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5 **Retrospective assessment of pregnancy exposure to particulate matter from desert dust**
6 **on a Caribbean island: could satellite-based aerosol optical thickness be used as an**
7 **alternative to ground PM₁₀ concentration?**

8

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10

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18 **Abstract**

19 Desert dust transported from the Saharan-Sahel region to the Caribbean Sea is responsible for
20 peak exposures of particulate matter (PM). This study explored the potential added value of
21 satellite aerosol optical thickness (AOT) measurements, compared to the PM concentration at
22 ground level, to retrospectively assess exposure during pregnancy. MAIAC MODIS AOT
23 retrievals in blue band (AOT₄₇₀) were extracted for the French Guadeloupe archipelago. AOT₄₇₀
24 values and PM₁₀ concentrations were averaged over pregnancy for 906 women (2005-2008).
25 Regression modeling was used to examine the AOT₄₇₀-PM₁₀ relationship during pregnancy, and
26 test the association between dust exposure estimates and preterm birth. Moderate agreement
27 was shown between mean AOT₄₇₀ retrievals and PM₁₀ ground-based measurements during
28 pregnancy (R²=0.289). The magnitude of the association between desert dust exposure and
29 preterm birth tended to be lower using the satellite method compared to the monitor method.
30 The latter remains an acceptable trade-off between epidemiological relevance and exposure
31 misclassification, in areas with few monitoring stations and complex topographical/
32 meteorological conditions, such as tropical islands.

33

34 **Keywords:** desert dust; aerosol optical thickness; particulate matter $\leq 10 \mu\text{m}$; satellite imagery;
35 MAIAC algorithm; epidemiology

36 **Declaration**

37 **Ethics approval and consent to participate**

38 The TIMOUN study was approved by the Guadeloupean Ethics Committee for studies
39 involving human subjects. Written informed consent was provided by each participant.

40

41 **Consent for publication**

42 Not applicable.

43

44 **Availability of data and materials**

45 The dataset used and analyzed during the current study is available from the corresponding
46 author on reasonable request.

47

48 **Competing interests**

49 The authors declare that they have no competing interests.

50

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54

55 **Author contributions**

56 S.T. analyzed and interpreted the data; E.U. performed the satellite data management and
57 processing; C.R. provided the air quality data; JFV conceived and planned the study,
58 interpreted the data, and prepared the first draft of the manuscript on which all coauthors
59 commented.

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65

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70 Jean-Francois Viel.

71 **Introduction**

72

73 On a global scale, most atmospheric particles are emitted by natural sources, mineral dust being
74 the second most abundant component (after sea-spray derived aerosols). The Sahara and Sahel
75 regions in Northern Africa generate the most dust in terms of emissions (Querol et al. 2019).
76 Most African dust particles travel westwards over the Atlantic over long distances and affect
77 areas in the Caribbean and the Americas, generating peak exposures to particulate matter (PM)
78 in these downwind regions. The dust plume extension varies throughout the year depending on
79 the displacement of the Inter-Tropical Convergence Zone (Prospero et al. 1981), inducing
80 marked seasonality (emissions peaking in spring and summer). Desert dust typically mixes with
81 locally- or regionally-emitted PM, but the median desert dust mass diameter was found to be
82 3.2 μm in Barbados and 3.5 μm in Puerto Rico (Reid et al. 2003).

83 Accurately assessing desert dust exposure in the Caribbean region is challenging due to
84 sparse ground monitoring networks. Conversely, satellite remote sensing, in terms of aerosol
85 optical thickness (AOT), has provided new methods to monitor PM air quality with fine spatial
86 and temporal resolution, since the launch of the Moderate Resolution Imaging
87 SpectroRadiometer (MODIS) (Xiao et al. 2017). AOT is based on the impedance of light
88 transmission by the absorption or scattering of light by aerosols through the vertical column of
89 the atmosphere from the ground to the satellite sensor (Duncan et al. 2014). However, satellite
90 data may be compromised by the non-random absence due to cloud cover, high surface
91 reflectance (desert and snow-covered surfaces), and extremely high aerosol loading, which can
92 be misclassified as clouds (Lee et al. 2012; Di et al. 2016). Thus, AOT data may not be available
93 for a large fraction of days (non-retrieval days).

