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Richard McKenzie, Ben Liley, Michael Kotkamp, and Patrick Disterhoft

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Peak UV: Spectral Contributions from Cloud Enhancements

Richard McKenzie[1, a)] Ben Liley[1] Michael Kotkamp[1] and Patrick Disterhoft[2]

[1]*NIWA, Lauder, Central Otago, New Zealand*
[2]*NOAA,GMD, Boulder, CO, USA*
[a)] Corresponding author: richard.mckenzie@niwa.co.nz

Abstract. We use multi-year datasets of UV spectral irradiances, measured to the exacting standards required by the Network for the Detection of Atmospheric Composition Change (NDACC), to investigate the enhancement effects of clouds and their wavelength dependence at sites that span a wide range of altitudes. These enhancements are derived by comparing weighted UV irradiance measurements with corresponding model calculations at each site for clear skies. We find that the frequency, magnitude, and wavelength-dependence of cloud enhancements are insufficient to explain the repeatedly high values of UVB and UVI observed by Cabrol et al., 2014, and that ozone amounts lower than have ever been seen there would be required.

INTRODUCTION

In 2006 we reported that the highest area-averaged clear-sky UVI value in the world, deduced from an analysis of over a decade of gridded TOMS satellite data, would be UVI=25, occurring around Cusco Peru (average altitude 3.4 km) [1]. Higher values are expected when effects of cloud enhancements (up to ~30%) are factored in, and at the highest peaks. But how much higher? Outside Earth's atmosphere, the UVI can exceed 300, but it has been estimated that the highest value that can practically occur anywhere on Earth's surface is UVI=38.5 [2]. This peak occurs for overhead sun (i.e., solar zenith angle (SZA) = 0). We were therefore surprised when UVI=43.3 (with no error bars quoted) was reported by Cabrol et al., 2104 (C14 hereafter) [3] at Mt Licancabur, near the Bolivia-Chile border, for a SZA close to 30°. Model calculations show that for those SZA's and realistic ozone amounts (more than 200 DU), the UVI should reach "only" ~33, even allowing for maximal cloud enhancement effects.

We raised our concerns in a note to the authors [4], who responded [5], speculating that (a) ozone levels may have been much lower than expected due to a phenomenon called "Blue Jet Sprites", in which electric discharges from cloud tops propagate upwards through the stratosphere and destroy ozone, and (b) cloud enhancements in the UVB region can be much higher than in the UVA region.

Here we investigate the plausibility of C14's results by (a) comparing their peak UVI values with previous measurements, (b) investigating the likely range of ozone values, (c) investigating the likely range of cloud enhancements, and (d) comparing their measurements (and ratios of measurements) with measured values from high quality spectro-radiometer data and with calculations using a radiative transfer model.

METHODS

We make use of a large database of UV spectral irradiances that meet the stringent demands of the Network for the Detection of Atmospheric Composition Change (NDACC, formerly NDSC) [6]. At each site selected (see Table 1), spectral measurements have been undertaken continuously for at least 15 years, with a measurement frequency of 10 or 15 minute steps over the midday period (2 to 3 hours centered on local solar noon), and at 5-degree steps in SZA outside that period. Typically, 200,000 scans are available at each site. Although the 3 sites selected cover a wide range of altitudes, none is as high as Mt Licancabur. However, the attenuation of irradiance depends more on atmospheric pressure than altitude *per se*; and, as shown in Table 1, changes in pressure between Lauder and Mauna Loa Observatory (MLO) are much larger than the changes in pressure between MLO and Licancabur. Therefore,

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any altitudinal differences between Lauder and MLO should exceed those between MLO and Licancabur. The numbers in parentheses in the UVI column are values corrected to match the Earth-Sun separation during C14's measurements. Even with this correction, peak UVI values at Boulder are not significantly higher than at Lauder, despite its lower latitude and higher altitude. This is mainly due to pollution, but differences in stratospheric ozone also contribute, as has been discussed previously [7]. In contrast, neither Lauder, nor MLO are significantly affected by tropospheric pollution.

