyranometer registers this decrease in radiation at a faster rate than the iButtons – estimated to be somewhere between 1 and 10 minutes. (A finer grained estimation is not possible as the sampling intervals were 10min.). Similarly, after the cloud had passed, the pyranometer readings increased at a faster rate than the iButtons. In other words, the response time of the instruments is different. This is due to the pyranometer using a photovoltaic cell to measure light radiation (readings are almost instantaneous), whereas the iButtons are measuring heat and their thermal mass affects their response time. An example of this effect is shown in Fig. 2. Another factor affecting the apparent response time is the time at which readings are taken by the pyranometer and the iButtons. These times can differ slightly due to experimental start-up conditions, meaning that the two readings can be out by 1 – 2 minutes.

To artificially increase the response time of the pyranometer, a 2-point moving average was used on JH SR (see the curve added in Fig. 2). The averaged JH SR data were then used in the calibration curves.

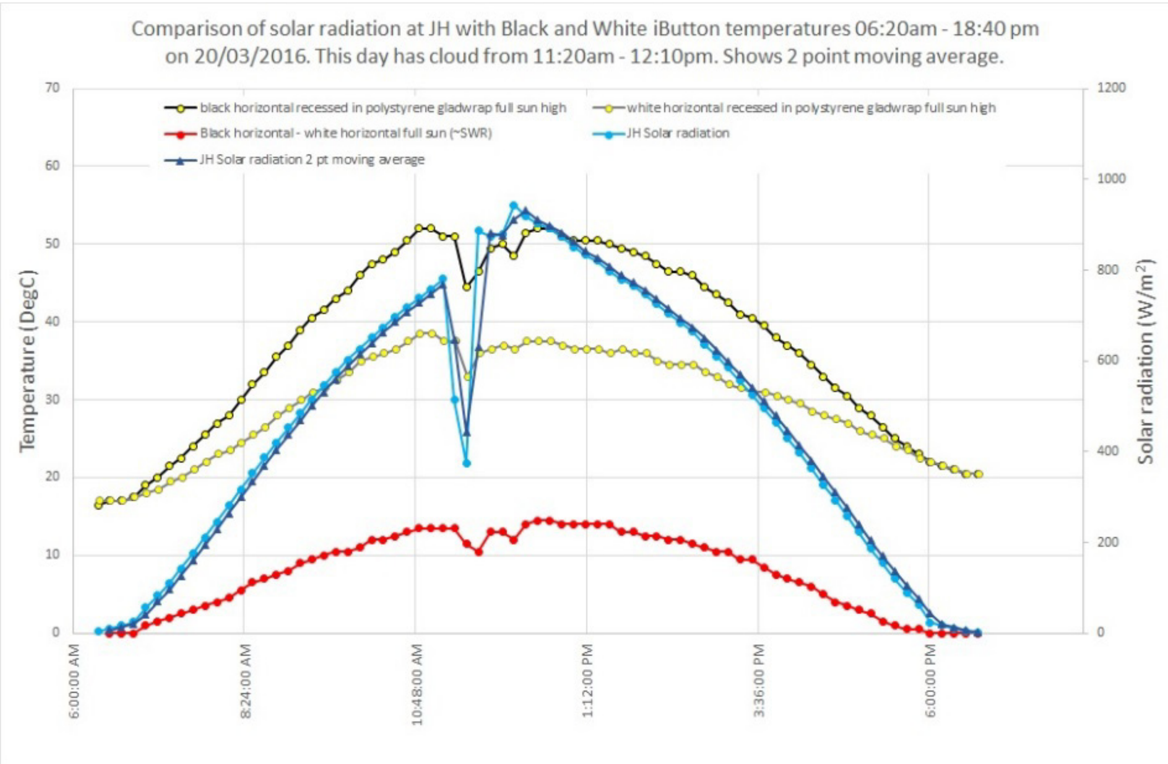

Fig. 2. Comparison of solar radiation at JH with Black and White iButton temperatures 06:20am - 18:40 pm on 20/03/2016. This day has cloud from 11:20am - 12:10pm. Shows 2 point moving average.

