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Impact of traffic emissions on air quality in Cabo Verde

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Abstract Air quality degradation due to road traffic emissions is one of the topics of major interest for the scientific community and urban planners worldwide. Cabo Verde does not have regulations for traffic emission control or air quality guidelines, although the number of road vehicles has grown steadily over the past decade. Moreover, studies focusing on the impact of road transport on air quality in this archipelago are sparse. In this study, we present a first detailed air pollutant inventory of road traffic emissions through a bottom-up methodology, along with snapshots of the state of air quality on the islands of Santiago, São Vicente, and Sal. For the year 2017, emission estimates for the main island (Santiago) are 654 tons of CO, 35 tons of PM_{10}, 562 tons of NO_x, and 84 tons of NMVOCs. The air quality assessment was carried out using the TAPM model for a period of 6 months from January to July 2017. The results showed that the mean concentration values for Sao Vicente, Sal, and Santiago Islands ranged between 2.0 and 18 μg m^{-3} for NO_2 and 3.8 and 5.6 μg m^{-3} for PM_{10}. NO_2 concentrations show an increasing trend from January to July in Santiago and Sal, and no clear trend in São Vicente Island. The simulated PM_{10} concentrations showed values in the same range over the year, even though they appeared slightly higher in July than in January. It was observed that both NO_2 and PM_{10} average concentrations have been consistently above healthful levels, according to air quality guidelines fixed by the WHO.

Keywords Cabo Verde · Emission inventory · Road traffic · Air quality

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Introduction

The growth of the urban population worldwide leads to an intensification of road traffic and, consequently, to an increase in the emission of pollutants from the burning of fossil fuels from households and vehicles. Road traffic has been considered a major anthropogenic source of air pollution along with emissions from agriculture and industry (EEA 2016; Querol et al. 2001; Suarez-Bertoa et al. 2016). Many studies have been conducted to assess the impact of traffic emission on air quality in different countries such as Portugal (Ribeiro et al. 2016; Slezakova et al. 2011), Sweden (Ferm and Sjöberg 2015), South Africa and Lesotho (Ferm and Sjöberg 2015), Greece (Progiou and Ziomas 2012), and Lebanon (Waked and Afif 2012). The results of these studies have clearly shown that there is a strong correlation between road traffic emissions and air pollution in these regions that also affects global warming and climate change (IPCC 2007). It has assumed been shown that the large number of vehicles in cities has negative impact on air quality and consequently on public health (Gu et al. 2017; Degraeuwe et al. 2016; EEA 2016; Figueiredo et al. 2013; Jonson et al. 2017; Slezakova et al. 2011; Smith et al. 2013; Naddafi et al. 2012; Zhang and Batterman 2013).

The concentration of exhaust gases such as hydrocarbons, carbon monoxide (CO), and nitrogen oxides (NO_x) depends on vehicle age and technology, fuel type, and vehicle mileage, as well as the city's fleet size and road network characteristics (Brimblecombe et al. 2015). A study conducted by Jaiprakash et al. (2017) shows that the contribution of diesel, gasoline, and compressed natural gas (CNG) to total CO, CO_2, and NO_x emissions were 7:84:9, 50:48:2, and 58:41:1, respectively. The authors also found lower CO and higher NO_x emissions in 2010 manufactured diesel cars compared to the 2005 cars. These results suggest that new technological advances in diesel fueled passenger cars reduce CO emission while the use of turbo charger in diesel cars to achieve high temperature combustion can increase NO_x emissions. According to Suarez-Bertoa et al. (2016), the oldest fleet, NO_x emission factors show some relatively high emissions when compared with the Euro V legislative (ETC cycle) limit of 2 g/kWh.

On the other hand, recent studies on air quality influence by traffic emissions show that modern cars have lower impact on air pollution (Bździuch and Bogacki 2017; Kousoulidou et al. 2008). According to Vestreng et al. (2009), in Europe, road transport has been the dominating source of NO_x emissions which accounts for 40% to the total emissions in 2005. A shift towards sustainable and innovative transport, access restrictions and speed limits implemented have played an important role in decreasing the European pollutant emissions; however, according to European Environment Agency (EEA) (2018), the road transport sector continued to contribute the highest proportion of NO_x emissions (39%) in the European Union (EU) in 2016.

Although the majority of existing cars in Cabo Verde are imported from Europe, there are no numbers available about; additionally, there is a lack of legislation and regulatory instruments for transport emission control in Cabo Verde.

Cabo Verde's automobile fleet (on the road) has increased by 68.1% in 10 years, from 41,014 vehicles in 2006 to 68,951 vehicles in 2016, with an average annual growth of 5.4%. Such evolution, combined with other important emission sources as domestic wood combustion, contributes to harmful emissions and poses serious risks to the health of the population. To the best of our knowledge, there are no studies on traffic emission inventories of air pollutants and their impact on air quality in Cabo Verde. Previous atmospheric studies (Almeida-Silva et al. 2013; Fomba et al. 2014; Salvador et al. 2016; Alves et al. 2018) have been focused on the contribution of the Sahara dust transport events to local particulate matter concentration and compositions.

Thus, the main purpose of this study is to present a detailed traffic emission inventory in Cabo Verde and to assess the impact of the pollutants on local air quality. To accomplish this objective, a bottom-up approach was applied using The Air Pollution Model (TAPM) (Hurley et al. 2005) to assess the impact of traffic emissions on air quality. The results from the current study would benefit future emission inventory studies and help in the national and local planning transport policies for controlling vehicle emissions.

The study area

The Archipelago of Cabo Verde is located 455 km from the Western African coast between latitudes 14° 23′ and 17° 12′ North and longitudes 22° 40′ and 25° 22′ West, as illustrated in Fig. 1a. The Cabo Verde territory extends for 4033 Km^2 in total and consists in 9 islands and several islets, divided into two major groups: (i) *Barlavento* (windward) Group which includes the islands of Santo Antão, São Vicente, Santa Luzia, São Nicolau, Sal, and Boa Vista and (ii) Sotavento (Leeward) Group which includes the islands of Maio, Santiago, Fogo, and Brava (Fig. 1b).

