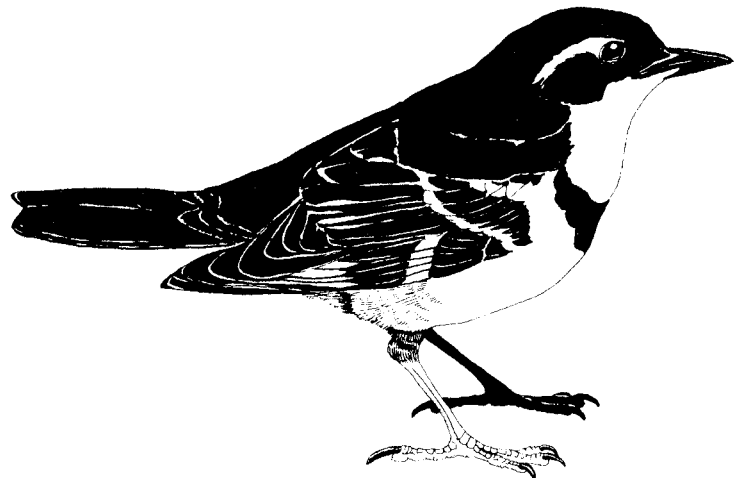


INTERPRETING THE MORTALITY OF SEABIRDS FOLLOWING THE *NESTUCCA* OIL SPILL OF 1988-1989: FACTORS AFFECTING SEABIRDS OFF SOUTHWESTERN BRITISH COLUMBIA AND NORTHERN WASHINGTON

Alan E. Burger



TECHNICAL REPORT SERIES NO. 178

Pacific and Yukon Region 1993

Canadian Wildlife Service



Environment
Canada

Environnement
Canada

Canadian Wildlife Service
Service Canadien
de la faune

Canada

TECHNICAL REPORT SERIES CANADIAN WILDLIFE SERVICE

This series of reports, established in 1986, contains technical and scientific information from projects of the Canadian Wildlife Service. The reports are intended to make available material that either is of interest to a limited audience or is too extensive to be accommodated in scientific journals or in existing CWS series.

Demand for these Technical Reports is usually confined to specialists in the fields concerned. Consequently, they are produced regionally and in small quantities; they can be obtained only from the address given on the back of the title page. However, they are numbered nationally. The recommended citation appears on the title page.

Technical Reports are available in CWS libraries and are listed with the DOBIS system in major scientific libraries across Canada. They are printed in the official language chosen by the author to meet the language preference of the likely audience. **To determine whether there is significant demand for making the reports available in the second official language, CWS invites users to specify their official language preference. Requests for Technical Reports in the second official language should be sent to the address on the back of the title page.**

SÉRIE DE RAPPORTS TECHNIQUES DU SERVICE CANADIEN DE LA FAUNE

Cette série de rapports donnant des informations scientifiques et techniques sur les projets du Service canadien de la faune (SCF) a démarré en 1986. L'objet de ces rapports est de promouvoir la diffusion d'études s'adressant à un public restreint ou trop volumineuses pour paraître dans une revue scientifique ou l'une des séries du SCF.

Ordinairement, seuls les spécialistes des sujets traités demandent ces rapports techniques. Ces documents ne sont donc produits qu'à l'échelon régional et en quantités limitées; ils ne peuvent être obtenus qu'à l'adresse figurant au dos de la page titre. Cependant, leur numérotage est effectué à l'échelle nationale. La citation recommandée apparaît à la page titre.

Ces rapports se trouvent dans les bibliothèques du SCF et figurent aussi dans les listes du système de référence DOBIS utilisé dans les principales bibliothèques scientifiques du Canada. Ils sont publiés dans la langue officielle choisie par l'auteur en fonction du public visé. **En vue de déterminer si la demande est suffisamment importante pour produire ces rapports dans la deuxième langue officielle, le SCF invite les usagers à lui indiquer leur langue officielle préférée. Il faut envoyer les demandes de rapports techniques dans la deuxième langue officielle à l'adresse indiquée au verso de la page titre.**

Cover illustration is by R. W. Butler and may not be used for any other purpose without the artist's written permission.

L'illustration de la couverture est une œuvre de R. W. Butler. Elle ne peut dans aucun cas être utilisée sans avoir obtenu préalablement la permission écrite de l'auteur.

INTERPRETING THE MORTALITY OF SEABIRDS
FOLLOWING THE *NESTUCCA* OIL SPILL OF 1988-1989

Alan E. Burger

Technical Report Series No. 178
Pacific and Yukon Region 1991
Canadian Wildlife Service

This series may be cited as:

Technical Report Series No. 178. Canadian Wildlife
Service, Pacific and Yukon Region, British Columbia.

Burger, A.E. 1993. Interpreting the mortality of seabirds
following the *Nestucca* oil spill of 1988-1989; factors affecting
seabirds off southwestern British Columbia and northern Washington.

Printed on recycled paper

Issued under the Authority of the
Minister of Environment
Canadian Wildlife Service

©Ministry of Supply and Services Canada 1988
Catalogue No. CW69-5/178E
ISBN 0-662-20829-5
ISSN 0831-6481

Copies may be obtained from:
Canadian Wildlife Service
Pacific and Yukon Region
P.O. Box 340,
Delta, British Columbia
Canada V4K 3Y3

TABLE OF CONTENTS

	Page
ABSTRACT	ii
RÉSUMÉ	iii
1. INTRODUCTION	1
2. GENERAL PROCESSES APPLYING TO SEABIRDS	2
2.1 Seabird energetics and ocean productivity	2
2.2 General factors supporting seabird aggregations	2
2.3 Foraging ranges of seabirds	3
3. THE IMPORTANCE OF TEMPORAL AND SPATIAL SCALES	3
4. LARGE SCALE OCEAN PROCESSES IN THE NE PACIFIC	4
5. MESO- AND COARSE-SCALE PROCESSES ON THE CONTINENTAL SHELF ..	5
5.1 Features of the continental shelf	5
5.2 Winds and currents	5
5.3 Freshwater runoff	6
5.4 Upwelling	6
5.5 Effect of gyres and fronts on productivity	6
6. FINE SCALE OCEAN PROCESSES AFFECTING SEABIRDS	7
7. DISTRIBUTION OF THE PREY OF SEABIRDS	8
7.1 Zooplankton	8
7.2 Seasonal patterns among zooplankton	8
7.3 Spatial distribution of zooplankton	8
7.4 Distribution of fish	9
8. DISTRIBUTION OF SEABIRDS	9
8.1 Responses to ocean processes and prey densities	9
8.2 General distribution of Common Murres	10
8.3 General distribution of Cassin's Auklet	11
8.4 Bird distribution off Vancouver Island and Washington	11
9. IMPLICATIONS FOR ASSESSING THE NESTUCCA SPILL IMPACTS	12
9.1 Large-scale trends	12
9.2 Coarse-scale trends	13
10. LITERATURE CITED	14

ABSTRACT

- 1) Both the body count (12,535 carcasses) and the estimated overall mortality (56,000 birds) resulting from Nestucca oil spill in 1988-1989 are exceptionally high relative to the amount of oil spilled and in comparison with other spills.
- 2) Seabirds have high energy demands. Large populations exist only in productive seas, such as continental shelf zones where upwelling and other oceanic processes cause high productivity and prey concentrations.
- 3) The Upwelling Domain in which the Nestucca spill occurred is among the most productive in the North Pacific. Seabird densities in this domain ranked fourth out of 20 in the entire North Pacific. Large populations of birds overwinter here and were thus exposed to the spill.
- 4) Coarse- and fine-scale oceanic processes, such as temperature and salinity fronts, Langmuir cells, and tidal upwelling have profound effects on the distribution of zooplankton and small schooling fish, and hence on the birds that prey on them. Dense aggregations of euphausiids and other important prey occur at fronts over the shelf, at the shelf edge and off the mouth of the Strait of Juan de Fuca.
- 5) Seabird distribution is highly clumped off Washington and Vancouver Island, in response to physical processes affecting prey distribution. Common Murres aggregate at places across the entire shelf zone, whereas Cassin's Auklets are most common at the shelf-edge. The Nestucca oil obviously passed through dense flocks of these birds over the shelf.
- 6) Small-scale physical processes (Langmuir cells and convergent fronts) cause aggregations of drifting debris, epipelagic zooplankton and fish. They probably also concentrate drifting oil. Seabirds attracted to such places to feed would thus have a greater chance of getting oiled. Such processes occur in the shelf zone in winter and might account, in part, for the high rate of oiling in the Nestucca spill.

RÉSUMÉ

- 1) Tant l'effectif dénombré (12 535 carcasses) que la mortalité globale estimée (56 000 oiseaux) à la suite de la marée noire causée par le naufrage du Nestucca en 1988-1989 sont exceptionnellement élevés par rapport à la quantité d'hydrocarbures déversée et en comparaison avec d'autres marées noires.
- 2) Les oiseaux de mer ont une forte demande énergétique. On ne trouve de grandes populations que dans les mers productives, comme les zones du plateau continental où la présence de remontées d'eau et d'autres processus océaniques cause une forte productivité et une concentration de proies.
- 3) Le domaine de remontées d'eau où s'est produit le naufrage du Nestucca compte parmi les plus productifs du Pacifique Nord. Les densités d'oiseaux de mer y étaient au quatrième rang sur vingt pour l'ensemble du Pacifique Nord. De grandes populations d'oiseaux hivernent dans cette zone et ont donc été exposées à la marée noire.
- 4) Les processus océaniques à échelle plus ou moins fine, comme les fronts de température et de salinité, les cellules de Langmuir et les remontées d'eau causées par les marées, ont un effet prononcé sur la répartition du zooplancton et des petits poissons vivants en bancs, et donc sur les oiseaux qui s'en nourrissent. On observe sur les fronts de fortes aggregations d'euphausiacés et d'autres proies importantes sur la plate-forme continentale, au rebord de la plate-forme et à l'entrée du détroit de Juan de Fuca.
- 5) La distribution des oiseaux de mer est fortement groupée près de l'État de Washington et de l'île de Vancouver, ce qui correspond à des processus physiques affectant la répartition des proies. Les marmettes de Troil se rassemblent par endroits sur l'ensemble de la plate-forme, tandis que les alques de Cassin se concentrent surtout sur le rebord. Il est évident que la nappe du Nestucca est passée au travers de troupeaux denses de ces oiseaux sur la plate-forme continentale.
- 6) Les processus physiques à petite échelle (cellules de Langmuir et fronts convergents) causent des aggregations de débris flottants, de zooplancton épipelagique et de poisson. Ces processus concentrent aussi probablement le pétrole qui dérive. Les oiseaux de mer qui recherchent ces endroits pour s'y nourrir risquent donc davantage d'être mazoutés. Ces processus se produisent sur la plate-forme continentale en hiver et pourraient expliquer en partie le taux élevé de mazoutage lors de la marée noire du Nestucca.

