Interactive comment on "Breakup of nocturnal low-level stratiform clouds during southern West African Monsoon Season"

Dear reviewer 1,

We thank the reviewer for his/her helpful suggestions, which led to significant improvements of our paper. Below we detailed how his/her comments are addressed in the revised version of the paper. The major corrections of the paper are cited here in *italic. We refer to specific pages by "P" and lines by "L". For example, "**P1, L1**" refers to page 1, line 1.*

General comment: I got confused at times, even after reading this twice, keeping track of the large number of acronyms made throughout this text. I see and acknowledge their importance for keeping the paper at an appropriate length, however, I think the authors should take care to re-state some acronyms through the text to clarify what is being discussed.

We fully understand this difficulty and we tried to re-state the different acronyms through the text and figure captions.

Section 1: Since this paper describes in great detail many processes responsible for nocturnal cloud maintenance and subsequent breakup, this section (and paper in general) would benefit greatly with some discussion about the land-surface types of the 3 supersites. The a priori knowledge of the typical land surface over this part of the continent may be unknown to several readers, and is especially worth noting since boundary layer heights depend somewhat on the land-surface.

We thank the reviewer for this remark. We added the climatic zones of West Africa affected by the LLSC in the introduction ***P2, L12-15***: "*During the West Africa monsoon season, the LLSC form frequently at night over a region extending from Guinean coast to several hundred kilometres inland (van der Linden et al., 2015), which includes the coastal, Sudanian and Sudanian-Sahelian climatic zones (Emetere, 2016).*"

In addition, this statement in section 3: *"The ground sites were located at roughly the same distance from the Guinean coast (200 km in land) but with different topography (Kalthoff et al., 2018)"*, has been modified as follow, ***P6, L25***: *"The DACCIWA supersites were located at roughly the same distance from the Guinean coast (200 km in land, Fig. 1), between the coastal and the Sudanian areas, but with a different topography (Kalthoff et al., 2018). The supersites are part of the savannah ecosystem, where grassland is intercut with crops and degraded forest."*

P2, First Paragraph: In this section, you state "However, the diurnal cycle of those clouds is still poorly represented in numerical models" and cite Hannak et al. (2017). This is definitely a strong motivation, but I do not think this point is expanded upon enough in this paragraph. Furthermore, I had some trouble reading through this paragraph as this text seemed is jointed and unclear as to the main motivation. I recommend re-writing this paragraph focusing on the importance of stratiform cloud cover in a global context (e.g. earth's radiation budget, difficulty representing these clouds in climate models; I included a reference that may be of interest and relevant here) and expand upon the processes that make this difficult. Move Fig. 1, the discussion of Fig. 1, and the discussion about "scarce weather monitoring over West Africa" to elsewhere in the text.

We thank the reviewer for this comment. The paragraph was modified:
1/ The comment on figure 1 was moved in the next paragraph.
2/ We improved the first paragraph of section 1, as follow, ***P2***:
"The low-level stratiform clouds (LLSC) are Earth's most common cloud type (Wood, 2012). During the West Africa monsoon season (WAM), the LLSC form frequently at night over a region extending from Guinean coast to several hundred kilometres inland (van der Linden et al., 2015), which includes the coastal, Sudanian and Sudanian-Sahelian climatic zones (Emetere, 2016). The LLSC coverage persists for many hours during the following day, reducing the incoming solar radiation, impacting the surface energy budget and related processes such as the diurnal cycle of the atmospheric boundary layer (ABL) (Schuster et al., 2013; Adler et al., 2017; Knippertz et al., 2017). However, the diurnal cycle of those clouds is still poorly represented in numerical weather and climate models, especially over West Africa (Hannak et al., 2017). Indeed, their lifetime is generally underestimated in the numerical simulations, causing high incoming solar radiation at the surface in this region where the meteorological conditions are governed by convection activities and by surface thermal and moisture gradients (Knippertz et al., 2011). That could be an important factor for which the forecasts of WAM features still have a poor skill (Hannak et al., 2017). Therefore, a better understanding of the processes behind LLSC over SWA is useful to improve the numerical weather prediction and climate projection quality. Due to the scarce weather monitoring network over West Africa, the first studies addressing the LLSC over this region were mostly conducted with satellite images and traditional synoptic observations (Schrage and Fink, 2012; van der Linden et al., 2015), as well as with numerical simulations at regional scale (Schuster et al., 2013; Adler et al., 2017; Deetz et al., 2018). They emphasized that the physical processes, spanning from local to synoptic scale such as, horizontal advection of cold air associated to WAM, lifting induced by topography, gravity waves or shear-driven turbulence, are relevant for the LLSC formation during the night. However, the LLSC evolution after the sunrise received little attention."

