DO LOW RATES OF OILED CARCASS RECOVERY IN BEACHED BIRD SURVEYS INDICATE LOW RATES OF SHIP-SOURCE OIL SPILLS?

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SUMMARY

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Oil pollution is a serious threat to marine ecosystems. Beached bird surveys, which are networks of volunteers who survey beaches for seabird carcasses, are conducted worldwide. Data from these surveys have played a major role in determining that chronically occurring small-scale oil pollution can have cumulative ecosystem-level impacts. Within Canada, Newfoundland and Labrador has reported high rates of oiled carcasses in beached bird surveys (62%), whereas oiled carcass densities in British Columbia are low (12%) compared with Newfoundland and Labrador and other parts of the world. Here, we present a "risk model" as an approach to interpreting beached bird survey data. The model incorporates spatiotemporal distributions of seabirds that are considered vulnerable to oil pollution, shipping densities as a proxy for risk of oil spills, and the proximity of both to areas where beached bird surveys are conducted. Using the model, we identify BC surveys along the west coast of Vancouver Island as most similar to surveys conducted in Newfoundland and Labrador, and we note that 56% of carcasses reported in the BC surveys were oiled, a rate that is similar to rates found in the Newfoundland and Labrador surveys. Finally, we emphasize that wind (speed, direction and persistence) and the location of beach surveys (relative to seabird distributions and high-traffic shipping lanes) must be considered when interpreting beached bird survey results. Because wind data are archived and publicly available, they can be used in reanalyzing older beached bird data from British Columbia. Wind data would also be useful for coordinating future survey efforts, leading to better documentation of the oiling rates of birds off the coast of British Columbia. Finally, our model provides a framework for estimating the risk to seabirds of oiling at sea and for identifying information gaps.

Key words: Shipping, oil pollution, British Columbia, seabirds, beached bird survey, wind

INTRODUCTION

Oil contamination affects marine organisms at various trophic levels, and those effects can persist over long periods of time (Esler *et al.* 2002, Peterson *et al.* 2004). Marine bird mortality attributable to oil spills is often used to index the ecosystem-level impacts of those spills, because seabirds are acutely sensitive to oil through toxicity and feather fouling (Furness & Camphuysen 1997) and because oiled birds and bird carcasses are a highly visible and quantifiable consequence of oil pollution (Burger 1992, Camphuysen & Heubeck 2001). Oiled seabirds that turn up as stressed, often flightless, individuals or as carcasses in publicly accessible coastal areas raise general awareness of marine oil pollution. That awareness, in turn, often leads to better documentation. In some parts of the world, where accessible beaches exist near urban centers, documented cases of beachcast oiled seabirds date back many decades. In response, organized networks of volunteers have been created to conduct what are commonly called "beached bird surveys" (Camphuysen & Heubeck 2001).

The ecological effects of large-scale catastrophic oil spills (e.g. *Exxon Valdez* in Prince William Sound, Alaska) are well documented worldwide, but compelling evidence is accumulating that smaller-scale chronic ship-sourced oil pollution may have far greater effects (Camphuysen 1989). Oil discharges at-sea often result from accidental or intentional dumping of oily bilge residues that build up during the normal operation of any ship. Most ships have oil–water separation systems that allow for the at-sea disposal of the water component of the build-up in the bilge, leaving a remaining "oily sludge" that legally must be disposed of at an authorized portside facility. An unknown, but probably small, proportion of ship operators opt to forego the cost of ship downtime and the service fees associated with using these facilities, and they illegally dump residues at sea. Such relatively small-scale pollution events frequently go undetected except in areas where factors facilitate the deposition of oil-contaminated carcasses of marine organisms (typically seabirds) along coastlines that are publicly accessible. Data from well-established beached bird surveys are being used to monitor annual rates of oil fouling of seabirds, and potentially can help to estimate the seabird mortality associated with chronic oil pollution (Burger & Fry 1993, Camphuysen & Heubeck 2001). Such surveys are a principal indicator of small-scale ship-source oil spills and their ecological effects in many regions of the world (Burger & Fry 1993).

In Canada, estimates suggest that as many as 300 000 seabirds are killed annually off the coast of Newfoundland and Labrador as a result of chronic oil pollution (Wiese & Robertson 2004). That estimate is equivalent to or exceeds the estimated loss of seabirds following the *Exxon Valdez* spill (Ford *et al.* 1996, Piatt & Ford 1996). In contrast to the situation on Canada's east coast, evidence of a similar problem (attributable to chronic oil pollution) on the west coast is largely absent. Vermeer and Vermeer (1975) suggested that oil pollution is one of the principal threats to seabirds in British Columbia, but more recently, Burger (1993) concluded that densities of oiled carcasses recovered in British Columbia are low compared to those recovered in surveys conducted in other regions of the world. In a Newfoundland and Labrador study (Weise 2003), 62% of beachcast seabird carcasses were oiled (presumably from chronic oil pollution), but Burger (2002) reported that only 12% of carcasses found on beached bird surveys in British Columbia showed evidence of oil contamination. However, a direct comparison of the proportions of oiled carcasses between regions is inappropriate. Results from Newfoundland and Labrador are based on a few survey areas having known high rates of oiled beachcast carcasses; surveys in British Columbia are conducted over a large geographic area exposed to wider variation in environmental factors that potentially bias survey results. A more sophisticated interpretation of regional differences in oiled carcass recovery is needed for risk assessment, monitoring and reduction of impacts associated with ship-source oil pollution.