To calibrate the readings of the iButtons against the readings from the pyranometer, a graph of solar radiation versus $T_B - T_W$ was plotted for data from only clear skies. The data used was from a test at JH from 12/3/2016 to 24/3/2016 (Fig. 3). Clear skies were determined by visual examination of the solar radiation data and choosing the data which followed a smooth sinusoidal pattern. The linear fit to this was:

$$SR = 56.772 * (T_B - T_W) + 17.407 \quad (1)$$

with an R^2 value of 0.9857.

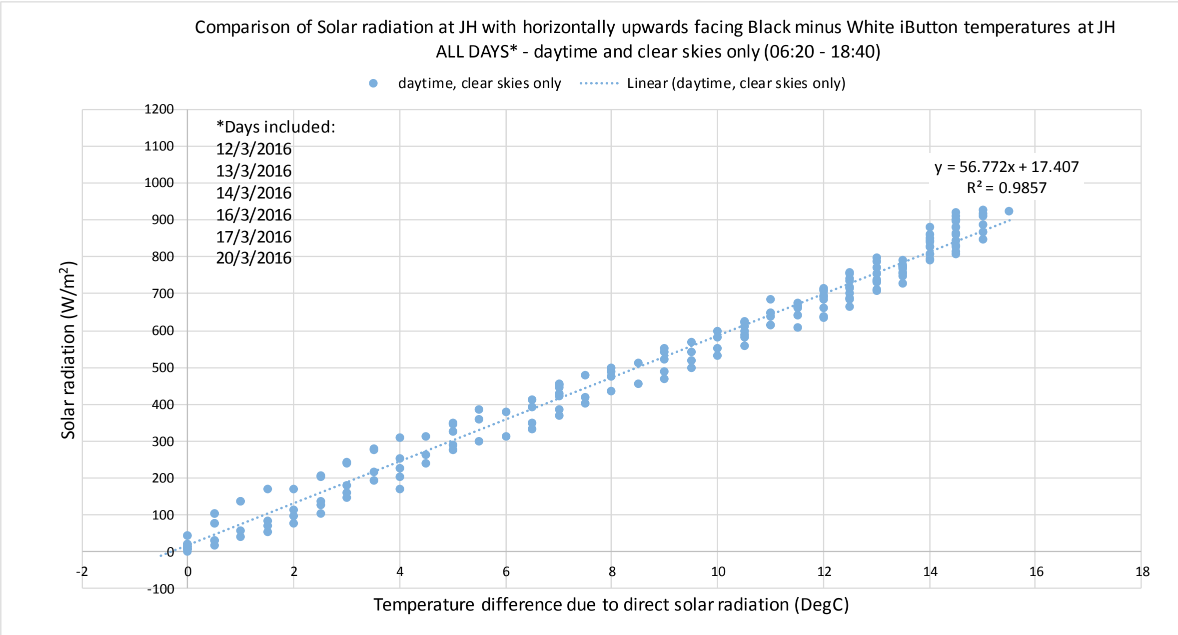

Fig. 3. Solar radiation at JH versus horizontally upwards facing Black minus White iButton temperature at JH. ALL DAYS* - daytime and clear skies only (06:20 - 18:40).

To examine the effect of cloud shade, a graph was plotted for one day (20/3/2016 as per Fig. 2) during this test where there were mostly clear skies but which had a short period of cloud around the middle of the day (Fig. 4). It would be expected that the points relating to the time of cloud shade would lie on the clear sky line but at a lower radiation level as there would be less solar radiation incident on both the pyranometer and the iButtons during this time. In this case however, the cloudy data points were also scattered at a distance from the main line. This discrepancy can be explained when looking at the raw time based data of the solar radiation and the black and white iButton temperatures and their differing response times as described earlier (Fig. 2). The error in the pyranometer due to forward scattering from heavy cloud can be as much as 10-20% [24] so this will also significantly influence the scatter in the cloudy data.