P3, L9: I recommend adding a short description of what a "supersite" is.

The sentence has been modified to define a supersite as a site gathering a comprehensive set of instrumentation, ***P3, L8-10***: *"To this end, three so-called "supersites", which gather a large set of complementary instruments, were installed at Kumasi (6.68° N, 1.56° E) in Ghana, Savè (8.00° N, 2.40° W) in Benin, and Ile-Ife (7.55° N, 4.56° W) in Nigeria (Fig. 1)."*

P4, L23: "... due to the cooling..." at what level of the atmosphere does this cooling occur? Also, change "their formation" to "cloud formation".

The sentence has been corrected and completed as follow **_P4, L26-28_**: *"The increase of relative humidity (Rh) within the ABL leading to saturation and LLSC formation is due to the cooling which mainly occurs during the stable and the jet phases in the monsoon layer, up to around 1.5 km above ground level (a.g.l.)."*

Section 4: I really liked this section and found the intricate level of analysis excellent, though I have to admit – again – I needed to read this multiple times to understand it due mostly to the authors' writing style.

We thank the reviewer for this comment. The section 4 was deeply modified and, we hope, improved. We added a section (4.3, **_P26_**) in order to discuss the different processes possibly responsible for the LLSC coupling with the surface during the stratus phase.

Section 4: I will leave it up to the authors to proceed with this next comment as they see fit. Have you looked into the role of nocturnal cloud thickness as a possible reason why coupling sometimes does (or does not) occur (e.g. Fig. 5)? This is an interesting hypothesis that can (I think) be easily tested using your data. I would expect thicker cloud cover to inhibit surface warming enough to delay or possibly prohibit coupling if other meteorological factors cannot enable the transition. Likewise, could entrainment or precipitation – two sink terms for nocturnal cloud fraction under most conditions – correlate to a delayed coupling? These are questions bred from pure scientific curiosity based on the results you have shared.

We had the same questions as the reviewer and all the reviewer suggestions were tested. We know that it is a bit frustrating but no clear reason explaining the cloud coupling during the stratus phase was highlighted and so only hypotheses were suggested. Concerning the cloud thickness, we showed in Figure 6 that there are no obvious differences between coupled and decoupled LLSC thickness. We were not able to compare the liquid water path of coupled and decoupled LLSC, which could also play an important role.
However it is not a question of convection at that time of the day, since section 4 shows that the stratus phase ends more or less when the convection starts.
The entrainment at the end of the stratus phase is small and very similar in coupled and decoupled cases, but we were not able to check if it was also the case before the coupling. The estimation of the entrainment term along the stratus phase was not possible either.
At last, the precipitation hypothesis could be excluded since only LLSC without precipitation recorded at surface are considered. Of course, precipitation above the LLSC from higher clouds could not be investigated but is one of the hypotheses.

P4, L20: This is an unusual title for a section in a manuscript. Did you mean "State of Art"? Maybe call this section "Review"?

We actually meant "State of Art". "*Review*" is now the title.

P5, paragraph beginning at L19: There are several recent studies from the Cloud System Evolution over the Trades (CSET) experiment that, I believe, can really strengthen this paragraph and provide additional interesting results to compare & contrast your own results with. I believe intertwining principle results from these works will make your paper more interesting and accessible to research groups studying stratiform cloud breakup elsewhere across the globe, especially since the topic of stratocumulus-to-cumulus (or stratiform cloud breakup) has received increasing attention over the past several years.

