Response to reviewer of manuscript

egusphere-2026-2092

"Thermohaline gradients and frontal regimes in the northwestern Tropical Atlantic"

by Napolitano et al.

Reviewer: Maya Jakes, University of Southampton

General comments

The manuscript provides a thorough assessment of submeoscale frontal characteristics in the northwestern Tropical Atlantic, where the North Brazil Current interacts with the Amazon River freshwater plume.

Using surface observations from four saildrones, the authors compute horizontal velocity and buoyancy gradients ithin and outside the Amazon plume and assess the relative contributions of temperature and salinity in setting the strength of the density gradients. Density gradients are stronger at small scales and are dominated by salinity gradients within the plume region.

The saildrone observations are complemented by a high-resolution model, revealing the spatiotemporal variability of submesoscale fronts both within the plume region, driven by variability in the NBC and Amazon outflow, as well as outside the plume region driven by the seasonal mixed-layer cycle.

Overall, the manuscript is detailed and well-written. The combination of observations and a high-resolution model provides confidence in the model representation of surface fronts in this region, while also providing insights into the spatial and seasonal variability of submesoscale fronts that are difficult to obtain from observations alone. It makes a valuable contribution to our understanding of submesoscale variability in general, as well as the specific dynamics in the region.

The manuscript is of high quality and should be accepted following some very minor technical corrections. Most of the comments below are just suggestions or questions to consider.

We thank the reviewer for their kind comments and the interest shown in our work. Below we address the comments and corrections proposed. Line numbers refer to the track-changed version.

Specific comments

1. You show the seasonal variability of submesoscale fronts very clearly in the model. What was the basis behind the choice of 2008 and 2009? Is this due to the availability of the model output? I am wondering how often the NBC and Amazon plume configuration match that of EUREC4A-OA? Did you consider doing an EOF analysis to assess the dominant configurations of the NBC and Amazon Plume (using model/satellite data)? Is it dominated by seasonal variability or is there also strong interannual/decadal variability?

   Answer: The model dates comes from realistic forcing and boundary conditions. We use the available timeseries for the 1 km simulation of the GIGATL series (Gula et al., 2021).

The NBC-Amazon Plume configuration during EUREC4A-OA matched what is expected for the season (Jan-Feb), with a growing plume in the end of the “dry season” pushed by a retroflecting NBC entering it’s eddying season (Feb-Sep.; e.g., Johns et al., 1998). With conditions during EUREC4A-OA usually described in the literature, we did not perform an EOF analysis.

With marked seasonal variability in both the Amazon plume and the NBC, the interannual variability would play a role during anomalous large-scale meteorological conditions that imprint in the Tropical Atlantic and influences both the SSS distribution (Da and Foltz, 2022) and the NBC (Johns et al., 1990).

2. Did you look at the depth extent of the submesoscale fronts in the model?

   Answer: We briefly looked at the vertical structure and depth extent of fronts in the model. We are preparing a follow-up study focusing on the velocity structure and dynamics from both the saildrones and the model. Outside the plume, fronts are oriented vertically and reach deeper levels, with typical enhancement of cyclonic motions. Within the plume, fronts are often tilted and shallower, constrained by the plume, and present strong shear at the subsurface.

3. You compute the along-track mean gradients across the four saildrone tracks. How much difference does it make if you use this approach compared to if you had along-track gradients from only one saildrone?

   Answer: For the analysis presented in Figure 2 of the manuscript, we used the density gradients computed from the mean temperature and salinity values obtained from Equation 1 using all saildrones. To compare with one saildrone, we take SD1026, the drone used as reference for the mean trajectory showed in Figure 1b.

   Below, we show a duplicate of Figure 2, with data from SD1026 only (Fig. R1). The magnitude of the gradients remain consistent, with the sharp increase at small scales and overall higher variance within the PLUME. Therefore, using four drones provided statistical confidence without compromising the results from along-track gradients of a single saildrone.

