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Atmospheric Measurement Techniques Discussions

Interactive comment on "Integrated System for Atmospheric Boundary Layer Height Estimation (ISABLE) using a Ceilometer and Microwave Radiometer" *by* Jae-Sik Min et al.

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Response to referee #1 comments

Authors gratefully thank to referee #1 for his/her thorough reviews and valuable comments which would contribute to improve the manuscript. Authors have revised the manuscript to respond the referee's comments. Authors tried to improve the manuscript by clarifying the ambiguous expressions, and adding 3 Figures (Figs. 5, 10, and 11) with scatter plots between ISABLE_ABLH and conventional ABLHs with respect to time zones and cloud covers. The revised manuscript was edited by a professional Editing company. Major changes are marked in RED in the revised manuscript. I hope that

this manuscript will be accepted for the publication in AMT.

General comments:

On grammar:

- The revised manuscript was again edited by a professional editing company to improve grammatical and language faults.

On improvement and possible benefit of this study

- Poor performance was due to multiple factors, such as strong backscattering signals in the residual layer, presence of clouds, and too week backscattering signals. Overall, the performance of this study was found to be better than that of the conventional methods. It is difficult to estimate the consistent ABLHs under aforementioned atmospheric conditions. As the ABLH was estimated using as much data as possible, regardless of time or atmospheric conditions, their performances seemed to be somewhat lower (L499-501 and L505-507).

- The study station is located in an urban residential area with complex geography and topography, where can be affected by several types of local circulation such as sea-land breeze, mountain-valley breeze, and urban-rural breeze (L86-91). Moreover, the formation of evolution of SBL were not active over the station due to the heat release at nighttime by the heated materials during the daytime (L367-371).

- Nonetheless, it is found that the performance of ISABLE_ABLH was found to be better than that of the conventional methods (Section 5 and L499-501).

Further, as ISABLE merges existing methodologies, it should be contrasted to similar algorithms which also merge various methodologies.

- There were several previous studies on the merging algorithm such as Pal et al. (2013) and Hicks et al. (2015). Par et al. (2013) combined the gradient methods based on a first derivative of the Gaussian wavelet covariance analysis and the spatial/temporal variance method. Hicks et al. (2015) combined the error function-ideal profile method and wavelet covariance transform method to estimate ABLH (L67-69).

Similarly, although ISABLE in this case, slightly outperformed the individual methodologies in this study, it does not show improvements in the known challenges across all ABL ceilometer retrievals (ABL layer attribution, precipitation, lofted aerosol layers, low aerosol conditions, clouds, etc.).

- The possibilities of further improvement were discussed in L513-520 such that: Although ISABLE-estimated ABLH exhibited better performance than those estimated by the earlier conventional methodologies, there are still many limitations. In particular, ABLHs estimated from the ceilometer in the lower layer are not reliable due to near-range artifacts, especially under intense solar radiation. ABLHs at higher levels at nighttime could be supplemented by the temperature profile obtained by the MWR. ABLHs are challenging in terms of estimating under cloudy sky or precipitation, severe fog, and smog events. Since the ISABLE is in the early stage of development, it did not address the all known issues yet, such as precipitation, lofted aerosol layer, and too clean (little aerosol) condition. These limitations and drawbacks should be overcome by combining enough observation data, instrumental advances, and the corresponding improvements of ISABLE.

These challenges have been addressed in more recent methodologies which improve retrievals through various tracking tools. Properly addressing the literature, would give further insight into the benefits or challenges of using ISABLE for ABLHs and may justify the suggested use of ISABLE.

- Authors had reviewed the applicability of the recent methodologies within the range of the available data in Section 1 (Introduction).

- Several integrated methodologies are added in L67-70: Previous studies integrated multiple methodologies, i.e., Par et al. (2013) combined the gradient method based on a first derivative of the Gaussian wavelet covariance analysis and the spatial/temporal

variance method; and Hicks et al. (2015) combined the error function-ideal profile method and wavelet covariance method to estimate ABLH.

- Challenges are addressed in L71-76: Even though several methods have been developed, no consensus on a specific algorithm has been reached. Different methodologies provide different ABLHs with respect to weather conditions and phenomena. Under complicated ABL structures, the ABLH could be determined as different values according to the methodology used. Therefore, this study aims to develop an integrated system for ABLH estimation (ISABLE) to determine a single optimized ABLH with statistically significant results from several ABLH candidates.

The manuscript states improved results using ISABLE in comparison to VAR, GM, WAV, CLST methodologies. However, improvements in correlations when compared to sondes are slight and RMSE (above 300m) are substantial. These results and bias should be further discussed as a RMSE of 300m+ can be quite significant in the ABL.

