

# The Ultraviolet Radiation Environment of a Tropical Megacity in Transition: Mexico City

## 2000-2019

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### Abstract

Tropical regions experience naturally high levels of UV radiation, but urban pollution can reduce these levels substantially. We analyzed 20 years of measurements of the UV Index (UVI) at several ground-level locations in the Mexico City Metropolitan Area and compared these data with UVI values derived from satellite observations of ozone and clouds (but not local pollution). The ground-based measurements were systematically lower than the satellite-based estimates, by ca. 40% in 2000 and 20% in 2019. Calculations with a radiative transfer model and observed concentrations of

9 air pollutants explained well the difference between satellite- and ground-based UVI,  
10 and showed specific contributions from aerosols in the boundary layer and the free tro-  
11 posphere, O<sub>3</sub>, NO<sub>2</sub>, and SO<sub>2</sub>, in decreasing order of importance. Such large changes  
12 in UV radiation between 2000 and 2019 have important implications ranging from hu-  
13 man health (skin cancer and cataract induction) to air pollution control (photochemical  
14 smog formation).

## 15 Introduction

16 Ultraviolet (UV) radiation is an important component of the urban environment, affecting  
17 human populations directly through UV exposure of skin and eyes<sup>1–3</sup> and less directly (but  
18 with great impact) by driving the formation of photochemical smog, including tropospheric  
19 ozone and other oxidants, as well as secondary aerosols containing nitrates, sulfates, and  
20 organics.<sup>4–6</sup> These pollutants, along with others of primary origin commonly found in ur-  
21 ban atmospheres (e.g., black carbon, sulfur dioxide), can in turn scatter and/or absorb UV  
22 radiation, alter its vertical distribution, and so modify the photochemical rate of their own  
23 formation. Such feedback complicates the calculation of both the UV radiation field (in-  
24 cluding at the surface), and the evolution of photochemical smog in the urban boundary  
25 layer.

26 The question of how air pollution alters the urban UV environment (and *vice versa*) is  
27 not new, but studies have relied mostly on numerical models,<sup>7–9</sup> with relatively few available  
28 observations (e.g., McKenzie et al.<sup>10</sup>, Panicker et al.<sup>11</sup>, Palancar et al.<sup>12</sup>, reviewed by Bais  
29 et al.<sup>13</sup>). Increases in UV have been estimated as a consequence of emission reductions  
30 over the last decades, e.g. in China,<sup>14–16</sup> and have led to less-than-expected reductions in  
31 photochemical smog, in part due to stronger UV photochemistry.<sup>17–19</sup> Emission reductions  
32 have also occurred globally during the 2020 COVID-19 pandemic,<sup>20,21</sup> but ground-level ozone  
33 in some polluted areas has actually increased,<sup>22,23</sup> due at least in part to the increased UV  
34 radiation. Unfortunately, the observational data base of relevant UV radiation remains

35 rather sparse to evaluate such model-predicted feedbacks between chemistry and radiation.

36 The environment of Mexico City is of particular interest for several reasons: (1) Nearly  
37 23 million people inhabit the Mexico City Metropolitan Area (MCMA), and the UV en-  
38 vironment has direct implications for their health, both in terms of skin/eye UV exposure  
39 and *via* photochemical smog formation. (2) As a tropical megacity, it is to some extent  
40 representative of the situation of many others, with year-round intense midday UV irradia-  
41 nce, a shallower atmosphere due to the city's high elevation of 2240 m above sea level,  
42 and a transition toward newer and cleaner technologies, leading to gradual improvements  
43 in air quality. (3) Air quality within MCMA has undergone extensive scrutiny, with a well-  
44 established monitoring network operating since 1986,<sup>24</sup> numerous intensive field campaigns  
45 to study the meteorology, emissions, and photochemistry of smog formation,<sup>25–27</sup> and numer-  
46 ical modeling incorporating the evolving knowledge.<sup>28–31</sup> This extensive body of knowledge  
47 provides the foundation for understanding our study.

48 Here, we analyze two decades of continuous measurements of the UV Index at multiple  
49 locations within the MCMA, collected by the Secretariat of the Environment (Secretaría  
50 del Medio Ambiente, SEDEMA)<sup>1</sup> of the Mexico City government as part of an intensive  
51 monitoring network over the MCMA. The UV Index is defined as:

$$UVI = 40 \int_{250nm}^{400nm} E(\lambda, t) \cdot S_{er}(\lambda) d\lambda \quad (1)$$

52 where  $E(\lambda, t)$  is the solar spectral irradiance in units of  $\text{W} \cdot \text{m}^{-2} \cdot \text{nm}^{-1}$  and  $S_{er}(\lambda)$  is  
53 the erythemal sensitivity of human skin.<sup>32,33</sup> Multiplication by 40 was chosen historically to  
54 express the UVI in small integer numbers, but is otherwise scientifically arbitrary.

55 The UVI is recognized by the World Health and Meteorological Organizations (WHO  
56 and WMO) as a standardized measure of UV radiation<sup>32</sup> for global public information. An  
57 advantage of using the UVI as (one) measure of UV radiation is that it is being increasingly  
58 observed or calculated and disseminated, enabling more objective comparisons among seasons

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<sup>1</sup><https://www.sedema.cdmx.gob.mx/>

59 and locations. The UVI observations from Mexico City, considered here, are an important  
60 element of this global picture.

61 While the UVI at the surface cannot be translated directly into photolysis frequencies  
62 for various photo-labile molecules, the spectral weighting of the UVI (ca. 300-320 nm) is  
63 approximately similar to that for the photolysis of ozone to singlet oxygen atoms. Other UV  
64 wavelengths are of course also important, e.g. for the photolysis of nitrogen dioxide, and  
65 may be affected differently depending on the pollutant. With these considerations and a few  
66 other caveats, UVI trends examined here can also be used to infer accompanying trends in  
67 photolysis frequencies and influences on photochemical smog formation.

