ISSN/2499-5347

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Abstract
A climatology of the Atmospheric Boundary Layer (ABL) height is presented. It was retrieved from measurements made by an automated lidar-ceilometer (ALC) running within the Italian Alice-Network (ALICENET), and located in San Pietro Capofiume (SPC), a rural station in the eastern Po valley. Three years of continuous ALC data have been acquired within the SUPERSITO project. The ABL height (ABLh) was retrieved starting from the gradient method applied to the ALC range-corrected signal (RCS), This record was then compared with the ABLh estimates of two different models, COSMO and CALMET. Statistics of such comparisons based on hourly and monthly averages are provided. This comparison showed that differences between observations and model outputs mainly arise during the afternoon. Origin and magnitude of these discrepancies are evaluated and discussed.

Keywords: *Planetary boundary layer, aerosol, lidar, atmospheric modelling.*

Riassunto
Viene presentata una climatologia dell'altezza dello strato limite planetario, come determinata dal lidar automatico ceilometer (ALC) sito in San Pietro Capofiume (SPC), una stazione rurale nella pianura padana orientale. Tre anni di acquisizioni continue sono state collezionate nell'ambito del progetto Supersito. L'altezza dello strato limite è stata determinata mediante metodo del gradiente applicato al segnale range-corrected (RCS); questo insieme di misure è stato poi confrontato con l'altezza determinata tramite due differenti modelli, COSMO e CALMET. Vengono poi presentate le statistiche di questi confronti basati su medie mensili e orarie. Questo confronto mostra che le differenze tra modello e osservazioni si accentuano nel pomeriggio; vengono infine discusse l'origine e l'entità di questi disaccordi.

Parole chiave: strato limite planetario, aerosol, lidar, modellistica atmosferica.

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Introduction

The atmospheric boundary layer (ABL) is the region where the impact of the ground processes and orography bear an immediate effect on the atmosphere [Stull, 1988]. Being the atmospheric layer where virtually all the non-aquatic life on Earth is confined in, the ABL then represents an important subject in many fields of the Earth sciences. All the exchanges of heat, momentum, moisture, and emissions (including aerosols), between the surface and the atmosphere take place within the ABL. The budget of these exchanges drives the mixing and transport processes within the lower atmosphere, as well as the exchanges with the upper atmospheric layers. The thickness of the ABL (usually referred to as ABL 'height'-ABLh) represents an important quantity for air quality, as it defines the volume available for pollutant dispersion. Therefore, the ABLh is also a typical output of air dispersion and meteorological models.

Unfortunately, in spite of its importance in atmospheric studies, no direct techniques for measuring the ABL height are available. Therefore, a variety of methods have been developed and used to indirectly infer the ABL height from different atmospheric parameters, and a still valid review on these methods is given by Seibert et al. [2000].

One of the most common methods for estimating the ABLh is represented by the identification of inflection points in the aerosol backscatter cross section, usually provided by elastic lidars (gradient method, see Endlich et al., [1979]), and the determination of the ABL height from lidar data has been widely investigated in the past decade [Angelini et al., 2009, Haeffelin et al., 2011, Uzan et al., 2016]. It also represents an opportunity, given the wide distribution of automated elastic lidars/ceilometers nowadays operational in Europe [Flentje et al., 2010]. The assumption at the base of this methodology is that aerosol is well mixed within the ABL (which is thus often also referred to as 'mixing layer'), and can therefore act as passive ABL tracers. Lidars and ceilometers provide continuous profiles of the aerosol backscattering cross section, so that the changes on this quantity can be linked to the changes in aerosol concentration, as described in literature cited so far.

Usually, the algorithms determining the ABLh on the basis of gradient method consist in two steps:

1) Identification of aerosol layers: all the aerosol layers in the operative range of the instrument are identified;

2) Selection of the layer identifying the ABLh: among the layers identified at point 1 the selection of the layer defining the top of the ABL is performed (layer attribution).

As demonstrated by Haeffelin et al. [2011], while the first step is quite viable, reliable automated algorithms for the attribution step are not yet available, so this second task is still matter of investigation.

From a modelling perspective, the determination of the ABLh be very different depending on the model and on the principles of calculation. Simplest models are based on parameterization of heat fluxes or turbulence parameters from standard meteorological measurements at ground, and the Monin-Obukov theory to infer the vertical profiles of the needed quantities. As data availability increases (turbulence parameters, wind and temperature profile, radiation, humidity), a virtually infinite combination of equations can be used to numerically determine the ABL height. In this work, we employ both a simple dispersion model (CALMET) and a more sophisticated one (COSMO).

