Chapter 2
Impact of Oporto Metropolitan Area Carbon Dioxide Emissions over the Adjacent Coastal Zone

Rogério Carvalho, Nelson Barros, and Pedro Duarte

Abstract Concerns about global warming over the last years have stimulated a large number of studies regarding atmospheric and oceanic carbon dioxide (CO_2) concentration and its consequences. In spite of the available data on global atmospheric CO_2, there is only limited knowledge on CO_2 variability at regional scales. Moreover, there is an important gap in our understanding of the contribution of high CO_2 emission regions, such as metropolitan areas, to CO_2 concentrations over nearby coastal areas–considered by several authors as an important CO_2 sink. A possible working hypothesis is that, large littoral metropolitan areas may have a significant influence on CO_2 atmospheric concentrations over those areas and exert an important influence on sea-air CO_2 exchanges. Therefore, the main objective of this study is to estimate CO_2 concentration at a regional scale, under the influence of Oporto Metropolitan Area (OMA) emissions as a first test of this hypothesis. To fulfil this objective, an emission database was built and used to force, together with meteorological synoptic data, a mesoscale atmospheric dispersion model. The model was used to simulate several weather scenarios and estimate CO_2 concentrations along a ca. 90 km stretch of the Portuguese northern shore. The results obtained suggest that emissions from OMA have an important influence on CO_2 atmospheric concentrations up to 6–12 km offshore, particularly in autumn and winter. However, this CO_2 increase does not seem to have the potential to significantly affect sea-air CO_2 exchanges, although this is just a preliminary conclusion that has to be tested by field work.

Keywords Carbon dioxide • Global warming • Coastal zone • Metropolitan area • Atmosphere • Ocean • Regional scale • Emission • Air–sea exchange • Model

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R. Carvalho (✉), N. Barros, and P. Duarte
CIAGEB – Global Change, Energy, Environment and Bioengineering R&D Unit,
University Fernando Pessoa, Praça 9 de Abril, 349, 4249-004 Porto, Portugal
e-mail: carvalho@ufp.edu.pt; nelson@ufp.edu.pt; pduarte@ufp.edu.pt

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2.1 Introduction

Environmental issues began to be studied, with greater emphasis, at the end of the 1970s, because the scientific community, society and some governments felt the need to intensify the development of research in this area. In recent decades, concerns about global warming led to a large number of studies on emissions and concentrations of greenhouse gases, especially CO_2, and their consequences. Climate has changed in the past due to cyclic variations in the eccentricity of Earth's orbit around the sun, Earth's precessional motion and axis tilt, and in periods of intense volcanic activity (Jahn 2005). However, it is concern about the potential contribution of mankind to climate change that is stimulating much of the current debate on global warming.

In 1988, the UNEP (United Nations Environment Programme) created the IPCC (Intergovernmental Panel on Climate Change) (United Nations 1998). The first IPCC report (IPCC 1990) pointed out the need to reduce anthropogenic emissions of greenhouse gases to the atmosphere in order to decrease global warming trends. This first recommendation was confirmed in subsequent IPCC reports (IPCC 1995, 2001, 2007). The Kyoto Protocol was created, in 1997, within the United Nations Framework on Climate Change (UNFCC), leading to a commitment, between 2008 and 2012, of many governments to reduce greenhouse gas emissions to values below 1990, and drawing more attention to the role of carbon dioxide in the atmosphere (Baliunas 2002). In spite of IPCC claims through their assessment reports and the apparent political willingness of many governments to reduce carbon dioxide emissions, the links between the so-called "greenhouse gases" and climate change is still a matter of debate (e.g. Gerlich and Tscheuschner 2007).

CO_2 emissions increased throughout the twentieth century and continue to increase, mostly as a result of energy production followed by changes in land use, especially deforestation (IPCC 2007). Beginning in the 1950s, an increasing number of CO_2 monitoring stations were established worldwide (http://www.esrl.noaa.gov). However, the average distance between these stations is on the order of thousands of kilometres, making it difficult to have a clear picture of regional CO_2 variability. Without this degree of detail, it is hardly possible to access the influence of important emission areas, such as highly industrialized and urbanized regions, over nearby coastal zones, considered to be important CO_2 sinks according to the "continental shelf pump hypothesis" (Tsunogai et al. 1999; Thomas et al. 2004). Several papers have dealt with the evaluation of global air–sea CO_2 fluxes in coastal environments, such as Borges (2005), Borges et al. (2005, 2006), Cai et al. (2006), Chen and Borges (2009). Presumably, this role may be influenced by local CO_2 concentrations, since its partial pressure in the atmosphere will partly determine its exchanges across the sea-air interface. There are several papers that have shown that there is a local influence of land masses in atmospheric CO_2 measured at sea: Bakker et al. (1996), Borges and Frankignoulle (2001, 2003). Working on Dutch Coastal waters, the first of these authors found that existence of atmospheric CO_2 over the sea was influenced by the nearby land areas, with a high and variable CO_2 concentration in off shore winds.

From the above reasoning, a possible working hypothesis is that metropolitan areas can have a significant influence on atmospheric concentrations of CO_2 over adjacent coastal zones and thus exert a significant influence on CO_2 ocean -atmosphere exchanges in those zones. Therefore, the main objective of this study was to test this hypothesis for the Oporto Metropolitan Area (OMA), as a starting point to development of a more general test.

2.2 Methodology

The first step of this work was to implement a CO_2 emission database, linked to a Geographic Information System (GIS). Data was obtained from the National Inventory of Anthropogenic Emissions by Sources and Removals by Sinks of Air Pollutants (INERPA) of the Portuguese Environment Agency (APA) (IA2007), from the European Pollutant Emission Register (EPER) (http://eper.eea.europa.eu/eper) (current E-PRTR – www.prtr.ec.europa.eu) and from the most recent demographic survey conducted in Portugal-Census 2001 (http://www.ine.pt). APA is responsible for conducting annual inventories of national emissions of air pollutants. Under the European and other international commitments regarding the United Nations Framework Convention on Climate Change (UNFCCC), Convention on Long-range Transboundary Air Pollution (UNECE) and the directive on National Emission Ceilings (EU), participating countries have to update, on a yearly basis, their inventories of greenhouse gases (GHG) and other air pollutants.

The results of the database and larger-scale meteorology provided by synoptic analyses information, representing different seasons, were used to force the atmospheric model "The Air Pollution Model" (TAPM) (Hurley 2005a) to simulate CO_2 dispersion from the OMA towards the nearby coastal area.

2.2.1 Study Area: Oporto Metropolitan Area

The OMA is formed by 14 municipalities (Fig. 2.1). Currently, OMA occupies an area of 1,575 km^2, counting today, with a population of approximately 1,550,000 residents (http://www.amp.pt).

The coast line of the study area has a length of about 90 km and width of c.a. 60 km. The municipalities along the coast line are: Póvoa de Varzim, Vila do Conde, Matosinhos, Oporto, Vila Nova de Gaia and Espinho. There are three major rivers and estuaries along this coast line: Ave, Leça and Douro. Table 2.1 shows population and area of each municipality, its relative contribution to the total area and population density.

