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Multi-year occurrence of sei whale calls in North Atlantic polar waters

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ABSTRACT:
In 2009–2014, autonomous hydrophones were deployed on established long-term moorings in the Fram Strait and Greenland Sea to record multi-year, seasonal occurrence of vocalizing cetaceans. Sei whales have rarely been observed north of ~72°N, yet there was acoustic evidence of sei whale presence in the Fram Strait for several months during all five years of the study. More sei whale calls were recorded at the easternmost moorings in the Fram Strait, likely because of the presence of warm Atlantic water and a strong front concentrating prey in this area. Sei whale vocalizations were not recorded at the Greenland Sea 2009–2010 mooring, either because this area is not part of the northward migratory path of sei whales or because oceanographic conditions were not suitable for foraging. No clear relationship between whale presence and water temperature data collected coincident with acoustic data was observed, but decadal time series of water temperature data collected in the eastern Fram Strait by others exhibit a warming trend, which may make conditions suitable for sei whales. Continued monitoring of the region will be required to determine if the presence of sei whales in these polar waters is ephemeral or a common occurrence. https://doi.org/10.1121/10.0000931

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I. INTRODUCTION

Passive acoustic monitoring has become an increasingly popular means of studying the occurrence and distribution of vocal, pelagic whales. Acoustic data can be gathered remotely, continuously, and in challenging weather conditions. Autonomous or cabled instruments do not require researchers to remain on site while data are collected, which can be cost-effective and especially useful in harsh and remote environments. In 2009, we began a passive acoustic survey in Arctic waters of the North Atlantic in areas where, until recently, very little acoustic work had been conducted. In this study, autonomous underwater hydrophones (AUHs) were deployed in the Fram Strait and Greenland Sea in 2009–2010 and at three sites in the Fram Strait in 2009–2014. From these data, we were able to identify numerous species of vocalizing animals and their apparent movements into and out of this little-studied area (Klinck *et al.*, 2012). In addition to the well-known calls of sperm whales (clicks), blue whales (18 Hz moans), and fin whales (20 Hz pulses), pairs of ~80–30 Hz downsweeping sounds from sei whales (Baumgartner *et al.*, 2008) were also recorded.

The sei whale (*Balaenoptera borealis*) is a pelagic species that migrates seasonally between sub-polar and tropical regions and, as a result of over-exploitation by modern whaling operations, is considered endangered throughout its range (Cooke, 2018). In the North Atlantic, the sei whale has been referred to as the "forgotten whale" (Prieto *et al.*, 2012) as there is no reliable population estimate for the species and scant information on distribution and habitat use. Sei whales are found primarily south of 70°N and are often associated with strong oceanographic fronts and eddies (Skov *et al.*, 2008). In summer, sei whales have been observed in such diverse areas as the deep waters of the Mid-Atlantic Ridge (~ 54°N, Skov *et al.*, 2008), the Davis and Denmark Straits (Horwood, 1987), and off Iceland and southern Greenland (Vikingsson *et al.*, 2010; Cooke, 2018). Only two sei whales were sighted during surveys of the northeast Atlantic in 1987, 1989, and 1995–2009 (NAMMCO, 2010). Summer distribution seems quite variable from year to year and winter distribution is unclear. Movements of satellite-tagged sei whales between the Azores and the Labrador Sea (Olsen *et al.*, 2009; Prieto *et al.*, 2014) provide some insight into migratory routes.

Currently the International Whaling Commission (IWC) recognizes three stocks of sei whales in the North Atlantic: the Nova Scotia stock, the Iceland-Denmark Strait stock, and the Eastern stock (Donovan, 1991). Recent genetic studies of sei whales lacked sufficient evidence to dispute this three-stock structure (Huijser *et al.*, 2018). Although there is no information on the pre-exploitation abundance of sei whales in the North Atlantic (Prieto *et al.*, 2012), records indicate over 14 000 animals were taken from this area during late-19th and 20th century commercial whaling. An additional 70 sei whales were caught during scientific whaling operations off Iceland in 1986–1989; this

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was less than half the targeted number of 160 whales, as sei whales were difficult to find during the survey (Vikingsson *et al.*, 2010). Globally, sei whale populations have been estimated to be ∼20% of pre-whaling numbers (Cooke, 2018). Reliable population estimates for these stocks are unavailable because survey data have been collected for only small portions of the three areas or because consecutive surveys were conducted at different times of the year (Prieto *et al.*, 2012). Mid-July to mid-August sighting surveys in 1987 and 1989 for the northeastern and central North Atlantic (North Atlantic Sightings Surveys; NASS) resulted in an abundance estimate of 10 300 sei whales [coefficient of variation (CV) = 0.268; Cattanach *et al.*, 1993]. More recently, the 2010–2014 summer abundance for U.S. and Nova Scotian waters was estimated to be 849 (CV = 0.42) whales (Palka *et al.*, 2017), and approximately 10 000 in the North Atlantic (Pike *et al.*, 2019).