In this study we aimed at comparing the ABLh obtained bymodels with those retrieved by ALC measurements in a Po Valley rural site (San Pietro Capofiume, SPC), in order to evaluate if, and in which conditions, the different approaches provide comparable results. A climatology of the ABL height in SPC is useful because the station can be considered as representative of most of the Po valley. Additionally, it represents a valuable benchmark for both automated algorithms and model evaluation of the ABLh under different atmospheric conditions.

Instruments and methods

The measurement site

The ALC measurements have been carried out in SPC in the framework of the SUPERSITO project (http://www.arpae.it/index.asp?idlivello=1459). San Pietro Capofiume is a rural site in the eastern Po valley, some 50 km west of the Adriatic sea coast, and 30 km north-east of the closest mountains (Figure 1). The Po Valley is a densely populated and heavily industrialized district, often affected by atmospheric stability. These conditions result into a complex aerosol vertical stratification in the ABL with a dense polluted nocturnal residual layer [Barnaba et al., 2010, Curci et al., 2015]. Its high aerosol loads were also demonstrated to affect the nearby Alpine region [Diémoz et al., 2019].

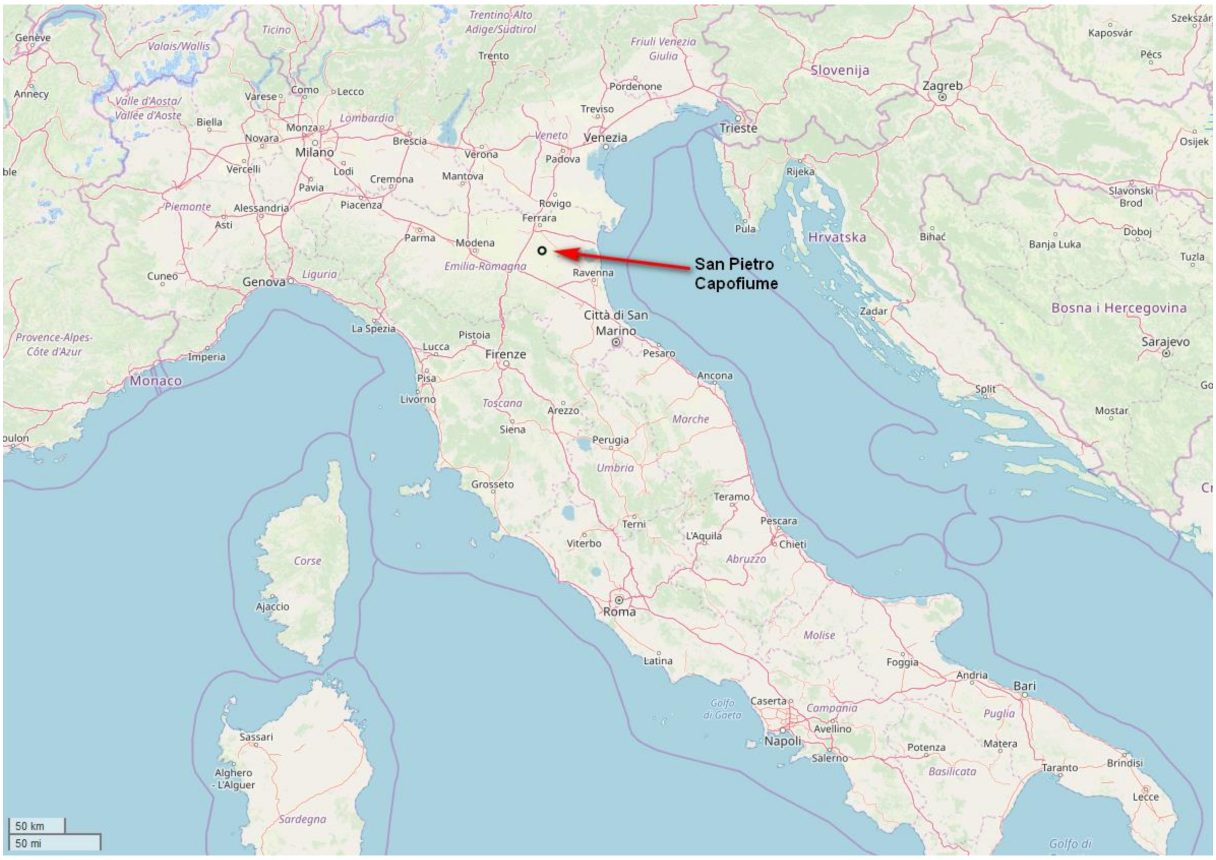

Figure 1. The measurement site. The arrows indicate the principal wind directions observed at the site, as discussed in 3.1.