## 68 Methods

### 69 Ground-based measurements

70 The Mexico City Metropolitan Area is located at 19.4°N, 99.1°W, 2240 meters above sea  
71 level (m asl), surrounded by mountain ridges exceeding 5000 m asl, with complex topog-  
72 raphy and thermal inversions that inhibit winds and favor intense air pollution.<sup>34-36</sup> Air  
73 quality monitoring and surface meteorological measurements in the MCMA are conducted  
74 continuously by the Automated Atmospheric Monitoring Network (RAMA, by its Spanish  
75 acronym) of the Atmospheric Monitoring System (SIMAT, by its Spanish acronym) of the  
76 Mexico City government. Since the year 2000, UV radiometers (model 501-A, Solar Light  
77 Company Inc., Glenside, PA) detecting wavelengths between 280-400 nm have been mea-  
78 suring erythemally-weighted solar radiation. The calibration of the UV sensors has been  
79 carried out annually by comparing against a factory-calibrated reference sensor. The out-  
80 put voltages from the network's sensors have been compared for at least one week against  
81 the UV readings from the reference sensor to derive a calibration factor. New calibration  
82 factors typically differ from the old ones by 2% or less. Reference sensors have been also  
83 calibrated by the manufacturer and updated periodically (between 3 to 5 years) to reduce

84 systematic errors due to drifts in sensitivity. Long term calibration drift are minimized by  
 85 these yearly re-calibrations. Although at the beginning only a few stations were in oper-  
 86 ation and have been changing, currently 11 stations are recording erythemal irradiances,  
 87 which are then multiplied by 40 (see Eq. 1) to give UV Indices. Table 1 describes the lo-  
 88 cation of the stations where the UV Index has been measured. Figure 1 shows how the  
 89 radiometers of the SIMAT have been distributed over MCMA, prioritizing sites with higher  
 90 population density. Near real-time data for each station are available on the SIMAT official  
 91 website <http://www.aire.cdmx.gob.mx/default.php>. Daily maximum values ( $UVI_{max}$ )  
 92 were extracted in each of the stations around solar noon from the time interval from 11:00  
 93 h-15:00 h CST (Central Standard Time). This database with 7305 continuous days of mea-  
 94 surements during the period 2000-2019 was analyzed.

Table 1: SIMAT stations and AERONET site\*, environmental descriptors and geographical positions. Abbreviations names: 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), Tlalnepantla (TLA) and National Autonomous University of Mexico (UNAM\*)

Station	Environment	Lat (°N)	Lon (°W)	El (m asl)
CHO	semi-urban	19.27	98.89	2253
CUT	ecological park	19.72	99.20	2263
FAC	urban	19.48	99.24	2299
HAN	urban	19.42	99.08	2235
LAA	urban	19.48	99.15	2255
MER	downtown	19.42	99.12	2245
MON	rural	19.46	98.90	2252
MPA	rural	19.18	98.99	2594
PED	residential	19.33	99.20	2326
SAG	urban	19.53	99.03	2241
SFE	residential	19.36	99.26	2599
TLA	urban	19.53	99.20	2311
UNAM*	University city	19.33	99.18	2294

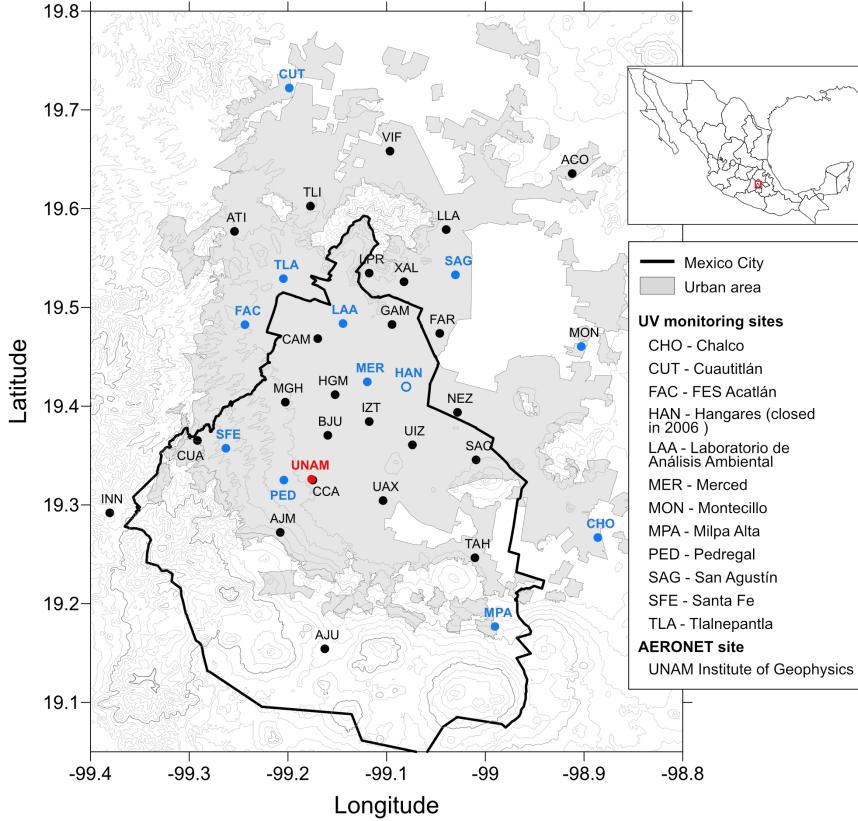


Figure 1: Map with the location of the SIMAT continuous monitoring stations over MCMA. Sites denoted by the blue solid dots correspond to SIMAT stations with UV measurements, while the black dots indicate SIMAT stations without UV measurements, the site indicated by an open blue dot represents a discontinued site, the red dot shows the location of the AERONET site. The location of Mexico City and the acronyms of the UV and AERONET site are shown at the upper and lower frames at the right respectively.

With the aim to explore the relationship between UVI and air pollutants levels, the hourly averages for ozone ( $O_3$ ), carbon monoxide (CO), nitrogen dioxide ( $NO_2$ ), sulfur dioxide ( $SO_2$ ) and particle matter with diameter sizes  $\leq 10 \mu m$  ( $PM_{10}$ ), were downloaded from the SIMAT.<sup>37</sup> For purposes of assessing the influence on the UV Index at solar noon, only values obtained between 11h and 15h CST were considered for the trends analysis. Pollutant measurements are conducted by the SIMAT using regulatory-grade commercial instruments. Measurement principles include ultraviolet photometry (model 400E, Teledyne-API) for  $O_3$ , chemiluminescence (model 200E, Teledyne-API) for  $NO_2$ , UV fluorescence (model 100E, Teledyne API) for  $SO_2$ , and infrared absorption (model 300E, Teledyne-API) for CO.