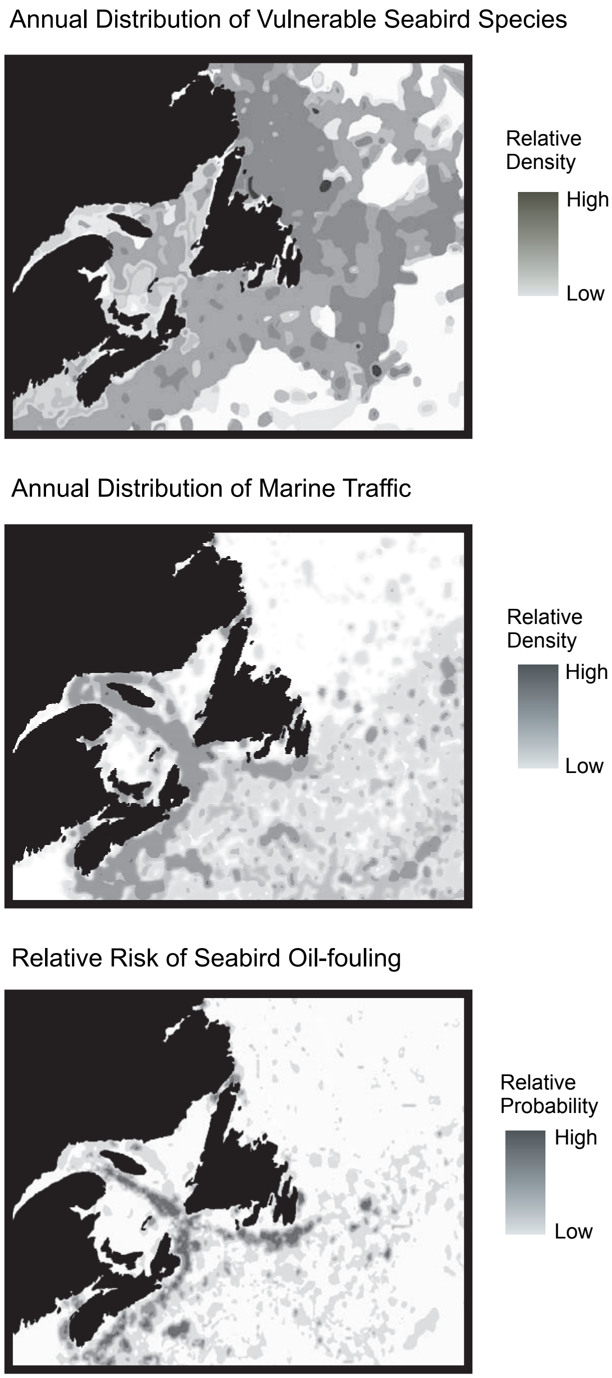

Fig. 1. Spatial model of relative risk of seabird oiling in Atlantic Canada (modified from Lock *et al.* 1994). Bottom panel ("Relative risk of seabird oil-fouling") derived by combining the two upper panels ("Annual distribution of vulnerable seabird species" and "Annual distribution of marine traffic").

A number of factors cause variation in beached bird survey results, and most of these factors act independently of actual seabird oiling rates. Important variables include beach characteristics, species composition of bird communities (i.e. specific vulnerabilities to oil pollution), local oceanographic and weather patterns, carcass persistence in the water and on surveyed beaches, and frequency of oil pollution in the vicinity of surveys. The possibility that low recovery rates of oiled carcasses in British Columbia reflect a low level of interaction between seabirds and oil pollution is attractive. But if the appearance of low oiling rates is an artefact of physical characteristics in the region, then the effects of oil pollution on globally significant populations of seabirds may be occurring in BC waters but going largely undetected.

Beached bird survey data are used to estimate and monitor chronic oiling rates (Burger 1993, Camphuysen & Heubeck 2001, Burger 2002), to extrapolate such estimates to marine regions (Ford *et al.* 1991, Ford *et al.* 1996, Wiese & Robertson 2004), and to assess the impacts of large-volume accidental discharges of oil at sea (Page *et al.* 1990, Ford *et al.* 1991, Ford *et al.* 1996, Piatt & Ford 1996). Extrapolated estimates are refined by controlling for beach characteristics (Burger 1993, Ford *et al.* 1996) and carcass persistence, both at sea (Ford *et al.* 1991, Wiese 2003) and onshore (Ford *et al.* 1991, Ford *et al.* 1996). Of particular relevance to beached bird surveys, wind appears to have a strong influence on the drift patterns of oiled carcasses (Ford *et al.* 1991, Burger & Fry 1993). For example, wind is the best predictor of surface drogue trajectories in Queen Charlotte Sound and Hecate Strait (Crawford *et al.* 1999).

Does the low rate of oiled carcasses found on beach surveys in British Columbia reflect low levels of oil pollution and of impacts on seabirds in BC waters? In the present paper, we describe an approach to that question inspired by the heuristic model of Lock *et al.* (1994). Those authors mapped areas of relative risk of oil fouling (Fig. 1) for the seabird species considered vulnerable to oil spills in the Atlantic region of Canada. We take a similar approach in estimating the risk of seabird fouling from chronic oil pollution in BC waters, and compare our results to those for Newfoundland and Labrador, where large numbers of birds are killed annually by chronic oil pollution. We extend the approach by incorporating wind patterns, and we discuss how beached bird survey results relate to actual oil-spill-associated seabird mortality on Canadian east and west coasts.

SPATIAL RISK MODEL

Two components of the model introduced by Lock *et al.* (1994) were the spatial distributions and densities of

- ship traffic (as a proxy for risk of oil spill), and
- seabird species considered vulnerable to oil pollution, particularly because of their foraging modes.

The authors included Northern Fulmars *Fulmarus glacialis,* Northern Gannets *Sula bassana,* all species of auks (Common and Thick-billed Murres *Uria aalge* and *U. lomvia,* Atlantic Puffins *Fratercula arctica,* Razorbills *Alca torda* and Dovekies *Alle alle*), Black-legged Kittiwakes *Rissa tridactyla,* and shearwater species. By overlapping spatial distributions of ships and seabirds, they created a marine "landscape" of relative oiling risk for Atlantic seabirds. Their model was designed to estimate relative probabilities of seabird oiling from chronic pollution, but it also yields insights into the high incidence of oiled seabird carcasses in beached birds surveys conducted on the southeastern coast of the Avalon Peninsula in Newfoundland and Labrador (Fig. 2, Wiese & Ryan 2003, Wiese & Robertson 2004). A large overlap between high-traffic shipping lanes and aggregations of vulnerable seabird species, and the proximity of both to surveyed beaches, is evident. Spatial proximity is crucial, because oiled carcasses typically sink in two weeks or less (Ford *et al.* 1991, Wiese 2003). Ocean surface flow, strongly influenced by wind patterns (Hlady & Burger 1993, Crawford *et al.* 1999, Crawford *et al.* 2002), is also important in determining whether oiled seabird carcasses reach surveyed beaches in the region.