ABL determination from lidar

The measurement-based evaluation of the ABLh has been carried out by the analysis of the lidar-ceilometer dataset collected during 36 months (December 2011 – January 2015) in SPC. The ALC system is a Nimbus CHM15k manufactured by Jenoptik (now Lufft). It operationally (i.e.24h/day, 7 days/week) collected vertical profiles of aerosol and clouds between 150 m and 15 km, with time resolution of two minutes.

The CHM15k is a simple, one-wavelength elastic backscatter lidar without depolarization discrimination. It was originally conceived for flight safety tasks, but advancements in both hardware and software made it a widely used tool for atmospheric [Dionisi et al., 2018]. In fact, excellent signal performance is achieved by a stable wavelength, narrow line width microchip Nd:YAG laser operating at 1064 nm. The used pulse energy and frequency of the laser allow for an eye-safe operating mode.

As a first step, all the SPC profiles have been processed to obtain a map of the daily, range-corrected signal (RCS). In order to minimize noise effects, vertical profiles were averaged over two minutes. Out of the three-year record (1095 days), 1024 days were analyzed, discarding those having a temporal coverage < 70% due to some instrumental problems. Among these, 649 days were selected as suitable to evaluate the ABLh. Further screening was in fact necessary due to cases of persistent fog (rather common in this region in winter) or to cases with too low aerosol load (unsuitable for ABLh determination). The analysis was performed using a software tool specifically designed to display the levels of maximum gradients and variance in the backscatter signal. Final visual inspection of these levels by a trained operator allowed the accurate selection of the aerosol layer associated to the evolving ABL profile ('supervised gradient method'). Occasionally, radiosounding profiles were also used in support to this layer attribution phase, especially during night time.

A limitation of this ALC system is that it becomes 'blind' in the lowermost atmospheric levels (< 150 m). This is because the partial overlap between the laser beam and the field of view of the receiving optics, which zeroes below about 150 m. Although an overlap correction function is applied to limit this effect, under stable conditions, or whenever the ABL is very shallow, the determination of ABL height by ceilometer data is impossible or ambiguous. In fact, this can lead to a systematic overestimation of the average ABLh during the night. It is also worth to highlight that aerosol-driven retrievals of ABLh can lead to results different from those calculated from other quantities, such turbulence or temperature profiles. In the following some aspects of this issue will be illustrated and discussed, bringing to the problem of the exact definition of ABL itself.

Analysis of ALC's data can produce profiles of atmospheric backscatter cross section with reasonably high spatial and temporal resolution. To be rigorous, each lidar profile should be calibrated over an aerosol-free region to uncouple the aerosol from the molecular signal. Moreover, in single-wavelength elastic lidars, some assumptions on aerosol optical properties must be imposed to retrieve the aerosol cross section. Both of these steps then require supervision, being therefore time-consuming and not well-suited for automated analysis. For this reason, instead of working on aerosol backscatter profiles, the gradient method is often applied directly to the raw range-corrected signal (RCS) or to its logarithm: this approach does not require supervision, still leading to equivalent results [Angelini et al., 2014].

The wind measurements at SPC were performed by means of a Vaisala QMW110 cup anemometer, placed 10 m high over grass. The Cartesian components were averaged over 1h and then converted into speed and direction, according to the WMO recommendations [WMO, 2014].

Models set up and operation

COSMO and CALMET are run by ARPAE (the Regional Environmental Agency of Emilia Romagna) on a daily basis, for air quality and weather forecast purposes. A summary of the two different model characteristics and settings is given in
Table 1. The COSMO-Model is a non-hydrostatic, limited-area atmospheric prediction model. It has been designed for both operational numerical weather prediction (NWP) and various scientific applications on the meso-β and meso-γ scale. The COSMO-Model is based on the primitive thermo-hydrodynamic equations describing compressible flow in a moist atmosphere. The Chemistry and Transport Model CHIMERE model is then run by ARPAE after COSMO meteorological forecast, and the ABL height is provided by the CHIMERE preprocessor DIAGMET, version V200501H (
Table 2).

model	*COSMO-I7*	*CALMET-SIM*
Type	Non-hydrostatic meteorological model	Mass-consistent pre-processor
Post processing	Chimere - diagmet	-
Resolution	7 km	5 km
Domain	Italy	Northern Italy

Table 1. Model characteristics and settings

Atmospheric condition	*reference*	*Driving quantity*
Stable/Unstable	Troen & Mahrt, 1986	Richardson number

Table 2. The criteria used in COSMO-CHIMERE for ABL height retrieval

Atmospheric condition	*Reference*	*Driving quantity*
Unstable	Modified Carson method based on Maul (1980)[15]	Heat flux
Neutral	Venkatram, 1980	u*
Stable	Venkatram, 1980	$u^{*\,3/2}$

Table 3. The criteria used in CALMET for ABL height retrieval

CALMET was developed in the '90s as a meteorological preprocessor for the CALPUFF and CALGRID dispersion models. It does not solve motion equation of air masses, but performs a best interpolation of measured meteorological data and estimates micrometeorological variables. The ABLh is then provided applying simple models as mentioned in Table 3.

