The diurnal cycle of cloud profiles over land and ocean between 51°S and 51°N, seen by the CATS spaceborne lidar from the International Space Station

Vincent Noel [1], Hélène Chepfer [2], Marjolaine Chiriaco [3], John Yorks

Reply to Reviewers
June 19th, 2018

Original reviewer comments are in blue italics, our replies in black.

Reviewer 1 comments and replies

This is a review of "The diurnal cycle of cloud profiles over land and ocean between 51◦S and 51◦N, seen by the CATS spaceborne lidar from the International Space Station"

This paper presents the cloud detection statistics from the CATS lidar that was operating on the ISS. Because of the non-sun-synchronous orbit of the ISS, these statistics sample all hours of day and night. This creates a unique dataset. This data is presented very well in the paper. I believe this is an excellent paper that will be cited a lot. I certainly recommend publication of the paper in ACP. There are a few minor issues that I recommend the authors to consider. Those are discussed below.

Like any lidar, CATS probes the first ∼3 optical depths of a cloud, as discussed in the paper. In the case of thin cirrus clouds, the full extent of the clouds will be sampled, but in many cases essentially only the top height will be detected. However, the authors confuse this sampled vertical cloud fraction with statistics of vertical extent. For example, the abstract states "the high clouds geometric thickness increases significantly from 1km near 5PM to 5km near 10PM". However, it could also be that the cloud top altitude is more variable later in the day, while the geometrical thickness is staying the same. The data could be analyzed in other ways to include transparent clouds only, which will allow a study of statistics of geometric thickness, but this is not done in the current study. I am not asking to change the study to include this analysis, but the authors should discuss the fact that real geometric extent is not always sampled here. Especially in the tropics a substantial part of the high clouds would be tops of convection that may have vary throughout the day. Other parts of the paper that refer to geometric thickness of clouds are at lines 340-344, 444, 492, 629, 636, and 642. There may be other instances. Please go through the paper and discuss this interpretation of the data correctly.

This interpretation is correct, and we thank the reviewer for pointing out this problem. We went through the paper (thanks for the pointers) and now try to present the reader a more correct interpretation of the results.

Line 172: If I understand correctly, lidar depolarization information is used for cloud classification. If so please briefly discuss this in the paper.

A sentence has been added to the CATS overview paragraph that briefly outlines the CATS cloud phase algorithm and references the appropriate papers for more details. The full description of the CATS cloud phase algorithm is presented in Section 4.3 of the CATS ATBD [1] and in an AMT paper soon to be submitted. High confidence liquid water clouds are classified if the cloud layer has a T_mid > 0 C and high confidence ice clouds are identified as cloud layers with a T_mid < -20 C. These ice clouds and liquid water clouds are assigned a CP score of 10 and -10, respectively. Next, the CP algorithm identifies high confidence ice cloud layers as those layers with 1064 nm depolarization ratios greater than 0.25 or T_mid < -10 C (CP Score = 9). High confidence liquid water clouds are classified if the cloud layer has a 1064 nm depolarization ratio< 0.15 (CP Score = -9). The remaining layers are determined to have lower confidence cloud phase and are assigned a CP Score with an absolute value of 7 or less. These thresholds are based on Yorks et al. (2011) and Hu et al. (2009). Comparisons with CALIOP have shown very good agreement between the two instruments for cloud phase.

[1] https://cats.gsfc.nasa.gov/media/docs/CATS_ATBD_V1-02.pdf

Line 372: It seems that a reference to Johnson et al. (1999; J. Climate, 12, 2397–2418) about the tri-modal nature of tropical convection is in place here.

We thank the reviewer for this very useful reference and comment, which are now both included in the text. Note however that CATS only reports a significant population of those midlevel clouds (5-7km) over land, and not over ocean. This is not consistent with those clouds being cumulus congestus, as these also appear over ocean (Masugana et al. 2005). Higher-altitude clouds, which cloud mask such clouds from the lidar view, are equally frequent over ocean and land, so this inconsistency is not explained by instrumental bias.

Following the references provided by Reviewer 2 suggests those clouds could be Altocumulus, as both share middle-level altitudes and locations over land in the summer hemisphere. This possibility is also now mentioned in the text.

Line 515: Another thing to note is that, besides cloud detection, retrieving a cloud top height from passive instruments is not as straightforward as it is for lidar measurements, especially for thin clouds and in multi-layered situations.

We agree with the reviewer and have modified the text to include this point.

Figure 5 (and A7): I would suggest to add a vertical scale to the Africa-North plot, or maybe to all of the plots.

Following this comment, we have added vertical scales to all the subplots of Figures 5 and A7.

Figure 6: Because of the ISS orbit, CATS samples between 51 degrees north and south, as explained in the paper. However, figure 6 and the discussion are not consistent with this geographical limitation and include statistics supposedly from latitude bands of 30-60 degrees north and south. This choice is made to be consistent with previous studies, but hides the fact that CATS is only sampling to 51 degrees, making the data not completely consistent with previous datasets. It is important to be consistent about the sampling region throughout the paper. Also, I find the labels of the latitude bands on the right side of figure 6 rather confusing. It makes it seem like vertical axis are latitudes in addition to cloud amount deviation somehow. I would propose adding the latitude bands on top or inside the figure as a label or legend.

We agree with the reviewer's position, and have updated figure 6 to be hopefully less confusing, and convey the actual sampling latitude range of CATS.

Reviewer 2 comments and replies

Review "The diurnal cycle of cloud profiles over land and ocean between 51◦S and 51◦N, seen by the CATS spaceborne lidar from the International Space Station" by Noel et al.
By using CATS measurement, the paper presents a first land-ocean contrast of cloud diurnal cycle. Results are very useful. However, there are many uncertainties associ- ated with CATS data for diurnal cloud studies, which need to be clearly discussed. I suggest the paper for publication after the following comments are properly addressed.

Major issues

1. There are many challenges in using CATS data to study diurnal cloud cycle. First, it is linked with space lidar observations itself. Although several points (day-night solar background difference, attenuation of lidar signal by upper and middle clouds) are touched in the paper, they are needed to be clearly presented and quantified. Results discussions need to consider these uncertainties.

The paper now includes more extensive comparisons with ground-based datasets, that we hope will help the reader understand the strengths and limitations of spaceborne lidar measurements, including the influence of attenuation by upper and middle clouds on the detected low-altitude clouds.

Regarding the day-night variation, the CATS minimum detectable backscatter (MDB) at 1064nm goes from 5.10-5 km-1 sr-1 in absence of sunlight to 1.30 10-3km-1 sr-1 in illuminated conditions (Yorks et al., 2016). CATS daytime profiles are horizontally averaged across 60km before cloud detection, which bring the daytime MDB down to nighttime levels. This has two implications for daytime data: 1) optically thinnest clouds detected during nighttime at 60km horizontal averaging might be absent from daytime detections, these represent roughly ~5% of nightime clouds. 2) cloud amounts might be overestimated when many clouds with small horizontal extent are present - this mainly concerns boundary layer clouds. In our evaluations, the associated decrease in SNR due to solar background has a bigger impact on aerosol layer detection than clouds.

CATS's MDB is smaller than CALIOP's 532nm daytime MDB (1.70 10-3 km-1 sr-1), so all other things being equal CATS should detect more clouds than CALIOP in daytime conditions. Both Sassen et al. (2009) and Gupta et al. (2018) successfully used CALIPSO cloud detections in both nighttime and (solar-affected) daytime conditions to document part of the diurnal variability of clouds and, like us, report more high clouds in nighttime measurements. They remark that the observed nighttime increase is considerably more than the uncertainty that might arise from the daytime loss of detection sensitivity. Since CATS cloud detection abilities are at least on par with CALIOP's in daytime conditions, and CALIOP daytime detections are found acceptable to document part of the diurnal cycle, it follows that the existence of solar pollution in the CATS dataset should not prevent its use to document the diurnal cycle of clouds. As in the Sassen and Gupta papers, we note that how much CALIPSO (and therefore CATS) daytime detections underestimate high clouds occurrence and overestimate low clouds need to be quantified.

These points are now made in the text (Sect. 2.1, 3.1 and 5).

In a similar way, how extinction from high clouds affects the retrieval of low-level clouds remains unquantified and hard to evaluate for all spaceborne lidars. Comparisons with ground-based datasets (see major point 3) suggest that high clouds do not impair significantly the retrieval of low clouds over any site. Over ARM-ENA (oceanic site), the limited amount of high clouds means CATS reports of low clouds amounts is very close to the ground-based one. Over ARM-SGP the relatively large amount of high clouds at night might explain why CATS misses half of the nighttime low and mid-level clouds observed by the ground radar. Supposing that 50% of unsampled profiles due to masking by high clouds are indeed cloudy (i.e. an hypothesis of random overlap) is not sufficient to fix the space-ground disagreement. We think extending these results to the global scale for CATS (and CALIPSO) would be a interesting future project.

The upcoming paper by Yorks et al. (In preparation for AMT) will quantify these points further. We have tried to discuss the importance of uncertainties on the results presented here in the last section of the article.

2. It needs to be very clear that CATS from ISS don't provide exact diurnal cycle cloud observations as ground-based observations. Due to the nature of ISS orbit characters, you need to combine over a month-long measurements together to cover the diurnal cycle. So, composed the diurnal cycle include seasonal cloud variations. Although it is fine to perform the seasonal study as discussed in the paper, it is important to make readers aware of the nature of CATS diurnal cloud properties. Thus, related information needs to be added in the introduction or the method section.

Following this comment, we have updated the introduction (before-last paragraph) to make clear 1) that the CATS lidar cannot track the evolution of cloudiness above a particular location along a particular day and 2) that we recreate the cloud diurnal cycle over a given location by aggregating over seasons the cloud detections made by CATS over that particular location at different times of day. We now make this point again in the relevant Data and Methods section (Sect. 2.2.a, 2nd paragraph).

3. One way to make these limitations well understood is by using ground-based observations to validate CATS results. Although there is one figure for this purpose, it is not enough. Tropical observations and over oceans are needed. ARM observations are available for the validations.

Following this comment, and major comment #2 from Reviewer 3, we have tried locating a well-documented, 24/24 dataset of cloud layers covering the period 2015-2017 based on measurements from a ground-based lidar operating in the Tropics, preferably close to the ocean. We have contacted several observatories (e.g OPAR) but it appears lidar-based cloud layer products are often unvalidated and/or suffer from irregular or non-diurnal sampling.

Following the Reviewer's suggestion, we investigated ARM data [1] and found several datasets based on Tropics measurements and promising cloud layer information. We found that:

- Datasets from Nauru Island and Darwin Australia did not overlap with CATS timeframe
- Datasets from Brazil and Ascension Island cover the CATS timeframe but only contained profiles of Attenuated Backscatter (without cloud detection) — doing the cloud detection ourselves would require external validation
- Only datasets from the ARM Eastern North Atlantic (ENA) atmospheric observatory [2] are close to our criterias above. This site provides cloud layers derived from ground-based lidar measurements made in an oceanic environment, unlike the SIRTA and ARM-SGP datasets considered in the initial article.

Since the ENA observatory is located at 39°N, it is at best sub-tropical. It is however the only oceanic ARM site we found that could provide a 24/24 robust dataset of cloud layers covering the CATS time period.

Our initial exploration of the enaarsclkazrbnd1kolliasC1 dataset (based on a combination of lidar and radar data) showed unusual results during the 2017 summer (see figure below). We contacted ARM people, who explained the problem comes from unresolved issues with lidar cloud detections and suggested rebuilding the cloud layers based on the cloud mask source product and ignoring the lidar-only detections. This resolved the problem, but in effect turned it into a radar-based product.

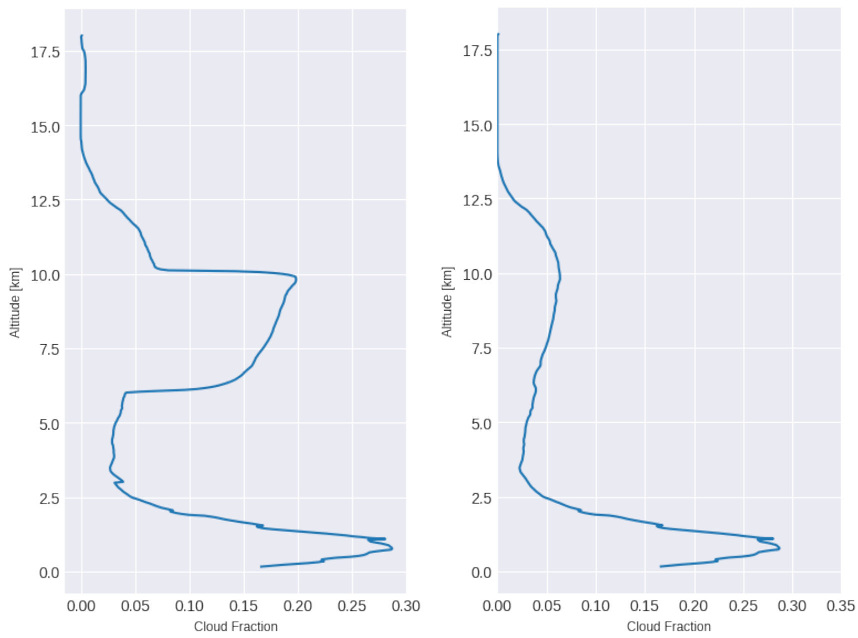

Figure 1 - Cloud fraction over ARM-ENA for 2017 JJA using both lidar and radar cloud detections (left) and radar-only cloud detections (right)

The paper now includes (Sect. 3.3) a direct comparison of the diurnal cycles of cloud fraction profiles as documented by CATS over the ENA site and from ground-based radar detections. We have also obtained the ARM-SGP ground-based lidar+radar cloud detections in order to directly include them in the paper for comparison with CATS data. Exploration of the sgparsclkazrbnd1kolliasC1 dataset showed artefacts similar to those from the ARM-ENA datasets (vertical steps in cloud fraction) when including lidar-only cloud detections. We thus had again to consider only radar detections, leading to results very similar to those presented in Zhao et al. (2016).

