USING A CFD MODEL TO ASSESS THE IMPACT OF CRUISE SHIP EMISSIONS ON THE FAÇADES OF WATERFRONT BUILDINGS IN NAPLES, ITALY

FABIO MURENA[1], BENEDETTO MELE[2] & DOMENICO TOSCANO[1]
[1]Department of Chemical, Materials and Production Engineering University of Naples "Federico II", Italy
[2]Department of Industrial Engineering University of Naples "Federico II", Italy

ABSTRACT

The port of Naples, with about 1 million of cruise passengers corresponding to about 400 calls and 5000 hours at berth per year, is one the most important in the Mediterranean Sea for cruise ships traffic. Therefore, cruise ship emissions can have an important impact on air pollution in Naples. Moreover, cruise ships terminal is very near to the center of the town, with some residential and commercial buildings at only about 200 m from cruise ships docks. The height of these buildings is very close to that of cruise ship funnels. Therefore, the impact of cruise ship emissions on the façades of these buildings may be very high, with negative consequences for indoor air quality and health of people living or working in these buildings. For this reason, a CFD model has been developed with the aim to assess the impact of atmospheric pollutants emitted by cruise ships at hoteling on the façades of the nearest buildings. A calculation domain of about 7 km^2 and 1 km height with 10 million cells has been created. Unsteady CFD simulations have been carried out adopting the Scale Adaptive Simulation (SAS) hybrid model that allows a satisfactory accuracy in the calculation of the turbulence. Most critical emissive scenarios have been identified based on cruise ships traffic assuming wind flowing from cruise ships at berth toward the buildings. Emission rates of each pollutant and each cruise ship, during the hoteling phase, have been evaluated. These data were used as input for CFD simulations. As a result, contour maps of SO_2 on the ground and on the buildings' façade were obtained. Results of CFD model are compared with results of simulations with CALPUFF.
Keywords: cruise ship emissions, hoteling, CFD, SO_2.

1 INTRODUCTION

Health risk associated with exposure to high concentration of pollutants in urban areas have led to increased researches. The assessment of air pollution at urban scale can be tackled by one of three approaches, or a combination of these: field measurements, wind tunnel measurements, and simulation with dispersion models.

Dispersion models are now widely used for assessing roadside air quality by providing predictions of present and future air pollution levels as well as temporal and spatial variations. In recent years the use of these models is growing rapidly. In fact, they can be very useful in giving insights into the physical and chemical processes that govern the dispersion and transformation of atmospheric pollutants.

The air quality models can be divided into two main categories: operational and numerical models. Operational models (OSPM, SIRANE, ADMS-Urban, etc.) have been developed as relatively simple tools at local or urban scale requiring not high computational resources. The main problem of operational models is their validation, as they include several empirical parameters often derived from experimental data. Moreover, the validity of results is limited to street geometries and dispersion conditions like those for which the validation was carried out [1]. In fact, building geometry, street dimensions, building packing density, wind speed and direction, thermal stratification, etc., all influence the pollutants concentration at a given site.

WIT Transactions on Ecology and the Environment, Vol 230,
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/AIR180171

The numerical models describe the main phenomena (fluid dynamics, thermal effects, mass transfer, chemical reaction and turbulence) determining the pollutant dispersion at local, regional or global scale. Among them CFD models are based on the numerical solution of the governing fluid flow and dispersion equations, which derive from the fundamental conservation and transport principles: (a) the mass conservation equation (continuity), (b) the Navier–Stokes equations; and (c) the transport equation for the concentration of pollutants. Due to the high computational time needed, CFD studies in urban areas are limited to a few street canyons but comparison with real data are often satisfactorily: Neofytou et al. [2], Galani et al. [3]; Murena et al. [1]; Di Sabatino et al. [4].

Recently many papers have been published concerning the assessment of the impact of ship emissions on the nearby urban areas using dispersion models. For example, Merico et al. [5] have studied air quality shipping impact in the Adriatic/Ionian area focusing on Brindisi and Venice (Italy), Patras (Greece), and Rijeka (Croatia) using a WRF-CAMx modelling system. Poplawski et al. [6] have used CALPUFF model to investigate the impact of cruise ship emissions on level concentrations of some pollutants in James Bay, Victoria, British Columbia (BC), Canada. The same model CALPUFF was used to assess the impact on local air quality due to atmospheric emissions of a new port in project in the Mediterranean Sea [7].

