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Movements of a deep-water fish: establishing marine fisheries management boundaries in coastal Arctic waters

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Abstract. Management boundaries that define populations or stocks of fish form the basis of fisheries planning. In the Arctic, decreasing sea ice extent is driving increasing fisheries development, highlighting the need for ecological data to inform management. In Cumberland Sound, southwest Baffin Island, an indigenous community fishery was established in 1987 targeting Greenland halibut (*Reinhardtius hippoglossoides*) through the ice. Following its development, the Cumberland Sound Management Boundary (CSMB) was designated and a total allowable catch (TAC) assigned to the fishery. The CSMB was based on a sink population of Greenland halibut resident in the northern section of the Sound. Recent fishing activities south of the CSMB, however, raised concerns over fish residency, the effectiveness of the CSMB and the sustainability of the community-based winter fishery. Through acoustic telemetry monitoring at depths between 400 and 1200 m, and environmental and fisheries data, this study examined the movement patterns of Greenland halibut relative to the CSMB, the biotic and abiotic factors driving fish movement and the dynamics of the winter fishery. Greenland halibut undertook clear seasonal movements between the southern and northern regions of the Sound driven by temperature, dissolved oxygen, and sea ice cover with most fish crossing the CSMB on an annual basis. Over the lifespan of the fishery, landfast ice cover initially declined and then became variable, limiting accessibility to favored fisher locations. Concomitantly, catch per unit effort declined, reflecting the effect of changing ice conditions on the location and effort of the fishery. Ultimately, these telemetry data revealed that fishers now target less productive sites outside of their favored areas and, with continued decreases in ice, the winter fishery might cease to exist. In addition, these novel telemetry data revealed that the CSMB is ineffective and led to its relocation to the entrance of the Sound in 2014. The community fishery can now develop an open-water fishery in addition to the winter fishery to exploit the TAC, which will ensure the longevity of the fishery under projected climate-change scenarios. Telemetry shows great promise as a tool for understanding deep-water species and for directly informing fisheries management of these ecosystems that are inherently complex to study.

Key words: *acoustic telemetry; Canadian Arctic; catch per unit effort; declining ice cover; fisher location; fisheries planning; Reinhardtius hippoglossoides.*

INTRODUCTION

For organisms that reside below the photic zone of oceans, daily, annual, and ontogenetic behavioral routines remain largely unknown. Fisheries catch data have historically provided insight on the spatiotemporal occurrence

of animals, but single time-point data represent a simplified model of actual behaviors. Given recent revelations over the scales and complexities of fish movements in the epipelagic zone (Hussey et al. 2015), it is likely that deep-water organisms show similar behaviors, but with additional habitat-specific effects that drive lower metabolic rates, and limit visual cues with the majority of species assumed to be stenotopic (Wilson and Hessler 1987). With increasing demands on global marine resources, there is mounting pressure for innovative fisheries

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exploration. Habitats below the photic zone are viewed as lucrative and profitable environments to assist in addressing this resource need, but data for management of these potentially fragile ecosystems is lacking (Norse et al. 2012).

To date, establishing deep-water fisheries has been controversial (Sissenwine and Mace 2007). Catch per unit effort (CPUE) has shown relatively fast declines in several fisheries, raising concerns over their sustainability. The orange roughy (*Hoplostethus atlanticus*) provides an example of over exploitation of a poorly understood deep-water species under a scenario in which management implementation was compromised by a paucity of basic data (Francis et al. 1995, Clark et al. 2000, Clark 2001). Deep-water fisheries are consequently considered complex given the *k*-selected traits identified among a majority of species, including slow growth, high longevity, and late maturity (Norse et al. 2012). The potential for exploitation remains, but detailed data on species life histories, including residency, movement, and migration patterns that define stock units is required for robust management.

When compared to temperate and tropical ecosystems, the Arctic represents a relatively untouched region for fisheries exploitation, given its remote and hostile location and inaccessibility due to landfast ice (Christiansen et al. 2014). The region is therefore considered promising for fisheries development, especially with receding ice cover as a result of global climate change (MacNeil et al. 2010). As a result, there are mounting concerns over fisheries development related to the lack of basic biological data and our understanding of the ecosystem as a whole (Christiansen et al. 2014). At present, one of the primary species that is fished in the Arctic is Greenland halibut (*Reinhardtius hippoglossoides*), a deep-water fish of high commercial value that is long lived (i.e., *k* selected; Gregg et al. 2006, Treble et al. 2008). Greenland halibut typically occur at depths between 200 and 2000 m and are distributed throughout the northwest and northeast Atlantic and northern Pacific Oceans (Scott and Scott 1988, Bowering and Chumakov 1989, Bowering and Brodie 1995, Treble and Jørgensen 2002). In Baffin Bay and Davis Strait, Canadian and Greenlandic commercial fisheries target this species in offshore waters (Jørgensen and Treble 2015), while community-based commercial fisheries also operate in coastal regions of Greenland and to a lesser extent Canada (Dennard et al. 2010, Jørgensen and Hammeken Arboe 2013, Nygaard and Boje 2013).

The Greenland halibut fishery in Cumberland, southeast Baffin Island, represents the only Inuit community-based fishery for this species in Canadian waters (Pike 1994) and provides a potential model for fisheries development in the region to address high unemployment and limited economic initiatives. It was first established in 1987 and is a coastal ice-based fishery that operates in the inner northern section of the Sound (Fig. 1). To inform management, a standard tag-recapture study was

undertaken in Cumberland Sound in 1994 and from 1997–2000 to better understand Greenland halibut movement patterns (Treble 2003). Fishing effort was relatively low and returns were limited; however, the results indicated that Greenland halibut located in the northern winter fishing grounds were resident, while fish tagged near the mouth of Cumberland Sound were migratory to offshore waters (Treble 2003). These observations suggested an isolated inshore stock of fish is present in the northern portion of the Sound, similar to that observed in western Greenland fjords (Boje 2002; i.e., a sink population, originating from the offshore but resident in Cumberland Sound). Based on available data, the Northwest Atlantic Fisheries Organization (NAFO) Scientific Council advised that a separate stock-management area could be established within the traditional Inuit winter fishing grounds in Cumberland Sound (NAFO SC 2004). This resulted in the designation of the Cumberland Sound Management Boundary (CSMB) that encompassed the northern section of the Sound and included the limit of land-fast ice and all known winter fishing locations since the fishery began (Fig. 1). The existing inshore allocation or total allowable catch (TAC) of Greenland halibut was assigned to this new management area. In 2009 and 2010, a trial summer fishery was started in the deeper portions of Cumberland Sound overlapping the CSMB (Young 2010) and, in 2010 and 2011, commercial fishing took place in the NAFO Division 0B region of the Sound, south of the CSMB (Fig. 1b). These test and commercial fisheries, using large offshore vessels (14.9–27.1 m length) and fishing more intensively than during the winter fishery, reported good catches of Greenland halibut indicating the potential for the growth of a summer commercial fishery in the southern region of the Sound. These findings raised questions over the stock affinity of fish found in the northern and southern regions of Cumberland Sound and the potential impact that a summer fishery would have on the current winter fishery.

The overall objective of the current study was to examine the spatial and temporal movement patterns of a deep-water commercially important fish species to elucidate residency and migration patterns in relation to Arctic fisheries management boundaries and TACs. While traditional tag-recapture data have revealed complex and large-scale movements of Greenland halibut (for example, Boje 2002, Treble 2003, Albert and Vollen 2015), these data typically lack sufficient detail to resolve management planning because they provide only a start and end point with no temporal data on spatial use. Through recent technological advancements, telemetry tools can now document the intricate movements and migration patterns of animals, generating novel insights in this difficult-to-study environment (Hussey et al. 2015). Importantly, these data are beginning to provide a cornerstone for fisheries management (Welch et al. 2014, Espinoza et al. 2015, Raby et al. 2015), but to date, only a handful of studies have examined

