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Monitoring Arctic Coastal Processes with Seafloor Distributed Acoustic and Temperature Sensing

Michael G. Baker[1], Robert E. Abbott[1], A. Christian Stanciu[1], Jennifer Frederick[1], Maddie Smith[2], Jim Thomson[3], Jake Davis[3], Andres F. Peña-Castro[4], Brandon Schmandt[4]

[1]Sandia National Laboratories, [2]Woods Hole Oceanographic Institution, [3]University of Washington, [4]University of New Mexico

Abstract

Fiber optic distributed sensing is a recent technology with an established capability for observing a wide range of geophysical signals. Buried or otherwise environmentally-coupled fiber optic cables, including those used for telecommunications, may be interrogated with a distributed acoustic sensor (DAS) or a distributed temperature sensor (DTS) for continuous and high frequency monitoring of seismoacoustic or thermal signals at meter-scale resolutions across linear apertures of tens of kilometers. We present results from the first-ever deployment of DAS to a polar seafloor environment, utilizing a 37 km portion of telecommunications cable located in the seasonally ice-covered Beaufort Sea, Alaska (Fig. 1). We show that this technology is capable of multi-seasonal, near real-time monitoring of ocean waves and sea ice dynamics, including formation, break up, extent, and thickness. We also discuss the prospects of a nascent, year-long continuous monitoring campaign leveraging both DAS and DTS to study seasonal variations in submarine permafrost in the Beaufort Sea.

Instrumentation & Data

Phase I consisted of eight one-week DAS-only campaigns across 2021 and 2022, targeting the seasons of the annual sea ice cycle: ice-bound, breakup, ice-free, and freezing (Fig. 2).

DAS signal-to-noise from the fiber optic cable was sufficient to record out to 37.4 km. Spatial and temporal resolutions were 2 m and 1000 Hz, respectively. Data volume was 3.1 TB/day, a total of ~160 TB.

Wave buoys were deployed above the cable in open water and on sea ice during the summer and shoulder seasons. Buoy spatial and temporal resolutions were ~5 km and 1 Hz, respectively.

Phase II consists of continuous DAS recording throughout 2023. Spatial and temporal resolutions have been reduced to 8 m and 100 Hz, respectively, for a data rate of ~550 GB/week.

DTS will be recorded at daily or sub-daily intervals with a spatial resolution of 2 m.

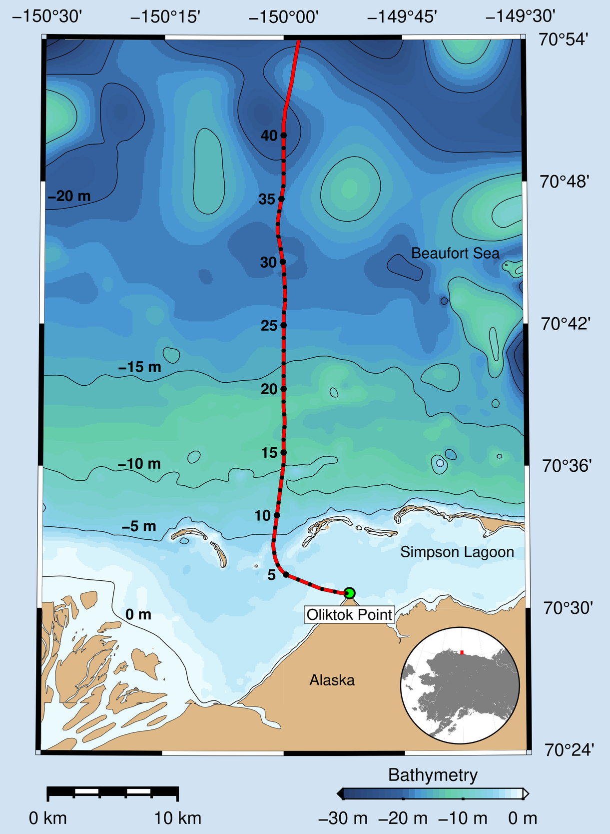

Figure 1. The telecom cable used to collect acoustic and temperature data. The cable is direct-buried 2 m below the seafloor.