1. INTRODUCTION

On 23 December 1988, the barge Nestucca was damaged off Gray's Harbor, Washington and 875,000 litres of Bunker C oil was spilled along a swath over the continental shelf. As the slicks drifted northward, they passed through concentrations of seabirds off Washington and Vancouver Island. This resulted in the direct mortality of an estimated 56,000 seabirds (Ford *et al.* 1991, Burger 1993). Many more seabirds, shorebirds and scavenging birds were debilitated and perhaps died from oiled plumage or the toxic effects of ingesting oil (Rodway *et al.* 1989, Larsen and Richardson 1990, Ford *et al.* 1991, Burger 1993a).

Both the carcass count (12,535 birds) and the overall estimated mortality (56,000 birds) resulting from the Nestucca spill were exceptionally high, relative to other spills (Ford *et al.* 1991, Burger in press). An analysis by Burger (1993b) showed that the numbers of birds killed in marine spills could not be predicted from the volume of oil spilled. Other factors, such as the densities and distribution of the birds at sea, movements of the slick, winds, currents and tides have a major effect on the resultant mortality. The present report is an attempt to explain the very high mortality caused by Nestucca. It reviews pertinent information on seabird distribution and behaviour, and physical and biological oceanography from published and unpublished sources.

The report was originally written to assist in litigation resulting from the Nestucca spill, but the information is also relevant to understanding the effects of future spills. The volume of shipping and the risks of oil pollution in the inshore and shelf seas of northern Washington and southern British Columbia are high (Vermeer and Vermeer 1975, Burger 1992). Movements of crude oil and refined petroleum products in this area average 26 million cubic metres (164 million barrels) annually (Shaffer *et al.* 1990). Probability models constructed by Cohen and Aylesworth (1990) predict that an oil spill exceeding 1000 barrels will occur every 1.3 years in this region, and a 10,000 barrel spill every 10.7 years. A thorough understanding of the distribution, abundance and behaviour of local seabirds will greatly assist preparedness and responses to future spills. This report contributes to that objective.

The continental shelf ecosystems off Vancouver Island and northern Washington are highly productive, supporting important fisheries, and large populations of resident and migratory seabirds. The oceanography here is complex, but many of the major oceanic processes have been identified (Thomson 1981, Thomson *et al.* 1989, Landry and Hickey 1989). Winter conditions have received relatively little attention (Thomas and Emery 1986).

This review identifies oceanic processes which might affect the distribution and abundance of seabirds in this region, with the goal of interpreting the Nestucca mortality. Attention will therefore be focused on ocean processes affecting overwintering seabirds, especially the two most affected species, the Common Murre *Uria aalge* and Cassin's Auklet *Ptychoramphus aleuticus*. Several studies discuss the distribution of seabirds off Vancouver Island (e.g. Martin and Myres 1969, Vermeer *et al.* 1983, 1987a, 1989, Morgan *et al.* 1991), and Washington (Wahl 1975, 1984), or both jurisdictions (Ford *et al.* 1991, Wahl *et al.* 1993). Less is known about winter distributions than in other seasons.

Studies of interactions between seabirds and physical, chemical and biological oceanic processes are relatively recent. In North America such studies were made in parts of California (Briggs *et al.* 1987, Ainley and Boekelheide 1990), areas of the Gulf Stream (Haney 1986a,b) and the Bering Sea (Hunt *et al.* 1990, Schneider *et al.* 1987). Typically, they incorporate simultaneous measurements of seabird densities, temperatures and salinity profiles in the ocean, hydroacoustic measures of plankton and prey fish abundance, and perhaps ocean currents, weather and seabird activities. Satellite images of sea surface temperatures and chlorophyll concentrations have also been incorporated (Briggs *et al.* 1987, Haney 1989).

There have been no studies of seabirds off British Columbia or Washington using these arrays of oceanographic measures (Wahl *et al.* 1993). This review therefore applies general principles of oceanography and seabird biology to local conditions in order to explain seabird distribution, and oceanic processes which might have prevailed at the time of the Nestucca spill.

2. GENERAL INTRODUCTION TO SEABIRD ECOLOGY

2.1 Seabird energetics and ocean productivity

Seabirds, being active homeotherms living in cool, wet environments, use more energy than any other animals. The Field Metabolic Rates (mass-specific measures of the overall daily energy needs of animals) of seabirds are higher than those of other birds (Nagy 1987). One consequence of this is that seabirds require predictable, highly productive foraging areas.

Oceans cover 70% of the earth's surface, but their annual net primary productivity (55.0×10^9 t) is about half of the terrestrial productivity (115×10^9 t; Whittaker 1975). Most of the ocean is relatively barren, and seabirds concentrate in those areas where high primary productivity supports many prey organisms such as crustaceans, squid or fish (Brown 1980, Croxall 1987). The coastal waters off Vancouver Island and Washington have such conditions.

2.2 General factors supporting seabird aggregations

Physical oceanic processes affect the availability and abundance of seabirds' prey in at least two ways (Brown 1980). First, large populations of seabirds can exist for extended periods only where biological productivity is high. Such productivity is strongly dependent on physical processes such as upwelling, wind-induced mixing and currents.

Second, physical processes cause clumping of potential prey or make them more accessible to seabirds. Oceanic "fronts" are boundary zones with sharp changes in water properties (e.g. temperature and salinity) in a relatively small horizontal space. Convergent fronts occur where relatively cold, rich water meets and sinks below a mass of warmer water. Objects at the surface and epipelagic plankton might be trapped near the surface at this boundary, leading to high densities of zooplankton (Fedoryako 1982, Haney 1986a). Concentrations of zooplankton at convergent fronts, or the schools of fish they attract, provide profitable feeding sites for

seabirds and other larger predators. Salmon fishermen monitor sea temperatures in order to locate such fronts. Alternatively, localized upwelling (divergent fronts) may bring deep prey into surface areas, making them accessible to birds.

2.3 Foraging ranges of seabirds

While breeding, most northern seabirds tend to forage within 10s of km of their colonies (Ainley and Boekelheide 1990). Consequently large colonies are situated near productive areas (e.g. the Scott Islands off northern Vancouver Island which offer access to a large area of continental shelf and shelf edge; Rodway 1991). In winter, seabirds may migrate, disperse into more oceanic waters, or aggregate in coastal areas away from their summer colonies. Individual birds may range over 10s or 100s of km per day in search of food.

Seabirds are restricted to prey available near the ocean surface. Gulls, albatrosses, fulmars and phalaropes feed at the surface. Diving species have access to a much wider range of prey, and consequently tend to have larger populations in temperate regions (Croxall 1987, Croxall *et al.* 1984). Murres may dive to 180 m or deeper, but do most of their foraging in the upper 60 m (Piatt and Nettleship 1985, Croll *et al.* 1992). Cassin's Auklets regularly dive to 40 m but probably do most foraging in the upper 20 m (Burger and Powell 1990).

3. THE IMPORTANCE OF TEMPORAL AND SPATIAL SCALES

It is important to consider the effects of scale in time (e.g. seconds through decades) and space (e.g. cm through 1000s km), when discussing ocean processes affecting seabirds (Hunt and Schneider 1987). Large scale processes, affecting global areas over periods of months (e.g. climatic variation), may have little impact or be impossible to identify at a small scale (e.g. within the time and space of a bird's feeding bout). Conversely, unexplained variation ("noise") at a small scale, could emerge as an important pattern when viewed at a larger scale.

Five general levels are used for analysing marine processes (Hunt and Schneider 1987):

- i) Mega scale systems (global biogeographic regions) covering >3,000 km with time scales of months or years;
- ii) Macro-scale systems embedded in the global regions with features 1000-3000 km in size (e.g. major current systems);
- iii) Meso-scale features with spatial scales 100-1000 km and time scales of days and weeks (e.g. upwelling events, gyres);
- iv) Coarse-scale features covering 1-100 km and lasting hours or days (e.g. plume-type upwelling events, tidal advection);
- v) Fine-scale events, covering metres or hundreds of metres and durations of minutes or hours (e.g. wind-streaks).

There are many overlaps in the processes identified in these levels, and this is not a rigid classification. In this review, I focus on macro- and meso-scale processes within the major domains of the NE Pacific Ocean, and on meso- and coarse-scale processes within the shelf zone.

4. LARGE SCALE OCEAN PROCESSES IN THE NE PACIFIC

At the mega-scale, numerous authors have identified associations between seabird species and particular water bodies, but because seabirds are so mobile and regularly use two or more global zones, the classical biogeographical boundaries do not apply (see Ashmole 1971; Hunt and Schneider 1987 for reviews). Three consistent trends have been identified, and referred to as "Shuntov's rules" (Hunt and Schneider 1987):

- i) the distribution of birds is more closely related to major current systems and water masses than to latitudinal zones;
- ii) bird density generally increases with latitude in both hemispheres; and
- iii) bird density is generally higher along the margins of oceans, particularly the eastern margins (such as the coast of the Pacific Northwest).

Several oceanic water bodies or "domains" have been identified within the north Pacific, with characteristic physical and chemical properties (Favorite *et al.* 1976). The coastal seas off Washington and Vancouver Island fall within the Coastal Upwelling Domain, which extends from Baja California (25°N) to the northern tip of Vancouver Island (50.5°N; Ware and McFarlane 1989). This is sometimes called the Eastern Boundary Current upwelling domain and or the California Current system (Mackas and Galbraith 1992). This domain is characterised in summer by consistent, strong, wind-induced upwelling extending over most of the continental shelf and in plumes beyond the shelf (Thomson 1981, Ware and McFarlane 1989). In summer, the prevailing NW winds blow parallel to the shore and, in concert with Coriolis forces, cause the surface water to move offshore, to be replaced by deep, cold, nutrient-rich upwelled water. The net result is that this is a region of high primary productivity, supporting dense populations of plankton, fish, marine mammals and seabirds.

Fisheries statistics demonstrate the richness of the Upwelling Domain. The annual yield, mainly from pelagic schooling fish (hake, sardines, anchovies and mackerel), averages 2.7 t km⁻² yr⁻¹ (Ware and McFarlane 1989). By contrast, fisheries yields in adjacent domains are less: 0.05 t km⁻² yr⁻¹, mainly in the form of salmon, from the Central Subarctic Domain (dominated by the Alaskan Gyre); and 1.4 t km⁻² yr⁻¹, mainly walleye pollock, cod, halibut, sablefish and herring, from the Coastal Downwelling Domain (Queen Charlotte Sound to the Aleutian Islands).

Densities of seabirds, estimated from shipboard transects made during summer months, show a similar pattern. Densities in the Upwelling Domain averaged 26 birds km⁻² (biomass 15 kg km⁻²; Wahl *et al.* 1989). This was the fourth highest value among 20 domains covering the entire north Pacific and Bering Sea. The only domains with more birds were the Eastern Bering Current (about 60 birds km⁻²), the Eastern Bering Gyre (about 45 birds km⁻²) and the

Confluence Domain east of Japan (about 50 birds km⁻²). The Dilute Domain, seaward of the Upwelling Domain, and the Alaska Current Domain (the Coastal Downwelling Domain) to the north, both supported fewer seabirds (<5 birds km⁻²). There are no comparable data for winter months.