Results and discussion

In this section, we first characterize the San Pietro Capofiume station in terms of typical circulation patterns and then present the derived ABL climatology.
In fact, the wind pattern directly affects the air quality, providing dispersion of pollutants. In a slightly indirect way, it can also affect the development of the ABL, introducing turbulence or capping, and determining a modulation of the dilution of PM and gases emitted at ground. Morgillo et al. have found a connection among the weather synoptic circulation patterns, the local wind regimes and air pollution in the Po Valley [Morgillo et al., 2018].

Wind regimes

Figure **2** shows, for each season, the daily frequency distributions of wind speed (left) and direction (right), averaged over 3 years. The magenta line represents the mean wind speed. Figure **2** clearly shows that during the late nighttime (1-5 UTC) a typical land-breeze regime (low average wind speeds, ~2 m/s, and westerly direction, ~ 270°) is usually observed in spring, summer and fall (b, c, d), while in wintertime this situation lasts all day long (a). During afternoon and evening (15-24 UTC), wind coming from ~ 100° suggests the presence of a sea breeze condition, in all seasons but winter. In the mid of the day, winds become a bit stronger but without any well-defined direction.
The analysis of backscatter data described in Section 2.1, allowed to determine the three-year climatology of ABL height at S. Pietro Capofiume. Since some constraints were imposed to the analysis (minimum aerosol backscattering, no fog or low clouds), not all months within each year or hour in a day presented the same amount of retrievals.

ABL climatology from measurements and models

Occurrence of valid retrievals are shown in Figure 3, a. Two main considerations arise from this figure: i) very few days during wintertime show a clear ABL evolution; ii) nocturnal ABL height is often below the minimum instrument overlap altitude, so that very few data are retrieved between 10 p.m. and 5a.m (UTC). Low level blindness, coupled with the presence of the residual layer can mislead the ABLh attribution during nighttime. As a consequence, nocturnal retrievals should be treated very carefully.

