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Corresponding author:
Julien Chaput; Email: jachaput@utep.edu

The singing firn

Julien Chaput[1], Richard C. Aster[2] and Marianne Karplus[1]

[1]Department of Earth Environmental and Resource Sciences, University of Texas at El Paso, El Paso, TX, USA and [2]Department of Geosciences and Warner College of Natural Resources, Colorado State University, Fort Collins, CO, USA

Abstract

Antarctic firn presents an exotic seismological environment in which the behaviors of propagating waves can be significantly at odds with those in other Earth media. We present a condensed view of the nascent field of ambient noise seismology in Antarctic firn-covered media, and highlight multiple unusual and information-rich observations framed through the lens of the firn's important role as a buffer for air temperature anomalies and a complex contributor to ice mass balance. We summarize key results from several recent papers depicting novel wind-excited firn resonances and point to the plethora of ways these observations could facilitate imaging and monitoring of glacial systems at single, isolated seismometers. Finally, we propose significant instrumental and computational objectives necessary to constrain resonance excitation mechanisms and broadly apply these observations as useful monitoring tools in Antarctica.

1. Introduction

Firn is broadly defined by the gradual transition from loose surface snow to solid ice through compaction, densification, pore closure and other effects, and is most often the uppermost structure for large glacial systems in polar regions. In Antarctica, firn covers approximately 99% of all glaciers (van den Broeke, 2008; Ligtenberg and others, 2011) and is both an integrated component of ice masses and a somewhat separate, exotic medium with significant structural variability. Accurately estimating the firn density profile has long been a primary objective of the glaciological community, but current models (e.g. Stevens and others, 2020) are unable to account for the swath of local effects that cause deviations from average assumptions. Ice flow and its related strain environment, for instance, have recently been shown to strongly affect layer density through settling (Horlings and others, 2021; Oraschewski and Grinsted, 2022). Effects related to environmental surface forcing, such as temperature changes and wind/deposition interactions, (e.g. Reeh and others, 2005; Reeh, 2008) can furthermore cause large perturbations in firn layering and density away from an assumed smooth gradient from snow to solid ice. Both effects cause significant uncertainties in firn profile estimates.

Beyond its global contribution as a challenging component of ice mass-balance estimates, the inherent porosity, parametric gradient and dynamic nature of the firn allow it to absorb environmental forcing in multiple ways, including pore space retention and refreezing of surface melt (Rennermalm and others, 2013; Steger, 2017; Vandecrux and others, 2020). In some cases, particularly with respect to ice shelves, the progressive loss of the firn can trigger catastrophic shelf failure due to melt ponding and hydrofracture (Kuipers and others, 2017), and ablation and reduction in albedo (Scambos and others, 2004; Leppäranta and others, 2012; Banwell, 2017; Kuipers and others, 2017; MacAyeal, 2018), as was the case for Larsen B Ice Shelf, resulting in accelerated ice flow across the grounding line following its 2002 collapse (Rignot and others, 2004).

Passive correlation-based seismic methods, which are widely applied to study structural temporal variability for seismic velocity and scattering properties, require the deployment of station arrays to construct interstation noise correlation functions (NCFs) through an approach called seismic interferometry (Campillo and Paul, 2003; Snieder, 2004; Wapenaar and Fokkema, 2006; Wapenaar and others, 2010). Such multi-station methods work best under conditions of ambient source stability and implement significant time averaging to reconstruct interpretable NCFs. Potentially large errors on the phase of reconstructed surface waves can be introduced when the noise source is not temporally and spatially stable, and this often precludes the use of higher ambient noise frequencies suitable for near-surface structures like the firn. Seismic inversions based on the surface wave components of the NCFs (e.g. Diez and others, 2016) are thus mostly insensitive to small-scale near-surface parametric contrasts such as ice lenses, hoarfrost layers and other embedded shallow features due to the averaging nature of the surface wave depth kernels at lower frequencies most often used in ambient seismic noise studies.

