

T-phase detection within spectrograms of hydroacoustic data from the Arctic Ocean

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Supplementary materials

S1 Earthquake signal quality

The different frequency and energy contents of the three seismic signal categories, strong, medium and weak, are shown in Figure S1. This quantitative PSD analysis aims to support Figure 2a-d.

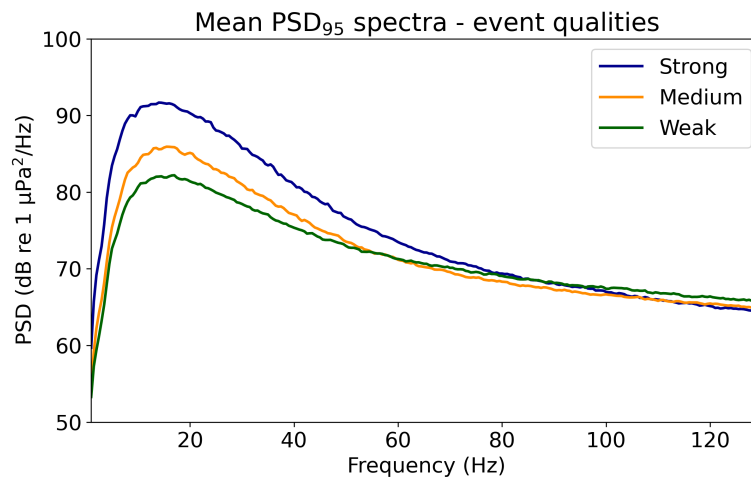


Figure S1 Mean 95th-percentile PSD values of T-phase signals associated with different signal quality categories. Blue: strong; orange: middle; green: weak.

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S2 Additional PCA projections

An additional representation of the PCA projection of ROI acoustic features, given in Figure 5, is presented in Figure S2. Distinctions have been made between T-phase and P_T phase detections.

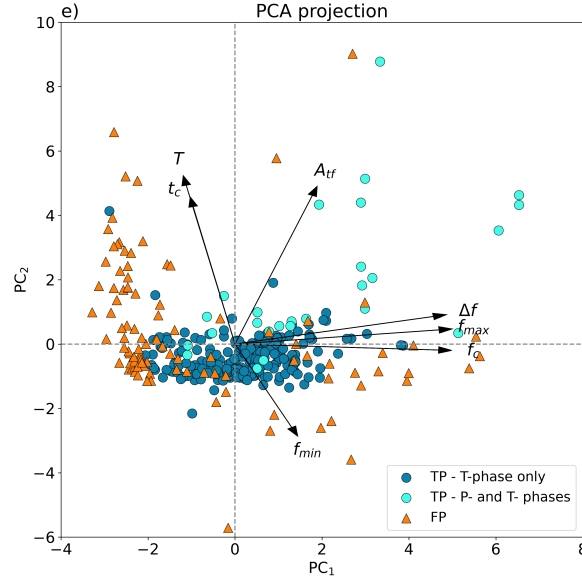


Figure S2 Additional PCA projection of ROI acoustic features, differentiating between T-phase and P_T phase True Positive detections, with blue and teal circles referring to T-phase and P_T phase, respectively. False Positive detections are shown by orange triangles.

S3 Key variables distribution

The distribution of values of the centroid time-frequency area found in True Positive and False Positive is shown in Figure S3.

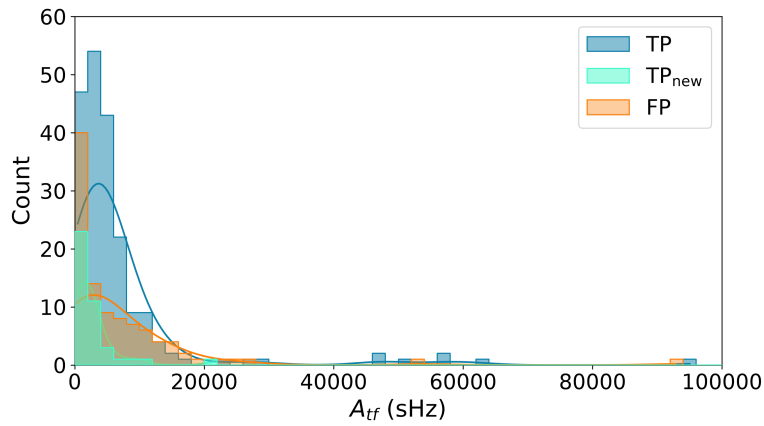


Figure S3 Histograms presenting distributions of ROI time-frequency area, A_{tf} . Blue and orange colours refer to True Positives and False Positives, respectively. Lines represent probability density functions for the two distributions.

S4 Summary of False Positive detections

Details of sounds responsible for False Positive ROI detections are given in Table S1. Among the 100 False Positive detections, 66 can be attributed to flow noise, in the form of continuous low-frequency (< 10 Hz) tones. Two of these occurrences featured other sounds that had merged into the ROI: One instance with a modulated tone (perhaps cryophonic) and one with an unverified broadband transient signal. False Positive detections linked to intermittent low-frequency sounds were a total of 20, which, when present, were observable across all hydrophones (but didn't always get picked up as an ROI). One instance occurred in September 2019, three instances in May 2020, one instance in June 2020, with the remaining occurrences between 23rd and 26th July 2020. The sources of these sounds have not been identified, and it is currently unclear whether the sound is related to the mooring designs.