We thank the reviewer for these recent studies based on CSET field experiment. They are now cited as many others previous studies addressing the stratocumulus-to-cumulus transition in marine conditions. These studies focused on aerosol microphysical role in the scenario of transition from stratocumulus-to-cumulus. Assessing the impact of low-troposphere aerosol loading on the LLSC diurnal cycle is not among the objectives of our study. But, this aspect will be addressed in future research work based on DACCIWA dataset. Thus, this perspective was added in section 6, ***P36, L25***: *"The aerosol loading in the low-troposphere is a potential factor controlling the LLSC evolution and lifetime (Deetz et al., 2018; Mohrmann et al., 2019). The airborne measurements of low-cloud properties over SWA during DACCIWA (Flamant et al., 2017) could be used to assess the microphysical role for aerosol in the LLSC evolution scenario. This may help to differentiate the scenarios DC and DD."*

End of P5: Again, this is an overall well-written section. This section seems to come to an abrupt end, however, with no suggestions or links as to how the described relevant dynamical processes relate to the observation studies presented in the remainder of the work.

We thank the reviewer for this comment. A sentence was added at the end of the paragraph to better link the LES study with the present observational work. ***P6, L7:*** *"Since the LES made by Pedruzo-Bagazgoitia et al. (2020) are set with atmospheric and surface conditions measured at Savè during the DACCIWA campaign, some simplifying assumptions used in our study are based on their results, and the simulated and observational results are compared."*

Section 3.1 Header: I recommend renaming this section as "Instrumentation" instead of "Observational Data Used"

We thank the reviewer for this suggestion. The modification has been done; "*Instrumentation*" is now the title.

P7, L2: Are missing CTH data from the ceilometer the result of attenuation from optically thick daytime cumulus cloud, or were there frequent instrument malfunctions? This would be useful to know.
Section 3.1: What measurements did the radiosondes collect? And what versions/ types of radiosondes were used? This section in general is also lacking descriptions of measurement uncertainties for each instrument. For example, how accurate are the cloud base and cloud top height estimates from the ceilometer? What uncertainty is expected with radiosonde temperature and humidity measurements? I noted some statements of measurement uncertainty and accuracy elsewhere in the text, but these need to be stated here. Finally,

presuming meteorological conditions are estimated from the radiosondes, I would put paragraph 2 after the current 3rd paragraph since its unclear at that point in the paper how the authors estimate SHF, LHF, etc.

We agree with the reviewer that some indications were missing in this section. The paragraph has been deeply modified and includes now:

1/ The reason why some CTHs are missing, ***P7, L24***: "*Unfortunately, several values of CTHs are missing, particularly during daytime for many selected cases, due to the retrieval technique limitation*."

2/ Radiosondes sensors measurements accuracy, ***P7, L26***: "*The thermodynamical and dynamical characteristics of the low troposphere are retrieved from the radiosondes of the MODEM radiosounding system. The MODEM radiosonde collects, every second (which corresponds to a vertical resolution of 4-5 m), the air temperature and relative humidity, and the probe GPS localization from which horizontal wind speed components, altitude and pressure are deduced (Derrien et al., 2016). The sensors accuracy is 0.2 °C, 2 % and 0.01 m for temperature, relative humidity and GPS localization respectively.*"

3/ Information on the data acquired by the surface station, ***P8, L5***: "*The meteorological conditions at the surface (temperature, relative humidity and pressure of the air at 2 m a.g.l), and some terms of the surface energy budget (net radiative flux (R_{n0}), sensible heat (SHF_0) and latent heat (LHF_0) fluxes at 4 m a.g.l) were continuously acquired. SHF_0 and LHF_0 are deduced from high-frequency (20 Hz) measurements processed with Eddy-covariance methods by using the TK3.11 software (Mauder et al., 2013).*"

P11, L11: "Therefore, it has a spatio-temporal variability" this is true but is out of place at this point in the text.

