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Tracking seabirds to identify ecologically important and high risk marine areas in the western North Atlantic

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ABSTRACT

Protection of the marine environment lags far behind that of terrestrial domains. To help ameliorate this circumstance, top predators are being tracked to identify important ocean habitats, biodiversity hotspots and high risk areas and to assess effects of anthropogenic developments, pollution and environmental perturbations. We used GPS, Global Location Sensors (GLSs) and satellite platform terminal transmitters (PTTs) to track foraging and migrating thick-billed and common murres and northern gannets along with vessel surveys to identify potential Marine Protected Areas, to assess risk and to evaluate the consequences of the recent Gulf of Mexico oil disaster. Multi-year persistent sites of forage fishes generated multi-species predator aggregations. Species- and colony-specific winter inshore and offshore distributions of murres are associated with risks of climate change (ice), by-catch in fishing gear, hunting and oil extraction. Some thick-billed murres wintered in oceanic areas beyond the continental slope, and an area of high biological diversity was identified west of the Mid-Atlantic Ridge that, owing to its location beyond national jurisdictions, presents unique challenges for protection. Migration research indicated a substantial proportion of the North American gannet population wintering in the Gulf of Mexico near the *Deepwater Horizon* pollution area. Northern gannets incurred the highest incidence of oiling/recoveries and were the third-most oiled avian species; distributions and exit dates suggest that sub-adult birds suffered much, likely most, of this mortality. Environmental risk is being assessed by tracking combined with stable isotope and blood assays to probe trophic interactions, habitat relationships and to identify and protect biologically significant marine areas.

1. Introduction

Marine animals have evolved to live in variable ocean conditions, yet in recent decades rapid global changes are inducing novel ocean scale regime shifts that pose new and unprecedented challenges (Perry et al., 2005). Climate variability and human activity in the forms of offshore hydrocarbon, wind and wave energy developments, fishing, oil pollution, artificial night lighting, hunting, and shipping pose incremental and cumulative risks for marine animals (Garthe and Hüppop, 2004; Hjermann et al., 2004; Lewison et al., 2004; Montevecchi, 2006; Wilhelm et al., 2009; Kaluza et al., 2010; Burkhard et al., 2011; Schwemmer et al., 2011). Hence, there is urgent need to investigate the movements and delineate areas of persistent aggregations of top predators and the diverse food webs on which they depend, to better understand the implications of these risks and to develop conservation approaches to protect ocean habitat and marine biodiversity effectively.

Marine biodiversity hotspots, where convergent ecosystem processes concentrate resources, are beneficial across taxa but are often temporarily active and difficult to identify and hence protect (Worm et al., 2003). Many of these sites warrant designation in the form of Marine Protected Areas (MPAs), Ecological and Biologically Significant Areas (EBSAs) or no-harvest zones (González-Solís et al., 2007; Harris et al., 2010; Lascelles et al., this issue; Pichegru et al., this issue). Application of data from animal-borne tracking and bio-logging devices to investigate the movements,

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distribution, behavior and ecology of free-ranging top predators is proving to be a key development in this pursuit (Burger and Shaffer, 2008; Block et al., 2011; Thaxter et al., this issue). Bio-logging techniques provide behavioral observations of free-ranging marine animals that can be used to integrate movement across multiple space/time scale with more restricted ecological snapshots from vessel surveys and banding data (Louzao et al., 2009; Camphuysen et al., this issue).

Existing MPAs are very few and far-between and are for the most part linked to benthic and coastal sites that lie within coastal shelf regions well within national boundaries. Yet open oceanic systems comprise most of the earth's biosphere, contributing nearly half of the planet's photosynthetic production. Effective conservation planning has to carefully consider these oceanic and off-shelf regions (Louzao et al., 2006; Game et al., 2009), where migratory seabirds and other top marine predators spend much of their lives (Block et al., 2005, 2011; Weimerskirch, 2007; Hedd et al., 2011b; Thiebot et al., 2011; Lascelles et al., this issue). Ideally, management frameworks should integrate conservation, oceanographic and demographic perspectives (Hooker et al. 2011; Montevecchi et al., 2011) and should be adaptive, involving temporal designations as appropriate (Melvin and Parrish, 2001).

In this paper, we use tracking and bio-logging techniques and vessel surveys to identify foraging and biodiversity hotspots, migration routes, persistent staging areas and regions of population connectivity in the North Atlantic. We focus on three seabird species – thick-billed murres (*Uria lomvia*), common murres (*Uria aalge*) and northern gannets (*Morus bassanus*) – from eastern Canadian colonies (Tuck, 1960; Garthe et al., 2011). We use examples to document how tracking and bio-logging research can: (1) delineate areas of temporally persistent aggregations during breeding, migration and in winter, (2) identify biodiversity hotspots when integrated with vessel-based prey and oceanographic surveys, and (3) complement concepts of MPAs and EBSAs by detecting high risk areas and key oceanic sites beyond national jurisdictions. Examples from anthropogenic activities and a recent ocean basin crisis (*Deepwater Horizon* blowout) demonstrate how this approach can help assess demographic consequences as well as local and far-reaching risks to improve conservation actions.

2. Methods

2.1. Foraging scale (during breeding)

2.1.1. Study sites, species and devices

At Funk Island (49°45′N, 53°11′W), Newfoundland, Canada (Fig. 1), northern gannets were equipped with GPS (earth & OCEAN; 65 or 70 g depending on sensor capabilities; <3% adult body mass) to track movements and diving activity during chick-rearing (3–5 weeks post-hatch) between July and August 2003–2005. Details about attachment protocols are reported in Garthe et al. (2011).