Although seismic interferometry has been leveraged successfully in a number of cryospheric studies (e.g. Diez and others, 2016; Mordret and others, 2016; Aster, 2019; Zhan, 2019) we focus here on spectral domain observations made at widely distributed individual isolated stations in Antarctica. Pervasive observations of high-frequency ambient spectral resonances at Antarctic seismic stations (Chaput and others, 2018) show a number of features that are relevant to firn structure and evolution. Wind-excited spectral peaks, termed firn resonances, manifest as patterns of sparse, spectral amplifications above 5 Hz that respond

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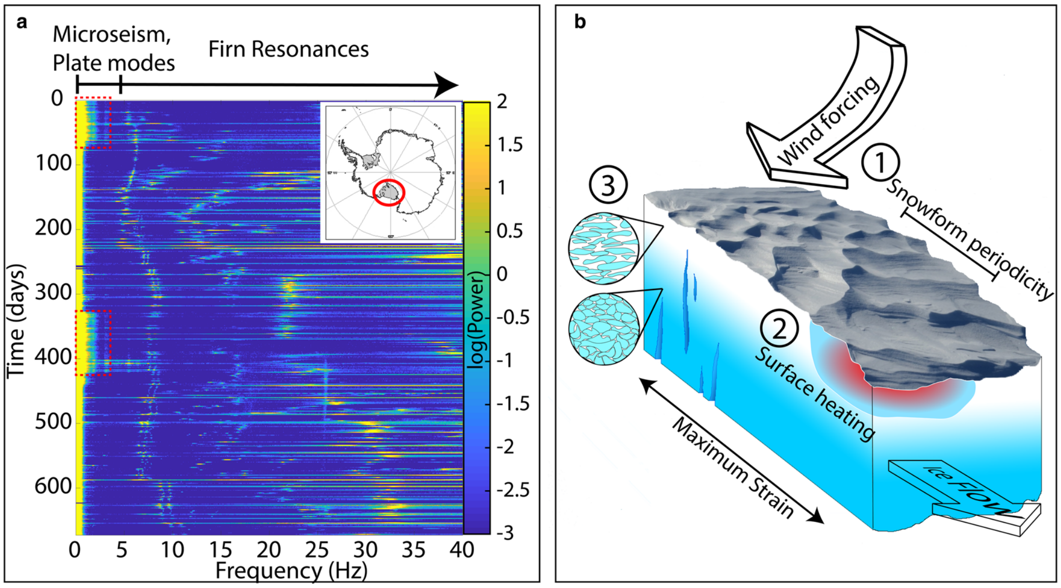

Figure 1. (A) Example of firn resonances from nearly two years of North component ambient seismic data recorded at station DR09 on Roosevelt Island from Ross Ice Shelf broadband array (red circle, inset map) displayed as a time/frequency plot (spectrogram) (Chaput and others, 2018). Red boxes indicate seasonal open sea ice conditions, and corresponding spectral effects are not observed at grounded sites. Stable shelf plate modes are visible as high amplitude temporally stable vertical bands below 5 Hz (notably during open sea ice conditions, red boxes), and temporally variable firn modes above roughly 5 Hz (observable year round). (B) Description of environmental effects that dictate the behavior of firn resonances. (1) Wind coupling with semi-periodic surface snowforms and the low-velocity/density firn structure excites unique firn mode patterns. (2) Firn is sensitive to anomalous near-zero surface temperatures, and the frequency range over which resonances are altered depends on the depth penetration of the temperature anomaly. (3) Firn accommodates strain associated with flowing ice masses in a ductile fashion at shallow depths where porosity is high, and in a brittle fashion where pores have largely closed.

strongly to environmental forcing phenomena such as storms and temperature anomalies, and are demonstrably sensitive to depth-dependent medium parameters such as anisotropy and layering. Here, we summarize three recent forays exploring these observations (Chaput and others, 2018, 2022a, 2022b) and emphasize the potential for significant information retrieval at single seismic stations deployed in firn media. We further elaborate on directions of study involving constraints on excitation physics that would allow these novel observations to be invertible quantities.

2. Firn resonances

Chaput and others (2018) first noted the presence of narrow band peaks in spectrograms of ambient seismic data on the Ross Ice Shelf (RIS; Bromirski and others, 2015, Fig. 1A), inferred to be excited by wind forcing. Such resonances have since been observed at other firn-covered locales including at the West Antarctic Ice Sheet (WAIS) Divide and South Pole, with varying types of instrumentation including completely snow-buried instruments with low to zero wind profile. Firn spectral peaks feature complex behaviors, including frequency shifts on the order of hours following strong wind events, response to surface softening or melt (e.g. Nicolas and others, 2017), multi-month drifts in peak frequency patterns, harmonic resonance patterns with broadband coherent drift or, conversely, behavior where multiple peaks shift independently of each other (Fig. 1A, basic forcing effects shown in Fig. 1B). These narrow band spectral peak patterns and their compelling spectrogram sonifications have further sparked interest from members of the arts community (e.g. Canadian audiovisual artist Sandra Volny and Emmy award winning composer Lucas Cantor, among others) who are developing multifaceted interpretive projects. The information content of firn resonances is surprising, particularly when one considers that observations are performed at single stations. We review primary results from three recent papers on the subject (Chaput and others, 2018, 2022a, 2022b), frame them in the context of broader community knowledge gaps and propose directions for future studies aiming to leverage sparse, single seismic stations for imaging and temporal monitoring efforts in firn media.

