Dear Editors and Reviewers,

Thank you for the additional reviews and for the time invested in evaluating our manuscript. We have carefully considered the new comments and have provided detailed, point-by-point responses below, along with corresponding revisions to the manuscript where feasible.

Reviewer #1: This manuscript presents a multi-sensor case study of the August 2024 extreme storm that impacted Romania's Black Sea coast. By comparing observations with ERA5 reanalysis, the authors analyze signals from broadband seismic records, infrasound, GNSS, and satellite lightning. While the multi-sensor approach is potentially valuable, in its current form the manuscript requires major revision. In addition, the title "evidence of climate change" is not supported by analyses conducted in this manuscript.

Thank you for the careful evaluation and constructive comments. In the revised manuscript, we have addressed all points raised, moderated the tone of the interpretations, revised the title to better reflect the scope of this case study, and clarified several methodological aspects including the PWV analysis and ERA5 comparisons.

Major comments

1) Title and scope

The title "Evidence of climate change and intensifying natural hazards" is not demonstrated by the current work. This study is essentially a single-event case study, and robust statements about climate change require, for example, long-term trend analysis, formal attribution methods, or counterfactual assessment. If the authors do not include such analyses, they should reframe the title and key concluding statements to match what the paper actually provides.

While multi-sensor observations can be valuable, the manuscript should clarify what benefit is gained. From a single case (or short time window), it is not possible to claim improved accuracy, robustness, or "early warning" capability without validation against longer historical observations and quantitative evaluation across multiple storms. Overall, the tone of the manuscript is frequently too strong for the presented evidence and should be rewritten with more careful and appropriate claims.

The title has been revised to better reflect the scope of the study:

"*Seismo-acoustic and GNSS observations of a record-breaking Black Sea storm:* ***repurposing geophysical sensors for environmental monitoring***."

In addition, the tone of the manuscript has been calibrated to better reflect the nuances of our findings. Specific modifications are detailed in the response to Comment 3.

2) PWV results

(a) Units for PWV: PWV is a column-integrated quantity, typically reported in mm, not "mm daily" or "mm hourly" unless the authors are explicitly presenting a rate of change (I think mm daily/hourly does not make sense). The manuscript reports PWV values such as >900–950 "mm per day" and "44 mm/hr", which are physically implausible for PWV as normally defined. In Figure 12, these values are compared with ERA5 humidity, but with the current units/magnitudes this comparison is not meaningful. The authors must verify the PWV derivation, units, and labeling.

Thank you for pointing this out. PWV in our study is estimated at hourly temporal resolution. In the revised manuscript, the daily values are calculated as the mean of the hourly PWV estimates for each day, ensuring that the reported quantities represent PWV itself rather than accumulated values. PWV is now consistently reported in mm, and the figure labels and captions have been revised to clarify that the terms "hourly" and "daily" refer only to the temporal resolution or averaging period, not to rates of change.

(b) Figure 12 inconsistency: Figure 12b is described as an hourly comparison for MNGA vs hourly ERA5 at a specific grid point, while Figure 12a shows daily PWV for multiple stations with daily averaged

ERA5. However, the ERA5 values shown in (b) do not appear compatible with those shown in (a), even allowing for hourly vs daily averaging. Please check and verify the ERA5 extraction method, spatial sampling (grid point vs area averaging), and aggregation procedure, and ensure consistency across panels.
For Figure 12a the daily values were computed by averaging multiple neighboring ERA5 grid cells contained in the extracted dataset, while Figure 12b used a single grid point corresponding to the MNGA location. We have now revised the analysis to use the same ERA5 grid point (nearest to 43.75°N, 28.5°E) for both hourly and daily comparisons. The daily values are calculated as the mean of the hourly ERA5 values at that grid point.

3) Results are over-generalized from a short window

Across Sections 4.1–4.3, the analysis is essentially a single-event, short-window demonstration (focused largely on 29–31 Aug, with selected "quiet days" for contrast). Nevertheless, the manuscript repeatedly uses language implying general reliability (e.g., "reliable tool," "early warning," "precursor," "can serve as…"). The authors should avoid general claims and rephrase the Results/Discussion so that conclusions are appropriately limited to what is supported by this case study, unless additional multi-event validation is provided.
We have toned down the language regarding stronger claims and the ones pointed out, as follows:

<u>Section 4.1</u>

*- "supports the interpretation that high-frequency seismic noise can ~~reliably track~~ **reflect** strong rainfall peaks"*

*- "seismic signals could potentially be ~~monitored in~~ **explored as a** near real time **indicator of** ~~to flag~~ intense rainfall events"*

<u>Section 4.3</u>

*- "rapid increase in PWV ~~strongly~~ suggests that the accumulation of atmospheric moisture **may precede** ~~is a precursor~~ to extreme weather events"*

