Exxon Valdez Oil Spill
Restoration Project Final Report

Restoration Project
Final Report EVOS
Project #10100742

Monitoring, Tagging, Feeding Habits, and Restoration of Killer Whales in Prince William Sound/Kenai Fjords 2010-2012

Craig O. Matkin
Graeme Ellis
Eva Saulitis
David Herman
Russ Andrews
Allison Gaylord

North Gulf Oceanic Society
3430 Main Street Suite B1
Homer, Alaska 99603

June 2013

STUDY HISTORY:

The North Gulf Oceanic Society (NGOS) independently maintained a monitoring program for killer whales in Prince William Sound from 1984-1988 (Matkin, et. al. 1994). This work was partially funded by a variety of non-profit foundations and government grants. Following spill, killer whales were monitored in Prince William Sound, Alaska with funding from the *Exxon Valdez* Oil spill Trustee Council in 1989, 1990, and 1991 (Dahlheim, M.E. and C.O. Matkin, 1993) and in 1993 (Dahlheim 1994). The North Gulf Oceanic Society (NGOS) independently maintained a monitoring program in 1994. An assessment of the status of killer whales from 1984 to 1992 in Prince William Sound was published (Matkin et al. 1994).
The current study builds upon this historical work as well as three other EVOS supported projects, initiated in 1995 as Restoration Project 95012 "Comprehensive Killer Whale Investigations" and followed by "Photographic and Acoustic Monitoring of Killer Whales" initiated in 1999 and completed in 2002. The combined final report for both these projects was accepted in 2003 and is available from ARLISS or from NGOS as C.O. Matkin, G. Ellis, L. Barrett Lennard, H. Yurk, E. Saulitis, D. Scheel, P. Olesiuk, G. Ylitalo. 2003 . Comprehensive Killer Whale Investigation (Restoration Project 00112 Final Report), North Gulf Oceanic Society, Homer, Alaska. The final report for work from 2003-2009 was also submitted: Craig O. Matkin, Graeme Ellis, Eva Saulitis,David Herman,Russ Andrews,Allison Gaylord, and Harald Yurk. 2010. Monitoring, Tagging, Remote Acoustics, Feeding Habits, and Restoration of Killer Whales in Prince William Sound/Kenai Fjords 2003-2009. Restoration Project 090742 Final Report. Notrh Gulf Oceanic Society, Homer, Alaska 99603

The following manuscripts have resulted from the current project:

Matkin, C.O., J.W. Durban, E.L. Saulitis, R. D. Andrews, J.M. Straley, D.R. Matkin, G.M. Ellis 2012. Contrasting abundance and residency patterns of two sympatric populations of transient killer whales (*Orcinus orca*) in the northern Gulf of Alaska. Fish. Bull. 110:143–155.

Bodkin, J.L, D. Esler, S.D. Rice, C.O. Matkin and B.E. Ballachey. In press. The effects of spilled oil on coastal ecosystems: Lessons from the Exxon Valdez spill. In: J.L. Lockwood and B. Maslo (eds), Coastal Conservation, Cambridge University Press.

Ford, John K. B., Graeme M. Ellis, Craig O. Matkin, Michael H. Wetklo, Lance G. Barrett-Lennard, Ruth E. Withler. 2011. Shark predation and tooth wear in a population of northeastern Pacific killer whales. Aquat Biol 11:213-224.

Filatova Olga A., V. B. Deecke, J. K. B. Ford, C. O. Matkin, L/ G. Barrett-Lennard. M. A. Guzeev, A. M. Burdin, E. Hoyt. 2012. Call diversity in the North Pacific killer whale populations: implications for dialect evolution and population history. Animal Behaviour 83:595-603

Filatova, Olga A., J.K.B. Ford, C.O. Matkin, L.G. Barrett-Lennard, A.M. Burdin, and E. Hoyt. 2012. Ultrasonic whistles of killer whales (Orcinus orca) recorded in the North Pacific (L). J. Acoust. Soc. Am. 132 (6)

ABSTRACT:

Both resident and transient killer whales have been monitored in Prince William Sound/Kenai Fjords since 1984. Following the *Exxon Valdez* oil spill 13 of 35 whales were lost from the resident AB pod and 9 of 22 whales were lost from the AT1 transient population. AB pod split into AB and AB25 pods following the spill and they rarely associate. Two matrilines (now AB25pod) split from AB pod following the spill. The remaining AB pod had numbered 26 whales in the year prior to the spill, declined to 16 whales following the spill and is still not fully recovered at 20 whales in 2012. The AB25 pod which numbered 10 whales and was part of AB pod prior to the spill, lost 3 whales following the spill but has grown comparably to the overall resident population and now numbers 18 individuals in 2012. The AT1 transient group as been stable at 7 individuals over the past three years, but has recruited no new calves and appears headed for extinction. Development ARGOS satellite based tags and tracking of individuals from various pods and groups has continued improving our description of details of important killer whale habitat. Important habitat for the pods studied included Montague Strait, Hinchinbrook Entrance, outer Resurrection/Aialik Bay and the area north east of Kodiak Island. Feeding studies were based on examination of prey remains/fish scales and on blubber chemistry including stable isotopes, fatty acids and environmental contaminants. Results suggested that in general, resident killer whales focused on Chinook salmon in spring and shifted to Coho and chum in early summer and to Coho salmon in late summer and fall. Field sampling indicated the AT1 transients focused predation on harbor seals and Dalls porpoise while the primary prey of Gulf of Alaska transients in the study area was Steller sea lions. Using a wind and solar powered remote hydrophone in outer Resurrection Bay/Kenai Fjords, we tracked winter movements and acoustically determined feeding behavior for specific pods of killer whales identified by pod specific vocal dialect. The hydrophone operated efficiently during the winter months when field operations were limited by weather and light.

KEY WORDS: acoustics, ARGOS, biopsy, *Exxon Valdez*, telemetry, Geographic Information System (GIS), feeding habits, foraging, genetics, killer whales, photo-identification, populations, *Orcinus orca*, Prince William Sound, Kenai Fjords, resident, transient, offshore.

PROJECT DATA: Identification data consists of frame-by-frame identifications of individual whales for all exposed films summarized by individuals present in each encounter. . Summary of all Daily Logs and Encounter Forms are stored in an ACCESS database at the North Gulf Oceanic Society office and Alaska Sea Life Center. All vessel tracklines and encounter tracklines and ARGOS tag ttracklines are stored as GIS shapefiles in an ARCView 9.3 sytem housed at the North Gulf Oceanic Society office and at Nunatechnolgies (Contact Allison Gaylord), both offices in Homer, Alaska. These data are available upon request and approval by the *Exxon Valdez* Oil Spill Trustee Council and the Executive Director, North Gulf Oceanic Society (NGOS), 3430 Main St Ste B1., Homer, Alaska 99603.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Killer whales were photographed in oil after the 1989 *Exxon Valdez* oil spill (the spill), but preliminary damage assessments did not definitively link mortalities to the spill and could not evaluate recovery. Photo-identification methods were used to monitor two killer whale populations five years prior to, and for 23 years following the spill. Here we report on the past three years of research, 2010-2012. One resident pod, AB pod, and one transient population, the AT1 group, suffered losses of 33% and 41%, respectively, in the year following the spill. Twenty two years after 1989, AB pod had not recovered to pre-spill numbers and two matrilines that left the pod following the spill travel as a separate pod (now AB25 pod) . Moreover, the rate of increase for AB pod was significantly less than that of other resident pods that did not decline at the time of the spill. The AT1 group, which lost 9 members following the spill, has continued to decline and is now listed as depleted under the Marine Mammal Protection Act. Although there may be other contributing factors, the loss of AT1 individuals, including reproductive-age females, accelerated the population's trajectory toward extinction. The synchronous losses of unprecedented numbers of killer whales from two ecologically and genetically separate groups and the absence of other obvious perturbations strengthens the link between the mortalities and *Exxon Valdez* oil spill

Resident (fish eating) killer whales *(Orcinus orca*) in the North Pacific have been the subject of long-term studies in several geographical regions. The current study examines population parameters in the southern Alaska resident population from 1984 to 2010 and develops a population model. The southern Alaska resident population ranges from southeastern Alaska through the Kodiak archipelago and contains over 700 individuals. We follow the life histories of 343 identifiable whales in 10 pods from two clans born before and during the study. Population parameters were comparable to those of the British Columbia northern resident population during the 1970s and 1980s, except that age of maturity was approximately one year earlier. The average annual rate of increase was slightly higher in Alaska (3.5%) than for the British Columbia northern residents (2.9%) and probably represents a population at r-max. Reasons for the high growth rate in Alaska could be a recovery following past anthropogenic mortalities, or more likely, a response to increasing salmon returns in recent decades, resulting in an increase in carrying capacity. The slow maturation and low rate of reproductive response makes these whales slow to recover from natural or anthropogenic catastrophes as exhibited by the case of AB pod.

We initially used thirteen years of encounter data (1984 - 1996) to examine killer whale distribution within Prince William Sound, Alaska (Matkin et al. 2003, Scheel et al. 2001). Previously, we intiated a program of ARGOS satellite based tagging and tracking for killer whales (Matkin et al. 2010). In the current study we continue the use of satellite tagging to provide greater resolution of range and important habitat. Tags were also used to re-locate pods for studies of behavior and feeding habits. Results support and expand on earlier findings. For example, AB pod appears to use areas outside Prince William Sound more extensively than initially thought, including the area northwest of Kayak Island and outside Hinchinbrook Entrance. AJ pod focuses on Montague Strait in fall/winter after spending much of the early summer offshore. Tagging results indicate each pod has unique home range, although there is substantial overlap. From long-term sighting data we suspect home range remains similar over decades, although areas of emphasis within that range may shift.

We have tagged two offshore type killer whales from a population that occasionally uses the northern Gulf of Alaska. Tracks show a pattern of movement into nearshore deepwater

areas, coupled with trips offshore to the continental shelf break. Tagged Gulf of Alaska (GOA) transient killer whales did not move off the continental shelf, but ranged widely in outside waters from offshore southeastern Alaska to Kodiak Island.

Feeding studies for resident killer whales using field observations techniques and sampling of prey have been a continuing effort since 1991 and observations of predation by transient killer whales extend back to the mid-1980s. Consistently, primary prey observed for AT1 transient killer whales have been harbor seals (nearshore foraging) and Dall's porpoise (offshore foraging). In our nearshore observations, Gulf of Alaska transients are observed to prey primarily on Steller sea lions.

From scale samples taken from fish kill sites, it appears resident killer whales prey primarily on Chinook salmon in spring. There is some geographic bias as most samples are from Resurrection Bay and not Prince William Sound. During early to mid summer whales transition to chum and then Coho salmon. Coho salmon appear the primary prey in the fall, although most samples from that time of year are from Prince William Sound. Chemical analysis of blubber biopsies (carbon and nitrogen stable isotopes, essential fatty acids, environmental contaminants) of skin and blubber biopsy samples from free-ranging resident killer whales was used to augment field observations and prey sampling. Results from blubber/skin chemistry supported the hypothesis of predation on Chinook salmon in the spring transitioning to chum and coho salmon in the later season. However there was a significant decline in N15 values over the years that suggests changing feeding habits over the years. Although there is also a slight decline in salmon N15 levels for most species, it is not large enough to explain the changes we are measuring in the whales. Blubber and skin chemistry also demonstrated the unique chemical signatures of different pods, and to some extent different matrilines, suggesting pod specific, and at times, matriline specific feeding habits.

INTRODUCTION

On March 24, 1989, the supertanker *Exxon Valdez* ran aground on Bligh Reef in northeastern PrinceWilliam Sound, Alaska, spilling 42 million liters of crude oil, the largest oil spill in U.S. history. Storms and currents eventually drove the oil through the western portion of the sound and south westward to Kodiak Island and the Alaska Peninsula, nearly 900 km from the spill site (Loughlin 1994). The unprecedented research effort following the *Exxon Valdez* oil spill (EVOS) resulted in a greater understanding of the long-term effects of large crude oil spills on species and on ecosystems (Loughlin1994, Rice et al. 1996, Peterson et al. 2003). However,detailed pre-spill censuses of free-ranging cetacean populations, such as those used in this study, are uncommon, and a lack of baseline data generally precludes the ability to assess damages caused by spills. Also, before the spill, little was known about the effects of oil on cetaceans because of the difficulty and ethical issues involved in conducting controlled experiments on whales in captivity and in finding carcasses, which often sink. From the few studies conducted prior to the spill, it was unclear whether free-ranging cetaceans would or could detect and/or avoid oil. Our work has used the long term evaluation of killer whale populations with annual photo census to map the effects of the Exxon Valdez oil spill on killer whales (Matkin et al. 2008).

In this report, we continue to document the impact of the spill on killer whales based on long-term population monitoring that has spanned thirty years. We examine the population trajectories of two groups of genetically and ecologically distinct killer whales in Prince William Sound, AB pod and the AT1 population, to track their recovery or lack thereof. In addition we examine the behavioral ecology and feeding habits of these killer whales, particular AB pod and other pods of the southern Alaska resident population. We use developing ARGOS satellite technology to map ranges and study feeding ecology of killer whales. This study uses tracking technology to continue an examination of home range, habitat use and delineate important habitat for killer whales in Prince William Sound and the northern Gulf of Alaska. We use field sampling of prey items/fish scales and recently developed techniques for chemical analysis of skin and blubber (Herman et al 2005, Krahn et al 2007) to uncover details of seasonal feeding habits of both resident and transient whales. This broad examination of killer whale population dynamics and ecology allows us not only to determine recovery trajectories and susceptibility of particular groups/populations to another oil spill or other perturbation, but to more closely understand the factors important in their long term success in the northern Gulf of Alaska.

OBJECTIVES

1. To provide photographic population monitoring of resident killer whale pods, including the non-recovered AB pod in order to determine status. Also monitor the depleted AT1 transient group which has lost over half its members since the spill.

2. To advance the design and attachment of satellite tags and use these tags to aid in detailing habitat use and to allow relocations of pods for food sampling studies.

3. Examine seasonal feeding habits, particularly of AB pod and other resident type pods, using molecular and observational methods. To determine specifics and timing and predation we will use observational methods based on collection of fish scales from kill sites and using stable isotope and lipid/fatty acid analysis to corroborate and/or extend field observations.

4. Extend our tracking data and feeding habits examination into the non-summer season (spring and fall) to develop a broader picture of killer whale feeding ecology

5. Suggest restoration alternatives from feeding habit and habitat use data. Also provide understanding of what pods/groups would be most susceptible to future spills or other perturbations within Prince William Sound and Kenai Fjords

6. To provide data for long term assessment of the role of transient and resident killer whales in the near-shore ecosystem; to monitor any changes in feeding habits in this area based on previously published dietary information (Saulitis et al 2000).

7. To continue to work to educate local, national and international groups and work with other EVOS projects. We will collaborate directly with the studies of humpback whale impact on herring and continue our annual program withtour boat operators/industry, as well as our volunteer sighting network.

FIELD METHODOLOGY

Fieldwork for the entire study period was completed from small vessels (less than 12 meters). The primary research vessel was the *R/V Natoa*, a 10.3 m inboard diesel powered vessel, capable of 14 knots and sleeping 4 researchers. Ocassionally other vessels were used opportunistically to conduct surveys. Data were recorded on daily vessel logs and killer whale encounter sheets and input into ACCESS and GIS databases.

Researchers attempted to maximize the number of contacts with each killer whale pod or group based on current and historical sighting information to insure sufficient photographs of each individual. Consequently, searches were centered in areas that had produced the most encounters with killer whales in the past, unless sighting or report information indicated changes in whale distribution. Whales were found visually, or by listening for killer whale calls with a directional hydrophone, or by responding to VHF radio calls from other vessel operators. Regular requests for recent killer whale sightings were made on hailing Channel 16 VHF. In Kenai Fjords, Channel 72 was also monitored. An encounter was defined as the successful detection, approach and taking of identification photographs. Accounts of whales from other mariners (generally by VHF radio) were termed "reports". Although reports were used to select areas to be searched, all identifications were made from photographs taken during encounters or provided on our website by other mariners. Photographs for individual identification were taken of the port side of each whale showing details of the dorsal fin and saddle patch. Digital images were taken at no less than 1/1000 sec. using a Nikon D-200 or D-700 camera and a 300mm f4.5 auto focus lens. When whales were encountered, researchers systematically moved from one subgroup (or individual) to the next keeping track of the whales photographed. If possible, individual whales were photographed several times during each encounter to insure an adequate identification photograph. Whales were followed until all whales were photographed or until weather and/or darkness made photography impractical.