TABLE 1. Comparison between NDACC measurement sites, showing the peak UVI values, and Licancabur. Numbers in parentheses are the measured UVI values with a correction applied to match the Earth-Sun separation in December/January. The last two columns show the 3σ thresholds in enhancement factors (see explanation at bottom of page).

Site	Latitude (°N)	Altitude (km)	Pressure (hPa)	Peak UVI	3σ enhancement factor	
					UVA	UVB
Lauder, NZ	-45	0.4	960	14 (14)	1.20	1.17
Boulder, Colorado	40	1.7	810	13 (14)	1.21	1.18
MLO, Hawaii	20	3.4	680	20 (21)	1.17	1.17
Mt. Licancabur	-23	5.9	480	43 (43)	--	--

Peak UVI values

Given the 50% increase in UVI between Lauder (960 hPa, UVI=14) and MLO (680 hPa, UVI=21), a peak at Licancabur (480 hPa) near UVI = 26 would be more plausible (assuming ozone differences are small, and that attenuation is proportional to atmospheric pressure). To date, the peak values observed from high quality spectral measurements in the Altiplano region have been approximately UVI=20 [8]. The same group showed that UV irradiances at altitude 5100 m are typically 20% greater than at unpolluted sites near sea level [9], in agreement with model calculations. To explain C14's results, an ozone amount of less than 150 DU would be required. Although such low ozone values do occur during the springtime Antarctic hole, ozone amounts less than 200 DU are extremely rare outside Antarctica. The presence of ozone anomalies <200 DU at the times in question is not supported by available ground-based ozone data, or from gridded data from the EP-TOMS or AIRS satellite instruments. C14's initial suggestion, that pockets of anomalously low ozone (< 150 DU) could occur through the long-range transport of ozone-poor air from Antarctica, is implausible; as is their subsequent suggestion that it arises from "Blue Jet Sprites" [5].

Cloud Enhancement Effects

It has been well-documented that cloud enhancements are larger for total solar radiation than for shorter wavelength erythemally-weighted radiation (UVI).[10-12]. This, and theoretical considerations, lead us to expect that enhancements will be larger for UVA than UVB irradiances, in contrast to the assertions of C14 [3, 5]. The effect of clouds is illustrated for MLO in Figure 1. In the left panel we plot UVA cloud modification factors (CMFs, ratios of measured to calculated clear-sky irradiances) as a function of UVB cloud modification factors. In the right panel we show their frequency distributions. Similar relationships are seen for Lauder and other sites. For CMFs < 1 they tend to be greater in the UVB than in the UVA region. Differences are largest at larger SZA, as was shown more than 20 years ago [13]. However, here we are interested only in cloud enhancement events, which corresponds to the subset of cases where the CMFs are greater than unity. In these cases, the CMFs are smaller in the UVB than in the UVA region. In each case, the model calculations are undertaken for aerosol-free conditions, and for a surface albedo of 5%. The CMF=1 values in the right panel correspond to clear sky values. For all sites, the highest frequency is close to that value. However, the turning point will also be influenced by calibration errors, the presence of aerosols, or high surface albedos. Differences from the most frequent CMF value (mode) were used to derive the values in the two right columns of Table 1, which illustrate that (a) less than 1% of all cloud enhancement factors are greater than 1.20, and (b) they tend to be smaller at UVB than at UVA wavelengths. The maximum enhancement factors observed at each site was ~1.4.