Sei whales are listed as endangered under the U.S. Endangered Species Act (Waring *et al.*, 2010) and by the International Union for the Conservation of Nature (IUCN; Cooke, 2018). A recent U.S. recovery plan (National Marine Fisheries Service, NMFS, 2011) for this species noted the lack of distribution and habitat use information available for sei whales, primarily because the pelagic nature of the species and the high inter-annual variability of feeding ground use make gathering such information via traditional line-transect and photo-identification surveys difficult and prohibitively expensive. Passive acoustic monitoring offers a cost-effective means of monitoring the occurrence and distribution of vocal, pelagic whales like the sei whale. Acoustic surveys have been used successfully to identify the presence of sei whales in the waters of Nova Scotia (Thompson *et al.*, 1979), New England (Baumgartner *et al.*, 2008), the Antarctic Peninsula (McDonald *et al.*, 2005; Gedamke and Robinson, 2010), and the Hawaiian Islands (Rankin and Barlow, 2007). In the Atlantic, Baumgartner *et al.* (2008) localized the source of the ∼1.5 s long, 80–30 Hz downsweeps they recorded in the Great South Channel and concluded they were from sei whales, and Newhall *et al.* (2012) opportunistically located calling sei whales off the coast of New Jersey. Here we report the geographic and seasonal occurrence of sei whale calls in the far North Atlantic to gain insight into sei whale Arctic habitat use patterns.

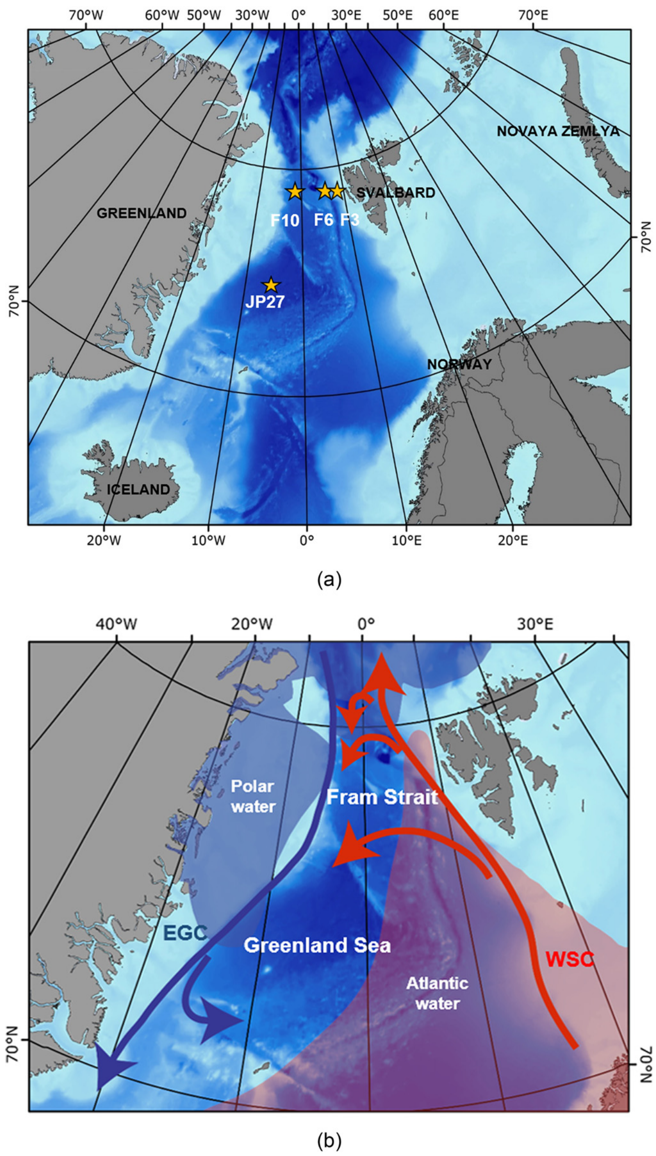

FIG. 1. (Color online) (a) Map of Fram Strait and Greenland Sea study area. Hydrophones (stars) were moored at established Alfred Wegner Institute moorings F6 and JP37 during July 2009–July 2010 and at F10, F6, and F3 during July 2010–July 2014. Hydrophones were not at all moorings in all years. (b) Currents influencing the oceanography of the Fram Strait [after Joiris and Falck, 2011, Fig. 1(a)].

II. MATERIALS AND METHODS

Instruments were deployed in the Greenland Sea during the first year of the study (2009–2010), and in the Fram Strait in all years of the study (2009–2014). The Fram Strait is a narrow region between the west coast of Svalbard and the east coast of Greenland (Fig. 1). This channel connects the Arctic Ocean and the Nordic Sea and is where most drifting sea ice exits in the Arctic. The juxtaposition of the West Spitsbergen Current (WSC), East Greenland Current (EGC), and Arctic Surface Water results in a clear front along both the east (Arctic Front) and west (Polar Front) sides of this Arctic water mass (Rudels *et al.*, 1994). This dynamic area of the Arctic has been monitored by numerous institutions, including the Alfred Wegener Institute for Polar and Marine Research, Germany (AWI), which has deployed a long-term array of oceanographic instruments (F1–F10) across the strait at 78° 50′ N (Mikhalevsky *et al.*, 2015).