Due to its geographical location, Cabo Verde has an arid and semi-arid, hot and dry climate with scarce rainfall and an average annual temperature of 25 °C. The wet season is normally between July and October with some irregularities and brief-but-heavy downpour periods. According to the last national report, the total resident population of Cabo Verde in 2016 was 531,240 inhabitants (INE 2016). Figure 2 shows its distribution by municipalities.

According to the National Institute of Statistics of Cabo Verde (INE 2016), there has been a slow growth in population density, with increase around 5% between 2012 and 2016, with a population density of 131.72 inhabitants/km^2. São Vicente island recorded the highest population density of Cabo Verde (361 inhabitants/Km^2), followed by Santiago (301 inhabitants/

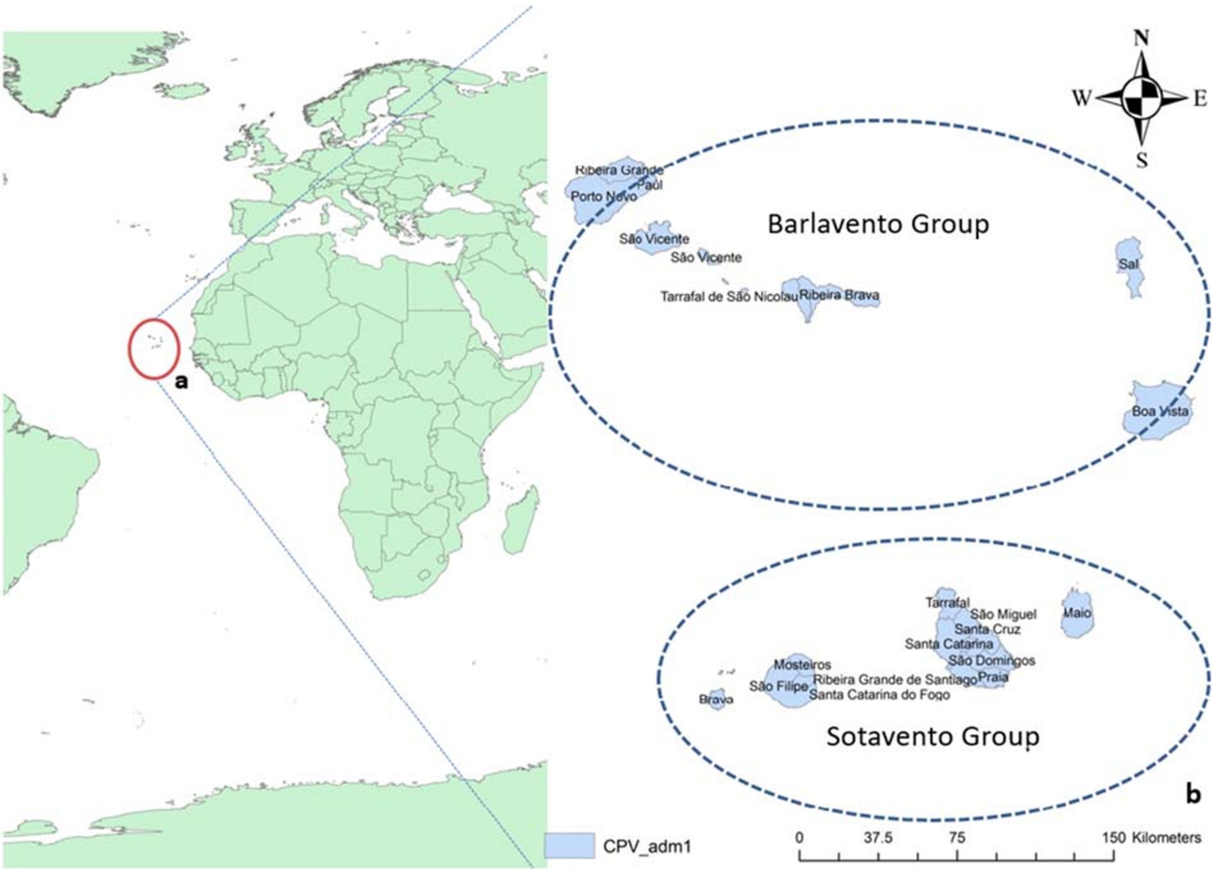

Fig. 1 The Cabo Verde Archipelago (**a**) and the geographical location of islands and of its municipalities (**b**)

km^2), with Boa Vista Island the lowest with about 25 inhabitants/km^2.

Characterization of road transport in Cabo Verde

The Cabo Verde road network includes asphalted and unpaved roads. According to the DGTR, in 2016, the Cabo Verde fleet was composed by 68,951 vehicles, mostly light (73%), followed by heavy (15%) vehicles, and motorcycles (12%). The vehicle classification is further subdivided according to fuel types, that is, petrol or diesel.

As observed in Fig. 3, the number of vehicles continuously increased in the last decade for all vehicle classes considered. The only exception is a slight decrease in heavy vehicles from 2016 to 2017.

pt?>All vehicle types show similar level of traffic growth with lower values in 2012. Between 2006 and 2016, motor vehicle traffic, with an estimate fleet age of 15.04 years, increased 68.1% due to an increasing number of registered vehicles. For the year 2017, motorcycle data were not available. Vehicles contribute with 4.7% to the total imports of Cabo Verde from 2015 to 2016, which is equivalent to 28 million EUR (INE 2016). The motorization rate in Cabo Verde is 122 per 1000 inhabitants with the larger amount of road transport vehicles concentrated in Santiago (69.6% of total vehicles) followed by, São Vicente and Sal islands as illustrated in Fig. 4.

Praia, Cabo Verde Capital, covers an area of approximately 102.6 km^2. In spite of the low population and vehicle number compared to Europe or to other Macaronesia countries, the city presents frequent traffic congestions. For example, on one of the avenues of the capital, China Avenue (700 m), between 8 and 9 a.m., 912 vehicles pass on average. The collecting traffic volume data was achieved by manual method of traffic volume count.

