Retrieval of boundary layer height from lidar using extended Kalman filter approach, classic methods, and backtrajectory cluster analysis

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ABSTRACT

This contribution evaluates an approach using an extended Kalman filter (EKF) to estimate the planetary boundary layer height (PBLH) from lidar measurements obtained in the framework of the European Aerosol Research Lidar NETwork (EARLINET) at 12 UTC ± 30-min for a 7-year period (2007-2013) under different synoptic flows over the complex geographical area of Barcelona, Spain. PBLH diagnosed with the EKF technique are compared with classic lidar methods and radiosounding estimates. Seven unique synoptic flows are identified using cluster analysis of 5756 HYSPLIT (HYbrid Single Particle Lagrangian Integrated Trajectory) three-day backtrajectories for a 16-year period (1998-2013) arriving at 0.5 km, 1.5 km, and 3 km, to represent the lower PBL, upper PBL, and low free troposphere, respectively. Regional recirculations are dominant with 54% of the annual total at 0.5 km and 57% of the total lidar days at 1.5 km, with a clear preference for summertime (0.5 km: 36% and 1.5 km: 29%). PBLH retrievals using the EKF method range from 0.79 - 1.6 km asl. The highest PBLHs are observed in southwest flows (15.2% of total) and regional recirculations from the east (34.8% of total), mainly caused by the stagnant synoptic pattern in summertime over the Iberian Peninsula. The lowest PBLHs are associated with north (19.6% of total) and northeast (4.3% of total) synoptic flows, when fresh air masses tend to lower PBLH. The adaptive nature of the EKF technique allows retrieval of reliable PBLH without the need for long time averaging or range smoothing, as typical with classic methods.

Keywords: boundary layer, lidar, cluster analysis, Kalman filter, EARLINET, bulk Richardson

1. INTRODUCTION

The planetary boundary layer (PBL) height is defined as the altitude of the inversion level separating the free troposphere (FT) from the boundary layer [1]. The PBL is the lowest layer to the Earth’s surface where constituents such as aerosols are mixed by turbulent convective processes. PBL height (PBLH) is an important input in numerical applications such as weather and air quality modelling as it delineates the top of the mixing layer. Lidsars (laser radars) with high spatial (< 30 m) and temporal resolutions (< 5 min) can be employed to monitor PBLH using the optical backscatter power from aerosols as tracers.

Lidar presents some advantages over the more traditional use of radiosondes to retrieve PBLH. These advantages include lidsars high-resolution temporal and vertical spatial coverage which can possibly be operated continuously and in a nearly automated status. Thus, an instantaneous recorded PBLH allows more in-depth analysis such as diurnal evolution and long-term climate studies. Typically radiosondes are launched only two times per day with limited vertical resolution and potential tracking problems at the low levels in the PBL.

Several methods have been applied in the literature to determine the PBLH from lidar observations. In this study we will refer to these past methods as the classic methods. They are comprised of both objective and subjective methods. Objective methods are based on analysis of the morphology or the lidar signal and comprise various forms of derivative methods [2-4], wavelet analysis methods [5, 6], threshold method [7, 8], and variance method [9, 10]. Visual inspection methods [11] are infrequently used as a subjective approach but they are not the best approach. Finally, an adaptive approach using an extended Kalman filter (EKF) has recently been developed and tested [12].
Several of these methods have been inter-compared in previous works \cite{13, 14}. The outcome of these previous studies has never determined an optimum method for estimating PBLH in all typical atmospheric scenarios, especially complex scenes with multiple aerosol layers.

The area of study is the urban metropolis of Barcelona, Spain. Barcelona is a complex geographical area located in the northeast Iberian Peninsula (IP). The climate of the region is affected by both synoptic and mesoscale meteorological processes \cite{15, 16}. Certain mesoscale processes in the northeast IP are a result of the orientation between topographic features (pre-coastal and coastal mountain ranges) and the Mediterranean Sea. Previous works have found that both synoptic circulations and mesoscale processes combine to influence the height of the PBL \cite{3}.

Two main objectives are the drivers of this contribution. The first objective is to provide an updated clustering of general synoptic flows which affect the northeastern IP. This will be accomplished utilizing a long period of kinematic backtrajectories and a cluster analysis algorithm. Results of the cluster analysis will be used as complementary information to evaluate an adaptive technique using an EKF to estimate PBLH from lidar observations. The technique will be compared with classic methods under different objectively determined atmospheric situations produced with the cluster analysis. Data are selected around the time of daily daytime radiosonde launches to ensure a significant analysis.

The rest of the paper will be presented as follows. Instruments used and the cluster analysis algorithm are briefly described in Section 2. The following section summarizes classic methods for estimating PBLH from lidar and presents information about the EKF technique. Section 4 reveals the results of the cluster analysis and the comparisons between lidar methods and radiosoundings. Conclusions and future work are drawn in Section 5.

\section{INSTRUMENTS AND CLUSTER ANALYSIS}

\subsection{Elastic backscatter lidar}

Data from two multiwavelength elastic Raman lidars \cite{17} were downloaded from the database of the Remote Sensing Laboratory (RSLAB) in the Department of Signal Theory and Communications (TSC) at the Universitat Politècnica de Catalunya (UPC) in Barcelona, Spain. The RSLAB lidar group at the UPC is a member station of the European Aerosol Research Lidar Network \cite{18}. Lidar observations were chosen around 12 UTC ± 30-min for a 7-year period performed between 2007 and 2013. A total of 45 individual measurement days have been selected.