A vessel log and chart of the vessel track were kept for each day the research vessel operated using a Garmin GPS 5 that was downloaded each evening. Tracklines were then converted to GIS shapefiles using Minnesota DNR Garmin 5.4 software. Similar logs were kept for all previous study years and stored as shapefiles with encounter tracks separated from overall vessel tracks and used to estimate effort (Scheel et al 2001). On daily logs, the elapsed time and distance traveled were independently recorded. Weather and sea state as it affected daily surveys was noted.

Specifics of each encounter with killer whales were recorded on standardized data forms originally developed in 1984. These forms were modified in 2005 to improve collection of data for GIS input and include satellite telemetry data Data recorded included date, time, duration, and location of the encounter. Rolls of film exposed/digital files created and the estimated number of whales photographed also were recorded. Specific group and individual behaviors (i.e. feeding, resting, traveling, socializing, milling) were recorded by time and location. Directed observations of feeding behavior and identification and collection of killer whale prey were made when possible. Only events that provided positive evidence of a kill were categorized as predation. Evidence included prey observed in the mouth of the whale, bits of hair or other parts, or oil slicks with bits of blubber. Incidents of harassment of potential marine mammal prey were also recorded. This included instances where evidence was not observed but a kill was suspected or when potential prey exhibited fright or flight response or other strong behavioral reaction to killer whales. Harassment was demonstrated by behaviors such as flipper slapping and lob tailing by humpback whales and fleeing behavior by small cetaceans, pinnepeds or mustelids. When predation on fish was observed, scales from the site of fish kills were collected and later identified by species. Scales were individually mounted and identifications were made by the fish scale and aging laboratory at the Pacific Biological Station, Nanaimo, B.C., Canada. Fish scales and marine mammal remains were collected with a fine mesh net on an extendible handle (4 m. maximum extension). The pod or group of killer whales and specific individuals present during kill or harassment incidents were recorded on the encounter data sheets.

Biopsy samples were collected using a pneumatic rifle and custom-designed biopsy darts (Barrett-Lennard, et. al. 1996). A small dart was fired from a specially outfitted rifle powered by air pressure from a .22 caliber blank cartridge. The setup is similar to that used to deliver tranquilizing drugs to terrestrial mammals in wildlife research. A lightweight plastic and aluminum dart (approx. 10cm long by 1.2cm dia.) was fitted with a beveled tubular sterile stainless steel tip that took a small core of skin and blubber (approximately 1.6cm long and 0.5cm dia.). The sterilized dart was fired from a range of 16-20m. The dart struck the animal in the upper back, excised a small tissue sample, bounced clear of the whale, and floated with sample contained until retrieved with long handled net.

From the biopsy samples, the epidermis, which is heavily pigmented, was separated aseptically from the other layers with a scalpel soon after retrieval. The dermal sample used for genetics and stable isotope analysis, was stored at about 4 deg C. in a sterile 1 ml cryovial. The dermis and hypodermis were made up primarily of collagen and lipid, respectively, and were frozen at -20C in autoclaved, solvent-washed vials for contaminant analysis. It is this frozen portion that was used for stable isotope/lipid-fatty acid analysis and contaminant analysis completed at Northwest Fisheries Science Center, Environmental Contaminant Laboratory.

ARGOS monitored, location only Spot 5 satellite tags or Mark10 time/depth/location tags produced by Wildlife Computers, Seattle, WA were attached to the dorsal fin of killer whales to track longer term movements, determine range and important habitat, map time and depth of dives to determine behaviors in particular locations. A small barbed dart protruding 5 cm into the dorsal fin of the adult male killer whale was implanted as part of the tag to anchor it in the connective tissue. Attachments were made from distances of approximately 8-15 meters by crossbow using a. Barnett Wildcat 170 pound bow or similar.

Acoustic recordings were made using an Offshore Acoustics omnidirectional hydrophone lowered over the side of the vessel in combination with Maranz professional digital recorder which created .wav files that were downloaded after each encounter. The hydrophone had a flat frequency response to signals ranging from 100Hz to 25 kHz. The tape recorder showed a flat response to signals up to 15 kHz.

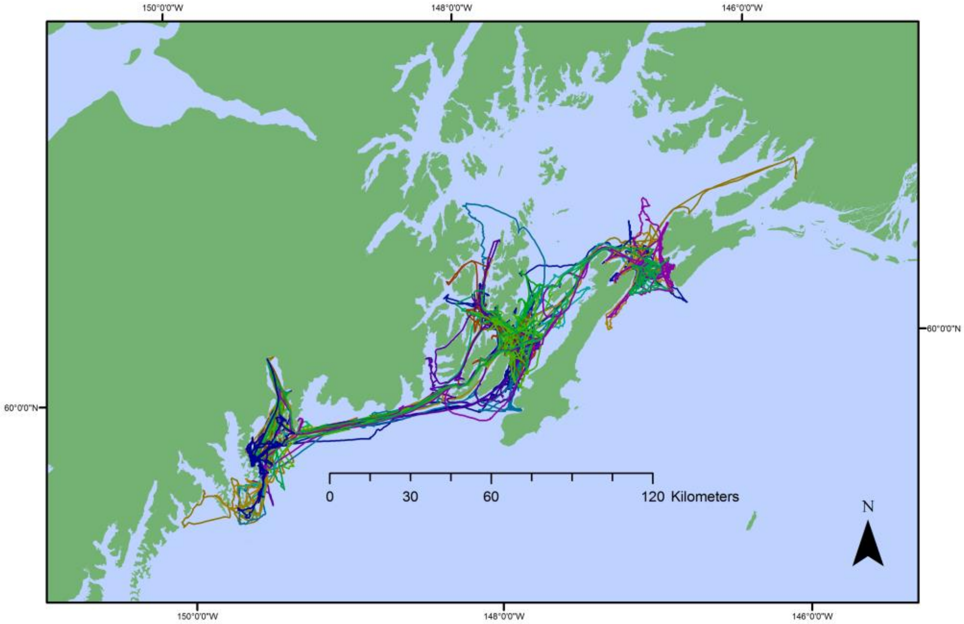
SUMMARY OF EFFORT AND ENCOUNTERS

During the period of this study, 2010-12, the R.V. *Natoa* spent a total of 186 days on the water searching for killer whales along 14,889 km of trackline for an average search distance of 80 km day. Killer whales were encountered on 135 occasions and followed over a distance of 3208 km, approximately 24 km per encounter (Tables 1,2 , Figures 1,2)

Table 1. Summary of Effort

Year	# Vessel days	Distance (km)
2010	64	4941
2011	68	5289
2012	54	4659
TOTAL	**186**	**14889**

Figure 1. Trackline of vessel R.V. Natoa 2010-12

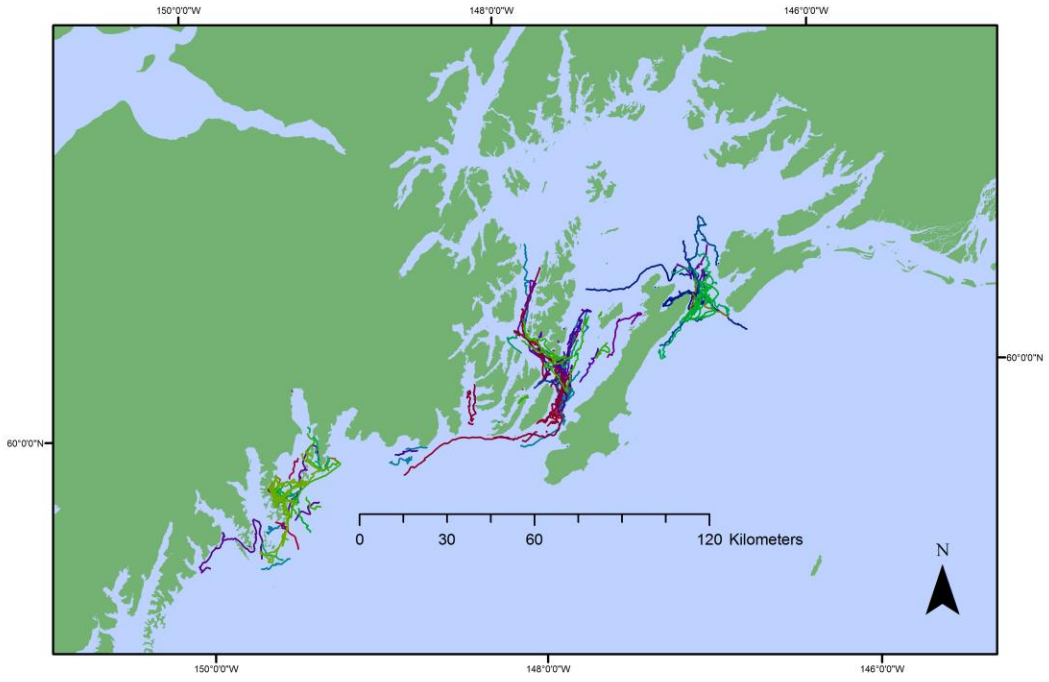


© North Gulf Oceanic Society. Map compiled on April ##, 2004.

Table 2. Summary of encounters

Year	# Encounters	Distance with whales (km)
2010	49	1350
2011	51	1090
2012	35	763
TOTAL	**135**	**3208**

Figure 2. Tracklines of killer whale encounters 2003-2009



© North Gulf Oceanic Society. Map compiled on April ##, 2004.

POPULATION STATUS

Introduction

Population monitoring of killer whales in Prince William Sound and adjacent waters has occurred annually since 1984. The existence of pre-spill data made it possible to determine that resident AB pod and the AT1 transient group declined dramatically following the Exxon Valdez oil spill (Matkin et al. 2008). This project continued using photo-identification to monitor changes in resident killer whale pods and monitor recovery of AB pod and the AT1 transient group. Recently a manuscript is in review for publication detailing the population dynamics of resident killer whales in the northern Gulf of Alaska from 1984-2005 (Matkin et al. in press)

Methods

Digital images were examined using PhotoMmechanic software (CameraBits Inc.) on an Apple computer with a 24 inch high resolution LCD screen. Identifiable individuals in each image were recorded. When identifications were not certain, they were not included in the analysis. Unusual wounds or other injuries were noted.

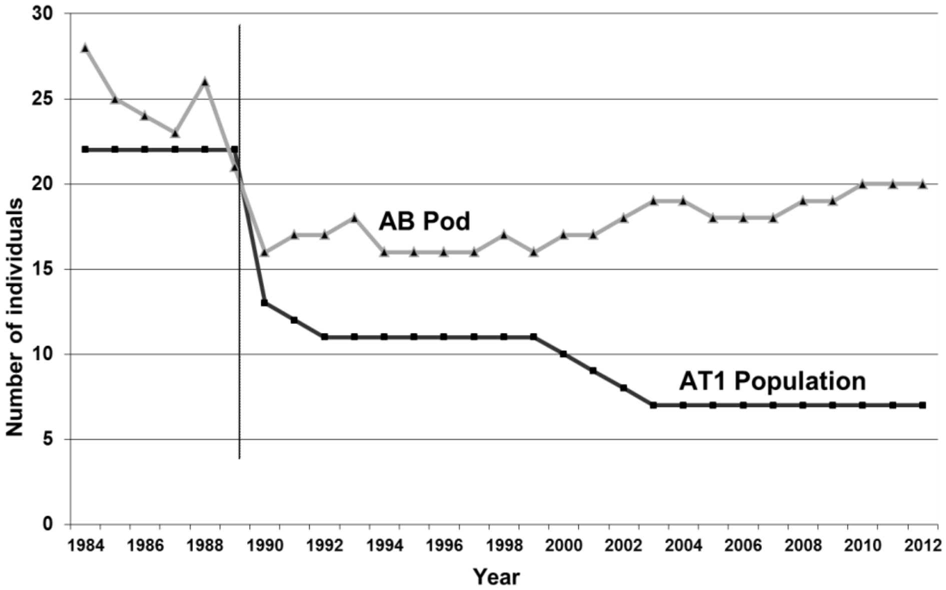
The alphanumeric code used to label each individual was based on Leatherwood, et. al. (1984) and Heise, et. al. (1992) and has been continued in the catalogue of southern Alaska killer whales (Matkin, et. al. 1999c). More recently we have posted an updated catalogue of individuals on our website (whalesalaska.org. The first character in the code is "A" to designate Alaska, followed by a letter (A-Z) indicating the individual's pod. Individuals within the pod receive sequential numbers. For example, AB3 is the third whale designated in AB pod. New calves were identified and labeled with the next available number.

Individual identifications from each roll of film were compiled on a frame by frame basis. Individuals present in each encounter were tabulated and recorded in an ongoing database. From this photographic database, the actual number of whales identified and pods of whales present for each encounter was determined and included with each encounter entered in the ACCESS database tabulating all surveys and resulting encounters.

Status of AB pod and the AT1 population

The history of individuals within AB pod before during and after the spill is detailed in Matkin et al (2008) and Matkin *et al*. (2010) and will not be detailed here. The matrilines that make up AB pod today had 26 individuals prior to the spill, declined to 16 following the spill, and now number 20 individuals. AB pod has still unrecovered from the spill. However, the structure of AB pod also changed in the years following the oil spill. A sub-pod (named for the matriarch AB25) consisting of 10 individuals in 1988, began to travel separately from the rest of AB pod following the spill after losing 3 of its members, including a reproductive female, a juvenile, and a calf. Since 1994, the sub-pod has traveled consistently with AJ Pod and as of 2010 it officially designated as a separate pod, although it was essentially functioning as a separate pod since 1994. Although pods may split along matrilineal lines to form new pods, no sub-pod had been previously documented to join and travel consistently with another pod(AJ pod) on such a consistent basis. Despite traveling with AJ pod for over a decade, the AB25 sub-pod still uses calls unique to the AB Pod dialect (Yurk *et al*. 2002, Yurk 2005). Interestingly, AB25 pod has recovered at a rate comparable to the growth of the population and now numbers 18 individuals. (Note: For all years, the total number of whales in AB pod in Figure 3 does not include whales in AB25 pod.)

Figure 3. Number of whales in AB pod and in the AT1 population 1984-2012.



Although AB pod declined following the spill, none of the other pods that we regularly track have declined. In fact, they have increased at an average rate of about 3% per year (Matkin *et al*. in press). In Table 3 we list the current numbers of individuals in the pods for which we have recent records and for individuals observed in the past eight years, but not observed frequently enough to assign to pods.

