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Use of smartphone apps to monitor human exposure to solar radiation: Comparison between predicted and measured UV index values

Giacomo Salvadori[a,*], Francesco Leccese[a], Davide Lista[a], Chiara Burattini[b], Fabio Bisegna[b]

[a] Dept. of Energy, Systems, Territory and Constructions Engineering (DESTeC), University of Pisa, Pisa, Italy
[b] Dept. of Astronautic, Electric and Energy Engineering (DIAEE), Sapienza University, Rome, Italy

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ABSTRACT

The Ultra-Violet Index (UVI) is widespread used to communicate the UV radiation intensity to the general public. The knowledge of the UVI value and of its daily variation is essential for many techniques for monitoring the personal exposure to UV radiation. The UVI values are usually provided by the meteorological services and nowadays it is very common to find UVI forecast tools even in smartphone apps. In this paper, with the aim to evaluate the prediction accuracy of six smartphone apps, a measurement campaign of UVI has been carried out. The measurements have been conducted for the site of Pisa (central Italy), using a portable photoradiometer equipped with a UV erythemal irradiance probe (operating range 250–400 nm). The measured UVI values have been compared with the predicted UVI values (using smartphone apps). Bland-Altman and Passing-Bablok methods have been used to compare the data, the comparison has been conducted on the basis of 90 different UVI measurements, taken at different times, different days and different sky conditions. From the comparison between measured and predicted UVI values it has been possible to observe a general poor accuracy of the apps. The percentage deviations between measured and predicted UVI values were quite high and only one app was able to predict more than 70% of the measured data with an average percentage deviation lower than 30%.

1. Introduction

Ultra-Violet (UV) radiation is a small part (about 5%) of the electromagnetic radiation emitted from the Sun reaching the Earth's surface (Modenese et al., 2018). UV radiation is included in the wavelengths between 100 and 400 nm but, due to the filtering effect of the Earth's atmosphere, the major part of UV wavelengths below 290 nm are absorbed by the stratospheric ozone O_3 (Ghetti et al., 2006). According to standard CIE 209 (Commission Internationale de l'Eclairage (CIE), 2014), UV radiation can be classified in three different spectral bands: UVC (wavelengths in the range 100–280 nm), UVB (280–315 nm) and UVA (315–400 nm).

1.1. UV radiation exposure risks of outdoor workers

The exposure to UV radiation induces several effects on the human body, some of which are positive but most are negative (Baczynska et al., 2019). Daily exposure, in small amounts, to UV radiation is vital for humans because UV radiation has a crucial role in the activation of the vitamin D production process (Kift et al., 2018; Rajakumar et al., 2007). Furthermore, UV radiation is adopted in the medical field for the treatment of certain diseases such as rickets, lupus vulgaris, psoriasis, vitiligo, osteoporosis, etc. (Chubarova and Zhdanova, 2013; Kryścin et al., 2015; World Health Organization (WHO), 2003). On the contrary, overexposure to UV radiation induces acute, chronic and long-term adverse effects on the skin and on the eye. The most frequent adverse effects are sunburns (erythemas), wrinkles (skin ageing), skin moles (nevi) and increased photosensitivity (photodermatoses) (Backer et al., 2001; D'Orazio et al., 2013;). The most serious adverse effects are melanoma cancers on the skin and cataracts on the eye (Arisi et al., 2018; Thieden et al., 2005). The International Commission on Non-Ionizing Radiation Protection (ICNIRP) recognizes UV radiation as the main photobiological risk factor for the human tissues and the International Agency for Research on Cancer (IARC) classifies UV radiation as carcinogenic to humans (Solar radiation was classified as Group 1of the IARC classification of the carcinogenic factors) (International Commission on Non-Ionizing Radiation Protection (ICNIRP), 2004; International Agency for Research on Cancer (IARC), 1992).

The complete absence of exposure to UV radiation cannot be considered a solution for the elimination of the connected photobiological risks, because, as aforesaid mentioned, it would entail other problems related to vitamin D deficiency (e.g. skeletal diseases). The optimal

* Corresponding author.
E-mail address: giacomo.salvadori@unipi.it (G. Salvadori).

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level of exposure to UV radiation is that able to maintain acceptable production of vitamin D (during summer, in most countries, adequate level of Vitamin D production is achieved with low sun exposure), minimizing the risks due to UV overexposure. Global estimation of the burden of disease caused by environmental risks, has been analysed by the World Health Organisation (WHO). With specific reference to the solar UV radiation, a detailed guide for assessing the burden of disease at country or local level is proposed in (Lucas et al., 2006), in order to respond to the need to quantify the health risks and to use it as input to rational policy making. Given the importance of appropriately dosing the exposure to UV radiation (neither low nor excessive), the knowledge of UV radiation received over time by each individual is very important, also in order to undertake adequate and timely corrective measures (Salvadori et al., 2019). For example, in reference to the risk of UV overexposure, it is proved that timely protecting behaviours, such the use of hats, sunglasses, sunscreens and UV protective clothing, are able to significantly reduce the harmful effects produced on humans (Modenese et al., 2016; Peters et al., 2016; Reinau et al., 2013).

The Sun is the main exposure source to UV radiation for humans and everyone is exposed to the Sun during his leisure time (recreational exposure) but many workers are exposed to the Sun also during their working activities (occupational exposure) (Grandahl et al., 2018). Outdoor workers are usually divided into two groups: workers potentially exposed to low levels of UV radiation (e.g. school teachers, police officers, delivery-persons, etc.) and workers potentially exposed to high levels of UV radiation (e.g. workers in the construction field, farmers, fishermen, ski resort guides, lifeguards, etc.) (Borra et al., 2018; Leccese et al., 2018; Vecchia, 2007). The ICNIRP establishes a maximum limit not to be exceeded to avoid the negative effects due to UV radiation overexposure. The daily exposure limit is fixed in 30 J/m^2 and is referred over a period of 8 h (International Commission on Non-Ionizing Radiation Protection (ICNIRP), 2010). At mid-latitude and in the hot season, the value of 30 J/m^2 is exceeded in few minutes (Gugliermetti et al., 2019), on the contrary exists a northern boundary beyond wich skin cancer does not constitute an occupational risk (Kenborg et al., 2010). For this reason, especially in the occupational field, the knowledge of the UV doses received is important to: protect and monitor the worker's health, help the institutes against accidents at work in the preparation of guidelines to avoid UV radiation overexposure, increase the awareness of UV radiation risks and adopt safety behaviours, this last two aspects are very important not only for workers but also for the whole population (Militello et al., 2016).

In order to evaluate and increase the awareness of the risks connected to UV radiation exposure, the World Health Organisation (WHO) introduced the Ultra-Violet Index (UVI) as an indicator facilitating the communication of the UV radiation intensity to the general public (for a definition of the UVI, see Appendix A) (World Health Organization (WHO), 2002). The UVI can be adopted for the evaluation of the UV radiation intensity also in the occupational field (Allinson et al., 2012). An improvement of the people's awareness about the UV radiation overexposure and its consequences may have a positive impact on the national public health systems, if the awareness produces a change in habits (spontaneous or induced by rules), it can reduce the number of subjects who manifest Sun exposure induced diseases and who require specific treatments (Militello et al., 2016).

1.2. Smartphone applications for UVI prediction

The use of widely spread smart devices, like smartphones and tablets, provided new possibilities for working anytime and anywhere, with a consequent increase in risks, on the other it has provided the possibility of monitoring the risks through data transmission, that is performed by commonly used devices (not by specifically safety dedicated devices, which often encounter the worker's resistance to their use).

