Referee #1

Review report

The authors investigate the connection between meteorological parameters and the morphology of low-level clouds in two regions: a portion of the Southern Ocean and the North Pacific. To identify three morphological classes (i.e., “closen”, “open”, and “other”) the authors apply a neural network that was prepared in a previous publication (Lang et al., 2022) to radiance fields from the geostationary HIMAWARI satellite. The article documents the cooccurrence of class frequency with average estimated inversion strength (EIS) and a marine cold-air outbreak index, M, mainly finding that closed cells are connected to greater EIS.

The article contributes to a topic that is of great relevance to the climate community. The authors importantly leverage imagery from a geostationary platform to identify cloud morphology on a great temporal resolution – a scientific advancement that was achieved in Lang et al. (2022). With respect to the previous paper, the present article falls short of making a substantial contribution. Below, I’m outlining major issues that lead me to recommend a rejection but encourage a resubmission in improved form. In a nutshell, the authors should (1) include statistics from the class “other”, (2) quantify their results, (3) contextualize the selected meteorology parameters and possibly widen the parameter space, and (4) inspect EIS throughout the text, table, and figures.

Major issues

(1) The classification resulted in peak frequencies of ~20% for “open cells” and ~15% for “closed cells”, leaving at least ~65% of the samples classified as “other”. The authors explain that “other” constitute cases of mid- and high-level clouds, but also low-level clouds that were different enough from the first two classes (ll. 94-96). Figure 1 shows a classification example in which apparent open cellular cloud decks (e.g., ~35degN, ~160degE) were classified neither as “open” nor as “closed” (leading me to believe they were joined “other” which is not shown here). Given that “other” makes up the bulk of the samples and that the nature of these samples is unknown to the reader, the authors need to (1) provide information on them, showing, for example, statistics of cloud-top height, cloud fraction, and cloud optical depth of “other” compared to “open” and “closed” and (2) include “other” where currently only “closed” and “open” is shown. Both aspects will become highly relevant for the diurnal cycle that shows a decrease of “closed” in the afternoon but no increase of “open” at the same time, leading to believe that the class “other” increased in the afternoon and begging the question why that is (e.g., truly a transition from “closed” to “disorganized” or an increase in local cirrus cloud fraction?).

R: Thank you for your comment. We acknowledge the importance of analyzing low-level clouds within the category "Other". However, it is important to note that in our study this category indeed encompasses a diverse range of covers, including not only other types of clouds but also land or ocean covers as seen from Himawari-8. As we discussed in Lang et al. (2022), one of the limitations of our study is that we did not include other low-level cloud types, such as disorganized MCC and no MCC clouds. To address this limitation and improve our Convolutional Neural Network (CNN), we plan to incorporate more training samples from both regions to include these additional categories.

Regarding the classification of open MCCs in Figure 1, in Lang et al. (2022), we openly acknowledged the uncertainties associated with using a CCN technique in the separation of disorganized and open MCCs. This uncertainty was also reported by Yuan et al. (2020). We understand the significance of refining the classification methods, and we appreciate your valuable input, which has been taken into account for future improvements in our research.

On the other hand, the Japan Aerospace Exploration Agency (JAXA) provides Himawari-8 cloud products such as cloud-top height and cloud optical thickness. However, these data are not available during nighttime. Therefore, in our first version of the manuscript, we made the decision not to use these products to calculate statistics related to the three categories since we lacked continuous access to the products 24 hours a day. This limitation of the Himawari-8 cloud products hinders the estimation and analysis of the diurnal cycle for the category “Others”. Nonetheless, we have addressed this limitation by extending our analysis to include the low-level clouds within the category "Others" and comparing them with the open and closed MCC categories using the Himawari-8 cloud products. To define the low-level clouds in the category "Others," we applied a filter considering only the diurnal clouds product, identifying clouds below 3.5 km, and selecting daytime open and closed MCC. The results of this analysis are presented in Section 3.4, where we examine and compare the characteristics of these low-level clouds with open and closed MCC. Additionally, we provide statistics of the cloud products available on the JAXA server for the three categories. This additional analysis allows for a more comprehensive understanding of the low-level cloud characteristics in the "Others" category and their relationship with open and closed MCC.

