Dear Editor,

We wish to thank you and all three anonymous referees for considering our initial submission and for giving us the opportunuty to submit a revised version of our manuscript. We are very grateful for the thoughful and constructive comments provided by the referees to improve our manuscript. Our manuscript has been revised significantly based on the comments received and we believe this version is very much improved.

A list of the major changes made in our manuscript is presented below. Addionally, the upadated responses to each of the referees' comments and suggestions are also included in this document.

Major changes:

- Discussion of atmospheric conditions significantly modified and presented more clearly.
    - Focused more on moisture flux (a new figure introduced (Fig. 7) to show the moisture before and after the LLC events in addition to Figures 5 and 6).
    - Removed the analysis on divergence and vertical velocity.
    - Additional information and figures added in Appendix to improve the discusions.
- Discussion on heat flux significantly modified to show impacts of LLC on the heat fluxes rather than the opposite.
- Introduced a new figure for the mean latent heat and sensible heat fluxes in addition to the anomalies.
- Removed the figure for Bowen Ratio since it can directly be inferred from the mean sensible and latent heat fluxes.
- Included a supplementary material with details on evaluation of the ERA5 cloud fraction and surface irradiance.

Responses to Referee #1

Referee Comment (RC1): This study, based on the analysis of the ERA5 hourly data from 2006 to 2015, shows the occurrence of daytime low level clouds in WA at two different latitudes (Sahelian and Guinean). It also aims at determining the atmospheric conditions for different LLC classes (based on cloud fraction) and their impact on the solar incoming radiation. This article can be improved at several points of view: motivation, methodology explanation, results interpretation.

On behalf of all the authors, I wish to thank the reviewer for the thorough assessment of our study and for providing us with comments that helped to improve the manuscript during the revision. Please see below the detailed responses to each of the reviewer's comments/questions. The reviewer's comments are shown in black font while our responses are shown in blue font. Where applicable, the changes that have been made in the manuscript are shown in italics.

Main comments:

(1) The LLC events are selected in this study with their cloud base height (< 2 km). This is in accordance with the definition of low cloud. However, the authors apply this definition at two very different places in Africa and at very contrasting seasons. The boundary layer varies from few hundred meters (during monsoon season in the Guinean region) to several kilometres (during winter season in the Sahelian region). Consequently, the LLC as defined by the authors may include or not boundary layer clouds according to the region and the season. This should be at least discussed (see specific comments) since it impacts consequently the different statistics presented in this study.

We thank the reviewer for this comment. We fully agree that the clouds analyzed in our work may or may not include all boundary layer clouds due to the definition of LLCs. In the revised manuscript, we this discuss this important issue. The following sentences, for instance, have been incorporated in Section 2.2.2:

Due to the definition of LLCs used, the present study does not consider the impact of the atmospheric boundary layer (ABL) that may considerably modify the altitude of the low cloud. Indeed, ABL clouds have their bases higher than 2 km especially in the Sahel region during the dry season. In addition, some studies (Lohou et al., 2020; Pedruzo-Bagazgoitia et al., 2020; Zouzoua et al., 2020) have shown that some LLCs can be decoupled from the surface and are therefore not influenced by the surface heat fluxes. Therefore, having a higher cloud base threshold for LLCs may alter the analysis of the surface heat fluxes.

(2) In addition to the previous comment, LLC with base below 2 km gather stratus, stratocumulus, cumulus and MCS (as mentioned in the paper). These clouds develop in quite different atmospheric conditions (specifically in terms of divergence). What is the interest of highlighting the atmospheric conditions of a mix of different clouds (see specific comments)?

We agree with the reviewer that different low-level clouds may develop under different atmospheric conditions. This question somehow mirrors comment #3 by Reviewer 2. Due to the nature of the ERA5 data, it is impossible to make the distinction between the different types of low-level clouds. However, while low clouds can be associated with different types of forcing (for example in terms of divergence or cold air advection for stratiform clouds as found in the DACCIWA studies), we assume that the moisture flux (which is analyzed in our work) will not differ significantly from one LLC type to the other.

We initially planned to include the divergence/vertical velocities for the different seasons and use that to postulate the kinds of low clouds that might be dominant (as mentioned in the first response to you). However, we finally decided to entirely remove the analysis of divergence and vertical velocity and focus more on the moisture associated with the LLCs. This is to avoid confusion especially since it is known (and as you mentioned in specific comments) that the different low cloud types exhibit different conditions of divergence. We think an analysis of divergence could be very interesting, but with a dataset that can make the distinction between the different low cloud types.

(3) The cloud fraction as a parameter to define different LLC classes in order to check their impact on solar radiation seems quite logical, but not to determine the atmospheric conditions of these classes.

We thank the reviewer for this comment. However, we believe these classes could be also be important for some of the atmospheric conditions. For example, we showed that the Class 2 LLC is associated with a much stronger moisture flux (and specific humidity) compared to the Class 1 (please see Figures 5, 6, and B1in the revised manuscript).

(4) Some explanations are missing to fully understand the analyzed atmospheric conditions, specially the surface flux anomaly.

This has been noted. We are grateful to the reviewer for this comment. In the revised manuscript, we have made a significant revision of the discussion on the surface fluxes. We have also introduced the figure for the mean flux in addition to the anomalies. We also showed how the anomalies were computed. Other questions pertaining to the surface fluxes are addressed in our responses to the specific comments.

Specific comments:

(1) P2, line 40: Perhaps the authors could add a reference to the work of Shrage et al. who first quantified the low level cloud frequency and fraction in southern WA.

• Schrage, J. M. and Fink, A. H.: Nocturnal continental low-level stratus over tropical West Africa: observations and possible mechanisms controlling its onset, Mon. Weather Rev., 140, 1794–1809,2012.

Thanks. Schrage and Fink (2012) has been referenced in this sentence.

(2) P2, line 48-57: Three very recent articles published in ACP (DACCIWA special issue) should be cited here since they focus on daytime phase of low level clouds. The first one estimates, with local measurements, the impact of LLC on the surface net radiation and on the convective surface fluxes which is one objective of the present study.

- Lohou, F., Kalthoff, N., Adler, B., Babic, K., Dione, C., Lothon, M., PedruzoBagazgoitia, X., and Zouzoua, M., 2020 : Conceptual model of diurnal cycle of low-level stratiform clouds over southern West Africa. Atmos. Chem. Phys., 20, 2263–2275, doi: 10.5194/acp-20-2263-2020.
- Maurin Zouzoua, Fabienne Lohou, Paul Assamoi, Marie Lothon, Véronique Yoboue, Cheikh Dione, Norbert Kalthoff, Bianca Adler, Karmen Babić, and Xabier Pedruzo-Bagazgoitia : Breakup of nocturnal low-level stratiform clouds during southern West African Monsoon Season, https://doi.org/10.5194/acp-2020-602
- Pedruzo-Bagazgoitia, X., de Roode, S. R., Adler, B., Babić, K., Dione, C., Kalthoff, N., Lohou, F., Lothon, M., and Vilà-Guerau de Arellano, J., 2020: The diurnal stratocumulus-to-cumulus transition over land, Atmos. Chem. Phys., https://doi.org/10.5194/acp-2019-659.

We thank the reviewer for this suggestion. In the revised manuscript, we have cited these works in this paragraph.

(3) P2-P3 : I do not understand the link between the last sentence of page 2 and the first one of page 3. Could the authors be more explicit? Or perhaps the word « consequently » is not appropriate in this sentence?

Thank you. 'Consequently' was not supposed to be there. The sentences have been revised and now read as:

"In the night, the nocturnal LLCs have no influence on the surface solar radiation due to the absence of sunlight. However, they persist long into the morning and early afternoon, thus, directly influencing the amount of incoming solar irradiance and having a considerable impact on the energy balance of the earth surface as shown by Lohou et al., (2020). The conditions associated with these low clouds during the daytime in the region are less documented."

(4) P3, Line 3 : « ...have been limited to the WAM season... »

Thanks. This has been corrected in the revised manuscript.

(5) P3, line 70 : « Few studies which were done with simulations, reanalysis, and satellite data in the region (e.g., Adler et al., 2017; Knippertz et al., 2011; van de Linden et al., 2015; Schuster et al., 2013) have nevertheless shown results similar to those of ground observational studies to some extent. » Could the authors precise to what observational studies they referred to?

Some findings of all these studies regarding conditions for nocturnal LLCs are similar to findings in the recent DACCIWA studies (e.g., Babic et al., 2019; Adler et al., 2019).
These observational studies have now been referenced in the sentence.

(6) P4, line 100-102: Could the author reword this sentence? Remove this part perhaps "and their surface heat fluxes explore » ?

Thank you. This sentence now reads as:

"*Other ERA5 variables are analyzed to show some of the atmospheric and surface conditions during the occurrence of LLCs in order to understand the possible interactions between the surface and the lower atmosphere."*

(7) P5, L127-134: This paragraph about upper clouds is very important at several points of view. Because the threshold on the base height (< 2 km) can mix a lot of cloud types (Stratus, Stratocumulus, Cumulus, MCS) I wonder if it would be interesting to add a statistic on the LLC top heights just to be aware of the cloud types mixed in the so large family of LLC.

We thank the reviewer for this comment and yes, it would be interesting to show this. However, there is no cloud top heights variable in the ERA5 product.

(8) P5, equ. 1:

- It seems to me that equation 1 gives the Moisture Flux. The moisture advection would be defined with the horizontal gradient of specific humidity. Qavd is named differently along the article: horizontal moisture flux advection, moisture advection,…

Yes, you are right. The quantity computed is moisture flux and not the moisture advection. We have significantly revised the discussion (in Section 4.1) to focus on the moisture flux rather than the moisture advection as we did not compute that. We have also changed the symbol to Q_{flux} as Q_{adv} may suggest advection.

- The sum should be between 1 and N and not between i and N.

Thank you. This was an error. It has been corrected in the revised manuscript.

- Why the chosen level for the moisture flux estimate is 950 hPa? Could the authors justify this choice? Why the integrated value over the vertical is not used in this study?

We used 950 hPa level because during the rainy season the SW monsoon flow is clearly shown at this level. We did not use the integrated value over the first 2 km because we plot also the winds over the moisture flux. The winds near the surface are different from winds at around 800 hPa which is also within the 2 km. Taking the average thus may not show the SW monsoon flow well.

(9) P5, L: Ek and Holstag study focuses on ABL clouds.

- The present study does not take into account all ABL clouds since a large part of them are higher than 2 km when the ABL is higher, which is very often the case in Sahelian region.
- Some Stratus or Stratocumulus low cloud are decoupled from the surface and are then not influenced by the surface flux (see previous suggested papers of Zouzoua et al., Pedruzo et al, and Lohou et al.).
These two points should be addressed in some way.

Thank you for these comments. We fully agree. As mentioned in the main comment #1, we have discussed this important issue in the revised manuscript.

(10) P6, Equation 2 & 3:

- CRE has two different definitions through equation 2 & 3. The authors could remove equation 2 and just keep equation 3.

We thank the reviewer for this suggestion. Equation 2 was removed.

- What are the clear sky events? Are they cases with no liquid water at all in ERA5? If so, how many cases are used for CRE estimate? Or are they theoretically calculated? This is important to understand the CRE for no-LLC cases.

Clear sky events are those events when the cloud fraction in the first 2km is zero – in the ERA5 data cloud fraction can be higher than zero when liquid water is zero as also shown in referee RC3 major comment #1 and our response to the comment. There may be higher level clouds which may have led to the CRE values during No LLC events. In the revised manuscript, we will modify Table 2 (which was not correct anyway) to show the number of cases that were used to calculate the CRE.

(11) P6, L163: "... SW↓ is the downwelling shortwave radiation in all-sky conditions..." If I understand correctly SW↓ is rather the downwelling short wave radiation for each LLC classes instead of "all sky conditions". This could be written in first place?

$SW^{\downarrow}$ refers to the actual radiation received with all atmospheric conditions of temperature, humidity, aerosols, clouds etc. (this is why we referred to it as 'all-sky radiation'). $SW_{CS}^{\downarrow}$ on the other hand, is computed based on the conditions but assuming there are no clouds. So, for each LLC class event, there is a corresponding $SW^{\downarrow}$ value. This point has been made clearer in the revised manuscript (in Section 2.2.3).

(12) P6, L169: The authors should make clear in the text and the legend that this daytime distribution gathers all the seasons.

Well noted. Thank you for this comment.
The following sentence will be added to the text: *"The distribution presents the total occurrence frequency of all seasons."*

Additionally, the following will be added to the caption: *"All seasons are included in the distribution shown."*

(13) P6, L180: "Additionally, the early morning peak in the events of LLC Class-2 could also be partly linked to contributions from tropical oceanic low-level convection which is maximum during the early morning (Yang and Slingo, 2001)." Could the authors check the Yang and Slingo paper? It seems to me that Yang and Slingo mentioned the "Tropical oceanic deep convection" (for example page 798-799 in Yang and Slingo, 2001). If this is so, the paragraph the authors certainly referred to finishes this way : "Some of these convective systems, under optimal environmental conditions, continue to grow and reach their mature stage some time later during the night and early morning". It is rather deep convection and MCS that Yang and Slingo are talking about. How do we know that LLC class 2 are deep convection if all seasons are mixed in fig 3? What is the proportion of deep-convection versus stratocumulus? In what extent the MCS can impact the statistic presented in Fig 3 for Guinean region? Did the authors try a diurnal cycle for each season?

We agree with the reviewer that Yang and Slingo were referring to deep convection and MCS. However, with the ERA5 data and based on our definition of LLC, the lower parts of these MCS (the convective parts) are also considered as LLCs. They showed that some of the tropical oceanic deep convections are maximum in the night and morning. The proximity of the Guinea region to the ocean means that some of these systems may move into the Guinean region. In our statement, we did not say that all Class 2 LLCs are due to the deep MCSs shown by Yang and Slingo. We indicated that those oceanic deep convections can **partly** explain the morning peak of the Class 2. In addition, there are residual nocturnal stratus clouds in the morning (as shown in the DACCIWA studies). Having all these clouds together will likely lead to higher cloud fractions (LLC Class 2).

We believe both points were addressed in the manuscript. Since it is not possible to make the distinction (of different LLCs) with ERA5, we attributed LLC Class-2 to these kinds of clouds (residuals of nocturnal St clouds and deep clouds in the morning) as they are the clouds with largest fractional coverage. We have mentioned this limitation of the inability to distinguish between the different LLCs in our conclusion.

Finally, yes, we have checked the diurnal cycle for each season. Please find below the diurnal cycle of occurrence frequency for each season below in Figures 1 and 2 for DJF and JAS respectively. Most of the LLC Class 2 are found during the JAS period – which are likely due to the occurrence of both stratus and MCSs.

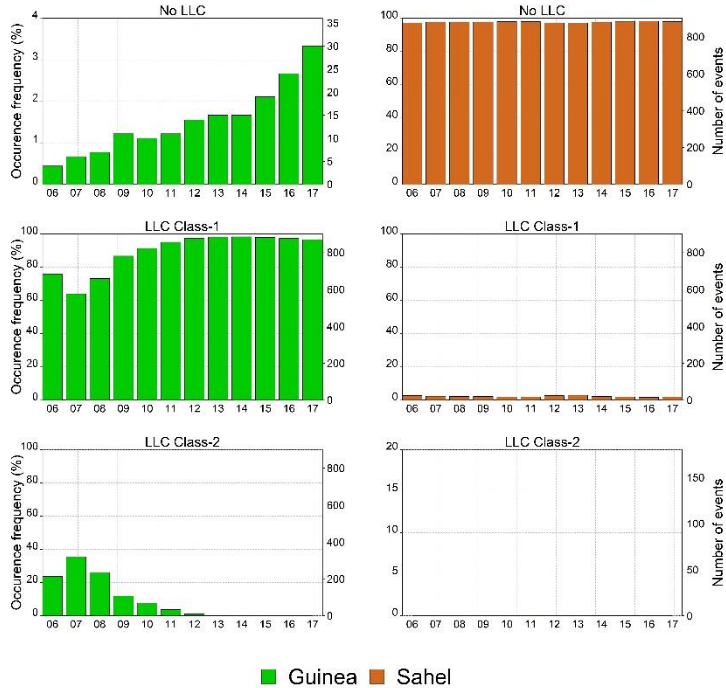

Figure 1: Occurrence frequency of the different classes in DJF

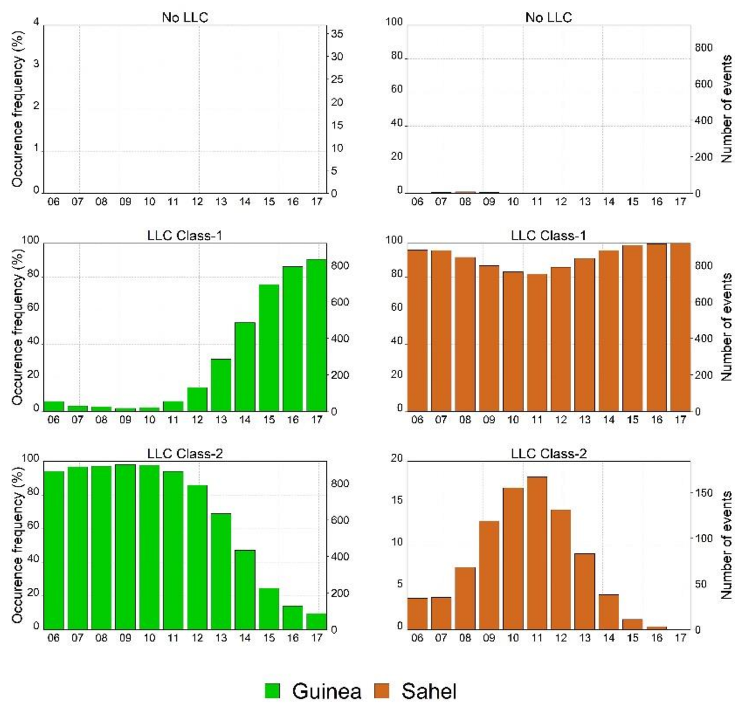

Figure 2: Occurrence frequency of the different classes in JAS

(14) P7, All comments on Figure 3: I don't know what the authors call "well-marked diurnal cycle" or "weak diurnal cycle"? For example, 10% of 2500 cases is a larger variation (LLC class-1 Sahelian region) than 4% of 200 cases (LLC class-2 sahelian region).

We understand and agree with the reviewer's point that there is a larger variation between the lowest and highest occurrence frequencies in Class-1 than in Class-2 over the Sahel. However, the diurnal cycle for Class-2 can easily be seen because the Class 2 events are limited to only JAS while Class-1 have a much larger spread over the different months (as shown on figure 4 in the original manuscript).

(15) P7, L189-192: I agree with this comment on the type of cloud included in the statistic. That helps to understand what really means this composite diurnal cycle.

Thank you.

(16) P7, L193-214:

- I think these two paragraphs should be moved at the beginning of this section. It would be interesting for the reader to have a first insight of the seasonal variation before the diurnal one.

  Thank you. We agree. We have moved the seasonal variation before the diurnal variations in the revised manuscript.

- The threshold of 2 km for the cloud base might impact the Sahelian region distributions. The number of no LLC class would decrease with a higher cloud base height threshold whereas LLC class-2 number would increase. That means that MCS, for example, can be sorted out as no-LLC class when ABL is higher than 2 km. Is that possible? In what extent this 2-km threshold impacts the atmospheric conditions for the different classes?

  Yes, you are right. With a higher threshold No LCC events may decrease. LLC Class-2 may not necessarily increase (but rather all LLCs) because it will depend on the cloud fraction at the base of such MCSs. In our opinion, having a higher than 2 km threshold may lead to significant changes in the analysis of the surface heat fluxes but not the moisture within the lower atmosphere. This issue is addressed in the revised manuscript in Section 2.2.2.

(17) P8, L228, Table 2:

- The total number of hours in season indicated in Table 2 should be presented and commented in the legend and the text?

  Thank you. We have commented the total number of hours in the text (1st paragraph of Section 4) and in the caption of the Table 2.

- There is zero No-LLC events detected in Guinean region during DJF season according to table 2. But there are atmospheric conditions for this class in figures 6 and 11 for example. I guess the table is wrong.

  You are right. The values presented in the table were not correct. This has been corrected. Thank you for bringing this to our attention.

(18) P8, L231: "...cold moist air from the ocean associated with the strong southwesterly winds (positive)..." Figure 5 and 6 are very nice. I am not used in analysing the moisture flux but according to the Figures 5 and 6, Q_{adv} seems rather dominated by the wind intensity than the moisture (and even less the temperature of course) from my point of view. I think, and some AMMA and DACCIWA studies show this, that the moisture advection is null in the Guinean region during the WAM (e.g. Adler et al., Babic et al.), whereas it is important in the Sahelian region. It depends on the moisture gradient. So what does the moisture flux show? The monsoon or the Harmattan horizontal expansion according to the season?

We thank the reviewer for this comment and question.

Firstly, even though the winds are strong, the moisture content is also very significant. Please see Figure B1 in the revised manuscript which shows a plot of only the specific humidity. As clearly shown in the Figure B1, there is a significant amount of moisture in the considered windows during cloudy events and almost no moisture during no LLC events. This is similar to a result from Babic et al. (2019) who showed that the most distinct difference between stratus and stratus free events is evident in the specific humidity (Figure 6c in Babic et al. 2019). From that result, they suggested that the "background moisture", could be an important factor in the formation of low clouds in the region. So, the moisture flux could show the monsoon flow direction (in JAS and the harmattan in DJF) but most importantly, it also shows the background moisture levels over the region, whatever the season.

We acknowledge our original discussions did not mention all of these. In the revised manuscript, we have significantly modified the discussion presented in Section 4 to take into account all of the points mentioned above.

(19) P8, L232: "Predictably, the horizontal advection of moist air is stronger during the occurrence of LLC Class-2 events than LLC Class-1 events." Moisture flux?

Yes, this was supposed to be moisture flux and not the advection. It has been changed. Thank you.

