Reply to Reviewer 1

Anonymous Referee #1

Received and published: 24 October 2019

Precise measurements of vertical winds are an important topic with many meteorological applications. The paper by Luce and Hashiguchi deals with the calculation of vertical winds from radiosonde ascent rate measurements. Recently, different publications described new methods to separate the different parameters influencing the ascent rate, like vertical winds, drag coefficient of the balloon and other effects. Nevertheless, direct comparisons of retrieved vertical winds with independent observations are rare. In the first part of their paper, Luce and Hashiguchi make use of collocated UAV measurements of atmospheric turbulence and vertical wind measurements by radar. This analysis is limited to altitudes below 7 km because the drift of the balloon and local inhomogeneities make further comparisons arbitrary. In the second part, they make a statistical analysis of a series of 376 radiosondes, confirming their results that the stability of the atmosphere influences the ascent rate of the balloon. In their main conclusion, the authors state that in a turbulent atmosphere the vertical winds can hardly be calculated without detailed knowledge of turbulence parameters. On the other hand, the ascent rate profile can be used to identify turbulence in the atmosphere. The paper is generally well written and concise. The arguments are described comprehensively and clearly. In the following, I describe only some minor comments that should be clarified before publication.

We thank the reviewer for his/her positive comments.

Minor comments:

ll. 82-83: I do not see the results of Gallice et al. (2011) limited to Tu=4%. The main "problem" is that they do not account for inhomogeneities in the turbulence field.

The statement is indeed wrong and has been suppressed in the revised version. We apologize for this erroneous interpretation. The experimental drag curves described by Gallice et al. (2011) "present a qualitative shape similar to the curves by Son et al. (2010) at *Tu=6%* and *Tu=8%*." (incidentally, not 4% as stated). They further indicated that their drag curves suggest a turbulence intensity (Tu) of the atmosphere of the order of 6% to 8 % (page 2241). This statement indicates that inhomogeneities in the turbulent field were not considered.

Lines 82-83 have been corrected as follows:

"Their drag curve presented qualitative similarities with the curves by Son et al. (2010) for a mean turbulent state of the atmosphere at Tu=6 % and Tu=8%. The fact that the model proposed by Gallice et al. does not consider the variability of turbulence with height is likely a weak point because turbulence is generally confined into layers of variable depth in the troposphere and the stratosphere."

The corresponding sentence, line 274, has been shortened. "This feature was likely not well appreciated by Gallice et al. (2011) who considered a mean value of turbulent intensity over the whole atmosphere for establishing a model of c_D." -> "This feature was likely not well appreciated by Gallice et al. (2011)."

Incidentally, in section 2.1, time sampling was $\Delta t = 2\ s$ and not 1 s as wrongly stated and a 20-sec rectangular window has been used for smoothing (not 10 sec). It is now corrected.

ll. 174-175: The agreement between V_Bc and W is expected from the calculation of V_z from the difference of W and V_B, and the definition of V_Bc. Is the calculation of V_z done in a different altitude than the V_Bc / W comparison?

No, it isn't. We agree that the estimation of V_z is not fully reliable because it is simply based on segments in the V_B profiles for which energy dissipation rates are low and Richardson numbers are high (i.e. "minimum of turbulence"). For these segments, it is assumed that the free lift and vertical air motions are the dominant contributions to V_B.

l. 179: I am sorry, but I cannot identify the oscillations from below 3.8 km in the MCT layer above 3.8 km. Looking at the dashed lines the higher frequencies seem to dominate. Please explain.

We agree that it is not as clear as in Figure 7 where fluctuations produced by a MCT layer were stronger. We simply removed this description because it does not provide any substantial information.

l. 235: Please explain in short, why <V_B>_ST is not exactly the ascent rate in still air in the stratosphere.

The calculation was made by including *all* balloon data above 17.2 km assuming that the balloons were not at all affected by turbulence. This hypothesis cannot be true and, on some occasions, we were able to identify positive disturbances of vertical ascent rates that may result from turbulence effects. Therefore, the mean ascent rate in still air estimated from data above 17.2 km should be slightly overestimated. This overestimation produces the negative centered values for tropospheric data, below 16.3 km (Figure 9c).

ll. 267-270: Houchi et al. (2014) state in Section 6 a) that turbulence should broaden the ascent rate profile but not induce a tendency to purely higher ascent rates. Here, mainly the influence of turbulence on the drag coefficient is emphasized, yielding a higher ascent rate but not a broadening of the distribution. This seeming contradiction may be a question of the scales of turbulence cells. I suggest adding a clarifying sentence.

Yes, we agree. The broadening of the distribution was indeed attributed to turbulence by Houchi et al. (2015, p. 1810). It is possible that turbulence does not only produce aerodynamic effects but also advection effects due to billows of scales much larger than the balloon diameter. These effects should be similar to those produced by Kelvin-Helmholtz waves at early stages of the shear flow instabilities. Figures 9 and 10 do not only show an increase of ascent rates when Ri $\lesssim$0.25, but also a broadening of the ascent rate distribution, consistent with both effects occurring at the same time.

Figure 10b has been removed (because not useful).

Around lines 267-270, the text has been corrected as follows:

Figures 10 show $V_{Bc} - < V_{Bc} >$ vs Ri for the troposphere. A larger scatter is observed between $Ri=0$ and $Ri_c = 0.25$. The broadening of the scatter, as noted by Houchi et al. (2015), cannot be explained by the decrease of the drag coefficient and is necessarily due to both positive and negative vertical velocities. It is thus more likely due to turbulent billows of scales much larger than the balloon size. In addition, Kelvin-Helmholtz (KH) waves can also produce updrafts and downdrafts up to a few ms^{-1} when Ri reaches Ri_c (see, e.g. Fukao et al., 2011). Therefore, the enhanced variability of V_{Bc} when Ri is small (Fig. 9a) is presumably the combination of turbulence effects and vertical air motion disturbances produced by large scale billows and KH waves.

The following sentence (243-245):

"Assuming that the mean curve shown in Fig. 9c is statistically representative of the turbulence effects, then the scatter plot shown in Fig. 10a should also be statistically representative of W fluctuations produced by shear flow instabilities if other sources of vertical air motions are negligible."

has been removed, because it was misleading. The scatter plot in Fig. 10a (now Fig. 10) still contains a contribution from turbulence effects.

Fig. 8: Please provide a scaling for the ascent rate and the offset.

Technical comments and typos:

Done. Please note that half of the profiles were missing. They are now shown in the corrected figure.

We thank the reviewer for his technical comments and typos. The errors have been corrected.

Reply to Reviewer 2, Prof. J. McHugh

John McHugh (Referee)

john.mchugh@unh.edu

Received and published: 14 November 2019

The authors have measured the ascent rate of weather balloons, along with corresponding radar and other measurements. They point out that when atmospheric turbulence is present, the drag coefficient of the ascending balloon is reduced, and the ascent rate increases as a result. They argue that this effect is stronger that other effects, and therefore these fluctuations in ascent rate actually indicate the strength of turbulence, except in the case where turbulence is very weak. For the three case studies that they discuss, I found their arguments plausible.

They also suggest that the same arguments explain previous results, in particular the experiments by McHugh, et al (JGR, 2008), which showed an increase in ascent rate near the tropopause over Hawaii. Thus they suggest that these increases in ascent rate over Hawaii are really due to turbulence rather than a local increase in vertical velocity. However I am unconvinced that turbulence really can explain the previous results of McHugh et al. The results here show a change an ascent rate on the order of 1 m/s, but McHugh et al found an increase that was at times more than 7 m/s, meaning the balloon ascended more than twice as fast for a short distance. I am unconvinced that turbulence can cause this large of an increase. Most of this increase I think is indeed due to an increase in vertical velocity. The authors arguments don't really contradict this, as their own data only shows small increases. However I am now convinced that the large increases in ascent rate were partially due to turbulence, and thus the increase in ascent rate is overpredicting the local velocity.

I think the paper is publishable with minor revision. The revisions should include rewording the discussion of McHugh et al results with some comments about the size of the change in ascent rate.

We deeply thank Prof. McHugh for his comments. His main recommendation is to revise the discussion we proposed about the interpretation of the strong localized increases in balloon ascent rates around tropopause over Hawaii reported by McHugh et al. (2008). Our study convinced him that turbulence may have contributed to these increases but still less than upward air velocity produced by mountain waves around their critical levels.

McHugh et al.'s interpretation in terms of gravity wave effects was made plausible owing to comparisons with a mesoscale model providing evidence of mountain waves in the conditions met by the balloons. We agree that interpreting McHugh et al.'s observations in terms of turbulence effects only may be speculative but we believe that it is not unrealistic. We discuss more thoroughly this hypothesis from additional materials and examples shown below.

The discussion about McHugh et al. results (lines 261-267) has been rewritten as follows:

"McHugh et al. (2008) interpreted isolated peaks of V_B of several ms^{-1} of amplitude near the tropopause and at the jet-stream level in terms of W disturbances around critical levels associated

with mountain waves. The absence of corresponding negative disturbances was explained by the three-dimensional nature of the flow. Even though our hypothesis remains speculative in absence of additional and independent measurements of vertical air velocity, we suggest that turbulence effects may have also contributed to the observed increase in ascent rates since critical levels are generally associated with turbulence. A careful scrutiny of their figures 3-7 indicates that V_B increased at altitudes where the horizontal wind shear was enhanced and temperature gradient was close to adiabatic (so that Ri was likely small)."

It must be noted that, even if mountain activity was highlighted by McHugh et al. during the balloon flights, the vertical wind disturbances produced by the model (up to +/- 0.2 m/s, their Figures 8b and 9) were much smaller than the maximum values of ascent rate increases (a few m/s). Therefore, as noted by the authors themselves (page 8), the model did not confirm such large updrafts. In absence of independent measurements confirming or not the presence strong updrafts produced by waves, we cannot deal with the issue. However, as partly stated in the manuscript, the main arguments in favor of turbulence are:

1) all the "narrow" maxima in ascent rates (Figure 3-6 of McHugh et al.) seem to be associated with horizontal wind shears (speed and/or direction shears) and nearly adiabatic lapse rates, so that the Richardson number may be small enough for shear-generated turbulence. It would be consistent with our observations. Because this assertion is based on a simple and inaccurate visual inspection of the figures, calculating Ri profiles for the cases shown in Figures 3-6 would be useful for a possible confirmation.
2) The absence of decrease in ascent rate is consistent with a reduction of the drag coefficient due to turbulence effects. Strong three-dimensional mountain wave effects were suggested by the authors in order to overcome the absence of negative disturbances.
3) Prof. McHugh noted that the changes in ascent rate reported in our manuscript were ~1 m/s (section 3 and section 4, statistics) but McHugh et al. observed increases up to 7 m/s, suggesting that turbulence effects alone cannot explain the phenomenon[1].
   a) The value of ~1 m/s is approximately the mean value obtained from statistics (Figure 9c). It means that it can be larger on many occasions. The distribution (scatter) obtained after removing the mean value is positively skewed (especially around Ri~0.25, Figure 10), possibly indicating a remaining contribution from turbulence effects.
   b) According to Figures 1, 2 and 3 of Gallice et al. (2011), the drag coefficient c_D strongly varies with the Reynolds number up to a factor ~ 4 in the range $10^{-6} - 10^{-5}$ for both idealized and experimental conditions [the drag crisis being inexistent for the experimental curves]. Then, based on these results and because $V_z \sim c_D^{-1/2}$(expression 3 of Gallice et al.), an increase in the ascent rate by a factor up to ~2 can be predicted if *Re* strongly and quickly varies. For a standard ascent rate of 5 m/s in still air, a maximum increase of ~5 m/s is then theoretically possible. In our manuscript (section 3), we reported balloon measurements with slow ascent rates in still air (~2 m/s) because we used underinflated balloons. Therefore, ascent rate increases cannot theoretically exceed ~2 m/s. We reported ~1-1.5 m/s in Figures 5 and 6 (V_z in still air was ≈1.8 m/s) and ~2 m/s in Figure 7 ($V_z \approx 2.3$ m/s). As a result, the differences between the changes in ascent rates reported in section 3 and

[1] These values may depend on the method used for their estimations. Disturbances of ~1-2 m/s and ~ 3-5 m/s with respect to a "slowly varying background" can be estimated from Figures 5-7 of our manuscript, and Figures 3-6 of McHugh et al., respectively.

in McHugh et al. can be primary due to the different ascent rates of the balloons in still air (~2 m/s and ~6 m/s[2] in our manuscript and in McHugh et al., respectively).

4) In section 4 of our manuscript, we showed scatter plots made from a large amount of balloon data from pre-YMC campaign without focusing on individual cases. In addition, Figure 8 was not clear enough for evaluating the changes in ascent rates[3]. The balloons were inflated for a standard ascent rate of 5 m/s in still air, comparable to the conditions described by McHugh et al.

Figure 1 below shows 8 consecutive profiles of balloon ascent rates V_B acquired on 19 December 2015, every 3 hours from 00:00LT above the altitude of 10 km[4] and shifted by $(n-1)*5\,m/s$ where n is the flight number. For easy reference, a profile of V_B shown by McHugh et al. (Figure 3) is superimposed to the profile at 06:00 LT (dashed blue line). Multiple fingers of strongly enhanced V_B values can be seen below the cold point tropopause CPT (blue dots). The enhancements are typically ~2-4.5 m/s and are thus now similar in amplitude to those reported by McHugh et al. The peaks of V_B are very often associated with Richardson numbers below the critical value (altitude ranges where Ri <0.25 are indicated by the red segments). Therefore, we feel that turbulence may produce ascent rate increases similar to those reported by McHugh et al. around the tropopause but we also agree that these observations are not sufficient for concluding that these increases are due to turbulence effects only.

