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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Diurnal cycle of clouds extending above the tropical tropopause observed by spaceborne lidar" *by* Thibaut Dauhut et al.

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We thank Anonymous Referee #1 for his/her comments. In the following we answer each of these comments. The line numbers refers to the version online since 8 October 2019, that differ of 6 with the line references used by Referee #1.

Note that we would like to slightly change the title for: "The diurnal cycle of the clouds extending above the tropical tropopause observed by spaceborne lidar". Also, to emphasize our results, a sentence will be added line 236: "These results highlight how much the evolution of stratospheric clouds can be undersampled by other spatial instruments restricted to 01:30 and 13:30 LT, that then miss for instance the first maximum and the deepest development of stratospheric clouds in the early night."

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Referee #1: The work focus on the use of the CATS lidar to look at stratospheric clouds. It provides a documentation of the diurnal cycle of these clouds over 5 regions of the tropical belt, during 3 summers (JJA) and 2 winters (DJF). Despite the interest of these clouds and the very attractive CATS dataset, I find the paper very light in terms of interpretation.This is currently only providing a documentation already available (as stated by the authors). There is no link with the diurnal cycle of convection (except a very very short mention to surface precipitation) and to the convective overshootings in general, while the regions that are sampled clearly link the observed clouds to the convective activity of the tropics. I thus propose a major revision: as it, the study do not bring somethingreally new, except the view proposed by CATS. This study could be very valuable if the link to convection, and its diurnal cycle, was made.

Authors' response: We agree to develop the discussion around the convection's diurnal cycle, and convection overshoots. The manuscript will be changed as described below.

Authors' changes in manuscript: We will add the following paragraph after the line 193 and the new paragraph [*] described below: "The very deep convection transports cloudy air masses beyond the tropopause via overshoots and then directly contributes to the stratospheric cloud fraction (Dauhut et al., 2016 and 2018). The diurnal cycle of the stratospheric cloud fraction observed by CATS can at the first order be explained by the diurnal cycle of very deep convection over land (Liu and Zipser, 2005), especially (i) the minimal value during daytime, and (ii) the first peak in the early evening. This first peak occurs with a delay of 3 to 4 hours compared to the very deep convection maximum. As the dataset used by Liu and Zipser (2005) is more sensitive to overshoots freshly developed into the stratosphere, this delay can be explain by the subsequent horizontal expansion of the overshoots and their spread by the winds (Dauhut et al., 2018; Lee et al., 2019). The convective generation of gravity waves, that produce transient cooling off the convective centres and in some conditions trigger cloud formation, can also contribute to the increase of the stratospheric cloud fraction after the

maximum of the very deep convection, and then explain the delay of the first peak and potentially the second peak. It may also explain the similar diurnal cycle over the ocean regions, either close (South Warm Pool Ocean) or remote (West Pacific) from land masses. This process remains to be investigated."

The sentences lines 236-238 will be changed for: "The very deep convective activity over tropical lands drives most of this diurnal cycle, and leads in particular to the minimal stratospheric cloud fraction during daytime and the second peak during nighttime, both consistent over all regions. Further investigation is though necessary to describe how convection contributes to this diurnal cycle, and to assess the role of other processes leading to stratospheric cloud formation like the gravity waves."

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Referee #1: Other comments - The first section is strangely organized : I suggest to start withthe current 2nd paragraph (starting with "Low-stratospheric clouds impact (...)", endingwith "evolution of such clouds") and then continue with the current 1st paragraph. The idea would be first to introduce the scientific question (low stratospheric clouds & their impact on the atmosphere) and second to present the way it will be looked at (spaceborne lidar).

Authors' response and Authors' changes in manuscript: We will exchange paragraph one and two (lines 23 to 50), thank you for the suggestion.

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Referee #1: At the end of the first section, the CATS liar is quickly mentioned. Since the CALIOP lidar is mentioned earlier, in the same section, it is not clear why to use CATS rather than CALIOP. The reader has to go to section 2.1 to understand why CATS is used. So a paragraph stating clearly the issue (obviously related to the 1:30pm/1:30am sampling, giving very few information on the diurnal cycle) with CALIOP is missing in section 1.

Authors' response: We will add a new paragrpah in the section 1 to motivate the use of CATS lidar observation

Authors' changes in manuscript: The following paragraph will be added before line 51: "Describing the diurnal evolution of the high-altitude clouds from a global perspective becomes possible with the CATS (Cloud-Aerosol Transport System) lidar operated from the International Space Station (ISS) between February 2015 and November 2017 (McGill et al., 2015). Thanks to the ISS non-synchronous orbit, CATS was able to probe the vertical cloud distribution of a particular region at different times of the day (not only 0130 and 1330 Local Time like CALIPSO instruments). Aggregating CATS detections over a region of interest and over enough time provides a statistical overview of the diurnal evolution of cloud vertical profiles over that region (Noel et al., 2018). Our work aims at using CATS observations to describe and understand better the diurnal evolution of the cloud fraction in the tropical stratosphere."

line 63 the acronym expansion will be deleted line 64 the reference will be deleted lines 70-76 will be deleted, only the following sentence is kept: "Between February 2015 and November 2017, the CATS lidar reported profiles at a vertical resolution of 60m every 350m along-track, with an average repeat cycle of nearly 3 days (Yorks et al., 2016)." and merged with the paragraph after. line 80, the time reference in the brackets will be deleted.