(20) P8, L234," This inland advection of moist air from the ocean has been found to play a major role in cooling (Adler et al., 2019b) which in turn enhances saturation of water vapour and consequently LLC formation (Adler et al., 2019, 2017; Babić et al., 2019b)." Moist air advection cannot induce a cooling. Adler et al., Babic et al. and Lohou et al. showed that there is no moist air advection but cold air advection. It is the cold air advection by the low level jet and Atlantic inflow which induces the saturation and the cloud formation in the Guinean region. That means that the monsoon flow is not moister than the air in the Guinean region where rain events are frequent. This can be different for the Sahelian Region which is much drier than the Guinean one. Please consider to change this comment and make different comments for the two regions.

Thank you. We agree. The whole discussion of the results on atmospheric conditions (Section 4) has been thoroughly revised to focus on moisture flux rather than moisture advection. We also used some findings of the DACCIWA studies to support our discussion wherever appropriate.

(21) P8-9, L245-259: this paragraph deals with the vertical velocity and the divergence of the horizontal wind.

We have removed the entire analysis on divergence and vertical velocity since the different LLC types have opposing signs for these parameters. This analysis was removed from the manuscript since it is not possible to make the distinction between the different cloud types with the ERA5 data. We mentioned this limitation in our conclusion.

- I would show only one of these parameters since they should be proportional. No need to comment both.

- The authors precise at the beginning that a negative value of these two parameters is favourable to cloud formation. Stratus and stratocumulus are characterized by positive vertical velocity (hPa s^{-1}). So this comment cannot be general and this shows the limit of searching for atmospheric conditions of a class which may mix different clouds.

- "It is also important to note that during JAS, the average vertical profiles of these processes (divergence and vertical velocity) are not similar to DJF (not shown).". If this is important, perhaps the authors should comment a little more on this or show the figures for JAS.

- I am not sure what the reader can conclude from this analysis.

(22) P9-10, section 4.2:

- Could the author precise how the monthly anomaly is computed because I am very surprised by these results?

  Since we used hourly data, the anomalies were first computed at hourly timescale and then the monthly means were calculated from those. Please the computation is explained below:

  There are ten different values for each hour of a given day and month (10 because ten years of data is used). For example, there will be ten different heat flux values at 12UTC on 1st Jan, one value for each year. The mean of all these ten values are first determined. Let's call this mean value $\overline{HF}$ and call each of the individual heat flux values as HF_i. So, the anomaly for the heat flux value at 12UTC on 1st January 2006 is computed as:

$$HF_{anom\_i} = HF_i - \overline{HF}$$

  This is done for all hours on all days and months for the period of the study. The monthly mean anomaly which was shown in the manuscript is then computed from the hourly anomalies.

  This has been explained in the revised manuscript (Section 4.2).

- The reduction of the net radiation at surface by the clouds induces a reduction of the surface sensible and latent heat flux. So, from my point of view, the figure 8 should rather show the cloud impact on the surface energy budget than the effect of the convective flux on the clouds.

  We fully agree with the reviewer. The discussion on heat fluxes presented in the previous manuscript was flawed since we are not considering heat fluxes before the clouds are formed but rather during the cloud occurrence. We have substantially revised the discussion on heat fluxes (Section 4.2) to show the effects of LLC on the surface energy budget.

- This is why I do not understand how the author can find a negative anomaly of the sensible heat flux during no-LLC event.

During No LLC events, the surface is warmer than the air in contact with it because emitted longwave radiation from the surface is not absorbed (by clouds as there are no clouds) and re-emitted into the atmosphere due to the vertical temperature gradient. Thus, sensible heat is transferred from the warmer ground upwards into the air. The ECMWF convention for vertical fluxes is negative upwards and positive downwards. Therefore, No LLC events involve larger negative sensible heat values and negative anomalies – indicating that sensible heat moves upwards from the surface.

This has been made clearer in the revised manuscript.

- The anomalies should be discussed in comparison to the flux itself. Do the author think that an anomaly lower than 10 W m^{-2} is significant when the surface flux is around 300 W m^{-2} and considering the error of the surface flux in the model.

It could be significant depending on which day and hour. But we may not be able to see this since we have only shown the monthly mean anomaly. An extreme value in the individual events may significantly impact the mean monthly anomaly value. We have included the mean fluxes in the revised manuscript (it is now Figure 8 and the anomaly is Figure 9) and discussed the two together.

Thank you for this comment.

- At last, the authors deduce from the surface flux anomaly a surface temperature anomaly. The surface heat fluxes are proportional to the temperature vertical gradient and not directly linked to the surface temperature. Such a discussion is misleading.

Thank you. The discussion on heat fluxes has been thoroughly revised.

(23) P11, L313-316: I fully agree with this statement. The surface convective flux should be also reduced according to the cloud fraction. So how the authors can detangle the effect of the cloud on the surface flux from the effect of the flux on the cloud triggering?

Thank you for this question. As already mentioned, we have revised the discussion on heat fluxes to focus on the impacts of LLCs on the surface heat fluxes rather than the opposite.

References

Adler, B., Babia, K., Kalthoff, N., Lohou, F., Lothon, M., Dione, C., Pedruzo-Bagazgoitia, X., and Andersen, H.: Nocturnal low-level clouds in the atmospheric boundary layer over southern West Africa: An observation-based analysis of conditions and processes. Atmos Chem Phys, 19, 663–681, https://doi.org/10.5194/acp-19-663-2019, 2019

Babić, K., Kalthoff, N., Adler, B., Quinting, J. F., Lohou, F., Dione, C., and Lothon, M.: What controls the formation of nocturnal low-level stratus clouds over southern West Africa during the monsoon season? Atmos Chem Phys, 19, 13489–13506, https://doi.org/10.5194/acp-19-13489-2019, 2019

Responses to Referee 2

Referee Comment (RC2): This paper presents the analysis of the daytime low level clouds (LLC) over West Africa using ERA5 dataset for the period 2006-2015 to investigate their occurrence frequency, seasonal and diurnal cycles, as well as the associated atmospheric conditions for the two contrasting regions, i.e. Sahelian and Guinean region. Based on the cloud fraction, three classes were formed (no LLC, LLC class-1, and LLC class-2) and the results indicate that during the summer months LLC class-1 has the peak occurrence frequency in the Sahel, while LLC class-2 is dominant in the Gulf of Guinean. Finally, this study also addressed the attenuation of the shortwave downwelling radiation due to the LLC and found that during the summer months it is on average between 44 % and 49 % for the Sahel and Guinean region.

Considering the importance of the LLC for the regional climate of West Africa and the general lack of studies addressing these clouds, I find the topic of this study to be relevant and suitable for publication in ESD. This study provides new results which in my opinion will be useful, especially considering the ongoing and future solar energy project. However, before this manuscript can be accepted for the publication, it should be carefully revised, since there are some shortcomings in the analysis and the presentation of the results needs to be more clear. My comments and suggestions are listed below.

On behalf of all the authors, I wish to thank the reviewer for the thorough assessment of our study and for providing us with comments that helped to improve the manuscript during the revision. Please see below the detailed responses to each of the reviewer's comments/questions. The reviewer's comments are shown in black font while our responses are shown in blue font. Where applicable, the changes that will be made in the manuscript are shown in italics.

Major comments:

1. I do not understand why authors extract reanalysis data of a higher resolution of 0.25o to a very coarse 1o resolution. What do you mean by "directly extracted" (Pg. 3, line 87)? Although the focus is on the analysis of large scale conditions, it is well known that some mesoscale processes are responsible for the formation and maintenance of LLC. Have you performed some sort of validation test to make sure that the conditions are properly presented with the data of coarser resolution? Additionally, sensible and latent heat flux analyzed here are not large scale phenomena.

   During the retrieval of ERA5 data, there are options to select the resolution of the grid (finer or coarser than the native grid) onto which the data will be given. In our case, we chose to retrieve the data on a 1°x1° grid. This is what we meant by 'directly extracted'. Retrievals and downloads at the finer resolutions could be very slow (especially for the data over several pressure levels). And since most of our analyses are based on large-scale features (moisture and winds), we have decided to use the 1° grid. However, we performed some comparison tests before going ahead to use the 1° resolution data.

   We made a comparison of the moisture flux and winds during LLC occurrence for the 1° resolution (Figure 1 upper row) and native ERA5 resolution = 0.25° (Figure 2 lower row). This comparison was made for only a small sub-period of 2006-2015 (one month of data). This comparison does not present any major discrepancy. Synoptic conditions seen by using the fine resolution are also presented very well by using the coarse resolution. Here we show only one month (August 2006) and for LLC occurrence in the Guinean region.

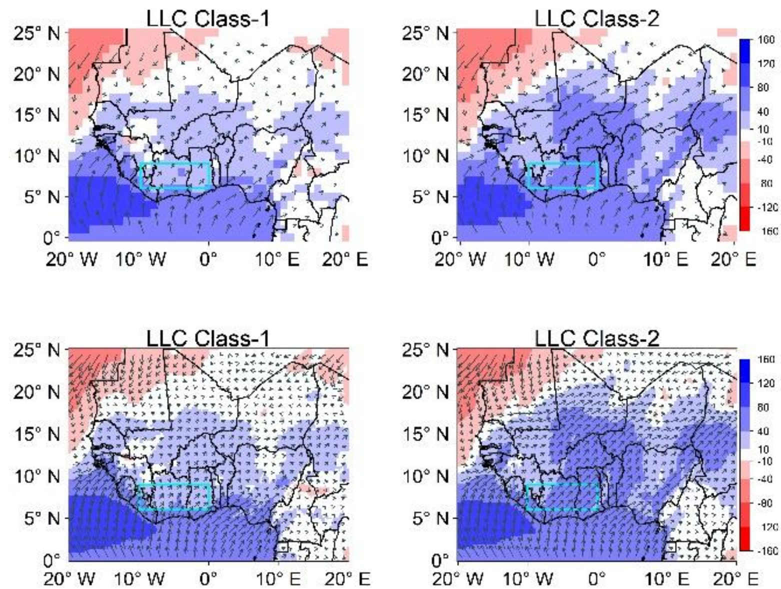

Figure 1: Comparison of moisture flux and winds for LLC occurrence using ERA5 data at 1° (top) and 0.25° (bottom) resolutions.

2. In my view, the analysis of the atmospheric conditions should be presented more consistently and more clearly.

The definition of the "horizontal moisture flux advection" is not correct (Pg. 5, line 141). Namely, eq. (1) presents the average moisture flux and not the advection of the moisture! Therefore, the presentation and discussion of the results regarding the advection of the moisture need to be carefully revised. If Figs. 5 and 6. show the quantity calculated according to the eq. (1), then they do not show moisture advection. The large majority of the paper discusses the role of moisture advection, however, this quantity is not calculated.

We thank the reviewer for this important comment. We acknowledge that the moisture flux advection was not computed. In the revised manuscript, we have significantly modified Section 4 which presents the analysis of atmospheric conditions. The discussion is now focused on the mainly on moisture flux.

On Pg. 6 Equation (2) is inconsistent with the text on lines 160-161: shouldn't the equation read as: CREswt=SWt-SWcs(t)?

You are absolutely right. We only presented eq2 as CREswt= SWcs(t)-SW(t) because we did not want to present CRA with negative values. In the revised manuscript, we have defined CRA as the difference, and then we take the absolute of the mean value. Please also note that based on the reviewer RC1 comment #10, we have removed equation 2 and just kept eqn 3. The new equation 2 is:

$$CRE_{SW\downarrow} = \left| \frac{1}{N} \sum_{i=1}^{N} \frac{SW^{\downarrow}(i) - SW^{\downarrow}_{CS}(i)}{SW^{\downarrow}_{CS}(i)} \times 100 \right|$$

3. Due to the definition of the LLC used in this study, i.e. all clouds with cloud base below 2 km, different cloud types are considered as LLC. This causes some confusion in understanding atmospheric forcing related to different LLC classes in the two regions. For example, the dominant LLC class-2 during the JAS period in the Guinean region is most likely related to the stratiform clouds and shallow cumulus, while the LLC class-2 peak in the same season most likely corresponds to deep convective clouds (as it corresponds to rain events). These different cloud types have different forcings and the authors need to make a more clear distinction between these throughout the manuscript. This is especially confusing in the Abstract.

The authors should refer to the recent finding from the DACCIWA regarding the physical processes responsible for the formation and maintenance of the LLC over the Gulf of Guinea during the WAM season.

We thank the reviewer for this comment. We totally agree. In the revised manuscript, we have entirely removed the analysis of divergence and vertical velocity since different low cloud types have opposing signs for these parameters. This was also pointed out by Reviewer 1. We now focus our discussion of atmospheric conditions mainly on the moisture flux and the discussion of results have been significantly modified.

Since it is impossible to make the distinction between different low cloud types in the ERA5 dataset, we attribute the low cloud types which are likely associated to certain events in a given season (and for which region). For example, we related LLC Class-2 in the Guinean region (in JAS) to stratiform clouds and linked this to the study of Lohou et al., (2020) who found that the daytime stratus clouds in the Guinean region causes a significant influence on the surface energy budget – a result that we also found in a our work (See the revised Section 4.2). This is also mentioned in the revised abstract.

We have also discussed the effects of having multiple cloud types in our definition on the results obtained (especially for surface heat fluxes (please see the revised Section 2.2.2)). Other DACCIWA studies are also used to support our work throughout the discussions.

4. In the recent DACCIWA papers (ACP special issue available at https://www.atmoschem-phys.net/special_issue914.html), the advection of the cold maritime air mass, related to the low level jet and the SW monsoon flow, is found to be the key process responsible for the LLC formation and not the advection of moist air. On the other hand, the advection of the relatively moist air could be important for the LLC formation in the Sahel. However, the authors do not assess the role of temperature advection. What is the reason for this?

As you mentioned in comment #3, the different cloud types have different forcings, and for low-level stratiform clouds, cold air advection is very important as shown in the DACCIWA papers (e.g., Adler et al. 2019 and Babic et al. 2019). We actually computed the horizontal temperature advection (H_{adv_T}) but did not introduce the figure in the manuscript. H_{adv_T} was computed as follows:

$$H_{adv\_T} = -\left(u\frac{\partial\theta}{\partial x} + v\frac{\partial\theta}{\partial y}\right),$$

where u and v are the zonal and meridional wind components respectively, and θ is the potential temperature.

The vertical profile of the H_{adv_T} for the first 2km is shown below in Figure 2 for LLC occurrence (Class 1 and 2) for the JAS season. The profile shown here (for the first 1km) is somehow similar to some of the results from the DACCIWA papers (*HADV in Adler et al., 2019 Figure 6a*), however the values here are rather very low compared to what was is shown in Adler et al., (2019). This difference is probably due to the fact that our LLC definition combines different low clouds (all types of clouds below 2km). Therefore, their combined effect could have led to such low values (as they may have different signs).

Although the LLC types have different conditions in which they occur, we do not expect the moisture flux to differ significantly for them. Therefore, we focused our revised discussion on the moisture flux (revised Section 4.1). The specific humidity component of the moisture flux, has been suggested to play a crucial role in the formation of low clouds (in Babic et al. 2019). Babic et al. (2019) found that the most distinct difference between stratus and stratus free events was evident in the specific humidity (please see their Figure 6c). Babic et al (2019) referred to this as the *"background moisture level"*. In our revised document, we showed the moisture flux before, during and after the occurrence of the LLC event (Figure 7 in the revised manuscript) and it clearly shown that the background moisture is very important for the occurrence of the LLCs. We suggested in our revised discussion that, the water vapour associated with the moisture flux is likely cooled by the cold air advection which in turn enhances saturation and consequently LLC occurrence. To support this, we added a plot of the potential temperature before and after the LLC events (Figure B2 in Appendix B) which showed that the temperature is strongly reduced before the LLC event – which may be due to the cold air advection. This was also supported with the findings of some of the DACCIWA studies.

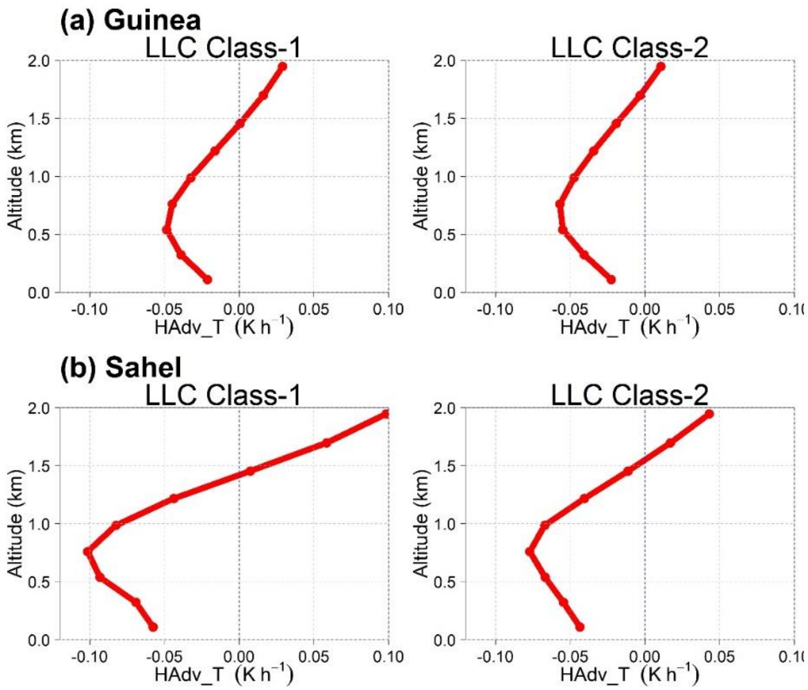

Figure 2: Vertical profiles of horizontal advection of temperature for LLC occurrence in Guinea and Sahel

Minor comments:

- Pg. 2, line 59-60: This statement is not correct. In the Guinean region the LLC form during the night and persist long into the morning and early afternoon hours, therefore have a direct impact on the surface solar irradiance. Please see the study of Lohou et al. (2020) and Zouzoua et al. (2020) regarding this.

  Thanks. The statement has been revised. It now read as:

  "In the night, the nocturnal LLCs have no influence on the surface solar radiation due to the absence of sunlight. However, they persist long into the morning and early afternoon, thus, directly influencing the amount of incoming solar irradiance and having a considerable impact on the energy balance of the earth surface as shown by Lohou et al., (2020)."

- Pg. 7, lines 198-200: Here it would be better to refer to recent DACCIWA publications which show that the advection of cold air, and not the advection of moist air, is the key process responsible for the formation of LLC in the Guinean region during the monsoon season.

  We thank the reviewer for this comment. We revised the sentence and referenced Adler et al. (2020) and Babic et al. (2020).

- Pg. 8, line 234-236: The reference here should be Adler et al. (2019) not (2019b). Additionally, all the studies referenced here find that the advection of cold air is the major factor in leading to saturation, not moist air! The authors should carefully revise the paper when discussing the processes leading to the formation of LLC in the two regions and when referring to previous studies to avoid making mistakes like these. Namely, based on the DACCIWA observational data it became clear that the advection of cold maritime air is the dominant process for the LLC formation in the Gulf of Guinea, while the advection of moist air into the Sahelian region is the most dominant process for LLC formation.

  Thanks. The whole discussion of atmospheric conditions has been revised significantly (in the revised Section 4.1).

- Pg. 8, line 242: It should be Saharan Heat Low.

  Thanks. The whole sentence was modified due to the significant revision made in Section 4.1.

- Pg . 8, line 243: What is the role of the cold air advection?

  In this sentence, we believe *"moisture advection"* and not *"cold air advection"* was mentioned. However, the appropriate term here should be *"moisture flux"* and not "moisture advection". Due to the revision in Section 4.1, the sentence was deleted. New comments have been made.

- Pg. 8, line 245: Consider here replacing "moist air" with cold air.

  Noted. Thanks. This was changed.

- Pg. 9, line 287: How can water vapor be cooled by moist air advection?

  This was wrong. In the revised manuscript, we mentioned that importance of cold air advection for LLC formation as shown by the DACCIWA studies. The original sentence was removed and new comments have been made.

- Pg. 10, line 304 and 312: Which region are you referring to? Is it entire West Africa?

  Line 304 to 307 in the original manuscript was related to the Sahel region. However, those lines have been removed from the revised manuscript.

  The entire West Africa was being referred to in the first five lines of Section 5. This has been clarified in the revised manuscript.

- Pg. 10, line 310: Figs. 10 and 11 also show the downwelling shortwave radiation attenuation for no LLC class.

  Yes, this is because there could be higher level clouds in those cases with no LLC. We mentioned this situation in the method section (line 127 to 129 in the original manuscript), and also shown in Figure 2.

- Pg. 11, line 329-330: The sentence "In Sahel, the mean attenuation during the occurrence of LLC Class-1 events is 16.3% *though* areas around the southern coast of WA can experience higher losses." should be rephrased since it is not clear what is the connection between the attenuation in the Sahel and the southern coast of WA.

  This has been rephrased. It now reads simply as: "*In Sahel, the mean attenuation during the occurrence of LLC Class-1 events is 16.3%."*

References:

Adler, B., Babia, K., Kalthoff, N., Lohou, F., Lothon, M., Dione, C., Pedruzo-Bagazgoitia, X., and Andersen, H.: Nocturnal low-level clouds in the atmospheric boundary layer over southern West Africa: An observation-based analysis of conditions and processes. Atmos Chem Phys, 19, 663–681, https://doi.org/10.5194/acp-19-663-2019, 2019

Babić, K., Kalthoff, N., Adler, B., Quinting, J. F., Lohou, F., Dione, C., and Lothon, M.: What controls the formation of nocturnal low-level stratus clouds over southern West Africa during the monsoon season? Atmos Chem Phys, 19, 13489–13506, https://doi.org/10.5194/acp-19-13489-2019, 2019

Responses to Referee 3

Referee Comment (RC3): This manuscript investigates daytime (06-17h) low-level clouds (LLC) over West Africa based on ERA5 (2006–2015) in two regions, the Sahel and Guinea Coastal region. LLC taken from the ERA5 archive describes cloudiness below 800 hPa (~2km). Foci of the study are on diurnal cycles in the dry and wet seasons, the seasonal variation of LLC, the atmospheric conditions related to different classes of LLC and the impact of the latter on the incoming solar radiation.

While the article describes an overall interesting topic and contains some interesting material, it also has weaknesses that shall be addressed in a major revision.