The history of the lidar program at the TSC RSLAB dates back to the first elastic backscatter lidar in 1993. For the time period selected in this work data from two different lidar systems have been used. From 2007 to August 2010 the instrument was a 2+1 elastic/Raman lidar. Since September 2010, a 3+2+1 elastic/Raman aerosol/water vapor system was integrated. Characteristics of the two instruments are shown in Table 1.

Raw lidar data obtained for this analysis are from the visible channel (532 nm elastic analog) with either 15 m (2007), 7.5 m (2008 - August 2010), or 3.75 m (after August 2010) raw vertical resolution and 1-min averaged temporal resolution. The 532 nm analog channel was selected considering a comparatively higher signal-to-noise (SNR) ratio and contrast between aerosol and molecular backscatter returns. Pre-processing of the lidar returns include removal of the molecular background using Rayleigh fit to achieve range-corrected signals (RCS).

Lidar RCS are used as input to the PBL-retrieval algorithms explained in Section 3. Range is limited at low levels due to the incomplete overlap between the laser transmitter and the telescopic receiver. For boundary layer studies overlap issues can make PBLH estimations unreliable or unavailable \cite{19}. The instruments used in this work have a maximum full overlap range of approximately 0.45 km, which is taken into account when retrieving the PBLH.
Table 1. List of instrument specifications for the two RSLAB lidar instruments used in this study (2007-2010) and (2010-2013). Also shown are the ranges determined for the initial state vector to the EKF method and the threshold ranges selected for the threshold (TH) method.

<table>
<thead>
<tr>
<th>INSTRUMENT SPECIFICATIONS</th>
<th>2007 - 2010</th>
<th>2010 - 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lidar model</td>
<td>lab 2+1 elastic/Raman</td>
<td>lab 3+3 elastic/Raman</td>
</tr>
<tr>
<td>Received wavelengths</td>
<td>elastic: 532/1064 nm Raman: 607 nm</td>
<td>elastic: 355/532/1064 nm Raman: 387/407/607 nm</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>7.5 m</td>
<td>3.75 m</td>
</tr>
<tr>
<td>Slant path line of sight</td>
<td>$\Theta = 50^\circ$</td>
<td>$\Theta = 38^\circ$</td>
</tr>
<tr>
<td>(elevation angle)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full-overlap height</td>
<td>250 m</td>
<td>450 m</td>
</tr>
</tbody>
</table>

**INITIAL STATE VECTOR RANGE**

<table>
<thead>
<tr>
<th></th>
<th>2007 - 2010</th>
<th>2010 - 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBL height ($R_{bl}$)</td>
<td>0.5 – 2.0 km</td>
<td>0.75 – 1.5 km</td>
</tr>
<tr>
<td>EZ scaling factor (a)</td>
<td>3.7 – 18.5 km$^{-1}$</td>
<td>7.4 – 36.9 km$^{-1}$</td>
</tr>
<tr>
<td>Transition amplitude ($A'$)</td>
<td>0.4x10$^{-3}$ – 0.1</td>
<td>0.08 – 35.0</td>
</tr>
<tr>
<td>Molecular background ($c'$)</td>
<td>0.001 – 0.05</td>
<td>0.1 – 8.5</td>
</tr>
</tbody>
</table>

**THRESHOLD VALUE RANGE**

<table>
<thead>
<tr>
<th>Threshold</th>
<th>2007 - 2010</th>
<th>2010 - 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$5.5x10^{-4}$ – 0.15 V · km$^{-2}$</td>
<td>$0.8$ – 22.5 V · km$^{-2}$</td>
</tr>
</tbody>
</table>

* Note: Year 2007 spatial resolution = 15 m

2.2 Radiosoundings

For the evaluation of lidar-based methods it’s important to have a reference value of PBLH to compare with the estimates from lidar observations. PBLH calculated from radiosounding measurements have become an accepted reference in many past studies and will be exploited in this evaluation. Upper-air meteorological measurements are obtained from daily daytime (12 UTC) radiosonde launches performed by the Meteorological Service of Catalunya in Barcelona (41.38 N, 2.12 E, 0.98 km asl). The meteorological service routinely launches the radiosondes approximately 0.72 km distance from the site of the UPC lidar. Radiosonde instruments record many atmospheric variables including temperature (°C), relative humidity (%), wind speed (ms$^{-1}$ or kt) and direction (°), and barometric pressure (hPa).

In this study PBLH is calculated from the radiosounding data using the bulk Richardson number (Ri_b) method$^{[20]}$. The Ri_b approach requires wind speed and direction, barometric pressure, and temperature as input variables at each altitude. With this technique the PBLH is determined where the wind flow transitions from turbulent to laminar, indicating the top of the PBL. Theoretically, PBLH is calculated at the altitude where Ri_b exceeds a so-called critical Richardson number (Ri_{bc}). In this work, $Ri_{bc} = 0.55$ is found to be the most appropriate. This critical value is higher than used in previous studies in Barcelona$^{[3]}$ but is still considered in the literature as a good transition value between turbulent and laminar flow$^{[21]}$.

