

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

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1	Stéphane Tuffier <sup>1</sup> , Erika Upegui <sup>2</sup> , Christina Raghoumandan <sup>3</sup> , Jean François Viel <sup>1*</sup> for the
2	BrumiSaTerre research group
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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 PM <sub>10</sub> concentration?
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11	<sup>1</sup> Univ Rennes, CHU Rennes, Inserm, EHESP, Irset (Institut de recherche en santé,
12	environnement et travail) - UMR_S 1085, F-35000 Rennes, France
13	<sup>2</sup> Faculty of Engineering, Universidad Distrital Francisco José de Caldas, CP 110001 Bogota,
14	Colombia
15	<sup>3</sup> Gwad'Air, Air quality monitoring agency, F-97170 Petit-Bourg, France
16	
17	* Correspondence: jean-francois.viel@univ-rennes1.fr, phone: +33 299 289 827

#### 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 (AOT<sub>470</sub>) were extracted for the French Guadeloupe archipelago. AOT<sub>470</sub> 24 values and PM<sub>10</sub> concentrations were averaged over pregnancy for 906 women (2005-2008). 25 Regression modeling was used to examine the  $AOT_{470}$ -PM<sub>10</sub> relationship during pregnancy, and 26 test the association between dust exposure estimates and preterm birth. Moderate agreement 27 was shown between mean AOT<sub>470</sub> retrievals and PM<sub>10</sub> ground-based measurements during 28 pregnancy (R<sup>2</sup>=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.

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Keywords: desert dust; aerosol optical thickness; particulate matter ≤ 10 µm; satellite imagery;
 MAIAC algorithm; epidemiology

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

- 67 BrumiSaTerre research group: Gulen Ayhan, Séverine Ferdinand, Céline Garbin, Stéphanie
- 68 Guyomard, Philippe Kadhel, Fabien Mercier, Léah Michineau, Luc Multigner, Philippe
- 69 Quénel, Christian Raghoumandan, Antoine Talarmin, Stéphane Tuffier, Erika Upegui, and
- 70 Jean-Francois Viel.

## 71 Introduction

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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). Most African dust particles travel westwards over the Atlantic over long distances and affect 76 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 the atmosphere from the ground to the satellite sensor (Duncan et al. 2014). However, satellite 89 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<sub>470</sub>) 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<sub>470</sub> 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).

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

118 through  $PM \le 10 \ \mu m$  (PM<sub>10</sub>) 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 Soufrière volcano (1,467 m high, located in Basse-Terre, the south-western part of 123 124 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).

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

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140 Materials and methods

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

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## 150 Ground PM measurements

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152 The assessment of exposure has been fully described elsewhere (Viel et al. 2019). Briefly, mean daily  $PM_{10}$  concentrations ( $\mu g/m^3$ ) recorded at the Pointe-à-Pitre monitoring station were 153 154 provided by Gwad'Air (the official air quality monitoring agency for Guadeloupe) from 2005 155 to 2008 (no data were available before 2005).  $PM_{10}$  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 qualifies as a U.S. Environmental Protection Agency equivalent method and 159 (http://www.epa.gov/ttn/amtic/criteria.html). No PM<sub>2.5</sub> concentrations were measured and no 160 other air quality monitoring station was operating in the Guadeloupe archipelago during this 161 period.

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## 163 MODIS AOT retrievals

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This study relied on MAIAC AOT<sub>470</sub> retrievals from both the Aqua and Terra satellites. We
used the MCD19A2 Version 6 data product, a MODIS Terra and Aqua combined MAIAC AOT
gridded dataset, containing 13 daily atmospheric properties at 1 km pixel resolution, in 1,200 x
1,200-km local tiles. MCD19A2 data were provided by the NASA Center for Climate
Simulations for the local tile HH12VV07 for the years 2005 to 2008.

170 AOT<sub>470</sub> 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  $3 \times 3$  window with the median of the nine pixel values 179 in the window.

As a result, we obtained daily Aqua and Terra  $AOT_{470}$  retrievals for the terrestrial part of the Guadeloupe archipelago (1,054 pixels) for the period from 2005 to 2008. We primarily used the Aqua  $AOT_{470}$  measurements, estimating their missing values from the Terra  $AOT_{470}$  values (if available) using an adjustment factor. This factor was equal to the ratio of the average Aqua  $AOT_{470}$  to Terra  $AOT_{470}$  for the days for which both the Aqua and Terra measurements were available (Lee et al. 2012).