We have additional arguments suggesting that the ascent rate increases shown in Figure 1 are mainly due to turbulence effects and are not the signature of updrafts produced by gravity waves. Except maybe at 12:00 LT, V_B was systematically enhanced between CPT and a secondary strong temperature inversion below (indicated by red dots). This systematic increase is recognizable in the mean profile of V_B in the height range 15-16 km (thick solid line on the right side of the figure). During the campaign, the 47 MHz Stratosphere-Troposphere (ST) Equatorial Atmosphere Radar (EAR) was operating at Kototabang (Indonesia), located about 450 km North-West from the balloon launching site (Bengkulu). EAR provides similar information as MU radar with a time resolution of about 3 min and a range resolution of 150 m. Time and range resolutions of ST radars are very well adapted for studying horizontal and vertical wind disturbances produced by mountain waves (e.g. Röttger, *ST radar observations of atmospheric waves over mountainous areas: a review*, Ann. Geophys, 18, 750-756, 2000) and internal gravity waves in general. Therefore, strong gravity wave disturbances as those suggested by McHugh et al. can be detected by EAR and the interpretation of the increase of V_b in terms of vertical air motions produced by waves can be tested.

Figure 2 shows time-height cross-sections of Signal to Noise Ratio SNR (dB), Doppler variance $\sigma^2\,(m^2/s^2)$ and vertical air velocity W (m/s) obtained from the vertical beam for 10 consecutive days (15-24 December 2015) in the height range 13-20 km (at time and range resolutions of 3 min and 150 m, respectively). A very persistent layer of turbulence was observed around the tropopause, between the two temperature inversions (blue and red dots) as indicated by the morphology of the SNR pattern (top panel) and, more importantly, by the persistent enhancement of Doppler variance, signature of dynamic turbulence (middle panel). The remarkable persistence of this turbulent layer (more than 10 days) and the presence of the two temperature inversions

[2] According to Figures 3-7, it seems to be larger than 5 m/s if we assume that the background (minimum) velocity is mainly due to the free lift.

[3] The figure will be corrected. In addition, the submitted figure showed half of the total balloon profiles only (by mistake)

[4] see Figure A1 (response to Prof. Drager) for the full profiles.

on both sides measured from balloons launched 450 km away from the radar site suggests that turbulence was produced over a very large horizontal extent and was observed at both locations. The average profile of Doppler variance $< \sigma^2 >$(green curve, right side of Figure 1) shows a peak at the exact location of the persistent increase in V_B (15-16 km). It is thus an additional clue of the turbulent origin of the increase of V_B. In addition, the measurements of W (bottom panel of Figure 2) do not exhibit values larger than +/-0.5 m/s; the profile of W averaged over 1 day on 19 December (thick blue line, $\langle W_{EAR} \rangle$, right side of Fig.1) is associated with small standard deviations (thin horizontal blue lines) *indicating a weak wave activity*. Thus, the large increases in V_B of a few m/s around the tropopause may not be attributed to waves.

These conclusions apply to the present data set and do not necessarily fit McHugh et al.'s observations but we believe that turbulence effects only may be enough for interpreting most part of the ascent increases reported by McHugh et al. It is an alternative interpretation, not a decisive conclusion refuting wave disturbances in the conditions described by the authors.

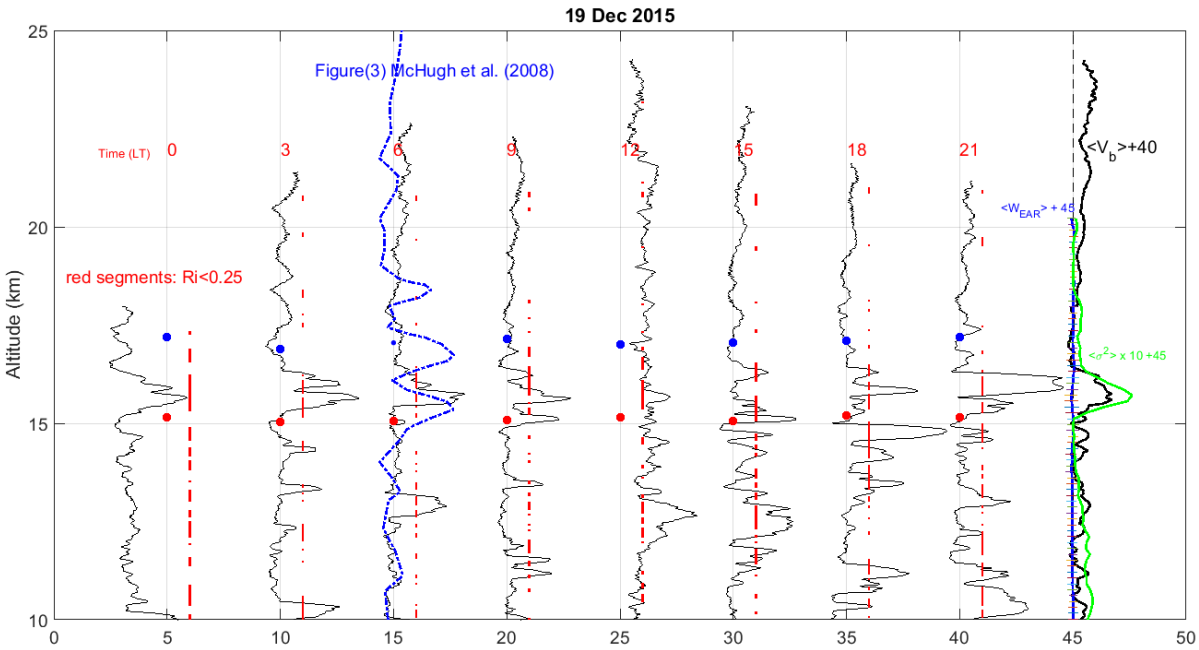

Figure 1. A series of 8 consecutive profiles of V_B obtained on 19 December 2019 at Bengkulu (Indonesia). (See text for more details).

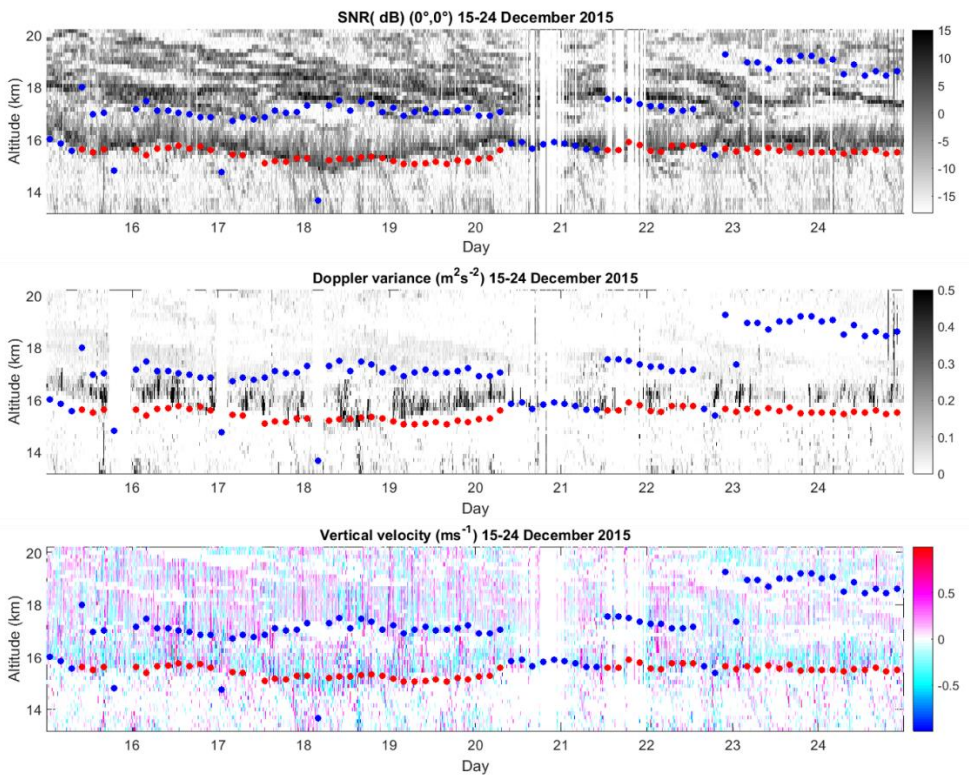

Figure 2: Equatorial Atmosphere Radar measurements of SNR at vertical incidence (top), Doppler variance (center) and vertical velocity (bottom)

1. In figure 8, I can clearly see the difference in structure between the troposphere and stratosphere in the profiles of V_B, but it is not clear to me that the difference is simply waves versus turbulence, as is suggested. I think that waves are still important in the troposphere.

Yes, we agree, but the balloon ascent rate should be the result of multiple contributions of variable intensities (wave, convection, and turbulence effects).

2. Figure 9, the 'peak' is quite broad and difficult to align with the critical R_i of 0.25 for stability. Is the breadth of this feature due to experimental error, or is the concept not quite right?

We believe that there are several factors that make the smooth transition around $Ri = 0.25$. Without being exhaustive, the dominant factors should be:

1) The Richardson number is a scale-dependent parameter, i.e. it depends on the vertical resolution of temperature and wind profiles. A coarser resolution leads to even smoother distribution.
2) $Ri < 1/4$ is a necessary condition for active turbulence, but turbulence can be sustained up to $Ri = 1$ (thus turbulence effects can be felt even for $Ri > 0.25$).
3) The Richardson number is defined as N_m^2/S^2 where S is the wind shear and N_m^2 is the square of the moist BV frequency, when air is saturated. Contrary to N^2 from dry air, there are various expressions of N_m^2 based on different models and hypotheses on hydrometeor effects. In particular, the Kirschaum and Durran (1994) model used in the present work does not consider the presence of condensed particles but should be more relevant than the BV frequency

calculated from the equivalent potential temperature. Therefore, slight biases on N_m^2 , and thus, on Ri can be expected.

Additional data quality controls (other than made by manufacturer) have not been applied to the data for this statistical analysis. Even if the balloon launches have been performed in accordance with the manufacturer's recommendations, contaminations by balloon wake, especially when wind shear is weak, cannot be excluded. In addition, unwinder problems are not uncommon: the rope length between the balloon and payload may be smaller than the recommended length (30 m) for some flights. This problem increases the risk of wake contaminations and introduces uncertainty in wind shear altitude. These effects may contribute to incorrect estimations of Ri.

3. On page 8, '...in R_i value bands of 0.25 in width' is not an adequate description of analysis that results in figure 9c,d. What was done exactly to the data to get

[this figure ?]

'averaged values of V_{Bc} in *Ri* value bands of 0.25 in width' has been replaced by:

'mean values of V_{Bc} averaged over *Ri* segments of 0.25 in width from *Ri=-2* to *Ri=9.75'*

4. Why is Figure 10 rotated by 90 degrees when compared to figure 9?

Figure 10 is now plotted ad Figure 9 and Figure 10b has been removed (because not informative)

5. Figures 5,6, and 7 I found to be a bit too messy, with different panels not separated by any space. It was hard to tell where one panel ended and the other began.

Thick vertical lines have been added for legibility of the figures. The legends have also been removed for clarity and a description of the curves has been added in the figure captions.

Reply to Prof. A. Drager and Prof. P. Marinescu

Reply to: Comment by Aryeh Drager (Colorado State University, aryeh.drager@colostate.edu) with contributions from Peter Marinescu (Colorado State University, peter.marinescu@colostate.edu)

We thank Prof. Drager and Prof. Marinescu for their interest to the present work and for carefully reading our manuscript. We think that our main conclusion is not very different from their point of view. There is a general agreement, based on the analysis described in section 3, that balloon ascent rates can increase due to the decrease of the balloon drag coefficient by turbulence. We somewhat differ on the strength of this effect. In particular, they suggest that the statistics shown in section 4 are not dominated by turbulence but by deep convection (i.e. the positive disturbances in ascent rates for low Richardson numbers are mainly the signature of vertical updrafts in convective cells). Without providing irrefutable evidence, we propose here additional clues and arguments suggesting that turbulence effects may rather be dominant in most cases. We hope that this information will open further discussions and investigations.

Summary:

This manuscript adds to a growing body of literature on the retrieval of vertical air velocity using balloon-borne, GPS-equipped radiosonde ascent rates. One unique aspect of this study is that it attempts to provide a robust independent validation of the radiosonde-derived vertical air velocity in the form of radar-derived vertical velocity from a vertically pointing middle and upper (MU) atmosphere radar. The focus of this study, however, is the effect of atmospheric turbulence on ascent rates. Atmospheric turbulence is assessed using both the MU radar and Unmanned Aerial Vehicles (UAVs). The authors' interpretation of the data is that the effects of turbulence on balloon ascent rates are comparable in magnitude to the effects of actual vertical air motions. The authors therefore conclude if the amount of turbulence and/or the turbulence's effects on ascent rates are unknown, then it is impossible to retrieve the atmospheric vertical velocity from the radiosonde ascent rate.

The authors also present a separate analysis of the flights of several hundred balloon-borne radiosondes from a recent field campaign. Rather than measuring atmospheric turbulence directly, the authors use the moist Richardson number (Ri)—calculated from the temperature, humidity, and horizontal wind measurements from the radiosondes—as a proxy for the likely amount of turbulence. The authors show that low Ri in the troposphere, which is associated with greater turbulence, is associated with greater (~+0.5-0.9 m s−1) balloon ascent rates. They therefore infer that the balloon ascent rates in the troposphere are affected significantly by turbulence.

Reply: The range of greater ascent rates ($\sim +0.5-0.9\, m\, s^{-1}$) mentioned above refers to the mean values shown in Figure 9c. In the submitted manuscript, this range was assumed to be "statistically representative of the turbulence effects" (line 243). However, it is somewhat incorrect and we removed the sentence. Indeed, the mean value $\langle V_{Bc} \rangle$ of ascent rates should include all contributions (waves, convection, large scale billows and decrease of the drag coefficient by turbulence). For example, if we assume that turbulence effects produce a mean

increase of X (> 0) m/s and that all other contributions can be equally positive or negative (so that the mean increase due to these contributions is 0)[5], then the total mean increase will be less than X m/s. Therefore, we believe that ascent rate increase due to turbulence effects may be significantly larger than +0.5-0.9 m/s on some occasions.

From comparisons with vertical velocities measured by MU radar (section 3), we reported ascent rate increases in stratified and clear air conditions larger than $+0.5 - 0.9\, m/s$: namely, ~1-1.5 m/s (Figs. 5 and 6) and ~2 m/s (Fig. 7). Very importantly, these values were obtained with <u>underinflated balloons</u> (V_z in still air was estimated to be ≈ 1.8 m/s and 2.3 m/s, respectively). Referring to Gallice et al. (2010) and references therein, the drag coefficient can vary by a factor ~4 for the expected range of Reynolds number so that ascent rate can increase by a factor ~2, i.e. the ascent rate disturbance can be as large as the value of V_z in still air, but not more. Thus, for standard balloon inflation (V_z~5 m/s, as is the case in section 4), the disturbance can theoretically reach ~5 m/s. The detailed reply #4 to Prof. McHugh (reviewer #2) describes cases for which values up to ~ 4 m/s are plausible (Fig. 2. See also figure A1 below).

