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Critical appraisal of data used to infer record UVI in the tropical andes†

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When the data sets that suggested record high UVI values at Mt Licancabur, and Laguna Blanca, Bolivia are reviewed in full, we find that the reported peak values are incorrect, probably due to instrumental problems. These affect the UVB, UVA and PAR channels at different times and different solar zenith angles, with distinct diurnal patterns in each case. The outliers are consistent with errors that would result from build-up of ice or snow on the surface of the entrance dome, combined with incomplete baffling of light within the integrating spheres that form the entrance optic of these instruments, but we cannot unequivocally attribute them to this cause. The analysis shows that for all three channels, cloud enhancements over clear-sky values by a factor of ~4 or more would be required to explain their highest values. Such repeated enhancements are not physically plausible and are more than twice those previously observed in the UV region. Further, at the time of peak reported UVB, the UVA cloud enhancement factor was less than 1.2 (*i.e.*, UVA radiation was increased by less than 20% over clear-sky values), which implies that to explain the high UVB values, an atmospheric ozone amount (~25 DU) far below the minimum ever observed would be required. The analysis also shows that the algorithm to convert from UVB to UVI is incorrect, and that if the correct algorithm had been used, the peak UVI values would have been even larger than reported. Disregarding the obviously incorrect measurements, the highest realistic values near solar noon from this dataset are in the range UVI = 25 ± 5, which is in agreement with previous estimates in the region.

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Introduction

UVI values exceeding 43 were recently reported at Mt Licancabur (22.48°S, 67.88°W, 5917 masl) at a solar zenith angle (SZA) near 20–25° by Cabrol *et al.*, 2014 (hereafter C14).[1] High UVI values were also reported at nearby Laguna Blanca (4340 m), which is approximately 10 km NE of Licancabur. These anomalously high values, which were derived from Eldonet radiometers, were subsequently questioned with the suggestion that more work be done to fully characterise these instruments.[2,3] Here we attempt to do that by examining the complete Eldonet data sets at Licancabur and Laguna Blanca (as provided by Dr Donat Häder, a co-author of C14), in the light of our experience with Eldonet instruments over several years at Lauder.

Locations and time zones

Location details are shown in Table 1. Horizon obscuration by terrain is not an issue at either site (see ESI, Fig. S1†). In C14's analysis, there is ambiguity about the locations. We used Google Earth to check the locations and found that the coordinates quoted in the text of C14 are approximately 55 km to the NE of the locations described. In this analysis, we used the location data in Table 1.

There is also ambiguity in the time offsets from GMT. In the data files as supplied, a time offset of −4 hours is indicated. However, from the morning to afternoon symmetry in the radiation data on clear days compared with model calculations, we found the best agreement is for a time offset of −4.5 hours from GMT (Fig. S2†). A time offset of −4.5 hours is also a good approximation to solar time, with highest UV

Table 1 Site details

Site	Lat (°S)	Lon (°E)	Alt (km)
Licancabur Bolivia/Chile	22.84	−67.88	5.917
Laguna Blanca Bolivia	22.80	−67.79	4.340
Lauder NZ	45.04	169.68	0.370

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† Electronic supplementary information (ESI) available: Solar trajectories and horizons at each site. Plots showing time zone, differences in SZA due to incorrect location and time in C14. Plots of entire raw data for the entire data period, along with statistics for various flag settings, ozone amounts. Table to convert from UVB to UV_{Ery}. Daily plots of all data. See DOI: 10.1039/c7pp00089h

values and smallest SZAs occurring near 12:00 ± 00:15 (rather than 12:30 ± 00:15). Instrument levelling errors, rather than timing errors, could potentially lead to such asymmetries. However, we don't believe that is the case here because misalignments larger than ~1°, and mis-oriented similarly (skewed towards the West), would be required. In the analysis that follows, we have assumed an offset from GMT of −4.5 hours.

Because of the differences in location and time zones between C14's analysis and ours, we recalculated all SZAs, using our own algorithm, which has been extensively validated. Differences in SZA are typically less than 5–10° at Licancabur and Laguna Blanca, due mainly to the incorrect time and co-ordinates being used (ESI, Fig. S3†). At Lauder, the SZAs are much closer, but differences of ±0.5° remain. Our analysis (not shown) found that the algorithm the Eldonet team used to calculate SZA incorrectly represents the seasonal equation of time.[4] Most of the anomalous UVI values at the high altitude sites occurred in the mornings, when the recalculated SZAs are smaller than estimated by C14. At these smaller SZA's, larger UVI values are expected. Hereafter we use our recalculated SZAs.

Data

Eldonet data at Licancabur and Laguna Blanca were logged at 10 minute intervals. However, at Lauder, the sampling period was 1 minute. Processed data files include the parameters shown in Table 2. For Lauder data (but not for the high altitude sites), Ery as reported is just a scaled version of UVB (Ery = 1.8 × UVB). Such an approximation would lead to large errors in Ery because the correct conversion factor is a function of solar zenith angle (SZA) and ozone.[4]

The full Eldonet data sets for Licancabur and Laguna Blanca, as logged, are summarised graphically in the ESI (Fig. S4 and S5†), along with statistics for the various data quality flags. Ozone values from E-P TOMS over the region are also shown in the ESI (Fig. S6†). The Eldonet data show occasional excursions in UVB, UVA, PAR, and UVI that are much larger than expected. Some of these are the data points discussed by C14. In the following sections we investigate these differences more closely.

Fig. 1 displays the UVI values from the Eldonet instruments from both sites, compared with Eldonet data from Lauder, New Zealand over a period of a week that includes clear days at each site as well as C14's highest UVI. The logged Ery values were scaled to match the UVI values as published by C14. The scale factor in this conversion is 40 × 2 × 100/(60 × 60) to convert to UV Index, which assumes 2 SED per MED.

