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Determination and climatology of the planetary boundary layer height above the Swiss plateau by in-situ and remote sensing measurements as well as by the COSMO-2 model.

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Answer to the third anonymous referee's comments :

The authors thank the referee for their constructive comments. The quality of the paper was greatly improved by these review process. In the following, all the comments are answered and the modifications introduced in the revised manuscript are described.

General comments:

- including indepth analyses and discussions on the source of errors in model PBL height predictions;

The authors do agree that an in depth analysis of the uncertainties would be valuable. As explained now in the manuscript, the uncertainties can be estimated either statistically or by analyzing the complete instrumental process. Several studies are presently performed at MeteoSwiss to develop uncertainties analysis for each instrument (see for example Philipona et al. (2014) for the radio sounding and Haefele et al. (2014) for the wind profiler). Since these procedures are not yet finalized for all instruments involved in this study, a complete uncertainties analysis is presently not possible. The uncertainties presented in this study relate therefore to statistical comparison of the results compared to a reference method (validation presented in Figs. 6-7) or to statistical dispersion of the results for cases considered as similar (climatology analysis presented in Figs. 9-12). The manuscript was consequently modified:

"Each of the considered method and instrument have their own uncertainties in the PBL height detection. The uncertainty minimum is usually obtained for fully developed CBL reported in Figs. 6-7. Several type of uncertainties can be however be estimated. First, a statistical uncertainty (see for example the climatology analyses Figs. 9-12) estimates the fluctuations of measurements for cases that are considered as similar; these fluctuations reflect the measurement uncertainties but also the variation of the atmosphere for "similar conditions", but are unable to detect systematic bias. A measuring uncertainty can also be derived for each instrument providing an estimation of systematic bias and fluctuations; such analysis have been up to now only partially made for some instruments, but not all, impeding our ability to propagate these errors on the various PBL height detection methods. Finally, the comparison to a "reference" (Figs 6-7) allows to statistically estimate the reliability of the other methods. The uncertainties bounded to the method and the instruments (see Sect 2.2) provide however a similar picture as the inter-comparison, with the greatest precision for methods based on T profile and the lowest for WP/SNR.

Finally, in addition to considering the differences in statistical and intrinsic uncertainties found between the various instruments and methods, one has to consider that the measured parameter (PBL height) is in reality not a fixed point but rather a transition layer between two atmospheric states. Both Stull [Stull, 1988] and Garratt [Garratt, 1992] estimate the thickness of the entrainment zone as large as half the mixed layer depth. This transition layer reaches therefore between some tens to some hundreds of meters. Moreover the remote sensing instruments measure an air volume with a thickness corresponding to the instrument level (see Sect 2.2) and not a precise point. The obtained differences between the experimental methods and their uncertainties remain in the same order of magnitude of this transition layer thickness."

- providing more quantitative evidence for supporting some statements

See the answer to the specific comments below.

- providing more clear and precise wording throughout the manuscript.

The corrected version of the manuscript was reviewed by a native English speaker.

Specific comments :

- Page 15422, the paragraph starting from Line 14: It is important to understand the strength/limitation of various methods for PBL heights reported in literature. Descriptions of this paragraph could be more concise and more quantitative.

I do understand that some more quantitative analysis could help the reader. However the cited papers include most of the time comparison between 2-3 setups. These setups comprise various instruments (RS, MWR, WP, lidar, ceilometer, sodar, Doppler wind lidar, measurements on mast, aircrafts measurements ,…), methods (parcel method, Bulk-Richardson (various equations and threshold), gradient analysis, wavelet method, fuzzy logic analysis, near surface thermal gradient), models (COSMO Germany, COSMO Switzerland, ERA), sites (several continents, urban, marine, continental and alpine environment,…), and length of the measurements (from 2 days to 10 years), so that it is impossible to obtain a clear view of the strength and limitation of the methods from all these papers. Having a lot of various instruments at Payerne, this study tentatively try to clarify this situation.

- Page 15422, Line 24: The sentence is not clear to me.

The sentence was reworded: "Non-convective weather situations corresponding in most of the cases to cloudy and rainy situations lead to much greater discrepancy in the PBL height estimations. In these cases, the difference becomes even greater if the methods/instruments are designed to detect various types of PBL such as CBL, NBL or RL."

- Page 15424, Line 21: What does "the low mode" mean? Please provide sufficient information for readers to understand.

The wind profiler description was completed in the revised version: "The WPs are Degreane PCL1300 (Degreane Horizon, 2006) with five antennas operating at 1290 MHz (λ=23.3 cm) alternatingly in low and high mode covering altitudes from 0.1 to 3 km and 0.3 to 8 km, respectively. For this study only the low mode has been used with a vertical resolution of 150 m and the first level at 105 m.".