The fact that we uncovered issues with those ARM datasets, which are apparently among the most reliable, confirms how difficult it is to obtain faultless lidar-based cloud retrievals over long periods. Providing our own analysis of the data allowed us to only use cloud detections made during the CATS operation period, making time periods consistent across all ground-based comparisons.

The article now includes comparisons between CATS and:

- Lidar-based cloud retrievals from a midlatitude continental site (SIRTA), already described in e.g. Noel et Haeffelin (2006)
- Radar-based cloud retrievals from a midlatitude continental site (ARM-SGP), already described in e.g. Zhao et al. (2016)
- Radar-based cloud retrivals from a subtropical oceanic site (ARM-ENA).

We hope these improvements to our comparisons between CATS and ground-based datasets better highlights the strenghts and limitations of spaceborne and ground-based lidar cloud sampling.

[1] https://www.arm.gov/data
[2] https://www.arm.gov/capabilities/observatories/ena

Minor issues

1. L23-24: change "high clouds maximum" to "high cloud thickness maximum." The interpretation of cloud thickness detected by a lidar has to consider cloud optical thickness.

Following the first comment from reviewer 1, the text referenced here has been modified. We hope it now satisfies the concern expressed here.

2. Line 88-101: Some references are needed her to support the discussion. For example, the Fig. 9 of Wang and Sassen 2001, will support your middle latitude discussion.

Wang, Z., and K. Sassen, 2001: Cloud type and macrophysical property retrieval using multiple remote sensors. J. Appl. Meteor., 40, 1665-1682.

Our initial idea was that paragraph would sum up the findings of the articles referenced in the previous paragraph ("Those studies…"). However, the first paragraph only references studies of cloud diurnal cycles documented from space, whereas the findings in the second paragraph are general. Following this observation, we have revised the first two paragraphs of the introduction, trying to support our assertions with appropriate references, including the one suggested by the reviewer. We thank the reviewer for that very on-point reference.

This comment echoes Major Issue #1 from reviewer 3.

3. Line 106-107: There are many more important related papers should be cited than your paper.

The thank the reviewer for pointing this out. We have updated the manuscript to include references to papers that are hopefully more important.

4. L165: "measured every 350m" not accurate. It is a 350 m average profile.

The Reviewer is correct. CALIPSO sends every 1/20th of a second a laser pulse, which travels to the Earth's surface and back before the satellite has time to move significantly and thus can be considered instantaneous. Unlike CALIPSO, CATS has a high repetition rate of 5kHz and monitors constantly for backscattered energy. The onboard data system accumulates 250 of these 5kHz profiles and reports the data every ±350m to approximate a 20Hz measurement rate.

The text has been changed to “CATS reports vertical profiles of Attenuated Total Backscatter (ATB) every 350m at 1064nm with a 60m vertical resolution (Yorks et al., 2016a). Each profile is created by accumulating backscattered energy from 250 5kHz pulses, 20 times per second.”

5. L 171: What is "L2O"?

Files for CATS level 2 layer products share the prefix "CATS-ISS_L2O_N-M7.2-V2-01_05kmLay”. The L2O designation identifies “Level 2 Operational” products. The updated text now includes this explanation.

6. L201-202: So you shouldn’t use this site considering it data collection biases.

Unfortunately, the number of site providing datasets containing 24-hour retrievals of cloud boundaries derived from active measurements and part of published research is currently limited, as we explained in our answer to major comment #3. Even lidar-based cloud retrievals from ARM sites suffer from artefacts that prevent their use in this study.

In the updated manuscript we now include, in addition to direct comparisons of CATS with SIRTA lidar retrievals (over midlatitude western Europe), comparisons of cloud retrievals from CATS with others based on measurements from ARM-ENA (subtropical oceanic) and ARM-SGP (midlatitude US) observation sites. As the ARM retrievals are radar-only, we decided to keep the SIRTA dataset as it is the only lidar-based ground-based cloud retrievals dataset.

7. L273-274, "low clouds have their base below 4km ASL": Do you sure that you mean cloud base height here. If so, it does not make sense. First, it is almost impossible for you to detect the base of optically thick clouds. Assuming that you can detect, we refer clouds with the base higher than 2 km as middle-level clouds. Using top height will make more sense.

The Reviewer is correct, the original sentence mixed up cloud base and top. Thanks for noticing that error. The text now includes the correct explanation: low clouds have their top below 4km ASL, high clouds have their base above 7km, and mid-level clouds are in between.

8. L308-308: Not necessarily true. How often do you detect low clouds below high clouds? Even if high cloud occurrences are high, they are not 100.

The reviewer is correct, the logic of the discussion was incorrect. We have modified the text to fix the discussion and hopefully better make the point we were trying to make.

9. L315-316: Solar-background variations need to be better quantified.

We adressed the solar background variations issue in our answer to major comment #1.

10. L336-346: To what extent, these variations are due to the lower daytime detection sensitivity, especially considering the contrast between N30-50 with S30-50?

We adressed the issue of solar background variations in our reply to major comment #1.

11. L368-374: The high occurrence of middle-level clouds are well documented by may early studies (Zhang et al. 2010; Sassen and Wang 2012, and other), which should be properly referenced.

Zhang, D., Z. Wang, and D. Liu (2010), A global view of midlevel liquid-layer topped stratiform cloud distribution and phase partition from CALIPSO and CloudSat measurements, J. Geophys. Res., 115, D00H13, doi:10.1029/2009JD012143.
Sassen, K. and Z. Wang, 2012: The Clouds of the Middle Troposphere: Composition, Radiative Impact, and Global Distribution, Surv Geophys (2012) 33:677-691,DOI 10.1007/s10712-011-9163-x

The mid-level clouds CATS detects over Africa, South America and Australia, in the North hemisphere in JJA and the South hemisphere in DJF, might very well be Altocumulus clouds that Wang and Sassen (2012) document in the same locations, altitudes and times. This possibility is now discussed in the text. We thank the Reviewer for this useful reference.

12. L411-473: This part of the discussion should occur early in the paper as validation efforts.

We present the results at global scale first on purpose, as we consider those are the most novel and interesting for potential readers. Since validation efforts are not the main purpose of the paper, we think nothing is lost by delaying their presentation.

13. L421-422: Considering the night time sampling biases, I don't think that you can trust this result.

We have modified the text to include this observation.

14. L449-452: It will good to include a panel for SGP ground-based observation results here.

As noted before, for the revision we have obtained the ARM-SGP ground-based lidar+radar cloud detections from the ARM site. From those, we have extracted radar-only detections (to avoid bias from spurious lidar detections) and derived the daily cycle of vertical cloud fraction profiles during the CATS period (JJA 2015-2017). These results are now included in the paper's Figure 4. They are very similar to those presented in Zhao et al. (2016).

15. L484-487: In Fig. 5, why cloud top in Europe JJA is significantly lower than the other regions?

Europe is the only region in Fig. 5 that does not include part of the Tropical band, where the tropopause reaches much higher altitudes. This leads to cloud tops over Europe

We included this information in the legend of Figure 5 in the updated manuscript version that we submitted in March (this version has "over land and ocean" in the title), which superseded our original submission in February and became the one available from the ACPD website during the open discussion [1]. We do not know why the reviewers were provided with the non-updated version and regret the confusion.

[1] https://www.atmos-chem-phys-discuss.net/acp-2018-214/acp-2018-214.pdf

16. L522: Where is ISCCP data? Is there any reason not to plot it?

Indeed, we have decided against directly including retrievals based on ISCCP in the paper. By doing so, our goal is to prevent the discussion from focusing on active-vs-passive detection differences, and spending too much time explaining why this instrument detects that much more high clouds here and that much less low clouds there. Those questions are valid, and require thorough discussions about the subtle interplay between instrumental sensitivities, the distribution of cloud properties on a global scale, and data analysis algorithmic choices, all of which require extensive studies of their own (e.g. Stubenrauch et al. 2012 which is 176 pages long). We were concerned that going down that path would detract the reader from the main novel results provided by CATS, i.e. the daily variability of the cloud vertical distribution. To do so we decided not to directly include retrievals based on ISCCP data. Instead, our goal was to verify that CATS retrievals capture the general qualitative feature of the daily cycle of cloud amounts, compared to the baseline dataset usually considered (ISCCP).

C. Stubenrauch, W. B. Rossow, and S. Kinne, 2012: Assessment of global cloud datasets from satellites: A project of the World Climate Research Programme Global Energy and Water Cycle Experiment (GEWEX) Radiation Panel. WCRP Rep. 23/2012, 176 pp.

17. L539-541: This could also due to the different day-night cloud detection sensitivities between lidar and ISCCP passive measurements.

This is a possible explanation that we now have included in the article. Thanks.

18. L574-579: You could try to use CALIOP 1064 only measurements to run the same detection to minimize the difference.

This could indeed diminish differences between CATS and CALIOP datasets that are related to the instrument's wavelength differences. Many other differences would remain, like laser pulse energy and repetition frequency (20Hz vs. 5kHz), beam width, telescope field of view, sampling rates, performance of optical elements, etc. Moreover, our focus here is on statistics over large regions and seasons, and the different altitude and orbital paths of both missions imply that comparisons will necessarily be statistical in nature — i.e. both datasets document different clouds anyway. Given this, it is unclear what understanding would be gained by going through the exercise suggested here.

The reviewer's suggestion will be useful though for future research aiming to clarify the reasons behind differences between CALIPSO and CATS cloud detections over case studies.

19. L585 "Cloud Fraction": either use CF or "cloud fraction".

Thanks for spotting this, we have corrected the error.

20. Section 5: It will good to have some discussion on the potential limitations here.

Section 5 now mentions the limitations of cloud fractions retrieved through spaceborne lidar measurements such as CATS and CALIOP, and highlights the problems that still need to be investigated.

Reviewer 3 comments and replies

"The diurnal cycle of cloud profiles over land and ocean between 51S and 51N, seen by the CATS spaceborne lidar from the International Space Station" by Vincent Noel et al. This paper documents the diurnal cycle of the cloud vertical profiles over a large part of the globe, using CATS lidar, operating on the International Space Station. Cloud fractions from different locations, seasons, instruments have been compared, by taking the advantage of this unique dataset. The study is interesting and useful. But it would be better to relate the role of dynamic and thermodynamic processes to the differences of CF found from different conditions, which is not clearly presented. I recommend some modifications to improve the paper before publication.

We thank the Reviewer for his or her appreciation. Relating the cloud diurnal cycles documented in this paper to the other processes driving the daily evolution of the troposphere (temperature, water vapor) is the focus of a soon-to-be-submitted paper we are currently working on.

Major issues:

1. The second paragraph of Introduction needs more support references to help the readers to better understand the background. For example, 'well documented by passive satellite imagery', it would be better to add in relative works. The same suggestion for 'b) cloud detections from ground-based active instruments' part. There are a lot of works have been done with ground- based instruments on cloud property analysis, I would appreciate if you can give a few references here.

Our initial idea was that paragraph would sum up the findings of the articles referenced in the previous paragraph ("Those studies…"). However, the first paragraph only references studies of cloud diurnal cycles documented from space, whereas the findings in the second paragraph are general. Following this observation, we have rewritten the first two paragraphs of the introduction, trying to support our assertions with appropriate references.

This comment echoes minor issue #2 from reviewer 2.

2. The authors chose ARM SGP site for the comparison, is there any particular reason to compare two mid-latitude continental sites with CATS? Comparing with oceanic type of clouds would be interesting, if there are any possibilities. Since you actually didn't really process the SGP dataset, I would suggest that you could keep this part as an additional material.