<sup>104</sup> The PM<sub>10</sub> continuous mass concentration was measured with Tapered Element Oscillating  
<sup>105</sup> Microbalance (TEOM 1400AB or TEOM 1405 DF, Thermo Scientific) monitors. Gaseous  
<sup>106</sup> pollutant levels are reported in ppb concentration units for O<sub>3</sub>, SO<sub>2</sub> and NO<sub>2</sub>, and in ppm  
<sup>107</sup> for CO. Particulate matter mass concentration is reported in  $\mu\text{g m}^{-3}$  at local conditions for  
<sup>108</sup> temperature and pressure.

<sup>109</sup> Aerosol optical depth at 340 nm was obtained from the Institute of Geophysics of the  
<sup>110</sup> National Autonomous University of Mexico (UNAM). Measurements were conducted with  
<sup>111</sup> a CIMEL sun photometer model CE-318, which is an automatic sun-sky-scanning spectral  
<sup>112</sup> radiometer of the AErosol RObotic NETwork (AERONET<sup>38</sup>). The data Product Level  
<sup>113</sup> 2.0 and 1.5 (only in 2019) were selected, and annual averages AOD<sub>340</sub> were calculated for  
<sup>114</sup> the period 2000-2019, except for the year 2011 which contained large data gaps and was  
<sup>115</sup> therefore not used. A previous study of the AOD behavior from 2000 to 2014 demonstrated  
<sup>116</sup> that data gaps did not significantly change the trends calculated for this.<sup>39</sup> Only 8% of the  
<sup>117</sup> data between the years 2014 and 2019 were missing. The largest data gap occurred in 2018  
<sup>118</sup> when the instrument was returned for calibration.

## <sup>119</sup> Satellite data

<sup>120</sup> The UV Index data derived from satellite-based measurements were used for comparison with  
<sup>121</sup> the ground-based measurements. These data were provided by the Ozone Monitoring Instru-  
<sup>122</sup> ment (OMI) on board of AURA-NASA satellite.<sup>40</sup> OMI is operated in cooperation between  
<sup>123</sup> the Netherlands Agency for Aerospace Programmes (NIVR), the Finnish Meteorological In-  
<sup>124</sup> stitute (FMI) and NASA. OMI performs observations over a geographical area of  $13 \times 24\text{km}^2$   
<sup>125</sup> at nadir. For the coordinates (19.33°N, 99.18°W) and elevation (2268 m asl) of Mexico City,  
<sup>126</sup> the satellite overpass time is between 19:00h - 21:00h UTC (20:00h - 22:00h CET). The OMI  
<sup>127</sup> instrument measures reflected and backscattered radiances of the atmosphere-surface sys-  
<sup>128</sup> tem at several UV wavelengths. The ozone column is estimated by differential absorption of  
<sup>129</sup> several adjacent wavelengths in the O<sub>3</sub> Huggins band<sup>41</sup>, while clouds are estimated from the

reflectivity at a wavelength not affected by O<sub>3</sub> absorption (360 nm, Tanskanen et al.<sup>42</sup>). A correction for absorbing aerosols is made using a global aerosol climatology.<sup>43</sup> The UV Index used for Mexico City corresponds to values at local noon time and clear sky from OMUVB Level 2 OVP data product, version 1.3 and collection 3.

## 134 TUV model

135 Calculations of the UV Index were also made with the Tropospheric Ultraviolet Visible (TUV  
136 v5.3) model.<sup>44</sup> The model atmosphere is represented by 80 vertical layers, each 1 km thick,  
137 starting at the 2.24 km asl elevation of MCMA, and for which the first three km constitute  
138 the atmospheric boundary layer (BL).<sup>45</sup> The ozone profile above the BL is from the US  
139 Standard Atmosphere, but rescaled to a value of 259.6 DU. Total ozone columns including  
140 the BL contributions (of 13.7 DU in the year 2000 and 9.8 DU in 2019, see below) were  
141 273.1 DU in 2000 and 269.2 DU in 2019, respectively. The climatological O<sub>3</sub> column for this  
142 latitude and season is about 270 DU (plus or minus ca. 5 DU) so in good agreement with  
143 the values used here.

144 Pollutants within the BL (including O<sub>3</sub>) are assumed to be well mixed, in agreement with  
145 observations from the MILAGRO field campaign that showed the disappearance of vertical  
146 gradients in the profiles of gases<sup>46,47</sup> and aerosols<sup>48,49</sup> by late morning. The UV-absorbing  
147 gases considered here are O<sub>3</sub>, NO<sub>2</sub>, and SO<sub>2</sub>, specified in ppb.

148 BL aerosols are modeled by prescribing the AOD at 340 nm (from AERONET observa-  
149 tions), scaled to other wavelengths inversely with wavelength (Angstrom coefficient = 1.0),  
150 asymmetry factor of 0.7, and a single scattering albedo of 0.85 at UV wavelengths, following  
151 the determinations made in Mexico City by Corr et al.<sup>50</sup> and Palancar et al.<sup>12</sup>.

152 Above the atmospheric boundary layer, the model atmosphere was specified to be, NO<sub>2</sub>,  
153 or SO<sub>2</sub>. In one sensitivity study, a total AOD of 0.7 was redistributed placing 0.2 in the free  
154 troposphere (decreasing vertically with an exponential scale height of 4 km, and 0.5 remaining  
155 in the BL). The calculated UVI differed by less than 1%. Thus, as long as the total AOD

<sub>156</sub> is known, knowledge of the exact vertical aerosol profile is not critical for ground-level UVI,  
<sub>157</sub> but would obviously affect the vertical structure of photolysis frequencies.

<sub>158</sub> Radiative transfer calculations were carried out with the pseudo-spherical 4-stream op-  
<sub>159</sub> tion, at 1 nm steps between 280 and 400 nm.