In 2009–2014, calibrated AUHs designed by Oregon State University and the National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory were deployed via the icebreaker *R/V Polarstern* on moorings operated by AWI (Fig. 1). The mooring sites varied from year to year and depended on AWI research cruise priorities. In the first year of the study, one hydrophone was in the Greenland Sea at mooring JP27, and the other hydrophone was moored at F6. In all other years,

TABLE I. Information on acoustic recorders in the Fram Strait and Greenland Sea. Instruments were deployed on established moorings maintained by the Alfred Wegener Institute, Germany. During the second year of deployment, instrument failure limited our data to two months at mooring F3 and nine months at mooring F6.

Year	Greenland Sea 74° 56′N 04°3 7′W	Fram Strait F10 78° 50′ N 02° 00′ W	Fram Strait F6 78° 50′N 05° 00′E	Fram Strait F3 78° 50′N 08° 00′E
July 2009–June 2010	X		X	
July 2010–June 2011			X	X
July 2011–June 2012			X	X
July 2012–June 2013		X		X
July 2013–June 2014		X		X

hydrophones were moored at F3, F6, or F10 (Table I). The recording system sensitivity was −137 dB re 1 V/uPa at 100 Hz. Acoustic signals were continuously digitized at 2000 Hz sampling rate and 16-bit resolution with a low-pass filter cut-off frequency of 840 Hz.

Atlantic sei whale call identification was based on the criteria described by Baumgartner *et al*. (2008) and Tremblay *et al*. (2019). To automatically detect these calls, a spectrogram correlation detector was configured (frame size 0.26 s; 512 samples, overlap 50%, Hamming window; effective filter bandwidth 15.5 Hz) in the software *Ishmael 3.0* (Mellinger, 2001). Exemplar pairs of downsweeping calls (Fig. 2) with a high signal-to-noise ratio (SNR) were measured, and beginning and end frequency, duration, and sweep rate were used to build the contour of a two-part spectrogram correlation kernel (part 1: start time = 0 s, end time = 0.4 s, start frequency = 60 Hz, end frequency = 42 Hz; part 2: start time = 0.4 s, end time = 0.93 s, start frequency = 42 Hz, end frequency = 33 Hz). The detection threshold was set conservatively so that only calls with a high SNR (>10 dB) were identified, minimizing the number of false detections. Low SNR calls missed by the detector were not quantified and are not included in the analysis; thus, detected downsweep calls represent a minimum number of calls in the data.

All detections were verified by an experienced analyst (SLN) using the MATLAB based software *Osprey* (Mellinger, 2014) and *Raven Pro* (version 1.5 beta, Center for Conservation Bioacoustics, Cornell University, Ithaca, NY). Because numerous species of baleen whales make downsweeping calls, we were extremely conservative in our identification of sei whale vocalizations. To discriminate sei whale downsweeps from false detections of irregular mid-frequency downsweeps produced by Atlantic fin whales (Ou *et al*., 2015; Clark, 2012) and blue whales (Mellinger and Clark, 2003; Berchok *et al*., 2006; Ou *et al*., 2015), the detection had to meet both of the following criteria to be counted as correct: (1) high-confidence "type A" (Tremblay *et al*., 2018) downsweeps needed to sweep from approximately 80–30 Hz, be concave, and occur in pairs or within 1 min of a pair of downsweeps of similar amplitude, and (2) once "type A" downsweeps were identified, if a blue whale AB call or a fin whale 20 Hz call occurred within 1 min of the downsweep, the call was not labeled as a sei whale. Due to analysis time constraints, not all calls were examined and counted; once a call was confirmed in a day, the analyst moved on to the next day. This likely resulted in an undercount of sei whale calls, but because sei whale call occurrence was summarized as present or absent each day, we are confident that our methods coarsely but accurately reflect time periods when sei whales were present in our study area. To describe the seasonal and yearly patterns of vocalizing sei whales, detections were summarized as the percentage of days in a month with calls.