3. Boundary layer monitoring

Chaput and others (2018) noted that firn resonances are responsive to atmospheric boundary layer processes, including surface snowform alterations following waning storms (e.g. Sommer and others, 2018), temperature fluctuations near the melting point and long-term (i.e. months to years) peak frequency decay and drift hypothesized to be related to firn compaction. Figure 2A demonstrates that some storms are capable of dramatically shifting the frequency content of resonance patterns with their passing, pointing to a direct involvement of surface snowforms (e.g. sastrugi) on the source mechanism responsible for resonance generation. Indeed, 2D numerical wavefield simulations (Chaput and others, 2018) have shown that by changing the spatial periodicity of surface sources as a proxy for wind coupling, different frequencies can be naturally amplified. The very low seismic velocities of firn caused by high porosity also tend to drive these amplifications to overall lower, and hence observable, parts of the spectrum, compared to what we might expect in normal Earth media. Particularly strong storms can overcome surface grain sintering and alter snowform distributions (e.g. Sharma and others, 2019), as can storms with high airborne snow budgets (i.e. with deposition effects). If relative calm follows such a storm, the new spectral pattern will often slowly decay back to its original state over the space of months (e.g. Fig. 1A, black boxes), suggesting a sensitivity to steady-state surface erosion and compaction processes.

Furthermore, firn resonances are highly sensitive to surface temperatures as they approach melting, without necessarily even crossing the threshold into meltwater generation, as for example

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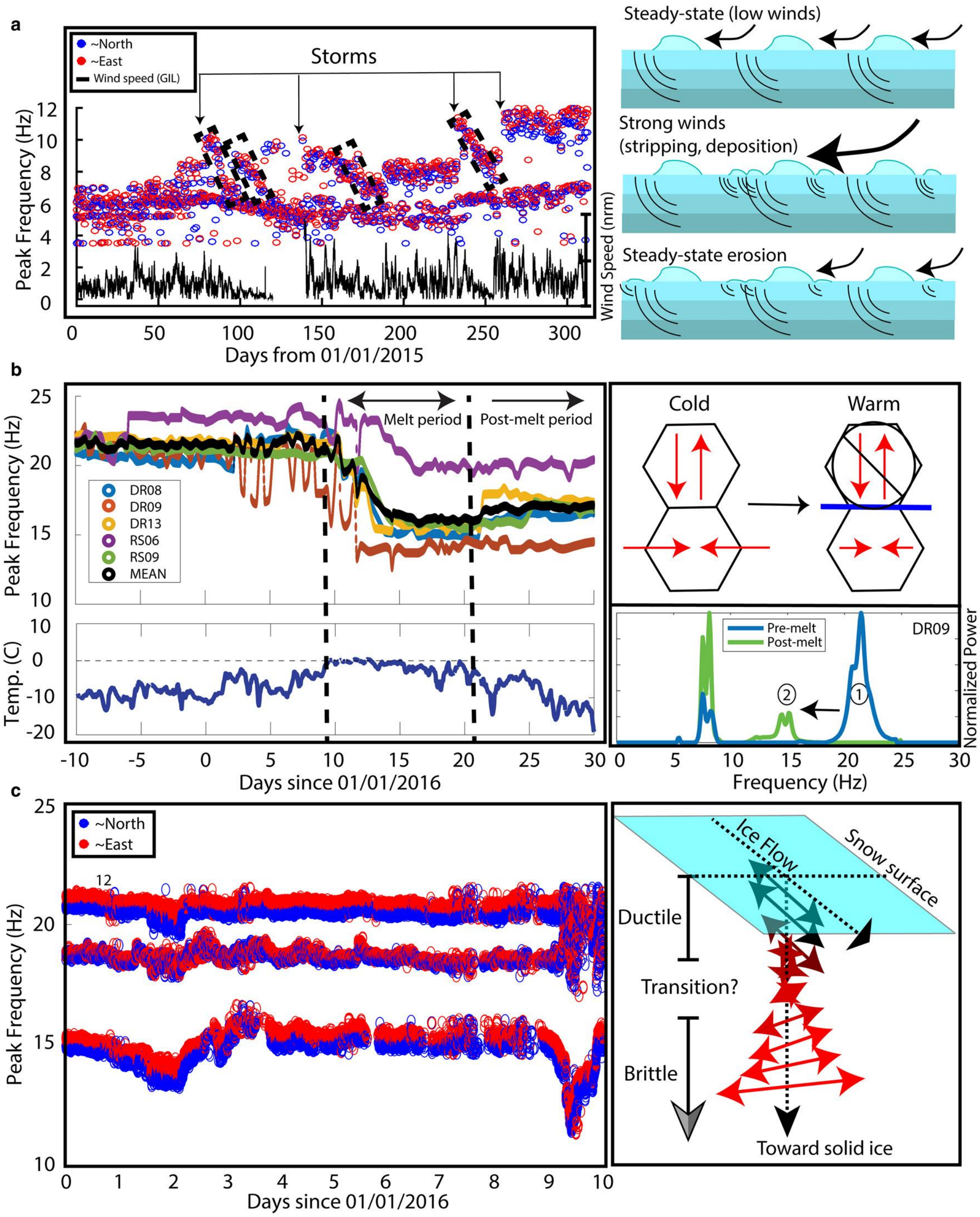