A False Positive detection occurred at NERSC3 in April 2020, when there was a brief increase in background noise that could have resulted from wind-ice interaction (similar to what was observed in Figure S10). The causes for the remaining 13 False Positives ROI detections have not been identified ("Unknown"), but are described briefly in Table S1.

Cause for False Positive ROI detection	NERSC1	NERSC3	NERSC2	Total
Flow noise (constant low-frequency tone)	2	15	49	66
Intermittent low frequency sounds with harmonics	2	8	10	20
Remnant of background noise	0	1	0	1
Unknown - at start/end of recording	1	1	2	4
Unknown - tones (either constant or modulated)	0	4	1	5
Unknown - broadband transient	1	1	0	2
Unknown - low frequency noise	0	1	1	2
Total	6	31	63	100

Table S1 Summary table of main causes of False Positive ROI detections across the CAATEX dataset.

S5 Comparison of seismic events from land station and hydrophone recordings

During the recording periods of the CAATEX hydrophones, only 16 events have been located by the land stations of the Norwegian National Seismic Network (NNSN) and reported by the International Seismological Centre (ISC; Fig.1). Although 3 events did not have a moment magnitude (M_w) reported, the values of those reported spanned from a minimum of 2.7 to a maximum of 4.7 (Tab. S2). Only 5 of the 16 events have also been found in the hydroacoustic recordings. Among these, only 3 events have been associated with a manually labelled event (Event ID: 52, 79, 89), while two belong to seismic activity discovered by the ROI algorithm (Tab. S2).

Earthquake origin time	Latitude	Longitude	M_w	Event ID	ROI onset time
2019-10-14 00:29:48.0	80.317	-0.985	3.5	TP _{new}	2019-10-14 00:30:56
2019-11-04 12:12:58.1	80.236	-1.714	Not given	Absent	-
2019-11-12 00:25:13.4	80.453	-2.394	Not given	Absent	-
2019-11-12 12:32:39.2	81.721	-5.053	Not given	Absent	-
2019-12-12 00:03:31.0	80.466	-2.342	3.5	TP _{new}	2019-12-12 00:04:37
2020-01-08 12:07:47.1	86.369	37.532	3.3	52	2020-01-08 12:08:21
2020-01-15 00:33:06.8	80.779	-2.349	3.2	Absent	-
2020-02-16 00:02:46.7	80.689	-3.103	3.1	Absent	-
2020-03-03 12:35:49.8	80.143	0.128	3.4	Absent	-
2020-04-13 00:10:01.5	81.917	-5.104	2.7	Absent	-
2020-05-01 00:31:14.9	82.616	-6.368	3.1	Absent	-
2020-05-10 12:43:53.0	81.975	-4.507	3.1	Absent	-
2020-05-28 12:09:51.9	80.476	-1.078	4.0	79	2020-05-28 12:10:39
2020-06-15 00:16:33.4	82.252	-6.298	2.9	Absent	-
2020-06-22 00:33:53.4	81.934	-5.153	3.2	Absent	-
2020-06-27 00:23:09.7	82.825	34.791	4.7	89	2020-06-27 00:23:24

Table S2 Summary of earthquakes recorded by NNSN land stations concurrent with the active recording periods of the CAATEX experiment. Data for Earthquake origin time, Latitude, Longitude and Moment magnitude (M_w) were taken from ISC and NNSN land station records. Only 5 earthquakes recorded by land stations were associated with a T-phase signal recorded and computed as an ROI during the CAATEX experiment. There were two occasions where newly discovered seismic signals from the ROI algorithm (TP_{new}) related to these earthquakes. The Event ID and ROI onset time (start time, t_{start}) are given where possible. All other earthquakes were unobservable in spectrograms, and are labelled as 'Absent' here.

S6 Oceanographic setting

The ocean circulation in this region is still a topic of active research. While the Atlantic Water Boundary Current dominates further south along the continental shelf break north of Svalbard, the three moorings discussed in this paper were all positioned over relatively flat bathymetry (Fig. 1) and away from sharp density fronts. Both these aspects are related to weak and inconsistent currents. Possible circulation pathways around the Yermak Plateau, i.e., upstream of the moorings, have been described in model studies such as Athanase et al. (2020) and the combined model/observations studies by Koenig et al. (2017). However, observational coverage of circulation, especially at depth, is lacking. A thorough analysis of observations from the CAATEX moorings in a physical oceanographic context is the subject of an upcoming study (Dundas et al., 2026, in prep.).

In the region of the CAATEX moorings in the Arctic Ocean, observations showed that the temperature mixed layer extends down to ~ 100 m depth, followed by a layer of strong stratification down to the temperature and salinity maxima at ~ 200 m depth. Contrary, in summer, the salinity recorded at the surface was very low (Dodd et al., 2022) (Fig. S4). This is reflected in the sound speed profile, with its minima at the surface and a tens of meters thick layer of constant speed followed by a layer of rapidly increasing speed within the thermo- and halocline down to 200 m depth (Fig. S4). During the mooring period, the temporal variability of the sound speed profile was stable at NERSC1 and more variable further south at NERSC2 (Dundas et al., 2026, in prep.).