## <sub>160</sub> Results and Discussion

<sub>161</sub> Figure 2 shows the diurnal variation of the UVI for several specific cloud-free days, for  
<sub>162</sub> different seasons and several locations (CHO, MER, MON, PED, SAG, SFE and TLA).  
<sub>163</sub> UV Index calculated with the TUV model was used as reference of the behavior during  
<sub>164</sub> clear sky days. According to the comparison of measurements minute by minute, the dates  
<sub>165</sub> with prolonged fluctuations along the day were discarded. However, during the rainy period  
<sub>166</sub> (from June to October) at least a brief episode of clouds, as shown at CHO station around  
<sub>167</sub> noon in 13 June 2017. Peak values range from 8 during autumn/winter to above 12 in  
<sub>168</sub> spring/summer, in correspondence to the respective December and June solstices. Although  
<sub>169</sub> the stations are all within a 25 km radius, substantial differences among them are notable.  
<sub>170</sub> Survey of the locations revealed that shadowing from nearby structures is not an issue. The  
<sub>171</sub> good agreement in the morning, followed by more divergence in the afternoon, is consistent  
<sub>172</sub> with the development of photo-chemical pollution hotspots during the day. Previous studies  
<sub>173</sub> (e.g., Castro et al. <sup>51</sup> and Palancar et al. <sup>12</sup>) have shown that surface UV radiation in Mexico  
<sub>174</sub> City is attenuated significantly by aerosols. The measurements shown in Fig. 2 are consistent  
<sub>175</sub> with this increasing pollution during the course of the day, with highest aerosol loading (and  
<sub>176</sub> highest variability) attained in the afternoon. Further support for the role of pollution in  
<sub>177</sub> suppressing the UVI comes from the observation made at the Santa Fe (SFE) site which in  
<sub>178</sub> Fig. 2 are seen to be systematically higher, e.g. by over 10% in autumn afternoons, compared  
<sub>179</sub> to the other stations. The SFE station is displaced to the west from the majority of the other  
<sub>180</sub> stations, and remains in the outskirts. This site is also approximately 300 m higher than

Mexico City downtown, so that the cleaner atmosphere at SFE is a result of the station's location farther away from pollution sources, both horizontally and vertically.<sup>52</sup> It is indeed expected to have higher values of the UVI, in agreement with the observations.

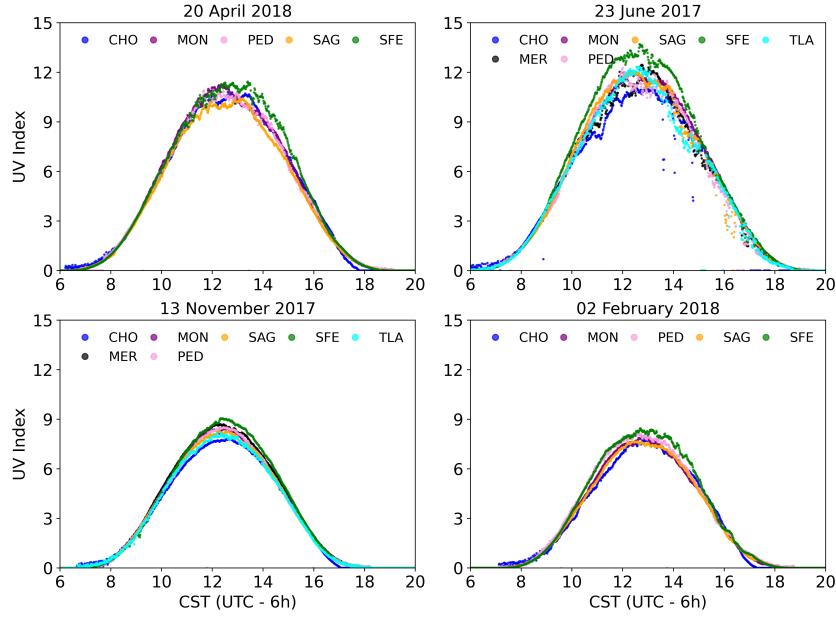


Figure 2: UV Index measurements at 1-minute resolution from several SIMAT stations within the MCMA under mostly cloudless conditions for representative days of the year.

The daily maximum UV Index of each station is denoted by  $UVI_{max}$ , these values were counted in the period 2000-2019. As shown in Figure 3, these values ranged from 1 to 16, with a majority (61%) of the days experienced  $UVI_{max}$  values between 6 and 10, and remarkably few, less than 1%, in the 13-16 range. The lowest values are likely due to winter days with heavy cloud cover and low sun angles, and UV attenuation by pollutants could also be amplified under such conditions, due to longer photon path lengths at low sun and within clouds. The extreme sparsity of high UVI values remains surprising, and may be an indication of the rarity of extremely unpolluted days within the city.

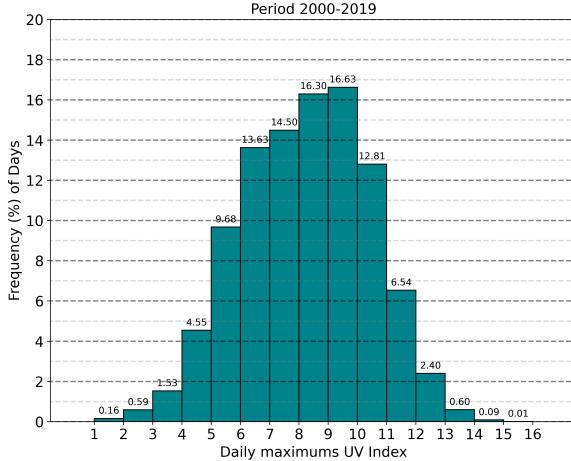


Figure 3: Frequency distribution of daily maximums UV Index values in Mexico City during 2000 -2019.

192 Similar patterns are found when considering the monthly average of the  $UVI_{\max}$  values

193 as shown in Figure 4. The long-term averages present a seasonal variation (as in Fig. 2) that

194 follows approximately the cosine of the noontime solar zenith angle. Notably, values rarely

195 if ever exceed 12 (as in Fig. 3). The lowest average UVI (near 7) occurs in winter while

196 from March to August the values seem to be flattened in the range 10-11. The rather low

197 monthly UV Index values could be a consequence of the presence of clouds in the rainy season.