Emissions inventory methodology

In order to quantify the emissions, a bottom-up approach was used, based on the fuel consumption for passenger cars (PC) and heavy-duty vehicles (HDV) existing in each island. This approach is

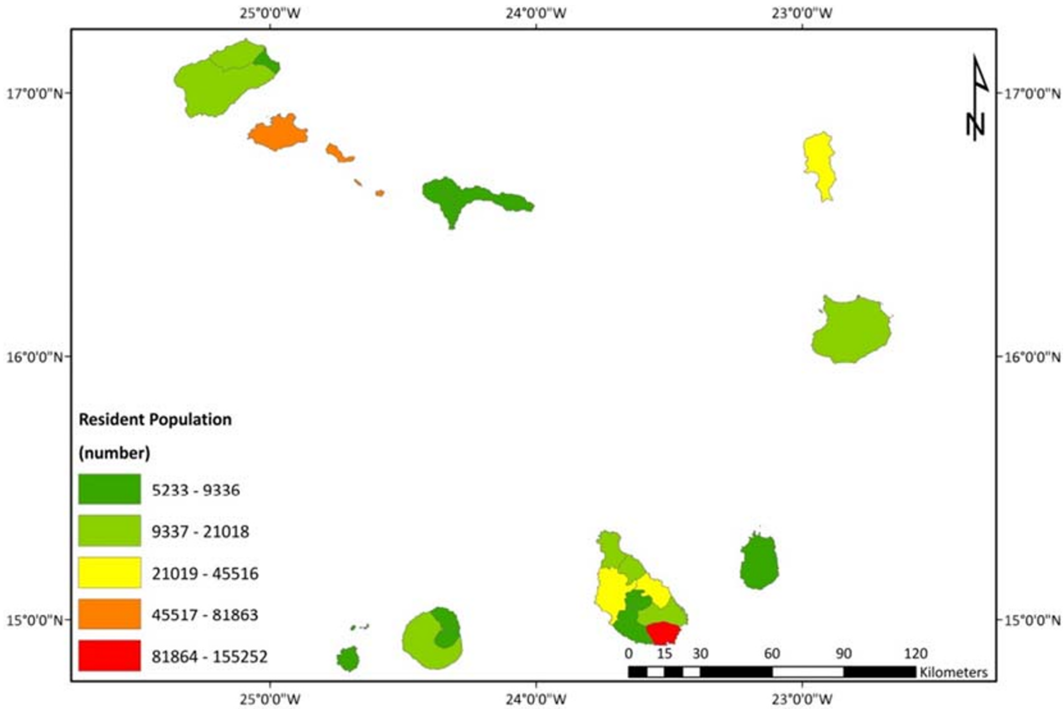

Fig. 2 The Cabo Verde distribution of resident population by municipalities

represented with a conceptual flow diagram in Fig. 5.

The emissions of the roads were calculated on the basis of fuel consumption for PC and HDV existing in each region, number of active population by district and road length as using appropriate emission factors according to Eq. 1.

$$Ei = \sum_j \sum_m (FCj, m \text{ is} \times EFi, j, m) \times p \times L^{-1} \quad (1)$$

where

- *Ei* is emission per road length per year (kg/year)
- *EFi,j,m* is fuel consumption-specific emission factor of pollutant *i* or vehicle category *j* and fuel *m* (g/kg)
- *FCj,m* is fuel consumption of vehicle type j using fuel *m* (kg) per year
- *p* is number of active population
- *L* the road length (m). The road length was calculated within a Geographical Information System (GIS); this system was also used for the management and detailed visualization of the maps.

The emission inventory covers the following air pollutants: CO (carbon monoxide), NMVOC (non-methane volatile organic carbon), NO_x (oxides of

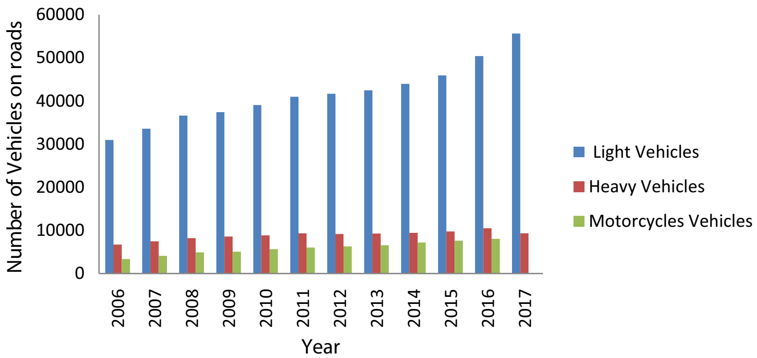

Fig. 3 Number of vehicles in Cabo Verde since 2006 by type of vehicle

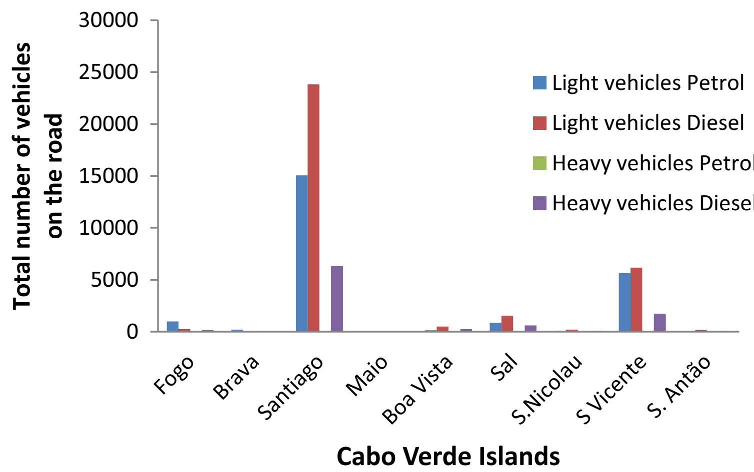

Fig. 4 Distribution of road vehicles in Cabo Verde islands in 2017

nitrogen), PM (particulate matter (PM $\leq$ 2.5 μm)), N_2O (nitrous oxide), NH_3 (ammonia), CO_2 (carbon dioxide), CO_2 (carbon dioxide from the combustion of lubricant oil), and SO_2 (sulfur content).