Moreover, during the CAATEX recordings, all three moorings were equipped with upward-looking Acoustic Doppler Current Profilers (ADCPs) located at ~ 45 m depth. The currents recorded were strongest at NERSC2. While all moorings were located on a relatively flat ocean floor (Fig. 1), NERSC2 is closest to persistent current systems guided by bathymetric contours, and thus expected to be influenced by the dominating circulation to a larger degree than NERSC3 and NERSC1. On average, the mooring drag on NERSC1 is northward, on NERSC3 northeastward, and on NERSC2 southward during deployment (Dundas et al., 2026, in prep.).

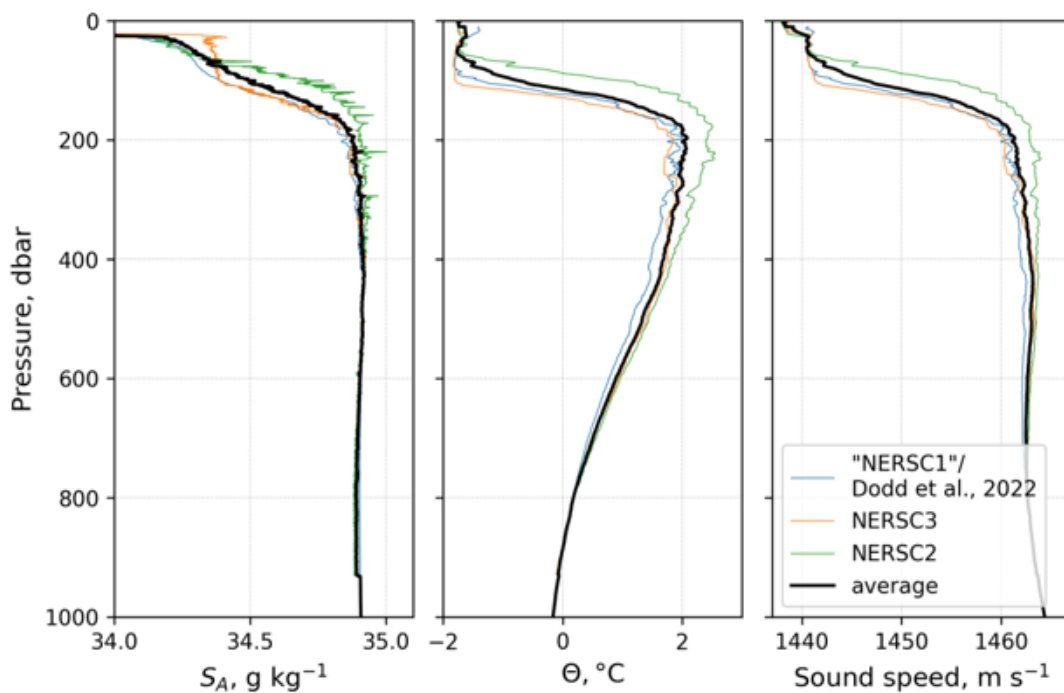


Figure S4 Profiles of absolute salinity (S_A), conservative temperature (θ), and derived sound speed at NERSC3 (orange), NERSC2 (green), and then NERSC1 from (Dodd et al., 2022) (blue), and their average value (black). Further analysis of hydrographic structure will be presented in Dundas et al. (2026, in prep.).

S7 Relationship between increased hydrostatic pressure and flow noise

The long-term spectrograms given in Figure 7 were compared to hydrostatic pressure data taken along the CAATEX moorings to understand the root cause of the low-frequency (< 20 Hz) continuous tones which resulted in the majority of False Positive ROI detections across the dataset. The spectrogram at NERSC3 is re-presented in Figure S5a alongside time series of hydrostatic pressure data collected at 160 m (Fig. S5b) and 1,020 m depth (Fig. S5c).

Among the CAATEX moorings, only NERSC3 had a pressure sensor placed at a depth near 1,000 m, which is comparable to the depths of the hydrophones used in this study. When comparing changes in hydrostatic pressure between the upper-ocean (shallow) sensor and lower-ocean (deep) sensor, the coefficient of determination (R^2) between the

two pressure time series was 1.0, indicating that the upper-ocean pressure can be used as a proxy for pressure at lower depths. Thus, shallow pressure sensors should suffice for determining depth changes of the moorings.

Across the data collected at NERSC3, the presence of the low-frequency tones appears to be concurrent with increases in hydrostatic pressure, and as such, it can be inferred that these tones are associated with flow noise during current-driven mooring pull-downs. However, it should be noted that there may be several other causes for these pressure increases unrelated to current-driven pull-downs, as the low-frequency phenomena seemed not to be present at each period of increased pressure. While the moorings NERSC2 and NERSC3 had simple spherical buoys, NERSC1 featured a hydrodynamic buoy (StableMoor®, DeepWater® Buoyancy, USA) and was notably less affected by both hydrostatic pressure anomalies and this noise phenomenon; therefore, it can be inferred that this design choice successfully reduced pull-down of the mooring cable.