Within the OMA there are industries of particular significance to the country's economy, such as a refinery, a power plant, a steel factory, manufacturing industries, an international airport, a large seaport infrastructure, a large co-generation and an

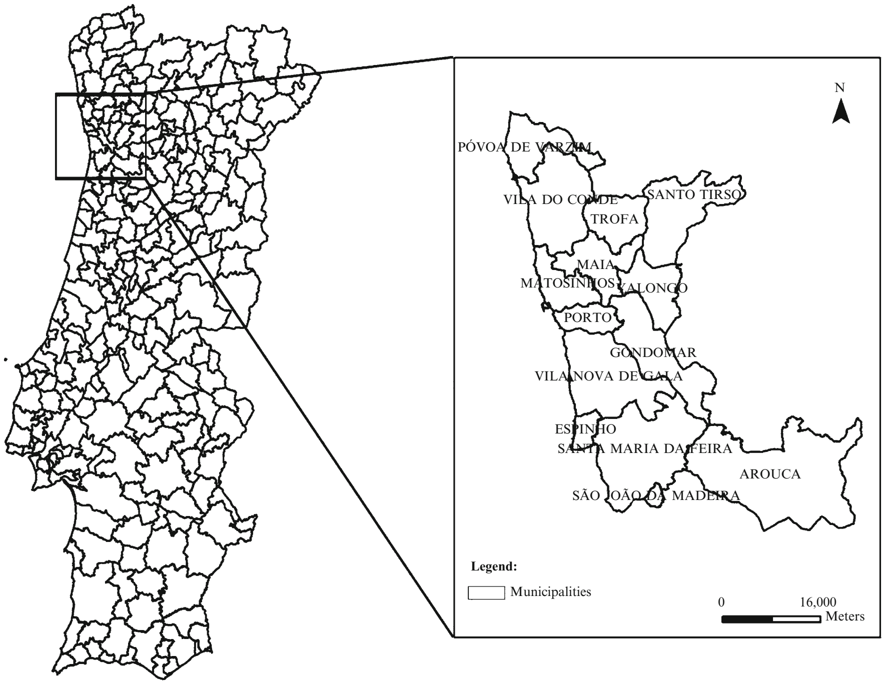

Fig. 2.1 Map of Portugal and Oporto Metropolitan Area

Table 2.1 OMA characterization in area and population (Census 2001)

Municipality	Area (km^2)	(%)	Population	Population density (inhab/km^2)
Espinho	21.1	1.3	33,701	1,596.6
Gondomar	131.9	8.4	164,096	1,244.4
Maia	83.1	5.3	120,111	1,444.7
Matosinhos	62.2	4.0	167,026	2,683.5
Porto	41.3	2.6	256,574	6,214.2
Póvoa de Varzim	82.1	5.2	63,470	773.5
Valongo	75.1	4.8	86,005	1,144.8
Vila do Conde	149.0	9.5	74,391	499.4
Vila Nova de Gaia	168.7	10.7	288,749	1,712.0
Arouca	329.1	20.9	24,227	73.6
Santo Tirso	136.5	8.7	72,396	530.4
São João da Madeira	7.9	0.5	21,102	2,659.4
Santa Maria da Feira	215.1	13.7	135,964	632.0
Trofa	71.9	4.6	37,581	522.8
Total	1,575		1,545,393	981.2

urban solid waste incineration facility. The major point sources in OMA are the Petrogal's Refinery, power plant Turbogás–Central da Tapada do Outeiro, the Solid Waste Treatment Facility (LIPOR II), the National Steel Factory of Maia and the company RAR–Cogeneration (Fig. 2.2).

In this area, apart from seasonal variations in air temperature, there are important variations in wind regime with predominance from northwest in spring (a) and summer (b), from southeast in autumn (c) and from northeast/east in winter (Fig. 2.3).

2.2.2 Emission's Database

The emission's database that was implemented contains carbon dioxide and carbon monoxide (CO) data, but in the study area there are no CO_2 monitoring stations. Therefore, CO data was used to validate the Air Pollution Model (TAPM) (cf. –2.3). As mentioned previously, the database was developed taking into account the public inventory available from APA, submitted to the UNFCCC in 2007, covering the period 1990–2005. The inventory contains information about the total national sources and sinks of several greenhouse gases and other pollutants, grouped in several categories. These categories were regrouped according to the following activity sectors: "Commercial and Institutional", "Residential", "Agriculture, Forestry and

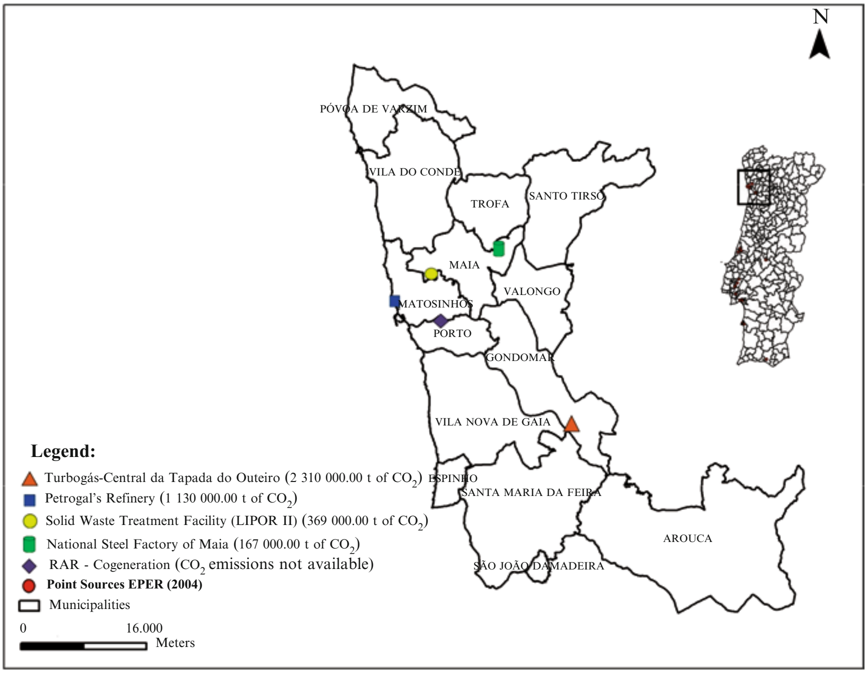

Fig. 2.2 Location and emissions of CO_2 point sources

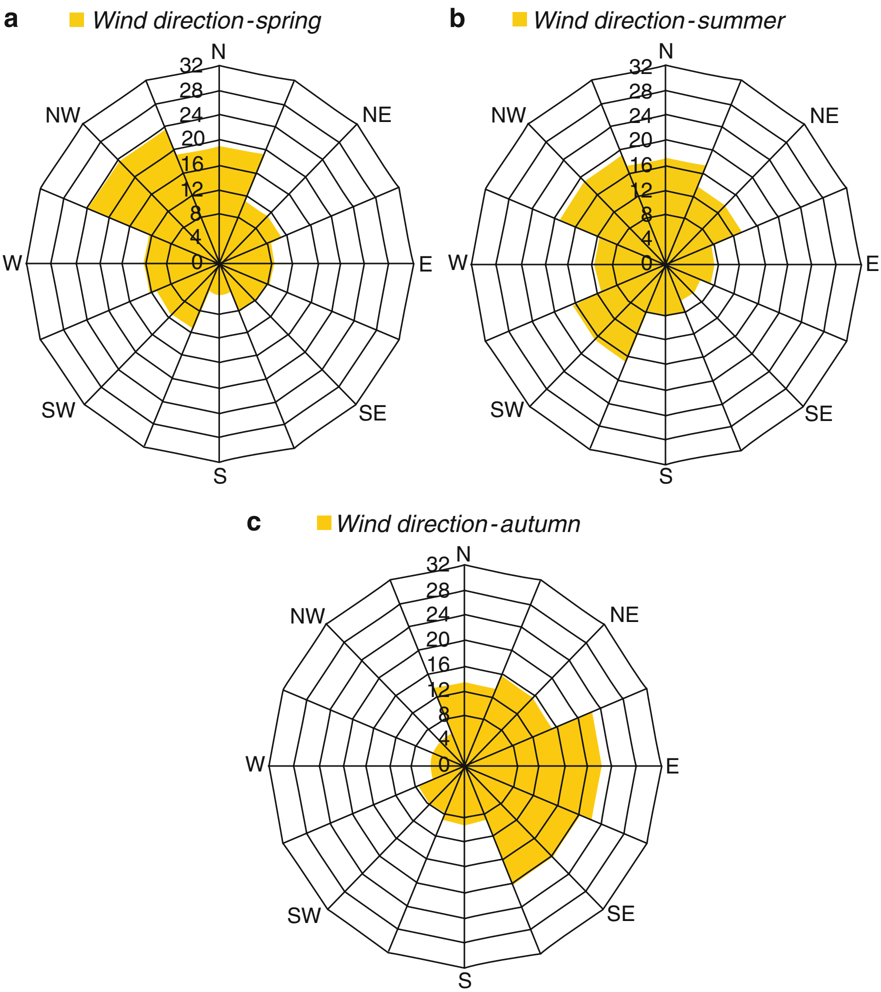

Fig. 2.3 Prevailing wind direction in (**a**) Spring, (**b**) Summer, (**c**) Autumn

