Revision of UV Intensity Data

Prepared for Ministry for the Environment

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Contents

Executive summary

We have updated the UV Index daily peak, solar noon and standard erythemal dose (SED) data from 1981 to the end of 2023 for sites in Leigh, Paraparaumu, Christchurch, Lauder, and Invercargill.

The data come from broadband instruments of Robertson-Berger type that approximate the standardised spectral response of erythema (reddening) of untanned human skin in response to solar UV radiation. Except for early measurements from Invercargill, which were half-hourly until 2007, the data are from 10-minute integrations transmitted to the NIWA Climate Database and converted there from millivolts to UV Index.

After subtraction of dark noise estimated from midnight values, the initial scaling relies on calibrations either from a laboratory or side-by-side measurements with a suitable reference.

Following WMO recommendations, there are corrections for departures of that instrument, or class of instruments, from the ideal spectral response and angular dependence. These corrections are functions of solar zenith angle, which can be calculated to high precision, and on total ozone column. For the latter, satellite measurements or other estimates can be used.

From budget constraints and instrument failures, procedures to maintain reliable calibrations have lapsed. The results are especially apparent for Leigh and Paraparaumu. As a result, we do not consider that the data as accessed from the Climate Database provide a reliable source for continuation of the past time series.

We initially proposed to attempt a retrospective ‘field calibration’, by comparison of the measurements with clear sky model values that are already used in the data processing and served with the measured UVI from the Climate Database.

Instead, we found significant variation ratio by season, suggesting large errors in the angular response. To better understand the results, we have reviewed all the SQL code for on-line processing, and implemented the same procedures in another computer package to check that the WMO algorithms are correctly applied.

As a result, we can reproduce the on-line processing, but also find that the simple clear-sky model suggested by WMO contributes much of the seasonal and diurnal ratio of measurement to model on clear days. We use instead a model that provides a better fit to Lauder spectrometer data, and similarly reduces the variation between measurement and model for clear days.

Applying all of the above, except for earlier data where some questions remain, we have revised the reprocessed all the data by deriving revisions of both the calibration and the correction records used in routine processing. We intend that these revisions will be implemented in the Climate Database, so that it would then serve the revised values.

Meantime, as required by the Ministry for the Environment and Ministry of Statistics, we have used the revised values to calculate daily peak and solar noon values of UVI, and the standard erythemal dose (SED) estimates for each day.

1 Introduction

1.1 Background

The Ministry for the Environment and Stats NZ are required, by the Environmental Reporting Act 2015, to report on the state of the environment using a pressure-state-impact framework. Reports include ‘UV intensity’, ‘Wildfire risk’, and ‘Annual glacier ice volumes’ indicators.

For the last report on UV intensity in 2017, NIWA analysis suggested that the source data showed variation over time that suggested varying instrument response. We suggested that the data quality could be improved by recalibration that used data on the clearest days, together with the best ozone data, to identify such changes .

In response, the Ministry contracted NIWA to:

- *Provide an update to UV Index daily peak, solar noon and standard erythemal dose (SED) data from 1981 to the end of 2023 for sites in Leigh, Paraparaumu, Christchurch, Lauder, and Invercargill.*
- *Provide a short technical report documenting the methodology, limitations, and results of the analyses.*

The contract further stipulated that:

> *existing methodologies in (Macara 2017) and (Liley et al. 2014) will be followed where appropriate. The report will include details on any data recalibration required. The report will be internally reviewed and signed off for release at NIWA to ensure appropriate quality and rigour of the work.*

1.2 Data Sources

The datasets for this analysis are retrieved from the NIWA Climate Database as records of UV Index derived from measurements with broadband instruments that are designed to measure erythemally-weighted UV irradiances (McKinlay and Diffey 1987). Measurement sites include Leigh (36.27° S, 174.80° E, 27 m asl), Paraparaumu (40.90° S, 174.98° E, 5 m asl), Christchurch (43.53° S, 172.61° E, 6 m asl), Lauder and Invercargill (46.42° S, 168.33° E, 1 m asl). The longest time series, beginning in 1981, is from Invercargill, where measurements from a Robertson-Berger (R-B) meter (Robertson 1968; Grainger et al. 1993), with 30 minute integrations, extend to February 2009. More recent data for Invercargill (since September 2007), and data for the other sites since the mid 1990s (McKenzie et al. 1996), have been acquired with new-generation temperature-stabilised versions of these old instruments, with 10-minute integration periods. Comparison of data from the two different Invercargill instruments in the overlap period show that they agree within measurement uncertainty.

Currently, all instruments in the network are UVB-1 pyranometers from Yankee Environmental Systems (http://www.yesinc.com/index.php/products/solar-radiation/8-products/54-uva-b-html). Daily data from the network (and from Callaghan Innovation’s recent additions to the network) are available to the public on the internet (https://www.niwa.co.nz/our-services/online-services/uv-and-ozone/yesterdays-uv-index) and past data can be retrieved from the NIWA Climate Database, now accessed via NIWA’s Datahub (https://data.niwa.co.nz/products/climate-station-10min-parameter?filter:parameter=UV&page=2). Note that this service is undergoing continued development and may change.

As described by Liley et al. (2014), past practice was that instrument calibration was periodically checked by comparison with model calculations under clear-sky conditions. If systematic errors greater than ±5% were observed, the instrument was switched and the old instrument sent back to Lauder for recalibration against the UV spectroradiometer system, thus providing traceability back to the NIST irradiance scale. Over the last decade, that scrutiny has not been applied, for several reasons.

Foremost has been the shortage of funding, which has not supported the staff time required.

Second, instrument failures have meant that NIWA has not had spare instruments to swap. In particular, the instrument at Paraparaumu has failed and has been at Lauder for repair. It is also possible that the YES UVB-1 instruments will be superseded by different instruments, and we are trying to do this in concert with other UV networks internationally.

Finally, the system to process UVB data was implemented by John Sansom, who passed away some years ago. Other NIWA staff had not mastered the theory or use of his code.

Data are processed according to procedures recommended by the WMO (Seckmeyer et al. 2008). This processing includes corrections that are functions of ozone amount (derived from satellite data) and solar zenith angle to account for (1) differences between the instrument band-pass and the target erythemal action spectrum, and (2) imperfect angular response of the instruments. Finally, the erythemally-weighted irradiances are converted to UV Index (UVI) values, which are used in public advisories. If UV_{ery} is measured in μW cm^{-2}, then $UVI = 0.4 \times UV_{ery}$.

In New Zealand, clear-sky noon-time UVI values range from winter values of ~1 in the south of the country, to summer values in excess of 14 in the north of the country. Peak values in New Zealand are about 40% greater than at corresponding northern latitudes (McKenzie et al. 2006; Seckmeyer et al. 1995; Seckmeyer and McKenzie 1992). However, peak values globally, which occur in the Altiplano region of South America, are nearly twice as high as the peak values observed in New Zealand (Zaratti et al. 2014). The measurement uncertainty for these broad-band measurements is approximately ±10% (Seckmeyer et al. 2008). Data are archived on the NIWA Climate data base.

2 Analysis

2.1 Data preparation

We initially assembled the datasets as used in previous reports and applied the same known error corrections and analysis to derive updates the same summary variables.