On behalf of all the authors, I wish to thank the reviewer for the thorough assessment of our study and for providing us with comments that helped to improve the manuscript during the revision. Please see below the detailed responses to each of the reviewer's comments/questions. The reviewer's comments are shown in black font while our responses are shown in blue font. Where applicable, the changes that would be made in the manuscript are shown in italics.

Major Comments

1) There needs to be a proper explanation between ERA-5 cloud fraction that usually depends on the subgrid-scale cloud scheme and the liquid and ice water paths that are relevant for the radiation scheme. Cloud fraction can be larger than zero for relative humidities below 100% and zero liquid or ice water content. There is an interesting discussion on this in Hannak et al. (2017, JCLIM). Thus cloud occurrence frequency at a gridpoint can be defined by a sub-grid scale cloud fraction or a hydrometeor content > 0. There needs to be explanations/discussion of this issue (see below).

   Thank you for this comment. In the revised manuscript, we have explained this in the data presentation section (Section 2.1). In addition, we have made some vertical profiles of the cloud water content during events with cloud fraction > 0 to further discuss this. These vertical profiles are shown in Fig. A1 of Appendix A in the revised manuscript.

2) My major concern that also needs some time in the revision relates to the degree of realism that hourly ERA5 data have in the representation of LLC. There was no evaluation of ERA5 in Danso et al. (2019), only a comparison of total cloud cover (all clouds, all levels) based on a very coarse cloud fraction partitioning of METAR reports for three stations in West Africa. From this one figure in the Suppl. Mat. it is not obvious that the CERES data set would be inferior to ERA5 – which it likely is according to the findings in Danso et al. I am very worried about that this study may show physically consistent errors of the underlying ERA5 model. For example high LLC fractions/frequencies may be related to errors in the Bown ratio in the ERA5 model etc (with causality being another point of concern). The Reviewer proposes two ways out of it: One is to use available ground and satellite observational evidence that exists, the other is to use two other re-analyses (e.g. MERRA2, JRA-55, NCEP). In terms of the former, van der Linden et al. (2015) have shown the usefulness of the 2B-GEOPROF-LIDAR tracks for cloud occurrence frequency in mean, 250m vertically resolved profiles, including the layer below 2 km (their Figure 6). The sampling argument given in the manuscript is not robust, as is the argument of the 1x1 grid resolution needed for PV application – the purpose is to validate the usefulness of ERA5 cloudiness and for this this the combined Cloudsat-Calipso at 01:30 LT would serve the purpose. Moreover, multi-year measurements of solar incoming radiation are available from AMMA-CATCH (http://www.amma-catch.org/?lang=fr), for the Upper Ouémé site even multiyear measurements of sensible and latent heat fluxes can be obtained. Radiation measurements for Parakou and Cotonou are also available from doi: 10.6096/baobab-dacciwa.1785. Kniffka et al. (2019, ACP) have shown large errors in surface solar radiation in ERA-I and it is questionable that this has been improved a lot in ERA5. Kniffka et al. (2020, QJRMS) have also shown that short-term forecasts of weather forecasting models, among which is the ECWMF IFS model have large errors in precipitation, radiation, and cloud cover. So there are strong arguments to validate ERA5 before drawing far reaching

conclusions. I prefer to use the few, but available observational evidence, but using two other reanalyses also allows inferences about the fidelity of the results. Clearly, I do not want the author to go to deep into validation, but some more validation is necessary (for some observational points and subperiods of 2006–2015).

We thank the reviewer this comment and the suggestions given.

We have carried out an evaluation of the ERA5 downwelling shortwave radiation with surface observations from the AMMA-CATCH database.

We also carried out a detailed evaluation of the cloud fraction and occurrence frequency with the merged 2B-GEOPROF-LIDAR dataset as you suggested. Since this evaluation was not the main focus of our work, we have presented the methodology and the results of the validation in a new supplementary material. Please find this in the supplementary files attached to the submission.

With regards to the latent and sensible heat fluxes, the available time series from the AMMA-CATCH stations have a lot of missing dates (percentage of missing data ranges from 45% to 100%). We feel this will make any evaluation of the ERA5 data with these observations will be unreliable.

3) LLCs and MCSs
Having been in the region many times, I can't understand why MCSs should explain a large fraction of LLCs in the Sahel, for example. There are LLCs in the "small" leading edge/in the convective part of the MCSs, but not in the stratiform part. And MCSs are relatively infrequent. LLCs in the rainy season over the Sahel occur in the morning, but dissipate in the afternoon when isolated Cu cong or CB develop. Please comment on this.

We thank the reviewer for this comment. In our manuscript, we did not generalize that all LLCs in the Sahel are likely explained by MCSs. When we said "*It is, therefore, reasonable to assume that most of these LLC Class-2 events in the Sahel are the well documented deep MCSs which are responsible for around 90 % of total rainfall in the region*" we were referring not to the Class 1 but the Class 2. The total number of the Class 2 events are very low compared to the Class 1 (with an LLC Class-1 to Class-2 occurrence ratio of about 13:1). In other words, the Class 2 LLCs are infrequent in the Sahel region just like the MCSs, as you mentioned.

We however, agree with your point on LLCs and MCSs and we also acknowledge that the link we made between LLC Class 2 and MCSs is perhaps not entirely "accurate". The part of the paragraph discussing this point has been revised and we added a figure in Appendix A of the revised manuscript to further explain. It now reads as:

Therefore, there is a higher likelihood of an MCS in the LLC Class-2 events than Class-1 and it is reasonable to assume that most of the LLC Class-2 events in the Sahel are the well documented deep MCSs that are responsible for around 90 % of total rainfall in the region (Mathon et al., 2002a; Goyens et al., 2012; Vizy and Cook, 2019). Indeed, a random plot. Indeed, a check of the vertical profiles of hydrometeor content of random LLC Class-1 and Class-2 events, reveals several LLC Class-2 events which that may be regarded as MCSs (Figure A1 in Appendix A).

4) I have not corrected all language errors and some statements are not very clear. The author should go over the manuscript meticulously in the revision to account for this deficiency.

Thank you. In the revised version, we have thoroughly revised the manuscript especially the in discussion of results. We believe the discussion is now clearer and language errors have been corrected.

Minor comments:

l. 29: “efficiently represent convection AND CLOUDINESS”

Thanks. *“cloudiness”* has been added to the sentence.

l. 35: “escalation” is not the right wording

The sentence has been revised. It now reads as: *“In the light of the recent increased interest in solar energy projects in WA…”*

l. 37: “remains”

Noted and corrected. Thank you.

l. 40: prefer references in a chronological order.

Well noted. All inline references have been presented in a chronological order.

l. 40: “van deR Linden”, please correct.

Thank you for this. It has been corrected.

l. 40: “Farther north”

Corrected. Thanks.

l. 43: “persisting into the early afternoon”

This has been corrected. Thanks.

l. 43: “as shallow convective clouds”?????

This sentence has been rewritten as:

“These LLCs consist of stratified clouds, most of which are nocturnal low stratus clouds covering wide areas and persisting into the early afternoons (Babić et al., 2019a; Schuster et al., 2013), as well as shallow convective clouds.”

l. 45-47: Here a reference to Kniffka et al. (2019, ACP) is appropriate.
Kniffka et al. (2019) has been referenced in this sentence in the revised manuscript. Thanks.
l 50: “The majority if these studies”
Thanks. Corrected.
l. 63: “limited TO the WAM season”
The sentence has been corrected. Thank you.
l. 84: “A better reference to ERA5 is now Hersbach et al. (2020, doi: 10.1002/qj.3803)

Thank you. We have changed the previous reference to Hersbach et al. (2020)

l. 101 “their surface heat fluxes explore”, awkward sentence

The sentence was rephrased. It now reads as:

“Other ERA5 variables are analyzed to show some of the atmospheric and surface conditions during the occurrence of LLCs in order to understand the possible interactions between the surface and the lower atmosphere.”

l. 147 “horizontal air divergence”, omit “air”, perhaps add “wind”.

The whole sentence was removed due to changes made in the manuscript.

l. 182 Reword “convected air”

Please the sentence now reads as:

“The proximity of the Guinean region to the ocean means that cold air over the Gulf of Guinea could be advected inland which will, in turn, enhance LLC formation.”

l. 188-192: Doubt that MCS contribute to LLC in reality (see major comment 3)

Please see our response to major comment #3 and Appendix A in the revised manuscript.

l. 202-204: What about the contribution of morning LLC?

Most of the morning LLC may probably be non-precipitating during that period.

l. 212: Did Mathon et al. (2002b) really refer to LLC below 2km?

Mathon et al. (2002b) did not explicitly refer to LLC below 2km. They studied organized convective systems, some of which may have their bases below 2km.

l. 232: the adverb “predictably” seems inappropriate here. Please rephrase.

Thank you. The whole sentence was revised. It now reads as:

“The moisture flux is stronger during the occurrence of LLC Class-2 events than LLC Class-1 events. This is true for LLC occurrence in both regions; however, the moisture flux is more intense for LLC occurrence in Sahel in terms of its inland penetration.”

l. 234 “...cold moist”. Sentence terminates awkward.

This sentence was revised entirely. It is the same as the response to the previous comment.

l. 240-242: q anomalies transported from the Atlantic in DJF and modulation by the WA heat low? The DJF heat low is somewhere over the Central African Republic/South Sudan at this time of the year. Please clarify.

The WAHL bit of the sentence was not correct. The sentence was revised. It now reads as:

"Additionally, the LLC Class-1 events during DJF (in Sahel) are related to positive anomalies of specific humidity that seem to have been transported onto the continent from the North Atlantic (not shown)."

Thank you.

l. 248: Very awkward explanation of divergence. Usually, the divergence of the 2-d wind field is a good approximation of mass divergence since horizontal gradients of density are small. Please rephrase.

This is actually the definition of horizontal divergence as provided by the ECMWF. Please see https://apps.ecmwf.int/codes/grib/param-db?id=155

However, we have entirely excluded the analysis of horizontal divergence and vertical velocity in the revised manuscript. As pointed out by both Reviewer 1 and 2, the different low cloud types have different forcings especially in terms of divergence and vertical velocity. Therefore, we removed this analysis to avoid a mix-up of the cloud types for these parameters.

Section 5: The liquid and ice water content is relevant for attenuation. I am pretty sure it is not the subgrid scale cloud fraction (please clarify this point here or in the data section, see major comment 1).

Thank you for this comment. The following sentences have been included in the data section (Section 2.1) to clarify this point:

"The occurrence frequency of clouds may be defined by the hydrometeor content or the CF value. Here, it is determined based on the value of the 2D single-level CF although, the liquid and ice water paths mostly determine the attenuation of incoming solar radiation in the atmosphere. The CF depends on the subgrid-scale cloud scheme in the ECMWF IFS and can be non-zero when the cloud water content is zero (see Appendix A)."

l. 363-365: "Other..." these processes or better features are only relevant in the wet season, not the dry season. Please mention this here.

Thank you. This will be added in the revised manuscript. It will now read as:

"Other processes such as the atmospheric waves and jets in the region (African Easterly wave, African Easterly Jet, etc.) may also contribute to the occurrence of LLCs but these not analyzed in this study. These processes are, however, only relevant in the wet season."

l. 393 "redaction" I think this is not the right word.

Thanks. This has been changed to *"...editing of the first draft"*.

Daytime low-level clouds in West Africa – occurrence, associated drivers and shortwave radiation attenuation

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Abstract. This study focuses on daytime low-level clouds (LLC) that occur within the first 2 km of the atmosphere ~~during the daytime~~ over West Africa (WA). These daytime LLCs play a major role in the earth's radiative balance, yet, their understanding is still relatively low in WA. We use the state-of-the-art ERA5 dataset to understand their occurrence and associated drivers as well as their impact on the incoming surface solar radiation in the two contrasting Guinean and Sahelian regions of WA. The diurnal cycle of the daytime occurrence of three LLC classes namely No LCC, LLC Class-1 (LLCs with lower fraction), and LLC Class-2 (LLCs with higher fraction) are first studied. The monthly evolutions of hourly and long-lasting LLC (for at least 6 consecutive hours) events are then analyzed as well as the synoptic-scale moisture flux ~~and local dynamics~~ associated with the long-lasting LLC events. Finally, the impact of LLC on the surface heat fluxes and the incoming solar irradiance is investigated. During the summer months in the Guinean region, ~~the occurrence of~~ LLC Class-1 occurrence is low while LLC Class-2 is frequent (occurrence frequency around 75 % in August). In the Sahel, LLC Class-1 is dominant in the summer months (occurrence frequency more than 80 % from June to October), however the peak occurrence frequency of Class-2 is also in the summer. ~~The occurrence of No LLC events does not present any specific correlation with the time of the day, whatever the region while as soon as LLC coverage becomes more pronounced (LLC Class-2), a diurnal evolution is noted and appears to be strongly different from one region to the other.~~ ~~During the summer months in the Guinean region, the occurrence of LLC Class-1 is low while LLC Class-2 is frequent (occurrence frequency around 75 % in August). In the Sahel, LLC Class-1 is dominant in the summer months (occurrence frequency more than 80 % from June to October), however the peak occurrence frequency of Class-2 is also in the summer.~~ In both regions, events with No LLC do not present any specific correlation with the time of the day. However, a diurnal evolution that appears to be strongly different from one region to the other is noted for the occurrence of LLC Class-2. ~~In both regions, the occurrence of LLCs during the rainy season is associated with an influx of cold moist air driven by strong southwesterly winds from the Guinean Gulf. Furthermore, the occurrence of LLC Class-2 is linked to strong surface heating and evaporation of soil moisture. During the dry season on the hand, the occurrence of LLCs is linked more to turbulent upward motion of air caused by surface heating (only in the Sahel) and the convergence of air masses near the surface.~~ LLC occurrence in both regions is associated with high moisture flux driven by strong southwesterly winds from the Gulf of Guinea and significant background moisture levels. LLC Class-2 in particular

leads to a significant reduction in the upward transfer of energy and a net downward energy transfer caused by the release of large amounts of energy in the atmosphere during the cloud formation. In JAS, most of the LLC Class-2 events may likely be the low-level stratiform clouds that occur frequently over the Guinean region while they may be deep convective clouds in the Sahel. ~~The results also showed that the occurrence of~~Additionally, LLC Class-2 causes high attenuation of the incoming solar radiation, especially during JAS where about 49 % and 44 % of the downwelling surface shortwave radiation is lost on average in Guinea and Sahel respectively.

1 Introduction

In West Africa (WA), the prediction of key features of the climate such as the West African Monsoon (WAM) is known to have large uncertainties (Christensen et al., 2013). Most of the uncertainties are essentially linked to the inability of climate models to efficiently represent convection and cloudiness, in particular low-level clouds (LLCs) (Hannak et al., 2017). Climate models struggle to properly reproduce the planetary boundary layer above the ocean and the continental surface as well as the land-ocean flux gradients that drive the triggering and the variability of LLC systems. These clouds and their temporal variation strongly influence the reflectivity of the atmosphere. As a result, large uncertainties exist in the prediction of surface solar radiation in the region (Knippertz et al., 2011). In the light of the recent ~~escalation of~~ increased interest in solar energy projects in WA (World Bank, 2019) after the Paris Agreement in 2015, predictability of surface solar radiation (Armstrong and Hurley, 2010; Kosmopoulos et al., 2015) thus, remains a key issue for any feasibility study concerning solar energy during either dry or wet seasons in the region.

WA is characterized by a frequent occurrence of different cloud types. Near the Gulf of Guinea in the southern part of WA, LLCs are prevalent all year round (Schrage and Fink, 2012; van der Linden et al., 2015; Adler et al., 2017; Danso et al., 2019). ~~Further~~ Farther north in the Sahelian region, these clouds are frequently observed during the WAM season from July to September (Bouniol et al., 2012). These LLCs consist of stratified clouds, most of which are nocturnal low stratus clouds covering wide areas and persisting into the early afternoon~~s~~ (Schuster et al., 2013; Babić et al., 2019a) ~~to~~ as well as shallow convective clouds. LLCs composed of liquid water are well known to have a large impact on radiative transfer (Liou, 2002; Turner et al., 2007; Hill et al., 2018;). As a result, they drive the diurnal cycle of convection and the planetary boundary layer (Grabowski et al., 2006; Gounou et al., 2012). During the daytime, these clouds block a large portion of the incoming shortwave radiation reducing the irradiance at the earth's surface (Kniffka et al., 2019).

Several studies have been carried out in WA to understand LLCs, their variability, and the processes that aid in their formation, maintenance, and dissipation (e.g., Schrage and Fink, 2012; Schuster et al., 2013; Kalthoff et al., 2018; Dione et al., 2019; Lohou et al., 2020; Pedruzo-Bagazgoitia et al., 2020). The ~~Majority~~ majority of those studies were carried out within the framework of two major field campaigns; the African Monsoon Multidisciplinary Analysis (AMMA) (Redelsperger et al., 2006) in 2006 and the Dynamics–Aerosol–Chemistry–Cloud Interactions in West Africa (DACCIWA) (Knippertz et al., 2015) in 2016. Both of these field campaigns provided an unprecedented database of surface-based observations of different cloud properties. Other studies on LLCs in the region have also been performed with satellite observations and model data (van der Linden et al., 2015; Adler et al., 2017; Hannak et al., 2017). These studies suggest that LLCs formation is linked to a number of processes including but not limited to cooling caused by horizontal cold air advection and the occurrence and strengthening of the nocturnal low-level jet (Schrage and Fink 2012; Adler et al. 2017; Babić et al. 2019b).

Most of these studies, however, focused on night-time LLCs in the southern part of WA (e.g., Schrage and Fink, 2012; Schuster et al., 2013; Adler et al., 2017, 2019; Babić et al., 2019b). In the night, the nocturnal LLCs have no influence on the surface solar radiation due to the absence of sunlight. However, they persist long into the morning and early afternoon, thus, directly influencing the amount of incoming solar irradiance and having a considerable impact on the energy balance of the earth surface as shown by ~~(~~Lohou et al., (2020). ~~These nocturnal LLCs do not have any direct impact on the surface solar irradiance during the daytime but their presence could provide an idea of the cloudiness the next day (at least early in the morning). Consequently, the conditions associated with LLC occurrence during the daytime in the region are less documented.~~ The conditions associated with these low clouds during the daytime in the region are less documented. As a result, our understanding of the impacts of these clouds on surface solar irradiance during the daytime is relatively limited. Moreover, most of the previous studies have been limited to the WAM season (e.g., Knippertz et al., 2011; Schuster et al., 2013; van der Linden et al., 2015; Dione et al., 2019). This is understandable as WA is cloudiest during the WAM season. However, it was shown that daytime LLCs exist in all seasons especially over southern WA (Danso et al., 2019). It is therefore important to understand the nature of such daytime LLCs over the whole region and not only during the WAM season. This is particularly challenging due to the lack of a long-term surface-based observational dataset in WA, thus, limiting our understanding of these cloud systems. Few studies which were done with simulations, reanalysis, and satellite data in the region (e.g., Knippertz et al., 2011; Schuster et al., 2013; van de Linden et al., 2015; Adler et al., 2017) have nevertheless shown results similar to those of ground observational studies (e.g., Adler et al., 2019; Babić et al., 2019b) to some extent.

In this general context, the main contribution of this study is to enhance our understanding of daytime LLCs in WA by focusing on daytime LLCs in both the dry and wet seasons with a state-of-the-art reanalysis dataset. Firstly, we will present the seasonal and diurnal distributions of the occurrence frequency of the daytime LLCs in two areas of WA with contrasting climate regimes (the Sahelian and the Guinean regions). We will then identify synoptic-scale ~~and local-scale~~ conditions (specifically the moisture flux) associated with the presence of the daytime LLCs. Additionally, we will investigate the impact of LLC on surface heat fluxes and estimate the percentage of incoming surface shortwave (SW) radiation that is attenuated when these clouds are present.

This paper is organized as follows: Sect. 2 describes the study area, datasets, and methodology. Section 3 presents the diurnal and monthly distribution of occurrence of daytime LLCs while the synoptic and local conditions associated with the occurrence of long-lasting LLCs are discussed in Sect. 4. Section 5 presents the estimated attenuation of incoming shortwave radiation during the occurrence of LLCs. Finally, conclusions are drawn in Sect. 6.

2 Data and Methods

2.1 Data

In this study, we analyze the 5th generation of the European Centre for Medium-range Weather Forecasts (ECMWF) Re-analysis – ERA5[1] ~~(Copernicus Climate Change Service, 2017)~~(Hersbach et al., 2020) to understand the occurrence of LLCs and their associated synoptic conditions and land surface fluxes and to discuss their impacts on incoming shortwave radiation

[1] Detailed documentation at https://confluence.ecmwf.int/display/CKB/ERA5+data+documentation

in WA (Fig. 1). The reanalysis is available at a temporal resolution of an hour and has a native horizontal resolution of 0.25°. However, due to more emphasis on large-scale conditions in this study, the data was directly extracted on a regular 1° x 1° grid from ECMWF. A period of 10 years from 2006 to 2015 was analyzed for the study. For this period a total of 43800 data points consisting of only daytime hours from 0600 h to 1700 h, were thus considered.

ERA5 provides different variables of cloud cover properties. These cloud variables are produced in CY41R2 of the ECMWF's Integrated Forecasting System (IFS) and documented in Part IV of the IFS Documentation[2]. The cloud cover variables consist of cloud fraction (CF) and cloud hydrometeors (liquid or ice water) and are available as 3D or 2D distributions. Here, we use the 3D distribution of cloud liquid and ice water content to show the atmospheric vertical profiles of clouds in selected areas over WA. The occurrence frequency of clouds may be defined by the hydrometeor content or the CF value. In this study, we determine the occurrence frequency based on the value of the 2D single-level CF, although, the liquid and ice water paths mostly determine the attenuation of incoming solar radiation in the atmosphere. The ERA5 CF depends on the subgrid-scale cloud scheme in the ECMWF IFS and can be non-zero when the cloud water content is zero (see Appendix A). ~~We then use the 2D single-level reanalysis of cloud fraction to define the occurrence of LLCs.~~ The atmospheric conditions and radiative impacts are analyzed based on this occurrence~~. In a recent study by Danso et al., (2019), the ERA5 cloud fraction was evaluated against some available synoptic in situ observations of the Integrated Surface Database (Lott et al., 2001). This assessment revealed a reasonable agreement between ERA5 and the in situ cloud fraction dataset (see Appendix S1 in Danso et al. (2019)).~~ In this study, we focus on low clouds defined by ECMWF in the ERA5 product as all clouds integrated from the surface to 2 km altitude in the atmosphere (≈ 800hPa). ~~In the ERA5 dataset, this~~ This includes all clouds with bases below 2 km. ~~Other ERA5 synoptic variables are analyzed to show some of the atmospheric conditions during the occurrence of LLCs and their surface heat fluxes explore to understand the potential interactions between the surface and the lower levels of the atmosphere.~~ Other ERA5 variables are analyzed to show some of the atmospheric and surface conditions during the occurrence of LLCs in order to understand the possible interactions between the surface and the lower atmosphere. These include specific humidity, zonal and meridional wind components, ~~vertical velocity,~~ and the surface sensible and latent heat fluxes. Furthermore, we use the incoming downwelling shortwave radiation variable in ERA5 to estimate the percentage of incoming solar radiation that is attenuated in the presence of LLCs. We first performed a detailed evaluation of the ERA5 cloud fraction and radiation data with surface and satellite-based observations for some locations in WA. This evaluation revealed a reasonably good performance by ERA5 in reproducing the observations (see supplementary material).