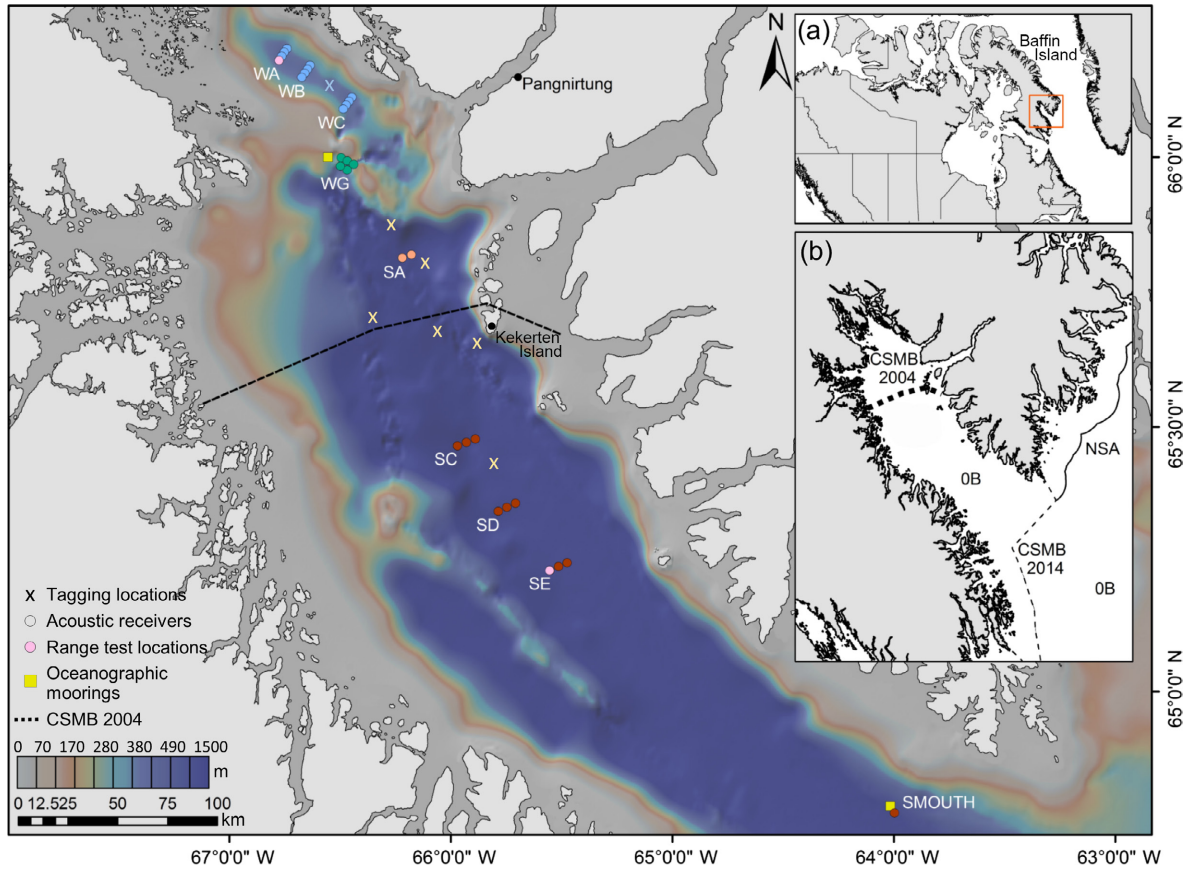


FIG. 1. Map of the study site within Cumberland Sound. Circles indicate the locations of individual acoustic receivers, where red identifies receivers located in the southern, deep-water environment; light red are receivers located in the deep water area north of the Cumberland Sound Management Boundary (CSMB); blue are receivers located in the northern, shallow-water environment; and green are receivers forming a gate across a deep-water channel dividing the shallow and deep-water regions. The label next to each row of receivers indicates the name of those stations. The locations of fixed oceanographic moorings, range tests and the CSMB established in 2004 are shown. Fish tagging locations are marked with X; yellow X are Greenland halibut tagged in August 2010 and 2011, and blue X is Greenland halibut tagged in April 2012. Inset (a) indicates the location of Cumberland Sound on the southeast side of Baffin Island, Nunavut, Canada. Inset (b) indicates fisheries and resource management boundaries in the region. The location of the CSMB in 2004 is designated with a thick dashed line within Cumberland Sound, and the relocated boundary (CSMB 2014) is shown by a thin dashed line connected to the Nunavut Settlement Area (NSA), a 12-nautical-mile (22.2 km) offshore boundary reserved exclusively for indigenous fishing rights. Northwest Atlantic Fisheries Organization (NAFO) management Division 0B (Southern Cumberland Sound prior to 2014 and Davis Strait) are also indicated. [Color figure can be viewed at wileyonlinelibrary.com]

movements of deep-water species due to the constraints of available technology (Priede and Bagley 2000, Afonso et al. 2012, Weng 2013). Through the first application of acoustic telemetry at depths >1000 m, Greenland halibut were tagged in both the Cumberland Sound Turbot Management Area (the area of the Inuit winter fishery north of the CSMB) and the Division 0B portion of the Sound (the region south of the CSMB that extends into the offshore; Fig. 1), and tracked over a 12-month period. A collaborative effort among research scientists, fisheries managers, and an Inuit community, the study (1) quantified the movements of Greenland halibut to assess whether the CSMB encompasses a discrete sink population, (2) examined environmental and biological factors driving observed fish behavior, and (3) assessed the utility of acoustic telemetry for generating rapid

data to inform fisheries management in deep-water ecosystems.

METHODS

Study site

Cumberland Sound is a large (~350 × 150 km) inlet located on the southeast coast of Baffin Island (65°20'02" N, 66°00'50" W; Fig. 1). The bathymetry of the Sound consists of shallow water margins encompassing a deep-water channel in the central region. The deep-water channel can be broadly divided into two bathymetric zones, the northern sector where maximum depths reach ~600 m and the southern sector where depths average ~1000 m, interspersed with isolated deep-water pockets

that reach ~1400 m, forming a mountainous terrain. The entrance of the Sound consists of a sill at ~300 m that divides the deep-water channel and shallower peripheral margins from Davis Strait (Fig. 1). Climatic and sea conditions in the Sound are characterized by two distinct seasonal periods, winter land-fast ice between late October and May and a summer open-water period (June–October), although, during the winter, the central and southern areas of the Sound largely consist of drifting pack ice and at times open water.

Acoustic array design and deployment

To determine the residency and movement patterns of Greenland halibut, an array of VR2W-69 kHz acoustic receivers was deployed and a combination of V16-6H, V16-4H, and V13-4L acoustic tags (VEMCO, Halifax, Nova Scotia, Canada) were surgically implanted in fish. Acoustic receivers were fixed to rope risers; each riser had a subsurface float (750 or 1500 m depth rated) at one end and was attached to a 90.7 kg circular cast iron anchor via an acoustic release (ORE offshore; EdgeTech, West Wareham, Massachusetts, USA) at the other end. Moorings were deployed at an average depth of 1056 m (range 882–1198 m) in the southern area, and 387 m (range 149–486 m) in the northern area. The rope risers connecting the releases to the subsurface float were 187 and 12 m in length in the southern and northern regions, respectively, reflecting the depth difference between regions. In the southern deep-water area, 2 m chain sections connected the acoustic release to the anchor through a swivel attachment, while in the northern region, a 2-m rope section was used. All VR2W receivers were attached 1 m below the subsurface float oriented with the hydrophone pointing downward. The array was specifically designed to provide coverage in four main regions of Cumberland Sound: (1) 11 monitors were deployed in the deep southern region south of the CSMB including one on the sill at the entrance to the Sound (SC, SD, SE, and SMOUTH); (2) two monitors were deployed at the most northern point of the deep southern region, north of the CSMB (SA); (3) five monitors were deployed in a gate across a deep-water channel connecting the southern and northern regions (WG); and (4) 14 monitors were deployed in the shallower northern region (WA, WB, WC; Fig. 1). All acoustic moorings were deployed in mid July 2011 and recovered at the end of August 2012 following an approximate 12-month deployment.

Fish capture and tagging

Greenland halibut were captured on bottom longlines set at ~900–1100 m depth in the southern region and ~400–600 m depth in the northern region. In the southern region, fishing was conducted aboard a commercial fishing vessel in August 2010 and the Nunavut Government research vessel, the *Nuliajuk*, during August

2011. In both years, longlines were ~400–2000 m in length with 200–2000 gangions of 0.3–3.0 m length and size 14–16 Mustad Duratin circle hooks (O. Mustad and Sons A.S., Gjøvik, Norway) baited with frozen squid (*Argentine Illex*). In the Northern region, bottom longlines were set through ice holes in April 2012 following traditional community fishing practices; see Dennard et al. (2010) for specific details. During all fishing, longlines were soaked for ~12 h.

Following soak, longlines were hauled to the surface and fish in good condition were selected for tagging. During the summer period, fish were either processed immediately or held in a large tank with continuous flowing seawater for a maximum of 1 h; in the winter fish were processed directly during longline retrieval. All fish were measured (fork length, FL) and a small incision was made into the peritoneal cavity on the non-ocular dorsal-ventral surface. Tags (type and [nominal delay in seconds]: V16-6H [90], V16-5H [90], V16-4H [300] and V13-1L [110 and 300]; number of tags deployed 20, 10, 178, and 15, respectively) were inserted lateral to the length of the fish and the incision was closed using three to four interrupted sutures (Ethicon VCP443, 2-0, FS-1 cutting; Somerville, New Jersey, USA). Fish were released following the insertion of an external marker tag (FLOY Tag, Seattle, Washington, USA) at the base of the dorsal fin. Tags and all surgical equipment were washed in betadine and the dorsal-ventral surface was swabbed with a 10% diluted betadine solution prior to making the incision (Fig. 2). No anesthetic procedures were used given that flatfish require a large dosage of MS222 and consequently recovery times are too long and the health of the fish may be compromised. Fish placed ocular surface down remained calm during all procedures (<10 min) and swam off strongly following release.

Acoustic range testing

To determine the effective range of acoustic receivers and tags implanted in fish, two range tests were performed in each of the southern (~1000 m) and northern (~450 m) regions over the study period (July 2011–August 2012; WA and SE; Fig. 1). Specific details of the range test design and a summary of the results are included in Appendix S1.

Environmental monitoring over sampling period

Bottom temperature and dissolved oxygen were recorded at two oceanographic moorings located in the northern (272 m depth) and southern regions (475 m depth) throughout the study (Fig. 1; see Bedard et al. 2015). Near-bottom temperature was collected using an RBR (Ottawa, Ontario, Canada) TR-1050 thermistor and near-bottom dissolved oxygen using a RBR DO-1050. Both instruments were calibrated prior to deployment and set to sample every minute. Accuracy of the temperature sensor was $\pm 0.002^\circ\text{C}$ and the dissolved oxygen



FIG. 2. Photograph of the tagging procedure involving the surgical implantation of acoustic tags, with life spans of 5–10 yr, into the peritoneal cavity of Greenland halibut prior to their release.

sensor $\pm 2\%$. Ice cover data (%) for the period of monitoring were obtained from the Canadian Ice Service archive (data *available online*).⁸ To define ice cover for the shallower northern and deeper southern regions, data for Cumberland Sound were first isolated and the southern deep-water region divided from the shallower northern region by a straight line between Imigen and Keker-tukdjuak Islands (Appendix S2). Ice cover for each region (north and south) was then calculated using the total concentrations of ice (reported in tenths for each region) multiplied by the percent area that concentration represents out of the total area of the focal region to provide a weighted average. Weighted ice cover data were then summed to provide percent ice cover per week for the entire focal region. Data for daily photoperiod (h), and wind speed (km/h) were obtained from Environment Canada (*available online*) and moon phase (illumination scale 0–1) from Time and Date AS (*available online*).^{9, 10}

Time series of ice data

In addition to ice cover data for the study period, ice data were extracted for the months the community winter fishery operates (January–May) and for each year from its establishment in 1987 through 2014. Specifically, we estimated percent landfast ice cover to examine long-term trends in sea ice extent as a measure of fishers' accessibility to their fishing grounds. Landfast ice cover (%) was calculated for the community fishing area (i.e., the region north of the CSMB; Appendix S2) as the area of landfast and 10/10 concentration ice divided by the total area north of the CSMB. For the years 1987–2007, ice data

were available on a monthly basis, whereas after 2007, weekly ice data were used.