94 A recent algorithm (released in 2018), called "Multi-Angle Implementation of Atmospheric
95 Correction" (MAIAC C6.1), has greatly improved MODIS AOT retrievals with a more accurate
96 detection of cloudy and clear-sky areas, enabling it to produce AOT data for partially cloudy
97 days (Lyapustin et al. 2018). It uses time series (up to 16 days) analysis to exploit multiangle
98 viewing effects and image processing to derive the surface bidirectional reflectance function.
99 MAIAC relies on dynamic land-water-snow classification from daily observations to select the
100 proper processing path. MAIAC AOT retrieval in blue band (AOT_{470}) is a unitless value ranging
101 from 0 (indicating extremely clear weather with maximum visibility) to a maximum of 4.0. The
102 fine spatial resolution (1 km) and high accuracy of MAIAC AOT_{470} makes it possible to
103 characterize local-scale aerosol heterogeneity.

104 The derivation of surface PM from satellite AOT is always challenging because of the effect
105 of various factors (such as aerosol composition, relative humidity, the vertical profile of the
106 particle concentration, and the altitude of the aerosol layer) (Duncan et al. 2014). The most
107 widely used method is empirical analysis, in which in situ PM measurements are regressed with
108 the corresponding satellite AOT value, adjusting for meteorological data and land-use variables,
109 in the framework of linear mixed effects models. MAIAC AOT retrievals have been used to
110 estimate ground PM distributions and support air pollution epidemiological studies in the USA
111 and Mexico (Di et al. 2016; Hu et al. 2014; Just et al. 2015; Strickland et al. 2016). However,
112 the AOT-PM relationship is spatially and temporally inhomogeneous. Thus, continued research
113 is needed for various regions of the world, especially in locations where few surfaced-based
114 PM measurements have been obtained, to date (Chen et al. 2013).

115 We recently showed an association between maternal exposure during pregnancy to desert
116 dust and preterm birth in the French Guadeloupe archipelago (an outermost region of the
117 European Union situated in the Caribbean basin) (Viel et al. 2019). We assessed exposure

118 through $PM \leq 10 \mu m$ (PM_{10}) concentrations recorded at the sole (urban) background air quality
119 monitoring station of Guadeloupe, located in Pointe-à-Pitre (central part of the Guadeloupe
120 archipelago), regardless of the location of the woman's residence. However, spatial
121 heterogeneity in terms of exposure can be supposed, as concentrations may be lower on the
122 island's leeward (i.e., western) side, which is partially sheltered from trade winds by the La
123 Soufrière volcano (1,467 m high, located in Basse-Terre, the south-western part of
124 Guadeloupe). This presumed spatial variability of air pollutants related to topography (and also
125 local micro sources) may not be captured by a single background air quality monitoring station,
126 and non-differential misclassification may occur.

127 To our knowledge, only two other studies have relied on satellite AOT data to estimate
128 average exposure to $PM_{2.5}$ during pregnancy, but at the lower spatial resolution of a 10 x 10-
129 km grid (across Connecticut and Massachusetts – USA), using daily calibration of PM ground
130 measurements from a dense network of monitoring stations (Kloog et al. 2012; Hyder et al.
131 2014). The Guadeloupe archipelago poses, however, several unique challenges in terms of air-
132 pollution assessment, both topographically and meteorologically. Land use is heterogeneous,
133 and the islands feature a complex topography (abrupt elevation changes and rugged terrain) and
134 a humid subtropical climate (tempered by trade winds), with frequent cloud cover and a long
135 rainy season (from July to November).

136 This feasibility study explored the potential added value of MAIAC AOT retrievals,
137 compared to the PM concentration at ground level, to retrospectively assess exposure during
138 pregnancy for epidemiological purposes in a tropical island environment.

139

140 **Materials and methods**

141

142 **Study domain and population**

143

144 Guadeloupe, with a population of 450,000 inhabitants, is an archipelago located in the Leeward
145 Islands in the Caribbean. Pregnancies of the 909 women enrolled in the TIMOUN mother-child
146 cohort occurred during the time period from March 30, 2004 to July 30, 2007 (last delivery on
147 April 28, 2008) (Viel et al. 2019). Home addresses during pregnancy were geocoded, showing
148 a median distance from the air quality monitoring station of 13.03 km, as the crow flies (Fig. 1).