Fisheries", "Transport", "Energy Industries" and "Manufacturing industries and construction". The reason for this regrouping was the need to disaggregate the results to different spatial scales according to demographic and other variables.

The emissions database includes only the area emissions. Point source emissions were treated in a different way. Area emissions included the relatively diffuse homogeneous sources that are difficult to identify separately such as: small industries, roads located within the urban perimeter, natural sources, etc.

The APA inventory does not distinguish between these area emissions and point sources. However, EPER has a national registry of industries with the greatest amount of emissions to the atmosphere, considered as point sources in this work. Therefore, large point sources (EPER emissions) were subtracted from the national

Table 2.2 The breakdown of atmospheric emissions in the study area according to sectors and dates

Activity sector	Municipality	Parish
Energy industries	Consumption of fuel oil and natural gas (2004)	Population (2001)
Manufacturing industries and construction	Number of enterprises and companies linked to extractive industry, manufacturing and construction (2004)	Population (2001)
Transport	Staff serving in societies (2004)	Population (2001)
Commercial and Institutional	–	Number of buildings (2001)
Residential	–	Population (2001)
Agriculture, forestry and fisheries	–	Utilized agricultural area (1999)

emission's inventory and allocated to their exact location in the emission's database and respective GIS files. The sectors of activity covered by this operation were "Industries of energy" and "Manufacturing and construction".

The breakdown (Table 2.2) of national emissions to different activity sectors and to the parish level was based on variables contained in the demographic Census survey conducted in 2001 (http://www.ine.pt). However, in some activity sectors ("Energy industries", "Manufacturing industries and construction" and "Transport") it was not possible to disaggregate national emissions directly to the parish level. The breakdown was made taking into account the proportionality between the variables at the national level and the variables at the municipality and/or parish. For example, the breakdown of the "Commercial and Institutional" sector was made directly to the parish level, taking into account the variable "number of buildings". The total number of buildings of the country corresponds to the known total emissions of that sector. By proportionality, the number of buildings of a parish will have its share of emissions.

The "Energy industries" sector emissions were first disaggregated to municipalities based on oil consumption and natural gas and then to the parish level based on population. In both cases a proportionality rule was followed (Table 2.2).

2.2.3 Dispersion Model (TAPM)

The results of the database and larger-scale meteorology provided by synoptic analyses information, representing different seasons (spring, summer, autumn and winter), were used to force the atmospheric model TAPM.

The TAPM uses the followings approaches: it solves approximations to the fundamental fluid dynamics and scalar transport equations to predict meteorology and pollutant concentrations for a range of pollutants important for air pollution applications. It consists of coupled prognostic meteorological and air pollution concentration components, eliminating the need to have site-specific meteorological observations. Instead, the model predicts the flows important to local-scale air pollution, such as sea breezes and terrain-induced flows, against a background of larger-scale meteorology provided by synoptic analyses. The TAPM is a model of air quality that allows a realistic assessment of the dispersion of pollutants and their environmental impact. The model is a versatile tool that can be applied to any location in the world. It predicts all of the required local meteorology, using global terrain and land-use data as well as global synoptic analyses. It can be used to predict meteorological and air pollution parameters at inter-regional, city, or local scales, for simulation periods from a day to a year or more (Hurley 2005b). The diagram depicted in Fig. 2.4 synthesizes TAPM functioning.

The grid used in the model was the 3,000 × 3,000 m² (31 × 31 cells) grid (Fig. 2.5). Vertically, the model considers a domain of 8,000 m, spread across 25 levels of uneven spacing, being closer near the ground, with the first level at a height of 10 m. This was the level considered in this work, the objective being to assess the significance of the

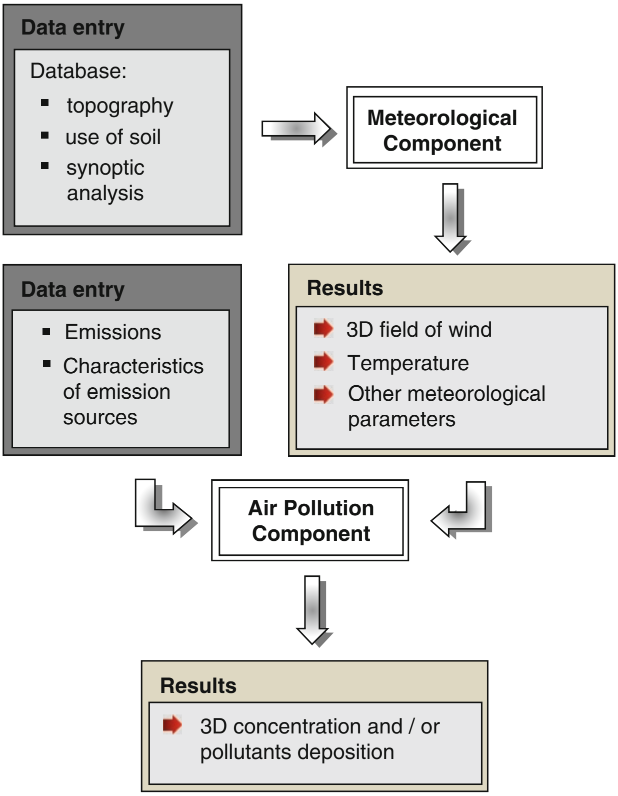

Fig. 2.4 Schematic representation of the Model TAPM (Adapted from Coutinho et al. 2007)