Figure 2. Examples of firn resonances show in 'peak tracked' form, where only peak maximums for both horizontal components of the spectrogram at each time bin are shown. (A) Firn resonance response to alterations in surface snowforms. Strong storm activity (arrows in left panel, matched with periods of high winds shown by the black trace), can deposit new snowforms that are then slowly eroded during periods of quiescence (right panel), resulting in slow spectral decay (time scale of months, black dotted boxes). (B) Peak tracked firn resonances at 5 stations on RIS during a shelf-wide near-zero temperature event in 2016 (bottom left panel, Nicolas and others (2017)). Firn undergoes up to a 40% reduction in elastic moduli (top right panel) as bonds between snow grains weaken, resulting in a downward drift in frequency for higher peaks and a reduction in amplitude (bottom right panel). (C) Peak tracked spectrogram at RIS station RS17 for 10 days during 2016, showing the obvious offset in frequency (also frequency dependent) between North and East components. Right panel: Shallow firn deforms plastically under extensional strain typical of RIS and features a strain-elongated pore space (black arrows aligned with ice flow), while deeper firn to solid ice responds in a brittle manner, often resulting in flow-perpendicular crevassing (red arrows) unless dominant crevassing is advected and rotated from past strain regimes.

observed during an extended period of near-zero temperatures on the Ross Ice Shelf in 2016 (Nicolas and others, 2017), and shown in Figure 2B. For all stations within the event area, the frequency content of higher frequency peaks drifted downward and fell in amplitude, hitting a minimum after 3–4 days, and partially recovered when a subsequent cold snap occurred. Takei and Maeno (2004) showed that snow undergoes up to a 40% reduction in elastic moduli as temperatures approach zero without even necessarily generating melt, pointing a direct link between increasing temperatures, decreasing seismic velocities and decreasing frequency content. The insensitivity of lower frequency firn modes (i.e. 5–10 Hz, shown in Chaput and others (2018)) to this event were physically interpreted through a surface-driven thermal diffusion model as noted in other snow studies (e.g. Gilbert and othets, 2014), where surface temperature anomalies without melt only reached a limited depth in the firn. Given