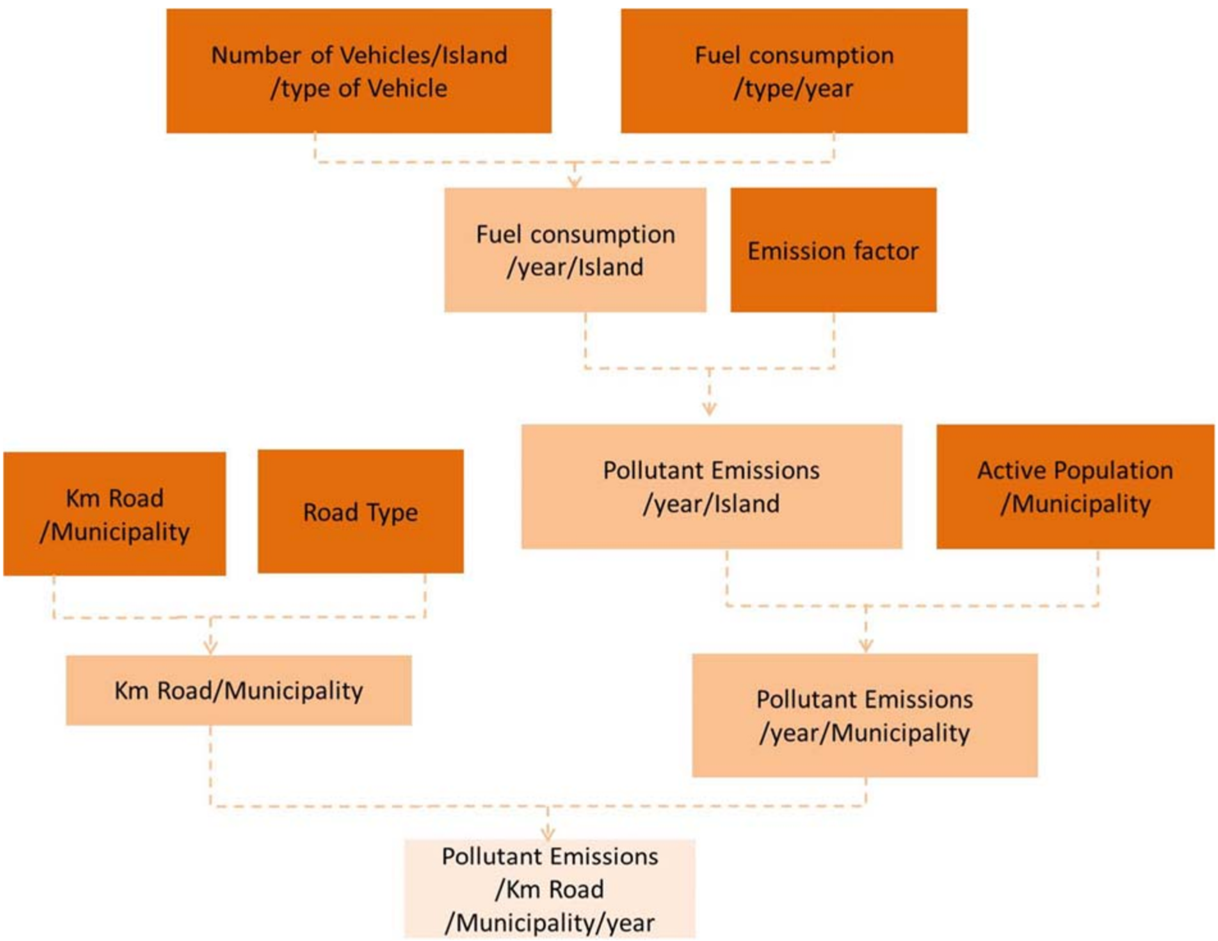

Fig. 5 Schematic methodology for developing estimates of emissions from on-road vehicles, based on Tier 1 approach

The emission factors applied for the estimation of pollutants are from EMEP/EEA Air Pollutant Emission Inventory Guidebook (EMEP/EEA 2016) and are presented in Table 1.

Data on total consumption of each fuel type for road transport on the national territory were provided by Caboverdian Economic Regulation Agency and were split by vehicles number per islands. In 2017, total petrol and diesel consumption was 9117 and 54,604 tones, respectively.

Emission inventory results

Table 2 summarizes the total emissions of different air pollutants from the different islands considered in this study for the year 2017.

The major amount of road traffic emissions are associated to CO (979.60 ton), NO_x (788.68 ton), CO_2 (200,447.35 ton), and CO_2 from lubricant oil (492.26 ton). Santiago Island presents the highest contribution of air pollutants, followed by São Vicente and Sal island (except for f-BC which is higher in Maio island). Results are consistent with Santiago vehicular fleet, which involves 69.6% of the total fleet, comprising 45,249 vehicles in 2017. It was also possible to verify that the total of 3.5E−03 ton of total PAHs (not shown in the Table 2) were emitted in Cabo Verde and the contribution of CO_2 from transport sector was 142.30 ton in Santiago. Last year, Cabo Verde presented the 3rd national communication reports of GHG emission inventory based on IPCC (2007) methodology. This report estimated a total emission of 2.07 Gg of NO_x from energy fuel combustion from the transport sector, in the year 2010, which represented a decrease of about 11.41% in comparison to the year 2005 (MAA 2017). The NO_x values corresponded to the emissions from the transport sector as a whole, whereas the estimated values from this study (790 ton) refers only to the emissions from road transport.

Figure 6 shows the spatial distribution of NO_x emitted in ton per road length (km) for Santiago and São Vicente islands. Also, in the figure are the network roads.

It can be clearly visualized in the figure that high range of values of such pollutant is observed mainly at town center area in comparison to other region of the islands, suggesting that higher emissions of NO_x pollutant where observed in regions where the number of vehicle were high. The same profile was also observed for other pollutants such as CO_2 and PM.