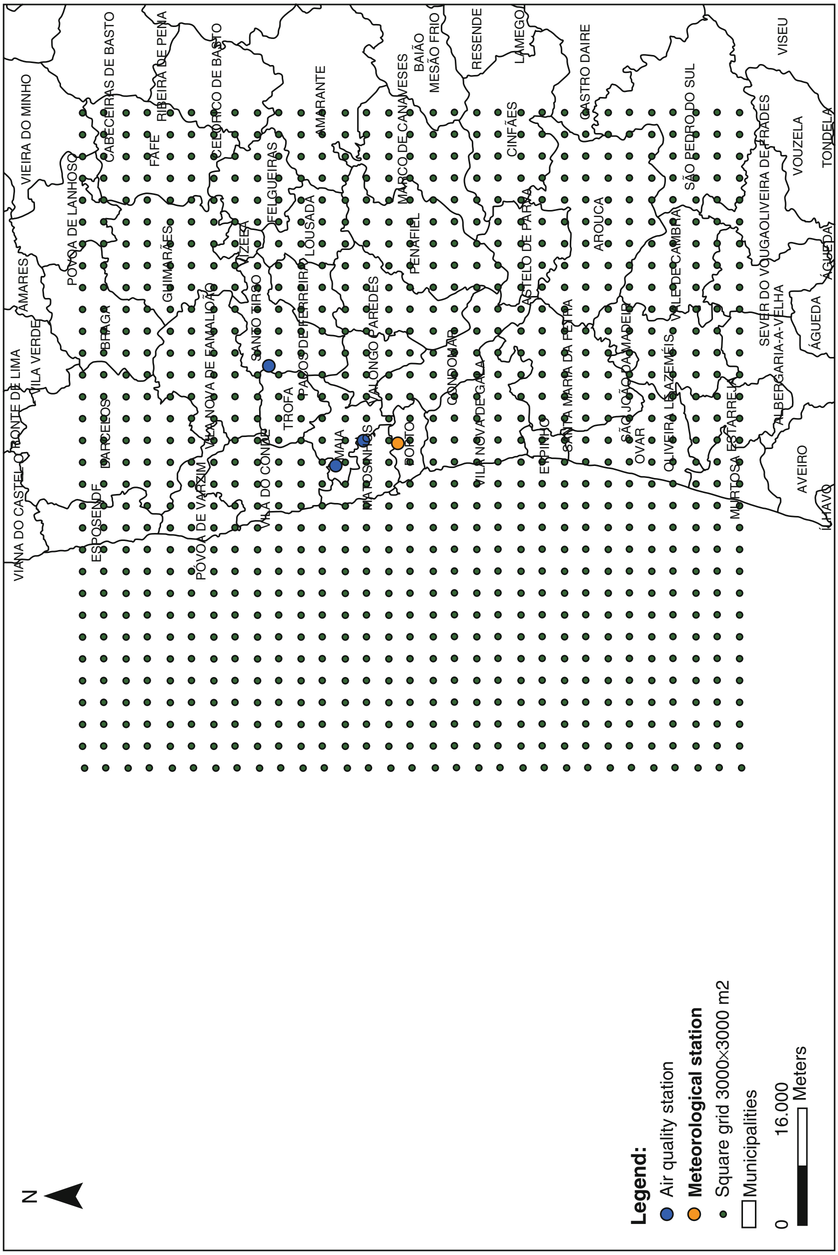

Fig. 2.5 Square grid 3,000 × 3,000 m^2 (186 × 186 cells) and location of the air quality stations and meteorological station

Table 2.3 Simulated periods

Seasonal period	Time period	Predominant wind direction
Spring	02/05/04 to 09/05/04	North (24.7%)/*Northwest* (30.0%)
Summer	15/08/04 to 22/08/04	North (21.3%)/*Northwest* (23.6%)
Autumn	21/11/04 to 28/11/04	Northeast (21.4%)/*Southeast* (28.1%)
Winter	01/02/04 to 29/02/04	Northeast/East/Southeast

increase in CO_2 concentrations on the coastal zone and the CO_2 flows between the ocean and atmosphere.

2.2.3.1 Modelling Scenarios

The modelling scenarios considered in this study included all four seasons with corresponding synoptic forcing for 2004, as depicted in Table 2.3. The start and end dates for each simulation were selected, taking into account the percentage of the prevailing wind direction. For example, the prevailing wind direction in spring is northwest (30.0%). Therefore, the chosen simulation dates corresponded to a time period with predominantly northwest wind. The meteorological data, such as wind speed and wind direction, were taken from a meteorological station located in VCI (Via de Cintura Interna) (Fig. 2.5).

Forcing data corresponds to year 2004, due to data availability constraints. In order to represent these data spatially, it was necessary to use demographic and administrative data from 2001–the most recent census done in Portugal.

2.2.3.2 Model Validation

The validation statistic model BOOT (Chang and Hanna 2005) has been used, mainly, to assess the performance of air dispersion models. However, the same procedures and approaches implemented in BOOT also apply to other types of models. In this validation model the following performance statistics are recommended: fractional bias (FB), geometric mean bias (MG), normalized mean square error (NMSE), geometric variance (VG), correlation coefficient (R) and the fraction of predictions within a factor of two of the observations (FAC2):

$$FB = \frac{\left(\overline{C_0} - \overline{C_p}\right)}{0.5\left(\overline{C_0} + \overline{C_p}\right)};$$

$$MG = \exp\left(\overline{\ln C_0} - \overline{\ln C_p}\right);$$

$$NMSE = \frac{\overline{\left(C_0 - C_p\right)^2}}{\overline{C_0}\,\overline{C_p}};$$

$$VG = \exp\left[\overline{\left(\ln C_0 - \ln C_P\right)^2}\right];$$

$$R = \frac{\overline{\left(C_0 - \overline{C_0}\right)\left(C_P - \overline{C_P}\right)}}{\sigma_{C_P}\sigma_{C_0}};$$

$$FAC2 = \text{fraction of data that satisfy } 0.5 \le \frac{C_p}{C_0} \le 2.0;$$

where:

C_P : predictions of the model

C_0 : observations

$\overline{C}$: average over the data

σ_C : standard derivation of data.

Park and Seok(2007) proposed ranges of values for these parameters, to allow classifying model performance as "Good", "Fair" and "Poor".

The model was validated with meteorological and carbon monoxide (CO) data. CO was used in the absence of CO_2 data because it is a relatively stable pollutant at the time scale of the simulations and, regarding the available data, the most conservative approximation at the present time (Table 2.3).

CO data used in the validation can be accessed at the Internet site of the Portuguese Agency for Environment, Qualar-Database Online on Air Quality (http://www.qualar.org). There are three types of stations, according to the type of influence: traffic, background and industries. The aim of this study is to evaluate the concentrations of CO without direct influence from industry and traffic. Accordingly, stations selected were: Vila Nova da Telha, Santo Tirso and Leça do Balio (Table 2.4).

Wind speed, wind direction and temperature data were taken from a meteorological station located in VCI. Figure 2.5 shows the stations used to validate the results of TAPM.

2.2.3.3 Approaches for Analysing the Significance of Model Predicted CO_2 Changes

The low spatial resolution of CO_2 monitoring turns the evaluation of significance of local and regional scale CO_2 variability into a difficult task. Therefore, in order to evaluate the significance of model predicted CO_2 increments over the coastal area under study, three approaches were followed: (i) Compare predicted spatial concentration gradients across the land-ocean boundary in the study area, with spatial gradients for

Table 2.4 Description of CO stations (http://www.qualar.org 2008) and meteorological station

Name/Parish/ Municipality	Start date	Type of environment/ Influence	Zone	Coordinate X[a] (m)	Coordinate Y[a] (m)	Altitude (m)
Leça do Balio/ Matosinhos	01/01/2000	Suburban/background	Porto Littoral (agglomeration)	158,043	472,397	40
Santo Tirso/ Santo Tirso	01/06/2003	Urban/background	Vale do Ave	171,307	486,432	–
Vila Nova da Telha/ Maia	01/01/1999	Suburban/background	Porto Littoral (agglomeration)	155,690	476,206	88
VCI/Porto	02/04/2004	–	Porto Littoral	158,906	467,238	10

[a]Military coordinates (Gauss)

monitoring stations located at approximately the same latitude; (ii) Compare differences between predicted CO_2 levels over the coastal zone and background concentrations with inter-annual and seasonal variability trends in these concentrations; (iii) Compare differences between predicted CO_2 levels over the coastal zone and background concentrations with the accuracy of CO_2 sensors.

In the first approach, stations located in Azores, Hungary and Romania were selected for calculating spatial gradients (Table 2.5).