2.1.2. Vessel surveys

To determine the distributional patterns of marine birds, mammals and forage fishes (primarily capelin, *Mallotus villosus*) in the vicinity of Funk Island, vessel survey transects were run during mid-July early August 2000–2009 (Fig. 2A) aboard Canadian Coast Guard research vessels (*Shamook:* 2000–2003; *Wilfred Templeman*: 2004–2006) and a commercial fishing vessel (FV *Lady Easton II*: 2007–2009; methodological details in Davoren et al., 2010). Briefly, 9 east–west (across shelf) hydro-acoustic survey lines were conducted at a 9-km north–south spacing as well as one survey line along the coast (Fig. 2A). All survey lines were completed in most years (2000–2003, 2007, 2009), and a subset (lines 1, 3, 6, 9, coastal) in other years owing to varying study objectives. During surveys, hydro-acoustic data and simultaneous counts of marine birds and mammals were continuously recorded using standardized strip transect methods (Tasker et al., 1984). Gravel at deep-water spawning sites of capelin ($n = 11$) was monitored regularly for the presence of eggs during June–August of 2003–2009 from the FV *Lady Easton II* using a 30 cm^2 Van Veen bottom grab system (details in Penton, 2007).

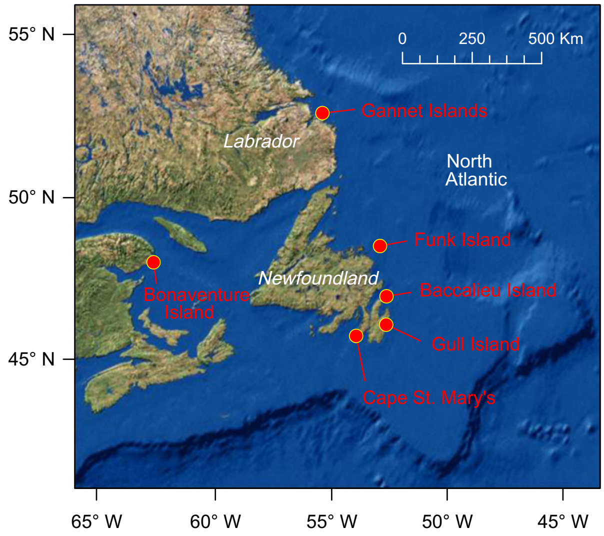

Fig. 1. Colonies where tracking studies have been carried out for common murres (Gannet, Funk and Gull Islands), thick-billed murres (Gannet Islands), and northern gannets (Bonaventure, Baccalieu and Funk Islands and Cape St. Mary's).

2.1.3. Diet sampling of northern gannets

Food samples were obtained by approaching roosting congregations of gannets that often regurgitated as they moved away from researchers (Montevecchi & Myers, 1995; Davoren et al., 2010). Samples were also obtained from birds captured for device attachments and removals and from discarded regurgitations and scraps in the colony. Regurgitated prey were identified to species, and prey landings are presented as percentages of total regurgitations during each year.

2.2. Migration scale (non-breeding)

2.2.1. Study sites, species and devices

Global Location Sensors (GLSs, see below) and satellite tags (Platform Terminal Transmitters, PTTs) were used to track the non-breeding seasonal movements of individual common murres, thick-billed murres and northern gannets (Table 1) from colonies in eastern Canada (Fig. 1) between 2004 and 2010. GLS were deployed on adult common murres at Gull Island in Witless Bay and Funk Island, Newfoundland, and on both common and thick-billed murres at the Gannet Islands, Labrador. Funk Island is the site of the largest common murre colony in North America (~400,000 pairs, Chardine et al. 2003), and the breeding ranges of common and thick-billed murres meet at the Gannet Islands where the species breed sympatrically (Birkhead and Nettleship, 1987). The study colonies for northern gannets cover the latitudinal extent of the species' North American breeding range and the bulk of the population, including the species' largest breeding colony. PTTs were used to study the post-fledgling movements of adult male common murres departing Funk Island with their fledged chicks. Adult (GLS) and juvenile (PTTs) northern gannets were tracked from four of their six North American colonies: Bonaventure Island, Quebec (the species' largest breeding colony),

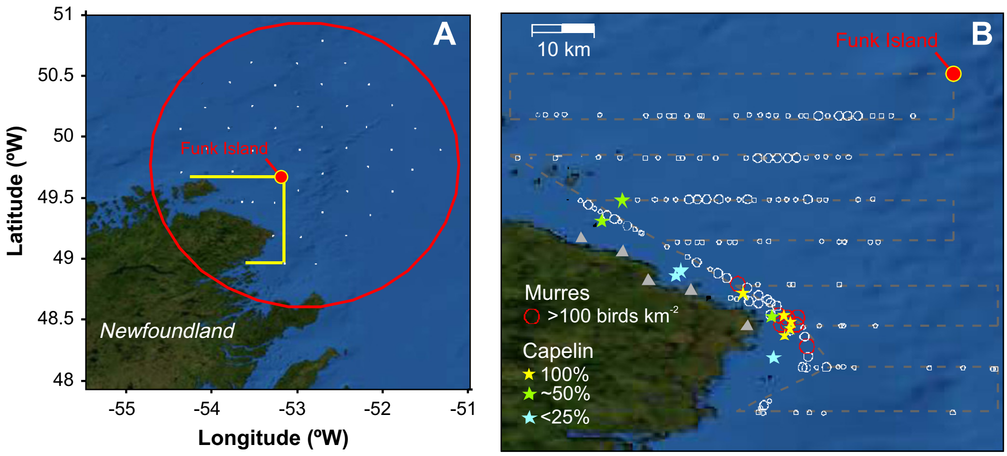

Fig. 2. (A). Vessel survey transect and oceanographic sampling sites (white dots) around Funk Island (red circle = meso-scale survey; yellow box = fine scale survey) where hydro-acoustic surveys for forage fishes and observations of marine birds and mammals were carried out. (B) Density of common murres on the water in 2007 (white circles), along with beach (triangles) and demersal (stars) spawning sites of capelin. Demersal spawning sites used in all years (yellow stars) were associated with persistent multi-species aggregations of marine birds and mammals (red circles; see Davoren, 2007).

Table 1
Details of seabirds tracked from colonies in eastern Canada, 2004–2010.