Following this comment, and major comment #3 from Reviewer 2, we have tried locating a well-documented, 24/24 dataset of cloud layers covering the period 2015-2017 based on measurements from a ground-based lidar operating in the Tropics, preferably close to the ocean. We have contacted several observatories (e.g OPAR) but it appears lidar-based cloud layer products are often unvalidated and/or suffer from irregular or non-diurnal sampling.

Following the Reviewer’s suggestion, we investigated ARM data [1] and found several datasets based on Tropics and/or oceanic measurements and promising cloud layer information. We found that:

- Datasets from Nauru Island and Darwin Australia did not overlap with CATS timeframe
- Datasets from Brazil and Ascension Island cover the CATS timeframe but only contained profiles of Attenuated Backscatter (without cloud detection) — doing the cloud detection ourselves would require external validation
- Only datasets from the ARM Eastern North Atlantic (ENA) atmospheric observatory [2] are close to our criterias above. This site provides cloud layers derived from ground-based lidar measurements made in an oceanic environment, unlike the SIRTA and ARM-SGP datasets considered in the initial article.

Since the ENA observatory is located at 39°N, it is at best sub-tropical. It is however the only oceanic ARM site we found that could provide a 24/24 robust cloud layers dataset covering the CATS time period.

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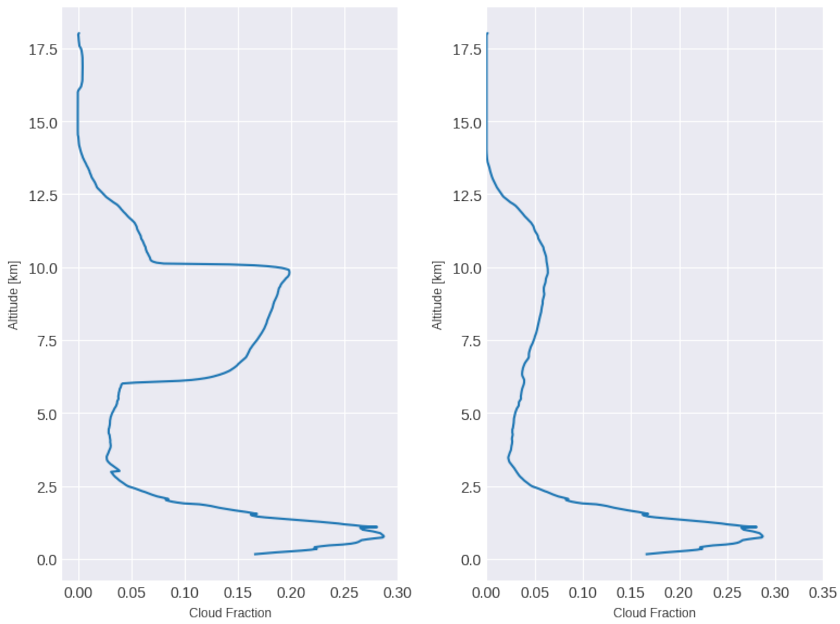

Figure 1 - Cloud fraction over ARM-ENA for 2017 JJA using both lidar and radar cloud detections (left) and radar-only cloud detections (right)

The paper now includes (Sect. 3.3) a direct comparison of the diurnal cycles of cloud fraction profiles as documented by CATS over the ENA site and from ground-based radar detections.

We have also obtained the ARM-SGP ground-based lidar+radar cloud detections in order to directly include them in the paper for comparison with CATS data. Exploration of the sgparsclkazrbnd1kolliasC1 dataset showed artefacts similar to those from the ARM-ENA datasets (vertical steps in cloud fraction) when including lidar-only cloud detections. We thus had again to consider only radar detections, leading to results very similar to those presented in Zhao et al. (2016).

The fact that we uncovered issues with those ARM datasets, which are apparently among the most reliable, confirms how difficult it is to obtain faultless lidar-based cloud retrievals over long periods. Providing our own analysis of the data allowed us to only use cloud detections made during the CATS operation period, making time periods consistent across all ground-based comparisons.

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We hope these improvements to our comparisons between CATS and ground-based datasets better highlights the strengths and limitations of spaceborne and ground-based lidar cloud sampling.

[1] https://www.arm.gov/data
[2] https://www.arm.gov/capabilities/observatories/ena

3. You talked about the pronounced mid-level clouds over continent many times which has been well documented, could you give a more detailed explanation for that, and the role of dynamic and thermodynamic processes.

The mid-level clouds CATS detects over Africa, South America and Australia, in the North hemisphere in JJA and the South hemisphere in DJF, might very well be Altocumulus clouds that Wang and Sassen (2012) document in the same locations, altitudes and times. This possibility is now discussed in the text.

Minor issues:

1. On Figure 1, is there any way to show the number of samples on the plots as well? In the text, the latitude range is 51S-51N, but on most of the plots, it's 55S-55N. It is better to keep it consistent.

Following this comment, the map in Figure 1 now shows the number of profiles sampled by CATS over the JJA 2015-2016-2017 period in 2°x2° grid cells. We thank the Reviewer for this suggestion that makes Figure 1 richer in information.

As noted by the Reviewer, the latitude ranges in figures and their legends were incorrect in the initial version of the manuscript we uploaded to ACPD in February. We fixed those in an updated version submitted in March (this version has "over land and ocean" in the title), which became the one available from the ACPD website during the open discussion [1]. We do not know why the reviewers were provided with the non-updated version and regret the confusion.

[1] https://www.atmos-chem-phys-discuss.net/acp-2018-214/acp-2018-214.pdf

2. The color bar need to be adjusted and extended to greater than 20%, add in unit, and keep the x axis and y axis consistent for the same figure group, specially figure 4.

Our attempts to increase the maximum to larger cloud fractions led to poor visibility for areas of weak cloud fractions, which are much more frequent and more frequently discussed in the text. Through experimentations, we found that limiting the color bar to a 20% maximum provided the best compromise between keeping variations of weak cloud fractions visible (e.g. at low altitudes) and not masking too many variations in large cloud fractions, for instance in high clouds in tropical summer conditions or low clouds over ARM-

ENA.

All cloud fraction colorbars should now include units (%). We have made sure all axes remain consistent within the same figure groups.

3. Figure 5, better to label A, B, C... on the subplot for each location.

We thank the reviewer for this useful suggestion that Figure 5 now implements.

4. Line 515: Using passive instruments to retrieve the cloud properties is different from active instruments, they don't have the same sensitivity for the thin clouds. It isn't a fair comparison here.

Our objective here is not to validate or depreciate either one of the detection approaches. All instruments have different sensitivities to different phenomenas. We do not think that confronting retrievals from passive instruments with retrievals from active instruments is unfair to the passive instruments — it shows how each instrument understands a scene, which we think helps the readers familiar with either one, or both, to understand what is actually going on. However, since the sentence in question did not bring any significant value to the manuscript, we have rewritten it to avoid any misunderstanding.

5. Another thing to note is that, besides cloud detection, retrieving a cloud top height from especially for thin clouds and in multi-layered situations.

We think some words are missing from the comment. We guess the Reviewer points out that cloud top heights retrieved from passive measurements can suffer from large uncertainties, especially in presence of thin clouds and multi-layered situations. We agree with his comment.

Reviewer 4 comments and replies

1. The paper discusses the diurnal changes in cloud fraction, but commonly CF is meant to represent the fraction of a grid box area or sensor field of view that is covered in cloud. Would it not be correct to give the results as cloud frequency instead, as that is what is actually being measured?

During the past years, interactions with co-authors and reviewers led to our adoption of the following naming scheme:

- "cloud cover" to name the fraction of a grid box area covered in cloud
- "cloud fraction profile" to name a vertical profile describing at each altitude level the fraction of shots containing clouds

Many articles use this distinction, for instance Reverdy et al. (2015), Chepfer et al. (2010) referenced in the main article. The following articles use the same naming scheme:

- Chepfer, H., Noel, V., Chiriaco, M., Wielicki, B., Winker, D., Loeb, N. and Wood, R.: The Potential of a Multidecade Spaceborne Lidar Record to Constrain Cloud Feedback, J. Geophys. Res. Atmos., 123(10), 5433–5454, doi:10.1002/2017JD027742, 2018.
- Cesana, G., et al. (2016), Using in situ airborne measurements to evaluate three cloud phase products derived from CALIPSO, J. Geophys. Res. Atmos.,121, 5788–5808, doi:10.1002/2015JD024334.
- Chepfer, H., V. Noel, D. Winker, and M. Chiriaco (2014), Where and when will we observe cloud changes due to climate warming?, Geophys. Res. Lett.,41, 8387–8395, doi:10.1002/2014GL061792
- Reverdy, M., Noel, V., Chepfer, H., and Legras, B.: On the origin of subvisible cirrus clouds in the tropical upper troposphere, Atmos. Chem. Phys., 12, 12081-12101, https://doi.org/10.5194/acp-12-12081-2012, 2012
- Chepfer H., S. Bony, D. Winker, M. Chiriaco, J-L. Dufresne, G. Sèze, 2008: Use of CALIPSO lidar observations to evaluate the cloudiness simulated by a climate model, Geophys. Res. Let., 35, L15704, doi:10.1029/2008GL034207.

We went through the paper to make sure that the paper always mentioned "cloud fraction profile", or specified an altitude range (e.g. "at low altitudes, cloud fractions are high..."). We hope this naming scheme is satisfactory.

2. Secondly, the figures' color bars max out at CF=20%, with values above 20% visible in many of the figures. It would be good to extend the color bar so that fewer figures saturate like this.

Our attempts to increase the maximum to larger cloud fractions led to poor visibility for areas of weak cloud fractions, which are much more frequent and more frequently discussed in the text (e.g. at low altitudes). Through experimentations, we found that limiting the color bar to a 20% maximum provided the best compromise between keeping variations of weak cloud fractions visible and not masking too many variations in large cloud fractions, for instance in high clouds in tropical summer conditions or low clouds over ARM-ENA.

The diurnal cycle of cloud profiles over land and ocean between 51°S and 51°N, seen by the CATS spaceborne lidar from the International Space Station

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4 - NASA GSFC, Greenbelt, Maryland, USA

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Atmospheric Chemistry and Physics

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Deleted: 21 Mar 2018

Abstract.

We document, for the first time, how detailed vertical profiles of Cloud Fraction change diurnally between 51°S and 51°N, by taking advantage of 15 months of measurements from the Cloud and Aerosol Transport System (CATS) lidar on the non-sun-synchronous International Space Station (ISS).

Over the Tropical ocean in summer, we find few high clouds during daytime. At night they become frequent over a large altitude range (11-16km between 10PM and 4AM). Over the summer tropical continents, but not over ocean, CATS observations reveal mid-level clouds (4-8 km Above Sea Level or ASL) persisting all-day long, with a weak diurnal cycle (minimum at noon). Over the Southern Ocean, diurnal cycles appear for the omnipresent low-level clouds (minimum between noon and 3PM) and high-altitude clouds (minimum between 8AM and 2PM). Both cycles are time-shifted, with high-altitude clouds following the changes in low-altitude clouds by several hours. Over all continents at all latitudes during summer, the low-level clouds develop upwards and reach a maximum occurrence at about 2.5 km ASL in the early afternoon (around 2 pm).

Our work also shows that 1) the diurnal cycles of vertical profiles derived from CATS are consistent with those from ground-based active sensors at local scale, 2) the cloud profiles derived from CATS measurements at local times of 0130AM and 0130PM are consistent with those observed from CALIPSO at similar times, 3) the diurnal cycles of low and high cloud amounts derived from CATS are in general in phase with those derived from geostationary imagery but less pronounced. Finally, the diurnal variability of cloud profiles revealed by CATS strongly suggests that CALIPSO measurements at 0130AM and PM document the daily extremes of the cloud fraction profiles over ocean and are more representative of daily averages over land, except at altitudes above 10km where they capture part of the diurnal variability. These findings are applicable to other instruments with local overpass times similar to CALIPSO's, like all the other A-Train instruments and the future Earth-CARE mission.

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1. Introduction

The diurnal cycle of clouds has been documented for decades by ground-based instruments (e.g. Gray and Jacobson, 1977) and geostationary satellites (e.g. Rossow et al., 1989). Even though climatologies give priority on how clouds change with seasons and geography, many studies noted the strong diurnal cycle of boundary layer clouds. During the day, low clouds form in the morning and expand, following the warming of the surface by incoming solar radiation (Stubenrauch et al., 2006). Maximum low cloud amount is often reached in the early afternoon. This sun-driven variation is maximum over continents, where it depends on orography (Wilson and Barros, 2017; Shang et al., 2018), and in summer. It is more limited over ocean and during winter (Rozendaal et al., 1995; Soden, 2000). When night falls, condensation in the boundary layer can create stratiform clouds, which stabilize and expand through nighttime radiative cooling at cloud top and reach maximal cover in the early morning (Greenwald and Christopher, 1999; Eastman and Warren, 2014).