There are several days at Licancabur and Laguna Blanca with UVI values exceeding 20, but on most days C14's peak values are less than UVI = 14. The largest outlier values exceeded the "normal" peak values by more than a factor of 3. There are no such outliers at Lauder, where the peaks reached UVI = 8.4, and the clear sky values were less than UVI = 8. The true UVI values at Lauder are approximately ~50% greater. The peak values at Lauder over this period, as measured by our NDACC-quality[5] UV spectroradiometer, reached UVI = 13.6 ± 0.5; and the peak modelled clear-sky value was UVI = 11.6. Agreement from the Eldonet instrument would be improved if 1 MED had been taken as 3.0 SED, rather than the assumed 2.0 SED. Using such a conversion factor would increase Eldonet UVI values would have increased by ~50%. Clear sky UVI values also look too small at Licancabur and Laguna Blanca, reaching peaks of UVI < 14 around solar noon, whereas model calculations and previous measurements suggest that peaks should exceed UVI = 20. Assuming that the same correction factor for Lauder also applies for these sites, the peak Eldonet value at Licancabur on 29 Dec 2003 would increase from UVI = 43 to UVI = 65, as discussed later.

In Fig. 2, we compare measured and modelled values for clear skies at Licancabur for PAR, UVA, UVB, and UVI over the

Table 2 Parameters logged in Eldonet data files

Parameter	Unit	Comment
Time	hh:mm	Time is given in hh:mm:ss for the 1 minute Lauder data
Sampling rate		Usually 10 samples per logged 10-minute data point (50 samples per minute for Lauder data)
PAR	W m^{-2}	Photosynthetically active radiation
UVA	W m^{-2}	Integral from 315 to 400 nm
UVB	W m^{-2}	Integral from 280 to 315 nm
Ery	MED per h	Erythemally weighted UV. Deduced from UVB. ([a], see text for conversion to UVI)
T_{ext}	°C	External temperature (scaled by an unknown factor at Licancabur)
T_{int}	°C	Internal temperature (scaled by an unknown factor at Licancabur)
Flag	[b]	Unspecified data quality indicator
SAR	Radians	Solar elevation angle (calculated using the latitude and longitude in file)

[a] 1 Minimum Erythemal Dose (MED) is approximately 2–3 SED for fair-skinned individuals, where 1 Standard Erythemal Dose (SED) is 100 J m^{-2} of erythemally-weighted UV. [b] An integer counter of data errors. However, all high-sun observations (SZA < 27°) have flag > 0 (see Table S1). We assume data is bad for flag > 1, and use an acceptance criterion of flag < 2. For this choice there is a daytime data loss of 5% at Licancabur and 17% at Laguna Blanca.

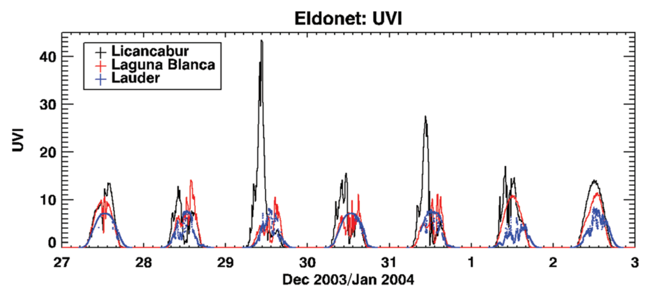

Fig. 1 Time series of UVI reported by Eldonet instruments from 27 Dec 2003 to 3 Jan 2004.

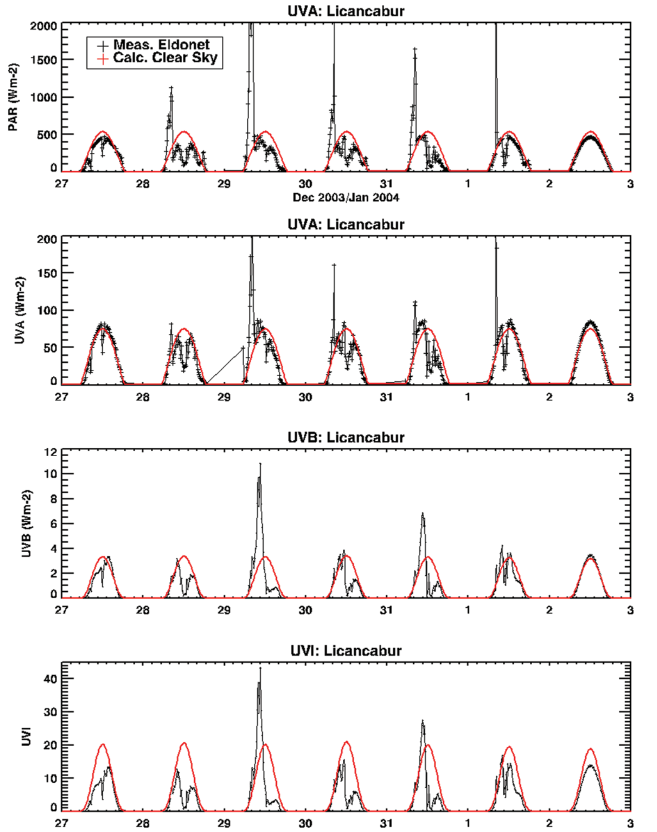

Fig. 2 Measured irradiances logged by the Eldonet instrument at Licancabur. (UVI values as in Fig. 1) compared with model calculations.