198 However, urban aerosol pollution sources, biomass burning for agriculture and wood cooking

199 also contribute to poor air quality between March-May<sup>53</sup>. Using the maximum  $UVI_{\max}$  from

200 all of stations every day (one daily point), the monthly averages ( $\overline{UVI}_m$ ) were calculated

201 along the period 2000-2019 (except for June 2003 due to there were no measurements). Long

202 term trends in  $\overline{UVI}_m$  are shown in Figure 5. A clear upward trend is seen, with a slope for

203 the linear fit of 0.9%/year or +1.5 UVI units over the two decades.

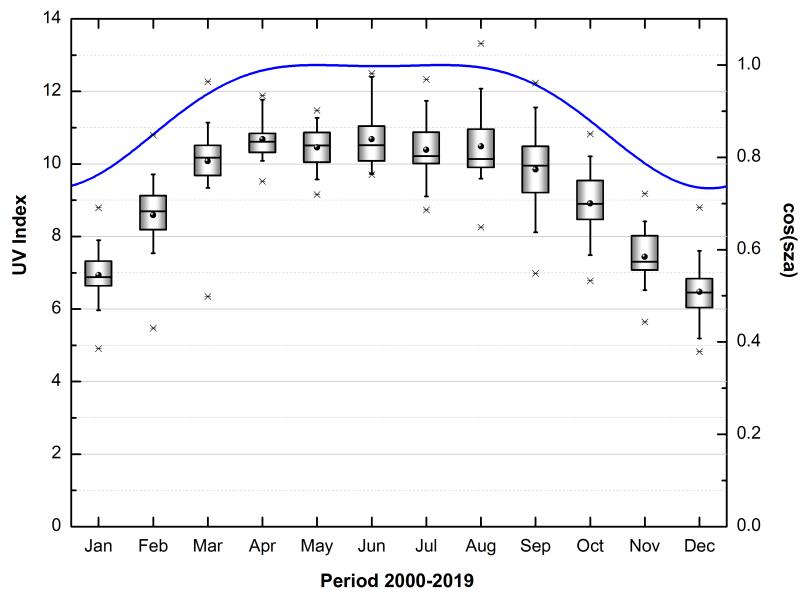


Figure 4: Boxplot of the monthly averages of the maximum UV Index values (black dot) in MCMA for the period 2000-2019: median (central bold line), interquartile range (box edges), 10% and 90% percentiles (the whiskers), the minimum and maximum values (asterisk) and the cosine of the solar zenith angle at solar noon (blue curve).

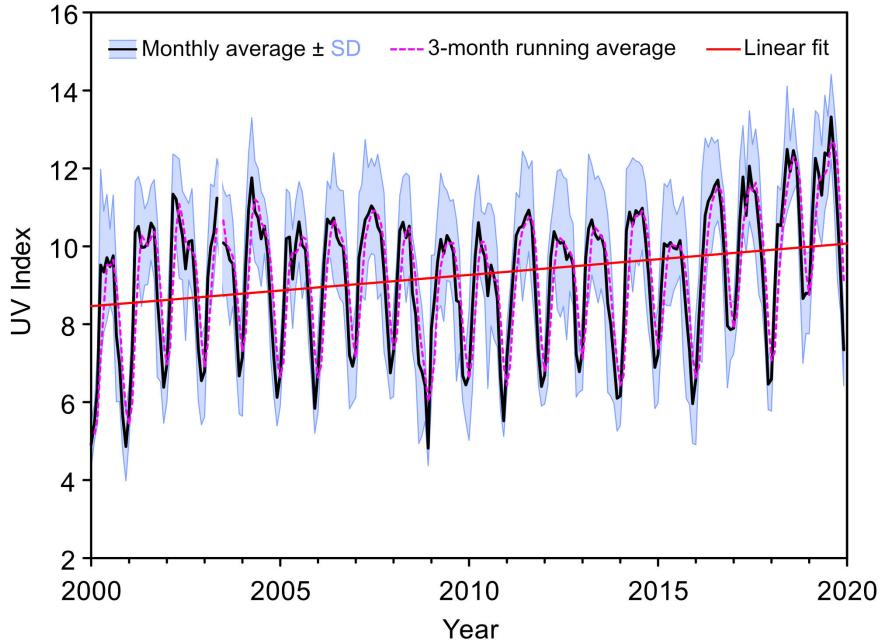


Figure 5: 3-month running average (violet segments curve) applied to monthly average UV Index (black line), the standard deviation (blue fill area) and linear fit (red line).

The UV Index computed from satellite-based observations over the period 2005-2019 is shown in Figure 6. The satellite-derived UVIs vary from 8 in winter to 16 in summer, these values being substantially higher than the ground-based observations (ca. 7 for winter and 11 for summer, see Fig. 4). The maximum values are reached in June and July of each year for both data sets. We hypothesize that this large difference between satellite-based estimation and ground-based observation of the UV index is due to the intense air pollution of Mexico City. A rather similar behavior was detected in Santiago city, Chile.<sup>54</sup> Although the OMI data are corrected for climatological aerosol absorption<sup>43</sup>, this correction likely underestimates the absorption within the polluted Mexico City BL.

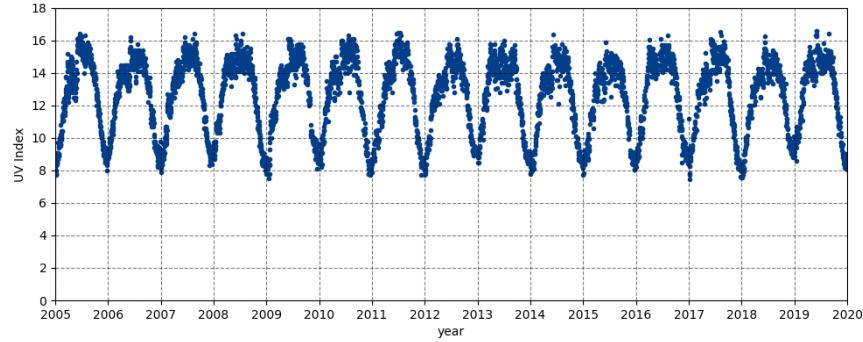


Figure 6: UV Index at solar noon for clear sky recorded by OMI-Aura/NIVR-FMI-NASA, from 2005 to 2019.