Table 3. Southern Alaska residents: number of whales in pods and unassigned to pods and the date of their last complete documentation. Unassigned whales were sighted in the past 8 years. Regularly monitored resident pods in **bold.**

Pod (may be a single matriline)	**Number of whales**	**Year last completely documented**
AA1 and AA30	32	2010
AB	**20**	**2012**
AB25	**19**	**2012**
AD05	**22**	**2012**
AD16	**9**	**2012**
AE	**17**	**2012**
AF5	**46**	**2010**
AF22	**33**	**2010**
AG	**42**	**2010**
AH01 and AH10	21	2010
AI	**8**	**2012**
AJ	**57**	**2012**
AK	**19**	**2012**
AL	23	2010
AN10	**36**	**2012**

AN20	30	AN29’s in 2007, AN15’s AN69’s and AN 32’s in 2005 and AN23’s in 2002
AS2	21	2012
AS30	19	2012
AW	27+	2010
AX01	29	2008
AX27	26	2010
AX32	18	2010
AX40	16	2010
AX48	23	2009
AY	**21**	**2012**
Unassigned to pods	220	All seen since 2004
TOTAL SEA to KODIAK	**751**	

The AT1 group remains at seven individuals. There have been no births or deaths in the group during the period of the current study (Table 4)

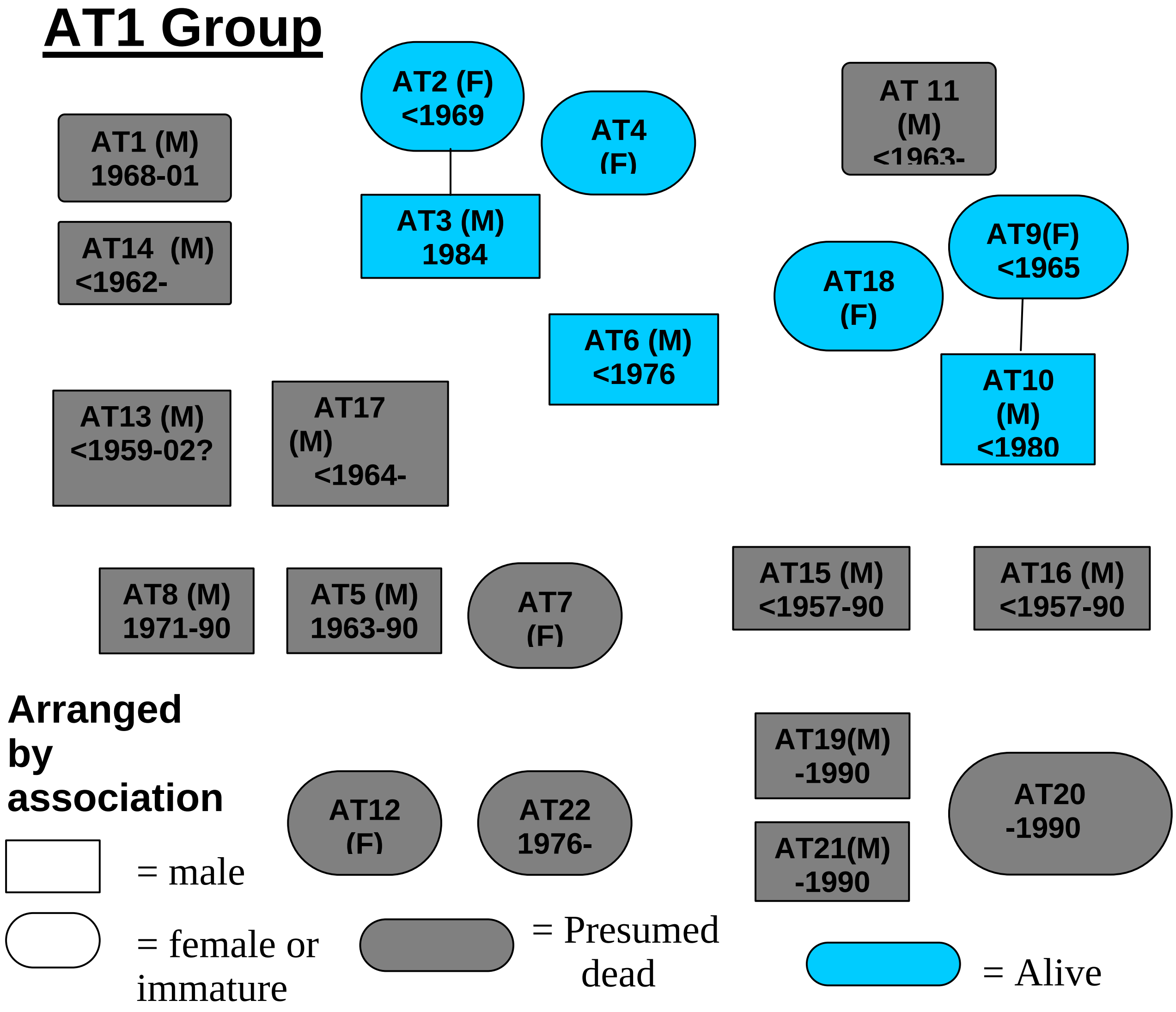
Table 4. Sighting histories for all AT1 transient whales for years with effort greater than 40 days.

YEAR	*AT1*	**AT2**	**AT3**	**AT4**	*AT5*	**AT6**	*AT7*	*AT8*	**AT9**	**AT10**	*AT11*	*AT12*	**AT13**	**AT14**	*AT15*	*AT16*	**AT17**	**AT18**	*AT19*	*AT20*	*AT21*	*AT22*
84	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
85	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
86	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X
88	X	X	X	X				X	X	X	X	X	X	X	X		X	X		X	X	X
89	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
90	X	X	X	X	-	X	-	-	X	X	X	X	X	X	-	-	X	X	O	-	-	-
91	X	X	X	X	-	X	-	-	X	X	-	X		X	-	-		X		-	-	-
92	X	X	X	X	-	X	-	-	X	X	-	-	X	X	-	-	X	X		-	-	-
93		X	X	X	-	X	-	-	X	X	-	-			-	-	X	X		-	-	-
94	X				-		-	-	X	X	-	-		X	-	-		X		-	-	-
95	X	X	X	X	-	X	-	-	X	X	-	-	X	X	-	-	X	X		-	-	-
96	X	X	X	X	-	X	-	-	X	X	-	-		X	-	-		X		-	-	-
97	X	X	X	X	-		-	-			-	-	X		-	-	X			-	-	-
98	X				-	X	-	-	X	X	-	-	X	X	-	-	X	X		-	-	-
99		X	X	X	-	X	-	-	X	X	-	-			-	-		X		-	-	-
2000	O				-		-	-			-	-	X	X	-	-	X			-	-	-
2001		X	X	X	-	X	-	-	X		-	-	X		-	-	X	X		-	-	-
2002		X	X	X	-		-	-	-		-	-	O?	X	-	-	-			-	-	-
2003		X	X	X	-	X	-	-	X	X	-	-	-	O?	-	-	-	X		-	-	-
2004		X	X	X	-	X	-	-	X	X	-	-	-	-	-	-	-	X		-	-	-
2005		X	X	X	-	X	-	-	X	X	-	-	-	-	-	-	-	X		-	-	-
2006		X	X	X	-	X	-	-	X	X	-	-	-	-	-	-	-	X		-	-	-
2007		X	X	X	-	X	-	-	X	X	-	-	-	-	-	-	-	X		-	-	-
2008		X	X	X	-	X	-	-	X	X	-	-	-	-	-	-	-	X		-	-	-
2009		X	X	X	-	X	-	-	X	X	-	-	-	-	-	-	-	X		-	-	-
2010		X	X	X	-	X	-	-	X	X	-	-	-	-	-	-	-	X		-	-	-
2011		X	X	X	-	X	-	-	X	X	-	-	-	-	-	-	-	X		-	-	-
2012		X	X	X	-	X	-	-	X	X	-	-	-	-	-	-	-	X		-	-	-

X PRESENT 0
DEAD
- PRESUMED DEAD

X whale present
O whale dead (stranded) (probable identify of AT1 carcass denoted by: **O?)**
- whale missing presumed dead

Figure 4. Diagramatic representation of the AT1 transient population as it appeared in 1988 prior to the *Exxon Valdez* oil spill. Individuals are grouped by their associations, animals in dark grey are missing and presumed dead. Males are in square boxes.



Discussion

Based on initial observations in the first few years following the EVOS, Dahlheim & Matkin (1994) suggested that increased mortality in the AB pod may have been attributable to the spill. Annual monitoring over the 16 yr following 1989 strengthened the case that oil was responsible for the deaths observed in AB pod as well as AT1 group in the year following the spill. The concurrent mortalities in the 2 ecologically distinct groups, anomalous deaths, lack of recovery in both groups and other indirect evidence (Matkin et al 2008) support this contention.

The results of our work underscore 3 key aspects of killer whale behavior and ecology that leave them highly vulnerable to natural or anthropogenic disasters such as oil spills. First, free-ranging killer whales do not or cannot detect or avoid crude oil sheens at the water's surface and are thus susceptible to inhalation of vapors and/or oil, skin contact, and, especially in the case of mammal-eating transients, to ingestion. Second, it is clear that resident killer whale pods, even under optimal conditions, may take decades to recover from the impacts of an oil spill or other disturbance, particularly if reproductive females and/or juvenile females are lost. Third, in a small, isolated and threatened population like the AT1 transients, a major environmental perturbation can greatly hasten the decline toward extinction. AB pod has still not recovered from the spill over two decades later and AB25 pod has apparently permanently split off from the original AB pod. The outlook for the AT1 group is bleak and the group will likely go extinct within the next several decades.

Given the small numbers of individuals in these apex predator populations, their potential role in structuring ecological communities, and their cultural value to coastal residents, indigenous populations and visitors from around the world, the deaths in AB pod and the impending extinction of the AT1 group represent losses of and damage to resources of international ecological and cultural significance.

POPULATION DYNAMICS OF SOUTHERN ALASKA RESIDENTS

Introduction

We used historic photoidentification data plus data collected in this project through 2010 to examine population dynamics of southern Alaska resident killer whales (excluding AB pod, see Matkin et al 2008). We modified methodologies originally developed by Olesiuk et al. (2005) to describe life histories, develop population parameters, and construct a population model for southern Alaskan resident killer whales. The study was based on systematic long-term photo-identification surveys conducted annually from 1984 to 2010. Here, we detail the parameters of the southern Alaskan resident killer whale population and develop a model to describe a population increasing at a rate approaching r-max but vulnerable to changes in environment or prey populations.

Methods

In our analyses the southern Alaska residents, which range from southern southeastern Alaska to southern Kodiak island, these whales were considered as a single and separate population consisting of two sympatric, freely interbreeding acoustic clans that were separable by mtDNA haplotypes and by acoustic repertoire (Yurk et al. 2002). Within our study population, genetic evidence indicates successful breeding occurs primarily between individuals from the more distantly related pods and occurs between clans (Barrett-Lennard 2000).

Our analysis focuses on a subset of pods from both acoustic clans that are most likely to be repeatedly encountered on an annual basis and whose size ranges from 6 to 42 individuals. Our approach is supported by data presented in Olesiuk et al. (1990) which indicated that subsets of a population reflect overall population characteristics. Our study required an annual census that was initiated in 1984 and continued through 2010, though effort declined following 2005 and some pods were not seen in all of the last five years. We annually attempted to photographically identify each individual whale in the 10 pods that composed our sample. We did not include the well-described AB pod in our analysis due to the anomalous mortalities following the Exxon Valdez oil spill reported elsewhere (Matkin et al. 2008). Data collection procedures followed those described by Bigg et al. (1990) and Matkin et al. (1999b). Although some fieldwork occurred in all months of the year, in all years the vast majority of effort and encounters with killer whales occurred from early May through October. Our data are considered annual surveys of the population that occurred during the spring, summer, and fall period.

Age Estimation. Following the approach developed by Olesiuk et al. (1990) and further developed by Olesiuk et al. (2005) for British Columbia and Washington State resident killer whales, we used genealogies developed for southern Alaska resident killer whales (Matkin et al. 1999a,b) to establish ages. Killer whales used in this analysis were aged using the following criteria:

1) Animals born during or just prior to the study were aged on the basis of year first observed, which in most cases corresponded with year they were born (n=187). Growth is rapid the first few years, facilitating age estimation up to about 3 years from size (Olesiuk et al. 1990, 2005). Animals estimated from their size to be ≤ 3 years old when first seen were assumed to be known-age (n=42).
2) Most older juvenile animals born prior to the study were aged based on the year they matured. However, for a few animals that died prior to maturation, birth year was estimated from size. Nine animals were aged in this group with a possible aging error of ±3 years

3) Females that were juvenile-sized when first seen but larger than average three-year-old whales were aged by subtracting mean age of first recruitment (13 years), as estimated from known-age animals from the year they were seen with their first calf . Twenty-one females were aged using this calculation with a possible aging error of ±2 years

4) Forty females that were adult-sized when first seen were aged by subtracting mean age of first birth (13 years) from year of birth of their oldest known calf We did not use a correction factor as in Olesiuk et al. (2005) to compensate for older calves that may have died before the beginning of the study (see Discussion)
5) Males that were juveniles when first seen but too large to estimate based on size were aged by subtracting mean age of onset of sexual maturity (13) determined in this study (below). There were 22 whales aged in this manner with a potential error of -3 to +2 years.

6) Males that were sexually but not physically mature when first seen were aged by subtracting mean age of onset of physical maturity (18) determined in this study (below). Six whales were aged in this manner with a potential error of ±3 years.

7) Males that were physically mature when first seen were aged on the basis of the year they were first seen by subtracting the average age of onset of physical maturity (18 years) These were considered minimum ages. A total of 16 whales were aged in this manner.

Age at Maturation and Reproductive Rates. We estimated the mean age at first reproduction using the method developed by DeMaster (1978) based on the proportion of females and males mature at each age. For females, we defined maturation as the age at which they began contributing to recruitment in the population, which was the age at which we observed their first calf. Since most calves were born prior to the annual census, which was not initiated until early May, we were essentially censusing the recruitment of calves to one to 6 months of age, not birth rate. No female less than 11 years old was observed with a calf, so only females seen each year from age 11 up to the recruitment of their first calf were included in the analysis. Known-age females excluded from calculations of mean age at first reproduction due to a missing observation were re-included in the analysis of other population parameters. .

Olesiuk et al. (1990) showed that the male fin of northern resident killer whales could be statistically distinguished from that of females when it reached a height-to-width ratio (HWR) of 1.4, which appears to occur during adolescence and concurrently with development of other secondary sexual characteristics such as enlargement of pectoral fins and the downturn of fluke tips. For males, we calculated maturation statistics for the age at which HWR reached this threshold, and for the age at which the dorsal fin reached its full height and males were judged to be completely mature.

In calculating variance, DeMaster’s (1978) method assumes that observations at each age are independent, which cannot be justified in longitudinal samples such as those obtained here (or by Olesiuk et al. 1990, 2005). We therefore used bootstrap sampling (Efron 1982) of individual whale sighting histories to estimate variances and confidence intervals around mean age of sexual maturity. A bias exists in this estimator as applied by Olesiuk et al. (1990, 2005) in that the sex of most juveniles is not determined until sexual maturity is reached, and some whales disappeared before their sex was known. This introduces a negative bias due to exclusion of some immature animals and overestimation of the proportion mature at a given age. We present estimates without correction for this bias in order to compare to results of Olesiuk et al. (2005), as well as estimates in which we include juveniles of unknown sex in our bootstrap sampling with an additional bootstrap assignment of sex from an even sex distribution to exclude approximately half of the unknown sample. This method still retains some bias due to the small difference in age at maturity of the two sexes, which creates a slight underestimate of age at maturity in females and an overestimate for males. This correction was not needed for male age at full maturity because of the long physical maturation period for males as evidenced by the gradual growth of the dorsal fin. The sex was known for all males used in that calculation well before the youngest age for full maturity had been reached. In all cases, the bootstrap median was closer to the direct calculation of mean age of maturity (DeMaster 1978) than the bootstrap mean, and we report only the median estimate.

We established one measure of female fecundity by estimating the intervals between successive calves and determining the probability of calving in a given year.

$$FEC = 1 / CI.$$

Where FEC is the proportion of females giving birth each year and CI is the interval between successive calves. For instance, if females gave birth once every five years, the probability of giving birth in any given year is 0.2. We used bootstrap sampling (Efron 1982) of individual calving records to determine the median and confidence interval.

Age-specific fecundity rates of females FECf(x) was defined as the proportion of females aged x giving birth to viable calves each year:

$$FECf(x) = NCf(x) / Nf(x)$$

where NCf(x) denotes the number of calves of either sex born to females aged x, and Nf(x) the total number of females aged x. We used all females, but inclusion of females aged by the birth of their first calf would have caused a spurious spike of births at age 13. We therefore distributed those births normally around the most unbiased estimated age of first successful reproduction (AFR) as calculated above for purposes of smoothing the age-specific rates around the AFR. We used a second order polynomial logit model in the R statistical package glm (R Development Core Team 2010) to smooth the age-specific reproductive curve beginning at age 11, the earliest observed age for a first surviving calf.

Mortality and Survival Rates. Mortality and survival rates were estimated by monitoring individuals over time. In 36 years of monitoring resident whales in British Columbia and Washington, and 26 years in Alaska, there is no evidence of dispersal from matrilines (Bigg et al. 1990, Matkin et al. 1999a, Olesiuk et al. 2005, Matkin et al. 2008). Animals that disappeared were thus assumed to have died. Rates were estimated as

$$MR(x) = 1-SR(x) = D(x) / N(x)$$

where MR(x) represents the annual mortality rate or probability of dying in the next year at age x, SR(x) the annual survival rate or probability of surviving the next year at age x, D(x) the number of animals aged x that died before reaching age x+1, and N(x) the number of animals in the study population aged x that were monitored to age x+1. Where year of death was uncertain, we amortized the death over the 2-3 years of uncertainty in the manner of Olesiuk et al. (2005). Because mortality and survival often changes most rapidly early in life, and to take advantage of larger samples sizes for younger age groups, we pooled data into progressively wider age categories: 0.5-1.5 years, 1.5-2.5 years, 3.5-5.5 years, 6.5-9.5 years, and 10.5-14.5 years, which are the same categories used by Olesiuk et al. (1990, 2005). New calves were assumed to be approximately 0.5 years of age since most births occur in winter and recruited calves are not observed until months later. Animals that were not seen as calves, but later aged by their size or apparent maturity, were excluded from analyses in the first year of sighting because of the positive bias created in survival to that age. The effect of uncertainty in the ages of larger juveniles was negligible due to the pooling of the older categories. Standard errors and confidence intervals of the estimates were calculated by bootstrap sampling of individuals (Efron 1982). To account for decreasing sample sizes and increasing imprecision in age estimates with age, we pooled observations in 5 or 10 year increments for the oldest age classes. Since we do not know the maximum ages with certainty, the older classes may encompass a larger range than indicated.