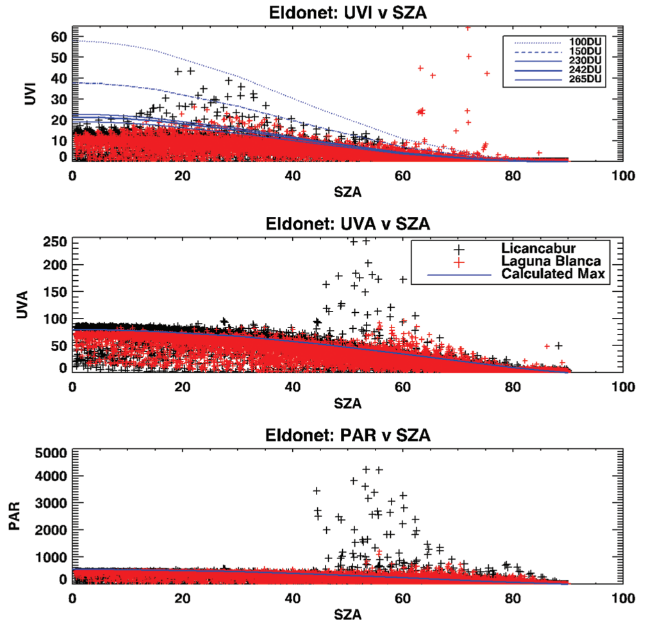

Fig. 3 Dependence of UV radiation on (recalculated) SZA, for each sensor: (a) UVI (as for Fig. 1), (b) UVA, and (c), PAR, along with values calculated for clear skies.

same period as shown in Fig. 1. For these calculations, we used the pseudo-spherical 8-stream discrete-ordinate version of the TUV radiative transfer model,[6] with ozone amounts from the NIWA ozone data assimilation,[7] as shown in Fig. S5.† Aerosol-free conditions were assumed, with the surface albedo set to 0.05. With these choices, there is good agreement between model and measurement on clear days, apart from for the UVI values, for which the values from the Eldonet instrument using C14's scaling are too low. Similar differences are seen at Laguna Blanca, as shown in the ESI (Fig. S7†).

The large excursions on 29 Dec look to occur at similar times, but a careful examination reveals that these times are in fact different, as discussed later. Furthermore, sometimes the excursions are larger in the UVA and PAR channel, but at other times they are larger in the UVB channel. There are several examples where excursions occur in one channel, but not in others.

Dependencies of outliers on solar zenith angle and solar azimuth angle

Fig. 3 shows the dependencies of all of the Andean Eldonet data on solar zenith angle (SZA), compared with corresponding calculated values for clear skies (blue curves). These calculations are shown for the range of ozone values that occurred. Over the period of interest, ozone ranged from 230 to 265 DU (mean 242 DU, Fig. S5†). Plots are also shown for 100 and 150 DU, which are unrealistically low outside the Antarctic ozone hole.

The envelope of the measurements at small SZAs shows that the UVI values published in C14 are generally much lower than expected. However, there are a few huge enhancements in UVI from Laguna Blanca at SZA between 60° and 80°, and a clustering of high UVI values from both sites for 20° < SZA < 40°. The largest UVI values at Licancabur occur for SZA ∼ 20°. The Laguna Blanca data show even larger values than reported by C14 (up to UVI = 64), occurring at SZA 60° to 80°. These are due to a clustering of high morning values from 15–18 Dec 2003 (see Fig. S5 and S8†). Taking C14's data at face value (*i.e.*, with a time offset of 4 Hours from GMT), the SZAs of these highest morning UVI values would be approximately 5–10° larger, making the extreme UVI values even more improbable. Recall that these UVI values are determined from the UVB sensor, which shows good agreement with the model values, showing that the conversion algorithm is faulty. The great majority of data points show the expected SZA-dependence.

In contrast, for the other two sensors, there is much better agreement between measurement and model, apart from a clustering of outliers for SZA > 45°. There are no outliers in the range of SZAs where the large UVI outliers occur. Surprisingly, for the PAR sensor in particular, there is little evidence of cloud enhancements for SZA < 45°. It is also surprising that for SZA < 40°, where outliers are not an issue, the highest PAR values are from the lower altitude Laguna Blanca site, whereas corresponding UVA (and UVI) values are highest at Licancabur. This is probably a calibration issue.

Some of the outliers exceed the clear sky envelope by factors much too large to be explained by enhancements due to clouds. Together, the three plots in Fig. 3 demonstrate that enhancements from clouds can contribute only a small part to the high UVI values reported by C14, because at the times of the largest UVI values, the UVA and PAR signals show little cloud enhancement.

Fig. 4 shows the corresponding solar azimuthal angle (SAA) dependencies. There appears to be a clustering of outliers near azimuth angles of 90°, especially in the morning data. Again there is an angular separation between the UVI outliers and the outliers from the other two sensors.

Converting UVB to erythemally weighted UV

The Eldonet instrument has three channels to measure UVB, UVA, and PAR. However, for the UVB channel at least, the omission of bandpass corrections in the conversion to erythemally-weighted UV (UV_{Ery}) is potentially important.[8] Here we assume that the reported Eldonet UVB measurements are the true UVB values, and use our previously-described method to convert to UV_{Ery}.[9] Typically UVB is about a factor 7.5 greater than UV_{Ery} for ozone amounts near 300 DU and for SZA near 30° (Table S3†). But the factor changes significantly for other ozone amounts and SZA.

We calculated SZAs from the location and time, and ozone column amounts were taken from the NIWA assimilation.[10] We then converted the result to the UV Index ($UVI = 40 \times UV_{Ery}$ in W m^{-2}) which is commonly used to inform the public.