In December 2003, the world average CO_2 concentration was around 375.7 ppmv (http://cdiac.ornl.gov). Measurements of CO_2 concentrations were effectively begun in the year of 1958 in Mauna Loa, Hawaii (NOAA1997). The concentration of this gas, in that year, was 315.98 ppmv. The average annual increase in this concentration has been around 0.41%, which means an annual increase of about 1.44 ppm (http://cdiac.ornl.gov).

Data for CO_2 monitoring stations were obtained from the Internet site of the Earth System Research Laboratory – National Oceanic & Atmospheric Administration (http://www.esrl.noaa.gov).

In order to perform the above comparisons, two areas were analysed separately: coastal waters and territorial waters (Fig. 2.6). The former is limited to 1 and the latter to 12 nautical miles offshore.

2.3 Results

2.3.1 Oporto Metropolitan Area–Emissions Characterization

As mentioned in Section 2.2.2, CO_2 emissions were grouped into six activity sectors. Figure 2.7 shows emissions of these activity sectors in 2001 and 2004.

The emissions databases for 2001 and 2004 (Fig. 2.7), suggest that the sectors with the greatest impact on emissions are "Energy industries", "Transport" and "Manufacturing industries and construction", mainly located in the municipalities of Gondomar, Maia and Matosinhos. From 2001 to 2004, the emissions of CO_2 decreased slightly in some sectors, as well as in some municipalities (Fig. 2.7).

Figure 2.8 shows areas, particularly in Gondomar, Maia, Matosinhos and Oporto, with a larger amount of emissions, explained by the location of large point sources such as Petrogal's refinery, Turbogás power plant – Central da Tapada do Outeiro, the Solid Waste Treatment Facility (LIPOR II) and the National Steel Factory of Maia, as mentioned in subchapter 2.1.

2.3.2 Validation of the Results from TAPM

As mentioned in Section 2.2.3.2, the BOOT model was chosen to perform the validation process. The evaluation of statistical parameters regarding CO

Table 2.5 CO_2 stations description (http://www.esrl.noaa.gov)

Station	Type	Longitude	Latitude	Altitude (m)	First measure	Last measure
Terceira Island – Azores	Surface	27.38° O	38.77° N	40	31/12/1979	11/09/2008
Canary Islands – Tenerife	Surface	14.48° O	28.30° N	2,360	16/11/1991	03/10/2008
Mace Head – County Galway – Ireland	Surface	9.90° O	53.33° N	25	03/06/1991	01/09/2008
Black Sea – Constanta	Surface	28.68° E	44.17° N	3	19/10/1994	22/09/2008
Hegyhatsal – Hungary	Surface	16.65° E	46.95° N	248	02/03/1993	30/07/2008
Mauna Loa – Hawaii	Observatory	155.58° O	19.54° N	3	1958	18/11/2008

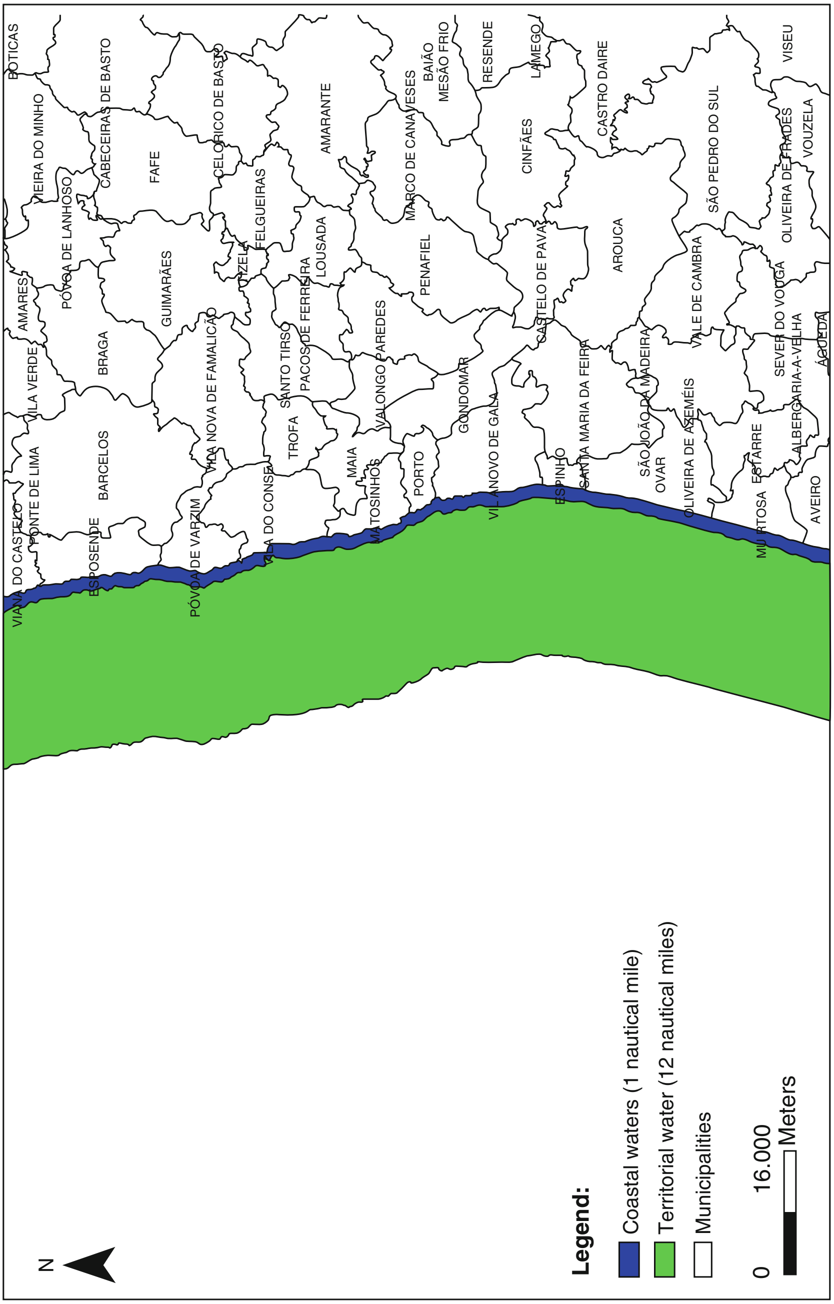

Fig. 2.6 Coastal waters (1 nautical mile – blue area) and territorial waters (12 nautical miles – green area)