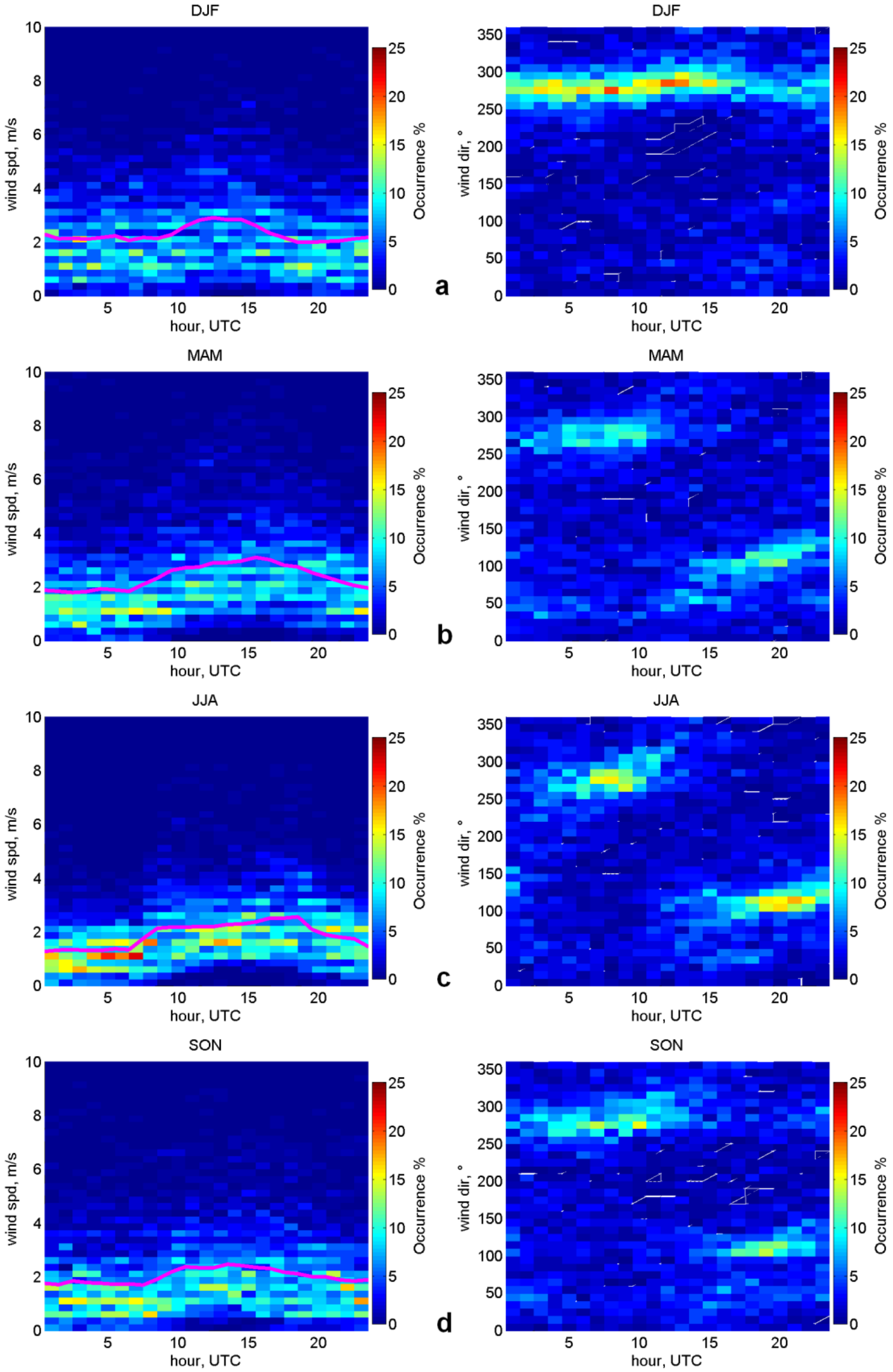

Figure 2. Seasonal daily patterns of wind speed and direction at SPC: a, winter; b, spring; c, summer and d, fall.

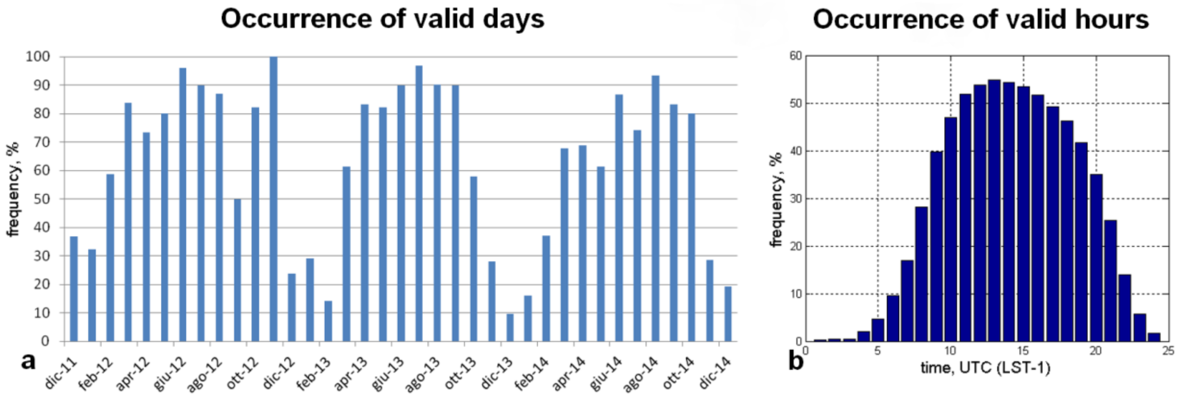

Figure 3. Distribution of days in which at least 1 hr of ABLh is detected (a) and distribution of successful ABLh determination per hour (b)

The seasonally-resolved, hourly distribution of ABLh as derived from ALC-measurements (first column) and models (second and third columns) is shown in Figure 4. The contour plots show the occurrence of ABLh at each hour. The superimposed magenta line represents the distribution average, i.e. the average ABLh at each hour.

As mentioned in Section 2.2, a likely overestimation of the night-time, stable nocturnal ABL retrieved from the ALC measurements is visible in all panels. As the sun rises, the convective ABL starts ascending to about 1500 m in summer, 1000 m in spring and fall. no convective ABL is clearly detected In wintertime. This is also due to the few valid data (e.g., Figure 3, b), leading to quite a noisy distribution.