Species	Study site	Latitude/ longitude	Life stage, season	Study years	Device type (manufacturer)	Analyzed datasets (n)
Common Murre	Funk Island, NL	49°45′N, 53°11′W	Adult, non-breeding	2007–2008	GLS (BAS)	10
			Adult, post-breeding	2009	PTT (Wildlife Computers	4
	Gannet Islands, NL	53°56′N, 56°32′W	Adult, non-breeding	2008–2009	GLS (BAS)	7
Thick-billed Murre	Gannet Islands, NL	53°56′N, 56°32′W	Adult, non-breeding	2008–2009	GLS (BAS)	5
Northern Gannet	Bonaventure Island, QC	48°29′N, 64°09′W	Adult, non-breeding	2004–2006	GLS (earth & OCEAN, Lotek)	40
			Adult, breeding	2003 + 2007	GPS (earth & OCEAN)	18
	Funk Island, NL	49°45′N, 53°11′W	Adult, breeding	2003 + 2005	GPS (earth & OCEAN)	26
			Adult, non-breeding	2003–2007	GLS (earth & OCEAN)	16
			Juvenile	2010	PTT (Sirtrack)	3
	Cape St. Mary's, NL	46°49′N, 54°49′W	Adult, non-breeding	2005–2008	GLS (earth & OCEAN)	4
			Juvenile	2008–2010	PTT (Sirtrack, Wildlife Computers)	33
	Baccalieu Island, NL	48°15′N, 52°80′W	Adult, breeding	2009	GPS (earth & OCEAN)	6
			Adult, non-breeding	2009–2010	GLS (BAS Mk 5, earth & OCEAN GeoLT)	5

*BAS is British Antarctic Survey (Cambridge).

Funk Island, Cape St. Mary's and Baccalieu Island, Newfoundland (Table 1). Seventeen gannets carrying geolocators were tracked in 2 consecutive years.

2.3. Data processing

2.3.1. GLS

GLS (BAS, earth & OCEAN or Lotek), representing <0.4% of the body masses of murres and <0.1% of the body mass of northern gannets, were attached to chick-rearing adults on plastic and metal leg bands. GLS were retrieved in the year(s) following deployment. At recapture, devices were removed, birds were re-weighed and a 1 ml blood sample was taken from the brachial vein to determine sex via DNA analysis. Light data from the GLS were processed using MultiTrace Geolocation software (Jensen Software, Germany). The BAS loggers used a correction factor for day/night movement set to 0.7, sunrise and sunset thresholds set to 1, using an angle of elevation of −5.5; the earth and OCEAN loggers' thresholds were set using calibration data from the static placements before deployment. The quality of light curves was validated on a case-by-case basis using standardized criteria (Phillips et al., 2004). During equinox periods, latitudes cannot be assessed accurately from light data (Hill, 1994), so when possible we obtained latitude estimates by reconciling GLS-derived sea surface temperatures (SSTs) with remotely sensed satellite SSTs (Teo et al., 2004). When GLS-derived SSTs were unavailable (Mk13) and when the SST algorithm produced unreliable results due to lack of SST matching or cloud cover, light-derived latitude estimates were retained. In the resulting data set, locations that were clearly affected by vernal equinox (8 September–8 October) and spring equinox (6 March–5 April) were excluded, as were clearly erroneous locations resulting from light level interference, locations that represented unrealistic movements (>500 km day^{-1}) and locations that were outside the likely species' range, though positions over land were retained to avoid biasing results by over-representing time spent in areas further offshore. The resulting validated data were smoothed twice with raw fixed positions maintained around periods of missing data (Phillips et al., 2004). Tracks were then plotted in ArcMap (ESRI 2009), using Spatial Analyst and Hawth's tools, respectively, to create kernel density surfaces and percent volume contours which describe habitat use distributions. The 50% contours were taken to define "core" areas. The northern gannets' winter range was partitioned on the basis of broad scale regimes into three North American oceanographic zones: northeast Atlantic (NE), southeast Atlantic (SE) and Gulf of Mexico (GoMex).

2.3.2. PTTs

In 2009, at Funk Island, Wildlife Computers AC1 PTTs (18 g, $\sim$2% body mass) were sutured to the lower back of adult male common murres to follow their post-fledging movements with accompanying fledglings. Birds were captured (male-fledgling pairs) as they departed the colony at night and 1 ml blood samples were taken for DNA determination of sex. Tags were programmed with a 90 s repetition rate and were duty cycled for 5 h on/19 h off, transmitting daily from 16:30 to 21:30 UTC. The dispersal of juvenile northern gannets from colonies at Cape St. Mary's (2008–2010) and Funk Island (2010) was studied using Sirtrack KiwiSat 202 (32 g, <1% body mass) and Wildlife Computers AC1 PTTs (18 g, <1% body mass). Birds were captured on the sea within days of fledging and transmitters were attached to the underside of the 4 or 5 central tail-feathers with TESA™ tape and cable ties. In 2008 and 2009, Sirtrack tags were programmed with a 60 s repetition rate and transmitted daily from 02:00 to 04:00 and 15:00–18:00 UTC. In 2010, tags were programmed with a 75 s repetition rate and they transmitted from 13:00 to 17:00 UTC every second day.

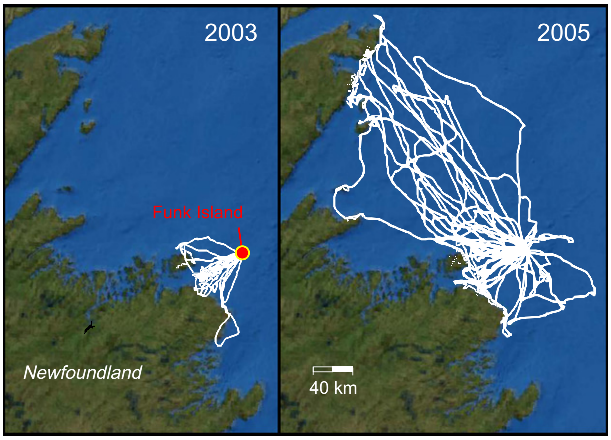

Fig. 3. Foraging trip tracks of Northern Gannets equipped with GPS loggers from Funk Island in 2003 and 2005.