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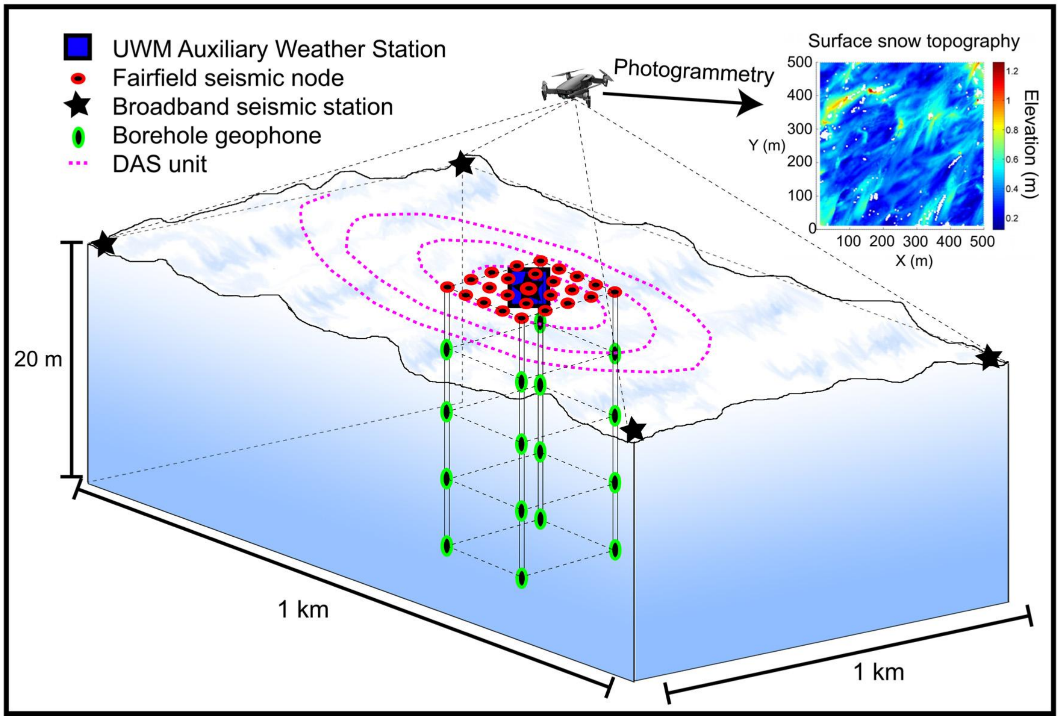

Figure 3. Multi-faceted seismic and distributed acoustic sensing (DAS) experiment coupled with drone-based photogrammetry aiming to make key firn seismic and environmental measurements to advance understanding of the firn medium and environmental forcing effects that govern resonance peak and other seismological observations, leveraging a long-running UW-Madison (UWM) autonomous weather or similar station (e.g. Lazzara and others, 2012).

strong evidence that firn resonances are related to surface wave excitation (Chaput and others, 2022a) with frequency-dependent depth sensitivities (i.e. lower frequency Rayleigh waves are on average sensitive to deeper structures than higher frequencies), firn resonances can be used to evaluate the depth penetration of temperature-related atmospheric forcing.

4. Constraining models of firn structure

As mentioned above, one of the most daunting barriers to accurately modeling firn density profiles lies in estimating fluctuations away from steady-state densification models. This encompasses, for example, elusive effects related to surface temperature forcing (e.g. Reeh and others, 2005; Reeh, 2008) and constraining the firn's settling behavior under different strain regimes (Horlings and others, 2021; Oraschewski and Grinsted, 2022). While studying past, and thus buried, strain effects and imaging fine layering due to ice lens and melt layers remain difficult problems, firn resonances offer potential avenues of study with the added benefit that the necessary observations can be performed on single sensors. Firn resonances present several interesting quantities that are at least partially invertible. Firstly, the spectral patterns themselves may offer constraints on firn structure, as shown by Bayesian explorations of resonances for 2D models Chaput and others (2018), with the caveat that resonance peaks are a combination of both surface source distributions and firn structure. Chaput and others (2022a) furthermore showed that resonance peak patterns are indeed affected by local structures, and their frequency content follows similar spatial variation trends to several other well-known site response metrics associated with Rayleigh waves propagating in strong parametric gradients, such as the widely used H/V ratio (e.g. Nakamura, 1989) and Rayleigh wave particle motions patterns (e.g. Tanimoto and Rivera, 2005; Denolle and others, 2012; Berbellini and others, 2016). Given that overhead satellite imagery offers the potential for estimating surface snowform distributions, firn resonances could be coupled with these other metrics in a joint inversion of firn profiles (particularly with H/V, since it is another single station measurement).

Chaput and others (2022b) noted that spectral patterns can be mined for another interesting parameter set, as they almost universally display a frequency offset between the seismometer's orthogonal horizontal components (referred to here as 'peak splitting') that can be interpreted in the context of azimuthal anisotropy. This link was confirmed with active sources at WAIS Divide as part of the TIME project (Chaput and others, 2022b). Azimuthal anisotropy from firn resonances was interpreted as being governed at greater depth and lower frequencies (<∼25 Hz) by remote-sensing visible advected crevasses in the ice governed by strains imparted through accelerating flow (Ledoux and others, 2017), and at shallow depths and higher frequencies (>∼25 Hz) by plastic elongation of the pore space in the shallow firn. Although this latter mechanism has not been directly observed in snow, it has been widely studied in materials engineering (e.g. Melon and others, 1995, 1998; Tita and Caliri Junior, 2012) and medical physics (e.g. Hosokawa and Otani, 1998; Lee and others, 2007) in terms of anisotropic properties of open-celled foams. For snow, this results in fast anisotropic directions that are aligned with ice flow (i.e. maximum extension) at higher frequencies and with crevassing at lower frequencies (Fig. 2C, right panel).