(2) The authors compare class frequency and meteorological fields and often speak of “correlation” (e.g., ll. 161-164, l. 194, ll. 254-255) or even “high correlation” (ll. 267-268) when visually comparing maps. However, there is no actual calculation of correlation. The paper would benefit from a more quantitative rather than qualitative analysis. Given the great temporal resolution, the authors could not only compare seasonally averaged maps but actually compute correlation on a pixel-by-pixel basis using the native 10-min resolution.

R: We thank you for this comment – we agree. In the revised manuscript, we have calculated correlation maps (new Figure 4) to ensure consistency in assessing the correlation between both categories of MCC and the meteorological indices *M* and EIS. We have also extended our analysis to include correlation maps for near-surface wind speed and sea surface temperature (SST). These correlation maps provide a quantitative analysis of the associations between monthly MCC cloud frequency and monthly averages of *M* index, EIS, SST, and near-surface wind speed in both study regions. The correlations were computed using the monthly mean MCC cloud frequencies in each grid box, and they demonstrate statistical significance at a 95% confidence level for a 36-point correlation. Based on this correlation analysis, we have diligently revised the manuscript to include the quantitative analysis in all sections and paragraphs as suggested by the referee. The inclusion of these correlation maps has provided us with deeper insights into the relationships between the meteorological variables and both open and closed MCC cloud types, thereby enhancing our understanding of their spatial patterns and behavior. We believe that these additional analyses strengthen the validity and significance of our findings, and we are grateful for the referee's valuable input in improving the quality of our research.

(3) The authors selected EIS and the M index as meteorological parameters, and it is unclear why they selected these two and why the analysis excludes other parameters. For example, near-surface wind speed was recently connected to cloud morphological transitions in Eastman et al. (2023). Also, the authors examine the diurnal cycle of class frequency but leave out diurnal cycles of meteorological parameters that were used for the seasonal analysis a few pages before.

R: The selection of both meteorological indices is well-founded on previous studies where the relationship of these indices with MCC clouds has been demonstrated. However, in response to the referee's suggestion, we have performed an additional analysis of near-surface wind speed and its relationship with both open and closed MCC cloud types as shown by the correlation maps in Figure 4 in the revised manuscript. By including this new analysis, we aim to provide a more comprehensive examination of the factors influencing the spatial patterns and behavior of both MCC clouds, thereby enriching the overall findings of our study. We are appreciative of the referee's valuable input, which has led to further improvement and robustness of our research.

To address the absence of the diurnal cycle for the meteorological parameters in our study, we have now included the diurnal cycle of the four variables considered in the correlation maps (*M* index, EIS, SST, and near-surface wind speed) in the Supplementary Materials. These results indicate that no distinct signal or consistent pattern was observed throughout the cycle.

(4) The authors equate EIS with static stability in this paper (e.g., l. 11, 164), even though it was introduced as an indicator of which (ll. 110-111). Given that sea-surface temperature can exceed lower-tropospheric air temperature (giving positive M but possibly negative LTS), EIS can become negative, as the authors show in Figure 4. The authors should explain what a negative EIS means and whether EIS still holds as an indicator of static stability in cold-air outbreak conditions. In addition to revising EIS language, there seem to be inconsistencies across Figure 4, Figure 2, and Table 1: Figure 4 shows mostly negative EIS, yet in Figure 2 and Table 1 EIS is shown to be positive. The authors need to explain why that is (e.g., do composites in Figure 2 and statistics in Table 1 cover different time frames compared to Figure 4?).

R: Thank you for your insightful comment. In our revised manuscript, we have provided further clarification: while EIS is indeed an indicator of static stability, it should not be considered equivalent to it. We appreciate your bringing this to our attention.