Finally, we overlaid a map of the mothers' residence onto the grid cell maps to obtain a
median smoothed AOT<sub>470</sub> value for each place of residence and each day. To avoid temporal

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

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192 Statistical analyses

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194 We averaged the AOT<sub>470</sub> values and PM<sub>10</sub> 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<sub>470</sub> 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 PM <sub>10</sub> -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 $PM_{10}$ -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
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225	Descriptive results
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227	During the 1,214-day study period, $PM_{10}$ concentrations ranged from 9.3 to 157.0 $\mu$ g/m <sup>3</sup>
228	(median: 21.0 $\mu$ g/m <sup>3</sup> ), with data missing for 55 days because of routine maintenance or
229	mechanical failure. Of the 1,279,556 expected AOT <sub>470</sub> 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 $PM_{10}$
235	concentrations to range from 13.2 to 34.9 $\mu$ g/m <sup>3</sup> (median: 28.2 $\mu$ g/m <sup>3</sup> ) and the mean AOT <sub>470</sub>

values to range from 0.042 to 0.283 (median: 0.189). Three women were excluded because of
childbirth in early January 2005 and the absence of daily AOT<sub>470</sub> estimates during this short
period of observation.

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#### 240 Spatial variability

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The mean AOT<sub>470</sub> values during pregnancy, according to the place of residence of the mothers, are presented in Table 1. We plotted the mean AOT<sub>470</sub> retrievals during pregnancy, over Guadeloupe across time to examine both spatial variability and potential space x time interactions (Fig. 3).

Univariate analysis showed higher values on the windward (eastern) side of the island ( $p < 10^{-4}$ ). However, the spatial difference was no longer found when adjusting for time period (p = 0.30), whereas the difference between all semesters was significant ( $p < 10^{-15}$ ), as well as three space x semester interactions (p < 0.05). Finally, we found no significant difference in the mean AOT<sub>470</sub> values when considering urbanization (Table 1).

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252 AOT<sub>470</sub>-PM<sub>10</sub> association during pregnancy

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Average AOT<sub>470</sub> values showed moderate agreement with average PM<sub>10</sub> ground-based measurements (both calculated during pregnancy), with a squared correlation coefficient (R<sup>2</sup>) of 0.289 (slope 0.006,  $p < 10^{-15}$ ) (Fig. 4). The offset (equal to 0.005) did not differ significantly from zero (p = 0.50).

259 Associations between preterm birth and AOT<sub>470</sub>-based exposure estimates

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The crude and adjusted associations between AOT<sub>470</sub>-based exposure estimates and preterm birth were very similar and elevated, but not significantly (OR = 1.19, 95% CI = 0.98 - 1.46, p = 0.08, and OR = 1.18, 95% CI = 0.95 - 1.47, p = 0.14, in univariate model and multivariate model, respectively).

265

#### 266 **Discussion**

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Here, we used recent high-resolution (1 km) AOT MODIS data based on the MAIAC

algorithm to assess past exposure (2005-2008) of pregnant women to desert dust and to check

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  $AOT_{470}$  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 AOT<sub>470</sub> 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 AOT<sub>470</sub> retrievals and PM<sub>10</sub> 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 PM<sub>10</sub> 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  $PM_{10}$  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  $\mu$ g/m<sup>3</sup>), 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

14/24

308	main factor affecting $PM_{10}$ data (Euphrasie-Clotilde et al. 2017). This is the reason why the
309	local air quality monitoring agency classifies desert dust episodes according to $PM_{10}$
310	concentrations: light, 28–38 $\mu$ g PM <sub>10</sub> /m <sup>3</sup> ; moderate, 39–54 $\mu$ g PM <sub>10</sub> /m <sup>3</sup> ); intense, $\geq$ 55 $\mu$ g
311	$PM_{10}/m^3$ (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 $PM_{10}$ -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

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- 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 PM<sub>10</sub> 331 exposure (assigning ground-level measurements to populations within a specified distance of

15/24

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 AOT<sub>470</sub> 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 in areas with few monitoring stations and complex topographical/ meteorological conditions, 338 339 such as tropical areas.

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		Univariate analysis			Multivariate analysis <sup>a</sup>			
Place of residence	mean (sd)	ß	95% CI	95% CI <i>p</i> -value		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 <sup>-4</sup>	-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	

**Table 1** Mean AOT<sub>470</sub> values during pregnancy and comparisons according to the place of residence ofpregnant women (n = 906, mother-child cohort, 2005-2008, Guadeloupe)

Aerosol optical thickness (AOT<sub>470</sub>), confidence interval (CI).

<sup>a</sup> 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 PM<sub>10</sub> concentrations (red line) and average daily AOT<sub>470</sub> 411 values calculated from 1,054 1x1 km pixels (green line) (2005-2008, Guadeloupe)

- 412 Fig. 3 Average AOT<sub>470</sub> 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 AOT<sub>470</sub> values and ground-based PM<sub>10</sub> concentrations
- 415  $(\mu g/m^3)$  during pregnancy (n = 906, 2005-2008, Guadeloupe)