5. MESO- AND COARSE-SCALE PROCESSES ON THE CONTINENTAL SHELF

5.1 Features of the continental shelf

The topography and physical oceanography of the continental shelf off Washington and Vancouver Island are described by Thomson (1981), Landry and Hickey (1989), and Freeland (1992). The 200 m isobath represents the shelf edge; the shelf slopes steeply beyond this depth. The shelf is generally 20-50 km wide, with the narrowest section (<5 km) off the Brooks Peninsula (Vancouver Island) and the broadest portion (about 70 km) off SW Vancouver Island.

More than a dozen deep canyons cut into the shelf (Fig. 1). The largest is the Juan de Fuca canyon, cutting across the entire shelf to the mouth of Juan de Fuca Strait. These canyons modify the deep northward flowing currents to create anticlockwise circling currents or gyres (Hickey 1989). Most of these gyres do not appear at the surface, but can enhance the advection of deep, nutrient-rich water into the upper ocean (Hickey 1989, Freeland and Denman 1982). During summer there is a large, semi-permanent surface gyre at the mouth of the Strait of Juan de Fuca which entrains cold, nutrient rich water and enhances local productivity. High densities of phytoplankton and zooplankton occur over shallow banks, notably the Swiftsure and La Perouse banks off SW Vancouver Island, in summer and winter (Mackas *et al.* 1980, Denman *et al.* 1981, Thomas and Emery 1986).

5.2 Winds and currents

The prevailing winds blow from the NW in summer (May through September) and SE in winter (October through March), with a fairly rapid transition between these regimes (Thomson *et al.* 1989). The NW winds favour upwelling over the shelf, but the SE winds suppress upwelling and cause downwelling.

The Vancouver Island Coastal Current persists year round, flows northward along the inner shelf and is driven by buoyancy gradients resulting from freshwater runoff of coastal rivers (Fig. 2; Thomson *et al.* 1989). This current may be temporarily reversed at the surface during strong NW winds in summer, but is reinforced by the prevailing SE winds in winter. Beyond the shelf break the surface currents follow the wind patterns and flow toward the SE in summer and the NW in winter. The winter flow is a northward extension of the warm Davidson Current which extends from California. The inshore surface waters off central Washington tend to flow S or SW in summer, under the influence of upwelling and the NW winds, but flow strongly N in winter (Landry *et al.* 1989).

5.3 Freshwater runoff

The voluminous runoff from rivers and streams affects the coastal oceanography, creating salinity gradients and inducing coastal currents. The persistent Columbia River plume extends tens of km to the SW in summer, but is carried northward in winter and affects inshore waters as far north as Cape Flattery (Landry *et al.* 1989). Fraser River runoff is mixed with advected deep ocean water by tidal friction in the Strait of Juan de Fuca, and the resultant nutrient-rich water circulates within the Juan de Fuca gyre or moves northward over the shelf (Thomson 1981, Thomson *et al.* 1989). Freshwater runoffs contribute to the salinity and thermal gradients and coarse-scale fronts over the inner shelf in both summer and winter (Thomas and Emery 1986, R. E. Thomson pers. comm.). Such fronts form boundaries to aggregations of plankton (Thomas and Emery 1986), and hence affect foraging by seabirds.

5.4 Upwelling

Upwelling in this area is driven by several processes (Denman *et al.* 1981, Thomson 1981, Landry *et al.* 1989):

- i) longshore NW winds moving surface water offshore;
- ii) interactions between current fields and the complex bottom topography bringing deep water to the surface;
- iii) tidal movements causing mixing and advection into shallow areas.

Wind appears to be the major agent, and significant upwelling occurs between April through September when favourable NW winds prevail (Denman *et al.* 1981, Thomson *et al.* 1989). Rates of upwelling may increase 10 fold during periods of strong NW winds, and persistent plumes of cold, upwelled water can move > 100 km offshore. There are generally several pulses of increased primary productivity through the spring and summer (Denman *et al.* 1989, Mackas and Galbraith 1992). Biological productivity is not, however, limited to such episodic events, but can persist throughout the summer over shallow areas with adequate nutrient supplies. On the other hand, atypical winds can induce brief periods of upwelling during winter (Landry *et al.* 1989).

The strong tidal currents in the Strait of Juan de Fuca, coupled with advection of deep water in the Juan de Fuca gyre result in nutrient rich water moving north over the banks off SW Vancouver Island. Denman *et al.* (1981) described two persistent bands of high plankton biomass off SW Vancouver Island in summer: one along the outer edge of the continental shelf; the other in more shallow water (ca. 80 m) within 20 km of the shore.

5.5 Effect of gyres and fronts on productivity

Increased nutrients supplied by upwelling or mixing can result in blooms of phytoplankton in a matter of days, but water bodies need to persist longer if the benefits are to extend up food

chains. An upwelling plume might not benefit zooplankton, or ultimately seabirds, if the phytoplankton are rapidly dispersed by downwelling or currents.

Denman *et al.* (1989) examined biomass transfer up marine food webs off British Columbia. They concluded that a pulse of primary productivity would take 90 days to create a peak in biomass in euphausiids and fish larvae (food for Cassin's Auklets) and 270 days in 30 g fish (food for Common Murres). Aggregations at the sites of blooms by the more mobile animals in the food chains could, of course, occur far more quickly. Denman *et al.* (1989) showed that eddies, such as the Juan de Fuca gyre prolonged the retention time of plankton concentrations and hence enhanced energy flow up food chains. Similarly shelf water may be retained along the continental margin for long enough for significant energy flow to occur. The net result is that seabird food tends to be highly clumped even within the productive shelf zone.

6. FINE SCALE OCEAN PROCESSES AFFECTING SEABIRDS

At this scale we are interested in processes that affect a seabird's decision on where to feed during a specific foraging bout. Fine-scale physical processes which are known to influence seabirds' foraging include the following (Brown 1980, Haney 1986a, Hunt and Schneider 1987):

- i) Langmuir cells or wind-streaks, containing concentrations of surface debris and plankton, which result from spiral, wind-induced circulation in the upper few metres of ocean (Fig. 3a);
- ii) aggregations of debris and surface plankton at tidal slicks formed in relatively calm inshore water ;
- iii) concentrations of plankton formed at small convergent fronts as strong tidal flow creates a mini-upwelling (Fig. 3b);
- iv) cells of water (diameter in 100s of m) containing high densities of prey, as a result of advection of deep water over a shallow bank, or an eddy broken off from a larger current flow.

All of these processes occur off British Columbia and Washington (Thomson 1981), but their influence on seabirds has not been studied in detail.

Fedoryako (1982) showed that small-scale physical processes, like Langmuir cells, which collected surface debris also produced concentrations of plankton and small fish. Floating oil is also likely to aggregate at small fronts where seabirds come to feed. Small schooling fish are known to gather below floating objects and if they respond in this way to oil slicks this could lead to increased oiling among the predatory birds (Kerley *et al.* 1987).

In addition, fine-scale biological processes lead to aggregations of seabirds, including tendencies for euphausiids, and small fish to form swarms or schools, and tendencies for seabirds to be attracted to the sights and sounds of other birds feeding. Mixed-species feeding flocks, centred on schools of fish near the surface, are a distinctive feature of seabird communities off Vancouver Island (Porter and Sealy 1981).

7. DISTRIBUTION OF THE PREY OF SEABIRDS

The distribution of birds at sea is strongly dependent on the distribution and abundance of their prey, although there is seldom a simple linear correlation between the two. There have been no intensive, simultaneous studies of seabirds and their prey off B.C. or Washington but information on some local prey species is available.

7.1 Zooplankton

Macrozooplankton is the principal food for many seabirds off Washington and B.C., including Cassin's Auklets, and is also eaten in winter by piscivores, such as Common Murres (Vermeer *et al.* 1987b). Euphausiids (principally *Thysanoessa spinifera* and *Euphausia pacifica*) and larger copepods (especially *Neocalanus* spp.) are most often eaten, but chaetognaths, hyperiid amphipods, crab larvae and gelatinous medusae and salps may also be taken (Vermeer *et al.* 1987b, Mackas and Galbraith 1992). The distribution and densities of plankton also reflect general patterns of marine productivity and indicate where fish or squid might be aggregated. Mackas and Galbraith (1992) reviewed the distribution of zooplankton and their availability to seabirds off the west coast of Vancouver Island. Their major points are given here, along with additional material.

7.2 Seasonal patterns among zooplankton

The composition and densities of macrozooplankton vary seasonally (Fig. 4). Densities decline through the winter to reach a low in February. The density of macrozooplankton fluctuates much less than that of phytoplankton or smaller zooplankton, which decline by an order of magnitude during winter (Thomas and Emery 1986). Euphausiids occur in significant quantities in winter. They are relatively long-lived (0.5-3 years), but it is not known whether they are resident off Vancouver Island. Local euphausiid populations might be supplemented in spring by currents carrying euphausiids from the dense shelf-break aggregations off northern Vancouver Island and the Queen Charlotte Islands, and in winter from populations in Oregon (Simard and Mackas 1989).

The larger *Neocalanus* copepods undergo marked vertical migrations: they remain in shallow depths during the spring and summer blooms, but move to deep water, beyond the reach of seabirds in the fall where they remain through the winter (Mackas and Galbraith 1992).

7.3 Spatial distribution of zooplankton

Euphausiids are important prey for fish and seabirds because their swarming behaviour concentrates large amounts of food. Off Vancouver Island, euphausiids are highly localized and >50% of the biomass was reported from <5% of the area surveyed by Simard and Mackas (1989). Localized upwelling of shelf-break water can trap swarms of euphausiids over shallow banks, preventing their return to deep water (Simard and Mackas 1989), and making them more

accessible to diving birds. Dense concentrations can be found at shelf-break fronts, over the Juan de Fuca canyon and La Perouse Bank (Pearcy 1976, Fulton and LeBrasseur 1984, Simard and Mackas 1989). Concentrations of euphausiids and other macrozooplankton suitable for birds off Vancouver Island are shown in Fig. 5 (from Mackas and Galbraith 1992).

There is less information on zooplankton distribution in winter, but shelf-break fronts which exist in winter can concentrate plankton (Denman and Powell 1984). Thomas and Emery (1986) reported the highest densities from a surface front situated 15-25 km off Cape Beale, SW Vancouver Island in November and December. This appeared to be a convergence front between the cold, less saline Coastal Current water and the warmer, less productive Davidson Current water. Similar winter fronts exist off Washington between shelf water influenced by the Columbia River runoff and the warmer Davidson Current water (Landry *et al.* 1989).

7.4 Distribution of fish

Schooling fish which are important prey for seabirds in this region include sandlance *Ammodytes hexapterus*, Pacific Herring *Clupeus harengus*, Northern Anchovy *Engraulis mordax*, Eulachons *Thaleichthys pacificus*, Pacific Saury *Cololabis saira*, juvenile Rockfish *Sebastes* spp., and juvenile greenling *Hexagrammos* spp. (Vermeer *et al.* 1987b, Hay *et al.* 1992). Market Squid *Loligo opalescens* are also eaten by several species. Year-round information on the distribution and abundance of these prey is sparse (Hay *et al.* 1992). Piscivores such as Common Murres feed more extensively on crustaceans, such as euphausiids, in winter, when schooling fish appear to be less readily available.