Negative EIS can indeed occur when the SST exceeds the lower-tropospheric air temperature. This typically suggests a condition of atmospheric instability, where the temperature profile of the atmosphere does not inhibit vertical movement of air parcels. In such cases, EIS could become a less reliable indicator of static stability. It is been previously established by McCoy et al., (2017) that the development of open MCC clouds can be driven by two primary factors: enhanced surface forcing, stemming from the contrast between warmer ocean and cooler air temperatures (signified by a positive *M* index), and static instability, indicated by negative EIS values. In the revised version of our manuscript, we have elaborated on the conditions associated with a positive *M* index and negative EIS, as depicted in Figure 4 (now referred to as Figure 5).

Regarding the inconsistencies mentioned, we have double-checked our calculations. Figure 2 shows the mean values that are independent of the location of MCC clouds and cover the entire area, as defined in Section 2.3 (between 60°N-60°S and 80°E-160°W). In contrast, Figure 4 and Table 1 were calculated using a filter based on the location of open and closed MCC clouds for each time step from 2016 to 2018. We can confirm that both Figure 4 (new Figure 5) and Table 1 utilize the same data to compute the EIS values, and the results are presented as such. For further clarity, we have appended text to the captions of Figure 4 (new Figure 5) and 6 (new Figure 7). This addition to the captions and Table 1 explains that both the EIS and *M* indices were determined using a filter derived from the MCC cloud locations and times, identified for each region.

Minor issues

ll. 10-11 This sentence is hard to understand. Please rephrase.

R: We have rewritten the sentence in the abstract to explain the difference in behavior between closed and open MCC clouds.

ll. 23-26 Please also cite a recent paper by McCoy et al., (2023).

R: This is a great suggestion. We have added McCoy et al., (2023) as reference in the examples of closed MCC clouds over the SO.

ll. 26-27 This sentence seems out of context.

R: Thank you noticing this sentence. We have removed this sentence in the revised manuscript.

ll. 95 Please clarify whether low-level clouds can be categorized as “other”.

R: Thank you for this suggestion. We have indicated that the category called “Other” is used for all other coverage, including mid- and high-level clouds, as well as other types of low-level cloud types such no MCC, disorganized MCC clouds, and even clear skies. In addition, the analysis of a subcategory, which considers low-level clouds within the category “Other” is presented in Section 3.4.

Fig. 1 “Other” is included in the legend, but not shown in the map. Perhaps selected a color different from white.

R: The category “Other” encompasses all cover types other than open and closed MCC clouds, including oceans and land. To simplify the representation of the two main categories examined in this study, open and closed MCC, we have excluded the “Other” category from the legend.

Fig. 1 Please label the size of each box or add a reference bar to show distance.

R: Thank for this good idea. We have included the size of each box within the green squares in the caption of Figure 1.

Fig. 2 Please change label from “delta T (K)” to “EIS (K)”.

R: Suggested revision made.

ll. 131ff. Would NP have great M values even when the Kuroshio current was absent? Also please quantify SST gradient.

R: The Kuroshio Current brings warm water from the tropics, so its absence or weakening can lead to a decrease in SST along the NP (Wang et al. 2022). Following the definition of the *M* index in equation (2), at a lower SST, the values of the *M* will decrease.

We have added a figure of the SST gradient as a Figure S1 in Supplementary Material.

ll. 141-142 To follow this sentence, please explain how cloud cover is related to both classes.

R: Thank you for this comment. We agree that the sentence was unclear. To clarify, we have added a sentence to explain that we performed visual inspections of several cases and time periods to confirm that our algorithm is capable of accurately classifying open and closed MCC clouds over the NP.

l. 145 Please substitute “total time” by “total number of observations”.

R: Suggested revision made.

Fig. 3 Please mark maximum frequency to complement the text.

R: Suggested revision made.

Fig. 3 Please draw Kuroshio current in here.

R: Suggested revision made. We have added the Kuroshio current location to Figure 3.

ll. 150-151 (and also ll. 154-155 and ll. 174-175) It is unclear which class is referred to in this sentence.

R: We thank you for this comment. We have reorganized the paragraph to clarify the frequencies of occurrence and characteristics of both open and closed MCC categories.

l. 157 Please substitute “to the top” with “near the top”.

R: Suggested revision made.

l. 160 Please substitute “SST gradient” with “average SST”.