That being said, mapping these splitting observations to exact depths is a complex problem. Chaput and others (2022a, 2022b) numerically showed that Rayleigh waves propagating in realistic firn media (i.e. with strong shallow deviations away from a smooth densification model similar to those modeled by Reeh (2008)) will, at certain frequencies determined by fluctuations in structure, have their sensitivity become extremely focused at specific depths as opposed to smoothly distributed (Tanimoto and Rivera, 2005; Haney and Tsai, 2015). Thus, although it is clear that the transition between ductile and brittle strain accommodation in the firn occurs roughly at the same frequency for most seismic sites on RIS, suggesting a physical generality (Chaput and others, 2022b), it is unclear what that depth might be beyond conjecture or simple assumptions of smooth depth sensitivity. In the latter case, however, fundamental mode Rayleigh sensitivity kernels indicate a likely transition between 10 and 20 m for a firn profile derived by Diez and others (2016) for a dense array on RIS. Passive anisotropy measurements in firn settings describing a depth at which strain accommodation switches from ductile to brittle is an attractive goal, given that it describes a new form of depth transition in density that can be leveraged in profile estimations.

In light of the direct and physically justifiable causation between firn resonances and both structural and temporally variable metrics, there is a strong impetus for developing further physical models that reach beyond qualitative inferences. This push will require focused and interdisciplinary experiments.

5. Future work and directions

Although clear temporal and structural data products have been constructed from firn resonances through meticulous comparisons with other datasets, there remain multiple questions pertaining to the full physics that excite, propagate and induce temporal variations in firn mode frequency. A high-dimensional parameter space of cause and effect is expected here, and a commensurately focused multi-scale cross-disciplinary experiment should be employed, with a downstream goal of clarifying and interpreting these phenomena. We thus propose that the emerging field of cryoseismology (Podolskiy and Walter, 2016; Aster and Winberry, 2017) would greatly benefit from a dense multifaceted and sufficiently long-term experiment aiming to robustly constrain the seismic behavior of Antarctic firn. An experiment aiming to constrain the finer points of firn seismology should ultimately be able to document the following aspects of the Antarctic firn environment: (1) snowform topographic variability and its relation to the ambient seismic source, (2) the impact of strong near-surface layering and other structure on resonance patterns, (3) the types of seismic waves responsible for firn resonance observations, (4) 3D spatial variability of the resonance peaks with respect to ice cores and local structure imaged via other means and (5) influences of environmental forcing factors (e.g. temperature, wind strength and history, wind shear, wind direction, humidity, atmospheric pressure and depositional and stripping history) on the firn wavefield.

A concept sketch for such an experiment is depicted in Figure 3A. Wavefield separation into P and S components requires the calculation of the 3D wavefield gradient and curl, which in turn requires a 3D array of conventional three-component seismic instruments, rotational sensors or both (Schmelzbach and others, 2018). Mapping variability in surface structure (e.g. dunes and sastrugi) requires altimetry or photogrammetry methods (or both), and the ability to track changes over time. Assessment of influences due to any relevant above-snow mechanical instrumentation resonances requires on-instrument accelerometers (Qin and others, 2022). Characterization of environmental forcing and surface topography requires dedicated weather stations, such as the already long running Antarctic Automatic Weather Stations (AWS) Project (Lazzara and others, 2012) and optical camera, LIDAR or laser altimeter surveys. Accurately constraining the near surface velocity model and layering is also a key component of reducing parametric complexity in source effects. A dense nodal seismograph deployment combined with Distributed Acoustic Sensing (DAS) fiber optic strain rate, and snow core analysis (as an ancillary product of installing borehole seismometers, broadly supported by the US Antarctic Drilling Program) would provide directly sampled medium constraints. Finally, seismic modeling and inversion should be facilitated by a numerical model capable of replicating resonance patterns and other high-frequency seismic observables. For this, we require a framework capable of implementing a full 3D anisotropic velocity model with surface topography and distributed surface sources, such as SPECFEM3D (Komatitsch and Tromp, 2002).

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