Atmospheric
Chemistry
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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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Received and published: 12 April 2017

Below we address the comments of reviewer #1 and questions raised during the open discussion of the paper "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 time and effort reviewing the paper. We feel it has improved thanks to the constructive comments. We have listed all reviewer comments below and our 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.

Anonymous Referee #1

However, the manuscript lacks some structure in terms some structure to put analysis and findings into a wider context. The introduction is focused on simple boundary layer knowledge, instead it should discuss mechanisms critical for the complex setup of the current study, such as the structure of the valley, predominant wind directions relative to moisture and pollution sources etc.

More literature references should be included to introduce the reader to the state of knowledge on boundary layer dynamics in valley locations and under Monsoon season conditions. This will allow the manuscript to clearly identify where new or contradicting findings are made.

We have revised the introduction as suggested and included more literature mainly on mixing layer height observation in similar terrains and the valley and on the circulation, predominant wind direction and characteristic local flows in the Kathmandu Valley. Furthermore, we shortened the part on the general description of the planetary boundary layer and the mixing layer height. Please, find the corresponding changes directly in the text (see track changes version).

Some more information on the uncertainty of the applied method for mixing height detection, its limitations and data availability should be included. Especially the point of excluding cloudy periods needs to be better explained in the context of the monsoon analysis.

An uncertainty estimation has not been applied in this study. To our knowledge there is only one publication available on confidence levels and error bars for the detection of mixing layer heights by Vaisala ceilometers (Münkel et al., 2011) which is based on a measurement campaign at Athens airport. It is not possible to derive general conclusions for other sites from this. As already discussed in section 2.2 results from ceilometer measurements are in good agreement with mixing layer height observations determined with other techniques such as sodar or radiosondes also in mountain areas (e.g. Ketterer et al., 2014).

References:

Münkel et al., 2011: Christoph Münkel ; Klaus Schäfer and Stefan Emeis, Adding confidence levels and error bars to mixing layer heights detected by ceilometer, Proc. SPIE 8177, Remote Sensing of Clouds and the Atmosphere XVI, 817708 (October 26, 2011); doi: 10.1117/12.898122; http://dx.doi.org/10.1117/12.898122.

Ketterer, C., Zieger, P., Bukowiecki, N., Collaud Coen, M., Maier, O., Ruffieux, D., and Weingartner, E.: Investigation of the Planetary Boundary Layer in the Swiss Alps Using Remote Sensing and In Situ Measurements, Boundary-Layer Meteorology, 151, 317-334, doi:10.1007/s10546-013-9897-8, 2014.

The part on the data availability together with the next question is answered in the replies to the "minor comments".

P7, l10: Data availability? How many hourly mixing height estimates are obtained

within the study period? What are reasons for missing data? If all periods with boundary layers clouds are excluded from the analysis as stated in P5, l25, how representative are measurements during the monsoon season?

Please see replies to "minor comments" below.

Minor comments:

P2, l15 - P3, l10: Very basic, it might be more interesting to reference other studies investigating the PBL to introduce current research in the field. Generally, much more literature references should be discussed in the introduction.

As mentioned above, we shortened the text on the planetary boundary layer and mixing layer in the introduction and included more literature references on local dynamics. Please, find the changes directly in the introduction (see track changes version).

P2, l16: Might be the first study of this kind in Kathmandu Valley, but how about other locations with similar topography?

We included a literature reference on mixing layer height detection from radio wind profiler at a station in the central Himalayas (India) (Singh et al., 2016). In this study measurements have been taken for five months (p.3, l. 26).

P4, l31: What type of weather station? Model and manufacturer of radiation sensor, temporal resolution? For all sensors provide sensor height and characteristics of

immediate surroundings?

P5, l1: CL31 data also measured to hourly values? What is the original resolution in time and range?

P5, l10: State name of the algorithm.

P5, l25: Provide details on screening methods. How did you determine the cloud is 'within mixing height'? How do you define times with precipitation?

P5, l33: Does BLview have different versions? If so, which version of the software is used in this study?

"The algorithm used to determine the aerosol density and mixing layer height from ceilometer data collected in the Kathmandu Valley is the Vaisala BL-VIEW algorithm version 1.1, which has been slightly adapted according to the instrument settings used in this study."

P6, l5: How is the signal noise determined prior to averaging?

