Dear Augustin Colette,

On July 31 and August 28, 2014, we received the comments from two anonymous referees on our submission (#GMD-2014-51) titled as “On the Computation of Planetary Boundary Layer Height using the Bulk Richardson Number Method”. The two reviewers both gave very valuable advice and comments. We also made all necessary changes in order to address the reviewers’ concerns and have detailed how the points raised by the reviewers have been accommodated. From the changes made in the revised manuscript and the responses provided by us, we hope you are convinced that we have adequately addressed the reviewers’ concerns and made the paper stronger. I confirm that all authors listed on the manuscript concur with submission in its revised form. Should you have any questions, please feel free to let me know. Thank you very much for your efforts in evaluating our submission.

Response to comments by Anonymous Referee #1

We are very thankful to the reviewer for his/her valuable advice and comments, which helped us improve the manuscript significantly. We have addressed these comments and revised the manuscript accordingly. The detailed responses to the queries are below:

Major comments

1. *Page 4051, lines 7-9: This part is unclear: if the radiosondes are at15 minutes past the hour then the sounding during the next hour can always be used. So not sure what the authors mean by these lines.*

   Response: The radiosondes are not available for every hour. As mentioned in the manuscript, “during the experiment, radiosondes were released 2-4 times a day (around 05:15, 11:15, 17:15, and 23:15 LST).”As such, if the radiosondes are at 15 minutes past this hour, it is likely that there is no radiosonde data during the next hour. These lines (Page 4051, lines 7-9) have been modified to be:

   “**To ensure accuracy, only soundings released within 15 minutes around the hour were used in this study, yielding a total of 168 records.**”

2. *Equation 2, second line: I see that the condition on the second gradient is taken from a reference but the authors should elaborate on the physical rationale of such condition since it seems rather ad-hoc.*

   Response: The elaboration of the second gradient is added in page 4052, line 18, as follows:

"**For Type I SBL, PTG decreases with height and the inversion near the surface is relatively strong. There is always a sudden decrease of PTG at the PBL top (Fig. 1a1). As such, the derivative of PTG with respect to *z* should be negative, that is,** $d^2\theta / dz^2 < 0$**. For Type II SBL, PTG increases with height and the inversion is relatively weak. No sudden change of PTG at the PBL top is seen (Fig. 1a2) and thus** $d^2\theta / dz^2 \geq 0$**.**"

3. *Page 4052, lines 16-18: The selection of the value of* δ *seems rather arbitrary and seems due more to measurement accuracy. Also according to this picture there is an abrupt transition when H goes from -1 to 1 from a stable to an unstable PBL, but physically it is unclear if that actually happens. In a modeling framework, that would suddenly alter the height of the PBL by potentially hundreds of meters as the Ri_cr is switched from the SBL to UBL in the proposal model at* $H \approx 0$*.*

Response: We agree with the reviewer that the value of δ is specified through trial and error, which depends on measurement accuracy as well as surface properties. We have tested many different δ values from 0.1 to 10, and the most reasonable values based on the observations are used in this paper. According to the equation 2, a boundary layer is classified as an UBL when $H \geq \delta$ and a SBL when $H < \delta$. As such, when $\delta = 1$ as adopted in our study over land, cases with -1<H<1 (i.e., near-neutral conditions) is actually considered to be SBLs.

The reason that δ is specified as a small positive number instead of zero is to allow for near-neutral conditions to be handled by the methods for SBLs. Since under near-neutral conditions, stable stratification usually prevails above the boundary layer and wind shear is the only source of turbulence. Both of these features are similar to those of a stable boundary layer, and as a result, the near-neutral cases are treated as the SBL cases (Serbert et al., 2000), to be exact, Type II SBL cases, as mentioned in page 4055, line 21-22.