Time series of CPUE and fishing locations for the Cumberland Sound community-based ice fishery

To monitor catch and effort trends, Fisheries and Oceans Canada has provided fishermen with logbooks since 1991; however, the return of these logbooks has not been mandatory. These logbook data include the number of longlines set, longline soak time, the number of deployed hooks, the number of hooks lost during a set, the number of fish caught in a set, fisher identification and fishing location (latitude and longitude or position marked by hand on a printed map). Hand-marked positions were digitized using a georeferenced digital version of the printed map. To examine temporal trends in CPUE of the fishery, CPUE was calculated as follows:

$$CPUE = \frac{f}{H_s - H_L / S_D} \quad (1)$$

where f is the number of fish caught in a given set, H_s is the number of hooks per longline set, H_L is the number of hooks lost per longline set, and S_D is the number of hours between set deployment and retrieval (soak time). Previous examinations of CPUE patterns in the Cumberland Sound Greenland Halibut fishery found significant relationships between catch and both the number of hooks fished and soak time (Pike 1994, DFO 2008), although the relationships were highly variable in space and time. We opted to include soak time in the CPUE calculation as, although this can make the values susceptible to error due to gear saturation, only 87 out of >7000 reported sets have recorded more than 50 fish per 100 hooks over the history of the fishery. In contrast,

⁸ <https://www.ec.gc.ca/glaces-ice/>

⁹ http://weather.gc.ca/index_e.html

¹⁰ www.timeanddate.com

excluding soak time from the CPUE calculation, given the identified relationship, would affect the relative weighting of short and long sets in the overall CPUE calculation. Data on CPUE prior to 1991 were extracted from Pike (1994). Locations of fishers over time were examined to determine consistency in location of fishing relative to landfast ice cover and CPUE data.

Due to the non-mandatory nature of the monitoring program, logbook return rates have varied through time resulting in inconsistencies in the frequency and quality of records (how often the logbooks are submitted and the completeness of data entry), consequently these data represent general CPUE and fisher location trends rather than absolute values for the entire fishery over time (see Appendix S3 for further data).

Data analyses

Acoustic telemetry data were first screened to identify false tag detections produced as a result of environmental sounds or tag collisions (Heupel et al. 2006, Simpfendorfer et al. 2015). Filtering was then undertaken using the White-Mihoff Filtering Tool (White et al. 2014) to isolate detections of individual fish that occurred ≥ 1 h apart to identify any spatially unrealistic detections (fish that moved large distances above that of their sustained swimming speed) and/or were detected on multiple receivers in different locations, at the same time. These potential false detections were then manually screened to determine validity.

Detection data for each fish were plotted by date and region of occurrence (southern deep-water section, northern-most area of southern section located north of the CSMB, the gate, and the northern region; see *Methods: Acoustic array design and deployment*). Example movement behaviors of individual Greenland halibut based on their occurrence in the four defined regions of Cumberland Sound were then visualized using gradient bubble plots of percentage of detections at each monitor relative to total number of detections for that fish and color coded by season (open water summer 2011, ice-covered winter 2012, and open water summer 2012). Winter- and summer-tagged fish were plotted independently to determine if fish tagged at each location (north and south) and season (summer and winter) undertook consistent residency/movement patterns.

A residency index (RI) was calculated to examine seasonal residency and movement patterns of all tagged Greenland halibut within Cumberland Sound over the 1-yr period relative to the CSMB (management significance) and the deep-water and shallow-water regions (ecological significance). The RI was calculated as the number of days individual fish were detected on each receiver within the array divided by the total number of days respective fish were detected across the entire array. RI values range from 0 to 1, with 1 indicating 100% residency at a particular receiver and values near zero low residency near any given receiver. This measure was used instead of raw data to remove bias associated with a

higher number of detections on a monitor when only a few fish were present or a few detections tied with a large number of individual fish. These RI values were plotted by month and monitor location (from furthest north to furthest south) to examine fish spatial and temporal RI trends. As above, winter- and summer-tagged fish were plotted independently. RI data were overlaid over time series data for bottom sea temperature, percent ice cover, and bottom oxygen to visually examine correlations between RI and key environmental variables. To examine potential factors driving the observed daily residency/movement patterns of Greenland halibut in shallower vs. deeper water regions of Cumberland Sound, generalized linear mixed models (GLMM) with binomial error structure and a logit link function were constructed (Bond et al. 2012, Lédée et al. 2015). For this purpose, Greenland halibut presence/absence was determined each day throughout the study period from 1 September 2011 to 31 August 2012 where a value of 1 was assigned for days present and 0 for days absent. Two separate models were used to independently test for presence/absence of Greenland halibut at receivers (binary variable) in the shallow northern and deep southern regions respectively, relative to environmental and biological parameters (continuous predictor variables). The fixed environmental parameters were averages of daily wind speed and direction, photoperiod, moon phase, percent ice cover, bottom sea temperature, and bottom dissolved oxygen concentration; the biological parameter was fish size (fork length, FL [cm]). Greenland halibut ID and initial tagging location (southern and northern regions) were included as random effects to account for repeated measures in the data. Continuous predictor variables were screened for collinearity prior to analysis using a Pearson's correlation coefficient (≤ 0.6) and variance inflation factors (< 3.0). Most covariates were not collinear, except for month, which was highly correlated with percent ice cover (0.74) and was therefore removed prior to analysis. The GLMM was fit using the `glmmPQL` function in the MASS R package with a first-order autoregressive function to account for temporal autocorrelation in presence/absence and an α of 0.05. Model fit was assessed by calculating the marginal r^2 (solely fixed effects) and conditional r^2 (both fixed and random effects) using the methods described by Nakagawa and Schielzeth (2013). Raw acoustic detection data used in all the above analyses are available online through the Ocean Tracking Network Publication Data Repository (Hussey 2016).

Data on CPUE in the winter fishery and percent landfast ice cover in the northern area delineated by the CSMB were plotted against time since the development of the fishery. Two defined linear relationships were present in each data set, consequently piece-wise regression was used to examine temporal trends (Crawley 2007). Following an iterative searching approach, the data were modeled as follows:

$$y \sim x * I(x < c) + x * I(x > c) \quad (2)$$

where c is the breakpoint, * is the main effects and interactions and $I(x < c)$ and $I(x > c)$ are essentially dummy variables dividing the breakpoint in the data to model two sets of regression parameters. To estimate c , endpoint values surrounding the visual break point were selected and linear regression was fitted to consecutive breakpoint values within the defined range to identify regression parameters with the lowest mean square error.

To quantify annual fisher locations over the time of the fishery, the Bayesian estimate of the standard ellipse area using individual fisher locations per year, were calculated following the methods proposed by Jackson et al. (2011). The standard ellipse represents bivariate data estimated from the covariance of the longitude (x) and latitude (y) data. Each annual ellipse contains approximately 40% of the data representing the core fisher locations and accounts for variable sample sizes across years. All statistical analyses were conducted using R v.3.1.2 (R Development Core Team 2014).

RESULTS

Tagged Greenland halibut

A total of 223 fish were tagged (182 in the southern deep water region and 41 in the northern shallower water region) ranging in size from 48 to 96 cm (69.8 ± 0.1 cm [mean \pm SD]). Mean size was larger for fish tagged in the southern region (72.5 ± 8.5 cm) than those tagged in the northern region (64.5 ± 7.1 cm; $T_{61.55} = 4.6$, $P < 0.001$). Of all tagged fish, 167 (74.2%) were detected; 134 and 31 individuals tagged and released in the south, and north, respectively. The number of detections per fish ranged from 1 to 8846 with a mean of 732.1 ± 1179.8 and a total number of 122252 detections across the entire array (Fig. 3). When considering detection filtering, no false ID tags were found and of the 676 possible false detections identified by the White-Mihoff filter, all detections were either on the same monitor or on an adjacent monitor and consequently deemed viable given the species life history. Range testing found that deep-water monitors detected >60% of V16 tag transmissions at the furthest distance tested of 802 m, while V13 tags had an effective detection range of 308 m (Appendix S1). For the shallow-water moorings, the effective detection range was approximately 290 m and 273 m for V16 and V13 tags, respectively; however, this test was compromised by bottom topography (see explanation of possible issues with this test in Appendix S1).

