Discussions for “Cirrus and water vapour transport in the tropical tropopause layer – Part 2: Roles of ice nucleation and sedimentation, cloud dynamics, and moisture conditions” – Reviewer B

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We would like to thank the reviewer for the thoughtful comments that have helped us revise and improve the manuscript. Accordingly, additional descriptions for model configurations, ice number concentrations and in-cloud relative humidities have been added to the revised manuscript. Please see the highlighted text and the new Fig. 3 in the revised manuscript for the changes.

We have changed the title of the manuscript (now “Cirrus and water vapour transport in the tropical tropopause layer – Part 2: Roles of ice nucleation and sedimentation, cloud dynamics, and moisture conditions”). This work emerged from Dinh et al. (2012), i.e. Part 1, but it took us longer than expected to publish it. Hence, we originally did not call it Part 2, but in light of the reviewer's comments that wish for more thorough discussions of model setups and several important results that have been addressed in Dinh et al. (2012), we reconsidered our position, and label it as Part 2. References in the text to Dinh et al. (2012) are provided, including:

- “This work follows up on a case modelling study by Dinh et al. (2012), who simulated a TTL cirrus cloud with characteristics similar to observations.”
- “The simulations build on previous model development by Dinh et al. (2012), to which the readers may wish to refer for technical details omitted here.”
- “The base-state (unperturbed) temperature profile $\tilde{T}(z)$ is taken from a sounding typical for the tropics (see Dinh et al., 2012, Fig. 1).”

- “The 2D profiles of q_v and $\mathrm{RH_i}$ for the dry scenario are illustrated in Dinh et al. (2012, their Fig. 4).”
- “These initial conditions, in combination with the Kelvin wave forcing, produce thin cirrus clouds around the tropopause that are both similar to observations (see Dinh et al. (2012) for detailed comparison between model simulations and observations) and confined within the model domain for the entire duration of simulation.”
- “The cloud evolution in the 2D domain in the all-phys simulation for the dry scenario is illustrated in the supplemental animation of Dinh et al. (2012).”

Below please find our detailed responses to the reviewer’ comments.

1. ***Reviewer*** — The entry of water vapour into the stratosphere or equivalently the issue of dehydration is closely related to the microphysical issue of low ice number concentrations in the TTL. Low concentrations would lead to less effective relaxation to equilibrium of the clouds; thus, high water vapour concentrations will remain and may be transported into the stratosphere. This correlation should be emphasised in the study in more details. Actually, ice crystal number concentrations and relative humidities obtained during the long-term simulation should be evaluated. The number concentrations should be compared with measurements as reported by Krämer et al. (2009) and Jensen et al. (2010). The simulations should mostly produce low concentrations, since the large-scale forcing is quite small. Thus, I would expect that the cloud should contain (high) ice supersaturation; in terms of the analysis of the upward water vapour transport, this might be an issue since for downward moisture transport during cloud lifting, less supersaturation outside the cloud is required. Thus, the distribution of relative humidity inside/outside clouds should be checked carefully.

   Authors — Detailed comparison of cloud characteristics (cloud lifetime, ice number concentration, ice water content, ice crystal size distribution, cloud radiative heating, ...) between model simulations and observations (by Krämer et al. (2009); Jensen et al. (2010) as well as many others) have been provided in Dinh et al. (2012, Sects. 4.2 and 4.3). In the revised manuscript, we mentioned that the readers may find these comparisons in Dinh et al. (2012). The comparison indicates that the characteristics of the simulated clouds agree with observations.

We have shown the ice number concentration in Fig. 1b. In addition, the analysis for in-cloud relative humidities is now included and presented in Fig. 3. Please see the last paragraph of Sect. 3.1 for the relevant discussion. The results indicate that, on average over the cloudy area, the ice number concentration generated in the model is sufficiently high (but is within observations) such that the distribution of in-cloud relative humidities maximises at 100 %; that is, the largest fraction of the cloudy air is maintained close to saturation throughout the cloud lifetime. There is a realistic spread of RH_i to values above/below 100 % in regions subject to mixing with environmental air and/or where the ice number concentration is low.

2. ***Reviewer*** — Although the model might be explained in details in former publications, please repeat the key details of the microphysics parameterisation and the dynamics (e.g. underlying equations). The resolution of the model seems to be quite unbalanced, the horizontal grid spacing is quite large compared to the vertical spacing. The size distribution seems to be quite narrow, I would expect ice crystals larger than $50\,\mu$m in the TTL. The radiation parameterisation is not clear to me. Do you use an explicit radiation transfer model for calculating heating rates of ice crystals online? Please clarify these issues.

   Authors — The equations describing the dynamical core of the model are quite complex and have been provided in Dinh et al. (2012, their Sects. 3 and 4). Please see the descriptions for the microphysical processes in Sect. 2.2 of the revised manuscript. The radiation scheme is mentioned as in: "Additionally, we compute the cloud radiative heating that results from the absorption of radiation by ice crystals using the radiative transfer scheme described in Durran et al. (2009, their Sect. 3a)."