Studies using CFD models to assess the impact of ship emissions in port are until now very rare. The objective of this study is to assess the impact of cruise ships emissions in the port of Naples on nearest buildings using a CFD model.

2 METHODOLOGY

2.1 The CFD model

The Municipality of Naples extends for 119.02 km^2 with 970.185 residents and with a density of 8.151 inhabitants/km^2 (www.ISTAT.it). The port of Naples is formed by a total of 75 berths divided between terminals for hydrofoils and small ferries, cruise ships, ferries and commercial vessels. Cruise ships stop at "Stazione Marittima" terminal in correspondence of berths indicated with letters A, B and C in Fig. 1. As can be observed nearest residential buildings are at only about 200 meters from this terminal (Fig. 1) downwind in the NW direction.

The computational domain of the CFD model extends for an area of about 7 km^2 with a height of 1 km (see Fig. 2). The computational grid counts about 10 million tetrahedral cells with prism layers fitted near the walls to have an accurate description of the boundary layer. The unsteady incompressible formulation of Navier-Stokes equations has been adopted with species transport (air-SO_2 mixture) neglecting chemical reactions. Turbulence in the numerical simulations has been modelled adopting the SAS (Scale Adaptive Simulation) model by Menter and Egorov [8]. Second order central numerical scheme in space and time has been used. The SAS model is a hybrid turbulence model that allows a variation of solution from an LES type to URANS type depending on the time step size and grid resolution in such a way that URANS solution is adopted when the grid and time resolution are not sufficient to resolve the turbulence scales. The model is particularly useful when a LES grid and time step cannot be maintained in the whole computational domain such as in the case of a wide computational domain. The SAS model has been used with success by Murena and Mele [9] and [10] for street canyon flows.

The boundary conditions are velocity inlet at the inflow and outflow conditions with extrapolated variables at the outlet that depend on the wind direction (described in the next section) with respect to the computational domain. Symmetry boundary condition has been set on the top of computational domain and mass flow inlet (see Table 2 in Section 3) at the source points (funnels of the ships).

3 DEFINITION OF THE INPUT CONDITIONS

As shown by the wind rose diagram in Fig. 3, the prevailing wind directions in Naples are from SSW-W and N-NE, with the most frequent wind velocity between 1 to 3 m/s. Much less frequent are observations of wind blowing from E-SSE directions. This pattern is quite homogenous in the different seasons.

Figure 1: Map of Municipality of Naples (yellow line) and its port with indication of berthing points (A, B and C) of cruise ships. Buildings described in the CFD are inside the white line (bottom map).

www.witpress.com, ISSN 1743-3541 (on-line)

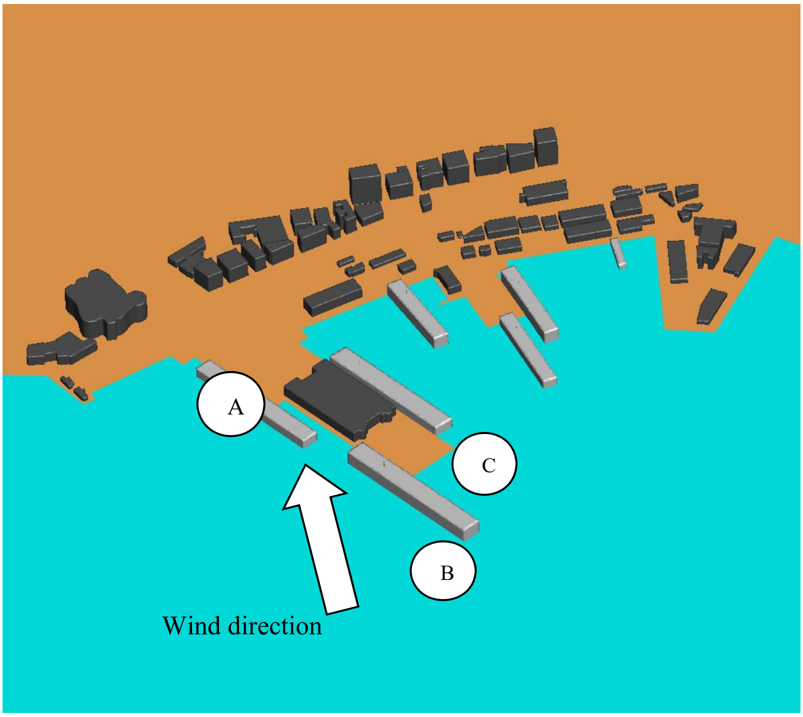

Figure 2: Computational domain. Cruise ships at berth are in grey in correspondence of letters A, B and C indicating mooring points. Other grey boxes are ferries boat whose emissions are not considered in present simulations.