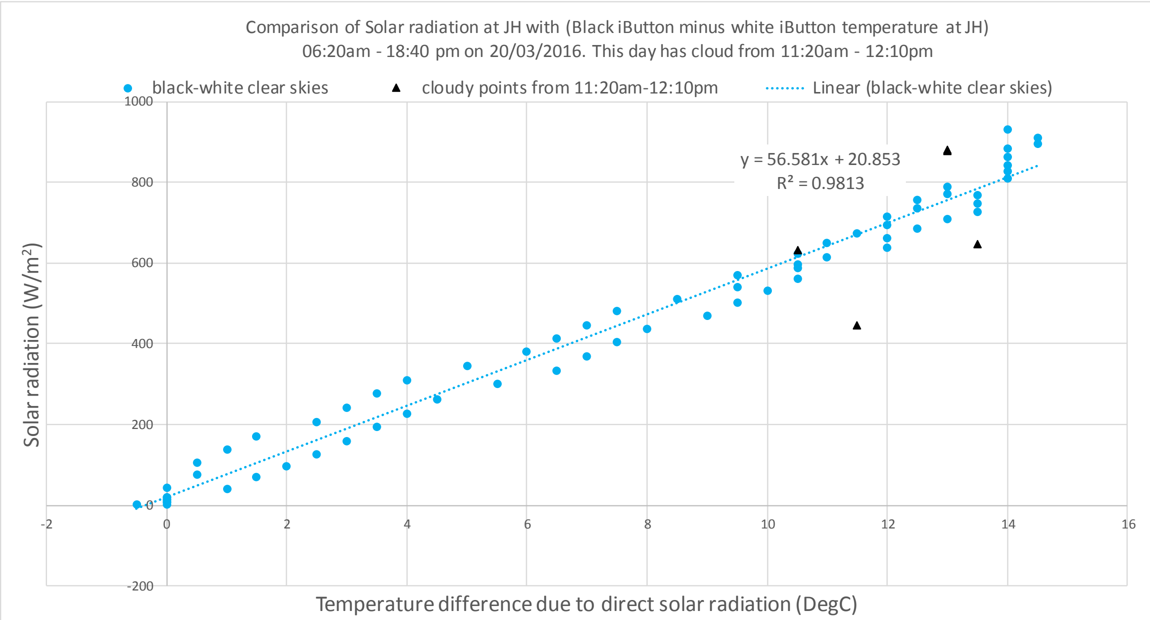

Fig. 4. Solar radiation at JH versus horizontally upwards facing Black minus white iButton temperature at JH. 06:20am - 18:40 pm on 20/03/2016. This day has cloud from 11:20am - 12:10pm.