Results and discussion

Air quality modeling setup

The road transport impact on air quality in several Cabo Verde islands was simulated using The Air Pollution Model (TAPM), version 4.0, developed by the CSIRO (Commonwealth Scientific and Industrial Research Organization) and involves a PC-based, nestable, prognostic meteorological and air pollution model (with photochemistry) with a graphical end-user interface, and is a viable tool for year-long simulations (Hurley et al. 2005). Taking into account its versatility, easier and quicker approach to assess air quality with high temporal and spatial resolution over the study area, TAPM has been widely used to compute air quality at different environments, such as, urban centers (Belhout et al. 2018; Luhar and Hurley 2003; Miranda et al. 2016; Relvas et al. 2017; Relvas and Miranda 2018) and rural (Luhar and Hurley 2003) and coastal areas (Figueiredo et al. 2013) as well as west coast air basin (Liang et al. 2016). TAPM employs twenty-five vertical levels, which comprises 10, 25, 50, 100, 150, 200, 250, 300, 400, 500, to 8000 m to simulate the pollutants dispersion and works under default databases of soil properties, topography (global

Table 1 Emission factors of pollutant by type of vehicle and fuel consumed

Category of vehicle	Fuel	CO g/kg fuel	NMVOC	NO_x	PM	N_2O	NH_3	CO_2 lubricant	CO_2 kg/kg fuel	Sulfur content (SO_2) 10–6 g/g fuel
PC (passenger car)	Petrol	84.70	10.05	8.73	0.03	0.206	1.106	8.840	3.180	40
	Diesel	3.33	0.7	12.96	1.1	0.087	0.065	8.740	3.140	8
HDV (heavy-duty vehicle)	Diesel	5.7	0.26	13	0.02	n.a.	n.a.	3.310	3.140	8

Table 2 Total emission pollutant by island in ton in 2017

Island	CO	NMVOC	NO_x	PM	N_2O	NH3	CO_2	CO_2 lubricant	SO_2
Boa Vista	8.95	1.12	13.04	0.70	0.07	0.11	3219.09	7.15	0.01
Brava	6.63	0.79	0.93	0.02	0.02	0.09	307.30	0.81	0.00
Fogo	35.02	4.17	10.21	0.37	0.11	0.45	2878.90	6.89	0.02
Maio	0.01	0.00	0.03	0.00	0.00	0.00	8.19	0.02	0.00
Sal	39.76	5.01	39.50	2.25	0.25	0.50	9906.15	23.27	0.04
Santiago	653.98	83.67	561.98	34.52	3.93	8.59	142,298.66	351.24	0.55
Santo Antão	2.60	0.32	4.55	0.24	0.02	0.03	1116.45	2.44	0.00
São Nicolau	4.50	0.57	5.10	0.29	0.03	0.06	1271.42	2.94	0.00
São Vicente	228.16	28.60	153.34	8.98	1.16	2.98	39,441.18	97.50	0.17
Total	979.60	124.24	788.68	47.38	5.58	12.81	200,447.35	492.26	0.80

terrain height data on a longitude/latitude grid at approximately 1 km spacing based on public domain data available from the US Geological Survey; Earth Resources Observation Systems (EROS) was used), and the monthly sea-surface temperature and deep soil parameters.

Pollutant emission inputs in the model was the emissions from line sources as described in session 3, and considering 3 domains centered on the 3 most relevant islands (São Vicente, Sal and Santiago). The study domains, as haunted areas, are presented in Fig. 7, and covers São Vicente, Sal, and Santiago Islands, between 16° 44′ N

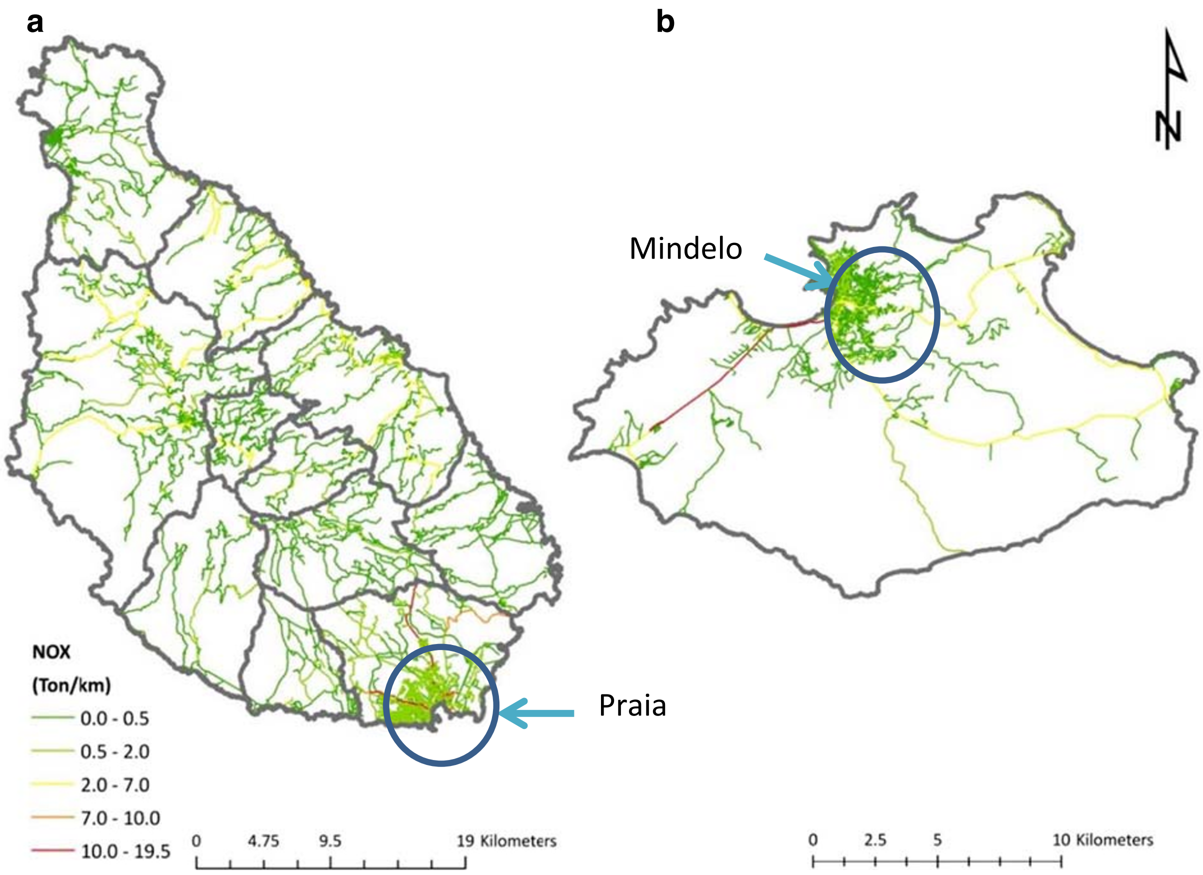

Fig. 6 Distribution NO_x in ton/km in **a** Santiago and **b** São Vicente islands