Lastly, anomalies in ocean circulation can also be caused by, e.g., eddy shedding from the main topographically steered currents and by ocean surface stress exerted by the wind and sea ice. The latter mainly affects the upper ocean, but could still be a source of noise on the mooring line.

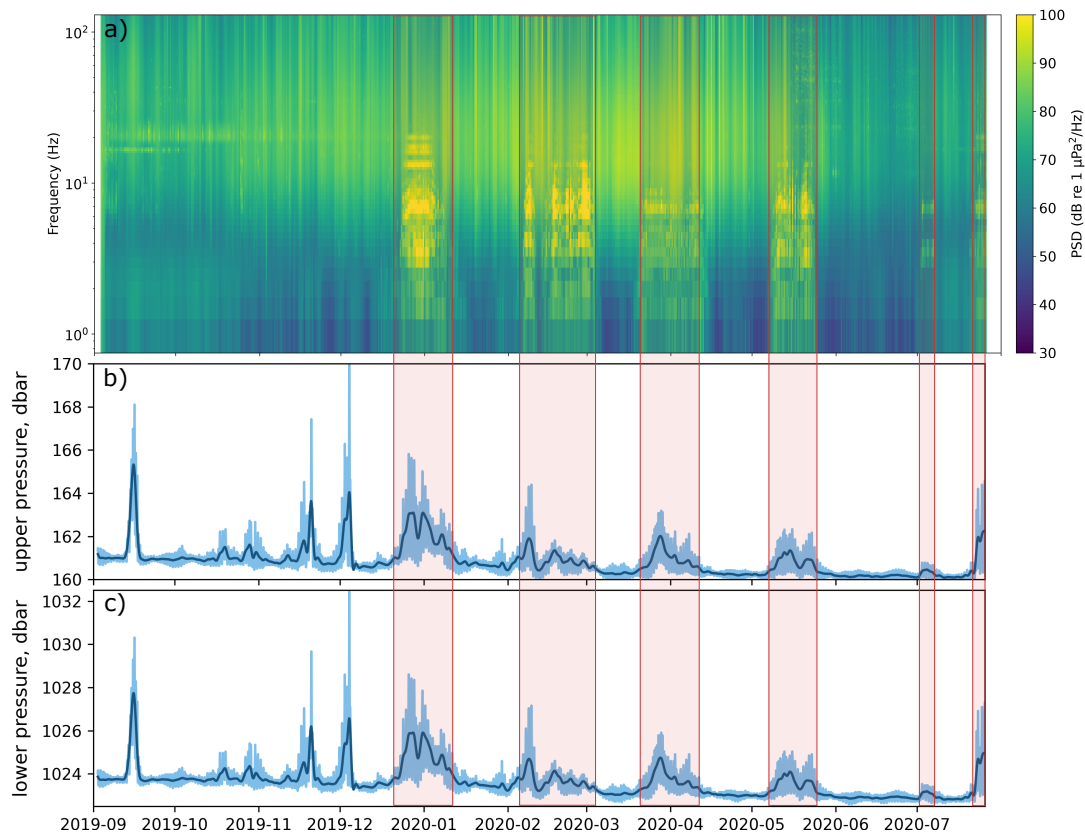


Figure S5 Time series from NERSC3: a) long-term spectrogram (reproduced from Figure 7), and observed hydrostatic pressure at the b) upper (160 m) and c) lower (1,020 m) pressure sensors. Pressure at 7-min resolution is shown in light blue and daily smoothed values in dark blue. For the smoothing, a 4th order Butterworth filter with a cut-off at one day is used. Red boxes highlight periods with elevated values of both noise and pressure. Further analysis of hydrostatic pressure data will be presented in Dundas et al. (2026, in prep.).

S8 Comparisons of background noise conditions in the Nansen Basin

The 50th percentile background noise spectra measured across the CAATEX dataset is plotted in Figure S6 alongside previous measurements of ambient noise spectra from a vertical hydrophone array drifting across the Nansen Basin (drifting from the North Pole to Fram Strait, from April to September 2013), reproduced from Ozanich et al. (2017). Ambient noise spectra from this study was only plotted selectively for a number of days between May and September 2013, the period of the year where sea ice coverage across the Arctic Ocean was past its maximum extent and began melting, reaching its minimum extent in September.

The high-pass filter implemented during the original recording during the CAATEX experiment had a cut-off frequency of 7 Hz, but the roll-off was undocumented. Therefore, the recorded background noise spectra below 7 Hz deviates from what is observed naturally, i.e. ambient noise gradually increasing with decreasing frequency. The spectra from Ozanich et al. were also affected by self-noise, with a peak prominent at 2 Hz, but *PSD* values appear to overall increase as frequency decreases. Above 10 Hz there is a broad peak centred towards 20 Hz, with *PSD* decreasing further along the frequency axis. Above 20 Hz, *PSD* spectra measured by Ozanich et al. are comparable

to spectra from CAATEX during the same months of the year. In the winter months of CAATEX (later-October 2019 to late-April 2020), background noise levels above 20 Hz were generally higher, something of which is observable from the long-term spectrograms given in Figure 7 (Sec. 4.5).