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Referee #1: Section 3 : If I count correctly DJF2015 does not exist since the CATS data start inFeb 2015. So there are 2 DJF and 3 JJA.

Authors' response and Authors' changes in manuscript: Indeed, only February and December are available in 2015. To make it more accurate we will change the titles of the panels of Figure 1 for "DJF months from Feb. 2015 to Nov. 2017 included" and "JJA months from Feb. 2015 to Nov. 2017 included".

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Referee #1: Section 3: the word "level" is used from time to time instead of "altitude" (lines 139;171). Please use "altitude" when it is adapted. The term level is too vague.

Authors' response: We will change the text accordingly. Authors' changes in manuscript: We will change "level" for "altitude" in lines: 99 (twice), 145, 177

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Referee #1: Section 3 / lines 147 to 175 : 3 paragraphs are dedicated to evaluate the distribu-tions found with CATS with respect to previous works performed with other instruments(HIRDLS - by the way, please expand : the reader don't know this one; CloudSat andSAGE-II). As underlined by the authors, it is difficult to compare the values obtainedwith the mentioned papers since they don't look at the same period. So the year-to-year variability explains largely the differences. That is why I don't understand thestructure of these 3 paragraphs. The year-to-year variability should be written at thebeginning, to explicitly say that the numbers found cannot be compared, and then go to the specificities of each instruments to explain the differences (occultation, radar,etc..). Now it is too repetitive.

Authors' response: We agree, the three paragraphs will be summarized into one.

Authors' changes in manuscript: lines 153 to 181 will be replaced by the following paragraph: "Our CATS results are also in very good agreement with the distributions of clouds near the tropopause from other space instruments: 2006-2007 HIRDLS (High Resolution Dynamics Limb Sounder) reported by Massie et al. (2010), 2006-2014 CloudSat observations (Kim et al., 2018), and the pioneering 1989 passive Stratospheric Aerosol and Gas Experiment (SAGE) II observations (Jensen et al., 1996). Besides the specificity in the cloud detection method employed by each instrument (occultation for HIRDLS and SAGE II, radar backscattering for CloudSat), the little differences between the distributions mostly come from the year-to-year variability. Larger differ-

ences can be found with the distributions of clouds penetrating the tropical tropopause derived from the 1998-2000 and 2002-2003 observations by the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (Liu and Zipser, 2005). The densities of overshooting systems with tops in the lower stratosphere (on which Liu and Zipser (2005) focused rather than all stratospheric clouds) are remarkably larger in Central America and Central Africa than over the Warm Pool. Since TRMM precipitation radar reflectivities are less sensitive to thin ice particles than CATS and CALISPO lidars, we can interpret this difference by the fact that the American and African systems, though frequently overshooting the stratosphere, produce less thin stratospheric clouds than the Asian systems, or other in-situ processes (like gavity wave cooling) are more efficient to produce stratospheric clouds over Asia than America and Africa.

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Referee #1: Also, I wonder if there is no diurnal cycle studies of these clouds performed using ground-based lidar. Is that so ?

Authors' response: Ground-based lidars have indeed already been used to document the diurnal evolution of high-altitude cirrus clouds. For instance using ground-based lidar measurements: Gouveia et al. (2017) documented the evolution of the integrated cloud fraction (no vertical distribution) over Amazonia, Sassen et al. (2003) documented the diurnal evolution of the composition of cirrus clouds over Salt Lake City, and Dupont et al. (2010) did the same over the SIRTA observatory in France. However, using ground-based lidar to document optically thin clouds extending above the tropopause, as we did in the present paper, is difficult for two reasons: 1) as our Fig. 1 shows, these clouds occur primarily in regions where operational ground-based sites are absent or very few (Pacific ocean, equatorial Africa, South America), and 2) these clouds are mainly associated with deep convection, which implies the presence of optically thick cloud systems in the troposphere beneath that will make in most cases impossible the successful probing of optically thin clouds near the tropopause due to the attenuation of lidar signal. This explains why we are not aware so far of any article

documenting the evolution of such clouds based on ground-based lidars.

