Response to Reviewer 2:

The authors present a new methodology for detecting precursors to landslide failure using InSAR, applied to the 2020 Achoma landslide in Peru. Rather than relying solely on displacement time series, they explore coherence loss and wrapped phase analysis to reveal early warning indicators. The study brings in an innovative use of SAR data that can complement more widely used InSAR and optical displacement metrics. Overall the paper is well written, in-scope, and should be published without too many changes. Nevertheless, I identify a few points that should be reworked before the work is published:

1. 2. 3. 4. In terms of the framing, the fact that many landslides collapse without precursory motion or signals needs to be more evident. While not specifically related to the work presented here, this is important for the framing of this project. Claims about the wider applicability of this technique need to be worded with some caution with this manuscript only presenting a single use case, and of a landslide known to have a complex displacement history and drivers of motion.

Thank you for the comment. Some text was added in the conclusions to clarify that this is a first important step to which larger regional studies will follow in order to determine the landslide types, sizes, mechanisms and material compositions for which similar precursors can be captured in regions with different geological and climatic settings. This is linked to your line-by-line comments for lines 18 and 19. We decided not to change the abstract for brevity, but we acknowledge this point more in-depth in the conclusions, particularly with respect to outlook and further work.

This manuscript does not currently demonstrate that this technique can be used to detect destabilisations in a predictive setting, with the information presented relying on the prior knowledge of the landslide location. I can see two ways to address this, either (i) running some new experiments to evaluate whether the landslide coherence loss and other signals are distinguishable from background signals on a meaningful scale or (ii) reword the text in a few areas to make it clear that this possibility has not yet been tested but would be a useful future direction. My initial thought, looking at the method and figures, is that dealing with false positives might make this challenging to apply on a large scale without bringing in additional datasets or substantial post-processing. If the authors choose to go with the second of these options, providing some discussion from their perspective of the possibilities and barriers to this 'blind detections' would be of value.

We thank the reviewer for this comment. This study does not claim predictive capability. Its aim is to demonstrate that additional InSAR metrics and signal characteristics—beyond traditional displacement time series—can provide a more cohesive picture for precursor detection. While the question of predictive detection is highly relevant, it lies beyond the scope of the present work. Rather, this study establishes a foundation for future research: future work will focus on 1) the generalisability of these signals will be tested across larger regions and diverse landslide types, and 2) the potential for identifying precursors in a predictive, "blind detection" setting will be evaluated, including through the use of wrapped phase signals. The manuscript has been revised to clarify these points, following your valuable suggestions.

The data/code availability statement needs improvement, the key datasets generated and code are not currently available in line with the journal requirements. Based on this, I recommend the paper be accepted following major revisions – though hopefully not requiring many new analyses.

I include additional line by line comments below.

Title – Please review the wording it is a bit convoluted at present.

Something like 'Alternate InSAR metrics for detecting landslide precursory signals at Achoma landslide, Peru'?

We thank the reviewer for the suggestion. We considered using a simpler phrasing, but the title is intended to convey the methodological focus of our study. "Beyond and beneath displacement time series" reflects our approach of exploring InSAR products at earlier processing steps—those generally left behind in conventional analyses—to extract additional information not captured by standard displacement time series. This phrasing highlights that our work goes further (beyond) and also taps into overlooked, lower-level data products (beneath), accurately reflecting the novelty and scope of the study.

L18 "catastrophic landslides often go unnoticed until immediately before failure" I think in reality they mostly go unnoticed until after failure.

We agree with this, and in fact it strengthens the point we intend to make. Reworded slightly in the abstract.

L19-20 Here and throughout – a key point to capture is that many landslides also fail without substantial precursory signals. Ground based detection doesn't always help there. Just mention this clearly so that the problem is framed correctly.

We believe this is largely true for shallower landslides in loose materials, and in fact a follow up to this work will be to understand for which landslides we can expect to see similar signals. To keep the abstract concise, we prefer not to add more detail in the abstract itself, but we have added some text in the introduction L.82-85 and in the conclusions (lines 725-729).

L33-34 "detect landslide precursors across extensive areas" I'll comment more below, but I think a couple of additional experiments would be useful to present to evaluate this specific point.