BC shipping routes and traffic volume

Shipping traffic lanes along the west coast of Vancouver Island are very busy (Fig. 3). Ships passing to the west of Vancouver Island generally follow the "Great Circle" route (shortest geographic distance) to and from Asia, or the outer Prince Rupert and Alaska route (as opposed to the Inside Passage, which uses a network of straits and fjords in British Columbia and Alaska). The Great Circle and the Prince Rupert and Alaska routes converge near the north end of Vancouver Island and run parallel to island's west coast before entering the Strait of Juan de Fuca. The Prince Rupert and Alaska route bifurcates north of Vancouver Island, with the Prince Rupert leg running through Hecate Strait and the Alaska route continuing along the west coast of the Queen Charlotte Islands. These major routes converge with others west of the mouth of the Juan de Fuca strait. Although many of the ships en route do not use Vancouver as a port of call, ship traffic to and from Vancouver itself is heavy by any standard. According to the Vancouver Port Authority, the port ranks first in North America in total foreign exports and first for the west coast of North America in total cargo volume. In Canada, the Port of Vancouver ranks first in total cargo handled and total container throughput (www.portvancouver.com/), handling more than 2700 foreign cargo vessels during 2004.

Data on ship traffic for 2003 (courtesy of the Canadian Marine Communications and Traffic Services [MCTS]) provide minimum estimates of ship densities travelling through the Canadian Exclusive Economic Zone (EEZ) (ships not bound for a Canadian port do not have to identify themselves to MCTS). Besides radio call-

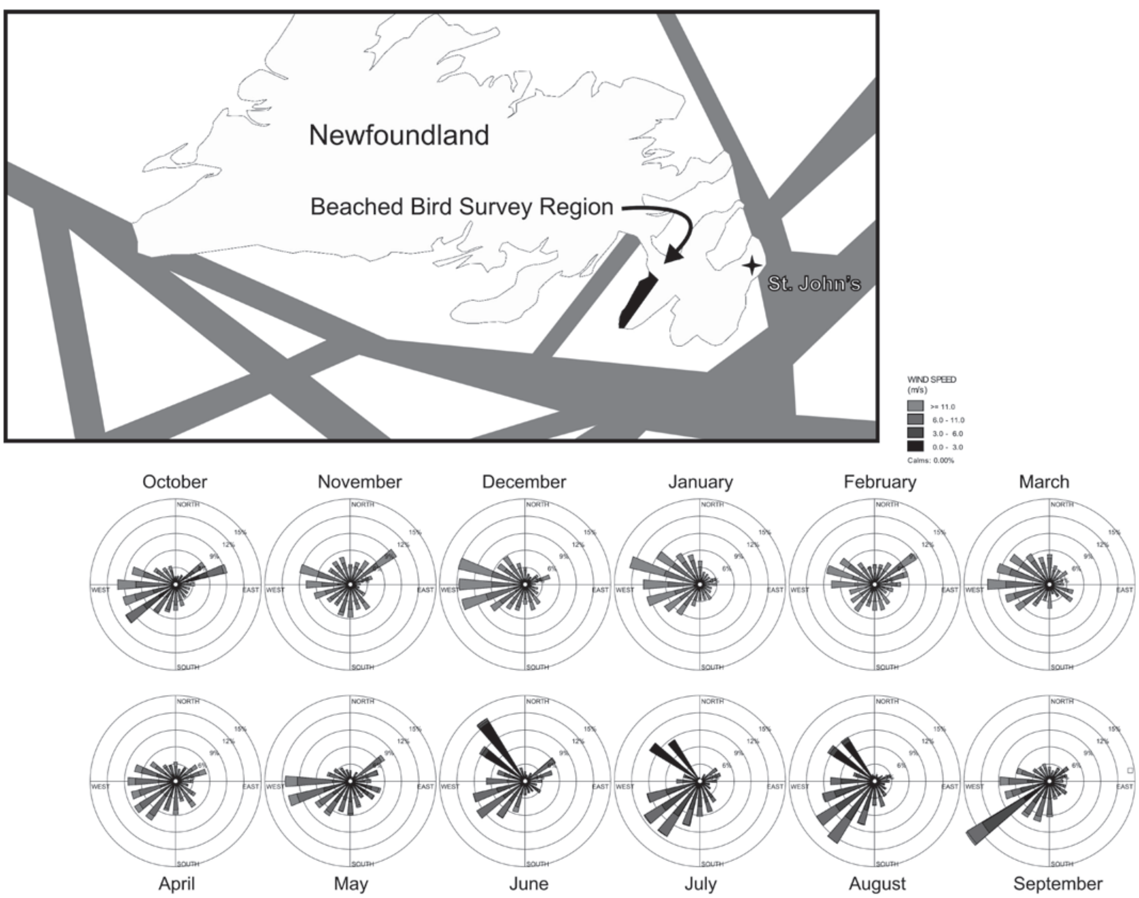

Fig. 2. Location of shipping lanes and beached bird surveys in the Avalon Peninsula region of Newfoundland. Bottom panel: Mean monthly (1999–2005) wind roses for an offshore ocean buoy in Newfoundland coastal waters (approximate location indicated by buoy symbol). Buoy is identified as C44251 "Nickerson Bank" by the Marine Environment Data Services (www.meds-sdmm.dfo-mpo.gc.ca). The base of the vanes indicates direction of wind source (that is, winds blow toward center of rose). Colours of vane sections indicate wind strength, and length of vanes indicates percentage of days during month that winds blow at given speed and in the given direction.

ins, position data consist of radar tracking and dead-reckoning of positions at four-minute intervals for every ship tracked. With the exception of vacation cruise ships, vessel traffic off British Columbia is approximately equal in summer and winter (Table 1).