Individual Greenland halibut movements

For southern-tagged fish, individual movement patterns were broadly divided into four behavioral types: (1) fish that remained in the southern deep water region south of the CSMB and were principally detected during open-water periods ($n = 37$, 27.6%; Figs. 3a, 4a); (2) fish detected only in the southern region but including the

northernmost monitors north of the CSMB ($n = 64$, 47.8%; Figs. 3a, 4b); (3) fish detected in the south and at the gate ($n = 22$, 16.4%; Figs. 3a, 4c); and (4) fish detected in all regions (south, gate, and north; $n = 9$, 6.7%; Figs. 3a, 4d). For individual fish displaying behaviors (2–4), detections followed a distinct seasonal south-north-south movement (Fig. 3a). For the northern-tagged fish, three key movement behaviors were evident: (1) fish only detected in the northern region predominantly during the ice cover period ($n = 16$, 48.5%; Figs. 3b, 5a); (2) fish detected only at the gate ($n = 5$, 15.2%; Figs. 3b, 5b); and (3) fish detected in all three regions ($n = 8$, 24.2%; Figs. 3b, 5c, d). A total of 52% of northern-tagged fish were detected outside of the northern region and movements followed the same spatial seasonal pattern as southern-tagged fish (Fig. 3b).

Greenland halibut residency index within the Sound

During the open-water summer period of 2011, all southern-tagged fish occurred in the deep-water southern region (Fig. 6a), with RI values ranging from 0.01 to 0.45 (0.1 ± 0.08 [mean \pm SD]) and the highest monthly RI values were recorded at monitor locations SA2 (0.45), SE3-R3 (0.23), SE1 (0.18), and SA2 (0.25) in August, September, October, and November, respectively (Fig. 6a). The majority of these fish were detected south of the CSMB (monitor locations SC–SE and SMOUTH; Fig. 6a). Between December 2011 and February 2012, fish were present in the southern and northern regions as they transitioned northward (Fig. 6a). Following this transition period, RI values for the core winter period (March to May) ranged from 0.002 to 0.29 (0.07 ± 0.08) with maximal values recorded in the deep channel connecting the two regions (March, WG4 = 0.29; April, WG2 = 0.27) and the northernmost deep-water section (May, SA3 = 0.26), both areas north of the CSMB. In June, fish transitioned southward, with most fish resident in the southern deep-water region during July and August (RI range 0.02–0.36; 0.10 ± 0.08 [mean \pm SE]; maximal values July, SA2 = 0.36 and August, SE3–R2 = 0.23; Fig. 6a). Greenland halibut tagged in the northern fishing ground showed similar temporal and spatial RI patterns to those tagged in the south (Fig. 6b). In April and May, the highest RI values recorded were at WG4 (0.28) and SA3 (0.44) north of the CSMB, while maximal RI values in June (SE2 and SE3–R3 = 0.26) and August (SE1 = 0.29) were located south of the CSMB (Fig. 6b).

Generalized linear mixed models

The GLMM for Greenland halibut presence/absence at receivers in the southern deep-water region found that fish detections decreased with increasing sea-ice cover, bottom dissolved oxygen concentrations, moon illumination, and body size; all other predictor variables were nonsignificant within the model (Fig. 7a, c, e, Table 1). For the shallow water northern region, the GLMM

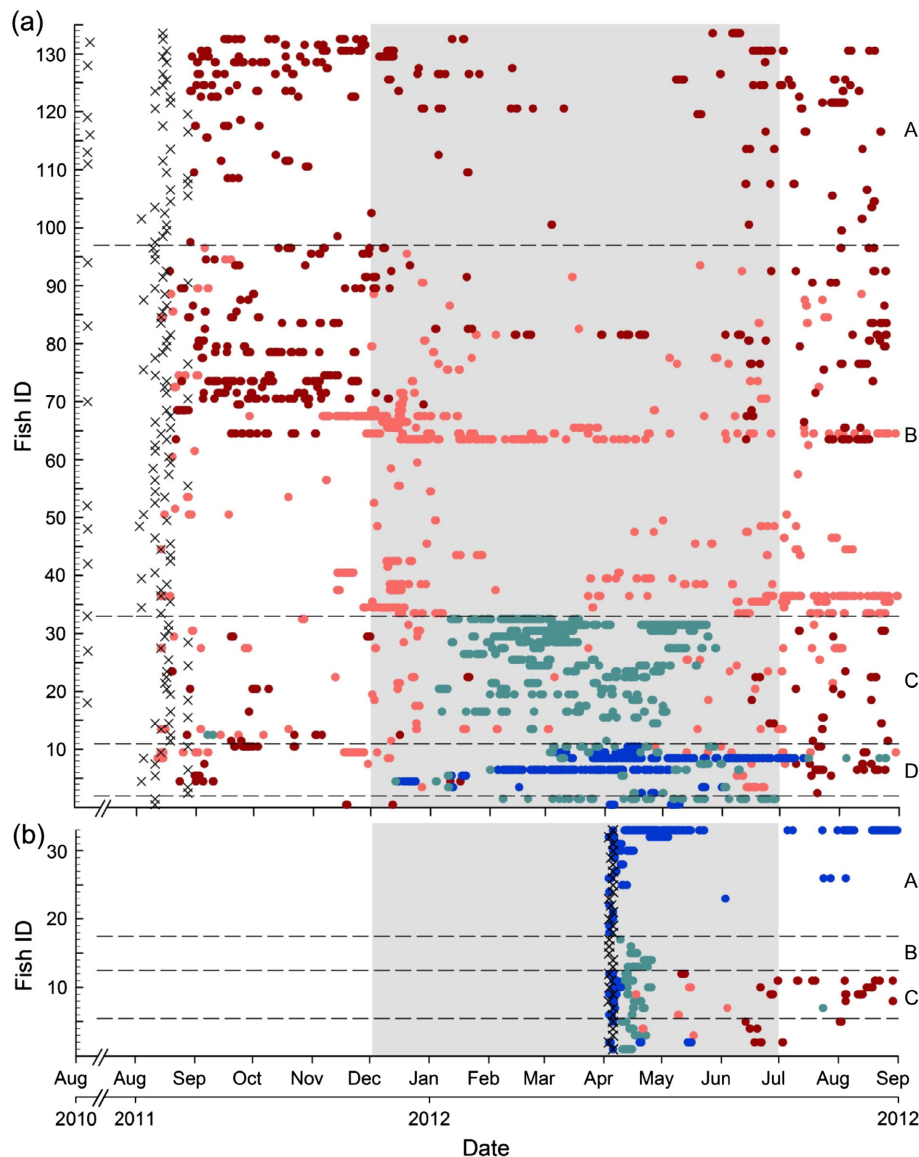


FIG. 3. Total detections of all Greenland halibut tagged and detected in Cumberland Sound. Black X marks the date each individual fish was tagged. Red dots are detections on deep-water receivers south of the Cumberland Sound Management Boundary (CSMB); pink dots are detections on deep-water receivers north of the CSMB; green dots are detections on the gate dividing the deep water southern and shallower northern regions; and blue dots are detections on the most northern shallower receivers. The gray shaded area indicates months during which the Sound was predominantly ice covered. Note the scale break on the x-axis between August 2010 and August 2011. (a) Greenland halibut tagged in the southern region of Cumberland Sound during the open-water period in August 2010 and August 2011. Greenland halibut that were tagged in section A remained south of the CSMB ($n = 37$, 27.6%), those in section B were detected in the southern region and also on the northernmost monitors north of the CSMB ($n = 64$, 63.4%), those in section C were detected in the south and at the gate between north and south regions ($n = 22$, 16.4%) and those in section D were detected in all regions (south, gate, and north; $n = 9$, 6.7%). The last two fish, depicted at the bottom of the panel, did not fit into any of the above categories. (b) Greenland halibut tagged in the northern region of Cumberland Sound in April 2012, where fish that were tagged in section A were only detected in the northern region ($n = 16$, 48.5%), in section B were only detected on the gate ($n = 5$, 15.2%), and in section C were detected in all three regions ($n = 8$, 24.2%). The four Greenland halibut below line C did not fit into any of these discrete categories. [Color figure can be viewed at wileyonlinelibrary.com]

estimated that fish presence was associated with higher sea ice cover and higher bottom dissolved oxygen concentrations (Fig. 7b, d). There was a significant negative relationship observed between fish presence and bottom temperature indicating fish were not detected at the higher temperature range (Fig. 7e). There was no effect

of wind speed and direction, moon illumination, or body size on fish presence/absence at receivers (Table 2). Both fixed and random effects accounted for most of the variation explaining Greenland halibut presence/absence at receivers in the northern region (marginal r^2 of 0.64 and a conditional r^2 of 0.85; Table 1) and a moderate amount