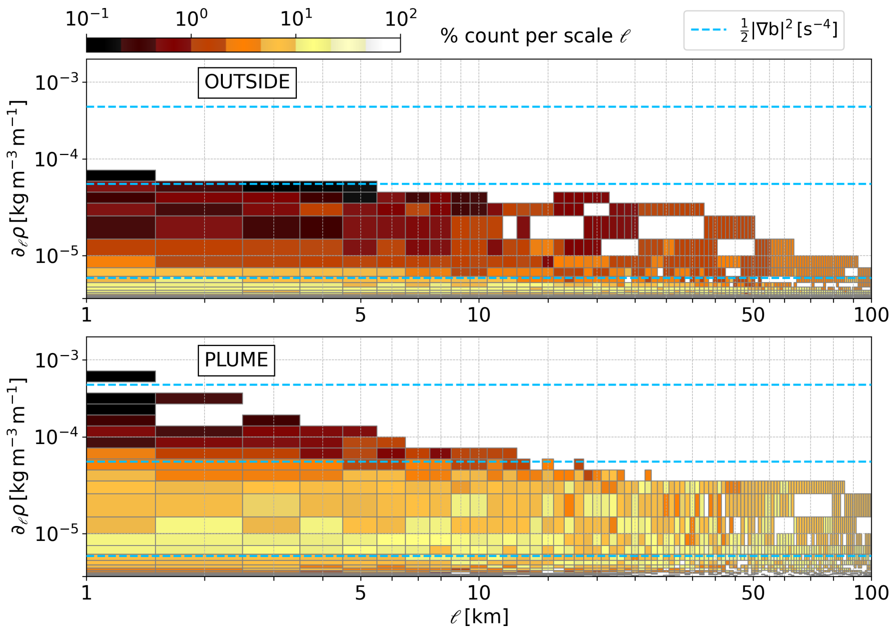

Figure R 1: Observed magnitude of surface along-track density gradients per horizontal scale ℓ along Saildrone SD1026 trajectory (a) OUTSIDE and (b) inside the Amazon PLUME. Colors represent the percentage of gradients for a given scale ℓ (each column sum up to 100% for every ℓ) and dashed lines represent the buoyancy frontal sharpness $\mathcal{B}$ reached for given density gradient thresholds.

4. Do the assigned errors account for the angle at which the saildrones cross the fronts?

   No. Our error estimate follows that of Bhuyan et al. (2026), which only accounts for random errors. The bias due to the angle at which the drones cross the fronts is not considered. We added this limitation in the new version, where we mention that the angle between the fleet route and the fronts could impact our results (L121–123).

5. In the model analysis of 1D gradients, you use density differences along zonal transects. What difference does it make if you use meridional transects instead? Or 2D gradients?

   Answer: Meridional transects (Fig. R2), as well as 2D gradients, still show stronger gradients and greater variability within the plume. However, the Saildrone tracks being usually nearly zonal, we opt to show zonal gradients from the model to ensure that the contrast between the PLUME and OUTSIDE regions depicted from observations at fine-scales was well represented by the simulation.

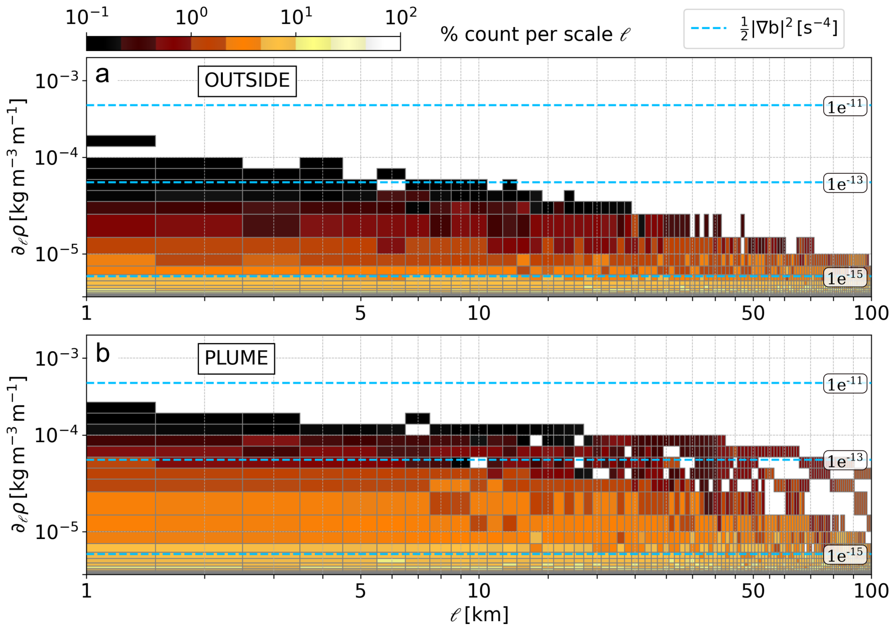

Figure R 2: Magnitude of surface density gradients, along longitudinal transects and per horizontal scale ℓ, OUTSIDE (a) and inside the Amazon PLUME (b). Colors represent the percentage of gradients for a given scale ℓ (each column sum up to 100% for every ℓ) and dashed lines represent the buoyancy frontal sharpness $\mathcal{B}$ reached for given density gradient thresholds.