2.2 Methods

2.2.1 Identification of LCC occurrence

Our analysis is based on the occurrence of LLCs in two sub-regional windows over WA (rectangular boxes in Fig. 1) denoted here as Guinea (10° W to 0° E and 6° N to 9° N) and Sahel (10° W to 0° E and 12° N to 15° N). These areas are chosen

[2] Available at https://www.ecmwf.int/en/elibrary/16648-part-iv-physical-processes

primarily due to their contrasting climate regimes (Gbobaniyi et al., 2014). The Guinea region which includes countries like Ghana and Cote d’Ivoire is currently undergoing significant economic and infrastructural developments and thus the need for clean energy keeps increasing. Consequently, there are many ongoing solar energy projects in this region such as the 155 MW Nzema solar PV power project in Ghana (Kuwonu, 2016), which when completed will be the largest solar farm on the African continent. Côte d'Ivoire has planned to increase its share of variable renewable energy up to 11 % by the end of 2020 and up to 16 % by 2030. Thus, a 25 MW solar power plant is under construction in the Northern part of the country in Korhogo while two solar power plants projects with a capacity of 30 MW each have been approved and will be built in the localities of Tuoba and Laboa in the northwestern part of the country (MPEER, 2019). Additionally, there are several planned and existing solar energy projects in the Sahel window, especially in Burkina Faso with the 33 MW-capacity Zagtouli solar power plant (Moner-Girona et al., 2017) which is currently the largest solar energy project in the Sahelian part of WA.

Occurrence ~~and~~ or no-occurrence of LLC are first identified from the extracted data points based on the quantitative value of the ~~cloud fraction (CF)~~ CF in ~~these~~ the two selected windows. This is used to show the diurnal and monthly distribution of the LLC occurrence. All timestamps with zero CF in the lower atmospheric level (up to 2 km) are designated as No LLC. Thus, hourly events of LLC occurrence are all timestamps with non-zero CF values including those with very small CF values. LLC events with very low CF values may show no or weak signals of the conditions that exist during their occurrence. Moreover, cloud radiative forcing is strongly dependent on the fractional coverage of clouds (Liu et al., 2011). Each LLC occurrence event is therefore classified as one of two classes depending on the CF value for that event. The definitions of the classes are provided in Table 1.

Though the focus of this study is on LLC occurrence and the definition of the different classes is based on the CF in the lower atmosphere only, the convoluted cloud climatology in WA with frequent multilayer clouds (Stein et al., 2011) may also mean that other clouds at higher altitudes may exist in addition to LLCs. Fig. 2 illustrates this multilayer nature of clouds in WA in connection with LLC occurrence, by showing the mean (of all hourly events) vertical profile of cloud water content of each class in the two selected regions. For LLC Class-1 and Class-2 in both windows, the trimodal vertical distribution of tropical convection (Johnson et al., 1999) indicates the presence of higher altitude clouds in addition to the LLCs. In the case of No LLC, high- and mid-level clouds could exist but with very low water content. This suggests and agrees with the satellite-based climatology of Stein et al., (2011) that LLCs frequently exist together with upper-level clouds in WA.

2.2.2 Identification of synoptic conditions during LLC occurrence

Recent studies (e.g., Adler et al., 2019; Babic et al., 2019b) have identified some physical processes relevant to the formation and maintenance of LLC in WA. They include but are not limited to the strengthening of the nocturnal low-level jet, horizontal cold air advection and background moisture level. Babic et al., (2019b) suggested the latter could play an important role in the formation of LLCs but this has not received as much attention as the other processes. Based on the different classes defined in Table 1, the regional atmospheric circulation and moisture flux were analyzed for the 10-year period of this study. For that, a composite approach was used to produce robust results based on a large number of events. We only take into account the occurrence of the different LLC classes that last for a sufficiently long time for their associated mean atmospheric and surface conditions to be significant at the regional scale. Therefore, an event here refers to the occurrence of a given LLC class that lasts for at least six consecutive hours during the daytime. Composite analysis of the ~~horizontal~~ moisture flux ~~advection (Q_{adv})~~ (Q_{flux}) and wind at 950 hPa was performed. Here, ~~Q_{adv}~~ Q_{flux} is defined as:

$$\cancel{Q_{adv} = \frac{1}{N}\sum_{i=1}^{N} q_i v_i} \qquad \cancel{(1)}$$

$$Q_{flux} = \frac{1}{N}\sum_{i=1}^{N} q_i v_i \qquad (1)$$

where q is the specific humidity (in $g \cdot kg^{-1}$), v is the meridional wind component (in $m\ s^{-1}$) and N is the total number of events in a given LLC occurrence class. Since q is always positive, ~~Q_{adv}~~ Q_{flux} can either be negative or positive depending on the wind direction, with positive or negative values indicating northward and southward air movements respectively. Over the sea, positive values of ~~Q_{adv}~~ Q_{flux} from the ocean toward the continent thus suggest that moisture is likely transported onto the land along with the wind. ~~In addition, the vertical velocity, horizontal air divergence, and anomalies of q are analyzed together with Q_{adv}.~~

~~Surface heat fluxes (sensible and latent heat) are known to have important contributions to the occurrence of LLCs (Ek and Holtslag, 2004). Air masses near the land surface can be lifted upwards by turbulent motions due to strong surface sensible heat fluxes. On the other hand, soil moisture can be transported upwards through the effects of turbulent air motion by strong latent heat fluxes at the land surface.~~ Lohou et al., (2020) have shown that LLC occurrence also has a considerable impact on the surface heat fluxes in WA. Here, we examine~~d~~ the local surface sensible and latent heat fluxes in the selected windows to understand the daytime interaction of the land surface with the boundary layer and LLC occurrence. Due to the definition of LLCs used, the present study does not consider the impact of the atmospheric boundary layer (ABL) that may considerably modify the altitude of the low cloud. Indeed, ABL clouds have their bases higher than 2 km especially in the Sahel region during the dry season. In addition, some studies (Lohou et al., 2020; Pedruzo-Bagazgoitia et al., 2020; Zouzoua et al., 2020) have shown that some LLCs can be decoupled from the surface and are therefore not influenced by the surface heat fluxes. Therefore, having a higher cloud base threshold for LLCs may alter the analysis of the surface heat fluxes. ~~Additionally, the Bowen ratio (*BR*) (Lewis, 1995), the ratio between the sensible heat flux and the latent heat flux, was used to investigate the energy transfer between the land surface and the atmosphere in the two selected windows.~~ The analysis was performed for two seasons representing two contrasting climate regimes associated with the southernmost position of the Inter-Tropical Convergence Zone (ITCZ) over Guinea (in December, January, February (DJF)) ~~(in July – August – September (JAS))~~ and the northernmost position of the ITCZ over Sahel ~~(in December – January – February (DJF))~~ (in July, August, September (JAS)).

2.2.3. Determination of cloud shortwave attenuation effects

To investigate the quantity of incoming downwelling shortwave radiation attenuated in the presence of LLCs (in $W\ m^{-2}$) at a given time *t*, the cloud shortwave radiative effect ($CRE_{SW\downarrow}$) was estimated by finding the difference between the downwelling shortwave radiation in all-sky conditions ($SW^{\downarrow}$) and the corresponding downwelling shortwave radiation in clear-sky conditions ($SW_{CS}^{\downarrow}$) ~~incoming shortwave radiation following Bouniol et al., (2012) and expressed with the simple equation:~~. The $SW_{CS}^{\downarrow}$ which is directly available in ERA5, is a theoretical value computed at a given time based on the same atmospheric conditions (temperature, humidity, aerosols, etc.) as the $SW^{\downarrow}$ but assuming there are no clouds. To eliminate the influence of the wide range of daytime hours on its mean value, we expressed $CRE_{SW\downarrow}$ as a percentage of the attenuated $SW_{CS}^{\downarrow}$. Since $SW^{\downarrow}$ is usually lower than $SW_{CS}^{\downarrow}$, the mean $CRE_{SW\downarrow}$ over all events in a given LLC class will be negative. To avoid presenting a negative mean $CRE_{SW\downarrow}$, the absolute of this value is used. Thus, the mean $CRE_{SW\downarrow}$ of all events for a given LLC class is given by:

$$CRE_{SW\downarrow} = \left| \frac{1}{N} \sum_{i=1}^{N} \frac{SW^{\downarrow}(i) - SW_{CS}^{\downarrow}(i)}{SW_{CS}^{\downarrow}(i)} \times 100 \right| \qquad (2)$$

$$\cancel{CRE_{SW\downarrow}(t) = SW_{CS}^{\downarrow}(t) - SW^{\downarrow}(t)} \qquad \cancel{(2)}$$

~~where, $SW^{\downarrow}$ is the downwelling shortwave radiation in all-sky conditions and $SW_{CS}^{\downarrow}$ is the theoretical value of the downwelling shortwave radiation in clear-sky conditions. It must be noted that $CRE_{SW\downarrow}$ is estimated for a given class of LLC occurrence. To eliminate the influence of the wide range of daytime hours on its mean value, we expressed $CRE_{SW\downarrow}$ as a percentage of the attenuated $SW_{CS}^{\downarrow}$. Thus,~~

$$\cancel{CRE_{SW\downarrow}(t) = \frac{SW_{CS}^{\downarrow}(t) - SW^{\downarrow}(t)}{SW_{CS}^{\downarrow}(t)} \times 100} \qquad \cancel{(3)}$$

3. Temporal distribution of occurrence of daytime LLCs

The monthly distribution of the occurrence frequency (hourly) of the three LLC classes is presented in Fig. ~~4~~3 for the two selected regions (occurrences that last for at least six consecutive hours are in shown as black bars). In Guinea, events of No LLC are very rare (less than 200 in the 10 years data) and occur only in the DJF. On the other hand, LLCs occur in all months in this area. The occurrence of LLC events with lower fractional coverage (LLC Class-1) shows a clear seasonal cycle with the highest number of events in the dry and transitional seasons and the lowest number of events during JJAS which corresponds to the core of the monsoon season (Sultan et al., 2003). Coincidentally, LLC events with higher fractional coverage (LLC Class-2) occur most during the monsoon season. This period is associated with increased moisture influx from the Gulf of Guinea (Sultan and Janicot, 2003; Thorncroft et al., 2011) and cold air advection which enhances low clouds formation over the region during this period as shown by Adler et al., (2019) and Babic et al. (2019b). Interestingly, the peak of LLC Class-2 events occurs in August, the so-called “little dry season” in southern WA (Adejuwon and Odekunle, 2006; Chineke et al., 2010; Froidurot and Diedhiou, 2017). Whether this peak of LLC Class-2 events in August which coincides with reduced rainfall in southern WA is due to an increased occurrence of non-rain-bearing low clouds (and a decrease in rain-bearing ones) or not is beyond the scope of this paper but needs to be investigated in future.

In Sahel, events of No LLC are rather frequent (unlike Guinea) and occurs in every month except in August when the monsoon is fully developed over the Sahelian region of WA (Sultan et al., 2003; Thorncroft et al., 2011). Similarly, LLC Class-1 events are frequent throughout the year but with the highest occurrences from July to October (with a slight decrease in August) and lowest occurrences during the dry season. LLC Class-2 events are marked with a strong seasonal signature, occurring only from July to October with a distinct peak occurrence in August when the Inter-Tropical Convergence Zone (ITCZ) is at its northernmost latitude over WA (Sultan and Janicot, 2000; Nicholson, 2009, 2018~~; Sultan and Janicot, 2000~~). This period also coincides with the maximum rainfall over the Sahelian region (Nicholson, 2013) and suggests a strong link between the occurrence of LLC Class-2 events and the Sahelian rainfall. This is an indication that LLC Class-2 in the Sahel are likely related to rainfall events in the region. Again, Mathon et al., (2002b) showed that cloud cover associated with a sub-population of Mesoscale Convective Systems (MCS)~~s~~ in the Sahel is modulated at the synoptic-scale during the African easterly wave activity, with an increase of the cloud cover in and ahead of the trough and maximum rainfall behind of the wave trough.

The daytime distribution of occurrence frequency of the three LLC classes are presented in Fig. ~~3~~ 4 for the two selected areas. The distribution presents the total occurrence frequency of all seasons combined. In Guinea, the occurrence frequency of No LLC events does not present a very well-marked diurnal cycle with a slightly higher number of events occurring at 1700 UTC, though these events are extremely rare (less than 25 for the 10 years). In contrast, both LCC Class-1 and Class-2 occurrences present well-defined diurnal cycles. The occurrence of LLC Class-1 events is low during the early morning (lowest at 0700 UTC) and increases progressively throughout the day to late in the afternoon. On the contrary, LLC Class-2 events are high early in the morning (highest at 0700 UTC) but decrease continuously over the course of the day to the late afternoon (1700 UTC). The early morning peak in the LLC Class-2 events could be as a result of the contribution of residuals from nocturnal low-level stratus clouds which persist long into the day (Kalthoff et al., 2018). These clouds usually have large fractional coverage during their occurrence in the night (van der Linden et al., 2015) but start to dissipate during the daytime (Kalthoff et al., 2018). The continuous decreasing and increasing in the event number of LLC Class-2 and LLC Class-1 respectively, from morning to late afternoon could, therefore, be linked to the gradual dissipation of those nocturnal low-level stratus clouds during the day. Additionally, the early morning peak in the events of LLC Class-2 could also be partly linked to contributions from tropical oceanic low-level convection which is maximum during the early morning (Yang and Slingo, 2001). The proximity of the Guinean region to the ocean means that ~~convected~~ cold air over the Gulf of Guinea could be ~~transported~~ advected inland which will, in turn, enhance LLC formation.

In the Sahel region, events of No LLC occur without a well-marked diurnal cycle but are slightly lower around midday. Similarly, LLC Class-1 events do not present a very distinct diurnal cycle. On the other hand, events of LLC Class-2 show a clear and well-marked diurnal cycle with a higher occurrence frequency in the late morning to midday (highest at 1100 UTC) and lower values during early mornings and late afternoon. This tendency seems to be strongly controlled by surface processes such as continental daytime solar heating (Mallet et al., 2009). Moreover, it could further be related to the occurrence of deep ~~mesoscale convective systems (~~MCSs~~)~~ whose convective parts will be considered as low clouds if found within the lowest 2 km of the atmosphere. ~~which~~ These MCSs present a fairly similar evolution (both seasonally (Fig. ~~4~~3) and diurnally) as the LLC Class-2 in this region of WA (Vizy and Cook, 2018). ~~It is, therefore,~~ Therefore, there is a higher likelihood of an MCS in the LLC Class-2 events than Class-1 and it is reasonable to assume that most of ~~these~~ the LLC Class-2 events in the Sahel are the well documented deep MCSs (Figure A1 in Appendix A) ~~which~~ that are responsible for around 90 % of total rainfall in the region (Mathon et al., 2002a; Goyens et al., 2012; Vizy and Cook, 2019).

~~The monthly distribution of the occurrence frequency (hourly) of the three LLC classes is presented in Fig. 4 for the two selected regions (occurrences that last for at least six consecutive hours are in shown as black bars). In Guinea, events of No LLC are very rare (less than 200 in the 10 years data) and occur only in the DJF. On the other hand, LLCs occur in all months in this area. The occurrence of LLC events with lower fractional coverage (LLC Class-1) shows a clear seasonal cycle with the highest number of events in the dry and transitional seasons and the lowest number of events during JJAS which corresponds to the core of the monsoon season (Sultan et al., 2003). Coincidentally, LLC events with higher fractional coverage (LLC Class-2) occur most during the monsoon season. This period is associated with moisture influx from the Gulf of Guinea (Sultan and Janicot, 2003; Thorncroft et al., 2011) which enhances low clouds formation over the region during this period. Interestingly, the peak of LLC Class-2 events occurs in August, the so-called "little dry season" in southern WA (Adejuwon and Odekunle, 2006; Chineke et al., 2010; Froidurot and Diedhiou, 2017). Whether this peak of LLC Class-2 events in August which coincides with reduced rainfall in southern WA is due to an increased occurrence of non-rain-bearing low clouds (and a decrease in rain-bearing ones) or not is beyond the scope of this paper but needs to be investigated in future.~~

~~In Sahel, events of No LLC are rather frequent (unlike Guinea) and occurs in every month except in August when the monsoon is fully developed over the Sahelian region of WA (Sultan et al., 2003; Thorncroft et al., 2011). Similarly, LLC Class-1 events are frequent throughout the year but with the highest occurrences from July to October (with a slight decrease in August) and lowest occurrences during the dry season. LLC Class-2 events are marked with a strong seasonal signature, occurring only from July to October with a distinct peak occurrence in August when the Inter-Tropical Convergence Zone (ITCZ) is at its northernmost latitude over WA (Nicholson, 2009, 2018; Sultan and Janicot, 2000). This period also coincides with the maximum rainfall over the Sahelian region (Nicholson, 2013) and suggests a strong link between the occurrence of LLC Class-2 events and the Sahelian rainfall. Again, Mathon et al., (2002b) showed that cloud cover associated with a sub-population of MCSs in the Sahel is modulated at the synoptic-scale during the African easterly wave activity, with an increase of the cloud cover in and ahead of the trough and maximum rainfall behind of the wave trough.~~

4. Synoptic conditions related to the occurrence of daytime LLCs

The synoptic conditions associated with the occurrence of the different LLC classes are mainly presented for the JAS and DJF seasons. The total number of daytime hours in JAS and DJF during the 10 years are 11040 and 10800 respectively. Only occurrences that last for at least six consecutive hours are considered to analyze these conditions (i.e., here, an event refers to an occurrence that persists for at least six consecutive hours). Table 2 presents the number of the ‘six-consecutive hours’ events extracted for each class and for both seasons over the 10 years. During the JAS season, no occurrence of No LLC events was detected in both Guinea and Sahel window (i.e., daytime LLCs are always present in both regions during the JAS). LLC Class-1 events dominated the Sahel region during JAS (with ~~824~~ 793 events) but on the contrary, LLC Class-2 events dominated the Guinea region (with ~~812~~ 852 events). In DJF, No LLC events dominated the Sahel (with ~~876~~ 877 events) and no LLC Class-2 occurrence has been identified in this area during this season. In Guinea, on the other hand, LLC Class-1 occurrences dominated the area during DJF (with ~~888~~ 878 events). Composites of the different variables are thus analyzed and then discussed only based on the extracted events for each class and each season, as presented in Table 2.

4.1. Atmospheric circulation and moisture ~~advection~~flux

The occurrence of daytime LLC events in the selected windows is related to large-scale dynamics of the atmosphere over the WA region. Fig. 5 and 6 present the composites of $\cancel{Q_{adv}}$$Q_{flux}$ and the atmospheric circulation at 950hPa for JAS and DJF respectively, and for the two studied regions. During JAS in both regions (Fig. 5), the occurrence of LLC Class-1 and Class-2 events is related to high moisture flux dominated by ~~an influx of cold moist air from the ocean associated with the~~ strong southwesterly winds (positive ~~Q_{adv}~~ Q_{flux}) from the Guinean Gulf ~~into the continent~~. ~~Predictably, the horizontal advection of moist air~~The moisture flux is stronger during the occurrence of LLC Class-2 events than LLC Class-1 events. This is true for LLC occurrence in both regions; however, the ~~advection~~ moisture flux is more intense for LLC occurrence in Sahel in terms of ~~the~~ its inland penetration ~~of the cold moist~~. There are no events of No LLC in both Sahel and Guinea during JAS. ~~This inland advection of moist air from the ocean has been found to play a major role in cooling (Adler et al., 2019b) which in turn enhances saturation of water vapour and consequently LLC formation (Adler et al., 2019, 2017; Babić et al., 2019b).~~ During DJF in both regions (Fig. 6), events with No LLC are characterized by dry northeasterly winds that inhibit LLC formation. The occurrence of LLC Class-1 events in Guinea and Sahel is characterized by southerly winds just at the southern coast but do not penetrate the area of the two windows. Nevertheless, both LLC Class-1 and Class-2 events are associated with significant specific humidity (true for both seasons) unlike No LLC events with very low specific humidity (see Figure B1 in Appendix B). This is in agreement with Babic et al., (2019b) who found that the most distinct difference between LLC and No LLC events is in the specific humidity, suggesting that the background moisture may play a crucial role in the formation and maintenance of low clouds in WA. Additionally, the LLC Class-1 events during DJF (in Sahel) are related to positive anomalies of specific humidity that seem to have been transported onto the continent from the North Atlantic (not shown). LLC Class-2 events in Guinea are associated with a much stronger moisture flux in the region (Fig. 6) as well as a positive anomaly of specific humidity within and around the window (not shown).