We fully agree with the reviewer that evaluating the applicability of this approach across larger areas and multiple sites is a valuable and in fact key next step (We originally had in our conclusions: "further research across a broader range of case studies is needed to validate coherence loss patterns as reliable precursors for landslides with minimal ground displacement.". Our intention in this paper, however, is to present this as a proof of concept focused on the Achoma landslide to demonstrate how coherence loss can be used as a precursor indicator without relying on traditional time-series analysis. Expanding the analysis to additional landslides is certainly necessary and feasible and, as mentioned above, it is our intention to provide important validation and some degree of generalisation. However, we believe that such an extension would be best addressed in a dedicated follow-up study. This would allow for a more systematic comparison across different landslide types, materials, and environmental settings, and ensure that each case is analysed with the level of detail required to draw robust general conclusions. Some text added L.731-735

L42 Could you double check this number – and perhaps also some more up-to-date

publications. In Petley 2012 I read "7 yr period, causing a total of 32,322 recorded deaths" which does not quite align with this sentence.

Thanks for spotting this mistake. Corrected.

L45-50 This is good, but I think needs to capture the concept that only a subset of landslides will show these early signs.

Added at L.82-85

L52-53 Again I'd possibly argue that failure with no precursors is a larger overall problem here. It is important to communicate that these are helping us 'identify more dangerous landslides' rather than 'identify all dangerous landslides' – which can sometimes be unclear to readers.

We have added text to reflect this at L.82-85, 125-128 and 725-729.

L67 can you clarify 'new generation satellites'?

This indicates satellites like Sentinel-1 (and newer satellites like NISAR) with shorter repeat cycles, consistent acquisition geometry, and frequent global coverage, unlike the older ERS, ENVISAT and, to an extent ALOS, which, with the longer repeat passes are not well suited for monitoring. Added example in text at L.67.

L75-76 Reword here. The 'universal reliability' is known to not be the case for a variety of reasons as discussed here.

Thank you for the comment. We agree, and our intention in this sentence was precisely to highlight that point. We have clarified this further in the revised text (see lines 82–85, 125–128, and 725–729), which should make our meaning more explicit.

L80 Just a thought but a summary figure of the ways in which InSAR can break down might help illustrate some key points.

Thanks for the comment. We thought that this may become a rather complex introductory figure with a long caption, which may break the flow of our work somewhat. Instead, to illustrate further some of the problems mentioned we added some references.

L108 'high frequency'

– you mean with short temporal revisit times, right?

Yes, clarified in text L.111.

L113 'optical image correlation of SAR images'

SAR, so delete 'optical' – is it optical or SAR? I think you mean

Yes! Thanks for spotting it, deleted.

L133 This summary is good, but is presenting a retrospective analysis that is slightly different than the stated objective of identifying unknown signals.

We thank the reviewer for this comment. We would like to clarify that our objective is not to demonstrate the operational detection of unknown landslides, but rather to show that clear precursory signals exist in InSAR coherence and wrapped phase data. The analysis is retrospective, but the signals identified are genuine precursors of gravitational deformation, observable in the data well before failure. We show that this data can be extracted without constructing full displacement time series. The study therefore establishes the physical and methodological basis upon which prospective applications *can be developed*, rather than focusing on predictive implementation at this stage. Establishing which of these features can be detected prospectively (i.e., in a blind detection setting) and the false-positive/false-negative trade-offs at scale is an important follow-on question; it is a principal focus of our planned future work. Clarifying sentence added L. 142-144.

L181 Section generally clear and with enough information to reproduce.

Thanks for acknowledging this.

L230 This is an area with substantial land use – do we know that there is no local or long- range signal associated with this (in particular irrigation-related subsidence)?

All the crops of the valley, small in size, are irrigated but not in an intensive way. Furthermore, the gradient of the area allows water to naturally drain towards the river. We do not think we are in the situation of a basin or a flat area where a piezometric dome can happen. Here, irrigation distributes water in a non-intensive way over all the crops, with excess water draining toward the river. Thus, we do not expect local or long-range signal associated with this.

L283 Is this rainfall instrumental or model data? If instrumental, how close is the data to Achoma?

This is rain gauge data; the station is Chivay and it is 9 km northeast of the site. This is specified in section 3.6.2.