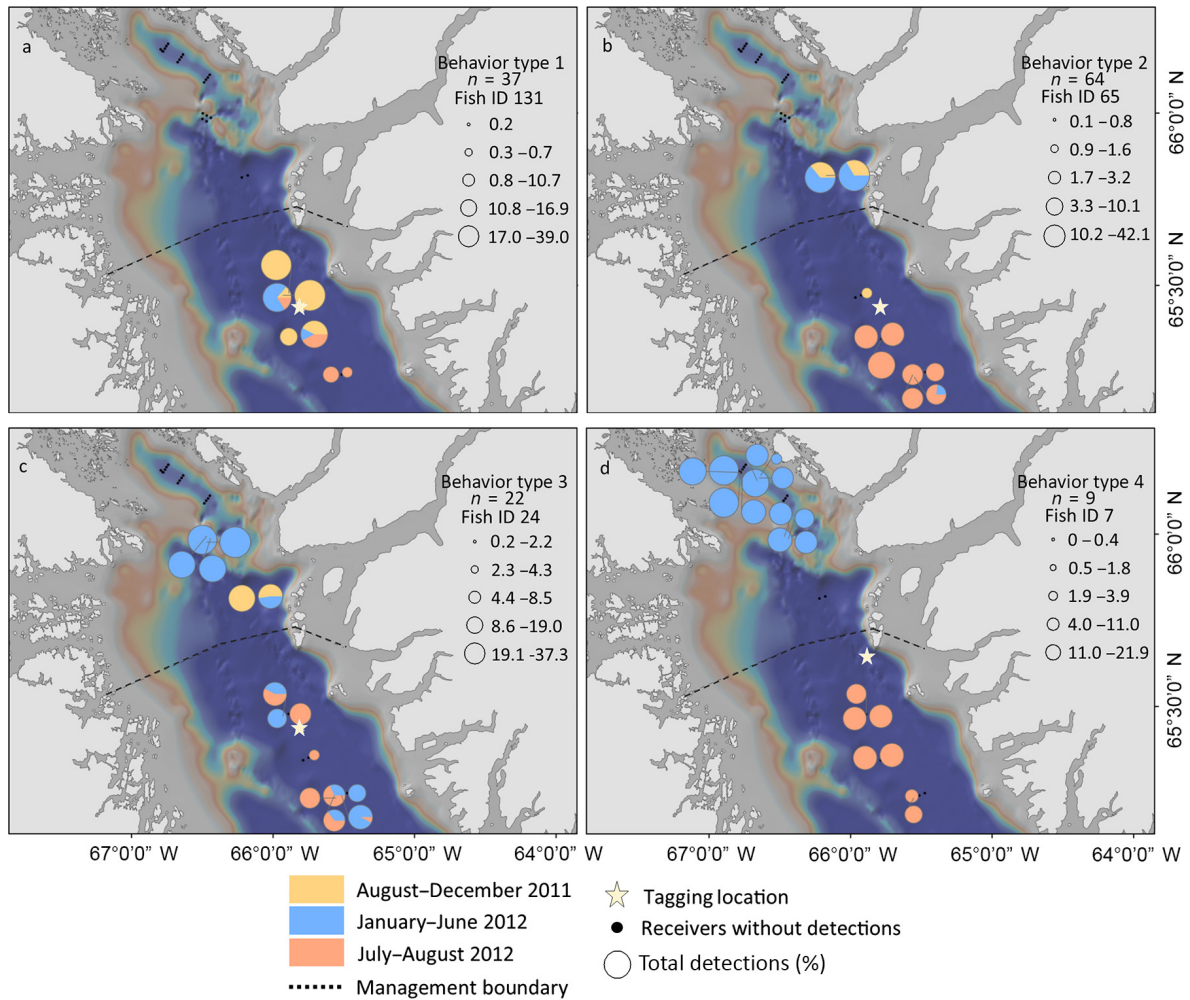


FIG. 4. Detection profiles of individual Greenland halibut tagged in the southern region of Cumberland Sound in August 2010 and 2011, showing the four representative behavioral types that were observed in this study. Pie charts on each map represent the proportion of detections (as a percentage of the total number of detections for that individual) on each unique receiver for the months August–December 2011 (open water), January–June 2012 (ice covered), and July–August 2012 (open water). The size of the pie chart varies dependent on the percentage of detections recorded for each receiver over the entire study period, with the data range displayed on the right side of each map. The star indicates the tagging location of each fish, and the Cumberland Sound Management Boundary (CSMB) is shown by a dashed line. (a) Greenland halibut ID 131, only detected in the most southern area of Cumberland Sound; (b) Greenland halibut ID 65, detected in the southern region as well as on the deep-water monitors north of the CSMB; (c) Greenland halibut ID 24, detected in both southern regions and at the gate; and (d) Greenland halibut ID 7, detected in >3 regions of Cumberland Sound. Note the detection profile scales are different for each behavior type. [Color figure can be viewed at wileyonlinelibrary.com]

of the variation for the southern region (marginal r^2 of 0.10 and conditional r^2 of 0.53; Table 2).

CPUE fishery data, ice cover, and fisher locations

The maximum reported catch rate of Greenland halibut in the fishery was 0.090 fish·hook⁻¹·h⁻¹ in 1987, at the start of the fishery. The catch rate declined through the 1990s to a low of 0.014 in 1999, subsequently increased between 1999 and 2002 and then leveled off at an average catch rate of 0.040 ± 0.010 for the remaining period. The catch rate in 2013 was 0.057 fish·hook⁻¹·h⁻¹ (Fig. 8). The initial decline in CPUE was correlated with an overall decrease in percent

landfast ice cover within the fishing grounds (Fig. 8). Since 2002, the time period over which CPUE was relatively stable, average landfast ice cover of 68.4% ± 0.1% was lower than that at the start of the fishery, but fluctuated on an annual basis between highs and lows of 92.7% and 50.2%, respectively (Fig. 8). Piece-wise regression analysis identified a break point in both CPUE and landfast ice cover data in 2001. Prior to 2001, both CPUE and landfast ice cover showed a significant decline, while, after 2001, no significant relationship was found for either parameter (Fig. 8). When considering the location of fishers within the Sound, the fishery occurred at its most southerly point west of Kerketen Island in the deep-water region in 1987 (Fig. 9). Over

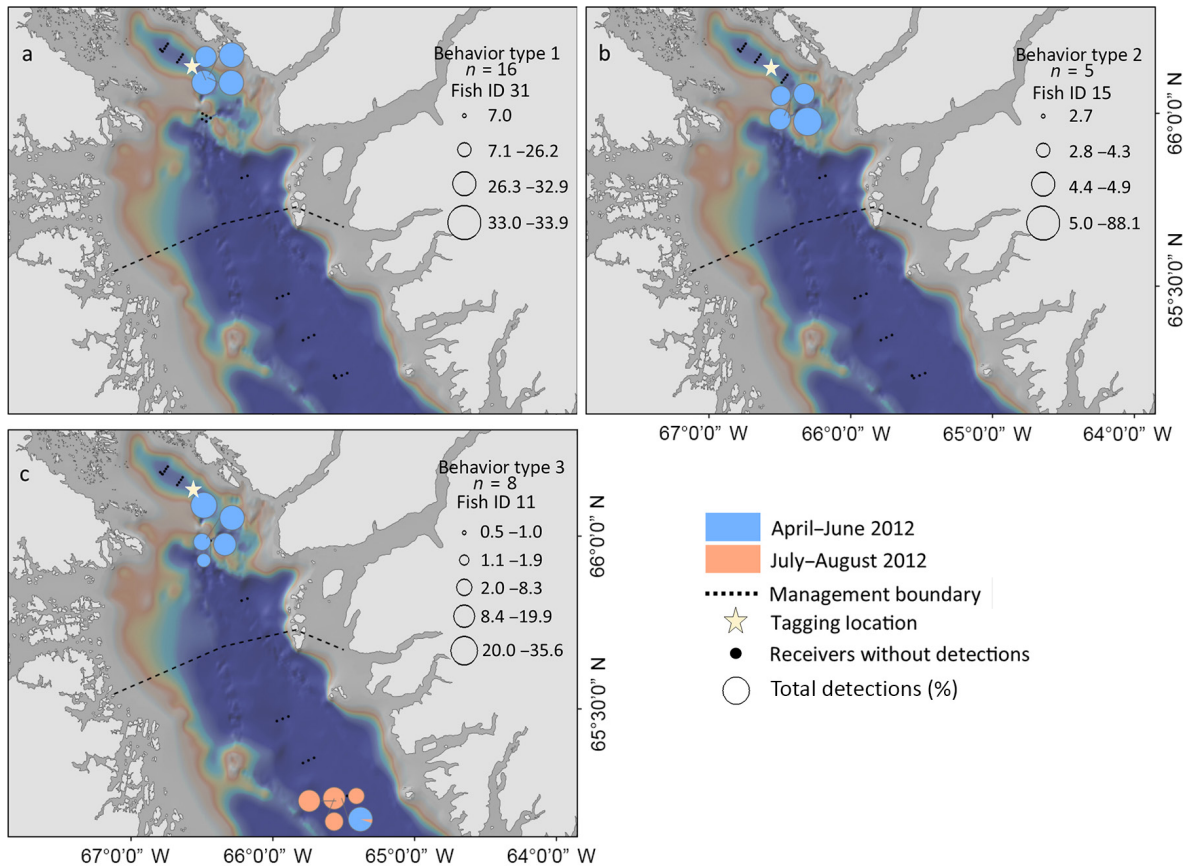


FIG. 5. Detection profiles of individual Greenland halibut tagged in the northern region of Cumberland Sound in April 2012, showing the three representative behavioral types that were observed in this study. Pie charts on each map represent the proportion of detections (as a percentage of the total number of detections for that individual) on each unique receiver for the months April–June 2012 and July–August 2012. The size of the pie chart varies based on the percentage of detections recorded for each receiver over the entire study period, with the data range displayed on the right of each map. The star indicates the tagging location of each fish, and the Cumberland Sound Management Boundary (CSMB) is shown by a dashed line: (a) Greenland halibut ID 31, detected only in the northern region of the Sound; (b) Greenland halibut ID 15, detected only on the gate connecting the northern and southern regions; and (c) Greenland halibut ID 11, detected in >3 regions. Note the detection profile scales are different for each behavior type. [Color figure can be viewed at wileyonlinelibrary.com]

subsequent years, the location of the fishery moved progressively northward, as ice concentration reduced and then fluctuated, and most recently fishers were located in the northern region near monitor lines WA and WB (Figs. 1, 9).

DISCUSSION

These data, the first of their kind for examining the long-term movements of fish at ~ 1000 m depth, demonstrate that a demersal fish, Greenland halibut, undertook seasonal movements within Cumberland Sound. Through linking telemetry and environmental data, sea ice cover was found to be the principal factor driving the observed movement northward into the inner Sound, but variability in movement behavior among individuals was recorded. Reductions in sea-ice extent north of the CSMB since the beginning of the fishery were associated with declining CPUE and the progressive northward changes in the location of the fishery over time. The seasonal

movements of Greenland halibut across the CSMB have implications for the management of this fishery, specifically questioning the current location of the CSMB, and have led to its conditional relocation to the entrance of the Sound. In a broader context, these data demonstrate that acoustic telemetry can provide a rapid method to obtain detailed information on spatial and temporal residency and movement patterns of deep-water species to inform management. Given increasing interest in exploiting deep-water fish stocks in conjunction with rapid advancements in telemetry technology, it is anticipated that telemetry will provide an important tool for future monitoring of deep-sea ecosystems.