We included some sentences on p. 8, l. 22-26 to explain the determination of the signal noise:

"For noise detection the far range between 6200 m and 7200 m is investigated for every profile reported by the ceilometer. This far range profile contains 30 s average data. Two values are calculated for each profile in order to minimize the influence on high cloud signal: standard deviation of the profile values between 6200 m and 6700 m, and standard deviation of the profile values between 6700 m and 7200 m. The minimum of those values is the noise value used to determine the averaging time interval."

P6, l10: State explicitly: if aerosol load is low, BLview does not report any layer?

We added the following sentence on p. 8, l. 32-33:

"An aerosol layer is reported if a minimum threshold of $200 \cdot 10^{-9}$ m^{-1} sr^{-1} is exceeded in the attenuated backscatter signal."

P6, l13: repetition with line 9

We deleted this sentence.

P6, l15: So BLview does not provide one estimate for mixing height but rather several to choose from? Explain the physical meaning.

The lowest detected aerosol layer is regarded as the mixing layer height. We rephrased the sentence as follows (p. 9, l. 3-4):

"For the evaluation in the frame of the SusKat project, the height of the lowest detected aerosol layer was regarded as the mixing layer height and the nocturnal stable boundary layer, respectively."

P6, l20: At what time resolution is the tracking of layers performed?

This is now mentioned on p. 5, l. 19-24:

"In this study the measurements with a Vaisala ceilometer (CL31, Finland) (Münkel, 2007) are used to study the vertical structure of the atmosphere, especially the mixing layer height. To cover a whole annual cycle, data from March 2013 to February 2014 are used here. The report interval of the CL31 is every 2 minutes with a vertical range resolution of 20 m. From that aerosol layer heights are calculated for every 10 minutes and mixing layer heights for every hour according to the description in section 2.2."

P7, l2: Provide reference or reasoning for 'settings fitting best for mixing layer height assessment'

We added the following explanation (p. 9, l. 22-25):

"The settings fitting best for the mixing layer height assessment with the CL31 are 16 s report interval and 10 m height resolution because the CL31 internal memory stores only up to 16 s accumulation time. These recommended settings provide the best possible signal-to-noise ratio with the minimum required data flow."

P7, l3: Not quite clear, it is stated that 'best settings' for mixing height detection are used, however, a resolution of 20 m is chosen even though a resolution of 10 m is required as stated in line 3. Check paragraph for consistency. Move whole paragraph to instrumentation section.

The text says that the instrument has *NOT* been operated with the settings fitting best (p. 9, l. 25-26):

"During the time period investigated in this study, it had not been operated with settings fitting best for mixing layer height assessment."

The 20 m instead of 10 m height resolution is an example for that.

P7, l10: Data availability? How many hourly mixing height estimates are obtained within the study period? What are reasons for missing data? If all periods with boundary layers clouds are excluded from the analysis as stated in P5, l25, how representative are measurements during the monsoon season?

The data availability per season is given in Table 1. We included a sentence on that to the corresponding paragraph (p. 6, l. 35 - p.7, l. 8):

"The availability of the mixing layer height data per hour varies between the

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four seasons (70 to 93 %, Tab.1). Least data are available in the monsoon season which is likely due to a more frequent occurrence of clouds, fog and precipitation in this season, as the BL-VIEW algorithm excludes profiles with fog, precipitation or low clouds. We consider a data availability of 70 % as sufficient for our analysis."

P7, l11: Comment on seasonal variations in sunrise and day-length.

Here we collected some data on sunrise, sunset and day-length:

- Pre-monsoon season: sunrise between about 5 and 6:30 a.m., sunset between about 6 and 7 p.m., day-length between about 11.5 and 13.75 h

- Monsoon season: sunrise between about 5 and 6 a.m., sunset between about 5:50 and 7 p.m., day-length between about 12 and 14 h

- Post-monsoon season: sunrise between about 6 and 6:40 a.m., sunset between about 5:10 and 5:50 p.m., day-length between about 10.5 and 11.8 h

- Winter season: sunrise between about 6:30 and 7 a.m., sunset between about 5:10 and 6 p.m., day-length between about 10.5 and 11.5 h

We also included a sentence on that in the text (p. 10, l. 6-10):

"Sunrise varies between about 5 and 7 a.m. during the year with times between about 5 and 6:30 a.m. in the pre-monsoon season, 5 and 6 a.m. in the monsoon season, 5:10 and 5:50 a.m. in the post-monsoon season and 6:30 and 7 a.m. in the winter season. The day length during a year varies between about 10.5 and 14 hours, with 11.5 to 13.75 h in the pre-monsoon season, 12 to 14 h in the monsoon season, 10.5 to 11.8 h in the post-monsoon season and 10.5 to 11.5 h in the winter season."