In the Tropics, the near-surface daily increase in water vapor triggered by solar warming (Tian et al., 2004) is transmitted to higher altitudes through deep convection (Johnson et al., 1999). This imposes a diurnal cycle to high clouds, which is delayed by several hours compared to low clouds (Soden, 2000). Their maximum amount is reached in the evening (Rossow and Schiffer, 1999; Stubenrauch et al., 2006). At midlatitudes, without deep convection most of the troposphere is free from surface influence (Wang and Sassen, 2001), and diurnal changes in the distribution of high-altitude clouds are limited. Changes are rather driven by the local atmospheric circulation (e.g. Storm-tracks), leading to less predictable patterns which are more location-dependent.

More recently, geostationary imagery documented the diurnal variations in the composition of cloud cover above Central Africa (Philippon et al., 2016) and cloud top temperatures (Taylor et al., 2017). In any case, the vertically-integrated nature of passive imagery means it cannot resolve the vertical variability of clouds and its diurnal cycle, which is key to better understand the atmospheric heating rate profile (L'Ecuyer et al., 2008). By comparison, active remote sensing instruments, such as radars and lidars, document the cloud vertical distribution with great accuracy and vertical resolutions finer than 500m. Long-running datasets from active instruments operated from ground-based sites have led to useful time

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Those studies found the most significant diurnal changes of clouds over continents in summer: low-level boundary layer clouds eand throughout the day, following the warming of the surface by incoming solar radiation, a process significantly affected by orography. In the Tropics, this near-surface activity is transmitted to higher altitudes through deep convection, driving a diurnal cycle in high-level clouds. The time needed for this process to occur delays the cycle of high clouds, whose maximas and minimas occur hours late compared to low-level clouds. At midlatitudes, without deep convection most of the troposphere is free from surface influence, and diurnal changes in the distribution of high-altitude clouds are rather driven by the local atmospheric circulation (e.g. Storm-tracks), leading to less predictable patterns. Over oceans, the largest low-level cloud covers happen in the morning, when the expansion generated by nighttime radiative cooling at cloud top stops. These patterns are supported by understood physical principles and are well documented by passive satellite imagery. But these observations do not provide information on the diurnal cycle of the detailed cloud profiles, which is key to better understand the atmospheric heating rate profile. ¶

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Deleted: , building extensive datasets from which series and statistics about clouds (e.g. Sassen and Benson, 2001; Hogan et al., 2003; Protat et al., 2009; Dong et al., 2010; Hoareau et al., 2013; Zhao et al., 2016). From space, Liu and Zipser (2008) were able to derive information on the clouds diurnal cycle from the spaceborne Tropical Rainfall Measuring Mission radar, launched in 1997 (Kummerow et al., 1998), but the instrument was not designed to detect clouds with accuracy. The CALIPSO lidar (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations), since its launch into orbit in 2006 (Winker et al., 2010), has provided transformative vertically-resolved data on clouds (Stephens et al., 2017; Winker et al., 2017). Cloud detections from CALIPSO have, among other things, helped pinpoint and improve significant cloud-related weaknesses in climate models (e.g. Cesana and Chepfer, 2013; Konsta et al., 2016), helped improve estimates of the surface radiation budget (Kato et al., 2011) and of the heating rate profile (Haynes et al., 2013; Bouniol et al., 2016). Due to its sun-synchronous polar orbit, CALIPSO samples the atmosphere at either 1:30AM or 1:30PM local time (LT), like the CloudSat radar (Stephens and Kummerow, 2007) and all A-Train instruments (L'Ecuyer and Jiang, 2010). Even though measurements at two times of day can offer insights into the day-night cloud changes (Sèze et al., 2015; Gupta et al., 2018), they are insufficient to fully document the diurnal evolution of cloud profiles. This observational blind spot explains why very little is known so far about how the vertical distribution of clouds changes diurnally in most of the globe, leading to inconsistencies amongst climate models (Yin and Porporato, 2017).

Here we take advantage of measurements from the Cloud Aerosol Transport System (CATS, McGill et al., 2015) lidar on the International Space Station (ISS), to document the diurnal evolution of the vertical distribution of clouds in regions of the globe. As the ISS orbits the Earth many times a day between 51°S and 51°N, CATS measurements cannot track the evolution of individual clouds over a given location and a given day. Instead, cloud detections over a given location at variable times of day can be aggregated over seasons, to create statistics that eventually document the seasonal average diurnal cycle of clouds over that location. Thus far, the CATS dataset is the only one to contain active vertically-resolved measurements made from satellite with variable local times of overpass.

We first describe how data were selected and processed to derive diurnal cycles of cloud Cloud Fraction (CF) profiles and Cloud Amounts (CA) from CATS and all other instruments included for comparison (Sect. 2). Then, using CATS retrievals we document, for the first

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Deleted: : the CATS lidar can document cloud profiles at different times along the day between 51°S and 51°N following the ISS orbit time, the diurnal cycle of detailed Cloud Fraction profiles in large regions of the globe in two seasons over ocean and land (Sect. 3.1 and 3.2). In Sect. 3.3 we describe CATS-derived diurnal cycles of cloud profiles over selected sites and continents with two goals in mind: (i) to compare them with independent ground-based observations to check the validity of the CATS retrievals, and (ii) to document the diversity of the continental cloud profile diurnal cycles over the globe. In Section 4 we discuss implications of our results: We compare the diurnal cycle of the Low and High cloud covers derived from CATS with ones from geostationary satellites (Sect. 4.1), and discuss the agreement between CATS Cloud Fraction profiles derived at the times of CALIPSO overpass with actual CALIPSO retrievals (Sect. 4.2.a). Finally, we consider CATS profiles at overpass times from current and future sun-synchronous spaceborne lidar missions (Sect. 4.2.b) to understand which part of the diurnal cloud cycle is sampled by these instruments. We conclude in Sect. 5.

2. Data and Methods

2.1 Data

a) Cloud detections from the CATS spaceborne lidar

In this study, our primary data consist of clouds detected during June-July-August (JJA) and December-January-February (DJF) periods using data from the CATS lidar system (Yorks et al., in preparation). CATS operated from the ISS between February 2015 to late October 2017. Although CATS was originally designed to operate at 3 wavelengths (355, 532 and 1064nm) with variable viewing geometries, beginning in March 2015 technical issues limited operation to a single 1064nm wavelength and a single viewing mode. The CATS instrument went on providing single-channel high-quality data (Yorks et al., 2016a) until a fault in the on-board power and data system ended science operations on October 30, 2017.

Being located on the ISS means measurements from CATS are constrained to latitudes below 51°, giving it access to ~78% of the Earth's surface (Figure 1, top). This prevents our study from covering polar regions, but leads to densely distributed overpasses at latitudes above 40°. CATS sampling is particularly good in populated midlatitude regions and above the Southern Ocean.

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CATS reports vertical profiles of Attenuated Total Backscatter (ATB) every 350m at 1064nm with a 60m vertical resolution (Yorks et al., 2016a). In the mode 7.2 in which CATS operates since February 2015, each profile is created by accumulating backscattered energy from 200 4kHz pulses, 20 times per second. The CATS vertical feature mask algorithms use these calibrated ATB profiles, averaged to 5 and 60 km, to detect atmospheric layers, discriminate clouds from aerosols, and determine cloud phase (Yorks et al., 2016b and in preparation). The CATS layer-detection algorithms are based on a threshold-profile technique similar to the one used for CALIOP (Vaughan et al., 2009) but, unlike for CALIOP, they rely primarily on 1064nm ATB (Yorks et al., 2016b). CATS cloud-aerosol discrimination algorithm uses a probability density function technique that is based on the CALIPSO algorithm but relies on horizontal persistence tests to differentiate low-level clouds and aerosol because backscatter color ratio, used in the CALIOP algorithms (Liu et al., 2009), is not available in

Mode 7.2. For cloud phase, CATS uses layer-integrated 1064 nm depolarization ratio and mid-layer temperature thresholds based on Hu et al. (2009) and Yorks et al. (2011). Minimum horizontal average was 5km in nighttime and 60km in daytime, a choice that brings the same cloud detection sensitivity to both (Yorks et al., 2016a). This has two consequences: 1) optically thinnest clouds detected during nighttime at 60km horizontal averaging might be absent from daytime detections (these represent roughly ~5% of nighttime clouds) and 2) the horizontal extent and cloud amount of fragmented boundary layer clouds might be overestimated in both daytime and nighttime compared to single-shot detections (as in Chepfer et al., 2013; Cesana et al., 2016). Cloud top and base heights, phase, and other properties are reported in the CATS Level 2 Operational (L2O) products every 5 km along-track. Hereafter we used such cloud properties from CATS L2O data files v2.01 (Palm et al., 2016), including only layers with a feature type score above 5, to avoid including wrongly-classified optically thick aerosol layers near deserts.

To document the diurnal cycle (Sect. 2.2.a), we used CATS cloud detections from JJA and DJF seasons between March 2015 and October 2017. CATS cloud data being still novel at the time of this writing, we document and discuss several of its characteristics in Appendices A and B, including sampling variability and the sensitivity of cloud detection in presence of solar pollution. This exploration of CATS data (and the upcoming comparisons with other instruments) made us confident that its sampling and cloud detections are robust enough to be used for scientific purposes.

b) *Cloud detections from ground-based active instruments*

Like with any lidar, the CATS laser beam gets fully attenuated when passing through clouds with optical depths larger than typically 3 (e.g., Chepfer et al., 2010). This can lead to the Cloud Fractions being underestimated in the lower troposphere. Meanwhile, horizontal averaging during daytime can lead to Cloud Fractions being overestimated at low altitudes. To estimate how much the CATS Cloud Fraction is biased at low altitudes, we compare CATS detections with independent observations collected from ground-based active instruments.

Ground-based observation sites provide long-term records of atmospheric properties over periods that often cannot be reached by satellite instruments (Chiriaco et al., 2018).

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CATS cloud data being still novel at the time of this writing, we document and discuss several of its characteristics in Appendices A and B, including sampling variability and the sensitivity of cloud detection in presence of solar pollution. This exploration of CATS data (and the upcoming comparisons with other instruments) made us confident that its sampling and cloud detections are robust enough to be used for scientific purposes.¶

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Nowadays such sites are often well equipped with active remote sensing instruments. Data acquisition, calibration and processing are often homogenized in the framework of specific observation networks (e.g. EARLINET, the European Aerosol Research Lidar Network, Pappalardo et al., 2014). Descriptions of the clouds diurnal cycle based on active ground-based measurements are however scarce. In this study, we compare CATS cloud cycles with those derived from active measurements at three ground-based sites, two continental and one oceanic:

- The Site Instrumenté de Recherche par Télédétection Atmosphérique (SIRTA, Haeffelin et al., 2005) is continental, located 20km South-West of Paris at 48.7°N, 2.2°E. From SIRTA we used cloud detections from the Lidar Nuages et Aérosols (LNA, Elouragini and Flamant, 1996), which were curated, packaged and made available in the framework of the SIRTA-reOBS project (Chiriaco et al., 2014, 2018). The LNA requires human supervision and does not operate under precipitation, leading to irregular sampling and almost no nighttime measurements. Thanks to its long operation time, its cloud dataset covers almost 15 years and was used in many studies (e.g. Noel and Haeffelin, 2007; Naud et al., 2010; Dupont et al., 2010). Cloud layers were detected in LNA profiles of attenuated backscatter following a threshold-based approach similar to CATS and CALIPSO.
- The Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site is continental too, at 97°W, 36°N. From ARM-SGP we used the sgparsclkazr1kolliasC1 cloud dataset (DOI: 10.5439/1393437), which contains vertical cloud detection profiles for every second every day based on measurements from the 35GHz Ka ARM Zenith Radar. This instrument has been operating since 2011 (Kollias et al., 2014). Based on these profiles we reconstructed hourly averages of Cloud Fraction profiles over seasons during the CATS operation period. Our results closely match those Zhao et al. (2017) derived from the same instrument, and those Dupont (2011) derived from the ARM-SGP Raman lidar.
- The ARM Eastern North Atlantic (ENA) site is oceanic, located on Graciosa Island in the Azores archipelago (28.03°W, 39.1°N). From ARM-ENA we used cloud detections from the enaarsclkazr1kolliasC1 dataset derived from a 35GHz radar similar to the one found at SGP, which we processed in a similar way.

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c) Cloud detections from passive and active spaceborne sensors

In addition to the datasets from CATS, LNA and two ground-based radars, in the upcoming sections we use cloud retrievals from two spaceborne datasets to put CATS cloud retrievals into a referenced context. First, we consider the baseline reference for the description of the clouds diurnal cycle from space: the analysis of data from the ISCCP done by Rossow and Schiffer (1999), hereafter RS99. Their results are based on aggregated and homogenized infrared and visible radiances from imaging radiometers on the international constellation of weather satellites. They are widely considered as the reference for describing the diurnal cycle of the cloud cover at large scales from space measurements. We did not reprocess any ISCCP data for the present study, instead we rely on the description of the diurnal cycle of low and high clouds RS99 documented in their Fig. 11 based on ISCCP, to which we confront CATS retrievals in Sect. 4.1.

