Reply to Prof. McHugh

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 (our discussion will be tempered in the revised version) but we believe that it is not unrealistic. We discuss more thoroughly this hypothesis from additional materials and examples shown below.

It should be stressed 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, 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. (NB: Calculating Ri profiles for the cases shown in Figures 3-6 would be useful for confirming or not the present assertion based on a simple and inaccurate visual inspection of the figures).
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 of the order of 1 m/s (section 3) but McHugh et al. observed increases up to 7 m/s, suggesting that turbulence effects alone cannot explain the phenomenon[1].

   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 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

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[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.

[2] According to Figures 3-7, it seems to be larger than 5 m/s.

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

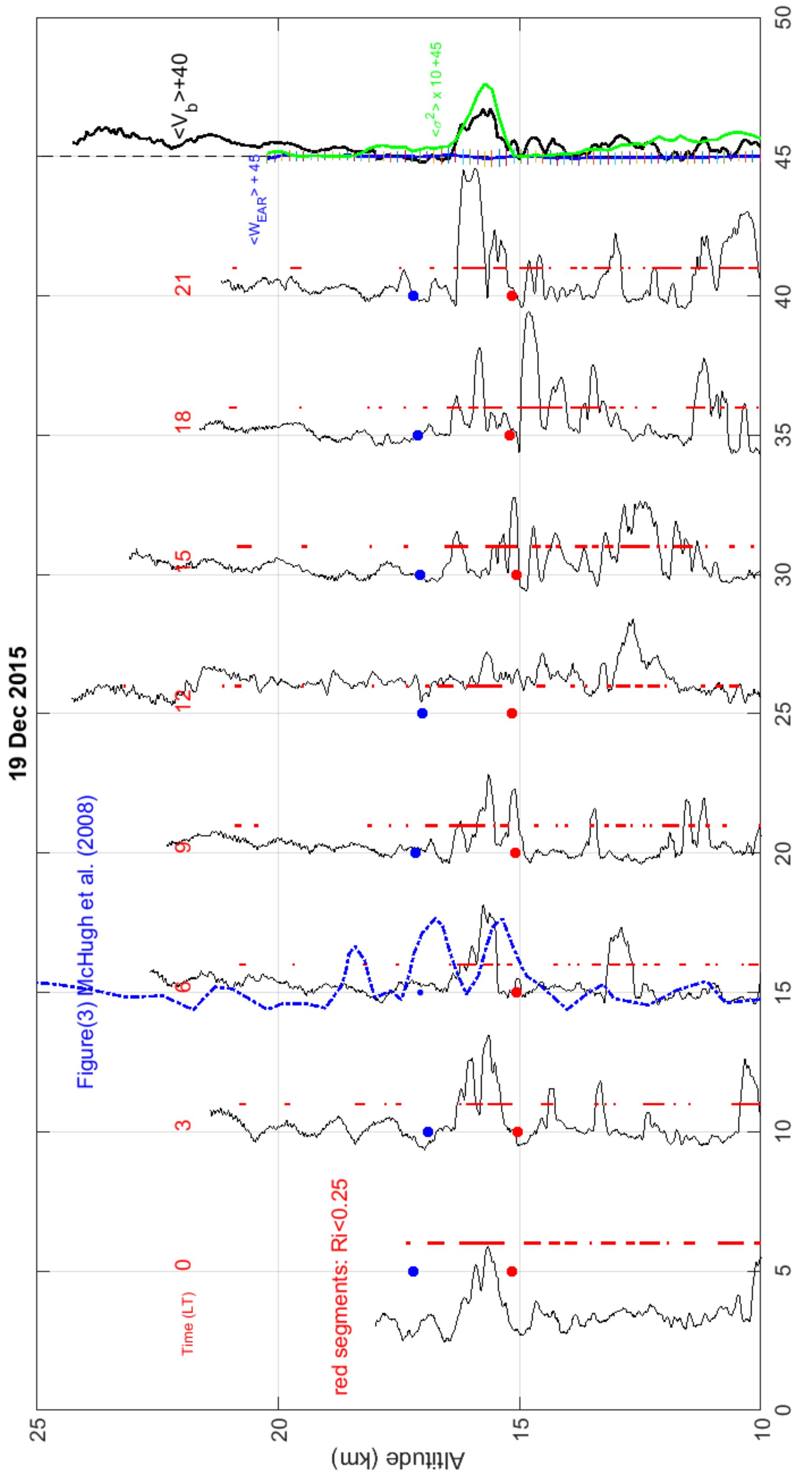
[4] The results below 10 km are not shown for legibility of the figure.

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 believe that turbulence may produce ascent rate increases similar to those reported by McHugh et al. if the balloons are inflated for an ascent rate of ~5 m/s in still air.

We now provide 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, A*nn. 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 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 cannot 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.



b

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

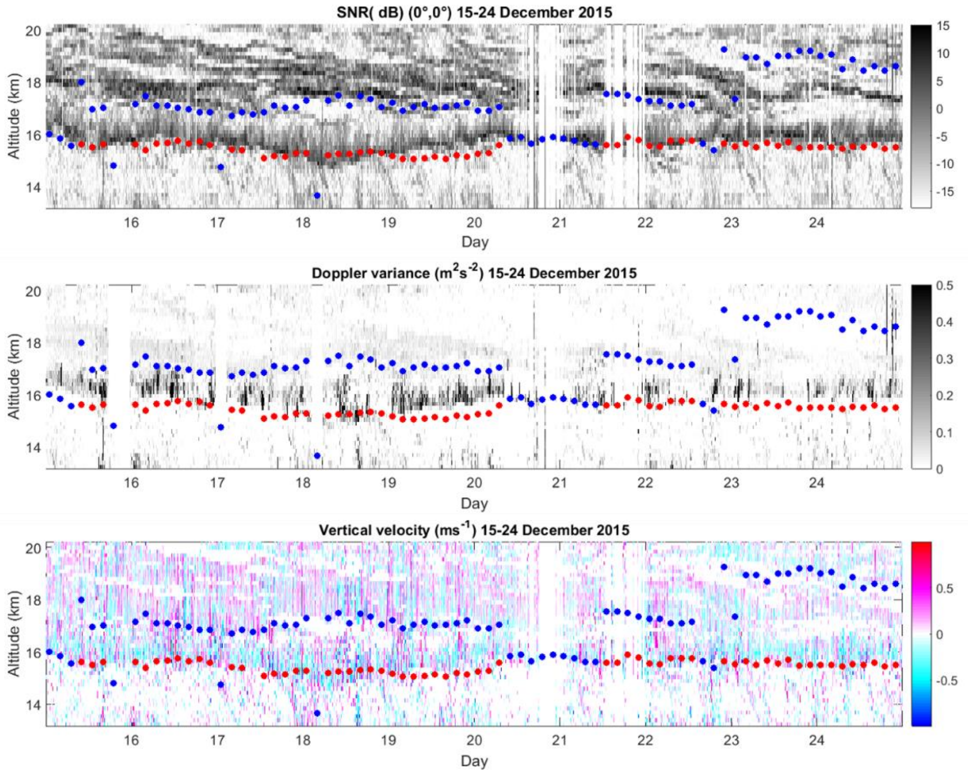


Figure 2: Equatorial Atmosphere Radar measurements of SNR at vertical incidence (top), Doppler variance (center) and vertical velocity (bottom)