Ultraviolet climatology of a megacity in transition: Mexico City 2000-2019

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Abstract

Mexico City is one of the most populated cities in the world. It could experience large exposures due to its location at 2240 m above sea level, and its intertropical latitude. The present study analyzed around 2 million ground-based UV Index measurements along two decades (2000-2019) over the Mexico City Metropolitan Area. An increasing trend in the UV Index of 0.66 % per year was found. In contrast, the trends in criteria pollutants PM_{10}, CO, NO_2, O_3 and in AOD_{340} decreased, as a consequence of the policies aimed at the improvement of air quality. UV Index data derived from OMI-Aura/NIVR-FMI-NASA measurements of ozone and clouds ranged between 6.4 and 14.9. The comparison of the maximum UV Index from satellite data and the highest UV Index ground-based revealed similar values, both in the Extreme qualification range of the World Health Organization. As a limit to avoid sunburn, the exposure times were calculated for two skin phototypes from the Standard Erythema Dose per hour, with high sun in clear sky conditions. The results contribute to knowledge of the UV climatology in the region, the long-term effects of air pollution on UV and its levels under different sky conditions. This assessment can be of interest for validation of satellite data and radiative transfer models, forecast, solar energy applications, and alert the public to the need for skin protection.

Keywords: UV Index, Climatology, Ground-based measurements, Criteria pollutants, Standard Erythema Dose.

Introduction

Mexico City is the largest city in North America by number of inhabitants and one of the largest urban agglomerations in the world (UN, 2014). The latitude and longitude coordinates for the city are 19.4°N and 99.1°W, at an average height of 2240 meters above sea level. The Mexico City Metropolitan Area (MCMA) is surrounded by mountain ridges exceeding 5000 m asl and has been the subject of multiple studies related to air quality due to intense anthropogenic activity (Doran et al., 1998; Molina et al., 2007, 2010; Tzompa-Sosa, Sullivan, Retama, & Kreidenweis, 2017). The complex topography and thermal inversions inhibit winds that sweep away pollution and influence the surface energy balance (Whiteman, Zhong, Bian, Fast, & Doran, 2000; Tejeda-Martínez & Jáuregui-Ostos, 2005; Zhang, Dubey, Olsen, Zheng, & Zhang, 2009). Solar radiation varies along the hours of the day and the days of the year, as well as via its dependence on atmospheric components that attenuate the different wavelengths. The ultraviolet (UV) range is only a small part of total incident irradiance, but plays a key role in atmospheric photochemistry (Leighton, 1961; Seinfeld & Pandis, 2016). On the pathway through the atmosphere, photons experience scattering by air molecules, aerosol particles (haze) and clouds, as well as absorption by gases such as ozone (O_3) and nitrogen dioxide (NO_2), and some aerosols. An increase in ozone concentration in polluted boundary layers is also generated by strong UV photon fluxes interacting with anthropogenic precursor emissions (Leighton, 1961; Finlayson-Pitts & Pitts, 2000). Conversely, aerosols may increase or reduce the insolation and photolysis rates, and thus affect photochemical smog formation (Dickerson, 1997). A modelization of actinic flux applied to Mexico City, showed a decrease at the surface and an increase aloft, mainly due to the presence of aerosols (Palancar et al., 2013). Likewise, a reduction in the measured and theoretical values of nitrogen dioxide photolysis rate was attributed to attenuation of spectral actinic solar flux by aerosols (Castro, Madronich, Rivale, Muhlia, & Mar, 2001).