149

150 **Ground PM measurements**

151

152 The assessment of exposure has been fully described elsewhere (Viel et al. 2019). Briefly, mean
153 daily PM₁₀ concentrations ($\mu\text{g}/\text{m}^3$) recorded at the Pointe-à-Pitre monitoring station were
154 provided by Gwad'Air (the official air quality monitoring agency for Guadeloupe) from 2005
155 to 2008 (no data were available before 2005). PM₁₀ concentrations were measured using the
156 Thermo Scientific Tapered Element Oscillating Microbalance (TEOM) models 1400ab and
157 1400-FDMS. The TEOM is widely used in air quality programs in Europe and the United States
158 and qualifies as a U.S. Environmental Protection Agency equivalent method
159 (<http://www.epa.gov/ttn/amtic/criteria.html>). No PM_{2.5} concentrations were measured and no
160 other air quality monitoring station was operating in the Guadeloupe archipelago during this
161 period.

162

163 **MODIS AOT retrievals**

164

165 This study relied on MAIAC AOT₄₇₀ retrievals from both the Aqua and Terra satellites. We
166 used the MCD19A2 Version 6 data product, a MODIS Terra and Aqua combined MAIAC AOT
167 gridded dataset, containing 13 daily atmospheric properties at 1 km pixel resolution, in 1,200 x
168 1,200-km local tiles. MCD19A2 data were provided by the NASA Center for Climate
169 Simulations for the local tile HH12VV07 for the years 2005 to 2008.

170 AOT₄₇₀ retrievals were extracted from each atmospheric properties file. Pixel maps were
171 orthorectified using NASA SeaDAS 7.5.1 software, the Global Earth Topography and Sea
172 Surface Elevation (at 30 arcsecond resolution - GETASSE30) model, the linear polynomial
173 method, and five photo-identified ground control points (extracted from ESRI World Imagery).
174 Positional accuracy was assessed through the root-mean-square error (RMSE), representing an
175 averaged difference between the rectified imagery and ground truth. RMSE was 0.00812°
176 (901.6 m) in latitude, and 0.00996° (1108.7 m) in longitude, respecting the general rule of an
177 RMSE equivalent to the size of a pixel in the output image. We applied a sliding-window spatial
178 filter, replacing the center value in the 3 x 3 window with the median of the nine pixel values
179 in the window.

180 As a result, we obtained daily Aqua and Terra AOT₄₇₀ retrievals for the terrestrial part of the
181 Guadeloupe archipelago (1,054 pixels) for the period from 2005 to 2008. We primarily used
182 the Aqua AOT₄₇₀ measurements, estimating their missing values from the Terra AOT₄₇₀ values
183 (if available) using an adjustment factor. This factor was equal to the ratio of the average Aqua
184 AOT₄₇₀ to Terra AOT₄₇₀ for the days for which both the Aqua and Terra measurements were
185 available (Lee et al. 2012).

186 Finally, we overlaid a map of the mothers' residence onto the grid cell maps to obtain a
187 median smoothed AOT₄₇₀ value for each place of residence and each day. To avoid temporal

188 mismatch between the PM_{10} and AOT_{470} values, the time period spanned from January 1, 2005
189 (first PM_{10} concentration available) to April 28, 2008 (last delivery in the TIMOUN cohort)
190 (1,214 days).

191

192 **Statistical analyses**

193

194 We averaged the AOT_{470} values and PM_{10} concentrations over each pregnancy to assess desert-
195 dust exposure (for the 234 pregnancies which started in 2004, the means were calculated for
196 their 2005 component). Then, we considered topographical and land-cover contrasts to control
197 for spatial variability of the AOT_{470} values for exposure. First, we split the Guadeloupe territory
198 into the windward and leeward sides of La Soufrière volcano to investigate the potential effect
199 of trade winds. Second, we distinguished the capital city (Pointe-à-Pitre) and its suburbs (as the
200 city spreads beyond the old municipal boundary lines) from the rest of Guadeloupe because a
201 recent study showed lower correlations between MAIAC AOT retrievals and ground-truth data
202 over bright areas than those over vegetated areas (Martins et al. 2017). We used linear
203 regression modeling with average AOT_{470} values during pregnancy as the dependent variable
204 and the geographical contrast (windward vs. leeward) as the independent variable. We
205 introduced time (autumn-winter semester vs. spring-summer semester of each year of the study
206 period, defined a priori as the semester including week 14 of the corresponding pregnancy) and
207 space (geographical contrast) x time (semester) interaction terms in multivariate models, as
208 pregnancies occurred throughout the study period and as desert-dust episodes can vary between
209 years. We created a similar model but with the urbanization contrast as the independent
210 variable. Finally, the association between the average AOT_{470} value and PM_{10} concentration
211 during pregnancy was examined by univariate linear regression.