We again agree with the reviewer that indeed there is possibly an abrupt change of Ri_{bc} between 0.30 (type II SBL) and 0.39 (UBL) when H crosses the threshold $\delta = 1$. However, we note that such change of Ri_{bc} has little effect on the PBL height determination, because under near neutral condition the Ri_b increases drastically with height at the PBL top, and using 0.30 or 0.39 as Ri_{bc} only changes the PBL height by about 15 m (or 3%). Figure S1 shows the calculated boundary layer height from the LLJ method (the black arrow) and the bulk Richardson number (the green and purple arrows) with Ri_{bc} = 0.3 and 0.39. As can be seen, Ri_{bc} does not affect the calculated PBLH significantly.

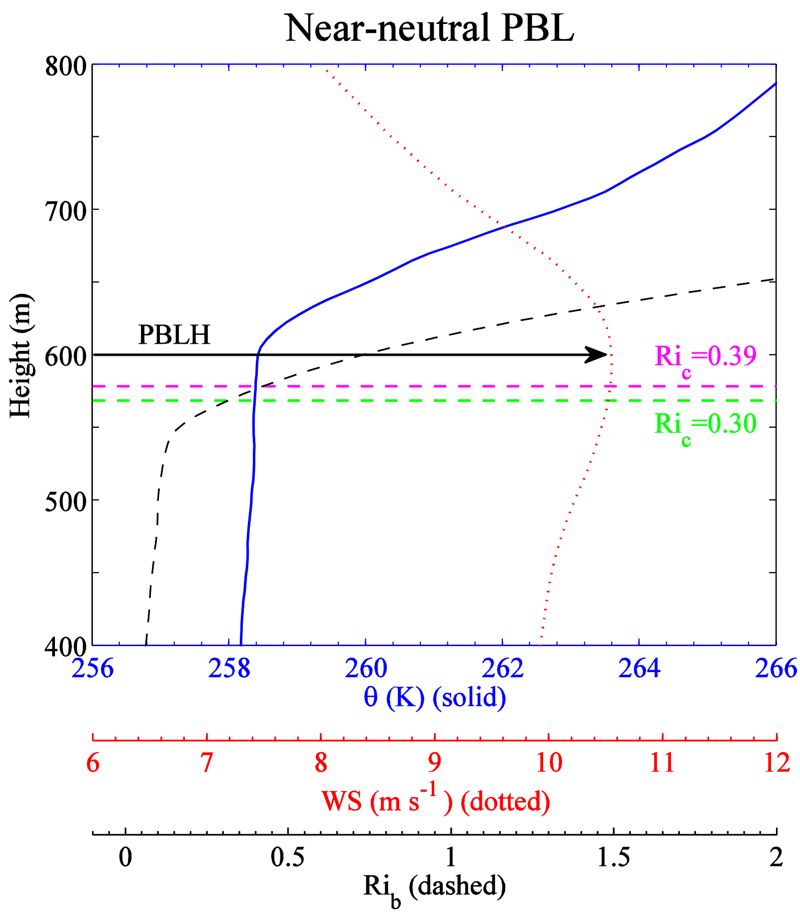

Figure S1: Typical profiles of potential temperature (blue), wind speed (red), and Ri_b (black) for a near-neutral PBL (from SHEBA on 19 October, 1997 0515 LST). The PBLH indicated by the black arrow is calculated by the LLJ methods and the PBLH indicated by the green and purple arrows are calculated by the bulk Richardson number method with Ri_{bc} = 0.30 and 0.39, respectively.

The relative discussion has been added in section 3, as following:

"**Note that cases with $-\delta < H < \delta$ (i.e., under near-neutral conditions) are typically treated as Type II SBL cases according to our classification. This is because stable stratification usually prevails above the boundary layer and wind shear is the only source of turbulence under near-neutral conditions. Both these features are similar to those of a stable boundary layer, and as a result, the near-neutral cases are treated as SBL cases (Serbert et al., 2000). It appears there might be an abrupt change in the calculation of PBLH at $H \approx \delta$ if different values of Ri_{bc} are used for SBLs and UBLs, which is the aim of this study. However, we note that changes of Ri_{bc} at $H \approx \delta$ from SBLs to UBLs have little effect on the PBL height determination, because the Ri_b increases drastically with height at the PBL top under near neutral condition and using Ri_{bc} for either SBLs or UBLs gives reasonable estimates of PBLH.**"

4. *Page 4053: line 4: what is the magnitude of the drop, particularly that the drop in*

the figure seem to be of different magnitudes? Is it automated?