Despite multiple efforts to monitor and characterize air quality in the Mexico City basin, few studies have specially focused on global solar radiation (Galindo, Castro, & Valdes, 1991; Quiñones & Almanza, 2014; Matsumoto et al., 2014). In the mid-1990s, two studies about UV solar irradiance measurements in the Mexican Valley, in periods shorter than 3 years, were published. One of these studies suggested a significant attenuation of UV intensity due to tropospheric ozone, comparing measurements in downtown and outskirts of the Mexico City (Acosta & Evans, 2000). Another study reported that Mexico City had lower ultraviolet fluxes (around 25% at noon and 50% in the afternoon) compared to Colima, a city placed at the same latitude, lower elevation (ca. 300-500 m asl) and almost pollution-free. (Galindo, Frenk, & Bravo, 1995). Short-term measurements and comparisons with radiative models were reported by (Palancar et al., 2013). Other UV measurements have been carried out to estimate aerosol optical properties at UV wavelengths, e.g. using UV Multi-Filter Rotating Shadowband Radiometers (MFRSRs) to estimate aerosol single scattering albedo (Goering, 2005; Corr et al., 2009), but did not focus on the UV Index.

UV Index (UVI) is an indicator related to the intensity of the solar UV radiation at the Earth's surface and the risk for persons to suffer sunburn, and may be relevant to chronic effects due to prolonged exposure, such as skin cancer. Fitzpatrick classification defines six phototypes (I-VI) or skin colors from pale to dark, correlated to the UV radiation sensitivity (T. B. Fitzpatrick, 1974). The International Commission on Illumination (CIE) established an action spectrum for erythema (or erythemal sensitivity) of human skin using phototype II from Fitzpatrick classification (CIE, 2014). According to the World Health Organization (WHO) the UVI is expressed mathematically as follows:

$$UVI = \int_{250nm}^{400nm} k_{er} \cdot E(\lambda, t) \cdot S_{er}(\lambda)\, d\lambda \tag{1}$$

where $E(\lambda, t)$ is the solar spectral irradiance in units of W/(m^2 ·nm), $S_{er}(\lambda)$ is the erythemal sensitivity defined by CIE and k_{er} is a factor equal to 40 m^2/W. The WHO standardized the UVI scale as: low (0, 1 and 2), moderate (3, 4 and 5), high (6 and 7), very high (8, 9 and 10) and extreme (11 or more) (WHO, 2002). Even values of UVI above 20 have been recorded in La Quiaca, Argentina (Cede, Luccini, Nuñez, Piacentini, & Blumthaler, 2002). An extended recommendation of the WHO version is unfolding UVI values larger than 11 and modifying the color scale (Zaratti et al., 2014). This suggestion could be appropriate for the Mexico City due to UVI reaching values considered as high, almost all year in this latitudinal band (Tanskanen, Krotkov, Herman, & Arola, 2006; Herman, 2010). The skin reddening (or erythema, as a sign of possible sunburn or even more complicated skin diseases (T. B. Fitzpatrick, 1974)) depends on intensity of the source, skin phototype and exposure time. For an interval time $(t_2 - t_1)$ the erythemal dose or erythemal radiant exposure (Braslavsky, 2007) is calculated as:

$$H_{er} = \int_{t_1}^{t_2} E_{er}(t)dt = \int_{t_1}^{t_2} \frac{1}{k_{er}} \cdot UVIdt \tag{2}$$

where the term $E_{er}(t)$ is the erythemal irradiance obtained from $\frac{1}{k_{er}} \cdot UVI$. The H_{er} value, when applied to each skin phototype, predicts the appearance of erythema some hours after exposure. For example, minimal erythema in skin type II requires a dose between 250-300 J/m^2 (T. Fitzpatrick, 1988; Molina et al., 2010; Pérez et al., 2014; Serrano, Cañada, Moreno, & Gurrea, 2017; Lehmann, Pfahlberg, Sandmann, Uter, & Gefeller, 2019). This H_{er}value to produce erythema was established as the Minimal Erythemal Dose (MED), which has been widely used as a primary and preventive measure of skin damage. Several studies have examined values of MED for different skin phototypes (MacKie, 2000; Meinhardt, Krebs, Anders, Heinrich, & Tronnier, 2008; Miller et al., 2012). CIE proposed the Standard Erythemal Dose (SED) with a value of 100 J/m^2 as an erythemally weighted unit dose, independent of skin phototype (CIE, 2014). The lowest values of the MED ranges defined by Fitzpatrick under UVB radiation for each phototype, are taken as reference in this work (T. Fitzpatrick, 1988). The Table 1 shows the $H_{er}$for each skin phototype in units of SEDs.