Seabird abundance and distribution in British Columbia

A rich diversity of marine avifauna uses BC waters, with at least 62 species of seabirds and an additional 48 species of marine-associated coastal birds recorded to date in nearshore and offshore areas (Campbell *et al.* 1990; Morgan *et al.* 1991; Wahl *et al.* 1993; K.H. Morgan, unpubl. data). Islands on the British Columbia coast host an estimated 5.6 million breeding seabirds, including major proportions of the world breeding populations of some species. Approximately 80% of all Cassin’s Auklets *Ptychoramphus aleuticus,* 74% of Ancient Murrelets *Synthliboramphus antiquus* and 56% of Rhinoceros Auklets *Cerorhinca monocerata* nest in British Columbia (Rodway 1991). Other species considered especially vulnerable to oiling include the endangered Marbled Murrelet *Brachyramphus marmoratus,* of which an estimated 20%–25% of total numbers breed in British Columbia (D. Bertram, unpubl. data). In addition to breeding populations, a million or more nonbreeding birds visit the BC coast during the boreal breeding season, and upwards of 10 million marine birds occur within western Canada’s EEZ during spring and fall migration periods.

Seabird species that aggregate are more susceptible to many kinds of local perturbations than are non-aggregating species (Vermeer & Vermeer 1975), and large fractions of the global populations of some species aggregate closely during the breeding season. Cassin’s Auklet provides a striking example, given that roughly 70% of the species population nests within the Scott Island archipelago (northwest of the northern tip of Vancouver Island).

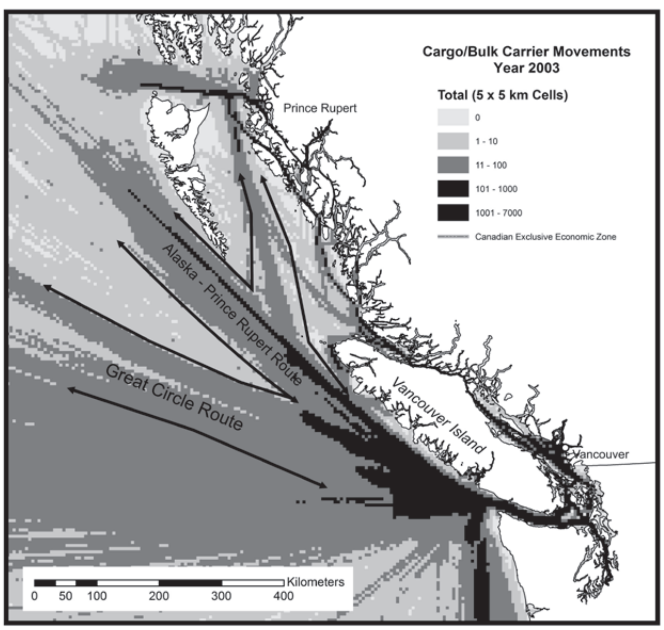

Fig. 3. Seasonal densities in 2003 for shipping classified as “carriers”—cargo, bulk, rho-rho and container vessels. Ship densities summarized by 5×5-km grid cell and per season (see Table 1 for seasons). Only uniquely identifiable ships used in this summary (that is, no repeats of same ship). Generalized ship routes identified as Great Circle Route (shortest distance between Asian and North American ports) and Alaska–Prince Rupert Route (for ships travelling west of Vancouver Island between Vancouver and Puget Sound ports and Alaska and Prince Rupert ports). Data courtesy of Marine Communications and Traffic Services (Canadian Coast Guard).

Seabirds are most likely to contact oil while foraging, and the preferred foraging areas for most species during nesting are at least partly defined by proximity to nesting sites. As well, oceanographic features that enhance biologic productivity may serve to aggregate both nonbreeding and breeding populations of many species of seabirds. For example, large congregations of Sooty Shearwaters *Puffinus griseus* form in the Juan de Fuca Eddy region (shelf-break west of the Strait of Juan de Fuca) during the austral nonbreeding season (Morgan *et al.* 1991).

Mapping data from the Canadian Wildlife Service at-sea survey program reveals that many species considered vulnerable to oiling (Lock *et al.* 1994) aggregate along the west coast of Vancouver Island (Fig. 4). Species that we considered vulnerable to oiling include all alcids, other diving species, and some surface or near-surface foragers (Northern Fulmars, Black-legged Kittiwakes, shearwaters). Densities of those species are highest along the shelf break, especially in areas close to major breeding colonies such as Triangle Island (Fig. 5, Scott Island archipelago), and in the area just seaward of the entrance to the Strait of Juan de Fuca. Radiotelemetry at Triangle Island (Ryder *et al.* 2001; D.F. Bertram, unpubl. data) provides further evidence of the importance of shelf-break habitat to Cassin’s Auklets.

Data from at-sea surveys and radiotelemetry provide useful information, but are often lacking in spatio-temporal resolution, making it difficult to account for variation at different spatiotemporal scales. To compensate, we identified potential seabird foraging habitat by characterizing areas oceanographically. A number of oceanographic processes appear to be important, because they are

TABLE 1
Number of uniquely identified ships passing through the Canadian Pacific Exclusive Economic Zone during 2003

Ship category[b]	Season[a]	
	Summer	Winter
Carriers	2489	2661
Cruise	495	147
Fisheries	1696	1496
Tugs	3141	3319
Tankers	317	359
Total	8138	7982

[a] Summer season extends from 1 May to 30 September; winter season includes 1 January to 30 April and 1 October to 31 December.