Response: In the turbulence method, continuous wavelet transform is applied to the absolute magnitude of turbulent fluctuations of each velocity component. The PBLH is automatically determined to be the level at which the absolute magnitude of these velocity fluctuations shows the most rapid decrease with height. This is similar to the methodology as detailed in Dai et al. (2014).

It is true that the heights determined by u', v', w' are usually different, so we did a weighted average using the absolute magnitude of the reciprocal velocity fluctuations as weights.

The related discussion has been modified in section 3 (page 4053, lines3-5), as follows:

"**In the turbulence method, continuous wavelet transform is applied to the absolute magnitude of turbulent fluctuations of each velocity component. The PBLH is automatically determined to be the level at which the absolute magnitude of these velocity fluctuations shows the most rapid decrease with height (Dai et al., 2011; 2014). The PBLHs determined by u', v', w' are then averaged using the absolute magnitude of the reciprocal velocity fluctuations as weights.**"

References:

Dai, C., Wang, Q., Kalogiros, J. A., Lenschow, D. H., Gao, Z, and Zhou, M.: Determining boundary-layer height from aircraft measurements, Bound.-Lay. Meteorol., 152, 277-302, doi:10.1007/s10546-014-9929-z, 2014.

5. *Page 4054, line 20: defining the lowest level as the PBLH seems ad-hoc and may be these periods should instead not be used.*

Response: Following the suggestion of the reviewer, we have removed these cases in the latest results. Since the number of these removed cases is small and the PBLHs of these cases are also small, removing these cases has little impact on the error analysis and there is no visible change in the results of Ri_{bc}.

The related figures have been modified, and page 4054, line 20-21 has been modified as follows:

"…**if there is a LLJ, the case is reclassified to a Type II SBL; if not, the case is removed.**"

6. *Page 4059, last line: The absolute bias the authors use should in fact be able to reflect the dispersion since negative and positive errors would not cancel out as with the regular bias (by the way this should be called absolute bias rather than bias). So the first part of the line should be removed.*

Response: This suggestion is adopted. "…because the bias cannot reflect the dispersion of data" in page 4059, last line has been removed. In page 4059, line 12-13 has been modified, as follows:

"**Bias, SEE, and NSEE is the absolute bias, standard error, and normalized standard error of h_{Rib} against h_{obs}, respectively ...**"

7. *It seems the model performance is in general sensitive to zs, so why not optimize for the value of z_s also?*

   Response: Thanks for the constructive suggestion. We indeed tested many values of z_s, as can be seen from Figure 9 and 10 and Table 1. It is found that the model performance is not significantly sensitive to z_s in the stable boundary layer. In Figure 9, we can see the errors for z_s = 40 m and 80 m are close, especially for ARM with a large number of samples. In Figure 8, the better performance for z_s = 40 m than z_s = 80 m is mainly due to that the sample size for z_s = 40 m is much larger. However, the model performance is indeed sensitive to z_s in unstable boundary layer. We did many different tests with z_s as 40 m, 80 m, 120 m, 160 m, 0.1 PBLH, and z_{SAL} (the level of the first minimum potential temperature from surface). As shown in Figure 10, we found $z_s = z_{SAL}$ was optimal among these tests, and the impact of z_s on Ri_{bc} was also not significant as compared to the impact of thermal stratification on Ri_{bc}. The optimal Ri_{bc} with the total sample are close for different z_s, as shown in Table 1.