### <sup>213</sup> Effect of pollutants on UV radiation

<sup>214</sup> Trends and averages in aerosol optical depth  $AOD_{340}$  and criteria pollutants  $PM_{10}$ , CO,  
<sup>215</sup>  $NO_2$ ,  $O_3$  and  $SO_2$  observed at the SIMAT stations over 2000-2019, are shown in Figure 7  
<sup>216</sup> and summarized in Table 2 together with the  $UVI_{max}$ . Similar trends in pollutants have  
<sup>217</sup> been noted before<sup>55-57</sup> and reflect the long-term success of emission reduction policies and  
<sup>218</sup> programs.

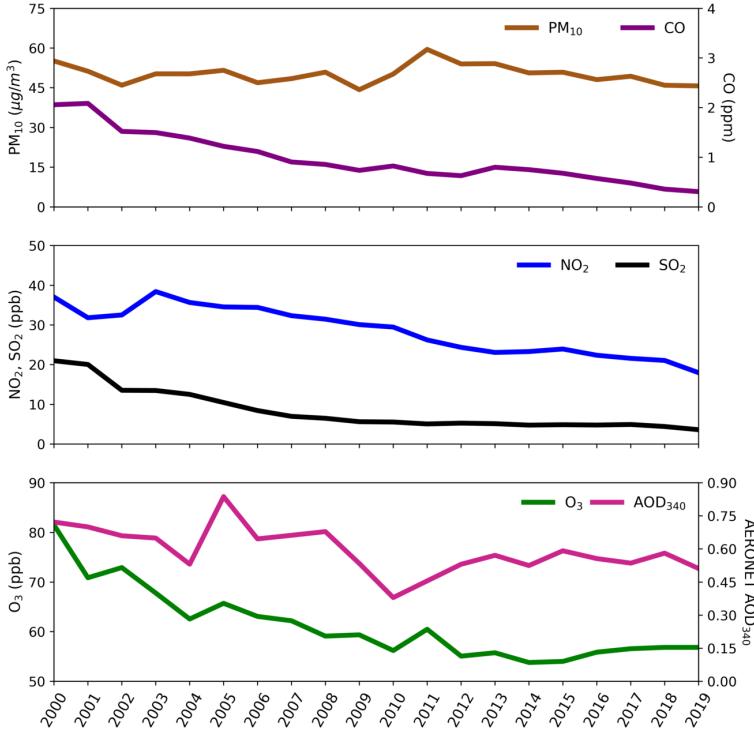


Figure 7: Air quality trends in MCMA for the period 2000-2019 from annual averages obtained between 11h to 15h CST every day: PM<sub>10</sub> (brown curve), CO (purple curve), NO<sub>2</sub> (blue curve), SO<sub>2</sub>(black curve), O<sub>3</sub> (green curve) and AOD<sub>340</sub> (pink curve).

Table 2: UV Index and criteria pollutants: the absolute change per year for the period 2000-2019, averages in units of  $\mu\text{g}/\text{m}^3$ (PM<sub>10</sub>), ppm (CO), ppb (SO<sub>2</sub>, NO<sub>2</sub> and O<sub>3</sub>), dimensionless (UV Index and AOD<sub>340</sub>) and annual percentage change (%/year).

Variable	$\frac{\text{absolutechange}}{\text{year}}$	Avg <sub>2000–2019</sub>	$\Delta(\%/\text{year})$
UVI	0.08	9.2	0.9
PM <sub>10</sub>	-0.10	50.2	-0.2
CO	-0.08	1.0	-8.2
NO <sub>2</sub>	-0.96	28.6	-3.4
O <sub>3</sub>	-1.05	61.3	-1.7
AOD <sub>340</sub>	-0.01	0.6	-1.6
SO <sub>2</sub>	-0.76	8.4	-9.1

The observed changes in the concentrations of these air pollutants have significant implications for surface UV radiation, as can be demonstrated with the TUV radiative transfer model. Table 3 summarizes UVI values for the June-July time period, estimated by the three

222 methods: OMI satellite-derived UVI, SIMAT ground-based observations, and TUV model-  
 223 ing using air pollution estimates. Two groups of values can be readily identified: (1) SIMAT  
 224 daily record values, OMI with or without BL aerosols, and TUV for very clean conditions, all  
 225 with UVI values around 15-16; and (2) the average of daily maxima of SIMAT observations  
 226 and TUV UVI results using MCMA pollutants as input. Note that SIMAT and TUV values  
 227 are in good agreement for both 2018-2019 and 2000-2001 and are considerably lower than for  
 228 case (1). Compared to the OMI estimate that included the climatological aerosol correction  
 229 (15.3), observed SIMAT values were lower by 35% in 2000 and by 20% in 2019. Similarly,  
 230 TUV values were 35% lower in 2000 and 22% lower in 2019 relative to the TUV values of  
 231 15.6 for a pristine atmosphere.

Table 3: UVI maxima for June-July: averages and standard deviation from ground-based data for the years 2018-2019 and 2000-2001. UVI maximum value reached in the period 2000-2019 for UVI ground-based and the same for satellite in the period 2005-2019. TUV calculations for specified conditions.

<b>Conditions for estimation in June-July</b>	<b>UV Index</b>
SIMAT average maxima 2000-2001	$9.9 \pm 1.2$
SIMAT average maxima 2018-2019	$12.3 \pm 1.3$
SIMAT maximum value reached in period 2000-2019	15.0
OMI maximum value reached in period 2005-2019	16.6
TUV "zero" pollution	16.1
AOD 0, O <sub>3</sub> 0 ppb, NO <sub>2</sub> 0 ppb, SO <sub>2</sub> 0 ppb	
TUV pristine pollution	15.6
AOD 0.05, O <sub>3</sub> 10 ppb, NO <sub>2</sub> 0 ppb, SO <sub>2</sub> 0 ppb	
TUV 2019:	12.1
AOD 0.5, O <sub>3</sub> 50 ppb, NO <sub>2</sub> 20 ppb, SO <sub>2</sub> 1 ppb	
TUV 2000:	10.2
AOD 0.7, O <sub>3</sub> 70 ppb, NO <sub>2</sub> 40 ppb, SO <sub>2</sub> 20 ppb	

232 The agreement between SIMAT observations and TUV model estimates is excellent but  
 233 also probably a bit fortuitous. Clouds on average reduce the irradiance impinging on the  
 234 surface, but scattering from them can also cause transient enhancements (these are only  
 235 possible if the disk of the Sun is visible) that could be recorded as daily maxima – with  
 236 cancellation between these cloud effects resulting in improved agreement with the cloud-free

model. We cannot exclude that some of the observed trend in UVI is due to changes in cloud cover. However, the modeled fractional UVI reductions due to pollutants, shown in Table 3, are in such good agreement with the observed UVI reductions, that a compelling case can be made for a dominant role of air pollutants in the long-term UVI trends.