The sort of multi-platform analysis provided by this manuscript is sorely needed in the balloon derived vertical air velocity literature, and therefore, I appreciate the authors' time and effort towards such a study. However, after a careful reading of the manuscript, I take issue with the authors' interpretation of the data, and therefore with their main conclusions. My opinion is that the data are ambiguous as to whether turbulence or vertical air motions are affecting the balloon ascent rates. These concerns are outlined below.

Main major comments:

• *One of the manuscript's key conclusions (stated in, e.g., line 22 and line 255) is that vertical air velocity W cannot be estimated using the ascent rate of meteorological balloons in the presence of turbulence. This absolute statement fails to consider situations, such as turbulent updrafts and downdrafts in deep convective storms, in which vertical motions are so strong (~tens of meters per second) that the error attributable to turbulence (seemingly ~a few meters per second) may become unimportant. The conclusion that it is "impossible" to estimate W from balloons in the presence of turbulence is therefore at best (see next major comment below) only applicable to the comparatively weak vertical air motions examined in the present study. The authors should rethink this conclusion and should, at minimum, clearly state under which atmospheric conditions their conclusions are relevant (e.g., weak versus intense vertical air motions).*

Reply: To the authors' knowledge, vertical motions of several tens of m/s are extremely rare even if they are sometimes sources of aviation hazards. However, we quite agree with the remainder of the comment. Turbulence effects do not necessarily prevent us to detect vertical air motions from balloon ascent rates, especially if these vertical motions are very strong.

Lines 70-73, last sentence of paragraph 4 Introduction, have been modified as follows: "This alternative purpose seems to be more achievable than retrieving *W*, except at stratospheric heights and during very calm tropospheric conditions, as shown by earlier studies, and likely during deep convective storms during which strong vertical motions are expected. "

[5] It is obviously not the case, in particular if upward motion dominates due to convection. This hypothesis is made for a simple description.

The interpretation of the balloon ascent rate is indeed always ambiguous (as rightly mentioned below by the reviewer) except when the vertical wind disturbance significantly exceeds the disturbance expected from the sole turbulence effects (see the previous reply and reply #4 to reviewer 2). In principle, the *absolute* error in vertical air motion W does not depend on W[6] and the *relative* error decreases with W. If turbulence produces and absolute error of +2 m/s when W=+2 m/s and W=+20 m/s, then the relative error is 100 % (apparent W=+4 m/s) and 10% (apparent W=+22 m/s), respectively. The importance of the turbulence effects depends on whether absolute or relative errors must be considered for given applications.

• *One major reservation I have regarding the analyses presented in this paper is the horizontal displacement of the balloon relative to the locations of the UAV and MU radar. These displacements of >10 km are hardly negligible. How do we know that there are not major horizontal inhomogeneities in the turbulence and vertical velocity that are leading to the observed discrepancies between the radiosonde and UAV/MU radar observations?*

Reply: A long horizontal distance between the instruments (and a large time lag between the measurements) can be a cause of uncertainties. This is a perennial problem we tried to minimize in the present work by providing a variety of information from UAVs and radar. It must be noted that the horizontal displacement of the balloons did exceed 10 km when comparing with MU radar data above the altitude of ~5 km, <u>but not</u> in the range of comparisons with UAV data (the horizontal distance was less than ~10 km for the 3 cases, see Figure 1).

We have several arguments indicating that the radiosondes crossed the turbulent layers detected by UAVs and the MU radar.

(1) From a general point of view, turbulent layers of $10^2 - 10^3$ m in depth can have a horizontal extent exceeding $10^1 - 10^3$ km in stratified conditions, likely because they are usually associated with meso- or synoptic scale sources. There is no extensive literature focusing on this specific topic but earlier observations suggest this feature (e.g. Luce, H., R. Wilson, F. Dalaudier, H. Hashiguchi, N. Nishi, Y. Shibagaki, *Study of tropospheric turbulence from radar observations and radiosonde data using Thorpe analysis*, Radio Sci., 49, 1106-1123, 2014).
According to the MU radar observations, all the layers identified by T1, T2, …, KHI, MCT (Figs 2-4) persisted for at least 1 hour or even much more. Assuming a wind advection (~5-10 m/s in the present case), their horizontal extent should have exceeded ~30 km, i.e. the maximum horizontal distance between the balloons and radar/UAVs within the range of comparisons (Fig. 1).

(2) The comparisons between TKE dissipation rate profiles (Figs. 5-7) give extra-credence to the hypothesis that the 3 instruments detected the same turbulent layers. These profiles estimated from radar data *at the time of the balloon flights* and UAV data show reasonable agreements in shape and levels (Figs 5-7), indicating that UAVs detected turbulent events of intensities similar to those detected by the MU radar in the same altitude range and at the time of the balloon measurements despite a time lag up to about 1 hour for V16 (see Fig. 3).

The detection of the same turbulent layers by all the sensors is a necessary condition but not sufficient. On some occasions, and especially in clouds, we agree that the horizontal inhomogeneity in the vertical velocity field within a turbulent layer may potentially explain differences between W measurements. However, this hypothesis is hardly defensible from a

[6] This assertion may not be true. For example, we do not consider the response time of the balloon to the disturbances it faces. It is thus at best an approximation.

statistical point of view. From the case studies (Figs 5-7) (and some others we did not show), vertical velocities from balloon ascent rates in the turbulent layers are systematically larger than W measured by the MU radar. This tendency is not consistent with a horizontal inhomogeneity of W because the reverse observation should also happen. In addition, if positive vertical air velocities of the order of those indicated by the peaks of V_{Bc} in Figs. 5-7 are, by chance, often detected by the balloon but not by the radar at the same time, they should occur at other times on a statistical basis. Time-height cross-sections of vertical velocities in Figs 2-4 do not show any positive disturbance corresponding to the levels of the peaks of V_{Bc} during the observation time (1-2 hours).

This is of particular concern given the presence of clouds. In general, the conditions that give rise to turbulence should also give rise to inhomogeneous vertical motion, so it is hardly surprising that W and VBc do not agree as well in more turbulent layers. I do not see how one can conclude that the balloon ascent rate is changing solely due to turbulence effects on the balloon rather than at least non-negligibly due to actual vertical air motions given the potential inhomogeneities. I therefore question the paper's main conclusion that turbulent effects dominate the vertical air motion effects on balloon ascent rate.

Reply: Houchi et al. (2015, p1810) reported a *broadening* of the ascent rate PDF attributed to turbulence. This broadening can indeed be due to local updrafts <u>and</u> downdrafts produced by the "largest" turbulent billows (i.e. of dimensions significantly larger than the balloon size). The ascent rate disturbances should be equally positive or negative because they are outside the mechanism of deep convection causing stronger updrafts. On some occasions, during past field campaigns, we experienced such situations with underinflated balloons: balloons were forced to "sink" due to strong downdrafts in the vicinity of intense turbulent layers. Vertical advection by turbulent billows can thus be the cause of the broadening of the scatter plots for Ri<0.25 (Figs. 9-10), in addition to KH waves. This point is now clarified in the manuscript (as required by reviewer 1).

• *In a similar vein, I question the conclusions drawn from the statistical analysis of 376 balloon-borne radiosondes launched in Indonesia during a recent field project. The main result for this analysis is shown in Figure 9c, in which tropospheric radiosonde ascent rates are greater for low Ri than for high Ri by ~+0.5-0.9 m s−1. with a transition near the theoretical critical Ri value of 0.25. Since lower Ri is associated with enhanced atmospheric turbulence, the authors conclude that the greater values of tropospheric radiosonde ascent rate for low Ri are due to turbulence.*

(intermediate reply to the last sentence above): (a) We conclude that turbulence should be the dominant factor on many occasions (see below), but we agree that it cannot be the unique contribution when convection does occur. (b) This conclusion appears quite peremptory outside its context but it is based on the results obtained in section 3: when Ri was low, turbulence was directly observed and was found to be responsible for greater values of ascent rate owing to comparisons with radar data. In section 4, turbulence is not directly detectable and collocated radar data are not available[7]. A low Ri value (<0.25) is used a proxy of turbulence. Without the results described in section 3, attributing greater values of ascent rate to turbulence effects in section 4 would be largely speculative.

[7] Radar data are shown later in this document but they were not collocated. They are provided for a statistical analysis only.

My concern here is that lower Ri also ought to be associated with stronger vertical air motions, and these motions ought to have a net positive average vertical velocity given that these strong vertical air motions are likely to be associated with convective clouds, and updrafts in tropical convective clouds are stronger than downdrafts (e.g., LeMone and Zipser, 1980).

Reply: The above comments seem to combine two distinct aspects: (1) enhanced turbulence when Ri is low (2) strong updrafts associated with convection.

The range $0 < Ri < 0.25$ characterizes dynamic shear instabilities in a statically stable background and convective instabilities are associated with $Ri < 0$ ($N^2 < 0$). The largest positive disturbances occur when Ri is positive, indicating that they are rather associated with turbulence produced by shear flow instabilities. A more detailed discussion with additional data is given below.

Bengkulu, Indonesia's location near or within the ITCZ, combined with its coastal location (which creates susceptibility for sea breeze convection), seem to have made it a locus for the formation of convective clouds during the observing time period of November/December 2015 (NASA Worldview). Therefore, an alternative interpretation of the presented data is that the enhanced radiosonde ascent rates for low Ri are due to vertical air motions induced by convective clouds rather than due to turbulence.

We do not think that it is the most probable hypothesis for the following reasons:

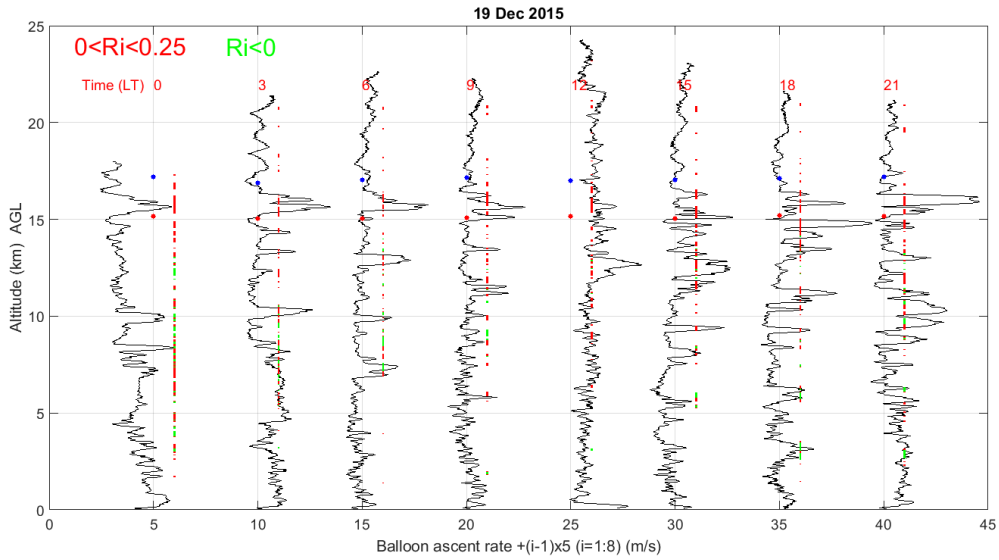

Figure A1. A series of 8 consecutive profiles of V_B obtained on 19 December 2015 at Bengkulu.

1. Morphology of the ascent rate profiles

A striking feature (<u>common to each observation day</u>) is the presence of narrow peaks of V_B in the troposphere (Fig A1). They are generally associated with low values of Ri (sometimes negative). In the altitude range 15-17 km (tropopause layer), the peaks are almost systematic and coincide with an enhanced wind shear (and low Ri) persisting for more than 10 days (not shown). Below 15 km, they randomly occur at various heights from one flight to the other (separated by 3 hours). Their interpretation in terms of updrafts produced by deep convection is unlikely: (1) Ri is not low in the lower troposphere. (2) Assuming that the balloons are

embedded within large scale convective cells and are horizontally advected by the background wind, narrow spike structures can hardly be produced[8].

2. Statistical comparisons with radar data

During the campaign, the 47 MHz Stratosphere-Troposphere (ST) Equatorial Atmosphere Radar (EAR) was operating at Kototabang (Indonesia), located about 450 km North-West from the balloon launching site (Bengkulu). EAR provides similar information as MU radar with a time resolution of about 3 min and a range resolution of 150 m. Despite the very large distance between the EAR and balloon launching sites, we think that the radar observations can help interpret the balloon ascent rates in a statistical sense, assuming that these observations are statistically representative of the conditions met at Bengkulu.

(1) The time-height cross-section of Signal to Noise Ratios (SNR) at vertical incidence from 15 December to 24 December 2015 (10 days) generally show a layered structure, not consistent with strong convection (Fig A2). This feature is consistent with the characteristics of the temperature and humidity profiles measured at Bengkulu: Figure A3 shows the skew-T log-P diagrams for the flights shown in Figure A1 (19 December). The tropopause level was around 150 hPa. The troposphere was close to saturation or even likely saturated (with respect to ice) on some occasions in the upper troposphere but also showed a significant stratification in humidity (large variations of the dew point temperature with height). These humidity gradients, expected to be horizontally stratified, should be the main cause of the stratified echoes. More uniform echoes associated with deep convection can sometimes be observed in the afternoons.

(2) These (short) periods of convection are usually associated with enhanced Doppler variances (i.e. enhanced turbulence) (Fig. A4). Sporadic patches of enhanced variances can be observed in the whole troposphere, consistent with local decreases of Ri in the balloon profiles.

(3) The vertical velocity W measured by EAR does not show significant disturbances (up to ~+/-0.5 m/s), except during convection periods (but not more than +/-2 m/s). The disturbances are either positive or negative (Fig A5).

(4) The histogram of W values shown in Fig A5 (Fig A6 top panel) is not positively skewed, contrary to the histogram of V_{Bc} (Fig A6 bottom panel). The absence of skewness is not consistent with the interpretation of the large positive values of V_B in terms of (real) updrafts associated with deep convection.