212 As external validation, a multivariate logistic regression model was used to estimate the
213 association between the AOT-based desert dust exposure and preterm birth while adjusting for
214 numerous individual risk factors, as in our previous PM₁₀-based analysis (place of inclusion,
215 maternal age, marital status, years of education, body mass index, parity, prior preterm birth,
216 prior miscarriage, prior induced abortions, lupus, asthma, chronic hypertension, gestational
217 weight gain, gestational hypertension, gestational diabetes, urinary tract infection, sex of the
218 newborn) (Viel et al. 2019). To compare the impact of this exposure proxy with the PM₁₀-based
219 proxy, we calculated the odds ratios (ORs) per standard deviation (SD) change (0.037).

220 Statistical analyses were performed using R software (R Foundation for Statistical
221 Computing, Vienna, Austria, 2020).

222

223 **Results**

224

225 **Descriptive results**

226

227 During the 1,214-day study period, PM₁₀ concentrations ranged from 9.3 to 157.0 µg/m³
228 (median: 21.0 µg/m³), with data missing for 55 days because of routine maintenance or
229 mechanical failure. Of the 1,279,556 expected AOT₄₇₀ values (1,054 pixels x 1,214 days),
230 only 252,630 were retrieved (19.7%), ranging from 0.002 to 0.964 (median: 0.199).

231 Plotting of all daily mean values against the day-of-the-year yielded much the same
232 irregular picture for both series (Fig. 2). The month-to-month variation (reflecting more
233 frequent dust outbreaks in the late spring – early summer) was not similar between years.

234 Averaging the available daily measures over the entire pregnancy showed the mean PM₁₀
235 concentrations to range from 13.2 to 34.9 µg/m³ (median: 28.2 µg/m³) and the mean AOT₄₇₀

236 values to range from 0.042 to 0.283 (median: 0.189). Three women were excluded because of
237 childbirth in early January 2005 and the absence of daily AOT₄₇₀ estimates during this short
238 period of observation.

239

240 **Spatial variability**

241

242 The mean AOT₄₇₀ values during pregnancy, according to the place of residence of the mothers,
243 are presented in Table 1. We plotted the mean AOT₄₇₀ retrievals during pregnancy, over
244 Guadeloupe across time to examine both spatial variability and potential space x time
245 interactions (Fig. 3).

246 Univariate analysis showed higher values on the windward (eastern) side of the island ($p <$
247 10^{-4}). However, the spatial difference was no longer found when adjusting for time period ($p =$
248 0.30), whereas the difference between all semesters was significant ($p < 10^{-15}$), as well as three
249 space x semester interactions ($p < 0.05$). Finally, we found no significant difference in the mean
250 AOT₄₇₀ values when considering urbanization (Table 1).

251

252 **AOT₄₇₀-PM₁₀ association during pregnancy**

253

254 Average AOT₄₇₀ values showed moderate agreement with average PM₁₀ ground-based
255 measurements (both calculated during pregnancy), with a squared correlation coefficient (R^2)
256 of 0.289 (slope 0.006, $p < 10^{-15}$) (Fig. 4). The offset (equal to 0.005) did not differ
257 significantly from zero ($p = 0.50$).

258

259 **Associations between preterm birth and AOT₄₇₀-based exposure estimates**

260

261 The crude and adjusted associations between AOT₄₇₀-based exposure estimates and preterm
262 birth were very similar and elevated, but not significantly (OR = 1.19, 95% CI = 0.98 - 1.46,
263 $p = 0.08$, and OR = 1.18, 95% CI = 0.95 - 1.47, $p = 0.14$, in univariate model and multivariate
264 model, respectively).

265

266 **Discussion**

267

268 Here, we used recent high-resolution (1 km) AOT MODIS data based on the MAIAC
269 algorithm to assess past exposure (2005-2008) of pregnant women to desert dust and to check
270 its accuracy for epidemiological purposes.

271 The mean coverage of AOT values in Guadeloupe was poor (19.7%), due to cloud cover
272 and unfavorable surface conditions. This is similar to the fraction (19.8%) reported for
273 another complex terrain (Switzerland) (de Hoog et al. 2018) and slightly lower than results
274 reported for Taiwan (a much broader, more highly populated, and more industrialized island
275 than Guadeloupe but sharing a similar climate), with a mean overall coverage of Terra and
276 Aqua AOT values of 23.0% (Jung et al. 2018). Despite continuous improvements of cloud
277 detection and atmospheric corrections over inlands and coastal water, missing MAIAC AOT
278 values due to cloud cover and bright surfaces is still a major limitation and challenge. The
279 MAIAC algorithm consistently misses a specific type of cloud cover (moderately thin and
280 homogeneous cumulus) over water, generating high AOT values (Lyapustin et al. 2018), and
281 MAIAC retrievals over bright surfaces are generally poorer than those over vegetated areas
282 (Chen et al. 2013). The high concentration of the Guadeloupean population in coastal areas is
283 another challenge. Indeed, because of the inherent uncertainties of gridding on the coastline

284 (and the different land/water processing paths), the area within 2 km of the coastline may
285 contain frequent artifacts in cloud mask (usually over-detection) and AOT (higher values)
286 (Lyapustin et al. 2018), potentially biasing individual exposure estimates.