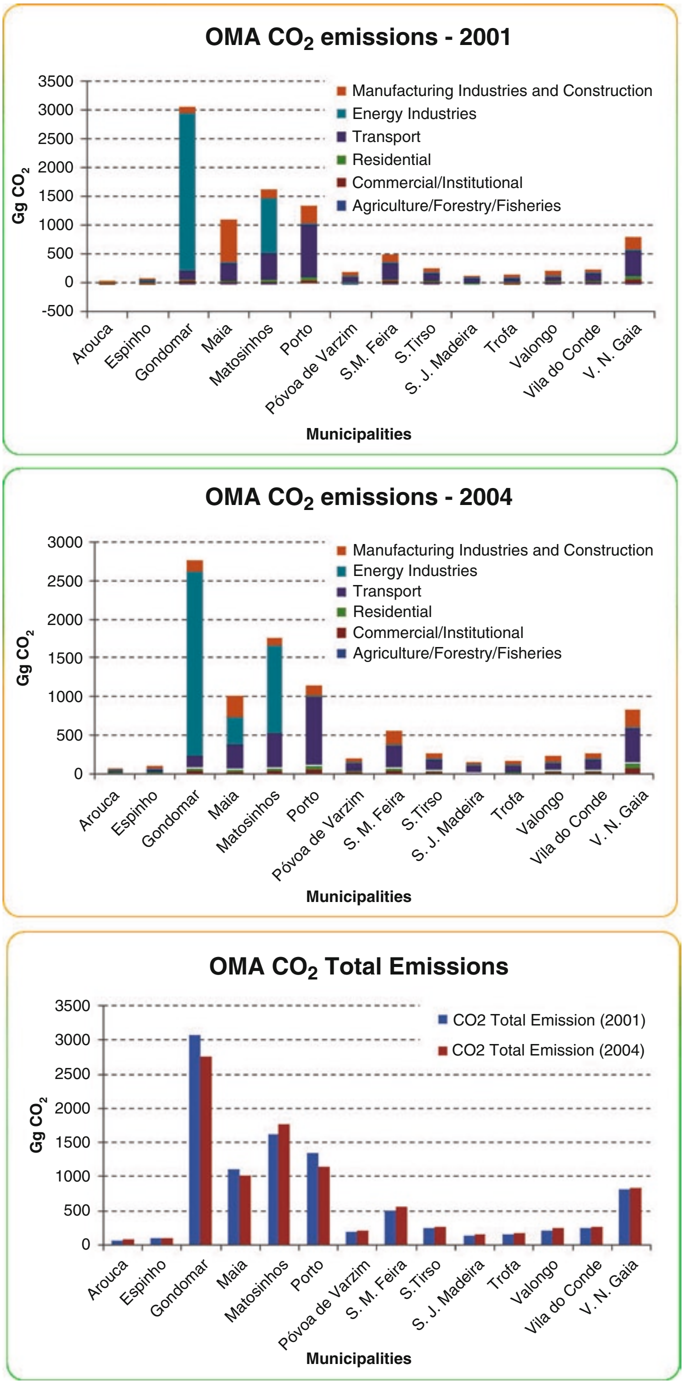

Fig. 2.7 CO_2 emissions (Gg) by activity sectors in 2001 (upper formed) and 2004 (middle formed); CO_2 total emissions (Gg) in 2001 and 2004 (lower formed)

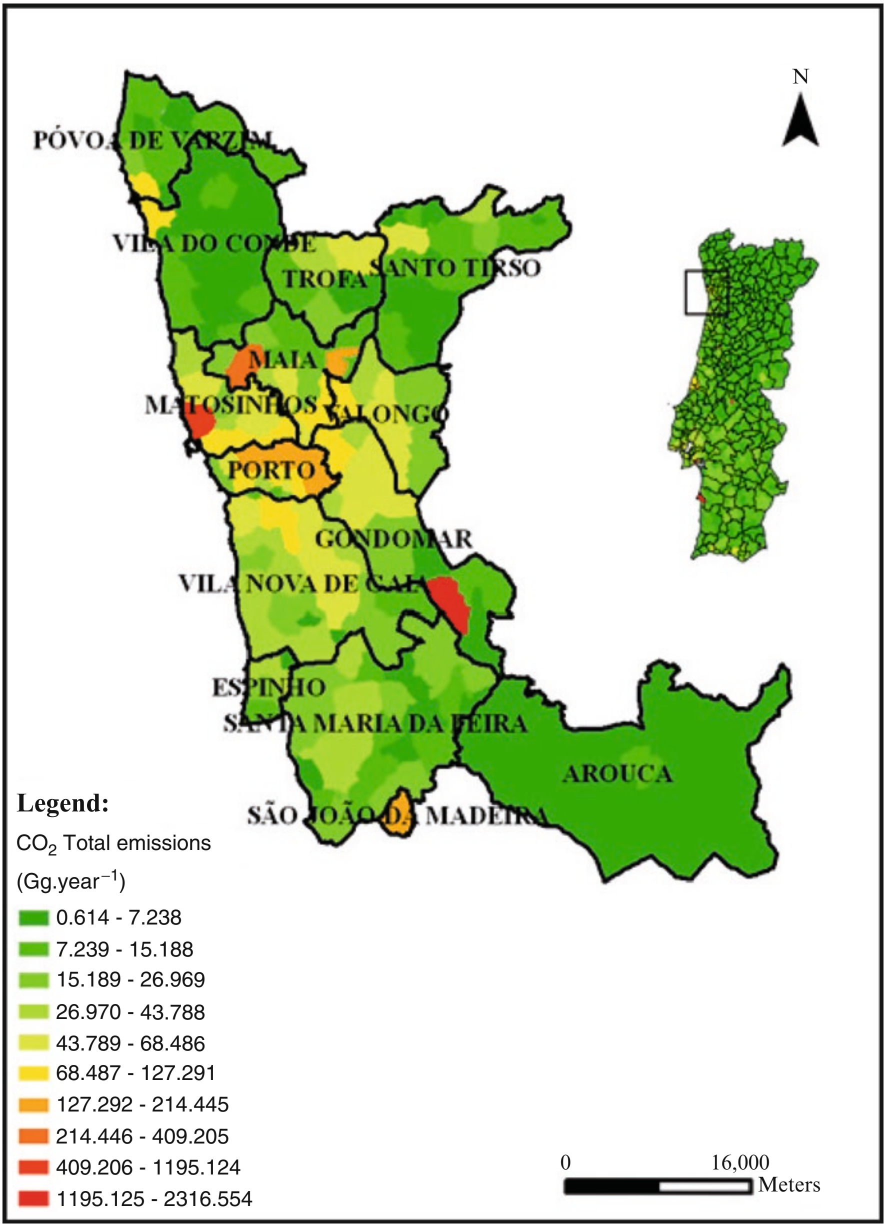

Fig. 2.8 CO_2 total annual emissions from OMA municipalities

concentrations and meteorological parameters simulated for the periods reported in Table 2.3, were good for the former and fair for the latter, according to the BOOT classification scheme (cf. 2.3.2). Figures 2.9 and 2.10 show some examples of observed and simulated data for CO concentration and meteorological parameters respectively.

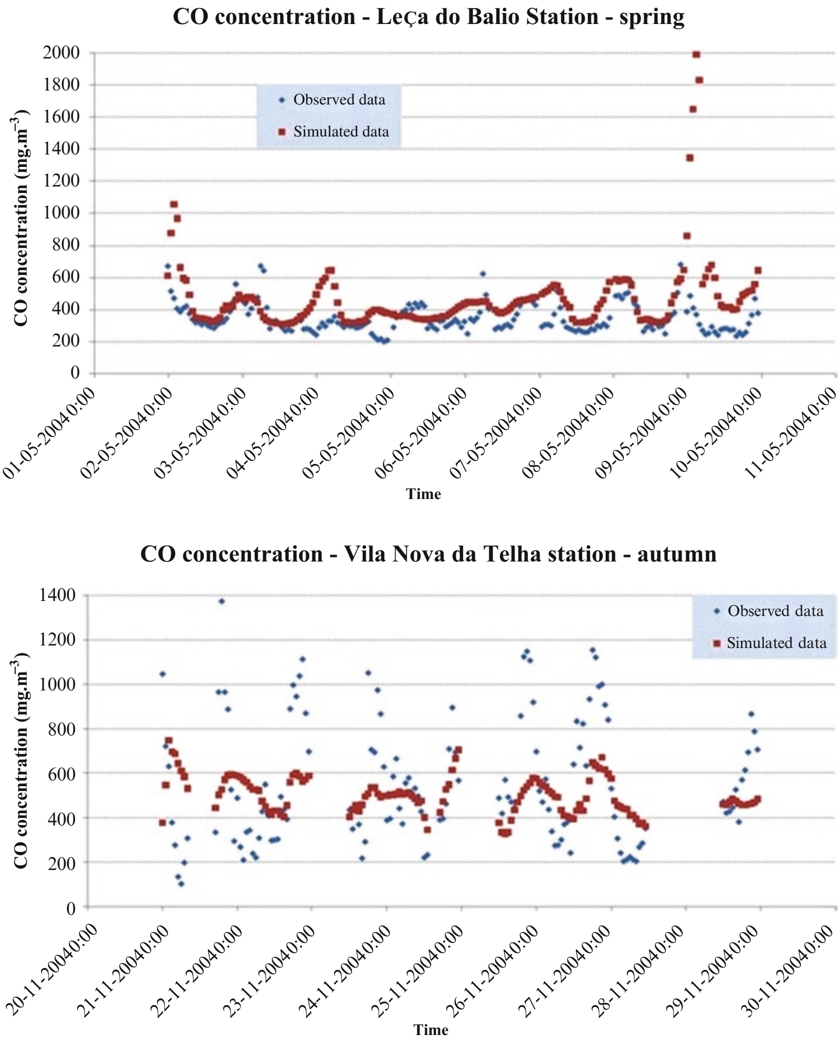

Fig. 2.9 Evaluation's examples between observed and simulated data for CO concentration