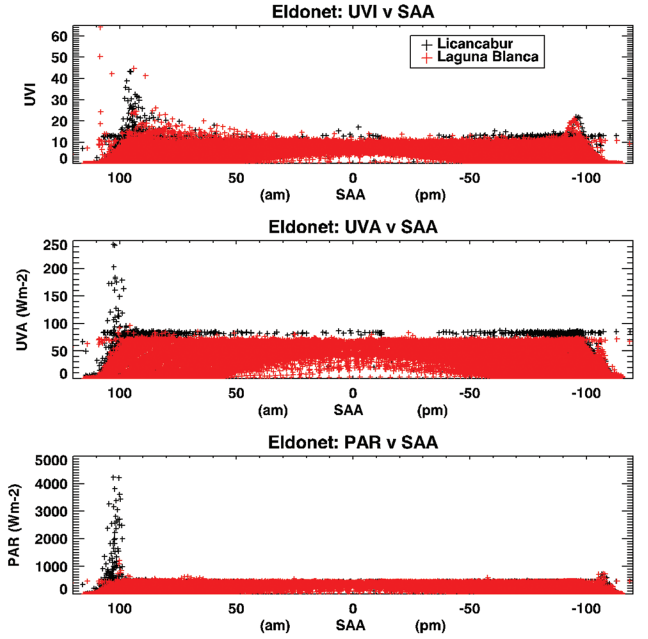

Fig. 4 Solar azimuth angle (SAA) dependence of Eldonet measurements.

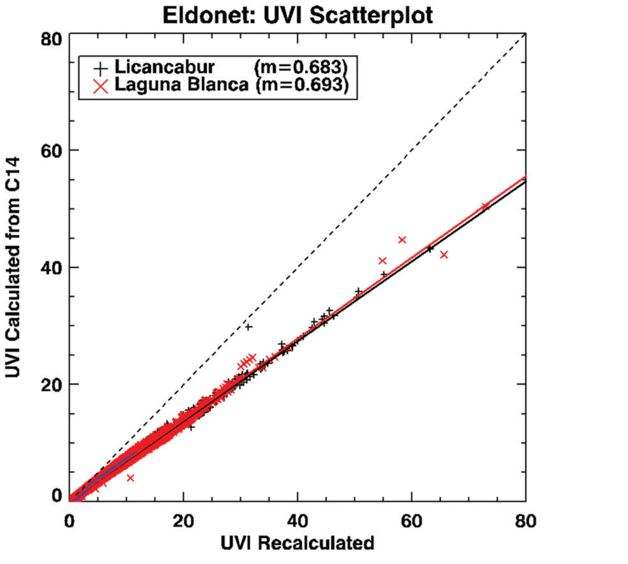

Fig. 5 UV Index values derived from Eldonet UVB measurements reported by C14, and re-estimated using conversion factors discussed in text.

Using realistic ozone amounts, the UVI values we derive from C14's UVB data are much larger than reported by C14. If the lower ozone values postulated by C14 had been used, our deduced UVI values would be even larger.

The recalculated UVI values are approximately 45% higher than reported by C14, as shown in Fig. 5. The error in C14 may be due to ambiguity in converting from MED per h to UVI. To obtain agreement with C14's values, we used a conversion factor of 1 MED = 2 SED (*i.e.*, 200 J m^{-2}), whereas this factor can range from 2 to 3 SED for skin type I, and can be much higher for other skin types.[11] As noted earlier, a value of 3 SED/MED would be more consistent with our more direct conversion. Note that using our derived UVI values, there would be much better agreement between measured and calculated clear sky values for overhead sun (Fig. 2 and 3).

From this point on, we use these re-derived UVI values. We calculated ratios of measured to model clear-sky values of UVI, UVA and PAR. These ratios are sometimes called cloud modification factors (CMFs), although they include effects of changes in other parameters, such as surface albedo, aerosol optical depth, or, in this case, measurement errors. Results are shown in Fig. 6.

Measurements compared with clear-sky model

Fig. 6 shows ratios of measured to clear-sky model values for the Eldonet sensors. By plotting ratios it is now more apparent that there is a group of outliers that occurs for all three detectors for SZA > 45°. However, for SZA < 50°, the large outliers occur only for the UVB detector, and there is no evidence for CMFs much greater than 1 in the UVA or PAR data-sets. For all

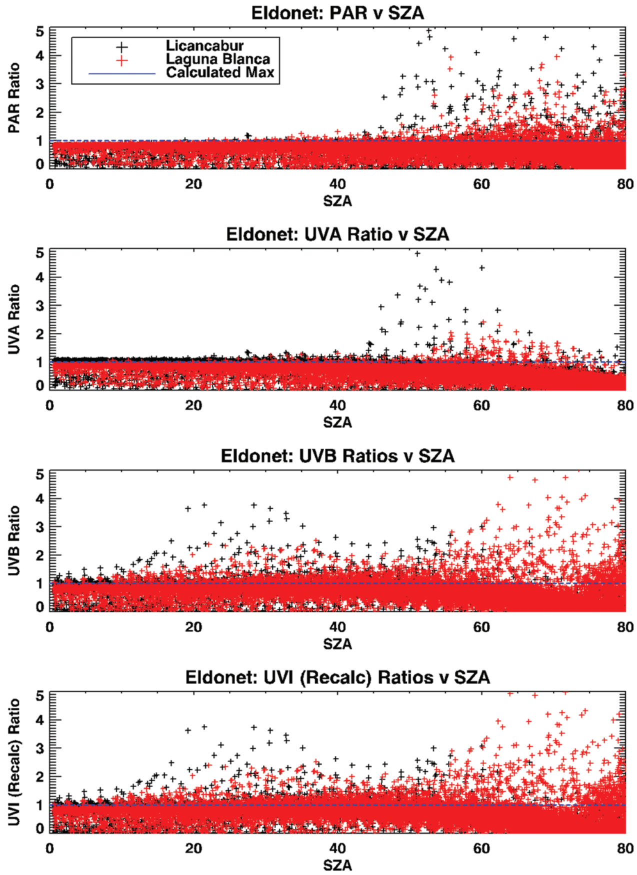

Fig. 6 Ratios of measured values to clear sky model values for all data as a function of SZA.

three channels, the outliers reach values that exceed the calculated clear sky values by more than a factor of 4. Recalculated UVI ratios are very similar to the UVB ratios.