Smartphones are nowadays very common and diffuse among population. Surveys show that the smartphone market has skyrocketed, even in the economies of the emerging Nations, from 1 billion of pieces sold at the beginning of the decade, to 2 billion in 2017 and with a prevision to over 5 billion in 2025 (Götz et al., 2017). Smartphone applications have been proven to be useful for young people in emerging Nations (Do et al., 2018). The success of smartphones is due to their portability: in a relatively small case, smartphones are fairly unobtrusive, remotely accessible, sensor-rich and computationally powerful at the point that they may soon become more common than computers (Wang et al., 2016). Furthermore, the use of the operative systems of smartphones and of their apps is very simple and intuitive, not requiring particular skills by the user (Xu et al., 2011). For these reasons, smartphones and their apps may become an instrument of very simple use not only to monitor, evaluate and reduce the occupational risks, but also to monitor the well-being of people subjected to particular psycho-physical conditions, such as during a polluting crisis or during a postnatal period (Zhang et al., 2014, 2017). Nowadays, smartphones are particularly used to reduce the risk of driver collisions (Botzer et al., 2017; Papadimitriou et al., 2019) and for the location of workers in construction sites or production plants, in order to promptly intervene in the event of accidents (Ansaldi and Bragatto, 2019; Soltanmohammadlou et al., 2019). With reference to protection against the risks of UV exposure, the UVI values are usually provided by the meteorological services and nowadays it is very common to find UVI prediction tools even in smartphone applications (*apps*). If the accuracy of smartphone and apps is ascertained, smartphones with their apps can even become a tool to control the regulatory limits by the official of the institutes against accidents at work.

Previous researches on evaluating UVI with smartphone devices and apps can be classified into two categories. The first category is retrieving UVI data from web servers to personal devices with the help of an app. The data usually came from the bureau of meteorology or related government departments. The second category is retrieving UVI values with a combination of external UV sensors and the smartphone, since in commerce there are no smartphones equipped with an UV sensor (Mei et al., 2017). In the first category, the use of an internet connection is required to deliver to the user real-time data while in the latter case the UVI values are measured using an external sensor that communicates with the user's smartphone. The smartphone thereby acts as a user interface to present the measured data (Fahrni et al., 2011). However, users have to carry this accessory sensor in hand, which is not convenient not to mention the extra-cost due to the sensor purchase. According to (Tellez et al., 2017), the 69.6% of free apps in English language in the Apple and iOS market store providing sunscreen information do not have an institutional certification which is important to guarantee the quality of the information provided. In the scientific literature, there is no evidence of studies conducted for the accuracy assessment of apps (very common and diffuse among population and consulted by a very large number of people) in predicting UVI values (a very useful tool to estimate risks arising from sun exposure).

The aim of the research is to evaluate the accuracy of smartphone apps in UVI prediction. Such accuracy is tested comparing UVI values predicted using apps with UVI values measured with portable radiometric instrumentations. The assessment campaign of this study can be useful for health professionals to recommend smartphone apps to their patients, for app developers to improve their apps content and for researchers to choose smartphone apps for their studies.

Table 1
Main features of the six selected apps for the comparison of Section 4.

ID app	Name	Version	Developer	Last update	Operative system	Server of data origin/app website	Data refresh time
A.1	Meteo	8.0.0.351	Huawei Technologies	15/04/18	Android	AccuWeather.com www.huaweimobileservices.com/appgallery	1 h
A.2	UV Lens	2.4.0	Spark 64 Ltd	23/05/18	iOS 12.1	Server not specified www.uvlens.com	not selectable
A.3	MSN Meteo	3.1.5.0	Microsoft Corporation	2015	Windows Phone	msn.com www.msn.com/it-it/meteo	not selectable
A.4	UV Index	1.0.2	Alex Ershov	2017	Android	Server not specified www.uvimate.com	not selectable
A.5	MSN Meteo	3.1.6	Microsoft Corporation	2016	Windows Phone	msn.com www.msn.com/it-it/meteo	not selectable
A.6	iOS Meteo	2.5.4	Apple Inc.	June 2018	iOS 12.1	Server not specified www.support.apple.com/en-gb/guide/iphone/iph1ac0b35f	1 h

2. Materials: description of the selected smartphone apps

For the assessment campaign of the smartphone apps accuracy in UVI prediction, six apps have been selected from the app market stores of the three main operative systems present on commerce (Android, iOS and Windows Phone). For every operative system, two apps have been selected. The two apps (for each operating system) were chosen as the most present on a sample of 70 smartphones belonging to randomly selected workers on the building construction sector, who perform tasks mainly outdoors.

2.1. Apps features

All the six selected apps are free for download and retrieve data from web servers requiring an active internet connection to properly function. The six selected apps are summoned up in Table 1. Since the UVI data are retrieved from internet, the model and the specific brand of the smartphone on which the app is downloaded and installed is not important, as it does not affect the app's operation. The servers from which the UVI values are downloaded are declared only in three apps (A.1, A.3 and A.5) while in the other apps servers of data origin are not specified. For all the apps, the algorithm or the methodology to evaluate the UVI values is neither specified in the settings, nor in the "About" sections, nor on the online sites. Therefore, it can be stated that apps work as "black boxes" for the users giving UVI values with an uncertain origin.

2.2. Procedure for data collection from apps

UVI data from apps have been collected in the month of July 2018 from 9th to 20th, usually being one of the hottest periods of the year for the selected location of Pisa (latitude 43.72°N, longitude 10.39°E). The UVI values of nine days have been collected (in three days data collection has not been possible due to rainy conditions). During the period of data collection, the UVI values shown, using apps, have been collected with steps of 1 h starting at 9:30 and ending at 18:30. In the app settings, the geographical position of Pisa has been selected. The data refresh time in two apps (A.1 and A.6) is selectable and has been selected to refresh and update data every 1 h. In the other four apps, the data refresh time is not selectable in the settings and it is not clear how often the UVI value is refreshed. For each day and for each app, 10 UVI values have been collected for a total of 90 UVI values for each app during the period of data collection.

3. – Methods: description of the UV Index measurement campaign

In Subsection 3.1 the used instrumentation is shown, in Subsection 3.2 the procedure for the UVI measurement campaign is described, in Subsection 3.3 the data post-processing procedure for the collection of 90 UVI values to be compared are summarized.

3.1. Used instrumentation

For the UVI measurement campaign, portable radiometric instrumentation has been adopted. In particular a photoradiometer, composed of data logger *Delta Ohm mod. HD2102.2* equipped with *LP471A-UVeff* probe, has been used. The probe is able to measure the UV erythemal irradiance in the range from 250 to 400 nm. The UV erythemal irradiance is weighted according to the erythema action spectrum defined in the international standards ISO CIE 17166 (ISO and CIE, 2019). In Fig. 1, the spectral response of the adopted instrumentation compared with the ISO/CIE erythema action spectrum is

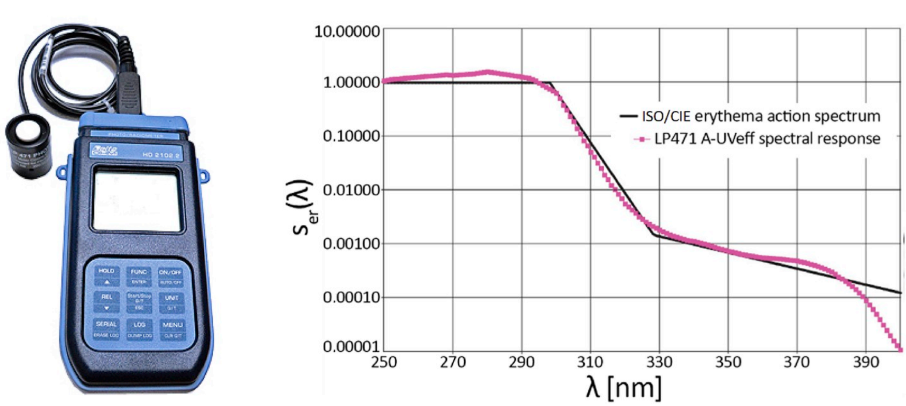

Fig. 1. Image of the photoradiometer (left) used in the experimental activity; spectral response of the probe (*LP471A-UVeff*) compared with the ISO/CIE erythema action spectrum (right), as specified in technical documentation made available by the manufacturer (https://www.deltaohm.com/en/).

shown (for the ISO/CIE erythema action spectrum, see Appendix A). The probe measures the UV erythemal irradiance in the range from 0.001 W/m^2 to 20 W/m^2, with a maximum resolution of 0.001 W/m^2 and a linearity deviation (ISO and CIE, 2014) lower than 3%. Before the present activity, the measurement chain (data logger + probe) was subjected to calibration at the manufacturer's laboratories; the calibration was performed by a calibrated reference photodiode (calibration uncertainty lower than 15%).