Water temperature data collected by instrumentation on AWI moorings was downloaded via the PANGAEA portal

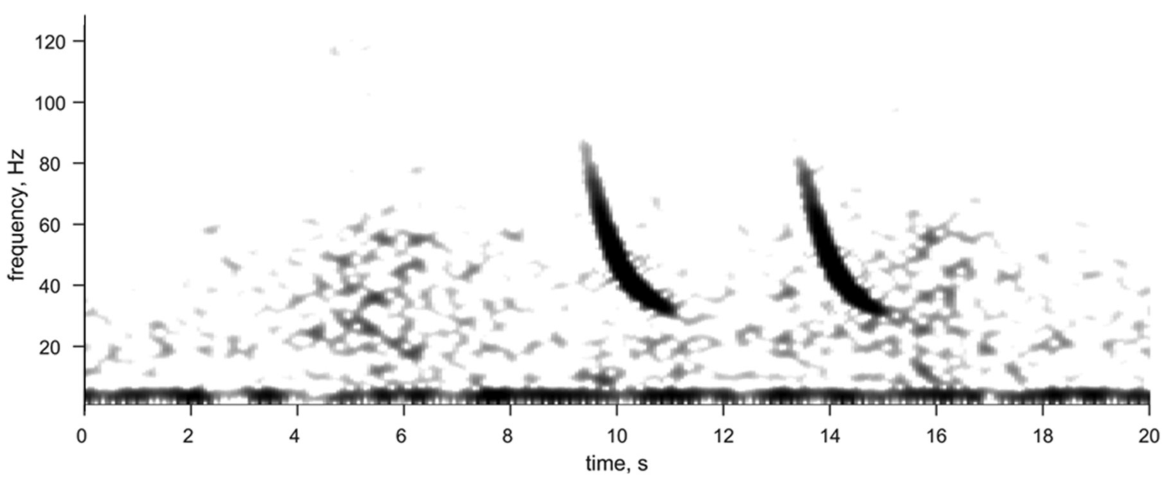

FIG. 2. Spectrogram of sei whale downsweeeps recorded 30 September 2010 on the Fram Strait F6 hydrophone [spectrogram parameters: 0.512 s frame and fast Fourier transform (FFT) length (1024 samples), 87.5% overlap, Hamming window, effective filter bandwidth of 7.9 Hz].

(von Appen *et al.*, 2019) and was used to investigate temperature fluctuations at our study site during 2009–2014. Depth of the temperature readings (20–1000 m) fluctuated with changes in instrumentation over the course of the study; we chose data likely relevant to diving sei whales collected at two relatively "shallow" depths (∼75 and ∼250 m) because sei whales are believed to be relatively shallow divers. Temperature data were not always available during time periods when acoustic data were collected. Sparse datasets for both the sei whale calls and water temperature data precluded a rigorous statistical analysis of correlation trends.

III. RESULTS

Between July 2009 and August 2014, over 85 000 h of data were recorded by our ten autonomous instruments deployed at the mooring JP27 in the Greenland Sea and at moorings F3, F6, and F10 in the Fram Strait. On average, the measured exemplar sei whale calls ($n = 246$) swept from 73.1 Hz [standard deviation (SD) = 9.2 Hz)] down to 29.1 Hz (SD = 1.4 Hz) over 1.85 s (SD = 0.47 s) and occurred alone, in pairs, and occasionally in groups of three to five downsweeps [Figs. 3(a) and 3(b)]. A second type of downsweep was observed that could have also been produced by a sei whale. A series of 3–5 quick calls downsweeping from 63.3 Hz (SD = 8.9 Hz) to 42.9 Hz (SD = 7.3 Hz) over 1.53 s (SD = 0.22 s, $n = 68$ calls) co-occurred with loud single or pairs of downsweeps of the same amplitude [Fig. 3(c)], suggesting the calls were potentially produced by the same animal or group of animals. These were not included in the daily summary of sei whale calls but noted for potential future investigation.

Sei whale calls were not detected in the 2009–2010 Greenland Sea data. In the Fram Strait, sei whale call detections occurred from late spring to early fall with most in summer (Fig. 4). Detected downsweeps were more numerous and were detected earlier in the season on the more eastern Fram Strait hydrophone, but precise trends are difficult to discern because of a lack of data from the hydrophone moored at F6 after July 2012.

Temperature data fluctuated seasonally (warmer in summer/fall) at both depths throughout the year at all Fram Strait locations, but later in the year (late fall) at the deeper moorings and less so at the F10 mooring (Fig. 4). There was no obvious warming trend in the temperature data and no clear correlation between these temperature data and sei whale calls perhaps because of a substantial lack of concurrent sei call and temperature time series data.

IV. DISCUSSION

The acoustic data collected in this study confirm multi-year presence of sei whales in the Fram Strait. The calls we recorded closely resemble Atlantic sei whale calls described by Baumgartner *et al.* (2008) and Newhall *et al.* (2012). Sei whale downsweeps have the potential to be confused with the downsweeping calls of other baleen whales; thus, we were extremely conservative in confirming vocalizations and only counted high-confidence "type A" calls. Because of this, and because our acoustic data represent calling animals only, our data likely underestimate sei whale presence in the Fram Strait. Trends in the number of calling sei whales are difficult to assess. We cannot estimate the number of vocalizing sei whales because we do not have enough information on the calling behavior of individuals. However, given the source level of sei whale calls [177 dB (root-mean-square, rms) re1 μPa, Romagosa *et al.*, 2015; 173.5 dB re1 μPa @ 1 m, Wang *et al.*, 2016), the distance between hydrophones (>60 km), and the complex oceanography of the Fram Strait, it was unlikely that the same whale call was recorded at two hydrophone stations simultaneously (cf. Stafford *et al.*, 2007), and, therefore, multiple calling whales were present at the same time in different parts of our study area in all years.