To define the emissive scenario as input of the CFD model, the cruise ship's arrive/departure calendar was examined with the aim to evaluate the number of hours during which one or more cruise ships were at berth. The cruise ships' traffic depends on the seasons of the year. The activity is at a maximum from May to October with a peak in September, while minimum is in the winter season from December to March. Daily pattern during the year is quite constant: cruise ships arrive in the port of Naples at 7:00 or 8:00 a.m. and leave after about 10–12 hours.

The presence of one or more cruise ships at the different berths is reported in Table 1 in terms of hours at hoteling in the year. The most frequent figure (1184 hours in the year) corresponds to the presence of a single cruise ship at berth C. But the simultaneous presence of three cruise ships (A+B+C), with 284 hours in the year, is also quite frequent.

The most critical emissive scenario was then selected to run the CFD model: presence of three cruise ships at berths A, B and C; wind blowing from SE with speed of 1.5 m/s.

To evaluate emission rates of atmospheric pollutants the three cruise ships simultaneously present at berth have been selected among those with the most frequent simultaneous presence in the port of Naples. Their main characteristics are reported in Table 2. The emission rates have been calculated both for NO_x and SO_x as the product of respective emission factors [11] multiplied for the power applied in the hoteling phase by each ship (Table 2). The S content in fuel was assumed at 0.1% wt in consequence of a deliberation of the Port Authority of Naples.

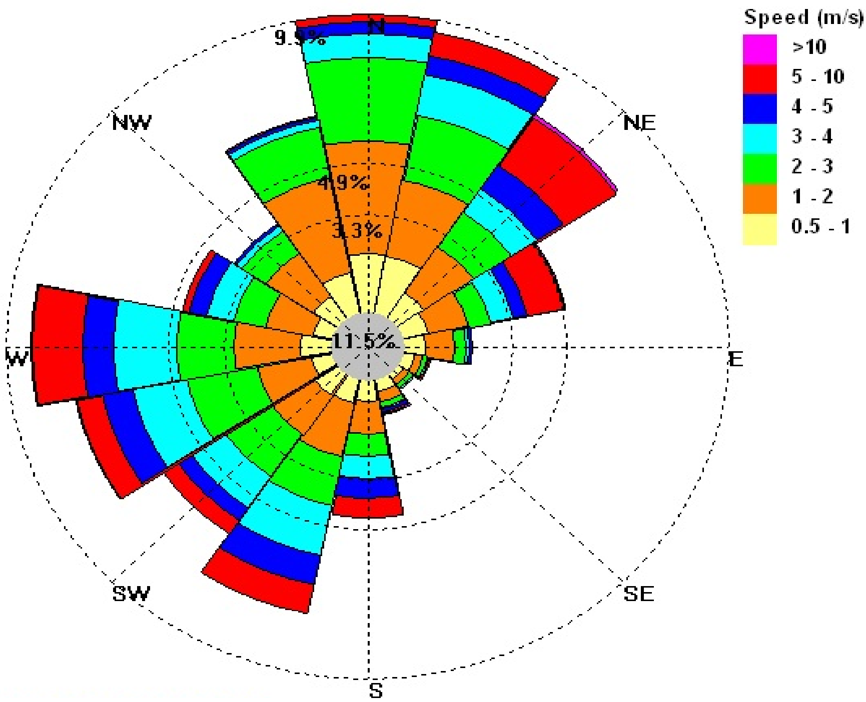

Figure 3: Wind rose at h = 10 m in Naples obtained from data of year 2016.

Table 1: Distribution of hoteling hours as function of berths occupancy in 2016.

Berth	A	B	C	A+B	B+C	A+C	A+B+C
Hotelling hours in 2016	104	698	1184	124	718	81	284

Table 2: Main characteristics of cruise ships assumed at berth for CFD simulations. Emission rates correspond to hoteling phase. GT= gross tonnage, H=funnel height; D=funnel diameter.

