Reviews of Lin et al., “Detection of hidden low-frequency earthquakes in southern Vancouver Island with deep learning”

Review Round 1:

Dear Editor,
We are grateful for the constructive feedback from both reviewers, which has significantly improved our manuscript. Specifically, in this revised version:
1. We have added a more detailed background introduction and comparison of various approaches in this region to enhance the comprehensiveness of our manuscript.
2. We ran our model, on a large scale (with 16 years of data), extend to southern Cascadia (with 18 PB stations), to discuss its transferability and limitations. The new results are added in the new section: 4.3 Limitations and future opportunities.
3. In addition to LFE and tremor catalogs, we have added a comparison of our model with the SSE catalog. The new comparison across all 4 catalogs is summarized in our revised Figure 6.
4. Revised the manuscript thoroughly to improve the readability.
Please see our point-by-point response to the reviewers below. We hope these changes are sufficient. Thank you very much.
Sincerely,
Jiun-Ting Lin & co-authors

Reviewer 1:
This manuscript describes the application of a convolutional neural network earthquake-source detection and location algorithm to tectonic tremor in southern Vancouver Island. It employs an existing low-frequency earthquake catalogue in the training phase and then examines the algorithm's performance in recovering both known (but "unexposed") and new events. Statistics are provided that indicate high fidelity in detection, but appraisal of location is more limited and downplayed. In particular, the authors present an example of tremor activity in May 2010 that likely manifests the occurrence of a modest SSE (slow-slip event) but one which went completely undetected in the standard PNSN tremor catalogue. I am left with the impression however that the spatiotemporal behaviour of said event is poorly resolved at scales of less than ~20 km and that general location precision may be no better than the baseline Wech and Creager approach.

We gratefully thank your efforts for reviewing our manuscript and the positive feedback. We have made substantial revisions to address all the comments. Please see our point-by-point response below.

The motivation for the work is clear and worthy: improvement of automated tremor/lfe catalogues will lead to improvements in both the characterization of SSE occurrence and kinematics and, potentially, provide opportunities for improved imaging of Cascadia forearc structure that is otherwise characterized by generally low levels of seismicity. However, I think there are a couple of areas where the paper falls short. First, southern Vancouver Island is a region that has been subject to a number of similar detection/location exercises, notably Kao et al, 2005, 2009; Armbruster et al., 2014; Savard et al, 2015; Bombardier et al., 2023; not to mention extensions of the Armbruster work by Rubin and colleagues - references in annotated manuscript). The first 4-5 studies all employ different algorithms with the same basic objective as the present study but with differing sensitivities and completeness, yet they are not referenced here. This needs to remedied with the present study's relative advantages and shortcomings clearly indicated.

We have added these references to the manuscript and briefly introduced these different approaches in the introduction.

Second, since southern Vancouver Island is/has been well sampled, I think it would be useful to provide some indication of the performance of the CNN algorithm, at least in the detection (vs location) sense, in (a) less well sampled region(s). Central Oregon and central Vancouver Island come to mind. Both regions have significantly lower station density. Central Vancouver Island would provide a simpler test since crustal transparency and tremor amplitude are comparable to southern Vancouver Island. Central Oregon could be a more stringent test since the presence of Siletzia may significantly alter the crustal response. Inclusion of at least one (and preferrably both) of these examples (through figures analgous to Figure 6) would be useful in demonstrating the potential of the CNN approach for the greater Cascadia region something which has been largely unaddressed in previous studies aside from the (baseline) Wech & Creager work.

Thank you for the comment. We agree that it would be useful to apply the CNN algorithm in less sampled regions. This is a feasibility study in Cascadia following the success of Thomas et al. (2021) in Parkfield, CA. So we first compared this approach with the well-validated baseline studies to identify its limitations. Additionally, because the CNN model relies heavily on training data, our initial step involves testing it in Southern Vancouver Island with the existing dataset(s). We applied the model to other parts of Cascadia using 16 years of data from 2006-2022 recorded on 18 PB stations. The result (Supplementary Figure S9), suggests that although the peak LFE detections from our model align with the timing of large SSEs from Michel et al. (2019), the results are much noisier because the model was not trained on data from these Regions.

This is not surprising. From our generalization tests (Figure 6, Supplementary Figure S3), we know that the model has the capability of temporal extrapolation (detecting events beyond the training data’s time span) and spatial extrapolation (detecting events from new stations). However, the performance declines as it is applied in regions further afield from where it was trained that have different noise characteristics and source-station paths.
We have added the detailed discussion in our Limitation and Future Work section in the Discussion.

In addition to the main comments above, I have made numerous minor suggestions in the attached annotated manuscript.

Thank you for the suggestions, we have revised the main text.

Michael Bostock, Reviewer 2:
This manuscript reports new detection of LFEs associated with SSEs in Cascadia. The results on finding hidden LFEs inconsistent with tremor is interesting and valuable for slow earthquake study. The authors should carefully show the reliability of your results. This manuscript should be published after appropriate revision.