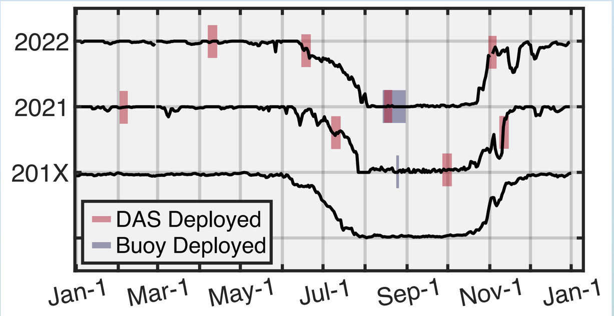

Figure 2. Sea ice concentrations at Oliktok Point during the Phase I campaign. '201X' is the median for 2010–2020.

Sea Ice Extent

Sea ice extent has been detected as a function of broadband spectral band power (Fig. 3) and machine learning-based classification of acoustic signals from water-ice collisions (Fig. 4).

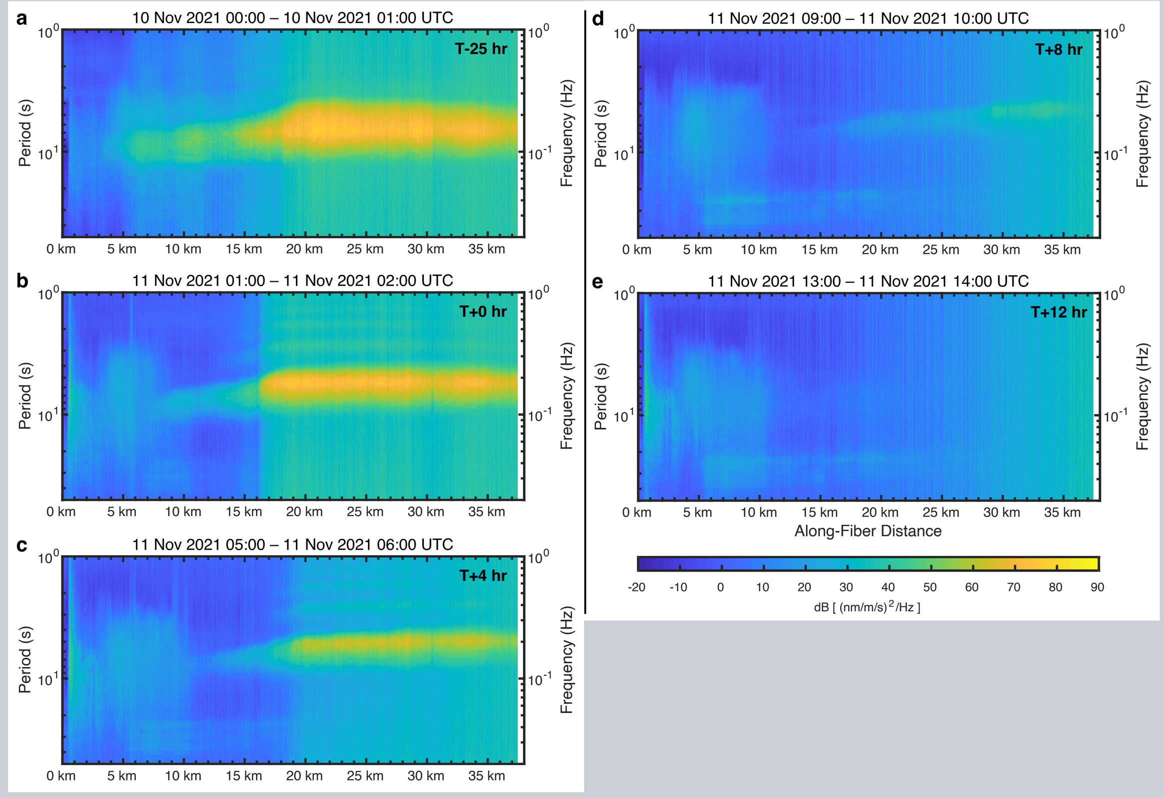

Figure 3. PSD estimates showing the rapid advancement of the sea ice front in response to a -10°C cold snap. The sea ice edge can be identified as the sharp transition from low (blue) to high (green) ambient noise. (Baker & Abbott, 2022).

