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RETRIEVING THE HEIGHT OF THE PLANETARY BOUNDARY LAYER OVER STOCKHOLM FROM LIDAR MEASUREMENTS

Abstract
LIDAR data from the Polly system on the roof of the Arrhenius laboratory at Stockholm University are used to determine the planetary boundary layers (PBL) height distribution. To this end, a wavelet covariance transform method is employed to analyze LIDAR measured data signals from the years 2011-2012. Only data with high pressure cloud free condition are used to reduce "bad" data. The main results are as follows: average height was about 600 m; night time PBL around 360 m and midday PBL top was in winter 950 m, spring 1100 m, summer 1440 m and autumn 1120 m. Growth rates between 6-7 and 11-12 UTC in 2011 were on average in winter 30 m/h, spring 100 m/h, summer 130 m/h and autumn 70m/h. Measurements of the boundary layer height like the ones presented here can contribute to a better understanding of the boundary layer for application in weather prediction and air quality.

Abstrakt
LIDAR-data från mätstationen Polly, som är en del av Arrhenius-laboratoriet och belägen på Stockholms universitets tak, används för att bestämning av planetära gränsskiktshöjden. För detta ändamål användes en stabil ”wavelet covariance transform” metod för analys av LIDAR-datasignalerna från åren 2011-2012. Endast molnfria dagar med högtrycks-förhållande är med i undersökningen för att minska mängden dålig data. Dataanalysen visar att genomsnittliga höjden beräknas till omkring 600 m; under natten omkring 360 m och mitt på dagen är gränsskiktshöjden för vinter 950 m, vår 1100 m, sommar 1440 m och höst 1120 m. Tillväxthastigheten som mätts mellan kl 6-7 och kl 11-12 UTC var i genomsnitt för vintern 30 m/h, vår 100m/h, sommar 130m/h och höst 70m/h. Mätningar av planetära gränsskikts-höjden så som denna kan ge förbättrade gränsskiktsappliceringar i prognoser av väder och luftkvalitéer.

LIST OF ACRONYMES:

LIDAR	Light Detecting And Ranging
PBL	Planetary boundary layer
TKE	Turbulent Kinetic Energy
WCT	Wavelet Covariance Transform
SMHI	Sveriges Meteorologisk och Hydrologiska Institut
ÍTM	The Department of Applied Environmental Science
TKE	Turbulent Kinetic Energy
NWP	Numerical Weather Prediction

1. INTRODUCTION

Every step, every breath, in fact nearly your entire life is spent within the planetary boundary layer (PBL). Defined by *Stull, R.* (*1988*) the PBL is the turbulent layer of troposphere from surface to 100-3000 meters height that is affected by surface forcing within one hour. As the PBL contains most of the atmosphere's airborne particles and moisture, the characteristics of the PBL are important to better understand and predict local/regional weather changes and air quality. Specifically, we will investigate the difference of height and change over diurnal/seasonal time scales of the PBL.

Measurements of PBL height have no perfect method so far, but Light detection and ranging measurements (LIDAR) have proven trustworthy (*Baars et al, 2008*). The instrument is a laser based measuring tool, where the beam is sent up into the sky and is backscattered after interactions with aerosol/molecules. The wavelength will then be detected (*Baars et al, 2008*). More about how this method and how the collected data can be handled are presented in the background section.

The aim of this report is to determine PBL height from LIDAR measurements over Stockholm for the years 2011-2012. The data collected by a LIDAR shall be adapted to produce for diurnal and seasonal time scales a minimum, maximum and average height of PBL and growth rate (that appears between morning and midday). At the end a comparison of the analyzed produced PBL height with a forecast model, HARMONIE-AROME, will be given.

2. BACKGROUND

2.1 Planetary Boundary layer and its height

The troposphere from ground and up is 6-18 kilometers high, lowest at poles in winter and highest in tropics at summertime (*Ahrens, D. 2012*). The troposphere itself can also be divided into two distinct separate parts. The planetary boundary layer (PBL) is the lower one and has its top at heights between 100 to 3000 meter the remainder part named the free troposphere (*Stull, R. 1988*). Figure 1.1 below is an example of how the PBL height distribution during the day might look like, adapted of theory by *Stull, R.* (*1988*).

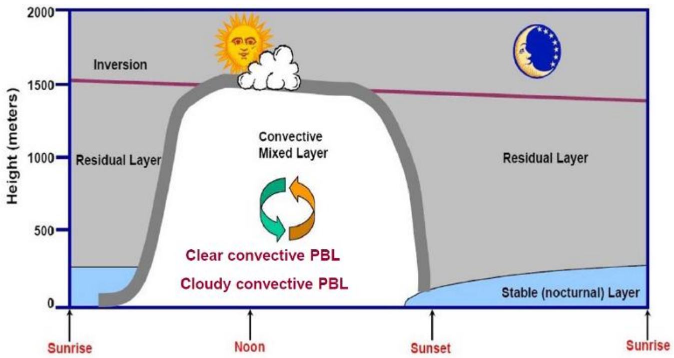

Figure 1.1 *Example of how the PBL diurnal distribution might look like by theory adaption.*

The PBL is defined as the part of troposphere that is influenced by surface in a time scale of one hour or less (*Stull, R. 1988*). Vertical mixing is generated by convection and turbulence mixes airborne particles, small molecules and larger aerosols. Aerosols are small particles in liquid or solid form suspended inside a gas (*Seinfeld J., Pandis S. 2006*). Besides volcanic eruptions, the surface of the earth is the main source of anthropocentric and natural aerosols. Since the top of the boundary layer is the transition zone between the PBL and the free troposphere, any gradient in PBL characteristics, such as temperature, moisture and momentum will be strongest in this transition zone (*Stull, R. 1988*). The same goes for aerosols generated in the boundary layer.

Vertical mixing in the PBL is generated by convective plumes and turbulent eddies produced by insolation which heats the Earth's surface (*Holton, J. 2004*). Turbulent flow is created by a number of eddies, which are irregular swirls in motion (*Lautrup, B., 2011*). The main source of turbulent kinetic energy is convective instability and wind shear, which occur when the wind speed goes to zero at the surface (*Stull, R. 1988*).

The differences in amount and sizes of particles will be measured as described later in section 2.2. To get as smooth measurement signal as possible the data set is chosen from days with high-pressure cloud-free condition, since the more compact particle distribution enhances the distinction between the particle-rich PBL and the particle-sparse free troposphere (*Baars, et. al. 2008*).