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Finally, we also confront CATS cloud detections with retrievals based on measurements from the CALIOP lidar, routinely made since 2006 from the sun-synchronous CALIPSO platform at 13:30 and 01:30 LT in Sect. 4.2. To enable comparison with CATS retrievals, we used cloud layers retrieved from CALIPSO measurements during the period of CATS operation (March 2015 to October 2017) and documented at a 5km horizontal resolution in CALIPSO Level 2 V4.10 Cloud Layer Products (Vaughan et al., 2009). We processed both CATS and CALIPSO data alike as described in Sect. 2.2.a.

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2.2. Methods

a) Building the diurnal cycle of Cloud Fraction profiles from lidar cloud detections

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Analyzing CATS lidar echoes lets one identify at which altitude a cloud is present above a particular location on Earth at a given moment. By aggregating such information over a long period, vertical profiles of Cloud Fraction can be derived. A CF(z) profile documents at which frequency clouds were observed at the altitude *z* over a particular location. Cloud Fractions are conceptually equivalent to the Cloud Amounts derived from passive measurements

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From CATS level 2 data files, we extract profile-based cloud detections and use the measurement UTC time and coordinates to deduce their local time of observation. Using the resulting list of cloud layer altitudes, coordinates and local times of detection, we count the number *n* of cloud detected within half-hour bins of local time, 2°x2° lat-lon boxes and 200m altitude bins. We also count the number of valid data points n_0 within those bins. Eventually, we derive the Cloud Fraction $CF = \frac{n}{n_0}$, either in individual local time/lat-lon/altitude bin or by aggregating *n* and n_0 over a selection of bins. Thus, we recreate a statistically accurate representation of the diurnal cycle of Cloud Fractions profiles, over any location between 51°S and 51°N, through the aggregation over long periods of cloud detections made over that location on different days and local times.

CATS reports cloud layers as opaque when no echo from the surface is found in the profile below a detected cloud, following the same methodology as in Guzman et al., 2017. Below an opaque cloud layer, there is no laser signal left to propagate, and clouds potentially present at lower altitudes will not be sampled by the lidar. To account for this effect, we consider the portions of profiles below an opaque layer unsampled, and they do not count in the number of valid data points n_0. This approach limits the influence of laser attenuation on cloud detections but cannot totally cancel it. For very low clouds (top below 2km), we make an exception to this rule and consider the lower part of the profile cloudy, as we found this creates the best agreement with ground-based observations.

To enable comparisons with CATS CF profiles (Sect. 3.3 and 4.2), we followed a similar approach to build CF profiles using cloud detections from SIRTA-reOBS and ARM datasets (Sect. 2.1), and from CALIPSO Level 2 products (Sect. 2.1.c). In both cases, we counted the number of cloud detections and valid (non-attenuated) measurements in hourly local time bins and 200m altitude bins. For CALIPSO, only 01:30AM and PM time bins were filled.

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b) Building the diurnal cycle of Low and High Cloud Amounts from CATS data

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As ISCCP data are based on radiances, clouds therein are characterized according to their retrieved top pressure P as low (P > 680hPa), middle (440 < P < 680hPa) or high (P < 440hPa). To enable a direct ISCCP-CATS comparison, we derived Cloud Amounts (CA) from CATS data for low and high clouds as defined by altitude: low clouds have their top below 4km ASL, high clouds have their base above 7km, and mid-level clouds are in between. Using the list of cloud layer altitudes, coordinates and local times of detection derived from CATS detections (Sect. 2.2.a), we count the number of occurrences n' of at least part of one cloud layer in half-hour bins of local time, 2°x2° lat-lon boxes and the three altitude ranges (0-4km, 4-7km and higher than 7km ASL). We also count the number of occurrences n'_0 that could possibly be reported given the measurements sampled by CATS within each bin, taking into account the existence of opaque layers. Eventually, we derive the Cloud Amount $CA = \frac{n'}{n'_0}$ for low, mid and high-altitude clouds layers, either in individual local time/lat-lon bin or by aggregating n' and n'_0 over a selection of bins. Like RS99, we separated CATS cloud detections over land and ocean, based on the International Geosphere-Biosphere Programme surface flag present in CATS L2 products on a profile basis (Palm et al., 2016).

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3. Results

3.1. Diurnal Cloud Fraction profiles observed at Global scale

Figure 1 shows the global diurnal cycle revealed by CATS during JJA from March 2015 to October 2017 over Ocean and Land (bottom left and right). Low and high clouds are clearly separated, with a band of minimum cloudiness in-between (near 4km ASL). Above both surfaces, CATS data show an increase of high clouds during nighttime. Sassen et al. (2009) explain this increase by the infrared radiative cooling of the upper troposphere. The vertical spread of high clouds is most narrow near noon, at which point their apparent base is the highest. These findings are consistent with CALIPSO retrievals (Sassen et al., 2009; Gupta et al., 2018). The vertical evolution in the fraction of sampled atmosphere due to attenuation by atmospheric components, for these diurnal cycles and all that follow, is documented in Appendix C.

Significant differences exist between the cloud profiles diurnal cycle above land and ocean. Clouds generally extend higher over land during nighttime: high clouds are vertically most frequent near 10km over ocean, while they extend up to 14km above continents until 5AM. Over ocean, high clouds appear to rise late in the afternoon (3-6PM) and fall soon thereafter as the sun sets. Land-ocean differences are most striking at low altitudes: over Ocean low clouds are present almost all day long between 0 and 2km ASL, their CF decreasing from a 20% maximum near 4AM to ~10% between 11AM and 5PM. Over land, low clouds are most significant during daytime: they appear near 2km ASL at 10AM and extends upwards to reach 4km ASL near 4PM. The associated CF remains low, at most 8%. These planetary boundary layer (PBL) clouds are most certainly associated with turbulence and convection activity occurring near the surface. They disappear after 4PM without connecting to the higher layers. The clear-sky band (CF < 2%) near the surface is largest at night (almost 2km) and thinnest in the late morning.

An aside on cloud detection: over the ocean, CATS detects more low and high clouds during nighttime. This means that the increase in high clouds does not prevent the lidar measurements to represent faithfully at least part of the nocturnal increase in low clouds.

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During daytime, the decrease in detection sensitivity due to solar pollution could underestimate the retrieved frequency of clouds (low or high). However, CALIPSO cloud detections also reveal a nighttime increase in high clouds, which Sassen et al. (2009) and Gupta et al. (2018) found much too large to be attributed to detection bias from solar noise. Since CATS daytime cloud detection abilities at 1064nm are at least as good as CALIOP's at 532nm (Yorks et al., 2016), it follows that CATS cloud retrievals should provide a reliable qualitative assessment of their diurnal cycle, as comparisons with ground-based measurements will later show (Sect. 3.3). How much solar noise leads to an underestimate of high clouds in CALIOP and CATS datasets still needs to be quantified.

While these seasonal mean results are informative, they mix together unrelated cloud populations from hemispheres with opposite seasons driven by different circulation regimes. We thus describe the daily cycles of clouds in zonal bands in the next section.

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3.2. Diurnal Cloud Fraction profiles observed over mid-latitudes and Tropics

In this section, we consider cloud populations over four latitude bands: midlatitude (30°-51°) and Tropics (0-30°), in the North Hemisphere (NH) and South Hemisphere (SH), over land and ocean. We first examine the differences between the diurnal cycles affecting the cloud vertical profiles over ocean and land in JJA (Sect. 3.2.a and 3.2.b, Fig. 2), then we discuss how these cycles are affected by the season by considering DJF results (Sect. 3.2.c, Fig. 3).

a) High clouds

As expected, Fig. 2 shows that high clouds are located at higher altitude in the tropics (12-16km ASL) than in midlatitude (8-12km), following the variation of the troposphere depth with latitude. Also as expected, the occurrence of high clouds is largest (CF > 20%) in deep convection along the Inter-Tropical Convergence Zone (ITCZ), located between 0° and 30°N in JJA, and minimum (CF < 8%) in the subsidence branch of the Hadley cell (0°-30°S in JJA). In mid-latitudes, high clouds (7-9km ASL) are far more frequent (CF ~ 20%) over the Southern Ocean (30°S-51°S) than over the northern ocean (30-51°N).

The CF of oceanic high clouds follows a strong diurnal cycle, with a maximum at nighttime and a minimum at noon, in mid-latitudes and tropics (even in subsidence region). This cycle is more pronounced where the high clouds are more numerous: along the ITCZ (0-30°N) and in the Southern Ocean (30-51°S). In addition to the variation in the high cloud occurrence, the vertical distribution of these clouds also follows a marked diurnal cycle along the ITCZ: detections spread vertically over more than 4km near midnight, but over less than 1km at noon. This spreading out occurs between 5PM and 10PM, and disappears much faster during the morning. A wider spread of detection altitudes can either indicate the presence of geometrically thicker clouds, or a wider distribution of optically thick clouds tops only partially sampled by CATS. By comparison, over the Southern Ocean high cloud detections occur over the same altitude range throughout the day.

Overall, high clouds behave very similarly above land (Fig. 2, right column) and ocean (Fig. 2, left column) at all latitudes, except between 30-51°S where the continental surface is too small to conclude.

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b) Low clouds

Over ocean in JJA (Fig. 2), the occurrence of low clouds (0-3km ASL) changes significantly with latitude: The Southern Ocean region (30-51°S) is by far the cloudiest, the mid-latitude north (30-51°N) and the subsidence tropics (0-30°S) are moderately cloudy, and even less low clouds are observed along the ITCZ (0-30°N). The oceanic low clouds show only small variations along the day. A weak diurnal cycle occurs at all latitudes except along the ITCZ (possibly because low clouds there are in part masked by higher clouds affected by an out-of-phase diurnal cycle). Low-level clouds are more numerous in nighttime (CF near 20%) compared to daytime (CF~12%) in subsidence tropics (0-30°S) and mid-latitude north (30-51°N). The southern oceanic low clouds exhibit a very faint diurnal cycle: their CF gets over 20% nearly all day long, with a very small decrease near 2PM.

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In contrast to high clouds, the differences between land and ocean are striking for the low and mid-level clouds. Both the occurrences and the diurnal cycles of clouds over land differ significantly from their oceanic counterparts. The low clouds are very few over land (CF~4%) compared to over ocean (>16%), all day long. Moreover, the continental low cloud diurnal cycle exhibits a maximum in the early afternoon (around 2PM) that does not show up over ocean: a maximum CF appears around 2.5 km of altitude in the upper edge (or just above the top) of the atmospheric boundary layer; it is linked to convective activity between 10AM and 5PM.

Another noticeable difference between land and ocean is the presence of well-defined mid-level cloud population over NH tropical land (0-30°N, 2nd row on the right in Fig. 2) in the free troposphere between 5 and 7 km ASL. These mid-level clouds show a diurnal cycle opposite to PBL clouds and similar to the high clouds in that its minimum occurs at midday and its maximum at night, although the magnitude of this cycle is much more limited. This altitude range would be consistent with cumulus congestus (Johnson et al., 1999). Those, however, are present above both land and ocean (Masugana et al. 2005) and CATS finds little clouds at these altitudes over ocean. Rather, the clouds altitudes and location, over land in the summer hemisphere, are consistent with Altocumulus clouds as described by Sassen and Wang (2012) using CALIPSO and CloudSat measurements. Bourgeois et al. (2017) discussed the diurnal cycle of similar clouds observed over West Africa: they found these clouds reach maximum occurrence early in the morning, which is consistent with our results.

c) Seasonal differences

Figure 3 presents diurnal cycles of Cloud Fraction profiles over the same latitude bands as Fig. 2 but based on data collected during the boreal winter (DJF). As seasons switch hemispheres, we anticipate cloud populations to undergo symmetric changes across hemispheres, in agreement with large-scale dynamic processes driving their spatial distribution on seasonal time scales. This is verified for high clouds (Fig. 2 vs. Fig. 3): in the Tropics the ITCZ moves to South and with it the large CF at high altitudes, in midlatitudes the high clouds are more frequent during the winter season, due to more frequent low-pressure conditions.

Interestingly, the mid-altitude clouds visible near 6km ASL in the NH Tropics over land (Fig. 2, 2nd row on the right) also move to the SH Tropics in DJF (Fig. 3, 3rd row on the right). This confirms the year-long persistence of midlevel clouds over continental tropical regions found by Bourgeois et al. (2017).

