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Atmospheric Chemistry and Physics
Discussions

Interactive comment on "Case study of wave breaking with high-resolution turbulence measurements with LITOS and WRF simulations" *by* Andreas Schneider et al.

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Author response to Anonymous Referee #3

Major comments

- *The main point made by the authors is that an increase in GW breaking is associated to the increase in turbulence dissipation. If the authors mean that high GW* leads *to stronger turbulence, I agree. But the I would be cautious to generalize this statement implying (as the authors say at the end of Conclusions), that turbulence in the atmosphere is generated by continuous GW activity because*

  the latter is only one *of the causes triggering turbulence in the atmosphere (other drivers are large-scale convention, shear instabilities, etc. which do not necessarily involve GW).*

  We mean that high GW leads to stronger turbulence. This is seen in our measurements by large dissipation for large GW amplitudes and low dissipation for small GW amplitudes. Of course, other sources could contribute to turbulence as well when present. At the end of our conclusions, we have removed the word "generally" which may have been mistakable, i. e. the sentence now reads: "Altogether, observed dissipation is weaker during lower wave activity (as seen in WRF), and larger where larger wave amplitudes are seen."

- *I do not believe that WRF can provide reliable information on turbulence characteristics in the chosen simulation set-up, at least the authors didn't show substantial evidence it can. The main is reasons is of course the coarse resolution: 2 km is not even close to resolve eddies in a substantial (and potentially relevant to observational data) portion of the inertial range, should turbulence develop following GW breaking. Indeed, the discussion on the simulation results rely entirely on the supposed correctness of the modeled TKE transport rather than the resolution of turbulent scales! In addition, there are no details on the TKE parameterization used in the runs so it is not clear whether such parametrizing is correctly tailored to the cases analyzed. There's a huge literature on DNS/LES modeling of turbulent stratified flows -which apply to atmospheric turbulence as wll- discussing these issues. You can refer to the review study by Brethauwer et al, JFM 2007 and to more recent works such as Kani and Waite, JFM 2014, and Paoli et al, ACP 2014 in addition to the work by Fritts and coworkers on GW breaking that you cited.*

  We agree that our WRF simulations cannot simulate GW breaking of small-scale GWs with horizontal wavelengths smaller than about 10 km. Wave breaking can, however, also occur for larger-scale GWs, which are explicitely resolved by the model. Ehard (2016) show regions of wave breaking at altitudes between 25 km to 30 km by means of convective overturning and reduced Richardson numbers, which was simulated by WRF with grid distances of 2 km. In our paper we use WRF to get an overview of the meteorological situation and to detect regions along the balloon ascent, where increased subgrid-scale turbulent diffusion (increased TKE) was simulated by means of the boundary layer scheme. This scheme is described in Nakanishi and Niino (2009). We added some additional sentences and citations about this issue in Section 2.2.

- *I agree with your consideration on Richardson number and the difficulty to match the theoretical Ri=0.25 threshold for shear instability in real atmospheric situations. To support your discussion, you may also refer to the work by Paoli et al, ACP 2014 where they used high- resolution LES (with grid sizes of order of meters) to study atmospheric turbulence at the tropopause level. They observed similar trend of Ri as a function of altitude (ex their Figs. 9- 10), and discussed the impact of turbulence intensity and the sensitivity to resolution, which can also apply to the measured profiles shown in your Fig 1c, 3c etc.*

  We agree that the vertical resolution has an impact on the Richardson number. Usually, a larger vertical resolution (i. e. smaller scales resolved) yields locally smaller Ri because for lower resolution Ri is potentially averaged over regions with low and high Ri. This has already been examined, e. g., by Balsley et al. (2008) and Haack et al. (2014). We have added a few sentences in our manuscript discussing this issue:
  "It should be kept in mind that the Richardson number depends on the scale on which it is computed (e. g. Balsley et al. 2008; Haack et al. 2014). A higher resolution (i. e. computing Ri on smaller scales) may result in locally smaller Ri numbers, because the computation on large scales yields a kind of average. Similarly, Paoli et al. (2014) found in LES simulations larger Richardson numbers for smaller model resolutions (i. e. larger scales). Here, due to measurement noise

a smoothing over 150 m has been applied before computing Ri, determining the resolution. However, this issue cannot explain the whole discrepancy. Haack et al. (2014) examined the impact of the scale on which Ri is computed on the relation between small Richardson numbers and turbulence. They found many turbulent patches for $Ri > 1$ even even when computing Ri on a scale of 10 m."

- *It would very much benefit to the paper showing turbulence spectra or structure functions, particularly in the inertial range, and especially for the cases of developed turbulence where an inertial range should be neatly detected.*

  Examples of anemometer voltages and corresponding spectra for the LITOS retrievals are shown in previous papers, e. g. Theuerkauf et al. (2011); Haack et al. (2014); Schneider et al. (2015). Since in principle we use the same retrieval, these are not shown again.

Minor comments

- *What is the reason for adding a legend of K/d in addition to W/kg in the dissipation profiles of Figures 1d, 3d, etc? In fact, I also found a little weird to label the units of dissipation rate as W/kg instead of m^2/s^3 or cm^2/s^3 which is more customary in turbulence literature.*

  In some communities it is usual to give dissipation rates as heating rates in K/d, which are connected via $\mathrm{d}T/\mathrm{d}t = \varepsilon/c_p$; thus we have added this scale as second axis. W/kg is the same as m^2/s^3.

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