Stull, R. (*1988*) determines that PBL itself can usually be explained by three different structural conditions: mixed layer, stable boundary layer and residual layer. Besides, also cloud layer and sub-cloud layer can be found within the mixed layer. The surface forcing that reaches these layers first goes through two layers. Absolutely nearest ground there is a micro layer only a few centimeters where the forcing starts at molecular level. Above this the surface layer contains about 10% of the total PBL and it creates the surface forcing that is spread out to the atmosphere (*Stull, R. 1988*).

The mixed layer appears usually between sunrise and sunset which is very turbulent mainly driven by the buoyancy as a consequence of solar heating (*Stull, R. 1988*). After sunset and before sunrise the mixed layers turbulence calms down and can become a residual layer. Underneath this layer, or whenever the surface is colder than the surrounding air, the nearly non-turbulent stable boundary layer will establish until sunrise.

About 50% of the kinetic energy in the atmosphere is developed inside the PBL (*Holton, J. 2004*). Thus, turbulent kinetic energy (TKE) is a measurement of turbulence intensity in micrometeorological scale (*Stull, R. 1988*). The same author derives the parameterization that shortly can be described by adding squared mean winds in all directions and divide by two. TKE is closely related to heat, moisture and momentum fluxes through the PBL, and due to the upward directed motion, it is closely related to the extension of the PBL (*Stull, R. 1988*). TKE will be part of the forecast model comparison against the PBL data later on in the report.

2.2 Light detection and ranging measurement

The principle of light detection and ranging (LIDAR) is to release laser light in the atmosphere, collect the light that is scattered back to the instrument by molecules and particles in the air, and detect this light in a receiver unit. Using pulsed laser light allows for range-resolved measurements of clouds and aerosols in the atmosphere (*Weitkamp C., 2005*).

The measured intensity of the backscattered light is related to the concentration of aerosol particles in the atmosphere. A gradient in particle load causes a strong gradient in the LIDAR signal at the transition height between the PBL and the free troposphere. There is no influence of molecules to this effect since the molecular density of nitrogen and oxygen is constant in the troposphere. Solar radiation reaching the surface causes heating of the lowermost air layers which initiates turbulent mixing of air and aerosols within the PBL (*Stull, R. 1988*).

Different scattering processes are of relevance for LIDAR observations. Most common are Rayleigh scattering at air molecules and Mie scattering at larger aerosol particles. These two processes causes elastic scattering, i.e., the wavelength of scattering is the same as that of the incident light. Inelastic scattering on the other hand describes a process in which the wavelength of the scattered light is shifted with respect to that of the incident light. Inelastic Raman scattering at nitrogen molecules (*Raman C. V., 1928*) is often applied in LIDAR measurements for obtaining additional information.

Raman LIDAR is used to detect the inelastic Raman scattering at molecules and the elastic signal of aerosols particles. The latter is detected at the same wavelength as the emitted laser light. LIDAR wavelengths are determined by the wavelengths at which solid state lasers operate. The most common choice is λ = 532 nm. This excitation wavelength causes vibrational Raman signals of nitrogen at λ = 607 nm. Although this N_2 signal has a smaller cross section than for O_2, the four times higher N_2 abundance gives more reliable Raman signal. Only elastic signals at 532 nm are used to obtain the results presented in the framework of this thesis.

The collected signal is described by the so-called LIDAR equation (*Weitkamp C., 2005*),

$$P(z) = KG(z)\beta(z)T(z), \qquad [eq.\ 2.2.1]$$

where *P* is the detected signal at distance *z*. *K* and *G* are system-specific parameters that are independent and dependent on range, respectively. The two other parameters are those of interest, $\beta(R)$ is a backscatter coefficient that counts the amount of scattering aerosols and molecules at exactly 180 degrees and $T(R)$ is a transmission term that describes the attenuation (extinction) of the laser light on its way through the atmosphere.

2.3 Raman LIDAR - Polly

Polly is a Raman LIDAR system for quasi-continuous, semi-automated measurements of aerosols in the lower troposphere (*Leibniz Institute for tropospheric research, 2005*). Measurements are performed according to a pre-set schedule that consists of hourly measurements of several minutes for PBL height monitoring and longer measurements for aerosol observations. *Baars et al,* (*2008*) have shown that continuous Polly measurement can be used to study PBL development.

Polly uses a frequency-doubled Nd:YAG laser operating at 532 nm, with pulse energy of 120mJ, a frequency of 15 Hz (*Leibniz Institute for tropospheric research, 2005*). The receiver of the system collects the backscattered light by means of a 20 cm Newton telescope and guides it to the detector (*Leibniz Institute for tropospheric research, 2005*).

The whole station set up is shown in Figure 2.1 that contains computers, air-conditioning, rain sensor and all devices that are required for this type of monitoring station.

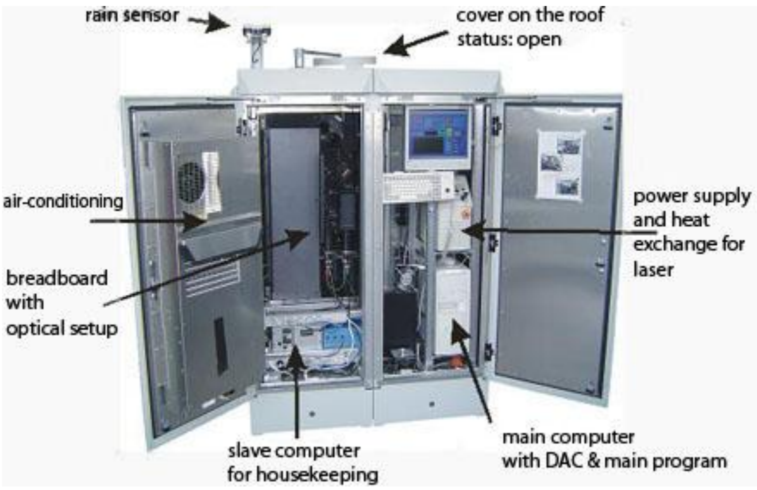

Fig. 2.1 *Picture of the cabinet of the Polly LIDAR at the roof of Stockholm University's Arrhenius laboratory.*

Polly features a safety system that stops measurements during rain and in case of passing aircraft (*Leibniz Institute for tropospheric research, 2005*). By instruction from the computer, placed at the right side in the station, the strong intense laser pulse is built up, in the middle of same side (*see Figure 2.1*). The pulse is then released out to the atmosphere by a hole in the middle of the roof and the backscattered pulse is then measured by the detector at the left side of Polly (*see figure 2.1*), and the signal is saved in the computer below it (*Leibniz Institute for tropospheric research, 2005*).