Telemetry to understand the ecology of deep-water marine species

The overall seasonal movement pattern of Greenland halibut within Cumberland Sound at 600–1000 m depth

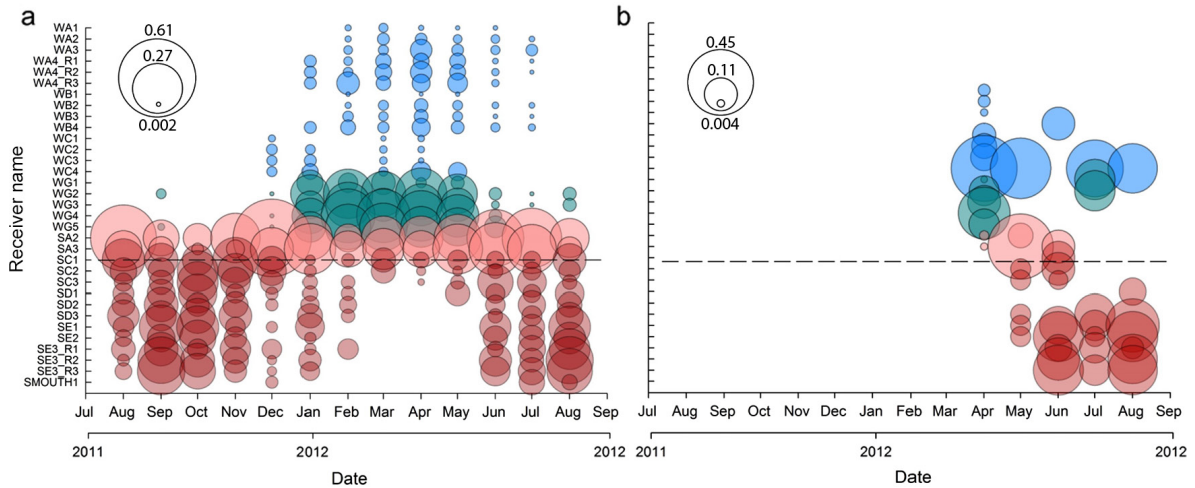


FIG. 6. Monthly residency index (RI) values associated with the detections of Greenland halibut at the specified acoustic receivers within Cumberland Sound. The area of each circle is representative of the RI, calculated as the number of days individual fish were detected on each receiver within the array divided by the total number of days respective fish were detected across the entire array. Red circles identify receivers that were located in the deep-water southern environment of Cumberland Sound, south of the Cumberland Sound Management Boundary (CSMB); pink circles are receivers located in the deep-water environment, but north of the CSMB; green circles are RI values for the gate receivers connecting the deep and shallower-water regions; and blue represents the shallower-water, northern-most receiver RI values. The black dashed line is the location of the CSMB, where receivers below the line are south of the CSMB, and receivers above the line are north of the CSMB. (a) RI values of Greenland halibut tagged in August 2010 and 2011 in the southern region of Cumberland Sound; (b) RI values of Greenland halibut tagged in April 2012 in the northern region of Cumberland Sound. [Color figure can be viewed at wileyonlinelibrary.com]

mirrors observations for numerous species in the photic zone (Hayden et al. 2014, Kessel et al. 2014). Seasonal movements are typically correlated with environmental factors such as temperature, photoperiod, current strength, and direction (Binder et al. 2011, Hussey et al. 2015), which dictate the tolerance of fish, their prey and/or predators, and consequently the habitat that they occupy. For Greenland halibut in Cumberland Sound, percent ice cover was a strong predictor of fish occurrence in the northern region during the winter months. In addition, the transition of fish to, and returning from, the northern section of the Sound occurred during ice formation/break up. For the southern region of Cumberland Sound, ice cover was not a strong predictor of fish occurrence, but this may relate to our inability to accurately characterize ice concentrations in that region. During winter months in the central and southern section of the Sound, ice may not be consolidated, with the occurrence of a polynya toward the Sound entrance. Ice chart data cannot discriminate ice concentration at this resolution. Marine mammals, specifically beluga (*Delphinapterus leucas*) and narwhal (*Monodon monoceros*) overwinter in the polynya region in the Sound (Kilabuk 1998, DFO 2008) and are known to prey on Greenland halibut (Laidre and Heide-Jorgensen 2005). Decreased predation risk linked with landfast ice formation in the northern region and the seasonal occurrence of marine mammals in the south during the winter, may be a key factor driving the observed seasonal movement of Greenland halibut.

Seasonal movements of Greenland halibut tied with ice cover have also been observed in the inshore fjords of

northwestern Greenland (Boje 2002) and Disko Bay (central western Greenland; Boje et al. 2014). The dynamics of the seasonal movement patterns in these regions, however, differ from those observed in our study. In Cumberland Sound, fish move from the southern deep-water region (>1000 m) northward, either to the same depth or shallower (~600 m) water with the onset of ice. In Disko Bay, fish displayed the same movement to the inner area of the fjord associated with ice formation but the seasonal depth of occurrence was reversed (summer 300 m vs. winter 800 m; Boje et al. 2014). In contrast, in northwestern Greenland, whereas fish also moved to the inner section of the fjord, this occurred during the summer ice-free period, although fishing effort may have biased the observed distribution pattern (Boje 2002). Nonetheless, the movement of fish to the inner sections of coastal fjords would seem a consistent migration strategy among these geographically isolated sites, but the timing and environmental conditions at each appear variable.

Boje et al. (2014) reported Greenland halibut occupying colder waters during the winter months in the deep inner icefjord of Disko Bay, a similar trend observed in this and a previous study in Cumberland Sound (Peklova et al. 2012). The negative relationship between presence of fish in the northern region of Cumberland Sound and temperature may suggest a thermal preference. As a result, fish time their movements southward to depart waters that are still cooling despite the diminishing ice as summer approaches and to occupy deeper southern waters where temperatures are higher in order to maintain their thermal

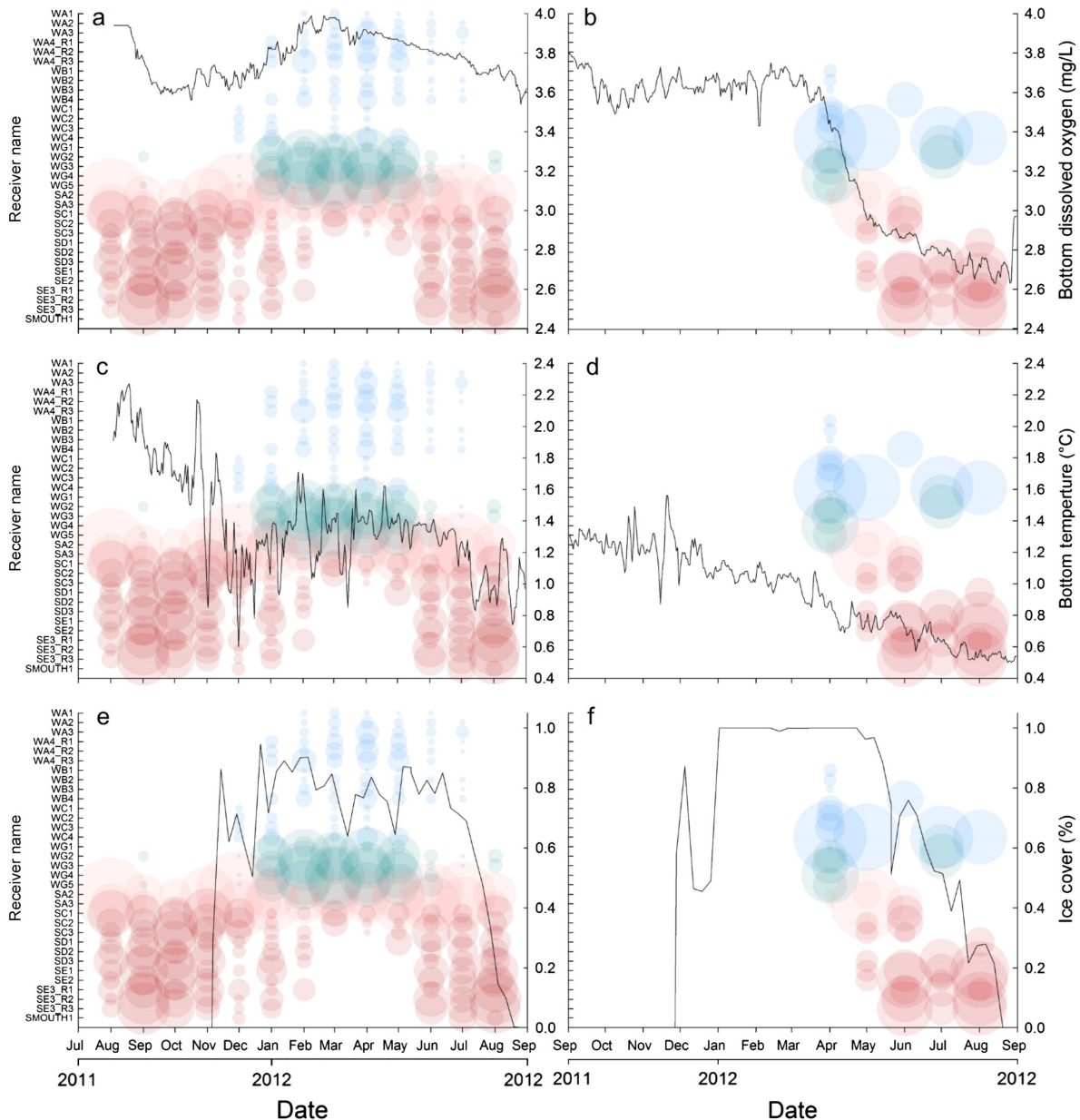


FIG. 7. Environmental variables recorded within Cumberland Sound, with residency index values (RI, see Fig. 5) depicted in the background. The left panels (a, c, and e) are environmental variables recorded in the southern region of Cumberland Sound, including bottom dissolved oxygen and percent ice cover data for the entire deep water southern region (see Appendix S2; both significant factors in the GLMM) and temperature readings from near the mouth of the Sound (SMOUTH, Fig. 1; nonsignificant factor in GLMM). The RI values are for Greenland halibut tagged in the southern region. The right panels (b, d, and f) are bottom dissolved oxygen and percent ice cover for the entire northern region of Cumberland Sound (both significant factors in the GLMM) and temperature recorded in the channel connecting the deep and shallower-water areas of the Sound (Fig. 1; nonsignificant factor) and. The accompanying RI plots are for Greenland halibut tagged in the shallower northern region. [Color figure can be viewed at wileyonlinelibrary.com]