~~During DJF in both regions (Fig. 6), events with No LLC are characterized by dry northeasterly winds that inhibit LLC formation. The occurrence of LLC Class-1 events in Guinea and Sahel is characterized by southerly winds just at the southern coast but do not spread into the area of the windows. Other factors are likely responsible for the formation of these events in both regions during DJF. Nevertheless, the LLC Class-1 events during DJF (in Sahel) are related to positive *q* anomalies that seem to have been transported onto the continent from the North Atlantic (see Fig. A1a in Appendix) through a modulation by the West African Heat Low (Lavaysse et al., 2009) but this needs to be investigated further. LLC Class-2 events in Guinea are associated with a much stronger moisture advection into the region (Fig. 6) as well as a positive anomaly of *q* within and around the window (Fig. A1b in Appendix).~~

The moisture flux presented so far are those present during the occurrence of the events which may be important for the maintenance rather than the triggering of the LLC. However, it is also interesting to investigate the moisture flux before and after the LLC occurrence. To do this, we analyze the composite moisture flux (at 950 hPa) of the first hour just before the LLC event ($1h_{Before}\ LLC$) and the first hour just after the LLC disappears ($1h_{After}\ LLC$), and the difference between the two periods. This is illustrated for LLC Class-2 during the JAS season in both Guinea and Sahel (Fig 7). In both regions, the moisture flux during $1h_{Before}\ LLC$ is larger than $1h_{After}\ LLC$ and there is a significant difference between the two periods as shown in Fig. 7. This is also true for the composites of specific humidity only (not shown). During $1h_{Before}\ LLC$, the water vapour associated with the moisture flux is likely cooled by some cold air advection into the region which leads to saturation and consequently, LLC formation. Indeed, the vertical profile of the potential temperature in the lower atmosphere during the two periods shows a strong temperature decrease just before the LLC occurrence and an increase after its disappearance (Figure B2 in Appendix B). This result, which is in agreement with the finding of Babic et al., (2019b), may be an indication of the cooling caused by the cold air advection. Over the Guinea region, studies have shown that cooling by the horizontal advection of cold air from the Gulf of Guinea contributes significantly to the formation of LLC (e.g., Adler et al., 2019; Babic et al., 2019b). In the Sahel region, moist air advection may be crucial for LLC formation as suggested by Parker et al. (2005) and Monerie et al. (2020). However, before LLC formation in the Sahel region, there may also be some cooling due to meridional advection (Marsham et al., 2013) as well as cold air advection from the North Atlantic, which could explain the strong temperature reduction during $1h_{Before}\ LLC$ (Figure B2).

~~Unlike in JAS, the lack of moist air advection from the Guinean Coast during LLC occurrence in DJF (at least for LLC Class-1 events) in both regions suggests that other factors are at play. Fig. 7 shows the mean vertical profiles of horizontal air divergence and the vertical velocity in the two regions for the first 2 km of the atmosphere during DJF. The horizontal divergence is used to quantify the rate at which air is spreading out of a point per unit area, while vertical velocity measures the speed of air motion in the upward or downward direction. In keeping with the ECMWF convention, negative values for both quantities will be favorable for cloud formation i.e., converging air has negative divergence, and ascending air has~~

~~negative vertical velocity. In both regions, the occurrence of LLC Class-1 events is associated with the convergence of air within the first 1km of the atmosphere (negative mean divergence, Fig. 7). Additionally, the occurrence of LLC Class-2 events in Guinea is also associated with converging air. Similarly, the vertical motion of the air is in the upwards direction on average (negative vertical velocity) in both regions during LLC occurrence. The upward air motions are likely caused by the convergence of air masses near the surface as shown in Fig. 7. It is worth noting that on average during No LLC events in Guinea, there is a weak upward motion associated with a maximum convergence around 500 m and a maximum divergence at 1500m when in the Sahel, the vertical velocity is on average neutral while the maximum convergence at the surface is very weak and close to the surface (250 m) and the maximum divergence is reached at 750 m. It is also important to note that during JAS, the average vertical profiles of these processes (divergence and vertical velocity) are not similar to DJF (not shown).~~

4.2. Surface heat fluxes

~~Fig. 8 presents the monthly mean anomalies of both surface sensible and latent heat fluxes computed over the two selected regions for the three LLC occurrence classes.~~ Fig. 8 and 9 respectively present the monthly mean and anomalies of the surface heat fluxes, computed over the two selected regions for the three LLC occurrence classes. For a particular hour *i*, on a given day and month during the 10 years, the heat flux anomaly is the difference between the actual heat flux value and the 10-year mean. For example, the heat flux anomaly at 12 UTC on 1st January 2006 was determined by taking the difference between the actual heat flux at 12 UTC on 1st January 2006 (HF_i) and the 10-year mean of all heat flux values at 12 UTC on 1st January ($\overline{HF}$) i.e.,

$$HF_{anom_i} = HF_i - \overline{HF} \qquad (3)$$

where, HF_{anom_i} is the heat flux anomaly. The mean monthly anomaly is then computed by finding the mean of hourly anomalies in the month. The ECMWF convention for vertical fluxes including the sensible and latent heat fluxes, is positive downwards and negative upwards.

~~For the No LLC events class, in both regions, a land surface cooling is present throughout the year as shown by the negative anomalies of the sensible heat. This surface cooling thus reduces upward motions of the air masses near the surface and contributes to inhibiting cloud formation regardless of the positive anomalies of surface latent heat flux (at least from April to June over Sahel). The lack of upward motion of air in both regions during No LLC events is also seen in the vertical velocity profiles in Fig. 7 (almost neutral mean vertical velocity). During the summer months there can be moisture influx extending into Sahel region but the surface cooling (negative anomaly of sensible heat) reduces the upward rise of air near the surface.~~During No LLC events in both regions, there is high negative sensible heating in all months (Fig. 8) indicating an upward transfer of sensible heat. Due to the absence of LLC, a large portion of the incoming irradiance is used to warm the surface which in turn emits longwave radiation upward. Both regions are characterized by negative anomalies of sensible heat (Fig. 9) suggesting a much stronger than usual upward transfer of sensible heat. The mean latent heat fluxes during No LLC events are also negative but significantly lower than the sensible heat (Fig. 8). Thus, most of the energy from the surface is used to heat the atmosphere rather than evaporating moisture. This is due to the lack of moisture in the region during No LLC events (see Figure B1 in Appendix B) which inhibits the formation of LLC during these events. In the Sahel region, there are positive anomalies of latent heat (from April to June), which indicates a downward transfer of energy from the atmosphere to the surface.

During LLC occurrence, a portion of the incoming SW radiation is blocked. Therefore, the warming of the surface is reduced during LLC occurrence in both regions. However, due to the higher cloud fraction during LLC Class-2 events, a larger quantity of the downwelling shortwave radiation is blocked. Consequently, the associated surface warming is much lower during LLC Class-2 than the Class-1 events (lower negative sensible heat fluxes than Class-1 events in Fig. 8a). This result suggests that the LLC Class-2 events are most likely the low stratiform clouds which are known to cover large portions of the sky or the deep convective clouds which extends to the upper levels of the atmosphere, generating anvils in the process. With regards to the former, Lohou et al., (2020) have shown that these low stratiform clouds have significant impacts on the energy balance of the earth's surface during the daytime in the Guinea region. The latter has also been shown to have large impacts on the incoming shortwave radiation, especially in the Sahel region during the monsoon season (Bouniol et al., 2020).

In terms of anomalies, the LLC Class-2 events present positive values (Fig. 9a) over both regions which suggest a net downward transfer of sensible heat. This could be due to the large amounts of energy released in the lower atmosphere during the formation of these clouds, which tends to make the lower atmosphere warmer than the surface. Therefore, the atmosphere tends to warm the surface by transferring sensible downwards. On the other hand, LLC Class-1 in the Guinean region presents negative anomalies of sensible heat which suggest a net upward transfer of sensible heat during these events. As these LLCs do not cover a large portion of the sky, a large amount of shortwave radiation still warms the surface and the surface, in turn, warms the atmosphere by emitting longwave radiation. It is rather surprising that the Sahel region presents positive anomalies (except in JAS) for sensible heat. As suggested by Bouniol et al., (2020), such a result should not be interpreted exclusively in terms of the radiative effects of clouds but rather the coupled interactions between fluctuations in temperature, water vapor, and clouds in this region. However, this is beyond the scope of the present study.

During LLC occurrence, the large mean negative latent heat values indicate more evaporation from the surface (Fig. 8b). Interestingly, the transfer of latent heat upwards is higher in Class 1 than in Class 2. Since only a small portion of the sky is covered during LLC Class-1 events, the surface still receives a significant amount of downwelling shortwave radiation. Therefore, the surface continues to be warmed better by the sun's radiation during LLC Class-1 events than Class-2 events. As a result, the evaporation of moisture at the surface is much higher during the occurrence of the former. There are negative anomalies of the surface latent heat (Fig. 9b) in both regions during LLC Class-1 events in all months (except in November and December in the Sahel). This signifies a more intense upward transfer of latent energy from evaporation during these events. On the other hand, LLC Class-2 events are associated with positive anomalies of latent heat. This is likely due to two main reasons. Firstly, the reduced incoming downwelling shortwave radiation decreases evaporation at the surface. Secondly, large amounts of latent heat of condensation are released in the atmosphere during the formation of the clouds. There is therefore a greater amount of latent energy in the atmosphere than at the surface and a net downward transfer of this energy.

~~In Sahel, the occurrence of LLC Class-1 events in all months except in JAS is associated with surface warming (positive anomalies of surface sensible heat, up to about 25 W m^{-2} in January). This surface warming could explain the upward air motion in DJF (Fig. 7) that could lead to the LLC formation. During JAS, these events occur with negative anomalies of sensible heat (about -3 W m^{-2} in August when cloud coverage in Sahel is strongest (Fig. 4)). It is possibly due to relatively intense cloud coverage which reduces incoming shortwave radiation to warm the surface. Similarly, negative anomalies of the~~

~~surface latent heat flux are associated with these events in the Sahel during most of the year (except in November and December even though these anomalies are rather small). This may indicate that the occurrence of LLC Class-1 events during the JAS season in the Sahel is more linked to the large-scale factors (such as Q_{adv} as shown in Fig. 5) rather than local factors such as the surface heat fluxes. However, during the DJF season, the surface sensible heat flux (but not the surface latent heat) and possibly other large-scale processes mainly drive the occurrence of LLC Class-1 events in Sahel. Moreover, the surface sensible heat flux seems to play a more important role in the occurrence of LLC Class-1 events in Sahel (except in JAS) than in Guinea. In the latter region, both surface sensible and latent heat fluxes do not seem to play a crucial role in the occurrence of the LLC Class-1 events, since they present negative anomalies during the occurrence of these events with the lowest values during the core of the monsoon season when cloud coverage is much intense in the region.~~

~~On the contrary, the occurrence of LLC Class-2 events is more linked to the surface heat fluxes in both regions. Both regions show positive anomalies for both surface sensible heat flux and the latent heat flux indicating surface warming and soil moisture evaporation. This suggests that the occurrence of these types of LLC depends on both regional-scale dynamic features and local-scale features. Surface sensible and latent heat fluxes combined with low-level convergence (Fig. 7) lead to turbulent upward motion of water vapour which is further cooled by moist advected air from the Guinean Coast, leading to saturation and then LLC formation. The role of the surface heat fluxes though appears to be much critical in Sahel than in Guinea. This is shown by the very large anomalies of surface sensible and latent heat fluxes in Sahel compared to Guinea (sensible heat anomaly of about 45 W m^{-2} against 5 W m^{-2} in July and latent heat anomaly of about 40 W m^{-2} against 5 W m^{-2} in in October). Furthermore, surface sensible heat flux seems to have a large influence on the LLC occurrence than the surface latent flux at the beginning of JAS in the Sahel. This outcome is in agreement with Couvreux et al., (2012) who found that in this semi-arid region of WA, the existence of a large surface sensible heat flux is responsible for the occurrence of deep convective systems (as already mentioned in Sect. 3 most of these Class-2 events in Sahel are clouds with deep vertical extents). In other parts of the world (e.g., Bosman et al., 2019 and Tang, 2004), it was shown that the surface sensible heat flux has a much significant role in LLC formation than the surface latent heat flux.~~

~~In addition to the surface sensible and latent heat flux anomalies, the monthly mean BR computed over the two selected regions associated with the three LLC occurrence classes is presented in Fig. 9. For the occurrence of both LCC Class-1 and Class-2 events, BR values are much larger before and after the monsoon season. This is very clear especially in the Sahel (for LLC Class-1 occurrence) and is a result of large sensible heat fluxes and low latent heat fluxes at the surface due to lack of moisture in the soil during this time of the year (Ramier et al. 2009). This means that most of the energy for heat transfer near the surface goes into heating the ground (and the air in contact with it) rather than evaporating ground moisture. It further confirms our assertion that sensible heat (and large-scale features) plays a much important role in the occurrence of LLC Class-1 events (mostly during the dry season in this region) than latent heat. However, during the monsoon season, the occurrence of both LLC Class-1 and LLC Class-2 events is characterized by low values of BR. Soil moisture becomes a particularly important variable to initiate deep convections which leads to the occurrence of LLC (especially Class-2), as indicated by the low values of BR. This is in agreement with the findings of Alonge et al., (2007) over the Sahel region.~~

5. Attenuation of incoming shortwave radiation during LLC occurrence

In Fig. 10 and 11, the regional distribution of cloud radiative effect on incoming downwelling shortwave radiation during JAS and DJF is presented respectively as the percentage of incoming shortwave radiation attenuated during the occurrence of LLCs in the two regions as computed with Eq. (3) ($CRE_{SW\downarrow}$). In this section, we will focus more on the mean $CRE_{SW\downarrow}$ in each of the regions. Firstly, there is a strong seasonal variability of $CRE_{SW\downarrow}$ ~~in~~ over the entire WA region. It is obvious that shortwave attenuation is much higher during JAS than during DJF over the entire region as a result of increased cloud coverage during the monsoon season (Bouniol et al., 2012; Danso et al., 2019). This is true whether LLCs are present or not. During the occurrence of LLCs, the values of $CRE_{SW\downarrow}$ are much lower for LLC Class-1 than LLC Class-2 events, whatever the region and the season. This clearly shows the strong dependence of $CRE_{SW\downarrow}$ on the fractional coverage of clouds as previously discussed by (Liu et al., 2011).

In JAS, the strong impacts of LLCs on incoming shortwave radiation is seen from the high $CRE_{SW\downarrow}$ values during LLC occurrence. During the occurrence of LLC Class-1 events, the mean percentage attenuation of incoming shortwave radiation becomes 29.9 % and 17.5 % respectively in the Guinean and Sahelian regions. In the same way, 49.1 % and 44.2 % of incoming shortwave radiation are attenuated on average in Guinea and Sahel, respectively during events of LLC Class-2. Though these values are attenuated in the two regions under consideration, higher losses can be experienced in different areas over the region during those events. For instance, during LLC Class-2 events in the Sahel, the areas around the southern coast and the Guinea highlands experience much higher $CRE_{SW\downarrow}$ values (up to 65 %). This could be due to the presence of more clouds in those areas which extend into the Sahel region.

During DJF, during events of No LLC in Guinea and Sahel, about 2.2 % and 2.3 % (Fig. 11) of the incoming shortwave radiation is lost on average respectively. Even though there is no LLC occurrence during these events, this attenuation value is due to the possible presence of other cloud types at the upper levels. However, similar to the JAS season, the occurrence of LLCs leads to higher $CRE_{SW\downarrow}$ in both regions. In Guinea, 13.3 % of incoming shortwave radiation is lost on average during the occurrence of LLC Class-1 events while 32 % is lost during LLC Class-2 events. In Sahel, the mean attenuation during the occurrence of LLC Class-1 events is 16.3 %~~ though areas around the southern coast of WA can experience higher losses~~.

The large attenuation of incoming shortwave radiation during LLC occurrence (especially LLC Class-2) could be detrimental to planned solar energy application projects if not properly planned. For instance, during the JAS season in the Guinea region (and southern part of WA in general), the dominance of LLC Class-2 events (Table 2 and Fig. 3) means that surface solar radiation will be significantly reduced for a large number of periods. Although there are equally high losses of incoming solar radiation in the Sahel during LLC Class-2 events in JAS, these events are much lower than in the Guinea region. Besides, the Sahel region has several persistent periods with no LLCs compared to the Guinea region in the other months of the year, especially during DJF. However, other issues that are not discussed in this paper such as dust (e.g., Bonkaney et al., 2017) could severely hinder solar energy projects in the Sahel region. In all cases, the implementation of large-scale solar energy projects in both regions requires meticulous planning to ensure that the intense cloudiness over the region and the high variability of these clouds as shown by Danso et al., (2019) do not compromise the long-term aims of those developments.

6. Conclusion

In this paper, we made use of the state-of-the-art hourly reanalysis dataset from ECMWF – ERA5 from 2006 to 2015 to analyze the occurrence of daytime LLCs in WA. The analysis was performed for both the wet (JAS) and dry (DJF) seasons and focused on two climatically contrasting areas in the region (i.e., Guinea and Sahel). We have first identified events of LLC occurrence in both regions. We then analyzed some regional- and local-scale environmental conditions which occur during those events of LLC occurrence. This analysis mainly focused on the moisture flux before, during and after the LLC occurrence. We also analyzed the impacts of the LLC occurrence of on the surface heat fluxes. ~~horizontal moisture transport by atmospheric circulations, vertical motions, and surface heat fluxes.~~ Finally, the attenuation of incoming shortwave radiation during the occurrence of LLC in the region was estimated. To account for the influence of fractional coverage of LLC on the attenuation of incoming shortwave radiation, we classified the events of LLC occurrence into two groups: events with low fractional coverage (LLC Class-1) and events with high fractional coverage (LLC Class-2). The main findings of the study are summarized below:

- The occurrence frequency of daytime LLCs is characterized by significant diurnal and seasonal variations: (i) Over Guinea, the occurrence of LLC Class-1 events is lower during the core of the monsoon season (JJAS) while LLC Class-2 events are much higher during this period. During the day, LLC Class-2 events occur frequently during the early morning while LLC Class-1 is rather frequent during the late afternoon. (ii) Over Sahel, the occurrence of both LLC Class-1 and LLC Class-2 events is higher during the core of the monsoon season. Occurrence frequency of LLC Class-2 events is higher around midday while for LLC Class-1 events, it does not show a strong diurnal variation.
- During JAS, the occurrence of LLCs (both Class-1 and Class-2) in both Guinea and Sahel is associated with high moisture flux dominated by significant background moisture and strong southwesterly winds from the Gulf of Guinea.~~an influx of cold moist air transported from Guinean Coast by the strong southwesterly winds.~~ We also found that just before the occurrence of LLC, the temperature in the lower atmosphere is significantly reduced (Appendix B). This is due to cold air advection which leads to saturation as shown in previous studies (e.g., Adler et al., 2020 and Babic et al., 2020). ~~This horizontally advected cold moist air cools and enhances saturation of water vapour and thus leads to the formation of clouds in the region.~~
- In the dry season, the ~~horizontal advection of moisture~~ moisture flux is not as intense as in JAS but the background moisture content is significant during occurrence of LLCs. ~~does not seem to be related to LLC occurrence (except for a weak advection in Guinea for LLC Class-2 events) as the~~ The region is dominated by dry northeasterly winds during this period. ~~Instead, turbulent upward motions, likely triggered by the convergence of air masses near the surface appear to be associated with the occurrence of LLC events.~~ Other processes such as the atmospheric waves and jets

in the region (African Easterly wave, African Easterly Jet, etc.) may also contribute to the occurrence of LLCs but these are not ~~specifically~~ analyzed in this study. These processes are, however, only relevant in the wet season. ~~may have also contributed to the occurrence of LLCs.~~

- ~~Surface heat fluxes play a major role in the occurrence of LLC Class-2 events than for LLC Class-1 events. Furthermore, the role of the surface heat fluxes appears to be more important for LLC occurrence in Sahel than in Guinea. For LLC Class-1 events in Sahel, the surface sensible heat flux appears to be very important for LLC occurrence during the dry season (sensible heat anomaly of about 25 W m^{-2} in January). This perhaps explains the turbulent upward air motions that associated with the occurrence of LLCs in DJF.~~ The occurrence of LLCs has significant impacts on surface heat fluxes. LLC Class-2 events lead to a significant reduction in the transfer of energy (both sensible and latent) upward and significant release of energy in the atmosphere which causes a net downward transfer of energy.
- Attenuation of incoming shortwave radiation is higher during JAS than DJF and depends on the fractional coverage of LLCs. In JAS, the occurrence of LLC Class-1 leads to mean attenuations of 29.9 % and 17.5 % respectively in Guinea and Sahel. LLC Class-2 leads to mean attenuations of 49.1 % and 44.2 % in Guinea and Sahel respectively. In DJF, mean attenuations of 13.3 % and 32 % are experienced in Guinea for LLC Class-1 and Class-2 events respectively. In Sahel, the occurrence of LLC Class-1 events leads to a 16.3 % attenuation of incoming shortwave radiation.

By using the ERA5 cloud cover dataset in this study, ~~previously evaluated in Danso et al., (2019),~~ we have provided important information on daytime LLCs ~~which have not been studied~~ in WA – a region notably known for its lack of surface observations. Previous studies have mostly focused on nighttime LLCs in the southern part of WA and only during the WAM season. Here, we expanded to the Sahel region and investigated the occurrence of LLCs during the dry season as well. The study helps to identify some conditions such as the background moisture level which is known to contribute to LLC formation in the region. Again, this study also helps to provide an idea on the impacts of these clouds on the surface energy budget especially on the attenuation of incoming shortwave radiation during LLC occurrence. ~~horizontal moisture advection, turbulent upward motions, the convergence of air masses as well as surface heat transfer that occur in association with the occurrence of LLCs.~~ The results on the seasonal and diurnal distributions of LLCs as well as on that on the attenuation of incoming shortwave radiation during LLC occurrence could be useful when making feasibility studies for large-scale solar energy projects.

Appendix A: Vertical profiles of cloud hydrometeor content during LLC occurrence

~~**During DJF, positive anomalies of specific humidity (Fig. A1) are related to the formation of LLCs in Sahel (Class-1) and Guinea (Class-2). In both regions, the positive anomalies appear to be as a result of moisture influx from the North Atlantic Ocean aided by northwesterly wind anomalies. These positive moisture anomalies combined with the near-**~~

~~**surface processes such as turbulent upward motion due to surface heating and convergence of air masses play contribute significantly to the occurrence of LLCs during the dry season in both regions.**~~

The occurrence frequency of clouds may be defined based on the value of the cloud water content (liquid and ice) or the cloud fraction (CF). In this study, we defined the occurrence frequency of low-level clouds (LLC) based on the value of CF. LLC occurrence was first classified as Class-1 ($0 < CF \leq 0.5$) or Class-2 ($CF > 0.5$). In ERA5, CF can be larger than zero for zero liquid or ice water content. This is illustrated in Figure A1 which shows the vertical profiles of cloud water content during the occurrence of random LLC Class-1 and Class-2 events. It can be seen in some of the profiles (for Class-1) that the liquid and ice water content in the lowest 2km is null (but these events have $CF > 0$ in the lowest 2km in the profile).