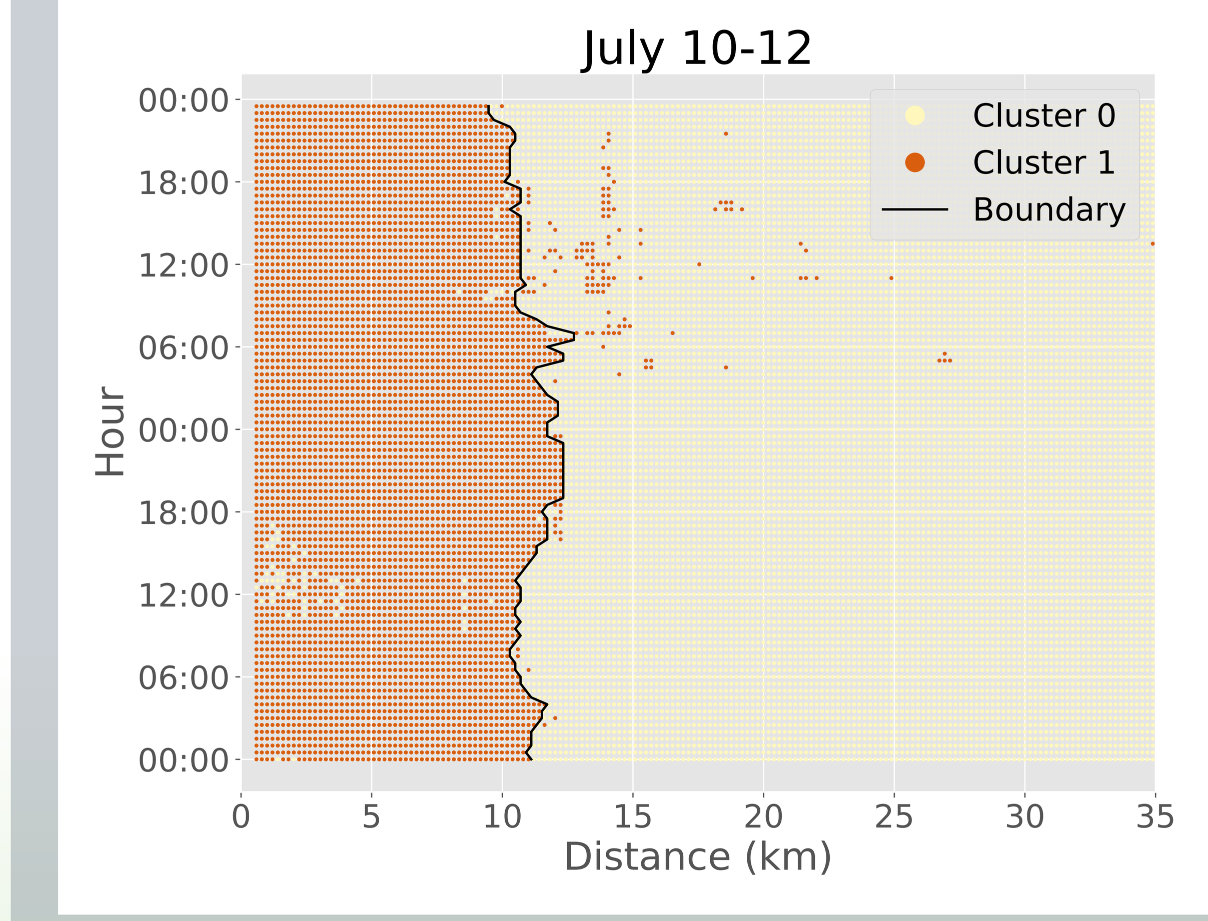

Figure 4. Spatio-temporal cluster classification of scalograms over a two-day span in July. Clusters 0 and 1 represent open water and sea ice, respectively. The black line represents the boundary between the two clusters. We use a spatial resolution of ~200 meters and a temporal resolution of 30-minute segments for the scalograms. The sea-ice boundary moves up to 3.2 km in the two days of data presented.

Ocean Surface Wave Height

Comparison with in situ wave buoys deployed during open water period (Fig. 5) are used to determine spatially-varying and frequency-dependent transfer coefficients.

Preliminary analysis of observations suggest DAS can capture low-frequency waves with high spatial resolution during both open water and partially ice-covered periods.