3.2. Measurements procedure

The UVI measurement campaign has been made in the month of July 2018, in the same period of data collection from apps. The UVI values of 9 days have been collected (in 3 days data collection has not been possible due to rainy conditions). The UV erythemal irradiance, I_{er} (see Appendix A for its definition) has been measured and then the UVI values have been calculated with Eq. (1) shown in Appendix A. The UV erythemal irradiance measures have been acquired from 9:15 to 18:45 with steps of 1 min at the geographical position of Pisa. The time periods from sunrise to 9:15 and from 18:45 to sunset have been neglected because the UVI values, even in the hottest periods, are always less than 2 and so the UV radiation is not harmful according to the WHO scale of UVIs (see Figure A2 in Appendix A). During the measurement campaign, the adopted instrumentation described in Sub-Section 3.1 has been placed on the roof top of a building at the height of 12 m above the sea level. The probe sensor has been placed in a horizontal position without any shielding element projecting shades on the probe sensor. During the measurement campaign, the sky conditions have been collected with steps of 1 h from 9:30 to 18:30. The sky conditions have been classified into 4 categories: cloud coverage of the sky less than 10%, cloud coverage of the sky less than 50%, cloud coverage less than 90% and cloud coverage equal to 100%, evaluated on the basis of the international standards (ISO, 2004).

3.3. Data post-processing procedure

In the data post-processing, 10 values of the UVI have been selected for each day and they have been used for the comparisons discussed in the next section; in such a way the discussion is made on a basis of 90 UVI values (10 values for 9 days). The selected UVI values are those obtained from measurements carried out at all half hours in the interval from 9:30 (morning) to 18:30 (afternoon), obviously the same time of data acquisition from apps. The 10 selected UVI values for each day have been obtained as the product between the constant k_{er} and the mean value of the UV erythemal irradiance at the different times. The mean values of the UV erythemal irradiance have been calculated as the average of the irradiance values recorded every minute starting from a quarter of an hour before up to a quarter of an hour after the considered time. For example, the mean UV erythemal irradiance value at the 9:30 is the average of the UV erythemal irradiance values recorded every minute from 9:15 to 9:45. In order to analyse the agreement between predicted and measured UVI values, the Bland-Altman method have been used. Furthermore, a linear regression analysis has been performed using the least squares method and then calculating the coefficient of determination (R^2).

4. Results and discussion

In this Section the comparisons between the UVI predicted values (using smartphone apps described in Section 2) and measured values (with the procedure described in Section 3) are shown. For each day, the 10 UVI values collected with apps have been compared with the 10 UVI values obtained by measurements. The UVI trends of predicted and measured values are shown for both a typical sunny day (see Subsection 4.1) and a day with very variable sky conditions (see Subsection 4.2). The comparisons between the UVI predicted and measured values are shown, for each app, during the whole period of data collection.

4.1. UVI trend in a typical sunny day

In Fig. 2, the UVI trends carried out the 9th July are shown for both predicted and measured values. This day is shown because it was a typical sunny day with clear sky conditions and a cloud coverage of less than 10% (only at the 15:30 the cloud coverage was less than 30%). The trend of the measured values is represented by a bell curve, symmetrical with respect to the solar noontime. In fact, in the graph, the measured UVI peak is at the 13:30. The solar noontime for the geographical position of Pisa and for the 9th July has been at 13:23 (considering +1 h due to Summer Time). All apps give an overestimation of the UVI values in the early hours of the day (9:30/10:30). In the case of the apps A.1 and A.4, the predicted value is more than twice the measured value. At the UVI peak (13:30), four apps (A.2, A.3, A.4 and A.5) give an underestimation of the UVI value while two apps (A.1 and A.6) give a very accurate prediction of the measured value. The underestimation in the period in which the peak of the measured values is recorded is a critical element if these apps are used for health protection purposes. At the 15:30, when the cloud coverage increases and the measured UVI value decreases with respect to the case of clear sky, not all the apps predict

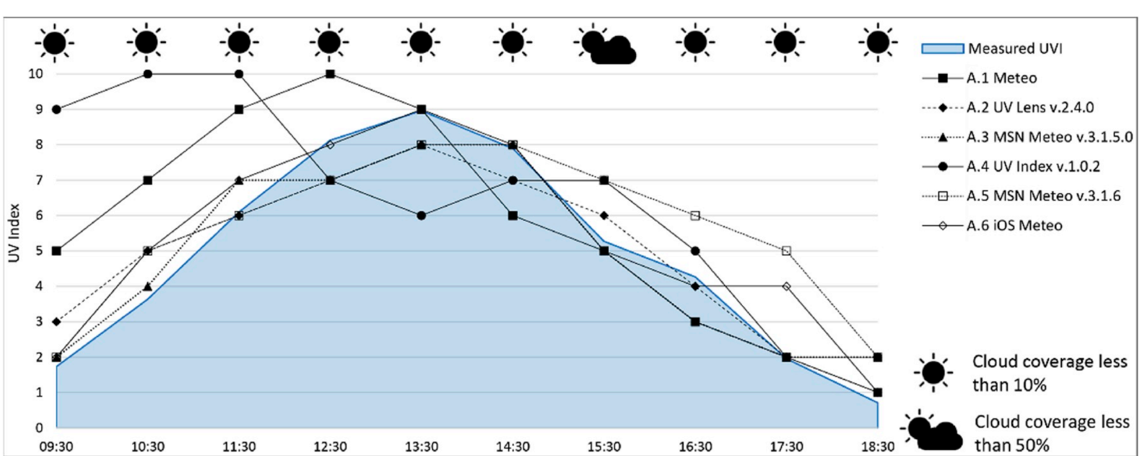

Fig. 2. UVI trends on the 9th July (clear sky day).

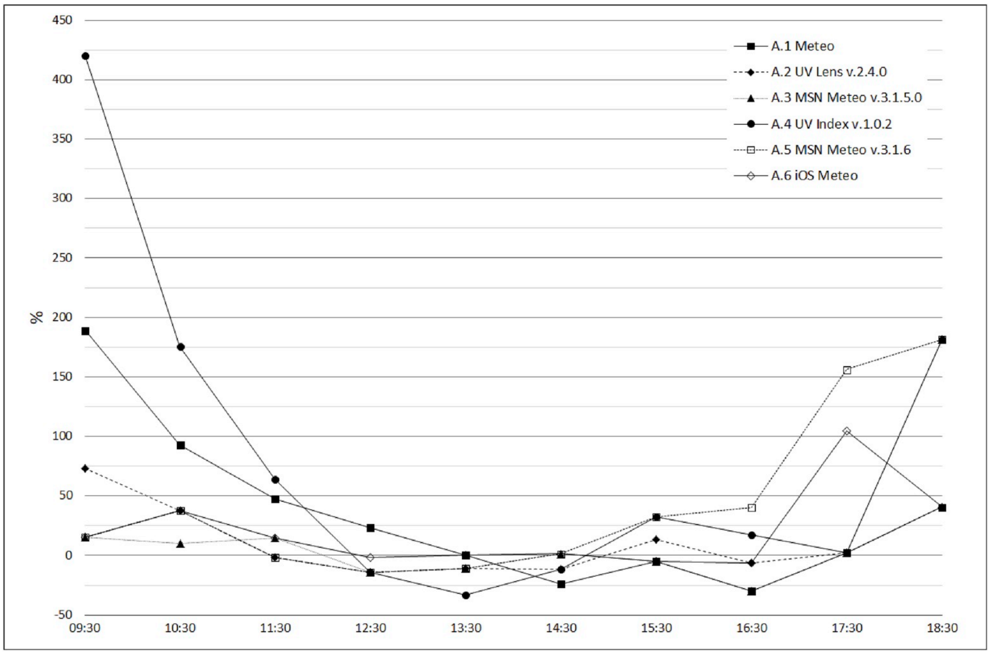

Fig. 3. UVI percentage differences between predicted and measured values on the 9th July (clear sky day).

this decrease but only apps A.1, A.3 and A.6. In the hour before sunset (18:30), as in early hours of the day, all apps predict UVI values greater than the measured one.