Thanks for the positive comment and the effort in reviewing the manuscript. We have revised our manuscript based on your comments and suggestions. Please see our point-by-point response below.

Main comments
To demonstrate validity of your new LFE catalog, you should compare your LFE catalog with existing tremor catalog by Wech (2021) and/or LFE catalog by Bostock et al. (2015) during each ETS episode. From Figure 9, there are at least four major ETS episodes and some intermediate or minor episodes. You should plot spatial distribution maps for each episode including snapshots indicating spatiotemporal evolution like as Figure 10.

Thank you for the comment. We have revised the Figure 6 by adding our model comparison with the LFE catalog and SSE distributions from Michel et al. (2019). Please note that our study region is a relatively small region compared to those studies. We compare their distribution at the center of our study region (i.e. near latitude 48.5) by filtering the catalogs, which should best reflect the comparison in the same geographical reference. Our results show good agreement between the catalogs.

You interpret that LFEs detected in May 2010 are generated by many small and intermediate magnitude SSEs that do not generate tremors. Before the interpretation, you should define both LFE and tremor, and clearly distinguish LFE from tremor.
Thank you for the comment. We have actually already introduced SSE, LFE and tremor in the Introduction section. Following your suggestion, we have expanded upon these topics, providing additional details on the various approaches.
A traditional idea for the relationship between LFE and tremor is that tremor is composed of swarm-like activity of LFEs distributed on the SSE fault plane. In this case, tremor and LFE are equivalent; however, observable LFEs are identified due to its large amplitude or isolation from tremor wavetrain. In this case, observable LFEs might reflect larger events within tremor sequence. Based on this idea, your interpretation that detected LFEs are generated by small SSEs that do not generate tremor might be strange. Of course, it depends on the definition of the relationship between LFE and tremor. Therefore, you must define them before discussion.
If I believe your LFEs inconsistent with the existing tremor catalog, the LFEs might have shorter

duration compared to ordinary tremor.

Please note that LFEs, and tremors (and also SSEs) occur on different time scales. Even the physical processes generating them may be similar, different detection methods have different sensitivities, making it possible to have some variations between catalogs. One possible interpretation is that these are short-term events that are undetected by the time window of Wech (2021) approach. We have revised this section to enhance clarity.

Minor comments

Line 45-46 You must demonstrate the consistency of your resulting catalog with the tremor catalog during periods of large-magnitude SSEs in the result section.

Thanks for the comment. We have added the large SSEs in Figure 6.

Line 61 What is the SSE catalog? If you use pure SSE catalog obtained from GNSS data, you should cite the catalog appropriately. If you use tremor catalog to recognize large-magnitude SSEs, you should explain it honestly.

Sorry for the confusion. The SSEs are from GNSS inversion of Michel et al. (2019). We have added the reference in the Introduction.

Michel, S., Gualandi, A., & Avouac, J. P. (2019). Interseismic coupling and slow slip events on the Cascadia megathrust. Pure and Applied Geophysics, 176, 3867-3891.

Line 92-94 I agree with the explanation that the tremor catalog tends to miss shorter timescale phenomena compared to tremor analyzing timescale. Is this related to your interpretation for LFEs inconsistent with the existing tremor catalog?

Thanks for the confirmation. Yes, that is correct.

Line 97-98 In this sentence, you compare the frequency content between LFEs and shallow earthquakes. Why do you use shallow earthquakes?

They are shallow by the definition (0-70km) compared to intermediate earthquakes (70-300km) and deep earthquakes(300-700km).

Line 132-135 These sentences are not suitable in the section of Introduction.

Thanks for the suggestion, we have revised the sentences.

Line 301 VGC should be VGZ if Figure 1 is correct.

Thanks for catching the typo. It should be VGZ and we have corrected it.

Line 321 You must explain the source information for known large magnitude SSEs.

Thanks for the comment. Large magnitude SSEs are SSEs detectable by those geodetic methods. We have revised the sentence to avoid confusion.

Line 337-339 What is the bottom tremor catalog? You should explain appropriately. Relating to this Figure, you should explain the consistency of the time series and large-magnitude SSEs in the main text.

We have revised the sentence and the figure. Thanks for the suggestion.

Line 394-395 You use “slow earthquake” here only once except the name of database. You should define “slow earthquake” in relation to slow slip event, LFE and tremor.

Thanks for the comment. We have revised the sentence.

Line 440-443 In Figure 10G, the spatial footprint of the cluster 10 extends over most of the study area and reach to mainland of Canada. However, the tremors by Wech (2021) are limited within Vancouver Island. You must evaluate the uncertainty of your LFE catalog.

We have shown the model statistics in 3.1 Assessing model performance; the arrival time uncertainty in 3.3 P and S-wave arrival time estimates; and location uncertainty analysis in 3.4 Location uncertainties. The uncertainty of the catalog (location travel time residual) has also been provided in the catalog file. Thanks for the comment.