Population Model The age-specific survival and fecundity rates were used to develop life tables and a population model. Estimated age-specific survival and birth rates were applied to the starting population age/sex structure in 1984 and projected forward until a constant growth rate and stable structure was reached. This was verified by life table analysis using Lotka’s fundamental equation (Lotka 1907,Olesiuk et al. 2005). The survival and birth schedules for the northern resident killer whale population studied by Olesiuk et al. (2005) was also modeled, duplicating the model described by those authors but allowing direct comparison of our results without ambiguity that might arise from rounding-off and other discrepancies in demographic estimates. Since we were uncertain of maximum ages in our study, we allowed the same maximum ages (age 90 for females and age 70 for males) in our model as did Olesiuk et al. (2005). In practice, truncation at age 60 for females and age 40 for males had negligible effect on age structure. Applying the population model to the starting age/sex structure in the population allowed a comparison of population growth and structure which should have occurred if vital rates were constant as estimated over the study to those actually observed.

Our modeling efforts were, in part, intended to confirm the validity of our vital rate estimates, but also to explore the implications of subtle differences that might be seen in between our observed and modeled growth and age structure, and between our results and those of Olesiuk et al. (2005) for the northern resident killer whales of British Columbia. We used the survival data in Table 2 and the polynomial regression of calving rates in Figure 4 to estimate population growth and age/sex structure from the observed population size and age/sex composition in 1984. We used the most precise estimates of survival and calving rates available from Olesiuk et al. (2005; Tables 7&8 for survival and Table 10 for fecundity) for the northern resident killer whale population during its period of exponential growth (1973-1996) to recreate their life table model and standardize comparisons between the two populations. The "post-reproductive" class in both studies is somewhat problematic because the reproductive criterion (no calves in last 10 years) used by Olesiuk et al. (1990, 2005) is of limited utility at the end of a study lasting only 20 or 30 years, and because the gradual decline in reproduction with age (Figure 4 and Olesiuk et al. 2005: Figure 15) makes such determination ambiguous. We have used the "average age of senescence" of 40.5 years (Olesiuk et al. 2005) as the youngest age of "post-reproductive" females as a general cut-off between reproductive and post-reproductive classes in our analysis.

Results

We have identified over 700 whales in the southern Alaska resident population during this study. However, we were able to regularly locate and re-identify only the 342 of these whales, which composed 10 pods. Of these, 131-237 were alive at any one time. There were four pods from the AD clan (AD05,AD16,AE, and AK) and six from the AB clan(AF05,AF22,AG,AI, AJ, and AN10). We excluded two other pods (AB and AB25) that experienced atypical mortalities following the Exxon Valdez oil spill (Matkin et al. 2008). These 10 study pods and the number of whales in each are presented in Table 1.

Table 5. Recruitment, mortalities, and total number of whales by pod, 1984-2010, with exceptions of AF05 and AF22 (last counted in 2005), and AG, (last counted in 2008).

POD	**Total 1984**	**Total Recruited**	**Total Died**	**Total**
AD05	*13*	*16*	*10*	*19*
AD16	*6*	*8*	*6*	*8*
AE	*13*	*13*	*9*	*17*
AF05	*12*	*32*	*6*	*38*
AF22	*12*	*25*	*9*	*28*
AG	15	30	6	39
AI	6	4	3	7
AJ	25	42	12	55
AK	7	15	7	15
AN10	12	29	10	31
TOTAL	**121**	**182**	**78**	**264**

The number of whales in 10 pods that were seen from 1984 to2005 increased from 121 whales to 240 at a mean annual growth rate of 3.4%. The seven pods seen from 1984 to 2010 increased from 82 to 152 at a mean annual rate of 2.6% (Figure 1). Because 3 of the pods (AF05,AF22,AG) in southeastern Alaska (Matkin et al. 1997, 1999a) were usually out of our study area, they could not be tracked consistently between 2005 and 2010 and our examination of population characteristics is based on the 1984-2005 data from all pods. The difference in growth rates (Figure 1) is at least partly explained by a female-skewed adult sex ratio in these 3 large pods that were not observed consistently in the final years. It is likely that the inter-pod variance in growth rate also is due to variance in adult reproductive output based on individual life histories (Brault and Caswell 1993).

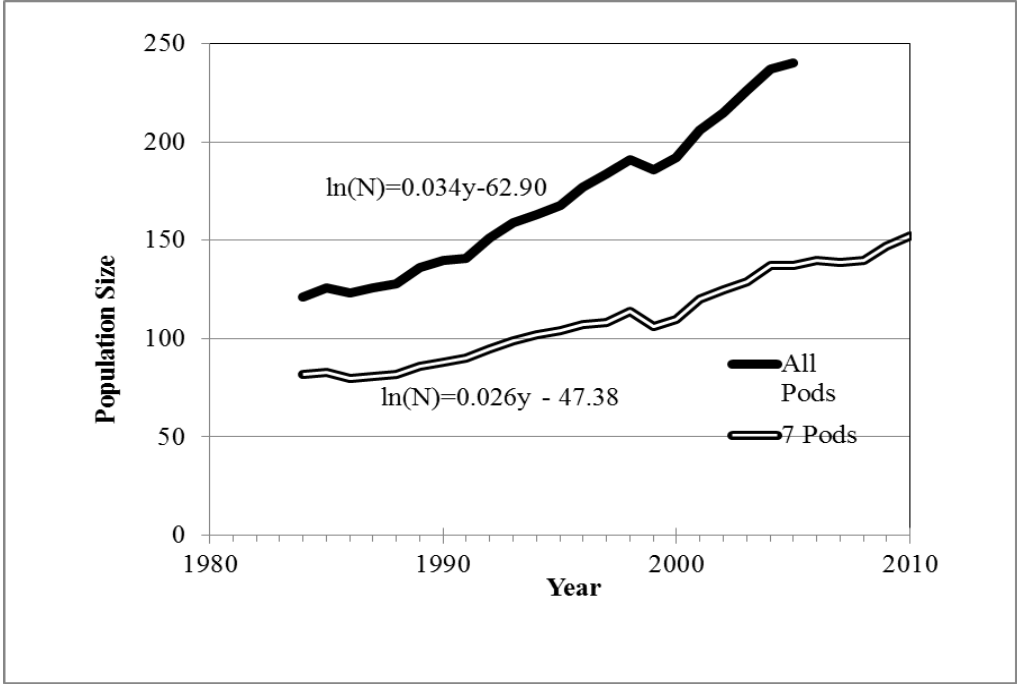


Figure 5. Population trend for 10 pods of southern Alaska resident killer whales from 1984 to 2005 (top) and for 7 of those pods that were monitored through 2010.

Life History Parameters

Age at Maturation and Reproductive Rates Thirty-eight known-age females >10 years of age were considered for analysis of AFR, but seven were excluded because of gaps in their sighting history in the period when they were 11-15 years of age, the age range at which first calves were observed among females without resighting gaps. Excluding the 9 juveniles of unknown sex led to a calculated mean (after DeMaster 1978) AFR of 12.8 (SE = 0.15), and a bootstrap median AFR of 13.1 (bootstrap 95% CI=12.6-13.7, SE = 1.40). Median AFR including 9 unsexed juveniles was 13.3 (bootstrap 95% CI=12.7-13.8, SE = 1.18; Figure 2). Among known-age females observed with a first calf, the modal AFR was 12 years, indicating a positive skew in the distribution of AFR.

At an age range of 10-16 years, the fins of a total of 44 known-aged males were estimated to have attained a height to width ratio (*HWR)* of 1.4, which is the ratio that marked the onset of sexual maturation developed by Olesiuk et al. (1990) in British Columbia. The estimated mean

age at onset of sexual maturation (after DeMaster 1978), excluding juveniles of unknown sex, was 12.4 (SE = 0.14). The bootstrap median age at onset of sexual maturation of that sample was 12.4 years (bootstrap 95% CI=12.0-12.9, SE = 1.12); for the entire sample (n=54) the median was 12.5 years (bootstrap 95% CI 12.1-13.0, SE = 1.01 Figure 2).
At tje age range of 15 to21 years, 22 known-age males reached physical maturity during the study as indicated by a fully developed dorsal fin. Direct calculation of the average age of full maturity (after DeMaster 1978) from 36 known-age males ≥15 years of age produced an estimate of 18.3 years (SE = 0.19). Bootstrap median age of full maturity was 18.3 (bootstrap 95% CI=17.6-19.0, SE = 1.45, Figure 2).

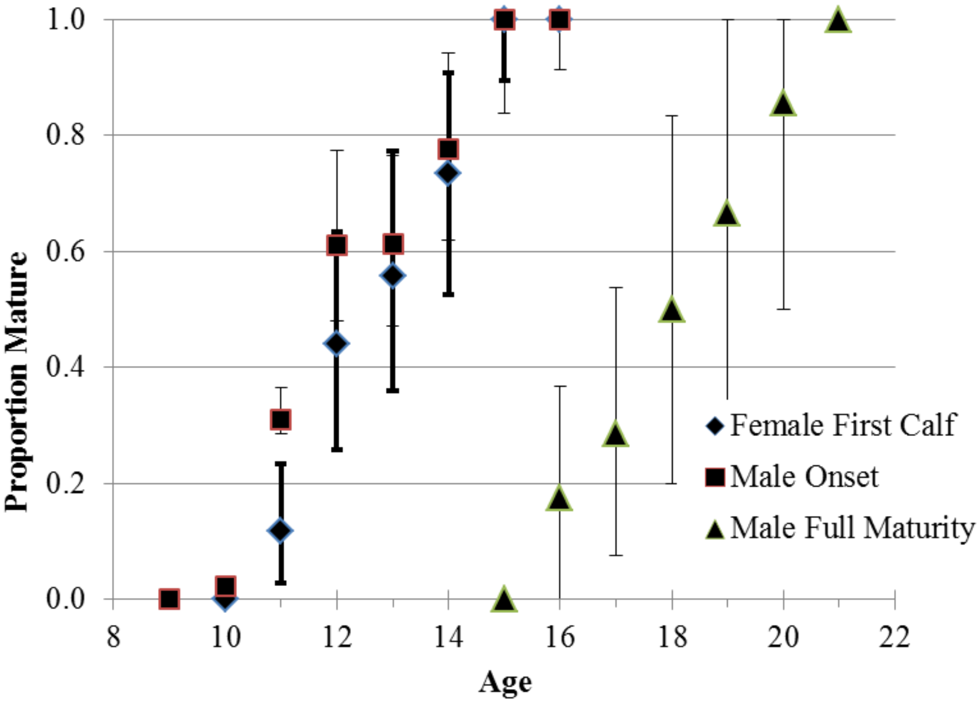


Figure 6. Age of sexual maturity (first calf) in known-age females and males (onset of dorsal fin growth) and male full maturity as judged by dorsal fin development for southern Alaska resident killer whales.

We documented the intervals between births of 198 viable calves of 59 females for which at least two births were recorded (139 intervals). Calves were produced at intervals of 2-14 years (Figure 3), but most were separated by 3-7 years (mean 4.9, bootstrap median = 4.8, SE 0.63, 95%CI = 4.4-5.2). The bootstrap median annual calving rate (FEC) among these reproductive females was 0.21 (SE = 0.01, 95%CI = 0.19-0.23). There was little evidence that calving intervals changed over the period of the study (regression slope = 0.05, P = 0.15). Mean calving intervals increased significantly (regression slope = 0.22, P << 0.01) with age of the mother, from 4.3 years at age 20 to about 6.5 years by age 40. The number of calves produced by each individual per year declined with age (Figure 4) due to the longer calving intervals and apparent onset of senescence. This pattern was also observed in the northern resident killer whale population in

British Columbia (Olesiuk et al. 2005) and in the short-finned pilot whale (*Globicephala macrorhynchus*) (Marsh and Kasuya 1986).

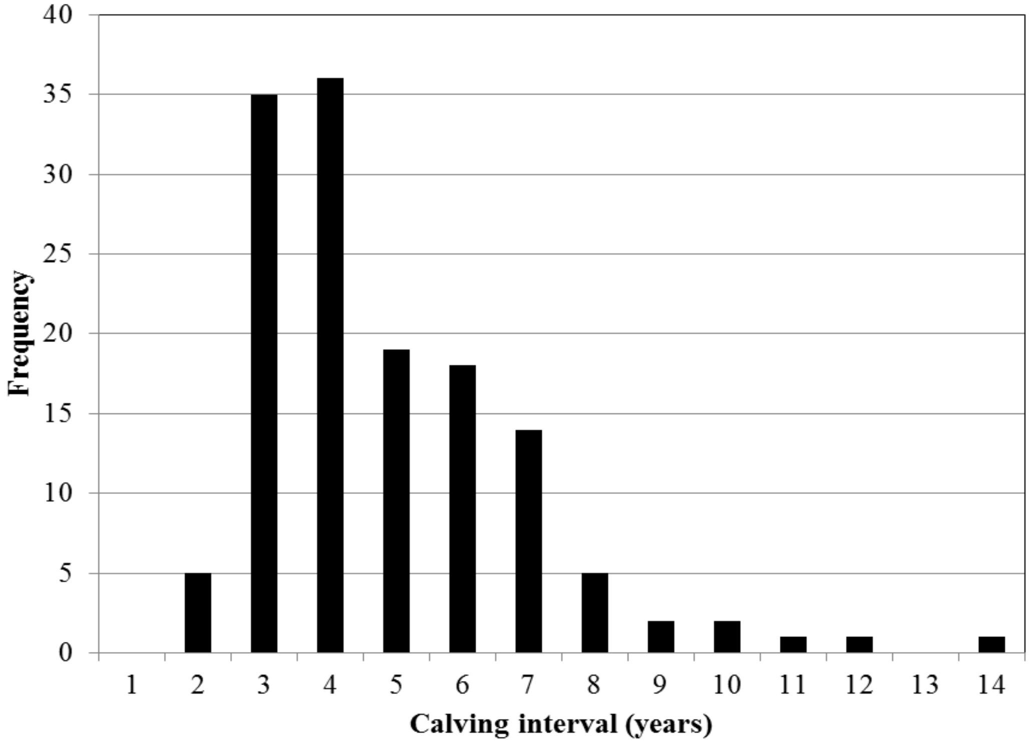


Figure 7. Frequency distribution of calving intervals for southern Alaska resident killer whales.

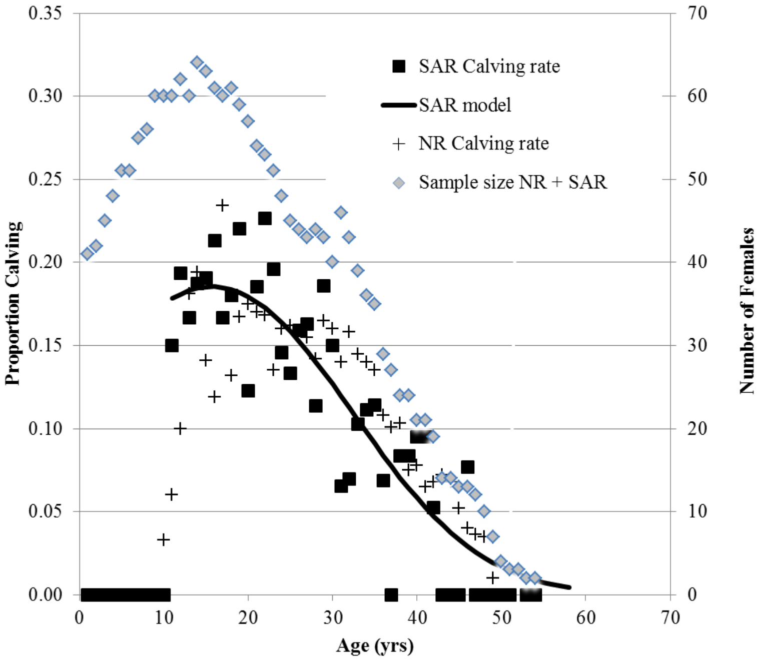


Figure 8. Age-specific fecundity (calves/female) for both southern Alaska resident (SAR) and northern resident (NR) and sample sizes for all females (both populations). Sample shown includes 21 SAR females that were first observed as juveniles and aged by the year in which they were first seen with a calf; these were distributed normally around the estimated age of first reproduction (13.3 years) from ages 11-16. Model for SAR was a 3rd order logit polynomial fit to ages 11-52.