Minor comments:

1. *Page 4048, lines 1-2: The statement is very generic and I do not recall seeing it in Stull stated in that way. For example, when the turbulence diminished to what? It should be revised.*

   Response: Page 4048, line 1-2 has been revised, as follows:

   "**The PBL is characterized by the presence of continuous turbulence, while turbulence is lacking or sporadic above the PBL. Therefore, the PBLH can be viewed as the level where continuous turbulence stops (Wang et al, 1999; Seibert et al., 2000).**"

2. *Page 4048, lines 13: in the SBL the buoyancy force can be positive or negative, depending on whether the parcel is displaced upwards or downwards from its equilibrium position, so please remove the word "negative" (it is the buoyancy TKE term that is on average negative in the SBL).*

   Response: The word "negative" has been removed.

3. *Page 4049, line 26: delete "there is even" or fix the next line to be grammatically correct.*

   Response: "there is even" has been removed.

4. *Page 4051, line 8: add "a" before "time"*

   Response: Revised.

5. *Page 4052, line 19: replace "noises" by "variability"*

   Response: Revised

6. *Page 4054, line 20: replace "classified" by "reclassified"*

   Response: Revised

7. *Page 4056, line 18: replace "replaced by" by "estimated as the"*

   Response: Revised

8. *Figure 10,11 and related figures: It would be good if the authors can homogenize they-scales and make them similar for a given metric*

   Response: Figure 8-11 have been revised.

9. *The legend of Figure 11 seems wrong. For example it is unclear which part of the figures or lines correspond to the SBLs and UBLs mentioned in the caption.*

   Response: For this part, we gathered all types of soundings instead of distinguishing them. Our goal was to get an optimal Ri_{bc} for all types of soundings by error analysis. So in this figure the comparison between estimation and observation did not distinguish boundary layer type.

   The caption of Figure 11 has been modified to emphasize this, as follows:

   "**Figure 11. Comparison between estimated PBLH using the bulk Richardson number method and observed PBLHs for all types of PBLs. The correlation coefficient (a), bias (b), standard error (c), and normalized standard error (d) are shown. The sounding data are taken from Litang (plus sign), ARM Shouxian (diamond), and SHEBA (pentacle). The curved lines are obtained by quadratic curve-fitting, the black vertical dashed lines indicate a representative Ri_{bc} for all three sites, and the error bars indicate the range of Ri_{bc} across the three sites.**"

Response to comments by Anonymous Referee #2

We are very thankful to the reviewer for his/her valuable advice and comments, which helped us improve the manuscript significantly. We have addressed these comments and revised the manuscript accordingly. The detailed responses to the queries are below.

1. *Although, as far as I know, some of the data used here have never been used for this purpose, the manuscript lacks the necessary consideration of related work (although cited) that face the same problem in a rather similar and, possibly, more accurate way. Richardson et al. (2013) suggest a "continuous" relationship (as opposite to the one proposed here, which is based on very broad classes) and Basu et al. (2014) refine the coefficient also using one the experiment considered here. Authors must account for those papers, and discuss their results accordingly.*

Response: We thank the reviewer for his/her constructive suggestions. Richardson et al. (2013) did propose a stability-dependent relationship for Ri_{bc}. However, their "continuous" relationship is only applicable to stable boundary layers. Their equation $Ri_{bc} = \alpha \frac{h}{L}$ implies that $L < 0$ (unstable) cannot be used since Ri_{bc} should be positive in the bulk Richardson number method. This is also clearly stated in their papers, as follows:

"We only focused on (non-intermittent) stably stratified flows" (Richardson et al., 2013) and

"Data points with L > 500 m (near-neutral condition) and $L < L_{min}$ (very stable conditions) are not included" (Basu et al., 2014).

As a result, our study examines a wider range of atmospheric thermal stratification conditions as compared to Richardson et al. (2013) and Basu et al., (2014).