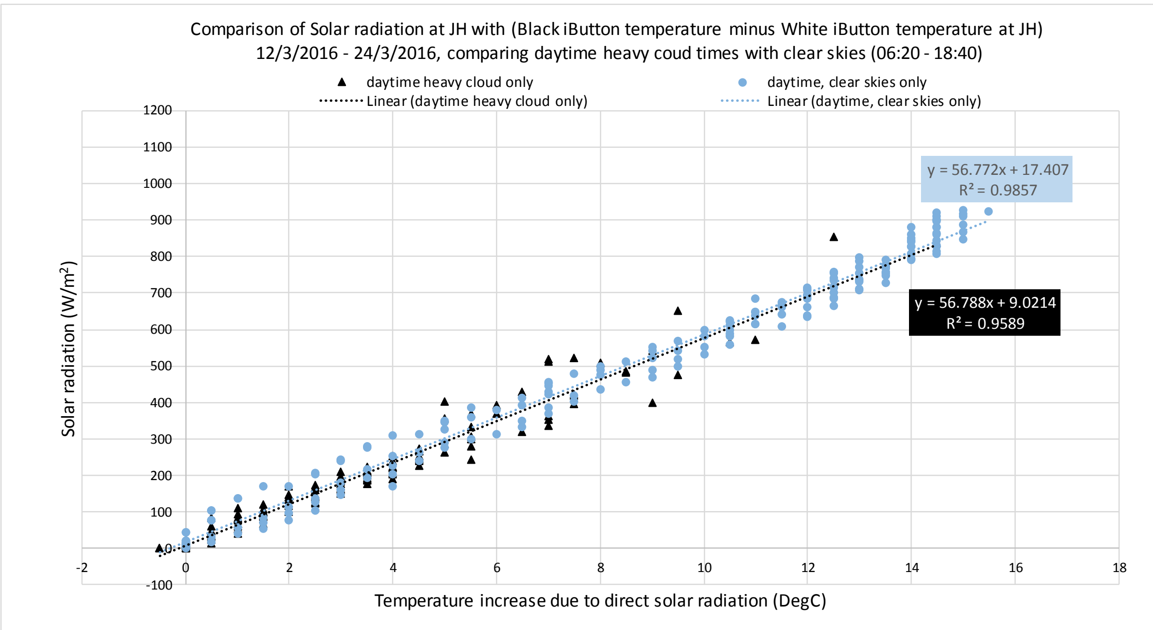

Fig. 5. Solar radiation at JH versus (horizontally upwards facing Black minus White iButton temperature at JH) 12/3/2016 – 24/3/2016 clear skies only and 19/3/2016 and 23/3/2016 daytime heavy cloud only (06:20 - 18:40).

To minimise the effects of both the different response times and the different off-set times, a similar graph was plotted for two days during this test (19/3/2016 and 23/3/2016) where the cloud shade was consistently quite heavy (as determined by the solar radiation readings from the pyranometer being below 400 W/m^2 for most of the day). This is shown in Fig. 5 as a comparison to the clear sky data. The linear fit to this curve was:

$$SR = 56.788 * (T_B - T_W) + 9.0214 \tag{2}$$

with an R^2 value of 0.9589.

The similarity between the curves shows that under conditions of cloudy or clear skies, the relationship between the temperature difference of the black and the white iButton is consistent with the solar radiation they receive. With the clear sky data giving more accurate measurements, the linear fit (trendline) from this data (Equation 1) was thus used as the calibration curve for solar radiation versus $T_B - T_W$.

The uncertainty in the solar radiation measurements from this trendline is 34.6 W/m^2 which gives a percentage uncertainty of 10% or less for solar radiation values greater than 350 W/m^2. Below 350 W/m^2 the error becomes significantly worse and the calibration curve would be of decreasing value.

All night time data (SR = 0 W/m^2) of $T_B - T_W$ was between -1.0 and 0.5 °C indicating that within the accuracy of the iButtons (±1°C, or ±0.5°C, depending on the type used), the emission of longwave radiation from both black and white iButtons is the same.

2.1.2. Generating a clear sky radiation table

This calibration curve (Equation 1) was used to calculate the amount of radiation incident on the iButtons given a measured $T_B - T_W$ at a particular date and time. If the solar radiation incident under clear skies in Perth at that same time and day of the month were known then the fraction of radiation actually incident (as determined from the iButtons) could be calculated. This would give a quantitative measure of cloud shade.

In lieu of going into the complexity of modelling incident solar radiation for all times and days of the year, existing pyranometer data for a two year period was used to generate a table of solar radiation incident on Perth versus time of day and year. The data from JH during 2014 and 2015 were used to extract three whole clear sky days of radiation data per month, with the days spread as evenly as possible across each month, for a one year period. It was assumed that the variation in radiation readings at each time of day, over the timeframe of a third of a month, would not be significant. To confirm this, an example of three days clear sky radiation is shown in Fig. 6.

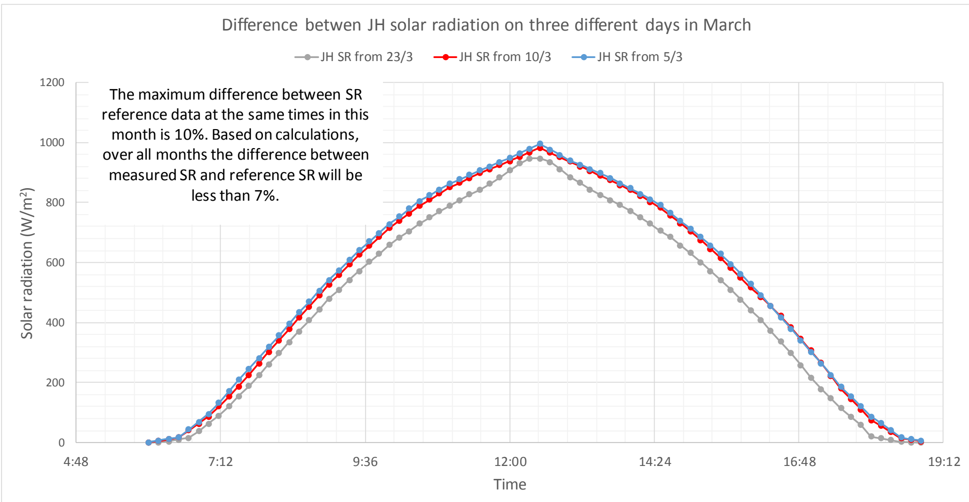

Fig. 6. Three days of clear sky radiation from JH SR in the month of March.

