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Comparing Handheld Meters and Electronic Dosimeters for Measuring UV Levels Under Shade and In The Sun

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Abstract

This study aimed to compare the validity, reliability and practicality of alternative portable methods for measuring erythemal UVR levels in passive recreation areas in public parks. UVR levels were measured for point in time comparisons between Solarmeter 6.5 handheld meters and time-stamped electronic dosimeters in a large central park in Melbourne, Australia. Observations were made at 20 locations in the park by two research assistants under two conditions 1) matched shade 2) contrasting shade - no shade. Comparisons were also made with scientific instruments on the UVR monitoring station rooftop and by remotely selecting UV records and forecasts on cloud-free dates of park observations. There was good agreement between the portable UVR instruments in the park setting as confirmed via Bland Altman plots, while the dosimeter appeared less sensitive to change in shade conditions. The rooftop measurements showed the Solarmeter 6.5 UVR readings were comparable to those of the adjacent rooftop instruments. The practicalities of using the dosimeters and Solarmeters for behavioural studies are discussed. These findings provide a basis for use of the Solarmeter 6.5 to measure changes in UVR levels due to different environmental conditions with relative accuracy for intervention studies in outdoor settings.

Graphical Abstract

Comparisons of UV measurements and other practical information are provided to assist public health researchers with choice of portable radiometers for future studies.

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INTRODUCTION

The World Health Organisation (WHO) recommends that people use sun protection when ultraviolet radiation (UVR) levels reach Ultraviolet Index (UVI) 3 and above to minimize their risk of skin cancer (1). Where shade is readily accessible it can offer an important means of reducing people's exposure to UVR, especially where people have not equipped themselves with hats or other sun protection items. Shade use is consistently associated with fewer sunburns, as compared with use of other forms of sun protection with the exception of minimising time outside (2). Different types of shade from trees, buildings, verandas, roofed structures and shade-sails all offer reductions in UVR (3–5).

Intervention studies to assess the effects of increasing the availability of shade can provide a strong catalyst for generating funding for future shade developments. In Australia the effectiveness of a randomised trial that built 23 shade-sails in secondary schools was assessed on increased students' use of the newly shaded areas at the intervention schools (6). However, this study did not measure the outcomes in relation to reduced UVR exposure of students using the shade, which might have made an even stronger case for the benefits of shade development. The study was limited by portable UVR measurement instruments available at the time and the potential for bias introduced by asking students to wear dosimeter badges. In planning the next intervention for assessing the effectiveness of built shade, various options for measuring potential reductions in UVR exposure in the park setting were sought.

Polysulphone film has been widely used to measure personal UVR exposures (7). This technology, and that of biological spore dosimeters (8, 9), have provided important information about total accumulated doses of UVR received by people in different settings. One limitation of this technology is that the UVR doses are continuous and not easily matched to exposure during specific times of the day or under different conditions. Researchers have utilised concurrent self-report diaries as a means of validating and explaining variations in UVR doses among participants (10). The next wave of dosimeters incorporated a time-stamping function. Thieden and colleagues have conducted considerable personal dosimetry research using time-stamped electronic data loggers worn on the wrist

(11–16) to measure people's UVR exposures in Standard Erythral Doses (SED) (17) at specific times of the day. Similarly, Allen and McKenzie (18) developed a low cost small electronic dosimeter to continuously measure and record time-stamped UVR exposures when worn (on clothing or a wrist-strap) by participants in studies of outdoor workers (18–20). As mentioned above it is important to assess reductions in UVR exposures of participants to fully evaluate any benefit of a built-shade intervention. One problem with this assessment is that participants might avoid or leave newly shaded (intervention) study areas if their activities are interrupted by research assistants measuring UVR levels. Ideally the natural usage of the sites needs to be assessed rather than the effects of the research methods. Measurements of UVR assessed by research staff immediately following observations of participants' shade use minimises the method bias and provides time-relevant exposure data. This approach lends itself to use of both the time-stamped dosimeters and portable handheld meters to measure local UVR levels. A number of handheld meters are commercially available which have the advantage of being relatively small, require no set up calibrations, and provide instantaneous outputs of UVR levels that can be recorded manually.

