A modelling case study of a large-scale cirrus in the tropical tropopause layer

February 13, 2016

We would like to thank the reviewer for the insightful evaluation of our work. Please find below our point-by-point reply.

 Reviewer — 1) Motivation for this study: In the introduction the authors explain that they focus on this specific cirrus event as it was previously observed and described in Taylor et al. (2011). They should add in the introduction some description of the results of Taylor et al. (2011) so that the readers can understand what were the main results of this study to better justify the focus of this specific cirrus event. There is only one sentence at Line 13 "Taylor et al. (2011) have discussed observations of this cloud" and this sounds rather brief.

Authors — We agree, we have added a paragraph in the introduction with a short description of the results of Taylor et al. (2011) and some motivation for our study.

2. Reviewer — 2) Section 2.2 provides a description of the parameterizations used in the WRF simulations. For cloud microphysics, the scheme of Thompson et al. (2004) is used but later in the paper other schemes are used for the sensitivity study (WSM5 and Morrison). Please add these schemes to Section 2.2 and a short description of how they handle ice cloud microphysics. The WRF model has many options for cloud microphysics and some justifications for the use of the scheme of Thompson are missing. Also please add when the simulations are initialized in this section. You mentioned that you performed a 4-day integration but not the initial date. It will help the readers understand that your simulations actually cover the full cloud life cycle.

Authors — Thanks for this comment. We have added the two other schemes in section 2.2, along with the references that were missing. A paragraph has also been added to describe the microphysical assumptions in the Thompson microphysics scheme and justify our choice. We have also added more tests on the sensitivity to ice nucleation, see the text and response to reviewer 1. Also, the time of the start of the simulation is now specified (January 27, 00:00 UTC).

3. **Reviewer** — 3) Comparison with CALIPSO observations: On Figure 1 do you understand why the WRF simulation does not show the extension of the cirrus cloud beyond 5N?

CALIOP shows a rather symmetric cirrus structure that is not seen in the WRF simulation. You later explained that a PV intrusion caused a large-scale uplift and corresponding TTL cooling that is important for the cloud formation. Do you think that extending the northern boundaries of the domain beyond 18N could have helped to improve the representation of the cirrus cloud in WRF?

Authors — Following the reviewer's comment, we have run an additional simulation using a larger domain, extending up to 28N and a 1-way nested domain run whose boundary conditions are taken from the run with a larger domain. The IWP above 14 km from the 1-way nested run is shown on figure 1 of the present reply. The northern limit of the cloud is not much changed. Also, we want to emphasize that, if along CALIPSO path the cloud does not extend beyond 5N in the reference simulation, a few degrees to the East the cloud field almost reaches 10N (see figure 1 of the paper). So this disagreement along the track does not necessarily mean that the actual and simulated clouds are so dissimilar regarding their northern extension. We have added a sentence mentioning this point in the paper.

4. **Reviewer** — 4) You mentioned a large difference of 3K between simulated and analyzed temperature fields in section 2.3. Since TTL water vapor and temperature are important for in situ cirrus cloud formation and thus for this case event, have you compared the model representation of TTL water vapor and temperature with observations? e.g. water vapor from MLS and temperature from COSMIC since there are very few radiosondes for this region.

Authors — We thank the reviewer for this comment, that allows us to discuss a difficult point. Actually, we have carried a comparison with MLS water vapour measurements, which are almost synchroneous and colocated with CALIOP measurements. The comparison did not prove satisfactory: while values at 100 hPa were much comparable, the observations below 100 hPa (around 121-147 hPa) were systematically dry biased compared to the simulations. The disagreement is of the same order as discrepancies between ECMWF analyses and MLS reported by Jiang et al. (2015) (up to 5 ppmv for our simulation without applying the averaging kernels). This discrepency could be a concern because 121-150 hPa is actually the main level of cirrus formation in the simulation. We do not think it is a major concern for our simulation, for the following reason: comparison of MLS and frost point measurement have shown a mean bias of 3 ppmv at 147 hPa in the tropics (after applying the averaging kernels) and differences have been reported to reach more than 2 ppmy at 121 hPa and 6 ppmy at 147 hPa, according to a comparison with Frost Point Hygrometer measurement on which the MLS averaging kernels were applied (Hurst and Coauthors, 2015). The sharp water vapour vertical gradients in this region, due to the cirrus, seem to make MLS measurements less reliable at that altitude. This points out the difficulty linked to the lack of in situ measurements in the tropical tropopause layer for real case simulations.

Regarding COSMIC observations, the ECMWF analyses assimilate them so we regarded the analyses as representative of those observations.

5. **Reviewer** — 5) "We do not look for any further validation of the microphysical properties of the cloud either (such as in cloud supersaturation and ice crystal number), because of the absence of observational data for this case." Even though you do not observational data for

this specific case, you could use results from other observational studies of cirrus clouds in the Eastern Pacific (e.g. Davis et al. [2010] or Jensen et al. [2013]) to compare qualitatively the properties (ice crystal number concentration, particle size, supersaturation) of this cirrus event. It could help to assess whether this specific cirrus event is representative of cirrus formation in the Eastern Pacific.

Authors — Following this reviewer's comment, and the comment of reviewer 1, we have added some comparison of our simulation and in situ observations in Table 2 of the revised paper and in the text; see also answer to reviewer 1.

6. **Reviewer** — 6) Lagrangian trajectories and air parcels on Figure 2. Could you add some descriptions release time and location of the air parcels? On Figure 2, does one point correspond to the center of mass of different points?

Authors — We have changed this figure and the displayed trajectories following reviewer 2's comments. The trajectories now displayed on the figure are released at 360 K on January 28, 10:00, at the horizontal position shown on the corresponding panel of figure 2; they are individual trajectories. This has been specified in the paper.

7. **Reviewer** — 7) For the radiative heating rates shown on Figure 8, in addition to the the comparison with ERAi radiative heating rates, you could also compare the WRF estimates with Figure 3 of Corti et al. (2006). Of course, the comparison would be only qualitative since you have heating rates from a 4-day simulation while Corti et al. used 6 years of balloon sonde measurements of temperature, ozone, and water vapor profiles from the SHADOZ network and cloud observations to compute mean full sky radiative heating rates in the tropics.

Authors — We have added their estimation on figure 7 of the paper. Corti et al.'s calculations predict a substantially stronger effect of local clouds but, as stressed by the reviewer, the comparison can only be qualitative as we examine here a specific cloud field over a specific region. We discuss the curves in the text.

References

- Hurst, D. and Coauthors: Water Vapor Measurement Biases in the TTL: MLS vs Frost Point Hygrometers, in: CT3LS meeting, Boulder, Colorado, URL http://esrl.noaa.gov/csd/events/CT3LS/presentations/wed-posters-4-hurst.pdf, 2015.
- Jiang, J. H., Su, H., Zhai, C., Wu, L., Minschwaner, K., Molod, A. M., and Tompkins, A. M.: An assessment of upper troposphere and lower stratosphere water vapor in MERRA, MERRA2, and ECMWF reanalyses using Aura MLS observations, Journal of Geophysical Research: Atmospheres, 120, 11,468–11,485, doi:10.1002/2015JD023752, URL http://dx.doi.org/10.1002/2015JD023752, 2015.



Figure 1: (Left) Simulated ATB along CALIOP track for the nested model run, on January 28 at 10:00 UTC. (Right) Ice water path above 14 km on January 28 at 10:00 UTC.