R: Suggested revision made.

l. 163 Please finish sentence; “as highly … as” is missing an object.

R: Thanks for noticing this error. We have corrected this sentence in the revised manuscript.

l. 164 Please refer to EIS as an indicator of static stability rather than equating both (see above major points).

R: Thank you for this suggestion. We have modified the revised manuscript to refer separately to the concepts of EIS and static stability in the correct sense.

ll. 159-175 Please provide correlation maps (see above major points).

R: We have provided correlations maps (Figure 4) in the revised manuscript according to the point 2 of major issues.

l. 167 Please change “44” to “4”.

R: Suggested revision made.

ll. 171-172 Please check for redundancy is both sentences.

R: We have rewritten both sentences to clarify that closed MCC clouds are linked to larger EIS values compared to open MCC clouds, which is consistent with the correlation maps of the revised manuscript.

ll. 181-183 Does this mean the portion of “other” has increased?

R: Taking into account the definition of the category “Other”, when the frequency of occurrence of open and closed MCC types reduces during the summer, it leads to a corresponding increase in the proportion of the category “Other” for this season. This relationship can be attributed to the fact that the category “Other” encompasses all coverage types apart from Open and Closed MCCs, causing its relative representation to grow as the frequencies of the specific MCC types decline during the summer months.

ll. 196-198 Please elaborate – currently unclear how land masses explain seasonality.

R: Thanks for noticing this. What we suggested is that the differences for the same season, either winter or summer, between the SO and NP regions can be as well attributed to the contrasting land mass surfaces between both hemispheres. We have rephrased this idea in the revised manuscript.

ll. 196-201 Perhaps a sketch or cartoon image would be useful here to illustrate the point.

R: While we appreciate the suggestion, we believe that a sketch or cartoon image might not be the most effective approach to illustrate the point. Instead, we have incorporated the seasonal variation of the SST gradient and reworded the sentence for clarity. This, combined with the correlation maps, should enhance the clarity of the study. Such analyses provide a more robust and detailed understanding of the spatial patterns and behaviors of the MCC cloud types during both summer and winter seasons.

ll. 200-201 Please rephrase. Currently hard to follow. Substitute "that" with "than".

R: We thank you for this comment. We have rewritten the paragraph to explain the characteristics of open and closed MCC distributions during wintertime.

ll. 199-200 Are lower SST connected to a greater frequency of open MCCs?

R: Based on the correlation maps presented in the revised manuscript, high frequency of open MCC clouds is not directly linked to lower SST values. While higher latitudes show stronger correlation coefficients, the frequency of open MCC clouds is actually lower in these regions. However, an important finding is the strong correlation between the frequency of open MCC clouds and the *M* index, which includes the difference between SST and air temperature. This observation suggests that the occurrence of open MCC clouds is influenced by the presence of MCAOs. Hence, it is the MCAOs' presence, rather than the absolute SST values, that plays a more significant role in shaping the frequency of open MCC clouds.

Fig. 7 Please explain how and why these regions were selected. Is the diurnal cycle of "closed" similarly and oppositely seen in "other" (given that "open" remains unchanged)?

R: Both regions were selected based on areas with a higher frequency of occurrence for both open and closed MCC clouds compared to surrounding areas. This approach ensured that the daily cycles of both categories were as representative as possible within each region. Regarding the diurnal cycle of the category "Other", as previously mentioned, this category includes all other coverage types, making it challenging to derive a specific diurnal cycle for any particular coverage type. Additionally, JAXA's Himawari-8 cloud products are not available during nighttime, which hinders the separation of low-level clouds within the category "Other" to estimate a daily cycle of these clouds.

Fig. 7 Is there a diurnal cycle in EIS or M?

R: We have added a sentence indicating that the diurnal cycles of the *M* index and EIS do not display a discernible signal or pattern throughout the day. Furthermore, the Supplementary Material includes the diurnal cycles for both EIS and the *M* index.

ll. 231-233 Please rephrase, perhaps to "The geolocation of cloud types matches those in other studies".