6. What determines the location of the "submesoscale soup"? There is a large region between the plume edge and the "submesoscale soup" in Fig 8b with little to no small-scale fronts—why do you not get the same seasonal intensification of fronts here?

   Answer: In this study, we determine the location of the submesoscale soup visually based on the presence of anisotropic gradients associated with strong frontogenesis. In addition to the seasonal mixed-layer dynamics, the surface fronts in this regions seemed also influenced by low SSS from the plume of previous years. The plume expands to the north-northwest away from NBC domain, and when the NBC gets stronger again, it "cuts off" the plume from the western boundary, creating the temperature-driven region between the plume-NBC and the submesoscale soup (Fig. 8), with little to no fronts.

   We can see this region getting smaller (while fronts from the submesoscale soup evolve and get bigger) on a snapshot 2 months later (Fig. R3), where the plume is already larger and the NBC stronger than those depicted during EUREC4A-OA and the snapshot discussed in the paper.

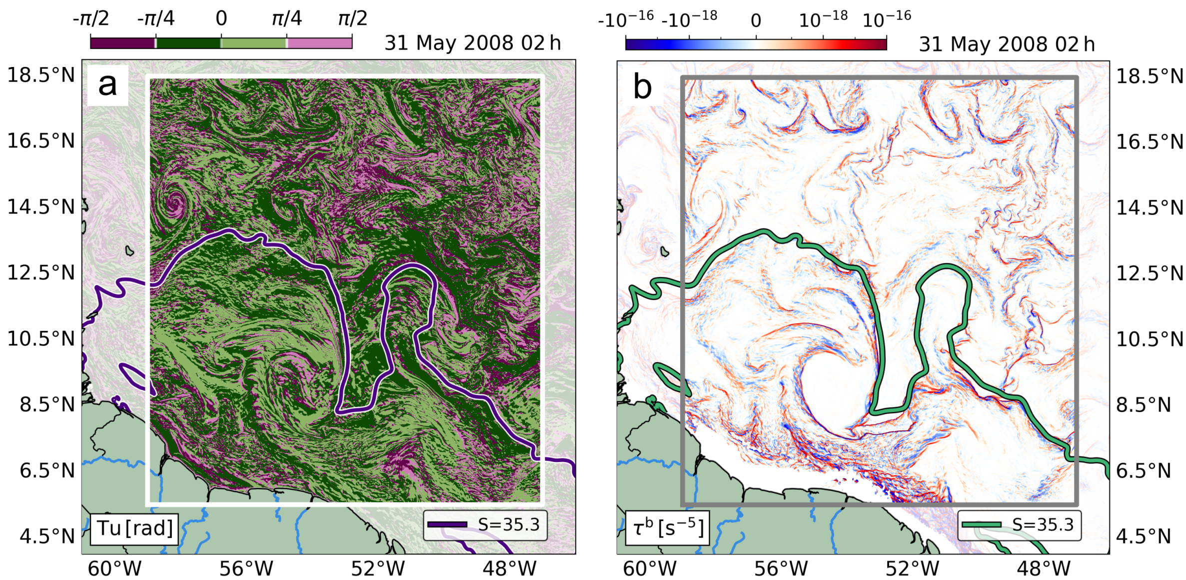

Figure R 3: Spatial distribution of (a) the Turner Angle Tu and (b) the Frontogenetic Tendency of Buoyancy τ^b for the snapshot on 31 May 2008 02h. The PLUME region is delimited by the isohaline representing the 0.25 quantile of the salinity probability distribution (dark blue and green lines).

Technical corrections

L2 - clarify *horizontal* scales Done.

L5 - I found this sentence a bit confusing, maybe rephrase as something like "density gradients are reinforced or partially compensated by temperature-salinity variability."