The maximum values are peak UVI values for the period within 30 minutes of solar noon each day; a period chosen for comparability with spectrometer data around solar noon. Daily UV doses are expressed in Standard Erythemal Doses (SED), where 1 SED is 100 J m^{-2} of erythemally-weighted UV (McKenzie et al. 2014). On a clear summer day, there can be ~70 SED. The Minimal Erythemal Dose (MED), causing first perceptible skin reddening, depends on individual skin type, sun protection, and pre-existing tan; 1 MED ~ 2 SED for the most sensitive skin types (Fitzpatrick 1988).

Daily peak UVI for the five sites, as retrieved from the NIWA Climate Database, is shown in Figure 1, as similarly illustrated in Liley et al (2014). Failure of the Paraparaumu instrument in August 2022 is readily apparent, but the data for Leigh also look suspect. The steady decline in peak UVI since 2014, or possibly earlier, is not expected for any physical reason, such as a marked increase in cloudiness or in ozone column. The ozone in a column above in New Zealand is typically 90% stratospheric; the country does not have the substantial air pollution responsible for tropospheric ozone production. Ozone amounts anywhere over NZ are mostly driven by that stratospheric flow, and consequently mean amounts are reasonably uniform over the country.

Similarly, there is no record of marked change in cloudiness over Leigh or the wider area that could explain the change. The most likely explanation is that the instrument response has declined for some reason, and the sensor should be swapped out as in past practice.

As described above, this is no longer an option, for Leigh or Paraparaumu. Instead, we proposed to base the recalibration for Leigh, and other sites if appropriate, on a comparison with model clear sky values. In fact, this is facilitated by John Sansom's implementation of the WMO-recommended procedure.

2.2 Routine processing

The algorithms implemented in SQL within the NIWA Climate Database proceed in several steps. The primary requirement is a calibration factor to convert measured millivolts to µW cm^{-2} but, as elaborated below, understanding calibration procedures is facilitated if we first consider subsequent corrections, which use calculated solar zenith angle and ozone values as available.

2.2.1 Correction factors

Ozone enters the correction calculation via the instrument band-pass. This effect arises because the spectral response of the filter and sensor combination does not exactly match the CIE action spectrum. The balance of UVB and UVA wavelengths in daylight depends primarily on the solar zenith angle and the total ozone amount. There is a much smaller dependence on cloud cover at UV wavelengths because most of the light is diffuse even on clear days at mid-latitudes.

As described by Seckmeyer et al. (2008), the correction factor is derived from a ratio of Radiation Amplification Factors (RAF) measured or calculated for the specific instrument.

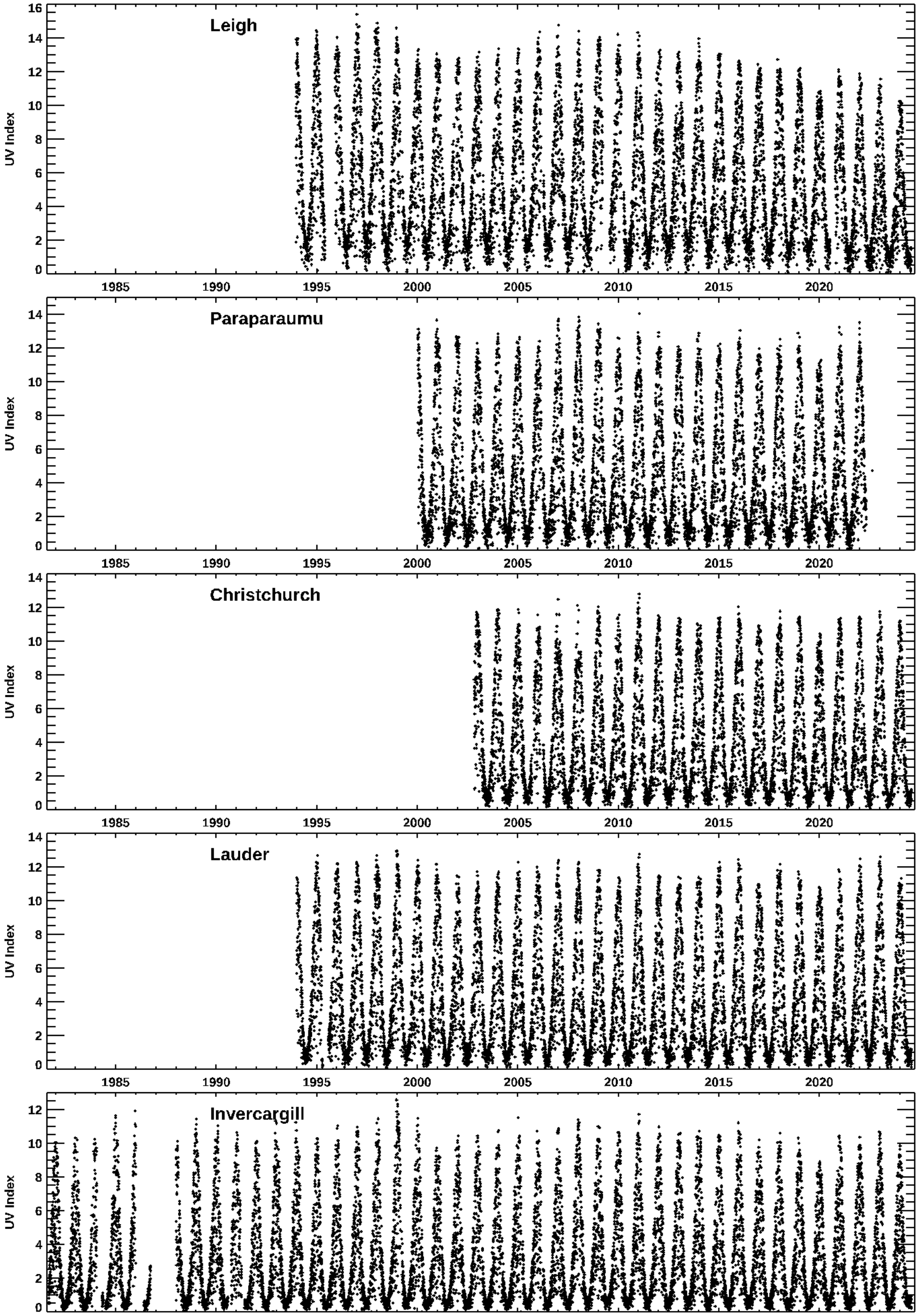

Figure 1. **Daily peak UVI for the five New Zealand sites.** The Leigh data are suspect, as there is no expectation on physical grounds for reduction in peak UVI of this magnitude.

The RAF for any given spectral response describes how the integrated irradiance is affected by a small change in ozone. For example, around 300 DU of ozone, a 1% decrease in ozone causes a 1.1% increase in erythemal irradiance, so RAF = 1.1 for the standard erythemal action spectrum.

From the measured spectral response of an instrument, its RAF for different incidence angles and total ozone column can be calculated, and the ratio of the RAF for erythema to that instrument RAF gives the correction factor.

For example, the values in Table 1 are used to correct measurements for YES1, as deployed at Lauder.