Comparison of the UVR measurements recorded by these personal dosimeters and handheld meters with a recognised reference instrument is essential for valid use. Spectroradiometers and biometers located at UVR monitoring stations across the world provide accurate measures of solar UVR according to the CIE erythral action spectrum (21, 22). Commercially available portable UVR meters, watches and weather stations have shown variable accuracy when tested against spectroradiometers in rooftop conditions (23, 4).

The current research aimed to compare the validity, reliability and practicality of two alternative portable instruments for measuring UVR levels in passive recreation areas in public parks for a planned shade intervention. The instruments tested were a time-stamped electronic dosimeter and a commercially available handheld electronic meter.

MATERIALS AND METHODS

Study design and setting

UVI measurements were conducted between 10AM Daylight Saving Time (DST) and 3PM (DST) during one summer at Carlton Gardens, a large park with established shade trees in central Melbourne (37° 48' 51" S, 144° 57' 48" E), Australia. To improve equivalence of comparisons with remote rooftop UVI measurements the data were collected on forecast sunny days and ceased if conditions became heavily overcast. Two research staff conducted the UVI measurements at 20 sites within the park across five dates in February 2011 (9/2, 14/2, 15/2, 17/2 & 23/2), a month with high UVR in the southern hemisphere. Records of ground based column ozone for these dates were 261 DU for 9/2, 283 DU for 14/2, 274 DU for 15/2, 283DU for 17/2 and 263 DU for 23/2. Each of the five days of the study had some time periods when there was clear sky, some periods when there was slight cloud and some time periods when the cloud was highly variable and rapidly changing. The researchers spent approximately 30-minutes at each park site to undertake UVI measurements in a synchronised fashion each using both a time-stamped dosimeter (purchased Scienterra Ltd, Oamaru, Otago, New Zealand) and a handheld meter (Solarmeter model 6.5, Solarmeter

Australia, www.solarmeter.com.au) and recording UVI at the same points in time. The UVI measurements were made under two conditions: 1. Under matched conditions (shaded) with measurements made standing side-by-side. 2. Under contrasting conditions (in shade and in sun) with measurements made simultaneously at a distance not more than 5–10 meters apart. Condition 1 enabled assessment of both agreement of UVI measures taken by each person using the two different instruments and inter-rater reliability comparing two people measuring UVI with the same instrument type. Condition 2 enabled tests of the sensitivity of each instrument to changes in UVI levels in sun and in shade. At each park site two UVI observations were made for each condition using the handheld meters and later compared with the UVI data downloaded from each dosimeter at the identical time points.

The park UVI measurements were also compared with records for these observation times with rooftop instruments calibrated to international standards including a spectroradiometer (a double monochromator system, Model DTM 300, Bentham Instruments Ltd, Reading, Berkshire, UK) and Biometer (Model 501, Solar Light, Glenside, PA 19038, USA) located in Melbourne ~17.8 km from Carlton Gardens at the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA). The spectroradiometer is the primary instrument with traceable calibration to the CSIRO National Measurement Institute; this is transferred to the Biometer by doing in situ comparisons. The spectroradiometer is in an air-conditioned hut, while the Biometer is outside in the open. Daily comparisons can be used to derive a scaling factor between the instruments.

UVI measurements were also made across one whole day under clear skies (December 16, 2011) with the handheld meters on the ARPANSA rooftop (next to the rooftop instruments). Observations of direct solar UVR and diffuse solar UVR were made with two handheld meters by two researchers and ARPANSA staff.

Time stamped electronic dosimeters

Each dosimeter consists of a disc of 35 mm diameter and 12mm depth, with the UVR detection capability based on a solid-state Schottky photodiode with a responsivity matched to the erythral action spectrum according to test results of dosimeters of equivalent type (18). The detector was encased in a weatherproof PTFE enclosure that also acts as a diffuser to improve the cosine response of the instrument. Data transfer was performed 'wirelessly' via a dosimeter cradle and technical software (Scienterra Ltd/University of Canterbury) which also stored the calibration details for each device. Each dosimeter was set to record UVR readings at 60-second intervals daily between 10AM (DST) and 4PM (DST). The dosimeters were tested via exposure to UVR for an extended period on two clear-sky days (5–6/3/2011 column ozone: 255–288 DU) to confirm these recorded UVR as expected in a bell-shaped curve across the day. UVR was recorded by the dosimeters as a digital count (on a scale from 1 to 1023) that was later converted to erythemally-weighted UVR irradiances (UVI) via calibrated scaling factors based on comparison with the spectroradiometer data across the two clear-sky dates.