range. Alternatively, movements to colder waters in the northern region may occur to reduce metabolic activity during the ice-cover period when primary productivity is limited (Peklova et al. 2012), but the duration of the residency in the north may be limited by thermal range of Greenland halibut. Equally, GLMM showed that, with decreasing bottom oxygen concentrations, fish moved

from the northern region southward. In the southern deep region, fish occupied waters with oxygen concentrations of $\sim 3.6\text{--}3.7$ mg/L, similar to the values recorded during peak fish occurrence in the northern region. While Greenland halibut and flatfish generally have a low aerobic scope when compared with pelagic fishes (Dupont-Prinet et al. 2013) and are reported to occur in high abundances at low

TABLE 1. Parameter estimates from generalized linear mixed model predicting Greenland halibut presence in the deep-water southern region of Cumberland Sound relative to fork length and abiotic factors.

Predictor variables	Value	SE	<i>t</i>	<i>P</i>
Intercept	6.769	1.870	3.62	0.003
Fork length	-2.215	1.103	-2.01	0.046
Wind speed	0.004	0.002	1.44	0.15
Wind direction	0.003	0.003	1.30	0.19
Photoperiod	0.010	0.006	1.56	0.12
Moon illumination	-0.239	0.099	-2.41	0.02
Sea ice concentration	-0.004	0.002	-2.52	0.01
Sea bottom temperature	0.078	0.140	0.56	0.58
Sea bottom dissolved oxygen	-2.494	0.495	-5.04	<0.001

Notes: Random effects: halibut ID estimated variance = 0.77 ± 0.88 ; tagging location estimated variance = 0.00002 ± 0.004 (both are mean \pm SE). Boldface type highlights $P < 0.05$.

TABLE 2. Parameter estimates from generalized linear mixed model predicting Greenland halibut presence in the shallow northern region of Cumberland Sound relative to fork length and abiotic factors.

Predictor variables	Value	SE	<i>t</i>	<i>P</i>
Intercept	-11.830	2.738	-4.32	<0.001
Fork length	1.761	1.967	0.89	0.37
Wind speed	0.005	0.004	1.46	0.15
Wind direction	-0.005	0.004	-1.21	0.22
Photoperiod	0.065	0.035	1.88	0.06
Moon illumination	0.015	0.182	0.08	0.93
Sea ice concentration	0.042	0.004	9.57	<0.001
Sea bottom temperature	-3.619	0.776	-4.66	<0.001
Sea bottom dissolved oxygen	1.682	0.580	2.90	0.003

Notes: Random effects: halibut ID estimated variance = 0.78 ± 0.88 ; tagging location estimated variance = 0.36 ± 0.60 (both are mean \pm SE). Boldface type highlights $P < 0.05$.

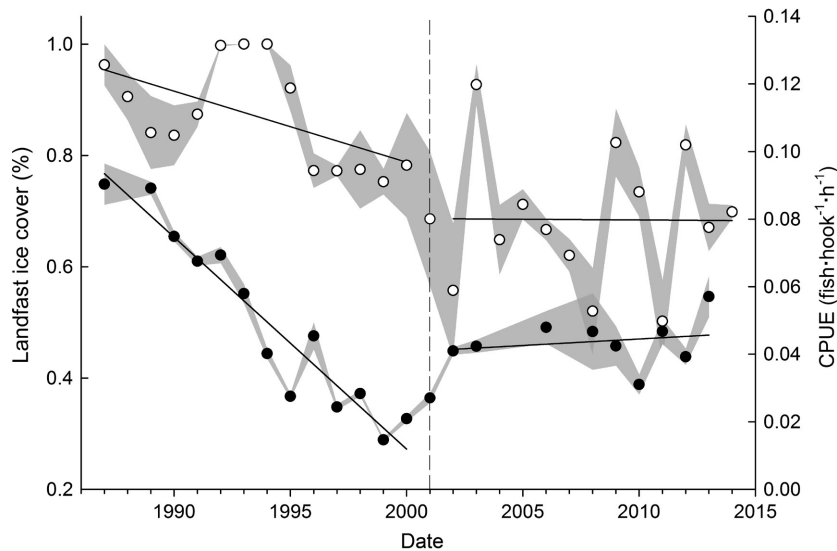


FIG. 8. Piecewise regression of percent landfast ice cover (open circles) for the area north of the Cumberland Sound Management Boundary (CSMB) and catch per unit effort (CPUE, filled circles) of the community-based winter fishery that takes place in the same region. Landfast ice was used as a measure of accessibility of fishers to the fishing grounds. Significant declines in both landfast ice and CPUE were found (landfast ice, $R^2 = 0.325$, $y = -0.013x + 26.314$, $P = 0.03$; CPUE, $R^2 = 0.917$, $y = -0.006 + 12.562$, $P < 0.0001$) up until a break point at the year 2001 (indicated by the vertical dashed line), after which no significant relationship exists for either variable (landfast ice, $R^2 = 0.0007$, $P > 0.05$; CPUE, $R^2 = 0.044$, $P > 0.05$). The gray shading represents \pm SE for each year for each variable.

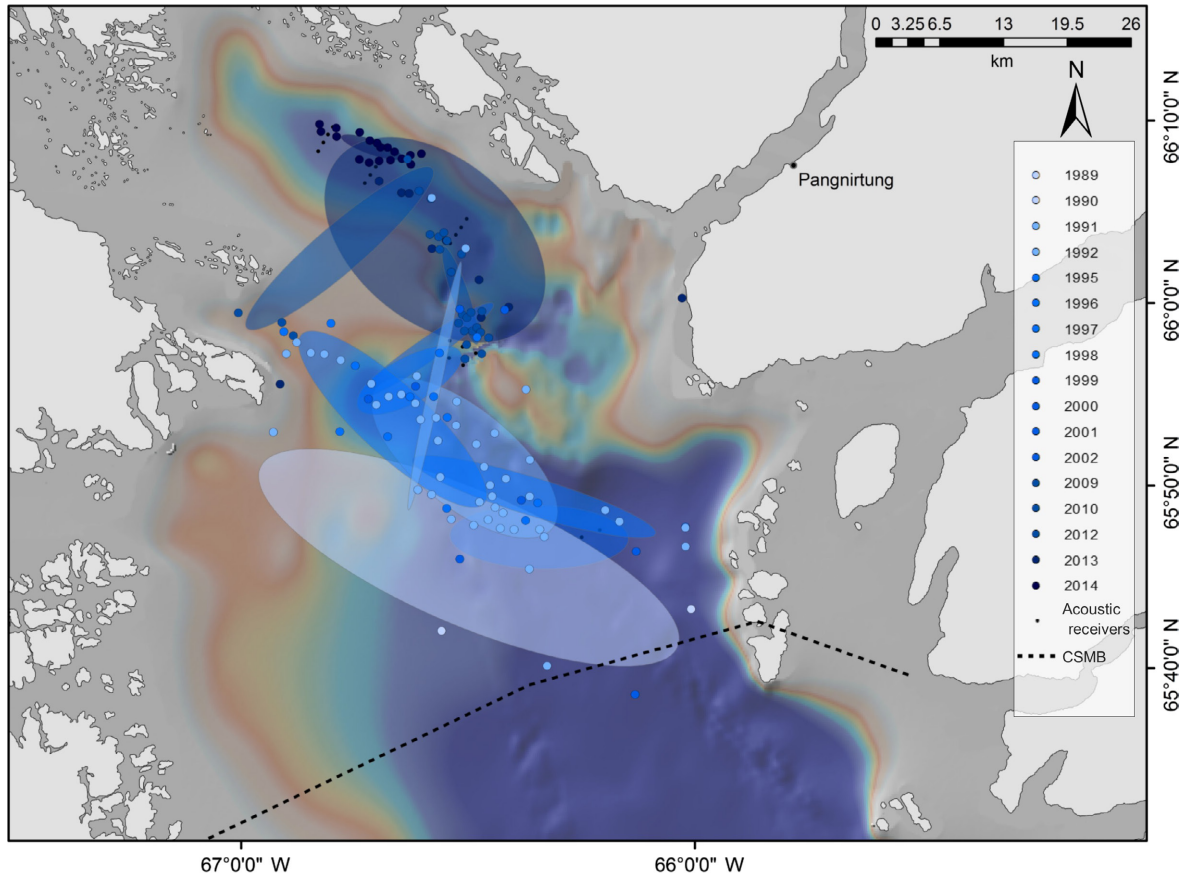


FIG. 9. Map showing fishers' locations in Cumberland Sound over the lifespan of the fishery (1987–2013). Bivariate ellipses encompass the core 40% of the fishing areas used within a given year, with individual locations of fishers marked by dots. Colors of ellipses and dots are graduated from the lightest blue in the first year to darker colors in more recent years. Small black circles are acoustic receiver locations from the present study. Note that, for some years, ellipses were not calculated either because no data were reported by fishermen or because sample size was too small. [Color figure can be viewed at wileyonlinelibrary.com]

dissolved oxygen concentrations (Youcef et al. 2013), it is possible that dissolved oxygen concentration regulates the occurrence of these fish, through sensitivity to changes such as were previously documented for spotted ratfish (*Hydrolagus colliei*) and petrale sole (*Eopsetta jordani*; Keller et al. 2015). Overall, these data suggest that a combination of biotic and abiotic factors drive these seasonal movements including potential thermal and oxygen-saturation regimes, predator avoidance or prey availability (Boje 2002, Hovde et al. 2002).