Table 4 shows the contribution of different pollutants to the UVI increase between 2000 and 2019, computed with the TUV model. The year 2000 was taken as the base case, and each pollutant was decreased to its 2019 value individually while the others were maintained at their 2000 value. Decreasing aerosol AOD has been the largest driver of the UVI changes, but the absorption by gaseous pollutants has also decreased significantly. Additional future reductions in AOD, NO<sub>2</sub>, and O<sub>3</sub> could increase the UVI further, while the low SO<sub>2</sub> levels reached by 2019 are expected to have negligible effects in the UVI.

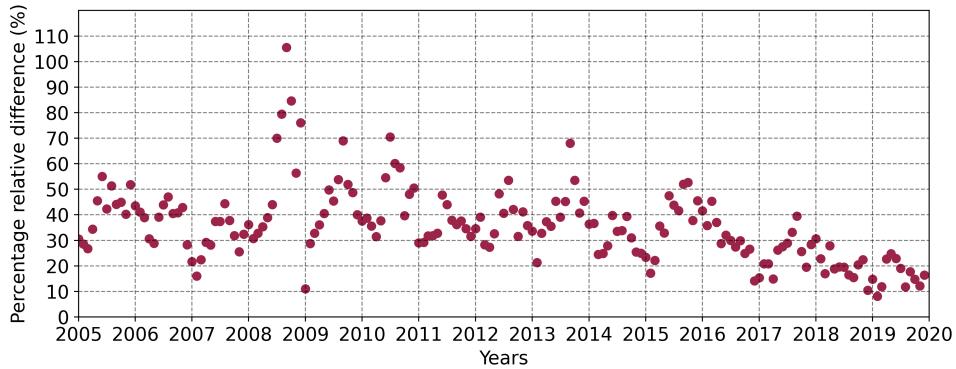


Figure 8: The percentage relative difference (% RD) of the satellite and ground-based monthly means UVI for the period 2005-2019.

Figure 8 shows the percentage relative difference between monthly means satellite-based and ground-based data with respect to the last one. The mean percentage relative difference was 35% in the period 2005-2019. Comparable UV reductions, of 30-40% due to aerosols, were reported by Panicker et al.<sup>11</sup> over Pune, India from April 2004 to March 2005, with sensitivity coefficients (i.e. change in UVI per unit change in AOD) similar to those found here in Table 3.

Comparisons of OMI with ground-based UV measurements have been reviewed recently

255 by Zhang et al.<sup>58</sup> and Vitt et al.<sup>59</sup>. OMI-derived UV generally overestimates ground-level  
256 measurements by 1-10% in relatively clean conditions (e.g. rural U.S), by 10-30% in Southern  
257 Europe and by 40% or more in Santiago, Chile<sup>54</sup> and Thailand<sup>60</sup>. The overestimations appear  
258 related in large part to incomplete accounting of UV absorption by BL aerosol, although  
259 other factors such as the correction to solar noon may also introduce some bias.<sup>58</sup> Over  
260 Europe, ground-based UVI observations for several decades are systematically lower than  
261 those estimated from satellites even after consideration of climatological aerosol distributions,  
262 showing the importance of local pollution not resolved from space.<sup>59</sup> However, difference  
263 between satellite-derived and ground-based UVI was less than 1.0 UVI units in over 90% of  
264 the cases, in contrast to the difference of 3-5 units found for Mexico City (Table 3).

265 UV reductions by air pollutants are expected to be most severe near the surface, while  
266 chemical reactions leading to photochemical smog occur throughout the vertical extent of the  
267 BL. Figure 9 shows the vertical profiles of photolysis coefficients (the reciprocals of photolytic  
268 lifetimes) computed with the TUV model, for two key reactions, the photolysis of O<sub>3</sub> to yield  
269 excited oxygen atoms O(1D), and the photolysis of NO<sub>2</sub>. In the absence of optically active  
270 pollutants, these coefficients would be nearly independent of altitude in the BL. However,  
271 the presence of pollutants leads to a strong decrease toward the surface, with notably more  
272 severe reductions in 2000 compared to 2019. While the specific values shown in the figure  
273 are only illustrative for typical conditions, routine daily air quality modeling should carefully  
274 account for the long term variations in these photolysis coefficients.

