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Mixing height determination by tethered balloon-based particle soundings and modeling simulations

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ABSTRACT

Vertical profiles of particle number concentration, potential temperature and relative humidity were measured in the Po Valley using an optical particle counter and a portable meteorological station attached to a tethered balloon. The field campaign covered the period 2006–2008, providing an extended dataset of vertical profiles in both stable and convective boundary-layer conditions. These vertical profiles were used to estimate an experimentally retrieved mixing height (MH).

The MM5 meteorological model was also used to simulate the atmospheric dispersion characteristics for the same period, using a variety of different boundary-layer and land surface parameterization schemes (Medium-Range Forecast; high-resolution Blackadar; Gayno–Seaman; and Pleim–Chang). The model simulated MHs were compared among themselves, and then with that measured from balloon soundings. MRF parameterization represented the best compromise solution to simulate increasing MHs in the Po Valley. The MM5 simulations showed the regional character of meteorological forcing on PM ground-concentrations in the Po Valley.

1. Introduction

Atmospheric conditions (i.e. MH and turbulence) modify people's exposure to particulate matter (PM) and to other gaseous pollutants as a result of dispersion and dilution, and they can lead to cases of severe pollution (Carbone et al., 2010; Rodriguez et al., 2007; Fischer et al., 2006; Maletto et al., 2003; Seibert et al., 2000). Hence there is a need for a careful assessment of the absence/presence of such conditions, and the role they play, especially in hot spots such as the Po Valley (Northern Italy). According to the Italian Reports on Urban Air Quality (APAT, 2007a,b, 2008 and 2009), PM_{10} concentration exceeded 50 μg/m^3 (daily average) for 150, 125 and 100 days in the Milan metropolitan area in 2006, 2007 and 2008, which are substantially over the required levels established by the recent European Directive (2008/50/EC) which resumes and substitutes the previous Framework and Daughter directives (EU Air Quality Directives: EC/96/62, EC/99/30, EC/2002/3). As already reported in the literature, in the Po Valley, and in particular in the Milan metropolitan area, there is very little wind (Rodriguez et al., 2007; Vecchi et al., 2004), if we exclude certain sporadic cases of advection mainly resulting from Föhn winds (Gandino et al., 1990), pollutant concentration is undoubtedly affected by the seasonally-modulated dispersive capacity of the atmosphere (Carbone et al., 2010; Ferrero et al., 2007; Sesana et al., 2003). This seasonally modulated dispersive capacity is not limited to the Milan metropolitan area: PM_{10} concentrations, which are regularly measured by the Lombardy Environment Protection Agency, show a similar trend in the Po Valley basin (APAT, 2007b).

The need for a clearer definition of MH stratification also derives from remote-sensing applications for air-quality management (Levy et al., 2007). In this sense, MH has been used in literature (Di Nicolantonio et al., 2009; Liu et al., 2007;

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Engel-Cox et al., 2006; Liu et al., 2005; Sarigiannis et al., 2004) as a proxy for effective scale height (Kaufman and Fraser, 1983), in order to relate satellite aerosol optical depth to ground PM concentrations; PM concentration maps based on satellite remote sensing, enable to estimate the exposure of those people in areas that are not covered by the monitoring network.

In recent years, despite significant progress in experimental and theoretical work on the characterization of atmospheric turbulence, the determination of MH remains one of the most uncertain parameters; and due to its rather vague definition, it is not surprising that many methods exist for the experimental and modeling estimation of MH for convective and stable boundary layers (Seibert et al., 2000 and the references contained therein).

Information on MH stratification can be inferred from PM vertical distribution, using various different techniques (both direct and indirect). The simplest direct techniques are based on sampling devices positioned at different altitudes using towers (Erisman et al., 1988) and buildings (Tripathi et al., 2004; Morawska et al., 1999a,b; Rubino et al., 1998); conventional techniques (i.e. gravimetric sampling) can be used to collect and chemically analyze particulate matter samples at different displacement heights. A few measurement points can provide useful information about the PM's vertical distribution, although no information about MH can be easily derived. Indeed, the observation of particle soundings with sufficient height resolution and temporal continuity is needed in order to infer the influence of atmospheric dispersion on particulate matter loading. To this end, indirect techniques such as the use of lidars or ceilometers (Kim et al., 2007; Amiridis et al., 2007; Eresmaa et al., 2006), or wind-profilers (Cohn and Angevine, 2000), have been successfully employed to retrieve useful parameters, e.g. aerosol backscattering, related to nature of MH. Unfortunately, the indirect nature of this experimental approach means that a subsequent data analysis is required in order to identify stratifications and discard interferences from clouds, and no absolute measure of particle concentration can be achieved; moreover, MH can be calculated using lidars starting from 100 to 300 m above ground level, and is thus not suitable for the detection of thin boundary layers close to the surface, e.g. when stable conditions such as those observable in the Po Valley persist.