[b] Carriers include all cargo, bulk and container vessels. Cruise ships include all commercial passenger vessels except ferries. Fisheries include all vessels and fish processors related to fishing activities. Tugs include all vessels that tow. Tankers include vessels that carry all forms of fossil fuels or oils and oils produced agriculturally. Summary excludes repeat passages by the same vessel within a season.

consistently associated with foraging seabirds during the breeding and nonbreeding seasons alike (e.g. Hyrenbach & Veit 2003). Mesoscale processes that enhance biologic productivity in the ocean and thus attract concentrated seabird foraging include tidal mixing, upwelling and other mechanisms that entrain or transport nutrients and pelagic organisms: fronts, jets, estuarine outflow and eddies (reviewed by Wahl *et al.* 1993, Bakun 1996). Important features on the west coast of Canada are tidal mixing and estuarine outflow from Johnstone Strait and the Strait of Juan de Fuca (Fig. 5), cyclical eddies formed seasonally at the entrance of the Strait of Juan de Fuca (Burger 2003) and off the west coast of the Queen Charlotte Islands (“Haida Eddy”), the continental shelf-break along the west coast of Vancouver Island, and submarine canyons that cut across the shelf (Burger 2003). Seamounts and banks are also important bathymetric features, in particular, Learmonth Bank (western end of Dixon Entrance), Dogfish Bank (northeastern end of Queen Charlotte Islands), North Bank (off Cape St. James) and Swiftsure, La Perouse and Amphitrite Banks (seaward of the Strait of Juan de Fuca, Fig. 5). All support higher densities of seabirds than do the surrounding areas (Burger *et al.* 1997; K.H. Morgan, unpubl. data).

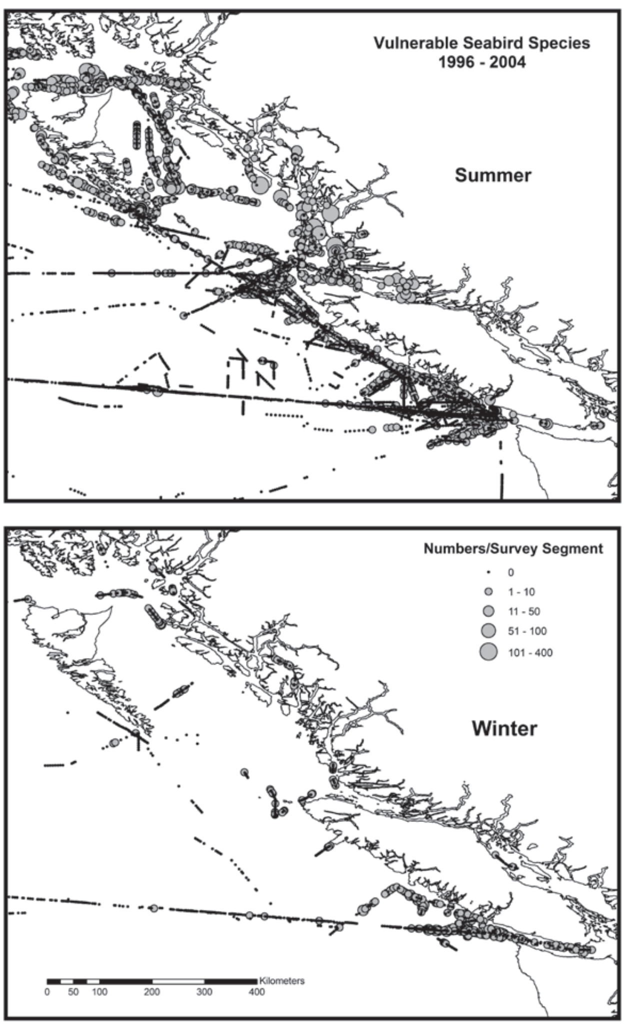

Fig. 4. Distribution by season of species vulnerable to oil spills. Seasons defined as in Table 1. Vulnerable species include all alcid species, Northern Fulmars *Fulmarus glacialis,* Black-legged Kittiwakes *Rissa tridactyla* and all shearwater species.

Identifying regions of high risk of oil fouling for seabirds in BC waters

In the Canadian Pacific EEZ, there is considerable spatiotemporal overlap between shipping routes (Fig. 3) and the distribution of seabirds considered vulnerable to oil spills (Fig. 4). Ship traffic also overlaps with the areas that we defined oceanographically as potentially important for foraging seabirds (Fig. 5). Overlap implies that, in BC waters, high-risk areas exist where ship-source chronic oil pollution and oil-fouling of seabirds probably occur. This assumes, of course, that a correlation exists between ship traffic and oil pollution (see “Conclusions”). As previously noted, the proportion of oiled carcasses found on beached bird surveys is lower in British Columbia than in Newfoundland and Labrador, in part probably because BC surveys cover a broader area and a wider range of beach types. Because aggregations of oil-vulnerable species overlap with active shipping lanes near the west coast of Vancouver Island, we consider that surveys conducted there are most comparable to the surveys conducted in Newfoundland and Labrador (Fig. 2). Unsurprisingly, therefore, beaches on the west coast of Vancouver Island have rates of oiled carcasses (56% of 56 carcasses assessed; Burger 2002) similar to the rates documented for beaches monitored in Newfoundland and Labrador.