During time periods when acoustic data were available, sei whale calls were recorded during late spring, summer, and fall. This is not surprising, because like other baleen whales, sei whales are a migratory species, moving from low-latitude wintering areas to higher latitude summering grounds when the ice recedes (Horwood, 1987; Prieto *et al.*, 2012; Prieto *et al.*, 2014). In other studies, Ingebrigtsen (1929) reported six sei whales, including a female with a calf, at 79°N and 180 km west of Spitsbergen in June 1920. Jonsson (1965) reported that sei whales were caught off Iceland as early as June but most often in August and September. Sei whales were occasionally sighted off Greenland (Heide-Jorgensen *et al.*, 2007; Hansen *et al.*, 2019) from August to October and were recorded via autonomous hydrophones in the Davis Strait during the fall (Prieto *et al.*, 2012). High densities of sei whales have been reported in areas southeast of Cape Farewell, Greenland, during June and July (Sigurjónsson and Víkingsson, 1997; Waring *et al.*, 2008).

One of the surprising results of this study was that we recorded sei whale calls in the Fram Strait (∼79°N) during five consecutive years. Historically, the sei whale, a subpolar species, was rarely sighted in Arctic waters and was not typically found beyond approximately 72°N (Ingebrigtsen, 1929; Horwood, 1987). On occasion, whalers identified "sei whale years," where atypical numbers of animals moved north (Ingebrigtsen, 1929; Prieto *et al.*, 2012), but this was unusual. What could account for the difference between these historical and recent observations? One explanation could be that the consistent multi-year presence of sei whales in the Fram Strait identified in this study may be a reflection of the increased survey effort afforded by a passive acoustic survey. Historical data are based on visual observations of sei whales, which are difficult to spot due to their cryptic nature and small size (Pike *et al.*, 2019). Visual surveys in this polar area are conducted episodically and for only a few months a year and in appropriate sea states. In contrast, passive acoustic data can be collected year-round, at all hours of the day and during challenging weather conditions. It may be that a passive acoustic survey is a more efficient way of identifying the presence of cryptic species in this remote environment.