*- "significant increase in water vapor content precedes heavy precipitation, **highlighting the potential usefulness of** ~~providing further evidence of the potential for~~ GNSS-based PWV monitoring **for studying pre-storm atmospheric moisture variability** ~~to serve as an early warning tool for extreme weather~~."*

*- "This ~~accelerated~~ increase in PWV **may act** ~~can serve~~ as an ~~early~~ indicator of a developing weather"*

<u>Section 5</u>

- "~~supports its utility as a reliable tool~~ suggests that it may provide useful information for tracking storm-related phenomena,

- "highlighting the potential of GNSS-based PWV monitoring ~~as a real-time tool~~ for tracking moisture and understanding short-term atmospheric fluctuations."

*- "~~demonstrates~~ **illustrate**s the potential of repurposing non-conventional sensors for meteorological analysis"*

*- "rising moisture levels in the troposphere **were observed prior to the** ~~can serve as an early indicator of impending~~ intense precipitation **in this event**. "*

*- ~~We believe~~ **This case study suggests** that this multi-sensor approach may help ~~holds promise for~~ improv~~eing~~*

<u>Section 6</u>

*- "with infrasound **providing useful observations of** ~~serving as a reliable tool for tracking~~ lightning activity"*

*- "The storm **analysed here represents an exceptional meteorological event and one of the most intense storms recorded in the region in recent years. An attribution analysis using the ClimaMeter framework (Antonescu et al., 2024) identified a detectable anthropogenic climate change signal associated with this event, placing it within the broader context of intensifying extremes in a warming climate."***

*- "innovative tools **may contribute to future developments in multi-sensor monitoring and** ~~holds great potential for improving~~ early-warning **research** ~~systems~~, enhancing"*

- "Looking forward, ***such multi-sensor approaches may support future developments in integrated environmental monitoring and research into early-warning capabilities, ultimately contributing to improved understanding and characterization of high-impact atmospheric events."***

4) Infrasound clustering

The manuscript states that K-means was performed with seven clusters in the Methods, but the Results describe the data being separated into six groups. Moreover, unsupervised clustering can be sensitive to feature scaling, feature choice, k-selection, and initialization (depending on random seeds), yet the Results mainly interpret clusters qualitatively. The authors should provide additional methodological details (e.g., normalization/scaling, cluster selection criterion, stability across seeds) and/or add quantitative support for the physical interpretation of clusters.

In the Methods section, we mentioned the use of the elbow method and feature pruning for our cluster selection and feature choice. To improve transparency, we have now included Figure S1 (elbow plots) and Figure S2 (correlation matrix) in the new **Supplementary Material** to provide more visual and quantitative justification, as well as equations for each feature, as requested by the second reviewer. We also added an explicit statement in the Methods section confirming the use of Z-score normalization ("***Prior to clustering, the features were standardized using z-score normalization, to ensure comparable scaling across variables***.").

5) Microseism interpretation

The text attributes storm-time changes in the secondary microseism band to "wind-induced pressure fluctuations in the shoaling seafloor." While such an interpretation may be plausible, the manuscript does not provide enough evidence to support it. To justify this claim, the authors should either (i) provide stronger supporting analysis (ideally using longer periods and/or independent wave parameters), or (ii) rewrite the interpretation more cautiously and clearly, with appropriate references and uncertainty acknowledged.

The increase of secondary microseismic energy during storm conditions and its link to wind-driven wave activity and wave-seafloor coupling is well established in the literature (e.g., Bromirski et al., 2002; Ardhuin et al., 2019; Ebeling et al., 2012). In our study, the storm-time amplification of the secondary microseismic band coincides with elevated wind and wave conditions derived from ERA5 and follows the expected temporal evolution of storm-driven sea-state changes, consistent with these established mechanisms. We have revised the manuscript to clarify this interpretation and to avoid wording that could be read as implying a more detailed source decomposition than intended, while maintaining the physically grounded interpretation within the accepted conceptual framework. In Section 4.1 we have revised the 6th paragraph as follows: "The secondary microseismic band, in particular, shows a significant rise in amplitude during storms, ***consistent with established mechanisms linking storm-driven wave activity and seafloor pressure fluctuations to enhanced secondary microseism generation, while local factors such as bathymetry or wave direction may modulate the response (Bromirski et al., 2002; Ebeling et al., 2012; Ardhuin et al., 2019)***."

6) ERA5 "high-resolution"

The manuscript refers to ERA5 as "high-resolution" and states it has 1-hour temporal and 0.25° × 0.25° spatial resolution. In a relative sense this is higher resolution than older global reanalyses, but the authors should avoid implying that ERA5 resolves convective-scale storm structure or peak precipitation intensities. A 0.25° grid corresponds to ~25–30 km and remains too coarse to represent many coastal events. Please clarify what "high-resolution" means in the manuscript's context and discuss how ERA5 averaging may affect comparisons to point measurements.