2.3 Backtrajectory cluster analysis

The aerosol load in the boundary layer can be developed and modified depending on the predominant synoptic wind flow and therefore affect PBLH thickness. Changes in the aerosol load, especially in the PBL to lower FT, can affect the PBLH estimation from lidar. To enhance the robustness of the analysis, the methods to obtain PBLH from lidar are evaluated under different synoptic flows determined with an objective procedure. In order to objectively quantify the atmospheric dynamics from a synoptic perspective and select representative lidar cases from varying atmospheric flows, a cluster analysis is initiated.
A cluster analysis of three-day backtrajectories is calculated using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model [22]. The automated analysis is performed using the methodology of a previous study [23]. The database chosen for the backtrajectories was composed for the period: 1998-2013 (16-year) from the National Centers for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS). NCEP GDAS data are interpolated onto a 1° x 1° grid with a 6-hourly temporal resolution.

Kinematic backtrajectories from HYSPLIT for three days duration with endpoint of the Barcelona lidar are computed at three vertical levels: 0.5 km, 1.5 km, and 3 km agl. These levels are selected as altitudes representing within the boundary layer, near the top of the PBL, and within the low FT, respectively. The back trajectories are calculated once per day ending at 12 UTC.

3. METHODS TO ESTIMATE PBLH FROM LIDAR

3.1 Classic methods

A commonly used method to objectively determine PBLH from lidar observations are wavelet-based methods, in particular the wavelet covariance transform (WCT) with a Haar wavelet. The general approach is to employ the Haar wavelet function to extract scale-dependent information from the original lidar RCS profile. It is defined as a means of detecting step changes in the RCS. The WCT method has been used by many authors [5, 6] and has proven to be a very computationally robust technique.

With the WCT, the maximum value of the covariance transform corresponds to the strong step-like decrease in the lidar RCS, where the gradient in aerosol concentration is the most defined. The corresponding height of the resulting maximum is identified as the PBLH. It has been discovered [14] that key uncertainties in the determination of PBLH by this technique lie in the choice of the upper and lower limits of integration for calculating the WCT and proper choice of the dilation parameter. Baars et al. [5] introduced a modified version of the WCT in an attempt to find an appropriate dilation depending on the atmospheric situation. For simplification of applying the WCT method we use a constant dilation for the entire lidar dataset.

Recently, it has been shown [25] that the wavelet method (WCT) is completely equivalent to the gradient method applied to a spatially low-pass filtered RCS. Therefore, in this study we will ignore the use of derivative-based methods, and use the WCT method as described above. The WCT method has the advantage of performing the PBLH estimate in a single, computationally efficient step.

Another classic method to be employed in this study is the threshold (TH) method [7, 8]. This simple technique functions using an operator-defined critical threshold value in the lidar RCS. The method requires the operator to input a threshold value to distinguish the PBL from the FT. Threshold values vary for the two instruments used in this work with their ranges shown in Table 1. Typically the method also requires the user to select an upper and lower altitude to constrain the search for the threshold value. For our purposes we constrain to a lowest altitude of 0.45 km in coincidence with the overlap range of the UPC lidar and a highest altitude of 4 km as a realistic estimate of the possible highest PBLH.

Finally, the variance (VAR) method [9, 10] makes use of the vertical profile of the variance of the lidar RCS. With this method the PBLH is the height at which there is a clear maximum in the variance profile. We subject 15 profiles with a 1-min temporal resolution to the variance algorithm to estimate the PBLH.

3.2 RSLab extended Kalman filter technique

An adaptive approach utilizing an extended Kalman filter (EKF) [26] has been developed and tested in the TSC RSLAB at the UPC to track the evolution of the PBL [12]. The technique builds upon previous works [27, 28]. In Lange et al. [12] they found that the main advantages of the EKF are the ability to track PBLH without need for long time averaging and range smoothing and the ability to perform well under low SNR conditions. The EKF technique benefits from knowledge of past PBLH estimates and their associated errors and from the convenient way the estimation error is minimized on a mean-squared-error sense over time.

The developed and tested EKF approach is based on estimating four time-adaptive coefficients of an oversimplified Erf-like curve model, representing the PBL transition. It is important in the EKF technique to initialize the state vector properly: \( R_{bl} a' c' \), where \( R_{bl} \) is an initial guess of the PBLH, \( a \) is the entrainment zone (EZ) scaling factor, \( a' \) is the
amplitude of the Erf transition, and $c'$ is the average molecular background at the bottom of the FT. Since we use two different lidar instruments in this study there will be differences in the initial state vector choices. The ranges of the initial state vector variables for the two instruments are shown in Table 1. If the state vector is not initialized correctly one can expect not so reliable estimates of PBLH.

It is important to note RCS input to the lidar-based estimation methods have not been range-smoothed or long temporally averaged, as an objective of this work is to display the power of the EKF technique under these criteria. For all methods (classic and EKF), PBLH is estimated from the lidar RCS using 1-min temporal resolution and the raw spatial resolution of the instrument (15 m or 7.5 m or 3.75 m).

Estimates of PBLH from all lidar-based methods are evaluated with a 5-min average of PBLH closest to 12 UTC for two reasons. The main reason is to compare closely to the radiosoundings which are routinely launched each day at 12 UTC. The second reason is PBLH can vary dramatically over short time periods (minutes to hours), meaning an average PBLH represents a reasonable comparison. Other time-averaging windows (10-min and 15-min) were tested, with very similar results to a 5-min average.