Table 1. Bandpass correction factors for YES1. The tabulated values are interpolated to ozone values and calculated solar zenith angle for each measurement.

Ozone	Solar Zenith Angle																			
DU	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
100	1.61	1.61	1.60	1.59	1.57	1.55	1.52	1.49	1.45	1.40	1.35	1.29	1.23	1.16	1.09	1.03	0.98	0.99	1.09	1.11
150	1.37	1.37	1.36	1.35	1.33	1.31	1.29	1.26	1.23	1.19	1.15	1.10	1.06	1.01	0.97	0.94	0.94	0.99	1.09	1.08
200	1.22	1.22	1.21	1.20	1.19	1.17	1.15	1.12	1.10	1.07	1.04	1.00	0.97	0.94	0.93	0.92	0.95	1.03	1.14	1.10
250	1.12	1.11	1.11	1.10	1.09	1.08	1.06	1.04	1.02	1.00	0.97	0.95	0.93	0.92	0.92	0.93	0.98	1.09	1.21	1.14
300	1.05	1.04	1.04	1.03	1.02	1.01	1.00	0.98	0.97	0.95	0.94	0.92	0.91	0.91	0.92	0.96	1.03	1.15	1.28	1.19
350	1.00	1.00	0.99	0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.92	0.91	0.91	0.92	0.94	0.99	1.08	1.23	1.36	1.25
400	0.96	0.96	0.96	0.95	0.95	0.94	0.93	0.93	0.92	0.91	0.91	0.91	0.91	0.93	0.97	1.03	1.14	1.30	1.44	1.32
450	0.94	0.94	0.94	0.93	0.93	0.92	0.92	0.91	0.91	0.90	0.90	0.91	0.92	0.95	1.00	1.07	1.20	1.37	1.51	1.38
500	0.92	0.92	0.92	0.92	0.91	0.91	0.91	0.90	0.90	0.90	0.91	0.92	0.94	0.97	1.03	1.12	1.25	1.45	1.59	1.45
550	0.91	0.91	0.91	0.91	0.91	0.90	0.90	0.90	0.90	0.91	0.92	0.93	0.96	1.00	1.06	1.16	1.31	1.52	1.66	1.52
600	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.91	0.91	0.93	0.95	0.98	1.03	1.10	1.21	1.37	1.58	1.73	1.58

The spectral response should be measured for each instrument by comparison with a spectroradiometer, but if this is not possible then generic values for that make and model can be assumed. The variation is illustrated in Figure 2, for NIWA's YES instruments 1 to 4.

As can be seen in both Table 1 and Figure 2, the instruments measure significantly less than the actual erythemal UV for two extremes. For high sun (low SZA) it occurs for very low ozone, but the correction is large for ozone values only observed in the tropics (e.g., 200 – 250 DU) or under the ozone hole (less than 220 DU). For the latter, SZA is always large (low sun).

At the other extreme, the instruments under-read markedly when the sun is very low (e.g., SZA > 80°) for a large range of ozone amounts. This situation can arise at any latitude around sunrise or sunset, but then UVI is already very low so there is little risk of UV damage.

For reference, ozone column amounts over Aotearoa NZ are almost always in the range 225 – 450 DU. The minimum SZA depends on latitude, ranging from 11° at North Cape to 23.8° at South West Cape. Amongst the five UV sites, the range is from 12.8° at Leigh to 23° at Invercargill.

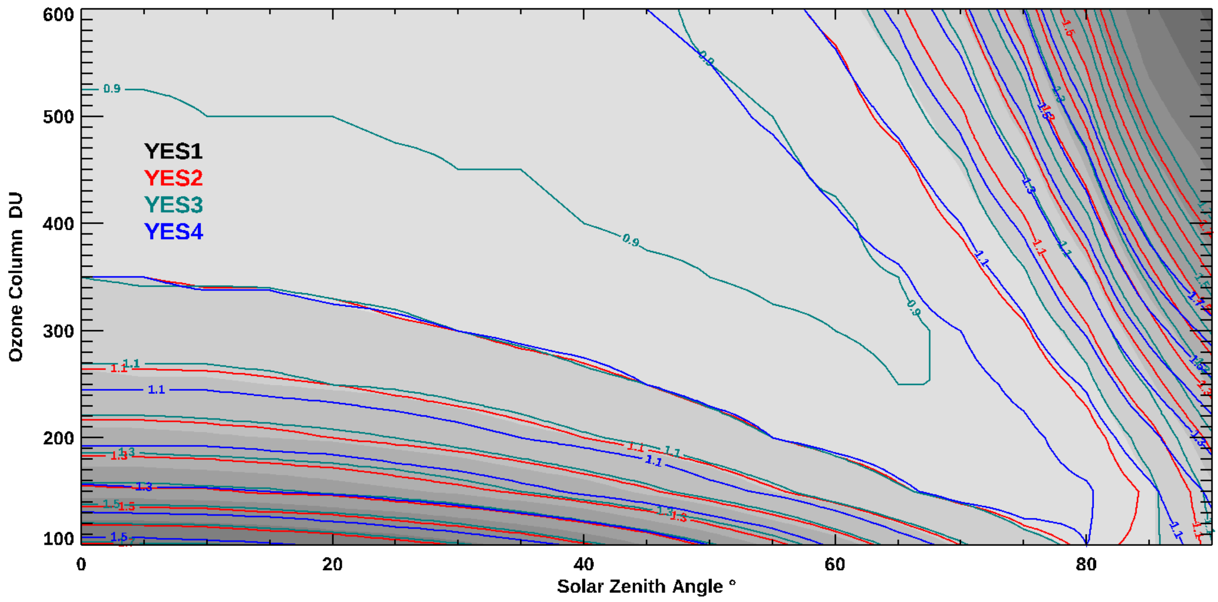

Figure 2. Bandpass correction factors for four YES instruments. The shaded contours are for YES1, with coloured contours for instruments 1 – 3 overlaid for comparison.

The other factor applied in data processing attempts to correct for departures from the ideal angular response. Because the measurements are of irradiance – the flux onto a horizontal surface – the normal-incident radiation coming from any direction is in principle weighted by the cosine of SZA (or equivalently, the sine of elevation angle), so that correction for imperfect angular response is usually referred to as a 'cosine correction'. It is not difficult for instruments to achieve the ideal cosine response for zenith angles from 0° to 45°, but for larger SZA the required correction can be large. For example, for the YES instruments the cosine correction factors are given in Table 2.

Table 2. Cosine correction factors for YES UVB-1. The same factors are used for all NIWA YES instruments.

SZA	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.96	0.92	0.88	0.79	0.67	0.53	0.36	0.20

The ideal cosine response is applicable to direct beam radiation, such as from a collimated source or a solar-tracking telescope. Even for high sun under clear skies, UV radiation is strongly scattered, so that half of the erythemal irradiance is diffuse. For lower sun, progressively less of the erythemal irradiance is in the direct beam, and below 5° of solar elevation none of it is. The cosine correction procedure accounts for this effect by applying the correction for given SZA only to the estimated direct component, and applying an area-weighted hemispheric mean of the correction factors to the diffuse component. The estimate of diffuse fraction for unpolluted clear sky, for solar zenith angle Z degrees, used in the processing is:

$$f = 0.51 - 0.003 \cdot Z + 0.0001 \cdot Z^2 \tag{1}$$

Finally, if the UV Index derived from the sensor is less than half of the model clear-sky value, it can be assumed that the sun is obscured by cloud, and all the erythemal irradiance is diffuse. Then only the hemispheric mean cosine correction is used.