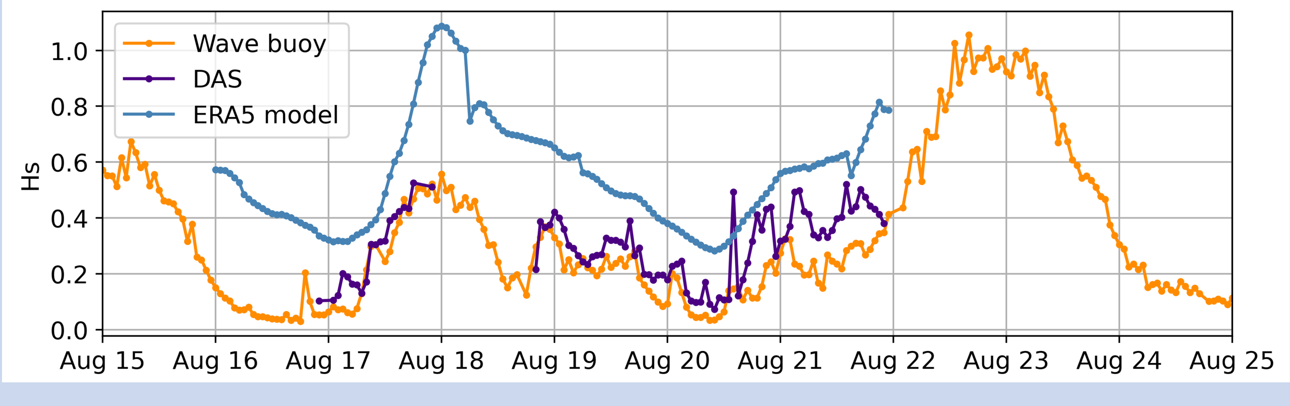

Figure 5. Comparison of wave heights during ice-free conditions in August 2022, as measured by a wave buoy at 16 km along-fiber distance, estimated by DAS, and hindcast by the ERA5 model. DAS is able to capture most of the variability in observed wave heights over the observation period. The DAS was powered off Aug 17 23:00 to Aug 18 20:00 UTC.

Spatial density of wave measurements from DAS enable high-resolution estimation of sea ice-wave attenuation coefficients (Fig. 6), with reasonable values for new sea ice (e.g., Cheng et al., 2017). In the example shown, the increase in attenuation coefficient with along-cable distance suggests an increase in along-cable ice thickness not resolvable with most wave measurement methods.

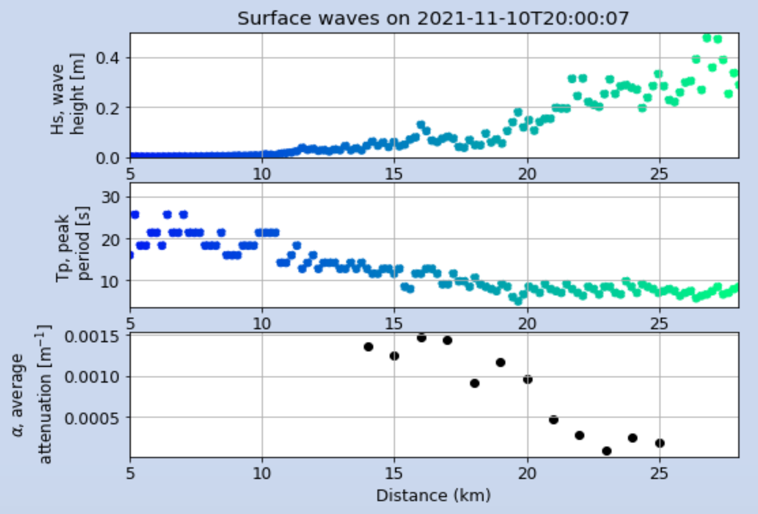

Figure 6. Temporal snapshot of wave conditions as estimated from DAS during a moderate wave event observed in partial ice cover, November 11, 2021. Wave heights decrease from approximately 27 to 10 km along-cable distance. Wave spectra are used to calculate average wave attenuation coefficients over the frequency band 0.2–0.3 Hz, which show reasonable values. See Fig. 7 for color scale.