We meant to say that despite the spatial and temporal variability of A, this parameter is very often considered as a constant. The sentences were modified, ***P12, L8***: "*A varies with $\Delta\theta_l$, Δq_t, wind shear at the cloud top, surface turbulent fluxes and cloud microphysical processes via the buoyancy flux vertical profile (Stevens et al., 2005; Stevens, 2006). Despite the spatial and temporal variability of A, its value is generally fixed and treated as a constant parameter in several research studies (e.g. van Zanten et al., 1999; van der Dussen et al., 2014).*"

P20, L7: What do you mean by "help us to depart the cases"? Do you mean "differentiate" instead of "depart"? This is confusing and needs clarified since this is obviously a key science question motivating subsection 4.2.

We apologize for this word which was misleading. The sentence was modified as follow, ***P21, L7***: *"Does the LWP budget analysis help us to differentiate the cases C and D?"*

P20, L12: "Indeed, the crossing of the cloud wets the probe" this sounds very flowery. I recommend rewriting this entire sentence. Suggestion: "Liquid water buildup on the radiosonde's sensors possibly renders some measurements suspect, especially near cloud top."

We thank the reviewer for this suggestion. *The correction was made accordingly, **P21, L13**.*

P20, L23: Again, it is critical to know what the instrument uncertainties (or accuracy) are, such that these over/underestimations have context. This will elucidate the magnitude and seriousness of liquid water condensation on the sensors and subsequent computations using these measurements.

The accuracy of the radiosonde sensors is now introduced in section 3. See response to previous comment.

P28, L18-19: "... for which the hydrometeors radar reflectivity from the cloud radar reveals light precipitations above the LLSC layer" The way this sentence is written implies that precipitation is occurring above the cloud layer, which is physically not possible. Did you mean to say that there is precipitation occurring inside the cloud layer? I have a stylistic comment here too: its fine to simply say "collocated cloud radar data revealed precipitation inside the LLSC layer" or something to that effect. "hydrometeors radar reflectivity" is confusing and does not make much sense.

We thank the reviewer for this suggestion. The paragraph is certainly unclear. There are sometimes higher clouds above the LLSC. In that case, the radar reveals light precipitation between the higher clouds and the LLSC which was not recorded at surface. The sentence was modified, ***P31, L23***:
"The latest breakup time occurring at 16:00 UTC corresponds to the 02-03 July 2016 case for which the collocated radar reveals light precipitations from higher clouds, above the LLSC layer, during the first hours of the convective phase (not shown) while nothing was recorded by the surface rain gauge."

P29, L17: "30% lower" what exactly is 30% lower? the cloud base height? Also, the beginning of this sentence should be "The latter..."

We thank the reviewer for this comment. The sentence was clarified, ***P32, L21***: *"The LLSC breakup time impacts the radiative budget at surface over the day, then the surface fluxes, and consequently, the vertical development of the ABL, as shown by Lohou et al., 2020. They estimated that the ABL height is about 900 m when the LLSC* *breaks up at 09:00 UTC and is 30% lower when the LLSC breaks up at 12:00 UTC. Consequently, one can expect a quite different vertical development of the ABL in C/DC cases than in DD cases."*

P31, L26: "This could favour the convection in the cloud..." just state "This favours convection which..."

We thank the reviewer for this suggestion. The sentence was corrected, ***P34, L25***: *"This favours convection in the LLSC which enhances the entrainment, at the expense of the cloud moistening by the underlying turbulent mixing."*

P34, L11: "more significantly impact" is this because the coupled cases generally result in longer lasting cloud cover and therefore decrease the total amount of solar insolation received at the surface? I would be much more specific here since and this statement as written is pretty bold yet a bit hand-wavy.

We fully agree with this comment. The discussion concerning the LLSC impact on surface energy budget is now, ***P36, L15***: *"It determines the LLSC lifetime and the way by which the transition towards shallow convective clouds occurs. The coupled LLSC last longer (breakup time at 12:00 in average) than decoupled cases (breakup time at 10:00 UTC in average). According to Lohou et al. (2020), such a difference in breakup time leads to a reduction of about 15% of net radiation at surface and of ABL vertical development during the day, for coupled cases compared to decoupled one."*

Figure captions (general comment): It would be helpful to the reader to re-state or spell out acronyms. I found it tough at times to try to dig variable abbreviations from the text while also trying to follow and learn from the figures.