4. RESULTS

4.1 Synoptic meteorological flows determined from cluster analysis

As result of the cluster analysis, seven individual synoptic clusters are determined at each arriving altitude (0.5 km agl, 1.5 km agl, and 3 km agl). Overall, cluster types at the three arriving altitudes show similar patterns (Figure 1). However, some key differences are found when assessing the results of the cluster analysis at the different levels and when comparing to previous results [23] at 1.5 km and 3 km arriving altitudes.

The seven individual synoptic clusters arriving at 1.5 km and their associated centroids are shown in Figure 1b. The 1.5 km arriving altitude is used as a proxy for near the top of the PBL in a complex area such as Barcelona. The monthly temporal frequency of the different clusters is shown in Figure 1d. The monthly temporal frequencies for the clusters at 0.5 km and 3 km show a similar pattern as 1.5 km, so they are not presented in this work.

Regional recirculations from the east (Re) or west (Rw) directions are the most predominant synoptic clusters throughout the year, accounting for 44.5% of the total (5756) backtrajectories. Re and Rw clusters occur most often in the summertime when the synoptic situation is stagnant, leading to strong mesoscale processes in the low levels of the atmosphere [15].

The frequency of lidar days in a particular cluster is presented in Table 2. It can be seen that over half (55.6%) of the lidar data falls into the Re or Rw categories at 1.5 km. The next most frequent cluster is synoptic flow from the north (N; 20%), followed by flow from the southwest (SW; 15.6%). The other three synoptic clusters; flows from the northeast (NE), west (W), and fast west-northwest (Fast WNW), account for less than 10% of the available lidar days.

Atmospheric flows arriving at 0.5 km are important as it represents an altitude typically within a well-defined PBL. Centroids of the seven individual synoptic clusters arriving at 0.5 km are shown in Figure 1c. We observe similar results as the clusters at 1.5 km, with Re and Rw clusters still being the most predominant synoptic patterns. The predominance of Re and Rw clusters at both altitudes is easily attributable to complex diurnal mesoscale processes which result from the location of Barcelona between mountains and the Mediterranean Sea.

The frequency of lidar days in synoptic clusters arriving at 0.5 km altitude is shown in Table 3. Re and Rw clusters show an even greater dominance (73.4%) of the available lidar days than at 1.5 km. This is mainly due to the topographic features of the area acting as a barrier to the other synoptic flows. This can be confirmed by the lack of lidar days with flows from the SW and northwest (NW), with only 4.4% of the total.

Finally, seven distinct synoptic clusters arriving at 3 km were determined and the centroids are shown in Figure 1a. This higher arriving altitude was selected as being representative of the low FT. The main difference between cluster types at this altitude and the two lower levels is the substitution of regional recirculation (Re and Rw) patterns for slow southwest (Slow SW) and easterly (E) synoptic flows. This is most likely due to the lack of the topographic barriers found at the lower altitudes. This finding is a departure from a previous study [23] where they found regional recirculations at both 3 km and 1.5 km altitudes.
The frequency of lidar days in a particular cluster arriving at 3 km altitude is presented in Table 4. Different from the frequencies of occurrence at 1.5 and 0.5 km altitudes, Slow SW and NW synoptic flows are the most predominant, accounting for 24.4% and 22.2% of the available data, respectively. If we combine Slow SW and SW flows into one group, they account for 42.2% of the lidar days. Synoptic flows originating from the SW are a major contributor to desert dust outbreaks in the northeast IP.

It is well evident from Figure 1 that the overall patterns (curvature) of the synoptic clusters are similar at all arriving altitudes selected for this study. The primary difference between synoptic clusters at different altitudes is the length (magnitude) of the centroid. It can be seen from Figure 1 that the length of the centroid increases with an increase in arriving altitude, indicating faster wind speeds.

In the following areas of this section we will present statistical comparisons between lidar-estimated and radiosonde-calculated PBLH for each synoptic cluster. Also, a representative case for each of the four most dominant atmospheric flows will be shown.
Table 2. Seven selected synoptic clusters from HYSPLIT backtrajectories arriving at 1.5 km altitude. Total (%) of backtrajectories assigned to each cluster during 1998-2013, number (%) of lidar days with certain synoptic flow, and associated mean PBLH (km asl) for each lidar method and difference (km asl) between PBLH estimated by lidar method and that derived from radiosoundings for Extended Kalman filter (EKF), threshold (TH), wavelet covariance transform (WCT), and variance (VAR) methods. Values in bold typeface indicate an under-estimation by the lidar method.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>% of total</th>
<th>% of lidar days</th>
<th>EKF mean PBLH</th>
<th>EKF-sonde</th>
<th>TH mean PBLH</th>
<th>TH-sonde</th>
<th>WCT mean PBLH</th>
<th>WCT-sonde</th>
<th>VAR mean PBLH</th>
<th>VAR-sonde</th>
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</thead>
<tbody>
<tr>
<td>Re</td>
<td>23.4</td>
<td>35.6</td>
<td>1.30</td>
<td>0.03</td>
<td>1.29</td>
<td>0.02</td>
<td>1.19</td>
<td>-0.08</td>
<td>1.25</td>
<td>-0.03</td>
</tr>
<tr>
<td>Rw</td>
<td>21.1</td>
<td>20.0</td>
<td>1.38</td>
<td>0.05</td>
<td>1.33</td>
<td>0.00</td>
<td>1.33</td>
<td>0.00</td>
<td>1.11</td>
<td>-0.22</td>
</tr>
<tr>
<td>NE</td>
<td>12.5</td>
<td>4.4</td>
<td>0.91</td>
<td>-0.11</td>
<td>0.91</td>
<td>-0.11</td>
<td>0.86</td>
<td>-0.16</td>
<td>0.75</td>
<td>-0.27</td>
</tr>
<tr>
<td>SW</td>
<td>11.9</td>
<td>15.6</td>
<td>1.33</td>
<td>0.13</td>
<td>1.38</td>
<td>0.18</td>
<td>1.15</td>
<td>-0.05</td>
<td>1.17</td>
<td>-0.03</td>
</tr>
<tr>
<td>N</td>
<td>11.6</td>
<td>20.0</td>
<td>1.24</td>
<td>-0.09</td>
<td>1.19</td>
<td>-0.14</td>
<td>1.34</td>
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<td>1.17</td>
<td>-0.16</td>
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<tr>
<td>W</td>
<td>11.4</td>
<td>2.2</td>
<td>0.73</td>
<td>0.01</td>
<td>1.04</td>
<td>0.32</td>
<td>1.26</td>
<td>0.54</td>
<td>1.06</td>
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<tr>
<td>Fast</td>
<td>8.2</td>
<td>2.2</td>
<td>1.09</td>
<td>-0.24</td>
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<td>-0.11</td>
<td>1.09</td>
<td>-0.24</td>
<td>0.90</td>
<td>-0.43</td>
</tr>
</tbody>
</table>