Each dosimeter was attached to the centre top of a light-beige coloured wide-brimmed hat using a large safety pin and worn on the head with the sensor pointing up for each 10-minute observation period at the park sites. The hats were kept in a dark coloured bag while

readings were not being recorded. The data were downloaded daily via the cradle software at the end of observations, and the data observation times were verified with the paper records for each park site.

Handheld meter

For the park measurements the electronic handheld UVI detector (Solarmeter UVR 6.5 SiC purchased from www.Solarmeter.com.au, for published spectral responsivity of this model refer to www.solarmeter.com/model65.html) was removed from its protective case and held at arm's length from the researcher in a vertical position pointing the sensor directly up. The researcher pressed the button until a stable reading was determined and manually recorded the reading. On the ARPANSA rooftop alternating measurements with the handheld meters of global solar UVR (measured with the meter pointing at the sun), global solar UVR (holding the handheld detector vertically so that they measured UV on a horizontal surface) and diffuse UVR (shading the detector optics with a 2.5 cm wide metre rule held at arm's length to remove the direct solar UVR from the sun but allowing a full view of the rest of the sky) were collected.

Forecast UV Index Records

ARPANSA UVI forecast data for 1:30pm were obtained for comparison with UVI measurements taken at a similar time in the sun at the park for the five observation dates. The ARPANSA UVI forecast utilizes the forecast ozone for that day and derives the expected UVI with time of the day for clear sky conditions i.e. it does not include cloud cover.

Other observations

Observations of the type of cloud cover (none, thin, thick, overcast) and the percentage of the sky covered by clouds, and a subjective rating of wind speed (5-point scale: none to very strong) were made at each park site.

Analysis

The UVI levels recorded for each instrument and condition were described using descriptive statistics (means and standard deviations). The cloud fraction was calculated from observed cloud type and percentage cover of the sky.

Agreement of measures (by instrument type, between staff, with ARPANSA records) were described using Bland Altman plots (24) including the mean UVI and 95% limits of agreement (equivalent to approximately ± 2 SD). Comparisons with ARPANSA measurements used the UVI records equivalent to the park observation times (either within 3 minutes or the average of the two next closest records) and the first unshaded park observation at each site. Comparisons of the UVI measures recorded across the day on the ARPANSA rooftop were made by plotting the diffuse and direct solar UVI measured by the two handheld meters and the records from the spectroradiometer and the Biometer. Global solar UVI was also plotted (the sum of diffuse and direct solar UVI). Comparisons with UVI forecasts used a descriptive analysis of the data for comparable time points. Stata 12.1 (StataCorp, Texas, USA) and Microsoft EXCEL 2010 were used for analyses.

RESULTS

Park UV measurements

The UVI measurements at the 20 park sites were conducted mostly under thin clouds ($n=12$) or clear sky conditions ($n=4$); the mean cloud fraction was 20% of the sky ($SD=23.4\%$). Wind was observed to be 'moderate' for 5%, 'slight' for 85% and no wind for 10% of the locations at the time the park UVI measurements. The mean temperature across all the observations was 24.8°C ($SD=3.6^{\circ}\text{C}$) as recorded by researcher 1 and 24.9°C ($SD=4.3^{\circ}\text{C}$) as recorded by researcher 2. For the matched shaded condition UVI measurements were taken at two time-points (10-minutes apart) at each park site, resulting in a total of 40 observation times at 20 sites. The UVI recorded under shade in this condition ranged from 0 to 4.5 UVI. Simultaneous UVI measurements under shade and in the open (shaded-unshaded condition) were made at a further 40 observation times. In this condition the UVI recorded under shade ranged from 0 to 4.0 UVI and unshaded from 0.6 to 10.3 UVI. Table 1 describes the mean UVI values recorded in each condition.