LIDAR measurements are strongly affected by the background noise of sunlight and the range-dependence of the signal. However, in this work the focus is on finding the region of a strong signal gradient in the transition region between the PBL and the free troposphere. Furthermore, during night time residual layer are more prevailing (*Stull, R. 1988*) which can cause more fluctuation of the planetary boundary layer height than expected.

Baars et al, (*2008*) analyzed the signal with wavelet covariance transform (WCT) and stated that it was reliable. Therefore, the same method is chosen for this report. Also, a small comparison with the gradient method is shown here.

2.4 Wavelet Covariance Transform and gradient method

Both the gradient method and WCT are based on the same assumptions already mentioned, namely that in the two-layered troposphere the lower PBL contains most aerosol and molecules, while the upper free troposphere is almost clear of aerosols (*Stull, R. 1988*). Distinctness of particle concentration gives a strong reduction of the detected backscattered signal at a reasonably well defined height *z*. At this point, the PBL height top is found (*Baars, et. al. 2008*).

The gradient method is a simple derivate of height of the function below, $f(z)$, (*eq. 2.3.1*). The largest gradient of the signal peak is defined as the PBL top, while the WCT method goes through some steps in order to avoid wrong peak termed as PBL. The used WCT method is of the simplest form based on a Haar function that moving like a step function with height over the signals and thereby creating a stronger more distinct peak that is defined as PBL height. Polly data signal is range-corrected following *Brooks, I.* (*2003*)

$$f(z) = P(z)z^2 \qquad [eq.\ 2.3.1]$$

The function $f(z)$ is the range-corrected signal of the detected backscatter $P(z)$ as defined above in section 2.2. For the WCT method, the function is then used in an integral of height that contains a Haar function. A Haar function is a step function that gives a negative, positive or zero integral depending of height *z*. The dependence of *z* is defined with the two variables *a* and *b*, where *a* determines the dilation, i.e. how large the steps shall be, while *b* describes where the dilation shall occur (*Brooks I, 2003*). In written form the equation looks as

$$W_f(a,b) = \frac{1}{a}\int_{(z_1)}^{(z_2)} f(z)\,h\left(\frac{z-b}{a}\right)dz \qquad [eq.\ 2.3.2]$$

Below in Figure 2.2, an example is given of how the WCT method works. Through the use of the Haar function, the strong reduction of the detected signal $f(z)$ at the PBL top generates a strong peak for the WCT method.

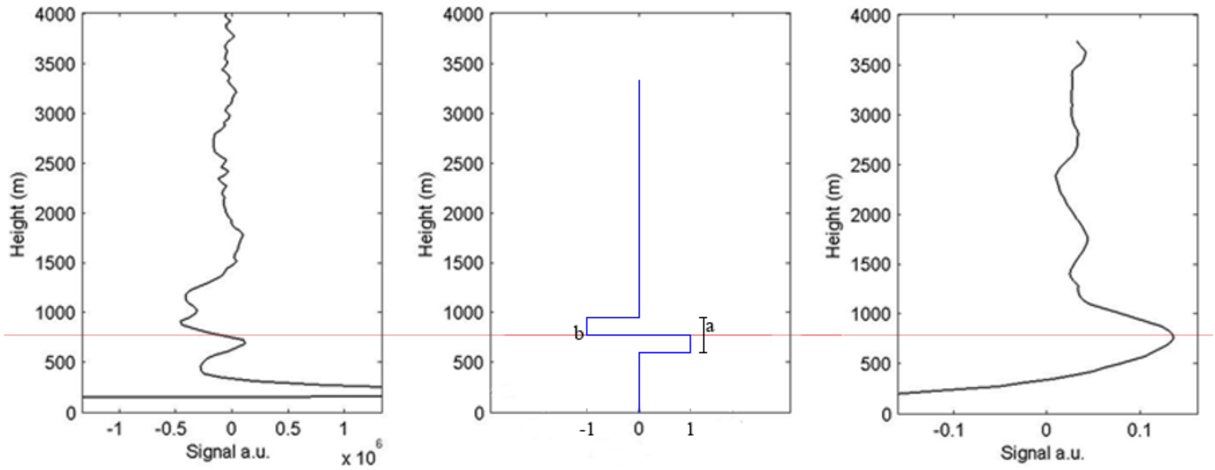

***Fig. 2.2** Left hand side smoothed LIDAR signal, middle Haar function (only a sketch of how it works) and right hand side WCT method applied at same signal.*

The values of the parameters *a* and *b* have to be established. Here, it is especially difficult to determine the "best" dilation. The thought is that it has to be larger with height, due to larger noise for higher altitude (*Baars et al, 2008, Brooks I, 2003*). To avoid small tilts in the signal *Baars et al, 2008, Brooks I, 2003* introduce a threshold value of the WCT that is applied to reliably define the top of the PBL. This threshold value has to be varied according to the measurement conditions, and thus, shows daily and seasonal changes in the range from 0.02 to 0.15. *Baars et al.* (*2008*) suggested that the dilation should increase with height to maximize the performance of the method.

In the WCT method *Baars et al,* (*2008*) found that clouds within PBL gave a strong rise of signal declared by direct optical effect followed by a quickly sinking of signal caused by the depth of cloud. This enables the use of the WCT method for cloud-screening. However, this work is restricted to cloud-free conditions only.

3. METHOD

A program for reading Polly signals and applying a basic WCT to these data was provided by *Tesche Matthias,* (*2013*) for reading the signals from the Raman LIDAR, Polly, by WCT and gradient method. Some adjustment and quality assurance were performed during the analysis, by comparing plots like the left hand side in figure 2.2 with a signal plot like the one below in figure 3.1 so the peak height is at comparable height. The latter figure also contains both the gradient (black line) and the WCT method (blue line). The plot shows the distribution of particles from the middle of the night, and thus the PBL is expected to be rather low. The figure reveals that the gradient method indicates a PBL top at 1250 meter, whereas WCT indicates that the PBL top is below 500 m. The reason why the two methodologies deviate so much in this case is likely that the gradient method finds the residual layer, which then constitutes as top. If the gradient method would be used, the height error would not only affect the night time height; the average height per day/month/season would also be statistically higher and the lowest PBL would be very much higher than expected.