4.2 Comparisons of PBLH estimates between lidar methods and radiosounding

The comparison of PBLH estimates between the different lidar methods and radiosoundings will be divided into two focus areas. First, we discuss comparisons for the total collection of lidar observations (2007-2013) collected. Then, comparisons will be made with respect to the atmospheric flows objectively determined through the cluster analysis shown in the previous section.

Over the 2007-2013 data collection period the 45 individual measurement days yield an average PBLH of 1.28 ± 0.4 km asl at 12 UTC via the EKF method. As mentioned previously, 12 UTC was the selected observation time for two main reasons. The first reason is 12 UTC is very close to the time of maximum solar insolation, which typically leads to the daytime maximum PBLH. The second reason was to better compare with 12 UTC launches of radiosondes, which we use as the true PBLH.

The average PBLH estimated with the EKF technique is very close to the average determined with the threshold method (PBLH = 1.27 ± 0.5 km asl), but further apart when compared with estimates from the WCT (PBLH = 1.23 ± 0.5 km asl) and VAR (PBLH = 1.16 ± 0.6 km asl) methods. This result is due to the high signal-to-noise ratio (SNR > 5) at the PBLH, which enables to set a consistent threshold for the whole lidar time-height series [12]. Even though the average PBLH may be different the standard deviation from each method are quite similar. The average PBLH estimated with the EKF method is very similar to the results found in previous works over Barcelona [3, 4]. In Sicard et al. [4] they estimated an annual average PBLH of 1.21 km using a gradient method. It is well known from previous studies that the PBLH in the northeast IP doesn’t vary much with time of the year.

The correlation between PBLH estimated with the EKF technique and PBLH calculated with radiosoundings is very strong (R² = 0.77, N = 45). Due to a lack of observations in some synoptic clusters, the correlation statistics were only calculated for the total collection of observations. The TH method shows the next best correlation (R² = 0.19), as compared with radiosoundings. The correlations become much weaker with the other classic methods (R² = 0.02 for WCT and R² = ~ 0.0 for VAR), most likely due to the lack of range smoothing and temporal averaging of the RCS which these methods perform best with.
Differences between PBLH determined by the various lidar methods and radiosoundings can be further highlighted by grouping the lidar data into synoptic clusters at the different altitudes (Tables 2, 3, and 4). These results are highlighted next.

Table 2 presents the results when the lidar data are grouped into the seven synoptic clusters at 1.5 km. It can be seen that the highest PBLH estimated by the EKF method (1.35 km asl) occur in SW flows and regional recirculations from the east or west (Re and Rw). The lowest PBLH from the EKF method (0.73 km asl) are associated with W flows. Some comparisons can be made with another study in Barcelona [29] using a ceilometer. In Pandolfi et al. [29] the highest PBLH were observed in cold Atlantic (1.88 ± 0.29 km agl) air mass, followed by stagnant regional (1.77 ± 0.31 km agl), and north African air mass (1.57 ± 0.43 km agl).

At 1.5 km altitude the largest differences between any lidar-based method and radiosoundings occur in both NE and Fast W-NW flows. Both synoptic situations influence an across-the-board underestimation of the PBLH by the lidar methods, with as much as an 0.43 km asl underestimation with the VAR method.