The maximum number of days between each clear sky reference day was 17, (with the average being 10 days), which means that the maximum number of days between measured and reference data would be half of this (8.5). Looking at all reference data which were less than 9 days apart showed that the maximum difference between SR reference readings was 7%. Hence the error in comparing measured data to the reference data would be less than 7%, but on average around 4% (looking at data from less than 5 days apart).

This extracted year of data was used as a lookup table for measurements done at a particular time and for the date closest to the extracted data as possible. This gave the solar radiation expected to be incident on the iButtons at that time which was then compared with the radiation calculated from Equation 1. The resultant fraction of measured radiation over clear sky radiation quantified the percent cloud shade according to:

$$\%Cloud\ shade = \left(1 - \frac{SR_{measured}}{SR_{clear\ skies}}\right)\ \% \qquad (3)$$

where $SR_{measured}$ is the solar radiation determined from the $T_B - T_W$ calibration curve and $SR_{clear\ skies}$ is the solar radiation extracted for the same day and time from the existing pyranometer data for clear skies.

The uncertainty in the % cloud shade is calculated from the uncertainty in $\mathrm{SR}_{\mathrm{measured}}$ (up to 10%) and the uncertainty in $SR_{clear\ skies}$ (up to 7%) and is approximately 12%.

As an example, the % cloud shade for the 20/3/2016 as per Fig. 2 is plotted in Fig. 7 where the errors during the clear sky part of the day can be seen to be up to ~10%.

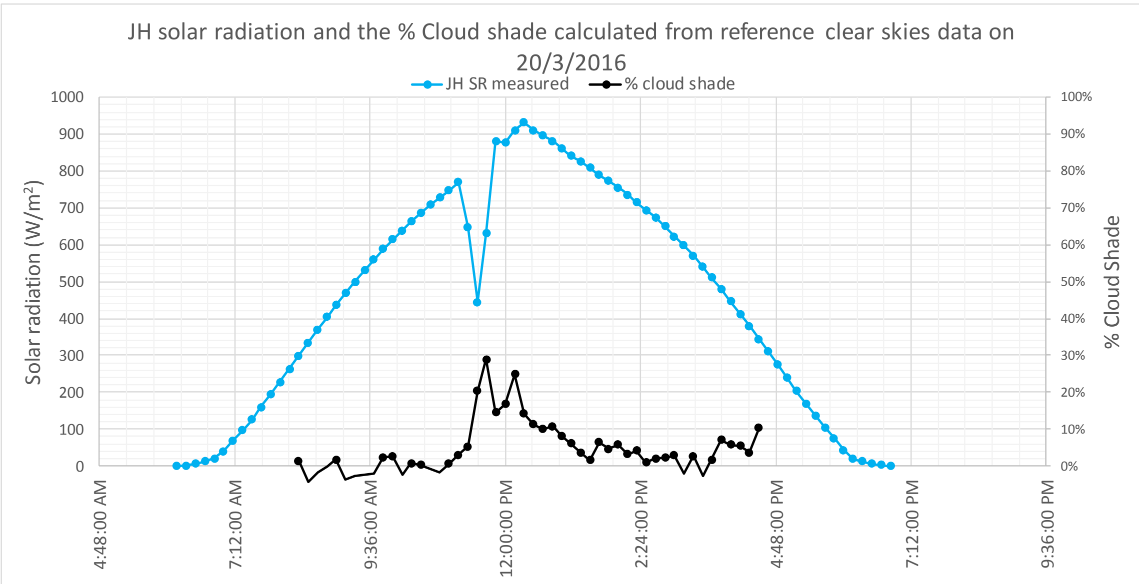

Fig. 7. JH solar radiation and the % Cloud shade calculated from reference clear skies data on 20/3/2016.