In Fig. 3, the UVI percentage differences between measured and predicted values on the same day 9th July are shown. The differences are greater in the early hours of the day and in the hours before sunset. The app accuracy increases in the hottest hours of the day near the solar noontime (from 11:30 to 14:30) while at 15:30, when the cloud coverage increases, the app accuracy decreases.

4.2. *UVI trend in a typical partly cloudy day*

In Fig. 4, the UVI trends for the 11th July for both predicted and measured values are shown. This day is shown because it was a day with a great variability of sky conditions. During the day, clear sky conditions with a cloud coverage of less than 10% (at the 12:30, 13:30, 17:30 and 18:30) were alternating with partly cloudy conditions with cloud coverage of less than 50% (at the 15:30 and 16:30) and with cloudy conditions with cloud coverage of less than 90% (in the morning from 9:30 to 11:30 and at 14:30). Unlike Fig. 2, UVI trend from apps is not similar to UVI trend from measured values. In the morning, from 9:30 to 11:30 with a cloud coverage of less than 90%, all apps overestimate the measured UVI values. In the case of the apps A.1 and A.4, the predicted value is more than twice the measured value. At 9:30, only the apps A.3 and A.6 predict UVI values very close to the measured one. At 10:30, only app A.3 predicts a UVI value very close to the measured one while at 11:30 no apps are able to predict the decrease of the UVI value due to an increase of the cloud coverage. Near the solar noontime at 13:30 with a measured UVI value of 8.5, two apps (A.4 and A.5) predict a UVI value of 9 while three apps (A.2, A.3 and A.6) predict a value of 8. App A.1 predicts a great underestimation of the UVI peak because shows a UVI value of 5. At 14:30, no apps are able to predict the great decrease in UVI value due to the increase of the cloud coverage (from less than 10% to less than 90%). The predicted values are between 7 and 8 while the measured one is 3.4.

In Fig. 5, the UVI percentage differences between measured and

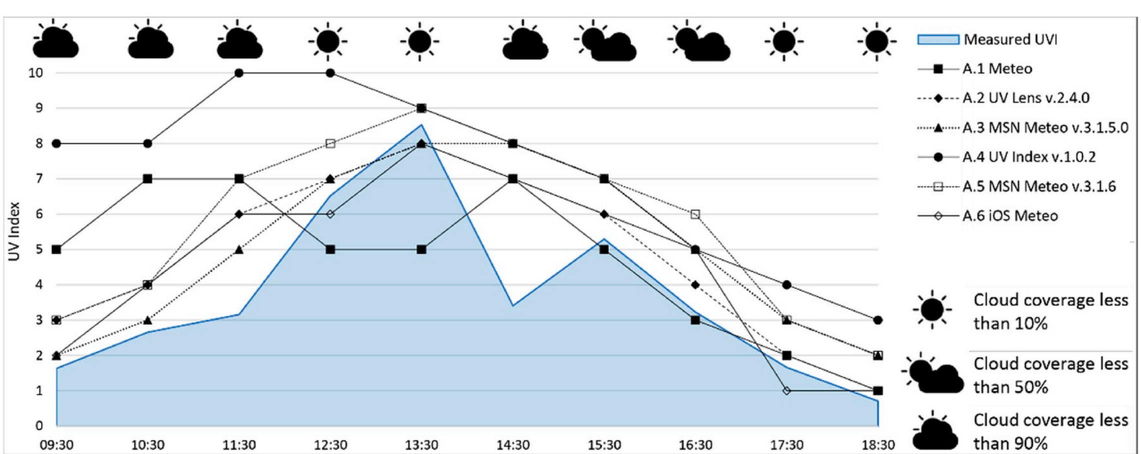

Fig. 4. UVI trends on the 11th July (clear/partly cloudy sky).

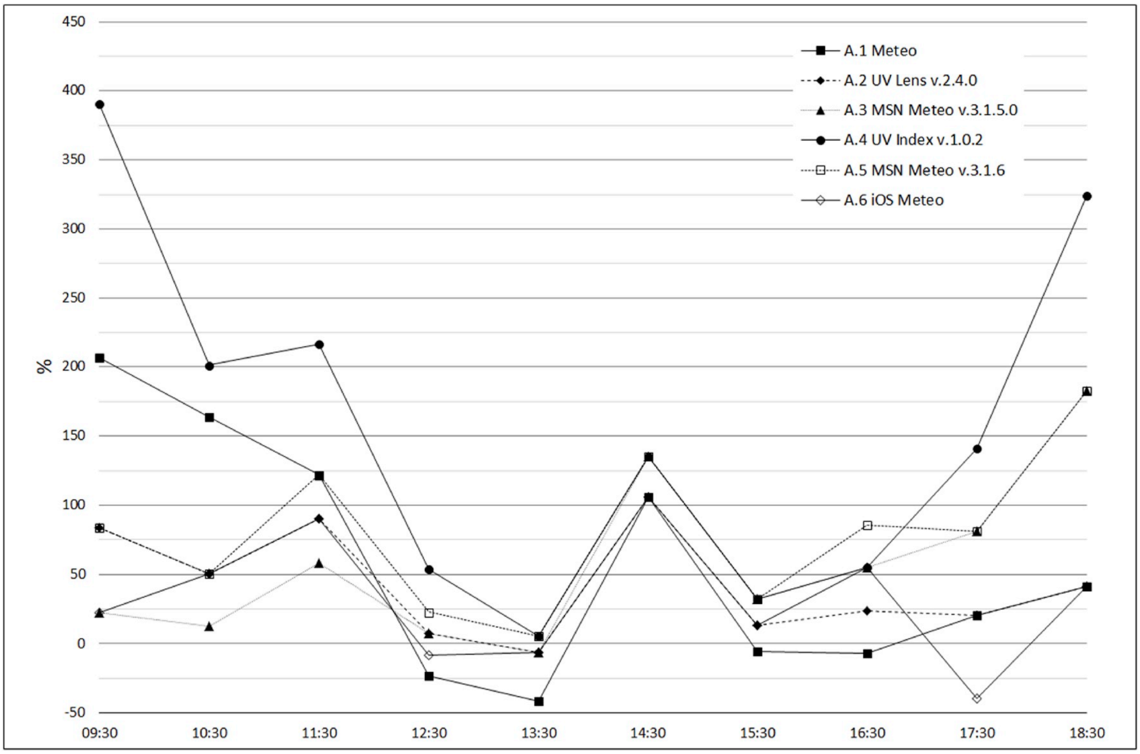

Fig. 5. UVI percentage differences between predicted and measured values on the 11th July (clear/partly cloudy sky).

predicted values on the same day 11th July are shown. As in the previous case of Fig. 3, the differences are greater in the early hours of the day and in the hours before sunset while the app accuracy increases in the hottest hours of the day near the solar noontime (from 12:30 to 13:30). The app accuracy decreases when increases the cloud variability. At 14:30, when the sky conditions change abruptly from clear to cloudy, there is a peak in the graph of the percentage differences and the predicted UVI values are more than twice the measured value.

4.3. – Comparison between predicted and measured UVI values in the whole period of data collection

In Fig. 6, the comparison between predicted (using the selected apps) and measured UVI values is shown for the whole period of data collection, by way of Bland-Altman charts, extensively used to evaluate the agreement among the results of two different assessment techniques.

The charts have been realized by placing on the x-axis the mean values between predicted and measured UVI, and on the y-axis the difference between predicted and measured UVI. The mean value of all the differences (M) and its 95% confidence interval (CI), evaluated as 1.96-fold standard deviation (SD) increase or decrease, are also shown in each chart. Since the UVI values obtained by the apps are expressed through integer numbers (ranging from 1 to 11, see appendix A), the charts in Fig. 6 have been obtained by rounding the measured UVI values to the nearest integer. By observing Fig. 6, it is possible to notice how the best predictions of the UVI values are made by the app A.2, which has the lowest M value (0.444) and also the narrowest CI (from 1.51 to 2.40). The most critical predictions are made by the app A.4 which, on the contrary, has the highest M value (1.58) and the widest CI (from 3.70 to 6.86). It should be noted that when the lower limit of the CI falls below 2 (as happens for apps A.1 and A.4), the predictions could lead to significant underestimations of the real UVI value, and the predicted category of risk could be one level below the real one (see ranges for categories of risks due to UV radiation exposure based on the UVI shown in Appendix A).