In multiple studies, notions about the variety of skin colors and risk were associated to 'the race', 'ethnic skin' or 'Hispanic skin' (Taylor, Arsonnaud, Czernielewski, & Group, 2005; Rouhani, Hu, & Kirsner, 2008; Robinson, Penedo, Hay, & Jablonski, 2017) that, based on nationality or appearance alone, would be classified as of low-risk sensitivity (Wolbarsht & Urbach, 1999; Lancer, 1998; Bino & Bernerd, 2013). Nonetheless, these labels may accentuate the problem of inadequate generalization (Cuevas, Dawson, & Williams, 2016; Marcheco-Teruel et al., 2014). A publication concluded that skin color is itself relevant to cutaneous biology and disease research, independent of racial background (Torres, Herane, Costa, Martin, & Troielli, 2017). This argument supports the choice of Fitzpatrick convention for this study, excluding ethnic terminology to calculate the erythemic dose thresholds (H_{er}) according to skin color.

In this study, a palette of skin colors has been adapted from the last edition published by the National Survey About Discrimination (ENADIS) together with the Latin American Race and Ethnicity Project (PERLA) (ENADIS, 2017). These skin colors were grouped into Fitzpatrick phototypes and their respective percentages present in Mexican people (see Table 1). Since the largest fraction (83.2%) of the people has skin colors on phototypes III (24.0%) and IV (59.2%) , these were considered as representative to calculate the exposure times to avoid sunburn. Some reports have indicated that outdoor workers receive between 10% and 80% of ambient UV radiation (Larkö & Diffey, 1983; Makgabutlane & Wright, 2015; Silva, 2016; Moldovan et al., 2020). Skin cancer is one of the most damaging effects of long-term solar exposure and is very common in most regions the world, according to the World Health Organization (WHO, 2002). In Mexico, the incidence is probably under-reported since the majority of skin cancers are not cause of death (Jurado-Santa-Cruz, Medina-Bojórquez, Gutiérrez-Vidrio, & Ruiz-Rosillo, 2011). Notwithstanding the high UV levels reported in other States of the country (Castanedo-Cázares, Torres-Álvarez, Ondarza, Pérez, & Moscoso, 2012), a percentage of the Mexican population is still uninformed about the harmful effects of prolonged exposure under the sun (Castanedo-Cazares, Torres-Álvarez, Medellín-Pérez, Aguilar-Hernández, & Moncada, 2006). With over 21 million persons living in the MCMA, exposure to solar UV radiation constitutes a public health subject. A wide daylight window takes place almost all year, so that the UV Index is a useful and indispensable reference to prevent unwanted skin exposure.

The assessments of the UV irradiance contribute to the knowledge of the regional climatology as well as the global monitoring of the atmosphere (Madronich, 1993; Fioletov et al., 2004; Staiger & Koepke, 2005; Luccini, Cede, Piacentini, Villanueva, & Canziani, 2006; Herman, 2010; Bech, Sola, Ossó, & Lorente, 2014; Utrillas et al., 2018). Likewise, a lot of scientific publications around the world describe the importance of understanding the UV irradiance behavior along the time and its relation with the MED (Rivas, Araya, Caba, Rojas, & Calaf, 2011; Rivas, Rojas, Araya, & Calaf, 2015; Lehmann et al., 2019; Parra, Cadena, & Flores, 2019; Cadet et al., 2019). Despite the relevance to climatology and the skin health, there are no studies focused on UV Index in this intertropical megacity. The purpose of this work is to analyze twenty years of UV Index measurements, the long-term effects of air pollution on UV, the levels in different sky conditions and the exposure times as a photoprotection measure.