In Section 3.5 , paragraph #1, we added: "*to generate* ***relatively*** *high-resolution atmospheric parameters* ***compared with earlier global reanalyses".*** In paragraph #2: "*With* ***a*** ~~*high*~~ *temporal* ***resolution of*** *1 hour and spatial resolution of 0.25° x 0.25°*~~*) resolution*~~*, ERA5 allows for a* ~~*detailed*~~ ***mesoscale*** *comparison of* *the storm's meteorological characteristics over time.* ***While its spatial averaging cannot resolve localized convective-scale precipitation, it provides a vital benchmark for qualitative comparisons and for testing multi-sensor monitoring potential."***

Minor comments
Figure 11
There appears to be a mismatch between the plot and caption regarding the distance metric ("distance from coast" vs "distance from Constanța"). Please clarify and make the labeling consistent.
Label updated, as suggested

Figure 12
● No legend/colorbar is provided to explain the colored circles.
We updated the caption to include "***In both panels, GNSS data points are represented by colored circles where the color scale corresponds to the PWV magnitude, consistent with the vertical axis.***"

● PWV units/magnitudes appear implausible and require verification.
We corrected the PWV magnitudes.

● The ERA5 series appears inconsistent between panels (a) and (b); this is not explained.
We corrected the averaging over multiple neighbouring data grids and only considered the one where MNGA station is located.

● Clarify whether panel (a) uses the same ERA5 variable and spatial sampling approach as panel (b) (e.g., same grid point vs area average).
We corrected the ERA5 averaging method and clarified this aspect in the answer to question 2b.

Reviewer #2: The manuscript describes a multidisciplinary approach for monitoring storms. The authors include seismic, infrasound and GNSS data alongside with meteorological data and examine a record-breaking event that occurred in August 2024 at the Black Sea. The concept is strong, the research is interesting and the manuscript is well organized. Compared to the original paper, it has been greatly improved during previous review, although some questions arise. My questions are mainly related to infrasound data processing and interpretation.
Thank you for the positive evaluation of our manuscript and the constructive suggestions. In the revised manuscript, we have clarified several methodological aspects, particularly regarding the infrasound processing and clustering approach, improved figures and terminology, and added supplementary material to provide additional details supporting the analysis.

General comments
In your response to the Reviewers, you mention that: elements of the methodology are already being incorporated into ongoing projects and operational platforms. Looking at the links therein I found a set of very interesting resources. Have they been published elsewhere? If not, would you include them here in the discussion for example?
Thank you for the suggestion. The referenced platforms are operational tools developed at NIEP that provide near-real-time access to processed geophysical data. As they primarily serve as data-access and visualization resources, we have included references to them in the Data Availability section of the manuscript: "***Processed infrasound, seismic, and GNSS-derived integrated water vapour data can be visualized and accessed via the INFP monitoring platforms: https://infp.ro/dashboard-reactive.php and https://reactive.infp.ro/events/***"

Overall, I found the figures to be informative, and they indeed help the understanding, however some standardization could be done to improve them.
- Please standardize date and time formatting as currently a variety of them is in use. They even vary in the same figure, for instance see Figure 10.b and 10.c.
We standardized time and date formats where possible, among subfigures. However, minor variations persist due to the different software packages used to generate specific plots.

- In Figure 10. the color-coding by azimuth seems to be redundant.
We would prefer to keep the current representation. The color-coding by azimuth helps visually emphasize directional groupings and facilitates quick interpretation of the propagation patterns in the rose diagram.

- Also, in Figure 10.a and 10.b the term azimuth is used, whereas the y label in 10.c is BAZ which is used throughout the main text. (Also, I found back-azimuth and backazimuth in the text.) Please stick to any of them.
We corrected the label for backazimuth and removed the hyphen from the backazimuth term throughout the text.

- Some subfigures within a figure seem to be misaligned horizontally, even when they share the x axis for comparison. (Figure 4., 9., 12.)
We now aligned Figures 4, 9, 12 and added coherent labels among subfigures

- What do the colors mean in Figure 12? Is the color bar the same as is in Figure 11?
In Figure 12, the color of the GNSS data points corresponds directly to the PWV magnitude on the vertical axis to enhance visual clarity. To ensure this is explicit, the caption has been updated as follows: "***In both panels, GNSS data points are represented by colored circles where the color scale corresponds to the PWV magnitude, consistent with the vertical axis.***" The color scale in Figure 12 is independent of Figure 11, as it is scaled to the specific ranges of the daily and hourly data shown in each sub-panel.