- The MB and RMSE for nocturnal SBLH were as good as 6.7 m and 72 m, respectively, although the number of available data was not sufficient (L411-412).

- The performance of each methodology and ISABLE were discussed in L180-181, L369-371, L394-395, and L513-520: Firstly, radiosonde sounding data has a possibility to determine the SBLH as a residual layer due to the large variations of temperature and wind in the residual layer (L180-181); Secondly, the SBL over urban areas is not always developed because the sensible heat flux does not show strong negative values even at a clear night due to heat release by the heated materials during the daytime. So, formation and evolution of SBL were not active over compact urban surfaces such as the station (L369-371). Thirdly, ABLH via ceilometer is inclined to be estimated as a residual layer at nighttime due to the overlying aerosol layers. Scatter diagram shows that RLs during nighttime or cloud layers in daytime existed (Figs. 10-11) (L394-395). Finally, larger differences between ABLH_ISABLE and ABLH_RS were mainly due to the existence of residual layer and clouds as well as too clean (little aerosol) atmosphere. Exact determination of ABLH above cases remains to be still challenges. These could be overcome by combining enough observation data, instrumental advances, and the corresponding improvement of ISABLE (L517-520).

Section 2: Please provide references for ceilometer and MWR instrumentation. Additionally, the net radiometer is overlooked and left without description.

- The references on ceilometer (Vaisala, 2010), MWR (RPG, 2015), and net radiometer (Kipp&Zonen, 2014) were added in L94, L98, and L106 in Section 2, respectively.

Section 3.3: Please provide references to the entire methodology in this section.

- Relevant references such as Cimini et al. (2006) and Holton and Hakim (2012) were addressed in L152 and L157 in Section 3.3.

Section 4.2.4: Was the cluster analysis applied to averaged (z) or $\sigma\beta$SNR profiles or else?

- The cluster analysis was applied to the backscattering coefficient βz in Figure 3d (L243-244).

Section 4.3: MWR have also gone through extensive ABL retrieval evaluations and these should be discussed. The selection of the methodology should also be supported with further literature discussion. Additionally, is there a reason why MWR are only used for SBLH retrievals and not ML and RL heights?

- The surface-based temperature inversion (SBI) using the radiosonde data was introduced in L179-185: SBLH is determined as a surface based temperature inversion (SBI) height at which the temperature decreases with height (ΔT/Δz <0).

- In order to estimate SBLH using the MWR data, critical lapse rate (CLR) method was applied instead of SBI. To find the height affected by surface cooling, the critical lapse rate (CLR) method was proposed (L254-260). The reason why SBLHs obtained by the CLR method was explained and was compared with those obtained by the SBI method

(L261-278) in Section 4.3.

- But, during the RS intensive observation period, only 4 SBL were detected using the SBI methods from radiosonde (L292-293).

Minor comments:

L23-24: Definitions of the ABL are unclear in this sentence. This reads as both the stable and residual layers are nighttime lofted layers. Please clarify.

- In this study, the ABL is confined as a single layer, which is consisted of a mixed layer (ML) or a stable boundary layer (SBL) to exclude its complexity. Accordingly, the ABLH includes only a MLH or a SBL. The above explanation is added in L32 and L35.

L24: "By convection and turbulence" implies separate mechanisms independent of each other. Please review

- The sentence is rewritten as in L26-29: The ABL is repeated in a daily cycle with a mixed layer (ML) in daytime and a stable boundary layer (SBL) at nighttime. The former mixes air vertically via convection which results from surface heating or mechanical turbulence due to vertical wind shear, while the latter appears in the lower ABL, and a residual layer (RL) remains in the upper ABL without any external force.

L26: "Besides" is incorrectly used here.

- The term 'Besides' is removed in the revised manuscript.

L26-27: the reduced dilution volume of the SBL should also be noted as this can increase surface pollutant concentrations.

- The following explanation is added in L30-31: In the presence of well-developed SBL at night, air pollutants near the surface tend to be trapped inside the SBL because of the low vertical diffusivity, and their concentrations could increase sharply.

L28-30: Although the ABL can influence pollutant concentration, it cannot be used to determine air pollutant concentrations as stated. The interactions between pollutant concentration and the ABL height are not the only drivers in air pollutant concentrations. Emission sources, transport, photochemistry etc. may have large impact in pollutant concentrations and must not be neglected.

- As you mentioned, ABL height is not only one drivers to determine the air pollutant concentration. But, the ABLH is an important factors to explain the vertical diffusion of air pollutants in the ABL. In the context, the sentence is rewritten as in L29-32: The ML is one of the essential meteorological factors that affects the vertical mixing of air pollutants. In the presence of well-developed SBL at night, air pollutants near the surface tend to be trapped inside the SBL because of the low vertical diffusivity, and their concentrations could increase sharply.

