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**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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Abstract

Desert dust transported from the Saharan-Sahel region to the Caribbean Sea is responsible for peak exposures of particulate matter (PM). This study explored the potential added value of satellite aerosol optical thickness (AOT) measurements, compared to the PM concentration at ground level, to retrospectively assess exposure during pregnancy. MAIAC MODIS AOT retrievals in blue band (AOT₄₇₀) were extracted for the French Guadeloupe archipelago. AOT₄₇₀ values and PM₁₀ concentrations were averaged over pregnancy for 906 women (2005-2008). Regression modeling was used to examine the AOT₄₇₀-PM₁₀ relationship during pregnancy, and test the association between dust exposure estimates and preterm birth. Moderate agreement was shown between mean AOT₄₇₀ retrievals and PM₁₀ ground-based measurements during pregnancy ($R^2=0.289$). The magnitude of the association between desert dust exposure and preterm birth tended to be lower using the satellite method compared to the monitor method. The latter remains an acceptable trade-off between epidemiological relevance and exposure misclassification, in areas with few monitoring stations and complex topographical/meteorological conditions, such as tropical islands.

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

Declaration

Ethics approval and consent to participate

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

Consent for publication

Not applicable.

Availability of data and materials

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

Competing interests

The authors declare that they have no competing interests.

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Author contributions

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

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Introduction

On a global scale, most atmospheric particles are emitted by natural sources, mineral dust being the second most abundant component (after sea-spray derived aerosols). The Sahara and Sahel 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 areas in the Caribbean and the Americas, generating peak exposures to particulate matter (PM) in these downwind regions. The dust plume extension varies throughout the year depending on the displacement of the Inter-Tropical Convergence Zone (Prospero et al. 1981), inducing marked seasonality (emissions peaking in spring and summer). Desert dust typically mixes with locally- or regionally-emitted PM, but the median desert dust mass diameter was found to be 3.2 μm in Barbados and 3.5 μm in Puerto Rico (Reid et al. 2003).

Accurately assessing desert dust exposure in the Caribbean region is challenging due to sparse ground monitoring networks. Conversely, satellite remote sensing, in terms of aerosol optical thickness (AOT), has provided new methods to monitor PM air quality with fine spatial and temporal resolution, since the launch of the Moderate Resolution Imaging Spectroradiometer (MODIS) (Xiao et al. 2017). AOT is based on the impedance of light 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 data may be compromised by the non-random absence due to cloud cover, high surface reflectance (desert and snow-covered surfaces), and extremely high aerosol loading, which can be misclassified as clouds (Lee et al. 2012; Di et al. 2016). Thus, AOT data may not be available for a large fraction of days (non-retrieval days).

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

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

through $PM \leq 10 \mu m$ (PM_{10}) concentrations recorded at the sole (urban) background air quality monitoring station of Guadeloupe, located in Pointe-à-Pitre (central part of the Guadeloupe archipelago), regardless of the location of the woman's residence. However, spatial heterogeneity in terms of exposure can be supposed, as concentrations may be lower on the 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 Guadeloupe). This presumed spatial variability of air pollutants related to topography (and also local micro sources) may not be captured by a single background air quality monitoring station, and non-differential misclassification may occur.

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

Materials and methods

Study domain and population

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).

Ground PM measurements

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

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

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).

Statistical analyses

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

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

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

Results

Descriptive results

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

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

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

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 AOT₄₇₀ estimates during this short period of observation.

Spatial variability

The mean AOT₄₇₀ values during pregnancy, according to the place of residence of the mothers, are presented in Table 1. We plotted the mean AOT₄₇₀ 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 AOT₄₇₀ values when considering urbanization (Table 1).

AOT₄₇₀-PM₁₀ association during pregnancy

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

Associations between preterm birth and AOT₄₇₀-based exposure estimates

The crude and adjusted associations between AOT₄₇₀-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).

Discussion

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.

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

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

In Guadeloupe, the maximum AOT value was 0.964, in agreement with results from South America, where 98% of AOT values ranged from 0.01 to 1.0 (Martins et al. 2017).

Unfortunately, we could not use aerosol optical measurements from the local AERONET site as "ground trust" in satellite retrieval calibration and aerosol characterization because of numerous missing data during the study period (695 of 1214 days).

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

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

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

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

Conclusion

Given the above-mentioned limitations, the AOT-based proxy does not appear to be more appropriate than the PM-based proxy to retrospectively assess the exposure of pregnant women to desert dust in the Caribbean. We believe that the conventional estimation of PM₁₀ 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)

		Univariate analysis			Multivariate analysis ^a		
Place of residence	mean (sd)	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

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

Each circle represents a mother's place of residence. The location of the air quality monitoring station is indicated by the diamond symbol. The location of the La Soufrière volcano is indicated by the triangle. Pointe-à-Pitre city 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 (µg/m³) during pregnancy (n = 906, 2005-2008, Guadeloupe)