Community Comment— egusphere-2026-6338

Three decades of permafrost seismic velocity variations from ambient noise at the SPITS array, Svalbard

Statistical identifiability of the multi-decadal velocity trend, instrumental consistency, and ambient-noise source variability at SPITS

The manuscript provides a valuable analysis of more than three decades of continuous seismic observations from the SPITS array, offering an unusual opportunity to investigate long-term changes in the mechanical properties of Arctic permafrost. The combination of ambient-noise characterization, frequency–wavenumber analysis, selective stacking, multi-component interferometry, and comparison with borehole temperatures represents a substantial methodological effort. In particular, the extensive archive quality-control procedures documented in Appendix A, the evaluation of different stacking estimators, and the sensitivity analysis involving alternative reference epochs are important strengths of the study.

The reported seasonal anticorrelation between relative seismic velocity variations (dv/v) and ground temperature is physically plausible and consistent with previous investigations at SPITS.

However, the principal new result—a secular velocity decrease of approximately 0.033% per decade over 1992–2025—requires a particularly rigorous assessment of statistical and methodological uncertainty. The inferred cumulative change is only about 0.11%, making the distinction between physical velocity changes and systematic observational effects especially important.

After considering the analyses presented in the main manuscript and Supplement, I would like to raise the following points.

1. Statistical uncertainty and robustness of the secular velocity trend

The negative trend reported for the array-median ZZ component is one of the most important results of the manuscript. The authors estimate a slope of −0.0033% yr⁻¹, with $R^2 = 0.51$, using ordinary least squares applied to the Gaussian-smoothed daily dv/v series. However, the coefficient of determination does not establish the statistical significance or uncertainty of the estimated slope.

The manuscript appropriately acknowledges, in Section 7.2, that the bootstrap envelope shown in Figure 6b is not a formal confidence interval for the secular trend because it does not account for temporal dependence after smoothing or instrumental changes. I consider this an important limitation that deserves further quantitative treatment, particularly because the conclusions interpret the observed decrease as evidence of gradual permafrost mechanical weakening.

A possible approach would be to represent the observations as:

$$y(t) = \beta_0 + \beta_1 t + s(t) + u(t),$$

where $s(t)$ describes the seasonal component and $u(t)$ is a temporally correlated residual process.

The seasonal representation need not be strictly sinusoidal, given the possible asymmetry between freezing and thawing. The uncertainty of β_1 could then be evaluated using generalized least squares, an appropriate temporal block bootstrap, or another dependence-aware procedure. Such an analysis would make it possible to report confidence intervals for the secular trend and assess whether the inferred decrease remains statistically distinguishable from zero.

It would also be useful to test the influence of the early observational periods identified as having comparatively low stretching correlations, particularly 1993–1998 and 2001–2003. The sensitivity test using the alternative 2015–2025 reference in Supplementary Figure S19 is valuable: the negative trend persists, changing from −0.0033 to −0.0029% yr⁻¹. Nevertheless, stability with respect to the reference epoch does not, by itself, quantify uncertainty arising from temporal correlation, instrumental transitions, or other processing choices.

I therefore suggest extending the uncertainty assessment from the daily dv/v estimates to the secular trend itself.

2. Bootstrap formulation and dependence among station pairs

A related methodological issue concerns the bootstrap procedure described in Section 5.2. The text indicates that daily correlation functions are resampled with replacement for each station pair, followed by

reconstruction of the selective-stack reference and re-estimation of dv/v. However, Section 7.2 describes the bootstrap uncertainty as treating station pairs as the resampled units. These descriptions appear to refer to different resampling procedures and should be reconciled. The distinction is important because resampling daily observations, resampling station pairs, and resampling temporally contiguous blocks address different sources of uncertainty.

Furthermore, the 36 inter-station combinations are constructed from only nine stations. Individual pair estimates therefore share sensors and may exhibit substantial cross-pair dependence. An uncertainty analysis that assumes independent station-pair contributions could consequently underestimate the variability of the array-median estimator. I would welcome clarification regarding the actual resampling units, whether resampling preserves temporal and cross-pair dependence, and how these assumptions affect the uncertainty assigned to the final velocity series.

A station-level or appropriately structured hierarchical resampling strategy could provide an additional robustness check.

