Round 1 of Reviews

Anonymous Reviewer #1

Note: Comments in black indicate reviewer comments whereas comments in blue represent the author's response.

We thank the reviewers for their constructive and helpful comments and the Editor for managing the manuscript. Reviewers' comments are shown in black and italics and our answers in blue. All lines and Figures numbers in the reviewers' comments refer to the initial manuscript. All lines and Figures numbers in our answers refer to the revised manuscript (without track changes) accompanying this response letter. A summary of the main changes is provided at the end of letter. In addition to this response letter, we have also provided a revised manuscript file where all the changes made are clearly visible.

Reviewer: 1

Comments: 1. Major Strengths

This new detection and location method combines low-frequency template matching, differential arrival-time measurements, and high-frequency spectral ratios to detect and classify VLFEs. The method seems to improve location consistency relative to earlier VLFE catalogs. The authors rigorously applied their method to two decades of data from the Ryukyu subduction zone and compared their detected VLFEs with previous catalogs, ensuring a robust analysis. I found it particularly interesting that the detected VLFE events are located only in areas with no regular earthquakes, which recalls recent work of Gaspard Farge on LFEs in Japan. Figures are clean, well designed, and effectively illustrate the detected VLFEs and regular earthquakes in their case study. Overall, the paper makes a valuable contribution to both methodology and regional seismology.

We thank the reviewer for this general evaluation.

2. Areas of Improvements In my opinion, the overall flow of the manuscript could be improved. While the first part focuses on explaining the methodology in detail, no figures are used to help guide the reader. Many "Method" sections describing the detection, relocation or classification steps could use some of the later figures to help illustrate them. The "Results" sections could also be slightly reorganized to group relevant information and results together, followed by a deeper analysis in a final section (for instance, could section 4 be merge with another one?). While the figures were mostly clear, a few could have been regrouped or slightly changed to facilitate the reading. Lastly, when the authors refer to "detected events", it is not always clear whether this includes both VLFEs and regular earthquakes or only VLFEs.

- Section 2 is intended to be a general method section (which can therefore be useful to readers for applications to other contexts), not limited to its application to the VLFEs of the Ryukyu subduction zone. In order to show figures at this stage, all the specificities of the stations used in the Ryukyu case should be explained, which is precisely the objective of section 3. We therefore believe that the illustrative figures better find their places in section 3.

- We have followed the suggestion of the reviewer to merge section 4 with section 5 (see below).
- We have modified most of the figures (see below).
- We indeed found a few occurrences where the term "detected events" was ambiguous and accordingly modified the sentences (l. 440 & 463)

Specific comments: - 1- Introduction (page 2): NEIC and ISC could be written in full (as it is the first time they're mentioned I think).
Done (l. 41-42). Citation to the NEIC has also been added.

2- VLFE_DRL Method (page 3): More a general question because I never worked on detecting VLFEs, is it expected to find VLFEs using regular earthquakes as templates, or were you testing this theory?

For VLFEs sharing a similar mechanism and depth with the regular earthquakes, correlation is expected as soon as low enough frequencies are considered. Our study thus confirms that it is possible to use regular earthquakes to detect VLFEs.

2- VLFE_DRL Method (page 4): typo line 108 "we extract the all the couples …"

Corrected.

- 3- Application to Ryukyu (page 8): I don't know if I missed the explanation, but why aren't you using the INU-NACB pair in the study?
Explanation is provided is section 2.3 (l. 158-161) : "Redundant pairs (e.g. the 2-3 pair in the case of three stations) can also be considered with the goal to improve the location robustness. However, this makes the association criterion more difficult because C_i 23 is not expected to have a local maximum for time t_j . In the first application of the method, we will remain in the configuration of solving system (10)."

- 3- Application to Ryukyu (page 8-10): Figure 2 and 3 could be already used in the Method section to illustrate a few steps showing the template waveforms and how they're concatenated. Additionally, Section 3.2 repeats some of the method that was already explained in the Method section of the paper. I would either remove the repeated parts or reorganize.
As mentioned above, we believe that there is an interest to have a purely methodological section (section 2, possibly useful for other applications), separated from the section 3 where the method is concretely applied to the Ryukyu case. Repetition between section 3 and section 2 also appears quite limited, as section 3 mostly gives technical details and numbers(that allow the work to be replicated) without explaining again the ideas of the method.

- 3- Application to Ryukyu (page 11-12): Line 276-278. Why did you change what station is selected depending on if the event is detected by the 2 pairs or 1 pair?

This is mentioned in section 3.1 (l. 219-220) : "At high frequency (above 1Hz), NACB station (k=3) is quieter than TATO, which helps the final detection of VLFEs". In order to recall this fact in the sentence mentioned by the reviewer, we have replaced "the NACB station is selected" by "the quiet NACB station is selected" (l. 279).