Survival Rates, Survivorship for both males and females conformed to the classic mammalian U-shaped curve (Table 2), indicating that the youngest and oldest animals experienced the highest mortality; however, the curve was narrower for males than females with a significant uptick in mortality for males in the 30-41 year range and for females in the 50-54 year range, indicating a longer lifespan for females. Mortality rates for juveniles could not be estimated separately for each sex because deaths of immature animals (as old as 15 years) could not be accurately assigned to sex. For this reason, and to facilitate comparison to northern resident killer whales, survival rates were estimated for both sexes pooled up to the age of 15.5 years, as per Olesiuk et al. (2005).

Table 6. . Age and sex-specific annual survival rates from bootstrap analysis of southern Alaska resident killer whales.

	Age Class	n	Upper 95%	Median Survival	Lower 95%	Mean	SE
Both Sexes							
	0	165	0.976	0.945	0.903	0.946	0.019
	1-2	181	1.000	0.997	0.991	0.997	0.003
	3-5	179	0.998	0.991	0.981	0.990	0.004
	6-9	163	0.996	0.989	0.979	0.988	0.005
	10-14	141	0.998	0.992	0.983	0.992	0.004
Females							
	15-19	63	1.000	0.996	0.988	0.996	0.004
	20-24	56	1.000	0.987	0.970	0.987	0.008
	25-29	44	1.000	0.990	0.973	0.989	0.007
	30-34	43	0.984	0.960	0.924	0.959	0.016
	35-39	27	0.992	0.968	0.932	0.968	0.016
	40-50	19	0.989	0.958	0.922	0.958	0.016
	50-54	4	1.000	0.800	0.500	0.783	0.146
Males							
	15-19	66	0.998	0.986	0.967	0.985	0.008
	20-24	47	0.985	0.964	0.933	0.962	0.014
	25-29	32	0.993	0.965	0.932	0.964	0.015
	30-34	20	1.000	0.970	0.921	0.966	0.020
	35-41	11	0.945	0.857	0.731	0.854	0.054

Population Dynamics

While the average annual population growth rate (λ) of all pods from 1984 to 2005 was 1.035 ($e^{0.0341}$; Figure 1), the initial modeled growth declined during the course of the study, and converged to 1.024 at stable age distribution. However, the sex ratio of whales observed as juveniles and reaching the age of 15.5 years was skewed toward females (55:45). While not a statistically significant deviation from an even sex ratio ($P = 0.18$), in this study, where all individuals are tracked, it creates observed effects on population growth. It is not known whether the skewed sex ratio was present at birth or the result of differences in neonatal and juvenile mortality up to maturity. To compensate we modified our model by creating a 55:45 female to male ratio which elevated the modeled growth rate from 1999 to2005 slightly (1.026 vs. 1.024 in 2005), and gave a growth rate of 1.029 when stable age structure is achieved (Figure 5). Mean annual growth rate and number of deaths in the modeled population were identical to those observed (1.033 and 69, respectively), while calf production differed by 1 (190 vs. 191).

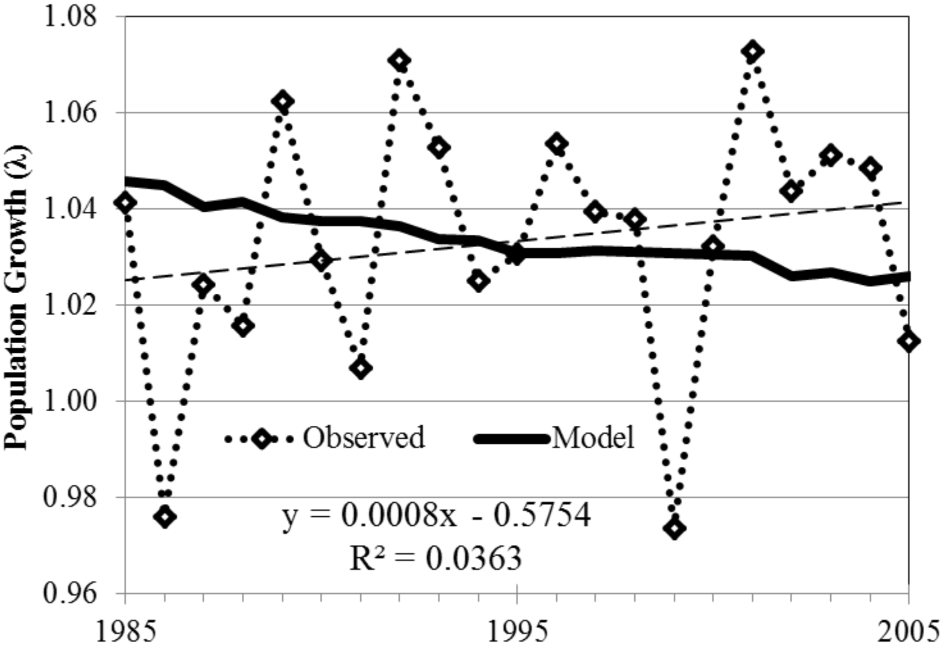
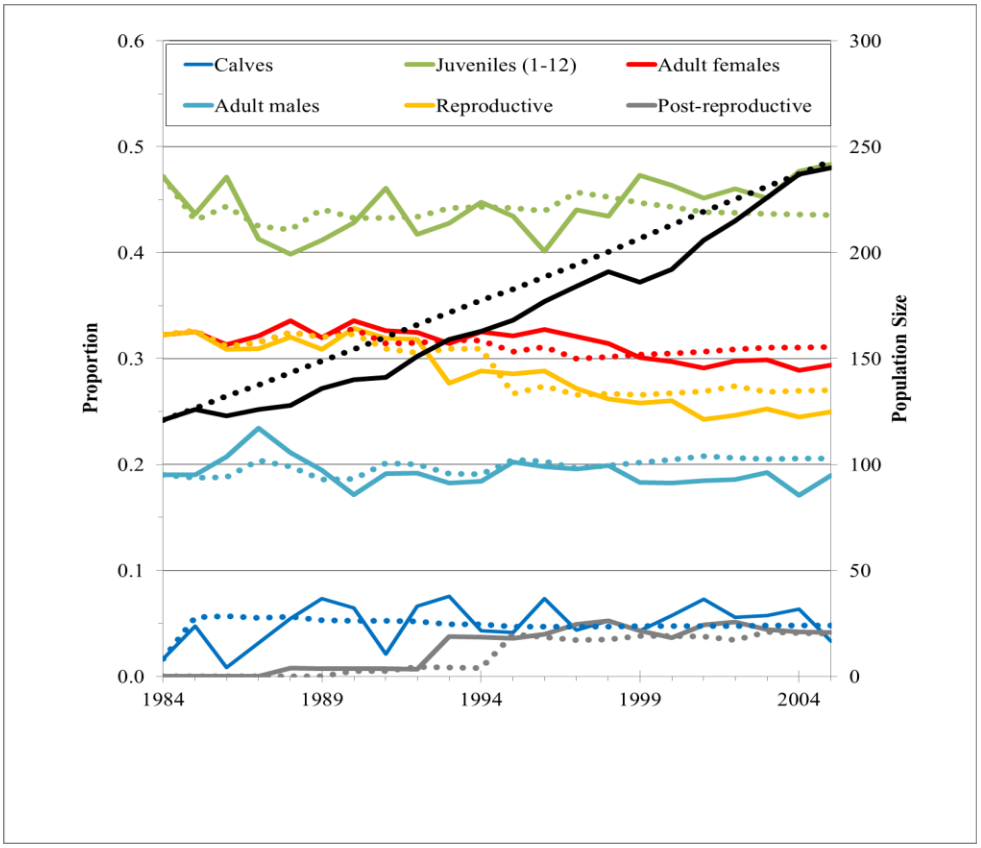


Figure 9. Observed and modeled rates of annual population growth of resident killer whales, demonstrating a weak positive trend from the observations. Model estimates were based on estimated average rates of survival and calving applied to the starting age/sex structure of killer whales in 1984, and an observed skew toward females (55:45) in newly matured whales.

The observed rate of population growth lagged the model growth early in the study (Figure 5) with somewhat higher than average rates of calving and juvenile recruitment in the final six years (Figure 6). The decline in modeled growth rate (Figure 5) is the result of a higher proportion of adult, particularly reproductive, females at the start of the study in comparison to a stable distribution, but the increased calf and juvenile recruitment after 1999 appears to have increased the juvenile proportion relative to earlier in the study, and brought it up to a higher proportion than predicted by the model at stability (Figure 6).

There are some minor artifacts in the model that largely stem from the averaging of estimated demographic parameters. The shift in reproductive and post-reproductive females beginning in 1993 (Figure 6) is likely an artifact of underestimating the age of females that should have been in the post-reproductive class at the beginning of the study, and this may be responsible for the model over estimating population growth in the early years of the model, and under estimating growth later due to having underestimated fecundity. There were eight females that were classified as post-reproductive in 1984 by the criterion that they produced no offspring in the next 10 years, but their ages were likely underestimated by a conservative age determination referenced to the likely age of their oldest known offspring. If those animals (estimated ages 18-36 years, mode=31) were distributed across the 40 to 55 year old ages, the modeled population growth would have declined to ~1.034 at the beginning of the study instead of 1.043 (Figure 5).

Figure 10. Observed (solid lines) and modeled (dotted lines) population size and age/sex structure in 10 pods of southern Alaska resident killer whales. Black lines are total population



The rates and stable age/sex structure of the model developed for southern Alaska resident killer whales is very similar to that of northern resident killer whales in their period of unrestrained population growth (Olesiuk et al. 2005, Table 3). Vital rates in our study produced slightly more reproductive females and juveniles, and slightly fewer males and fewer post-reproductive females. Expected lifetime production of calves was slightly higher in the northern residents, but stable population growth was essentially equal. The evidence for a difference is strongest in age of maturity, where southern Alaska residents of both sexes were estimated to mature roughly a year earlier than those of Olesiuk et al. (2005). However, the bootstrap variation was substantially higher, and our inclusion of unsexed juveniles lead to higher estimates such that there was virtually complete overlap in the estimates of all age-specific parameters from the two populations (see Figure 4 and Table 2). In both studies it is likely that some bias occurs in prime-age survival and reproductive rates as a result of underestimating the ages of mature females at the beginning of the study, but the exercise of distributing some of these to later ages indicated that the numbers and bias are probably small.

Table 7. Comparison of age/sex structure of Southern Alaska resident killer whales as observed from 1984-2005, as modeled to a stable age structure, and as modeled for northern resident killer whales from parameters given by Olesiuk et al. (2005) for that population's period of unrestrained growth (1973-1996). Age categories were standardized, though Olesiuk et al. (2005) estimated a longer juvenile stage (1-15) due to later estimated ages of maturity.

	S.A.R Population Average	S.A.R Stable Model	B.C. Northern Residents
Calves	0.050	0.049	0.046
Juveniles (<13)	0.443	0.444	0.412
Adult Females (>13)	0.314	0.309	0.331
Adult Males (>13)	0.192	0.199	0.211
Reproductive Females (>13, <40)	0.286	0.275	0.254
Post-reproductive Females (>40)	0.027	0.033	0.077
Population growth (λ)	1.035	1.029	1.027
Lifetime Reproduction		3.41	3.92

Discussion

Although the two populations are geographically and genetically distinct (Barrett-Lennard 2000, Matkin et al. 1999a), the population biology of the southern Alaska residents was remarkably similar to that of the northern residents of British Columbia during the 1970s through early 1990s when that population was increasing at 2.9% annually (Olesiuk et al. 1990, 2005). The slightly higher 3.5% rate of growth reported for the southern Alaska residents is the highest rate of increase measured for a killer whale population, and we suspect it reflects a population at r-max. The expansion of the Alaska population continued through 2005 while the rapid expansion of the northern resident population apparently ended in 1996 (Olesiuk et al. 2005). There was such extensive overlap in the estimates of vital rates in these populations, and our use of bootstrap methods points to substantial underestimation of parameter variance for the northern resident study, that it is difficult to conclude that there was anything but stochastic differences in the life history traits of these two populations during comparable periods of unrestrained growth.

Olesiuk et al. (1995, 2005) noted that the estimated ages of females that were fully adult at the start of the study would be biased low by the potential deaths of their oldest offspring prior to the study. Based on calving rates and survival rates of calves, a probabilistic correction factor was calculated by Olesiuk et al. (2005) to compensate for older calves that may have died before the beginning of the study. The corrections increased as a function of the age of the oldest known offspring when first seen, and ranged from 0.7 when the oldest known offspring was first seen at age 0, to 1.4 when first seen at age 10, to 2.8 when first seen at age 20, to 5.4 when first seen at age 30. We found this method flawed because (1) it takes no account of the number of known offspring for these females (usually several); (2) the correction factor is largely irrelevant because the oldest known offspring could rarely be established at >20 years old when first seen; and (3) demographic calculations for older females required pooling of samples across age ranges much larger than the correction factor. Their correction factor also had extremely wide confidence limits, typically ranging from <0 to over 20 years, and failed to impart the actual effect of not observing the oldest offspring, pushing a small number of females into a much older age category rather than incrementing the ages of most older females by 1-3 years. Eliminating the correction factor slightly decreases the age-specific reproductive and survival estimates in the older female age categories but has negligible effect on classification of females into post-reproductive age classes.

The overall mortality pattern for killer whales in this study as well as studies in British Columbia (Olesiuk et al. 2005) followed the typical mammalian U-shaped curve (Caughley 1966), with mortality rates highest for the youngest and oldest animals of both sexes. The curve was broader and shallower for females than males; male mortality increased at the time they reached physical maturity and started breeding. Barrett-Lennard and Ellis (2001) found that all genetically identified fathers were older, physically mature males indicating the importance of survival of the older males for their genetic contribution.

Pregnancy rate may be substantially higher than the recruitment rate (Olesiuk et al. 1990), with calves not surviving in years in which the mother cannot support the newborn nutritionally. Pregnancy has a relatively small energetic cost compared to the energetic cost of rearing a calf that may nurse for several years. The upward skew in reproductive intervals of up to 10 years between successful calves in some cases reflects decreased fecundity due to age. However, it also may reflect the inability of females to support new calves energetically in some yearsduring the first few months after birth due to nutritional stress.

Because there have not been marked changes in the rate of growth of our population during the period of this study, it is difficult to assess the role of various population parameters in response to changing conditions. The decline in AB pod was due to the *Exxon Valdez* oil spill (Matkin et al. 2008) and not reflective of changes in natural conditions. In our actual and modeled population structure over the course of the study (Figure 6) the greatest fluctuation from the model is in the proportion of calves and juveniles and although there may be some stochasticity involved, this indicates the potential importance of these groups in population response. Olesiuk et al. (2005) suggested that slow steady growth of resident killer whale populations with periods of higher mortality due to unfavorable conditions or catastrophes may be the typical pattern, However, responses to negative long-term changes in carrying capacity may be more complex. In this regard, the killer whale cannot be compared to terrestrial predators such as the grey wolf (*Canis lupus*) which has an early age of first reproduction (2-4 years), the ability under favorable conditions to produce multiple offspring (4-8 per litter), and a relatively short lifespan (8-16 years) (Mech 1970, Peterson et al. 1984, Fuller 1989). These characteristics allow wolf populations to respond relatively quickly to changes in prey density or other environmental factors and create the potential for relatively rapid shifts in abundance of predator and prey. Southern Alaska resident killer whale life history parameters indicate more modulated changes in numbers and less dramatic shifts in predation pressure since life history parameters constrict population response (Cole 1954, Testa et al. in press). This implies a slower ability to recover following a catastrophic event such as an oil spill (Matkin et al. 2008) or other perturbations.

Both in our study population and in the British Columbia northern resident population from 1973 to1996 there was a steady increase in numbers. This may reflect a recovery from some past perturbation that reduced the population size. Although Olesiuk et al. (2005)

suggested the possibility of mass strandings, there is little evidence that resident type killer whales are prone to these events. In the past, shooting of killer whales may have been a regular occurrence as evidenced by bullet wounds observed in 25% of the whales taken into captivity in the 1960s and early 1970s in British Columbia (Hoyt 1981). Bullet wounding and unexpected mortalities in AB pod during interactions with commercial long-line fisheries in the mid-1980s suggests that historic interactions also may have had a negative impact on southern Alaska resident killer whale numbers. No direct evidence for this exists, however. The *Exxon Valdez* oil spill resulted in long-term impact on both a large resident pod and transient group in Prince William Sound (Matkin et al. 2008). This was followed by a slow and prolonged recovery period for AB pod and is a contributing factor to what appears to be the eventual extinction of the AT1 transient population. However, this is a modern anthropogenic effect and does not have historical implications.