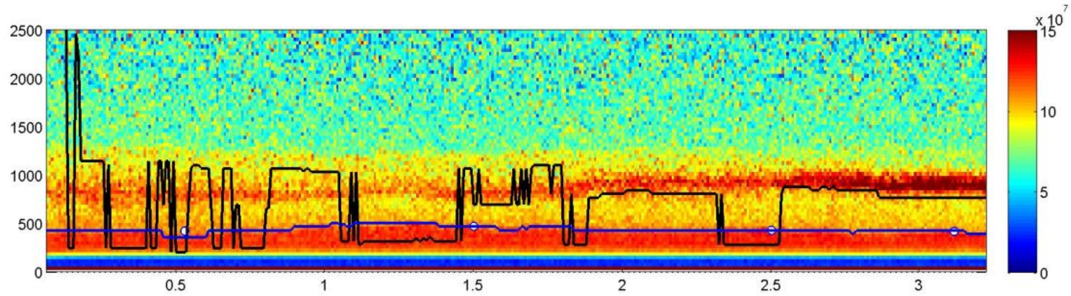

Fig. 3.1 *The diagnostic figure for August 3rd 2011 at midnight: A good example of how diverse the gradient (black line) and WCT method (blue line) are occasionally.*

Furthermore, the threshold value will be investigated by its effect on data coverage (amount of not a number or NaN values) and the mean PBL-height, see Figure 3.2 a, b. The data used in the figure summarizes 12820 profiles from January, 2011 and 23380 values from June, 2011. Compared with the mean altitude, the impact on the PBL-height depending on the threshold values chosen is not very large.

Too low threshold value generates higher amount of height profiles. However as a consequence, the PBL height can be erroneous, since it is possible to detect lower lying peaks. When too high a value is chosen, the peak that indicates the PBL height is instead missed and can, for example at midnight, give a height which could go up to 3000 meters. Such errors were not detected for the selected values.

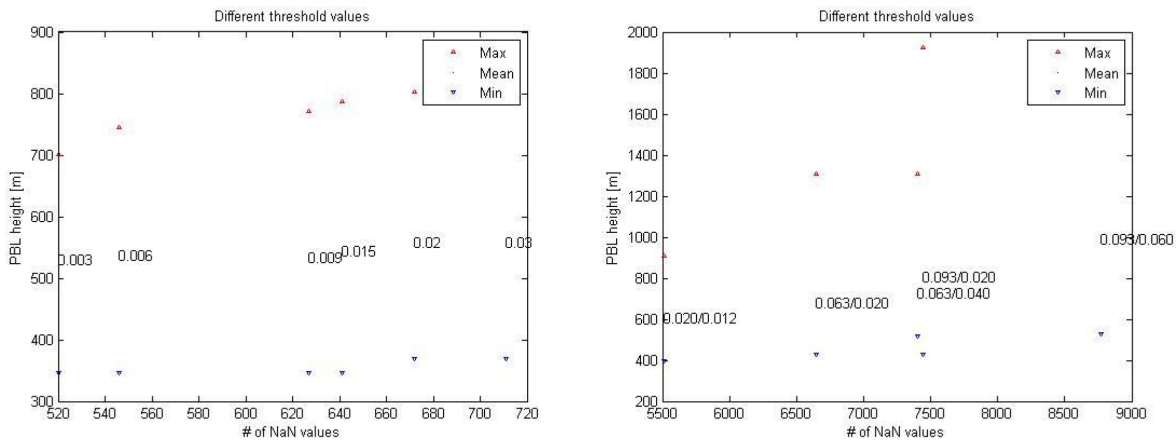

Fig.3.2 a, b *The effect of the choice of the threshold value of the peak of the WCT for PBL-top detection on the amount of unusable (NaN) profiles for the examples of January 2011 (a) and June 2011 (b). The analysis in June was performed with "one daytime threshold value" /"one nighttime threshold value", as marked in the plot.*

The mean standard deviation of the PBL-height for January, 2011 was found to be just a few tens of meters and similar for the maximum and minimum. It is not straight forward to select a suitable threshold value that will work for all months. However, based on Figure 3.2a and the investigation of individual measurements like the one in Figure 3.1, the value 0.009 was chosen as a threshold value for the months September to April. For the months May to August, where the daytime PBL-height can grow very large, it was found suitable to use two thresholds; one larger threshold which is used for 8-15 UTC and one smaller threshold used for the remaining hours. In the same way as for winter month the investigation found a standard deviation for the average height to be 400m, with maximum almost 1000m and minimum 100m. The values 0.063 and 0.020 were chosen to be the most appropriate threshold values.

With the above threshold values, the median values per hour are found for each month. After that, the maximum and minimum for each month are determined. Then the growth rate will be calculated between the hours 6-7 and 11-12 UTC for the days with available signal data at these times. First the growth rate was tried to be found by the total monthly median height of the two indicated times, but then unreasonable velocities where found as example negative result for winter months. This may indicate that the stable boundary layer is not the only source of turbulence in the winter mornings, or that the stable layer is much dependent of the heights of mixing layer the day before or even that the measurements have a weakness in determine the early morning PBL height.

Figure 3.3 shows the range-corrected LIDAR data with PBL height from the WCT method for that date. In that plot the range-corrected signal is shaded; the back line shows the PBL height from the gradient method and blue line for the WCT method. The red line is the hourly mean distribution from the WCT method. In chapter 4 below a comparison between PBL height measured by LIDAR and the corresponding height modeled by a weather forecast is made for May 20th , 2011.

