

Authors' Response to the Review Comments

Response: We sincerely appreciate the time and effort invested by the editor and reviewers in providing helpful suggestions and constructive comments on this manuscript. We have carefully addressed all the comments raised in their review reports. Detailed point-by-point responses to the specific comments are provided below (in blue).

Review #1

This study investigates the impact of enhanced uniform warming and enhanced SST gradients on cloud characteristics during cold-air outbreaks events. With high-resolution WRF model, the authors identify distinct responses under the two warming scenarios: enhanced uniform warming leads to a warmer and moister boundary layer with larger cloud size and deeper cloud development, whereas enhanced SST gradient results in a drier and colder boundary layer in regions of negative SST anomalies and a reduction of post-frontal cloud areas. Overall, the manuscript present interesting analyses and provide insights into the how clouds and boundary layers respond to warming near the Gulf Stream. However, some aspects of the manuscript could be revised to improve clarity of the manuscript and strengthen the implication of the results.

Response: We thank you for your encouraging feedback and constructive comments. We have carefully considered all the suggestions below and have undertaken a comprehensive revision accordingly. The line numbers refer to the manuscript after revision.

Comments:

- L53: I would recommend using a different term than “shifting” temperature patterns, as the Gradplus experiment represents an intensification of the SST gradient rather than a shift in the pattern.

Response: We have revised the words “shifting temperature pattern” to “increasing temperature contrasts” in lines 53-54.

- L190: The text states “from the inner domain.” Should Figure 1 refers to the outer domain instead of the inner domain?

Response: Yes. We have corrected it to “outer domain” in line 191.

- L240: Please briefly explain the calculation of smoothed liquid water path and specify the thresholds for each zone, so that readers do not need to refer to another paper for the definition.

Response: We have added the explanation in lines 242-245: “The cloud water path is smoothed by a uniform filter of 30 grids, which removes the high-frequency variations in the complex cloud structure. Then we separate out the clear coastal zone and zones 3 – 6 with the values of smoothed water path of <40, 40 – 200, 200 – 500, and >500 g m⁻², respectively.”

- L328-330: Could the author elaborate on why the mass flux magnitude is one order larger in q_v isopleths compared to θ_e and θ isopleths, and how this indicates a stronger relationship between mass flux and q_v ?

Response: We realized that the original sentence was incorrect and have revised lines 334-337 to: “suggesting a stronger transport of q_v by mass flux than θ , because upward and downward transports compensate each other on isopleths, and the mass fluxes defined on isopleths represent the fluxes that effectively transport the corresponding quantities.”

- L345-346: My understanding is that both Zones 4 and 5 correspond to the cloud street regime. Please clarify why the alignment with zone 5 represents an extension of the frontal system (zone 6).

Response: We have revised the text in lines 351-354 to "Because the higher θ_e value (287.75 K) in the southern upward band is comparable to the θ_e values in the upward bands of Zones 5 and 6, we speculate that the southern upward energy transport band may represent an extension of the frontal system, indicative of large-scale frontal influences."

- Section 3.2: This section presents the energy transport response using isentropic analysis. However, the discussion seems somewhat disconnected from Section 3.1 and 3.3. The implications of energy transport for cloud morphology and to the boundary layer are not entirely clear, and the results are only briefly mentioned in the conclusion and abstract. I believe providing additional explanation and clarification, such a short summary of the results at the end of Section 3.2, would help improve the clarity and flow of the manuscript.

Response: Following the suggestion, we have now added a summary paragraph at the end of Section 3.2: "In summary, the analysis of mass fluxes on isentropic coordinates indicates two distinct influences on the development of the cloud street zone: one influenced by the frontal system and the other by the SST gradient. The upward mass-flux band at the northern edge of the Gulf Stream illustrates the role of the SST gradient in affecting the post-frontal cloud system."

- L382-383 "Temporal variations in Gradplus are more pronounced": Did the authors intend to suggest the temporal variations in Gradplus are more pronounced than in Plus4? I would tend to disagree as the ranges of colorbars in Figs 9-11 are much smaller than in Fig 8. Please revise accordingly, and remind the readers the differences in colorbars.

Response: We have revised the text in 393-395 to "The temporal variations in Gradplus are less straightforward, as shown in Figures 9 – 11, with the magnitude of the differences being much smaller than in the Plus4 experiment and the sign being less consistent."

- L437-438: It is difficult to discern from Figs 10f, 10i, and 11i that stronger convergence and convection closely correlate with hydrometeor mixing ratio. In particular, the structure in Fig 11i does not appear to resemble Fig 10f and 10i. Please elaborate on this.

Response: We have elaborated on which specific part of the figure we are referring to in lines 450-453: “We examine the hypothesis of cloud interference described above in Figure 11, which shows that a stronger low-level convergence (below ~2 km) and larger vertical velocities before 08:00 EST in Gradplus (Figures 10f and 10i) closely associate with larger ice-phase hydrometeor mixing ratios during the same period.”

Text:

- L85, “GCM data”: “data” is redundant and can be removed

Response: We have removed the word “data” in line 85.

- L123: duplicated use of “field campaign”

Response: We have removed the redundant words in line 124.

- L200-202: The phrase “intensive fossil fuel burning and rapid economic growth” is mentioned twice. Please revise the text accordingly.

Response: We have removed the redundant words in line 200-202.

- L324: Should this refer to Fig 4a instead?

Response: Yes, we have corrected it to Figure 4a in lines 329.

- L376: The hydrometeor mixing ratio is not shown in Figure 8, please revise the text.

Response: We have changed the “hydrometeor mixing ratio” to “cloud liquid and ice water mixing ratio” in line 387 to be consistent with the figure.

- Figure 10 label: Please use the Greek letter omega to represent vertical velocity

Response: We have revised the label to use the Greek letter omega to represent the vertical velocity in Figure 10.

- Figures 9-11 label: I would recommend adding “Neg. Anom.”, “GS”, “Pos. Anom.” in the titles to be consistent with the labeling used in Figure 7.

Response: In Figures 9 – 11, we use three regions to better illustrate the transition between regions of negative and positive anomalies. These regions are therefore not exactly the same as those in Figure 7, and we cannot use the same labeling as in Figure 7.