We modified the legends and we hope they are clearer.

Finally, all the minor comments suggested by the reviewer were taken into account in the new version.

Adler, B., Kalthoff, N. and Gantner, L.: Nocturnal low-level clouds over southern West Africa analysed using high-resolution simulations, Atmospheric Chemistry and Physics, 17(2), 899–910, doi:10.5194/acp-17-899-2017, 2017.

Deetz, K., Vogel, H., Knippertz, P., Adler, B., Taylor, J., Coe, H., Bower, K., Haslett, S., Flynn, M., Dorsey, J., Crawford, I., Kottmeier, C. and Vogel, B.: Cloud and aerosol radiative effects as key players for anthropogenicchanges in atmospheric dynamics over southernWest Africa, Atmos. Chem. Phys. Discuss., 1–36, doi:10.5194/acp-2018-186, 2018.

van der Dussen, J. J., de Roode, S. R. and Siebesma, A. P.: Factors Controlling Rapid Stratocumulus Cloud Thinning, J. Atmos. Sci., 71(2), 655–664, doi:10.1175/JAS-D-13-0114.1, 2014.

Emetere, M. E.: Investigations on aerosols transport over micro- and macro-scale settings of West Africa, Environmental Engineering Research, 22(1), 75–86, doi:10.4491/eer.2016.080, 2016.

Flamant, C., Knippertz, P., Fink, A. H., Akpo, A., Brooks, B., Chiu, C. J., Coe, H., Danuor, S., Evans, M., Jegede, O., Kalthoff, N., Konaré, A., Liousse, C., Lohou, F., Mari, C., Schlager, H., Schwarzenboeck, A., Adler, B., Amekudzi, L., Aryee, J., Ayoola, M., Batenburg, A. M., Bessardon, G., Borrmann, S., Brito, J., Bower, K., Burnet, F., Catoire, V., Colomb, A., Denjean, C., Fosu-Amankwah, K., Hill, P. G., Lee, J., Lothon, M., Maranan, M., Marsham, J., Meynadier, R., Ngamini, J.-B., Rosenberg, P., Sauer, D., Smith, V., Stratmann, G., Taylor, J. W., Voigt, C. and Yoboué, V.: The Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa field campaign: Overview and research highlights, Bull. Amer. Meteor. Soc., doi:10.1175/BAMS-D-16-0256.1, 2017.

Hannak, L., Knippertz, P., Fink, A. H., Kniffka, A. and Pante, G.: Why Do Global Climate Models Struggle to Represent Low-Level Clouds in the West African Summer Monsoon?, J. Climate, 30(5), 1665–1687, doi:10.1175/JCLI-D-16-0451.1, 2017.

Kalthoff, N., Lohou, F., Brooks, B., Jegede, G., Adler, B., Babić, K., Dione, C., Ajao, A., Amekudzi, L. K., Aryee, J. N. A., Ayoola, M., Bessardon, G., Danuor, S. K., Handwerker, J., Kohler, M., Lothon, M., Pedruzo-Bagazgoitia, X., Smith, V., Sunmonu, L., Wieser, A., Fink, A. H. and Knippertz, P.: An overview of the diurnal cycle of the atmospheric boundary layer during the West African monsoon season: results from the 2016 observational campaign, Atmospheric Chemistry and Physics, 18(4), 2913–2928, doi:10.5194/acp-18-2913-2018, 2018.

Knippertz, P., Fink, A. H., Schuster, R., Trentmann, J., Schrage, J. M. and Yorke, C.: Ultra-low clouds over the southern West African monsoon region, Geophysical Research Letters, 38(21), doi:10.1029/2011GL049278, 2011.