Fig. A1 is also used to suggest the kind of cloud types that may be dominant in each class. In this case, we say that, in the Sahel region, there is a higher probability of getting a Mesoscale Convective System (MCS) in the LLC Class-2 than Class-1. Fig. A1 is the vertical profile of 12 random events of LLC Class-1 and Class-2 in the Sahel region. Based on the work of Storer and Van den Heever (2013), we designate an event as a 'MCS event' when there is a column containing at least 0.01 $g \cdot kg^{-1}$ cloud water (black dashed vertical line in Fig. A1) through a continuous depth of 8 km. From the twelve random profiles in Fig. A1, there are at least seven LLC Class-2 events (and just one for LLC Class-1) that satisfy this MCS definition. The number LLC Class-2 events are extremely low compared to LLC Class-1 (see Fig. 3), therefore, the likelihood that an event will be an MCS is relatively higher in the LLC Class-2 events.

Appendix B: Specific humidity associated with LLC occurrence and potential temperature before and after LLC formation

Figure B1 shows the composites of specific humidity (colours) and winds (vectors) during the occurrence of the different LLC occurrence classes in both Guinea and Sahel for the DJF season. During No LLC events, the moisture content in the region of the two windows is very low or zero. However, during LLC occurrence, the moisture content in the region is significant. This indicates that the background moisture plays an important role in the occurrence of these clouds. This result is confirmed in the recent study of Babic et al., (2019b) who found that in southern WA, the most distinct difference between LLC and No LLC events is in the specific humidity.

Figure B2 presents the composite vertical profile of the potential temperature for the hour before ($1h_{Before}\ LLC$) and after ($1h_{After}\ LLC$) the occurrence of LLC Class-2 in both regions for DJF and JAS. The profile is shown for the lowest 2 km of the atmosphere. There is no LLC Class-2 event in the Sahel during DJF, hence the empty plot. The profiles presented here suggest that before the LLC occurrence, there is a significant temperature decrease in the lower atmosphere. In the Guinea region, this is likely due to the well documented horizontal cold air advection from the Gulf of Guinea (Adler et al., 2019; Babic et al., 2019b) which leads to saturation of water vapour and consequent formation of LLCs. There could also be some cold air advection in the Sahel region, as suggested by Marsham et al., (2013). The temperature sharply increases after the disappearance of the LLC and this could be due to enhanced surface warming from incoming shortwave radiation (since attenuation of the incoming radiation is less in cloudless conditions).

Author contributions. DKD, SA, AD fixed the analysis framework. DKD carried out all calculations, produced the figures and wrote the first draft. KK and ATK contributed to the interpretation of the figures. All authors contributed to the analyses and to the ~~redaction~~editing of the first draft.

Competing interests. The authors declare that they have no conflict of interest.

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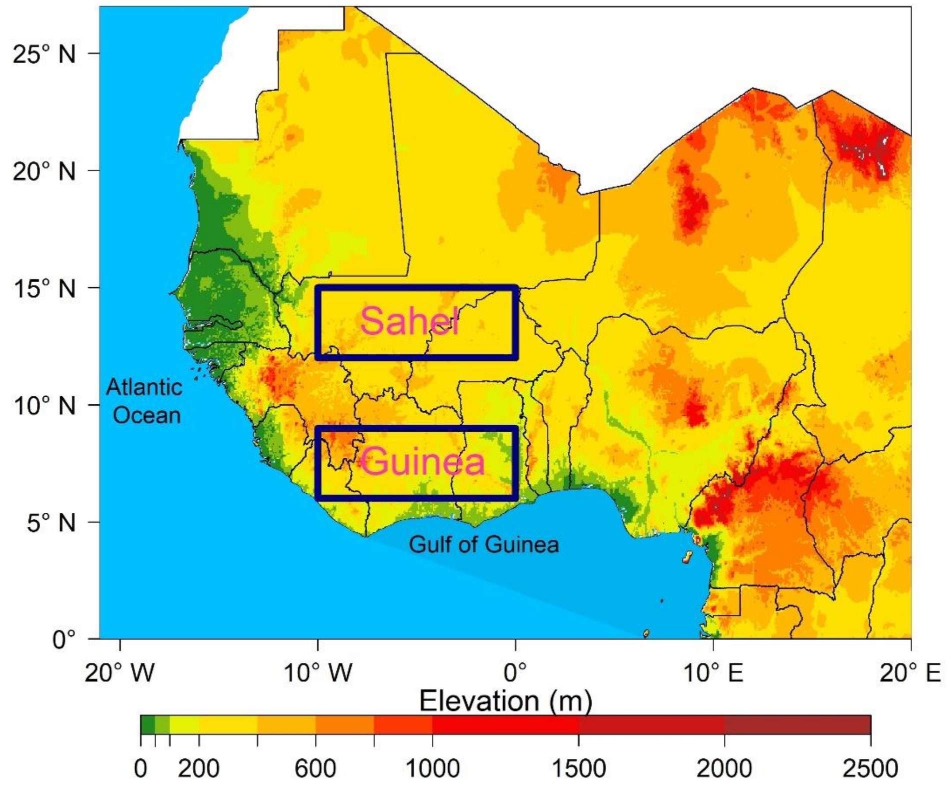


Figure 1: Map of West Africa showing the two selected windows (dark blue rectangles) used for identification of LLC events. The name denoted for each window is based on the climate zone of the window in the region.

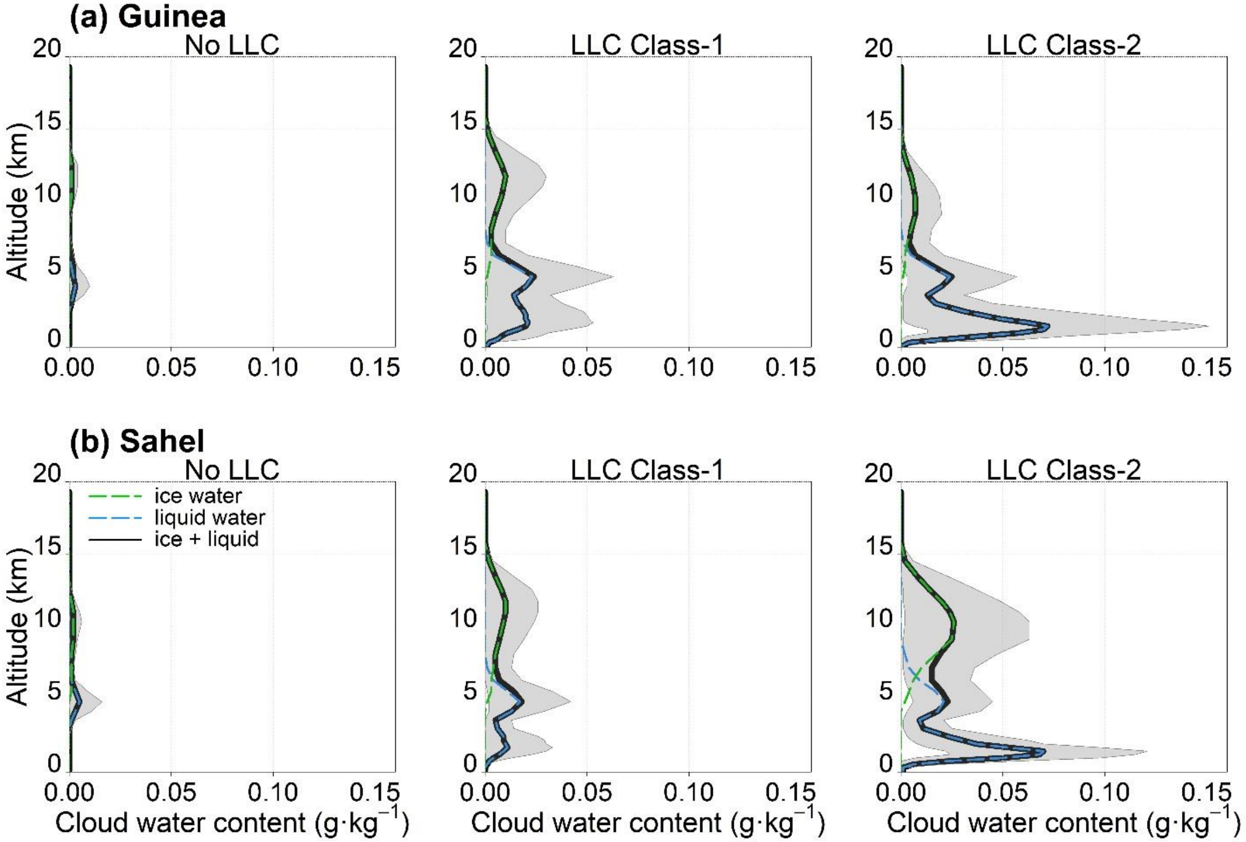
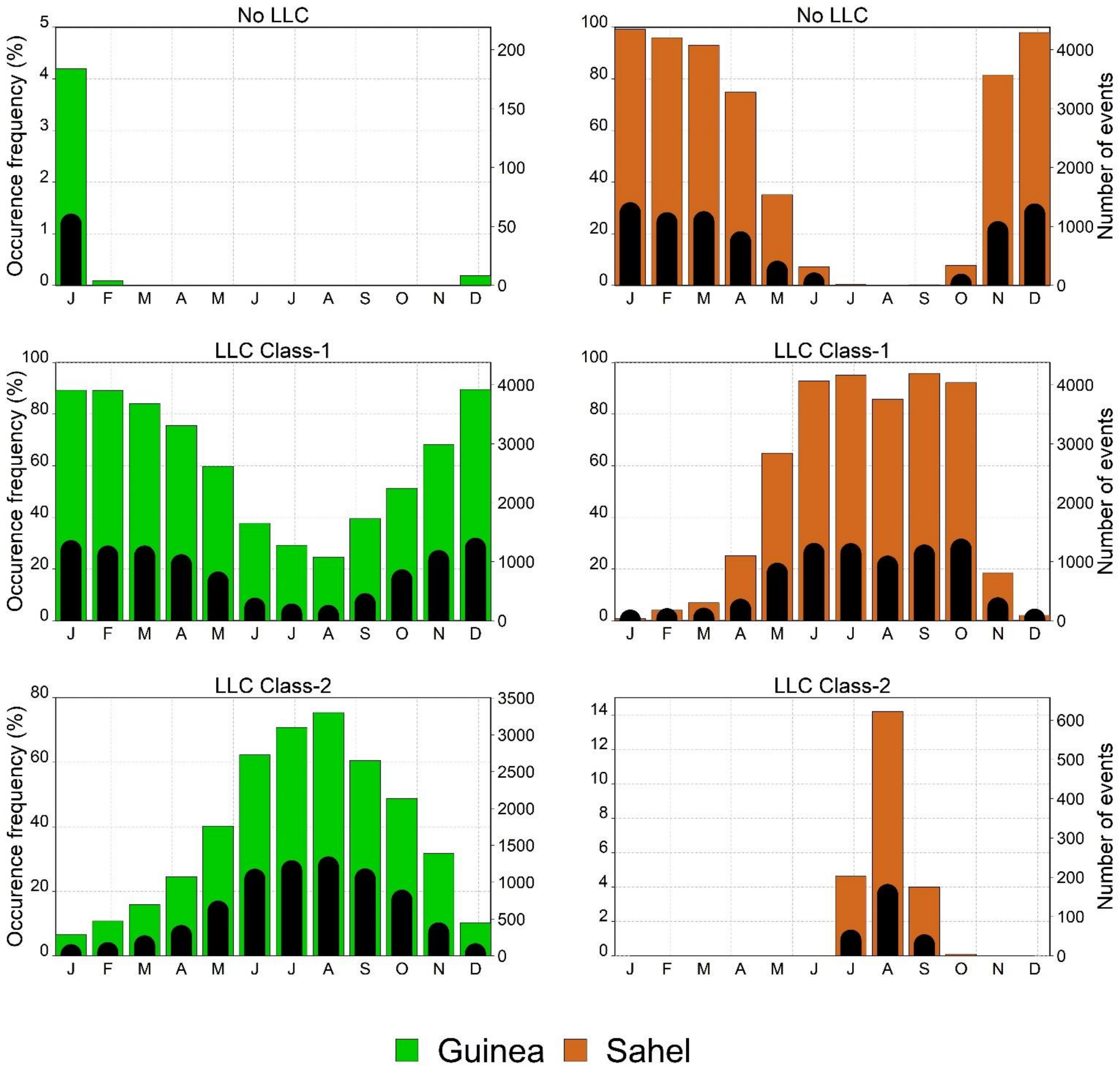


Figure 2: Mean vertical profiles of cloud water content (ice water (dotted green line), liquid water (dotted blue line), and total water content (black line)) during the occurrence of each LLC class in Guinea (top) and Sahel (below). Shaded areas refer to the 90th and 10th inter-percentile range.



770 **Figure 3: Monthly distribution of the occurrence frequency of hourly events for the three daytime LLC classes during the daytime in the Guinea (green bar) and Sahel (orange bar) regions defined in Fig. 1. The shorter black bars are the distribution of occurrences that last for at least six consecutive hours (the actual value has been multiplied by a factor or 4 to improve the legibility of the distribution).**

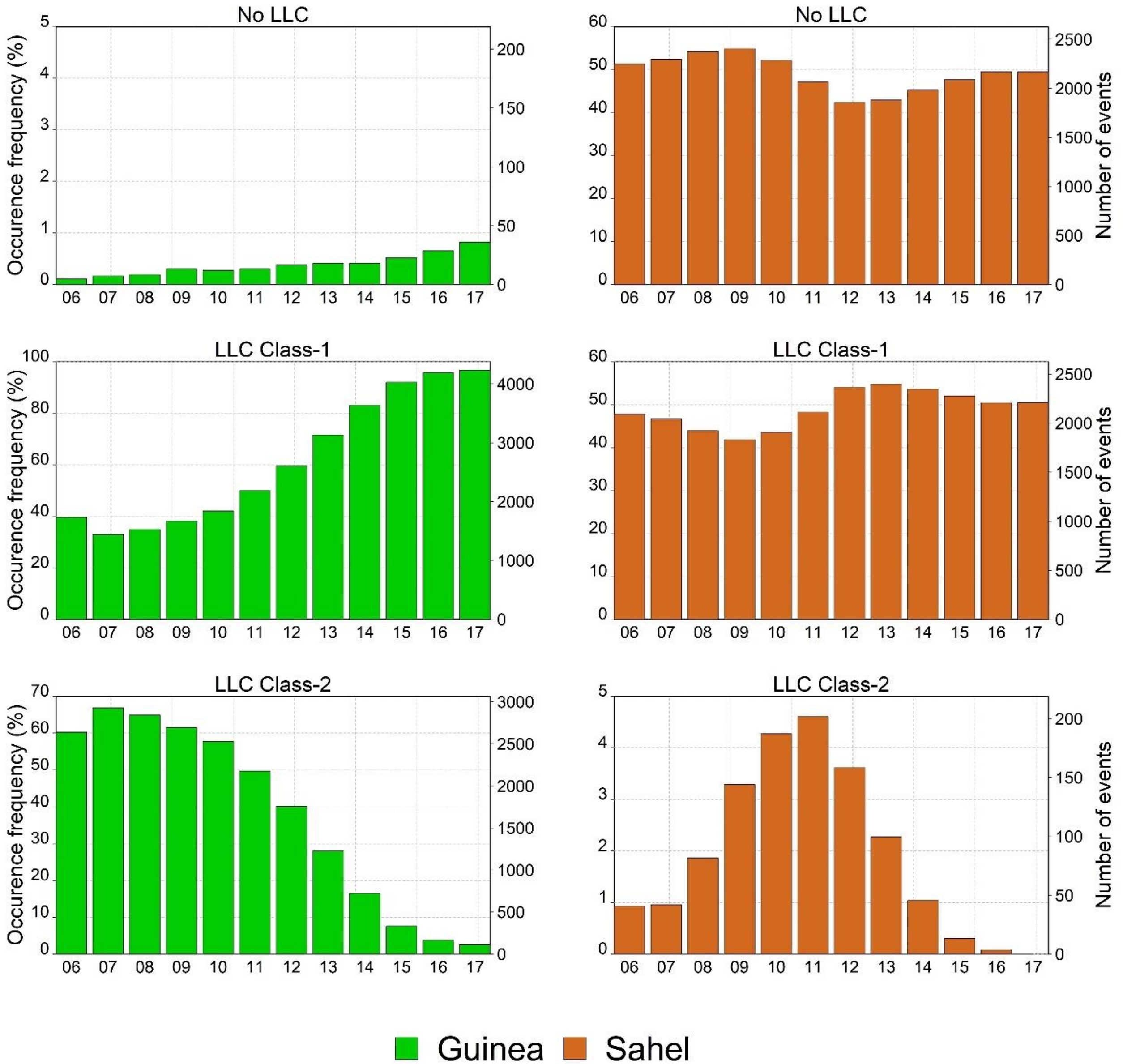
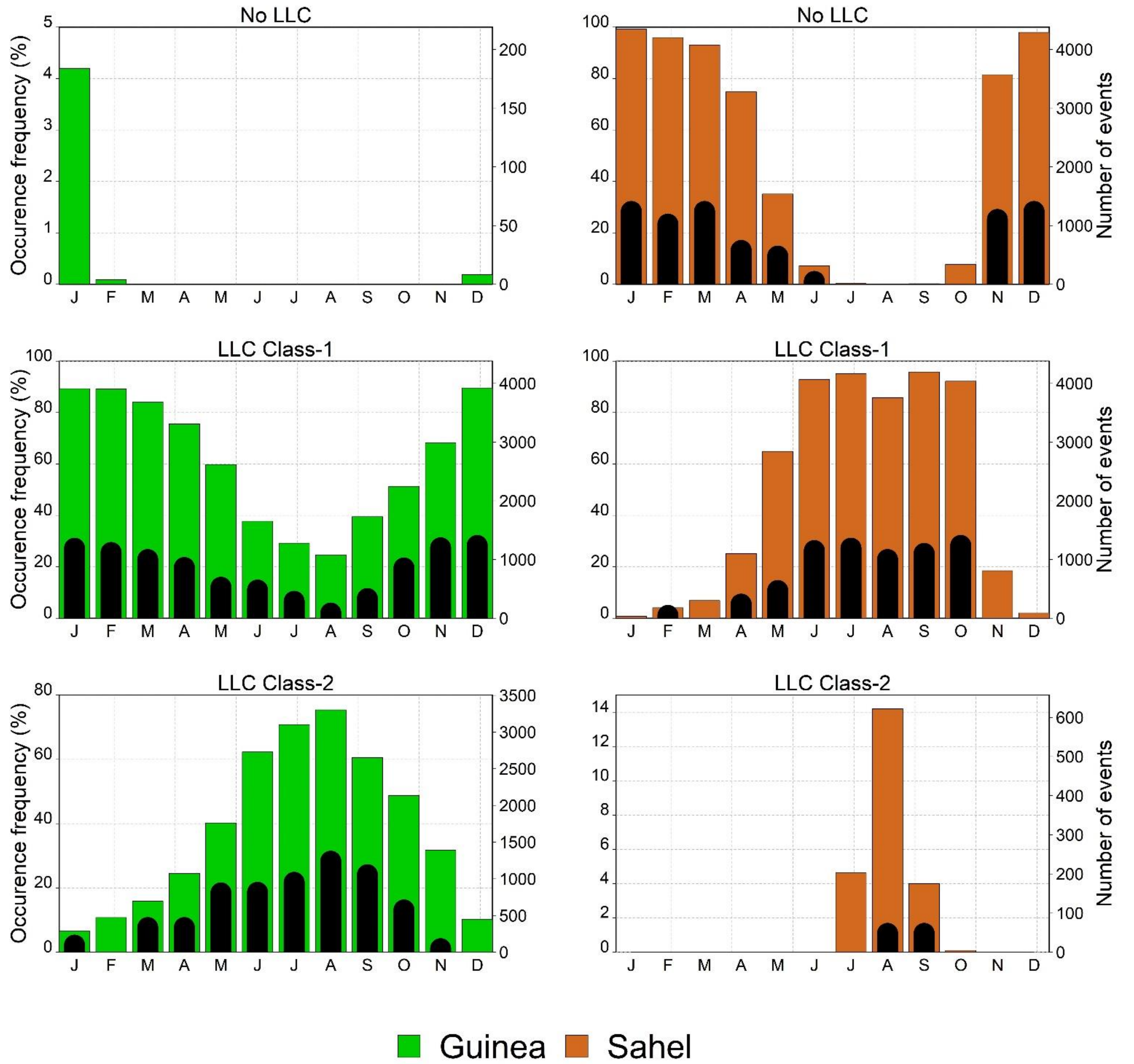


Figure 4~~3~~: Diurnal distribution of occurrence frequency of the three daytime LLC classes during the daytime in the Guinea and Sahel regions as defined in Fig. 1. All seasons are included in the distribution shown.