Scatter diagrams between lidar methods and radiosoundings for each cluster type arriving at 1.5 km altitude are shown in Figure 2. In these plots the PBLH estimates have been color-coded according to their respective cluster type at this altitude. The correlation statistics and reference line (solid red) are for the total lidar observations, as discussed previously in this section. From these diagrams it is clearly seen that the EKF method performs the best in all synoptic situations, followed by the threshold method. The overall comparison is similar to the correlation between lidar and radiosonde. The largest deviations from the 1:1 line occur with flows from the southwest (SW) and regional recirculations (Re and Rw). Scatter plots were also analyzed for synoptic clusters arriving at 0.5 km and 3 km altitudes, which show similar patterns to 1.5 km, and will not be shown in this paper.
Table 3. Seven selected synoptic clusters from HYSPLIT backtrajectories arriving at 0.5 km altitude. Total (%) of backtrajectories assigned to each cluster during 1998-2013, number (%) of lidar days with certain synoptic flow, and associated mean PBLH (km asl) for each lidar method and difference (km asl) between PBLH estimated by lidar method and that derived from radiosoundings for Extended Kalman filter (EKF), threshold (TH), wavelet covariance transform (WCT), and variance (VAR) methods. Values in bold typeface indicate an under-estimation by the lidar method.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>% of total</th>
<th>% of lidar days</th>
<th>EKF mean PBLH</th>
<th>EKF-sonde</th>
<th>TH mean PBLH</th>
<th>TH-sonde</th>
<th>WCT mean PBLH</th>
<th>WCT-sonde</th>
<th>VAR mean PBLH</th>
<th>VAR-sonde</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re</td>
<td>29.2</td>
<td>46.7</td>
<td>1.25</td>
<td>0.05</td>
<td>1.26</td>
<td>0.05</td>
<td>1.12</td>
<td>-0.09</td>
<td>1.14</td>
<td>-0.07</td>
</tr>
<tr>
<td>Rw</td>
<td>24.9</td>
<td>26.7</td>
<td>1.30</td>
<td>0.06</td>
<td>1.27</td>
<td>0.03</td>
<td>1.30</td>
<td>-0.06</td>
<td>0.99</td>
<td>-0.24</td>
</tr>
<tr>
<td>N</td>
<td>10.7</td>
<td>6.7</td>
<td>1.47</td>
<td>-0.12</td>
<td>1.41</td>
<td>-0.18</td>
<td>1.32</td>
<td>-0.27</td>
<td>1.26</td>
<td>-0.33</td>
</tr>
<tr>
<td>W</td>
<td>9.8</td>
<td>6.7</td>
<td>1.41</td>
<td>-0.01</td>
<td>1.58</td>
<td>0.16</td>
<td>1.53</td>
<td>0.11</td>
<td>1.52</td>
<td>0.10</td>
</tr>
<tr>
<td>SW</td>
<td>9.6</td>
<td>2.2</td>
<td>1.27</td>
<td>-0.07</td>
<td>1.42</td>
<td>0.08</td>
<td>2.82</td>
<td>3.09</td>
<td>1.75</td>
<td>1.23</td>
</tr>
<tr>
<td>NE</td>
<td>9.4</td>
<td>8.9</td>
<td>1.16</td>
<td>-0.08</td>
<td>0.95</td>
<td>-0.29</td>
<td>0.98</td>
<td>-0.26</td>
<td>1.02</td>
<td>-0.23</td>
</tr>
<tr>
<td>NW</td>
<td>6.5</td>
<td>2.2</td>
<td>1.01</td>
<td>-0.25</td>
<td>1.19</td>
<td>-0.07</td>
<td>0.86</td>
<td>-0.40</td>
<td>0.82</td>
<td>-0.44</td>
</tr>
</tbody>
</table>

Next, the results are shown from grouping the lidar data into the seven synoptic clusters arriving at 0.5 km (Table 3). To recall, the synoptic clusters at 0.5 km are similar to the synoptic clusters at 1.5 km, except the magnitude of the NW flow is less at this altitude. Similarly, the largest differences in PBLH between lidar estimates and radiosoundings occur in the NE and NW flows, with an underestimation by as much as 0.44 km asl with the VAR method. The synoptic situations determined at 0.5 km altitude are the most complex due to unique mesoscale processes induced by topography and close proximity to the sea. However, the EKF method outperforms the classic methods, with an average underestimation of only 0.06 km asl.

Finally, in Table 4 we display the results of the synoptic cluster groupings arriving at 3 km. At this altitude we lose the influence of regional recirculations, replaced by slow southwest (Slow SW) and easterly (E) flows (Figure 1c). The EKF method estimates an average PBLH of 1.17 km asl and 0.86 km asl, in Slow SW and E flows, respectively. The low PBLH diagnosed in E flows is possibly the result of low level cloud development, which forms with moisture being transported from the sea. The largest differences in PBLH between lidar and radiosoundings also occur in E flows, with an underestimation around 0.30 km asl among the methods. This result highlights the effects of clouds on lidar RCS.

In this section we have presented the results of a comparison between lidar-estimated and radiosonde-calculated PBLH. It has been shown that the EKF method is a top performer with both total lidar measurement comparisons, and also when categorized into synoptic clusters at different arriving altitudes.