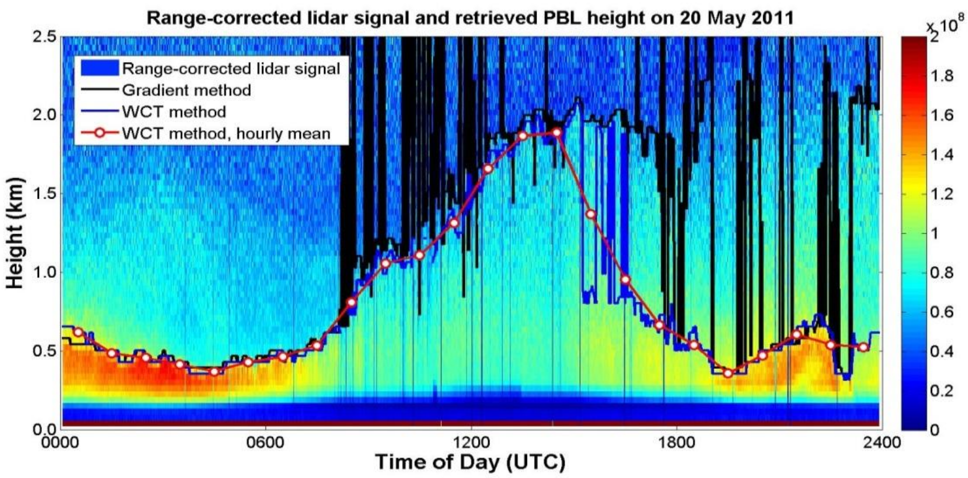

Fig. 3.3 *Range-corrected LIDAR signal for Polly observations on 20th May 2011. The lines show the results of the gradient method (black), the WCT method (blue), and the hourly mean values of the WCT method (red).*

4. RESULT

4.1 Diurnal distribution

The median diurnal distribution might not be totally usable for any direct applications. However, it may still be of interest in order to understand, for instance, the importance of incoming solar radiation in the buildup process of the planetary boundary layer. It is evident that the insolation at northern latitudes is higher during summer than winter (*Ahrens D, 2012*). Looking at the mean diurnal PBL height presented in Figures 4.1a and 4.1b it is easy to recognize that the PBL height in 4.1a has to belong to a winter month and the PBL height in 4.1b to a summer month, since the summer time boundary layer is characterized by the buildup of turbulence and convection, whereas the wintertime boundary layer tends to be more stable (e.g. *Stull. R, 1988*).

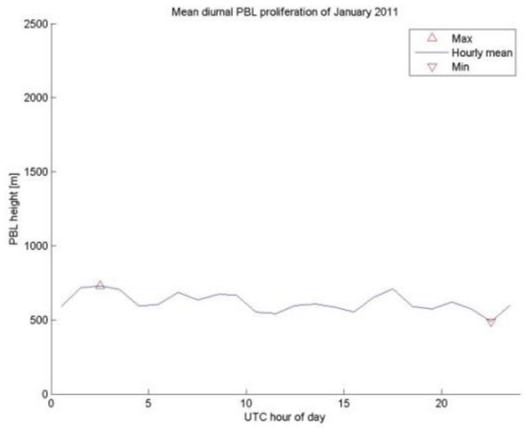

Fig. 4.1a *Diurnal distribution of PBL as a mean height per hour for January 2011. Also the highest and lowest altitudes are marked.*

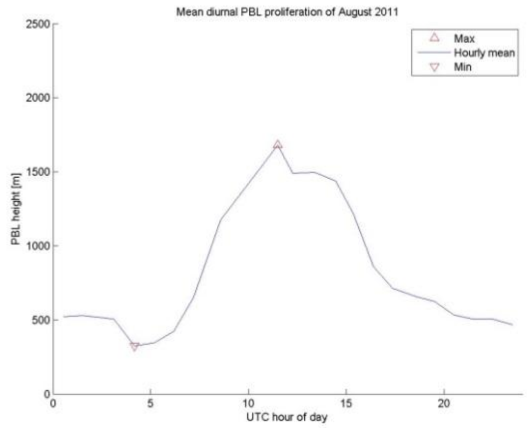

Fig. 4.1b *Diurnal distribution of PBL as a mean height per hour for August 2011. Also the highest and lowest altitudes are marked.*

In order to compare the diurnal cycle of PBL, it is efficient to use the hourly mean of every season. Figure 4.2 illustrates the mean for every season and yearly diurnal distribution in 2011. It can be seen that the winter exhibits almost no growth rate, since there is less solar radiation reaching the surface. On the other hand, the summer month has a distinct height peak during midday. This can be explained by the higher amount solar radiation reaching surface.

For all seasons and the whole year the diurnal distribution is also plotted as average median PBL height per hour, see below in figure 4.2. Due to non-continuous time sequence in 2012 this year is excluded to maintain a more statistically accurate result. It can be seen that winter daily values do not show a tendency but merely fluctuate and that autumn values are lower all day except for midday. It can be speculated if there are other phenomena raising the average winter PBL or if it depends on some uncertainty of the measurements that can occur in the near-field of the instrument. It is believed that this phenomenon partly can be due to residual layer falling towards the ground surface after sunset and also the nighttime outward net radiation disordering the measurement. That also could explain the large deviation around night time when PBL height is lowest. In an earlier investigation these hours were excluded (*Baars et al., 2008*). Anyhow, in the middle of day for all seasons the PBL height distribution is as expected.

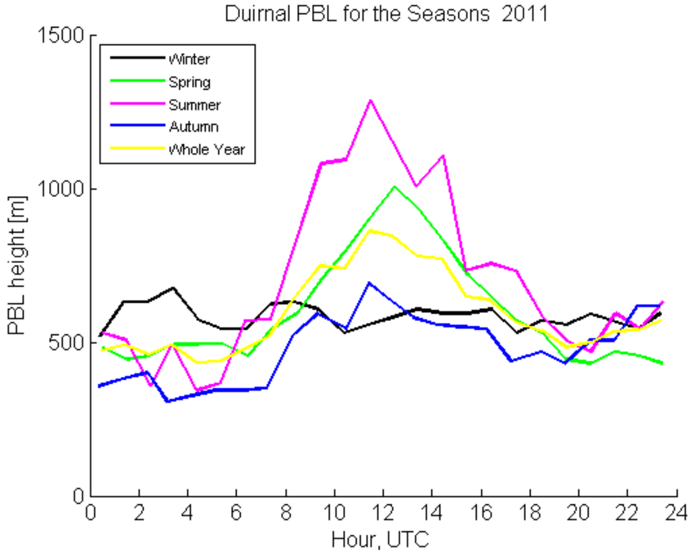

***Fig.4.2** The diurnal cycle of PBL height over the whole year of 2011 and separated for all seasons.*

4.2 Median height

In order to list the monthly median height values for the two years, and to give an indication of the highest and lowest median points of the PBL, the reader is referred to Figures 4.3. Unfortunately, in August 2012 there was not enough data, so that only August 2011 was used. Above each column in the figure the number of available days is written.