When sun irradiance lowers in the afternoon, the ABLh lowers as well, and after 20 UTC a new strong aerosol layer becomes evident below 500 m, indicating the setting of a new stable layer. Still, an overestimation of the average is probable due to the mentioned limited field of view of the ceilometers below 150 m. In fact, as visible in Figure 3, ALC-derived data dramatically reduce at night time. CALMET (second column of Figure 4) sharply distinguishes between stable and unstable conditions, and the calculation of the mixing layer strongly differs under different atmospheric stability conditions. For this reason, nocturnal ABLh results to be quite uniform being driven by u* (parameterized from 1h-averaged wind speed), while a quick rise after sunrise is visible, up to 2500 m in summer, depending on cloud coverage and consequent radiative budget at the ground. In the afternoon, it simulates a sudden drop of the ABLh, as soon as the atmosphere becomes neutral, and then stable. A new stable layer is predicted, which persists till the following day sunrise. Overall, this approach of CALMET seems to be too simplified, leading to large difference with the observations.

Conversely, COSMO (last column of Figure 4) provides results more similar to the ALC-based ones. A more symmetrical shape of the daily ABLh is evident in each season, with peak values closer to those observed.

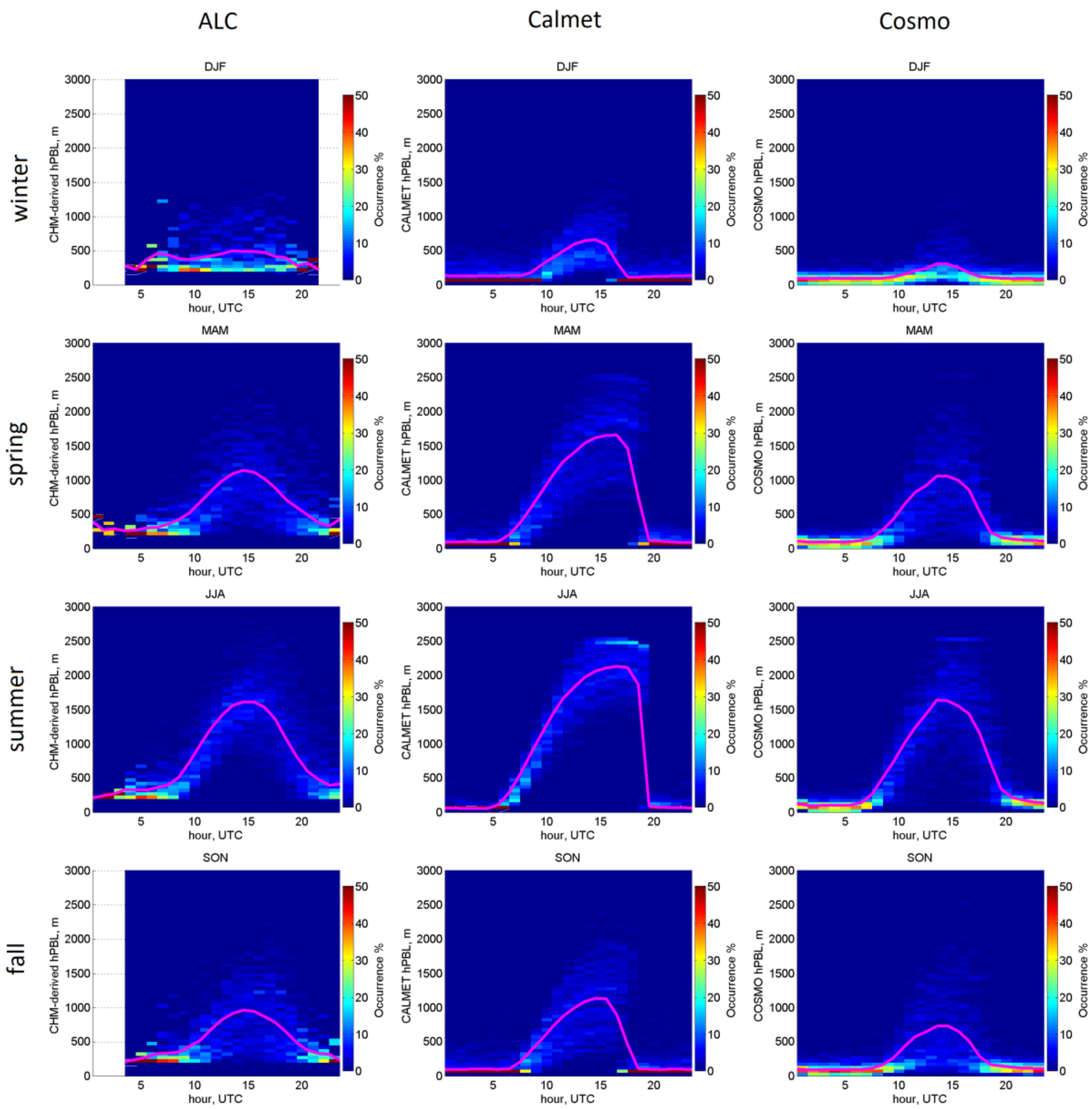

Figure 4. Distributions and averages of the seasonal ABLh daily cycles observed at San Pietro Capofiume. Left column: lidar-ceilometer retrievals; central column: CALMET model simulations, and right column: COSMO simulations.