Measurement methodology

Ground-based

United Mexican States is in the latitudinal fringe 14.53°N - 32.71°N of the Americas, where its capital (Mexico City) lies in a basin 70 km northwest from Popocatepetl volcano, one of three highest peaks of the country with an altitude nearby 5426 m asl. The Secretariat of the Environment of the Mexico City Government

(SEDEMA) of the Atmospheric Monitoring System (SIMAT) is in charge of the air quality monitoring in the Mexico City Metropolitan Area (Figure 1).

Mexico City has a temperate climate with an extended wet season, although the rainfall is relatively high between June and August. The MCMA is in the North American Central Time Zone (CT) and uses the Central Standard Time (CST) i.e. six hours behind Coordinated Universal Time (UTC). In early spring, the local time changes five hours behind UTC due to the daylight saving time.

Since the year 2000, UV radiometers installed at the SIMAT network stations have been measuring erythemally-weighted solar radiation. These instruments are Model 501-A manufactured by Solar Light Company (SCL) with sensors detecting wavelengths between 280-400nm. The calibrations were carried out every year, using a reference sensor by the same manufacturer. Although at the beginning only a few stations were in operation and have been changing, currently 11 stations are recording solar erythemal irradiances, which are converted to UV Indices, as given in Equation 1. The station names are: Chalco (CHA), Cuautitlán (CUT), FES Acatlán (FAC), Hangares (HAN), Laboratorio de Análisis Ambiental (LAA), Merced (MER), Montecillo (MON), Milpa Alta (MPA), Pedregal (PED), San Agustín (SAG), Santa Fe (SFE), Centro de Ciencias de la Atmósfera (CCA) and Tlalnepantla (TLA). The radiometers of the SIMAT have been distributed over MCMA, prioritizing the sites with more density of population, as it is shown in Figure 1 right. The coordinates of the stations conforming the radiometers network are described in Table 2. On the SIMAT website http://www.aire.cdmx.gob.mx/default.php, UV Index measurements for each station are available almost in real time.

Even if there is no SLC radiometer at the station of the Centro de Ciencias de la Atmósfera (CCA) that belongs to the SIMAT, it has a photometer of the AErosol RObotic NETwork (AERONET see (Holben et al., 1998)). This instrument measures in situ the Aerosol Optical Depth (AOD) at 340nm. Additionally, we include measurements from the Automated Atmospheric Monitoring Network (Red Automática de Monitoreo Atmosférico, RAMA), a SIMAT subdivision, that is in charge of assessing the air quality. These dataset were used to perform a brief analysis about the criteria pollutants recorded by RAMA: Ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2) and concentration of particles with diameter less or equal than 10 µm (PM_{10}). The O_3 and NO_2 are reported in parts per billion (ppb), using ultraviolet photometry (Teledyne API model 400E) and chemiluminescence (Teledyne-API model 200E) respectively. The CO in parts per million (ppm) is derived by absorption of infrared light in a correlation cell (Teledyne API model 300E) and PM_{10} (in microgram per cubic meter) is measured by the beta attenuation method (Thermo Model 1405-DF FDMS).

The available data set is rather large, spanning two full decades for 5 stations and many years for the others, and with a measurement frequency of about 1 minute, thus resulting in ca. 2 million data points. Accordingly, significant averaging was carried out to highlight the main features of the data.

Satellite data

Satellite measurements of the Radiative Cloud Factor, the Total Ozone Column (TOC) and UV Index were used for the current study. These data were provided by the Ozone Monitoring Instrument (OMI) on board of AURA-NASA satellite and the Total Ozone Mapping Spectrometer (TOMS) on board the Earth Probe (EP)-NASA satellite. OMI was created in cooperation between the Netherlands Agency for Aerospace Programmes (NIVR), the Finnish Meteorological Institute (FMI) and NASA. OMI (hereafter OMI-Aura/NIVR-FMI-NASA) performs observations over a geographical dimension of $13 \times 24\text{km}^2$ at nadir. For Mexico City, the satellite overpass time is between 19:00h - 21:00h UTC and data are specific for the coordinates and elevation of Mexico City. The TOMS-EP/NASA satellite instrument was also considered to complete the examined period. It is a version that precedes OMI and it was retrieving the TOC from spectral UV measurements.