L45: "back into the atmospheric aerosol" implies that the laser originated in atmospheric aerosol and returns back to its origin. Please revise.

- The expression is clarified in L49-52: An aerosol lidar and a lidar-type ceilometer measure the intensity of signals which have been backscattered by atmospheric materials, such as aerosol, cloud, mineral dust. The intensity of backscattered signal at each level can be converted to backscattering coefficient at the level with several assumptions.

Equation (1): the variable N is not defined in the text.

- The variable N is defined in L131: N denotes the number of levels between 12 km and 15 km (N = 300).

L126-130: Can you comment on how much of the improvement of hSNR may be due to the applied averaging?

- Improvement of hSNR and the related explanation are added in L136-145: Strong noises with random backscattering coefficients were found at heights above 2,500 m throughout the day. When the shortwave radiation was intense during the daytime, the

noise was mainly due to sunlit scattering and low SNR values. Especially, in the presence of daytime clouds (1400 to 1600 LST), the SNR became smaller, and the hSNR became low. After pre-processing, noise signals at higher altitude have decreased with maintaining their main features in Fig. 2a (Fig. 2b). But vertical broadening at heights with intense signals was shown as a result of the moving average. And the mean hSNR became 331 m higher than the before. The pre-processing made the value much more stable, although under poor circumstances with strong radiation and daytime clouds. Also artifacts at high altitudes were mitigated.

L162-167: It is unclear if residual layer heights are not being identified in radiosondes as the current text seems to imply aerosol profiles are sufficient for residual layer identification. Is the 'final ABLH' alternating between SBLs and RLs? Please clarify. It is unclear what method was used in the final ABLH attributed to the SBL.

- Actually, it is not easy to detect a residual layer using the radiosonde sounding. This is because the vertical variations of temperature and wind in the RL can be more substantial compared to those in the SBL. Thus, the SBLH has been generally estimated using the methodologies with temperature inversion. In this study, the ABLHs were estimated with RiB in both daytime and nighttime, and if a SBL was formed at nighttime, the SBLHs were determined via the SBI method. Nonetheless, top of RL can be determined as a SBLH due to the effect of temperature and turbulence (Collaud Coen et al., 2014). The above explanation is added in L180-185.

L177: Please describe how $\sigma\beta$SNR profiles were smoothed

- The σ_(β_VAR) profile was smoothed using a local quadratic polynomial regression to eliminate spurious variance peaks at small-scale fluctuations and above hSNR (Cleveland and Loader, 1996). The sentence is modified in L195-196.

L193-195: How is this consistent with Emeis et al. (2008), please specify.

- The sentence is clarified in L211-212: The fact that hGM is slightly higher than hIPM, and lower than hLGM is consistent with the findings of previous studies (e.g., Emeis et al., 2008).

L207-208: How were these settings chosen?

- The settings were just followed by those of de Haij et al. (2006; 2007). The reference is added in L227.

L223-224: Please define what 'distribution' is divided

- The term 'distribution' was changed to 'height' in L242.

L284, 296-297: Is this an artificial gap or a threshold marking? A follow up to the previous comment, does the final ABLH average include the added 150m or was this removed at some point? Please comment on how averaging the final cluster group can affect the ABLH, uncertainty, and validation.

- The reasons for choosing the 150 m and more explanation are added in L310-314: The minimum distance between the nearest two ABLH candidates was set to 150 m. The reason is that the typical thickness of a well-defined entrainment zone was reported to be between 100 and 300 m (e.g., Angevine et al., 1994). If there were multiple peaks chosen using an individual methodology within 150 m interval, the remaining peaks except for the most significant one were removed from the ABLH candidates for the method.

L313-316: How was the 500m limit defined and what artifacts were observed? Please expand.

- The following sentence is added in L139-140 and L346-351: As shown in Fig. 2a, it was found that backscattering signals were weakened at about 120 m high and 400-500 m during the daytime with intense solar radiation. Due to the weakened signal by instrumental reason, the 400-500 m was often estimated as an ABLH. So, ABLHs below 500 m at the time were assumed to be unreasonable and were neglected.

L333: This reads as the surface will only cool under clean air. Please review.

- More explanation is added in L367-371: The SBL over rural areas is well developed over rural surfaces via surface cooling through earth radiation at night, especially under clear skies. However, that over urban areas is not always developed because the sensible heat flux in urban areas does not always show strong negative values even at a clear night due to heat release by the heated materials during the daytime (Hong et al., 2013; Park et al., 2014). So formation and evolution of SBL were not active over compact urban surfaces such as Jungnang station.