287 In Guadeloupe, the maximum AOT value was 0.964, in agreement with results from South
288 America, where 98% of AOT values ranged from 0.01 to 1.0 (Martins et al. 2017).
289 Unfortunately, we could not use aerosol optical measurements from the local AERONET site
290 as "ground trust" in satellite retrieval calibration and aerosol characterization because of
291 numerous missing data during the study period (695 of 1214 days).

292 Consistent with our epidemiology-oriented approach, also shared by other researchers
293 (Kloog et al. 2012; Hyder et al. 2014), available daily AOT₄₇₀ estimates were averaged to
294 pregnancy values for the place of residence of each woman (with some uncertainty because of
295 the missing retrievals). We found little evidence of geographical variability for AOT₄₇₀
296 retrievals during pregnancy over Guadeloupe when considering a windward/leeward or
297 urbanization contrast. The correlation found in this study ($R = 0.537$) between average
298 AOT₄₇₀ retrievals and PM₁₀ ground-based measurements during pregnancy was moderate.
299 This could be partially due to the fact that satellite-derived AOT is a measure of light
300 attenuation in the column, which is affected by ambient conditions, whereas PM₁₀ is a
301 measure of dry particle mass near the surface. However, the regression line passing through
302 the origin suggests that the same phenomenon is measured by both metrics.

303 Quantifying the fraction of PM₁₀ concentrations attributed to the African dust outbreak for
304 the days with identified African influence was unfortunately out of reach because particle
305 filters were no longer available for the study period. However, Guadeloupe anthropogenic
306 particle pollution is low (approximately 20 $\mu\text{g}/\text{m}^3$), because of the absence of heavy industries
307 and the year-round presence of trade winds. As a result, desert dust natural pollution is the

308 main factor affecting PM₁₀ data (Euphrasie-Clotilde et al. 2017). This is the reason why the
309 local air quality monitoring agency classifies desert dust episodes according to PM₁₀
310 concentrations: light, 28–38 µg PM₁₀/m³; moderate, 39–54 µg PM₁₀/m³; intense, ≥ 55 µg
311 PM₁₀/m³ (Viel et al. 2019).

312 Unfortunately, a number of geo-climatic features distinguish the Guadeloupe archipelago
313 (territory of rather limited size, complex topography, humid sub-tropical weather and
314 maritime surroundings), precluding any comparison with results reported in Connecticut and
315 Massachusetts – USA (Kloog et al. 2012; Hyder et al. 2014). In Guadeloupe, the magnitude of
316 the association between desert dust exposure and preterm birth tended to be lower using the
317 satellite method compared to the monitor method. Indeed, the crude and adjusted ORs per SD
318 change for the PM₁₀-based proxy were significantly increased (OR = 1.36, 95% CI 1.07, 1.73,
319 $p = 0.01$, and OR 1.40, 95% CI 1.08, 1.81, $p = 0.01$, respectively) (Viel et al. 2019). One
320 explanation could be that when AOT retrieval is successful, the variability of PM
321 concentrations is dominated by its temporal component and concentration levels tend to be
322 spatially smooth (Liu et al. 2009). Because of the high proportion of non-retrieval days
323 (80.3%), the satellite method cannot compete regarding the temporal dimension, attenuating
324 associations towards the null.

325

326 **Conclusion**

327

328 Given the above-mentioned limitations, the AOT-based proxy does not appear to be more
329 appropriate than the PM-based proxy to retrospectively assess the exposure of pregnant
330 women to desert dust in the Caribbean. We believe that the conventional estimation of PM₁₀
331 exposure (assigning ground-level measurements to populations within a specified distance of

332 the monitoring station) remains an acceptable trade-off between epidemiological relevance
333 and exposure misclassification, given the specific local conditions of the Guadeloupe, the
334 spatial homogeneity of the AOT₄₇₀ retrievals, and the short median distance, as the crow flies,
335 between the places of residence and the monitoring station. More generally, estimating
336 historical levels of PM concentrations on a small spatial and temporal scale to support
337 epidemiological studies on the air pollution related health burden is still challenging, at least
338 in areas with few monitoring stations and complex topographical/ meteorological conditions,
339 such as tropical areas.