Answer: We have slightly edited the suggestion to avoid ambiguity, as reinforcement can also be partial. The new sentence reads "Density gradients are partially reinforced or compensated by temperature-salinity variations,. . . " (L6)

L10 - clarify *seasonal* mixed-layer cycle Done.

L12 - clarify *density-compensated* fronts Done.

L18 - include more references in addition to Muller-Karger et al. 1998

Answer: We added two additional references showing the propagation of low SSS in the Tropical Atlantic from observations (L19): Reverdin et al. (2021) and Olivier et al. (2024).

L19 - Coles et al. 2013 as well as Flagg et al., 1986? Done.

L39 - "we revisit density gradients observed at fine scales" Maybe another word for revisit? E.g. analyze / investigate

Answer: Thank you for the suggestion. This dataset was used in previous studies, thus the choice for "revisit". To clarify, we now say "To reach our goals, we revisit *in-situ* observations from Stevens et al. (2021), Coadou-Chaventon et al. (2024), to analyze density gradients at fine scales" (L41–42).

L46 - "hit the road" is a bit ambiguous. Maybe replace with "travel"? Done.

L94 - "saildrone observations" rather than "saildrones observations" Done.

L94 - "intensify" rather than "soar"?

Answer: Changed to "intensify rapidly"

L95 - Instead of "where more and more sharp fronts originate", what about "where buoyancy frontal sharpness is greater" or "where more sharp buoyancy fronts are present"?

Answer: We changed to option 2, "where more sharp buoyancy fronts are present". (L99–100)

L100 - "latter" rather than "later"

Answer: Good catch, thank you! Fixed.

L109 - "loss of synopticity" wording here is a bit confusing. Maybe delete and rephrase as "...interpreted with caution, since the effects..."?

Answer: We rewrote the sentence: "with caution, since the effects of temporal variability are non-negligible for $\ell \gtrsim 40$ km (i.e., the local synoptic scale; Coadou-Chaventon et al. (2024)." The sentence is now placed on the next paragraph (L120–121)

L118 - "reinforce or partially cancel each other effect on density" rephrase as "partially compensate or reinforce the density gradients"?

Answer: This was indeed a bit confusing, thank you.

L134 - ". And" - continuation of the previous sentence. Change to " ...and ..."?

Answer: Removed "And".

L145 - where does the buoyancy error = $7{\times}10^{-6}$ value come from?

Answer: This is the mean standard error of the buoyancy from the Saildrone CTD measurements. We added the information in L153–154.

L150 - use italicized / math font for "f". Also in equation 7. Done.

Figure 3 caption - "driven by salinity **(blue)** or temperature **(red)**"

Answer: Added in the caption of Figure 3 and also Figure 6

L184 - "probability density functions (pdfs)" Done.

L203 - "intensify" rather than "soar"? Done.

L208 - Sometimes plume is capitalised after "Amazon", sometimes just P is capitalised and sometimes none of the letters are.

Answer: Thank you for this remark. We adjusted the notation. In the revised version, "Amazon Plume" refers to the river plume, while Amazon PLUME appears specifically when we discuss the PLUME region defined in Section 2.

Figure 6 caption - "clockwise from $-\frac{\pi}{2}$ for frontogenesis..."

Answer: Added in the caption of Figure 6 and also Figure 3

L288 - "mesoscale and submesoscale **motions**" Done.

L296 - maybe quote the Tu values after "uncompensated front" Done.

Figure 8b - The wavelike structures along the southeast part of the plume edge are interesting.

Answer: They are, right? These structures seem to generate at the edge of the recirculating branch, or could also be associated with the strong internal tides generated at the shelf break that interact with the North Brazil Current (Tchilibou et al., 2022). Their location in the model snapshot also coincides with recent SWOT observations of these structures (Tchilibou et al., 2025).

We now mention the presence of these wavelike structures in L343–344.

L315 - delete space before comma Done.

Figure 10c caption - "compensation (orange) and reinforcement (green)"

Answer: We added "compensation (green) and reinforcement (orange)" to the caption of Figure 10.

L407 - text quotes 0.02, but caption quotes 0.01

Answer: We apologize for this oversight. The caption was the correct one. We fixed the text (L445).

L410 - "appears" Done.

L414 - "**With** the region..." Done.

L419 - "budgets **of**"? Done.

L432 - “associated **with**” Done.

We once again thank the Reviewer for their corrections and questions which showed us different possibilities to analyze and discuss our dataset and model.

References

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