The seasonal changes in low clouds are less symmetric than in higher clouds, as they are more closely related to surface conditions. Over ocean, in DJF the amount of low clouds increases dramatically in NH midlatitudes compared to JJA (Fig. 2 and 3, top left), but does not change noticeably in the SH midlatitudes: the diurnal cycle that sees a slight decrease in the huge population of low clouds over the Southern Ocean is present in both seasons (Fig. 2 and 3, bottom left). Over land, in the Tropics, low clouds appear similar in frequency and behavior in both DJF and JJA: PBL clouds extend vertically between ~7AM to 5PM (Fig. 2 and 3, rows 2 and 3 of right column). The NH midlatitudes show the strongest seasonal change in low clouds, as they become present all day long: the diurnal cycle associated with PBL development in JJA disappears in DJF (Fig. 2 and 3, top right). SH midlatitude retrievals over land are noisy in DJF and JJA, but the DJF data (Fig. 3, bottom right) suggests that low clouds there extend vertically a lot more than in JJA, up to 4km ASL.

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3.3. Diurnal cycle of cloud profiles above selected continental regions

In this section, our first goal is to compare the diurnal cycle of the Cloud Fraction profiles from CATS against independent observations collected by active instruments from ground-based sites (Sect. 3.3.a and 3.3.b). In particular, we want to understand if the behaviors found so far (Fig. 1-3) are valid for low clouds despite the attenuation of the space laser signal (Sect. 2.2.a). Our second goal is to compare, for the first time, the diurnal cycle of the Cloud Fraction profiles over different continental regions all over the globe as observed with a single instrument (Sect. 3.3.c).

It is important to note that since detection sensitivity, penetration depths and algorithmic choices (e.g. averaging times and distances) change significantly from one instrument to the next, we do not expect the various datasets to agree on absolute values of Cloud Fraction profiles or Cloud Amounts. Rather, our interest is in whether different instruments agree on the behavior of the diurnal evolution of clouds when they document the same location. Thus the following comparison focus on the main features of the daily cycles and not on absolute values.

a) Over South of Paris in Europe

Figure 4 shows the diurnal evolution of CF profiles seen by the ground-based LNA lidar (top left) operated on the SIRTA site south of Paris (Sect. 2.1.b) and seen by CATS in a 10°x10° box centered on SIRTA, keeping only profiles sampled over land (top right). Both datasets report a well-defined high-altitude layer, with a clear-cut cloud top near 12 km ASL that rises up a few hundred meters in the morning until 10AM and slowly falls during the afternoon by at most 1 km. In both figures, the bottom of this layer is not sharply defined: the CF decreases almost linearly from 11-12km ASL to near-zero at 4km ASL. Both instruments also report a low-level cloud layer that initiates in the morning and extends upwards from ~1km ASL at 5AM to ~4km ASL near 8PM.

Regarding differences, CATS sees more high-altitude clouds. In the late afternoon (starting near 5PM), in particular, the ground-based lidar instead sees much less high clouds; that instrument, however, suffers from poor sampling at this late hour. CATS reports less

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boundary layer clouds, particularly in the late afternoon, when the ground-based lidar reports low-level CF above 20% (again, a time of poor sampling). The large number of high-altitude clouds observed by CATS at that time could impair its ability to detect lower clouds, while at the same time the many low clouds observed by the ground lidar can impair its ability to detect high clouds. The absence of precipitating clouds from the LNA dataset could also explain this difference.

b) Over the US Southern Great Plains ARM site

Figure 4 shows the diurnal evolution of CF profiles seen by the SGP-based radar (2nd row, left) and CATS (right) in a 10°x10° lat-lon box centered on the SGP site (Sect. 2.2.b), keeping only profiles sampled over land. During nighttime, both datasets report frequent high-level clouds near 12km ASL, with large CF between 16:00 and 03:00 LT. At night, high clouds are also more distributed vertically, between 9 and 14km ASL. CATS and SGP datasets agree that the importance of high-level clouds strongly drops during daytime (7AM-5PM), with a minimum CF at midday. During daytime, the vertical distribution of high-level clouds is more narrow, from 11 to 12km ASL at its thinnest point (near 10AM). This rather strong cycle of high-level clouds can be explained by possible influence from Tropical dynamics at the 36°N latitude of the SGP site. There are slightly more midlevel clouds (4-8km ASL) at night, with increasing CF between midnight and 7AM. PBL clouds form near the surface at 9AM, rise and thicken almost up to 4km ASL near 4PM.

There are of course differences. The SGP radar detects PBL and midlevel clouds twice more frequently than CATS, even though few high clouds are present. CATS also misses low-level clouds observed by the SGP radar between 6PM and 6AM, probable stratiform clouds that could either be too optically thin for CATS or miscategorized by its cloud detection algorithm.

c) Over the subtropical Eastern North Atlantic ARM site

Figure 4 shows the diurnal evolution of CF profiles seen by the ENA-based radar (bottom row, left) and CATS (right) in a 10°x10° lat-lon box centered on the ENA site (Sect. 2.2.b). The vertical distribution of clouds appears very different over this oceanic site. Both CATS and

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the ENA radar agree on the day-long persistence of low-level clouds below 2km ASL, and on their slight drop in Cloud Fraction and vertical spread between noon and 6PM. This is consistent with persistent stratiform clouds that are maximum at night. CATS sees more high clouds (8-12km ASL) than the ENA radar (4-12km ASL). CATS also reports a Cloud Fraction minimum between 0300-0500LT that is not present in groud-based dataset.

These three comparisons between CATS and ground-based measurements suggest that, in general, the spaceborne lidar sees more high-level clouds and the ground-based instrument more low-level clouds. This sampling bias affects all space lidar comparisons with ground instruments (e.g. Dupont et al., 2010). Even so, we find similar behavior in the diurnal cycles reported by CATS and ground instruments over the same locations. Dataset discrepancies appear acceptable given the much smaller size of the CATS dataset (infrequent overpasses over 3 seasons compared to daily local measurements) and the instrumental and algorithmic variations already mentioned. It is reassuring to find that CATS results retain the major features of the clouds profile daily cycle, most notably an acceptable representation of the daytime low-level boundary layer clouds at all three sites despite the presence of high-level clouds.

In this section, we have seen that retrievals from ground-based instruments suggest CATS measurements reliably document the clouds diurnal cycle. Due to the distribution of ground-based sites, however, this approach is limited to mostly midlatitudes from the Northern Hemisphere. Next, we compare CATS detections with global spaceborne retrievals.

d) Diurnal cycles of the cloud profiles over continents

Continents are diverse in ground type, orography, latitude, exposition to large-scale atmospheric circulation, and transport of air masses from the local environment. These factors influence the atmosphere above the continent, leading to possible variations in the cloud diurnal cycle profiles. Ground-based observations let us document these different cycles, but differences between instruments and operations in the different ground sites make comparing diurnal cycle observed from ground at different locations difficult. Thanks to CATS data, for the first time we compare here the cloud diurnal cycle profiles observed over different continents by a single instrument and with a relatively large space sampling,

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compared to single-site ground-based observations. Figure 5 illustrates how the diurnal cycle of CF varies among seven large continental areas across both hemispheres, considering only cloud detections made by CATS over land within lat-lon boxes (defined in the inset map) during the summer seasons (JJA in the NH, DJF in the SH).

During summer most continents share a development of PBL clouds during sunlit hours (with similar Cloud Fractions, hours and vertical extents), except NH Africa where low clouds are almost absent. Most continents also share a nighttime maximum and daytime maximum of high clouds, with an associated narrowing of their vertical distribution during morning and a spreading out during the afternoon. Variations in cloudiness and cloud vertical distribution are particularly intense over South America and SH Africa, while they are minimal over Australia. A mid-altitude cloud layer is present almost all day long, with a faint daytime minimum, over all SH continents and NH Africa.

Note that the present comparison is less robust in the lower troposphere than higher in the troposphere, due to the attenuation of the space lidar signal as it penetrates the atmosphere.

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4. Discussion

Hereafter we use our results for answering the following questions: How does the diurnal cycle of low, mid, high cloud covers from geostationary satellites compare with CATS ones? Do the existing lidar space missions document extreme or average behaviors of the cloud profile diurnal cycle? What about upcoming sun-synchronous lidar space missions?

4.1 About the Diurnal cycles of Low and High Cloud Amounts

CATS observations provide an opportunity to compare the cloud diurnal cycle derived from the ISCCP dataset (Sect. 2.1.c) with completely independent observations at near-global scale (excluding latitudes higher than 51°). In particular, we expect cloud retrievals from an active sensor such as CATS to be independent of the surface, even above highly reflective surfaces such as ice and deserts and to include optically thin clouds. Since CATS sampling is constrained between 51°S and 51°N, its data cannot be used to document the diurnal cycle in the polar regions, like ISCCP does: our comparison will extend at most to midlatitudes. Figure 6 shows the diurnal cycle of the Low and High cloud covers observed by the CATS space lidar.

Over ocean CAs are very stable, the diurnal cycle is almost flat (Fig. 6, left column). CATS shows a weak cycle for low clouds, with a maximum in mid-morning and a minimum in early-afternoon, which is also visible in ISCCP data. For oceanic high clouds, CATS exhibit almost no diurnal cycle except in the Tropics where they follow the same cycle as low clouds. ISCCP also shows a weak cycle for high clouds, but opposite to the CATS one. This might be related to the fact that CATS can detect optically thin high clouds better than ISCCP. The optically thicker high clouds seen by ISCCP are thus probably more linked to deep convection activity. CATS can better detect optical thin high clouds, which should be more decoupled from convection and less affected by diurnal cycles.

Over land, between 15°S and 51°N, CATS reports that low-clouds have a pronounced diurnal cycle with a maximum of low-level clouds at midday (+10%) and a minimum at midnight (-5%). This is consistent with ISCCP observations (Figure 11 in RS99), but in the Northern mid-

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latitudes the amplitude of the cycle is weaker for CATS than ISCCP (minimum at -4% instead of -12%). For high-level clouds over land in the Tropics (15°S-30°N) CATS observes a maximum during night-time and a minimum at noon; the timing is consistent with ISCCP but the amplitude is slightly more pronounced with CATS than ISCCP (-12% instead of -7% at midday). In the Southern hemisphere (15°S-51°S) the similarity between CATS and ISCCP gets lost, probably because the land surface is small in those latitude ranges and the observations are not significant.

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In summary, CATS confirms the shape of the Low and High cloud diurnal cycles observed by ISCCP except for high tropical clouds. This could be due to the space lidar detecting a larger number of optically thinner clouds not directly linked to deep convection, or to the different day-night cloud detection sensitivities of active and passive measurements. In most cases, the amplitudes of the diurnal cycle observed by CATS differ from those observed by ISCCP.

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Both CATS and ISCCP miss some low clouds that are masked by the presence of high thick clouds. So even if CATS and ISCCP diurnal cycles are roughly consistent in low clouds, both results might be biased in the same direction. The high clouds diurnal cycle presented here are more robust than the low clouds ones.

4.2 About the Cloud Fraction profiles observed at fixed local times by space lidars

The CALIOP lidar has provided detailed Cloud Fraction profiles since 2006 at 0130AM and 0130 PM LT. The next spaceborne atmospheric lidar missions ADM-Aeolus, to be launched in late 2018 (Culoma et al., 2017) on a sun-synchronous orbit, will enable measurements at 0600AM and 0600PM LT. After that, the ATLID lidar on the Earth-CARE platform (Illingworth et al., 2015), expected to launch in 2020, will operate at fixed local times close to CALIOP (02:00AM and PM). The CATS dataset may remain for the near future our single source of diurnally distributed cloud profile lidar measurements from space.

a) Comparison between CATS and CALIPSO

In this section, we first check how CATS sees the day/night variation in cloud profiles also documented by CALIOP through its two daily overpasses. Figure 7 shows vertical profiles of

Cloud Fraction reported by both datasets at 0130AM and PM, over ocean (left) and land (right), latitude-weighted and averaged between 51°S and 51°N over JJA between 2015 and 2017. The black lines show the CF obtained when considering all measurements from both instruments. Over land and ocean, we find that both CALIPSO and CATS overall report larger Cloud Fractions at 0130AM (blue) than 0130PM (red), in agreement with the findings of Gupta et al. (2018). Below 2.5 km, this difference is stronger over ocean (+7% in 0130AM CF) than over land. Both datasets report a strong increase in 0130AM CF (almost +7% compared to 0130PM) above 15km over land.

The CF profiles reported by both datasets agree very well over Ocean (left) in both daytime and nighttime conditions. Over land (right) in daytime (red) conditions, CATS reports slightly more low-level clouds (CF~7% near 1km ASL, ~5% for CALIOP). This difference, which is present at all latitudes above land during daytime (not shown), might be due to the so-called single-shot low clouds, for which CALIOP data undergoes a specific processing (Winker et al., 2009). The strongest differences appear for nighttime CF over land (right, blue): CALIPSO CF is larger than CATS CF by a 2-3% throughout the entire profile. A perfect agreement between CF from both datasets should not be expected, as the CATS and CALIOP lidars operate in different configurations – wavelengths, pulse repetition frequencies and signal-to-noise ratios are different, for a start. These technical variations lead to differences in, for instance, how fast the laser pulse energy of both instruments gets attenuated as it penetrates atmospheres of various compositions, or differences in cloud detection performance, e.g. when sampling optically thin clouds in the upper troposphere, or fractionated boundary layer clouds (see Reverdy et al., 2015 for a study of the impact of design choices on lidar retrievals). Both datasets agree quite well on the general vertical pattern of the profile, though. A useful conclusion is that considering CALIPSO observations at both overpass local times (i.e. 0130AM and 0130PM) apparently provides a good approximation of the daily average Cloud Fraction profile.