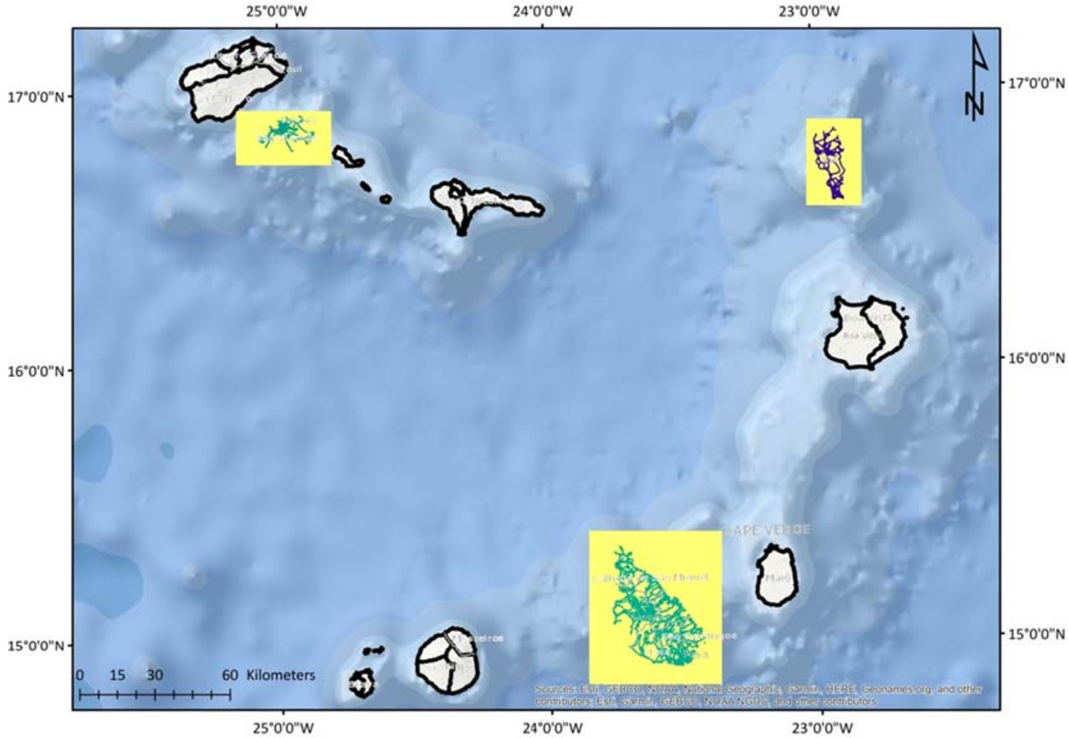

Fig. 7 Representation of the simulation domain for the select islands

to 16° 56′ N, 16° 34′ N to 16° 52′ N, and 14° 50′ N to 15° 33′ N latitude, and 25° 10′ W to 24° 47′ W, 23° 1′ W to 22° 49′ W, and 23° 51′ W to 23° 21′ W longitude, respectively.

For TAPM application, it was considered that all selected islands had the same innermost domain with a resolution of 1 × 1 km^2, centered on each island. The horizontal resolutions of the grids for nesting was specific for each island, namely, 9, 3, and 1 km^2 for São Vicente, 11, 6, 3, and 1 km^2 for Sal, and 10, 3, and 1 km^2 for Santiago. Figure 8 shows the three simulated grid domains for Santiago Island, as an example.

Regarding the simulation of pollutant dispersion, the model was simulated in chemistry and deposition mode for the innermost domain of each island, for 2 different

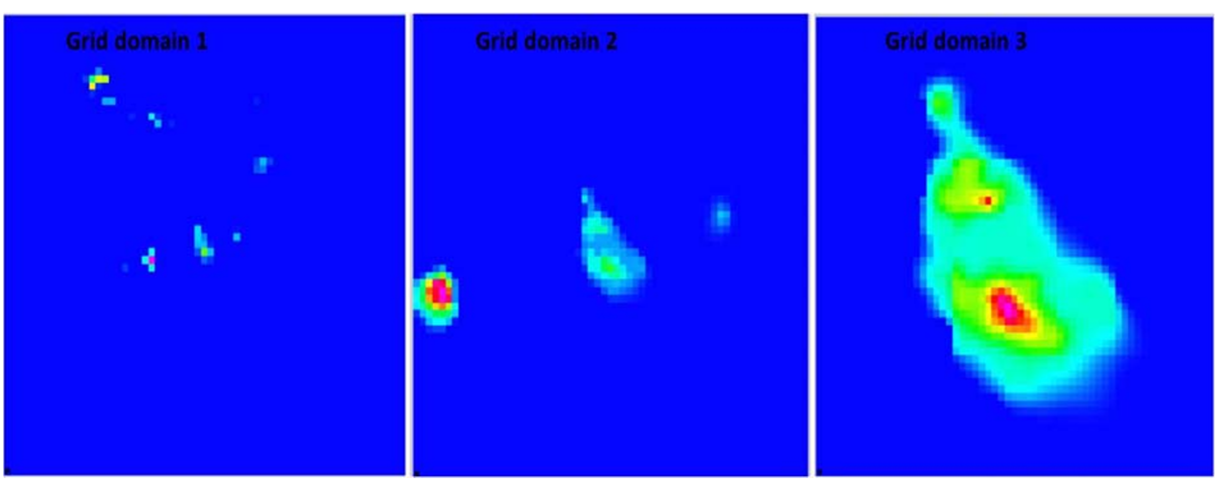

Fig. 8 Simulation grid domains for Santiago Island

months of the year 2017, January and July, as representative of winter and summer periods.

Air quality modeling results

Figures 9 and 10 present the monthly average concentrations for NO_2 and PM_{10} in μg $m^{-3}$for São Vicente, Sal, and Santiago Island for the months of January and July.