~~**Figure 4: Monthly distribution of the occurrence frequency of hourly events for the three daytime LLC classes during the daytime in the Guinea (green bar) and Sahel (orange bar) regions defined in Fig. 1. The shorter black bars are the distribution of occurrences that last for at least six consecutive hours (the actual value has been multiplied by a factor or 4 to improve the legibility of the distribution).**~~

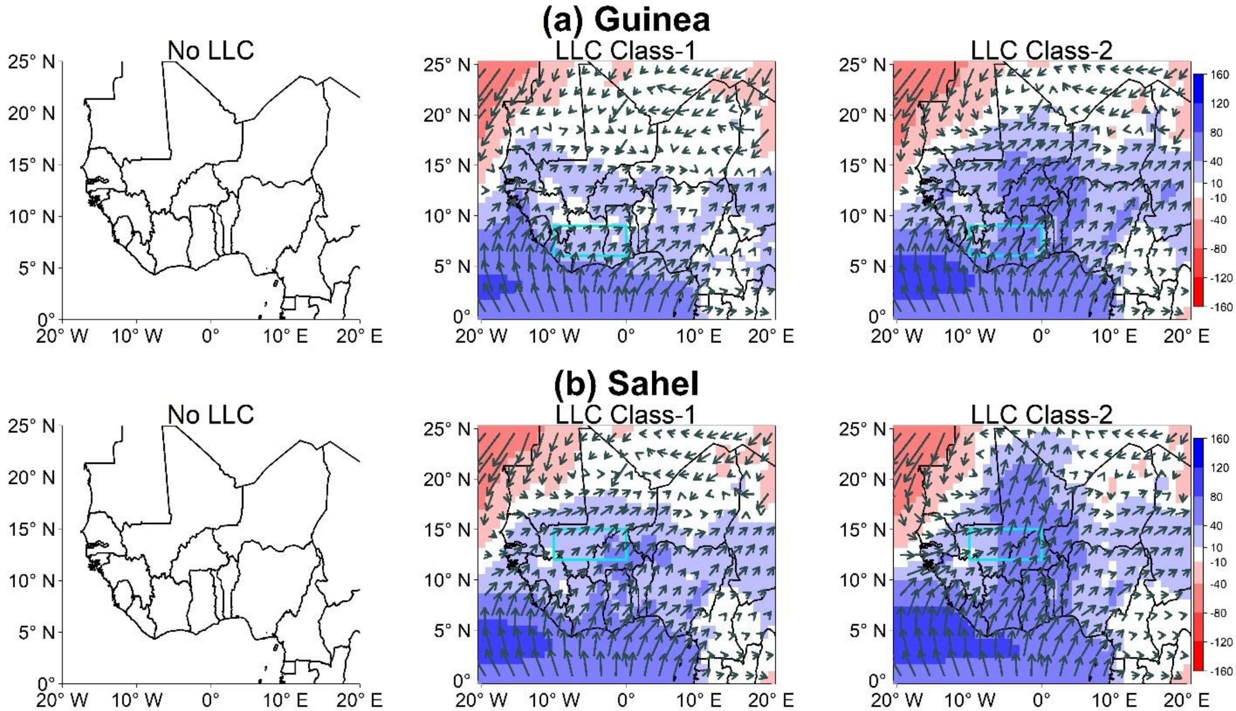


Figure 5: Composites of 950 hPa ~~horizontal advection of~~ moisture flux (colours, ~~Q_{adv} in~~ g·kg^{-1}·ms^{-1}) and wind (vectors, m s^{-1}) over WA for the three LLC occurrence classes in the Guinea (top) and Sahel (below) windows during JAS from 2006 to 2015. Only occurrences that last for at least six consecutive hours are considered. Wind vectors are averaged over 2 grid points in both the x and y directions. No event of the No LLC class has been extracted in the Guinea and Sahel regions during JAS, hence the empty plots.

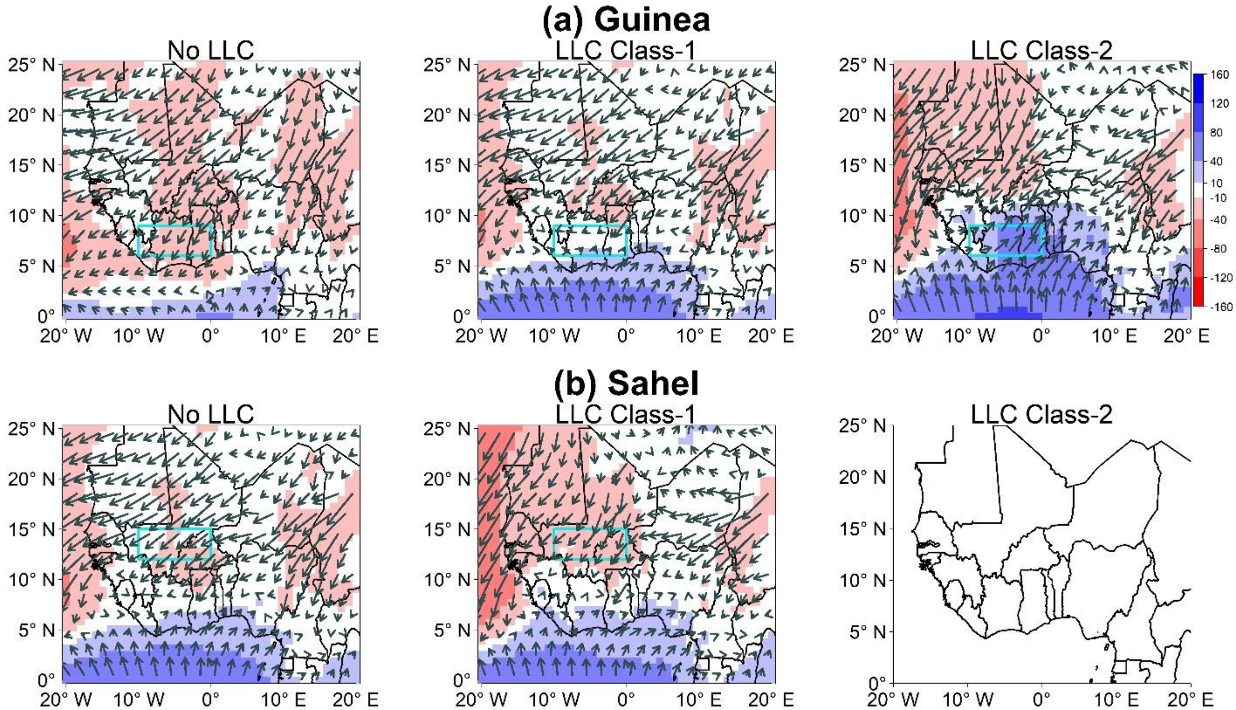


Figure 6: Same as Fig. 5 but for DJF. No event of LLC Class-2 has been extracted in the Sahel area during DJF, hence the empty plot.

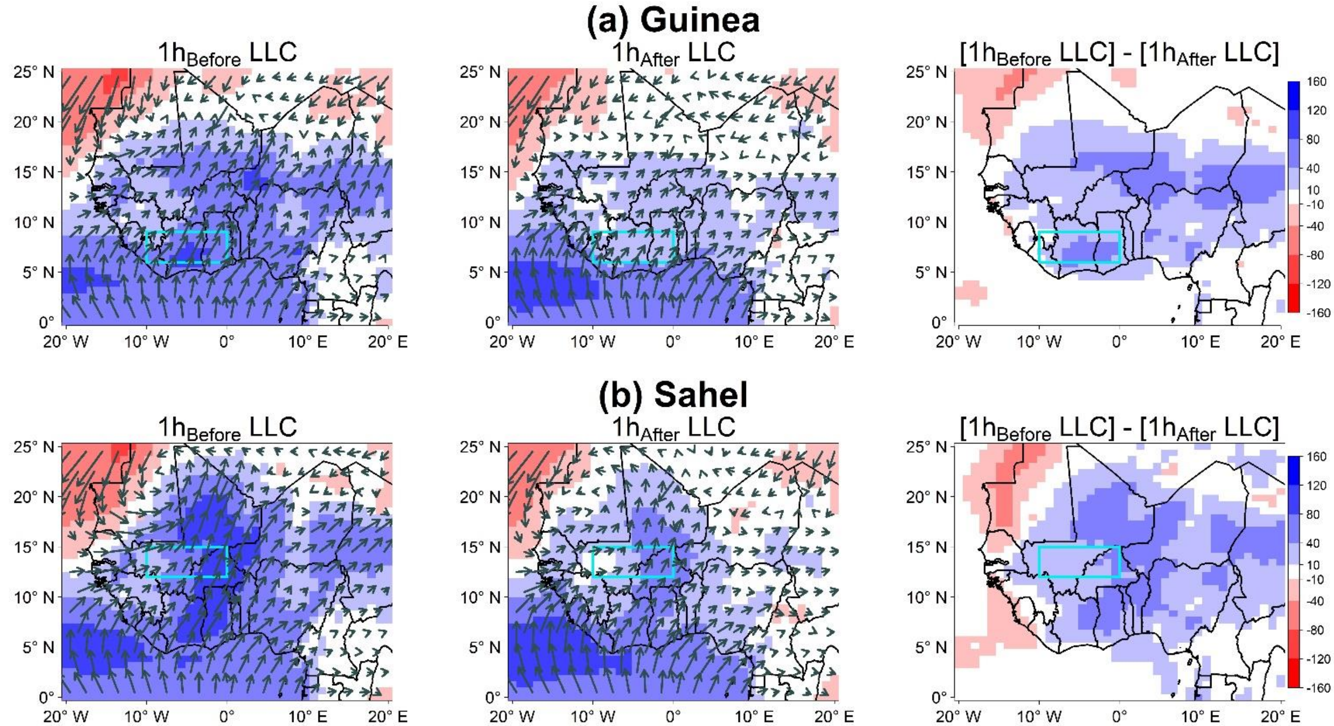
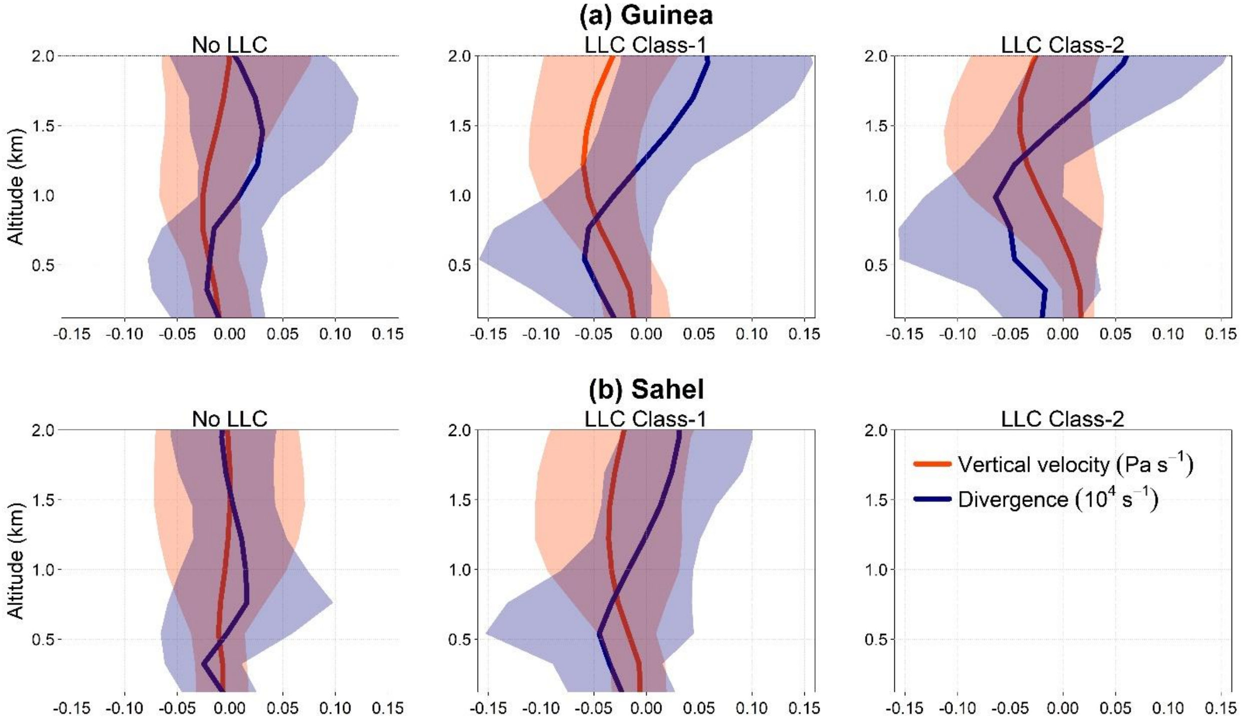


Figure 7: Composites of 950 hPa moisture flux (colours, g·kg^{-1}·ms^{-1}) and wind (vectors, m s^{-1}) over WA for the hour preceding LLC Class-2 occurrence ($1h_{Before}\ LLC$) and after it disappears ($1h_{After}\ LLC$) and the difference between the two periods during JAS from 2006 to 2015. Wind vectors are averaged over 2 grid points in both the x and y directions.



~~Figure 7: Composite mean vertical profiles (solid curves) of horizontal air divergence and vertical velocity from the surface to 2 km altitude in the Guinea (top) and Sahel (below) regions for the three LCC occurrence classes during DJF from 2006 to 2015. Divergence has been multiplied by 10^4 in order to have a similar scale as vertical velocity. Shaded areas refer to the 10^{th} and 90^{th} inter-percentile range. No event of LLC Class-2 has been extracted in the Sahel window during DJF, hence the empty plot.~~

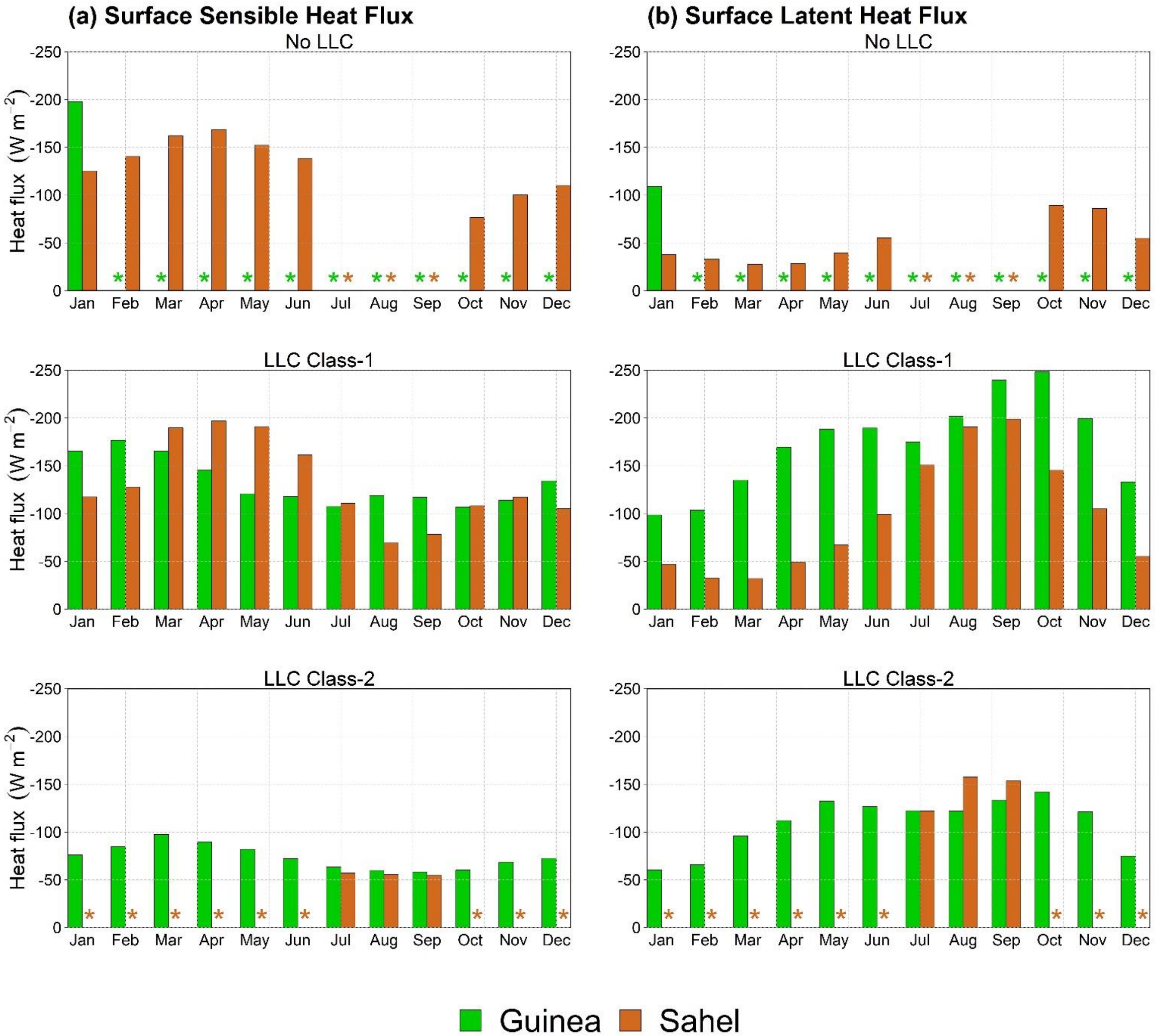
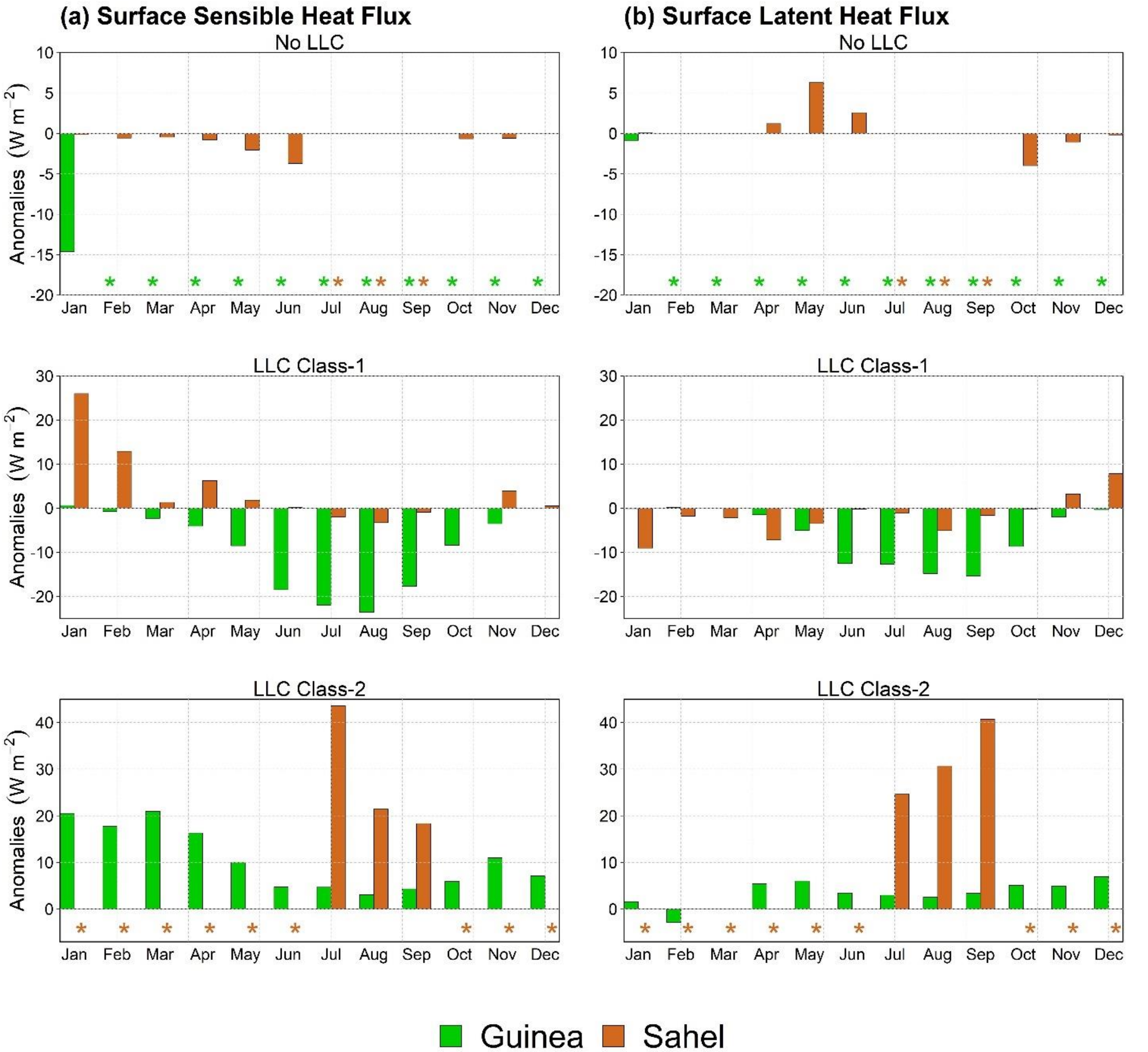
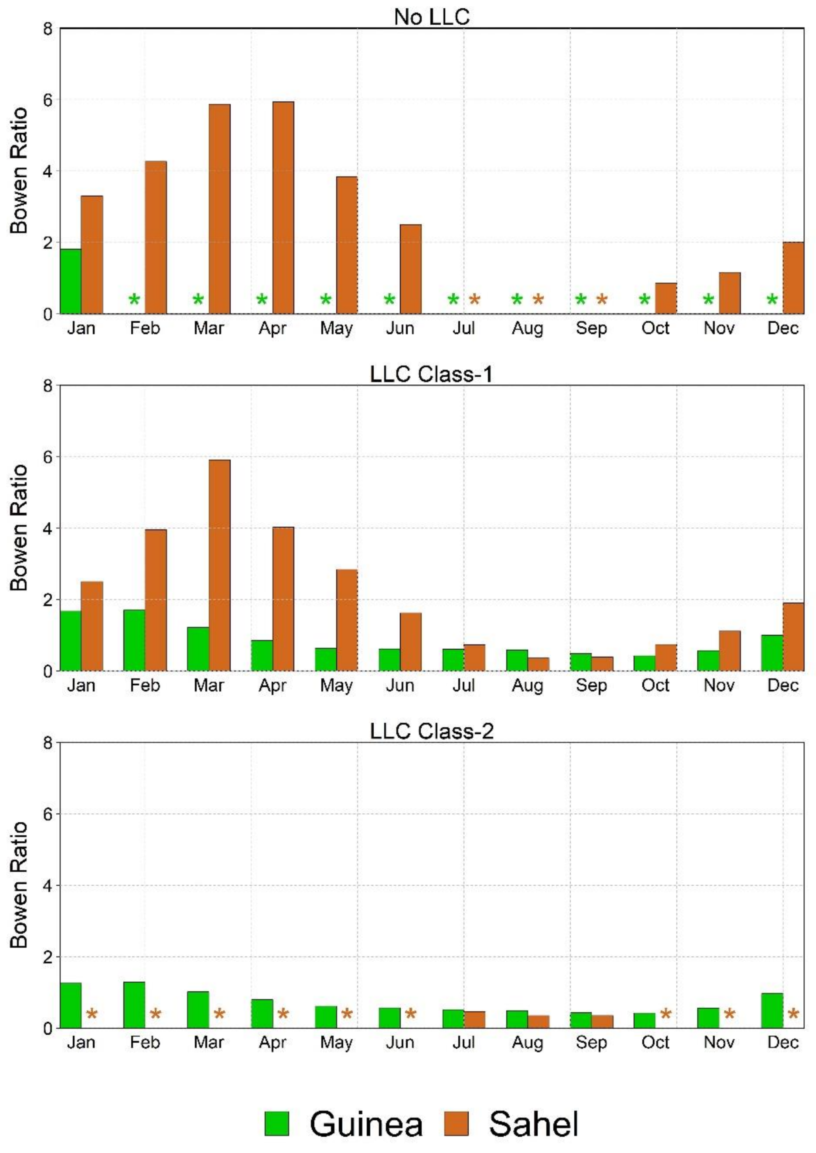