3. Results

3.1. Foraging scale: prey aggregations and seabird foraging behavior

3.1.1. Capelin, marine bird and mammal distributions

Monitoring of demersal spawning sites of capelin delineated inter-annually persistent sites within the foraging ranges of murre and gannet colonies on Funk Island (Fig. 2B). Spawning sites that were used in all years (100%) were associated with a persistent multi-species aggregation of marine birds and mammals,

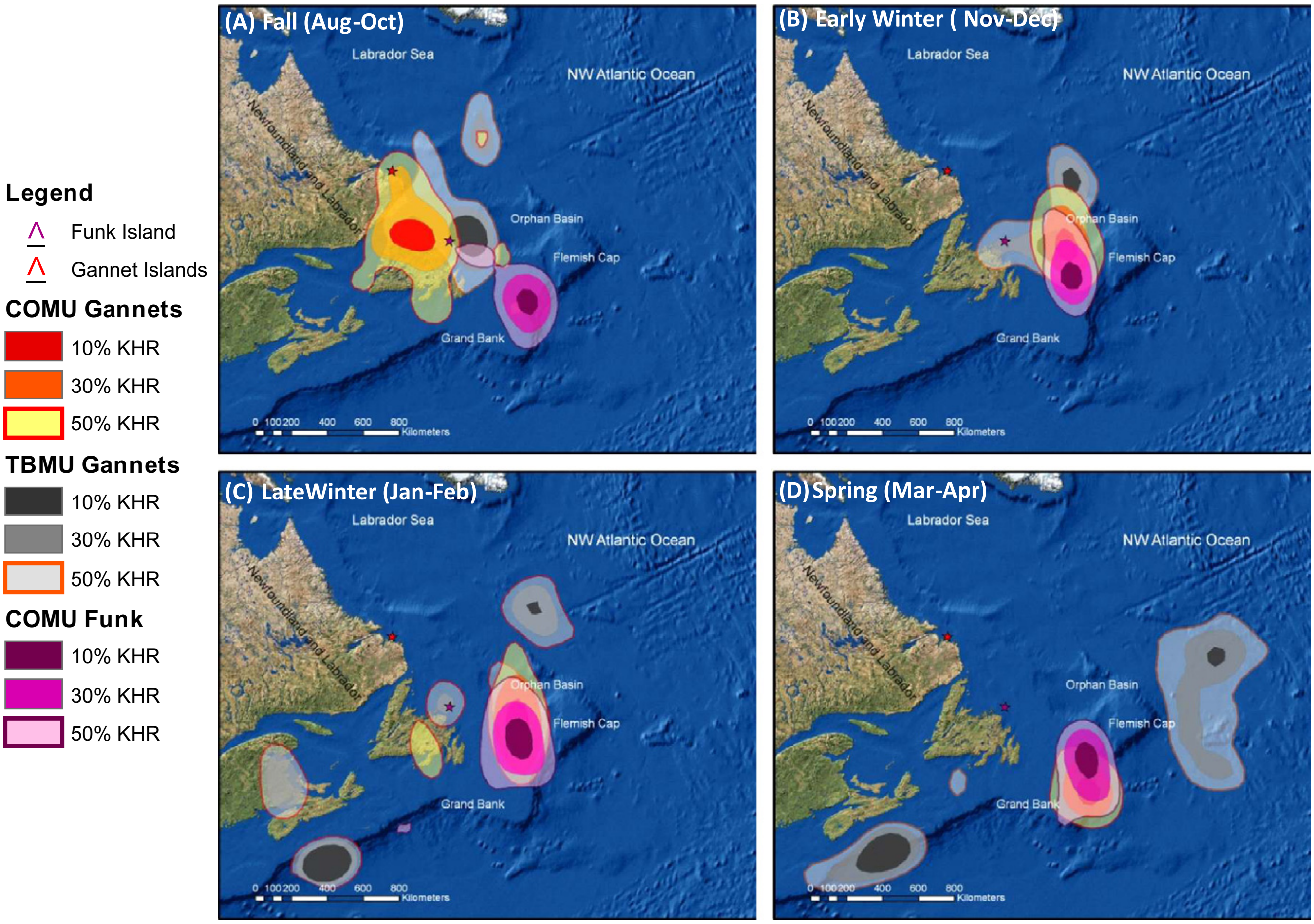

Fig. 4. (A) Autumn (August–October), (B) early winter (November–December), (C) late winter (January–February) and (D) spring (March–April) 50% Kernel Home Ranges of thick-billed murres and common murres from the Gannet Islands and common murres from Funk Island.

previously described as biological hotspots (Davoren, 2007). This is illustrated by overlaying the density of common murres (on water) in 2007 on the location of persistent demersal spawning sites (Fig. 2B). These distribution patterns are representative of bird biomass in all years, owing to the prevalence of murres (Davoren, 2007). Other dominant species at this aggregation included other breeding birds from Funk Island (mainly northern gannets) as well as trans-equatorial migrant great and sooty shearwaters (*Puffinus gravis* and *P. griseus*), and humpback (*Megaptera novaeangliae*), minke (*Balaenoptera acutorostrata*) and fin whales (*Balaenoptera physalus*; Davoren, 2007; Davoren et al., 2010).

3.1.2. Northern gannets

Gannets exhibited considerable foraging flexibility during chick-rearing, and inter-annual variability was pervasive (Montevecchi et al. 2009; Garthe et al. 2011). During 2003, the waters along the northeast Newfoundland coast were cold and the gannets fed almost exclusively on capelin (89%; 310 of 348 regurgitations sampled). In contrast, during 2005, regional waters warmed considerably and migratory warm-water fishes (Atlantic mackerel *Scomber scombrus*; Atlantic saury *Scomberesox saurus*) moved into the area. Correspondingly in 2005, the gannets consumed a diversity of prey, including capelin (13%; 27 of 210), mackerel and saury (combined 77%; 162 of 210). Furthermore, their foraging range essentially doubled (mean = 122 ± 81 km) and the 95% kernel feeding range was more than 50 times larger in 2005 when they pursued large pelagic fishes as well as capelin compared to 2003 (62 ± 12 km) when they fed almost exclusively on capelin. During 2005, foraging trip destinations were very variable and distributed along the entire northeast Newfoundland coast (Fig. 3).