2.2.2 Calibration factor

As noted earlier, the above description departs from the actual sequence. The first step in converting instrument output in millivolts to UVI is to subtract the 'dark signal' (last midnight record) and apply the calibration factor. The source of calibration factor affects how it is applied.

If the calibration factor comes from laboratory testing on a standard source, it is applied directly to convert from measured mV to a first estimate of UV_{ery} in $\mu W\ cm^{-2}$. The above corrections are then applied.

The alternative source of instrument calibration is from comparison with erythemal irradiance derived from a spectroradiometer, such as those at NIWA's Lauder site, which meet the exacting standards of the international NDACC and are traceable to NIST. In that event, the broadband measurement is expected to agree with the spectrometer value only after correction factors have been applied. Thus, to obtain the raw calibration factor, the corrections must reversed. The spectrometer-derived UVI is divided by the dark-corrected sensor output, and the result is divided by the bandpass correction and cosine correction applicable to the time of measurement. Adjustment for overcast conditions is not required, as all such comparisons are made on clear days, and for high solar elevation.

2.3 Revised calibration

As noted in section , there has not been any opportunity to return instruments to Lauder for calibration against the spectroradiometers there. Instead, for this contract we proposed a 'field calibration'; testing measurements on clear sky days against model calculations. Though UVI can be affected by atmospheric aerosol, and by ground cover of high albedo, especially snow, these are not a problem for this exercise. New Zealand has very low aerosol optical depth in most places and times; especially at the five NIWA sites. Significant air pollution is a problem in sheltered valleys in winter, but not in the summer months used for calibration. Snow rarely lies at any of the sites, and again not in summer.

The analysis was facilitated by the fact that UV radiation data in the NIWA Climate Database already contain estimates ozone amount, and also calculated clear sky UVI for those ozone values and the solar zenith angle at the mid-point of the measurement – five minutes prior for the 10-minute data, and 30 minutes earlier for hourly data. Standard meteorological convention is that all measurements representing a time interval are time-stamped at the end of that interval.

In order to check the routine processing, and consider how it could be improved, we implemented all the same steps in another language (IDL), which allows us to quickly test any changes to assumptions or algorithms.

3 Results

We first examined the Lauder data, because of the availability of spectrometer data for additional confirmation.

3.1 Clear sky model

The first requirement is to identify clear sky days, and the context is illustrated in Figure 3 showing daily means of the ratio of measured UVI to the clear-sky model. The wide scatter of points is due to cloud, and the points clustered near the upper envelope are clear days. We tested several objective methods to identify the clearest days.

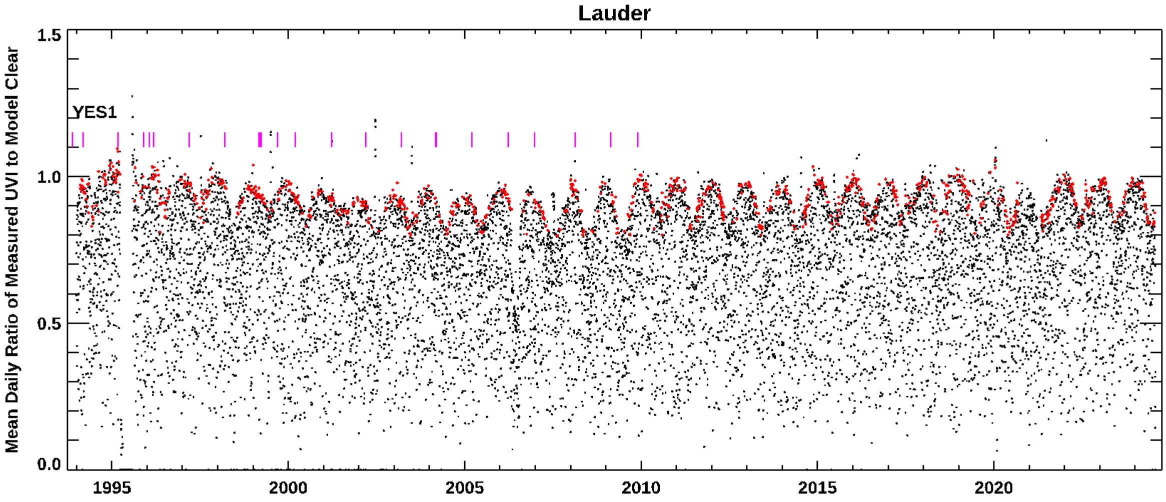

Figure 3. Daily mean ratio of measured to modelled clear sky UVI for Lauder site 5535. The main cause of scatter is cloud, and the envelope of high points represent the clear sky days. Days selected as clear by the method described in the text are highlighted in red. The vertical crimson lines show times when calibration records were derived from comparison with Lauder's UVM spectrometer.

Choosing just the highest values in each year would bias toward the summer months. Although these are preferred for calibrations, to represent the full dynamic range, for our present purpose we also wish to consider winter values.

A simple approach, within each day, is to regress the measured UVI on the clear sky model. For a standard linear fit, any intercept with the ordinate (measured UVI axis) shows imperfect removal of the dark signal, so we restricted to fits with intercepts of magnitude less than 0.2 in UVI units. Low values for the slope are characteristic of cloud, so we limited to slopes greater than 0.8, where the main cluster of close fits lay. Within those limitations, we then selected the 20% of days with the lowest χ^2 values in each year, resulting in 951 days of the 11171 in the Lauder time series. Those days are highlighted in red in Figure 3.

The seasonal cycle apparent for the clear sky values in Figure 3 prompted further analysis. In particular, it prompted the question of whether it results lower sun elevation in winter, together with incorrect values for the cosine correction, or some other seasonal effect such as temperature.

Figure 4 shows the ratio of measured to model UV for all the 10-minute data (1.58 million values), with the data for clear days shown in red. For clarity, mid-winter values of cos(Z) at Lauder only extend up to 0.37 (~68° SZA), and the highest values of cos(Z) = 0.93 occur in mid-summer, but low values of cos(Z) occur all year as the sun rises and sets. Thus, the band of red points shows the combined effects of time of day and time of year. Separating the points by season (not shown), we find they all lie in the same band, so the dependence is just on SZA, not other seasonal change.