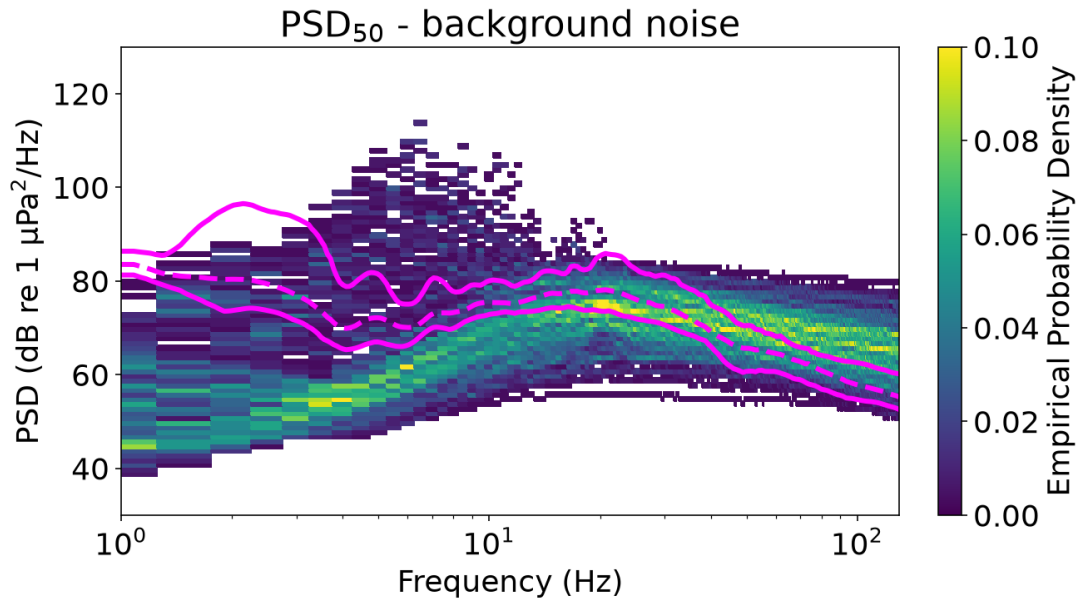


Figure S6 Empirical probability density plot of the 50th percentile PSD spectra (PSD_{50}) across all hydrophones of the CAATEX experiment, representing average noise spectra between recordings. This plot is compared with ambient noise spectra presented in [Ozanich et al. \(2017\)](#), shown in pink, with the upper/lower bounds of ambient noise given as solid lines and the mean given as a dashed line. Adapted from Ozanich, E., Gerstoft, P., Worcester, P. F., Dzieciuch, M. A., and Thode, A., Eastern Arctic ambient noise on a drifting vertical array, *The Journal of the Acoustical Society of America*, 142(4):1997–2006, 2017, Figure 9, with permission of the Acoustical Society of America. Copyright 2017, Acoustical Society of America.

S9 Summary of outcomes from benchmark test

The ROI algorithm was run against publicly available hydrophone datasets to test how it performed under different, lower latitude, underwater noise conditions. The two datasets, HYDROMOMAR-2013 and OHASISBIO-2020, previously used by [Raumer et al. \(2024b,a\)](#) to explore earthquake detection using Machine Learning tools, were selected for this task. The two datasets are provided by IFREMER (*Institut Français de Recherche pour l'Exploitation de la Mer*, Brest, France).

The HYDROMOMAR-2013 dataset consisted of four hydrophone moorings placed south of the Azores Archipelago for studying seismic activity along the Mid-Atlantic Ridge. Data from 11th to 17th November 2013 were available on the IFREMER data server. The OHASISBIO-2020 dataset consisted of 6 hydrophone moorings placed across three mid-oceanic ridges in the southern Indian Ocean. Data from 4th to 10th June 2020 were available on the IFREMER data server. All given hydrophones were placed at a depth of ~1,100 m, recording continuously at a 240 Hz sample rate, saving data to 6 hour long .wav files. For the benchmarking, the .wav files were truncated into shorter 45 min long files to match the recordings taken during CAATEX. Hydrophone calibration was provided by Raumer (pers. comm., July 2026): hydrophone sensitivities ranging between -164.5 and -163 dB re 1 V/μPa, and an analogue-to-digital conversion voltage of 2.5 V (0-peak). No pre-amp gain was used.

Firstly, ROIs were computed across the two datasets, without making any changes to the setup of the algorithm described in Section 3.3, and secondly, they were compared to the annotation datasets provided by IFREMER. All 82 annotated T-phase signals reported in the HYDROMOMAR-2013 and OHASISBIO-2020 datasets were identified as ROIs (Figs. S7 and S8). In the annotated datasets, there were many instances of signals labelled as ‘uncertain’, i.e., potentially seismic-related, many of which were picked up as ROIs (Fig. S7). Generally, higher background noise conditions, environmental or system-related, were encountered throughout these datasets compared to CAATEX. This resulted in more non-seismic ROIs, False Positives, being computed across files, which were distinguished by their short duration (< 10 s) and narrow bandwidth (< 5 Hz) (Fig. S8). These arose due to the low amplitude thresholds used in the binarisation mask stage of the algorithm (same as in the CAATEX dataset), which would pick up remnants of background noise across the spectrogram that were not fully suppressed during the Gaussian smoothing stage. Using higher amplitude thresholds would reduce the number of these small, non-seismic ROIs from being computed, or additional filters, based on the acoustic features, could be applied to ignore these ROIs (e.g., minimum duration and bandwidth limits).