Seasonal patterns of marine winds in British Columbia

Wind vectors are the best predictors of the trajectories of objects floating on the ocean surface in the offshore region of British Columbia (Crawford *et al.* 1999). Using publicly available data from the Marine Environmental Database Service (www.meds-sdmm.dfo-mpo.gc.ca/), we compared wind patterns between survey sites in British Columbia and Newfoundland and Labrador. In British Columbia, winds typically blow from the northwest during the summer and from the southeast during the winter, at oblique angles to the coastline (Fig. 6). Objects floating in BC waters tend to be driven at speeds that are approximately 2%–3% of surface wind speeds with a rotation (Coriolis effect) of approximately 30 degrees clockwise to the wind direction (Crawford *et al.* 1999). Coupling the persistent seasonal wind patterns with the Coriolis

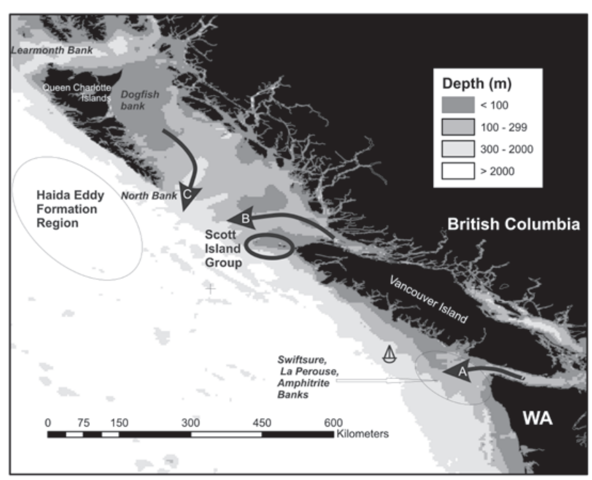

Fig. 5. Oceanographic features that affect ocean productivity and foraging seabird distributions. The Haida Eddy forms in the oval region west of the Queen Charlotte Islands, and the Juan de Fuca Eddy forms in summer at the entrance to the Strait of Juan de Fuca (oval outline west of the entrance). Banks mentioned in the text are labelled in italics. Estuarine outflows labelled as follows: arrow a is the Strait of Juan de Fuca outflow; arrow b is the Johnstone Strait outflow; arrow c is the Hecate Strait outflow.

effect suggests that BC winds tend to push floating objects offshore during the summer and onshore during the winter. In addition, upwelling and Eckman pumping tend to occur during the summer, further ensuring that carcasses oiled in BC shipping lanes are carried offshore. This prediction is supported by data from beached bird surveys conducted along the west coast of Vancouver Island, with peak carcass deposition rates occurring in the winter (Burger 2002). In contrast, prevailing wind patterns near the Avalon Peninsula (site of beached bird surveys in Newfoundland and Labrador) are generally onshore and strong throughout the year (Fig. 2). Wind-driven surface currents off Newfoundland would also be influenced by the Coriolis effect, but the degree to which surface current vectors would rotate clockwise to wind vectors is not clear. If the degree of the effect were important, coupling wind patterns with the Coriolis effect would mean that, at times, carcasses would drift seaward rather than be pushed ashore onto beaches surveyed in Newfoundland and Labrador. In general, however, winds are more likely to blow onshore throughout the year at beaches surveyed along the Avalon Peninsula than at similar beaches (in terms of proximity of high-risk oil-fouling areas to beaches surveyed) along the west coast of Vancouver Island.

CONCLUSIONS

Our spatial model of the risk of oil fouling to seabirds provides an intuitive framework for understanding why rates of oil fouling may not be similar in beached birds surveys in British Columbia as compared with surveys conducted elsewhere in the world. We do not suggest that BC beached bird surveys are ineffective, but that comparisons of survey results between regions should consider and analytically control for factors that affect those results—for example, surface currents and proximity to surveyed beaches of areas of high risk of oil fouling. Because of an extensive array of ocean buoys and coastal anemometers, surface wind vectors are measured throughout the BC marine EEZ with high spatial resolution. The data are publicly available through a Canadian government Web site. Wind vector arrays ("wind stress fields") can be interpolated from these wind vector data, and appropriate algorithms can be used to estimate trajectories of floating objects from the wind stress fields (e.g. Crawford *et al.* 1999). Furthermore, the resolution and accuracy of these wind fields can be improved by using predictive surface wind models (i.e. calculated using barometric pressure differences) coupled with field data (e.g. Wikle *et al.* 2001) such as those downloaded from the ocean buoys.

Ocean surface currents estimated from wind stress fields can be used both in coordinating future beached bird survey efforts and in analyzing results. We suggest that the timing of beached bird surveys might be better managed opportunistically, with coordinators asking surveyors to scan their beaches following periods of local wind patterns favourable for beach deposition of carcasses. Wind vectors can also be used to estimate the area of ocean sampled in any given survey (i.e. "catchment area" sensu Wiese & Robertson 2004). For example, if winds are strong and onshore for a sustained period of time, seabirds can be oiled in areas distant from the shore and their carcasses may drift fast enough and in the right direction to reach shore where a beach survey is conducted. If winds are light and variable, then only carcasses of birds oiled closer to shore are likely make it to the survey site (i.e. smaller catchment area). Finally, if winds are persistently offshore, then the local recovery of carcasses would be artificially zero (i.e. not representative of any ocean area where seabirds may have been oiled). Because wind data from BC ocean buoys are archived from approximately 1989 to the present (www.meds-sdmm.dfo-mpo.gc.ca/meds/), reanalysis of archived beach survey data for British Columbia, taking wind stress into account, is possible and would be a worthy undertaking.

