Atmospheric Research 213 (2018) 57–69

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Relationship between the planetary boundary layer height and the particle scattering coefficient at the surface

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ARTICLE INFO

Keywords:
Planetary boundary layer height
Particle scattering coefficient
Scattering Ångström exponent
Lidar measurements
Integrating nephelometer
HYSPLIT model

ABSTRACT

The relationship between the Planetary Boundary Layer (PBL) height and the particle scattering coefficient (σ_p) at the surface has been investigated with the main goal of estimating the PBL height from the ground-level particle optical properties that are simpler to measure and are provided by instruments as nephelometers, which can run continuously. A lidar system and an integrating nephelometer operating within the European infrastructure ACTRIS (Aerosols, Clouds, and Trace gases Research InfraStructure) have been used to simultaneously monitor the daily evolution of both the PBL height and σ_p. Measurements have been performed at a coastal site of south-eastern Italy, characterized by a shallow PBL (< 1000 m), during a two-year period. The standard deviation technique has been applied to lidar signals to determine the daily evolution of the PBL height, being this technique independent on the lidar overlap function. The maximum value of the PBL height hourly mean was reached around midday and was equal to 470 ± 160 m in spring-summer (SS) and 580 ± 170 m in autumn-winter (AW). A statistically significant inverse correlation between the PBL height and σ_p was found both in AW and in SS, since σ_p decreased with the increase of the PBL height, because of the increase of the ground-level particles' vertical dispersion. The retrieved relationships between the PBL height and σ_p have been used to estimate the daily evolution of the PBL height from σ_p values both in SS and in AW. We found a satisfactory accordance, within experimental uncertainties, between estimated and experimentally determined PBL heights. Therefore, a new experimental methodology to estimate the PBL height from ground-based nephelometer measurements has been suggested in the paper. The analysis of the scattering Ångström exponent has revealed that in AW the mean size of the particles at the surface on average increased during the central hours of the day, since the PBL height increase likely favoured the vertical dispersion of fine particles more than the coarse ones. The comparison between the lidar-derived PBL heights and the corresponding ones calculated by the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model has revealed that the HYSPLIT PBL height seasonal and daily trends were similar to the corresponding ones retrieved from lidar measurements. Nevertheless, the HYSPLIT model on average overestimated by 40% and underestimated by 20% the experimentally determined PBL height in autumn-winter and in spring-summer, respectively.

1. Introduction

The planetary boundary layer (PBL) has been defined by Stull (1988) as the lowest layer of the troposphere that is directly influenced by the Earth's surface and responds to surface forcing with a time scale of about an hour or less. Processes occurring within the PBL control energy, water vapour, and pollutant exchanges between the surface and the free atmosphere. As a result, the characterization of the PBL is of primary importance for climate, meteorological forecasts, pollutant dispersion, and air quality studies. The PBL experiences a marked diurnal cycle that depends on both the synoptic and the local weather conditions. A detailed description of the PBL vertical structure and its daily evolution is provided by Stull (1988). The PBL (particularly over land surfaces) exhibits a diurnal variation due to the exchange of energy and momentum between the surface and the atmosphere. It tends to be lower in depth at night, while during the day it tends to expand because of the convective and mechanical forces inducing turbulence, which result in the mix of pollutants in the commonly referred to as mixing layer (Lewis et al., 2013). At night, the PBL contracts due to a reduction of rising thermals from the surface and since cold air is denser than warm air. Consequently, the PBL height can be estimated from the measurements of the mechanical turbulence, the temperature enabling convection, or the concentration of the atmospheric constituents. Collaud Coen et al. (2014) have recently provided an overview on the

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https://doi.org/10.1016/j.atmosres.2018.04.017
Received 10 November 2017; Received in revised form 16 April 2018; Accepted 24 April 2018