- 1e-7 is rather tiny in Figure 4. c. Could you update the y axes (and the label accordingly) to nanometer or micrometer?
We updated the units to nm

- In Figure 6. the bottom right subfigure seems to be misaligned. The Period [s] above that is not completely visible.
Corrected

- In Figure 1. c.ticklabels are hardly readable.
We increased the label size

- Figure 2. b and caption. Is the time given in local time or UTC?
UTC, we now added in caption

Infrasound
As far as I understood, the feature extraction and K-means clustering are a key part of the manuscript as such investigation has not been made in infrasound research to analyze thunderstorms, therefore both methodology and interpretation should be slightly more detailed.
You separate single-station and array analysis in Section 3.2 and 4, but as I understand in both subsections (4.2.1 and 4.2.2) a single-station approach is used as you only processed the data from one station, namely AGIR. Please clarify these two. In the unsupervised machine learning part did you use only one selected array element? Or were all sensor's data utilized and averaged, or was a beam calculated?

Thank you for this comment. Perhaps there is an ambiguity in our terminology and presentation. In Section 3.2, AGIR is introduced as an infrasound array composed of multiple sensors. Two distinct analysis strategies were then applied to the same dataset: one using single station analysis and another algorithm using data from all the sensors in the array. In Section 3.2 we revised the following paragraph as follows: "*To analyze the seismo-acoustic characteristics of the August 30-31 Black Sea storm, we used a two-pronged approach: (1) single-~~station~~**sensor** signal analysis based on feature extraction and unsupervised machine learning, and (2) array-based analysis **using all the sensors of AGIR and** classic multi-channel correlation algorithms.*" Then in Section 4.2.2 (Array analysis and lightning detection) we also added: "***Using multiple sensors from the AGIR infrasound array with the** PMCC algorithm allowed us to extract coherent infrasound signals and to estimate their propagation parameters, such as backazimuth and arrival times, across the sensor network."*

Could you please add definition to the used features with equations?
We added the equations in the new Supplementary Material.

Is it possible to involve lightning data as well in the interpretation besides windspeed and precipitation? For instance, to plot number of lightning strikes within 50 km range as a function of time (Figure 9.)?
We have updated Figure 9 to include the number of lightning strikes within increasing radial distances from the AGIR station, shown as histograms, and added a brief interpretation in the text.

Maybe even provide a proxy for wind noise level such as present in the cited paper Listowski et al., 2022 (Remote monitoring of Mediterranean hurricanes using infrasound).
To compare the infrasound observations with wind conditions, we use measurements from a nearby meteorological station (Figure 9a). Thus, we would prefer to use these direct measurements rather than introducing a proxy derived from the same infrasound dataset.

(Did other infrasound station in Romania (or in the region) detect the event?)
Infrasound signals associated with this storm and others were also observed at the Romanian infrasound arrays IPLOR and BURAR. These observations are part of a broader multi-array analysis of thunderstorms generated by extratropical cyclones over the Black Sea currently under preparation (Ghica et al., 2025; EGU General Assembly).
Ghica, D., Antonescu, B. and Ene, D., 2025, April. Using Romanian infrasound observations to analyze thunderstorms generated by extratropical cyclones over the Black Sea. In EGU General Assembly Conference Abstracts (pp. EGU25-5592).

Infrasound and satellite observations
Is the efficiency of MTG Lightning Imager known? Is the accuracy of the lightning strike locations known?
In Section 3.3 in paragraph #2, we added: "***The MTG Lightning Imager detects total lightning (cloud-to-cloud and cloud-to-ground) optically at 777 nm, with 4.5 km pixel resolution at the sub-satellite point and 1 ms frame rate (Holmlund et al., 2021; Kokou, 2023). Level-2 achieves detection efficiencies of ~80-90%, capturing even weak flashes reliably, with false alarm rates <0.3 (Enno et al., 2025). Flash geolocation uncertainty reaches 5-10 km near the edge of the instrument's field of view, where off-nadir viewing geometry amplifies parallax effects (Bližňák & Sokol, 2026).***"

What causes uncertainty in the travel time estimation?
In Section 3.3, we added: "*accounts for timing uncertainty* ***associated with the simplified propagation assumption. In particular, infrasound travel time from thunder sources can vary due to atmospheric temperature and wind variations along the propagation path, which affect the effective sound speed and may introduce deviations from the assumed constant-velocity, straight-path propagation.***"

Minor comments:
line 280-284: where ddd is the distance should simply be d? Corrected.
line 144: *Bromirski etnal.l 2002;* Corrected
line 193: Do you mean Campus and Christie, 2010? Corrected to Campus and Christie, 2009
line 298: *Iliescu et al.., 2019* (two dots) Corrected
line 375: *Figure 5 shows three snapshots... Four snapshots?* Corrected
line 472: Figure 10A… to a Corrected