Alternately, there may have been an increase in carrying capacity for southern Alaska resident killer whales in recent decades. Salmon populations in the region have rebounded from low population levels recorded during the period from 1945 to 1975 that appear linked to the Pacific Decadal Oscillation (Kaeriyama et al. 2009). Coho salmon *(Oncorhynchus kisutch)* and Chinook salmon (*Oncorhynchus tshawytscha*) appear to primary prey for this population (Saulitis et al. 2000, C.Matkin unpublished data). In Prince William Sound and the Copper River the average permitted catch (based on run strength) for Chinook salmon from 1950 to 1975 was 17,576(s.d .7,228) fish, and for coho salmon 231,500 (s.d. 131,000) fish which essentially doubled during the 1976 to 2010 period to 36,342 (s.d. 15,695) Chinook, and 476,228 (s.d. 242,000) coho. The substantial increase in southern Alaska resident killer whales observed during the period of our study may be a result of the increased abundance of salmon species important in killer whale diet. Eventually we would expect to see increased mortality and a leveling of the southern Alaska resident population as occurred in British Columbia after 1996 (Olesiuk et al. 2005). The cessation of growth in the northern resident population was linked to a decline in prey availability, specifically, Chinook salmon (Ford et al. 2005). From feeding habits studies in our area it is likely that the trajectory of the resident killer whale population is tied to the strength of Chinook and coho salmon returns.

.

SATELLITE TELEMETRY

Introduction

In collaboration with Wildlife Computers in Seattle, WA we have developed transmitters, tags and techniques for remote attachment of both location only (SPOT 5) and time/depth/location (MARK10 tags) to free ranging killer whales. Tags transmit data at regular intervals to the ARGOS satellite sytem. The first prototype tags were applied in 2004 using a single post design. These tags remained attached to the fin for up to one week. A two post system was developed that resulted in attachments averaging about one month in duration. In 2011 we began experimentation with time/depth/location tags.

Tracking by satellite allows a more detailed picture of distribution and range than vessel surveys and is a potential aid in relocating whales for observational and feeding studies. Tagging data coupled with feeding habits data (see feeding habits section) can provide the information necessary to delineate important killer whale habitat. This has ramifications in understanding killer whale ecology and the possible effects of development and future perturbations on killer whale populations. This segment of the study has focused on AB pod and other resident killer whales that are known to consistently use the nearshore waters of Prince William Sound/Kenai Fjords although some tags were applied to infrequently observed pods to determine the full range of the southern Alaskan killer whale population.

Methods

Although we explored various design concepts for a killer whale satellite tag, our most successful design was a barnacle-type tag with two barbed darts constructed from titanium (Andrews et al. 2008). It is termed a barnacle-type of tag because the main electronics package is held outside the body by small darts that anchor the tag to the whale, but we now call the tag and attachment design the Low Impact Minimally Percutaneous External-electronics Transmitter (LIMPET) tag. These tags were constructed with a SPOT5 (Wildlife Computers, Redmond, Washington, USA) Argos-linked, location-only Platform Transmitter Terminal (PTT) (Andrews et al. (2008). Tag dimensions were 65 x 30 x 22 mm. Each tag incorporated two 6.5 cm long medical-grade titanium darts that were fixed to the bottom of the tag, for a total mass of 49 g. The darts were designed to penetrate the connective tissue in the dorsal fin and remain embedded with a series of backwards facing ‘barbs’ which acted as anchors for the darts.The method of deployment for the LIMPET tag used a crossbow to launch an arrow with the LIMPET tag held onto its end in a special rubber boot.

This type of satellite tag transmits ultra-high frequency (UHF) radio signals to ARGOS receivers on-board five NOAA TIROS-N weather satellites in sun-synchronous polar orbits. To conserve power, transmissions are limited by a submersion sensor to times when the whales are at the surface. Locations are determined by Service ARGOS from Doppler shift of tag transmissions created by the speed of the satellite passing overhead. The accuracy of locations depends upon the number of and time between messages received during the time the satellite passes overhead from horizon to horizon. ARGOS provides an estimate of location accuracy by assigning each location fix to one of six classes. Sixty-eight percent of location classes 1, 2, and 3 (abbreviated LC-1, LC-2, and LC-3) are predicted to be within 1.0, 0.35, and 0.15 km, respectively. Service ARGOS does not provide an accuracy estimate for Location classes 0, A, and B. We determined the plausibility of each location using the Douglas Argos filter v.7.03 (Douglas 2007). This filter consists of a systematic algorithm that considers location class (LC), proximity to previous and subsequent locations, rate of movement, and the acuteness of the angle formed by the previous and consecutive locations. We considered locations to be plausible and retained them for analyses if the LC index was 3 or 2 or if the distance to the previous or subsequent location was <3 km. All other locations were removed if the rate of movement between consecutive locations exceeded 25 km h^{-1} or the angle formed by the previous and subsequent locations indicated extreme return-movements that we considered characteristic of typical ARGOS error and not representative of plausible behavior of killer whales (i.e., the farther an individual moves, the less likely it is to immediately return back to the same vicinity with no intervening location fixes on the outward or return path). Killer whales can travel at over 30 km hr-1 for short periods of up to 15 min (pers. obsv.), with an estimated maximum sustainable swimming speed of 20 km hr^{-1} (Guinet et al. 2007); therefore we chose 25 km hr^{-1} as the upper limit for our purposes.

Data was filtered of poor "hits" by use of a Douglas filtering program and by visual inspection. Location data was imported into Google Earth for basic visual inspection into a ArcMap 9.3.1 for further analysis. Distance traveled was calculated for each tagged animal as well as a calculation of oceanic home range developed by subtracting the land area from the total area in the Minimum Convex Polygon, which was the polygon that described the perimeter of all satellite locations. Shapefiles were plotted in ArcMap 9.3.1 and examined visually.We applied fixed kernel density estimators from Hawth's tools for ARCGIS 9 to combined shapefiles of ARGOS tracks for all attachments from individuals from specific pods to determine focal activity areas and examine range. Kernel estimators are non-parametric and provide direct output of density uninfluenced by grid size and placement. In the program the most important parameter is bandwidth which was set at levels of 0, 15, 30, 50, and 100 per cent for our analysis. The contours are represented by a suite of colors that reflect the number of sightings in each area. Density of use increases as the color changes from yellow/orange to solid red, the more red the higher density (Figure 5)

Results

We received data from a total of 20 tagged whales between 2010 and 2012 (Table 8). Transmission time from tags ranged from 4 to 71 days with an average transmission time of approximately 18 days. Resident killer whales were tracked for a total of 30,234 km over 312 days with an average daily travel distance of 97 km. One offshore whale was tagged for 12 days and traveled a total 996 km with an average of 83 km/day. Three GOA transient whales were tagged for a total of 26 days of tracking and these whales traveled 1740 km with an average of 67 km/day.

Table 8. Summary of ARGOS data from tagged killer whales with calculations of oceanic home range 2010-2012.

Whale	**Tracking Time Period**	**Days attached**	**Distance (km)**	**km/day**	**Oceanic Home Range (km2)**
Resident					
AB53	9/17/2010-9/25/2010	9	767	85	4353
AJ27	8/13/2010-8/28/2010	16	1969	123	16025
AJ4	6/9/2010-6/10/2010	2	126	63	
AJ42	7/16/2010-7/28/2010	13	1714	132	5685
AJ37	6/11/2010-9/23/2010	71	6817	96	26276
AJ44	9/20/2010-9/30/2010	11	608	55	2244
AX111	6/9/2010-6/22/2010	14	424	30	8068
AF46	7/23/2011-8/17/2011	25	3235	129	91941
AI9	9/22/2011-9/28/2011	7	733	105	5539
AJ15	9/25/2011-11/29/2011	66	6845	104	21718
AY7	6/6/2011-6/27/2011	22	2435	111	22810
AB49	8/30/2012-9/5/2012	7	101	few hits	436
AD28	9/4/2012-9/29/2012	26	2262	87	7195
AF45	8/15/2012-8/22/2012	8	863	108	27170
AJ26	10/10/2012-10/13/2012	4	92	23	63
AX109	8/14/2012-8/25/2012	11	1244	113	21345
TOTALS		**312**	**30234**	**97**	
Offshore					
	7/3/2012-7/14/2012	12	996	83	27140
Transient	**GOA**				
AT73	9/21/2010-9/27/2010	7	625	89	2615
AT122	6/12/2010-7/1/2010	19	1115	59	36222
TOTALS		**26**	**1740**	**67**	
	AT1				
AT9					
	8/17/2010-8/22/2010	5	473	95	3982

Note: Distance and area calculations based on GIS data stored in Alaska Albers Equal Area Conic map projection. The shoreline data used in the land area calculations for Alaska was at the 1:63,360 scale.

We examined range and important habitat for selected pods where significant additional tagging data was available. We combined tracks for tag attachments for each individual tagged within this study period with earlier tag attachments from the same pod (Table 9). We used Hawth's fixed kernel density estimator (in ArcMap 9.3.1.) to evaluate the most heavily used areas (Figs. 11-13). For the AF22 and AG pods, offshores and transients we added significant new range points and present that data in the form of filtered tag locations (Figs. 14-17)

Table 9. Combined tagging data by pod(s) used in examination of focal areas and range

POD	Whale	Tracking Period	Days	Focal Areas
AB				
	AB11	9/13/06-11/7/06	55	Inside Kayak I., Hinchinbrook Ent.
	AB43	8/14/08-8/20/08	7	Montague Strait ,Port Bainbridge
	AB45	6/21/08-7/26/08	36	Ouside Montague shoreline
	AB53	9/17/2010-9/25/2010	9	Montague St, Hinchinbrook
	AB49	8/30/2012-9/5/2012	7	Montague St
AJ				
	AJ21	10/8/2004 - 10/13/2004	5	Montague Strait, KIP,
	AJ21	9/2/2006 - 9/27/2006	26	Inside Kayak I
	AJ7	9/3/2006- 9/4/2006	2	Day Harbor
	AJ21	6/20/2008-6/23/2008	3	Hinchinbrook Ent.
	AJ33	9/15/2009-10/2620/09	42	Kayak Is, Copper R, Mont Str
	AJ27	8/13/2010-8/28/2010	16	GOA, Hinch Entr, Montag Str
	AJ4	6/9/2010-6/10/2010	2	Hinch Entr, Kayak I
	AJ42	7/16/2010-7/28/2010	13	Hinchinbrook, CopperR delta
	AJ37	6/11/2010-9/23/2010	71	Gulf of AK, Hinchin. ,PWS
	AJ44	9/20/2010-9/30/2010	11	Mont Str., Kenai Fjords,Port Bain
	AJ26	10/10/2012-10/13/2012	4	Montague Str.
AX48				
	AX106	8/3/2007 - 8/13/2007	10	Kenai Penn, Shelikof Str, GOA
	AX111	6/3/2009-6/29/2009	27	Kenai Fjords,Hinch Entr, GOA
	AX111	6/9/2010-6/22/2010	14	Gulf of AK, Kodiak
	AX109	8/14/2012-8/25/2012	11	Mont Str., Shelikof Str.
AG,AF				
	AG3	8/14/2007 - 9/3/2007	21	Kenai Penn, GOA, SEA
	AF46	7/23/2011-8/17/2011	25	Kenai Fjords, Mont Str, SEA
	AF45	8/15/2012-8/22/2012	8	Gulf of Alaska, Mont Str.
GOA	**TRANSIENT**			
	AT109	7/4/07-7/20/07	17	
	AT73	9/20/2008-10/19/2008	30	
	UnID_GOA_Trans.	7/1/2009-7/2/2009	2	
	AT73	9/21/2010-9/27/2010	7	
	AT122	6/12/2010-7/1/2010	19	

Resident pods AB (20 whales) and AJ (57 whales) are northern resident haplotypes and had ranges somewhat similar ranges to each other during the tracking periods, but with different areas of emphasis (Figs.11,12). Both used outside waters extensively, in particular the area between Montague Island and Kayak Island, south of the Copper River delta. AB was the only pod that traveled east of Kayak Island. AB pods focal areas included Hinchinbrook Entrance particularly in spring and early summer and the outside of Montague Island as well as the area east of Kayak I. AJ pod focused on Montague Strait in fall and winter (winter encounters courtesy J. Moran). Although both these pods used used Montague Strait and Port Bainbridge, only AJ pod repeatedly used Day Harbor in fall.

Figure 11. Results of kernel analysis for all AB pod locations from tags

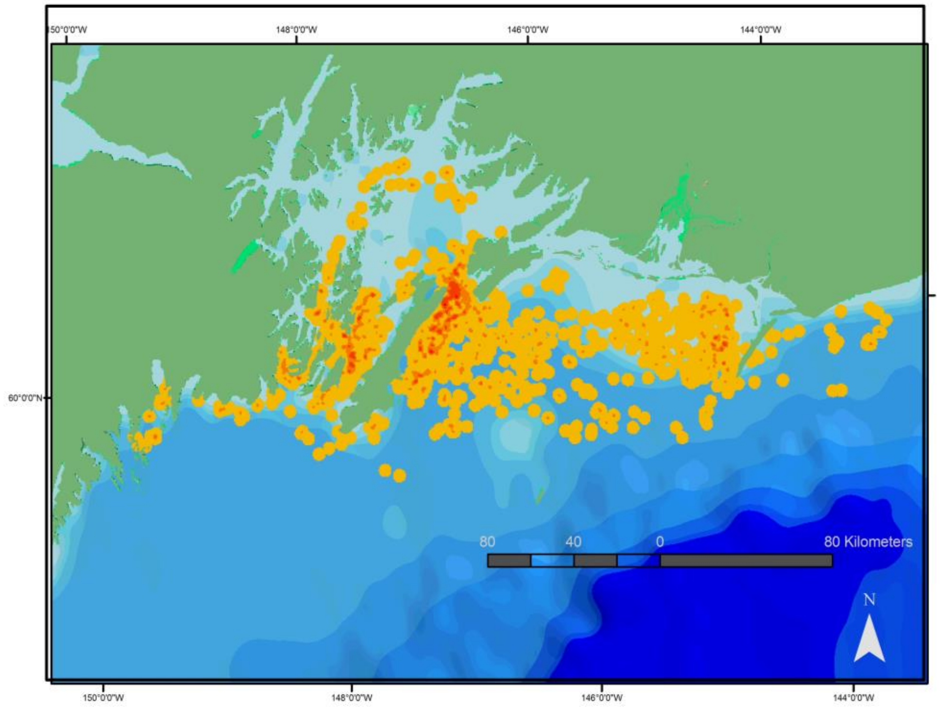
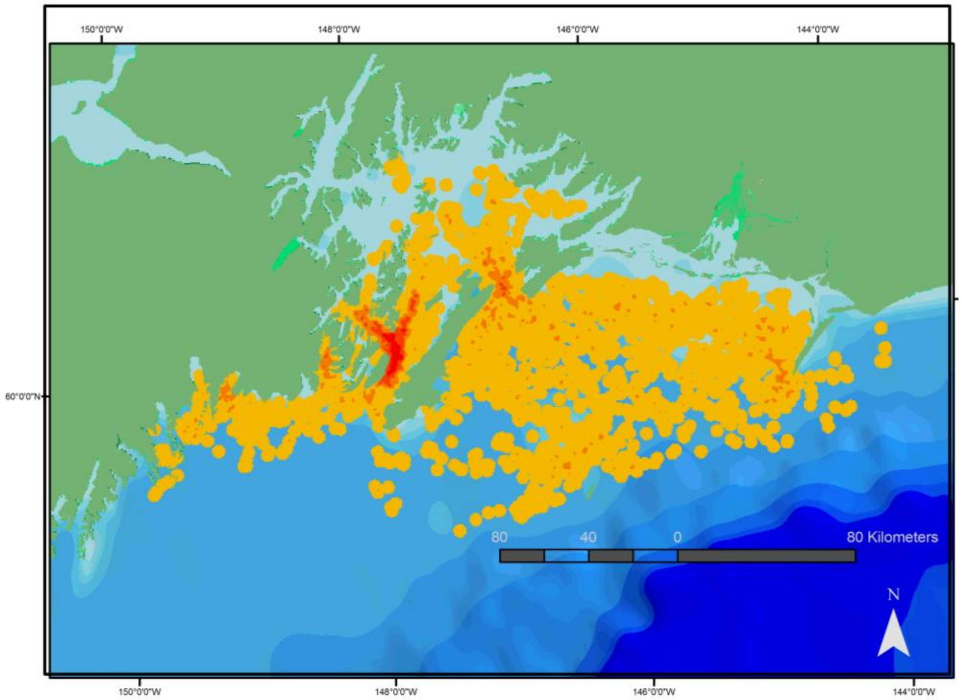
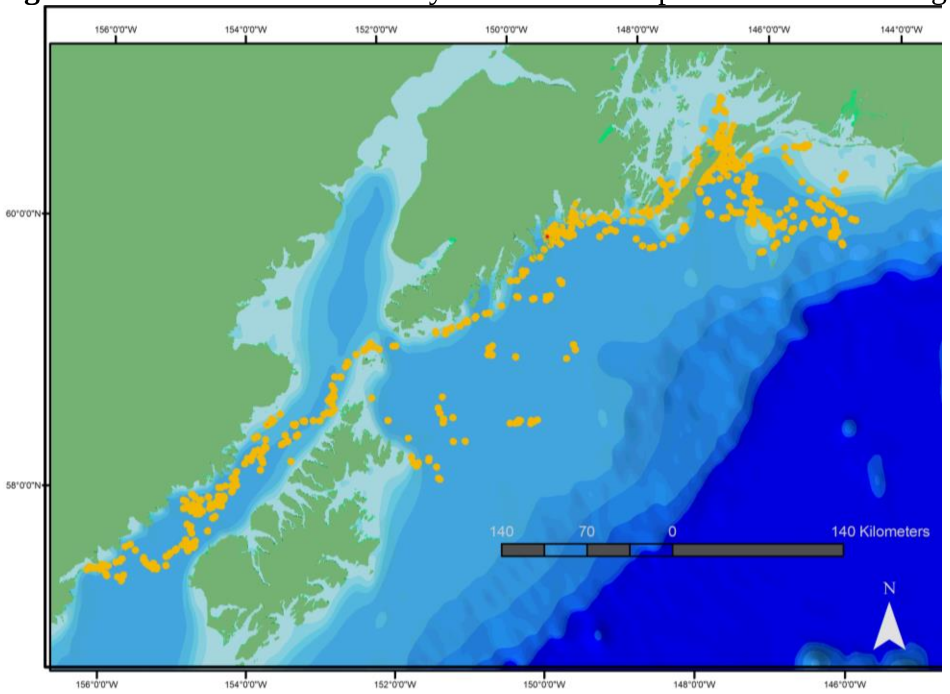