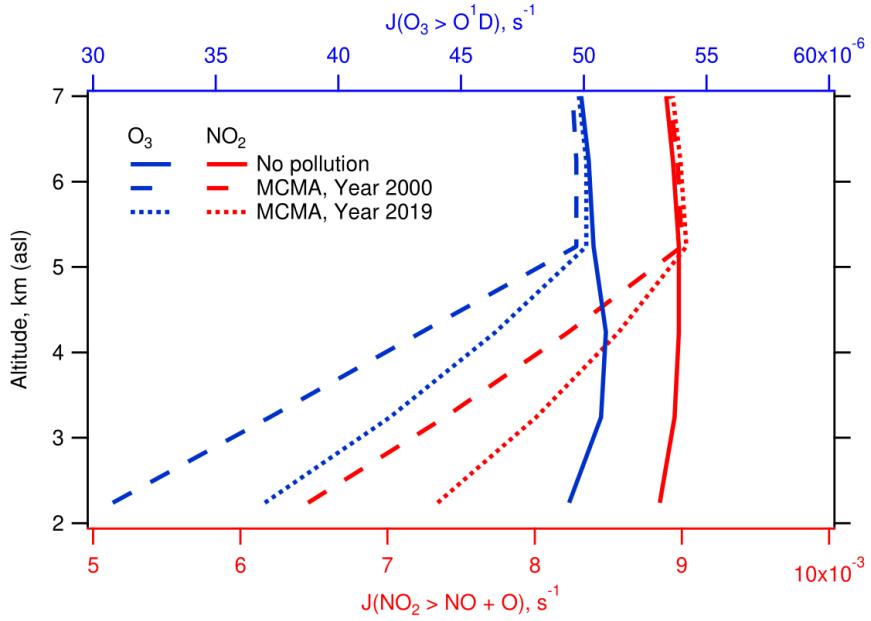


Figure 9: Vertical profiles of the photolysis coefficients for the reaction  $O_3+h\nu\rightarrow O(1D)+O_2$  (top axis, blue)  $NO_2+h\nu\rightarrow O+NO$  (bottom axis, red) for zero pollution (solid) and Mexico City in the years 2000 (dashed) and 2019 (dotted)

An issue that is beginning to gain relevance in radiative balance models is the influence of a group of organic compounds known as “brown carbon” that are capable of strongly absorbing in the UV region.<sup>61</sup> Some of these compounds are related to emissions from local and regional wildfires.<sup>62</sup> Mexico City is frequently exposed to regional fire smoke transport during the dry part of the year (November to May)<sup>63</sup>, which sporadically modify the optical properties of the aerosols.<sup>64</sup> This could partly explain the relatively minor reductions in PM<sub>10</sub> (see Fig. 7), compared to the larger reductions of CO, NO<sub>2</sub>, and O<sub>3</sub> that are more directly related to urban activities, as well as some of the seasonal asymmetry seen in Fig. 3.

The UVI is specific to wavelengths mainly in the 300-320 nm range, and so the question remains whether these results can be applied at longer UV wavelengths, e.g. those important for NO<sub>2</sub> photolysis (<420 nm). Absorption by SO<sub>2</sub> and O<sub>3</sub> vanishes for wavelengths larger than about 330 nm, while NO<sub>2</sub> photolysis is mostly driven by UV-A radiation and typical aerosols optical depth decrease with wavelength. These changes can easily be modeled, but

289 unfortunately far fewer measurements of these longer wavelengths are available in Mexico  
290 City or elsewhere.

291 Two decades of observations in Mexico City demonstrate unequivocally that air pollution  
292 reduces UV radiation at the ground. The ground-based observations are well below values  
293 derived from satellite-based observations. Although ideally both data sets should match,  
294 the satellite has a limitation to seeing boundary layer absorbers. When typical values of  
295 the pollutants: aerosols, tropospheric ozone, and to a lesser extent NO<sub>2</sub> and SO<sub>2</sub>, are in-  
296 cluded in a model (e.g. TUV), the differences between satellite-derived and ground-based  
297 measured values are explained and can be attributed quantitatively to individual observed  
298 pollutants. Long term improvements in air quality over the last two decades, are accompa-  
299 nied by statistically significant increases in the observed UVI, again in good agreement with  
300 the model-predicted changes.

Table 4: Contributions of individual pollutants to the 2000-2019 UV Index changes. Baseline calculation for 2000 conditions (AOD = 0.7, O<sub>3</sub> = 70 ppb, NO<sub>2</sub> = 40 ppb, SO<sub>2</sub> = 20 ppb). Individual pollutant contributions are estimated by adjusting each pollutant, one at the time, to its 2019 value (AOD = 0.5, O<sub>3</sub> = 50 ppb, NO<sub>2</sub> = 20 ppb, SO<sub>2</sub> = 1 ppb), while maintaining the others at their 2000 value.

Pollutant	UVI Change
AOD	0.8
O <sub>3</sub>	0.4
NO <sub>2</sub>	0.4
SO <sub>2</sub>	0.5

301 The reductions in surface UV radiation with respect to an ideally clear atmosphere –  
302 by nearly 40% in 2000 and still 20% in 2020 – are large, both within the context of hu-  
303 man UV exposure and air quality mitigation. In urban areas where ozone production scales  
304 proportionally with UV levels and with volatile organic compound (VOC) emissions (the  
305 VOC-limited regime), a 10% increase in BL average photolysis rates means that VOC emis-  
306 sions will need to be reduced by 10% to meet the same goals, or else successful reductions  
307 in aerosols would lead to unwanted UV-driven increases in O<sub>3</sub>. Such UV changes must be  
308 considered carefully in air quality mitigation strategies. For human exposure, a 20% increase

309 in UV irradiances over two decades should be seen as a non-negligible public health issue  
310 requiring some reassessment of preventive behaviors to minimize the risk of skin cancer,  
311 cataract, and other UV-related health effects. The efforts that Mexico City has made to  
312 improve air quality have reduced levels of most air pollutants. Nevertheless, they caused an  
313 increase in UV radiation that reaches the surface.

314 Finally, based on our results, the solar radiation monitoring network could be improved  
315 by adding observation sites within or close to the Valley of Mexico, with minor influences of  
316 the urban plume (e. g., Amecameca; latitude: 19.13°N, longitude: 99.76°W, elevation: 2420  
317 m asl), and the complementing of sensors in existing monitoring sites that are at elevations  
318 above the urban boundary layer like Ajusco (AJU, elevation: 2953 m asl) or Instituto de  
319 Investigaciones Nucleares (INN, elevation: 3082 m asl). These sites would provide valuable  
320 observations to assess quantitatively the effects of urban pollution on solar radiation levels.

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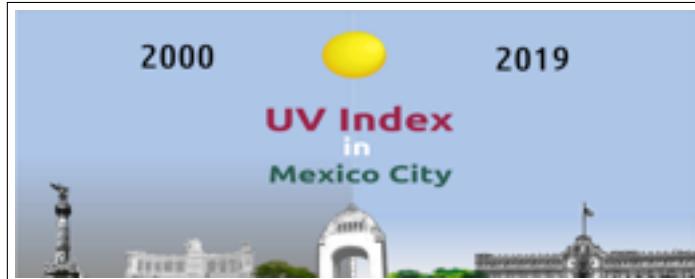
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533 Graphical TOC Entry

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