The simulated NO_2 average concentration due to road traffic in São Vicente, Sal, and Santiago Islands are similar in both periods, respectively. It was 4.0 μg m^{-3}, 2.0 μg m^{-3}, and 14 μg m^{-3} in January and 3.6 μg m^{-3}, 2.4 μg m^{-3}, and 18 μg m^{-3} during July. With regard to PM_{10}, the simulated average concentrations reached 4.03 μg m^{-3}, 3.8 μg m^{-3}, and 5.0 μg m^{-3}, in January and 5.0 μg m^{-3}, 3.8 μg m^{-3}, and from 5.6 μg m^{-3} in July. These results suggest some trend of higher levels of NO_2 and PM_{10} in July month for Sal and Santiago Islands. Mean concentrations of simulated NO_2 for São Vicente island, in turn, showed little variation between both months. High concentrations of pollutants are usually found during winter or cold periods, contrasting results found here. These findings indicate the influence of local meteorological conditions on pollutants transport. The study conducted in Athens, Greece (as coastal urban region), have shown that pollution episodes were connected with specific meteorological surroundings such as weak synoptic forcing and sea-breeze circulations (Kotroni et al. 1999).

Regarding the variation of the pollutants along the islands, NO_2 concentrations were higher in the island of Santiago, showing good accordance with the traffic-related urban center (Fig. 9). This finding is in agreed with Degraeuwe et al. (2016) who linked the increase in NO_2 to an increase in the fraction of NO_x emission from vehicles. Figure 10 shows that average PM_{10} concentrations are high in all islands at specific region which match with each island urban centers. Concentration hotspots are seen in the islands over to the Mindelo center and airport area for São Vicente, Espargos and Santa Maria region for Sal and Praia, Santa Catarina, and São Miguel municipalities for Santiago and the spatial pattern of both NO_2 and PM_{10} concentrations are very similar. It was also possible to observe that both NO_2 and PM_{10} dispersion emitted plumes are transported inland towards the west and south regions, where they can mix with local emissions, affecting air quality. This behavior may increase the pollutant levels in that region since it also has large population and vehicles. This finding suggested the Cabo Verde air quality is significant influenced by the Cabo Verde wind direction, which is mostly Northern/North-eastern (during year) according to the Meteorological Institute of Cabo Verde.

It was also observed that in 2017, both NO_2 and PM_{10} average concentrations in the considered months have been consistently above healthful levels, according to air quality guidelines fixed by the WHO (200 μg m^{-3} (1 h—hour) and 50 μg m^{-3}(daily average)) (WHO 2006) and the European Union (200 μg m^{-3} (1 h—hour) and 50 μg m^{-3}(daily average, not to be exceeded more than 35 times a calendar year)) (European Environment Agency 2017) for NO_2 and PM_{10}, respectively.

Conclusions

This paper estimates the Cabo Verde road traffic emissions and asses the air quality concentrations of two main pollutants, NO_2 and $PM_{10,}$ in the São Vicente, Sal, and Santiago Islands for the year 2017. As expected, the main emitted pollutants were CO, NO_x, CO_2, and CO_2 from lubricant oil, and Santiago Island is the Island with the highest amount of emission for all the pollutants in 2017, followed by Sao Vicente and Sal island.

The TAPM model in combination with meteorological and emission inventory data showed great potential in assessing monthly pollutant levels as well to identify the hotspots of pollutant concentrations. The mean concentrations of NO_2 are higher for São Vicente islands during January, while those for Sal and Santiago, the higher levels were achieved in July. Results revealed that the mean concentrations of PM_{10} were higher in July for the Sal and Santiago Islands while São Vicente island shows a contrary trend. In general, findings of this study revealed low average concentration levels of both simulated pollutants, 2.0–18 μg m^{-3} for NO_2 and 3.8–5.6 μg m^{-3} PM_{10}, despite the fact that the urban centers of Cabo Verde begin to become congested with vehicles that are getting older.

This study works was the first quantitative traffic emission inventory and related air quality assessment in Cabo Verde. Foreseen future work includes an update of traffic emission calculations using vehicle counting, estimate emissions from other relevant sources such as industry, waste management and domestic/rural biomass burning, which have been identified as an important contributor to fine PM concentrations in other urban