The Bland Altman plots in Figures 1a and 1b compare the UVI under shade as measured by each observer using the two instrument types. These figures show there was generally good agreement between the handheld meter and dosimeter UVI measurements under shade (more than half the data points agreed within ± 0.5 UVI). However, the difference in handheld and dosimeter readings tended to increase as mean UVI levels increased. Each researcher's observations had positive values for the mean difference between the handheld and dosimeter measurements (Figure 1a mean=0.3, $SD=0.5$; Figure 1b mean=0.4, $SD=0.3$). This indicates that on average the handheld meters measured higher UVI levels than the dosimeter under shade.

Figure 2 shows there was high inter-rater agreement between the different observers using the same type of instrument. Most of the paired UVI measurements under shade were within ± 0.5 UVI for both the handheld meters and the dosimeters. There was somewhat greater variability in the dosimeters' measurements compared with the handheld meters' measurements as mean UVI levels increased.

Figure 3 shows generally good agreement between the handheld meters and dosimeters' measurement of the difference in UVI at a shaded location and an unshaded location at the same time point. The variation was greater (i.e. most of the paired measures agreed within ± 3.5 UVI) than in Figures 1a, 1b, and 2 given we are measuring the difference in the handheld meters and dosimeters measuring the reduced UVI in shaded compared with unshaded conditions. However, Table 1 highlights the measured mean reduction in UVI under the tree shade was numerically lower for the handheld meters compared with the dosimeters.

Comparisons with ARPANSA UVI records

Figure 4 shows a comparison of the global horizontal UVI measurements at the park with the remote ARPANSA UVI records. The UVI measures of both the handheld meters and dosimeters in the park setting were generally lower compared with the rooftop instruments for the equivalent time-points at ~ 17.8 km distance. For these 20 time-points the mean UVI

measurements were 6.3 UVI (SD=1.9) for the handheld meters, 5.7 UVI (SD=2.5) for the dosimeters and 8.6 UVI (SD=2.9) for the spectroradiometer (Table 2).

Figure 5 compares the UVI measurements from the two handheld meters whilst located on the ARPANSA rooftop with the adjacent spectroradiometer (labelled SRM) and Biometer. With a few small aberrations these data show the horizontal global solar UVR measured with the handheld meter had good concordance with the standard UVR monitoring instruments and had a relatively smooth bell-shaped curve reflecting the change in solar angles across the day. The diffuse UVR measurements across the day were not as closely correlated with the ARPANSA instruments, but indicate that the handheld detectors respond to shading of the optics. This also indicates that the handheld meters had at least some cosine response. The direct UVR was calculated from the measurements of global solar UVR (with the handheld meter pointed toward the sun) minus the measurements of diffuse solar UVR. The direct UVR component changed slightly across the day, as the handheld meters did not have as good a cosine response as the spectroradiometer, with teflon diffuser input optics. Global horizontal UVR measurements from the two handheld meters were at their peak (both 11.9) but at different times, with generally less than half a UVI unit difference for times within a few hours around solar noon (mean difference was 0.21 ± 0.51 UVI units across the day).

Comparisons with UVI Forecasts

The park measurements also showed relatively good concordance with the UVI forecast models at 1:30pm on the observation dates (Table 3). This suggests during clear skies these UVI forecast data could provide a good proxy for any missed ambient UVI measurement data needed in future studies.

DISCUSSION

This study uniquely compared measures of UVR levels from a handheld meter and time-stamped dosimeter by researchers at simultaneous time points in a setting people access for outdoor recreation, i.e., a public park. The Bland Altman plots confirmed there was good agreement between the handheld meters and dosimeters in measuring UVI in the park setting in shade, albeit with slightly lower mean UVI recorded for the dosimeters. Similarly, there was good replication of measurements made by different operators using the same instrument type in shade. However, there were a few more outliers among the measurements by different operators using dosimeters compared with the handheld meters. The position of the dosimeters may partly explain this greater variation, given the dosimeters would be subject to different solar angles from the tilting and height of each researchers' head compared to the handheld meter that researchers held with the sensor pointing up. Downs and Parisi (25) documented considerable variation in UVR doses measured by dosimeters on different parts of the head. Small aberrations due to position were also evident in the handheld readings on the rooftop compared with the spectroradiometer and Biometer which measure from a stable horizontal plane. Concurrent measurement of different UVI levels in the sun and in shade suggests the handheld meters also displayed a greater sensitivity to a decrease in UVR levels.