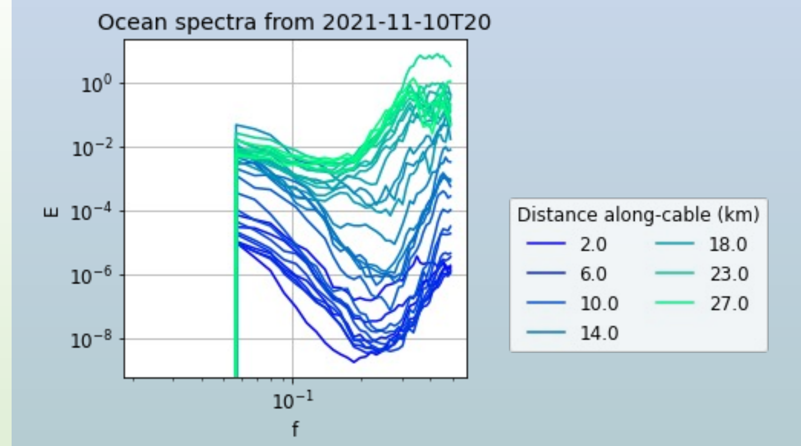

Figure 7. Select surface wave energy spectra from time shown in Figure 6, November 11, 2021. Colors correspond to distance along-cable, with blue denoting on-shore and green off-shore. Relatively high-frequency waves further off-shore are gradually attenuated along the cable by the ice.

Sea Ice Thickness

Flexural-gravity (FG) waves are dispersive and dependent on ice thickness and water column depth. Wind-driven FG waves occur only when wind speed is greater than FG wave speed. An empirical dispersion curve can be constructed by sampling FG wave spectral energy at a range of wind speeds. This dispersion curve can be inverted to provide an estimate of snow and sea ice thicknesses.

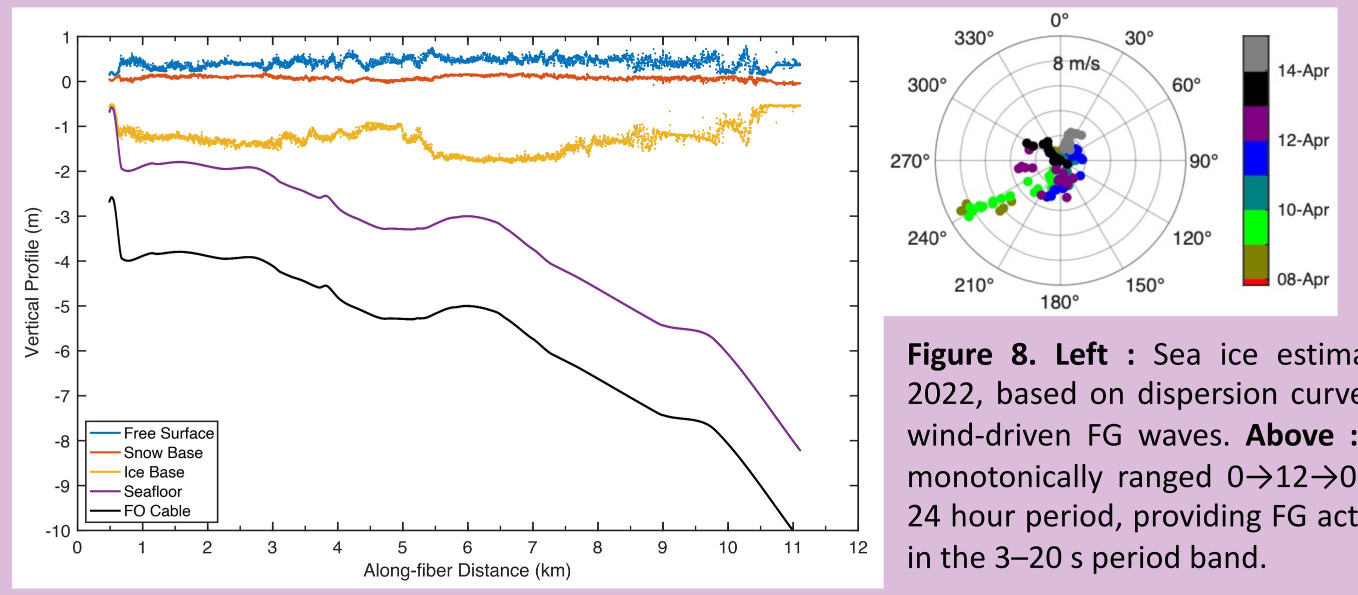

Figure 8. Left : Sea ice estimates for April, 2022, based on dispersion curve matching for wind-driven FG waves. **Above :** Wind speeds monotonically ranged 0→12→0 m/s during a 24 hour period, providing FG activation speeds in the 3–20 s period band.

Permafrost Thermal Modeling

DTS measurements will be used to calibrate dynamic models of the seafloor to study instabilities in the Beaufort Sea permafrost. PFLOTRAN (pflotran.org) will be used to simulate multiphase free gas, gas hydrate, ice, and liquid water systems in marine sediments under significant thermal and pressure perturbations, over geologic length- and time- scales.