Measurements analysis

Criteria pollutants: Ground-based measurements of PM_{10}, CO, O_3 and NO_2 from 11h to 14h CST were extracted from the SIMAT data to compute the daily averages at solar noon and the absolute maximums.

Aerosol Optical Depth: The AERONET Aerosol Optical Depth at 340 nm (AOD_{340}) data Product Level 2.0 were selected. The annual averages AOD_{340} were calculated from the continuous measurements during at least 7 months.

Cloud Factor and Total Ozone Column: The Radiative Cloud Factor and TOC derived from OMI-Aura/NIVR-FMI-NASA, for the OMTO3 v8.5 dataset, Collection 3 and L2 quality were collected. The Cloud Factor is dimensionless, from 0 to 1 for the cloudless days and overcast sky, respectively. TOC data were obtained from TOMS-EP/NASA. The 1461 observations were acquired of the: TOMS-EP/NASA instrument during the period 2000 to 2003 and OMI-Aura/NIVR-FMI-NASA data from 2004 to 2019, both dataset covering the complete time series of the ground-UV Index measurements.

UV Index: We developed a general code in `Python` to process the hourly averaged UV Index, 24 hours per day, 365 days a year, along two decades. Hereinafter, we refer to hourly averages simply as UV Index unless otherwise specified. The script also identifies the maximum UV index and ignores empty spaces and invalid values, product of the maintenance of the equipment. The algorithm creates a matrix with the maximum UV Index ($UVI_{\max}$) values sorted by date, hour and years. It selects the highest UV Index values of the network and a counter as an extension of the code was executed to quantify the values and their percentage frequency during 2000-2019 period. Thereupon it also calculates the hourly, monthly and annual averages. In particular, the values from 11h to 14h CST were isolated to compute the daily averages around solar noon and the absolute maximums. For the UV Index calculated from OMI-Aura/NIVR-FMI-NASA, we take into account all available daily values in the period 2000-2019 under the same specification of the Cloud Factor and TOC data.

Results and Discussion

The daily $UVI_{\max}$ were selected in the time interval 11:00 h-14:00 h CST from all ground-based measurements over MCMA. The results indicated that, from a total of 7305 days of continuous measurements, the daily UVI_{max} reached values between 6 and 9 on 62.37% of the days (Figure 2).The highest UV Index values were in the 13-14 range, with a frequency of less than 1%.

Figure 3 shows the diurnal variation of the UVI for several specific cloud-free days, for different seasons and several locations. Although the stations are all within a 25 km radius, substantial differences among them are notable. The differences are particularly evident in the afternoons, suggesting that their origin is not related to calibration differences between the instruments. Photographs of the locations also indicate that shadowing from nearby structures is not an issue. It is more likely that local differences in air pollution, particularly aerosols, are the cause of this variability.

Previous studies (e.g., (Castro et al., 2001; Palancar et al., 2013)) have shown that surface UV radiation in Mexico City is attenuated significantly by aerosols. The measurements shown in Figure 3 are consistent with increasing pollution during the course of the day, with highest aerosol loading (and highest variability) attained in the afternoon. Further support for the role of pollution in suppressing the UVI comes from the observation made at Santa Fe (SFE) which in Figure 3 are seen to be systematically higher, e.g. by over 10% in autumn afternoons, compared to the other stations. The SFE station is located at 2600 m asl, approximately 300 m higher than Mexico City downtown, and so avoids a substantial fraction of the polluted MCMA boundary layer. It is expected to have higher values of the UVI, in agreement with the observations.