Following the reviewer's suggestion, we have added the discussion of Richardson et al. (2013) method in section 4 and Fig. 1 has been revised:

"**After Ri_b is computed from Eqs. (3-6), the PBLH can be determined as the height where the Ri_b exceeds Ri_{bc}. In our study, instead of calculating the PBLH using a prescribed Ri_{bc}, we infer a representative Ri_{bc} for each type of PBLs using the 'observed' PBLH (see Section 3) and examine the variation of the inferred**

***Ri*$_{bc}$ with thermal stratification. It is pointed out here that our methodology is different from that of Richardson et al. (2013), who proposed a stability-dependent *Ri*$_{bc}$ for SBLs:**

$$\mathrm{Ri}_{bc} = \alpha \frac{PBLH}{L} \tag{7}$$

where $PBLH/L$ is a bulk stability parameter, *L* is the surface Obukhov length, α is a proportionality constant, which depends on surface characteristics and/or atmospheric conditions. It varies between 0.03 and 0.21 with suggested values of 0.045 and 0.07 (Richardson et al., 2013; Basu et al., 2014). As shown in Fig. 1c1-c2, in the Type I SBL case, a relatively reliable PBLH (133 m) was calculated with α = 0.045, but an overestimation (184 m) occurs when α = 0.07. While in the Type II SBL case both α values (0.045 and 0.07) yield too small estimates of PBLH, because the two values are determined by idealized stably large-eddy simulation datasets (Richarsdon et al., 2013) and observational datasets under weakly and moderately stable conditions (Basu et al., 2014), respectively. In addition, Eq. (7) is only applicable for SBLs but not UBLs. As such, instead of adopting this equation, we inferred a representative *Ri*$_{bc}$ value for each type of PBLs in our study.”