Radiation enhancement by clouds has been well established for many years.[12] Enhancement factors up to ~2.25 are theoretically possible (see Appendix), but the probability of such a value is vanishingly small as it assumes a surface albedo of 1.0, and uniform heavy overcast, except for a small gap in the cloud to allow the direct beam sunlight through. Recurrent enhancements of the magnitude seen by C14 are not credible. Previous studies have shown that CMFs > 1.5 are rare.[2,13–15] In 16 years of 1 min BSRN pyranometer data at Lauder, represented by over 2.4 million data points for SZA < 70°, less than 0.06% of the measurements had CMFs greater than 1.5, and the absolute maximum was 1.8. For 10-minute means (as reported by C14), less than 0.02% of CMFs exceeded 1.5 at Lauder, and the absolute maximum was 1.7. As noted previously,[2,3] maximum CMFs are smaller in the UV region, where peak CMFs even at high altitude rarely exceed a factor of 1.2.[3,16]

Outliers where the measured values are more than 2.5 times the calculated clear sky values (*i.e.*, where the measured values are not credible) are shown in Fig. 7 as a function of SZA and SAA to see if there is any evidence of clustering that might be related to hot spots in the angular response.

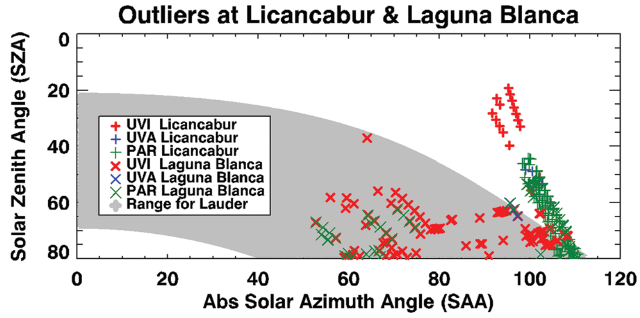

Fig. 7 Outliers as a function of solar position (*i.e.*, SZA and SAA) colour coded by sensor at Licancabur and Laguna Blanca. The grey area shows the range of solar position angles sampled at Lauder, 45°S, where no such enhancements were seen over the study period.

With the relatively short (~3-month) sampling period at Licancabur, only a small range of SZA/SAA combinations was sampled. Although the frequency of outliers is higher in the morning than in the afternoon data, the azimuth angles at which they occur seem to be symmetrical about the N–S plane, so we have plotted them as a function of the absolute azimuth angle. The distribution of outliers varies between the two instruments, and also from sensor to sensor. No such outliers were seen in the data from Lauder over the period 2003–2004. The grey region shows the range of angles sampled at Lauder over a full year. All of the outliers at Licancabur occurred for solar positions that do not occur at Lauder, while most of the outliers at Laguna Blanca occurred within the range of solar positions sampled at Lauder. Ice build-up was occasionally seen on the dome of the Eldonet instrument that we hosted at Lauder from 1999 to 2010, but only on particularly cold and frosty winter days. In the period analysed for this study (2003–2004) no instances were recorded in the log sheets and no anomalously high irradiances were recorded. However, ice build-up may have been a contributor to outliers outside the study period.[17]

The cause of these outliers may be incomplete baffling of light inside the integrating sphere of the Eldonet instruments. For a good angular response in solar irradiance applications, baffling is needed to avoid direct sunlight, or once-reflected light from the sphere walls, reaching the detectors. As discussed by C14, correct instrument orientation is needed to avoid these issues. It may be that there were remaining instrument orientation problems at these low latitude sites, with incomplete baffling of the integrating sphere which led to the outliers at Licancabur, especially in the UVB channel for SZA < 40°. Errors of this sort would be expected to manifest themselves differently for each sensor, because their locations are different. The errors at Laguna Blanca are more difficult to explain, but may be attributable to dislocated baffling. In the Eldonet instrument that was deployed to Lauder, the baffle was positioned with a single screw (pers. comm. Michael Kotkamp, NIWA Lauder). It is therefore possible that its position could have shifted in transit.

Plots showing the variability of all logged values day by day throughout the measurement period are shown in the ESI (Fig. S8†). These show that on a clear-sky day (2 Jan 2004) between the two highest UVI days at Licancabur (29 Dec 2003 and 17 Jan 2004), the peak UVI reached ~20, as would be expected.[18]

The 29th of December 2003 is the highest UVI day reported by C14. The huge UVB and UVI enhancements in the later morning at Licancabur are not matched by corresponding enhancements in UVA or PAR. Even allowing for a cloud enhancement factor of 1.5, the peak UVB value of 10.8 W m^{-2} near SZA = 20° would require an ozone amount of ~35 DU, which is far less than has ever been observed. There are large enhancements in the UVA signal, and even larger enhancements in the PAR signals, but they occur earlier in the day at larger SZAs. In the afternoon, measured and calculated values are in reasonable agreement for all channels. For all channels outliers sometimes exceed clear sky values by more than a factor of 4. There is no obvious correlation with nearby Laguna Blanca, where the data suggest cloudy conditions throughout the morning.

On 2 Jan 2004 the instrument operated without serious problems. The results from all three channels are in reasonable agreement with clear-sky calculations at both sites. In most cases, measurements and model agree to within 10–20%. The flag values and temperature ranges are similar to those shown for the highest UVI day (see Fig. S8†).