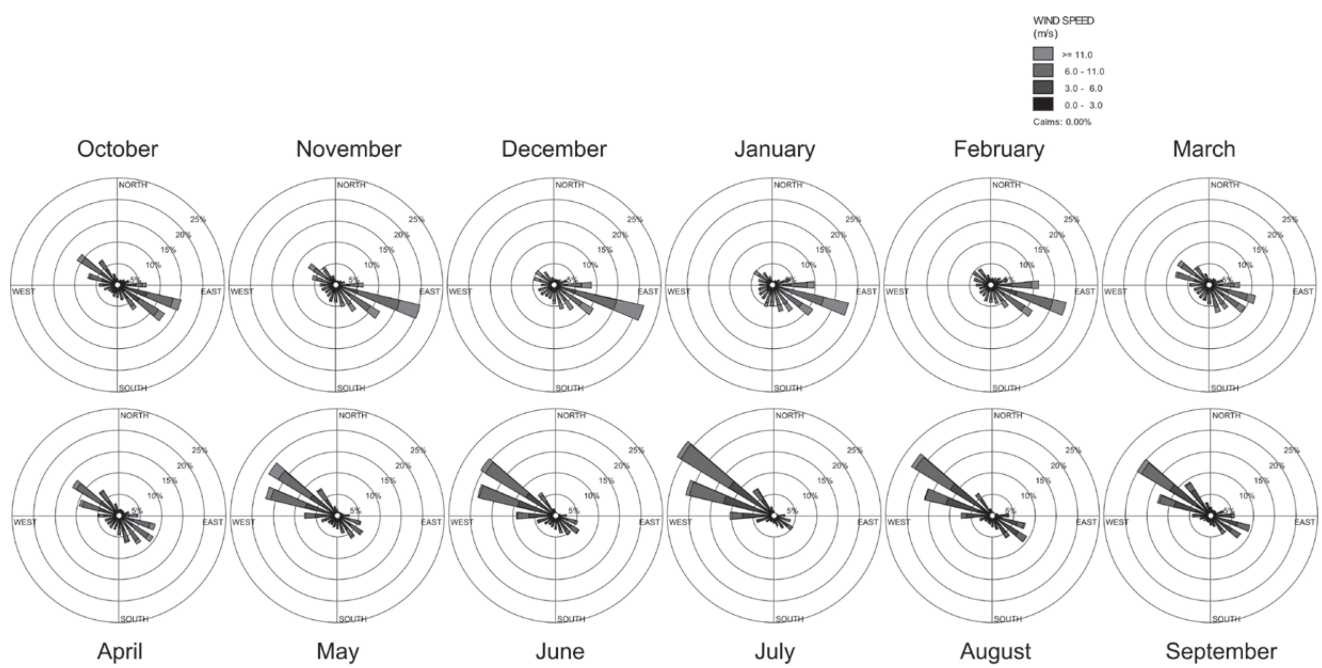

Fig. 6. Mean monthly (1989–2003) wind roses for an offshore ocean buoy in BC coastal waters (approximate location indicated by buoy symbol). Buoy is identified as C46206 "La Perouse Bank" by the Marine Environment Data Services (www.meds-sdmm.dfo-mpo.gc.ca). Mean monthly wind patterns are similar for ocean buoys throughout the BC Exclusive Economic Zone. The base of the vanes indicates direction of wind source (that is, winds blow toward center of rose). Colours of vane sections indicate wind strength, and length of vanes indicates percentage of days during month that winds blow at given speed and in the given direction.

The spatial model can also be used as a framework for estimating the impact of chronic ship-source oil pollution on BC seabirds and for identifying information gaps. Under clearly identified assumptions, marine areas of high oil-pollution probability and the distribution of vulnerable seabirds can be overlapped to estimate mortality associated with ship-source chronic oil pollution in the EEZ of British Columbia.

Work in progress

In our current version of the model, we use ship density as a proxy for risk of oil spills. We are attempting to quantify the occurrence of oil spills more directly by using shipping data and oil spill reports from sources including the National Aerial Surveillance Program (NASP, coordinated by Transport Canada), Department of Fisheries and Oceans Surveillance (Canada), and the Integrated Satellite Tracking of Oil Polluters (ISTOP) program, which uses synthetic aperture radar imagery to identify anomalies possibly caused by oil spills. With this information, we hope to systematically associate the spatiotemporal variation of oil spill risk in the marine environment with factors such as harbour locations, ship densities, distance to shore, distance from cities, vessel types, flag state, origin (last port of call) and visible surveillance efforts (i.e. use of surveillance aircraft as a form of deterrence). We will extrapolate oil-risk probabilities to areas that are not surveyed or that are surveyed infrequently for oil slicks. Similarly, it is important to augment our understanding of seabird distributions by defining ocean characteristics indicative of important pelagic habitats for birds. For example, using satellite Advanced Very High Resolution Radiometry, O'Hara *et al.* (2006) associated a number of seabird species distributions with steep gradients in sea-surface temperature—indicators of convergent oceanic frontal systems. Having characterized potential key habitats, it may be possible to impute with reasonable accuracy the seabird densities of marine areas not currently covered by at-sea surveys. These improvements to key data "layers" in the spatial model will enhance our ability to correctly interpret the reported rates of oiled seabird recovery in British Columbia, relative to rates reported elsewhere, and to better estimate the impacts from current rates of small-scale ship-source oil pollution in ocean areas not represented by beach bird surveys.

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REFERENCES

BURGER, A. 2002. Beached bird surveys in British Columbia, 1986–1997. Victoria, BC: Nestucca Trust Fund. 48 pp.

BURGER, A. 2003. Effects of the Juan de Fuca eddy and upwelling on densities and distributions of seabirds off Southwest Vancouver Island, British Columbia. *Marine Ornithology* 31: 113–122.

BURGER, A., BOOTH, J. & MORGAN, K. 1997. Preliminary identification of processes and problems affecting marine birds in coastal and offshore areas of British Columbia. Delta, BC: Canadian Wildlife Service. 110 pp.

BURGER, A. & FRY, D. 1993. Effects of oil pollution on seabirds in the northeast Pacific. In: Vermeer, K., Briggs, K., Morgan, K. & Siegel-Causey, D. (Eds). The status, ecology, and conservation of marine birds of the North Pacific. Ottawa: Canadian Wildlife Service. pp. 254–263.

CAMPBELL, R., DAWE, N., MCTAGGART-COWAN, I., COOPER, J., KAISER, G. & MCNALL, M. 1990. The birds of British Columbia. Victoria, BC: The Royal British Columbia Museum. 642 pp.

CAMPHUYSEN, C.J. 1989. Beached bird surveys in the Netherlands 1915–1988: seabird mortality in the southern North Sea since the early days of oil pollution. Amsterdam: Werkgroep Noordzee. 322 pp.