Figure 12. Results of kernel analysis for all AJ pod locations from tags



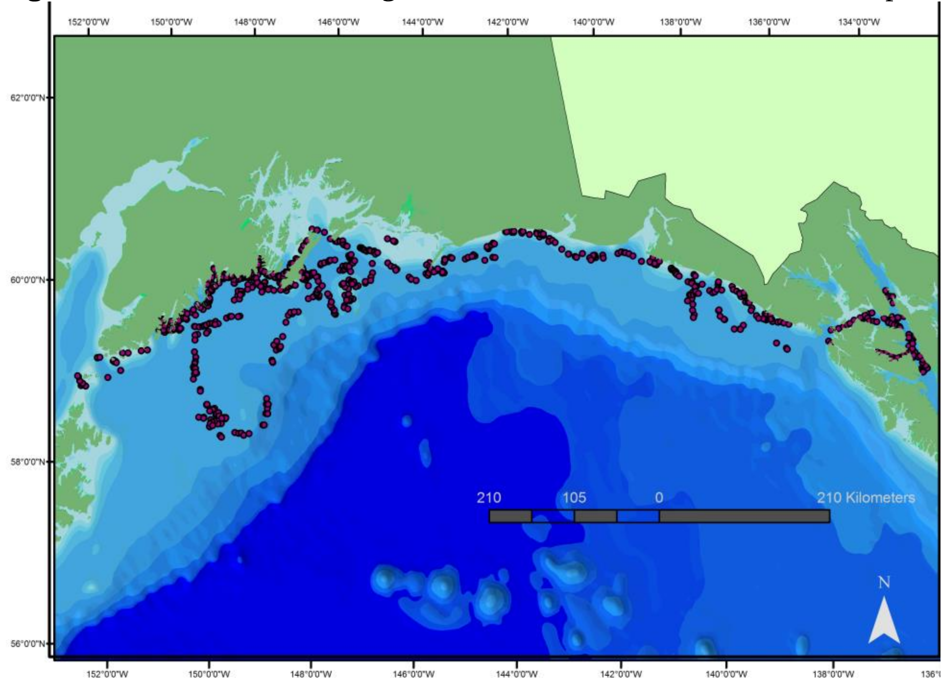
The lesser known AB48 pod primarily used Hinchinbrook Entrance and Kenai Fjords regions during periods of tag attachment, although it also used areas offshore Kodiak Island (at times over 100km offshore). We suspect the AX48s spend considerable time in the Kodiak/Shuyak area based on photo data (C. Matkin unpublished data

Figure 13. Results of kernel analysis for all AX48 pod locations from tags



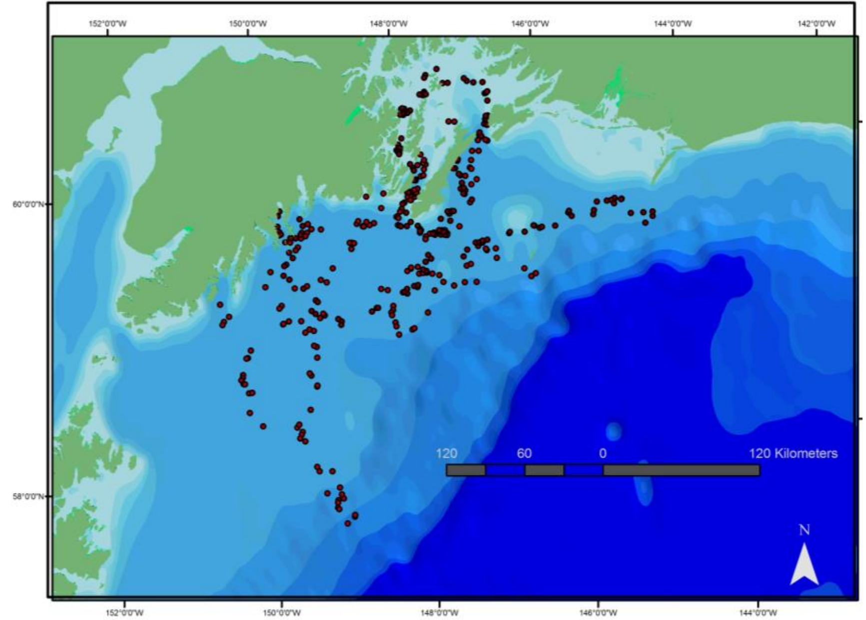
AF22 and AG pods are resident pods, along with AF5 pod, that spend most of their time in southeastern Alaskan waters. These two pods make frequent trip across the Gulf of Alaska from southeastern Alaska and have been recorded in Kachemak Bay and Resurrection Bay even during the winter months. The satellite tag data from the three tagged whales from AF22 and AG pods indicates they traverse a generally near-coastal route but may go offshore over 100km at times

Figure 14. Locations from tags on three whales from AF22 and AG pods**.**



Offshore whales may occur annually in the northern Gulf of Alaska for short periods, but are difficult to approach for tagging. We managed to tag a second offshore killer whale in 2010 although the tag only transmitted for 12 days. From sampling of the prey of offshore killer whales (see feeding section) it appears that these whales are entering inshore waters such as Resurrection Bay and Prince William Sound to feed on Pacific Sleeper sharks. Tagging data also shows movements offshore to the edge of the continental shelf as far as 225 km off the coast (Figure 15). These whales are most frequently observed off California, Washington, and British Columbia (Dahlheim et al 2008) although they have been seen briefly but regularly in June and July in Kenai Fjords and Prince William Sound (Ford *et al*. 2011, Matkin *et al.* 2010) and irregularly in the eastern Aleutians (Matkin *et al.* 2007) as well as occasionally in southeast Alaska (D. Matkin unpublished data).

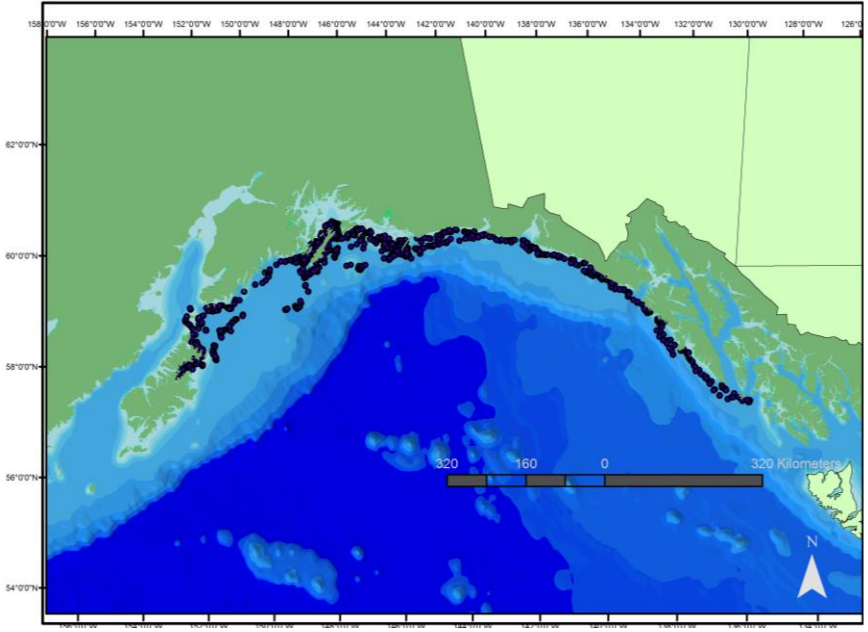
Figure 15. Locations from tags on two Offshore type killer whales



Gulf of Alaska transient whales occur only occasionally in Prince William Sound and our tracking data indicated tagged whales spent most of their time on the outer coast from Kodiak Island through southeastern Alaska, relatively nearshore, with movements offshore of up to 80km. (Fig 16**)**

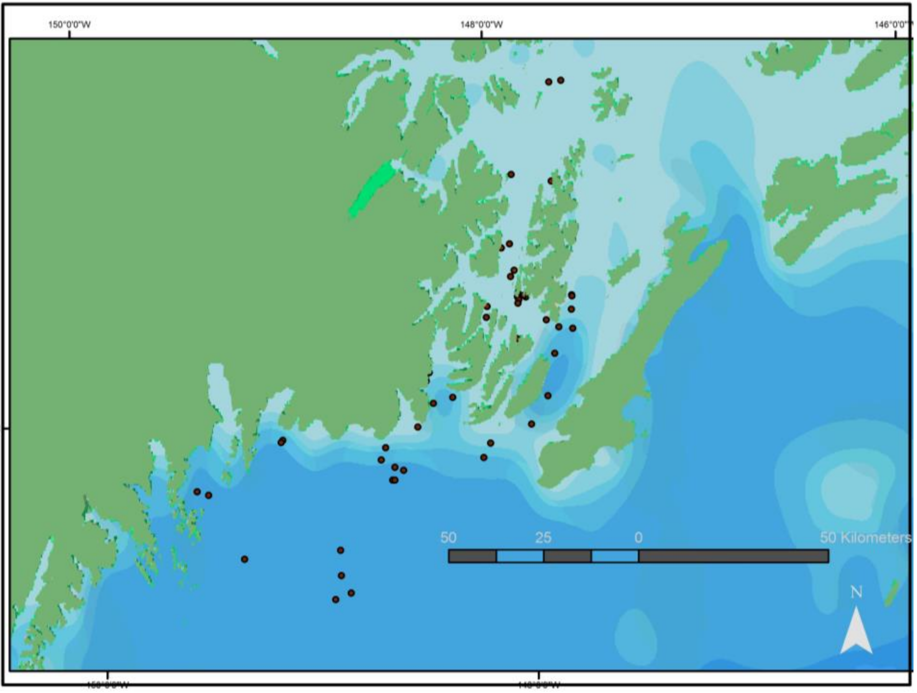
On one occasion the GOA transients have been recorded mixing with parapatric and genetically distinct west coast transient population (Matkin et al. 2012) , however our data suggests GOA transients occupy outside coastal waters of southeastern Alaska while west coast transients are found primarily in the inside waters of that region.

Figure 16. Locations from tags on five GOA transient population killer whales



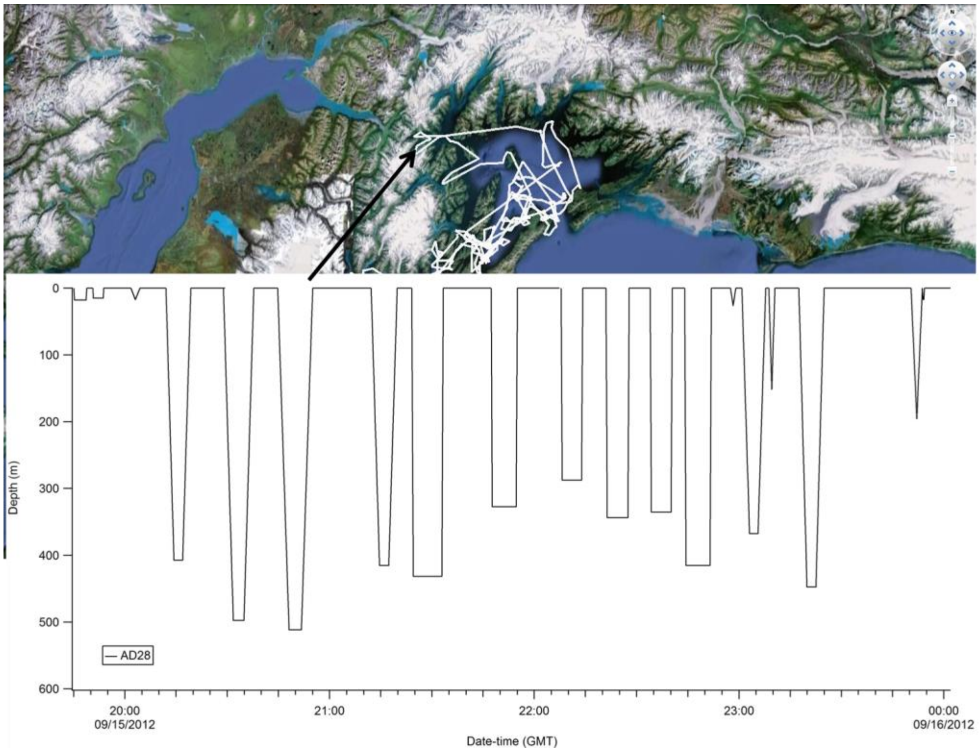
Although the GOA transients also have a range that overlaps the AT1 transients in Prince William Sound/Kenai Fjords, the two populations have not been seen to intermingle over 30 years of observations and they have different population trajectories (Matkin *et al.* 2012) The single AT1 transient (AT109) tagged moved into Prince William Sound further than any of the tagged GOA transients, but the whale also moved offshore nearly 100km while remaining in Blying Sound.

Figure 17. Locations from tag on AT9 whale from the AT1 transient population



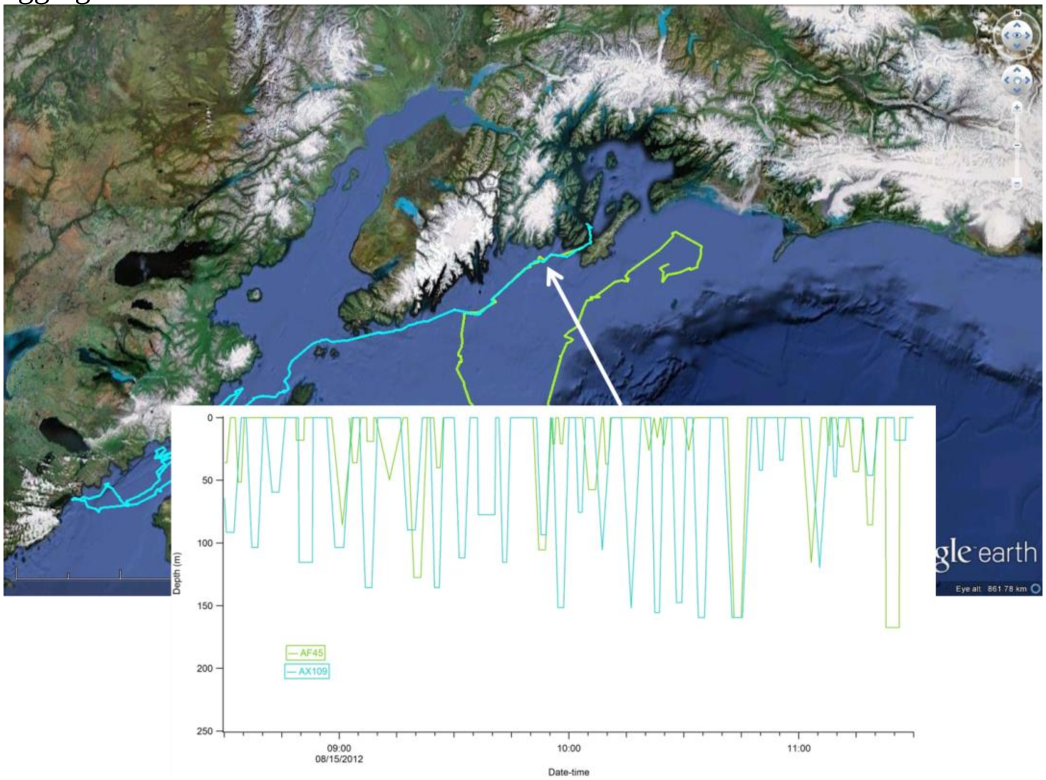
In 2011 and 2012 we attached our first Mark 10 time/depth/location tags that successfully transmitted to AI9 in 2011 and AD8, AF45, and AX 108 in 2012. Dive depths were significantly deeper than expected considering salmon was the suspected prey during this late summer/fall period when tags were attached. During the thirteen deep diving bouts that we recorded for AB28 over a four hour period on15 September 2012 in Blackstone Bay, two dive bouts were deeper than 500m, eight were 400 meters or deeper and 12 were deeper than 300 meters (Fig 18). These dives occurred during hours of darkness (2000 to 2359) and must have involved extensive use of echolocation. Extensive rest periods of up to 20 minutes occurred between diving bouts.