In Fig. 7, the differences between predicted and measured UVI are shown, using a box plot diagram. The app A.2 shows again the best results with null median value and very small box. App A.2 shows best results with respect to app A.3 (even if the box of app A.3 are very similar to those of app A.2) because the median of the differences is closest to the value of zero and the whiskers of app A.3 are wider than those of app A, 2. Apps A.1 and A.4 show a great dispersion of the points having the biggest box and the longest whiskers.

In order to make the comparison even clearer, in Table 2, having defined with D the deviation between predicted and measured UVI values, some significant ranges of $|D|$ are indicated. Table 2 shows, for each app, the percentage of data whose predictions fall in the significant ranges of $|D|$. Observing Table 2, it is possible to note that app A.2 predicted more than half of data (57%) with $|D| \leq 15\%$. Apps A.4 and A.5 predicted, on the contrary, less than one third of data (23% and 32% respectively) with $|D| \leq 15\%$ and about half of data (57% and 44% respectively) with deviations $|D| > 45\%$.

Moreover in Fig. 8, predicted and measured UVI values are compared by way of Passing-Bablok non parametric regression charts. This type of regression is particularly suitable for the analyses such as the present one, since it allows to include the outliers and it does not need that the error have a normal distribution. In the charts of Fig. 8, the 95% confidence interval lines and the ideal lines are shown together with the regression lines. For each regression line, the values of the slope (S) and the intercept (I) are indicated together with their 95% confidence intervals (S95 and I95 respectively). Each chart has been

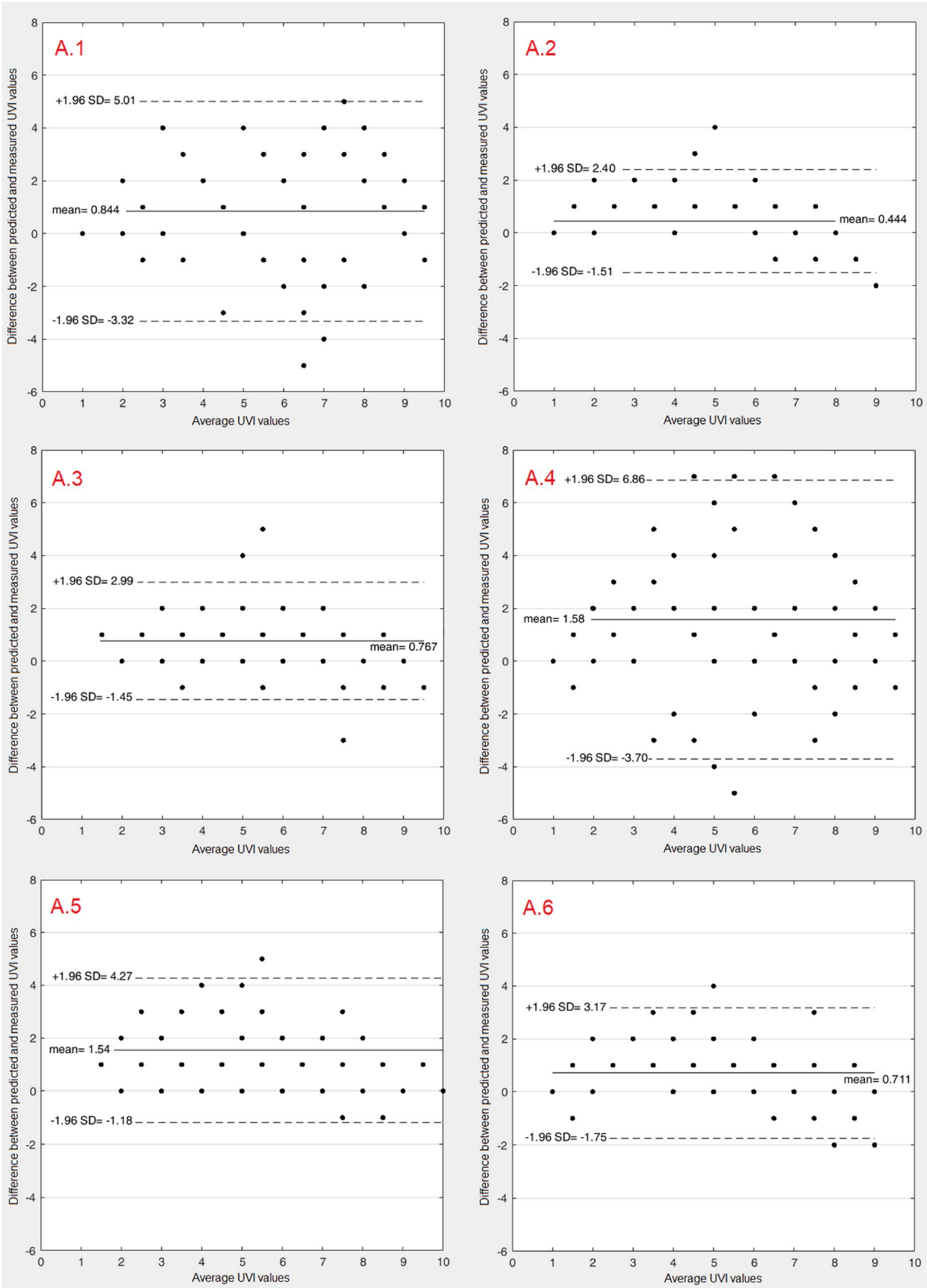

Fig. 6. Bland-Altman charts for predicted and measured UVI values, for all the selected apps. In each chart, the mean value of the differences (solid lines), the range in which the 95% of the differences falls within (± 1.96 SD, dashed lines) are shown together with the scatter plot of the data.

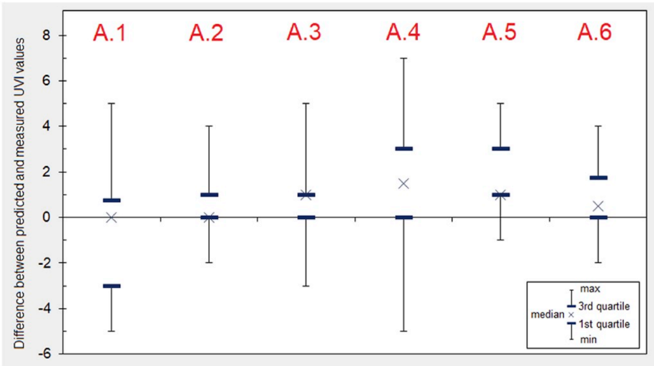

Fig. 7. Box plot of the differences between measured and predicted (by apps) UVI values.

realized using all the data (90 couples of measured and predicted UVI values), in the charts some couples of measured and predicted UVI values can occur more than once. From the charts of Fig. 8 it is possible to observe that the regression lines of apps A.5 and A.6 have a slope different from the ideal line (S = 1), with S = 0.8 and S = 0.9 respectively, the regression lines of the other apps have the same slope of the ideal line. Among the regression lines with S = 1, only those of apps A.1 and A.2 have an intercept equal to the ideal line (I = 0), consequently these apps seems to have the regression more suitable to predict the data. However the data predicted by app A.2 are very less scattered with respect to those predicted by the app A.1, and hence the best prediction attitude of the app A.2 is confirmed again. The regression lines found, and the related confidence intervals shown in Fig. 8, can be useful to correctly interpret the predicted data obtained from the apps.

4.4. Limitations of the study, and recommendations for future research

The comparisons, between measured and predicted (by the smartphone apps) UVI values, discussed within the present study have been conducted on the basis of the results of a measurement campaign carried out in Pisa (central Italy). The climatic characteristics of the measurement location (representative of the central-northern Mediterranean area), the number of measurements made and the variability of the sky conditions for which the comparisons have been done, made it possible to obtain some significant indications, which allow a more conscious use of the analysed apps. Despite this, it is desirable that other studies and other comparisons are carried out by different research groups, extending the data obtained in the present study to other locations and for further smartphones apps, to make the considerations made on their use even more consistent. In addition, the prediction of the UVI values by the apps is carried out with specific spatial resolutions. This aspect has not been considered in the present study and the values obtained from the measurements have been compared with those predicted by the apps for the location identified by the automatic positioning system, integrated in each smartphone. An analysis of the impact of app spatial resolutions on the accuracy of UVI value estimation is currently underway by the Authors.