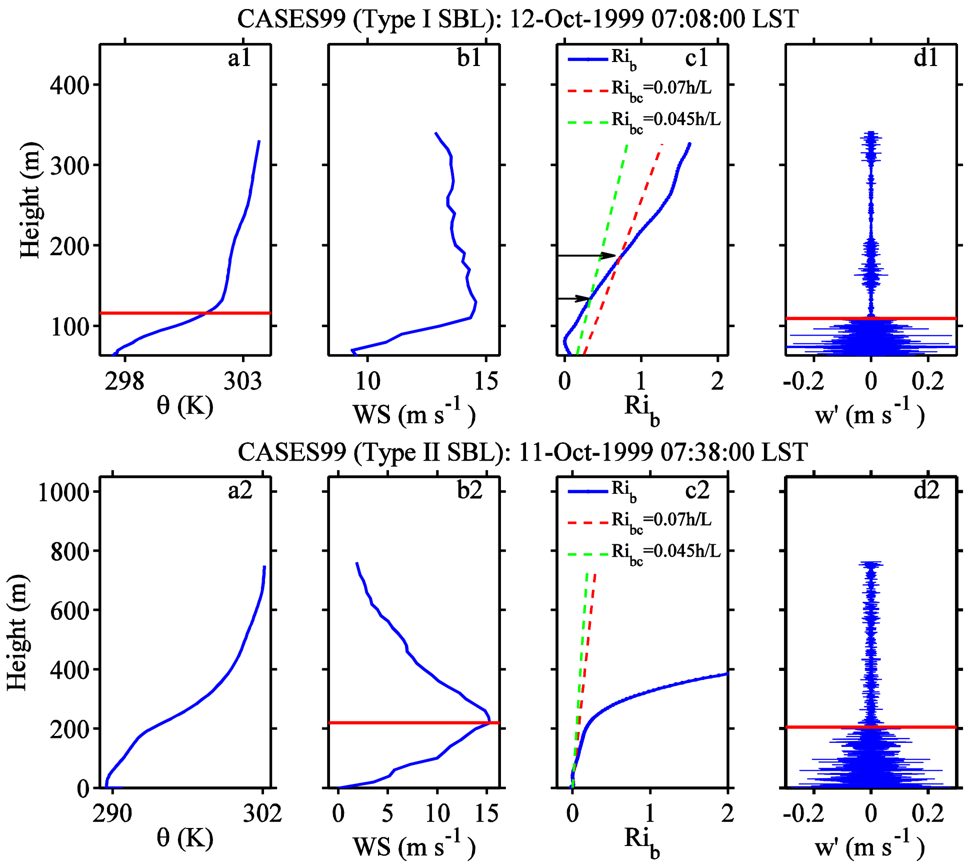

Figure 1. Examples of vertical profiles of the Type I SBL (upper panels) and the

Type II SBL (lower panels) from CASES99 aircraft measurements: (a) potential temperature (K); (b) horizontal wind speed (m s^{-1}); (c) bulk Richardson number Ri_b and Ri_{bc}; (d) *w* perturbation (m s^{-1}). The red solid lines on (a1) and (b2) denote the PBLH calculated by the PTG and LLJ methods, respectively, and those on (d) denote the PBLH determined by the Tur method. The black arrows on (c1) denote the PBLHs determined by the bulk *Ri* method with Ri_{bc} from Eq. (7).

2. *In case the authors are requested to submit a revised version of the manuscript, I strongly suggest revise carefully the language.*

Response: Thanks for the comment. We have revised the language carefully and thoroughly.

3. *It would also be very interesting to go a bit farther and show (or at least discuss) to what extent the proposed parameterization can improve model results in real applications.*

Response: Following the reviewer's suggestion, we also added a few discussion about real applications of the new Ri_{bc} values in the end of section 4.3, as follows:

"**To further investigate the improvements in estimating PBLHs with the new, variable Ri_{bc} values, simulations using CAM4 are conducted at the ARM site, with the default (= 0.3) and the new, variable Ri_{bc} values used to estimate PBLHs. Fig. 13 shows a comparison between the observed and the CAM4-simulated PBLHs with the default and new Ri_{bc} values over a six-day period. It can be seen that the simulated PBLHs with the new Ri_{bc} values have a more pronounced diurnal cycle, which are also closer to the observations. Over the whole observational period, results indicate that the Bias, SEE, NSEE are 270.1 m, 379.3 m, 0.75 with the new, variable Ri_{bc} values, respectively, and are 306.2 m, 417.5 m, 0.83 with the default Ri_{bc} value, respectively. Again, these results indicate that the impacts of thermal stratification on Ri_{bc} should be considered in calculating PBLH with the bulk Richardson number method and the new Ri_{bc} values determined in this study improves model results in real applications. It is pointed out here that there are still large biases in the CAM4-simulated PBLH even with the new Ri_{bc} values, which are probably related to the biases in the model physics and parameterizations (e.g., parameterizations of land-atmospheric interactions and boundary layer turbulence). Unraveling how biases in these model physics and parameterizations affect the PBLH is nevertheless out of the scope of this study.**"