3. Instrument-response consistency across the observational archive

Appendix A provides a detailed and useful account of instrumentation changes, timing offsets, component interchanges, polarity reversals, and other archive-related problems. The identification and exclusion of problematic daily correlations represent an important strength of the study.

Nevertheless, I would appreciate clarification regarding the treatment of instrument responses in the interferometric processing chain. Section 3.1 explicitly states that instrument responses were removed before calculating the probabilistic power spectral densities.

In contrast, Section 4.1 describes the preprocessing of the waveforms used to construct the noise correlations in terms of resampling, detrending, spectral whitening, amplitude clipping, and segment rejection, without explicitly stating whether instrument-response correction was also applied to these data. This distinction is relevant because the array operated with different sensor and digitizer configurations over the 1992–2025 interval. Although spectral whitening can reduce differences in amplitude spectra, it does not necessarily remove phase differences associated with dissimilar instrumental transfer functions. Consequently, changes in effective instrumental response could potentially influence the shape and timing of the reconstructed correlation codas. D'Alessandro (2026) provides a relevant methodological framework for considering instrument-response correction and the propagation of associated uncertainties. It would therefore be helpful to specify whether all data entering the interferometric calculations were corrected to a common physical quantity, how the relevant response metadata were handled across instrumental epochs, and whether residual phase-response differences could affect the stretching estimates.

An additional sensitivity analysis excluding particular instrumental epochs would help assess the robustness of the secular trend.

4. Temporal variability of ambient-noise sources and stretching-related bias

The manuscript provides a detailed characterization of the ambient-noise wavefield through multitaper spectral estimation, probabilistic power spectral densities, and frequency–wavenumber analysis. These analyses are appropriate and demonstrate that the authors have taken source variability seriously. In particular, the selection of the 0.5–2.0 Hz band is supported by the waveform-coherence analysis, while the frequency–wavenumber results suggest greater directional stability for the slower wavefield contributions in this band than at higher frequencies. However, much of the detailed directional characterization concerns 2022–2025, with additional examples from earlier years. The stability of the incident wavefield over these intervals does not necessarily demonstrate equivalent stability across the entire 1992–2025 observational period. Furthermore, the statistical properties of the incident wavefield are not identical to those of the reconstructed late correlation coda used for stretching.

Zhan et al. (2013) demonstrated that temporal variations in the frequency content of ambient noise can produce apparent velocity changes in the stretching method, even without modifications of the propagation medium. Daskalakis et al. (2016) further investigated this problem and demonstrated that suitable normalization procedures can reduce source-induced apparent velocity variations under appropriate assumptions. The relevance of these studies is particularly strong because the cumulative secular signal reported here is small. I suggest investigating whether the inferred trend is stable across alternative sub-bands within the frequency range where the correlations retain sufficient coherence, as well as reasonable variations in coda-window selection and correlation-normalization procedures.

A quantitative comparison between changes in the frequency content of the correlation functions and the corresponding dv/v estimates would also be informative. Where feasible, applying the moving-window cross-spectral method to a representative subset of the same observations could provide an independent methodological check. This would complement the comparison with the earlier MWCS investigation by Albaric et al. (2021), without assuming that agreement between studies covering different periods establishes estimator independence. The analysis could also benefit from examining the evolution of noise-power distributions and spectral characteristics across the instrumental epochs. D'Alessandro et al. (2021) and Catania et al. (2025) provide relevant examples of statistical approaches for characterizing the frequency-dependent, temporal, and spatial variability of ambient seismic noise.
Although these studies concern a different geographical environment, their methodological treatment of noise variability may be useful when assessing whether the effective excitation wavefield has remained sufficiently stable for multi-decadal interferometric monitoring.

5. Consistency of velocity trends across components and observational periods
The manuscript reports negative long-term velocity trends for multiple inter-station component combinations, including ZZ, NN, EE, RR, and TT. This agreement in sign is encouraging and provides evidence that the observed decrease is not restricted to a single component. However, the reported trends are estimated over different observational periods. The primary ZZ trend is calculated over 1992–2025, whereas the horizontal-component trends are calculated over 2005–2025. Consequently, differences in slope magnitude cannot be attributed solely to component-dependent or wave-type-dependent sensitivity.
An informative additional comparison would be to estimate the ZZ trend over the same 2005–2025 interval used for the horizontal components, applying identical temporal modelling and uncertainty estimation. This would provide a more direct assessment of agreement among the different correlation products.
Supplementary Figures S14 and S18 also identify a pronounced SPB5-related anomaly in 2016 that affects several station pairs but is considered not to dominate the array median. While median aggregation provides robustness against individual outliers, it would be useful to verify explicitly whether the secular trend changes when all paths involving individual stations are excluded in turn. Such a leave-one-station-out analysis would provide a stronger robustness assessment than treating the 36 station pairs as fully independent measurements. The comparison could help establish whether the multi-decadal decrease is a coherent property of the array or partly dependent on specific station histories.