The measurements using these portable instruments at the park showed consistently lower UVI than the scientific instruments at ~17.8 km distance. However, observations on the ARPANSA rooftop with the handheld meters demonstrated the expected bell-shaped curve in measured UVI levels across the day due to changing solar angles and close agreement with the spectroradiometer and Biometer. This suggests both portable instruments showed good concordance with the scientific instruments. The study protocols ensured that the park measurements were made on days of forecast clear skies, but some measurements across the day were made under partly cloudy or thin cloud conditions which may have contributed to the difference in UVR at the two sites. The measurements of the dosimeters may also have been subject to scatter from the hat position.

Studies comparing Solarmeters' and scientific instruments' UVI measures show some variation in accuracy of these UVI meters. Correa et al. (23) found their Solarmeters typically underestimated absolute UVI levels by 10–20%, while Gies et al. (4) found observations by three Solarmeters varied by 4–8%, with two overestimates and one underestimate. Thieden et al. noted UV observations by VioSpor dosimeters in a beach and holiday study were typically 20% higher than ambient UV as measured by a UV-biometer (9).

Large errors in measuring absolute UVR levels are problematic for comparisons between studies. It was encouraging that the Solarmeters performed well compared with the ambient readings when adjacent to the spectroradiometer and Biometer. Reporting of data from portable meters using a calibration factor validated against an internationally standardised spectroradiometer or Biometer would improve interpretation of differences across studies. Nonetheless, measurement of the relative UVR rather than absolute UVR is also useful within studies (9), for example in revealing different UVR levels under shaded compared with unshaded locations, and both types of sensors may be adequate for assessing relative UVR.

Few studies have reported use of the Solarmeters in recreational settings. Our mostly clear sky Solarmeter unshaded UVI measurements in the park (mean 6.5 UVI, 2.3–9.8 UVI) included higher UVI values than those measured on tourist walks in Paris (mean 5.3 UVI, 3.7–6.7 UVI) (26). This is consistent with the different latitudes, and increased UVR intensity in the Southern hemisphere (27). However, there did appear to be more variation in UVI measurements in our study with mostly grass surfaces compared with the paved streets on the Paris tourist walks. Similarly, in our study UVI measured in the park was consistently slightly lower when compared with the remote UVI records from rooftop scientific instruments despite measurements with Solarmeters on the rooftop at ARPANSA being in close agreement with the rooftop instruments. The reduced sky view and obstructed horizon at the park due to presence of large trees may partially explain these patterns, as well as reflection and scatter of UVR from trees and grass in the vicinity (28) in combination with any instrument cosine response. Researchers should be cautious when using rooftop UVR measurements to provide estimates of UVR at specific locations with obstructed horizons, especially when UVR is high.

In terms of the practicality (i.e. for ease of use) in outdoor recreation settings the handheld meters outperformed the time-stamped dosimeters. They also had less risk of missing data than the dosimeters. The procedure of pushing a button to obtain a UVI reading and recording the value manually was simple compared with the procedure to obtain the data from the dosimeter. The main advantage of time-stamped dosimeters is that they can possibly reveal consistent patterns of UVR exposures for the subjects wearing them. They can be programmed to enable frequent data to be collected over an extended period (up to 1 year), which is particularly valuable for studies of accumulated personal UVR exposures. For example, in a study on photo-production of Vitamin D, 201 volunteers wore dosimeter badges over 10 weeks at a sampling frequency of every 8 seconds generating 100,000s worth of personal UV exposure data points, (29) something that is impossible with a handheld meter. However, the necessity to read the dosimeter count data via a cradle connection, which required set up and calibration via hyperterminal software followed by complex calibrations was onerous at least for those who lacked familiarisation with this specific technology. These complexities may well erode any cost savings of data entry with dosimeters for smaller studies. Moreover, at times the cradle connections failed and data could not be downloaded. In the interim the developers have significantly improved the software and cradle to minimise some of these issues with the dosimeters. The main advantage of time-stamped dosimeters is that they can possibly reveal consistent patterns of UVR exposures for the subjects wearing them.