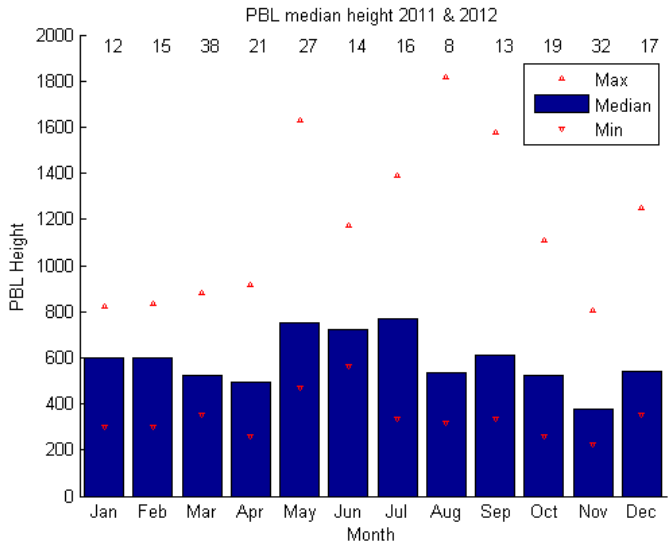

***Fig.4.3** PBL median height for years 2011 and 2012, with marks for top maximum and minimum per month. Above every column there is a number indicating how many days of measurement were used for that month.*

The lowest median height over the years appears in November at 400 meters and highest median PBL in July at 800 meter. The maximum and minimum can almost always be considered as midday and night PBL heights, respectively. The highest diurnal spread appears in August around 1400 m and for November and January-March this is only about 300 m. Only May and June have minimum PBL top height higher than 400 m, the highest PBL top height is found above 1500 m in May, August and September. This seems reasonable for months near summer.

The average PBL heights per month are presented as represented per season in Figure 4.4. For the separate seasons the median heights became in winter 600 m, spring 600 m, summer 680 m and autumn 500 m. Highest median PBL tops are in winter 950 m, in spring 1100 m, in summer 1440 m and in autumn 1120 m. Lowest median PBL tops for winter 360 m, for spring 390 m, for summer 420 m and for autumn 290 m. Briefly, the most significant difference between the years is the maximum PBL height distribution.

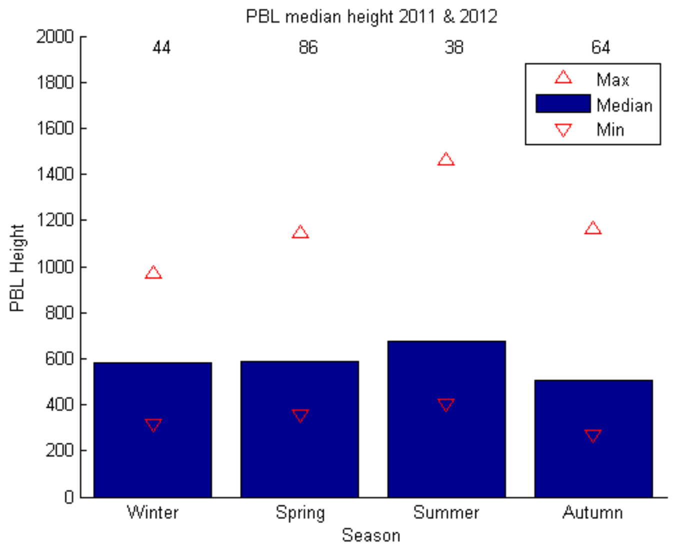

Fig. 4.4 *Seasonally averaged PBL mean, maximum and minimum height for years 2011 and 2012. The seasons from left to right: December – February, March – May, June – August and September – November. The numbers above indicate included days of measurement.*

4.3 Growth rates

Between the hours 6-7 UTC and 11-12 UTC the fastest growth of PBL seems to develop. Thus, the speed of the change in height during these hours is computed for all months in year 2011, see below in figure 4.5. Continuous measurements for each day were required for determining the growth rate; for 2012 that was a problem so the 2012 data are excluded. Even for 2011 there are rather few possible days for some months. This means poor statistics which should be taken into account on comparing this result with previous ones presented about the height. For 2011 the smallest average growth rate average was in December at 20 m/h. The largest growth rate occurred in August at 220 m/h but this is just calculated for one day and thereby not statistically significant. The second fastest growth rate was in April with 140 m/h.

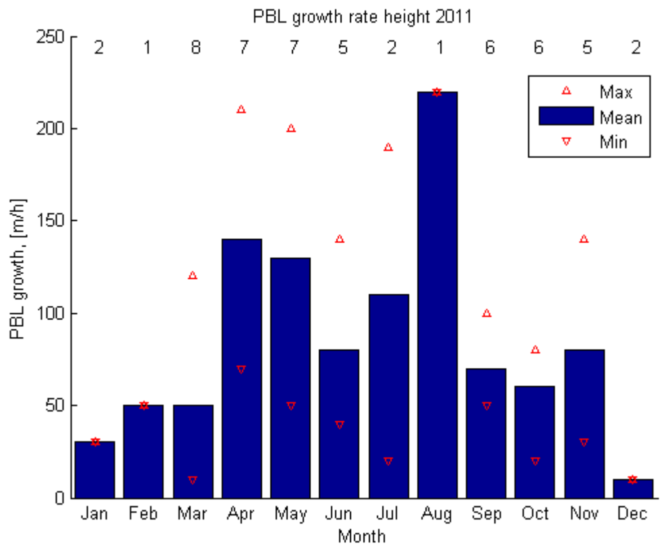

Fig. 4.5 *Mean growth rate per month for year 2011. The numbers above indicate included days of measurement.*

The growth rate is also plotted for each season. Figure 4.6 shows the seasonal growth rate for 2011, excluding 2012 due to too few days with continuous time sequence during the measured hours. The wintertime growth rate in 2011 was 30 m/h, the springtime growth rate was 100 m/h and the summertime growth rate was found to be 130 m/h. The autumn the growth rate was found to be 70 m/h. In winter there is no deviation but also just 5 days of measurement. Spring has growth rate differences of 130 m/h, while summer and autumn have 90 and 70 m/h, respectively. By just looking at the mean growth rates, the result indicates as expected that the growth rate is stronger the higher amount of solar radiation that possibly can reach the surface.