Berth	Length [m]	GT [t]	H [m]	D [m]	Power at hoteling [kW]	So_x [g/s]	NO_x [g/s]
A	268	73529	30	0.9	2822	0.34	10.19
B	330	155873	40	1.5	7596	0.92	27.43
C	293	90090	30	1.5	7415	0.89	26.78

In present CFD simulations only the impact of SO_x emission was studied. SO_x emissions were assumed corresponding to SO_2 and no reaction process was simulated by the CFD model.

4 RESULTS

Results of CFD simulations are reported in Fig. 4 in terms of distribution of SO_2 mass concentration at ground and on the surfaces of buildings. The greatest values of SO_2 concentration are observed nearby the emissive sources and on the port front façades of the first line of buildings. The presence of buildings influences the air flow leading the pollutants toward the open space (a large square) on the left of the line of building (Fig. 4).

A contour map is reported in Fig. 5 to better show the impact of cruise ships SO_2 emissions on the port front façades of first line buildings.

Results obtained with the CFD model are compared with those obtained with CALPUFF and reported in Figs 6 and 7. As can be observed concentration levels are quite similar. CFD seems to indicate higher SO_2 peak concentration at ground level (50 $\mu g/m^3$ vs 20 $\mu g/m^3$) and a minor distance of maximum concentration area to emission sources (funnels). Another difference between the results of the two models is the direction of ship emissions that in CFD calculation are deflected by buildings toward west direction due to the presence, as reported before, of a large open space (a square). As a consequence, following the CFD model, the highest impact on building façades is shifted on the left side (compare Fig. 5 with Fig. 7) of the buildings. But the maximum SO_2 concentration on building façades obtained

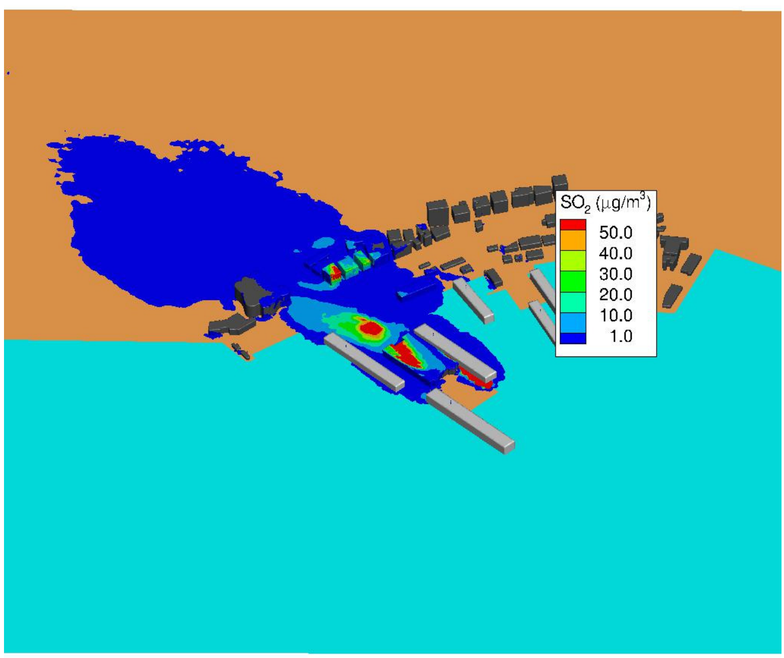

Figure 4: CFD – Distribution of SO_2 concentration [$\mu g/m^3$] in the calculation domain at ground level and on the surfaces of buildings.