It is probably not very surprising that a handheld meter with an in-built display is easier to use in measuring low frequency UVI levels at various geographical places in public parks than a dosimeter that is principally designed to measure higher frequency personal UVR exposures that can be worn on a wrist-strap or pinned to clothing. Nonetheless, we found considerable care was required to keep the UV detector of the handheld meter in the correct position (upright and pointing towards the sky) to provide repeatable measurements. Even fingerprints on the detector of the handheld meter could produce noticeable aberrations in the UVI readings, while the dosimeters did not appear to be subject to this potential error. This suggests that for the handheld meters taking the average of two to three consecutive UVI readings and/or training staff to take the readings using the correct upright position might avoid these errors. To assist with correct readings the manufacturers might consider inclusion of a spirit level in future models of the Solarmeter.

Our comparison of the dosimeters' and Solarmeters' measurements were not made in an exactly equivalent manner (e.g. height of the detector or temporal length of the observation). Moreover, we did not measure the cosine response errors of these instruments as this was outside the scope of our study. Reported cosine response for equivalent dosimeters was acceptable with 'an overall angular response to within 10% of a true cosine' (19). In conclusion, for small studies with discrete UV measurement needs (e.g. the planned shade intervention with few measures taken at specific time points), the Solarmeter 6.5 UVI meter was superior to the time-stamped dosimeter due to the Solarmeter 6.5 UVI meter's ease of use and sufficient sensitivity to changing UV levels between unshaded (i.e. sunny) and shaded conditions. It also appeared to be superior to relying on scientific measurement of UVR located at some distance from the study site.

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Figure 1.

(a) Mean UV Index of handheld 1 and dosimeter 3. (b) Mean UV Index of handheld 2 and dosimeter 4.

Figure 2.
Inter-rater agreement under shade.

Figure 3.
Handheld meter and dosimeter agreement measuring reduced UV sun to shade.

Figure 4.
Agreement of handheld meter and dosimeter to ARPANSA spectroradiometer (unshaded conditions).

Figure 5. Australian radiation protection and nuclear safety agency (ARPANSA) rooftop UV measurements across the day for the Solarmeter 6.5 compared with the spectroradiometer and Biometer. The agreement between the two Solarmeters and the ARPANSA SRM and Biometer is mostly between 5 and 10%.

Table 1

Summary of ultraviolet (UV) index measurements at the 20 park sites

Condition	Observation time points	HH_1 Mean (SD)	HH_2 Mean (SD)	DO_3 Mean (SD)	DO_4 Mean (SD)
1. Shade-shaded	40	0.8 (0.9)	0.9 (1.0)	0.5 (0.7)	0.5 (0.7)
2. Unshaded-shaded					
		Hand held [†]		Dosimeter [‡]	
		Mean (SD)		Mean (SD)	
Shade observations	40	0.8 (0.9)		0.5 (0.6)	
Sun observations	40	6.5 (2.0)		5.9 (2.4)	
Difference in UV sun to shade	40	5.7 (1.9)		5.5 (2.3)	

[†] Combined HH_1 & HH_2

[‡] Combined Do_1 & Do_2

N= 40 represents a start and end reading for each condition during the 10-minute observation period at each of the 20 park sites

Table 2

Comparison of unshaded park observations with ARPANSA spectroradiometer records at 20 time points[†]

Instrument	Mean	SD	Min	Max
Handheld	6.4	1.9	2.3	8.7
Dosimeter	5.7	2.5	0.6	9.6
ARPANSA spectroradiometer	8.6	2.9	3.3	12.3

[†]The first unshaded measurement at each park site was compared with ARPANSA spectroradiometer records

Table 3

Comparisons of unshaded park measurements with ARPANSA forecast models available in the daily UV Index Summary for Melbourne and the maximum UVI recorded, February 2011

Date	Park observation time closest to 13:30	Handheld UVI	Dosimeter UVI	Observed cloud type (and extent) at the park	ARPANSA forecast max. UVI [‡]	ARPANSA max. UVI recorded	UVI max time
9 th	13:26	9.5	10.3	Thin high (40%)	10	10	13:20
14 th	13:34	7.8	7.4	Clear sky	10	9	13:30
15 th	13:28	9.8	8.1	Thin high (50%)	10	9	13:30
17 th	14:11	9.0	5.9	Partly cloudy (20%)	9	9	13:30
23 rd	12:27	8.2	9.2	Thin high (10%)	9	9	13:30

[‡]UV forecast using clear sky model at 13:30