5. Conclusions

In the scientific literature and among the international organizations dealing with human health, the importance of receiving the right dose of daily UV radiation is well consolidated. The Ultra-Violet Index (UVI) is widespread used to evaluate the UV exposure of humans, facilitating the communication of the UV radiation intensity to the general public. The UVI values are usually provided by the meteorological services and nowadays it is very common to find UVI prediction tools even in smartphone applications (apps). In this paper, the accuracy of different smartphone apps in the prediction of UVI values has been evaluated. The evaluation involved six different apps running on the three operating systems, nowadays more widespread among smartphone users (i.e. iOS, Android, Windows phone). The accuracy of each app has been assessed by comparing the UVI values, obtained from the apps, with those obtained from a campaign of experimental measurements carried out for the month of July 2018 in the site of Pisa (Italy). The comparison has been conducted on the basis of 90 different UVI measurements, taken at different times, different days and different sky conditions. From the results it has been possible to observe that the deviations between the UVI values (predicted and measured) are quite high for all the analysed apps: the application that shows the better attitude to predict measured data is able to predict the 57% of the measured values with deviations lower than 15% and the 16% of the measured values with deviations higher than 45%. In general, all the apps tend, on average, to overestimate the actual values of the UVI, this can be considered a cautious aspect. However, it has also been observed that the major underestimations of the UVI values have been obtained in correspondence of the measured UVI peaks, this is an aspect to be taken into great consideration in order to use these apps to monitor human exposure to UV, especially for outdoor workers. From the Bland-Altman and Passing-Bablok analysis, one of the 6 tested applications showed a significantly better attitude to predicting the real data than the others, with less mean deviation compared to the measurements and less data dispersion.

The assessment campaign of this study can be useful for health professionals to recommend the use of smartphone apps, being conscious of their accuracies and limitations, for monitoring people who spend time outdoors, but also for app developers for improving their apps content and for researchers for comparing data obtained by their studies. Further studies are required to evaluate these smartphone apps based on information quality analysis from users' perspectives.

Table 2
Distribution of the deviations between predicted and measured UVI values for each app.

Range of deviation between predicted and measured UVI values	Percentage (%) of the data predicted by each app					
	A.1	A.2	A.3	A.4	A.5	A.6
$\|D\| \leq 15\%$	36	57	38	23	32	48
$\|D\| > 15\%$ and $\|D\| \leq 30\%$	27	16	17	12	9	10
$\|D\| > 30\%$ and $\|D\| \leq 45\%$	6	12	11	8	14	8
$\|D\| > 45\%$	32	16	34	57	44	34
Total	100	100	100	100	100	100

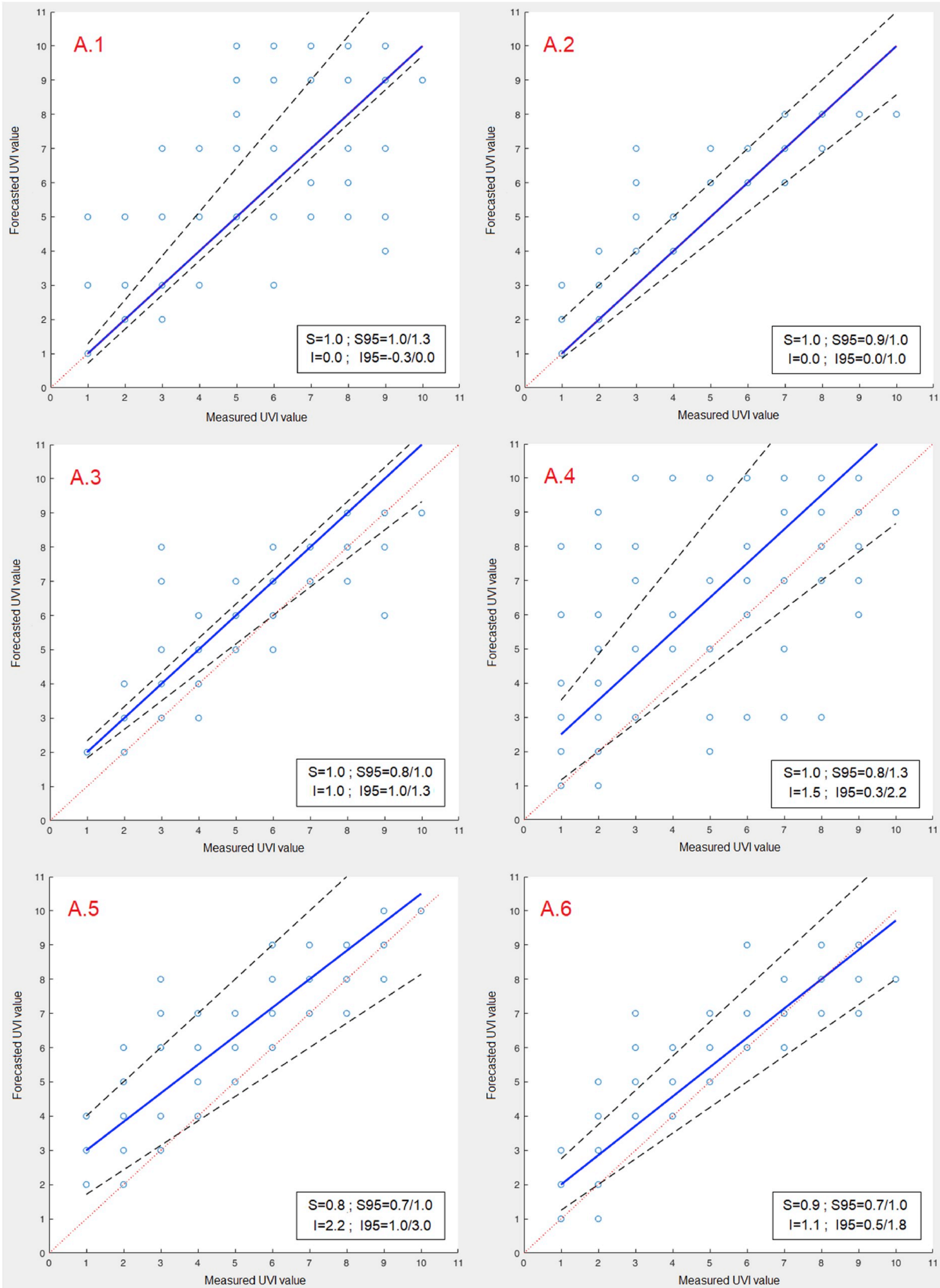

Fig. 8. Passing-Bablok non parametric regression charts of measured and predicted UVI values, for all the selected apps. In each chart, the regression line (solid blue line), the 95% confidence interval lines (dashed black lines), the ideal line (dotted red lines) are shown together with the scatter plot of the data. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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Appendix A. UV Index definition

UV Index (UVI) quantifies the erythemal potential of UV radiation to sunburn human skin (the first adverse effect occurring due to UV radiation overexposure). UVI gives a measure of the UV radiation at the sea level and an indicator of the potential for skin damage. UVI is defined as indicated in the technical standards CIE S007/E (Commission Internationale de l'Eclairage (CIE), 1999) according to Eqn A1:

$$\mathrm{UVI} = k_{er}\cdot I_{er} = k_{er}\cdot \int_{250\,\mathrm{nm}}^{400\,\mathrm{nm}} I(\lambda)\cdot s_{er}(\lambda)\,d\lambda \tag{A1}$$

where: k_{er} is a constant equal to 40 m^2/W, I_{er} is the UV erythemal irradiance expressed in W/m^2, $I(\lambda)$ is the UV spectral irradiance at the wavelength λ, $s_{er}(\lambda)$ is the erythema action spectrum and $d\lambda$ is the wavelength interval used for the integration. The integration is between 250 and 400 nm. The effects of UV radiation on the biological tissues are function of the particular wavelength. During the years, several action spectra have been developed with different weighting function to take into account the effects of UV radiation at the different wavelengths. The erythema action spectrum, $s_{er}(\lambda)$, provides an internationally accepted representation of the erythema-inducing effects on human skin because has been chosen by the WHO as the basis of the UV index used for public health information (Moshammer et al., 2016; Webb et al., 2011). The erythema action spectrum, graphically shown in Figure A.1, is defined with the following equations (International Organization for Standardization, 2019):

$$s_{er}(\lambda) = 1 \quad \text{for} \quad 250\ \mathrm{nm} \le \lambda \le 298\ \mathrm{nm}$$

$$s_{er}(\lambda) = 10^{a} \quad \text{for} \quad 298\ \mathrm{nm} < \lambda \le 328\ \mathrm{nm}$$

$$s_{er}(\lambda) = 10^{b} \quad \text{for} \quad 328\ \mathrm{nm} < \lambda \le 400\ \mathrm{nm}$$

with: $a = 0.094\cdot(298 - \lambda)$ and $b = 0.015\,(140 - \lambda)$.