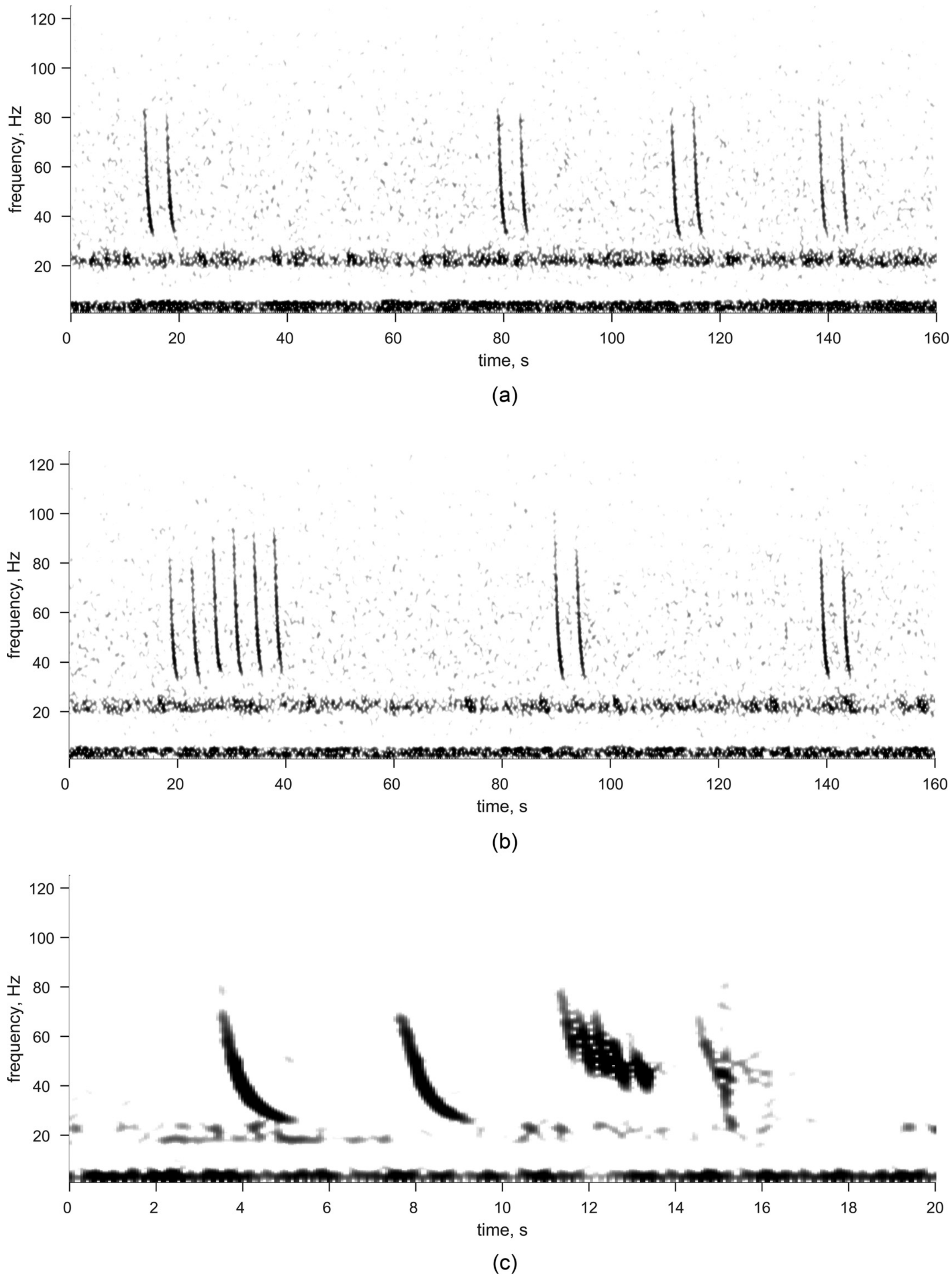

FIG. 3. (a) Example of a series of sei whale doublet ("type A") calls. (b) A series of six downsweeps and sei whale doublets similar to those reported by Tremblay *et al.* (2019). (c) Two sei whale downsweep calls and an additional series of 3–5 quick downsweeps with the same amplitude possibly produced by the same sei whale or one in the same group [spectrogram parameters: 1.024 s frame and FFT length (2048 samples), 87.5% overlap, Hamming window, for an effective filter bandwidth of 3.96 Hz]. Note different time axes.

An alternative explanation for the multi-year presence of sei whales at this latitude is that conditions are changing in the Fram Strait. Historically, the northern extent of sei whale distribution was thought to be limited by cold polar water, but in these areas and others around the Atlantic, periodic influxes or "invasions" of sei whales were reported to coincide with warm water intrusions into an area (Kapel, 1985). During a 2005 survey, a record number of sei whales off West Greenland coincided with the warmest recorded sea surface temperatures since 1876 (Heide-Jørgensen *et al.*, 2007). In our temperature data, we did not observe any clear warming trend at each mooring site beyond the typical