Based on ground measurements analysis under all sky conditions we make an assessment of the values reached around solar noon. From daily $UVI_{\max}$, the monthly averages ($\overline{UVI_m}$) and Standard Deviations (SD) were calculated. The `Simple Moving Average` function from `Python` was applied by quarter and a linear fit along the two decades was determined (Figure 4a).The linear equation has a slope m_{UVI} of 0.06 per year and the y-intercept (year 2000) has a UVI value of 8.5. For the sake of representing an annual behavior, the average, the median, SD, maximum and minimum of the UV Index were obtained (Figure 4a).The maximum and minimum monthly mean of the UV Index were 10.6 (in May) and 6.5 (in November), respectively.

In January the median and mean UVI values are near 8 (see Figure 4b).However, the UVI values and SD seem to be flattened (in the range 10-11) from March to August and decreasing to November (rainy period) with a slight rise in December. The rather low monthly UV Index values, may be a consequence of averaging measurements in presence of clouds and/or significant pollution. Both depend on the time of the year, with a cool dry season from November to February, warm dry March-April-May, and a rainy season from June to October. In addition to urban aerosol pollution sources, biomass burning for agriculture and wood cooking also contribute to poor air quality in the MCMA (Retama, Baumgardner, Raga, McMeeking, & Walker, 2015). In the warm season, faster photochemical oxidant formation, dust, and biomass burning all contribute to strong aerosol loading. In rainy months, UV Index values are lower due to the presence of clouds.

For assessing the influence of the aerosols and criteria pollutants in the UV Index, we processed the PM_{10}, CO, NO_2, O_3 and AOD_{340} ground-based measurements carried out at the stations mentioned in Table 2. From daily measurements from 11h to 14h CST the annual mean of PM_{10}, CO, NO_2, O_3 were calculated. For the case of the AOD_{340}, the measurements along of the day were averaged. Figure 5 shows the trends of the annual values from 2000 to 2019. On the other hand, to estimate the percentage change per year ($\epsilon\,(\%)$), the slope (m_X) of the linear fit and the average in all period ($\overline{X}_{2000-2019}$) were used. In the case of the UVI percentage change was 0.66 % per year. In the same way, Table 3 shows the values corresponding to PM_{10}, CO, NO_2, O_3 and AOD_{340}.

Policies aimed at the improvement of air quality simultaneously with urban and industrial development have taken place in the last years (Molina, de Foy, Vázquez-Martínez, & Páramo-Figueroa, 2009). Stephens et al (2008) determined the monthly variation of the concentrations of PM_{10} in the morning (between 7-12h CTS) and O_3 in the afternoon (from 11h to 17h CTS) for the years 2001–2007 with a negative trend (Stephens et al., 2008). These results reveal a transition towards cleaner air with the decreasing of criteria pollutants, that could be the cause of the slight increase in the UV index trend. Nevertheless, MCMA has a large period under typical cloudy days or wet seasons, in general from June to November.

A fundamental issue is to establish the influence of the clouds on the mean UV Index values. Cloudy days are frequent almost all year in MCMA. The attenuation on $UVI_{\max}$ by clouds could also be predominant out of the rainy period. However, a gap in our knowledge is to discriminate cloudy days only using hourly UV Index measured in situ. The Radiative Cloud Factor measurements by OMI-Aura/NIVR-FMI-NASA satellite instrument were extracted for the Mexico City coordinates. Figure 6a a depicts the daily Cloud Factor (5844 observations) recorded from 2004 to 2019 period. It revealed that cloud cover regularly appears in part of the warm dry and rainy seasons, and is frequent the rest of the months.

Moreover, to incorporate satellite information about the total ozone column (TOC) is fundamental for understanding the UV Index levels. Regarding the cold dry period (December to February) TOMS-EP/NASA and OMI-Aura/NIVR-FMI-NASA instruments estimated the lowest clouds coverage as well as the lowest TOC (Figure 6b). Conversely, higher ozone levels were registered from April to September.