- The temporal resolutions reported in this manuscript (e.g., 30 min, 40 min) are quite coarse. Is the best resolution that can be achieved? They seem really long!

The wind profiler has an operational time resolution of 40 min (gliding average of 10 min measurements). A temporal resolution of 30 min could be achieved, that correspond to the usual temporal resolution of wind profiler around the world and that is necessary to ensure a sufficient quality for all weather conditions. This sentence was added to the final version: "this time resolution is necessary to obtain a sufficient quality of the measurements under all weather conditions".

The lidar/ASR needs also an integration time of 30 min to obtain measurements of a sufficient quality.

Both instruments were used in their operational mode.

- Page 15427: Why can't cloud fraction be determined by ceilometer measurements?

The ceilometer is only measuring in one direction (at 90° from ground) and is only able to measure the presence of cloud above the instrument. The cloud fraction refers to the total sky fraction covered by clouds, what cannot be estimated by a single point measurement.

- Page 15428, the paragraph starting from Line 17: Please define when is "if needed" in line 20. Additionally, the sentence in Line 24 doesn't read well and I cannot understand it. Also, RH and rho are not defined.

The cases "if needed" was rephrased: "If the T profile was measured by the MWR and the PBL height is found between two measured levels, a linear interpolation between the two measured θ is applied to determine the PBL height.". The sentence Line 24 was also specified: "Far larger PBL height uncertainties up to 500 m were found just before the sunset, when the vertical heat flux becomes negative. ". The pressure p and relative humidity were defined.

- Page 15430, Line 4: shouldn't it be rho_0?

Yes of course, I missed this mistake in the proofs.

- Page 15430, Line 1–4: Please elaborate on this and provide sufficient information for readers to replicate results.

Further information concerning the time continuity algorithm were added: "the k SNR peaks ($s_{k,i}$) at time i with local maximum greater than 75% of the absolute maximum was weighted by a Gaussian function $g(s_{max,i-1}, \sigma)$ with mean equals to the PBL height of the former time step i-1 and standard deviation σ depending on the time of the day. At sunrise, the Gaussian mean (PBL height) is set to zero m a.g.l. (ground level) and σ to 3000 m, that is three time higher than during the afternoon. The PBL height is then attributed to the maximum of the weighted SNR peak $S_{max,i}$=max($s_{k,i}$*g($s_{max,i-1}$,σ)). The uncertainty of this method is considered equal to the full width at half maximum (FWHM) of the selected SNR peak after subtraction of the noise floor and is on the order of 100 to 500 m.".

- Page 15430, Line 8–10: Please describe clearly what "SNR slope and curvature" mean here.

We tested several algorithm to improve the PBL height detection taking into account either the SNR maximum, the minima of its first derivative (slope) and the maximum of the second derivative (curvature). The use of only the SNR maximum was found to be the most reliable method. The text was changed accordingly:" PBL detection algorithms involving first and second derivatives of the SNR peak were tested but have shown a lower consistency with respect to the other PBL height detection methods in addition to a higher rate of false detections. ".

- Page 15431, Line 17: Please double check if this should be WP or WR.

We checked and WP is correct.

- Page 15432, Line 17: Please elaborate on this sentence a bit more. The current explanation doesn't really help to explain the difference between two methods.

I'm really sorry, but I do not understand this question. At line 17, a very good agreement between all methods is described and not a difference. I think that the referee wanted to have more explanation on another sentence, but I don't know which one.

- Page 15433, Line 4: Really? Can WP/SNR detect cloud top no matter how thick clouds are?

The detection of the cloud top depends clearly of the cloud elevation. Cloud tops higher than the detection range of the wind profiler (some 8 km) cannot be detected. The presence of clouds does not however restrict the WP detection range. In cases of multi-layers of clouds, the region with the greatest SNR ratio will depend on each particular cases and no general statement on which atmospheric layer (highest or lowest cloud top, shear wind layers,…) would be detected can be made with our present knowledge.

- Page 15434, Line 10: Isn't this section talking about clear-sky conditions? How come outliers in PBL heights can be attributed to "elevated cloud layers'?

As it is now mentioned in the text, the selected "clear-sky convective cases" report to days with a clearly recognizable CBL pattern and with at least half of the sun radiation from sunrise to 13:00; the presence of some clouds is therefore not excluded and can generate outliers in the CBL heights detected by WP.

- Page 15435, section 3.4: Could the author please clarify if this comparison was conducted for all cases, or just for clear-sky cases? This should be clearly mentioned in the manuscript.