3.2. Migration scale (non-breeding)

3.2.1. Ocean basin and continental shelf movements and aggregations

Murres: During fall movements from colonies, murres exhibited species and inter-colony differences. Common and thick-billed murres moved southeast from the Gannet Islands off southern Labrador toward the northeast Newfoundland coast (Fig. 4A). The common murres showed a distinct pattern of autumn inshore habitat use (Fig. 4A) before moving offshore for winter and spring though some were in coastal regions in southern Newfoundland by late winter (Fig. 4B–D). In contrast, common murres from Funk Island migrated more rapidly to the eastern edge of the Grand Bank where they remained through winter (Fig. 4). The rapid offshore movement pattern of the Funk Island common murres is also highlighted in the satellite-tracks of parental males with accompanying fledglings (Fig. 5) that swam along the shelf edge, moving toward the Southeast Shoal region of the Grand Bank over ~20 days.

During winter and spring, murres exhibited both inter-specific segregation and conspecific overlap at sea. Through winter and spring, common murres from both colonies showed almost complete spatial overlap on the eastern portions of the Grand Bank continental shelf and adjacent pelagic waters (Fig. 4B–D). In contrast, by early winter, thick-billed murres exhibited a more northerly distribution concentrating on the northern edge of the Grand Bank (Fig. 4B) and to a lesser extent off the northeast Newfoundland coast through winter (Fig. 4B and C). Inter-specific segregation became more pronounced seasonally and was greatest by spring, when common murres were on the southeastern reaches of the Grand Bank (Fig. 4D), and some thick-billed murres had moved onto the edge of the Scotian Shelf and others moved eastward off the continental shelf to oceanic regions west of the Mid-Atlantic Ridge (MAR; Fig. 4D). The 50% KHR utilization distribution of the thick-billed murres that moved offshore to the MAR during spring covered an area between approximately 39–52°N and 32–44°W, where the birds remained for 56 ± 1.0 days before migrating north to the Gannet Islands.

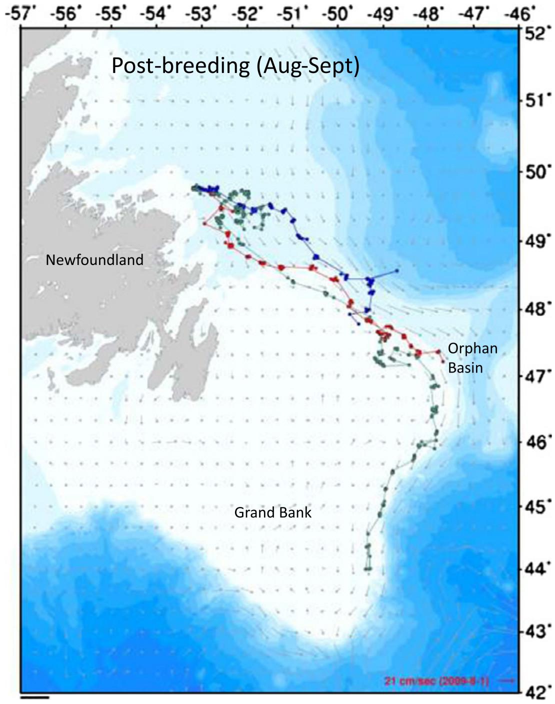

Fig. 5. Satellite tracks of four male common murres (2009) in relation to bathymetry (data from General Bathymetric Chart of the Oceans GEBCO) and sea surface current (geostrophic velocity vector) data layers obtained from (http://www.aviso.oceanobs.com). Positions were filtered by location classes of which classes 1–3 are shown. Oceanographic features and map created using the Satellite Tracking and Analysis Tool (STAT) program from SeaTurtle.org (Coyne and Godley, 2005).

3.2.2. Northern gannets

Northern gannets used primarily coastal shelf habitats, showing north–southwestward migratory movement from Canadian colonies along the eastern North American coast with many birds reaching the Gulf of Mexico. While bands and GLS indicated that about 60% of northern gannets wintered in the NE North American coastal shelf zone, these data sources resulted in different estimates of proportions of birds recorded in the other zones (Fig. 6; Fisher exact test, $p = 0.016$). About one-third of band recoveries occurred in the southeast compared to only 14% of GLS records. The largest discrepancy occurred in the Gulf of Mexico, where only 6% of adult band recoveries were obtained compared to 28% of GLS wintering northern gannets. Many of the northern gannets that wintered in the Gulf of Mexico were off the Louisiana coast in the immediate vicinity of the *Deepwater Horizon* explosion site and oil pollution area. There was no indication of any subpopulation or regional difference in the proportion of adults wintering in the Gulf of Mexico (26% overall, 12/46 GLS; 25% from Quebec, 7/28 GLS; and 28% from Newfoundland, 5/18 GLS). Fig. 7 shows the satellite tracks of 3 juvenile northern gannets from Cape St. Mary's to the Gulf of Mexico during November 2010. Like some thick-billed murres, some northern gannets at times moved to off-shelf oceanic regions.

4. Discussion

4.1. Prey aggregations, foraging behavior, and identification of local hotspots

Persistent forage fish aggregations were sites of multi-species marine bird and mammal assemblages. The multi-species trophic