To compare the ground-base measurements at solar noon, the UV Index measured by OMI-Aura/NIVR-FMI-NASA were mapped. Figure 7 represents the satellite UV Index data from 2005 to 2019 (there was no previous data in the analyzed period). As can be seen, the levels are higher than the monthly averages shown in Figure 4 (where the UVI maximum values barely exceed 11). From the middle of January to mid-November, the satellite UV Index varies from 8 up to about 15 ($UVI_{\max} = 14.9$). In particular, values equal or larger than 11, corresponding to the *Extreme* qualification for the UV index given by WHO, are commons from April to September.

The UVI derived from satellite observations is seen to be systematically larger than the mean UVI values measured at the ground. This is to some extent expected, since satellites fail to resolve local clouds and aerosols, particularly near surface levels. To examine this over-estimation in more detail, we selected a subset of the ground-based data that included only the maximum value from all stations and all years of measurement, for each hour and day of the year. The result for the compilation of this $UVI_{\max}$ is illustrated in Figure 8 . It can be seen that $UVI_{\max} \geq 8$ is very frequent at solar noon, as was seen in Figure 2, corresponding to the daily maximum near noon. The highest $UVI_{\max}$ recorded in the period 2000-2019 was 14.9, which is consistent with the maximum values obtained from satellite observations.

However, this comparison also suggests that satellite data estimates may be biased to low values under some conditions. The most noticeable difference is in December, when the $UVI_{\max}$ in situ are between 8-11 and satellite data ranging from 6 to 8.

A visual screening process was applied to the ground measurements to separate cloudless and cloudy conditions, as automated methods are still challenging (Badosa et al., 2014; Wild et al., 2019). In spite of the lack of information about the presence of clouds during the day, the data acquired each minute in the period 2016-2018 were a great identification tool. The measurements behavior minute by minute was used to recognize clear sky days. As expected, the monthly averages UV Index under cloudless sky were higher than $\overline{UVI}_m$, probably due to the clouds absence.

The SIMAT publishes a recommendation of protection according to the measured UVI. In this way, it would be more convenient to estimate in terms of SED/hr and then, to derive the exposure times. The H_{er} expressed as function of time can be obtained (by combining Eqs. 1 and 2)

$$\frac{SED}{hr} = 0.9UVI \tag{3}$$

As is indicated in Figure 9a, the interpolation of the UV Index (and corresponding SED/hr) at solar noon under cloudless sky, revels that these levels match better with the $UVI_{\max}$ values measured over the network (see Figure 8) and the highest UV Index value of 12.6 (11.3 SED/hr) in June. The values of SED/hr under all clear sky days were averaged for the three seasons: cold dry, warm dry and rainy, as is shown in Figure 9b. The warm dry and rainy seasons have a behavior almost coincident. Few data under clear sky were detected between September and October (part of the rainy season) being a negligible contribution on total average just when the UV Index decreased. Nevertheless, the daily asymmetries around solar noon shown Figure 3 could be caused by criteria gases and aerosol. An additional comparison between AOD ground-based measurements and derived data from models (Castro et al., 2001; Cabrera, Ipiña, Damiani, Cordero, & Piacentini, 2012; Palancar et al., 2013) are needed to confirm this hypothesis. However, the main reason for the seasonal variation of the cloud-free UVI is not due to aerosols, but rather simply to the annual cycle of the solar zenith angle, the cosine of which is also plotted in Figure 9a seen to correlate well with the UVI.

As was mentioned in the Introduction, the phototypes III and IV are the most frequents in Mexican inhabitants. The code in `Python` was executed to compute the accumulative doses H_{er} by means of Equation 2. Particularly, the solar exposure time as a function of the local hour (considering only clear sky days in the period 2016-2018) were estimated for the skin types III and IV by means of repetitive operation until reaching 3.0 SED and 4.5 SED, respectively. Figure 10 illustrates the result of exposure time to accumulate the corresponding H_{er} for each phototype.