ROI acoustic feature distributions for the T-phase signals detected in both the HYDROMOMAR-2013 and OHASISBIO-2020 datasets are presented in Figure S9. Annotated T-phase signals share similar distributions of acoustic features as the signals captured in the CAATEX dataset. T-phase durations were generally longer for both HYDROMOMAR-2013 and OHASISBIO-2020, partly due to several occasions where additional, proximate signals (potentially other T-phases) would be collected as part of the T-phase ROI (Fig. S9a). While the spectral features of T-phases from the HYDROMOMAR-2013 were comparable to those from CAATEX, those from OHASISBIO-2020 had greater variability in bandwidth and maximum frequency (Figs. S9b and S9c). The OHASISBIO-2020 dataset had a proportionally higher number of T-phase signals with bandwidths spanning the entire observable frequency range of the recording. Lastly, the spectral centroid distributions of the two datasets were comparable to those found in the CAATEX dataset (Fig. S9d).

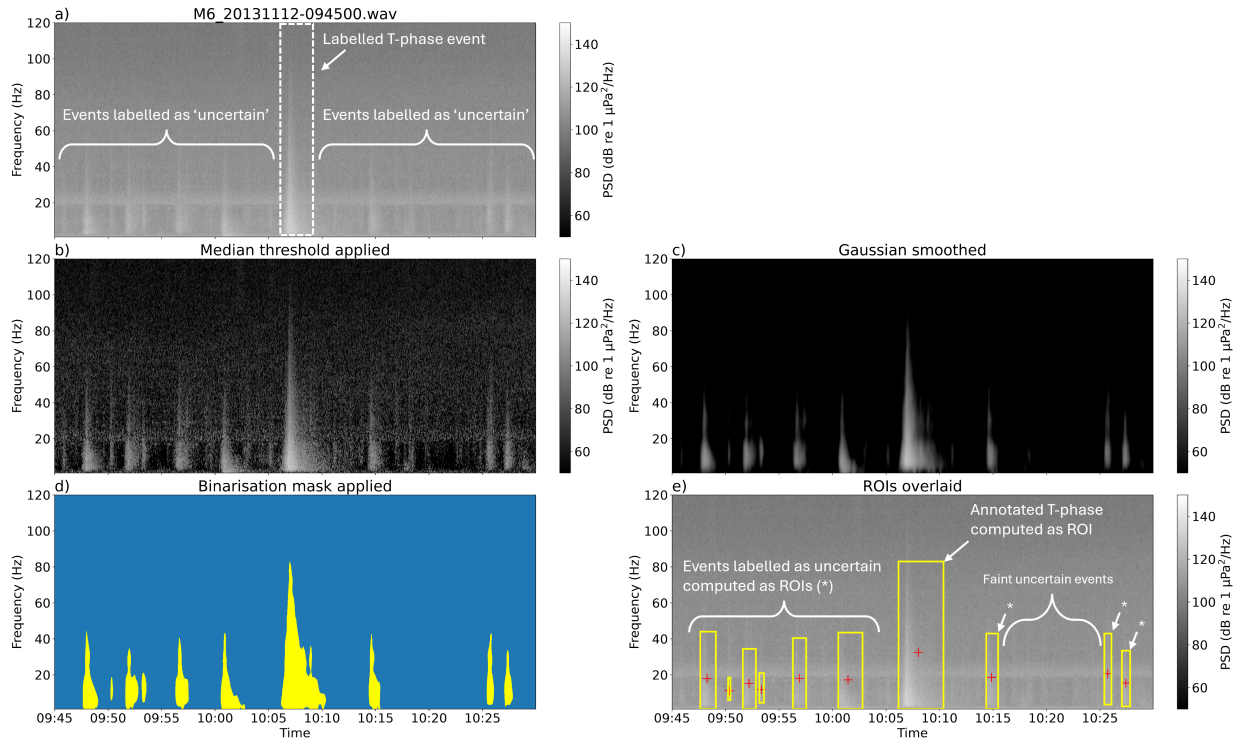


Figure S7 Spectrograms presenting the various stages of the ROI algorithm (described in the main text), using an example recording from the HYDROMOMAR-2013 dataset. A T-phase event (12/11/2013 ~10:06) that was verified in the IFREMER annotation dataset was successfully detected as an ROI. Across the recording, there are several other sounds that have yet to be verified as T-phase signals by IFREMER, many of which were also signalled as ROIs in the spectrograms.

S10 Example of rejected ROIs

When ROIs were computed along a spectrogram, a simple filter was applied to reject any ROIs that had a spectral centroid greater than 60 Hz, as they would not be associated with a seismic acoustic signal. Figure S10 presents an example spectrogram where several ROIs were computed, but ultimately rejected as they had spectral centroids exceeding 60 Hz. These ROIs were associated with intermittent increases in background noise due to wind-ice interactions.

