Modeling pollutant dispersion at the city and street scales: from wind tunnel experiments to complex network theory

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Summary

Air pollution in urban areas is a major concern for the health and safety of citizens. Hubs of economic, political and social activities, cities are densely populated and are exposed to a large number of pollution sources. These factors, together with the risk of malicious acts for terrorist purposes, make them extremely vulnerable to gaseous releases. To predict and manage air pollution scenarios, the understanding and modelling of dispersion phenomena in the urban atmosphere is crucial. Differently from transport processes far from boundaries, flow and dispersion in the urban canopy are primarily governed by the intricate geometry of the city. The aim of this thesis is to investigate and model the effect of urban form on the dispersion of pollutants at two different spatial scales: at the scale of the district and at the scale of the single street canyon.

Urban street pattern is the dominant geometry at the district scale. Starting from this observation, the first part of this thesis proposes a new perspective based on the theory of complex networks to analyze and model the transport of pollutants along the streets of a city. The urban canopy is modelled as a network. Street canyons and their intersections shape the spatial structure of the network. The direction and the transport capacity of the flow in the streets define the direction and the weight of the links. Adopting this mathematical interpretation, propagation is modelled as a spreading process on a network and the most dangerous areas in a city are identified as the best spreading nodes. To this aim, a novel centrality metric tailored to mass transport in flow networks is derived. Besides providing an operational tool to identify the places in a city with the highest potential for dispersion over large areas, the proposed approach is suitable to investigate which structural properties of a city make it fragile to air pollution. The comparison between four emblematic cities with different urban patterns evidences that vulnerability is driven by the topological properties of the urban fabric, i.e. street connectivity and the variability in the orientation of the streets with respect to the approaching wind.

At the scale of the single street, flow and dispersion dynamics are governed by the canyon geometry. The dispersion of pollutants can be decomposed in the longitudinal transport along the street and the vertical transfer between the canyon and the external flow. While advection drives the dynamics along the canyon axis, the mechanisms of mass exchange in the vertical direction are still not fully understood. The second part of this thesis investigates these processes by means of wind tunnel experiments of pollutant dispersion in a canyon oriented perpendicular to the wind direction. In this configuration, the vertical exchange is the dominant mechanism of canyon ventilation. Keeping the external flow unaltered, we analyse the effect of different boundary conditions at the building walls and the presence of obstacles within the canyon. The boundary conditions are modified by alternatively heating the downwind and upwind walls of the canyon, by changing its aspect ratio and by

introducing roughness elements at walls. Two rows of model trees are arranged at the sides of a street canyon to simulate urban vegetation. Velocity and concentration measurements are performed within the canyon and a characteristic exchange velocity between the street canyon and the overlying atmosphere is estimated to quantify the overall canyon ventilation in the different configurations. Results evidence that the efficiency of the vertical exchange between the canyon and external flow is mainly driven by the fluctuating component of the turbulent flow within the canyon. The intensity and spatial distribution of the turbulent kinetic energy field varies according to the geometry of the canyon, the conditions imposed at the walls and the presence of obstacles.

In short, this thesis contributes to our understanding of (i) the role of urban geometry in the dispersion of pollutants, and (ii) the physical mechanisms that govern urban ventilation. Moreover, the techniques and methods adopted in this study highlight the importance of a multi-scale approach and the potential of innovative tools, both conceptual and experimental, to develop operational models for the assessment of urban air pollution.