Dupont, J.-C., Haeffelin, M., Morille, Y., Noël, V., Keckhut, P., Winker, D., Comstock, J., Chervet, P., and Roblin, A. (2010), Macrophysical and optical properties of midlatitude cirrus clouds from four ground-based lidars and collocated CALIOP observations, J. Geophys. Res., 115, D00H24, doi:10.1029/2009JD011943

Gouveia, D. A., Barja, B., Barbosa, H. M. J., Seifert, P., Baars, H., Pauliquevis, T., and Artaxo, P.: Optical and geometrical properties of cirrus clouds in Amazonia derived from 1 year of ground-based lidar measurements, Atmos. Chem. Phys., 17, 3619–3636, https://doi.org/10.5194/acp-17-3619-2017, 2017

Sassen, K., Liou, K.-N., Takano, Y., and Khvorostyanov, V. I. (2003), Diurnal effects in the composition of cirrus clouds, Geophys. Res. Lett., 30, 1539, doi:10.1029/2003GL017034, 10.

Authors' changes in manuscript: - line 28: we added a reference to Gouveia et al. (2017) - The following paragraph will be added after line 50: "The diurnal evolution of the high-altitude cirrus clouds have been documented over some specific sites using ground-based lidars (Sassen et al. 2003; Dupont et al., 2010; Gouveia et al. 2017). Gouveia et al. (2017) documented the evolution of the integrated cloud fraction (no vertical distribution) over Amazonia, Sassen et al. (2003) documented the diurnal evolution of the composition of cirrus clouds over Salt Lake City, and Dupont et al. (2010) did the same over four observatories in France and in the United-States. However, using ground-based lidar to document optically thin clouds extending above the tropopause is difficult for two reasons: 1) as the studies based on CALIPSO observations show, these clouds occur primarily in regions where operational ground-based sites are absent or very few (Pacific ocean, equatorial Africa, South America), and 2) these clouds are mainly associated with deep convection, which implies the presence of optically thick cloud systems in the troposphere beneath that will make in most cases impossible the successful probing of optically thin clouds near the tropopause due to the attenuation

of lidar signal. This explains why the ground-based lidars do not document the diurnal cycle of the stratospheric clouds with a satisfying spatial and temporal coverage."

- [*] The following paragraph will be added directly after line 193: "The cirrus clouds observed over Amazonia by gound-based lidar (Gouveia et al., 2017) shows a very similar diurnal cycle: a first peak in the early night (at 18-19 LT), a second peak later in the night (at 2-3 LT). Though Gouveia et al. (2017) do not consider the cloud above the tropopause only, their distinction between subvisible, thin and opaque cirrus indicates that the opaque cirrus are predominant during the early night (18-21 LT) and the thin cirrus (and subvisible ones during the dry season) dominate during the later night (from 0 and 2 LT onward, in wet and dry seasons, respectively)."

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Referee #1: Fig 2: please add DJF/JJA at the top of the panels as a quick reminder. Also, the color code for the lines should refer to the color code of Fig 1 : blue for oceanic regions/ land for orange regions. This would make a more logical reading of the figures. Also,I don't see why the day starts at 8am. Is there a particular reason for that ? If there is no specific reason, then it should start at 0:00.

Authors' response: We will add "DJF months from Feb. 2015 to Nov. 2017 included" and "JJA months from Feb. 2015 to Nov. 2017 included" at the top of the panels and change the colors to have warm color for land and cold for ocean, thank you for the suggestions. We decided to present the diurnal cycle from 8 to 8LT, roughly matching with day time and then night time, to increase the readability of the figure: the two maxima of the diurnal cycle appear more clearly (they are not separated by the midnight line). See for instance the fig. 4a of Gouveia et al. (2017) to see the difficulty to compare evening and late night when diurnal cycle is presented from 0 to 0 LT.

Authors' changes in manuscript: The colors and panels' title used in Figure 2 will be changed.

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Referee #1: line 186: it is stated that all regions present a secondary peak at 0-1LT. The EquatorialAfrica doesn't have a secondary peak, while for the North Warm Pool, the 1:00LT peak is the first peak in terms of intensity. Please revise.

Authors' response: Thank you for the comment, we will rephrase these sentences.

Authors' changes in manuscript: Sentences lines 189-193 will be rephrased with: "They all present a first maximum at 19 or 20 LT (early-night peak), up to 16.5% over Equatorial Africa. For all regions except South America and North Warm Pool, this maximum is the largest cloud fraction of the day. All regions also present a second peak (late-night peak) at 0 or 1 LT (23 LT for West Pacific and 2 LT for Central Africa), up to 16.5% over South America. The midnight peak over Equatorial Africa is less clear than over the other regions because of the large variations between 23 and 3 LT. The capability of a longer dataset to produce a clearer signal is to be investigated." All other occurrences of "secondary" will also be changed for "second" : lines 218, 235, 238.

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Referee #1: Figure 3: the darker color for the very small values of % makes the reading of thefigure difficult. Please put white when it is 0, so that the small values of % can still be readable. I have the same comment than for fig 2 and the start of the x-axis at 8am.

Authors' response and Authors' changes in manuscript: We will change the color palette of Figure 3 to have white for zero values. Like for Fig. 2 we decided to present the diurnal cycle from 8 to 8LT to make the two peaks of the diurnal cycle more clear and easily comparable.

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