On clear days at both sites, the measured PAR tends to be lower than the model, the measured UVA tends to be higher than the model at Licancabur but lower than the model at Laguna Blanca, and the measured UVB tends to be lower than the model at both sites, especially Laguna Blanca. With such systematic differences, caution must be exercised if using measurement to model ratios to estimate cloud enhancement factors.

The 17th of January 2004 was 2nd highest UVI day reported by C14 and was the day they studied in most detail. By our calculation, based on their UVB values, the UVI exceeded 40 on this day, but again these data are clearly erroneous. Firstly because enhancements were much smaller in the longer wavelength channels, whereas they are expected to be larger at longer wavelengths for real cloud effects. Secondly, the SZA of the largest UVI value is more than 60°. To achieve a UVI value exceeding 40 at this SZA, an ozone amount of less than 20 DU would be required. The lowest ozone ever recorded is approximately 90 DU, within the Antarctic ozone hole. On 17 January 2004 there were enhancements at both sites. However, they were much smaller – though still not plausible in all cases – at Laguna Blanca.

Diurnal pattern in outliers

We further investigate these suspicious repeating patterns by plotting data from all three sensors at as a function of time of day. Results for Licancabur are shown in Fig. 8. Similar patterns, but with fewer excursions are seen at Laguna Blanca (see Fig. S8†).

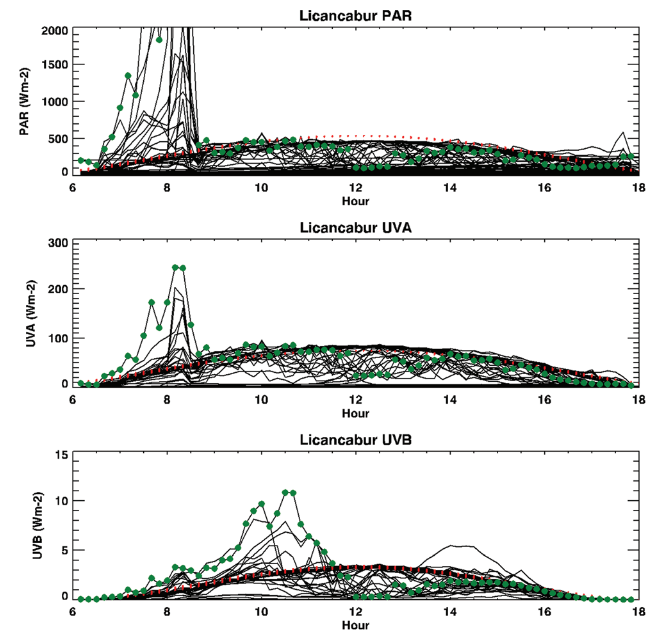

Fig. 8 Diurnal variability over the period 12 Nov 2003 to 25 January 2004. The dashed red curves are calculations for clear skies. The green points are the values for C14's highest UVI day, 29 Dec 2003.

The plots show clear repetitive features, whose timings are inconsistent with real atmospheric effects. For example the PAR signals (top) show a repeating pattern of extremely high values centred around 08:00 local time (GMT-4.5 h). There is some evidence of smaller outliers after 17:00. Similar patterns are seen in the UVA data (middle). In contrast, the repeatedly high values in the UVB channel (bottom) occur mainly between 09:00 and 11:00. One day shows a peak around 14:00.

At Laguna Blanca (not shown, see Fig. S8†), the outliers are generally smaller, but the repetitive patterns are more clearly defined. The PAR signals show a similar pattern of elevated values in the afternoon between 16:00 and 17:30 on several sequential days. Even larger outliers were repeated on two days around 09:00. Smaller outliers were seen in the UVA channel at the same times, but not in the UVB channel. In contrast, for the UVB channel, there is a bimodal pattern centred near solar noon, with maxima around 11:00 and 14:00.

The extrema are consistent with a build-up of ice on the entrance optic dome. With such a build-up, the direct beam component of radiation, which dominates for PAR and UVA, can be scattered from the surface of the dome into the instrument, including at angles for which the baffling is incomplete (*e.g.*, from the southern quadrant). The late afternoon enhancements at Laguna Blanca have a similar spectral pattern (Fig. S8†). There are two possible explanations for the UVB enhancements being less pronounced than for UVA or PAR. Firstly, the baffling for that detector may be better for these circumstances. Secondly, in the UVB region, less than half of the radiation is in the direct beam for these SZAs.

Apparent early morning enhancements, due to observed build-up of ice on unventilated pyranometer domes, occur on about 6% of days at Lauder, mainly in winter.

If the extrema observed in the UVB channel, which occur later in the day, are due to snow, rime, dew on the outside of the dome, or condensation inside the instrument (as occasionally occurred for the Eldonet instrument at Lauder), then the pattern of deposition must be different because the UVB channel is affected more than the other two channels. Interestingly, in the Laguna Blanca data, the highest extrema were for single 10-minute data points that occurred between 6:30 and 07:00 on four separate days for SZAs near 70° (see Fig. S8†). These may be attributable to electrical interferences from associated nearby equipment.

Unfortunately, the accuracy of the logged temperatures is insufficient to determine whether the events occur when temperatures are close to zero. However, at Laguna Blanca, the temperature was apparently frequently well below freezing point. Further, the incorrect temperature logging at Licancabur may have compromised instrument temperature stabilisation, thus making that instrument more sensitive to ice build-up.