On the other hand, tethered balloons (Laakso et al., 2007; Wiegner et al., 2006; McKendry et al., 2004; Stratmann et al., 2003; Maletto et al., 2003) and aircrafts (Taubman et al., 2006; Schneider et al., 2006) enable direct sampling to be performed, and they can be used as privileged observation platforms. In particular, balloon soundings are useful for studies conducted during stable conditions and at stable/convective transition times, when the MH is limited to the first hundred meters above ground level.

Generally speaking, very few direct measurements of particle vertical profiles exist, and are in any case limited to a handful of locations, and have been mainly conducted during short-term sampling campaigns (Laakso et al., 2007; Wiegner et al., 2006; McKendry et al., 2004; Maletto et al., 2003; Stratmann et al., 2003; Penner et al., 2001). Moreover, since MH is also important for air-quality forecasts, the lack of any monitoring network that can regularly monitor the diurnal, seasonal and annual variations in MH and its structure is a severe constraint on the further development of air-quality modeling.

In this study we used experimental (particle vertical profiles by balloon soundings) and modeling activities (MM5 simulations, Dudhia, 1993; Grell and Stauffer, 1994) in order to characterize the MH structure. PM vertical profiles provide experimentally estimated MHs and allow testing the accuracy of model simulations under different parameterization schemes. Comparisons of measurements and model simulations have been based on 3 years (2006–2008) of vertical particle profile measurements in winter and in summer. Moreover, the MM5 model provides spatially and temporally gridded data that would be difficult to obtain from any experimental procedure, but which are of great interest for both air-quality management and remote-sensing applications.

2. Materials and methods

2.1. Sampling site

Vertical profiles of atmospheric particles were carried out at the Torre Sarca site located in the Milan metropolitan area, close to the Milan-Bicocca University (45°31′19″N, 9°12′46″E). The site is located on the northern side of Milan, in the midst of an extensive conurbation that is the most industrialized, heavily populated area in the Po Valley. Vertical profile measurements were made from 2006 to 2008. Correspondingly $PM_{2.5}$ concentrations were continuously monitored at ground-level, using the dual channel FAI-Hydra low-volume sampler (EU sampling head, 2.3 m^3/h; PALL Teflon filters and WHATMAN pre-fired quartz fiber filters, Ø = 47 mm) in accordance with EN-14907 standard.

2.2. Balloon-based particle soundings

Vertical PM profiles were achieved using a spherical helium-filled tethered balloon (PU balloon, 4 m in diameter, 33.5 m^3 volume, manufactured by Aeronord Aerostati, Sesto S. Giovanni, Italy) capable of carrying 15 kg of instrumentation, leaving it with a further 7 kg of buoyancy force. The balloon was equipped with an optical particle counter (OPC, 1.108 “Dustcheck” GRIMM, 15 class-sizes ranging from 0.3 μm to 20 μm) and a portable meteorological station (BABUC-ABC, LSI-Lastem: pressure, temperature and relative humidity) deployed on a plexiglass platform at a distance of 5 m from the balloon; both instruments acquired data with a time resolution of 6 s.

Ascent and descent rates were controlled by an electric winch (manufactured by Orlandi & Orlandi, Turate, Italy). The chosen ascent/descent rate may vary from near zero to 50.0 ± 0.1 m/min; a fixed value of 30.0 ± 0.1 m/min was used for all the profiles in question, so that it was possible to take particle measurements at a high spatial resolution (approximately one measurement every 3 m) within a reasonable time of flight (10 min to reach 300 m AGL). The maximum height reachable by each balloon launch (600 m) was determined by our civil aviation authority which gives us the permission to fly (the whole Milan city, and surrounding areas, are in the middle of two main airports and a third private airport), than during each balloon launch the maximum reached height depended on atmospheric conditions and for most profiles it ranged from 300 to 600 m. Further details of the experimental approach can