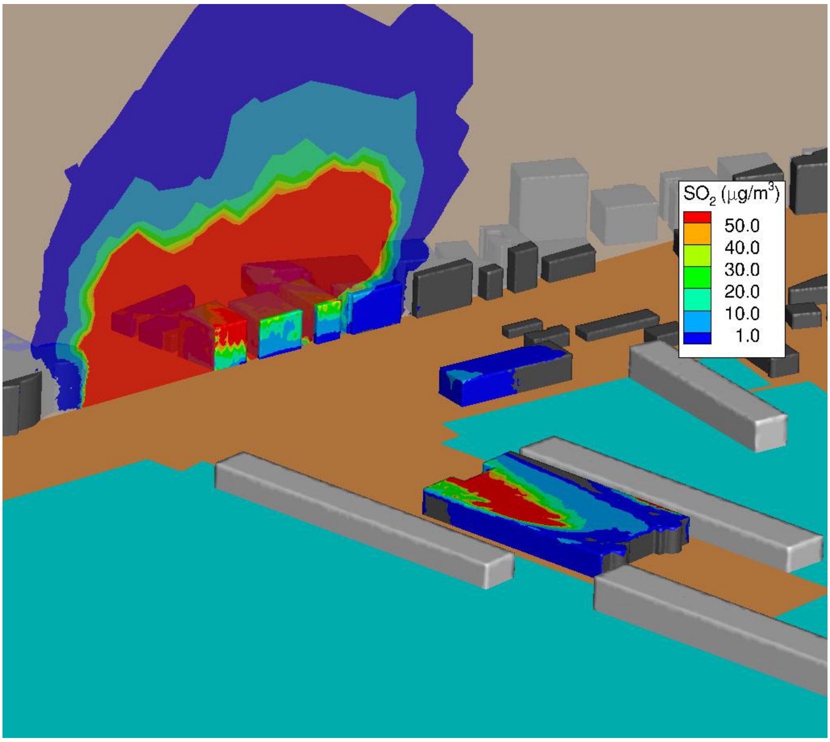

Figure 5: CFD – Contour map of SO_2 concentration at front port façades of first line buildings.

with the two models are very similar ≈ 50 μg/m^3. Even though, a definitive validation can be obtained only with experimental data, the good comparison of the results of the two models is promising.

5 CONCLUSIONS

CFD models could be very useful to more accurately assess the impact atmospheric emissions of ships on urban areas near to berths or terminals. In this case, the impact of SO_2 emitted from cruise ship funnels, during the hoteling phase in the port of Naples, has been modelled using a SAS (Scale Adaptive Simulation) model. Results show that the impact on the nearest area (few hundred meters) can be significant. In fact, concentration levels of about 50 μg/m^3 of SO_2 at ground level and at building façades have been estimated by the CFD model.

S content in the fuel was assumed = 0.1 wt% because of a deliberation of the Port Authority of Naples. In the case of use of fuels with higher S content, as in the past, even more than ten times SO_2 concentration could be expected! Comparison with CALPUFF simulations confirm the validity of results. Monitoring campaigns are necessary for a complete validation of CFD simulations. Results obtained are relative to the most critical emissive and meteorological scenarios. Therefore, on the average the real impact would be lower. On the contrary, only cruise ship emissions have been considered. Terminals of other categories of passenger ships (ferry boats, hydrofoils etc.) are quite close to cruise ship terminals. Therefore, in this case an additive effect could take place.

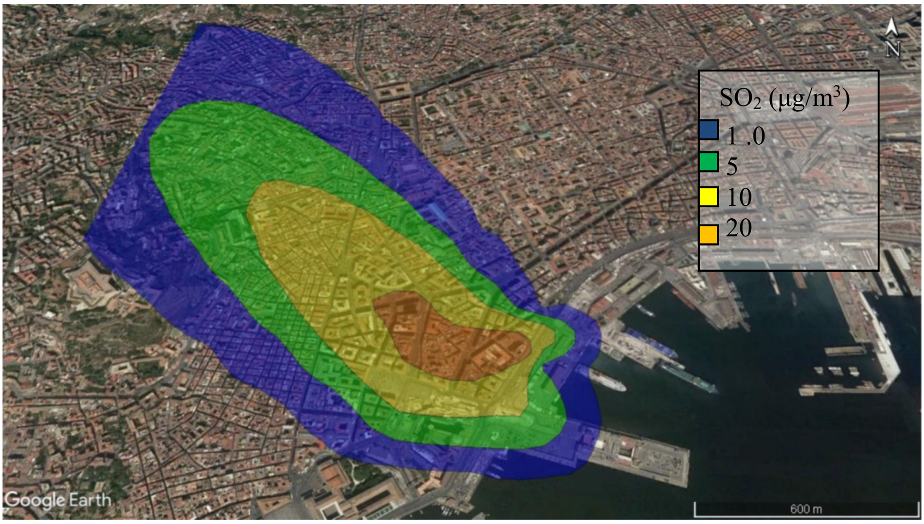

Figure 6: CALPUFF – Contour map of SO_2 concentration at ground level.