L420 and figure 4. These results are interesting and show clear precursory evidence of slope change. The key question that would be interesting to explore here in addition to what is currently presented is whether this could have been identified without prior knowledge of the landslide location – i.e. is the highlighted feature substantially different to others in the background noise etc. I wonder if you stacked the coherence maps whether the scarp stands out more compared to background 'noise'? I have the same question for the coherence drop

Thank you, this is indeed an important point. To partly address it, we computed the temporal mean coherence for every pixel in the scene and standardized these values relative to the background, generating a z-score map. Pixels intersecting the scarp were compared with the background using a Welch's t-test, confirming that the scarp coherence is statistically distinct from surrounding terrain. This demonstrates that the coherence signal we observe is a genuine precursor. Added in supplementary material, including supplementary figure 9 (see L.308-310 and L.448-450)
We note, however, that a pixel-by-pixel approach alone is insufficient, because many pixels in a scene naturally exhibit low coherence due to diverse factors unrelated to landslide activity (e.g., vegetation, moisture, or local noise). In order to identify a scarp reliably, it is critical to consider the spatial correlation of low coherence, particularly when associated with gravitational structures, rather than isolated pixel values. Coherence must be interpreted in combination with wrapped phase signals, topography, and geomorphic characteristics.
Finally, while these analyses confirm the presence of precursor signals, evaluating their predictive potential remains a separate, future task. Our study demonstrates that precursors exist and can be detected, but robust predictive applications require integrating multiple datasets and signal types.

in figure 5 – is this exceptional compared to the background of a large area, or does it require a-priori info to be interpreted? I recognise that this might be a challenging task, and an alternative would be to reword some of the sections of this manuscript to frame identifying unknown landslides as a future advance.

The point you are raising is indeed very important and it is the core of the issue in making a similar workflow predictive rather than retrospective. In our view, coherence should be interpreted relative to a local surrounding area rather than across an entire valley/region or an entire SAR frame. For Figure 5, we selected a surrounding area comparable to the landslide footprint to serve as a baseline for normal variability. The area is large enough to be comparable to the landslide but it's not too large as to include very different noise sources. The significant drop in the coherence ratio three months prior to failure indicates that the landslide area was losing coherence faster than its immediate (hence directly comparable) surroundings. Thus, this approach does not require the landslide to stand out across a much larger area; rather, the key signal emerges from local deviations detectable over a few km scale. In addition to this, wrapped phase patterns could be used to help delineate such areas (the boundaries separating the inside-unstable vs outside-stable) even without prior knowledge of the landslide, providing a pathway for future detection of unknown unstable slopes. Text added in methods at L. 303-308, results at L. 461-463 and discussion L. 681-689.

L477 and elsewhere – the term ‘gravitational morphological structures’ is not very clear could you describe this with other words?

This term is used in landslide studies (e.g. but not only Agliardi et al., Tecnonophysics 2009). It is used to refer to structures such as scarps, counterscarps, grabens, extensional structures that are associated to gravitational slope movements. Added brief explanation L. 285-286.

L491 This section is important to the physical interpretation of low vs high coherence. It would be good to expand this to provide a more comprehensive evaluation of the meaning of the signal presented, and its limitations in certain terrains. For example in a cultivated slope might crop changes also be a source of noise? And might certain types of landslide motion retain coherence over large surface areas despite large displacements if motion is highly localised/differentiated?

Thank you for this important comment. The influence of terrain type and land cover on coherence is indeed significant; however, this effect is largely mitigated in our analysis because we use a ratio between the landslide and its immediate surroundings. As long as both areas share similar landcover and environmental conditions, the ratio remains meaningful and largely independent of absolute coherence variations caused by vegetation, soil moisture, or cultivation. This design ensures that coherence changes highlighted in the ratio reflect primarily deformation-related processes rather than surface or dielectric differences. We also note that certain landslides can maintain high coherence despite substantial motion when deformation is spatially localised or occurs along narrow slip zones — likely the case for Achoma during the years preceding failure, when only subtle, rope-like coherence drops were observed along extensional structures. This is touched upon in the discussion, when we explain how we interpret the different phases.

L511 I wonder how different this result would be if you used the mean coherence over a large area rather than an ‘adjacent stable area’ (which requires manual input to find).

As mentioned in response to the previous comments, this is a valid and interesting point and it could be the object of future work aimed at the identification of patterns a-priori. However, we think the rationale of not including environments that substantially differ in their properties is valid in order to detect local changes associated with landslides.

L623 – Another complementarity I am interested in is how this can fit in with the potential of both InSAR (e.g. www.sciencedirect.com/science/article/pii/S0034425719304274) and optical data (e.g. https://onlinelibrary.wiley.com/doi/full/10.1002/esp.5775) to identify previously unknown unstable/moving areas at scale. It feels like this might be another feature that could prove valuable in e.g. a deep learning based 'unstable area' segmentation taking multiple of these data types as input.

