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Interactive comment on "Investigation of the mixing layer height derived from ceilometer measurements in the Kathmandu Valley and implications for local air quality" *by* Andrea Mues et al.

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Below we reply to the anonymous referee #2's comments and questions on our ACPD manuscript "Investigation of the mixing layer height derived from ceilometer measurements in the Kathmandu Valley and implications for local air quality". We would like to thank the reviewer for the constructive comments helping us to improve the paper. We have listed all reviewer comments below and answers are provided in blue. Unless otherwise noted, all page and line numbers refer to the "track changes" version of the revised manuscript provided as a supplement.

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Anonymous Referee #2

This MS describes a unique data set on the mixing height for a complete one year in the Kathmandu Valley and provides an essential information over this region. There are not many studies with such round the clock observations over the year period in this part of the world. However, I still see scope for a significant improvement in the MS.

Since there are very limited studies, it is better to provide some more information on the mixing height variations over this region. I strongly feel that it will be very good to show (Fig 3) monthly diurnal variation in-stead of seasonal. This will also provide a good reference for a region with very complex topography. Additionally, average (sunrise, noon and sunset time) mixing height with 1 standard deviation can be provided for each month in a tabular form.

Following the suggestion of the reviewer, we now show the diurnal cycle of MLH in the revised version of figure 3 (see below) for each month separately. Additionally, we included the daylight hours for the 15th of each month as yellow shading also showing the sunrise and sunset times. As median MLH and variability at sunrise, sunset and noon are now shown in figure 3, we think an additional table as proposed by the reviewer is not needed.

Some of the specific and general comments are - Abstract: Line 9-10: This is a common feature. It is better to add some quantitative information here. Like, height during night and day time, how does it changes with seasons?

We added the following sentences to the abstract (p. 1, l. 10-13):

> ”The monthly minimum median MLH values typically range between 150 and 200 m during night and early morning hours, the monthly maximum median values between 625 m in July and 1460 m in March. Seasonal differences are not only found in the absolute mixing layer heights, but also in the duration of the typical daytime maximum ranging between 2-3 hours in January and 6-7 hours in May.”

Additionally, we added numbers to the following sentence in the abstract (p. 1, l. 13-16):

> ”During the monsoon season a diurnal cycle has been observed with the smallest amplitude (typically between 400 and 500 m), with the lowest daytime mixing height of all seasons (maximum monthly median values typically between 600 - 800 m), and also the highest nighttime and early morning mixing height of all seasons (minimum monthly median values typically between 200 and 220 m).”

Introduction: It includes very basic discussion on the boundary layer and it can be trimmed down.

Following the suggestion of the referee, we shortened the part on the general description of the planetary boundary layer and the mixing layer height in the introduction (see track changes version).

Section 2.1: It is better to provide a brief description of BC instrument (Aethalometer) and if any data correction method is used.

We added the following description to the manuscript (p. 5, l. 34 - p. 6, l. 7):

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”The aethalometer is among the earliest BC measurement methods and has been applied since the early 1980’s (e.g. Hansen et al., 1982, 1984). This measurement is a filter-based method where air is drawn through a sampling filter and an increase in attenuation is detected with increasing aerosol loading on the filter. Its advantage is that it provides an absorption derived real time estimate of black carbon. However, the instrument measures absorption coefficient by all components of the aerosol besides black carbon over the broad region of visible spectrum. It requires therefore knowledge on the mass specific absorption cross section (MAC) of the BC-containing aerosol, which introduces some uncertainty to the measured values. The derived quantity is commonly referred to as ”equivalent black carbon” (EBC), which is the case if the MAC is exactly known (see e.g Petzold et al., 2013).”

New references:

Hansen, A. D. A., Rosen, H., and Novakov, T.: Real-time measurement of the aerosol absoprtion-coefficient of aerosol particles, Appl. Opt., 21, 3060-3062, 1982.

Hansen, A. D. A., Rosen, H., and Novakov, T.: The aethalometer - an instrument for the real-time measurement of optical absorption by aerosol particles, Sci. Total Environ., 36, 191-196, 1984.

Petzold, A., Ogren, J. A., Fiebig, M., Laj, P., Li, S.-M., Baltensperger, U., Holzer-Popp, T., Kinne, S., Pappalardo, G., Sugimoto, N., Wehrli, C., Wiedensohler, A., and Zhang, X.-Y.: Recommendations for reporting ”black carbon” measurements, Atmos. Chem. Phys., 13, 8365-8379, doi:10.5194/acp-13-8365-2013, 2013.

Section 2.2: The Ceilometer is a commercial instrument and it has been used widely. Therefore, a brief mention of methodology adopted by others on mixing height determination and also its average reporting (from minutes to hours) can be provided.

We added the following description to section 2.2 (p. 7, l. 13-16):

> ”Haeffelin et al. (2012) discuss the most common methods for mixing height determination with ceilometers; these include gradient methods investigating first or second derivative of the backscatter profile reported by the instrument, backscatter variance, wavelet and backscatter profile covariance, and fitting of ideal backscatter profiles. All methods involve temporal averaging ranging from 2 to 60 minutes, depending on the atmospheric conditions and the performance of the instrument.”

New reference:

Haeffelin, M., Angelini, F., Morille, Y., Martucci, G., Fry, S., Gobbi, G. P., Lolli, S., O’Dowd, C. D., Sauvage, L., Xueref-Rémy, I., Wastine, B., and Feist, D. G.: Evaluation of Mixing-Height Retrievals from Automatic Profiling Lidars and Ceilometers in View of Future Integrated Networks in Europe, Boundary-Layer Meteorology, 143, 49-75, doi: 10.1007/s10546-011-9643-z, 2012.