R: Thank you for this suggestion. We have rewritten the sentence to explain that the distribution of open and closed MCC clouds is consistent with other studies.

l. 233 With respect to "most prevalent", isn't the "other" class even greater in proportion?

R: The category "Other" is the most prevalent as it includes everything else besides open and closed MCC clouds. To avoid confusion, we have rephrased the sentence to indicate that open MCC clouds are more prevalent than closed MCC in both regions.

l. 235 Please check for redundancy (i.e., a similar content in sentence before).

R: Thank you for this suggestion. We have revised the sentence to eliminate redundancy.

l. 239 Perhaps is it worth noting in Section 2 how single and multi-layer clouds are handled in this study.

R: Geostationary satellites such as Himawari-8 cannot see multi-layer clouds in detail due to their viewing angle and the limitations of their remote sensing instruments. Geostationary satellites are positioned at a fixed point in the sky above the equator and continuously observe the same region of the Earth's surface. The viewing angle from the satellite's fixed position does not provide sufficient depth perception to identify individual cloud layers with precision. As a result, geostationary satellites tend to treat multi-layer clouds as a single, integrated cloud mass, leading to limited insights into the cloud structure and properties of each layer. Therefore, we have not handled multi-layer clouds due to the impossibility of Himawari-8 to identify these cloud structures.

l. 241 Unclear whether a specific type is being referred to or not.

R: In the revised manuscript, we have specifically referred in this sentence to the focus clouds of this study, corresponding to open and closed MCC clouds.

l. 243 Please check position of parenthesis here. Perhaps rephrase to “turbulent heat and moisture (i.e., sensible plus latent heat) fluxes”.

R: Thank you for this suggestion. We have changed the sentence as suggested by the referee.

l. 244 Perhaps better “frequency of occurrence” instead of “presence”.

R: Thank you for this suggestion. We have changed the word “presence” by “frequency of occurrence”.

l. 246 Please rephrase sentence for better understanding.

R: We have rewritten the sentence to indicate that the Kuroshio region and its western boundary current are distinguishable for exhibiting notably high frequencies of marine cold air outbreaks.

ll. 258-259 Please elaborate on “showing a strong relationship to the SST gradient”. Is SST gradient shown anywhere? How was a “strong relationship” detected?

R: Thank you this comment. In the revised manuscript, we have now included the annual and seasonal SST gradients in Figure S1. The SST gradients presented in Figure S1 demonstrate the variations between winter and summer, revealing a noticeable decrease in SST gradients during the summer months compared to winter. Furthermore, the highest values of the gradients are observed in the annual average and during winter for both regions. These results provide valuable insights into the seasonal changes in SST gradients and highlight the prominent influence of the SO and NP regions on the overall spatial patterns of SST variations.

l. 264 Please elaborate on “well-formed open cells”. Would not-so-well-formed open cells be problematic for the classification?

R: We have provided in Section 2 a sentence where we mentioned the criteria to identify open MCCs as explained in Lang et al. (2022). Open MCCs were identified as well-formed rings of low-level clouds arranged into distinctive patterns of hexagonally shaped cells with a clear region in the center.

l. 268 Please quantify “high correlation” (see above major points).

R: Thank you for this comment, as we mentioned it, we have included maps of correlations in the revised manuscript to be consistent with the mention of correlations between MCC clouds and the meteorological indices and variables.

l. 278 Please elaborate why other techniques and other classes are needed.

R: Thank you for your comment. As mentioned earlier, we have included maps of correlations in the revised manuscript to ensure consistency with the discussion of correlations between MCC clouds and the meteorological indices and variables. This addition allows to quantitatively assess the relationships between different variables and MCC cloud types, providing a more comprehensive analysis of their spatial patterns and behavior. We appreciate your valuable input, which has enhanced the clarity and robustness of our research.

ll. 280-281 Please briefly explain whether HIMAWARI has a precipitation product.

R: The Japan Meteorological Agency's Himawari-8 geostationary meteorological satellite does not provide a precipitation product. We have expanded the description of the Himawari-8 satellite in Section 2.1 and added a sentence on the satellite products provided by this.

References:

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