(NB:The other days from 08 Nov to 14 Dec show similar features (the radar echoes were sometimes contaminated by rain echoes, producing negative outliers of W)).

This information does not support the hypothesis that the balloon ascent rate disturbances are dominated by updrafts associated with deep convection and is more consistent with turbulence effects.

[8] In addition, horizontal layers of upwelling are also not physically acceptable and the shape of peaks clearly differs from the disturbances produced by waves above the altitude of 17 km. All these arguments are rather in favor of turbulence effects.

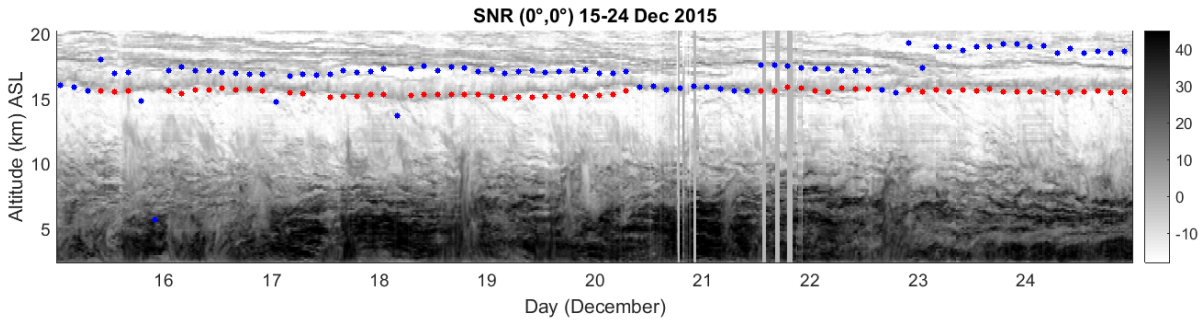

Figure A2: Time-height cross-section of Signal to Noise Ratio at vertical incidence measured by EAR. The blue and red dots show two temperature inversions associated with the tropopause (blue dots: cold point tropopause, red dots: secondary inversion at lower altitudes) measured by the radiosondes at Bengkulu (450 km away from EAR). A long-lived turbulent layer was detected by EAR between the two inversions (see also Fig A3).

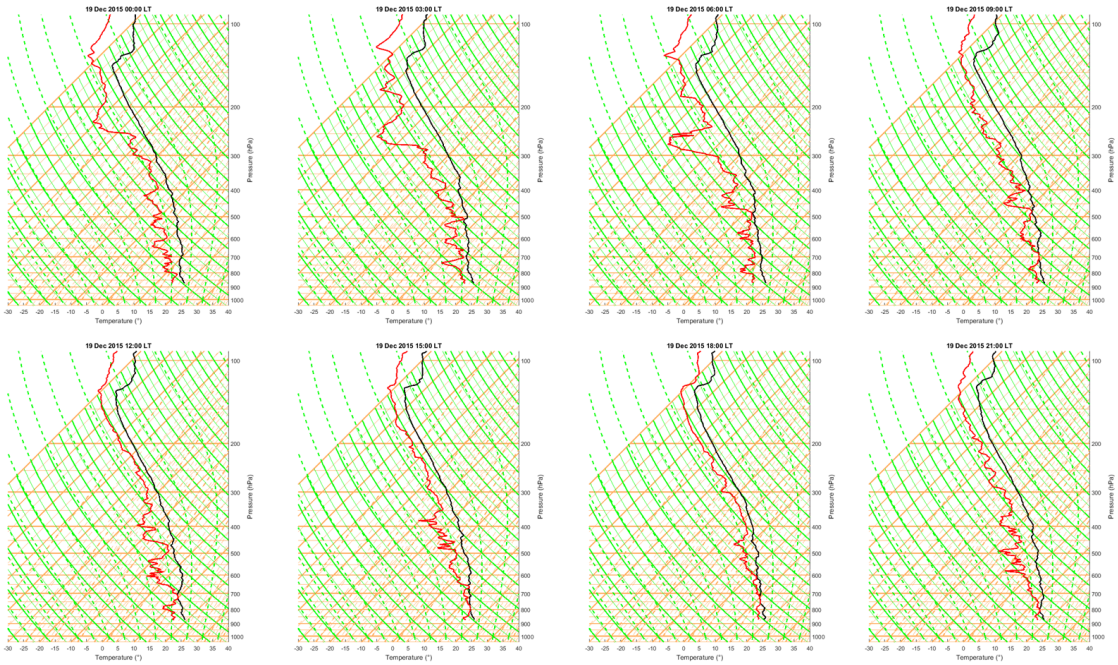

Figure A3: skew-T lop-P diagram for the 8 flights shown in Fig A1. (Black: temperature, red: dew point temperature)

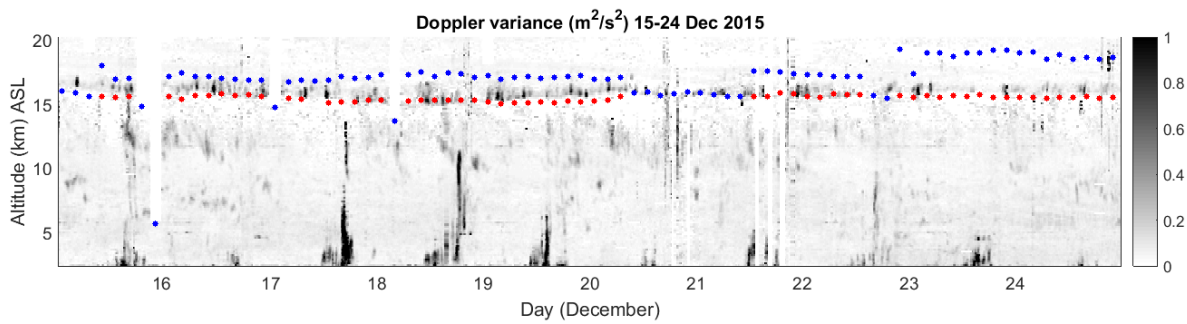

Figure A4: Time-height cross-section of Doppler variance produced by turbulence measured by EAR. The Doppler variance is generally used as a proxy of dynamic turbulence.

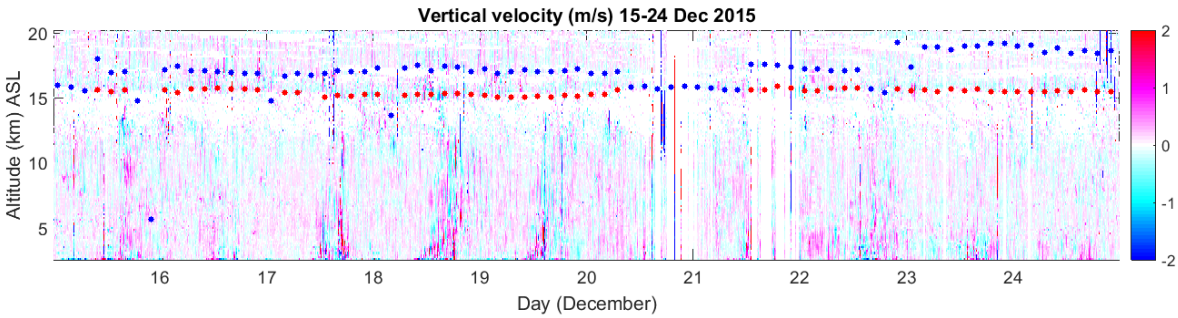

Figure A5: Time-height cross-section of Doppler velocity (m/s) measured by EAR at vertical incidence.

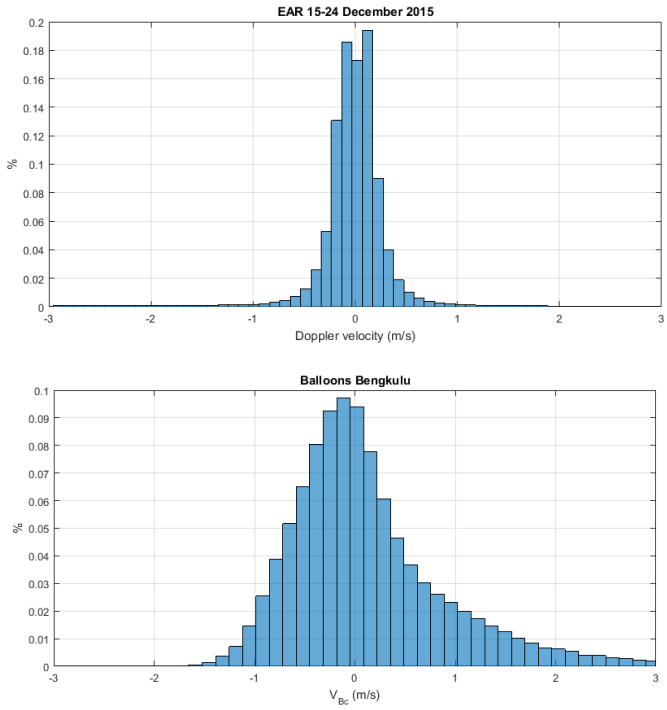

Figure A6: Histogram of vertical velocities measured by EAR (top) (15-24 December) and V_{Bc} (all 376 flights) (bottom).

3. Analysis of another balloon dataset at mid-latitudes

We performed an analysis similar to the one carried out in section 4 based on 59 balloon flights made in September 2011 at Shigaraki MU observatory, Japan, (i.e. at mid latitude where deep convection can be excluded). For various reasons (mainly few data in the stratosphere), it was not possible to estimate V_z for each flight accurately so that the profiles have not been detrended. Despite a smaller amount of balloons, the tendency is similar to the one shown in Figure 9 of the manuscript, i.e. an increase of V_B for low Ri. Therefore, we believe that the results shown in section 4 are "universal" and are not specific to the equatorial region.

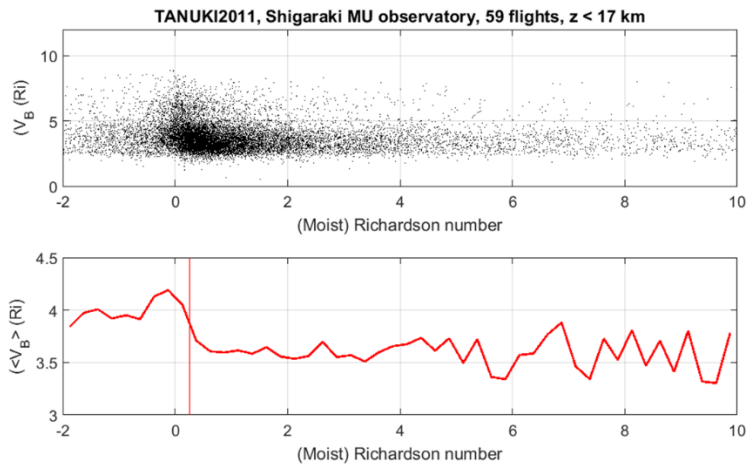

Figure A6: results similar to Figure 9 of the manuscript using 59 balloon flights performed in September 2011 at Shigaraki MU observatory (i.e. at mid-latitudes) (see text for more details).

References: 1) LeMone, M. A., and E. J. Zipser, 1980: Cumulonimbus vertical velocity events in GATE. Part I: Diameter, intensity and mass flux. J. Atmos. Sci., 37, 2444–2457, https://doi.org/10.1175/1520-0469(1980)037<2444:CVVEIG>2.0.CO;2. 2) https://worldview.earthdata.nasa.gov/?v=84.93837017059609,13.306520778973313,118.54774517059609,3.0235573460266867&t=2015-11-29T18%3A26%3A21Z

Other substantive comments:

• *Regarding line 82 and 274: To the best of my knowledge, the Gallice et al. (2011) method does not assume any particular value of Tu. Rather, this method obtains drag curves (drag coefficient as a function of Reynolds number) based on smoothed observed ascent rates and thermodynamic conditions across several launches. From page 2239 of Gallice et al. (2011): "To compensate for this lack of knowledge, and since parameters other than Re, Tu and E – such as unsteadiness or turbulence intensity length scale – are also known to affect the drag coefficient (e.g. Wang et al., 2009; Neve, 1986), an attempt is made here to derive a mean experimental drag curve for sounding balloons, based on a dataset of balloon flights."*

The statement is indeed wrong and has been suppressed in the revised version. We apologize for this erroneous interpretation. The experimental drag curves described by Gallice et al. (2011) "present a qualitative shape similar to the curves by Son et al. (2010) at *Tu=6%* and *Tu=8%*." (not 4% as stated). They further indicated that their drag curves suggest a turbulence intensity (Tu) of the atmosphere of the order of 6% to 8 % (page 2241). This statement indicates that inhomogeneities in the turbulent field were not considered.

• *Line 173: You seem to be assuming that Vz is height-invariant. What is the basis for this assumption? You seem to make the same assumption later in the paper as well, in line ~223. Given the many factors that influence a rising, expanding balloon, it is unclear to me why Vz should be assumed to have a single value throughout the troposphere and lower stratosphere.*

The examples of balloon ascent rates shown in Figure A1, indicate that assuming Vz as a constant is a reasonable approximation.

• *Line ~177-178: Shouldn't using a lag equal to a multiple of the wave's period produce essentially the same result as the non-lagged profile since you are sampling at the same phase each time? I think that using lags equal to multiples of perhaps one-eighth of the wave's period would better produce the variety that you are looking to achieve here. I can think of two additional problems with using a multiple of the wave's period: (1) if the wave propagating relative to the mean flow, then there will be a Doppler effect that produces the wrong apparent period at a given point, and (2) it takes the balloon time to ascend through a given layer – therefore, the phase of the wave it samples at the bottom of the layer will differ from the phase being sampled at the top of the layer.*

We were not able to identify with certainty the type of waves associated with these nearly-monochromatic W fluctuations revealed by the radar images. In any case, the period is only apparent (it is not the intrinsic period if there is a Doppler effect). We have some indications that they can be some kind of ducted waves according to analyses we made from other data sets in similar conditions. We did not expend the analysis because it is not related to the main topic of the manuscript.