References

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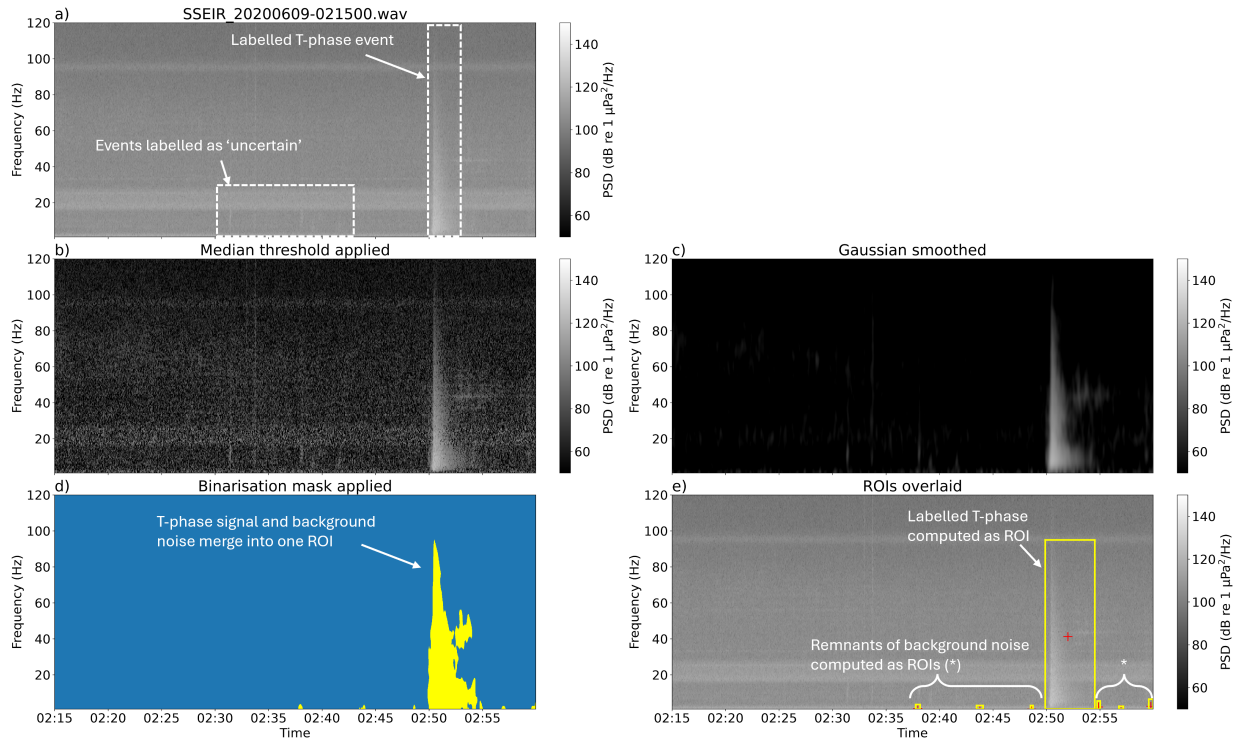


Figure S8 Spectrograms presenting the various stages of the ROI algorithm (described in the main text), using an example recording from the OHASISBIO-2020 dataset. A T-phase event (09/06/2020 ~02:50) that was verified in the IFREMER annotation dataset was successfully detected as an ROI. Note that some background noise close to the T-phase signal was not fully suppressed during the Gaussian smoothing stage, and ultimately was collected as part of the ROI. Across the recording, there are several ROIs computed for non-seismic acoustic phenomena (False Positives), resulting from unoptimised thresholds during the binarisation stage of the algorithm.