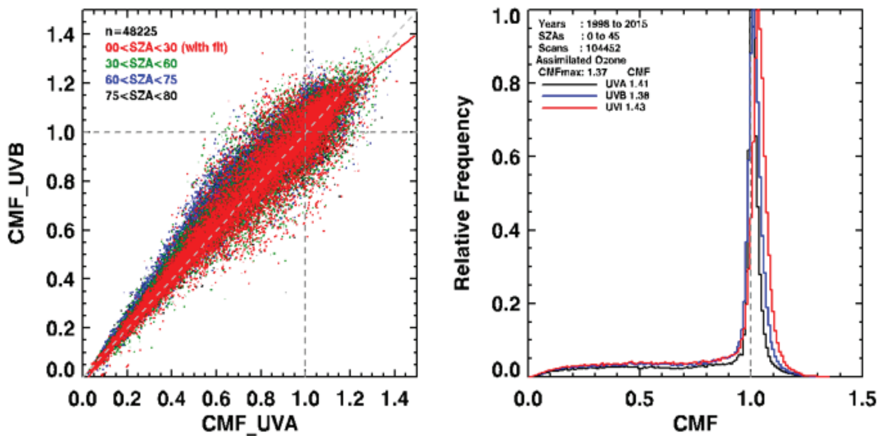

FIGURE 1. Cloud effects on Spectral measurements at MLO.
Left: UVA CMF as a function of UVB CMF. Right: histogram of relative frequencies.

Comparing C14's Results with Spectroradiometer Data and Model Calculations

The most convincing evidence against C14's results arises from their lack of self-consistency, which indicates that there may be an instrumental problem. Because anomalous UVI values are seen with two different instruments, this implies that there may be a design flaw in the Eldonet instruments, which comprise three separate diode detectors mounted behind a baffle inside an integrating sphere. These three diodes measure UVB, UVA, and PAR. There is no direct measurement of UVI, and a radiative transfer model - that includes ozone as an input - is needed to convert from UVB to UVI. In Figure 2, we compare noontime measurements from multiple years of NDACC-quality data at Lauder, Boulder, and MLO with model calculated and with the values reported for Licancabur. Fig. 2a compares erythemally weighted UV (UV_{Ery}) at the 3 spectrometer sites with corresponding model calculations for 250 DU, which is close the minimum that occurs at each site for the highest UVI values. The measurements are distributed as would be expected about the model curves. Most points lie below the corresponding curves, corresponding to cloud-attenuated measurements. However, a few are above the curve, corresponding to cloud-enhanced values (or for ozone < 250 DU). Fig. 2d shows the same data plotted on an extended UVI scale, but with C14's results added, along with calculated curves for ozone amounts of 250, 200, and 150 DU at that site. Most of C14's results are clustered about the 150DU curve. But for their highest value (on 29 December), ozone would apparently have to be less than 150 DU (unless the cloud enhancement is greater than 1.5). However, the corresponding UVA plot (Fig. 2c) shows that the UVA enhancement this day was approximately 1.3, and as shown above, enhancement factors tend to be smaller in the UVB, not larger. Unfortunately, 29/12 was only day for which the UVA value was reported by C14. The corresponding plot for UVB (Fig. 2b) shows an even more surprising result than the UVI values. The peak UVB is three times larger than any of the spectrometer values, and is more than a factor of two greater than the model calculation for 150 DU, indicating that an even lower ozone value would be appropriate. The last two panels show ratios of different weightings: UVB/UV_{Ery}, and UVB/UVA respectively. In both plots, the spectroradiometer data are distributed as expected, but C14's data are not. Most of their data in Fig. 2e seems to imply an ozone amount greater than 250 DU. However, a closer inspection reveals that ratios larger than 8 do not occur for any ozone amount for these SZAs, which indicates an error of at least 20% in C14's conversion from UVB to UVI. In contrast, C14's data in Fig. 2f would imply an ozone amount very much less than 150 DU, and probably less than 100 DU.