Knippertz, P., Fink, A. H., Deroubaix, A., Morris, E., Tocquer, F., Evans, M. J., Flamant, C., Gaetani, M., Lavaysse, C., Mari, C., Marsham, J. H., Meynadier, R., Affo-Dogo, A., Bahaga, T., Brosse, F., Deetz, K., Guebsi, R., Latifou, I., Maranan, M., Rosenberg, P. D. and Schlueter, A.: A meteorological and chemical overview of the DACCIWA field campaign in West Africa in June–July 2016, Atmospheric Chemistry and Physics, 17(17), 10893–10918, doi:10.5194/acp-17-10893-2017, 2017.

van der Linden, R., Fink, A. H. and Redl, R.: Satellite-based climatology of low-level continental clouds in southern West Africa during the summer monsoon season: Low-level clouds in southern West Africa, Journal of Geophysical Research: Atmospheres, 120(3), 1186–1201, doi:10.1002/2014JD022614, 2015.

Lohou, F., Kalthoff, N., Adler, B., Babić, K., Dione, C., Lothon, M., Pedruzo-Bagazgoitia, X. and Zouzoua, M.: Conceptual model of diurnal cycle of low-level stratiform clouds over southern West Africa, Atmospheric Chemistry and Physics, 20(4), 2263–2275, doi:https://doi.org/10.5194/acp-20-2263-2020, 2020.

Mauder, M., Cuntz, M., Drüe, C., Graf, A., Rebmann, C., Schmid, H. P., Schmidt, M. and Steinbrecher, R.: A strategy for quality and uncertainty assessment of long-term eddy-covariance measurements, Agricultural and Forest Meteorology, 169, 122–135, doi:10.1016/j.agrformet.2012.09.006, 2013.

Mohrmann, J., Bretherton, C. S., McCoy, I. L., McGibbon, J., Wood, R., Ghate, V., Albrecht, B., Sarkar, M., Zuidema, P. and Palikonda, R.: Lagrangian Evolution of the Northeast Pacific Marine Boundary Layer Structure and Cloud during CSET, Monthly Weather Review, 147(12), 4681–4700, doi:10.1175/MWR-D-19-0053.1, 2019.

S. Derrien, Y. Bezombes, G. Bret, O. Gabella, C. Jarnot, P. Medina, E. Piques, C. Delon, C. Dione, B. Campistron, P. Durand, C. Jambert, F. Lohou, M. Lothon, F. Pacifico and Y. Meyerfeld: DACCIWA field campaign, Savè super-site, UPS instrumentation, 2016.

Schrage, J. M. and Fink, A. H.: Nocturnal Continental Low-Level Stratus over Tropical West Africa: Observations and Possible Mechanisms Controlling Its Onset, Monthly Weather Review, 140(6), 1794–1809, doi:10.1175/MWR-D-11-00172.1, 2012.

Schuster, R., Fink, A. H. and Knippertz, P.: Formation and Maintenance of Nocturnal Low-Level Stratus over the Southern West African Monsoon Region during AMMA 2006, Journal of the Atmospheric Sciences, 70(8), 2337–2355, doi:10.1175/JAS-D-12-0241.1, 2013.

Stevens, B.: Bulk boundary-layer concepts for simplified models of tropical dynamics, Theor. Comput. Fluid Dyn., 20(5–6), 279–304, doi:10.1007/s00162-006-0032-z, 2006.

Stevens, B., Moeng, C.-H., Ackerman, A. S., Bretherton, C. S., Chlond, A., de Roode, S., Edwards, J., Golaz, J.-C., Jiang, H., Khairoutdinov, M., Kirkpatrick, M. P., Lewellen, D. C., Lock, A., Müller, F., Stevens, D. E., Whelan, E. and Zhu, P.: Evaluation of Large-Eddy Simulations via Observations of Nocturnal Marine Stratocumulus, Mon. Wea. Rev., 133(6), 1443–1462, doi:10.1175/MWR2930.1, 2005.

vanZanten, M. C., Duynkerke, P. G. and Cuijpers, J. W. M.: Entrainment Parameterization in Convective Boundary Layers, J. Atmos. Sci., 56(6), 813–828, doi:10.1175/1520-0469(1999)056<0813:EPICBL>2.0.CO;2, 1999.

Wood, R.: Stratocumulus Clouds, Mon. Wea. Rev., 140(8), 2373–2423, doi:10.1175/MWR-D-11-00121.1, 2012.