main detection methods of the PBL height and on the main PBL studies performed worldwide. They highlighted both that each detection method had good performances only for well-defined PBL structures and under specific meteorological conditions and that the combination of several methods and instruments was necessary to evaluate the complete diurnal cycle of the PBL. The complexity of the troposphere itself, which can be composed of several layers with different thermal structures, wind regimes, and concentrations of atmospheric constituents, was responsible for the difficulty of the PBL height detection. Consequently, good correlations were found in the case of strong or weak convective weather conditions with differences of 100–300 m between the various instruments and/or methods (Collaud Coen et al., 2014 and references therein). Greater discrepancies in the PBL height estimations were found under non-convective weather conditions. Seidel et al. (2012) analyzed the PBL over Europe and the continental U.S. for the period 1981–2005 and proved that an algorithm based on the bulk Richardson number was the most suitable method for application to large radiosonde, reanalysis, and climate model data sets. Note that radiosondes are typically launched only twice each day and, consequently, the radiosounding-based methodologies do not allow monitoring the PBL diurnal cycle. Active remote sensing instruments such as lidars present advantages over the more traditional use of radiosondes for PBL studies, because of their high spatial and temporal resolution, in addition to the possible continuous operation in a nearly automated way (e.g. Menut et al., 1999; De Tomasi and Perrone, 2006; Summa et al., 2013; Banks et al., 2015; Bravo-Aranda et al., 2017). The elastic backscattered signals from aerosol particles measured by lidar systems are used to determine the height and the internal structure of the PBL and, when possible, of the residual layer and aerosol layers within and aloft the PBL (e.g. Melfi et al., 1985; Di Girolamo et al., 1999). In fact, aerosols uplifted after sunrise by convective mixing can act as efficient tracers for the atmospheric portion over which mixing occurs (Flamant et al., 1997). Several methodologies have been developed to determine the PBL height from backscatter lidar signals. Lewis et al. (2013) developed an improved PBL depth algorithm, which uses a combination of the wavelet technique and image processing, to perform continuous lidar observations of the PBL height at the Micro-Pulse Lidar NETwork (MPLNET) site in Greenbelt, Maryland (USA). A new algorithm, called POLARIS (PBL height estimatiOn based on Lidar depolARISation), which applies the wavelet covariance transform (WCT) to lidar signals and to the perpendicular-to-parallel signal ratio profiles, has recently been developed by Bravo-Aranda et al. (2017). Matthias et al. (2004) determined the PBL height at 10 European Aerosol Research LIdar NETwork (EARLINET) stations by looking at the first significant negative gradient in the range corrected lidar signal, starting from the ground. Then, De Tomasi and Perrone (2006) identified, at the monitoring site of this study, the PBL height as the height at which the first measurable minima of the derivative of the lidar signal normalized to the backscatter molecular signal occurs (e.g. Flamant et al., 1997; Collaud Coen et al., 2014). They showed that the PBL heights retrieved by lidar measurements within two years were in good agreement with the corresponding ones obtained by radiosounding measurements from a close meteorological station. The gradient and wavelet techniques assume that more aerosol particles are within the PBL than the free troposphere so that a strong decrease of the backscatter lidar signal is observed at the PBL top (Baars et al., 2008). Note that the altitude where the lidar system achieves the full overlap limits the lowest PBL detection height when the gradient or the wavelet techniques are applied. The standard deviation analysis is another technique based on lidar signals (Menut et al., 1999). It makes use of the strong temporal fluctuations of the lidar signal between the PBL top and the free troposphere caused by the entrainment of clear air from the free troposphere into the PBL. Measurements of such fluctuations based on the variance or standard deviation of lidar signals as a function of altitude allow determining the PBL height (Baars et al., 2008). This last methodology has the advantage of being independent on the lidar overlap function (Wandinger, 2005). Therefore, it can also be used at partial overlap altitudes and it is well suited to monitor shallow PBLs. De Tomasi et al. (2011) used the standard deviation technique to investigate, on 14 July 2006, the daily cycle of the PBL height at the coastal site of this study, which is characterized by a shallow PBL. They showed that the PBL height was highly variable and that its evolution was counter-intuitive because of the proximity of the monitoring site to the sea and the sea breeze impact.

The standard deviation technique has been used in this study to investigate the daily evolution of the PBL height at a southeastern Italy coastal site, both in Spring-Summer (SS) and in Autumn-Winter (AW), by using lidar measurements performed in the years 2015–2016. As mentioned, lidar systems present advantages with respect to radiosondes in order to determine the PBL height, because of their high spatial and temporal resolution, and the possible continuous operation in a nearly automated way. However, they are very rare in the world and relatively expensive and, consequently, the need for estimating the PBL height from ground-level parameters that are simpler to measure and are provided by instruments that can operate continuously is still relevant. The capability of the particle scattering coefficients retrieved from integrating nephelometer measurements at the surface to provide an estimate of the PBL height has been exploited in this study. More specifically, one of the main goal of this study has been to investigate how well the daily evolution of the aerosol scattering coefficients at the surface could represent the PBL height daily evolution. To this end, co-located in space and time lidar and nephelometer measurements have been performed, with the main objective of obtaining a quantitative relationship between the PBL height retrieved from lidar measurements and the particle scattering coefficient (σ_p) calculated from integrating nephelometer measurements. Perrone et al. (2014a, 2015) have recently investigated the σ_p daily evolution and found that it was strongly linked to the vertical dispersion of the particles at the surface, which in turn depends on the PBL height. The impact of the PBL height on the mean size of the ground-level particles has also been investigated in this study by using the scattering Ångström exponent ($\mathring{A}$). Finally, the lidar-derived PBL heights have been compared with the corresponding ones calculated by the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess, 1998), on an hourly basis, to investigate the relationship between model and experimental parameters.

The paper is organized as follows. A brief overview of the lidar system and the integrating nephelometer is given in Section 2, in addition to the monitoring site description. The methodology applied to detect the PBL height is shortly outlined in Section 3. Main results on the daily evolution of the PBL height and the surface-particle optical properties are provided in Section 4. More specifically, two case studies are firstly analyzed and discussed in Section 4.1, with the main goal of highlighting the sea breeze impact on the PBL height temporal evolution at the study site. Sections 4.2 and 4.3 present the main findings on the seasonal dependence of the PBL height and the σ_p and $\mathring{A}$ daily evolution, respectively. The correlation between the PBL height and σ_p is analyzed and discussed in Section 5, in addition to the PBL height impact on the mean size of the ground-level particles. The relationships between the lidar-derived PBL heights and the corresponding ones provided by the HYSPLIT model are discussed in Section 6. Summary and concluding remarks are in Section 7.

2. Site description and instrumentation

2.1. Site description

Lidar and nephelometer measurements have been performed in Lecce (southeastern Italy), on the roof of the Mathematics and Physics Department of the University of Salento (40.33°N, 18.11°E, 30 m a.s.l.). The monitoring site is located on a narrow and flat peninsular area ~20 km away from both the Ionian and the Adriatic Sea (Fig. 1) and