For a more quantitative comparison, in Figure 5 and Figure 6 the ALC-derived ABLh is directly compared to the one modelled by CALMET and COSMO, respectively. In order to minimize the risk of mixing different thermodynamic atmospheric conditions, the comparison was performed differentiating four time slots: 0-6 (a), 8-12 (b), 13-17 (c) and 19-24 (d) UTC (schematically referred to as: night, morning, afternoon and evening). Figure 5 and Figure 6 show a different behaviour in terms of correlation between models and measurements, depending on the time slot. Morning and afternoon data show some degree of correlation in both figures (R >0.7, 0.6 respectively) night and evening data show virtually no correlation. For CALMET, a nonlinear dependence arises especially in the afternoon, probably because of the oversimplification of the CALMET ABLh scheme. In the afternoon, a cluster of data simulated at very low heights is visible, for which conversely the ALC still detects elevated ABL. This is due to the CALMET sudden change of criterion for calculating the ABL height when the convective daytime atmosphere becomes neutral and then stable in the afternoon. COSMO performs better in these cases, although the linear correlation is the same (0.75) but without any evident deviation from linearity. In both comparisons, evening data generally show ALC retrievals to be much higher than model outputs. These is likely related to two reasons: i) the mentioned ALC overlap problem, making it missing the presence of shallow (<150 m) layers, then favouring a systematic overestimation of the ABLh;

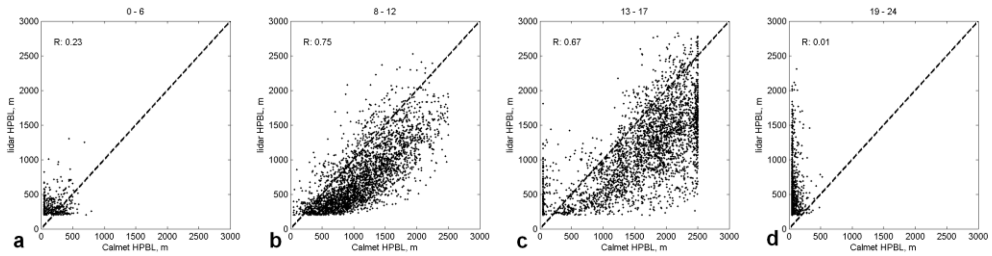

Figure 5. Comparison lidar-CALMET per different time slot (UTC). The linear correlation coefficient is shown in each panel, and the dashed line represents the ideal 1:1correspondence.

ii) models tend to force the stable boundary layer according to wind speed (actually u*), so nocturnal ABL usually results to be shallow and flat, while elevated aerosol layers are still present in the atmosphere. This problem is deeply rooted in the issue of ABL definition itself. In fact, the ABL could be interpreted either as the actual mixing capability of the atmosphere, or the actual mixing status of the atmosphere. In the first case, the strength of turbulence drives the ability of the atmosphere to mix the pollutants emitted at ground. Conversely, if we consider the mixing status, we must note that during the afternoon the aerosols transported aloft by daytime convection can remain there leading to the formation of the residual layer. In the transition between convective boundary layer and stable boundary layer, the atmosphere becomes neutral, and at this time the ABL can still be well mixed although its mixing capability is lower (at least the part driven by buoyancy).

We should therefore refer to *mixing* layer in the first case and *mixed* layer in the second one: determining which is the correct ABLh in this condition becomes a problem of definition.

The models used in this work actually calculate the ABLh from the mixing capability (both mechanical and by buoyancy, being based on quantities like friction velocity (u*), heat flux (H_0), and turbulent kinetic energy (TKE). ALC-based retrievals rely instead on the cross section of aerosol, used as the only proxy of mixing, regardless of the thermodynamics, and kinematic characteristics of the ABL.