The UVI is an important vehicle to raise public awareness of the risks of excessive exposure to UV radiation and of the need to adopt protective measures. As a simple measure of UV radiation levels at the Earth's surface, the values of the UVI range from zero upward (see Figure A.2). The higher the UVI values are, the greater is the risk of damage to the skin and eye (see Table A.1).

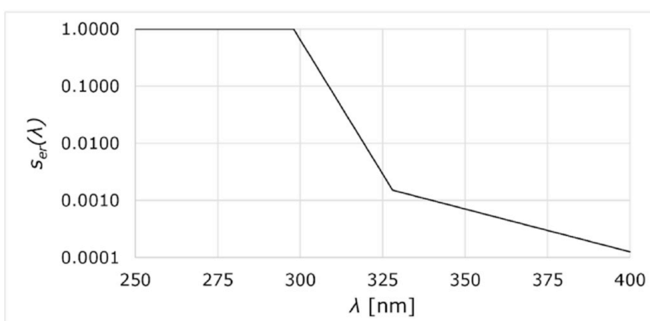

Fig. A.1. Graphical representation of the ISO/CIE erythema action spectrum.

Fig. A.2. UVI logo and scale as standardized by WHO.

Table A.1
Categories of risks due to UV radiation exposure based on the UVI.

Category of risk due to UV radiation exposure	UV Index ranges
Low	0 to 2
Moderate	3 to 5
High	6 to 7
Very high	8 to 10
Extreme	11 to ∞

References

Allinson, S., Asmuss, M., Baldermann, C., Bentzen, J., Buller, D., Gerber, N., Green, A.C., Greinert, R., Kimlin, M., Kunrath, J., Matthes, R., Pölzl-Viol, C., Rehfuess, E., Rossmann, C., Schüz, N., Sinclair, C., van Deventer, E., Webb, A., Weiss, W., Ziegelberger, G., 2012. Validity and use of the UV index: report from the UVI working group, schloss hohenkammer, Germany. Health Phys. 103 (301), 5–7. https://doi.org/10.1097/HP0b013e31825b581e. December 2011.

Ansaldi, S.M., Bragatto, P., 2019. Reducing accident hazard in chemical and petrol industries, through smart safety systems. In: 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I CPS Europe), pp. 1–5. https://doi.org/10.1109/EEEIC.2019.8783585.

Arisi, M., Zane, C., Caravello, S., Rovati, C., Zanca, A., Venturini, M., Calzavara-Pinton, P., 2018. Sun exposure and melanoma, certainties and weaknesses of the present knowledge. Front. Med. 5. https://doi.org/10.3389/fmed.2018.00235.

Backer, H.D., Koepke, P., Bais, A., Cabo, X. de, Frei, T., Gillotay, D., Haite, C., Heikkilä, A., Kazantzidis, A., Koskela, T., Kyrö, E., Lapeta, B., Lorente, J., Masson, K., Mayer, B., Plets, H., Redondas, A., Renaud, A., Schauberger, G., Schmalwieser, A., Schwander, H., Vanicek, K., 2001. Comparison of measured and modelled uv indices for the assessment of health risks. Meteorol. Appl. 8, 267–277. https://doi.org/10.1017/S1350482701003024.

Baczynska, K.A., Khazova, M., O'Hagan, J.B., 2019. Sun exposure of indoor workers in the UK – survey on the time spent outdoors. Photochem. Photobiol. Sci. 18, 120–128. https://doi.org/10.1039/C8PP00425K.

Borra, M., Grandi, C., Militello, A., Burattini, C., Gugliermetti, L., Mangione, A., Bisegna, F., Modenese, A., Gobba, F., 2018. Developing an algorithm to assess the UV erythemal dose for outdoor workers. In: 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I CPS Europe), pp. 1–5. https://doi.org/10.1109/EEEIC.2018.8494540.

Botzer, A., Musicant, O., Perry, A., 2017. Driver behavior with a smartphone collision warning application – a field study. Saf. Sci. 91, 361–372. https://doi.org/10.1016/j.ssci.2016.09.003.

Chubarova, N., Zhdanova, Y., 2013. Ultraviolet resources over northern eurasia. J. Photochem. Photobiol. B Biol. 127, 38–51. https://doi.org/10.1016/j.jphotobiol.2013.07.013.

Commission Internationale de l'Eclairage (CIE), 1999. Erythema Reference Action Spectrum and Standard Erythema Dose. CIE S007/E, Vienna.

Commission Internationale de l'Eclairage (CIE), 2014. Rationalizing Nomenclature for UV Doses and Effects on Humans. CIE 209, Vienna.

Do, T.T.T., Le, M.D., Van Nguyen, T., Tran, B.X., Le, H.T., Nguyen, H.D., Nguyen, L.H., Nguyen, C.T., Tran, T.D., Latkin, C.A., Ho, R.C.M., Zhang, M.W.B., 2018. Receptiveness and preferences of health-related smartphone applications among Vietnamese youth and young adults. BMC Publ. Health 18 (764). https://doi.org/10.1186/s12889-018-5641-0.

D'Orazio, J., Jarrett, S., Amaro-Ortiz, A., Scott, T., 2013. UV radiation and the skin. Int. J. Mol. Sci. 14, 12222–12248. https://doi.org/10.3390/ijms140612222.

Fahrni, T., Kuhn, M., Sommer, P., Wattenhofer, R., Welten, S., 2011. Sundroid: solar radiation awareness with smartphones. In: Proceedings of the 13th International Conference on Ubiquitous Computing - UbiComp '11, pp. 365. https://doi.org/10.1145/2030112.2030162. Beijing, China.

Ghetti, F., Checcucci, G., Bornman, J.F., 2006. Environmental UV radiation: impact on ecosystems and human health and predictive models. In: Proceedings of the NATO Advanced Study Institute on Environmental UV Radiation: Impact on Ecosystems and Human Health and Predictive Models Pisa. Nato Science Series: IV: Springer Netherlands, Italy June 2001.

Götz, F.M., Stieger, S., Reips, U.-D., 2017. Users of the main smartphone operating systems (iOS, Android) differ only little in personality. PloS One 12, e0176921. https://doi.org/10.1371/journal.pone.0176921.

Grandahl, K., Ibler, K.S., Laier, G.H., Mortensen, O.S., 2018. Skin cancer risk perception and sun protection behavior at work, at leisure, and on sun holidays: a survey for Danish outdoor and indoor workers. Environ. Health Prev. Med. 23 (47). https://doi.org/10.1186/s12199-018-0736-x.

Gugliermetti, L., Burattini, C., Militello, A., Borra, M., Asdrubali, F., Salvadori, G., Leccese, F., Bisegna, F., 2019. Real time UV erythemal personal exposure monitoring in outdoor workplaces. In: 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I CPS Europe), pp. 1–5. https://doi.org/10.1109/EEEIC.2019.8783314.

International Agency for Research on Cancer (IARC), 1992. IARC Monographs – evaluation of carcinogenic risks to humans. Solar Ultraviolet Rad. 55 (WHO Publication, United Kingdom).

International Commission on Non-Ionizing Radiation Protection (ICNIRP), 2004. Guidelines on limits of exposure to Ultra Violet radiation of wavelengths between 180 nm and 400 nm (incoherent optical radiation). Health Phys. 87, 171.