4.3 Case studies with representative synoptic situations

Representative days for the most frequent atmospheric situations are chosen via the cluster analysis, and then further validated with complementary information from satellite images, radiosoundings, dust simulations from a mineral dust model, and meteorological charts from the NOAA GDAS (Global Data Assimilation System) model. The most frequent synoptic flows over Barcelona are from the north, west and southwest, and east. The most predominant low-level pattern are regional recirculations of air masses. The objectively determined synoptic flows are similar to the subjective selection of representative cases used in a related study [29].
Table 4. Seven selected synoptic clusters from HYSPLIT backtrajectories arriving at 3 km altitude. Total (%) of backtrajectories assigned to each cluster during 1998-2013, number (%) of lidar days with certain synoptic flow, and associated mean PBLH (km asl) for each lidar method and difference (km asl) between PBLH estimated by lidar method and that derived from radiosoundings for Extended Kalman filter (EKF), threshold (TH), wavelet covariance transform (WCT), and variance (VAR) methods. Values in bold typeface indicate an under-estimation by the lidar method.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>% of total</th>
<th>% of lidar days</th>
<th>EKF mean PBLH</th>
<th>EKF-sonde</th>
<th>TH mean PBLH</th>
<th>TH-sonde</th>
<th>WCT mean PBLH</th>
<th>WCT-sonde</th>
<th>VAR mean PBLH</th>
<th>VAR-sonde</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow SW</td>
<td>22.6</td>
<td>24.4</td>
<td>1.17</td>
<td>0.01</td>
<td>1.13</td>
<td>-0.02</td>
<td>1.22</td>
<td>0.07</td>
<td>1.24</td>
<td>0.08</td>
</tr>
<tr>
<td>W</td>
<td>19.4</td>
<td>15.6</td>
<td>1.23</td>
<td>0.00</td>
<td>1.55</td>
<td>0.32</td>
<td>1.41</td>
<td>0.18</td>
<td>1.13</td>
<td>-0.10</td>
</tr>
<tr>
<td>N</td>
<td>14.6</td>
<td>13.3</td>
<td>1.34</td>
<td>0.07</td>
<td>1.29</td>
<td>0.01</td>
<td>1.17</td>
<td>-0.11</td>
<td>1.12</td>
<td>-0.15</td>
</tr>
<tr>
<td>NW</td>
<td>12.8</td>
<td>22.2</td>
<td>1.39</td>
<td>-0.03</td>
<td>1.20</td>
<td>-0.21</td>
<td>1.26</td>
<td>-0.15</td>
<td>1.09</td>
<td>-0.33</td>
</tr>
<tr>
<td>SW</td>
<td>10.7</td>
<td>17.8</td>
<td>1.34</td>
<td>0.12</td>
<td>1.30</td>
<td>0.08</td>
<td>1.12</td>
<td>-0.10</td>
<td>1.23</td>
<td>0.00</td>
</tr>
<tr>
<td>Fast W</td>
<td>10.5</td>
<td>4.4</td>
<td>1.29</td>
<td>-0.10</td>
<td>1.36</td>
<td>-0.03</td>
<td>1.26</td>
<td>-0.13</td>
<td>1.19</td>
<td>-0.20</td>
</tr>
<tr>
<td>E</td>
<td>9.4</td>
<td>2.2</td>
<td>0.86</td>
<td>-0.32</td>
<td>0.95</td>
<td>-0.23</td>
<td>0.80</td>
<td>-0.38</td>
<td>0.85</td>
<td>-0.33</td>
</tr>
</tbody>
</table>

4.3.1 Clean FT during north flows

The simplest type of atmospheric pattern for PBLH estimation is when there is a clear delineation between the convective boundary layer (CBL) and the FT. Most often, this will occur in flows from the north (N) or northwest (NW), when strong laminar winds clear the atmosphere above the PBL. A representative day for this atmospheric situation is shown in Figure 3a for 22 March, 2009 with a lidar RCS time-height series from 11:43 – 13:52 UTC. On this day, the synoptic flow is from the N at 1.5 km and 3km altitude, and from the NE at 0.5 km altitude. A clean FT can be confirmed with radiosonde (Figure 3b), which shows a dry atmosphere in the PBL. The relatively dry atmosphere is further validated by the relative humidity at 2 m (Figure 3c, colored contours) from a NOAA GDAS simulation valid for 12 UTC on 22 March, with most of the area less than 40% RH.

For this day the PBLH estimated by the radiosonde is 1.28 km asl. The EKF method provides the closest estimate to the radiosounding (1.24 km asl), followed by the WCT method (1.16 km asl), TH method (0.97 km asl), and VAR method (0.96 km asl). The PBLH estimate provided by the EKF method on this representative day is similar to the average for all lidar days in this synoptic cluster arriving at 1.5 km.

4.3.2 Regional recirculations at low levels

As explained in previous sections, regional recirculations from the east or west (Re or Rw) are the most predominant synoptic flows in the Barcelona area, accounting for over half of the days annually at both 0.5 km and 1.5 km arriving altitudes. Re and Rw are especially frequent in summertime when the synoptic pattern is stagnant and mesoscale convective processes dominate. A representative day for this frequent type is shown in Figure 4 for 03 July, 2012 with a lidar RCS time-height series from 12:01 – 12:30 UTC. Based upon the objective analysis, on this day we observe both Re and Rw flows, at 0.5 km and 1.5 km altitudes respectively. During this period in early July 2012 the UPC lidar was a participant in the pre-campaign for ChArMEx (The Chemistry-Aerosol Mediterranean Experiment).
Figure 3. Representative case of clean FT during north (N) synoptic flows. Lidar time-height series (a) for 22 March 2009, along with 1-min PBLH estimates from the EKF (magenta dot), TH (grey plus sign), VAR (green cross), and WCT (light blue asterix) methods. Also shown is radiosounding skew-T diagram (b) from launch at 12 UTC, and 2 m relative humidity (RH; colored contours) and 850 hPa wind (vectors) from the NOAA GDAS model (c) valid at 12 UTC.