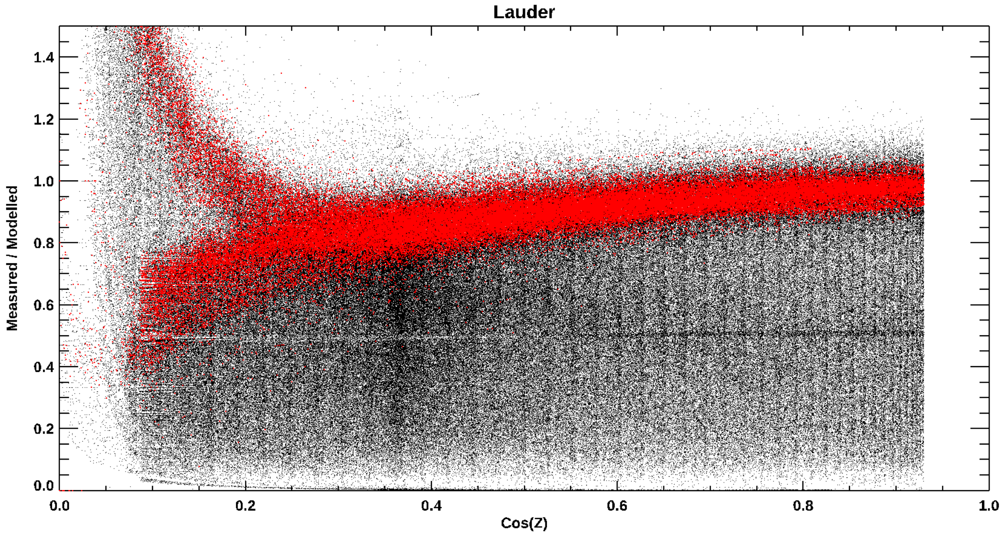

Figure 4. **Ratio of measured to modelled clear sky UVI vs cosine of SZA for Lauder site 5535.** This figure now includes all 10-minute data, with values for the above clear-sky days again highlighted in red.

On the other hand, the bifurcation occurring around cos(Z) = 0.3 in Figure 4 does not have any obvious explanation, either in the underlying physics or in the processing algorithms. We could also not associate it with time of day, season, or ozone.

After some exploration, we identified a problem with the calculation of clear sky UVI. The SQL code implements the simple model of Madronich (2007) to calculate UVI from SZA and ozone, but there seem to have been some problems with time alignment affecting SZA. Misalignment has negligible effect around the noon period, but it causes large proportionate error at large SZA.

Recalculating model values, again with the Madronich algorithm, and also repeating the correction of measurements, produces results as shown in Figure 5.

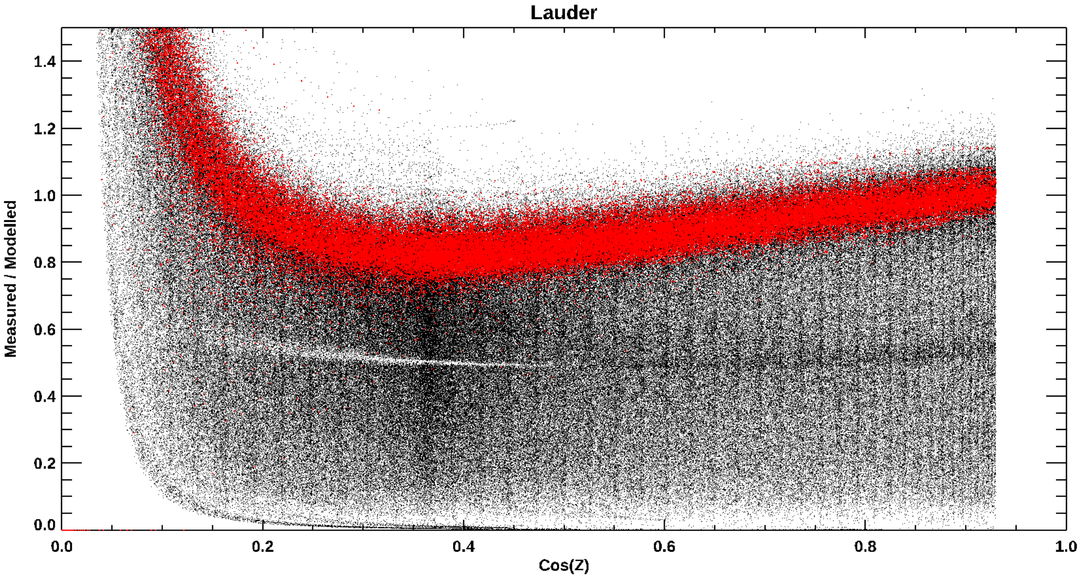

Figure 5. **Recalculated ratio of measured to modelled clear sky UVI vs cosine of SZA for Lauder.** This figure shows the result of recalculating the values in Figure 4.

The striking feature in comparing Figure 5 with Figure 4 is that it is the upper branch of the bifurcation in the original data that remains, rather than the lower. The recalculated data do now seem to suggest a consistent revision of the cosine correction, which should have the effect of bringing the cluster of red points near to unity. Before deriving such a revision, we considered a further change.

While the Madronich algorithm has been widely applied, its representation of the effect of ozone strictly via RAF does not closely match UVI values from Lauder spectrometer data. The Madronich formula is:

$$UVI = 12.5(\cos(Z))^{2.42} \cdot (O_3/300)^{-1.23} \tag{2}$$

with

UVI	UV index
Z	solar zenith angle
O_3	column ozone amount in Dobson Units.

We find much closer agreement to spectrometer data with an alternative formula that expresses the effect of ozone as a polynomial in the difference from the ansatz value of 300 DU:

$$UVI = 12.86(\cos(Z))^{2.65} \cdot (1 - 0.00457(O_3 - 300) + 0.0000155(O_3 - 300)^2) \tag{3}$$

with the same definitions as above.

Using Equation (3) for the same comparison as above gives much closer agreement between measured and modelled UVI for the identified clear sky days, as shown in Figure 6.

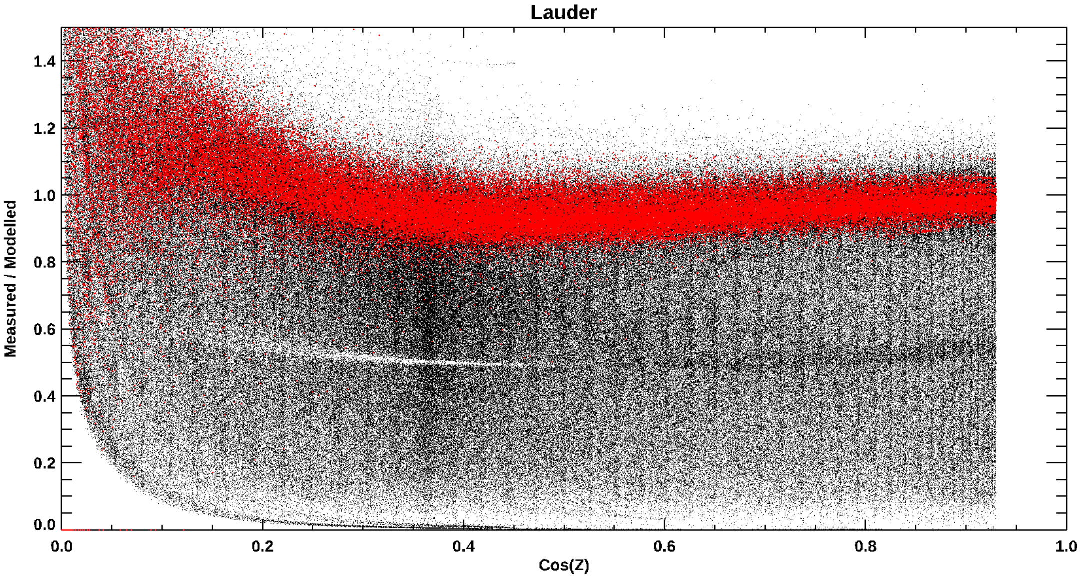

Figure 6. Ratio of measured to alternative model clear sky UVI vs cosine of SZA for Lauder. This figure shows the result of recalculating the values in Figure 4 using Equation (3).