The upper and lower wide curves are associated with measurements carried out in summer and winter seasons and the areas contain the exposure times between spring and autumn. The asymptote at 15h CTS represents that it will not be possible to achieve the MED after this hour. The representation along the hours shows that the exposure time range was narrower. As can be seen, during all year the exposure times that accumulate are H_{er} at noon, ranging between 17-25 minutes for phototype III and 25-38 minutes for phototype IV. Understanding that paler colors require shorter times and darker ones need longer times to generate sunburn. Specifying the threshold erythemal dose for each phototype is fundamental to the photoprotection as well as calculation of the exposure times. Prevention and timely diagnosis continue to be the main strategy to reduce the incidence and impact of skin cancer (Pinedo et al., 2009; Alfaro-Sánchez et al., 2016). These results can contribute to the properly information about the risk and skin care (Heckman, Liang, & Riley, 2019) and help to demystify the perception that darker skins can not have sunburn or are exempt to develop skin-cancer in Mexico (Castanedo-Cazares et al., 2006).

Conclusion

The purpose of this study was to characterize the UV climatology over Mexico City Metropolitan Area in the last 20 years. The location of this megacity is in a region prone to achieve high values of UV Index (Tanskanen et al., 2006; Zaratti et al., 2014). In spite of high altitude (2240 m asl) of Mexico City, the ultraviolet irradiance is lower than in Colima (485 m asl), a relatively pollution-free city and placed at about the same latitude (Galindo et al., 1995). The $\overline{UVI}_m$ ranging between 10 and 11 at solar noon under all sky conditions, almost all the year (see Figure 4). The high aerosols concentration and smog photochemistry products may affect the solar radiation reaching the surface (Castro et al., 2001; Palancar et al., 2013). Also the existence of cloud coverage almost all year round can be partially responsible for the not as high as expected UV Index values for Mexico city. In the period 2000-2019 the trends of PM_{10}, CO, NO_2, O_3 and AOD_{340} were decreasing due to policies aimed at the improvement of air quality. The transition towards cleaner air that has the side effect of increasing UV, showing a trend of 0.66 % per year with respect to the mean. Analogous results have been reported in China, India and Greece (Peng, Du, Wang, Lin, & Hu, 2014; Wang, Gong, Feng, & Hu, 2014; Panicker, Pandithurai, Beig, Kim, & Lee, 2014; Raptis et al., 2020). The UV Index trend is within the range of the values published by Herman (2010) about erythemal irradiance trend from 1979 to 2008 derived from satellite data (between -1.7% to 2.0% annually) in the latitudinal range of Mexico City. Regarding, the comparison of UV Index from satellite data (Figure 7) and the highest $UVI_{\max}$ ground-based values (in Figure 8) showed similar values (up to 14.9). The Mexico City experiment values of $\overline{UVI} \geq 6$ the majority of the year (see Figures 4, 7 and 8). under all sky conditions. These levels are in the *High, Very High and Extreme* qualification range of WHO (WHO, 2002) and involve an alert for skin protection of the population. Since the exposure times are a measure to avoid sunburn, these were calculated on a selection of clear sky days, for two phototypes of the inhabitants of the Mexico City. The highest UV Index reaches 12.6 (11.3 SED/hr) and the main reason for the seasonal variation of the cloud-free UVI is the annual cycle of the solar zenith angle. The minimum exposure times for accumulates 3.0 and 4.5 SED at noon on phototypes III and IV, were 17 and 25 minutes respectively. It is important to underline that, currently there are discrepancies between the MED values cited and defined by Fitzpatrick (T. Fitzpatrick, 1988; Sanclemente et al., 2008; D'Orazio, Jarrett, Amaro-Ortiz, & Scott, 2013; Serrano et al., 2017; Lehmann et al., 2019). Beside, imprecise terminology referring to ethnicity, accentuates the problems of classification (Cuevas et al., 2016; Marcheco-Teruel et al., 2014), hindering the comparison of results about the MED values and exposure times in other regions. A rigorous use of the threshold erythemal dose for each phototype is fundamental for the sake of an adequate calculation. This assessment can be of interest for validation of satellite data and radiative transfer models, forecast, solar energy applications, and alert the public to the need for skin protection.

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