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b) Comparison of Cloud Fraction profiles at various times of satellite overpass

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As a final analysis, we represent the range covered by CATS hourly CF profiles over a day (averaged over the globe - white envelope in Fig. 8) and show CF profiles observed by CATS ±1 hour around the fixed local observation times of the three sun-synchronous space lidar

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missions (CALIPSO, ADM-Aeolus, EarthCare).

Our first aim is to understand how wind observations made at fixed local time by ADM-Aeolus might be impacted by the cloud diurnal cycle. ADM-Aeolus will provide information on wind only in absence of clouds. Figure 8 indicates that ADM-Aeolus overpass times are quite cloudy in both AM and PM compared to the diurnal variability (white envelope). The PM overpass corresponds to the daily maximum in cloud profiles over both ocean and land, while AM observations correspond to a time representative of the daily average Cloud Fraction profile. As more clouds occur in the PM than AM observations, less wind information will likely be provided by ADM-Aeolus in the afternoon than in the morning. For the future, another ADM-Aeolus-like mission around midday (minimum Cloud Fraction profile) would increase the number of wind measurement with respect to the cloud occurrence.

Our second aim is to understand how well observations made at fixed local times by space lidar dedicated to clouds studies (CALIPSO and EarthCare) capture the daily variability of Cloud Fraction profiles. Figure 8 suggests that over land (right), CALIPSO and Earth-CARE retrievals capture only part of the daily CF variability above 8km ASL: the PM measurements overestimate the daily CF minima and the AM measurements underestimate the daily CF maxima. Below 8km ASL they are rather representative of the daily average, except below 5km ASL where PM measurements get close to the daily CF maxima. Figure 8 also shows that over Ocean (left) CALIPSO and Earth-CARE retrievals should be considered as the daily CF maxima during the nighttime (AM) overpass and as the daily CF minima during the daytime (PM) overpass. This has interesting implications: it suggests that not only CALIPSO but all the observations dedicated to cloud studies collected by the instruments within the A-train (CloudSat, CERES, MODIS, PARASOL, etc.) have documented the state of the atmosphere in the extreme states of the cloud profile diurnal cycle over the last 12 years over ocean. These conclusions suggest the A-Train observations are likely relevant and robust to constrain the cloud diurnal cycle extremes in climate models and climate studies.

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5. Conclusions

In this paper, we took advantage of the variable local time of overpass of the International Space Station to document the diurnal cycle of the cloud vertical profile as seen by the CATS lidar. This is the first time the diurnal evolution of the vertical cloud profile is documented on that vertical scale on a large part of the globe, between 51°S and 51°N. Our results are based on 15 months of systematic observations (3 boreal summers and 2 austral summers) collected during the 2015-2017 time period, which enable statistically significant results.

The main results follow. We observed that high tropical clouds begin to spread out vertically in the late afternoon (4-5PM). Their vertical distribution is largest (over 5km) near 10PM. This spread-out is particularly large in the Summer Hemisphere in DJF. A mid-level cloud layer (4-8 km ASL) persists all day long over the tropical continent during summer, with a weak diurnal cycle (minimum at noon). Southern Ocean results are quite unique; low clouds (0-2km ASL) cover this ocean all day long in summer and winter. A slight diurnal cycle sees their CF drop by a few percents during the afternoon (from noon to 6PM), but their vertical distribution stays constant. High clouds are also frequent over the Southern Ocean, more so in JJA. They follow a diurnal cycle in summer and winter, with an daytime minimum (from 8AM and 3PM). At all latitudes, continental low clouds are most frequent in the early afternoon (around 2PM) at about 2.5 km ASL. Finally, our results show that in summer the diurnal cycle of continental clouds is similar in both hemispheres: a rapid development of near-surface PBL clouds during sunlit hours, and an increase in cloudiness and wider vertical distributions during nighttime for high-altitude clouds (stronger over the SH and the Tropics). Exceptions are NH Africa, where PBL clouds are very few, and Australia, where high clouds appear only significant between 8 and 11PM.

We evaluated the diurnal cycle derived from CATS against independent ground-based observations and found satisfactory agreement. Moreover, our results suggest that over oceans CALIPSO and Earth-CARE should describe the daily minimum of the Cloud Fraction profile during their PM overpass, and its daily maximum during their AM overpass. This supports the idea that data collected by A-train instruments (not only CALIPSO) are very relevant to document the cloud diurnal cycle. This is also roughly the case over land at altitudes above 8km ASL, although the amplitude of the diurnal variability is quite

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underestimated.

Questions remain about how several factors could affect our ability to retrieve the vertical variability of clouds from lidar-based measurements through the day. More specifically, the irruption of solar noise in daytime conditions requires increased horizontal averaging to keep CATS detection sensitivity stable. High clouds with very small optical depths (lower than 0.005), which CATS can detect in the nighttime, will be probably missed in the daytime. Meanwhile, the occurrence and extent of fragmented boundary layer clouds might be overestimated. Even though prior work using the similarly-affected CALIPSO data suggests the observed diurnal changes in clouds are too large to be solely due to those effects, their impact on the retrieved cycles needs to be quantified. In the same manner, how extinction by high clouds impacts the retrieved Cloud Fractions at low altitude needs to be investigated.

In the future, it would be possible to consider CATS measurements at smaller scales, to identify regionally consistent cloud populations and diurnal behaviors over specific regions of interest. It would also be possible to use CATS detection of opaque cloud layers to identify the best local time of observation from space to study local cloud radiative effects. We will address these lines of research in upcoming papers.

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Acknowledgments

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References

- Ackerman, T. P., and G. M. Stokes (2003), The Atmospheric Radiation Measurement Program Phys. Today, 56, 38–44, doi:10.1063/1.1554135
- Bouniol, D., R. Roca, T. Fiolleau, and D.E. Poan, 2016: Macrophysical, Microphysical, and Radiative Properties of Tropical Mesoscale Convective Systems over Their Life Cycle. *J. Climate,* **29**, 3353–3371, doi:10.1175/JCLI-D-15-0551.1
- Bourgeois, E., D. Bouniol, F. Couvreux, F. Guichard, J. H. Marsham, L. Garcia-Carreras, C. E. Birch, and D. J. Parker (2018), Characteristics of mid-level clouds over West Africa, *QJRMS*, *113*, D04210–17, doi:10.1002/qj.3215.
- Ceppi, P., F. Brient, M. D. Zelinka, and D. L. Hartmann, 2017: Cloud feedback mechanisms and their representation in global climate models, WIREs Climate Change 2017, e465. Doi: 10.1002/wcc.465
- Cesana, G., and H. Chepfer (2013), Evaluation of the cloud thermodynamic phase in a climate model using CALIPSO-GOCCP, J. Geophys. Res., 118(14), 7922–7937, doi:10.1002/jgrd.50376.
- Cesana, G., H. Chepfer, D.M. Winker, B. Getzewich, X. Cai, H. Okamoto, Y. Hagihara, O. Jourdan, G. Mioche, V. Noel, M. Reverdy, 2016: Using in situ airborne measurements to evaluate three cloud phase products derived from CALIPSO, J. Geophys. Res. Atmos.,121, 5788▯5808, doi:10.1002/2015JD024334
- Chepfer, H., Bony, S., Winker, D., Cesana, G., Dufresne, J. L., Minnis, P., Stubenrauch, C. J. and Zeng, S.: The GCM-Oriented CALIPSO Cloud Product (CALIPSO-GOCCP), J. Geophys. Res., 115(1), 23073–13, doi:10.1029/2009JD012251, 2010.
- Chepfer H., G. Cesana, D. Winker, B. Getzewich, and M. Vaughan, 2013: Comparison of two different cloud climatologies derived from CALIOP Level 1 observations: the CALIPSO-ST and the CALIPSO-GOCCP, J. Atmos. Ocean. Tech., doi.10.1175/JTECH-D-12-00057.1
- Chiriaco M., S. Bastin, P. Yiou, M. Haeffelin, J.-C. Dupont, L. Klenov, M. Stéfanon, 2014: European heat-wave in July 2006: observations and modelling showing how

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local processes amplify conducive large-scale conditions. Geophys. Res. Let., 41 issue 15, 5644 – 5652.

- Chiriaco, M., Dupont, J.-C., Bastin, S., Badosa, J., Lopez, J., Haeffelin, M., Chepfer, H., and Guzman, R.: ReOBS: a new approach to synthesize long-term multi-variable dataset and application to the SIRTA supersite, Earth Syst. Sci. Data, 10, 919-940, https://doi.org/10.5194/essd-10-919-2018, 2018
- Culoma A., A. Elfving, R. Meynart, A. Straume, D. Wernham, "AEOLUS mission: the latest preparations before launch", Proc. SPIE 10423, Sensors, Systems, and Next-Generation Satellites XXI, 1042303 (29 September 2017); doi: 10.1117/12.2282159
- Dong, X., B. Xi, K. Crosby, C. N. Long, R. S. Stone, and M. D. Shupe (2010), A 10 year climatology of Arctic cloud fraction and radiative forcing at Barrow, Alaska, *J. Geophys. Res.*, *115*(D17), D17212, doi:10.1029/2009JD013489.
- Dupont, J. C., M. Haeffelin, Y. Morille, V. Noel, P. Keckhut, D. Winker, J. Comstock, P. Chervet, and A. Roblin (2010), Macrophysical and optical properties of midlatitude cirrus clouds from four ground-based lidars and collocated CALIOP observations, *J. Geophys. Res.*, *115*(D4), D00H24–15, doi:10.1029/2009JD011943.
- Elouragini, S. and Flamant, P. H.: Iterative method to determine an averaged lidar ratio and the range resolved extinction in cirrus, Appl. Opt., 35, 1512–1518, 1996.
- Gray, W. M., and R. W. Jacobson, 1977: Diurnal variation of deep cumulus convection. Mon. Wea. Rev., 105, 1171–1188, doi:10.1175/1520-0493(1977)105,1171:DVODCC.2.0.CO;2
- Greenwald, T. J. and Christopher, S. A.: Daytime variation of marine stratocumulus microphysical properties as observed from geostationary satellite, Geophysical Research Letters, 26(1), 1723–1726, doi:10.1029/1999GL900346, 1999.
- Guzman, R., H. Chepfer, V. Noel, T. Vaillant de Guélis, J. E. Kay, P. Raberanto, G. Cesana, M. A. Vaughan, and D. M. Winker (2017), Direct atmosphere opacity observations from CALIPSO provide new constraints on cloud-radiation interactions, J. Geophys. Res., 1–20, doi:10.1002/2016JD025946.
- Haeffelin, M. et al. (2005), SIRTA, a ground-based atmospheric observatory for cloud

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and aerosol research, Annales Geophysicae, 23(2), 253–275, doi:10.5194/angeo-23-253-2005.

- Haynes, J. M., T. H. Vonder Haar, T. L'Ecuyer and D. Henderson (2013) Radiative heating characteristics of earth's cloudy atmosphere from vertically resolved active sensors. Geophys Res Lett 40:624–904 630. doi:10.1002/grl.50145.
- Hoareau, C., P. Keckhut, V. Noel, H. Chepfer, and J. L. Baray (2013), A decadal cirrus clouds climatology from ground-based and spaceborne lidars above the south of France (43.9° N–5.7° E), *Atmos. Chem. Phys.*, *13*(14), 6951–6963, doi:10.5194/acp-13-6951-2013.
- Hogan, R. J., A. J. Illingworth, E. J. O'Connor, and J. P. V. Poiares Baptista (2003), Characteristics of mixed-phase clouds. II: A climatology from ground-based lidar, *QJRMS*, *129*, 2117–2134.
- Hu, Y. et al. (2009), CALIPSO/CALIOP Cloud Phase Discrimination Algorithm, *J. Atmos. Oceanic Technol.*, *26*, 2293–2309.
- Illingworth, A. J. et al. (2015), The EarthCARE Satellite: The Next Step Forward in Global Measurements of Clouds, Aerosols, Precipitation, and Radiation, Bull. Am. Met. Soc, 96(8), 1311–1332, doi:10.1175/BAMS-D-12-00227.1.
- Johnson, R. H., T. M. Rickenbach, S. A. Rutledge, P. E. Ciesielski, and W. H. Schubert (1999), Trimodal Characteristics of Tropical Convection, *J. Climate*, *12*(8), 2397–2418, doi:10.1175/1520-0442(1999)012<2397:TCOTC>2.0.CO;2.
- Kato, S., F. G. Rose, S. S. Mack, W. F. Miller, and co-authors (2011), Improvements of top-of-atmosphere and surface irradiance computations with CALIPSO-, CloudSat-, and MODIS-derived cloud and aerosol properties. J Geophys Res 116:D19209. doi:10.1029/2011JD016050
- Kollias, P., Bharadwaj, N., Widener, K., Jo, I. and Johnson, K.: Scanning ARM Cloud Radars. Part I: Operational Sampling Strategies, J. Atmos. Oceanic Technol., 31(3), 569–582, doi:10.1175/JTECH-D-13-00044.1, 2014.
- Konsta, D., J. L. Dufresne, H. Chepfer, A. Idelkadi, and G. Cesana (2016), Use of A-train satellite observations (CALIPSO–PARASOL) to evaluate tropical cloud properties in the

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LMDZ5 GCM, Clim. Dyn., 1–22, doi:10.1007/s00382-015-2900-y.