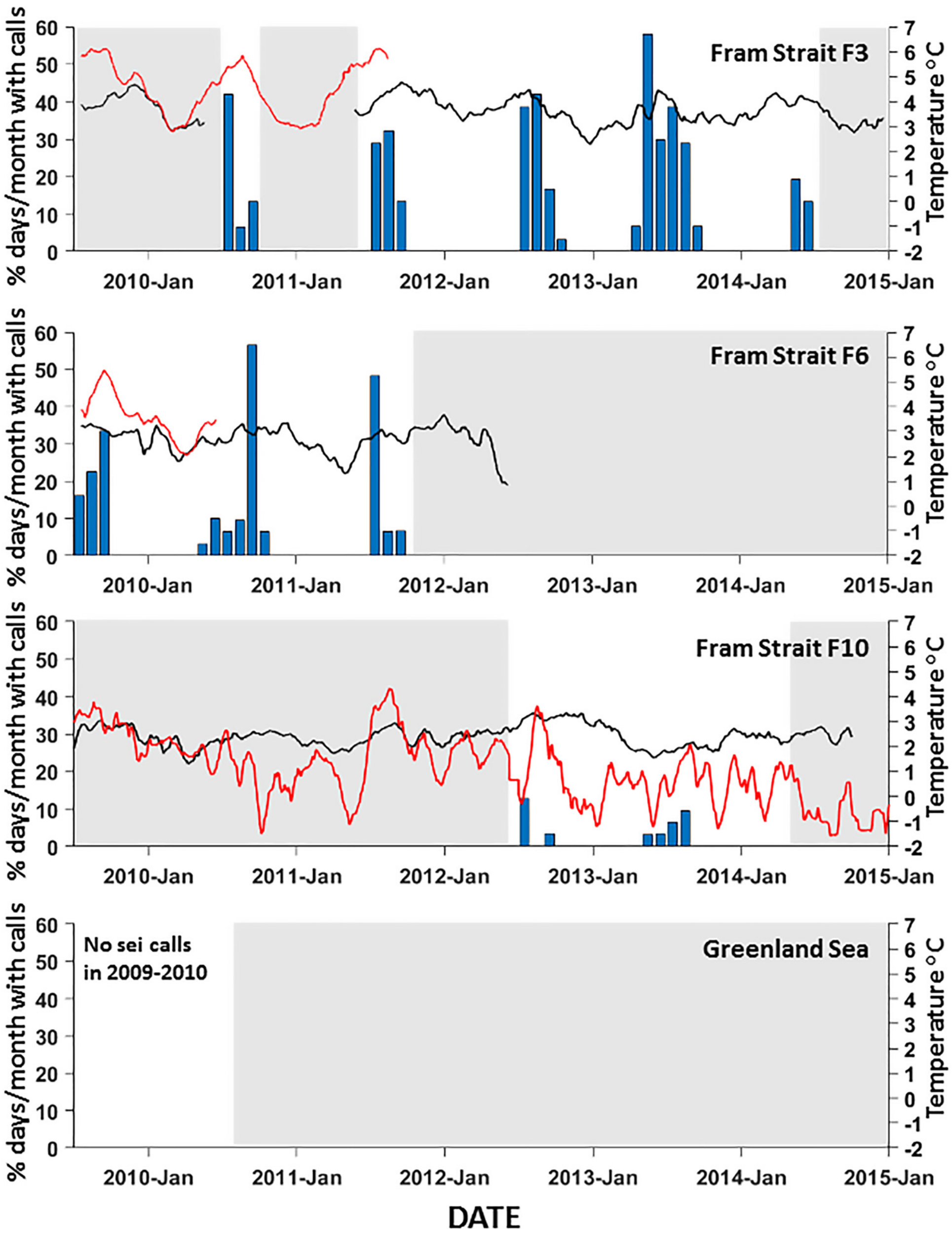

FIG. 4. (Color online) Percentage of days in each month with sei whale detections (bars) and water temperature (°C) at ∼ 75 m depth (red line) and ∼250 m depth (black line). Only high-confidence "type A" calls were included in this analysis. Water temperature data courtesy of von Appen *et al.* (2019) and downloaded from the PANGAEA database. Hydrophones were not moored at all sites in all years. Shaded areas represent no data. There were no detections of sei whale calls at the Greenland Sea site.

seasonal trends, but our dataset was sparse, precluding a rigorous analysis of any potential correlations. However, investigators working with a longer timeseries of Fram Strait temperature data (1997–2010) occurring before this study observed an increase in the mean temperature of Atlantic water of 0.06 °C/year (Beszczynska-Möller *et al.*, 2012). Others working with more recent data report a 0.05 °C/decade increase in the deep water of the Fram Strait (von Appen *et al.*, 2015) and the 10-yeare running mean temperature of the West Spitsbergen Current increased from 4.4 °C in 1963 to 5.8 °C in 2016 (MOSJ, 2019). In addition, it appears we detected more sei whale calls on the two moorings influenced by warm Atlantic water in the eastern Fram Strait; the westernmost mooring, F10, is influenced by both warm Atlantic water but also cold polar water (von Appen, 2019; Fig. 5).

In addition to warm water, sei whales are often associated with strong oceanographic fronts and eddies, most likely because these features concentrate prey (Nasu, 1966). The presence of numerous sei whales in 2004 along a front near the Mid-Atlantic Ridge was correlated with a concentration of *Calanus finmarchicus*, a preferred prey of sei whales (Skov *et al.*, 2008). In other studies, the novel occurrence of sei whales in inshore waters was in response to changes in prey distribution (Jonsgård and Darling, 1977; Schilling *et al.*, 1992). The Fram Strait is an area with strong oceanographic features that concentrate prey (Spielhagen *et al.*, 2011;