We thank the reviewer for this insightful comment and fully agree that integrating the proposed indicators with large-scale approaches based on InSAR and optical data has very strong potential. Combining coherence and wrapped-phase–based precursors with optical indicators of slope change could greatly enhance the detection of previously unknown unstable areas as well as making it more reliable. We also agree that these complementary datasets could be effectively integrated within deep-learning–based segmentation frameworks aimed at identifying actively deforming terrain at scale. While this integration falls beyond the scope of the present single-case study, we see it as an important next step and a promising avenue for future collaborative work. Text added L.695-708.

L662-665 "Our findings demonstrate the potential of satellite-based InSAR to detect destabilisation precursors before large displacements occur, particularly when continuous displacement time series are hindered by land cover or landslide behaviour." I'm not sure this is quite true here, as all the results presented require the previous knowledge of the landslide location. I mentioned above about the possible interest of evaluating the 'blind identification' of the unstable area – or perhaps rewording somewhat here.

We thank the reviewer for this observation. We agree that in this study the analysis was performed with prior knowledge of the landslide location. However, the results demonstrate that signals related to gravitational movement can be detected directly from coherence and wrapped phase, without generating displacement time series. While this work focuses on a retrospective case, the indicators identified here are transferable and can form the basis for future efforts aimed at the prospective, large-scale detection of unstable slopes. Text added to clarify L.142-144, L.681-689.

L668+ This is an important point that could be highlighted more in the discussion. This was only presented for the Achoma landslide which is not representative of all cases (in fact, it might be unusually complex in its context and multiple displacement drivers).

This section has now been expanded, in response to previous comments e.g. L.82-85, L.725-729, L.731-735.

L671+ It sounds above like the landslide was noticed pre-failure on the ground by the local community also? It might be worth mentioning that here, ultimately the 'landslide science monitoring' needs to be coupled with this on the ground situation for an effective warning system.

Added at L.740- 742.

L678 Ah yes nice – I see you have already mentioned what I wrote above (although I was thinking more along the lines of identifying new unstable areas in the first place before monitoring can be done).

Addressed in response to previous comments.

L680-681 Perhaps revisit this last sentence – I am not sure that this would typically feed into 'hazard mitigation', or whether it is specifically 'community resilience' that this would enhance if put in place.

We agree, thanks for spotting that. Changed in the text L.748-749.

L701 Better code/data availability section needed. Please deposit the (processed) images used in an online repository and upload the processing code to github/zenodo/similar – mentioned that they 'could be shared' is not aligned with the journal data policies (https://www.natural- hazards-and-earth-system-sciences.net/policies/data_policy.html).

See here for ease:

"Statement on the availability of underlying data Authors are required to provide a statement on how their underlying research data can be accessed. This must be placed as the section "Data availability" at the end of the manuscript. Please see the manuscript preparation guidelines for authors for the correct sequence. The best way to provide access to data is by depositing them (as well as related metadata) in FAIR-aligned reliable public data repositories, assigning digital object identifiers, and properly citing data sets as individual contributions. If different data sets are deposited in different repositories, this needs to be indicated in the data availability section. If data from a third party were used, this needs to be explained (including a reference to these data). Data Cite recommends the following elements for a data citation:

creators: title, publisher/repository, identifier, publication year (e.g. Loew, A., Bennartz, R., Fell, F., Lattanzio, A., Doutriaux-Boucher, M., and Schulz, J.: Surface Albedo Validation Sites, EUMETSAT [data set], http://dx.doi.org/10.15770/EUM_SEC_CLM_1001, 2015).

If the data are not publicly accessible at the time of final publication, the data statement should describe where and when they will appear, and provide information on how readers can obtain the data until then. Nevertheless, authors should make such embargoed data available to reviewers during the review process in order to foster reproducibility. The Copernicus review system allows to define such assets as 'access limited to reviewers' and reviewers must then sign that they will use such data only for the purpose of reviewing without making copies, sharing, or reusing. In rare cases where the data cannot be deposited publicly (e.g., because of commercial constraints), a detailed explanation of why this is the case is required. The data needed to replicate figures in a paper should in any case be publicly available, either in a public database (strongly recommended), or in a supplement to the paper."

Data statement corrected, all datasets archived in Zenodo. See Data Availability statement.

Overall, this is a valuable contribution, and I look forward to seeing it published once the revisions are addressed.

We once again thank reviewer 2 for such a comprehensive and careful review, that enabled us to make important changes to the text. We hope you find our manuscript improved.