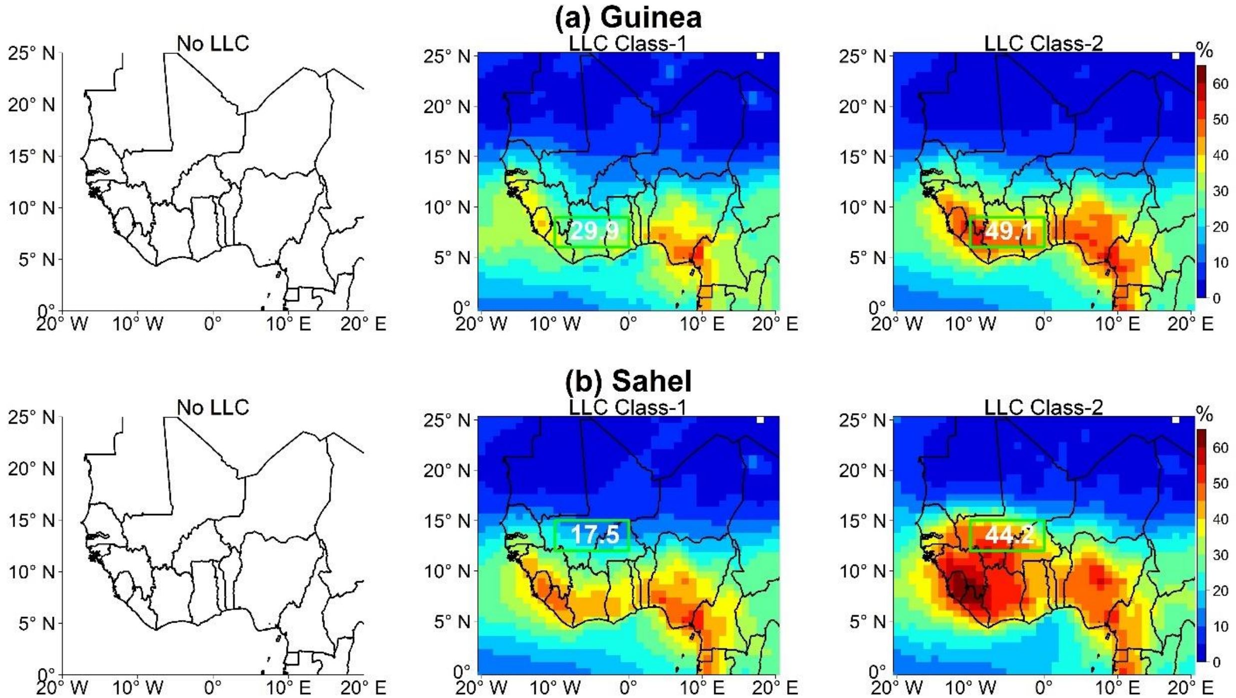
Figure 8: Monthly mean (a) surface sensible heat and (b) surface latent heat fluxes computed in the Guinea and Sahel regions during the occurrence of the three LLC classes from 2006 to 2015. The orange and green stars mean that there was no occurrence of the particular LLC class events in the region during that month, hence the composites were not computed. Only occurrences that last for at least six consecutive hours are considered.



[Figure 9:](#) Monthly mean anomalies of (a) surface sensible heat and (b) surface latent heat fluxes computed in the Guinea and Sahel regions for the occurrence of the three LLC classes from 2006 to 2015. The orange and green stars mean that there was no occurrence of the particular LLC class events in the region during that month, hence the composites were not computed. Only occurrences that last for at least six consecutive hours are considered.



~~**Figure 9: Monthly mean Bowen Ratio computed in the Guinea and Sahel areas for the occurrence of the three LLC classes from 2006 to 2015. The orange and green stars mean that there were no occurrences of the particular LLC class in the region during that month, hence the composites were not computed. Only occurrences that last for at least six consecutive hours are considered.**~~



825 **Figure 10: Mean attenuation of incoming downwelling shortwave radiation (%) during JAS from 2006 to 2015 over WA for occurrence of the three LLC classes in the Guinea (top) and Sahel (below) regions. Only occurrences that last for at least six consecutive hours are considered. Numbers in the box refer to the mean percentage attenuation of incoming shortwave radiation in that specific area. No event of the No LLC class has been extracted in the Guinea and Sahel regions during JAS, hence the empty plots.**

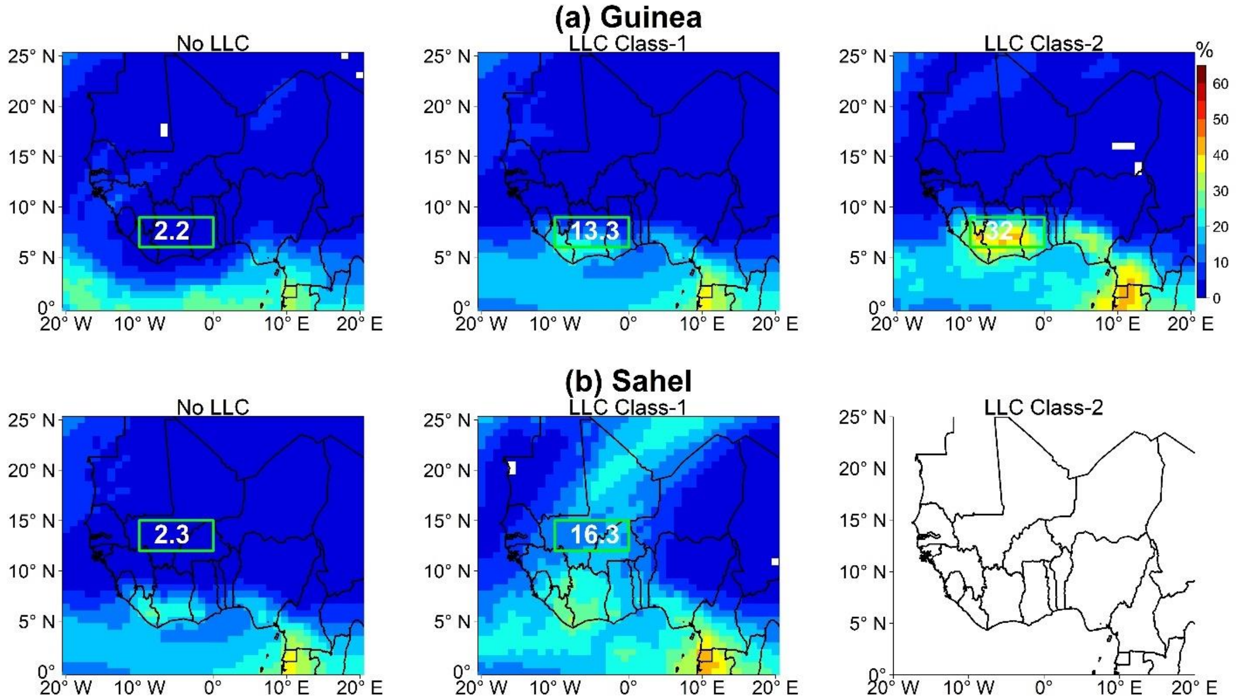


Figure 11: Same as Fig. 10 but for DJF. No event of LLC Class-2 has been extracted in the Sahel region during DJF, hence the empty plot.

Table 1: Definitions of the three classes of LLC occurrence based on cloud fraction.

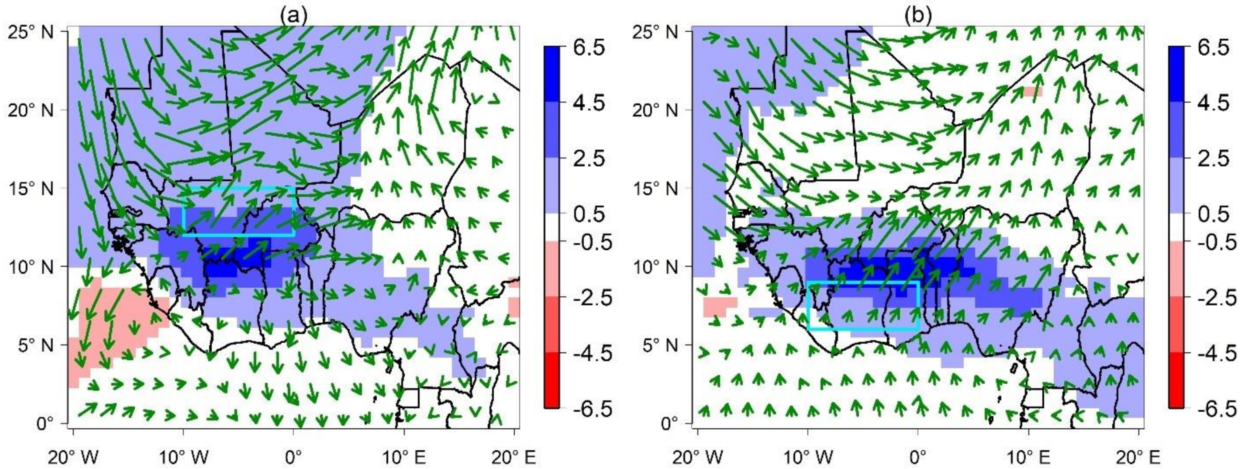
Class of LLC occurrence	**Description**
No LLC	$CF = 0$
Class-1	$0 < CF \leq 0.5$
Class-2	$CF > 0.5$

~~**Table 2: Number of events found for the occurrence of the three LLC classes in JAS and DJF. Composite analysis is performed based on these events for each class and season.**~~

	~~JAS~~		~~DJF~~	
	~~**Guinea**~~	~~**Sahel**~~	~~**Guinea**~~	~~**Sahel**~~
~~Number of No LLC events~~	~~**0**~~	~~**0**~~	~~**0**~~	~~**876**~~
~~Number of LLC Class-1 events~~	~~**178**~~	~~**824**~~	~~**888**~~	~~**12**~~
~~Number of LLC Class-2 events~~	~~**812**~~	~~**24**~~	~~**178**~~	~~**0**~~
~~Total number of hours in season~~	~~**11040**~~		~~**10800**~~	

Table 2: Number of events found for the occurrence of the three LLC classes in JAS and DJF. Composite analysis is performed based on these events for each class and season. For the study period, the total number of daytime hours are 11040 and 10800 in JAS and DJF respectively.

	JAS		**DJF**	
	Guinea	**Sahel**	**Guinea**	**Sahel**
Number of No LLC events	0	0	13	877
Number of LLC Class-1 events	122	793	878	16
Number of LLC Class-2 events	852	56	22	0
Total number of hours in season	11040		10800	



~~Figure A1: Composite of anomalies of specific humidity (colours) and wind direction (vectors) for LLC Class-1 in Sahel and LLC Class-2 in Guinea during DJF. Only occurrences that last for at least six consecutive hours are considered. These positive anomalies of moisture in both the Sahel (a) and Guinea (b) regions, seem to help in the formation of clouds during DJF.~~

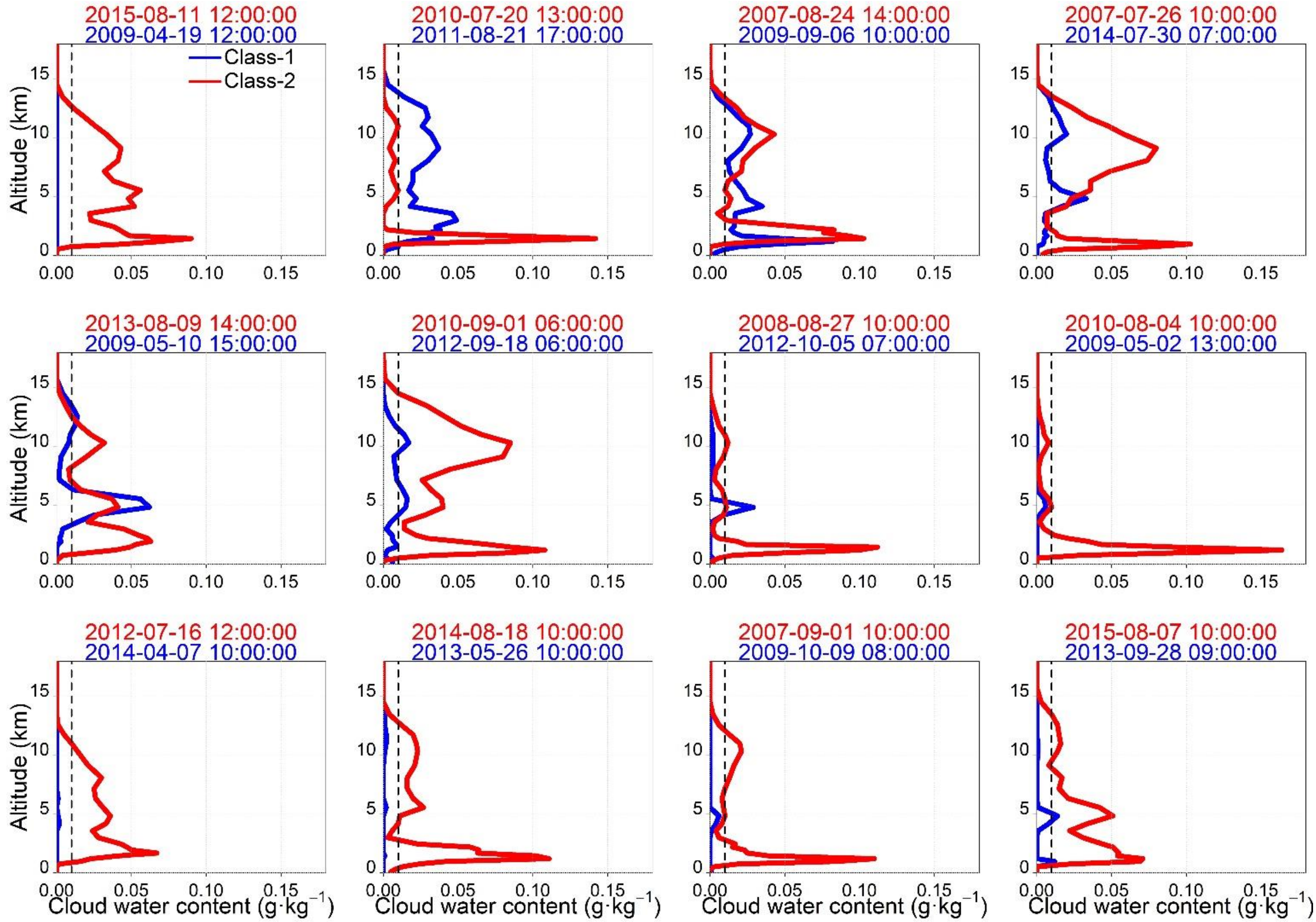


Figure A1: Vertical profiles of cloud hydrometeor content (liquid and ice water) during the occurrence of LLC Class-1 and Class-2 events in the Sahel region. These events are randomly chosen. The timestamps at the top of each plot are the times for those LLC events. The black dashed vertical line shows the threshold for deep convective clouds as defined by Storer and Van den Heever (2013).

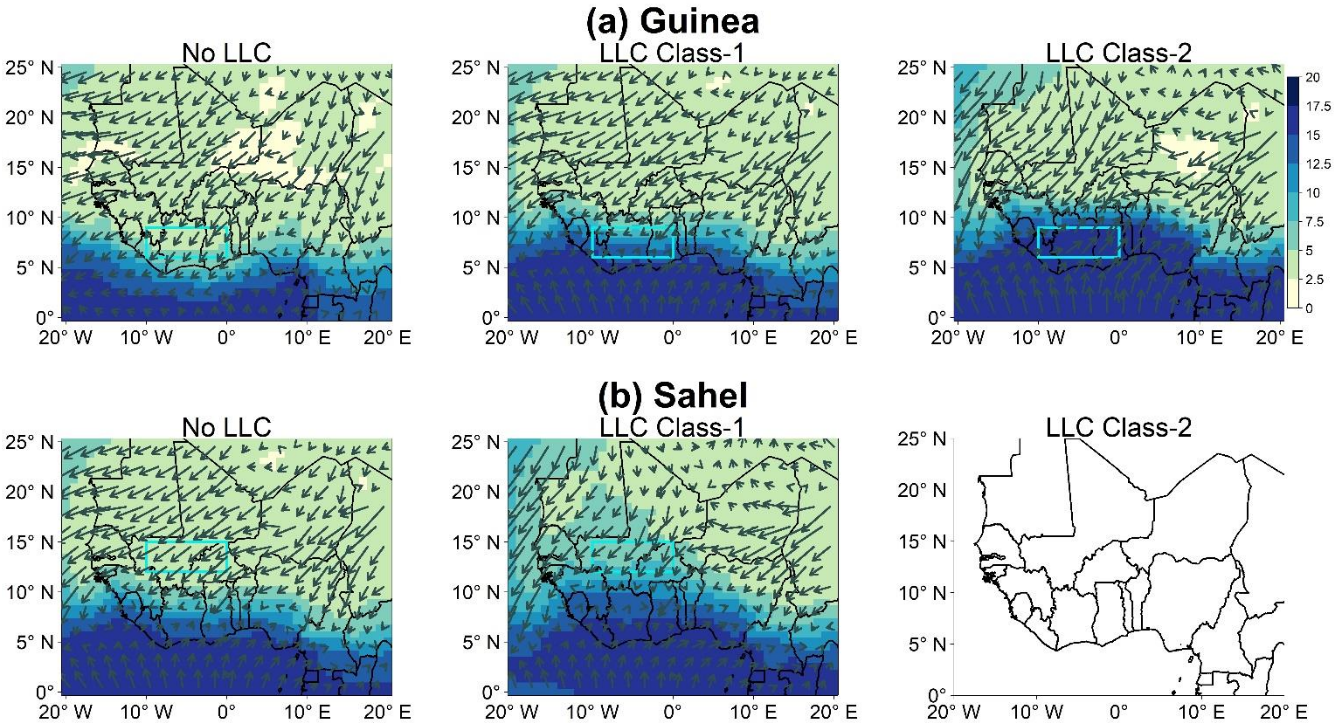


Figure B1: Composites of 950 hPa specific humidity (colours, g·kg^{-1}) and wind (vectors, m s^{-1}) over WA for the three LLC occurrence classes in the Guinea (top) and Sahel (below) windows during DJF from 2006 to 2015. Only occurrences that last for at least six consecutive hours are considered. Wind vectors are averaged over 2 grid points in both the x and y directions. No event of LLC Class-2 has been extracted in the Sahel area during DJF, hence the empty plot.

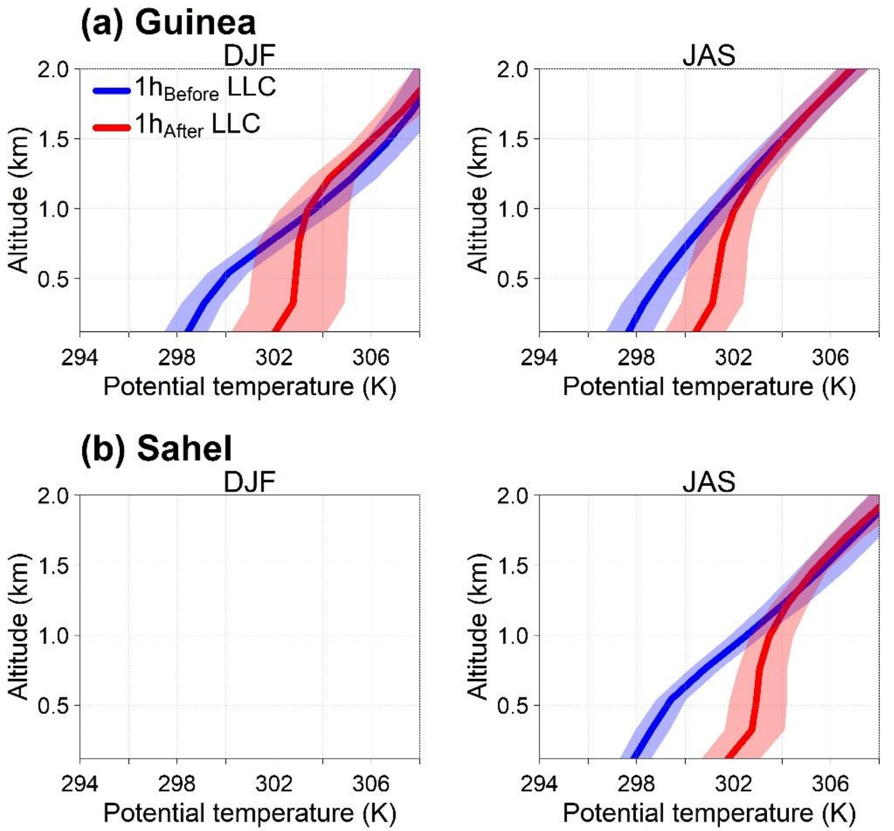


Figure B2: Vertical profile of the mean potential temperature (solid line) for the lowest 2 km of the atmosphere, computed in Guinea and Sahel for all the 'one-hours' preceding LLC Class-2 occurrence and all the 'one-hours' after its disappearance. The shaded regions represent the 10th and 90th interpercentile range. No event of LLC Class-2 has been extracted in the Sahel area during DJF, hence the empty plot.