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Table 1 Mean AOT₄₇₀ values during pregnancy and comparisons according to the place of residence of pregnant women (n = 906, mother-child cohort, 2005-2008, Guadeloupe)

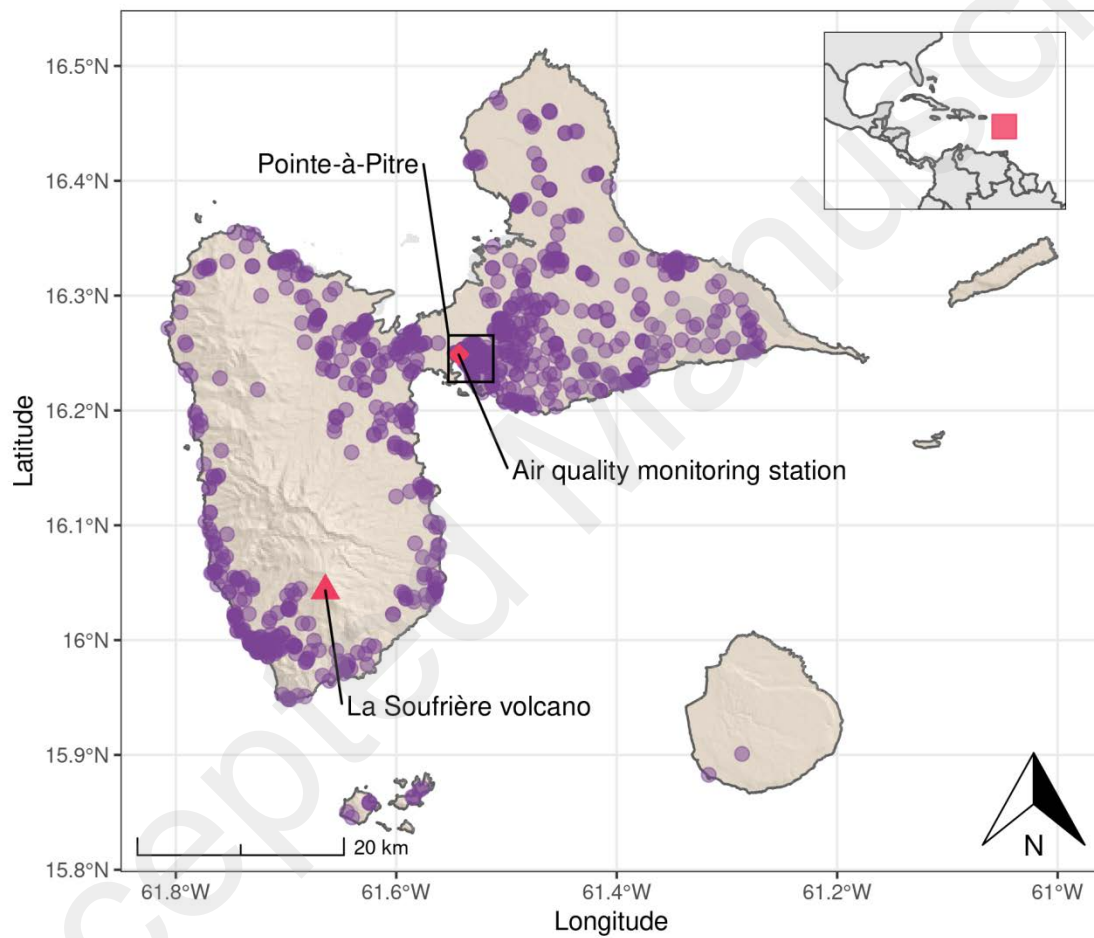
Place of residence	mean (sd)	Univariate analysis			Multivariate analysis ^a		
		β coefficient	95% CI	<i>p</i> -value	β coefficient	95% CI	<i>p</i> -value
Topography							
windward side	0.189 (0.038)	Ref.	-		Ref.	-	
leeward side	0.180 (0.035)	-0.009	-0.017, -0.006	< 10 ⁻⁴	-0.002	-0.017, -0.055	0.81
Urbanization							
capital city and suburbs	0.186 (0.038)	Ref.	-		Ref.	-	
rest of Guadeloupe	0.184 (0.028)	-0.003	-0.010, 0.004	0.40	-0.016	-0.036, 0.003	0.11

Aerosol optical thickness (AOT₄₇₀), confidence interval (CI).