2.3.3 TAPM Simulations

Figure 2.11 shows time integrated results from TAPM simulations for different seasons. From these results, it is apparent that the spring and summer concentration plumes, influenced mostly by northwest winds, tend to spread more inland than offshore. However, a weaker southeast wind component explains some offshore transport and dispersion. In autumn and winter, the predominant southeast and east winds are responsible for an important offshore CO_2 transport and dispersion.

It is no surprise that OMA emissions have some influence over the nearby coastal zone, as shown in Fig. 2.11.

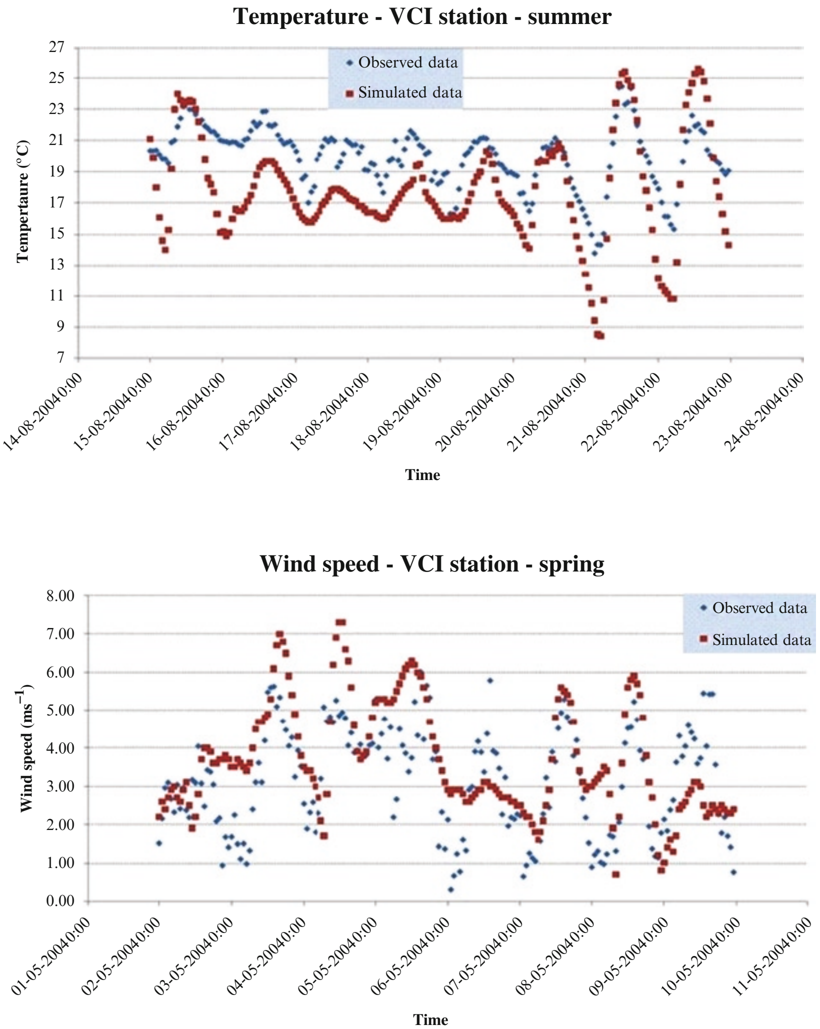

Fig. 2.10 Evaluation's examples between observed and simulated data for meteorological parameters

However, the important issue is to evaluate whether or not this influence is significant. In item 2.3.3, three approaches were mentioned to evaluate the significance of increases in CO_2 concentrations compared to the background concentration.

(i) Spatial gradients

Comparing the concentration gradient between stations (Table 2.6) (order of magnitude 10^{-3} ppm km^{-1}) with gradients of concentrations generated by TAPM (Table 2.7) (order of magnitude 10^{-1}–10^{-3} ppm km^{-1}), it appears that the latter are considerably higher than the former, regardless of the seasonal period, with only a few exceptions (Table 2.7). In the autumn, model predicted gradient is much higher for the seasons. As expected, the predicted gradient decreases offshore.

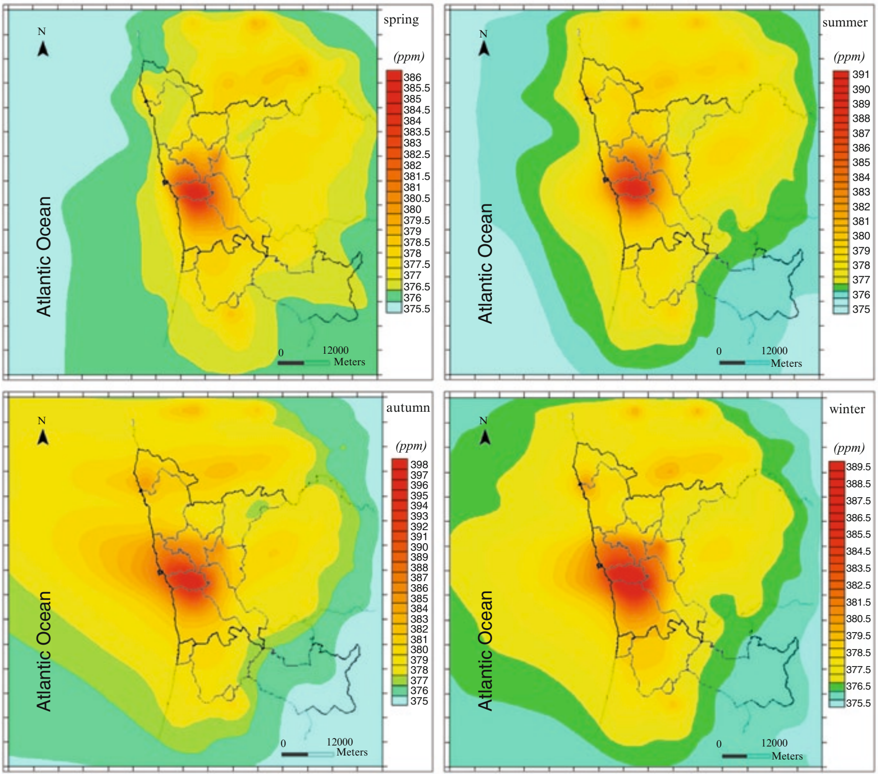

Fig. 2.11 CO_2 concentrations in the atmosphere in the study area

Table 2.6 Concentrations gradients between some stations (http://www.esrl.noaa.gov)

Stations	Distance (km)	Spatial concentrations gradient (ppm km^{-1})
Azores – Romania	4,618.60	2.40×10^{-3}
Hungary – Romania	922.11	6.99×10^{-3}

(ii) Predicted CO_2 levels and temporal variability

Table 2.8 shows the average concentrations and increased average suffered on the average tropospheric concentration in 2003, on “coastal waters” and “territorial waters”, during the season’s winter, spring, summer and autumn.