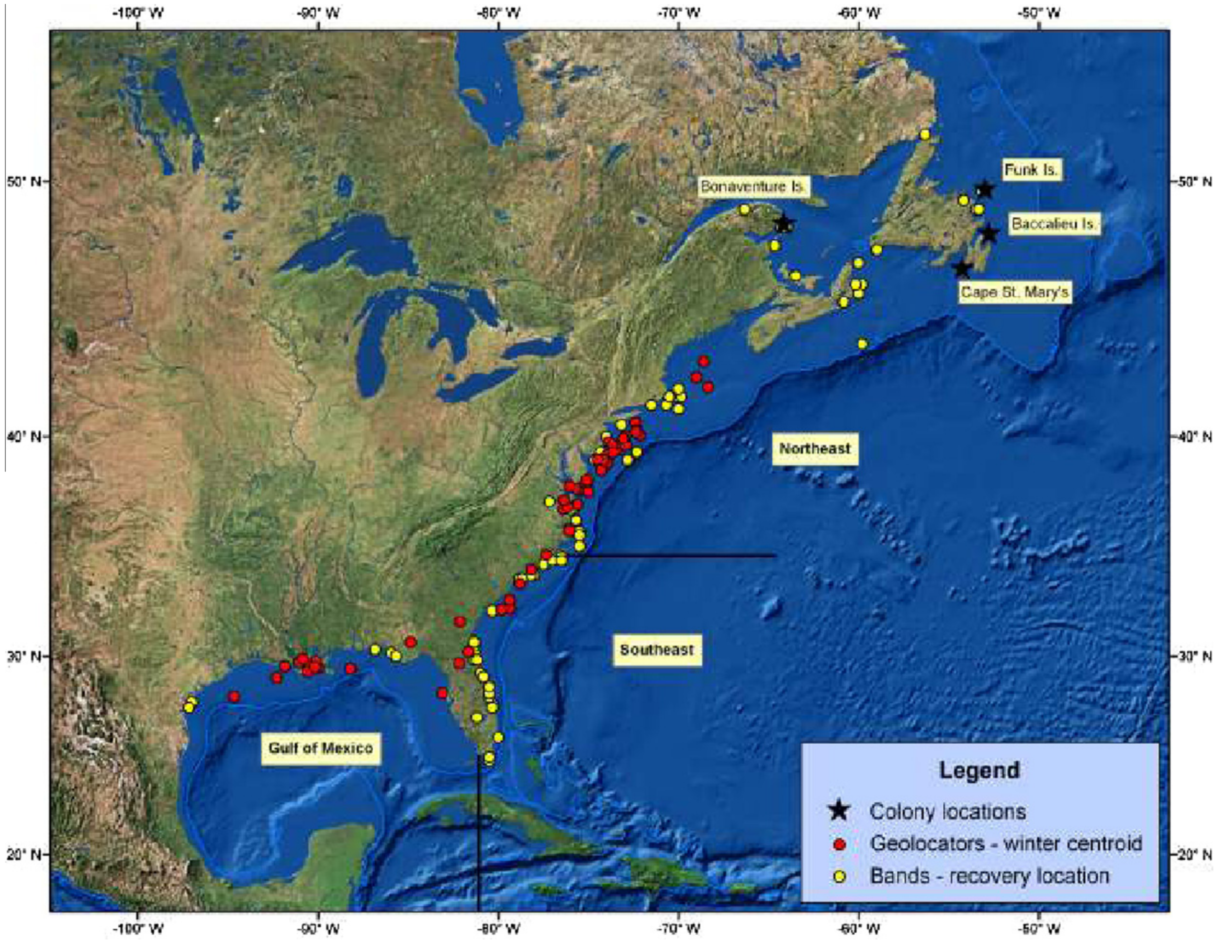

Fig. 6. Wintering (January–February) areas of northern gannets comparing band recoveries (yellow dots) and GLS mean winter positions (red dots) from 4 of 6 North American colonies. Wintering areas partitioned into three eastern North American oceanographic regions: Northeast, Southeast and Gulf of Mexico.

interactions at these sites make them key research sites with protected status potential. These forage fish aggregations also attract larger fishes and commercial fishers who target the large predatory fishes and often the forage fishes (Hjermann et al. 2004; Davoren, 2007). Hence protection of areas with persistent forage prey aggregations will be challenging and require multi-stake holder agreements and compromises.

The species-specific ecology and behavior of tracked marine predators influence conclusions drawn about marine spatial and temporal use, and largely dictate the application of tracking information to marine planning processes. For example, the foraging areas used by a capelin-dependent predator (common murres from Funk Island) targeting predictable forage fish aggregations during chick-rearing (Davoren and Montevecchi, 2003) were more consistent inter-annually than the areas used by a opportunistic (northern gannet; Montevecchi et al., 2009). Both these predators exhibit flexible foraging tactics (Burke and Montevecchi, 2009), but when forage fish aggregations were persistent, murres exhibited tighter spatial relationships with them. Our research highlights the necessity of conducting multi-year and multi-species studies when using top predators to detect important marine areas and emphasizes the importance of identifying and characterizing biological hotspots based on knowledge, not only of prey behavior and distribution, but also on predator flexibility in response to change (Block et al. 2011; Garthe et al., 2011).

4.2. Ocean basin and continental shelf movements and aggregations

4.2.1. Murres

Common and thick-billed murres originating from the same breeding colony showed considerable inter-specific segregation in non-breeding areas. In contrast, common murres from different colonies exhibited extensive overlap in wintering distributions. Some thick-billed murres were in inshore coastal regions through winter, though most moved well offshore and even off-shelf in late winter and spring. Most common murres remained well offshore on the continental shelf and shelf edge, though some were inshore in late winter. Satellite-tracked male common murres accompanying fledglings also moved offshore, swam along the shelf edge and through the Orphan Basin toward the Southeast Shoal of Grand Bank.

So how can we relate the marine spatial behavior of the murres to environmental risks, and how can these exercises aid in the identification of a network of candidate MPAs? Murres occupying inshore areas during summer are frequently drowned in gillnets set for cod *Gadus morhua* and other species (Piatt et al., 1984; Benjamins et al., 2008), while during winter they are subjected to ship-source oil pollution (Wiese and Robertson, 2004), a provincial murre hunt (Montevecchi et al., 2007), and at times, they are “wrecked” when trapped in bays by coastal ice conditions (McFarlane Tranquilla et al., 2010). Murres that winter on the