- Kummerow, C., W. Barnes, T. Kozu, J. Shiue, and J. Simpson (1998), The Tropical Rainfall Measuring Mission (TRMM) sensor package, J. Atmos. Oceanic Technol., 15, 809–817.
- L'Ecuyer, T. S., N. B. Wood, T. Haladay, G. L. Stephens, and P. W. Stackhouse Jr. (2008), Impact of clouds on atmospheric heating based on the R04 CloudSat fluxes and heating rates data set, J. Geophys. Res., 113, D00A15, doi:10.1029/2008JD009951.
- L'Ecuyer, T. S., and J. H. Jiang, 2010: Touring the atmosphere aboard the A-Train. Physics Today, vol .63 (7), 36-40.
- Liu, Z., M. A. Vaughan, D. Winker, C. Kittaka, B. Getzewich, R. Kuehn, A. Omar, K. A. Powell, C. Trepte, and C. Hostetler (2009), The CALIPSO lidar cloud and aerosol discrimination: Version 2 algorithm and initial assessment of performance, *J. Atmos. Oceanic Technol., 26*, 1198–1213.
- Masunaga, H., T.S. L'Ecuyer, and C.D. Kummerow, 2005: Variability in the Characteristics of Precipitation Systems in the Tropical Pacific. Part I: Spatial Structure. *J. Climate*, **18**, 823–840, https://doi.org/10.1175/JCLI-3304.1.
- McGill, M. J., J. E. Yorks, V. S. Scott, A. W. Kupchock, and P. A. Selmer (2015), The Cloud-Aerosol Transport System (CATS): A technology demonstration on the International Space Station, Proc. SPIE 9612, Lidar Remote Sensing for Environmental Monitoring XV, 96120A, doi:10.1117/12.2190841.
- Naud, C., Del Genio, A. D., Haeffelin, M., Morille, Y., Noel, V., Dupont, J.-C., Turner, D., Lo, C., and Comstock, J. M., 2010: Thermodynamic phase profiles of optically thin midlatitude clouds and their relation to temperature. J. Geophys. Res., 115 D11202
- Noel, V. and Haeffelin, M., 2007: Midlatitude Cirrus Clouds and Multiple Tropopauses from a 2002-2006 Climatology over the SIRTA observatory. J. Geophys. Res., 112 D13206
- Wang, Z., and K. Sassen, 2001: Cloud type and macrophysical property retrieval using multiple remote sensors. J. Appl. Meteor., 40, 1665-1682

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- Palm, S. P., D. L. Hlavka, P. Selmer, R. Pauly, 2016: the Cloud Aerosol Transport System (CATS) Data Product Catalog release 3.0. Retrieved on January 23rd 2018 from https://cats.gsfc.nasa.gov/media/docs/CATS_Data_Products_Catalog.pdf
- Pappalardo, G., Amodeo, A., Apituley, A., Comeron, A., Freudenthaler, V., Linné, H., Ansmann, A., Bösenberg, J., D'Amico, G., Mattis, I., Mona, L., Wandinger, U., Amiridis, V., Alados-Arboledas, L., Nicolae, D., and Wiegner, M.: EARLINET: towards an advanced sustainable European aerosol lidar network, Atmos. Meas. Tech., 7, 2389-2409, doi:10.5194/amt-7-2389-2014, 2014
- Philippon, N. et al. (2016), Analysis of the diurnal cycles for a better understanding of the mean annual cycle of forests greenness in Central Africa, Agricultural and Forest Meteorology, 223, 81–94, doi:10.1016/j.agrformet.2016.04.005.
- Protat, A., J. Delanoë, A. Plana-Fattori, P. T. May, and E. J. O'Connor (2009), The statistical properties of tropical ice clouds generated by the West African and Australian monsoons, from ground-based radar-lidar observations, *QJRMS*, *136*(S1), 345–363, doi:10.1002/qj.490.
- Reverdy, M., Noel, V., Chepfer, H., & Legras, B. (2012). On the origin of subvisible cirrus clouds in the tropical upper troposphere. *Atmospheric Chemistry and Physics*, *12*(24), 12081–12101. http://doi.org/10.5194/acp-12-12081-2012
- Reverdy, M., H. Chepfer, D. Donovan, V. Noel, G. Cesana, C. Hoareau, M. Chiriaco, and S. Bastin (2015), An EarthCARE/ATLID simulator to evaluate cloud description in climate models, *J. Geophys. Res.*, *120*(2), 11, doi:10.1002/2015JD023919.
- Rossow, W. B., 1989: Measuring cloud properties from space: A review. J. Climate, 2, 201–213
- Rozendaal, M. A., Leovy, C. B., and Klein, S. A.: An Observational Study of Diurnal Variations of Marine Stratiform Cloud, J. Climate, 8, 1795–1809, 1995.
- Sassen, K., and S. Benson (2001), A midlatitude Cirrus Cloud Climatology from the Facility for Atmospheric Remote Sensing. Part II : microphysical properties derived from lidar depolarisation, *J. Atmos. Sci.*, *58*, 2103–2112, doi:10.1175/1520-0469(2001)058<2103:AMCCCF>2.0.CO;2.

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- Sassen, K., Z. Wang, and D. Liu (2009), Cirrus clouds and deep convection in the tropics: Insights from CALIPSO and CloudSat, *J. Geophys. Res.*, 114, D00H06, doi: 10.1029/2009JD011916.
- Sassen, K., and Z. Wang (2012), The Clouds of the Middle Troposphere: Composition, Radiative Impact, and Global Distribution, *Surveys in Geophysics*, *33*(3-4), 677–691, doi:10.1007/s10712-011-9163-x.
- Sèze, G., J. Pelon, M. Derrien, H. Le Gléau, and B. Six (2014), Evaluation against CALIPSO lidar observations of the multi-geostationary cloud cover and type dataset assembled in the framework of the Megha-Tropiques mission, *QJRMS*, *141*(688), 774–797, doi:10.1002/qj.2392.
- Shang, H., H. Letu, T. Y. Nakajima, Z. Wang, R. Ma, T. Wang, Y. Lei, D. Ji, S. Li, and J. Shi (2018), Diurnal cycle and seasonal variation of cloud cover over the Tibetan Plateau as determined from Himawari-8 new-generation geostationary satellite data, Scientific Reports, 1–8, doi:10.1038/s41598-018-19431-w.
- Soden, B. J. (2000), The diurnal cycle of convection, clouds, and water vapor in the tropical upper troposphere. Geophys. Res. Lett. 27 (15), 2173-2176. doi: 10.1029/2000GL011436
- Stephens, G. L., & Kummerow, C. D. (2007). The Remote Sensing of Clouds and Precipitation from Space: A Review. *Journal of the Atmospheric Sciences*, *64*(11), 3742–3765. http://doi.org/10.1175/2006JAS2375.1
- Stephens, G., D. Winker, J. Pelon, C. Trepte, D. Vane, C. Yuhas, T. L'Ecuyer, and M. Lebsock, 2018: CloudSat and CALIPSO within the A-Train: Ten Years of Actively Observing the Earth System. *Bull. Amer. Meteor. Soc.*, **99**, 569–581, https://doi.org/10.1175/BAMS-D-16-0324.1
- Stubenrauch, C.J., A. Chédin, G. Rädel, N.A. Scott, and S. Serrar, 2006: Cloud Properties and Their Seasonal and Diurnal Variability from TOVS Path-B. J. Climate, 19, 5531–5553, https://doi.org/10.1175/JCLI3929.1
- Taylor, S., Stier, P., White, B., Finkensieper, S., and Stengel, M.: Evaluating the diurnal cycle in cloud top temperature from SEVIRI, Atmos. Chem. Phys., 17, 7035-7053,

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https://doi.org/10.5194/acp-17-7035-2017, 2017

- Vaughan, M. A., K. A. Powell, D. M. Winker, C. A. Hostetler, R. E. Kuehn, W. H. Hunt, B. J. Getzewich, S. A. Young, Z. Liu, and M. J. McGill (2009), Fully Automated Detection of Cloud and Aerosol Layers in the CALIPSO Lidar Measurements, *J. Atmos. Oceanic Technol.*, *26*(10), 2034–2050, doi:10.1175/2009JTECHA1228.1.
- Wilson, A. M. and Barros, A. P.: Orographic Land–Atmosphere Interactions and the Diurnal Cycle of Low-Level Clouds and Fog, J. Hydrometeor., 18(5), 1513–1533, doi:10.1175/JHM-D-16-0186.1, 2017.
- Winker, D., M. A. Vaughan, A. Omar, Y. Hu, and K. A. Powell (2009), Overview of the CALIPSO mission and CALIOP data processing algorithms, *J. Atmos. Oceanic Technol.*, *26*, 2310–2323.
- Winker DM, Pelon J, Coakley JA Jr, Ackerman SA, Charlson RJ, Colarco PR, Flamant P, Fu Q, Hoff RM, Kittaka C, Kubar TL, Le Treut H, McCormick MP, Mégie G, Poole L, Powell K, Trepte C, Vaughan MA, Wielicki BA. 2010. The CALIPSO mission: A global 3D view of aerosols and clouds. Bull. Am. Meteorol. Soc. 91: 1211–1229.
- Winker, D., Chepfer, H., Noel, V. and X. Cai. : Observational Constraints on Cloud Feedbacks: The Role of Active Satellite Sensors. Surve in Geophys (2017). Doi:10.1007/s10712-017-9452-0
- Wylie, D. (2008), Diurnal Cycles of Clouds and How They Affect Polar-Orbiting Satellite Data, J. Climate, 21(16), 3989–3996, doi:10.1175/2007JCLI2027.1.
- Yin, J., & Porporato, A. (2017). Diurnal cloud cycle biases in climate models. *Nature Communications*, *8*(1), 2269.
- Yorks, J. E., D. L. Hlavka, W. D. Hart, M. J. McGill, 2011: Statistics of Cloud Optical Properties from Airborne Lidar Measurements. *J. Atmos. Oceanic Technol.*, **28**, 869–883. doi: http://dx.doi.org/10.1175/2011JTECHA1507.1
- Yorks, J. E., M. J. McGill, S. P. Palm, D. L. Hlavka, P. A. Selmer, E. P. Nowottnick, M. A. Vaughan, S. D. Rodier, and W. D. Hart (2016a), An overview of the CATS level 1 processing algorithms and data products, Geophys. Res. Lett., 43, 4632–4639, doi:10.1002/2016GL068006.

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Field Code Changed

- Yorks, J. E., S. P. Palm, M. J. McGill, D. L. Hlavka, W. D. Hart, P. A. Selmer, E. Nowottnick (2016b), CATS Algorithm Theoretical Basis Document, Level 1 and Level 2 Data Products, release 1.2. Retrieved on February 13th 2018 from https://cats.gsfc.nasa.gov/media/docs/CATS_ATBD.pdf
- Yorks, J. E., S.D. Rodier, E. Nowottnick, P.A. Selmer, M.J. McGill, S.P. Palm, and M. A. Vaughan (2018), CATS Level 2 Vertical Feature Mask Algorithms and Data Products: An Overview and Initial Assessment, Atmos. Meas. Tech. Discuss., in preparation.
- Zhao, W., R. Marchand, and Q. Fu (2017), The diurnal cycle of clouds and precipitation at the ARM SGP site: Cloud radar observations and simulations from the multiscale modeling framework, J. Geophys. Res., 122(14), 7519–7536, doi:10.1002/2016JD026353.

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), while RL cloud detections are available since 1998 (Ackerman and Stokes, 2003).

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In the framework of the present study we did no specific processing of data from these instruments. Instead, we compare CATS cloud retrievals over the SGP site with the descriptions made by Zhao et al. (2017, Fig. 3a) and Dupont et al. (2011, Fig. 3) of the diurnal cycle of clouds over SGP based on 14 years of MMCR cloud detections and 10 years of RL cloud detections in Sect. 3.3

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Page 26: [3] Deleted **Vincent Noel** **6/13/18 4:15:00 PM**

we discussed the implications of our results for spaceborne instruments from sun-synchronous satellite missions (CALIPSO and the A-train, ADM, Earth-CARE). O