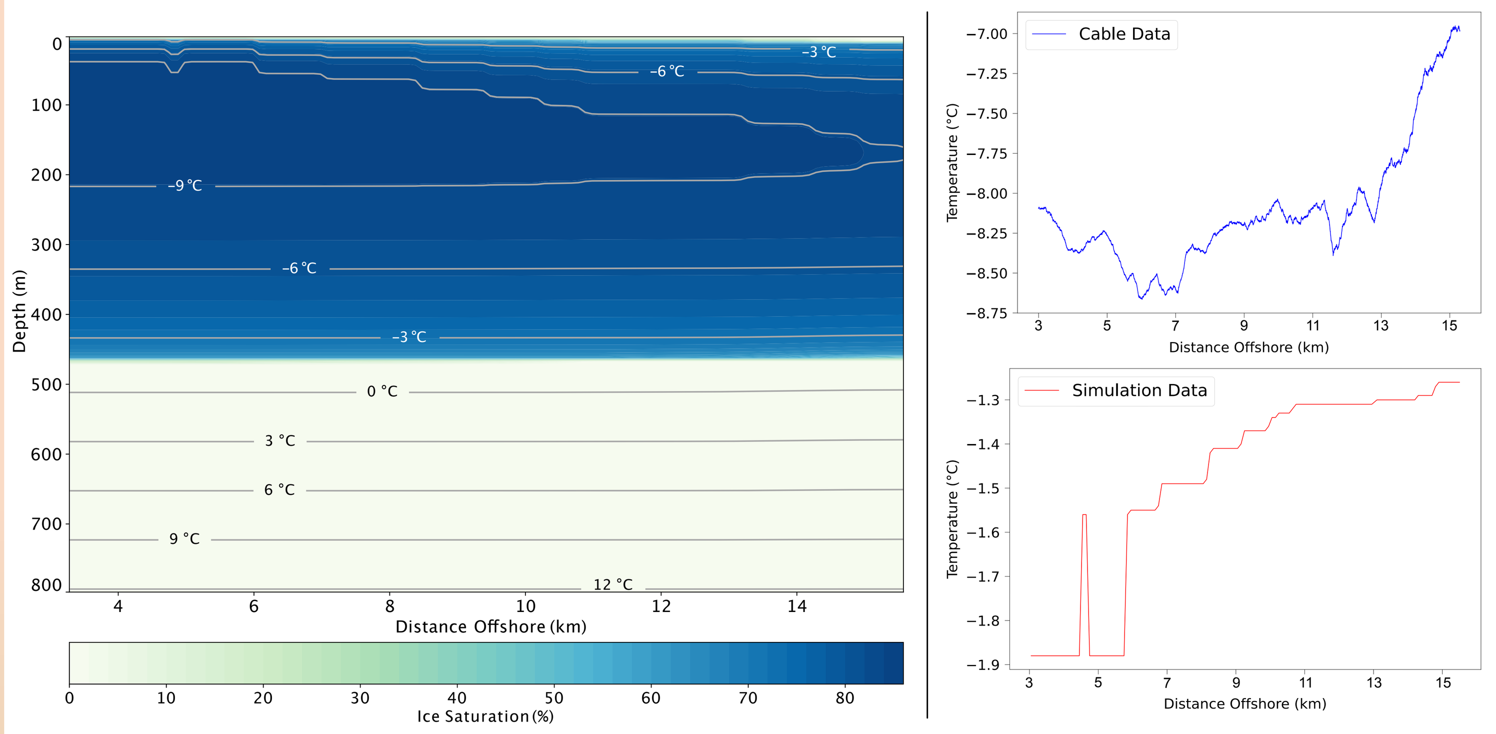

Figure 9. Left : A 2-D model domain, 800 m deep by 12.5 km wide, with bathymetry based on known cable depths. The boundary conditions applied to the top of the domain drive the evolution of temperature and submarine permafrost over the last 120,000 years. These are: Evolving pressure and temperature at the sediment surface which is location-specific and determined using the local bathymetry, and a relative sea level curve for the Beaufort Sea over the last 120,000 years that includes iso-static rebound. **Right :** Modeled temperature and ice saturation for theoretical present day conditions, compared to DTS measurements from Nov 2022. *In situ* boundary conditions provided by DTS will improve modeled estimates of permafrost stability.

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