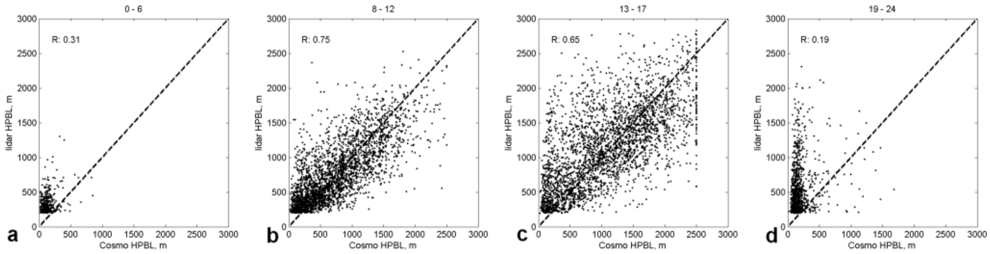

Figure 6. Comparison lidar-COSMO. The linear correlation coefficient is shown in each panel, and the dashed line represents the 1:1 regression.

Figure 7 shows daily cycles of the average differences between lidar-ceilometer and models over the three-year period. The better performance of COSMO with respect to the lidar is evident, though a mean bias and a systematic afternoon deviation are still visible. Conversely, CALMET suffers from the too simple parameterizations of ABL, leading to sharp transitions between different regimes, as it happens for example in the afternoon.

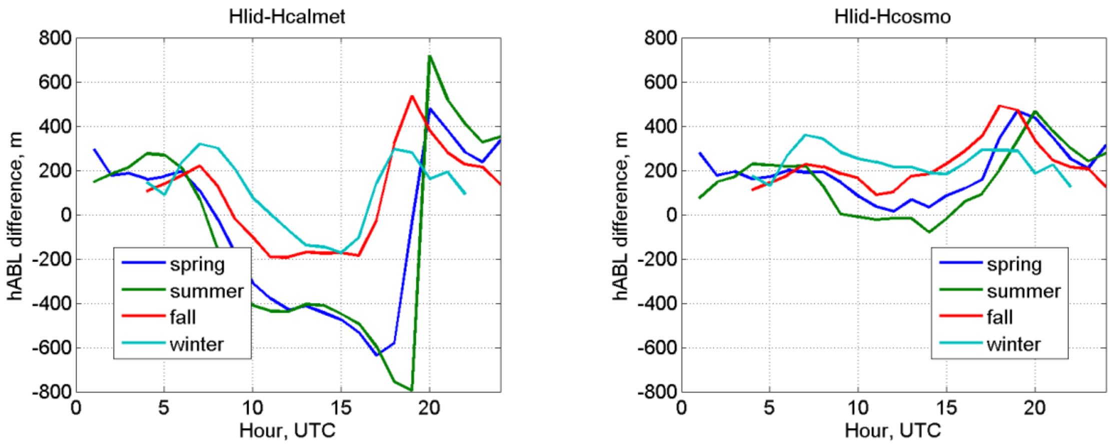

Figure 7. Absolute mean differences between lidar and model ABLh retrievals (left: Lidar-CALMET, right: Lidar-COSMO).

Summary and conclusions

A seasonally-resolved statistics of the ABLh over a rural site in the Po valley has been built using three-year ALC data collected at very high temporal resolution (< 1 minute), H24/7 at S. Pietro Capofiume at the heart of the Italian Po Valley. In spite of some drawbacks (e.g. low-level "blindness" of the lidar-ceilometer system below 150 m, affecting some night-time retrievals), this dataset can be considered a reliable benchmark to test automated algorithms for ABLh estimation by models.

In this study, hourly-resolved ABLh derived from lidar-ceilometer have been compared to those calculated by the COSMO-CHIMERE modeling chain and the CALMET mass-consistent meteorological preprocessor. Maximum mean differences between lidar and CALMET were found to reach ±800 m in the late afternoon and evening. Conversely, COSMO-CHIMERE predicts a pattern more similar to the observations, although retaining differences during the evening period when a mean model underestimation of about 400 m is present. However, it is worth emphasizing that these differences are directly linked to an ABL definition problem. In fact, while the lidar-based retrieval relays the aerosol mixing status, models generally exploit turbulence to infer the thickness of the ABL. In other words, when irradiance decreases in the afternoon, the model-simulated mixing strength drops dramatically, and thermals are no longer able to take aloft aerosols. Being the ALC blind under 150 m, it is not able to detect this new shallow layer, and it keeps tracking aerosols already mixed aloft and the part of them leading to a still turbulent residual layer (e.g.: Figure 7). We could then say that the aerosol-based retrievals mainly trace the mixed layer, while turbulence-based retrievals characterize the mixing layer.

Acknowledgments

This research was carried out in the framework of the “Supersito” Project, which was supported and financed by Emilia-Romagna Region and Regional Agency for Prevention, Environment and Energy.

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Stampa: Laboratorio Tecnografico ENEA - C.R. Frascati
luglio 2021