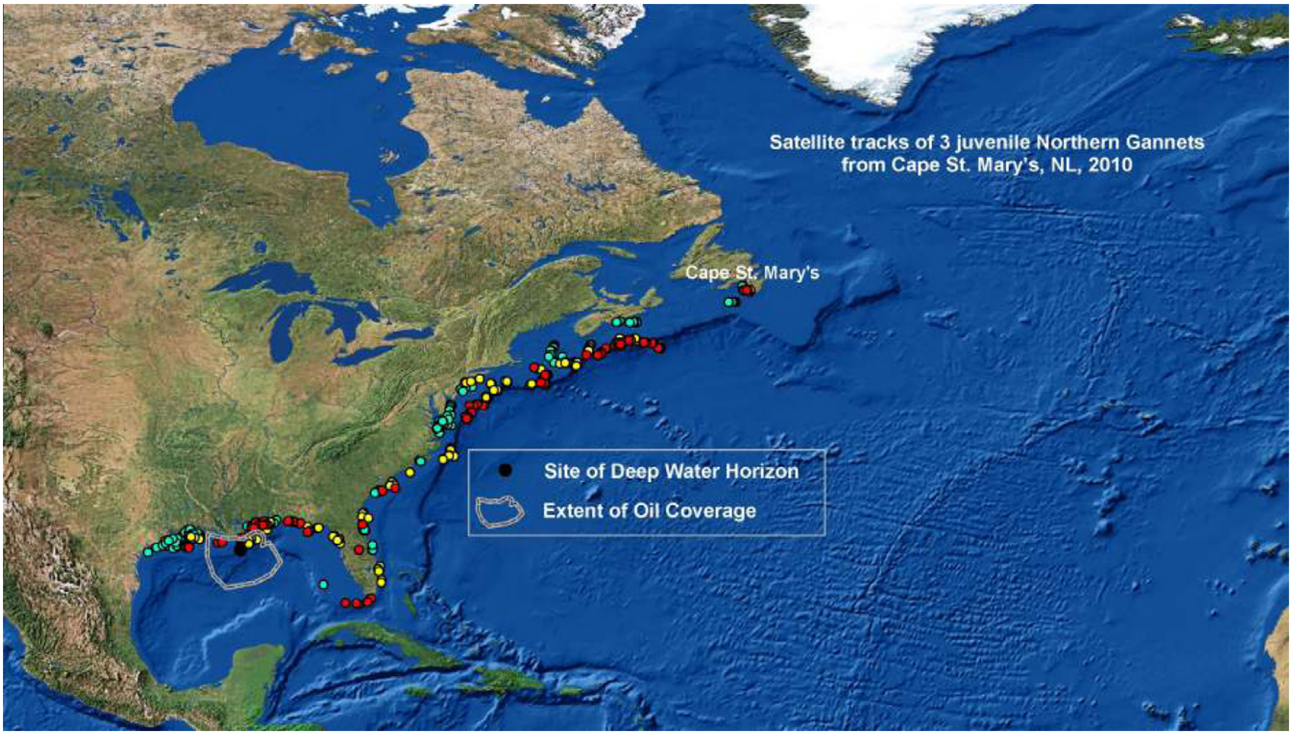

Fig. 7. Satellite tracks of three juvenile northern gannets from Cape St. Mary's, Newfoundland to the Gulf of Mexico during November 2010. The site of the *Deepwater Horizon* and area of surface oil slicks are indicated.

Grand Bank and shelf edge are clearly outside the range of these risks. They are however exposed to other risks including offshore petroleum activities (Hedd et al., 2011a) and its associated pollution (Wiese et al., 2001), night lighting (Montevecchi, 2006) and the artificial reefing effects (plant growth, fish attraction) associated with platform structures (Burke et al., 2005).

On an individual level, murres, northern gannets and other seabirds exhibit consistent inter-annual movements to the same wintering areas (McFarlane Tranquilla et al., unpubl.; Fifield, 2011; Phillips et al., 2005; cf. Dias et al., 2011). Given that the spatial and temporal distributions of common and thick-billed murres appears to be species- and colony-specific, we expect the potential impacts of anthropogenic and climate-related influences on marine habitat to have varying demographic and meta-population consequences.

This research can inform management decisions in ways that could help mitigate the synergistic effects of ratcheting episodic climatic and human influences (Piatt, 2011). Given the wide expanse of the murres' wintering areas, it is possible to identify key sites that are attractive to wintering murres such as the Orphan Basin, the continental shelf edge and the Grand Bank, that are also highly important for other species including key forage and commercial fishes. These sites are in immediate proximity to or downstream (Labrador Current) from offshore oil platforms and deepwater exploration sites, and they are exploited by non-Canadian fisheries. Shelf edges and slopes are well documented as important biodiversity hotspots and are in some locations included in MPA zoning (Hyrenbach et al., 2006). On the basis of our tracking studies and information from vessel surveys in eastern Canadian waters (Brown, 1986; Fifield et al., 2009) the shelf edge and the southern Grand Bank are significant productive biological hotspots that warrant protected status.

During late winter and particularly spring, thick-billed murres moved off the continental shelf exhibiting a wholly pelagic distribution. Movements were to an area west of the Mid-Atlantic Ridge that has only recently been appreciated as of major significance to marine birds and other taxa, including thick-billed murres from an Arctic colony at the Minarets, Nunavut (Gaston et al., 2011; McFarlane Tranquilla, unpubl. data), Arctic terns *Sterna paradisea* from Greenland and Iceland (Egevang et al., 2010) and long-distance southern hemisphere south polar skuas *Catharacta maccormicki* and sooty shearwaters (Kopp et al., 2011; Hedd et al., 2011b), as well as marine mammals (Doksætera et al., 2008) and large pelagic migratory fishes (Block et al., 2005; Fig. 8). Establishment of fully protected areas in international waters pose challenges, although there has been some recent progress, including the declaration of a protected area around the South Orkney Islands in the South Atlantic Ocean by the Commission for the Conservation of Antarctic Living Marine Resources (CCAMLR) in 2010. CCAMLRhas been quite successful in reducing longline and trawl bycatch of albatrosses, petrels and other seabirds by mandating proven mitigation techniques as a condition of fisheries operation in Antarctic waters (Croxall, 2008).

4.2.2. Northern gannets

Gannets from eastern Canadian breeding colonies migrated southwest along the North American continental shelf, the shelf edge and at times off-shelf. Inferences from tracking research indicate that many northern gannets moved through and wintered in the immediate vicinity of the Deepwater Horizon pollution area and that about a quarter of the North American population of northern gannets spend the winter in the Gulf of Mexico (Montevecchi et al., 2011). This estimate is more than four times greater than from banding data that until just a few years ago would have been all that could be used for such a risk assessment. Tracking research is also proving its value in locations such as the Gulf of Mexico where despite the presence of more than 3300 active oil platforms, there is no program of comprehensive systematic surveys for marine animals. Where environmental regulations are inadequate or nonexistent, tracking research holds important potential for biological information, risk assessment and effects monitoring.