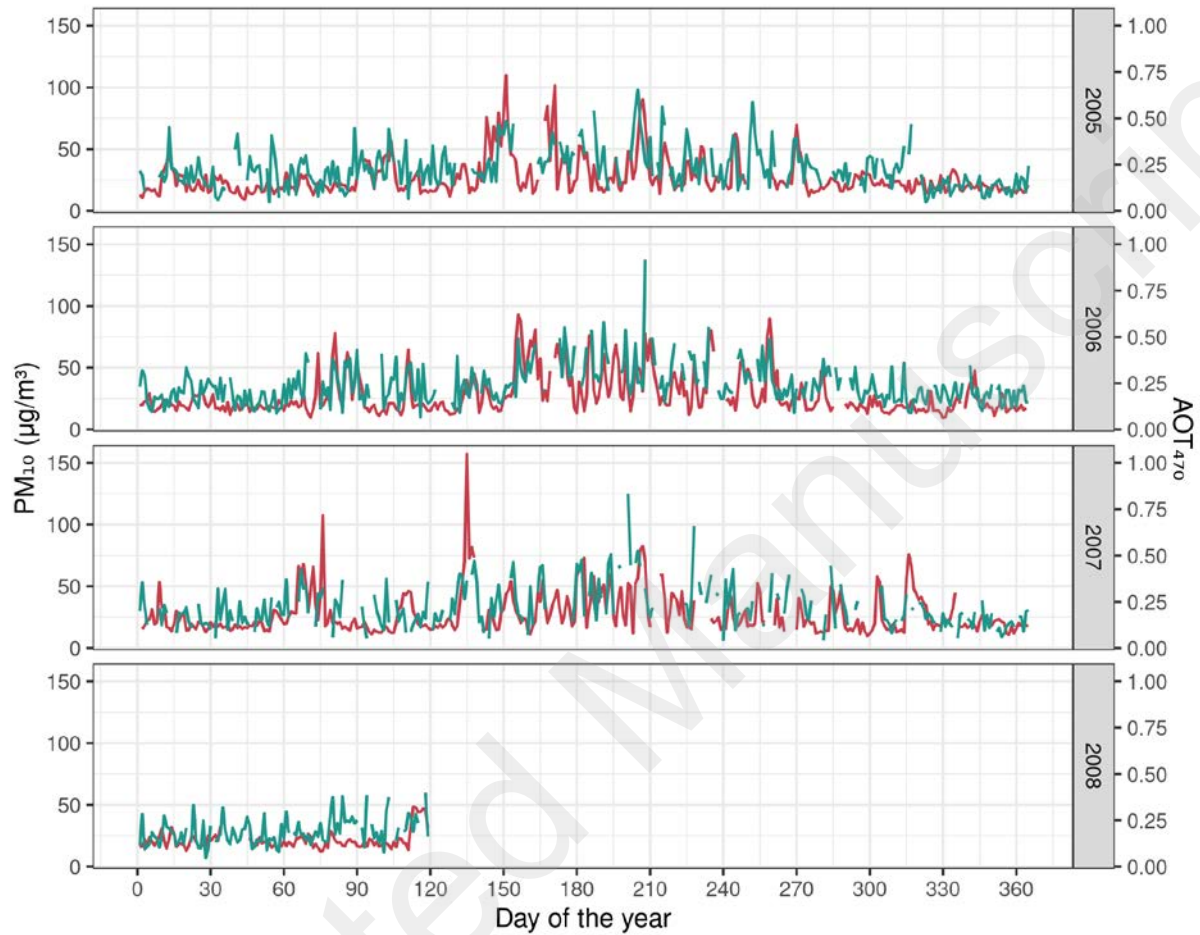
^a adjusting for time period (semesters) and space (geographical contrast) x time (semesters) interactions

405 **Fig. 1** Geographical features of the Guadeloupe archipelago and places of residence of
406 pregnant women (n=906, mother-child cohort, 2005-2008)