   The spatial resolution has been chosen specifically for TTL cirrus, which are very thin (~ 1 km in thickness) but very wide (hundreds up to a few thousand kilometres in width). Our model calculations (not shown) indicate that the results are more sensitive to the vertical resolution than the horizontal resolution. Also, Jensen et al. (2010) show that the relative humidities and cloud properties observed in TTL cirrus change sharply in very thin layers (of a few metres). In addition, Murphy (2014) suggests that high vertical resolution (again, on order of a few metres) is required to accurately compute ice sedimentation for TTL cirrus.

   Please see Dinh et al. (2012, Fig. 7), where we showed that the size distribution of ice crystals is consistent between model and observations.

3. ***Reviewer*** — The setup of the scenarios is not clear at all. Vertical profiles of relative humidity and temperature would help; it is not clear how the humidity profiles look like for the different cases (dry versus moist). In addition, the stratification is of high interest, since during the simulation the stable layers are destabilised by radiation feedback. As remarked above, it would be interesting if a change in stratification would crucially change the results (i.e. the moisture transport). Please be aware of that the absolute values of the $\mathrm{RH_i}$ profile in Jensen et al. (2005) are much too high and can be explained by measurement errors (see recent comparison and evaluation by Fahey et al. (2014).

   Authors — The vertical profile of temperature can be found in Dinh et al. (2012): "The base-state (unperturbed) temperature profile $\tilde{T}(z)$ is taken from a sounding typical for the tropics (see Dinh et al., 2012, Fig. 1)." We also added that "the 2D profiles of q_{v} and $\mathrm{RH_i}$ for the dry scenario are illustrated in Dinh et al. (2012, their Fig. 4)."

   The cloud radiative heating results in (i) a cloud-scale circulation and (ii) small-scale convection in the destabilized layer at the cloud top. Both of these have impacts on the cloud evolution and the water vapour transport. We have not specifically separated the impacts of the cloud-scale circulation from that of convection, and think the discussion provided is sufficient for this paper, but agree that in a next step this question could be addressed.

   We added a footnote:"Note that the recent comprehensive instrumentation evaluation by Fahey et al. (2014) suggests that measurement errors may have caused overestimation in the relative humidity reported in Jensen et al. (2005)."

4. ***Reviewer*** — The cloud evolution (as shown in Fig. 2) should be explained in more details, since this is the major result leading to differences between dry and moist profiles. For instance, you have to explain why the ice crystals become larger in the moist scenario. Which processes lead to larger crystals, is it just enhanced diffusional growth or do other processes play a role? 2D plots of relative humidity and ice mass/number concentrations might also help for clarification.

   Authors — The reason for larger ice crystals in the moist scenario has been provided in the manuscript, and as below:

   "The radiatively induced horizontal motions widen the cloud tops and narrow the cloud bases. As the clouds deform into trapezoidal shapes (Fig. 2), ice crystals fall into initially clear air at the (tilted) lateral sides of the clouds (and also at the bases of the clouds). At the sides of the clouds in regions subject to horizontal inflow of environmental air, ice crystals grow to larger sizes in the moist scenario (where the ambient air is supersaturated) than in the dry scenario (where the ambient air is subsaturated)."

Please see Dinh et al. (2012, Fig. 4) for the 2D profile of RH_i.

5. ***Reviewer*** — It seems that the forcing of the whole scenario is exclusively given by large-scale Kelvin waves. Although this might be appropriate for an idealised investigation, the role of gravity waves in the TTL and their impact on cirrus clouds should not be neglected. Former studies addressed this issue from a microphysical point of view (e.g. Spichtinger and Krämer (2013); Jensen and Pfister (2004) and it should be mentioned at least.

   Authors — The cloud radiative heating generates gravity waves, and these are resolved in the all-phys simulations. We have added the following discusssions to Sect. 2.2 of the manuscript: "As further discussed in Sect. 3.1, the cloud radiative heating induces (i) a cloud-scale circulation (itself a gravity wave signal) and (ii) small-scale convective cells at the cloud top, whose buoyancy forces generate small-scale gravity waves which propagate vertically outwards from the convective layer (see also Dinh et al. (2010)). The all-phys simulations fully resolve the perturbations (in both temperature and velocities) of these gravity waves generated by the cloud radiative heating. The importance of gravity waves to the microphysical processes in TTL cirrus has also been suggested by Jensen and Pfister (2004); Spichtinger and Krämer (2013)." We hope to address the roles of gravity waves more thoroughly in a follow-up paper by adding gravity waves generated by other sources outside clouds.

6. ***Reviewer*** — Figure 6 is very hard to understand; maybe you could try to make a simple version of it to explain the main features in a simpler way.

   Authors — We have not come up with a simpler way to present this information. However, we have rewritten a large part of Sect. 3.3, which is hopefully clearer now. Please also see our responses to Comments 6 and 8 of Reviewer A.

7. ***Reviewer*** — The supplement is not very user-friendly; it would be much better to upload the short movies in a common format instead of embedding

them into a pdf file. Please change the format of the supplement accordingly.

Authors — The movies will be also provided in GIF format. Also, we have used a frame at $t = 3.5\,\mathrm{d}$ of the movies as Fig. 6 of the revised manuscript.

References

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