On the estimation of vertical air velocity and detection of atmospheric turbulence from the ascent rate of balloon soundings

Hubert Luce[1], Hiroyuki Hashiguchi[2]

[1]Univ Toulon, Aix Marseille Univ., CNRS/INSU, IRD, MIO UM 110, Mediterranean Institute of Oceanography, La Garde, 83041, France

[2]Research Institute for Sustainable Humanosphere, Kyoto University, Kyoto, 611-0011, Japan

Correspondence to: Hubert Luce (luce@univ-tln.fr)

Abstract. Vertical ascent rate V_B of meteorological balloons is sometimes used for retrieving vertical air velocity W, an important parameter for meteorological applications, but at the cost of crude hypotheses on atmospheric turbulence and without the possibility of formally validating the models from concurrent measurements. From simultaneous radar and Unmanned Aerial Vehicles (UAV) measurements of turbulent kinetic energy dissipation rates ε, we show that V_B can be strongly affected by turbulence, even above the convective boundary layer. For "weak" turbulence (here $\varepsilon \lesssim 10^{-4}\ m^2 s^{-3}$), the fluctuations of V_B were found to be fully consistent with W fluctuations measured from MU radar, indicating that an estimate of W can indeed be retrieved from V_B if the free balloon lift is determined. In contrast, stronger turbulence intensity systematically implies an increase of V_B, not associated with an increase of W according to radar data, very likely due to the decrease of the turbulence drag coefficient of the balloon. From the statistical analysis of data gathered from 376 balloons launched every 3 hours at Bengkulu (Indonesia), positive V_B disturbances, mainly observed in the troposphere, were found to be clearly associated with $Ri \lesssim 0.25$, usually indicative of turbulence, confirming the case studies. The analysis also revealed the superimposition of additional positive and negative disturbances for $Ri \lesssim 0.25$ likely due to Kelvin-Helmholtz waves and large-scale billows. From these experimental evidences, we conclude that the ascent rate of meteorological balloons, with the current performance of radiosondes in terms of altitude accuracy, can potentially be used for the detection of turbulence. The presence of turbulence makes the estimation of W impossible and misinterpretations of V_B fluctuations can be made if localized turbulence effects are ignored.

Supprimé: in the vicinity of the turbulent layers

Supprimé: impossible

1 Introduction

The vertical ascent rates V_B of meteorological balloons are mainly the combination of the free lift and fluctuations due to vertical air velocities and variations of atmospheric turbulence drag effects. Despite their frequent use all over the world, a limited number of studies tried to extract information from V_B. Most of these studies focused on the estimation of the vertical air velocity because this parameter is very important for many meteorological applications (e.g. Wang et al., 2009) and for the characterization of internal gravity waves (e.g. McHugh et al., 2008). Evidence of internal gravity wave fluctuations in balloon

ascent rates was reported by Corby (1957), Reid (1972) and Lalas and Einaudi (1980). Shutts et al. (1988) and Reeder et al. (1999) described large amplitude gravity waves in the stratosphere from the analyses of V_B.

However, the models or methods used for retrieving vertical air velocity from balloon ascent rates are often based on crude assumptions about atmospheric turbulence: it is either considered as more or less uniform or neglected above the planetary boundary layer. Johansson and Bergström (2005) estimated the height of boundary layers from V_B considering that V_B is mainly affected by turbulence in convective boundary layers. In fact, the free stratified atmosphere usually reveals a "sheet and layer" structure (e.g., Fritts et al., 2003) consisting of more or less deep layers of turbulence (a few hundred of meters) separated by quieter and generally statically stable regions. In such conditions, turbulence intensity, often quantified by turbulence kinetic energy dissipation rates, can vary over several orders of magnitudes with height and can reach levels similar to those met in the convective atmospheric boundary layers (e.g. Luce et al. 2019).

In addition, most studies did not validate their estimations from concurrent measurements of vertical air velocities, making their models and hypotheses uncertain (e.g. McHugh et al., 2008; Gallice et al., 2011). Gallice et al. (2011) proposed a model to describe balloon ascent rates in presence of free-stream turbulence. Even if the variations of the drag coefficient with altitude were taken into account, their expression of the drag coefficient was based on a mean turbulent state and thus, the model did not consider the possibility of localized layers of turbulence, as acknowledged by the authors. Wang et al. (2009) retrieved vertical air velocity from radiosondes and dropsondes assuming that turbulence has a negligible effect above the convective boundary layer so that the drag coefficient was considered as nearly constant. Comparisons with wind profiler data (their Fig. 7) showed poor agreements. Most profiles revealed oscillations, signature of gravity waves. McHugh et al. (2008) noted large (always positive) variations in balloon ascent rate around the tropopause over Hawaii and interpreted these localized peaks as strong increases of W due to mountain waves around their critical levels. Independent measurements could not validate this interpretation and possible turbulence effects were not considered when interpreting observations. Houchi et al. (2015) used a model similar to Wang et al.'s (2009) model for statistical estimates of the vertical air velocity. The authors assumed that the balloon ascent rate is the sum of the ascent rate in still air and vertical air velocity.

Modelling the ascent of balloons is not an easy task especially if the free-stream turbulence effects are not correctly taken into account. In the present work, we studied the effects of turbulence on V_B from experimental data. For this purpose, vertical profiles of V_B were compared with profiles of turbulence kinetic energy (TKE) dissipation rate ε estimated from Unmanned Aerial Vehicles (UAV) data and from the 46.5 MHz Middle and Upper atmosphere (MU) radar data. These data were gathered during Shigaraki UAV-Radar Experiment (ShUREX) campaigns at Shigaraki MU observatory (Kantha et al., 2017). In addition, the MU radar provided coincident estimates of vertical air velocities so that quantitative comparisons with V_B could be made. We found that a balloon is likely a good "W sensor" in case of light turbulence only: under the conditions of our experiment, V_B is affected by turbulence, and thus cannot be used for estimating W when $\varepsilon \gtrsim 10^{-4}\ m^2 s^{-3}$ ($1\ mW kg^{-1}$). Therefore, a balloon is potentially more a "turbulence sensor" than a "W sensor" and very large errors on W can arise if the presence of free-stream turbulence is not properly considered. Alternately, statistics on the occurrence of atmospheric turbulence could be made from balloon ascent rates if the contribution of air motion is accurately taken into account. This

Supprimé: uncertain

Supprimé: he intensity of turbulence was considered as uniform in the free atmosphere. T

Supprimé: 4

alternative purpose seems to be more achievable than retrieving W, except at stratospheric heights and during very calm tropospheric conditions, as shown by earlier studies, and likely during deep convective storms during which strong vertical motions are expected.

The effects of turbulence on the balloon ascent rate can be understood considering that this parameter in still air is given by (Gallice et al., 2011):

$$V_z = \sqrt{\frac{8Rg}{3c_D}\left(1 - \frac{3m_{tot}}{4\pi\rho_a R^3}\right)}$$

where R is the radius of the volume-equivalent sphere, g, the acceleration of gravity, ρ_a, the air density, and m_{tot} the total mass of the balloon, including payload, ropes, gas, etc. c_D is the drag coefficient depending on the Reynolds number associated with the balloon $Re = \rho_a V_z R/\mu$. μ is the dynamic viscosity of air. The variation of c_D with Re for a perfect sphere in absence of atmospheric turbulence and for various values of turbulence intensity Tu defined as the ratio of the standard deviation of the incident air velocity fluctuations to the mean incident air velocity (e.g. Son et al. 2010) is shown in Fig. 1 of Gallice et al. (2011). c_D suddenly decreases by a factor 4 to 5 above a critical value of Re (called drag crisis) so that V_z can increase by a factor 2 or more. In presence of atmospheric turbulence, the drag crisis is displaced toward lower values of Re so that c_D can be reduced when crossing a turbulent layer. Recently, Söder et al. (2019) compared a profile of Re with a profile of balloon ascent rate (their figure A1) and clearly showed the existence of a drag crisis about $Re \sim 4 \times 10^5$ in close agreement with the theoretical expectation for a sphere (Fig. 1 of Gallice et al. 2011). Gallice et al. (2011) proposed another (smoother) model from experimental data with a more realistic shape of balloons and by considering heat imbalance between balloon and atmosphere. Their drag curve presented qualitative similarities with the curves by Son et al. (2010) for a mean turbulent state of the atmosphere at Tu=6 % and Tu=8%. The fact that the model proposed by Gallice et al. does not consider the variability of turbulence with height is likely a weak point because turbulence is generally confined into layers of variable depth in the troposphere and the stratosphere.

In section 2, we briefly describe the methods used for retrieving the atmospheric parameters analyzed in the present study. In section 3, we show comparison results between V_B, vertical velocity measured by MU radar, energy dissipation rate and Richardson number profiles from three case-studies selected from ShUREX2017. These comparisons clearly indicate that turbulence effects dominate the balloon ascent rate. The results of a statistical analysis from 376 balloons and based on the intimate relationship between turbulence and Richardson number Ri are shown in section 4. They confirm that V_B is dominated by turbulence effects when $Ri \lesssim 0.25$. Finally, conclusions of this work are given in section 5.

Supprimé: or

Supprimé: but considered a mean turbulent state of the atmosphere of $Tu \sim 4\%$.

Supprimé: T

Supprimé: is

Mis en forme : Couleur de police : Rouge

Supprimé: hypothesis does not hold considering the results of comparisons we obtained

2 Methods

2.1 Estimation of V_B

200-g rubber balloons manufactured by TOTEX were equipped with RS92SGPD radiosondes for pressure, temperature, relative humidity and horizontal wind measurements during ShUREX campaigns. Their ascent rate V_B was calculated from $\Delta z/\Delta t$ where z is the GPS altitude of the radiosondes and $\Delta t = 2\,s$. A 20-s rectangular window was applied to V_B to reduce the noise, likely due to pendulum effects, self-induced balloon motions, among other causes. For the case-studies, we focused on the data from the ground (384 m ASL at MU Observatory) up to the altitude of 7.0 km ASL. This is primarily because (1) the datasets were originally processed for comparisons with UAV data and UAVs did not fly above altitudes of a few km, (2) a limited height range makes the description of individual turbulent events less tedious, (3) the increasing horizontal distance between the radar and balloons with height due to the jet-stream becomes an important factor of uncertainty when doing comparisons, (4) the signal-to-noise ratio (SNR) of radar measurements is statistically decreasing with height in the troposphere and low SNR values produce additional uncertainties

Supprimé: 1

Supprimé: 1

2.2 Detection of turbulence from TKE dissipation rate ε

TKE dissipation rate ε is a key parameter describing the intensity of dynamic turbulence. It is thus well adapted for the present purpose, i.e. the identification of turbulent layers when the balloons were flying. ε can be calculated from UAV data using two methods described by Luce et al. (2019). A direct estimate is obtained from one dimensional (1D) spectra of streamwise wind fluctuation measurements. An indirect estimate is deduced from temperature structure function parameter C_T^2 calculated from 1D temperature spectra. Similar levels of ε and $\varepsilon(C_T^2)$ give credence to the results since the two estimates are independent. In addition, consecutive profiles can be obtained during UAV ascents and descents, depending on the configuration of the flights. Therefore, both vertical profiles of ε and $\varepsilon(C_T^2)$ during ascents and descents will be shown when available.

TKE dissipation rate can also be estimated from MU radar data using the variance σ^2 of Doppler spectrum peaks produced by turbulence. It is based on an empirical model proposed by Luce et al. (2018) and validated from comparisons with UAV-derived ε. The expression of the model is $\varepsilon(MU) = \sigma^3/L_{out}$ where L_{out}~$60\,m$. In the present work, an estimate of $\varepsilon(MU)$ at a given altitude z is obtained from an average of the values of σ^2 over +/-1 min (about 30 values since radar profiles were obtained every ~4 sec) around the time that the altitude z was reached by the radiosonde (see also Fig. 1 of Luce et al. 2018 for a schematic). This procedure should ensure that the estimates of ε are representative of those met by the balloons, assuming horizontal homogeneity over a distance at least equal to the horizontal distance separating the balloons and the radar (up to ~30 km, see section 3). The horizontal distance between UAV and balloon measurements did not exceed ~$10\,km$ up to the altitude of ~$4.0\,km$. Considering that all the turbulent events analyzed in the present study persisted for more than 1 hour and were likely associated with meso- or synoptic scale dynamics, the procedure may appear unnecessary but it is crucial for the vertical velocity (see section 3).

Consequently, we have three independent estimates of ε in the vicinity of the balloon flights. The two UAV estimates are obtained from the ground up to ~4.0 km and the radar estimates in the height range 1.27-7.0 km. The radar and UAV estimates are complementary below 1.27 and above ~4.0 km and redundant between 1.27 and ~4.0 km.

2.3 Estimation of vertical velocity profiles from radar data

Vertical velocities W can also be directly measured from Doppler spectra when the radar beam is vertical (e.g., Röttger and Larsen, 1990). Pseudo-vertical profiles of W were reconstructed in the same way as $\varepsilon(MU)$ by averaging over +/-1 min around the time that the altitude z was reached by the radiosonde. A two-minute averaging was applied in order to reduce the statistical estimation errors and is suitable for detecting W fluctuations of periods significantly larger than 2 minutes.

As shown by, e.g., Muschinski (1996), Worthington et al. (2001) or Yamamoto et al. (2003), W can be biased by a few tens of $cm\ s^{-1}$ or more because of refractivity-surface tilts produced by Kelvin-Helmholtz or internal gravity waves. However, this potential bias cannot explain the large differences of a few ms^{-1} between W and the vertical air velocities supposed to be deduced from V_B (see section 3).

3 Case-studies

Three balloon flights (hereafter called V6, V14 and V16) performed during ShUREX2017 on 18 and 26 June 2017 are analyzed in detail. Figure 1 shows the horizontal trajectories of the balloons up to the altitude of 7.0 km ASL. The nearly circular patterns of the UAV trajectories are also shown. The MU radar is at the position (0,0).

The balloons were intentionally underinflated with respect to standard procedures in order to get a mean ascent rate of ~2 ms^{-1} similar to the vertical ascent rate of the UAVs. V6, V14 and V16 reached the altitude of 7.0 km ASL within about 33, 52 and 53 min respectively and their mean vertical ascent rates were about 3.3, 2.1 and 2.1 ms^{-1}. V6 drifted by less than 15 km southwestward when reaching the altitude of 7.0 km. V14 and V16 drifted by about 30 km mainly eastward due to the influence of the sub-tropical jet-stream.