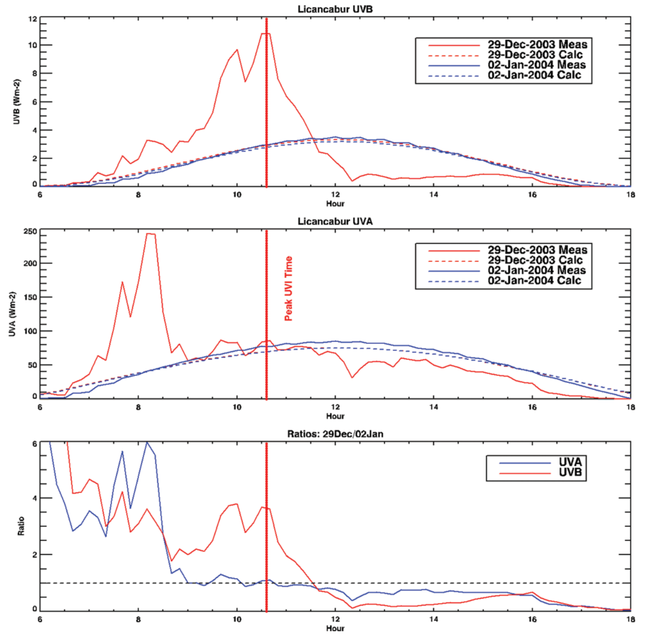

Fig. 9 Upper Panel. Comparison of measured and calculated UVB values at Licancabur on 29 Dec 2003 (C14's highest UVI day) and 2 Jan 2004 (the nearest clear-sky day). Middle Panel. Corresponding UVA values. Lower Panel. Ratios with respect to the clear sky day.

Cloud enhancement factors for C14's highest UVI

Discrepancies between measured and modelled values are too large to permit accurate calculation of cloud enhancement factors (CMFs) in the Eldonet data. So instead of using model calculations, we used measurements on the nearest clear-sky day. The largest UVI reported by C14 was at Licancabur on 29 Dec 2003. The closest clear-sky day was on 2 Jan 2004. Comparisons between these two days are shown in Fig. 9.

The upper panel of Fig. 9 shows unrealistically large UVB enhancements between 9 and 11 am, and unrealistically large UVA enhancements a couple of hours earlier. However, at the time of the peak UVI around 10:30, the UVA enhancements are much smaller. The ratios plotted in the lower panel show that the cloud enhancement at the time of the peak UVI is less than 20% for both UVA as it is for PAR (not shown – see Fig. S8†). There is similar pattern for the UVB channel, but it is greatly exaggerated, and as noted before, not physically realistic.

Can low ozone be the cause of C14's high UVI?

In their rebuttal of our initial paper questioning the validity of C14's measurements,[2] the authors suggested the low ozone values could result from "blue jets".[19] These are electrical discharges from high cloud tops that propagate upwards, and it has been postulated that they could deplete stratospheric ozone.[20–22] However, to our knowledge, no effect on ozone has ever been observed. In any case, we question whether such discharges could appreciably deplete the total ozone column (on several occasions) as (1) they are thought to be extremely rare, (2) calculated ozone depletions are small for the total column, (3) the ozone depletion is quite localised along the path of the discharge, (4) the photochemical recovery time for ozone is rapid (probably less than 5 minutes), and (5) wind speeds in the stratosphere vary strongly with altitude and can exceed 100 km per hour. For these jets to have an appreciable effect, the discharge would also have to deplete the ozone precisely along the same line as the light path from the sun to the instrument either repeatedly or persistently for two hours (see Fig. 10). Finally, such ozone depletions cannot explain the similarly large outliers in the UVA channel.

Possible explanation for the anomalous readings

The entrance optic of Eldonet instruments comprises a quartz dome, which covers the entrance aperture to an integrating sphere. To achieve the angular response necessary for accurate measurements of irradiance, baffles are inserted inside the integrating sphere to ensure that direct light or once-reflected light does not reach the detectors, which are embedded in the walls of the integrating sphere. However, for some angles, when looking down through the dome into the interior of the Eldonet instruments, the detectors are visible to the naked eye, showing that the internal baffling is incomplete. For this reason, it is necessary to orient the instruments carefully so

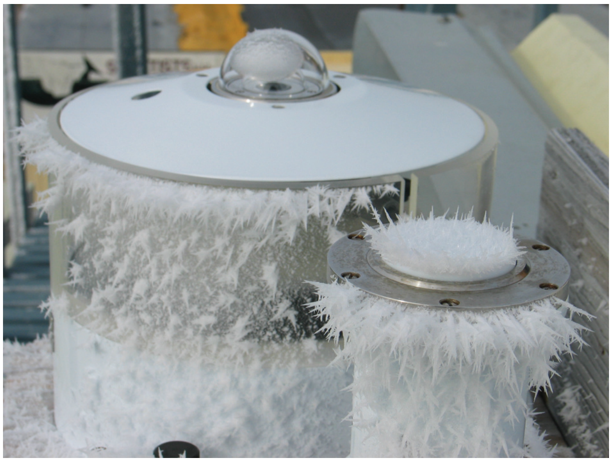

Fig. 10 A ventilated pyranometer at Barrow Alaska (top left) with asymmetric frost on the dome. Also shown is an unheated Eppley TUVR instrument, which is also affected by hoarfrost. Photo provided by Dr Germar Bernhard, Biospherical Instruments Inc.

direct beam sunlight cannot enter from that angle as noted by C14. Consequently, there are two potential causes for the erroneous readings observed.

Firstly, the instrument orientation may have been such that direct beam sunlight can reach the detector for some SZAs and SAAs. This can probably be discounted because there are some clear-sky days in the period of interest where these anomalies do not occur.