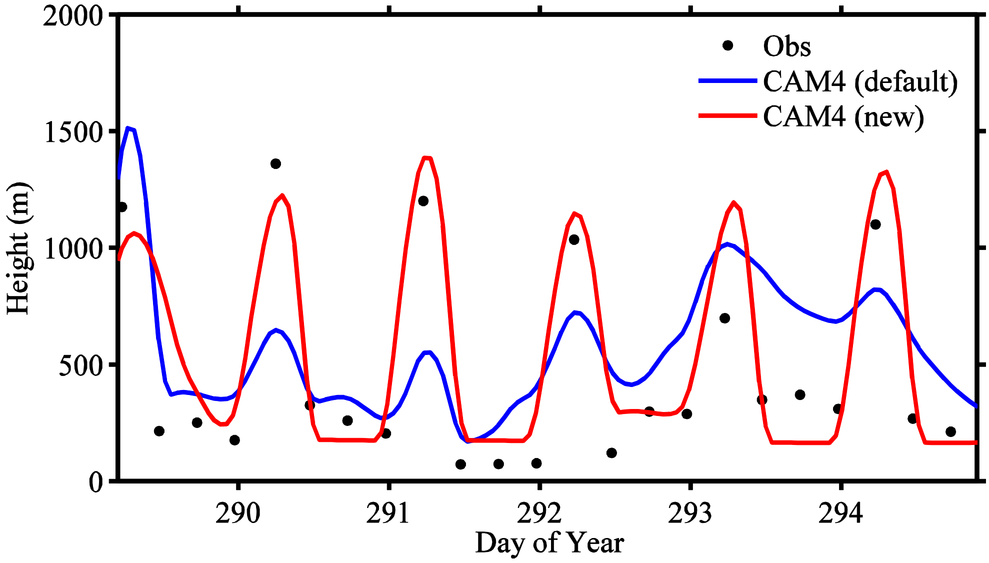

Figure 13. Comparison of observed and simulated PBLHs using CAM4 with the default and new Ri_{bc} values during 16-21 Oct, 2008 at the ARM site.

Minor comments:

1. *- the word "critical" referred to the Bulk Richardson number between the ground and the boundary layer height can be misleading because it does not indicate that the whole boundary layer undergoes a transition to laminar regime);*

Response: Following the reviewer's suggestion, using "the critical bulk Richardson number" is avoided in the revised manuscript since it causes confusion with 'the critical flux Richardson number' at which turbulence dies down and the flow starts to laminarize. We use "the bulk Richardson number of the entire PBL" in the revised manuscript.

2. *- it can be useful to define the range of stability parameters for the different classes (this can also help comparing to Basu et al. (2014);*

Response: Following the reviewer's suggestion, we have added Table 1 and the related discussion in the end of section 3, as following:

"**With these procedures, the obtained PBLHs by using these methods are treated as 'observed' PBLH hereafter. The observed PBLH and the bulk stability parameter (*PBLH/L*, where *L* is the surface Obukhov length) for these four field experiments are provided in Table 1.**"

Table 1. The ‘observed’ PBLH and the stability parameter at four observational sites.

PBL Types	PBLH(m)				*PBLH/L*			
	Litang	CASES99	ARM	SHEBA	Litang	CASES99	ARM	SHEBA
Type I SBL	45~265	25~157	54~593	42~414	0.12~323.0	1.5~94.2	0.22~327.2	0.4~38.3
Type II SBL (H<0)	68~543	\	131~670	97~312	0.64~74.8	\	0.36~113.1	0.1~21.3
Type II SBL (H>0)	357~678	\	152~879	138~414	-33.4~-0.32	\	-34.1~-0.2	-55.1~-0.01
UBL	315~2594	\	293~1693	121~981	-866.4~-4.3	\	-350.9~-1.3	-342~-0.03

3. *- numerical models using Richardson bulk method to estimate the PBLH are cited. It would be useful to add some details;*

Response: More discussion has been added in section 4 (Page 4055, line 8), as following:

"**…in the non-local PBL scheme of the Community Climate Model version 2 (CCM2), Eq. (1) is applied to estimate the PBLH with Ri_{bc} = 0.5. The computation starts by calculating the Ri_b between the surface and subsequent higher levels of the model. Once Rib exceeds Ri_{bc}, the PBLH is derived by a linear interpolation between the level with $Ri_b > Ri_{bc}$ and the level below.**

To avoid overestimating the shear production in Eq. (1) for relatively high wind speeds (i.e., in Type II SBL) and to account for turbulence generated by surface friction under neutral conditions, Vogelezang and Holtslag (1996) proposed an updated formulation, which is employed in the Community Atmosphere Model version 4 (CAM4), written as…"

4. *- figures presenting vertical profiles could be improved by increasing the line thickness;*

- in all of the figures, axes labels must be increased;

Response: All figures have been revised. The line width is increased and the font size of the axes labels is also increased.

5. *- as "h" is typically used for "fixed" height (e.g. boundary layer height) I suggest replacing it with "z" in equation (1).*

Response: Revised.

Best wishes.

Sincerely yours,

Zhiqiu Gao together with all authors

September 11, 2014