Pacific Herring predominates in the diet of Common Murres during winter in inshore waters (Vermeer *et al.* 1987b). On the outer coast herring are also important food in summer (pers. obs.), but their importance in winter is not known. Adult herring are probably too large for most seabirds, but the year-1 and year-2 juveniles, which are 70-150 mm long and 40-60 g in mass (Grosse and Hay 1988) are an ideal size.

Juvenile herring form dense schools in shallow inshore waters during the summer. In fall most move offshore into deeper water, although some remain close to the shore. Schools of millions of juveniles aggregate at the edges of banks and in the Juan de Fuca canyon (Grosse and Hay 1988). They tend to remain at depths of 100-200 m, which is within the maximum diving range of murres, but not within their regular foraging depths (Piatt and Nettleship 1985, Croll *et al.* 1992).

8. DISTRIBUTION OF SEABIRDS

8.1 Responses to ocean processes and prey densities.

Being very mobile and having high energy demands, seabirds might be expected to show strong correlations with prey densities and the oceanic processes which affect the prey densities. It has proved more complex than expected to determine such associations, for several reasons:

- i) It is extremely difficult to estimate prey abundance which is accessible to the seabirds. Hydroacoustic sampling of plankton and fish schools probably gives the most realistic estimates, but can never sample the entire stock available within the foraging range of a seabird colony or feeding aggregation, and there is always some uncertainty of the identity of organisms seen in the echo-traces.
- ii) The spatial and temporal scales used in analyses affect the probability of detecting associations (Schneider and Piatt 1986, Hunt and Schneider 1987). Correlations might not be found if an inappropriate scale is selected. Several studies have found that stronger correlations are found at coarse rather than fine scales (e.g. 2-15 km, Schneider and Piatt 1986; 9-22 km Hunt *et al.* 1990).
- iii) It is difficult to distinguish between foraging birds and those simply passing through an area. Hunt *et al.* (1991) discuss additional problems with sampling design.

At a coarse scale, several studies have found strong concordance between seabird densities and prey densities (reviewed by Hunt *et al.* 1991), although this is not reported from all studies (e.g. Woodby 1984). There is evidence of both spatial concordance (seabirds and their prey tend to occur at the same places) and numerical concordance (larger prey aggregations attract more seabirds), although the latter relationship is not a simple linear one. There might be a threshold density of prey, below which it is not energetically economical to forage (Piatt 1990). Conversely, large, profitable schools of prey may avoid detection by birds.

To find prey, a seabird probably depends on a combination of environmental cues (e.g. possibly the contrast in water colour between upwelled and other water), past experience (returning to feed at sites where it had previous success), random sampling, and behavioural interactions (e.g. cueing in on other successful feeders; flock-feeding). Our knowledge of these processes is very rudimentary, but birds are obviously adept at finding prey patches in the relatively featureless ocean (Briggs *et al.* 1987, Hunt *et al.* 1991).

8.2 General distribution of Common Murres

Common Murres forage in a variety of ocean sites, ranging from small, sheltered inlets to 100 km out in the open sea. Off Washington and Vancouver Island they tend to be most numerous in water less than 100 m deep over the inner shelf, but are also common in winter in the Strait of Juan de Fuca (Vermeer *et al.* 1989, Wahl *et al.* 1993). Comprehensive studies off California showed that murres were not necessarily associated with any particular water type, but were most common in water less than 150 m deep, and often aggregated at oceanic fronts (Briggs *et al.* 1987, Ainley and Boekelheide 1990). Elsewhere, significant correlations between the densities of murres and schooling fish have been reported (Schneider and Piatt 1986, Piatt 1990, Erikstad *et al.* 1990).

8.3 General distribution of Cassin's Auklet

Unlike murres, Cassin's Auklets show more clear-cut preferences in foraging sites. They tend to avoid inshore areas, form aggregations at the shelf edge or over sea-mounts, and are less commonly found over the mid-shelf (Briggs *et al.* 1987, Vermeer *et al.* 1989, Ainley and Boekelheide 1990, Wahl *et al.* 1993). Large aggregations, sometimes numbering thousands of birds are not uncommon, and may persist for days or weeks while the birds exploit dense, predictable swarms of euphausiids (Briggs *et al.* 1987, 1988). Auklets in California showed strong positive associations with temperature gradients in the sea, and negative correlations with depth, distance from land, and sea temperature (Briggs *et al.* 1987). They were often found in the core and the outer edges of filaments of cold, upwelled water (Briggs *et al.* 1988, Ainley and Boekelheide 1990).

8.4 Bird distribution off Vancouver Island and Washington

Morgan *et al.* (1991) summarised shipboard censuses of seabirds from 1981 through 1990. Meso-scale plots of the fall (16 Sep - 15 Dec) and winter (16 Dec - 15 March) data show the mean densities at the time of year of the Nestucca spill (Fig. 6). It is obvious that high densities of seabirds, including Common Murres and Cassin's Auklets, could be expected off SW Vancouver Island in December and January. Average densities exceeded 100 birds per km of transect in several quadrats. The murres were most abundant over the inner and mid-shelf, whereas the auklet's range extended just beyond the shelf edge (Fig. 6).

Aerial and shipboard surveys made off SW Vancouver Island by Vermeer *et al.* (1983, 1987a) are summarized in Fig. 7. Murres were most common over the inner and mid-shelf (within 60 km of shore), whereas Cassin's Auklets avoided the inner shelf and were most common near the shelf edge (ca. 60 km offshore). Murres and auklets seem less abundant than the gulls, but dark-coloured diving birds, like alcids, are always underestimated in these surveys. Densities of most seabirds, including murres and auklets, were higher off SW Vancouver Island in winter than in other parts of B.C. (Vermeer *et al.* 1983).

Unpublished data collected from the M.V. Alta out of Bamfield Marine Station have been analysed to show coarse-scale distributions of seabirds off SW Vancouver Island. A transect made on 19 August 1987 over the Swiftsure Bank, beginning near Pachena Bay, Vancouver Island, showed several aggregations of murres over the banks, whereas Cassin's Auklets were highly aggregated near the shelf edge (Fig. 8). Repeated transects made across the mouth of Barkley Sound show several trends (Fig. 9):

- i) seabirds, including Common Murres, were highly aggregated;
- ii) aggregations were often associated with coarse-scale fronts where sea temperature changed rapidly over a distance of a few 100 m;
- iii) the small schooling fish on which the birds fed were often aggregated near these fronts.

These trends are consistent with the principles discussed earlier, linking oceanography, prey distribution and seabird behaviour.

The aerial surveys over the Washington and B.C. coastal waters made by Ford *et al.* (1991) give seabird distributions on 3-14 January 1990 (Fig. 10). Unfortunately, the densities generated from these surveys cannot be compared directly with those from Morgan *et al.* (1991) or Vermeer *et al.* (1983, 1987a) because of differences in survey technique and density units used. Ford's data are, however, consistent with the other studies in several respects:

- i) seabird densities were high over the shelf region but much lower beyond the shelf;
- ii) aggregations of Common Murres were found from the inner to the outer shelf;
- iii) Cassin's Auklets avoided the inner shelf and were most dense at the shelf break or just beyond the break.

The maps clearly show the highly clumped distribution of birds, with dense aggregations over parts of the shelf (probably associated with fronts and aggregations of prey), at the shelf break, and in the region of the Juan de Fuca canyon (Fig. 10).

9. IMPLICATIONS FOR ASSESSING THE IMPACTS OF THE NESTUCCA SPILL

Several of the oceanic processes discussed above have bearing on the Nestucca spill.

9.1 Large-scale trends

Large numbers of pelagic seabirds regularly overwinter off northern Washington and SW Vancouver Island. Upwelling is largely absent in winter, but there are large residual populations of macrozooplankton and schooling fish over the shelf which support the seabirds. Densities of birds at sea are very similar to other parts of the California Current upwelling domain (Briggs *et al.* 1987) and the breeding population of seabirds in B.C. is the highest in this domain (Rodway 1991).

The exceptionally high mortality resulting from Nestucca is partly due to the oil being released in a shelf zone which regularly supports exceptionally dense seabird populations, within one of the most productive domains of the northeastern Pacific. The release of the oil over a swath of more than 50 km, perpendicular to the current, increased the probability of drifting oil contacting flocks of birds.

9.2 Coarse-scale trends

The significant findings here are:

- i) coarse-scale thermal and salinity fronts exist in winter, although they are weaker than in summer;
- ii) low salinity water within the Columbia River plume and from the Strait of Juan de Fuca create conditions favouring such fronts, strong winds might break them up;
- iii) aggregations of zooplankton are concentrated by ocean processes, including coarse-scale fronts over the shelf;
- iv) dense aggregations of euphausiids, and other prey types, can be found at the shelf-edge, at fronts over the banks, and at the margins of the Juan de Fuca canyon;
- v) Common Murres, Cassin's Auklets and other local seabirds have highly clumped distributions, corresponding to aggregations of euphausiids and other prey associated with coarse-scale fronts;
- vi) Both drifting oil and the prey of seabirds are likely to aggregate at convergent fronts, which would increase the chances of birds getting oiled.

Strong surface winds are likely to disrupt coarse- or fine-scale surface fronts and periods of strong SE winds occurred as the Nestucca oil drifted north. During lulls between storms, fronts might have been established (R.E. Thomson pers. comm.). Near-surface Langmuir circulation (see Fig. 3a) induced by strong winds might also have acted to concentrate drifting oil and plankton, although such patterns would probably not persist with very heavy wave action.

These coarse-scale processes account for the dense, but patchy distribution of seabirds. The Nestucca oil slicks drifted through dense flocks of seabirds causing exceptionally high rates of oiling. Little is known about how birds react to oil slicks. Bourne (1968) reported that seabirds ignored slicks until they were in contact with the oil, whereupon aerial species such as gulls usually flew away, but diving species such as alcids dived and were likely to re-encounter the oil. There are also suggestions, without much evidence, that birds might be attracted to slicks (Bourne 1968, Kerley *et al.* 1987). It is highly probable in the Nestucca event, that coarse- and fine-scale physical processes caused simultaneous aggregations of oil, prey and birds and hence contributed to the high mortality of seabirds.