- 4- Detection inside families (page 12): I don't understand why this is its own section and not just inside section 5 with the other results. Also, it's a bit unclear in the first sentence (line 288) if "all the seismicity" is VLFEs + regular earthquakes or just VLFEs. Also minor but, is line 297 "to Template 1 itself" a typo and should be "Template 2"?

We have followed the suggestion of the reviewer and section 4 is now merged with section 5. "all the seismicity" has been replaced by "all the events" in order to clearly state that it refers to VLFEs and regular earthquakes together (for the same reason, section 4.2 is now entitled "Events location, 2004-2024" rather than "Seismicity location, 2004-2024"). The typo Template 1 => Template 2 has been corrected.

5- Characteristics of VLFEs: Great part, but I believe slight changes to the organization of sections might improve the manuscript. Either merge Section 4 and 5, or rearrange them. For example, group section 4, 5.1 and 5.2 together into a sort of "Results" section, and then afterward make a new section for 5.3 and 5.4 to focus on the more "advanced" analysis/comparison (could also merge this one with the discussion).

As mentioned in the previous comment, sections 4 and 5 have been merged in a common section entitled "Very low frequency earthquakes and regular earthquakes in the Southern Ryukyu subduction zone". Former subsections 4.1 and 4.2 have also been merged into a unique subsection 4.1 entitled "Examples of detection of very low frequency earthquakes".

Figures: - Figure 1: Could add a small inset showing an "unzoomed" version of the region, but not essential. Having a little legend that says what are the thick vs thin circle would really help, but I think that using colors instead of the thick/thin representation to highlight events detected by the 2 different station pairs would be more effective (it could be changing the station triangle color for INU and NACB, and using the same colors for the circles). I would suggest trying to color events by depth (if assumed on the interface) to make it more obvious but it might be too much information on this figure.

We have added an unzoomed inset. Thick and thin circles are not a key information, it is mostly done to highlight the thick ones. Templates recorded by the TATO-NACB pair (thick) are most often also recorded also by INU, while templates only recorded by the TATO-INU pair (thin) are usually pre2004 templates (before operation of NACB, meaning that the detected events are not located). Adding colors would likely make the figures less clear (the important colors are the blue one for Template 1 and the red one for Template 2, that are used in the next figures)

- Figures 2: Great figure! If you need to reduce the number of figures, this one could be grouped with the map as it would directly show the template location and waveform together. This is a great figure to illustrate what templates look like and could be used in the Method section 2.

The manuscript now has 8 figures, which seems to be an adequate number, and grouping Figure 2 with Figure 1 would make a too dense figure.

- Figure 3: It took me longer than it should to realize that panel b and c are the same station (same waveforms) but in c, the event has been shifted in time to match the template. First, I would add a legend again just to highlight black is detected event, blue is original template. Then, I would change some of the colors, either different colors for the 2 different stations (could match colors of the triangles in the first map if changed), or different colors for the "original detected event" vs "shifted event" panels. Same as before, could be mentioned in the Method section 2 to illustrate the flexibility of this method compared to more rigid template matching methods.

A legend in the figure now highlights that blue is the Template and black is the detected event. Additionally, windowed waveforms in (b) are shown with a thin line and in (c) with a thick line, in order to facilitate the interpretation of the figure. The caption has been accordingly adapted. -

Figure 4: Good figure, could also have a small legend to say blue = regular earthquakes, magenta = VLFEs.

This legend "blue = regular , magenta = VLFE" has been added. The caption has been accordingly adapted.

Figure 5: Same as figure 4, good figure but having a legend to write down what color is what would help. This one can also be used in the Method section to illustrate how to differentiate between VLFEs and regular earthquakes.

The legend "blue = regular , magenta = VLFE" for (a) and "red = regular" for (b) has been added. The caption has been accordingly adapted.

- Figure 7: Same as before, good figure, but a legend would help better understand because there is a lot of different colors and information on this map (black =NS15, blue = A12 at least).

The legend "black = Nakamura and Sunagawa (2015), blue = Ando et al. (2012)" has been added.

- Figure 8 & 9: I'm not sure I understand why make 2 figures here. Either combine them, or use four panels (2 by 2). I think it would be easier to observe the slight changes and resemblances between the two panels b if they were on the same plot.

Following the reviewer suggestion, Figures 8 and 9 have been combined into a unique Figure 8. Figure 8a remains Figure 8a, Figure 9a is now Figure 8b, and Figures 8b and 9b have been merged in a unique Figure 8c. The caption of Figure 8 and text of section 4.5 have been accordingly adapted.

Anonymous Reviewer #2

1. Magnitude of VLFE: please discuss challenges in the estimation of Mw for VLFE, in general and within your approach'

The main challenge in estimating Mw for VLFE using amplitude ratios (equation 5) is mentioned in section 2.2 (l. 117-120) : "If the j event has a corner frequency fcj close to fl, its seismic moment derived from equation 5 is expected to be underestimated. As fcj is the frequency where the displacement amplitude drops below the half-value of the low frequency limit, this underestimation may reach 0.2 units in terms of moment magnitude." In the revised version, we now also recall this limitation in section 4.5, (l. 430-432): "Even if absolute magnitude values may be slightly underestimated (down to about -0.2 magnitude units, see section 2.2), this magnitude saturation effect remains."