3.1 Analysis of the radar data

Time-height cross-sections of MU radar Doppler variance σ^2 (m^2s^{-2}), echo power (dB) and vertical velocity (ms^{-1}) around the times of the UAV and balloon flights in the height range 1.27-7.0 km are shown in Figs. 2, 3 and 4 for V14, V16 and V6, respectively (they are not shown in time order for ease of the description made below). The red and blue lines indicate the altitude of the UAVs and balloons vs time, respectively. For easy reference, the most prominent and persisting turbulent layers identified from enhanced Doppler variance (or $\varepsilon(MU)$) and UAV-derived ε are labeled. The source of these layers is sometimes recognizable from the morphology of the corresponding radar echoes in the high resolution power images. When this is the case, the labels indicate the nature of the instabilities that gave rise to turbulence, otherwise the labels are “T1”, “T2”, etc. “KHI”, “MCT” and “CBL” refer to sheared flow Kelvin-Helmholtz Instability (e.g. Fukao et al., 2011), Mid-level

Supprimé:

Cloud base Turbulence (e.g., Kudo et al., 2015), and Convective Boundary Layer, respectively. The presence of saturated air is also indicated by the label "cloud". Note that enhanced σ^2 does not necessarily imply enhanced echoes (e.g. T1 in Fig. 2 and T2 in Fig. 4) because turbulence can sometimes produce faint echoes surrounded by enhanced echoes at their edges (e.g., Mc Kelley et al. 2005). The CBL in Fig. 2 is only guessed because the top CBL only slightly exceeded the altitude of the first radar gate but it was confirmed by the UAV observations.

The V14 case was characterized by weak turbulence except below ~1.3 km (CBL) and above ~5.0 km (MCT) (Fig. 2). The atmosphere was weakly turbulent between, but two events (T1 and T2) persisted around 2.3 km and between 4.0 and 4.5 km. The V16 case was also characterized by weak turbulence below 3.5-4.0 km and at least three well-defined layers associated with MCT and two instabilities within clouds (T2 and T3 in Fig. 3). The V6 case showed enhanced turbulence at almost all altitudes (Fig. 4) but distinct layers can be clearly noted: MCT around 5.0 km, KHI around 3.5 km (braided structures are clearly visible around 15:00 LT) and less intense events around 2.5 km (T2) and just above the cloud base (T3). Turbulent layers (T1) detected from UAV data below 1.27 km are not indicated on the figures.

Rapid W fluctuations (of period of ~1 min) are generally associated with MCT events. Nearly monochromatic oscillations of W likely due to ducted gravity waves can also be noted below 2.5-3.0 km during V16 and V6 (Figs. 3 and 4). Their periods are about 9 and 6 min, respectively. The amplitude of W did not exceed ~0.5 ms^{-1} except in the MCT layer during V6 where W fluctuated between +/- 2.0 ms^{-1}.

3.2 Profile comparisons

The results of comparisons between V_B and atmospheric parameter profiles are shown for V14, V16 and V6 in Figs. 5, 6 and 7, respectively. Panels (a) show vertical velocity profiles from MU radar data and radiosondes. Panels (b) and (d) show UAV- and radar-derived ε profiles in linear and logarithmic scales, respectively. Both representations are shown for ease of analysis. Panels (c) show Richardson number $Ri = N^2/S^2$ profiles estimated from balloon data at 20 and 100 m resolution. Two vertical resolutions are used because Ri is scale-dependent (Balsley et al., 2008).

The balloon ascent rate in still air V_z was estimated from the difference between W and V_B when turbulence was weak and the Richardson number was high. V_z was found to be 1.8, 1.8 and 2.3 ms^{-1} for V14, V16, V6, respectively and $V_{Bc} = V_B - V_z$ is shown in the figures. Indeed, the vertical fluctuations of V_{Bc} coincide well with those of W outside the labeled turbulent layers indicating that the variations in balloon ascent rate are dominated by the vertical air motions when turbulence is "sufficiently weak". It is particularly evident in Fig. 6 in the height range 1.3-3.8 km where the wavy fluctuations in W (of ~0.5 ms^{-1} in amplitude) coincide very well with those of V_{Bc}. Several radar estimates of W are shown for different time lags, multiple of ~9 min corresponding to the apparent period of the wave in the radar image (Fig. 3). The fluctuations of W and V_{Bc} are in phase. The W profile suggests that the oscillations still occurred above 3.8 km in the MCT layer. The V_{Bc} profile indicates enhanced values up to +1.8 ms^{-1} at 5.5 km that are clearly not related to vertical air motions.

Mis en forme : Police :Italique

Supprimé: even if they were affected by the higher frequency disturbances produced by the MCT layer around the altitude of 4.7 km (see the larger variability of the W profiles).

Supprimé: km

In contrast, wherever UAV- and radar-derived ε estimates are enhanced in the labeled height ranges, V_{Bc} is also enhanced and V_{Bc} and W strongly differ. Note that the UAV profiles of ε during ascents and descents are very similar and there is a good agreement with the radar-derived profiles obtained during the balloon flights. Therefore, we can reasonably assume that these profiles are representative of the turbulence conditions met by the balloons. In general, the height ranges of enhanced ε coincide with minima of Ri, close to the critical value of 0.25, as expected for shear-generated turbulence (e.g. KHI in Fig. 7), or even less than 0, expected for MCT. Ri is not necessarily small over the whole depth of the layers (e.g. around 6.0 km in Fig 5) and is surprisingly high for the whole depth of T2 in Fig. 7, but the overall results remain consistent. A puzzling result can be noted above the cloud base ($\gtrsim 6.0\ km$) during V6 (Fig. 7, as indicated by "??") where a strong increase of V_{Bc} (~4 ms^{-1}) was neither associated with an increase of W nor an increase of turbulence according to MU radar observations. A slow-down of the balloon due to precipitation loading would rather be expected. This thus remains unexplained and, by default, we must invoke horizontal inhomogeneity of W and/or turbulence intensity over the horizontal distance between the radar and the balloon (~10 km). Similar features were not observed in clouds during V14 and V16.

The case-studies provided experimental evidences that turbulence can strongly increase the balloon ascent rate, very likely through the decrease of the drag coefficient. The observed V_{Bc} is thus the combination of turbulence effects and vertical air velocities. Because W fluctuations appear significantly weaker than V_{Bc} fluctuations, turbulence effects are likely dominant. On some occasions, increase of V_{Bc} might be due to the sole turbulence effects, as in T1 of V14 (Fig. 5) since W does not show any particular variations in the range of T1.

In the present cases, $\varepsilon \sim 10^{-4}\ m^2 s^{-3}$ seems to be a threshold below which turbulence does not seem to affect significantly the balloon ascent rate. However, this value is likely specific to the present observations and may not be applicable to other conditions.

4 Statistics

The case-studies strongly suggest that increased balloon ascent rates are generally related to minimum values of Richardson number (negative or smaller than ~0.25 consistent with convective overturning or shear-generated instabilities in stratified conditions, respectively). This observation can be confirmed by analyzing the relationship between V_{Bc} and Ri from a large amount of data. For this purpose, we used data from 376 radiosondes launched every 3 hours in Indonesia (Bengkulu, Nov-Dec 2015) during a preliminary Years of Maritime Campaign (YMC) campaign (e.g. Kinoshita et al., 2019). The choice of this dataset is arbitrary but it ensures that the same type of balloons (TOTEX-TA 200) and radiosondes (RS92SGPD) were used with similar procedures of balloon inflation for all the datasets. Figure 8 shows all the V_B profiles with a slight offset for legibility. The balloons were inflated in order to get a mean ascent rate of 5 ms^{-1} (free lift). During the period of observations, the tropical tropopause layer (TTL) was often characterized by a strong temperature inversion just above the cold point temperature (CPT) around the altitude of 16~17 km (blue dots in Fig. 8) and a secondary temperature inversion of similar

intensity at slightly lower altitude (red dots). For ease of statistical analysis, we refer to altitude ranges 0-16.3 km as troposphere and altitude ranges above 17.2 km (up to the top of the radiosoundings) as stratosphere.

The profiles of V_B often display multiple peaks of variable widths in the troposphere especially in its upper part. In the stratosphere, the profiles are much smoother and show either weak variations or nearly monochromatic fluctuations undoubtedly due to internal gravity waves (Tsuda et al., 1994). Therefore, we suggest that the variations of V_B with height are primarily due to vertical air motions in the stratosphere and mainly due to turbulence effects in the troposphere. To confirm this hypothesis, we analyzed the relationship between Ri and V_{Bc} (V_B corrected from the free lift). We calculated (moist) $Ri = N_m^2/S^2$ where N_m^2 is the squared moist BV frequency using expression (5) of Kirschbaum and Durran (2004) at a vertical resolution of 50 m, a reasonable trade-off between 20 and 100 m used for the case-studies. Because V_B seems to be weakly affected by turbulence in the stratosphere, the mean value of V_B for stratospheric heights, $< V_B >_{ST}$, is expected to be a fair estimate of the ascent rate in still air (V_z), assuming that wave contribution is indeed removed after averaging and that other contributions are negligible. Thus, we have $V_{Bc} = V_B - < V_B >_{ST}$. $< V_B >_{ST}$ was calculated for each flight and removed to each profile of V_B in order to reduce the effects of variable mean ascent rates that may result from different balloon inflations. The mean value of $< V_B >_{ST}$ over the 376 flights was found to be precisely equal to the nominal value of 5 ms^{-1}.

First, the scatter plot of V_{Bc} vs Ri shows a very significant maximum around and below the critical value Ri_c~0.25 in the troposphere (Fig. 9a). This is an indirect confirmation that V_{Bc} peaks are indeed due to turbulence (Fig. 9a), considering that small Ri values are generally associated with turbulence. Second, this increase is accompanied by a larger scatter. There is no similar tendency in the stratosphere (Fig. 9b) because Ri rarely dropped below Ri_c, in accordance with the absence of significant turbulence guessed from the profiles of V_B. The variability of V_{Bc} increasing with decreasing Ri in Fig. 9b should mainly be due to waves.

In order to emphasize the tendency shown by Figs. 9a and 9b, averaged values of V_{Bc} in Ri value bands of 0.25 in width, $< V_{Bc} >$, are shown in Figs. 9c and 9d, respectively. For $Ri \gtrsim 1$, $< V_{Bc} >$ is roughly constant but slightly negative: ~-0.2 ms^{-1} (Fig. 9c) because $< V_B >_{ST}$ is likely not exactly the ascent rate in still air in the troposphere. This is not an important issue for the present purpose. When Ri drops below Ri_c, $< V_{Bc} >$ increases by ~+0.9 ms^{-1} and remains high when $Ri < 0$ (Fig. 9a). The values for $Ri < Ri_c$ are not reliable in the stratosphere (Fig. 9d) due to the lack of data. The results shown in Fig. 9c constitute a statistical confirmation of the observations reported in section 3.

Figures 10 show $V_{Bc} - < V_{Bc} >$ vs Ri for the troposphere. A larger scatter is observed between $Ri=0$ and $Ri_c = 0.25$. The broadening of the scatter was attributed to turbulence by Houchi et al. (2015). However, the broadening cannot be explained by a decrease of the drag coefficient because it is necessarily due to both positive and negative vertical velocities. The broadening is thus more likely due to turbulent billows of scales much larger than the balloon size. In addition, Kelvin-Helmholtz (KH) waves can also produce updrafts and downdrafts up to a few ms^{-1} when Ri reaches Ri_c (see, e.g. Fukao et al., 2011). Therefore, the enhanced variability of V_{Bc} when Ri is small (Fig. 9a) is presumably the combination of turbulence effects and vertical air motion disturbances produced by large scale billows and KH waves.

Supprimé: a and 10b

Supprimé: and the stratosphere, respectively

Supprimé: around

Mis en forme : Police :Italique

Supprimé: (as emphasized by the ellipse)

Supprimé: is cannot be explained by turbulence

Supprimé: but

Supprimé: by

Supprimé: that

Supprimé: shear flow instabilities

Supprimé: Assuming that the mean curve shown in Fig. 9c is statistically representative of the turbulence effects, then the scatter plot shown in Fig. 10a should also be statistically representative of *W* fluctuations produced by shear flow instabilities if other sources of vertical air motions are negligible.

Mis en forme : Couleur de police : Rouge

Finally, it can be noted that the scatter plot of $V_{Bc} - < V_{Bc} >$ (Fig. 10) is not symmetrical about 0 for $Ri > 1$ (for which turbulence is expected to be suppressed) and suggests peaks of V_B (without corresponding negative disturbances) even in absence of turbulence. However, this result must be tempered by the fact that turbulence can be observed even if the estimation of Ri at a given resolution is not small (see e.g., Fig. 7, T2). Measurement and estimation errors on temperature, humidity and winds cannot be discarded on some occasions and N_m^2 may not be the adapted parameter for all conditions. For all these reasons, this observation may not be indicative of more complex interactions between the balloon and the surrounding atmosphere.

5 Discussion and conclusions

We found that the possibility of retrieving the vertical air velocity W from radiosonde ascent rate V_B highly depends on the turbulent state of the atmosphere. In turbulent layers generated by shear or convective instabilities, W cannot be measured because V_B is very likely affected by the decrease of the drag coefficient c_D of the balloon. In contrast, in the calm regions of the atmosphere, the fluctuations of V_B are dominated by the fluctuations of W. These conditions were probably met by, e.g., Corby (1957), Reid (1972) and are most likely met in the lower stratosphere (Shutts et al., 1988; Reeder et al., 1999). It was also the case during the conditions analyzed by Wang et al. (2009) above CBL. However, in light of our observations, we speculate that Wang et al. also detected turbulent layers: localized increases of V_B (up to ~2 ms^{-1}) observed in the height range 8-10 km (their Figure 1) may be attributed to turbulent layers. McHugh et al. (2008) interpreted isolated peaks of V_B of several ms^{-1} of amplitude near the tropopause and at the jet-stream level in terms of W disturbances around critical levels associated with mountain waves. The absence of corresponding negative disturbances was explained by the three-dimensional nature of the flow. Even though our hypothesis remains speculative in absence of additional and independent measurements of vertical air velocity, we suggest that turbulence effects may have also contributed to the observed increase in ascent rates since critical levels are generally associated with turbulence. A careful scrutiny of their figures 3-7 indicates that V_B increased at altitudes where the horizontal wind shear was enhanced and temperature gradient was close to adiabatic (so that Ri was likely small). Houchi et al. (2015) attributed the spread of height increment "dz" probability density function to "turbulence". The authors likely implicitly refered to advection by large-scale billows. The decrease of the drag coefficient due to turbulence can explain upward-only motion anomaly noticed by the authors.