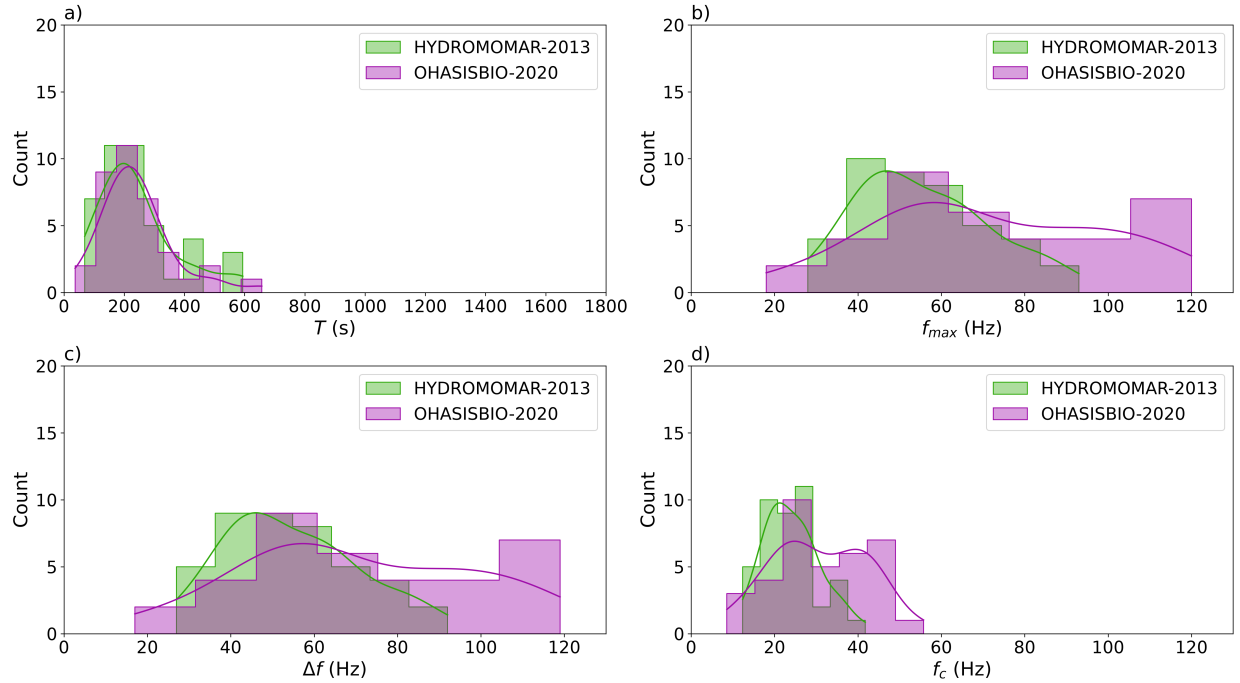


Figure S9 Histograms comparing the acoustic feature distributions for annotated T-phase signals detected as ROIs across the HYDROMOMAR (green) and OHASISBIO (purple) datasets: a) duration, T , b) maximum frequency, f_{max} , c) bandwidth, Δf , and d) centroid frequency, f_c . Lines represent probability density functions for the two distributions.

Raumer, P.-Y., Bazin, S., Cazau, D., Ingale, V. V., and Royer, J.-Y. Données hydro-acoustiques passives 240 Hz annotées en océan Atlantique 2013 et océan Indien Sud 2018 et 2020. *IFREMER*, 2024a. doi: 10.12770/b618b24e-82f9-4b3b-9753-048e1f043ca6.

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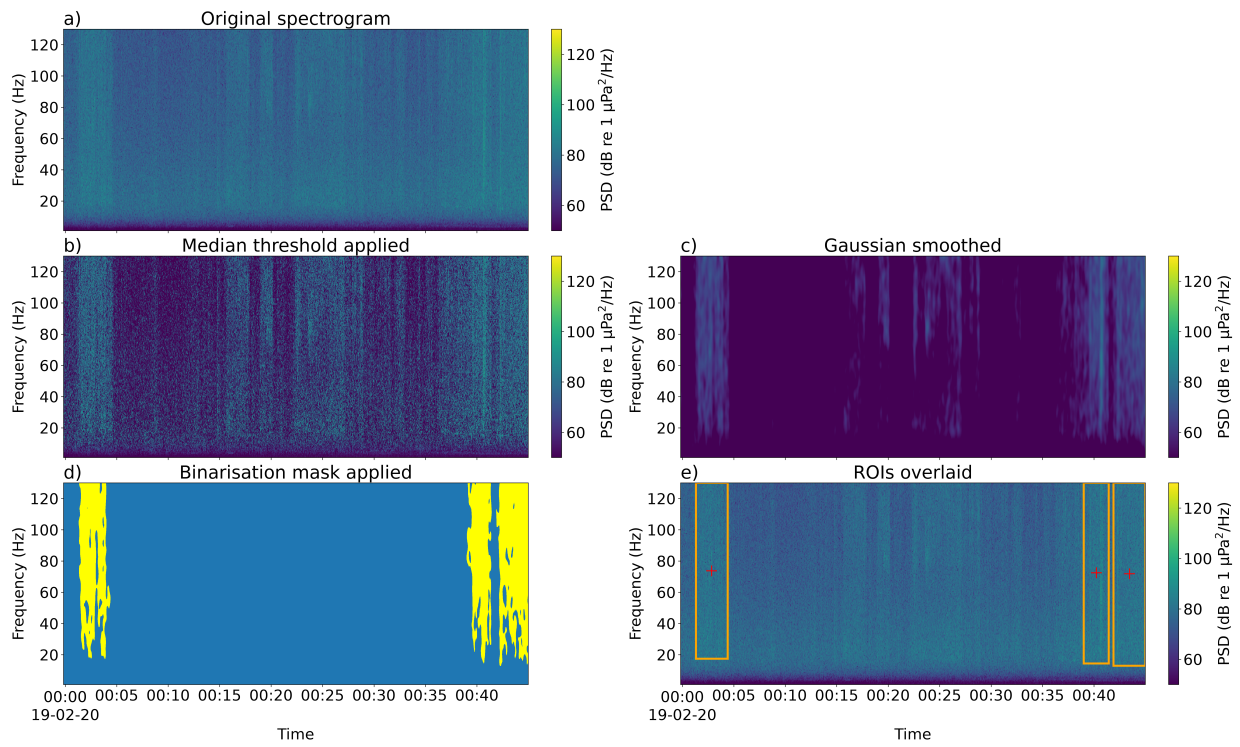


Figure S10 Spectrogram presenting an example of intermittent increases in background noise due to wind-ice interaction (Panel a), recorded at NERSC1. Components of this noise withstood the preprocessing stages (Panel b and c) and were computed as ROIs (Panel d), but due to the spectral centroid of these ROIs exceeding 60 Hz, they were ignored (as highlighted by an orange bounding box in Panel e).