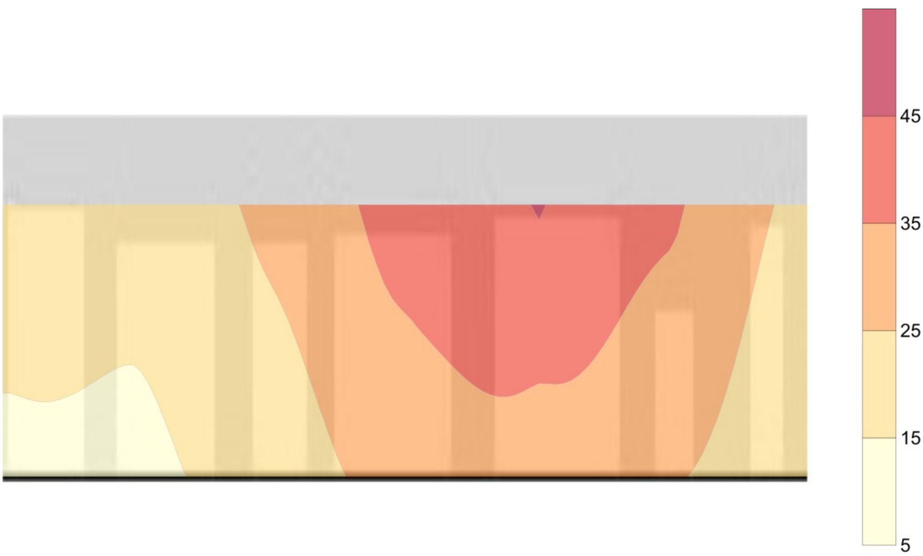

Figure 7: CALPUFF – Contour map of SO_2 concentration at front port façades of first line buildings. The buildings' aspect ratio is not in scale.

REFERENCES

[1] Murena, F., Favale, G., Vardoulakis, S. & Solazzo, E., Modelling dispersion of traffic pollution in a deep street canyon: Application of CFD and operational models. *Atmospheric Environment*, **43**, pp. 2303–2311, 2009.

[2] Neofytou, P., Haakana, M., Venetsanos, A., Kousa, A., Bartzis, J. & Kukkonen, J., Computational fluid dynamics modeling of the pollution dispersion and comparison with measurements in a street canyon in Helsinki. *Environ Model Assess*, **13**, pp. 439–448, 2008. DOI: 10.1007/s10666-007-9110-x.

[3] Galani, A., Neofytou, P., Venetsanos, A., Bartzis, J. & Neville, S., Prediction and study of pollutant dispersion in a street canyon in London using computational fluid dynamics techniques. *Global NEST Journal*, **11**, pp. 434–439, 2009.

[4] Di Sabatino, S., Buccolieri, R., Pulvirenti, B. & Britter, R.E., Simulations of pollutant dispersion within idealised urban-type geometries with CFD and integral models. *Atmospheric Environment*, **41**, pp. 8316–8329, 2007.

[5] Merico, E. et al., Atmospheric impact of ship traffic in four Adriatic-Ionian port-cities: comparison and harmonization of different approaches. *Transp. Res. Part D: Transp. Environ.*, **50**, pp. 431–445.

[6] Poplawski, K., Setton, E., McEwen, B., Hrebenyk, D., Graham, M. & Keller, P., Impact of cruise ship emissions in Victoria, BC, Canada. *Atmospheric Environment,* **45**, pp. 824–833, 2011.

[7] Lonati, G., Cernuschi, S. & Sidi, S., Air quality impact assessment of at-berth ship emissions: case-study for the project of a new freight port. *Science of the Total Environment*, **409**, pp. 192–200, 2010.

[8] Menter F.R. & Egorov, Y., The scale-adaptive simulation method for unsteady turbulent flow predictions. Part I. Theory and model description. *Flow. Turbul. Combust.,* **85**, p. 113, 2010. DOI: https://doi.org/10.1007/s10494-010-9264-5.

[9] Murena, F. & Mele, B., Effect of short-time variations of wind velocity on mass transfer rate between street canyons and the atmospheric boundary layer. *Atmos. Pollut. Res.*, **5**, pp. 484–490, 2014.

[10] Murena, F. & Mele, B., Effect of balconies on air quality in deep street canyons. *Atmos. Pollut. Res.*, **7**, pp. 1004–1012, 2016.

[11] EMEP/EEA, International Maritime Navigation, International Inland Navigation, National Navigation (Shipping), National Fishing, Military (Shipping), and Recreational Boats, 2016.