This comparison is done with the same cases selection as in § 3.3. This is now mentioned in the manuscript.

- Page 15435, Line 23: What does it mean by 'physically meaningful systematic positive bias"? Also, please elaborate on the explanation for this systematic bias.

The effect of taking into account the air moisture is described in § 3.1. We elaborate this paragraph to explain this phenomenon and refer to it in page 15435 Line 23:

"This positive difference can be clearly attributed to the effect of moisture that lightens the air and allows it to convectively rise to a higher altitude."

- Page 15436, Line 4: Please provide evidence to support this statement.

This statement can be directly deduced from equation (1) in convective situation: if $\theta(z_0)$ is overestimated, $(\theta(z)-\theta(z_0))$ and Ri_b will be smaller, so that Ri_b will becomes higher than the chosen threshold for higher z. This leads to an overestimation of the PBL height. Since this statement comes straightforward from the definition of the method, I did not described it extensively in the paper but just added the reference to the equation (1).

- Page 15436, Line 12: It is quite disappointing that this manuscript does not provide more analyses to identify the main sources of the model errors.

The current paper focuses on the various measurements. We are now studying the sources of errors in the COSMO-2 model and will present the results in a forthcoming paper. The model estimation includes a lot of parameters including the model estimation of the T at 2 m, the T, RH and wind profiles, the difference is using θ or θ_v, the use of PM or bR methods, the possible interpolation between the grid points, the possible use of excess temperature (see answer to referee #2), and the various atmospheric states during the year. Such a complex study is really beyond the scope of this paper.

- Page 15437, Line 20: The paragraph needs to be re-written in a more scientific way.

This paragraph was corrected in order to suppress all qualitative adverbs.

- Page 15438, Line 1: Please provide quantitative evidence to support the statement.
  An analysis of the cloudy-CBL detected by the wind profiler and the cloud base measured by the ceilometer shows that the cloudy-CBL is found at a higher altitude than the cloud base in 45% of the cases. This percentage increases to more than 50% if the cirrus as excluded by taking only cloud bases < 4000 m. This is now mentioned in the manuscript:" The WP/SNR cloudy-CBL heights are most of the time more than 500 m higher than MWR/PM ones; 45% of these cloudy-CBL heights detected by WP/SNR are however higher than the cloud-base detected by the ceilometer. The WP/SNR measures in that cases the cloud top (see for example Fig. 5).".

- Page 15438, Line 12: Could the author please comment why these two ground sites have almost the same monthly variations of the sample size? Is it expected?

In case of precipitation, the lidar is shut down, the radiometer does not provide reliable results and the windprofiler measures the precipitation velocity so that the PBL height can also not be estimated. All the experimental methods are therefore similarly limited by precipitation. Both stations are situated in the Swiss plateau at about 160 km. A correlation between raining days at both stations is therefore highly expected.

- Page 15438, Line 1–15: Not all data points in 0–5 hours on the same day would be selected in the analyses. Therefore, it would be more scientifically/statistically correct and useful to count the sample size in terms of each data point, and then convert them to an equivalent length in days.

The clear or cloudy nights were selected first as nights without precipitation. This mean that night with precipitation between 0h-5h are simply not taken into account at all for this analysis. This was reworded to avoid confusion: "Clear-sky (186 at PAY and 163 at SHA) and cloudy nights (126 at PAY and 151 at SHA) were selected with the criteria of no precipitation between 00:00 and 5:00 in addition to 0-2 and 7-8 octa of the sky covered by clouds estimated by APCADA, respectively.".

- Page 15438, Line 22: How was this statement made? Evidence or reference?

The reasons why the WP is more frequently subjected to false attribution than the other method is briefly described under § 2.2.2 (this was added at line 23) and the reasons are really inherent to the measurement methodology. The lower reliability of WP/SNR PBL height determination can also be noted by the size of the percentiles and whiskers on Figs 6 and 7 as well as on all plots describing the climatologies. We think however that a reference to the figures 6-7 and 9-12 would be redundant at this point and would make the description of the results more opaque.

References:

R. Philipona, A. Kräuchi, G. Romanens, G. Levrat, P. Ruppert, D. Ruffieux, B. Calpini : Upper-air radiosonde intercomparisons and uncertainty estimation, WMO technical conference on mtetorological and environmental instruments andmethods of observation, Saint Petersburg, Russian Federation, 07-09 July 2014, **(**http://www.wmo.int/pages/prog/www/IMOP/publications/IOM-116_TECO-2014/Programme_TECO-2014.html).

Haefele A., and Ruffieux, D.: Validation of a 1290 MHz windprofiler using radiosonde GPS wind measurements, Meteorological Applications, submitted, 2014.