CAMPHUYSEN, C.J. & HEUBECK, M. 2001. Marine oil pollution and beached bird surveys: the development of a sensitive monitoring instrument. *Environmental Pollution* 112: 443–461.

CRAWFORD, W., CHERNIAWSKY, J. & CUMMINS, P. 1999. Surface currents in British Columbia coastal waters: comparison of observations and model predictions. *Atmosphere–Ocean* 37: 255–280.

CRAWFORD, W., CRETNEY, W., CHERNIAWSKY, J. & HANNAH, C. 2002. Modelling oceanic fates of oil, drilling muds and produced water from the offshore oil and gas industry, with application to the Queen Charlotte Basin. Report No. 2002/120. Ottawa: Canadian Department of Fisheries and Oceans. 53 pp.

ESLER, D., BOWMAN, T., TRUST, K., BALLACHEY, B., DEAN, T., JEWETT, S. & O'CLAIR, C. 2002. Harlequin Duck population recovery following the "Exxon Valdez" oil spill: progress, process and constraints. *Marine Ecology-Progress Series* 241: 271–286.

FORD, R.G., BONNELL, M., VAROUJEAN, D., PAGE, G., CARTER, H., SHARP, B., HEINEMANN, D. & CASEY, J. 1996. Total direct mortality of seabirds from the *Exxon Valdez* oil spill. In: Rice, S.D., Spies, R.B., Wolfe, D.A. & Wright, B.A. (Eds). Proceedings of the Exxon Valdez oil spill symposium. American Fisheries Society Symposium 18. Bethesda, MD: American Fisheries Society. pp. 684–711.

FORD, R.G., VAROUJEAN, D., WARRICK, D., WILLIAMS, W., LEWIS, D., HEWITT, C. & CASEY, J. 1991. Seabird mortality resulting from the *Nestucca* oil spill incident winter 1988–89. [Unpublished final report]. Portland, OR: Ecological Consulting Inc. 77 pp.

FURNESS, R.W. & CAMPHUYSEN, K.C.J. 1997. Seabirds as monitors of the marine environment. *ICES Journal of Marine Science* 54: 726–737.

HLADY, D. & BURGER, A. 1993. Drift-block experiments to analyse the mortality of oiled seabirds off the coast of Vancouver Island, British Columbia. *Marine Pollution Bulletin* 26: 495–501.

HYRENBACH, K.D. & VEIT, R.R. 2003. Ocean warming and seabird communities of the southern California Current System (1987–98): response at multiple temporal scales. *Deep-Sea Research Part II—Topical Studies in Oceanography* 50: 2537–2565.

LOCK, A., BROWN, R. & GERRIETS, S. 1994. Gazetteer of marine birds in Atlantic Canada: an atlas of sea bird vulnerability to oil pollution. Ottawa: Environment Canada, Canadian Wildlife Service. 137 pp.

MORGAN, K., VERMEER, K. & MCKELVEY, R. 1991. Atlas of pelagic birds of western Canada. Occasional Paper Number 72. Ottawa: Environment Canada, Canadian Wildlife Service. 72 pp.

O'HARA, P.D, MORGAN, K.H. & SYDEMAN, W.J. 2006. Primary producer and seabird associations with AVHRR-derived sea surface temperatures and gradients in the southeastern Gulf of Alaska. *Deep-Sea Research Part II—Topical Studies in Oceanography* 53: 359–369.

PAGE, G., CARTER, H. & FORD, R.G. 1990. Numbers of seabirds killed or debilitated in the 1986 *Apex Houston* oil spill in central California. *Studies in Avian Biology* 14: 164–174.

PETERSON, C., RICE, S., SHORT, J., ESLER, D., BODKIN, J., BALLACHEY, B. & IRONS, D. 2004. Long-term ecosystem,response to the *Exxon Valdez* oil spill. *Science* 302: 2082–2086.

PIATT, J.F. & FORD, R.G. 1996. How many seabirds were killed by the *Exxon Valdez* oil spill? In: Rice, S.D., Spies, R.B., Wolfe, D.A. & Wright, B.A. (Eds). Proceedings of the *Exxon Valdez* oil spill symposium. American Fisheries Society Symposium 18. Bethesda, MD: American Fisheries Society. pp. 712–719.

RODWAY, M. 1991. Status and conservation of breeding seabirds in British Columbia. InternationalCouncil for Bird Preservation (ICBP) Technical Publication No. 11. pp. 43–102.

RYDER, J., BOYD, W., SHISKO, S. & BERTRAM, D. 2001. At-sea foraging distributions of radio-marked Cassin's Auklets breeding at Triangle Island, BC, 2000. Delta, BC: Canadian Wildlife Service. 32 pp.

VERMEER, K. & VERMEER, R. 1975. Oil threat to birds on the Canadian west coast. *Canadian Field-Naturalist* 89: 278–298.

WAHL, T.R., MORGAN, K. & VERMEER, K. 1993. Seabird distribution off British Columbia and Washington. In: Vermeer, K., Briggs, K., Morgan, K. & Siegel-Causey, D. (Eds). The status, ecology, and conservation of marine birds of the North Pacific. Ottawa: Canadian Wildlife Service. pp. 39–47.

WIESE, F. 2003. Sinking rates of dead birds: improving estimates of seabird mortality due to oiling. *Marine Ornithology* 31: 65–70.

WIESE, F. & ROBERTSON, G. 2004. Assessing seabird mortality from chronic oil discharges at sea. *Journal of Wildlife Management* 68: 627–638.

WIESE, F. & RYAN, P. 2003. The extent of chronic marine oil pollution in southeastern Newfoundland waters assessed through beached bird surveys 1984–1999. *Marine Pollution Bulletin* 46: 1090–1101.

WIKLE, C., MILLIFF, R., NYCHKA, D. & BERLINER, L. 2001. Spatiotemporal hierarchical Bayesian modeling: tropical ocean surface winds. *Journal of the American Statistical Association* 96: 382–397.