International Commission on Non-Ionizing Radiation Protection (ICNIRP), 2010. ICNIRP statement —protection of workers against ultraviolet radiation. Health Phys. 99 (66). https://doi.org/10.1097/HP.0b013e3181d85908.

International Organization for Standardization, (ISO) and Commission Internationale de l'Eclairage (CIE), 2014. Characterization of the Performance of Illuminance Meters and Luminance Meters. ISO/CIE 19476, Geneva.

International Organization for Standardization, (ISO) and Commission Internationale de l'Eclairage (CIE), 2019. Erythema Reference Action Spectrum and Standard Erythema Dose. ISO/CIE 17166, Geneva.

Kenborg, L., Jørgensen, A.D., Budtz-Jørgensen, E., Knudsen, L.E., Hansen, J., 2010. Occupational exposure to the sun and risk of skin and lip cancer among male wage earners in Denmark: a population-based case-control study. Cancer Causes Control 21, 1347–1355. https://doi.org/10.1007/s10552-010-9562-1.

Kift, R., Rhodes, L.E., Farrar, M.D., Webb, A.R., 2018. Is sunlight exposure enough to avoid wintertime vitamin D deficiency in United Kingdom population groups? Int. J. Environ. Res. Publ. Health 15 (1624). https://doi.org/10.3390/ijerph15081624.

Krzyścin, J.W., Guzikowski, J., Czerwińska, A., Lesiak, A., Narbutt, J., Jarosławski, J., Sobolewski, P.S., Rajewska-Więch, B., Wink, J., 2015. 24 hour forecast of the surface UV for the antipsoriatic heliotherapy in Poland. J. Photochem. Photobiol. B Biol. 148, 136–144. https://doi.org/10.1016/j.jphotobiol.2015.04.002.

Leccese, F., Salvadori, G., Lista, D., Burattini, C., 2018. Outdoor workers exposed to UV radiation: comparison of UV index forecasting methods. 2018 IEEE Int. Conf. Environ.Electric. Eng. 2018 IEEE Ind. Commercial Power Syst. Europe (EEEIC/I CPS Europe) 1–6. https://doi.org/10.1109/EEEIC.2018.8494621.

Lucas, R., McMichael, T., Smith, W., Armstrong, B., 2006. Solar Ultraviolet Radiation: Global Burden of Disease from Solar Ultraviolet Radiation. World Health Organization, Public Health and the Environment. 92 4 159440 3 Geneva.

Mei, B., Li, R., Cheng, W., Yu, J., Cheng, X., 2017. Ultraviolet radiation measurement via smart devices. IEEE Internet Things J. 4, 934–944. https://doi.org/10.1109/JIOT.2017.2717845.

Militello, A., Borra, M., Bisegna, F., Burattini, C., Grandi, C., 2016. Smart technologies: useful tools to assess the exposure to solar ultraviolet radiation for general population and outdoor workers. In: 18th Italian National Conference on Photonic Technologies (Fotonica 2016), pp. 1–4. https://doi.org/10.1049/cp.2016.0945.

Modenese, A., Bisegna, F., Borra, M., Grandi, C., Gugliermetti, F., Militello, A., Gobba, F., 2016. Outdoor work and solar radiation exposure: evaluation method for epidemiological studies. Med. Pr. 67, 577–587. https://doi.org/10.13075/mp.5893.00461.

Modenese, A., Korpinen, L., Gobba, F., 2018. Solar radiation exposure and outdoor work: an underestimated occupational risk. Int. J. Environ. Res. Publ. Health 15 (2063). https://doi.org/10.3390/ijerph15102063.

Moshammer, H., Simic, S., Haluza, D., 2016. UV "indices"—what do they indicate? Int. J. Environ. Res. Publ. Health 13 (1041). https://doi.org/10.3390/ijerph13101041.

Papadimitriou, E., Argyropoulou, A., Tselentis, D.I., Yannis, G., 2019. Analysis of driver behaviour through smartphone data: the case of mobile phone use while driving. Saf. Sci. 119, 91–97. https://doi.org/10.1016/j.ssci.2019.05.059.

Peters, C.E., Koehoorn, M.W., Demers, P.A., Nicol, A.-M., Kalia, S., 2016. Outdoor workers' use of sun protection at work and leisure. Saf. Health at Work 7, 208–212. https://doi.org/10.1016/j.shaw.2016.01.006.

Rajakumar, K., Greenspan, S.L., Thomas, S.B., Holick, M.F., 2007. SOLAR ultraviolet radiation and vitamin D. Am. J. Publ. Health 97, 1746–1754. https://doi.org/10.2105/AJPH.2006.091736.

Reinau, D., Weiss, M., Meier, C.R., Diepgen, T.L., Surber, C., 2013. Outdoor workers' sun-related knowledge, attitudes and protective behaviours: a systematic review of cross-sectional and interventional studies. Br. J. Dermatol. 168, 928–940. https://doi.org/10.1111/bjd.12160.

Salvadori, G., Lista, D., Burattini, C., Gugliermetti, L., Leccese, F., Bisegna, F., 2019. Sun exposure of body districts: development and validation of an algorithm to predict the erythemal Ultra violet dose. Int. J. Environ. Res. Publ. Health 16 (3632). https://doi.org/10.3390/ijerph16193632.

Soltanmohammadlou, N., Sadeghi, S., Hon, C.K.H., Mokhtarpour-Khanghah, F., 2019. Real-time locating systems and safety in construction sites: a literature review. Saf. Sci. 117, 229–242. https://doi.org/10.1016/j.ssci.2019.04.025.

Tellez, W.A., Nieto-Gutierrez, W., Taype-Rondan, A., 2017. Sunscreen mobile apps: a content analysis. Europ. Res. Telemed./La Rech. Europ. Téléméd. 6, 157–163. https://doi.org/10.1016/j.eurtel.2017.08.001.

Thieden, E., Philipsen, P.A., Sandby-Møller, J., Wulf, H.C., 2005. Sunburn related to UV radiation exposure, age, sex, occupation, and sun bed use based on time-stamped personal dosimetry and sun behavior diaries. Arch. Dermatol. 141, 482–488. https://doi.org/10.1001/archderm.141.4.482.

Vecchia, P., 2007. International commission on non-ionizing radiation protection, internationale arbeitsorganisation. Protecting workers from ultraviolet radiation, ICNIRP. Internat. Commission on Non-Ionizing Radiation Protection, Oberschleißheim 29–33 ISBN: 978-3-934994-07-2.

Wang, D., Xiang, Z., Fesenmaier, D.R., 2016. Smartphone use in everyday life and travel. J. Trav. Res. 55, 52–63. https://doi.org/10.1177/0047287514535847.

Webb, A.R., Slaper, H., Koepke, P., Schmalwieser, A.W., 2011. Know your standard: clarifying the CIE erythema action spectrum. Photochem. Photobiol. 87, 483–486. https://doi.org/10.1111/j.1751-1097.2010.00871.x.

World Health Organization (WHO), 2002. Global Solar UV Index. A Practical Guide. 9241590076 Geneva.

World Health Organization (WHO), 2003. INTERSUN the Global UV Project: a Guide and

Compendium. 9241591056 Nairobi.
Xu, Q., Erman, J., Gerber, A., Mao, Z., Pang, J., Venkataraman, S., 2011. Identifying diverse usage behaviors of smartphone apps. In: Proceedings of the 2011 ACM SIGCOMM Conference on Internet Measurement Conference - IMC '11. ACM Press, Berlin, Germany, pp. 329. https://doi.org/10.1145/2068816.2068847.
Zhang, M.W., Ho, C.S., Fang, P., Lu, Y., Ho, R.C., 2014. Usage of social media and smartphone application in assessment of physical and psychological well-being of individuals in times of a major air pollution crisis. JMIR Mhealth Uhealth 2, e16. https://doi.org/10.2196/mhealth.2827.
Zhang, M.W., Ho, R.C., Loh, A., Wing, T., Wynne, O., Chan, S.W.C., Car, J., Fung, D.S.S., 2017. Current status of postnatal depression smartphone applications available on application stores: an information quality analysis. BMJ Open 7, e015655. https://doi.org/10.1136/bmjopen-2016-015655.