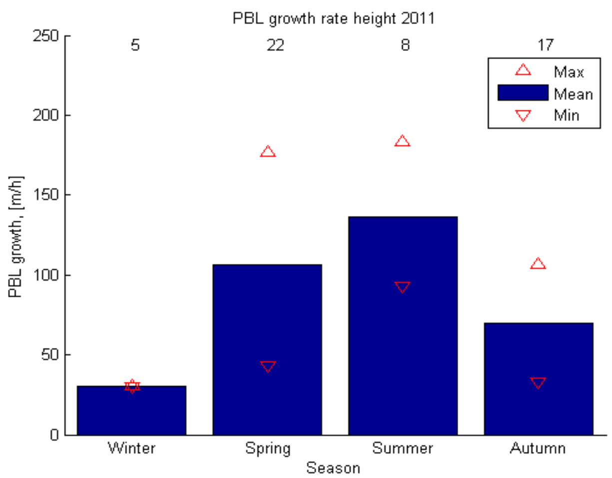

Fig. 4.6 *Seasonal growth rate in 2011. Number of measurement days are provided at the top.*

4.4 Comparison with PBL height in a numerical weather prediction model

One interesting application of using the above results would be to evaluate modeled PBL-height. The height of the planetary boundary layer is a very important input parameter for dispersion and chemistry transport models; thus there is a high need to evaluate it accurately with Numerical Weather Prediction (NWP) models (*Seity, et. al, 2011*).

The selected day was 20th of May, 2011. Figure 4.7 shows the synoptic weather chart for this day (*Wetterzentrale*, *2013*). The weather over Stockholm is dominated by high pressure, and the sky was cloud free during the whole period.

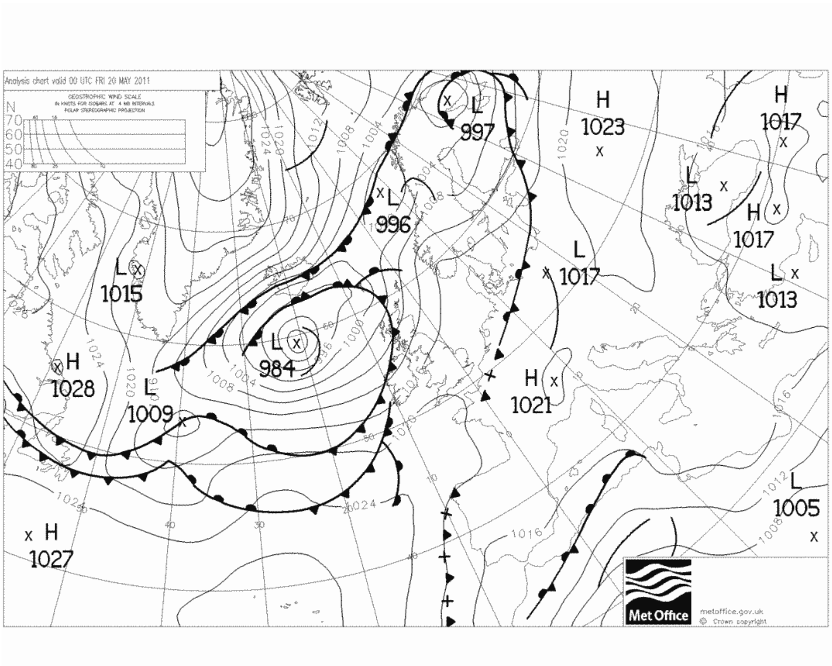

Fig. 4.7 *A weather forecast map over Europe the 20th May 2011.*

The diurnal development of the observed PBL height from the Polly data for the selected date and also for the seasonal mean are compared with the PBL-height provided by the mesoscale NWP model HARMONIE-AROME (*Bengtsson Lisa, 2013*) for the selected date over a grid-point representing Stockholm, Sweden (Figures 4.8a and b).

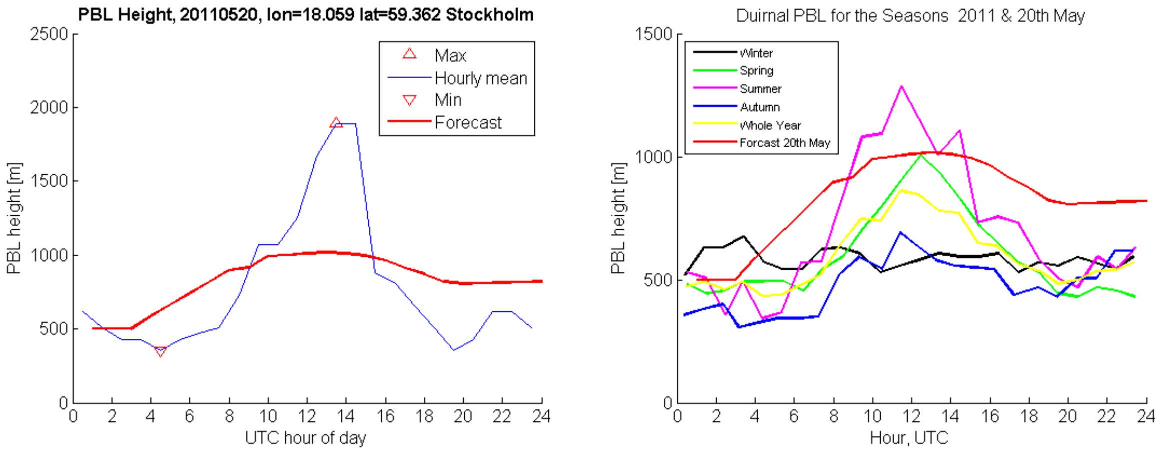

***Fig. 4.8a, b** Red-line shows the hourly PBL height distribution from the NWP model HARMONIE-AROME. Panel a shows the observed PBL height from Polly for the specific date, 20th of May 2011, while panel b shows the PBL height distributions for the seasonal means.*

Figure 4.9 a, b and c show the vertical distribution of turbulent kinetic energy (TKE), specific humidity and temperature, respectively for Stockholm, given by the numerical model and valid at 06, 12, 18 and 24 UTC. It can be seen that the temperature near the surface rises about 1 degree Celsius (from 11.5 to 12.5 degrees Celsius) from 06 to 12 UTC, and then drops down to 10.8 degrees at 00 UTC, indicating a rather modest daytime heating.