Results:

Section 3.2: Fig 4: It would be useful to discuss briefly the differences in the diurnal patterns of solar radiation and mixing layer height. Peak of mixing layer height is about 3-4 hours later than the peak in solar radiation, why?

The explanation of this can be found in various textbooks. Here a condensed description of the processes is taken from chapter 9 of ”Atmospheric Science” by Wallace and Hobbs:

The reason for difference in the diurnal timing can be understood considering the growth process of the mixed layer. Solar radiation heats the Earth’s surface. Due to the heating capacity of the ground, the temperature increase in the surface ground layer lags behind the increase in solar radiation during the day, and continues on after noon until it peaks in the afternoon, when the incoming solar radiation has decreased enough that the surface ground layer begins to cool again. After sunrise, the warmed surface ground layer in turn warms the overlying air in the so-called ”surface layer” (which is roughly the lowest 5% of the mixed layer depth). This typically results in a superadiabatic vertical temperature gradient, i.e., an unstable vertical layering. Small turbulent motions (e.g., overturning due to wind shear) initiate mixing, and once set in vertical motion, the heated parcels of air from the surface layer rise dry convectively, cooling adiabatically, until they reach their level of neutral buoyancy (determined by the difference in the ambient lapse rate and the dry adiabatic lapse rate), which over time becomes the capping layer of the vertically growing boundary layer. Due to the kinetic energy obtained while vertically accelerating, the heated parcels from the surface overshoot their level of neutral buoyancy, and simultaneously force air from the free troposphere down into the mixing layer. The overshooting parcels in a generally laminar free troposphere can remain largely intact and sink back down into the mixing layer. However, the air masses from the free troposphere that are forced down into the mixing layer are ”immediately torn and mixed into the mixed layer by the strong turbulence there. . . [and] become one with the mixed layer and never return to the free atmosphere.” This entrainment, which defines the entrainment zone, is the process by which the mixing layer grows. ”It can be thought of as a mixed layer that gradually eats its way upward into the overlying air.” Because this process takes time for the growth to occur, and also because of the lag described above between the peak in the surface ground temperature and the incoming solar radiation, the peak in the mixing layer height is in the late afternoon, as contrasted with the noon peak in incoming solar radiation (Figure 4).

In Section 3.2 of the submitted version of the paper (p. 8, l. 3-4), this was all indicated with the single sentence:

> ”This is due to a delayed response in the production of thermal turbulence to the warming of the ground by the incoming solar radiation.”

Since this is evidently too brief, but the full description above would be a bit disproportionately long to include in the paper, we have replaced the former brief sentence with the following (p. 11, l. 1-8):

> ”This is due to the growth process of the mixing layer, which is driven by the heating of the ground by incoming solar radiation. This heating causes thermals to rise from the surface layer, causing mixing when they overshoot into the more stable free troposphere at the entrainment layer, which in turn results in growth of the mixing layer by gradual assimilation of overlying free tropospheric air which is forced down into the mixing layer throughout the day. Because it takes time for the mixed layer to grow by this process, and also because the increase in the surface ground temperature lags behind the increase in incoming solar radiation during the morning, the peak in the mixing layer height is in the late afternoon, as contrasted with the noon peak in incoming solar radiation.”

Section 3.3.1: Page 11, line 14-17: I presume that this correlation is determined using 24 hours average data. I feel that if this correlation is calculated for 2-3 time windows

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(morning, noon, evening etc), it will give better information.

The temporal correlations given in section 3.3.1 have been calculated from the MLH and BC time series with a time resolution of 1 hour. The temporal correlations shown here reflect to a large degree the diurnal cycle. Further splitting the time series into different times of the day in addition to splitting the time series into different seasons would result in a further reduction of the correlation. Here, we show the differences between the seasons, we would therefore prefer to not split the time series into different times of the day. However, we clarified the calculation of the temporal correlations given in section 3.3.1 by rewriting the corresponding sentence and adding the following explanation (p. 12, l. 18-22):

> ”The correlation coefficients calculated for the time series of mixing layer height and black carbon concentration with a time resolution of 1 hour depend strongly on the season. While the pearson coefficient for the pre-monsoon season is -0.54, it is only -0.19 for the monsoon season (-0.40 for the post-monsoon and -0.46 for the winter season). This shows that a part of the variation in time of the black carbon concentration can be explained by atmospheric dynamics and that its magnitude depends on the season.”

General:

Page 3, line 11-15: These lines on ceilometer are not needed here and can be moved in to section 2.2.

We agree and shortened these lines as follows (leaving a reference to section 2.2) (p. 4, l.12-16):

> ”A ceilometer was deployed to measure vertical profiles of the aerosol attenuated backscattering during the SusKat-ABC campaign at Bode, the supersite of the SusKat-ABC campaign, located in a semi-urban setting in the Kathmandu Valley (more details are presented in section 2.2).”

Page 5, line 10-13: A reference for this comparison will provide a clear information to the readers. Briefly, outcome of the comparison can also be mentioned.

Following the suggestion of the reviewer, we added more details on the study Münkel et al. (2011) replacing lines 10-13 on page 5 of the original manuscript (p. 7, l. 21-26):

> ”In particular, Münkel et al. (2011) compare the mixing layer heights obtained during the Tall Wind measurement campaign in Hamburg, Germany, and routine measurements carried out in Vantaa, Finland, with mixing layer heights derived from potential temperature and relative humidity profiles reported by radio soundings. The example cases presented in the study show a good agreement with deviations not exceeding 10%.”

Figure 5 and 6: It is better to change the colour scheme. Yellow and green colours are not clearly visible.

We adjusted the colors of figures 5 and 6 in order to improve legibility. In particular the contrast between overlapping and non-overlapping parts of the boxes has been increased.