10. LITERATURE CITED

- Ainley, D.G. and R.J. Boekelheide. 1990. Seabirds of the Farallon Islands. Stanford Univ. Press, Stanford, Calif.
- Ashmole, N.P. 1971. Sea bird ecology and the marine environment. Pp. 223-286 in Avian biology, Vol. 1 (D.S. Farner and J.R. King, eds.). Academic Press, New York.
- Bourne, W.R.P. 1968. Observations of an encounter between birds and floating oil. Nature (Lond.) 219:632.
- Bourne, W.R.P. 1970. Oil pollution and bird conservation. Biol. Conserv. 2:300-302.
- Briggs, K.T., W.B. Tyler, D.B. Lewis and D.R. Carlson. 1987. Bird communities at sea off California: 1975 to 1983. Studies Avian Biol. 11, 74 p.
- Briggs, K.T., D.G. Ainley, J.B. Spear, P.B. Adams and S.E. Smith. 1988. Distribution and diet of Cassin's Auklet and Common Murre in relation to Central California upwellings. Proc. XIX Int. Congr. Ornithol., Ottawa: 982-990.
- Brown, R.G.B. 1980. Seabirds as marine animals. Pp. 1-39 in Behavior of marine animals, Vol. 4 (J. Burger, B. Olla and H.E. Winn, eds.). Plenum Press, New York.
- Burger, A.E. 1992. The effects of oil pollution on seabirds off the west coast of Vancouver Island. Pp. 120-128 In, The ecology, status and conservation of marine and shoreline birds of the west coast of Vancouver Island (K. Vermeer, R.W. Butler and K.H. Morgan, eds.). Occ. Pap. No. 75, Canadian Wildlife Service, Ottawa.
- Burger, A.E. 1993a. Effects of the 'Nestucca' oil spill on seabirds along the coast of Vancouver Island in 1989. Can. Wildl. Serv. Tech. Rep. Ser. No. 179. Pacific and Yukon Region, British Columbia.
- Burger, A. E. 1993b. Estimating the mortality of seabirds following oil spills: effects of spill volume. Marine Pollution Bulletin 26: 140-143.
- Burger, A.E. and D.W. Powell. 1990. Diving depths and diet of Cassin's Auklet at Reef Island, British Columbia. Can. J. Zool. 68:1572-1577.
- Cohen, P. and R. Aylesworth. 1990. Oil spill risk for southern B.C./northern Washington coast marine area. Final report of the States/British Columbia oil spill task force, Appendix VII. Publ. Province of British Columbia and the States of Washington, Oregon, Alaska and California. 105 p.

- Croll, D.A., A.J. Gaston, A.E. Burger and D. Konnoff. 1992. Foraging behavior and physiological adaptation for diving in Thick-billed Murres. *Ecology* 73:344-356.
- Croxall, J.P. (ed.) 1987. Seabirds: feeding ecology and role in marine ecosystems. Cambridge Univ. Press, Cambridge, U.K.
- Croxall, J.P., P.G.H. Evans and R.W. Schreiber (eds.) 1984. Status and conservation of the world's seabirds. ICBP, Cambridge, U.K.
- Denman, K.L., H.J. Freeland and D.L. Mackas. 1989. Comparisons of time scales for biomass transfer up the marine food web and coastal transport processes. *Can. Spec. Publ. Fish. Aquat. Sci.* 108:255-264.
- Denman, K.L., D.L. Mackas, H.J. Freeland, M.J. Austin and S.H. Hill. 1981. Persistent upwelling and mesoscale zones of high productivity off the west coast of Vancouver Island, Canada. Pp. 514-521 in *Coastal Upwelling* (F.R. Richards, ed.). Amer. Geophys. Union, Washington, D.C.
- Denman, K.L. and T.M. Powell. 1984. Effects of physical processes on planktonic ecosystems in the coastal ocean. *Oceanogr. Mar. Biol. Ann. Rev.* 22:125-168.
- Erikstad, K.E., T. Moum and W. Vader. 1990. Correlations between pelagic distribution of Common and Brunnich's Guillemots and their prey in the Barents Sea. *Polar Research* 8:77-87.
- Favorite, F., A.J. Dodimead and K. Nasu. 1976. Oceanography of the subarctic Pacific region 1960-71. *Int. N. Pac. Fish. Comm. Bull.* 33, 187 p.
- Fedoryako, B.I. 1982. Langmuir circulations and a possible mechanism of formation of fish associations around a floating object. *Oceanology* 22:228-232.
- Ford, R.G., J.L. Casey, C.H. Hewitt, D.B. Lewis, D.H. Varoujean, D.R. Warrick and W.A. Williams. 1991. Seabird mortality resulting from the Nestucca oil spill incident, winter 1988-89. Report for Washington Dept. Wildlife. Ecological Consulting Inc., Portland, Oregon.
- Freeland, H.J. 1993. The physical oceanography of the west coast of Vancouver Island. In *Seabirds of the west coast of Vancouver Island* (K. Vermeer, R.W. Butler and K.H. Morgan, eds.). *Spec. Publ. Can. Wildl. Serv.*, Ottawa.
- Freeland, H.J. and K.L. Denman. 1982. A topographically controlled upwelling center off southern Vancouver Island. *J. Mar. Res.* 4(4):1069-1093.

- Fulton, J. and R. LeBrasseur. 1984. Euphausiids on the continental shelf and slope of the Pacific coast of Canada. *La Mer* 22:268-276.
- Grosse, D.J. and D.E. Hay. 1988. Pacific Herring, *Clupea harengus pallasii*, in the northeast Pacific and Bering Sea. Pp. 34-54 in *Species synopses: life histories of selected fish and shellfish of the Northeast Pacific and Bering Sea* (N.J. Wilimovsky, L.C. Incze and S.J. Westrheim, eds.). Univ. of Washington, Seattle.
- Haney, J.C. 1986a. Seabird patchiness in tropical oceanic waters: the influence of Sargassum "reefs". *Auk* 103:141-151.
- Haney, J.C. 1986b. Seabird affinities for Gulf Stream frontal eddies: responses of mobile marine consumers to episodic upwelling. *J. Mar. Res.* 44:361-384.
- Haney, J.C. 1989. Remote characterization of marine bird habitats with satellite imagery. *Colonial Waterbirds* 12:67-77.
- Hay, D.E., M.C. Healey, D.M. Ware and N.J. Wilimovsky. 1992. Distribution, abundance and habitat of prey fish on the west coast of Vancouver Island. Pp. 22-29 In, *The ecology, status and conservation of marine and shoreline birds of the west coast of Vancouver Island* (K. Vermeer, R.W. Butler and K.H. Morgan, eds.) Occ. Pap. No. 75, Canadian Wildlife Service, Ottawa.
- Hickey, B.M. 1989. Patterns and processes of circulation over the Washington continental shelf and slope. Pp. 41-115 in *Coastal Oceanography of Washington and Oregon* (M.R. Landry and B.M. Hickey, ed.). Elsevier, Amsterdam, New York.
- Hunt, G.L. Jr., N.M. Harrison and R.T. Cooney. 1990. The influence of hydrographic structure and prey abundance on foraging of Least Auklets. *Studies Avian Biol.* 14:7-22.
- Hunt, G.L. Jr., J.F. Piatt and K.E. Erikstad. 1991. How do foraging seabirds sample their environment? *Acta XX Congr. Internat. Ornithol.*: 2272-2279.
- Hunt, G.L. Jr. and D.C. Schneider. 1987. Scale-dependent processes in the physical and biological environment of marine birds. Pp. 7-41 in *Seabirds: feeding ecology and role in marine ecosystems* (J.P. Croxall, ed.). Cambridge Univ. Press, Cambridge, U.K.
- Kerley, G.I.H., L. Bowen and T. Erasmus. 1987. Fish behaviour - a possible role in the oiling of seabirds. *S. Afr. J. Wildl. Res.* 17:128-130.
- Landry, M.R. and B.M. Hickey (eds.) 1989. *Coastal Oceanography of Washington and Oregon*. Elsevier, Amsterdam, New York etc.

- Landry, M.R., J.R. Postel, W.K. Peterson and J. Newman. 1989. Broad-scale distributional patterns of hydrographic variables on the Washington/Oregon shelf. Pp. 1-40 in *Coastal Oceanography of Washington and Oregon* (M.R. Landry and B.M. Hickey, ed.). Elsevier, Amsterdam, New York etc.
- Larsen, E.M. and S.A. Richardson. 1990. Some effects of a major oil spill on wintering shorebirds at Grays Harbor, Washington. *Northwestern Naturalist* 71:88-92.
- Mackas, D.L. and M. Galbraith. 1992. Zooplankton on the west coast of Vancouver Island: distribution and availability to marine birds. Pp. 15-21 In *Seabirds of the west coast of Vancouver Island* (K. Vermeer, R.W. Butler and K.H. Morgan, eds.). Spec. Publ. Can. Wildl. Serv., Ottawa.
- Mackas, D.L., G.C. Loutit and M.J. Austin. 1980. Spatial distribution of zooplankton and phytoplankton in British Columbia coastal waters. *Can. J. Fish. Aquat. Sci.* 37:1476-1487.
- Martin, P.W. and M.T. Myres. 1969. Observations on the distribution and migration of some seabirds off the outer coasts of British Columbia and Washington State, 1946-1949. *Syesis* 2:241-256.
- Morgan, K. H, K. Vermeer and R.W. McKelvey. 1991. Atlas of pelagic birds of Western Canada. Occ. Pap. 72, Can. Wildl. Serv., Ottawa.
- Nagy, K.A. 1987. Field metabolic rate and food requirement scaling in mammals and birds. *Ecol. Monogr.* 57:111-128.
- Pearcy, W.C. 1976. Seasonal and inshore-offshore variations in the standing stocks of micronekton and macrozooplankton off Oregon. *Fish. Bull.* 74:70-80.
- Piatt, J.F. 1990. The aggregative response of Common Murres and Atlantic Puffins to schools of capelin. *Studies Avian Biol.* 14:36-51.
- Piatt, J.F. and D.N. Nettleship. 1985. Diving depths of four alcids. *Auk* 102:293-297.
- Porter, J. M. and S.G. Sealy. 1981. Dynamics of seabird multispecies feeding flocks: chronology of flocking in Barkley Sound, British Columbia, in 1979. *Colonial Waterbirds* 4:104-113.
- Rodway, M.S. 1991. Status and conservation of breeding seabirds in British Columbia. Pp. 43-102 in *Status and Conservation of the world's seabirds* (ed. by J.P. Croxall). ICBP Tech. Publ. No. 11, Cambridge, U.K.

- Rodway, M. S., J. F. Lemon, J.-P. Savard and R. McKelvey. 1989. Nestucca oil spill: impact assessment on avian populations and habitat. Tech. Rep. Ser. No. 68. Canadian Wildlife Service, Pacific and Yukon Region, British Columbia.
- Schneider, D.C. and J. F. Piatt. 1986. Scale-dependent correlation of seabirds with schooling fish in a coastal ecosystem. *Mar. Ecol. Progr. Ser.* 32:237-246.
- Schneider, D.C., N. Harrison and G.L. Hunt, Jr. 1987. Variations in attendance at fronts by marine birds in the Bering Sea. *Cont. Shelf Res.* 5:241-257.
- Shaffer, M. and Associates Ltd. 1990. Crude oil and petroleum product traffic in British Columbia and Puget Sound. Final Report of the States/British Columbia oil spill task force, Appendix IV. Publ. Province of British Columbia and the States of Washington, Oregon, Alaska and California. 51 pp.
- Simard, Y. and D.L. Mackas. 1989. Mesoscale aggregations of euphausiid sound scattering layers on the continental shelf of Vancouver Island. *Can. J. Fish. Aquat. Sci.* 46:1238-1249.
- Thomas, A.C. and W.J. Emery. 1986. Winter hydrography and plankton distribution on the southern British Columbia continental shelf. *Can. J. Fish. Aquat. Sci.* 43:1249-1258.
- Thomson, R.E. 1981. Oceanography of the British Columbia coast. *Can. Spec. Publ. Fish. Aquat. Sci.* 56, 291 p.
- Thomson, R.E., B.M. Hickey and P.H. LeBlond. 1989. The Vancouver Island coastal current: fisheries barrier and conduit. Pp. 265-296. In R.J. Beamish and G.A. McFarlane (eds.) *Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models.* *Can. Spec. Publ. Fish. Aquat. Sci.* 108.
- Vermeer, K., R. Hay and L. Rankin. 1987a. Pelagic seabird populations off southwestern Vancouver Island. *Can. Tech. Rep. Hydrog. Ocean Sci.* No. 87:iii + 26 p.
- Vermeer, K., S.G. Sealy and G.A. Sanger. 1987b. Feeding ecology of Alcidae in the eastern North Pacific Ocean. Pp. 189-227 in *Seabirds: feeding ecology and role in marine ecosystems* (J.P. Croxall, ed.). Cambridge Univ. Press, Cambridge, U.K.
- Vermeer, K., K.H. Morgan, G.E.J. Smith and R. Hay. 1989. Fall distribution of pelagic birds over the shelf off SW Vancouver Island. *Colonial Waterbirds* 12:207-214.
- Vermeer, K., I. Robertson, R. W. Campbell, R. W. Kaiser and M. Lemon. 1983. Distribution and densities of marine birds on the Canadian west coast. *Can. Wildl. Serv. Rept.*, Vancouver, B. C.