PBLH estimated by the radiosonde is 0.91 km asl. Both the EKF and TH methods determine similar estimates (1.04 and 1.05 km asl, respectively), while the WCT (1.78 km asl) and VAR (1.78 km asl) methods follow the additional aerosol layer between 1.5 and 2 km asl. The additional aerosol layer around this altitude at this time of day is quite common in summertime. The estimates from the EKF and TH methods are around 0.20 km asl lower than the long-term average of all lidar days in the regional recirculations (Re and Rw combined) category.

4.3.3 Saharan dust episode from west and southwest flows

West and southwest advections of Saharan dust are a common occurrence over the northeast IP and can happen anytime during the year. A representative day (Figure 5a) is 03 August, 2007 with a 30-min lidar RCS time-height series from 11:51 – 12:20 UTC. On this day the synoptic flow is from the west at 3 km, with regional recirculations from the west prevalent at both 0.5 km and 1.5 km altitudes. The representative day is confirmed as a dust event using simulations from the BSC DREAM v1.0 mineral dust model (Figure 5b,c). A vertical dust concentration profile (Figure 5c) shows dust concentrations greater than 75 µg/m³ for a layer below 4 km agl.
On this day the PBLH estimated by the radiosonde is 1.43 km asl, which is close to the long-term average (1.33 km asl) of lidar cases in the SW synoptic cluster arriving at 1.5 km. The EKF method provides an estimate (1.5 km asl) closest to the radiosonde, while the classic methods (TH = 2.41, WCT = 2.3, VAR = 0.97 km asl) have issues with determining the correct altitude. EKF has a significant advantage over classic methods due to way it combines past PBLH estimates with the present lidar measurement at each succeeding discrete time.

4.3.4 Influence of cloud layers

The final atmospheric scenario which is frequent in the northeast IP are cases in which low level clouds affect the lidar RCS, which complicate PBLH retrievals. A representative day with clouds near the boundary layer is selected (Figure 6a) on 22 April, 2010 with a lidar RCS time-height series from 12:03 – 12:32 UTC. For this day the atmosphere is in an unstable, decoupled state with Re flow prevalent at 0.5 km, E flow at 1.5 km, and a Slow SW flow at 3 km altitude. The strongly reflective cloud layer from 2 - 3.5 km can be validated with radiosounding (Figure 6b) and an infrared satellite image from Meteosat-9 (Figure 6c). A synoptic low pressure area is clearly evident from the satellite image, with Barcelona situated in the easterly flow ahead of a weather front.

The PBLH on this day is the lowest of all the cases shown, with a PBLH estimated by the radiosonde of 0.58 km asl. This implies a heavy marine influence. In this situation the EKF method is the most accurate (0.57 km asl), while the TH method (0.38 km asl) is too low, and the WCT (1.66 km asl) and VAR (2.58 km asl) methods diagnose the PBLH somewhere below or in the cloud layer.
5. CONCLUSION

This work compares planetary boundary layer height (PBLH) estimates provided by traditional and advanced lidar-based approaches. The comparison is performed for seven objectively determined synoptic flows at different arriving altitudes for representing the planetary boundary layer (PBL), top of PBL, and free troposphere (FT) cases. The synoptic flow identification is based on an updated cluster analysis. Similar to previous studies, this analysis confirms that the most predominant synoptic cluster over the area of interest (the northeast Iberian Peninsula) is the regional recirculations from the east or west, and that the identified synoptic flows have multiple aerosol layers.

Advanced lidar-based approach utilizes an extended Kalman filter (EKF) and estimates PBLH within 0.79-1.6 km asl range, similar to previous studies. Moreover, the advanced approach tends to capture the PBLH evolution quite accurately. PBLHs retrieved by the EKF technique have a strong correlation ($R^2 = 0.77$), when compared with PBLH estimates from daily daytime radiosonde launches. Compared to the advanced approach, traditional lidar-based methods
have some limitations, such as a longer time averaging. Likely, these limitations are responsible for the observed weaker correlation between the PBLH estimates obtained by these methods and those from radiosonde launches.

Representative cases for a clean FT, regional recirculations, Saharan dust outbreaks, and low level cloud layers highlight the adaptability of the EKF technique when compared with classic methods. Except for cases of a clean FT, the classic methods typically have issues when multiple aerosol layers are present. If the user selects a proper threshold value the TH method performs second best to the EKF.

An approach using the EKF proves promising for continuous and automatic observation of PBLH from lidar measurements. The EKF technique can be applied directly to lidar RCS. It has been found that optimal parameters must be chosen for the state vector initialization for the EKF method to track PBLH accurately, depending on the instrument type.

Future work should include evaluation of the EKF method at other locations, especially an investigation of the potential differences between a coastal site (e.g., Barcelona, Spain) and a continental site (e.g., Leipzig, Germany). Also with the advantage of reliable tracking of diurnal PBLH the EKF method can be employed as a validation tool for PBLH simulations from numerical weather models.

Figure 6. Representative case of influence of cloud layers. Lidar time-height series (a) from 22 April 2010, along with 1-min PBLH estimates from the EKF (magenta dot), TH (grey plus sign), VAR (green cross), and WCT (light blue asterix) methods. Also shown is radiosounding skew-T diagram (b) from a 12 UTC launch, and an infrared satellite image (c) from Meteosat-9 valid around 12 UTC.
ACKNOWLEDGEMENTS

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