The inter-annual atmospheric CO_2 increase is around 1.74 ppm, corresponding to approximately a 0.41% increase. Model results suggest a potential CO_2 increase over the studied area that, on several occasions is larger than those figures, in winter, summer and autumn, within the 12 mile limit.

However, when the percent increases predicted by the model are compared to CO_2 seasonal coefficient variation, it is clear that the latter are much higher (Table 2.9).

Table 2.7 Concentrations gradient of TAPM between areas

		Seasonal period			
		Winter	Spring	Summer	Autumn
Zone		Spatial concentrations gradient (ppm km^{-1})			
Territorial waters	Between the shore to 3 miles offshore	2.32×10^{-1}	1.21×10^{-1}	2.58×10^{-1}	3.13×10^{-1}
	Between 3 and 6 miles offshore	8.77×10^{-3}	3.02×10^{-2}	7.76×10^{-2}	1.25×10^{-1}
	Between 6 and 12 miles offshore	4.59×10^{-3}	1.75×10^{-2}	5.01×10^{-2}	8.11×10^{-2}
Outside the territorial waters	Between 12 and 26 miles offshore	2.48×10^{-3}	6.89×10^{-3}	1.95×10^{-2}	5.37×10^{-2}

Table 2.8 Increasing concentrations of CO_2 in the zone "coastal waters", "territorial waters" and beyond that zone

		Seasonal period			
		Winter	Spring	Summer	Autumn
Zone		Average concentration (ppm)/percentage (%)			
Coastal waters	Between the shore to 1 mile offshore	379.01/0.88	376.71/0.27	378.22/0.67	381.47/1.56
Territorial waters	Between the shore to 3 miles offshore	378.40/0.72	–	377.60/0.50	380.57/1.30
	Between 3 and 6 miles offshore	377.74/0.54	–	376.91/0.32	379.67/1.06
	Between 6 and 12 miles offshore	377.23/0.41	–	376.41/0.19	378.89/0.85
Outside the territorial waters	Between 12 and 26 miles offshore	376.80/0.29	–	375.96/0.07	377.81/0.56

Table 2.9 Temporal variability of CO_2 concentrations in the stations in 2004 and seasonal variation coefficient (winter vs. summer) of CO_2 concentrations in the stations since the beginning of its activity

	Stations				
	Terceira Island Azores	Canary Islands Tenerife	Mace Head County Galway Ireland	Black Sea Constanta Romania	Hegyhatsal Hungary
	Concentration (ppm)				
Winter (February)	380.34	378.63	381.74	390.01	392.47
Spring (May)	380.49	379.36	381.21	382.61	376.79
Summer (August)	371.89	373.59	369.48	384.29	368.09
Autumn (November)	376.66	376.75	377.69	396.34	393.79
Seasonal variability	8.45	5.04	12.26	5.72	24.38
Seasonal variation of concentrations coefficient (%)	2.61	1.77	3.57	4.87	7.61

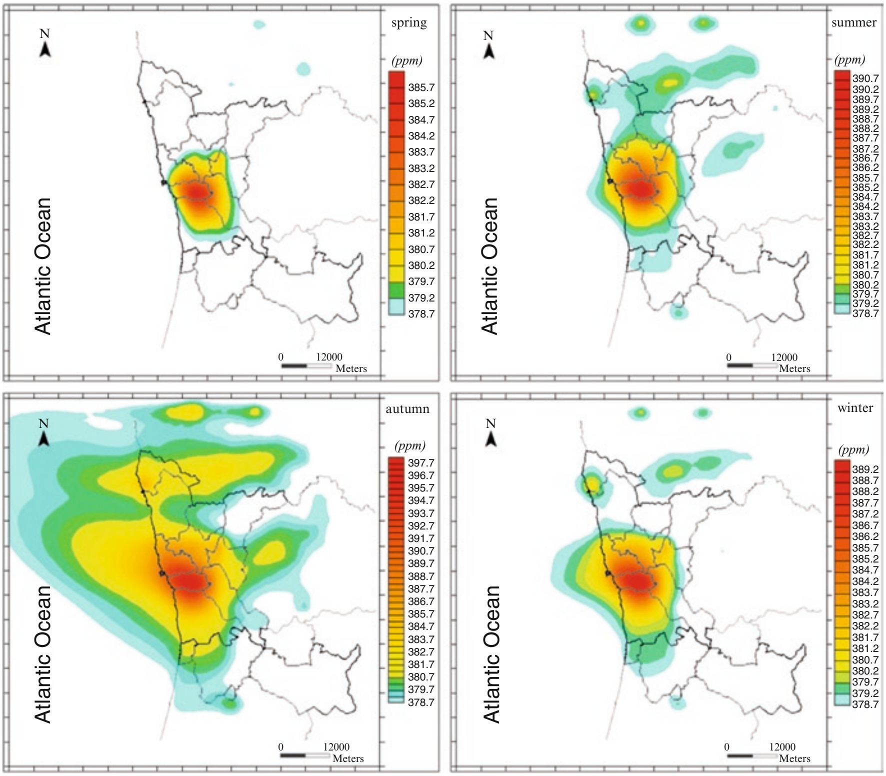

Fig. 2.12 Differences between expected concentrations and the average tropospheric concentration of atmospheric CO_2, higher than the sensitivity of the measuring CO_2 apparatus

(iii) Predicted CO_2 changes and accuracy CO_2 probe sensitivity

The measurement error of currently available CO_2 probe sensitivity is between ±0.5 and ±1 ppm. Figure 2.12 shows the locations where predicted concentrations are above the indicated accuracy.

This figure suggests that in spring and summer the model predicted influence of emissions from OMA on the adjacent coastal zone is hardly detected with present day technology. However, the same figure suggests the opposite for autumn and winter. Particularly in autumn, the "measurable" influence is over most of the model domain.

2.4 Discussion

Model simulations results presented before suggest that the CO_2 plume produced over the OMA may have an important offshore shift in winter and autumn as a result of the dominant wind offshore component. However, the main challenge here is trying to evaluate the significance of this effect over tropospheric CO_2 concentrations. In the absence of nearby CO_2 monitoring stations, comparisons between CO_2 model predicted increases at various distances offshore, on one hand, and spatial and temporal CO_2 variability data, on the other hand, suggest that OMA may produce a local "bump" on CO_2 levels with increases over the sea, within the 12 miles limit, that are above inter-annual CO_2 variability but below CO_2 seasonal variability. Furthermore, in winter and, specially, in autumn the predicted concentration changes are detectable by current CO_2 measuring technology. Therefore, it is practicable to empirically test these model results.

From the above reasoning, it seems likely that the OMA may exert, at least, a measureable change on CO_2 concentrations over nearby coastal areas within a limited distance offshore (<12 miles). The next logical step is trying to anticipate the potential that these CO_2 increases may have in influencing CO_2 air–sea exchanges and the sink-source CO_2 rate of the coastal area under study.

2.5 Conclusions

Obtained results, based on the atmospheric mesoscale model (TAPM), suggest that the OMA has a significant impact on atmospheric CO_2 concentrations over the adjacent coastal zone up to c.a. 12 miles offshore. Consequently, a similar result may be expected for other metropolitan areas.

Therefore, obtained results support the initial hypothesis, stressing the need for further studies about their potential implications on CO_2 sinking capacity of coastal zones. A natural follow-up to this study would be an empirical assessment of CO_2 concentrations over the adjacent coastal area under different seasonal and synoptic forcing and their consequences on CO_2 air–sea exchanges.

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