It turns out that V_B can also potentially be used for the detection of turbulence in the free atmosphere if the increase of V_B can be separated from the contribution of W. Turbulence is frequent in the free atmosphere but also very variable with height and generally distributed in layers, especially in stratified conditions. This feature was likely not well appreciated by Gallice et al. (2011). The authors themselves recognized that their model cannot work if localized turbulence –they proposed the example of turbulence generated by gravity wave breaking- occurs.

The amplitude of the V_B disturbances should depend on the variations of c_D with the Reynolds number, the intensity of turbulence and on the scales of turbulence with respect to the balloon size so that it might be difficult or even impossible to

Supprimé: a

Supprimé: Even if this interpretation is plausible,

Supprimé: t

Supprimé: can be an alternative explanation

Supprimé: This alternative explanation is also consistent with the absence of decrease of ascent rate.

Supprimé: 4

Supprimé:

Supprimé: the sole vertical air velocity effects

Supprimé: Our study suggests that part of the distribution is likely due to turbulence effects. These effects

Supprimé: who considered a mean value of turbulent intensity over the whole atmosphere for establishing a model of c_D.

Mis en forme : Couleur de police : Rouge

retrieve turbulence parameters from the sole V_B measurements. However, further comparisons such as shown in section 3 might be useful for establishing empirical rules on turbulence detection threshold.

Data availability. The balloon data are archived at the YMC Data Archive Center maintained by JAMSTEC. The radar and UAV data are still under processing for other purposes.

Author contributions. HL, with the help of HH, conceived of the study, carried out the analysis and retrievals, and wrote the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgments. Radiosonde observations were carried out by JAMSTEC, BMKG, and BPPT. UAV data were provided by CU university.

Financial support. This study was partially supported by JSPS KAKENHI Grant Number JP15K13568 and the research grant for Mission Research on Sustainable Humanosphere from Research Institute for Sustainable Humanosphere (RISH), Kyoto University.

References

Balsley, B. B., G. Svensson, and M. Tjernström, On the scale dependence of the gradient Richardson number in the residual layer, Bound.-Lay. Meteorol., 127, 57–72, 2008.

Corby, G. A., A preliminary study of atmospheric waves using radiosonde data, Q. J. R. Meteorol. Soc., 83, 49–60, 1957.

Fritts, D. C., C. Bizon, J. A. Werne, and C. K. Meyer, Layering accompanying turbulence generation due to shear instability and gravity-wave breaking, J. Geophys. Res., 108, 8452, doi:10.1029/2002JD002406, 2003.

Fukao, S., H. Luce, T. Mega, and M. K. Yamamoto, Extensive studies of large-amplitude Kelvin–Helmholtz billows in the lower atmosphere with VHF middle and upper atmosphere radar, Q. J. Roy. Meteor. Soc., 137, 1019 – 1041, 2011.

Gallice, A., F. G. Wienhold, C.R. Hoyle, F. Immler, and T. Peter, Modeling the ascent of sounding balloons: derivation of the vertical air motion, Atmos. Meas. Tech., 4, 2235-2253, 2011.

Houchi, K., A. Stoffelen, G.-J. Marseille, and J. De Kloe, Statistical quality control of high-resolution winds of different radiosonde types for climatology analysis, J. Atmos. Ocean. Tech., 32, 1796-1812, 2015.

Johansson, C., and H. Bergström, An auxiliary tool to determine the height of the boundary layer. Bound.-Layer Meteor., 115, 423–432, 2005.

Supprimé: 4

Kinoshita, T., R. Shirooka, J. Suzuki, S.-Y. Ogino, S. Iwasaki, K. Yoneyama, U. Haryoko, D. Ardiansyah, and D. Alyudin, A study of gravity wave activities based on intensive radiosonde observations at Bengkulu during YMC-Sumatra 2017. IOP Conf. Series: Earth and Environmental Science, 303, 012011, doi:10.1088/1755-1315/303/1/012011, 2019.

Kirshbaum D. J., and Durran D. R., Factors governing cellular convection in orographic precipitation. J. Atmos. Sci., 61, 682–698, 2004.

Kudo, A., H. Luce, H. Hashiguchi, R. Wilson, Convective instability underneath midlevel clouds: Comparisons between numerical simulations and VHF radar observations. J. Appl. Meteor. Climatol., 54, 2217-2227, 2015.

Lalas, D. P., and F. Einaudi, Tropospheric gravity waves: Their detection by and influence on Rawinsonde balloon data, Q. J. R. Meteorol. Soc., 109, 855–864, 1980.

Luce, H., L. Kantha. H., Hashiguchi and D. Lawrence, Turbulence kinetic energy dissipation rates estimated from concurrent UAV and MU radar measurements. Earth Planets Space, 70, 207, 2018.

Luce, H., L. Kantha, H. Hashiguchi, and D. Lawrence, Estimation of Turbulence Parameters in the Lower Troposphere from ShUREX (2016–2017) UAV Data, Atmosphere, 10, 384, doi:10.3390/atmos10070384, 2019.

McHugh, J. P., I. Dors, G. Y. Jumper, J. R. Roadcap, E. A. Murphy, and D. C. Hahn, Large variations in balloon ascent rate over Hawaii. J. Geophys. Res., 113, D15123, doi:10.1029/2007JD009458, 2008.

McKelley, C. Y. Chen, R. R. Beland, R. Woodman, J. L. Chau, and J. Werne, Persistence of a Kelvin-Helmholtz instability complex in the upper troposphere, J. Geophys. Res., 110, D14106, doi:10.1029/2004JD005345, 2005.

Muschinski, A., Possible effect of Kelvin-Helmholtz instability on VHF radar observations of the mean vertical wind, J. Appl. Meteorol.,35, 2210–2217, 1996.

Röttger, J., and M. F. Larsen. UHF/VHF radar techniques for atmospheric research and wind profiler applications. In Radar in Meteorology; Atlas, D., Ed.; American Meteorological Society: Boston, MA, USA, Chapter 21a, 1990.

Reid, S. J., An observational study of lee waves using radiosonde data, Tellus, 24, 593–596, 1972.

Reeder, M. J., N. Adams, and T. P. Lane, Radiosonde observations of partially trapped lee waves over Tasmania, Australia, J. Geophys. Res., 104, 16719–16727, 1999.

Shutts, G. J., M. Kitchen, and P. H. Hoare, A large amplitude gravity wave in the lower stratosphere detected by radiosonde, Q. J. R. Meteorol. Soc., 114, 579–594, 1988.

Söder J., M. Gerding, A. Schneider, A. Dörnback, H. Wilms, J. Wagner, and F.-J. Lübken, Evaluation of wake influence on high-resolution balloon-sonde measurements, Atmos. Meas. Tech., 12, 4191-4210, 2019.

Son, K., Choi, J., Jeon, W., and Choi, H. Effect of free-stream turbulence on the flow over a sphere, Phys. Fluids, 22, 045101, doi:10.1063/1.3371804, 2010.

Tsuda, T., Y. Murayama, H. Wiryosumarto, S. W. B. Harijono, and S. Kato, Radiosonde observations of equatorial atmosphere dynamics over indonesia Part2: Characteristics of gravity waves, J. Geophys. Res., 99, 104507–10516, 1994.

Wang, J., Bian, J., Brown, W. O., Cole, H., Grubisic, V., and Young, K., Vertical air motion from T-REX radiosonde and dropsonde data, J. Atmos. Ocean. Tech., 26, 928– 942, 2009.

Worthington, R. M., A. Muschinski, and B. B. Balsley, Bias in mean vertical wind measured by VHF radars: significance of radar location relative to mountains, J. Atmos. Sci., 58, 707-723, 2001.

Yamamoto, M. K., M. Fujiwara, T. Horinouchi, H. Hashiguchi, and S. Fukao, Kelvin-Helmholtz instability around the tropical tropopause observed with the Equatorial Atmosphere Radar, Geophys. Res. Let., 30, 1476, doi:10.1029/2002/GL016685, 2003.

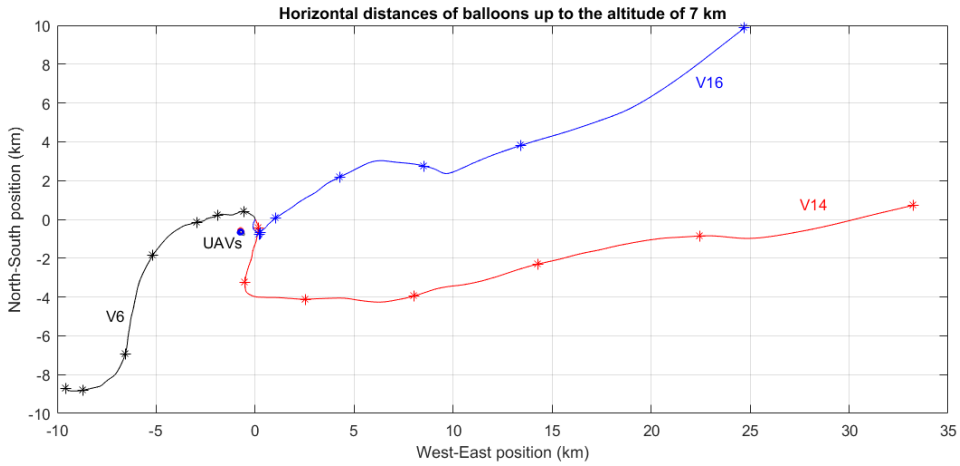

Figure 1. Horizontal trajectories of the meteorological balloons V6, V14 and V16. Each * symbol shows altitudes of 1 km, 2 km, etc, up to 7 km. The position (0,0) corresponds to the location of the Shigaraki MU Observatory. The circular patterns of the UAV trajectories are also shown.

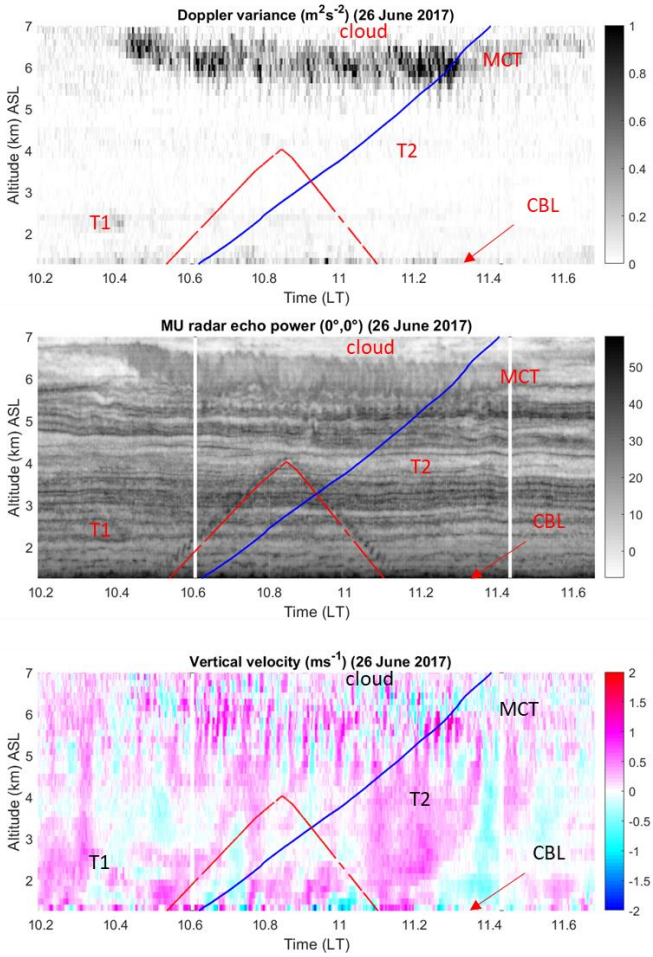

Figure 2. (Top) Time-height cross-section of variance of the Doppler spectrum peaks corrected from the beam-broadening effects obtained from MU radar measurements during balloon flight V14 and UAV flight SH29. The altitudes of V14 and SH29 vs time are given in red and blue lines, respectively. (Middle). Same as top for radar echo power (dB) in range imaging mode. (Bottom) Same as top for vertical velocity (ms^{-1}). See e.g. Luce et al (2018) for more details about these figures. Labels refer to the location of turbulent layers.

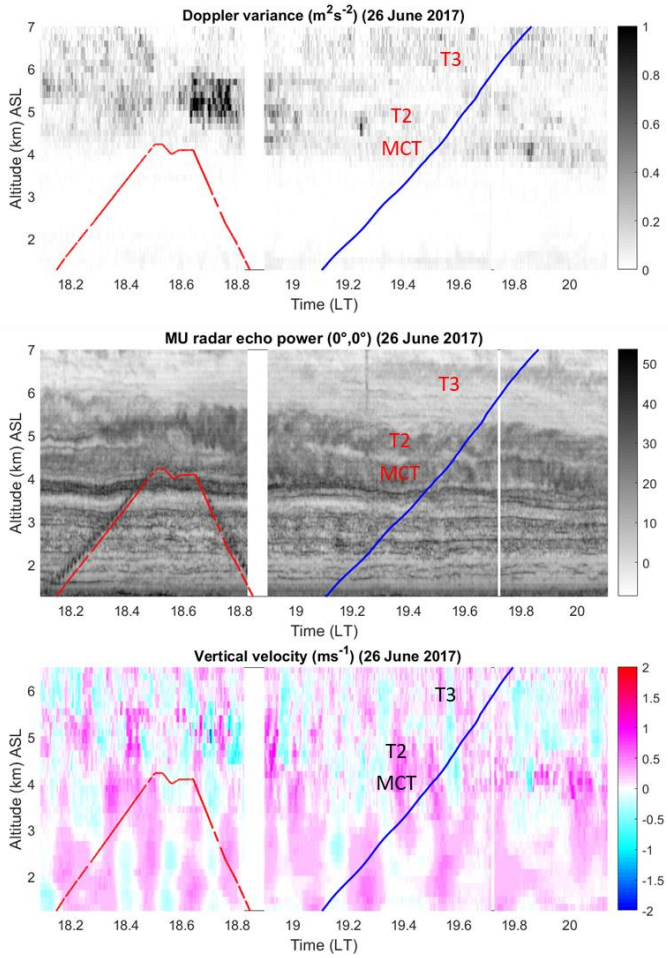

Figure 3. Same as Fig. 2 for SH31 and V16.