Using the same alternative model also produces a revision of Figure 3, as shown in Figure 7. The smaller dependence on SZA apparent in Figure 6 substantially reduces the seasonal variation in measured UVI as a fraction of the model values. We conclude that it is a better representation of clear sky UVI for revising the instrument calibration.

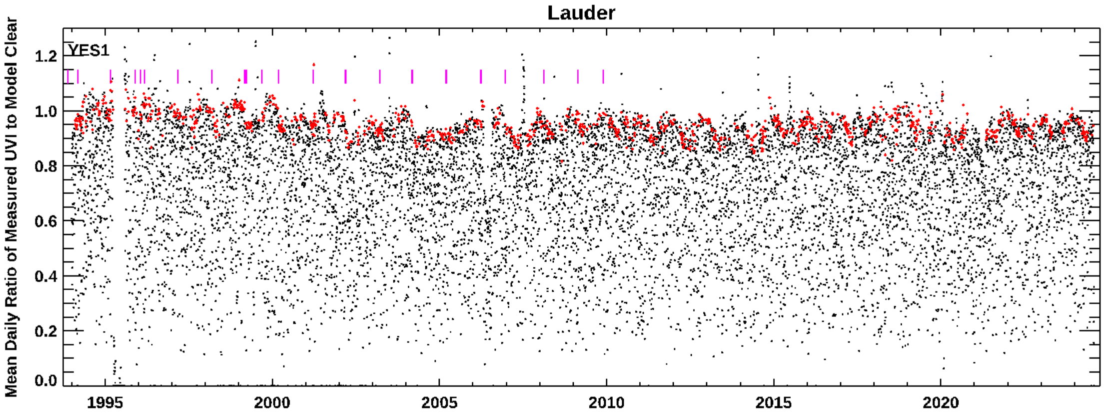

Figure 7. **Daily mean ratio of measured to alternative model clear sky UVI for Lauder.** The smaller dependence on SZA in the alternative model of clear sky UVI gives much less seasonal variation.

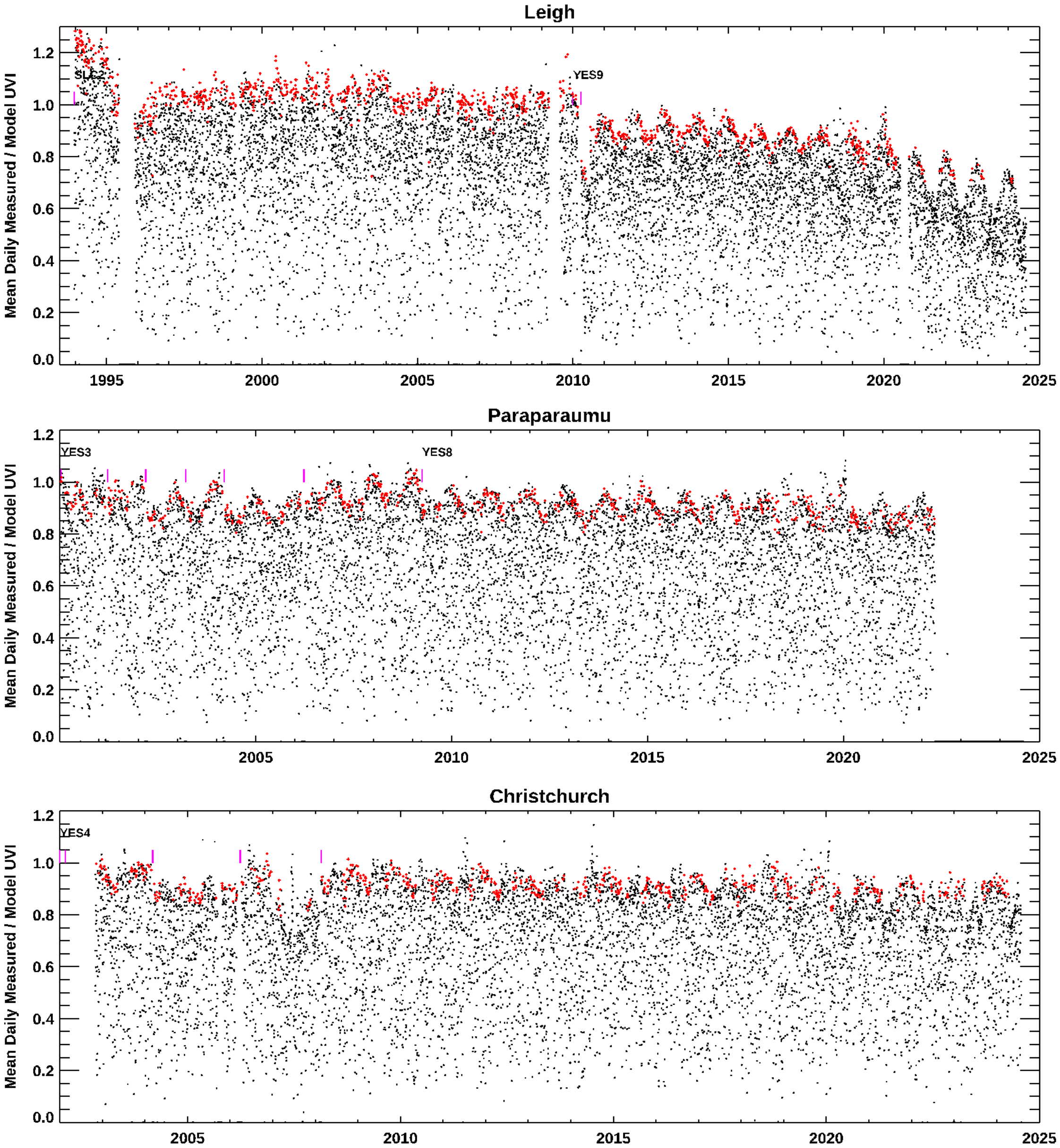

Figure 8. **Daily mean ratio of measured to model UVI for Leigh, Paraparaumu, and Christchurch.** These ratios all use the alternative model, providing a basis for recalibration independent of season.

Using the alternative clear sky model for the other four sites, as shown in Figure 8 and Figure 9, reduces the seasonality of the ratio of measured to model for clear days. This provides a better basis for recalibration both because more clear days are detected and it easier to distinguish instrumental change from seasonal effects.