6. Interpretation of the effective depth sensitivity
The reported correspondence between dv/v and ground temperatures at approximately 2–4 m depth is scientifically interesting. The systematic analysis of temperature–velocity lag across 15 thermistor depths represents a useful improvement over simple zero-lag correlation. Nevertheless, identifying the thermistor depth at which the seasonal phase difference is smallest does not necessarily identify the depth distribution of seismic sensitivity. The measurement represents a path-averaged response of the correlation coda, and its depth sensitivity depends on frequency, wavefield composition, scattering, and subsurface elastic structure.
The similarity between the dv/v series and temperatures at 2–4 m therefore supports a physical association with shallow freeze–thaw processes, but it does not independently establish that most of the observed velocity change originates within that depth interval. The manuscript already acknowledges that the proposed differences between Rayleigh-type and Love-type depth sensitivity would require confirmation through forward modelling. I suggest carrying this qualification more consistently into the interpretation of the results and conclusions. In particular, the 2–4 m interval could be described as the depth range showing the closest observed thermal phasing, while the effective seismic sensitivity remains model-dependent. Similarly, the interpretation of the secular velocity decrease as a progressive loss of ice-bonded stiffness is plausible but not unique. Changes in liquid-water content, stress conditions, and the spatial distribution of freezing and thawing may contribute to the observed velocity variations.

Concluding remarks
The manuscript represents a valuable extension of ambient-noise interferometric monitoring to an exceptionally long observational period in the Arctic. The comprehensive archive inspection, selective stacking, multi-component analysis, and comparison with independent ground-temperature observations provide a strong basis for investigating seasonal permafrost dynamics. The negative secular velocity trend is potentially the most significant new result. However, its small magnitude means that its statistical significance and robustness to observational and processing uncertainties deserve more explicit quantitative assessment.

I particularly recommend clarifying the bootstrap formulation, estimating a formal confidence interval for the secular trend that accounts for temporal dependence, documenting instrument-response consistency across observational epochs, and assessing possible stretching bias associated with long-term changes in ambient-noise characteristics.
A common-period comparison of the different seismic components and a station-level sensitivity analysis would provide additional evidence regarding the spatial coherence of the inferred trend. These refinements would help establish more convincingly whether the observed multi-decadal velocity decrease represents a statistically resolved change in the elastic properties of shallow permafrost.
They would also enhance the broader value of the study as a methodological reference for environmental monitoring using long-running permanent seismic arrays.

References

Catania, M., Figlioli, A., Vitale, G., and D'Alessandro, A. (2025). Seismic noise characterization of broad-band stations in the Italian region using power spectral density: a frequency, spatial and statistical analysis. *Geophysical Journal International*, 242, ggaf168. https://doi.org/10.1093/gji/ggaf168

D'Alessandro, A., Greco, L., Scudero, S., and Lauciani, V. (2021). Spectral characterization and spatiotemporal variability of the background seismic noise in Italy. *Earth and Space Science*, 8, e2020EA001579. https://doi.org/10.1029/2020EA001579

D'Alessandro, A. (2026). Causal and uncertainty-aware instrument correction in broad-band seismology: minimum-phase inversion, discretization effects and self-noise performance bounds. *Geophysical Journal International*, 246, ggag265. https://doi.org/10.1093/gji/ggag265

Daskalakis, E., Evangelidis, C. P., Garnier, J., Melis, N. S., Papanicolaou, G., and Tsogka, C. (2016). Robust seismic velocity change estimation using ambient noise recordings. *Geophysical Journal International*, 205, 1926–1936. https://doi.org/10.1093/gji/ggw142

Zhan, Z., Tsai, V. C., and Clayton, R. W. (2013). Spurious velocity changes caused by temporal variations in ambient noise frequency content. *Geophysical Journal International*, 194, 1574–1581. https://doi.org/10.1093/gji/ggt170