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P8, l7: What are the mixing height estimates during these 'very stable conditions'? Are those reasonable or is it possible that the detection algorithm has a limit for the lowest detectable height? What is the first range gate where BLview provides layer estimates?

The lowest gate where BL-VIEW provides mixing layer height estimates is 30 m. Because of the 20 m resolution setting used during SusKat, this configurable lower limit was set to 40 m.

P8, l15: What is the typical cloud base height of monsoon clouds over the region?

From the ceilometer data we could retrieve that during the monsoon season the monthly median cloud height was between 1360 m (June 2013) and 960 m (July and August 2013).

P8, l28: It is stated that reduction in solar energy is the dominant cloud effect, what is the physical explanation for the impact by rainfall?

We added some more explanation on p. 11, l. 31-33 and deleted "and rain" from the next sentence:

"The sum of precipitation per day is used here as a proxy for the cloud amount to study the impact of days with a large fraction of cloud amount on the mixing layer height. Therefore the presence of clouds in the monsoon season explains a large part of the on average lower mixing layer height and higher variability compared with other seasons."

P9, l9: Data availability of black carbon measurements? What data processing and

quality control/instrument calibration is applied?

The data availability of black carbon measurements is given in Tab. 1. The analysis presented in the paper was based on the 1 min-average data collected at the Bode station. Post processing of the collected data includes flagging and averaging to 1-hr values. The 1-min data were flagged based on a few operational parameters of the instrument such as status, flow ratio, tape advance etc. in addition, the time series of black carbon was plotted against data from other co-located particle mass, number and trace gas concentration measurements to identify noise or influence of nearby sources. The contributions of nearby sources were identified by "short duration (1-3 minutes) spikes" in the time series, also indicated by other co-located instruments. The flags were applied to 1-min data, and the flagged data were averaged to 1-h values. The averaging only considers time period with at least 75 % (of 1-min) data points available as a valid 1-h values. For clarification, we added the following paragraph to the manuscript (p. 5, l. 33 - p. 6, l. 26):

"The black carbon concentrations were measured by an aethalometer model "AE33" (Magee Scientific, USA). This particular is a dual-spot measurement for loading correction (Drinovec et al., 2015). The AE33 deployed in Bode was fully factory calibrated before commencing the field campaign. In Bode, the AE33 was set to measure aerosol absorption at a time resolution of 1-min time average and the sample flow was set at local volumetric flow of 5 litres per minute. The tape advance was based on an attenuation of 120 and each tape advance was followed by clean air test. The clean air test was also performed whenever a new tape was inserted in the aethalometer. Operationally the AE33 is designed for a fairly automated and continuous measurement. Some of the operational issues during the field campaign include the change of the bypass filter cartridge, which was replaced whenever the clean air test failed or when the colour of the filter

inside the cartridge changed from white to grey or dark. Additionally, the optical chamber was also cleaned in response to the failure of the clean air test. The analysis presented in the paper was based on the 1-min average data collected at Bode. Post processing of the collected data includes flagging and averaging to 1-h values. The 1-min data was flagged based on operational parameters of the instrument such as status, flow ratio, tape advance etc. in addition, the time series of black carbon was plotted against data from other co-located particle mass, number and trace gas concentrations to identify noise or influence of nearby sources. The contributions of nearby sources were identified by "short duration (1-3 min) spikes" in the time series, also indicated by other co-located instruments. The flags were applied to 1-min data, and the flagged data were averaged to 1-h values. The averaging only considered time periods with at least 75 % (of 1-min) data points available as valid 1-h values."

P9, l30: How are these temperatures determined? Include sensors in instrumentation section.

Please, see comment above on the weather station.

P9, l35: More references to local dynamic characteristics in the valley should be provided in the introduction to 'set the scene' for this study, i.e. what are the results of previous studies, what are the open research questions?

The general description of the location of the Kathmandu Valley has been moved from section 2.1 to the introduction in order to introduce the studied region earlier in the text. Two more references to articles on local dynamics in the valley are provided in the introduction (Shrestha et al., 2015 and Regmi et al., 2003)

describing the main characteristic local flows in the Kathmandu Valley. Two more studies on the local dynamics are mentioned and described at the end of section 3.2. Please, find the corresponding changes directly in the text (see track changes version).