For deep-water fish species, data on horizontal movement patterns have been particularly complex to collect. Typically, standard tag–recapture programs only provide the tag and recapture location with no detail on specific movement patterns between those two time points. More recently, archival data loggers that collect high-resolution depth and temperature time series data were attached to Greenland halibut off West Greenland (Boje et al. 2014). These tags, which must be physically recovered to access the data, provided detailed information on the thermal and vertical preferences of Greenland halibut over time, but data return rate was low (data were retrieved

from 10 of 181 tagged fish). In addition, these tags do not provide any horizontal movement data aside from the release and recapture locations. Similarly, satellite telemetry of Greenland halibut recorded high-resolution depth and temperature profiles for individual fish and provided the first evidence of seasonal movement within Cumberland Sound (Peklova et al. 2012). Although most of the deployed satellite tags transmitted data (eight of nine), the tags are expensive and cannot provide any horizontal location data at these deep depths because no light data are available for geolocation.

The known benefits of acoustic telemetry for monitoring fish in the epipelagic zone (Hussey et al. 2015) were expected to apply to monitoring deep-water species. Specifically, tags with long battery life (up to 10 yr) and of various sizes (can equip fish weighing as little as ~10 g) can be implanted in fish, enabling long-term monitoring of individuals. Following this approach, Weng (2013) successfully monitored the movements of three bottom-fish species, (scarlet snapper; *Etelis coruscans*; red snapper; *Etelis carbunculus* and pink snapper; *Pristipomoides filamentosus*) at depths of 100–400 m

for up to 40 d in Hawaii, while the deep sea shark, *Centrophorus zeehaani*, was monitored at depths of 300–700 m over an average of 408 d off Southern Australia (Daley et al. 2015). Acoustic telemetry studies, through the deployment of fixed receivers, provide the only viable option to passively track horizontal movements of these deep-water species. Long-battery-life receivers are now available (for example VEMCO VR4W) that can be deployed for 6 yr (rather than one) with data downloaded on a regular basis via hydroacoustic link (rather than physical retrieval). This reduces the costs of monitor deployment and maintenance on an annual basis and minimizes disturbance to the environment. At present, these monitors can only operate at depths <500 m, but given interest in commercial exploitation of deep-water fish and the requirement for movement data, it is anticipated that monitors will be developed for use in waters >500 m.

The role of telemetry data in Arctic fisheries management

Acoustic telemetry revealed that Greenland halibut tagged in Cumberland Sound crossed the CSMB, with most fish inhabiting the southern deep-water section during the open-water summer period and the region north of the management line encompassing the northern end of the deep-water channel, the gate, and the shallower northern basin, during the ice-covered winter period. Although individual variability in movement was observed, including a few fish detected either in the northern or southern region year round, RI values clearly showed a seasonally shifting distribution of the sampled population. These data identify that the majority of Greenland halibut are not resident in the Cumberland Sound winter fishing grounds as was previously assumed (Treble 2003). Consequently, a summer fishery in the southern deep-water region of Cumberland Sound south of the CSMB would target the same fish as the winter fishery. Given that the declaration of the CSMB was based on resident fish, i.e., a sink population that is considered discrete from the offshore population, a TAC solely assigned to the fishing region north of the CSMB would seem inappropriate. Moreover, when considering the development of a southern open-water fishery in Division 0B south of the CSMB using large offshore vessels that are able to fish intensively, these movement data raise concern over the long-term sustainability of the community based winter fishery. As a result, following consideration of these telemetry data by the Nunavut Wildlife Management Board, the Government of Nunavut and the Department of Fisheries and Oceans, the CSMB was conditionally moved to the entrance of Cumberland Sound in 2014. It was further requested that the community support continued telemetry monitoring within the Sound to determine if the seasonal movement of fish is replicated across years. In 2014, acoustic equipment was redeployed in Cumberland Sound

following consultation with the community for a further two years of data collection.

Since the inception of the community winter fishery, deteriorating ice conditions (ice extent, thickness, and stability) have occurred within Cumberland Sound, driving accessible areas northward and confining the fishing grounds to predominantly shallower water regions outside of the previously preferred sites. During the early years of the fishery, fishers targeted locations at the northern end of the southern deep-water region where catch rates were highest (Receivers SA2 and SA3; DFO 2008; Dennard et al. 2010). In 1996 a severe storm caused the edge of the landfast ice to break up, which led to significant loss of fishing gear on the ice and for the next 5 yrs the number of fishers dropped considerably. During that same period, fisher locations moved consecutively northward as a result of poorer landfast ice (Dennard et al. 2010; these data). From 2002, increased effort and a longer fishing season led to higher catches and more recently, based on these telemetry data, fishers located a deep-water productive area in 2013 in the northern region that led to improved CPUE and a renewed interest in the fishery. These telemetry data, however, suggest that the originally favored deep-water winter fishing grounds at the northern end of the deep-water channel (region of SA monitors) are still where most fish are resident during the winter period. Few tagged fish moved into the very northern regions. This suggests that poorer quality ice may limit the winter community fishery from accessing the most productive fishing grounds, but further telemetry monitoring and survey work is required in the northern deeper water pockets to determine to what extent fish move toward this area of the Sound.

Predicted reductions in Arctic sea ice extent (Stroeve et al. 2007) could mean that the community winter fishery as it stands will not exist in the future. With the critical need for economic growth through job opportunities in Arctic Inuit communities, coupled with the large investments that have been made in developing this fishery through establishing a fish processing plant and subsidizing fishing equipment, the only viable option for the community fishery as currently equipped may be as a summer, open-water fishery. In 2014, community members for the first time successfully fished from a larger vessel (~12.2 m) during the open water summer period (P. Kilabuk, *personal communication*), noting most vessels operated in Canadian Arctic communities are ~5.5 m long and too small to fish deep-water longlines. Future development of the fishery will rely on the growth of an open-water summer fishery using larger community-operated vessels to complement the ongoing winter ice fishery, similar to the Greenland fishery model (GN 2010). If this were to occur, over time, the fishery would likely transition to an open-water fishery with a longer fishing season as ice extent continues to decline. When considering long-term fisheries planning, the movement of the CSMB to the entrance of the Sound allows the community fishery to exploit the TAC across both winter

and summer fishing areas and addresses the long-term climate scenario. This is based on the assumption, however, that the loss of ice will not impact the overall food-web structure to such an extent as to modify the occurrence and abundance of Greenland halibut in the Sound (Morgan et al. 2013). Research is required to better predict the impact of sea-ice loss on deep-water ecosystems, especially when considering commercially important species whose populations will likely be placed under increasing pressure as the Arctic region becomes more accessible to fisheries (Steiner et al. 2015). Equally, there is a necessity for carefully considered long-term monitoring programs for these data limited stocks to ensure sustainable harvests.

Telemetry and its future application to Arctic Fisheries

While these acoustic-telemetry data clearly indicate that Greenland halibut were not resident within the winter fishing grounds in Cumberland Sound year round and the relocated CSMB accounts for the observed seasonal movements of fish, it is now imperative to investigate the connectivity between inshore and offshore Greenland halibut populations. These inshore populations of Greenland halibut have been considered to constitute “sink populations” whereby animals reach a certain size, enter inshore waters and then remain in these environments. The term “sink” arises from the fact that the fish are thought to remain in the system and there is little or no evidence of spawning occurring (Simonsen and Gundersen 2005), basically implying a dead end. To date, six acoustically tagged Greenland halibut ranging in size from 60 to 76 cm fork length (66.6 ± 5.6 cm [mean \pm SD]) have been detected at the entrance to the Sound and one has been caught in offshore waters. Similarly, previous tag–recapture data documented connectivity between the mouth of Cumberland Sound and the offshore, albeit through a small number of recaptures (Treble 2003). These data now question the “sink” hypothesis, raising questions over the levels of mixing of this population with other geographical populations and its contribution to overall recruitment and genetic diversity. Quantifying connectivity between Cumberland Sound and Baffin Bay and Davis Strait is extremely important for fisheries management since changes in the offshore fishery could have implications for the Cumberland Sound fishery, depending on the degree of connectivity. The deployment of a line of consecutive acoustic receivers across the deep water channel at the entrance to Cumberland Sound, spaced at intervals to maximize detection efficiency to approximately 100%, would make it possible to quantify immigration/emigration of tagged fish into/out of Cumberland Sound and allow managers to estimate how changes in either fishery will affect the other. This concept follows the gate array designs used to monitor river migrations (Welch et al. 2009), and would provide a method to quantify the level of subpopulation connectivity in species with diffuse

movement patterns, but whose movements are constrained in specific areas, such as deep water channels.

This study demonstrates the power of acoustic telemetry for improving our understanding of species ecology and our ability to effectively manage exploited populations. Ongoing technological improvements will only increase the opportunities for data collection and improve our understanding of frontier ecosystems.

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