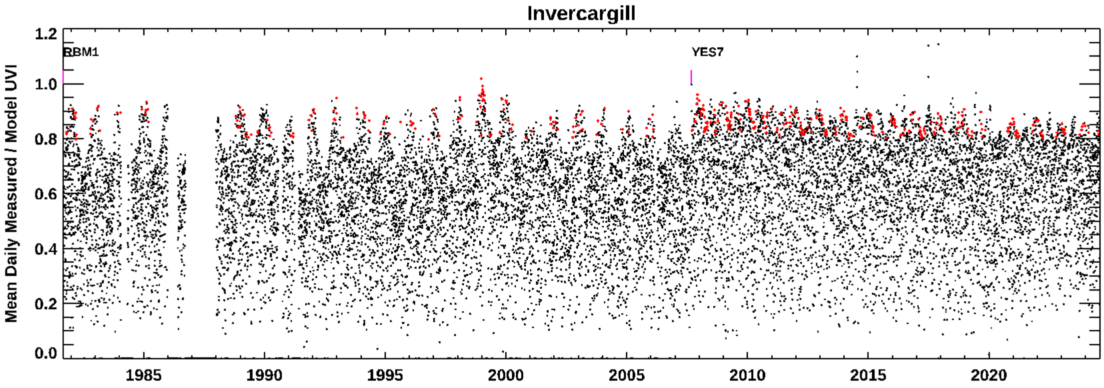

Figure 9. Daily mean ratio of measured to model UVI for Invercargill. The data before 2007 are from an original Robertson-Berger meter. Unlike the subsequent 10-minute YES7 data, the early values are half-hourly, and they were supplied as UV values rather than processed in the database.

In this analysis, the Leigh data more clearly show the decline, especially after 2020. The data for Paraparaumu, Christchurch, and Invercargill all seem to show some decline, which we address in the next sub-section.

The data for Invercargill before September 2007 are materially different from the later data, for several reasons. As noted in Section 1.2, they were obtained with an eponymous Robertson-Berger Meter deployed by the NZ Meteorological Service in 1991, and subsequently calibrated at Lauder (Grainger et al. 1993). The data were 30-minute integrations, recorded on disk and processed off-line. Though stored in the NIWA Climate Database, they were not converted to physical units by the standard processing described in Section 2.2, and revised herein.

To better understand these data, we fitted each day's data with a non-linear model allowing for a time offset:

$$UVI = UVI_0(\cos(Z(t-\tau))^b \tag{4}$$

with

UVI_0	fitted UVI for overhead sun ($Z = 0$)
Z	solar zenith angle
t	recorded time
τ	fitted (backward) time offset
b	fitted exponent.

The results for the fitted time offset are shown in Figure 10. There is wide scatter in the full dataset, (black points), which includes successful fits to 93% of all days. The result is better defined for the clear sky days identified in the earlier analysis, which are shown in red.

For 10-minute integrals that, by standard meteorological convention, are recorded at the end of the interval, the best fit for a clear sky day should show a (backward) time offset of five minutes. For the earlier 30-minute integrations, it should be 15 minutes. Figure 10 shows such values for data after

1996, but earlier data show a range of values. A time offset of zero minutes suggests data time-stamped for the centre of integration, while others suggest time offsets of 30 minutes backward or forward. Overall, we find too many uncertainties to attempt recalibration of these data at this time. We simply correct the time alignment, as we did for the 2014 analysis. We restrict recalibration for Invercargill to the YES7 data after September 2007.

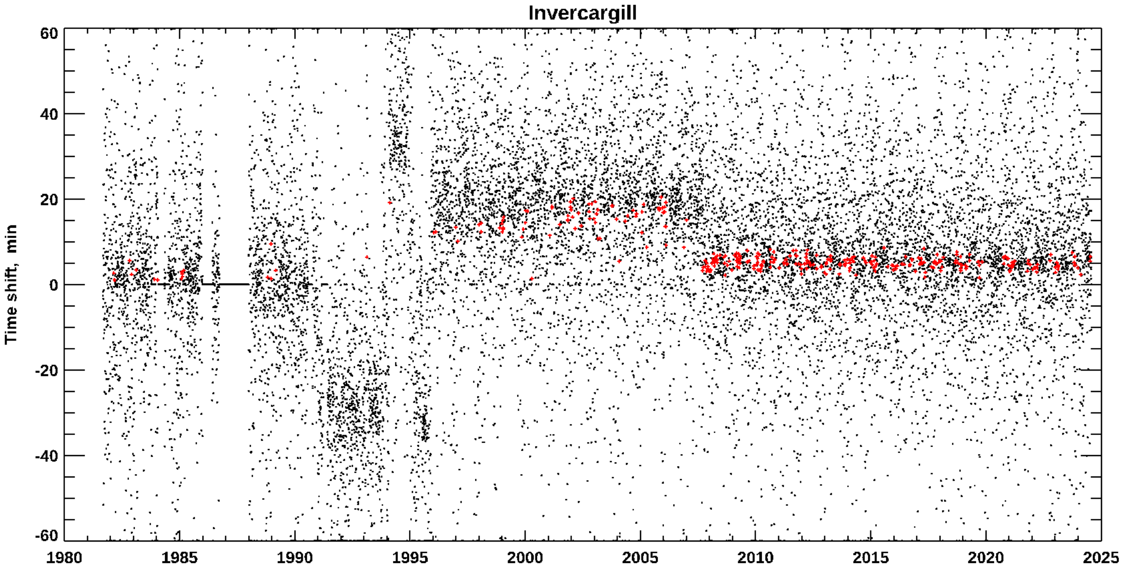

Figure 10. Time offsets from fitting a non-linear model to Invercargill UVI data. Black points show fits to all data, with clear-sky, identified previously, highlighted in red.

3.2 Revised UV Index values

3.2.1 Angular response

For each data series, we used the clear sky days to examine possible revision of the angular response function applied to the YES measurements, based on the series of plots like Figure 6 for all sites. Though not shown here, the other sites show consistent results, so that it did not seem necessary to derive a separate function for each instrument. The revised function is shown in Table 3.

Table 3. Revised cosine correction factors for YES UVB-1 instruments.

SZA	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
Factor	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.96	0.94	0.90	0.86	0.80	0.74	0.68	0.60	0.52	0.42	0.32	0.22

The revised angular response departs from unity at smaller SZA values than before (cf., Table 2), reflecting the small decrease visible in Figure 6 for measured / modelled around cos(Z) = 0.4 (winter noon) relative to cos(Z) = 0.8 (summer noon). The residual seasonality visible in Figure 7 to Figure 9 is correspondingly reduced.

The change does not affect the upward curve in measured / modelled for very small cos(Z) seen in Figure 6, because at such low sun conditions all the UV is diffuse. This might be corrected with a change to the bandpass correction, but we would only consider that in conjunction with spectral comparisons and a full radiative transfer model of clear sky UVI. In fact, the upward tail for low cos(Z) makes no material difference to the derived data. It is just the ratio of two very small numbers.

3.2.2 Revised calibrations

Using the revised angular response, we estimate calibration factors for each clear sky day as identified. In the absence of any recorded changes in the instrument or site with which to align a recalibration, we derive a single value for each July to June year, so that revision is centred on the summer months. The results are shown in Figure 11.