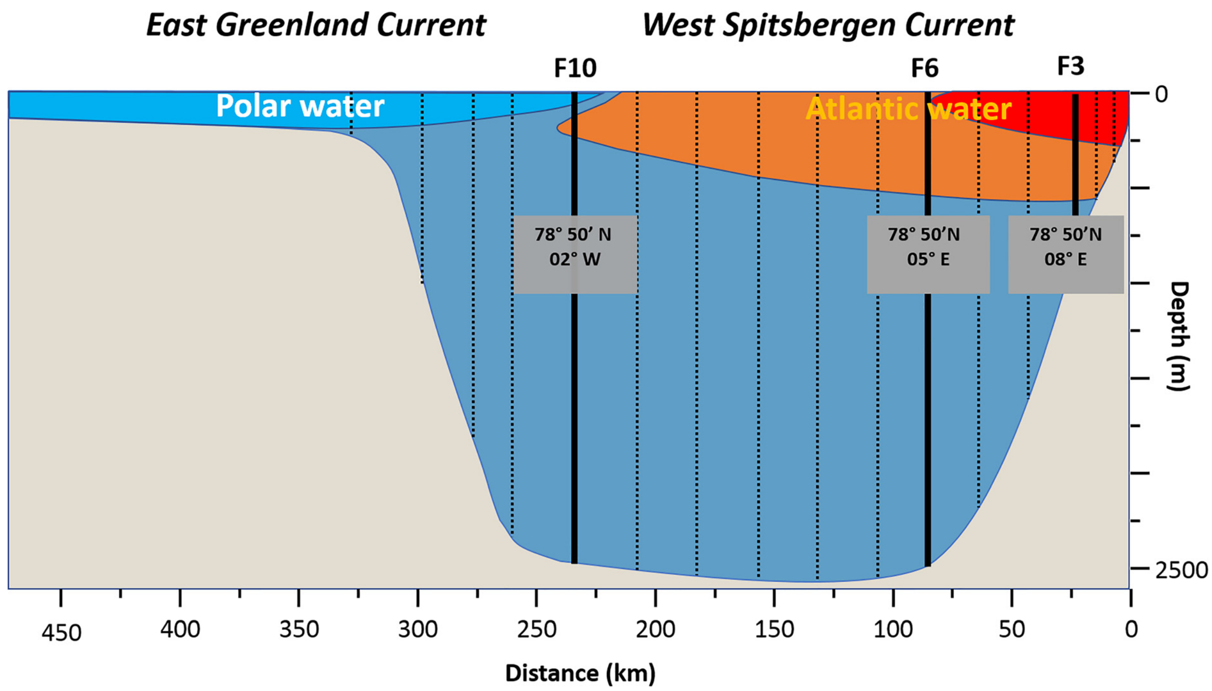

FIG. 5. (Color online) Location of hydrophones moored at stations F3, F6, and F10 in relation to major water masses in the Fram Strait. The WSC carries warm (>3 °C), highly saline Atlantic water north into the Fram Strait, while to the west the EGC carries cold (<0 °C) polar water south.[1]

Hattermann *et al.*, 2016), and the West Spitsbergen Current advects large numbers of *C. finmarchicus* into this area (Basedow *et al.*, 2018). The juxtaposition of the WSC, EGC, and Arctic Surface Water results in a clear front along both the east (Arctic Front), and west side (Polar Front) of this Arctic water mass (Rudels *et al.*, 1994). The combination of this complex oceanography and warming Atlantic water may have made the Fram Strait suitable for summering sei whales.

In the first year of this study (2009–2010), we deployed a hydrophone in the Greenland Sea to potentially detect calling whales as they moved north from their wintering grounds. Interestingly, we detected no sei whale calls at this site. This could be because migrating sei whales were not calling, the oceanographic conditions (deep cold water, no clear front to concentrate prey) were not suitable for sei whales, or the migratory route of sei whales moving north did not include this area. The first explanation, that sei whales were not calling while migrating, is unlikely as sei whales have been recorded virtually year-round in other studies in the Atlantic (Davis, 2019). In satellite tag studies, sei whales tagged in the Azores (Olsen *et al.*, 2009; Prieto *et al.*, 2014) migrated northwest into Labrador Sea feeding grounds. In the eastern North Atlantic, Ingebrigtsen (1929) suggested that sei whales migrated between the coast of northwestern Africa and the feeding grounds around Iceland and Scotland. If Fram Strait sei whales are part of this latter group, they may have migrated east of our Greenland Sea mooring, beyond the detection range of our hydrophone, and thus not been recorded by our autonomous hydrophone. This would also mean these whales are likely part of the eastern Atlantic stock.

In addition to the classic 80–30 Hz downseeping "type A" calls, we observed 50–30-Hz triplet and singlet downsweep vocalizations similar to the B, C, and D calls recently identified by Tremblay *et al.* (2019), and those recorded among sei whales off the coast of Maine (Golaski, 2102; Baumgartner, 2019). Interestingly, these sounds also closely resemble those recorded by Nieukirk *et al.* (2004) along the mid-Atlantic Ridge [see Figs. 6(b) and 6(c) in Nieukirk *et al.*, 2004]. More data will be needed to confirm that these are additional parts of the sei whale repertoire.

This study has provided information on the polar distribution of the Atlantic sei whale. Historically, sei whale habitat use varies between years, more so than for other baleen whale species (Jonsgård and Darling, 1977; Gunnlaugsson *et al.*, 2004). Sei whale presence this far north is typically rare (Prieto *et al.*, 2012), yet in this study, the species was detected in polar waters in five consecutive years. There is a clear warming trend in the eastern Fram Strait (MOSJ, 2019) where most sei whale calls were recorded, most likely because of Arctic amplification of global warming (Spielhagen *et al.*, 2011). Water temperature alone is often not a good predictor of range expansion of a species (McHenry *et al.*, 2019), and the drivers of baleen whale distribution are particularly complicated. Time series data on temperature, prey availability, and frontal strength in the Fram Strait are currently being collected by multiple institutions. This, combined with continued passive acoustic monitoring of baleen whales, may help clarify whether sei whale presence in the Fram Strait was a temporary phenomenon or a shift in species distribution.

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[1]After https://tinyurl.com/tz6r9j2.

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