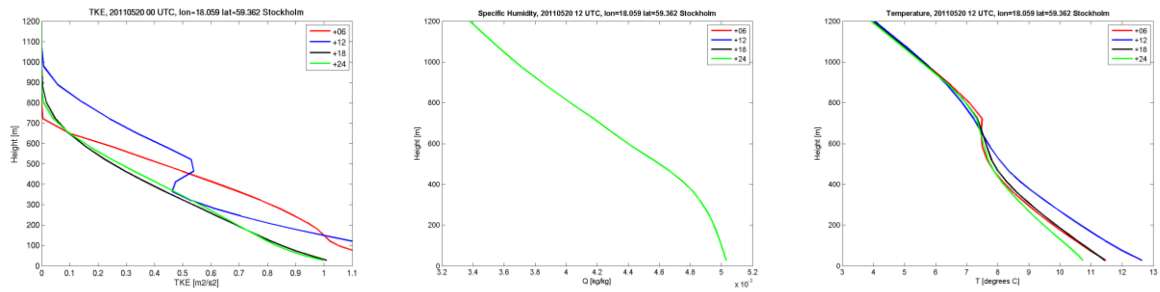

***Fig.4.9 a, b, c:** Vertical distribution of TKE, specific humidity and temperature for the 20th of May 2011at 06, 12, 16 and 24 UTC as modeled by HARMONIE-AROME.*

Figure 4.8a shows the observed hourly mean PBL height and the PBL-height given by the model, and Figure 4.9a shows the vertical distribution of turbulent kinetic energy given by the numerical model, valid at 06, 12, 18 and 24 UTC. Clearly the model reproduces the diurnal behavior, but it fails to capture the daily PBL growth as given by the observations for this case. It is not straightforward to understand the reason why the modeled PBL-height does not grow enough during the day. Temperature and wind are resolved model parameters which directly influence the amount of TKE. It would be interesting to compare vertical profiles of temperature and wind for the same location in a future study. Speculating, perhaps the model fails to forecast the wind profile appropriately for this case due to, for instance, lack of vertical resolution. Furthermore, it is not evident that the two methods, observations and numerical modeling, of determining the PBL-height are comparable. The first method uses the gradient in particle distribution, whereas the latter uses modeled turbulent kinetic energy.

5. DISCUSSION

5.1 PBL height

The lowest PBL top found is nearly the same over all seasons at around 360 meter. This seems accurate, since it can be considered the nighttime average height. The average height also has nearly equal height for all seasons, at about 600 meter. That is comparable with literature values for the top of the stable layer (*Stull, R. 1988*). Similarly, the lowest top is close to the expected height of the stable layer when the mixed layer at sunset ceases to affect the height.

Previous work has been done by *Baars et al.* (*2008*) where the same WCT technique was used, with the exception that they decided only to use the daytime measurements (08-20), and probably other threshold values. They concluded that the method was reliable and their measurements for highest PBL height from a LIDAR station in Germany gave for winter 800 m, spring 1400 m, summer 1800 m and autumn 1200 m. Comparing their result with the present study, the highest PBL height presented in the result section was in winter 950 meter, in spring 1100 m, in summer 1440 m and in autumn 1120 m. Since Stockholm is some degrees of latitude further north than Leipzig, Germany, it is expected that the top height would be slightly smaller here due to the reduced solar insolation.

When the two autumns were compared, the year 2011 had much lower maximum top PBL height than 2012. This large change might depend on differences in cloud-cover. Alternatively, during September when the sun still reaches an angle to the Earth surface at both sites enough to transfer substantial heat (*Ahrens D, 2012*) it is possible that the PBL height can reach rather high values. Thus, during a sunny September day, the PBL maximum can be much higher than the autumn average. This might affect average height not only in autumn, but also in spring; May is known to be the most non-cloudy and sunny month over Stockholm, so that could change the average height for the whole season. A way to investigate this closer might be instead of seasons to consider the PBL monthly; this seems reasonable for periods with a seasonal trend of insulation, i.e. spring and autumn.

5.2 PBL growth rate

Baars, et. al. (*2008*) also investigated the growth rate and concluded that it is in the interval 100-500 m/h, and most frequently appeared to be 100-300 m/h. In this investigation the highest growth rate was found to be 220 m/h and the lowest 20 m/h, and most frequently around 80 m/h. One difference between the two investigations is that different hours are used to calculate the PBL growth rate. Nevertheless, taking reasonable account to the latitude difference they can still be considered interesting to compare. If PBL height differences between the two studies discussed above in section 5.1 are considered significant, the growth rate changes appear reasonable.

From a seasonal point of view, the growth rate in 2011 was in winter 30 m/h, spring 100 m/h, summer 130 m/h and autumn 70 m/h on average. As mentioned above. The year 2012 had not enough amounts of continuous data. The seasonal difference looks reasonable if just thinking of solar irradiation onto the Earth surface, increasing towards summer and decreasing towards winter (*Ahrens, D. 2012*). Considering that spring and autumn have more or less comparable amount of incoming solar radiation, their difference could potentially instead be explained by different conditions of the Earth surface; the fact that moist soil in autumn is more thermally inert than drier soil in spring means different response time to varying diurnal irradiation (*Ahrens, D. 2012*). Thus, we expect higher growth rates in spring.

The growth rates were found in the interval 20-220 m/h. It should be noted that those values are rather uncertain. The seasonal PBL height values contain considerable uncertainties too. Further analysis and larger amount of continuous daily height profile signal-data are needed.

6. CONCLUSION AND FUTURE OUTLOOK

LIDAR signals over Stockholm for the year 2011-2012 have been processed and analyzed by the robust WCT method in order to study the PBL height. Several properties of the PBL have been studied such as the average height for whole year, the seasonal variation, monthly variation, diurnal cycle of the PBL top and growth rates. The average height was found to be around 600 meter and the minimum PBL height was found to be 360 m. The highest mean top for the same years was in winter 950 m, in spring 1100 m, in summer had 1440 m and in autumn 1120 m. Growth rate between 6-7 UTC and 11-12 UTC during 2011 was on average 30 m/h in winter, 100 m/h in spring, 130 m/h in summer and 70 m/h in autumn.

For the future one interesting application of the above results would be to evaluate PBL-height in NWP models. The height of the planetary boundary layer is a very important input parameter for dispersion and chemistry transport models. Thus, it is important to be able to estimate it accurately with NWP models. As an example, the observed PBL height given by the LIDAR measurements was compared with the PBL-height for a selected case provided by a mesoscale weather forecast model, HARMONIE-AROME (*Seity, et. al, 2011*), over a grid-point representing Stockholm, Sweden.

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