The second more likely cause of the anomalies is that they arise from reflections off snow or ice deposited on the outer surface of the quartz dome. This is a well-known problem with unventilated pyranometers in cold areas,[23] and in extreme climates, also for ventilated pyranometers (see Fig. 10). Pyranometer measurements from Lauder BSRN data show that these can lead to anomalous enhancements of a factor of 2 for SZAs near 70°, but with smaller enhancements at smaller SZAs. These could be even larger at high altitudes if specular reflections contribute to the problem because a larger fraction of light is in the direct beam. In Eldonet instruments, where radiation from certain angles is not properly blocked by the baffles, there is the potential for much greater errors from this source, especially if there are anisotropic reflections from ice, as would be the case in Fig. 10.

The three detectors are separately located, so the conditions for which incomplete baffling occurs would be different for each detector. Furthermore, the distribution of ice on the dome is not necessarily symmetrical, but can depend on wind flows. These asymmetries further decouple enhancements from detector to detector (as observed). Anomalous enhancement events from such effects would occur at similar times for both instruments, since they are similarly oriented in a similar environment as far as temperature, humidity, and wind patterns are concerned. Notably, there are no instances of these anomalous enhancements in the dry season (see results for Laguna Blanca in ESI, Fig. S2†).

Conclusions

For near noon conditions, when irradiances are expected to be largest, the results from all three instrument channels (PAR, UVA, and UVB) are plausible, and agree with clear sky model calculations to within ±20%. However, there are frequent periods when measurements are unrealistically high. For all channels, there are periods when the measured values exceed clear-sky values by factors of 4 or more. Such enhancements are not physically plausible, and cannot be explained by reflections from clouds, or from high surface albedos.

The high UVI values reported by C14 are not real but are due to instrumental problems. The values logged in the UVB channel at Licancabur are sometimes greatly elevated, reaching 10.8 W m^{-2}. The UVA and PAR channels showed that cloud enhancements at this time were less than a factor of 1.2. Since cloud enhancements are always larger in the UVA than at UVB wavelengths, this implies that the clear sky UVB would be at least 9 W m^{-2}. To achieve that value at these SZAs, an ozone amount less than 25 DU would be required. Such an ozone amount is far below the minima ever recorded (including the Antarctic "Ozone Hole").

The most likely explanation for C14's high readings is a design fault in the entrance optics, where each detector is exposed to different portions of the weather-protective quartz dome. This can lead to anomalously high values at different times for each detector, particularly if there are in homogeneously distributed deposits of ice or snow on the dome, as can be the case in extreme climates such as these. Similar outliers have been seen from Eldonet instruments in the past.[17,24]

C14's algorithm to convert UVB to UVI is also incorrect. Applying a method described previously,[9] the UVI would be much higher than reported, and even more implausibly high for their postulated ozone amounts. Disregarding the anomalous values, which are due to instrumental artefacts, it would appear that the highest UVI value would be 20–25, which is in good agreement with previous estimates for this region.[18,25–27] However, after the obviously wrong data have been removed, there is a suggestion of UVI values of around 30 in early Dec. 2003 (Fig. S8†). If this is not an instrument artefact, it may be due to an intrusion of ozone poor air, as suggested by C14.

Appendix

The theoretical maximum enhancement in solar irradiance due to multiple scattering from clouds can be estimated as follows (see Fig. 11): consider the space between two plane-parallel horizontally infinite media (*e.g.* between two cloud layers, or between cloud and ground). Define layer reflectivities R_1^* and R_2^* with respect to incident diffuse light, and a somewhat different reflectivity, R_1°, with respect to the direct solar beam irradiance I°. Multiple reflections between the two media generate a diffuse light field that can be separated into down-ward

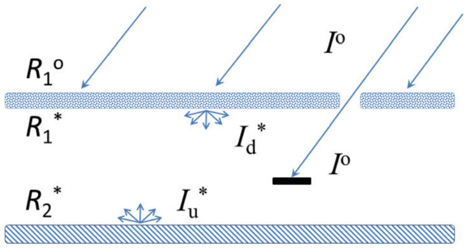

Fig. 11 Schematic showing notation in text for the propagation of solar radiation through clouds and reflected from the surface.

and upward propagating irradiances, I_d^* and I_u^*, related by conservation of energy:

$$I_d^* = (1 - R_1^\circ)I^\circ + R_1^* I_u^* \text{ and } I_u^* = R_2^* I_d^*.$$

Solving for I_d^* gives:

$$I_d^* = I^\circ(1 - R_1^\circ)/(1 - R_1^* R_2^*)$$

The maximum value of I_d^* is achieved when the lower medium (*e.g.*, ground or cloud/fog below the observation point) is highly reflective, so that $R_2^* \sim 1$. In this case, I_d^* simply equals the incident solar irradiance multiplied by a "photon trapping" ratio, which relates the ease of entry of the direct beam $(1 - R_1^\circ)$ to the ease of escape of diffuse light $(1 - R_1^*)$. Detailed radiative transfer calculations show that this ratio is not too far from unity for most conditions, and reaches a maximum value of about 1.25 for overhead sun.[28]

The maximum value of diffuse down-propagating irradiance, $I_d^* \sim 1.25I^\circ$, was derived here by considering the space between two plane-parallel horizontally infinite media. Based on symmetry and superposition arguments, no other configuration can give higher values (*e.g.*, broken clouds, multiple layers, Rayleigh scattering, absorbers), as long as the character of the reflection is strongly diffusive (*e.g.*, Lambertian) rather than anisotropic (*e.g.*, specular), for which focusing might be possible. One important limiting case is a configuration in which the sky is completely overcast except for a small opening in the clouds, so the total downwelling radiation is $I_o + I_d^* \sim 2.25I^\circ$. In any realistic situation where cloud and surface albedos are not exactly 1, this represents the maximum possible enhancement in the total (direct + diffuse) downwelling radiation relative to the irradiance of the direct solar beam, and is independent of wavelength over the solar shortwave spectrum.

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