CONCLUSIONS

Aside from C14's data, the highest UVI values reported in the literature are in the UVI range 20 – 25. We have shown that the values of UVI up to 43.3 (and UVB = 11 Wm^{-2}) reported by C14 are wildly inconsistent with other measurements of UVI and ozone, and that their deduced cloud enhancement factors in the UVB are unrealistically large. We have also shown that the data themselves lack self-consistency. Measurement uncertainties were unstated by C14. With this sort of instrument, it is likely that they are in the range 10-20% [2]. But even allowing a measurement error of 20%, the resulting UVI value of 34 (i.e., 0.8 of 43) is barely plausible. Furthermore, the inconsistency in Fig. 2e, with the ratios being 20% larger than possible for any ozone amount, suggest that either C14's measured UVB value is to large, or their derived UVI value is too small by 20%. So removing that inconsistency would lead to an even larger, and more implausible UVI value. More work is needed to carefully characterise the Eldonet instruments in question.

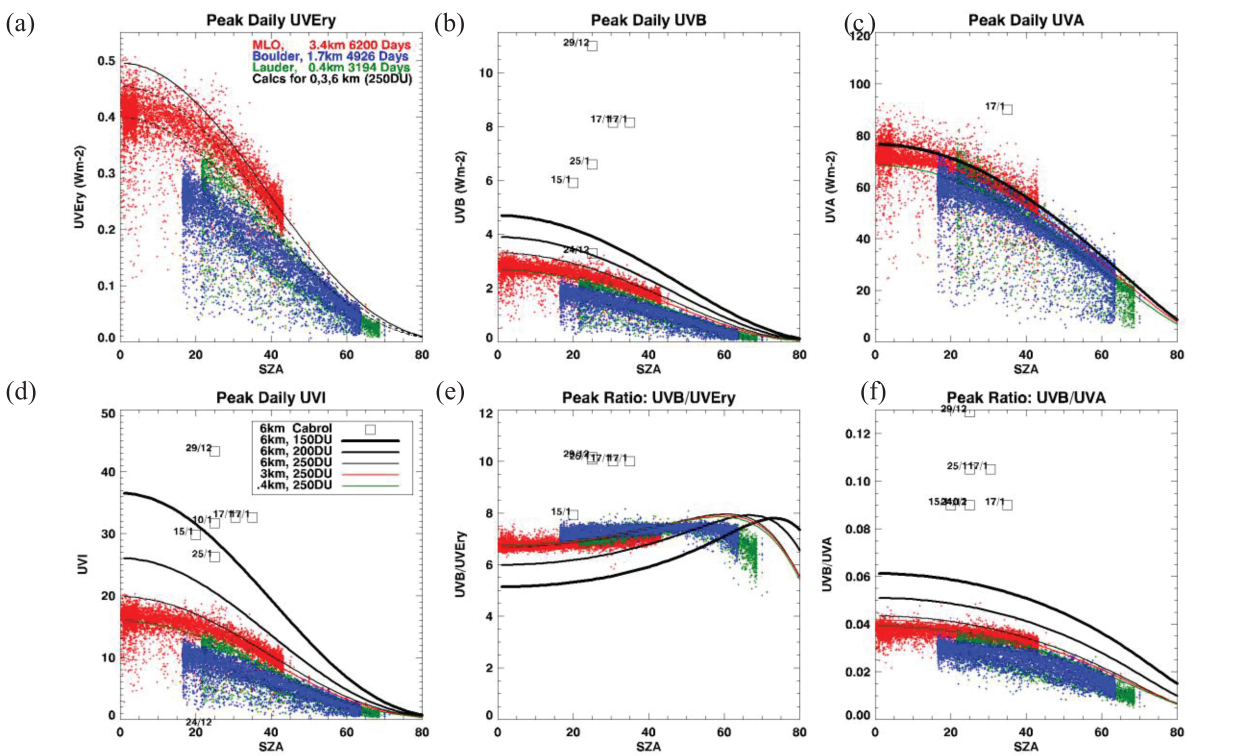

FIGURE 2. *Comparing noontime measurements as a function of SZA from multiple years of NDACC-quality data at 0.4, 1.7,* and 3.4 km with model calculated and the values reported for altitude 6 km by C14 (labelled by day/month).

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