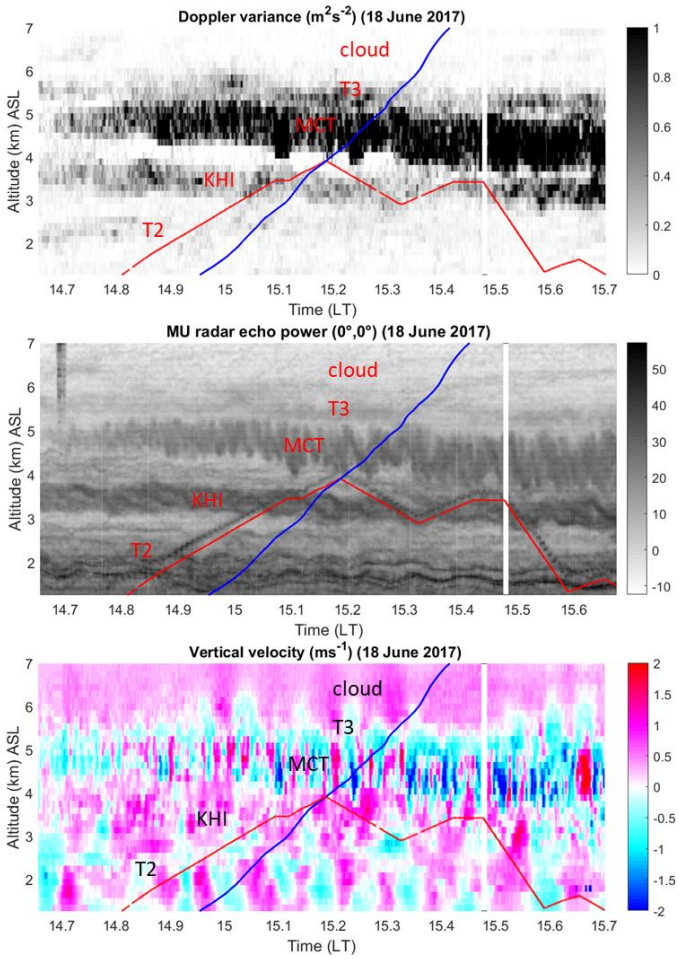

Figure 4. Same as Fig. 2 for SH14 and V6.

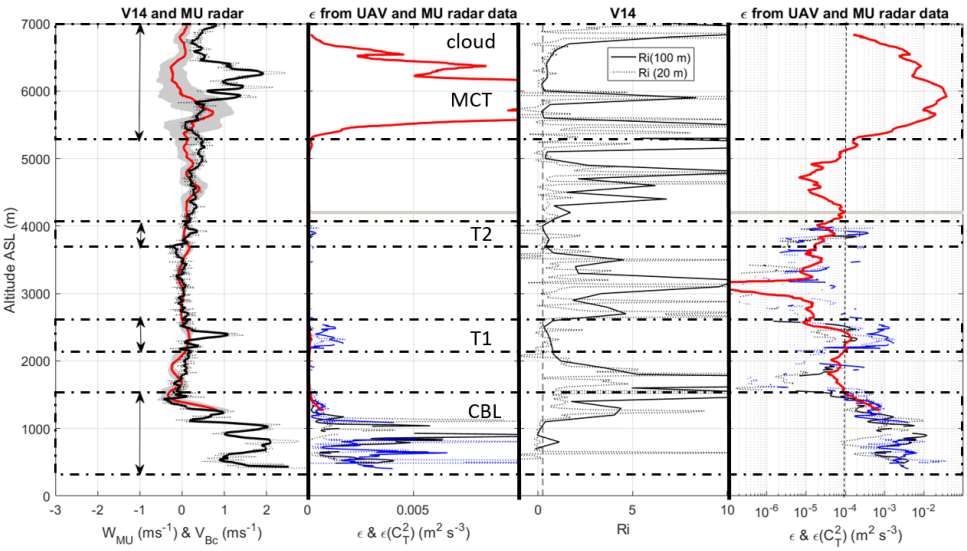

Figure 5. (a) Vertical profile of V_{Bc} (ms^{-1}) (solid black: smoothed, dotted black: raw) **for V14** and W_{MU} (ms^{-1}) (red) . The gray area shows the standard deviation of W_{MU} over the averaging time (2 minutes). The vertical arrows indicate the altitude ranges affected by turbulence. (b) Vertical profiles of TKE dissipation rates ε obtained from MU radar measurements (red) and UAV measurements during ascent and descent (black and blue) and using the direct and indirect methods (solid and dashed lines). The maximum altitude reached by the UAV is shown by the horizontal gray line. (c) Vertical profiles of Richardson numbers at resolution of 20 m (dashed) and 100 m (solid). The vertical dashed line indicates *Ri=0.25*. (d) Same as (b) in log scale. The vertical dashed line indicates the value of $\varepsilon = 10^{-4}\ m^2 s^{-3}$.

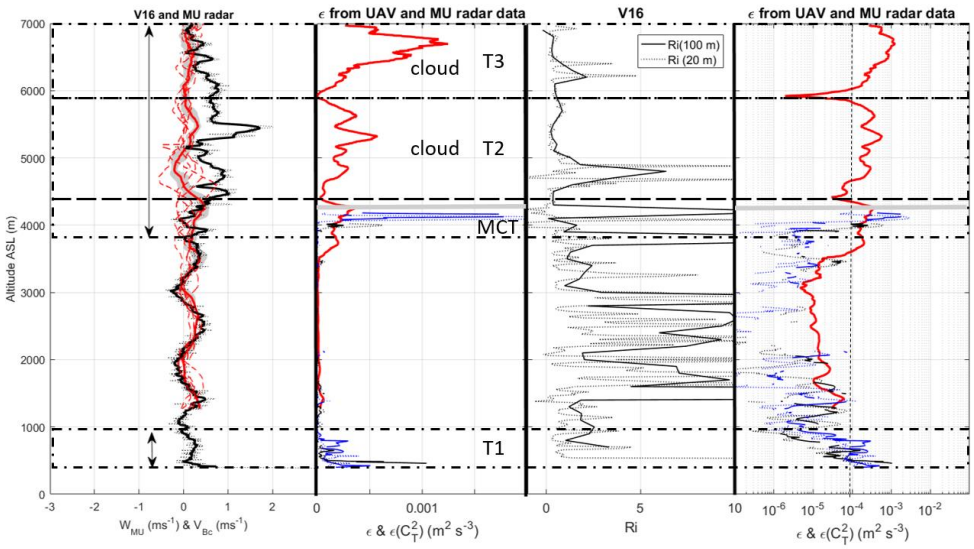

Figure 6. Same as Fig. 5 for V16.

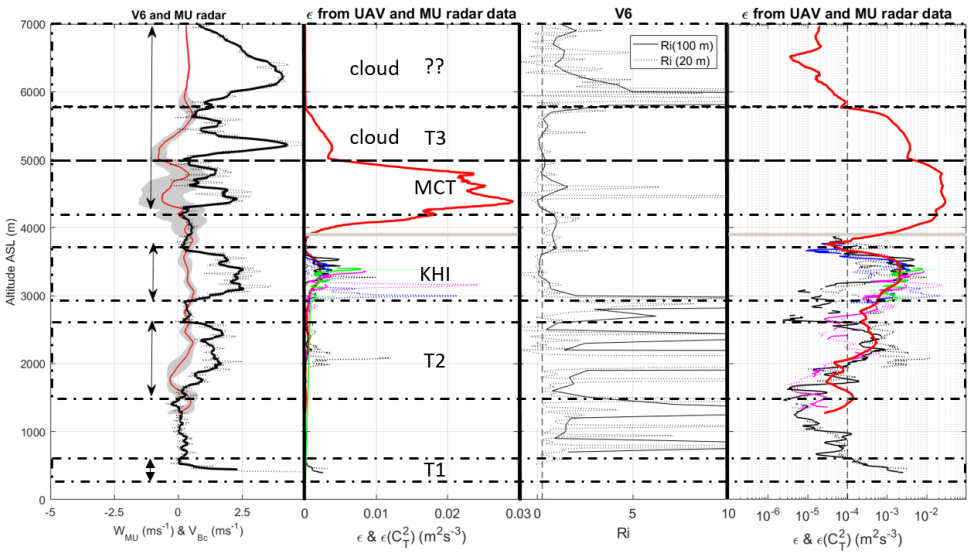

Figure 7. Same as Fig. 5 for V6.

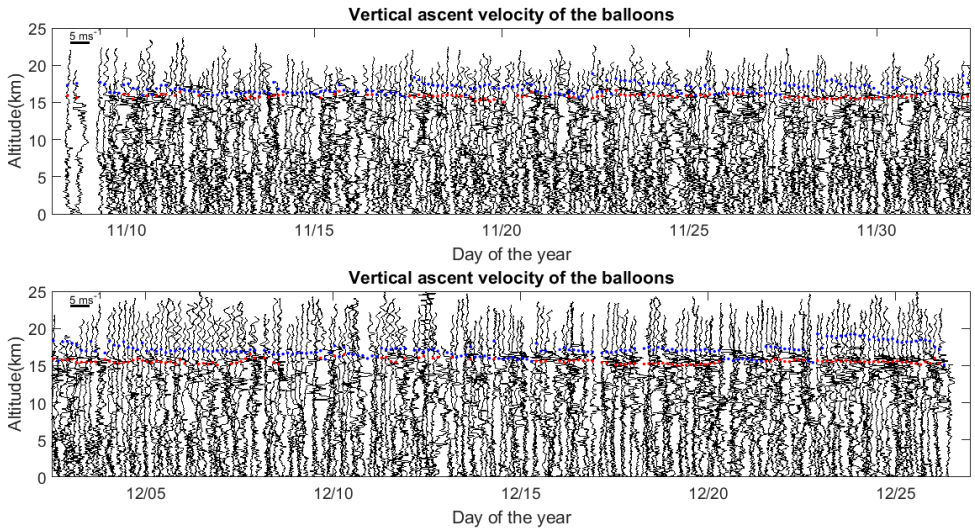

Figure 8. Vertical profiles of V_B from 376 consecutive balloons launched about every 3 hours from Nov 08 to Dec 27, 2015 during pre-YMC campaign at Bengkulu (102.26E, -3.79S, Indonesia). 0.5 day corresponds to 5 ms^{-1} and each profile was shifted by about 0.125 day (1.25 ms^{-1}). The cold point temperature tropopause and a secondary temperature inversion of similar intensity at lower altitude are shown in blue and red dots, respectively.

Supprimé: 6

Supprimé: in

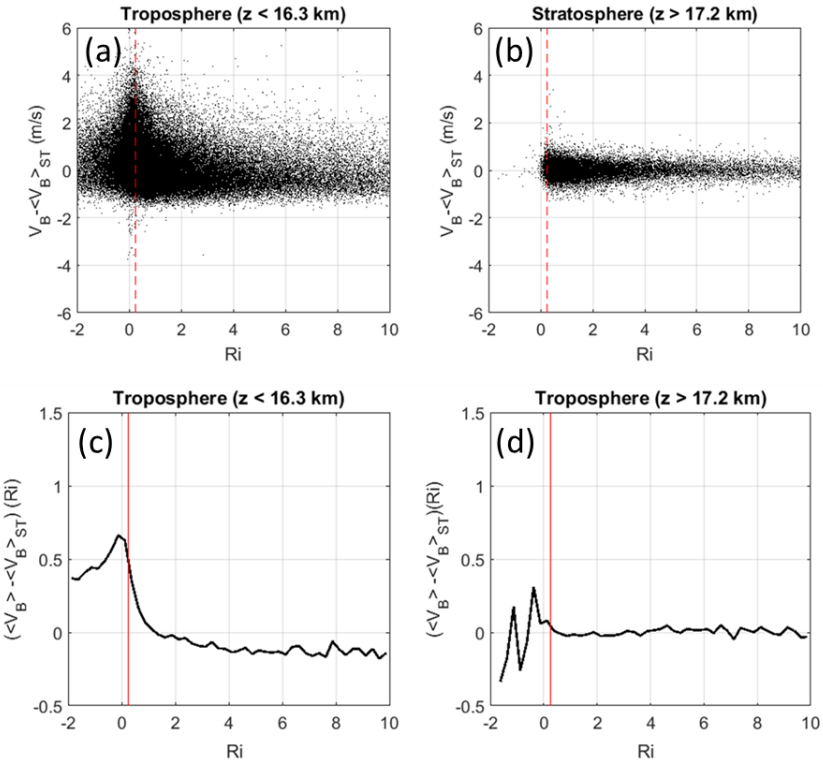

Figure 9. (a) Scatter plot of $V_{Bc} = V_B - \langle V_B \rangle_{ST}$ versus moist Ri for the troposphere. (b) Same as (a) for the stratosphere. (c) Mean values of V_{Bc} in Ri bands of 0.25 in width for the troposphere. (d) Same as (c) for the stratosphere. The vertical red lines show $Ri_c = 0.25$.

Mis en forme : Police :(Asiatique) MS Mincho, (Asiatique) Japonais

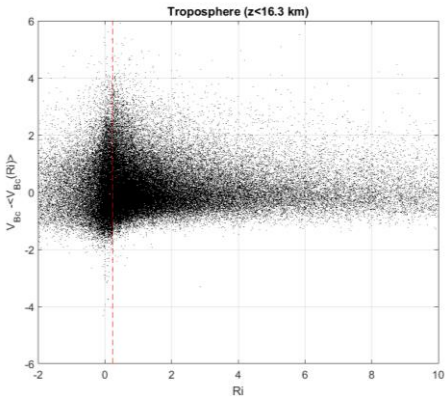

Figure 10. Same as Fig. 9a after removing the mean tendency shown by Fig. 9c for the troposphere. The vertical dashed lines shows $Ri_c = 0.25$.

Supprimé: (a)

Supprimé: . (b) Same as (a) for the stratosphere

Supprimé: horizontal