- Vermeer, K. and R. Vermeer. 1975. Oil threat to birds on the Canadian West Coast. *Can. Field. Nat.* 89:278-298.
- Wahl, T.R. 1975. Seabirds in Washington's offshore zone. *West. Birds* 6:117-134.
- Wahl, T.R. 1984. Distribution and abundance of seabirds over the continental shelf off Washington (including information on selected marine mammals). Washington State Dept. Ecology Unpubl. Report.
- Wahl, T.R., D.G. Ainley, A.H. Benedict and A.R. DeGange. 1989. Associations between seabirds and water-masses in the northern Pacific Ocean in summer. *Mar. Biol.* 103:1-11.
- Wahl, T.R., K.H. Morgan and K. Vermeer. 1993. Seabird distribution off British Columbia and Washington. In, *The status, ecology and conservation of marine birds of the North Pacific* (K. Vermeer, K.T. Briggs, K. Morgan and D. Siegel-Causey, eds.). Canadian Wildlife Service Special Publ., Ottawa.
- Ware, D.M. and G.A. McFarlane. 1989. Fisheries production domains in the Northeast Pacific Ocean. *Can. Spec. Publ. Fish. Aquat. Sci.* 108:359-379.
- Whittaker, R.H. 1975. *Communities and ecosystems*, 2nd. ed. Macmillan, London.
- Woodby, D.A. 1984. The April distribution of murre and prey patches in the southeastern Bering Sea. *Limnol. Oceanog.* 29:181-188.

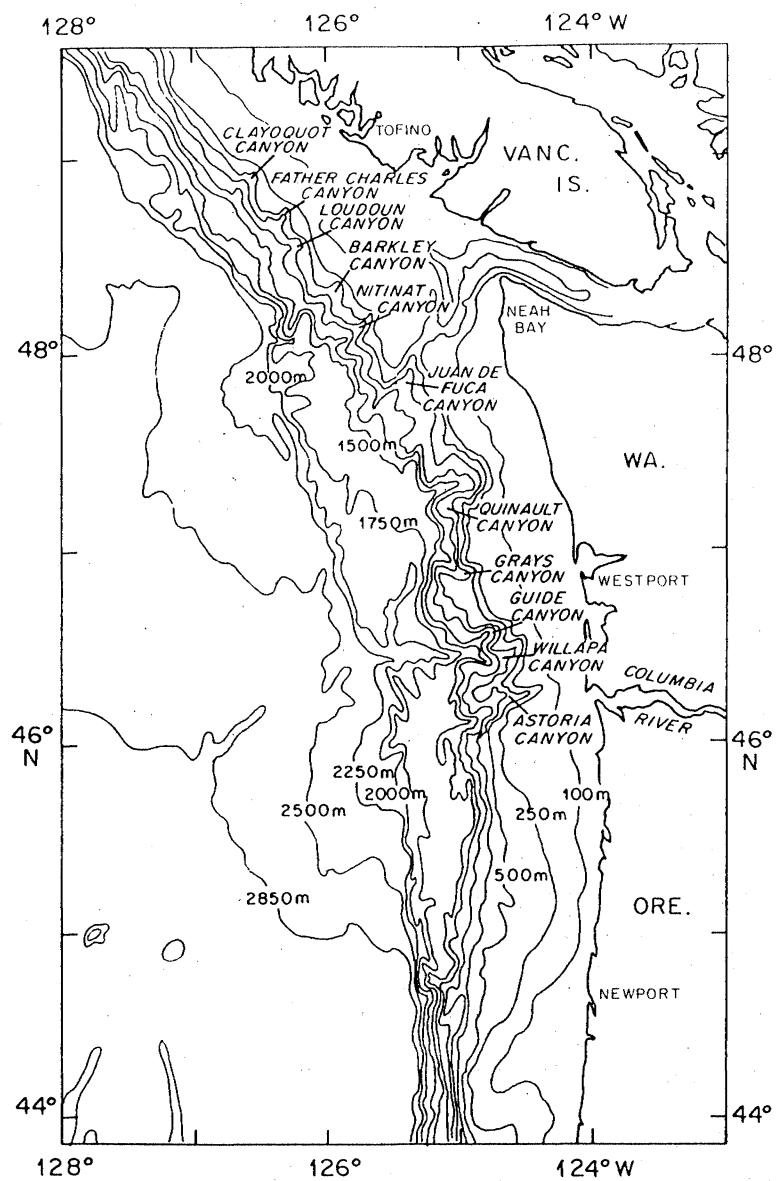


Figure 1. Bathymetry map of Washington and SW Vancouver Island, showing submarine canyons (from Hickey 1989).

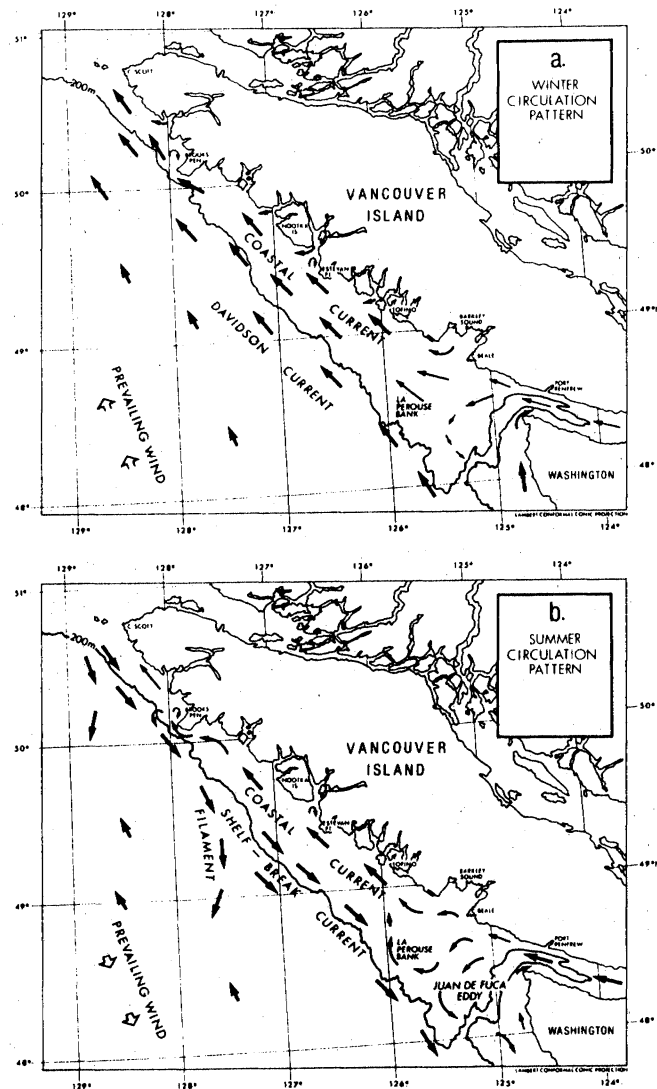


Figure 2. Schematic interpretation of the prevailing ocean currents over the Vancouver Island continental margin for (a) winter; and (b) summer (from Thomson *et al.* 1989).

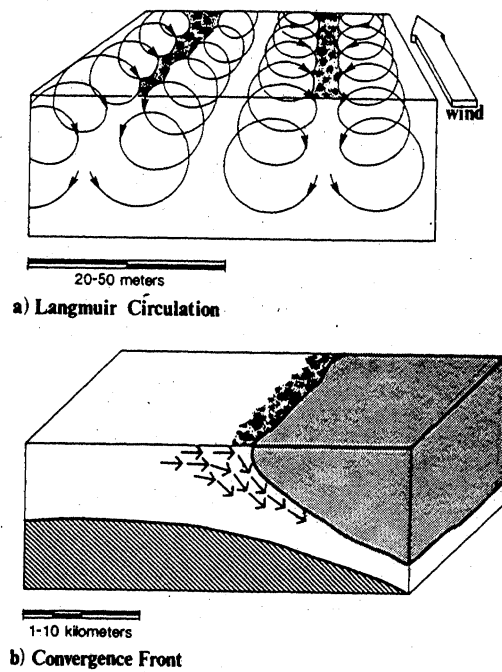


Figure 3. Examples of physical processes causing concentrations of floating and near-surface particles: (a) fine-scale Langmuir circulation in the upper few metres of ocean caused by winds; (b) a convergent front is formed when cool water, carrying particles such as plankton, meets and sinks below a warmer mass of water (shaded water mass). From Haney (1986a).

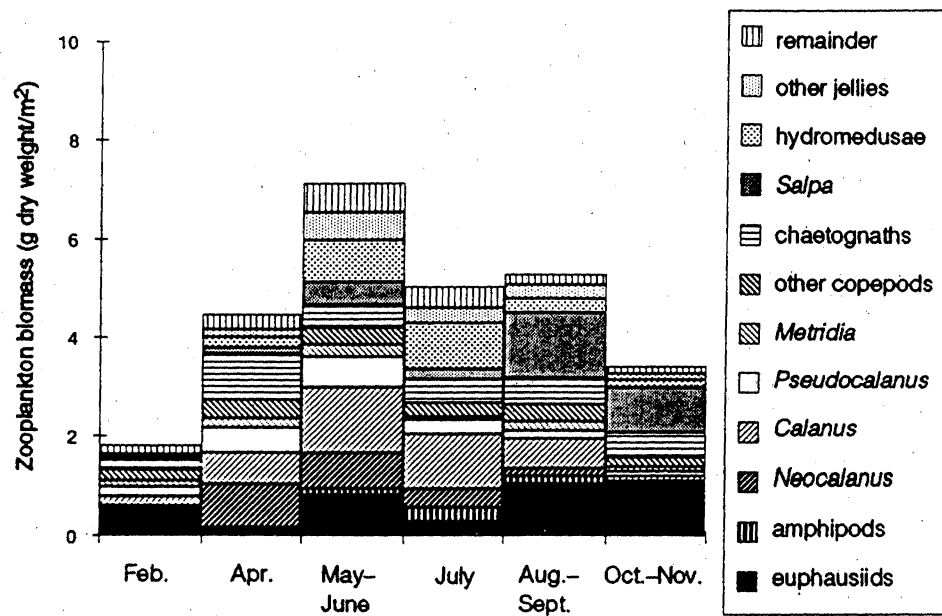


Figure 4. Area-weighted seasonal averages of zooplankton biomass (g dry weight m^{-2}) and species composition off Vancouver Island (from Mackas and Galbraith 1992).