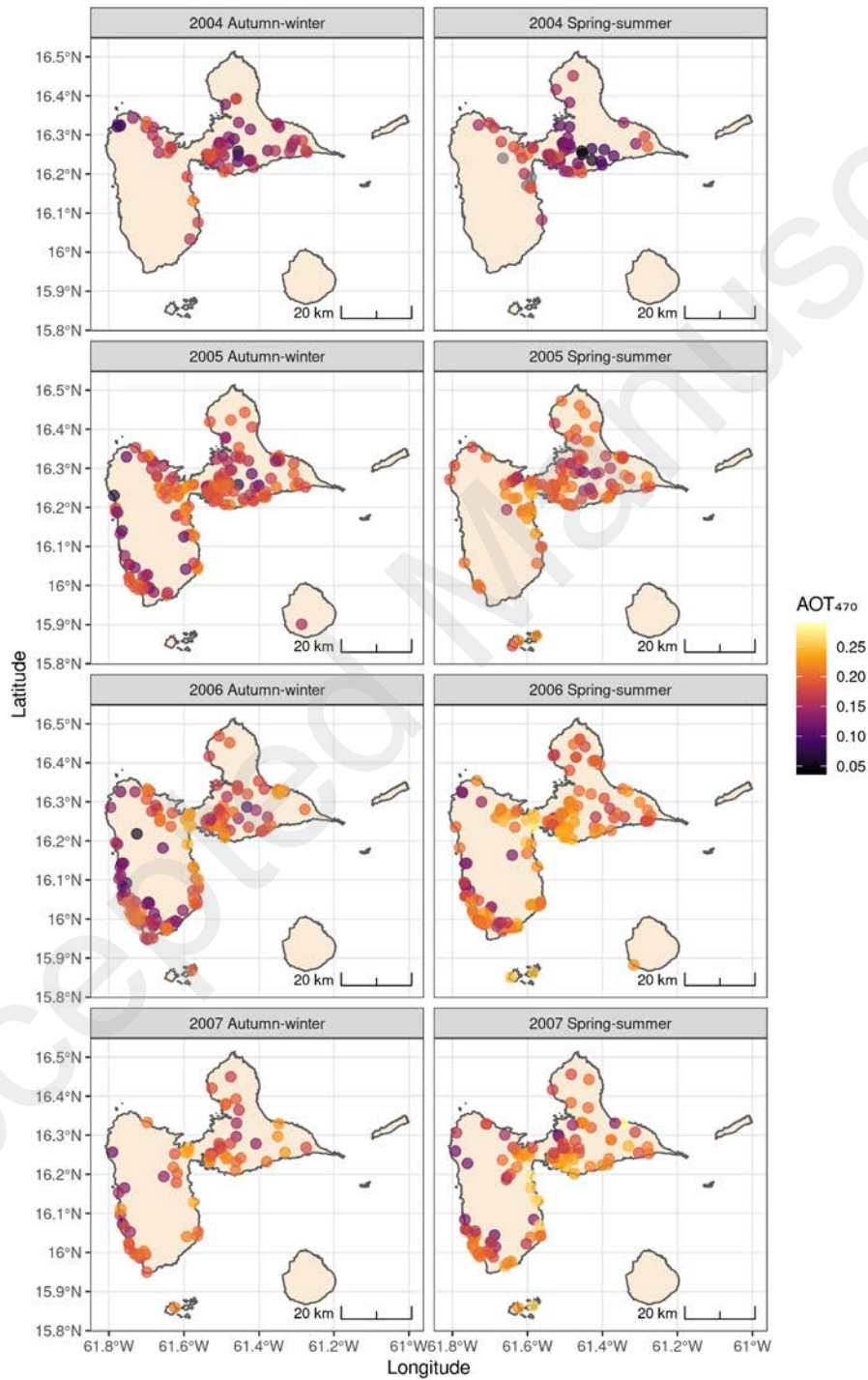
407 Each circle represents a mother's place of residence. The location of the air quality monitoring station is indicated
408 by the diamond symbol. The location of the La Soufrière volcano is indicated by the triangle. Pointe-à-Pitre city
409 and its suburbs are identified by the black rectangle.



410 **Fig. 2** Time series of average daily PM₁₀ concentrations (red line) and average daily AOT₄₇₀
411 values calculated from 1,054 1x1 km pixels (green line) (2005-2008, Guadeloupe)



412 **Fig. 3** Average AOT₄₇₀ retrievals during pregnancy according to the mother's place of residence
413 (at week 14 of pregnancy) and time period (n=906, mother-child cohort, Guadeloupe)



414 **Fig. 4** Linear regression between mean AOT₄₇₀ values and ground-based PM₁₀ concentrations
415 ($\mu\text{g}/\text{m}^3$) during pregnancy (n = 906, 2005-2008, Guadeloupe)