2.2. Estimating the quantity of tree shade

Data from the reference black and white iButtons were compared with those measured under the light, medium and heavy tree shade over the times of shading for each of the five periods of sampling. The area under the $T_B - T_W$ curves were calculated. This gave a number proportional to the amount of energy received by the iButtons over time. This was based on the fact that $T_B - T_W$ is linearly proportional to the incident radiation as shown by the calibration curve (Equation 1). The percent shade was then calculated using:

$$\%shade = \left(1 - \frac{Area\ under\ (T_B - T_W)_{tree\ type}}{Area\ under\ (T_B - T_W)_{reference}}\right)\ \% \tag{4}$$

Table 1. The shade quality measured under three different tree types: Light shade - peach tree with no leaves; medium – acacia saligna; heavy – adenanthos cunninghamii.

Date	Light	Medium	Heavy
24/05/2016	17%	64%	80%
25/05/2016	9%	73%	90%
26/05/2016	16%	61%	71%
27/05/2016	6%	75%	91%
31/05/2016	26%	65%	88%
Average % shade (Stdev%)	15% (8%)	68% (6%)	84% (9%)

The uncertainty in the iButton measurements ($T_B - T_W$) is between 4 and 10% (assuming their precision is ±1.0°C and temperatures from 14 to 35°C).

3. Discussion and conclusion

Tests have shown that the temperature difference between a black and a white painted iButton ($T_B - T_W$) remains linearly proportional to the amount of incident solar radiation, regardless of the quantity or quality of cloud cover. The following are three conclusions which can be drawn from these results.

Firstly, when the amount of solar radiation which would be incident if it were a clear day is compared to this measured temperature difference at a particular time of day and year, the percent of cloud shade present at that moment can be calculated. Although the error in these measurements is up to 12% (for solar radiation of greater than 350 W/m^2), the cheap cost of iButtons means that they could be used to approximate the more accurate and expensive solar pyranometer in field work where measurement at a number of test sites may be required concurrently. The accuracy of this would be improved if the particular iButtons to be used were initially calibrated against a solar pyranometer to generate their own calibration curve, as it is expected that the calibration curve would vary slightly depending on the individual iButtons used.

Secondly, (and the main use of these measurements) is that a pair of horizontally facing full sky black and white painted iButtons can be used as a reference when investigating the quality of shade incident on another pair of horizontally upwards facing black and white iButtons. This is due to their linear response to the amount of incident radiation as shown by the calibration curve. The reference set of iButtons can be easily located on the same measurement site as the other iButtons and would be responding to the same incident solar radiation, making them more indicative of local conditions than solar pyranometer readings from a fixed reference site possibly located a few kilometres away.

Thirdly, in a similar manner, a pair of horizontally upwards facing black and white iButtons underneath a tree or shrub is able to give an approximate measure of the quality of shading from that plant by comparing with the $T_B - T_W$ from a reference pair of iButtons. The cost of these measurements is minimal and because they can be taken over a longer period of time (several hours), they reduce the impact of sun flecks and leaf orientation on the result.

A limitation to consider when using this iButton system are the fairly large radiation losses of the black iButton due to its small size (experiments showed up to 30% loss when compared with an iButton placed at the back of a black painted aluminium plate of size 23 x 37 cm, around twice the size of the plate used by [6]). The smaller iButtons however, are more suited to tree shade measurements as the black and white need to be very close together to negate effects of parallax on the incident radiation through tree branches and leaves. The method of comparing the iButtons under a tree or cloud with the reference iButtons, means the effect of these radiation losses would be minimal.

Another consideration is that if the solar absorptivity of the white paint were closer to 0 (i.e. more reflective in the visible wavelengths), then the value of $T_B - T_W$ would more accurately measure the incident SWR (with an absorptivity of ~0.3, the white paint used here absorbs some of the incident SWR). For the current measurements however, the calibration of $T_B - T_W$ against the known solar radiation, allows $T_B - T_W$ to be used without having to determine the absolute value of the SWR.

In conclusion, the iButtons could be used for further investigation of the shading quality of different common types of native and introduced species of trees and shrubs. These measurements would relate directly to the amount of incident radiation the plants are reducing from both the ground (landscape) and/or house walls, which can affect both the human thermal comfort within that landscape and the energy use of the dwelling.

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