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 theta_e and theta 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.

Review #2

Summary

This paper, “Response of marine post-frontal clouds to Gulf Stream variability” by Chen et al., presents a well-structured and insightful modeling analysis of how variations in Gulf Stream (GS) sea surface temperature (SST) mean state and gradients modulate postfrontal cloud (PFC) morphology during a cold-air outbreak (CAO) over the western North Atlantic. Using high-resolution WRF simulations and complementary Lagrangian trajectory analysis, the authors effectively isolate the effects of uniform SST warming and enhanced SST gradients on boundary layer thermodynamics, cloud structure, and airmass origins. The study provides valuable mechanistic understanding relevant to marine cloud feedback and ocean–atmosphere coupling. The paper is scientifically sound, well-motivated, and clearly written. However, some aspects require clarification or refinement, particularly regarding experiment generality and several grammatical or formatting inconsistencies. I recommend minor to moderate revision before acceptance.

Response: Thank you for the encouraging feedback and constructive suggestions. We have carefully considered all the points raised and have undertaken a comprehensive revision accordingly.

General Revisions (Major Comments)

Scope of Analysis – Limited Case Study (p.8–9, §2.2–2.3)

The paper bases its findings on a single CAO event (March 1, 2020). While the case is well validated and mechanistically relevant, the generalization to long-term Gulf Stream variability should be qualified. Please clarify that the results represent a single-case process study rather than a statistical climatology and discuss how these findings might extend (or not) to other CAO regimes.

Response: We have added the following clarification in lines 542-543: “Nevertheless, as this study examines a single case, extending these findings to long-term Gulf Stream variability requires further investigation. ”

Quantitative Uncertainty and Statistical Significance (p.13–14, L277-287, Fig. 3)

Differences between experiments (e.g., “+20.8% reduction”, “−15.5% decrease”) are reported without statistical context. Please indicate whether these differences exceed natural variability or are visually interpreted only. Adding standard deviations or domain averaged variability estimates would strengthen the conclusions.

Response: In lines 262 – 264, the numbers refer to variations in the spatial area of each zone. For this quantity, each zone has a single area value; therefore, domain-averaged values and standard deviations are not applicable. Nonetheless, we have replaced the word “coverage” with “spatial area” to avoid confusion in line 262.

Aerosol–Cloud Interaction Context (p.6–7, §1)

The discussion of aerosol sources and composition is excellent background but is not directly analyzed in the experiments. Please clarify whether aerosol loading and composition were held constant across runs.

Yes, we use the Morrison two-moment microphysical scheme (as indicated in line 175), and the cloud droplet number concentration is held constant across all runs. The aerosol – cloud interaction context is instead inferred from air-mass trajectories, which have strong implications for aerosol sources, given that marine locally sourced aerosols and aerosols originating from continental regions are known to differ substantially. In Lines 497-503, we have revised the sentences to “Aerosols linked to clouds in the examined regions are influenced by a mix of continental and marine sources. Our results regarding the air parcel origins implicitly suggest that SST variations associated with the GS trigger distinct shifts in aerosol composition. Specifically, marine aerosols influence Boxes 2-4 in Ctrl experiments and all four boxes in Plus4 experiments via air parcels originated from sea surface, while continental aerosols influence the other boxes through air parcels originated from continents. This subsequently alters aerosol-cloud interactions over the WNAO region." to avoid the confusion.

Terminology Consistency (entire text)

"GradPlus" and "Gradplus" are used interchangeably. Standardize to one form throughout (e.g., GradPlus). Likewise, ensure consistent symbol formatting for θ_e, q_v, q , etc.

Response: We have now checked the manuscript and revised the text to make the terminology consistent.

Reference Formatting (p.29–33)

Several references contain duplicated author names (e.g., "Andrea F. Corral, Andrea F. Corral"; "Florian Tornow, Florian Tornow"). This appears to be a BibTeX export artifact. Please review and correct the bibliography for duplication and capitalization consistency.

Response: We have fixed the formatting issues and ensured consistency.

Minor Revisions (Editorial / Language)

Introduction

p.5, L69: "drive mesoscale air-sea interactions significantly influence..." → "drive mesoscale air-sea interactions that significantly influence..."

Response: We have corrected the sentence in lines 69-70.

p.6, L92–93: "composited to warming-induced SST increases and gradient weakening— affect cloud macro- and microphysical properties." →

“comprising both SST warming and gradient weakening—can affect cloud macro- and microphysical properties.”

Response: We have revised the sentence in lines 92-93.

p.7, L123–124: Remove duplication: “field campaign field campaign” → “field campaign.”

Response: We have removed the duplication in line 124.

Methods

p.10, L199–203: Redundant phrase — keep one: “(A1F1 scenario with intensive fossil fuel burning and rapid economic growth, IPCC, 2023)” → remove the repeated description after parentheses.

Response: We have removed the redundant phrase in lines 200-202.

Discussion

p.23, L425–426: “interfere with the interactions of θ and qv between north and south of the GS.” → “interfere with the interactions of θ and q_v between regions north and south of the GS.”

Response: We have corrected the sentence in lines 439-440.

p.24, L440–441: “dominate within the boundary layer in the middle and southern regions” → “dominate within the boundary layer of the middle and southern regions.”

Response: We have corrected the sentence in line 454.

p.27, L506: “Mean SST warming (+4 K) leads to a warmer, moister boundary layer, promoting larger cloud sizes.” → Add comma after “layer.”

Response: Done.

p.27, L521–523: Long sentence can be split for readability. Suggest:

“This study introduces two novel approaches: (1) isentropic analysis to isolate energy transport and (2) Lagrangian tracer tracking to quantify airmass sources. These methods reveal nonlinear PFC responses to SST variations.”

Response: We have revised the sentences in lines 538-540.