P10, l20: Discuss local emission sources

We added the following sentences to the text (p. 12, l. 24-27):

"Important local emission sources of black carbon in the Kathmandu Valley are brick kilns which emit relatively constantly throughout day and night during the time period of December to April and are located in different parts of the valley (Fig. 1). Other important black carbon emission sources with a much more pronounced diurnal cycle are cooking, traffic (see location of main streets in Fig.1) and trash burning."

P10, l25: Comment on the timing of rainfall during the day.

The whole day is deleted from the time series if the sum of precipitation is above 0.5 mm day^{-1} (p. 11, l. 23-25). For this reason, the exact timing of rainfall during the day has not been analysed in detail.

P11, l10: Comment on the implications of the site locations of the Bode site compared to the urban site. How is this related to timing of emissions? (see line 23: Make discussion on comparison to Puerto et al more consistent.)

We restructured section 3.3.1 to make the discussion more consistent (please see tack changes version).

P11, l30-10: Some of this should be moved to introduction.

Parts of this text are now moved to the introduction (please see track changes version).

P11, l26: Where is the pollution rose figure? Reference?

The pollution rose figures are not shown in the article, they were done only to check the relation between wind direction and black carbon concentration. We changed the corresponding sentence to (p. 15, l. 9-10):

> "Pollution roses (not shown) indicate that between about December and April most of the highest black carbon concentrations coincide with wind from the east and east south east."

P12, l1: mark emission sources in map of Figure 1.

We added the five major cities in the Kathmandu Valley (Kathmandu, Lalitpur, Bhakta-pur, Kirtipur and Madhyapur-Thimi) to the revised version of figure 1, highlighted major roads, and marked clusters of brick kilns.

P13, l1: Comment on the validity of these assumptions? Discuss mechanisms in that influence advection and stratification in the valley. Reference relevant literature.

The assumption that the horizontal advection of air pollutants into and out of the valley at night is small is based on the observed low nocturnal wind speeds and on the

studies by Panday and Prinn (2009) and Panday et al. (2009), who found that the timing of the ventilation of air pollutants from the valley is largely determined by the strong westerly wind blowing through the valley from late morning until dusk. They conclude that the "bulk of ventilation takes place during the afternoon when strong westerly winds blow though the valley", which is consistent with our assumption that horizontal advection of air pollutants into and out of the valley is small at night.

The assumption that vertical mixing of pollutants between the mixing layer and the free troposphere is small at night is based on (i) the observations that the mixing layer height does not change significantly during this time of the day and (ii) the study by Regmi et al. (2003), who concluded that "during the nighttime, strong surface inversion and a deep cold-air lake would be formed under weak wind".

We added the main mechanisms and the references to the text (p. 16, l. 20-24 and l. 27-30):

> "The assumption of negligible horizontal transport at night is consistent with the observed low nocturnal wind speeds, and with the studies by Panday and Prinn (2009) and Panday et al. (2009), who found that the timing of the ventilation of air pollutants from the valley is largely determined by the strong westerly wind typically blowing through the valley from late morning until dusk. The authors of these studies conclude that the bulk of the ventilation of air pollutants usually takes place in the afternoon. Consequently, the horizontal advection of air pollutants into and out of the valley is typically small at night. [...] The assumption that vertical mixing of pollutants between the mixing layer and the free troposphere is small at night is consistent with the findings by Regmi et al. (2003), who concluded that during night hours, the typically prevailing meteorology leads to a strong surface

P13, l6: What are the hours used for the calculation? You state here no times with entrainment are used but then black carbon is used during morning hours - line 21. Is that consistent?

The times used in the estimation of the black carbon emission flux are given in Tab. 2. As described on p. 16 of the revised manuscript, the estimation of the black carbon flux is based on the conclusion that the main process driving the increase of the black carbon concentration during the night is not the variation in the mixing layer height (Fig. 9), nor mixing of even more polluted air from above or from outside the valley, but rather, as assumed here, the emissions. The variation of the mixing layer height during the times used for the calculation is only small (see Tab. 2 and Fig. 9).

To clarify that in the text we added a reference to table 2 and figure 9 to the corresponding sentence (p. 16, l. 24-27):

"And the mixing of pollutants between the mixing layer and the free atmosphere (entrainment) occurs mostly when the mixing layer height increases or decreases significantly, which is not the case during the hours used for this calculation (Tab. 2 and Fig. 9)."