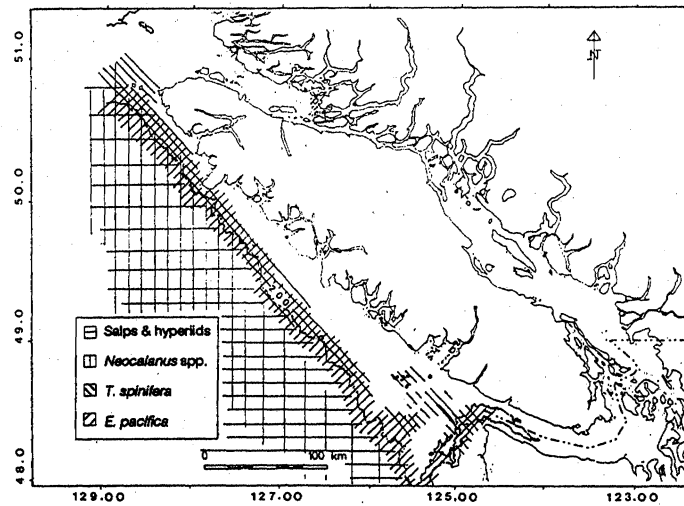


Figure 5. Regions of maximum abundance for the zooplankton types most heavily used by seabirds, including euphausiids (*Euphausia pacifica* and *Thysanoessa spinifera*), large copepods (*Neocalanus* spp.), gelatinous salps and the hyperiid amphipods commensal with the salps. Most were concentrated at the shelf edge over the 200 m isobath. From Mackas and Galbraith (in press).

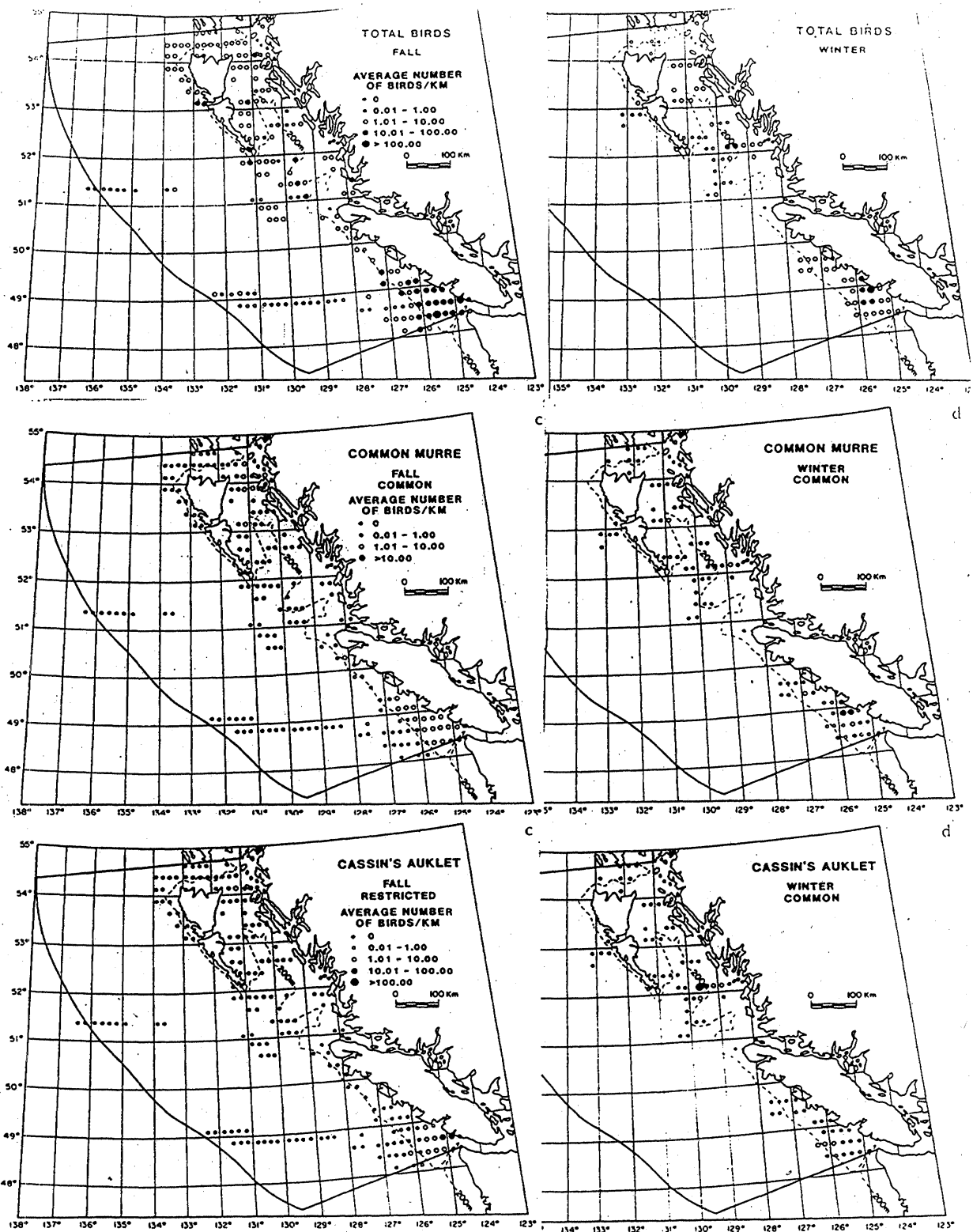


Figure 6. Maps summarizing the mean densities of all seabirds, Common Murres and Cassin's Auklets recorded in fall (16 September through 15 December) and winter (16 December through 15 March) on shipboard surveys made between 1981 and 1990 (from Morgan *et al.* 1991). Notice that the small solid dots indicate no birds sighted.

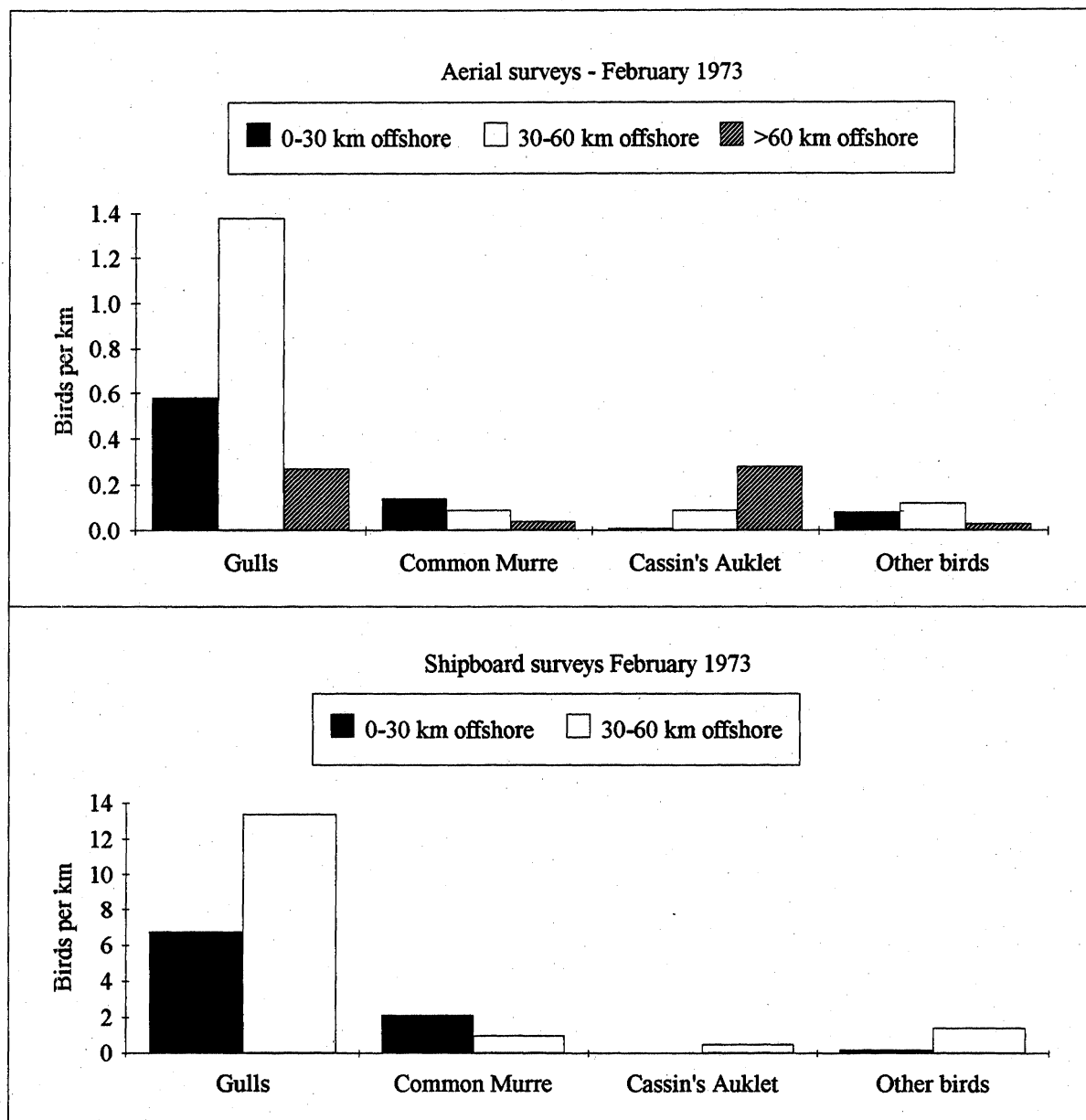


Figure 7. Mean densities of seabirds in winter at various distances offshore from Vancouver Island, measured by aerial surveys (upper) and shipboard surveys (lower). Data from Vermeer *et al.* (1983, 1987).