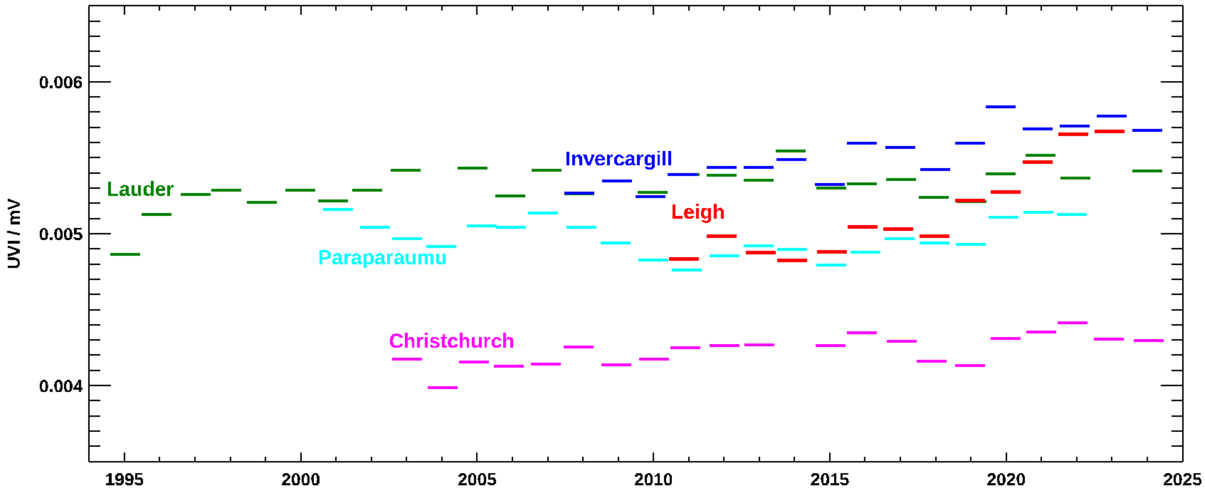

Figure 11. Calibration factors for YES instruments at the five NIWA sites. The sites other than Leigh appear to be in statistical control, so no recalibration is required.

From this analysis, we reassuringly find no need for recalibration of the data for Paraparaumu, Christchurch, and Lauder. Though there is variation, it appears to be random, with no consistent trend. In this situation of 'statistical control', applying a recalibration can actually increase the variance of individual days' variation.

The marked change in the YES9 at Leigh is in strong contrast, with a marked increase in the required calibration factor to give expected agreement between measurements and model values on clear sky days. We applied the calibration factors from the 2016/17 summer onwards to recalculate UVI values.

3.3 Daily peak and noon UVI, and SEDs

The data are output in the same format as previously, in a single CSV file with three columns for each of the five sites, listed in order from north to south: Leigh, Paraparaumu, Christchurch, Lauder, and Invercargill. Within each site, the order is: daily peak UVI, the mean within 30 minutes of solar noon each day, and daily UV doses are expressed in Standard Erythemal Doses (SED). One SED is 100 J m^{-2} of erythemally-weighted UV, so exposure to UVI=1 for one hour equates to a dose of 0.9 SED.

Daily peak UV for the revised dataset is shown in Figure 12, for comparison with values as originally retrieved from the NIWA Climate Database and shown in Figure 1.

In the above analysis we have attempted to apply objective criteria, and to refrain from changes unless clearly justified. They obviously were for the Leigh data, but we cannot have full confidence in the results without an understanding of how the instrument response has degraded. We will need to replace YES9 at Leigh, as well as restoring measurements at Paraparaumu now that YES8 has been repaired.

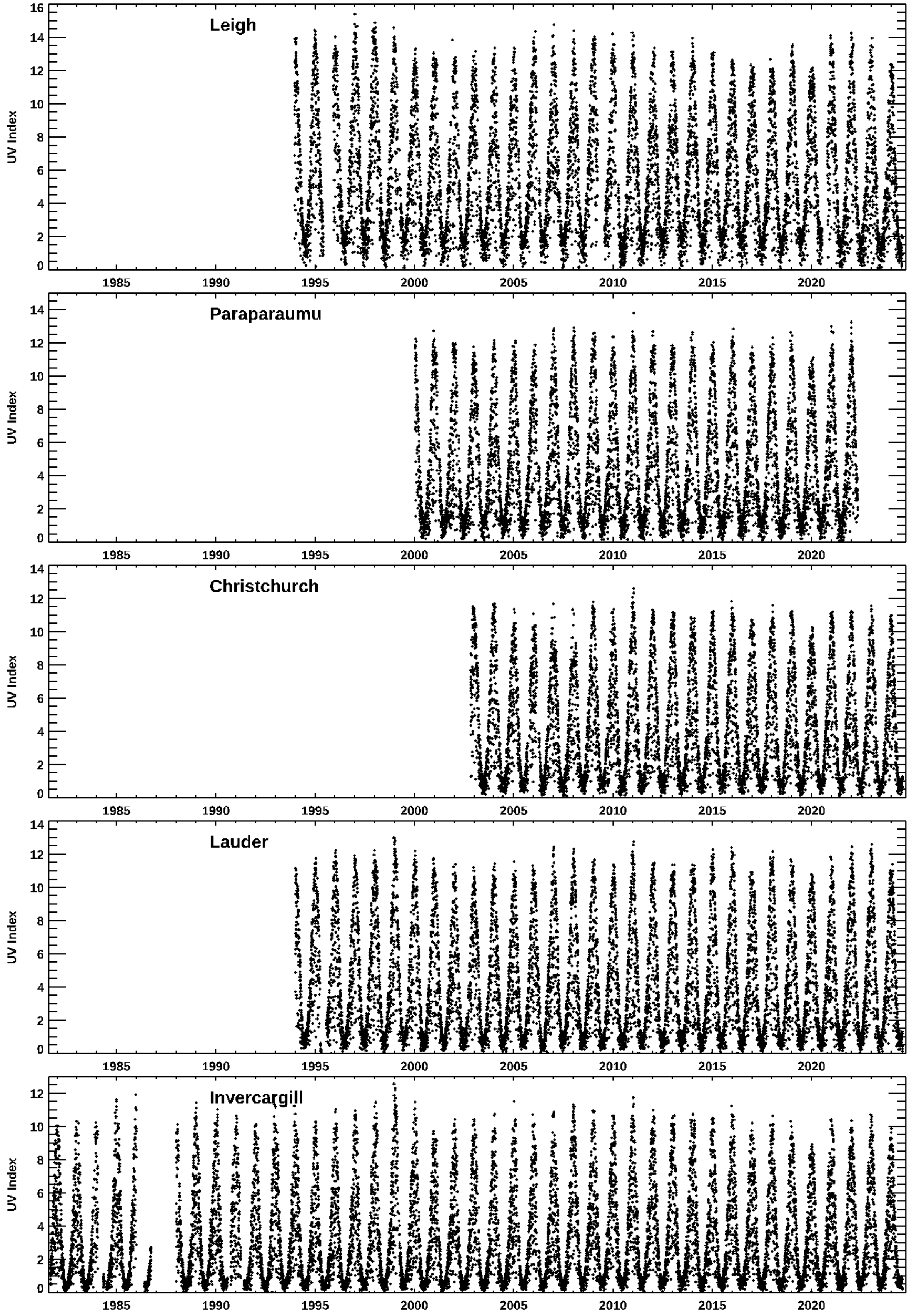

Figure 12. **Revised daily peak UVI for the five New Zealand sites.**

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