L335: the 'nocturnal heat island' effect is mentioned but not clearly connected to the results. Please expand on this effect and how at times (yet not always) it is responsible for high altitude outliers during nighttime.

- The outliers above 1 km results from a RL or cloud layer. When the nocturnal SBLH was estimated using aerosol-related variables at nighttime, the ABLH can be often detected as a top of residual layer. This is because the vertical variations of the backscattering signal in the RL can be more substantial compared to those in the SBL. The above explanations are in L180-182 and L372-373.

L340-342: why was this time period chosen?

- The period is chosen considering the consecutive observation period and missing ratios among available radiosonde sounding data. The period corresponds to the longest observation period with an interval of 3 h and without any missing data among available radiosonde data. The above explanation is added in L378-379.

L369-390, L369-375: No need to list all results already clearly presented in tables 2&3. Instead, insight into the possible culprits or conditions leading to the major findings should be presented and discussed. The clear and cloudy sky results (Figure 9b) shows very similar results across all methodologies (excluding WAV1&3) with a very small improvement in the ISABLE results. Can the benefits of ISABLE be expanded upon?

- The paragraph is fully removed and rewritten according to the suggestion. In order to find insight, analyses on ABLH with respect to 4 time zones (sunrise, daytime, sunset, nighttime) and cloud covers (clear and cloudy) are added in Section 5.2. As a result, the improvement of ISABLE was evident during transition time, sunrise and sunset, while the verification score was not good at nighttime. It seems to be the difference of SBLH estimation between the radiosonde and microwave radiometer, and further analysis is required on this problem. In this study, it is considered difficult to analyze due to the limitation of the number of radiosonde observation at nighttime. The above explanation is added in L378-412, Table 2-3, Figures 10 and 11.

- The variance (VAR) and the cluster (CLST) methods showed the best performances during the daytime. The scatter distribution of GM, WAV2, and CLST at sunrise, sunset, and nighttime could be fitted to two different linear functions. In cases where symbols were plotted below the trend line, RLs during nighttime or cloud layers in daytime existed at the layer. ISABLE showed significant improvement near sunrise and sunset time, but showed a lower correlation with the individual methods in nighttime because ABLH was often underestimated, as compared with RS. There were only four SBLH estimations via RS, while 24 SBLH were observed via MWR, which resulted in significantly lower ISABLE performance at nighttime, as compared with those of the four methodologies. The performances of WAV1 and 3 were significantly poorer than those of other individual methodologies. The shorter dilation used in WAVE1 seems to be unsuitable for estimating the ABLH, and it might affect the ABLH of WAV3 (L392-403).

Table 2 and 3, L452: The difference between these two tables is not explained. Table 3 hints at a removal of "major error factors", how is this defined? This explains now the difference between Table 2 and 3. The removal of these "error" retrievals should be specified and described in the results section. Additionally, these should be clarified as manual removal of retrievals deemed inadequate and are not representative of the overall performance of ISABLE itself.

- Tables 2 is rewritten from a point of view of four time zone (sunrise, daytime, sunset, nighttime) using the data listed in Table 1. On a while, Table 3 is based on the last three data listed in Table 1. It is because cloud cover was missing in the first data (23 to30 November 2015) in Table 1. Minor statistical errors were corrected in revised Table 3. The above explanation is added in L403-405.

- The explanation in Section 6 is moved to in L403-405 in Section 5.2.

- The limitation of this study is added in L513-520: Although ISABLE-estimated ABLH exhibited better performance than those estimated by the earlier conventional methodologies, there are still limitations. In particular, ABLHs estimated from the ceilometer in the lower layer are not reliable due to near-range artifacts, especially under intense solar radiation. ABLHs at higher levels at nighttime could be supplemented by the temperature profile obtained by the MWR. ABLHs are challenging in terms of estimating under cloudy sky or precipitation, severe fog, and smog events. Since the ISABLE is in the early stage of development, it did not address the known issues yet, such as precipitation, lofted aerosol layers, and too clean (little aerosol) conditions. These limitations and drawbacks should be overcome by combining enough observation data, instrumental advances, and the corresponding improvement of ISABLE.

L458-460: The impact of ISABLE retrievals as "great potential in parameterizing vertical diffusion" and to "understand severe haze/smog events fumigated from the upper layer" is unsupported. Such statements require further discussion and supporting evidence.

- The expression is not supported by clear evidences yet, and is removed in the revised manuscript.

Please also note the supplement to this comment:
https://amt.copernicus.org/preprints/amt-2020-18/amt-2020-18-AC1-supplement.pdf

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