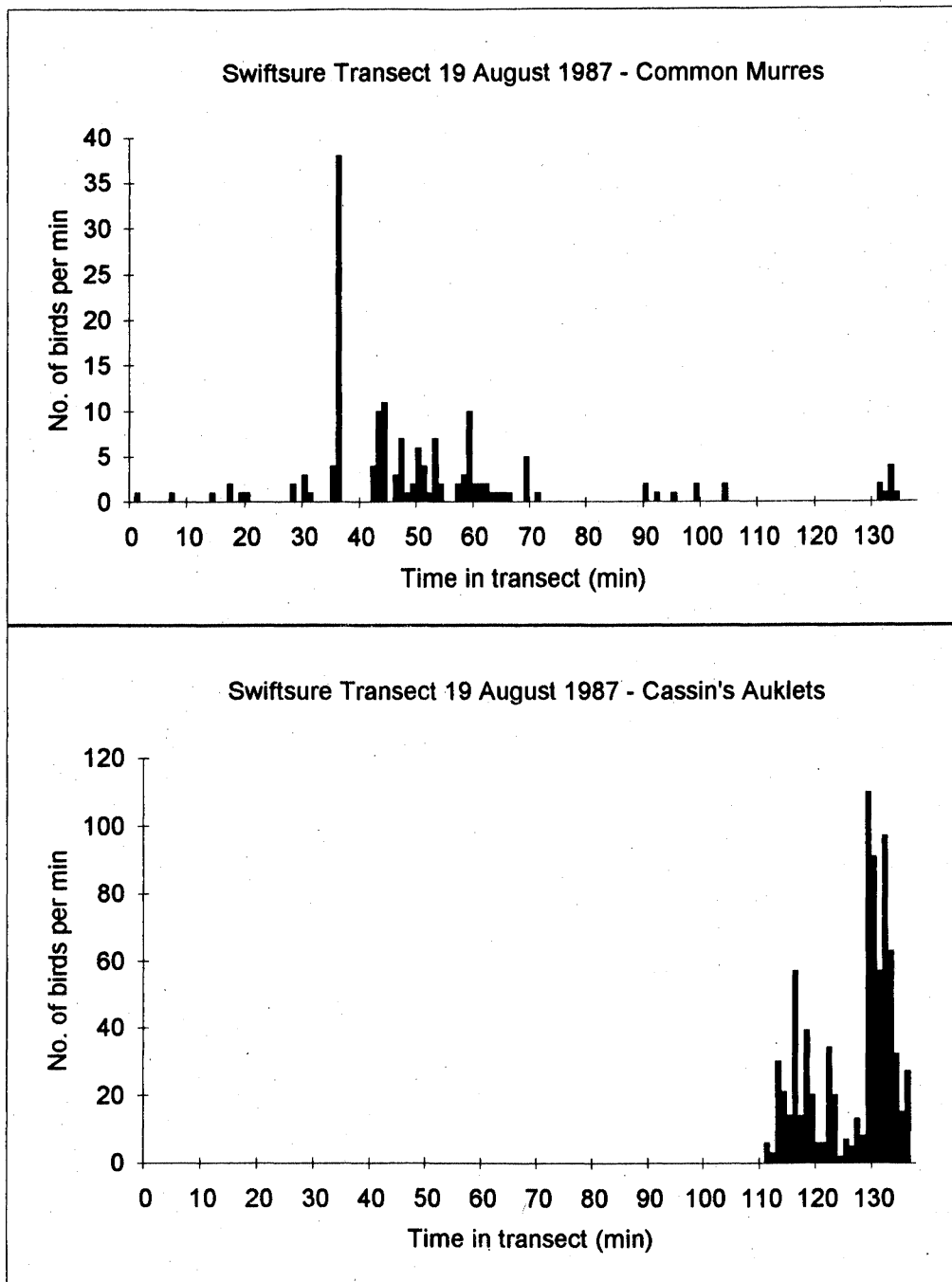


Figure 8. Densities of Common Murres and Cassin's Auklets reported per minute in a transect made over the Swiftsure Bank off SW Vancouver Island by the M.V. Alta on 19 August 1987. The transect began off Seabird Rocks near Pachena Bay and ended near the shelf edge.

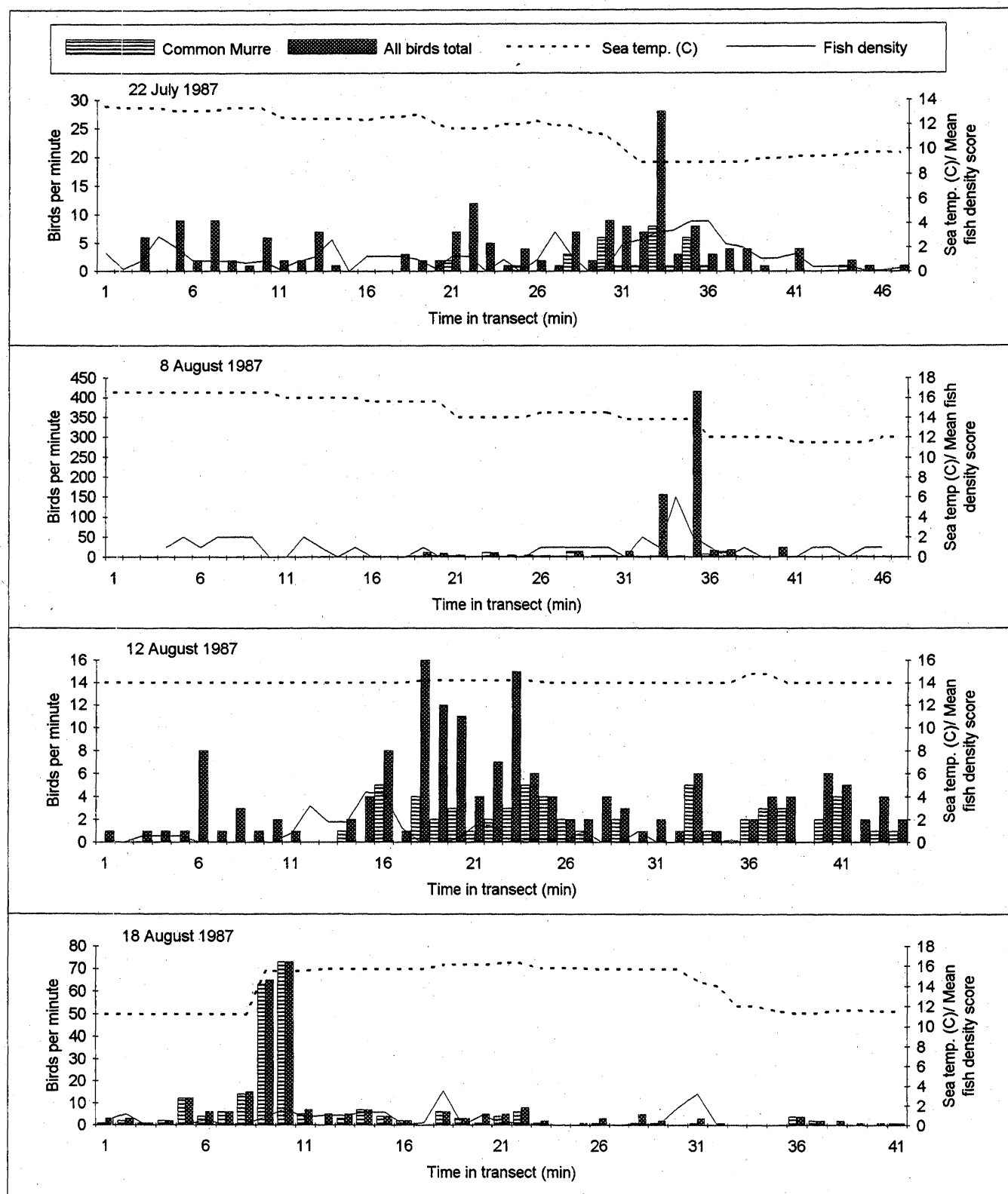


Figure 9. Results from a series of transects made by the M.V. *Alta* across the mouth of Barkley Sound near Cape Beale. The numbers of birds, sea surface temperature and an index of fish density (coded from an echosounder trace) were recorded for each minute in the transect. The vessel was travelling at approximately 8 knots. Unpubl. data from A.E. Burger.

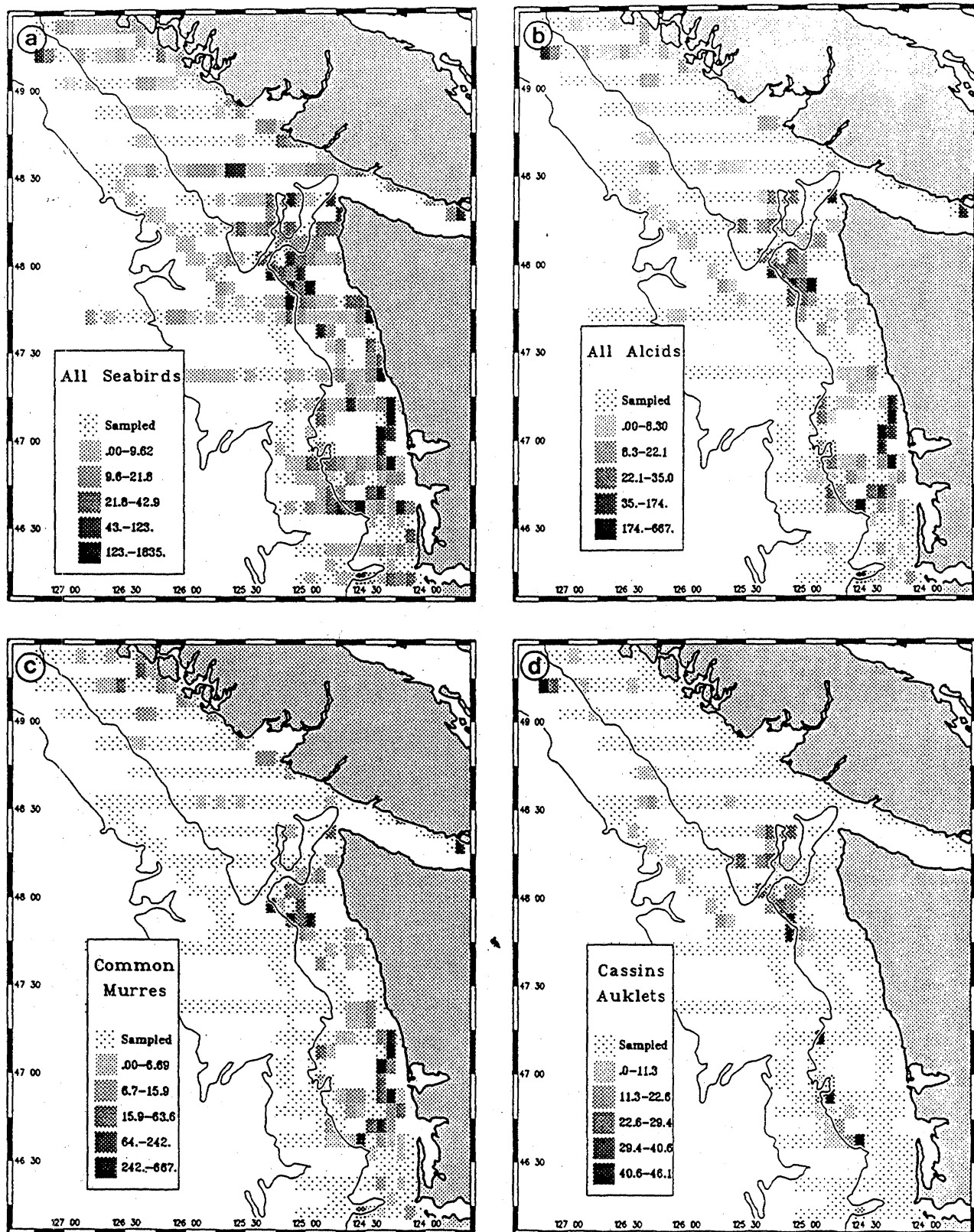


Figure 10. Seabird densities recorded during aerial surveys made between 3-14 January 1990. The bathymetric lines show the 200 m and 2000 m depth contours corresponding to the boundaries of the continental shelf and shelf slope. From Ford *et al.* 1991.