2. Three component template: While I can see the benefit of concatenating 3 component traces into a single correlation function, this may also have some limitations, and/or require some tuning with respect to the window length. How to choose the length? What happens if you have a succession of LFE signals, or long lasting signals, e.g. similar to LP events?

The definition of the window length does not appear more difficult when using a single component window or a 3-component concatenated window. The window length (for one component) is set to 300s(see section 3.1 and illustration in Figure 2) in order that surface wave packets are well recorded at the furthest station. If several events of similar magnitude occur within this window length, they will thus likely be missed (as in standard template matching techniques). We have included a sentence (l. 373-375) about this limitation when explaining why the VLFEs can be missed (see also answer to point 4 below).

3. multiple station pairs: I would agree that using multiple station pairs should improve both detection and location. The selection of station locations for the proposed case study, however, seems quite peculiar (i.e. from Fig. 1, two stations are very close by, the last one at completely different location). Do you have general recommendations how to choose station locations? Would you use each station pair in Eqs. 8? Can the approach be generalized to n stations?

The ideal configuration (when using three stations) is when the source-station azimuths are as different as possible, in order to avoid low values of the determinant (equation 11). Another constraint is to avoid stations too close from the events, for which the shape of the Green's function changes a lot even for a modest location difference between the template and the potential event (mentioned in section 4.4). And of course, broadband data quality has to be good and easy access to long time series has to be possible. Using each station pair and

generalizing to n stations is mentioned in section 2.2 as a potential improvement of the method (with additional care to manage the cases where one or several stations are not available). We however believe that this extension goes beyond the scope of the present study, which aims at presenting the method and a first application.

4. Detection performance I understand that the detected catalog is by no means complete, in the sense that, if the characteristics of the target (usual or LF) earthquakes would be different, e.g. in terms of focal mechanisms, they could remain undetected. These limitations should be discussed.

This is exact, VLFEs are missed if they are too different (in terms of location and/or focal mechanism) from the template. They can also be missed if they occur closely in time (previous comment). We have added the sentences (l. 372-375) : "The smaller number of detected VLFEs by the VLFE_DRL method can also be explained by other factors. VLFEs are not detected if they are too far (in terms of location and/or focal mechanism) from the existing templates and they can be missed if two (or more) of them occur within 300 seconds, i.e. within the duration of the template window." The first limitation was also already mentioned in the final section (l. 474-475): "In its present form, the method can only detect and locate events similar to past earthquakes, in terms of focal mechanism, depth, and relative location."

5. Data selection and processing To which extent is the pre-processing needed, e.g. the instrumental deconvolution, given that you look at cross-correlation on a given frequency band (which, by the way, is probably in the flat part of the spectra for those stations)? Conversely, if the data are corrected to true ground motions, is there any advantage to use velocity against e.g. displacement?

If focusing only on detecting events that are similar at low frequency, the pre-processing (deconvolution of the instrumental response) may not be required. But for seismic moment determination (and associated high-frequency scaling), it is very important to use at least the real global sensitivity, as the sensors or digitizers are likely to have changed over such a long period of analysis. If using displacement instead of velocity (which is likely possible), the high-pass filtering (0.0125Hz) may have to be increased, as the signals at this frequency will have a larger amplitude and may become noisy for small events.

6, a final minor comments: Overall the paper is well referenced, but a few references would be needed for each of the two sentences at lines 53-54 and 54-55

These sentences were implicitly using the references of the previous paragraph. In the revised version, we made this relation more explicit (l. 55-56).

Summary of the resulting changes made to the manuscript We first mention the main changes related to the reviewers' comments (detailed changes were mentioned above in the answers to the reviewers) :

- As suggested by reviewer 1, Figures 1, 3, 4, 5, 7 have been modified. And Figures 8 and 9 have been combined into a unique Figure 8. Associated captions have been modified.
- This has led to a re-organization of the subsection "Frequency magnitude distribution of very low frequency earthquakes, 1992-2024"
- We have merged Section 4 and Section 5.
- Limitations and challenges underlined by reviewer 2 (comments 1, 2, 4) have been further documented

Additionally, we have adapted and complemented the end of subsection 4..4 (l. 412-422) and Figure 7, in order to include the comparison with the recent VLFE catalog of Nakamura and Yakabu (2025).

Round 2 of Reviews (same anonymous reviewers)

Anonymous Reviewer #1

The authors considered my previous comments and those of another reviewer, providing a carefully revised manuscript. I think this makes a nice, interesting contribution, well suited to the journal. I have no further comments and I suggest to accept the manuscript in its present form.

Anonymous Reviewer #2

The authors answered my questions and considered my suggestions to improve the overall clarity of this manuscript. I believe that all my comments have been addressed in this modified version. I recommand this manuscript for publication. Great paper!