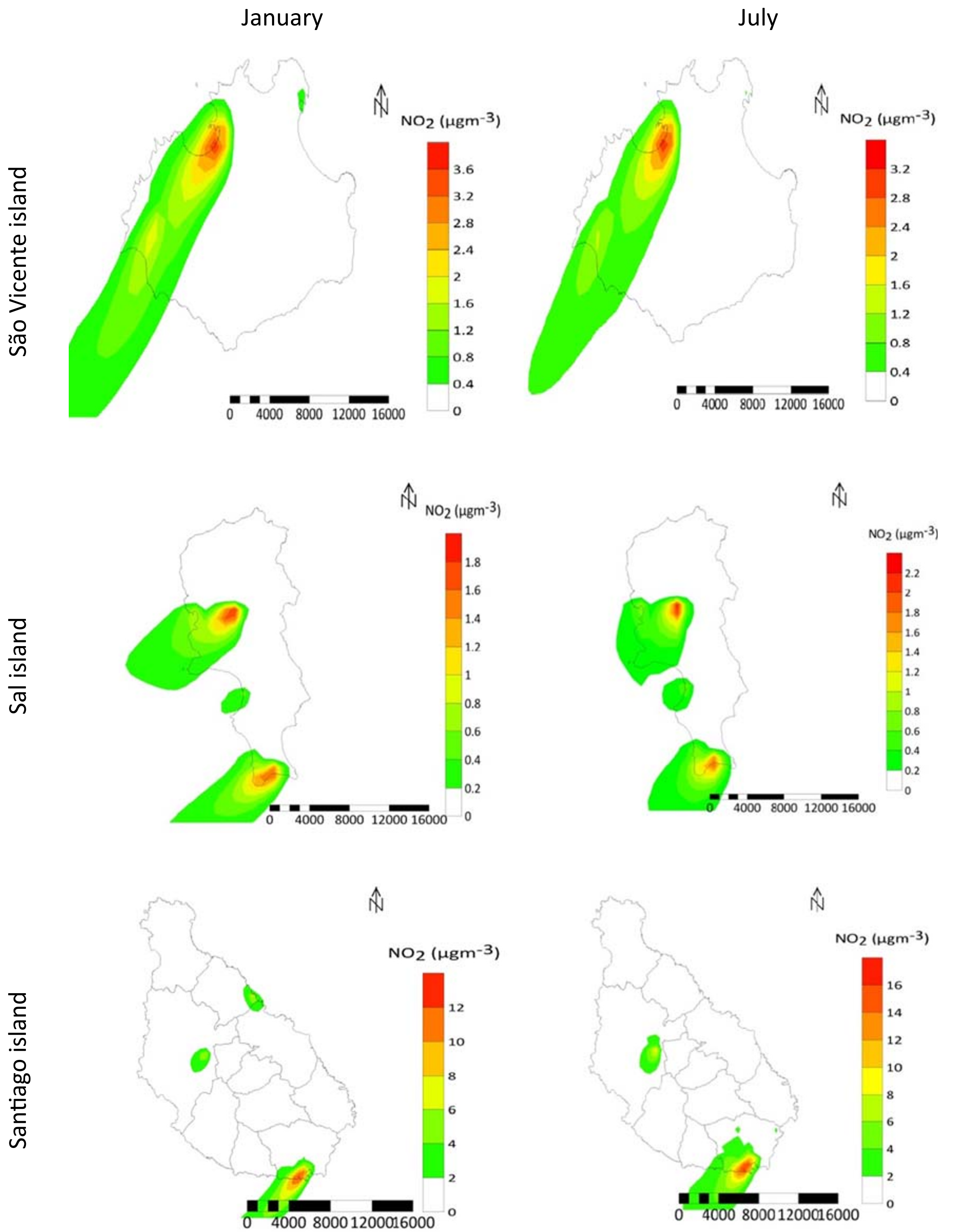

Fig. 9 Average concentrations of NO_2 in the 3 main Cabo Verde islands for January and July of 2017

areas, and update air pollutants concentration levels by considering all emission sources contribution. In addition, other emission reduction scenarios can be assessed using TAPM, namely, changes on road traffic

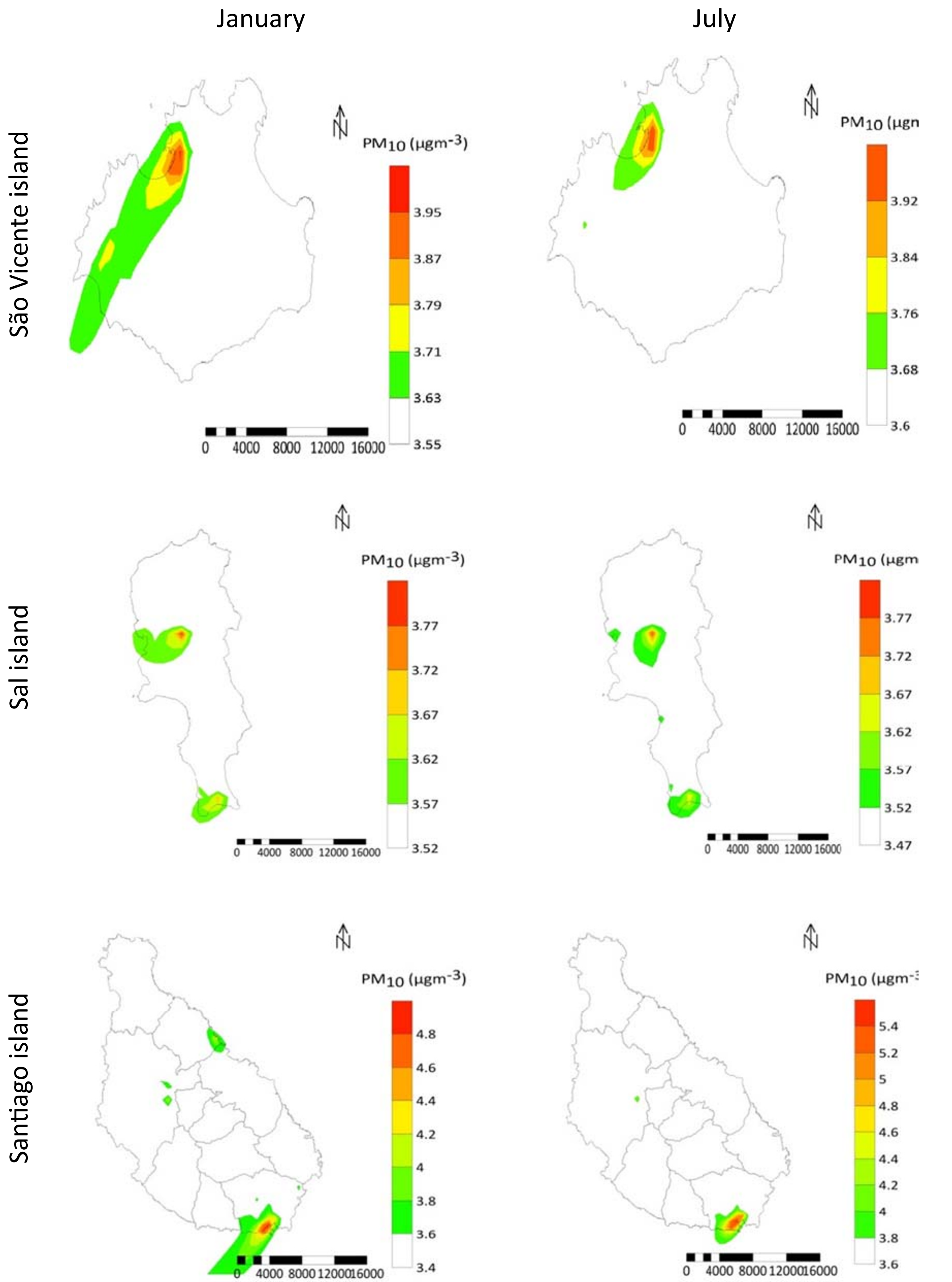

Fig. 10 Average concentrations of PM_{10} in the 3 main Cabo Verde islands for January and July of 2017

composition or improvements on the residential sector. We recommend the implementation of air quality limit levels for the most critical pollutants in terms of human health and an effective monitoring plan of air quality levels in Cabo Verde main cities.

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