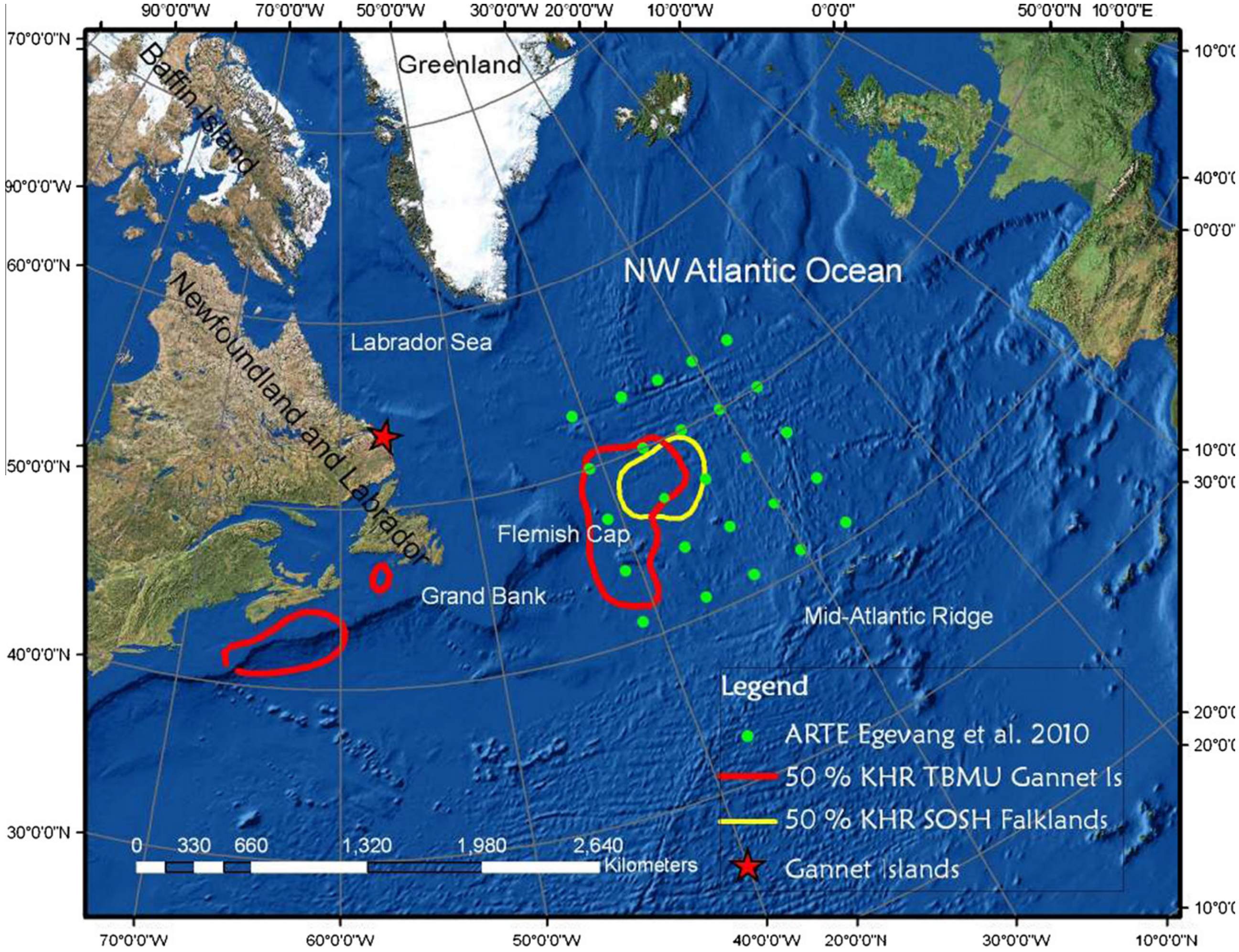

Fig. 8. Offshore spring distribution of thick-billed murres from the Gannet Islands (red star) overlaid on offshore area of spring distribution for sooty shearwaters from the Falkland Islands (yellow shape; from Hedd et al., 2011b) and spring and fall occurrence of Arctic terns (green dots; from Egevang et al., 2010).

Forage fishes may also be a major determinant of the choice of wintering areas used by northern gannets. Menhaden (*Brevoortia tyrannus*) are a key prey for northern gannets in the Gulf of Mexico where industrial fisheries are over-exploiting them (Franklin, 2007; Vaughan et al., 2007). Here too, there are cumulative anthropogenic influences, in this case oil pollution coupled with overfishing. Expansion of wind and wave energy production facilities are planned for offshore environments, and depending upon placement, could affect northern gannets' wintering and migrating along the eastern US seaboard. Healthy diverse seabird populations, and indeed healthy oceans, cannot be expected in the face of continued cumulative threats, and MPAs at forage fish hotspots identified by tracking top predators could indeed help facilitate the conservation of marine biodiversity.

4.3. Research implications for information and disturbance

Though device attachments on free-ranging animals can have negative behavioral, physiological and reproductive consequences (Burger and Shaffer, 2008), most of these are surmountable and cause much less colony disturbance than large-scale banding campaigns. Our analysis of tracking and banding data relied on the capture and associated disturbance of approximately 13,500 northern gannets at North American colonies over a 50+ year period compared to our tracking effort that involved just 80 birds over 7 years. Long-term mark-recapture efforts continue to provide important demographic information, but the dispersal and movement information derived from them is rudimentary. Band recoveries documenting seabird movements typically occur in coastal areas where humans encounter them (not where marine birds necessarily spend most of their time) and where incidences of recoveries tend to mirror human population distributions. Migratory, wintering and oceanic distributional patterns are much better known when even a few tracking devices are deployed. Similarly, seabird habitat occupancy on the open ocean cannot be documented comprehensively by vessel surveys, and the significance of tracking seabirds to detect more realistic spatial and temporal coverage of their remote oceanic distributions cannot be overstated (Adams et al., this issue; Garthe et al. this issue; Lascelles et al., this issue; Le Corre et al., this issue).

4.4. Overview and summary

As the rationale for the tracking and MPA symposium at the 2010 World Seabird Conference intended, it is evident that new and evolving tracking tools and technologies and their integration with biochemical probes and with vessel surveys will be essential in identifying biodiversity hotspots, habitat and prey associations and in clarifying mortality effects and risk assessments during environmental crises. Though not addressed in this symposium, the implications of tracking research for population connectivity, population genetics and conservation understanding and strategies are proving to be profound (González-Solís et al., 2007; Liedvogel et al., 2011).

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