Figure 18. Dive profile from Mark10 time/depth/location logging satellite tag on AD28



On 8 August 2012 were recorded logged dive data for two individuals from different pods, AF45 and AX108, that had been tagged the day before days previous when they were part of a multipod aggregation in lower Montague Strait. They were swimming as part of the same group the next morning when we recorded their dive profiles from 0800-1200 in the outside waters of Blying Sound (Figure 19) Many of the dive profiles were similar suggesting they were feeding on prey at a similar depths. There were 25 bouts recorded for AX108 and 21 bouts for AF45, most of the depths recorded were between 50 and 150 meters with shorter rest periods between bouts. Although some dive bouts were remarkably similar, AX108 made more deeper dives overall. The two pods split later in that day.

Figure 19. Dive profiles of AF45 and AX109 from Mark 10 tag while part of a multipod aggregationoutside Prince William Sound.



Discussion

The Spot 5 location only tags have allowed us to plot the range of a number of pods during the spring through Fall period including AB and AJ pods, whose range extended beyond the range of our research vessel. This tool has made it possible to examine details of ramge and define important habitat. In the case of these two pods, both have similar ranges which extend outside Hinchinbrook Entrance, across the Copper River delta and along Kayak Island and offshore to Middleton Island. Areas of focus are somewhat different, with AB pod spending more time in the Hinchinbrook Entrance and outside Montague Island and AJ pod spending more time in Montague Strait and offshore. Both occasionally visit Kenai Fjords but there is no evidence they travel out of the Copper River/Blying Sound region

The tagging results also indicate some pods may have a higher probability of exposure to various human perturbations. For example, the range of AE pod and AK pod would indicate a higher probability of encountering an oil spill inside Prince William Sound (Matkin et al 2010). Resident pods such as AB, AJ, AX48 and AD5; the Gulf of Alaska transients; and the offshore type killer whales would be more likely to be exposed to the effects of the increased Navy training activities (including mid range sonar testing and ordinance training) in the military training zone east of Kodiak and east of the Kenai Penninsula.

The introduction of Mark 10 tags that also relay time/depth information to ARGOS satellites adds substantially to our ability to look at important habitat, by definining periods and locations when animals are actively feeding and describing their feeding dives. Hopefully in the future we will be able to collect prey samples from areas where this feeding is occurring to link prey species to diving behavior and location.

FEEDING HABITS

Introduction

Killer whales in southern Alaska have been separated into three ecotypes by observations of association patterns (Matkin *et al*. 1999b, Matkin *et al*. 2003) and by genetics (Barrett Lennard 2000, Hoezel *et al*. 1998). In our study area, Prince William Sound and Kenai Fjords, the offshore ecotype is infrequently observed but we had some opportunity during the current study to directly sample their prey (Ford *et al.* 2011, current report). The the resident ecotype is observed to prey on fishes while the transient ecotype preys primarily on marine mammals (Ford *et al.* 1999, Saulitis *et al.* 2000). For the piscivorous resident killer whales, potential prey includes the Pacific herring (*Clupea pallasi*) and the five species of Pacific salmon (*Onchorynchus* sp.), and various species of bottom fish, including Pacific halibut (*Hippoglossus stenolepis*) and sablefish (*Anoplopoma fimbria*). These two bottom fish are also removed from commercial longlines by killer whales. Potential marine mammal prey for transient killer whales in Prince William Sound and Prince William Sound include Dall's porpoises (*Phocoenoides dalli*), harbor porpoises (*Phocoena phocoena*), humpback (*Megaptera novaeangliae*), minke (*Balaenoptera acutorostrata*) and gray (*Eschrichtius robustus*) whales, harbor seals (Phoca vitulina), Steller sea lions (Eumetopias jubatas) and river (*Lutra canadensis*) and sea otters (*Enhydra lutris*).

Confirmation of killer whale predation events and identification of prey species is often problematic. In Puget Sound, studies of southern resident killer whale feeding ecology have primarily relied upon indirect evidence such as the distribution and migration patterns of potential fish prey in relation to movements of the killer whales (Balcomb *et al*. 1982, Felleman *et al*. 1991). More recently, genetic analyses of scat samples obtained from the southern resident population has identified Chinook salmon as the primary prey of these whales in summer with a strong preference for adult returning Chinook from the Frasier River in southwestern British Columbia (Hanson *et al.* 2010). Studies of killer whales in British Columbia and Prince William Sound, Alaska have examined predation more directly with observational and prey sampling techniques similar to those used in this study (Ford *et al.* 1999; Saulitis *et al*. 2000). In addition chemical analysis of blubber and skin from biopsy samples has been developed as an additional tool for inferring feeding habits (Herman *et al* 2005, Krahn *et al* 2007a, 2007b, Matkin et al 2010) During this studyt we continued our collection of scale samples from resident feeding sites and continued our chemical analysis of blubber biopsies although with reduced emphasis within the total scope of work.

Materials and Methods

Dietary and behavioral data were gathered concurrently with census data (previous section) collected during this study although of reduced priority during this current study period (2010-2012). Although periods spent in the field varied among years, data collection occurred primarily May –August in all years of the study.

Offshore killer whales are encountered infrequently in our study area; generally no more that once or twice a season. Recently during these encounters we have maintained a close watch for evidence of foraging and successful feeding, such as sudden changes in swimming direction and speed, high arching dives and circling. In addition flocks of gulls often marked predation events as prey remains (generally pieces of shark liver), may float to the surface far behind the whales. Sites of suspected predation were approached once whales had moved on, and any prey remains visible at the surface or in the water column were collected using a fine mesh dip net with a 4 m telescoping handle). Prey remains were placed in 20 ml vials containing 95% ethanol for preservation. Vessel tracks and positions of predation events were recorded by GPS. Prey samples were composed of tissues that were extracted for DNA and for species identification, a 261 basepair (bp) portion of the mitochondrial 16S gene was amplified with 16SF1 and 16SallR primers (see Ford *et al*. 2011 for details).

Evidence of resident killer whale predation also was collected using an extendable, fine mesh, dip nets to retrieve fish scales or pieces of flesh from prey at the site of a kill. This collection technique provided prey species identification as well as data on the life history of the prey as determined from scale annuli. Scales were aged and identified at the Pacific Biological Station, Nanaimo, British Columbia by making acetate impressions and viewing the impressions on a Neopromar projecting scope. Magnifications of 10x to100x were used in the analysis (MacLellan 2004). Sampling of prey was coupled with standard killer whale photo-identification procedures (detailed in Bigg *et al*. 1990 and Matkin *et al.* 1999b) to determine the identity of the population, the pod, and, in some cases, the individual whale, using existing photographic catalogues (Matkin *et al*. 1999a). Sampling of prey remains occurred opportunistically during the period of our annual photo-census (April-September). Time and location of all predation events were also recorded.

Foraging behavior by a group of whales was initially identified acoustically by the presence of echolocation clicks and discrete calls detected using Offshore Acoustics omni-directional hydrophone (100Hz to 25 kHz). In addition, there were visual cues such as erratic movements of widely spaced individuals. As in our previous study (Saulitis *et al*. 2000), predation events accompanied by noticeable whale surface activity typically triggered our movement to the kill site and the attempted collection of scale samples. We also were successful in obtaining scale samples by following an individual (or cow/calf pairs) for extended periods during foraging and waiting for successful feeding to occur. However, the capture of prey at depth is not always accompanied by obvious surface activity, although the whale may occasionally carry prey to the surface. This made extended follows of individuals more productive at times than searching for obvious surface kills.

Marine mammal kills were confirmed by the observation of marine mammal parts in the mouths of the transient whales, bits of blubber, skin, viscera, hair, and/or blood in the water and/or oil on the surface in the vicinity of the whales. The species identity of marine mammal prey was usually determined during observations of attacks and chases. Fish predation by residents was confirmed by observations of fish in the mouths of whales or by fish scales in the water at the kill site.

When successful predation was suspected, the kill site was approached slowly. An observer on the bow of the research vessel scanned the area and retrieved fish scales or other prey fragments using a long handled dip-net. Samples were placed in envelopes labeled with the date, time, location of the kill site, and the identity and/or pod designation of the animal making the kill.

Harassment was considered to have occurred when potential prey animals exhibited an avoidance or alarm response in the presence of nearby killer whales or when killer whales chased, followed or lunged at potential prey without making a kill, or when, following an attack, a kill was suspected but could not be confirmed.

Biopsy samples were obtained from individually identified whales as described in Field Methodology (this report). Samples (skin and blubber) were stored as wet frozen materials at -80C until analyzed for their chemical tracers at the Northwest Fisheries Science Center

(NWFSC). Specifically, each biopsy sample was analyzed for their skin carbon and nitrogen stable isotope (SI) ratios, blubber fatty acids (FAs), and persistent organic pollutants (POPs). Lipid class analyses were also conducted on all blubber samples but those results will not be described here.

Measurements of skin SIs were conducted following the procedure described in Herman *et al.* (2005). In essence, the procedure involves freeze-drying ~50-200 mg of wet skin tissue, removing lipid by accelerated solvent extraction (ASE) using methylene chloride, pulverizing the lipid-free skin to a powder in a micro ball mill, loading ~500ug of powder into tin cups and combusting the powder in a Costech elemental analyzer attached to a Thermo-Finnigan Delta Plus Isotope Ratio Mass Spectrometer. Carbon (□13C) and nitrogen (□15N) isotope ratios were measured relative to Vienna Pee Dee Belemnite and atmospheric nitrogen, respectively.

Blubber fatty acids were analyzed following the procedure described in Herman *et al.* 2005). Prior to analysis, all blubber biopsy samples were sub-sampled by performing two lateral cuts, the first ~1mm from the inside edge of the epidermis tissue and a second cut exactly 20mm from the epidermis-blubber interface. Because FAs are highly stratified in killer whale blubber tissues (Krahn *et al.* 2004), it was necessary to standardize all blubber samples in this fashion in order to represent a constant blubber depth. These standardized blubber tissues were then extracted by accelerated solvent extraction using methylene chloride, an aliquot containing approximately 2mg total lipid (typically less than 4% of the total extract) transesterified to fatty acid methyl esters (FAMEs) using 3% sulfuric acid in methanol, the FAMEs extracted into iso-octane, and these final extracts separated and analyzed on a 60m DB-23 capillary column using a quadrupole gas chromatography/mass spectrometer (GC/MS). All FAME concentration data are expressed on a weight-percent basis (wt%) by dividing the concentration of each individual FAME by the sum of all FAMEs present in the sample.

Blubber persistent organic pollutants were analyzed following the procedure described in detail in Sloan *et al.* (2005). In short, the method involves clean-up of half or more of the lipid extract described above for the analysis of FAs (which also contains POPs) on a silica/alumina column to remove polar extraneous compounds, separation of the POPs from all lipids by High Performance Size Exclusion Chromatography (HPSEC), and finally separation and analysis on a 60m DB-5 capillary GC column equipped with a quadrupole mass spectrometer operated in the selected ion mode. POP concentration data were lipid normalized and expressed in units of ng POP/g lipid. In contrast, PCB profile data are expressed on a wt% composition basis by dividing the lipid-normalized concentration of each individual PCB congener by the sum of the lipid-normalized concentrations of all congeners measured in the sample.

All multivariate and univariate analyses of the chemical marker data obtained in this study were conducted using either JMP Statistical Discovery Software (PC professional edition version 5.01) or Primer-E Software (version 6.16). Unless indicated otherwise, all univariate comparisons between two groups were significance tested (□=0.05) using a simple 2-sample Student's t-test assuming unequal variances. Significant differences among multiple groups assumed to have approximately equal variances were evaluate using a Tukey HSD test (□=0.05).

Results

Feeding Observations of Offshore Killer whales

A large group of ~100 offshore killer whales was encountered entering Montague Strait, Prince William Sound, Alaska (59° 49' N, 148° 3' W) at 09:05 h. The whales were highly dispersed in small subgroups of 1 to 4 individuals over many square km, and frequently made long dives of up to 10 min duration, suggesting that they may have been foraging at depth. At 15:10 h, observers were alerted to the presence of prey remains at the surface by gulls picking up bits of tissue, and a piece of floating shark liver was collected. Over the next 3 h, an additional 6 predation events were observed and a sample of shark liver was collected from each (Table 2). Predation events took place from 0.2 to 4.9 km apart (median = 1.8 km) as the whales foraged northward up Montague Strait. Liver remains often floated to the surface several min after foraging whales had continued on, suggesting that predation events took place in locations with water depths of 180 to 300 m. Gulls were seen picking up prey remains in the vicinity of distant subgroups of whales, suggesting that more predation events took place than the 7 from which samples were collected.

On June 29, 2012, tour vessels reported a group of 30 to 100 killer whales in outer Resurrection Bay, suspected to be offshore killer whales. The whales were northbound into inner Resurrection Bay, prompting researchers to leave Seward harbor to document them. A group of 15 to 25 offshore killer whales were encountered near the Seward Shiplift (60° 04.0' N, 149° 21.2' W) at 19:20 h. The whales were dispersed, traveling in small groups of 1 to 5 individuals, changing direction regularly. Later identification of photos confirmed they were offshore type killer whales. Gulls were observed feeding at the surface, and a bit of flesh (apparent shark liver) was collected. Over the next hour, 4 more samples were collected for a total of 5 prey samples (Table 10). An attempt was made to collect only those samples that were more than 200 M from the previous sample.

Table 10. Details for samples taken at predation events by offshore killer whales, *Orcinus orca*, in Montague Strait, Prince William Sound, Alaska (13 June 2009) and Resurrection Bay, Alaska (29 June 2012).

Date	Predation	Local time	Latitude	Longitude	Shark species
13 June 2009	1	15:10	60.070	–147.755	Pacific Sleeper Shark
	2	16:00	60.105	–147.700	Pacific Sleeper Shark
	3	16:20	60.105	–147.689	Pacific Sleeper Shark
	4	17:00	60.128	–147.705	Pacific Sleeper Shark
	5	17:15	60.142	–147.720	Pacific Sleeper Shark
	6	17:38	60.152	–147.727	Pacific Sleeper Shark
	7	18:10	60.170	–147.727	Pacific Sleeper Shark
29 June 2012	8	19:41	60.083	-149.360	Pacific Sleeper Shark
	9	19:52	60.078	-149.350	Pacific Sleeper Shark
	10	20:15	60.070	-149.354	Pacific Sleeper Shark
	11	20:31	60.270	-149.378	Pacific Sleeper Shark
	12	20:50	60.105	-149.380	Pacific Sleeper Shark

Prey sampling and observation of kills by resident killer whales

A total of 167 scale samples were collected from 1991 to 2012 between April 1 and October 1 of each year of which 27 were collected in the current study (2010-12). Of these samples, 71 were collected from Prince William Sound (Figure 20), and 91 from Kenai Fjords (Figure 21). Of the total collected, 5 were from a sockeye salmon (*Onchorhynchus nerka*), 88 were from Coho salmon (*Onchorhynchus kisutch*), 22 were from chum salmon (*Onchorhynchus keta*) and 68 were from Chinook salmon (*Onchorhynchus tshawytscha*). No samples were obtained from pink salmon (*Oncorhynchus gorbuscha*) despite their frequent abundance in the areas of prey collection.

Figure 20. Species distribution of scales collected during southern Alaska resident killer whale predation events in Prince William Sound, Alaska 1991-2012

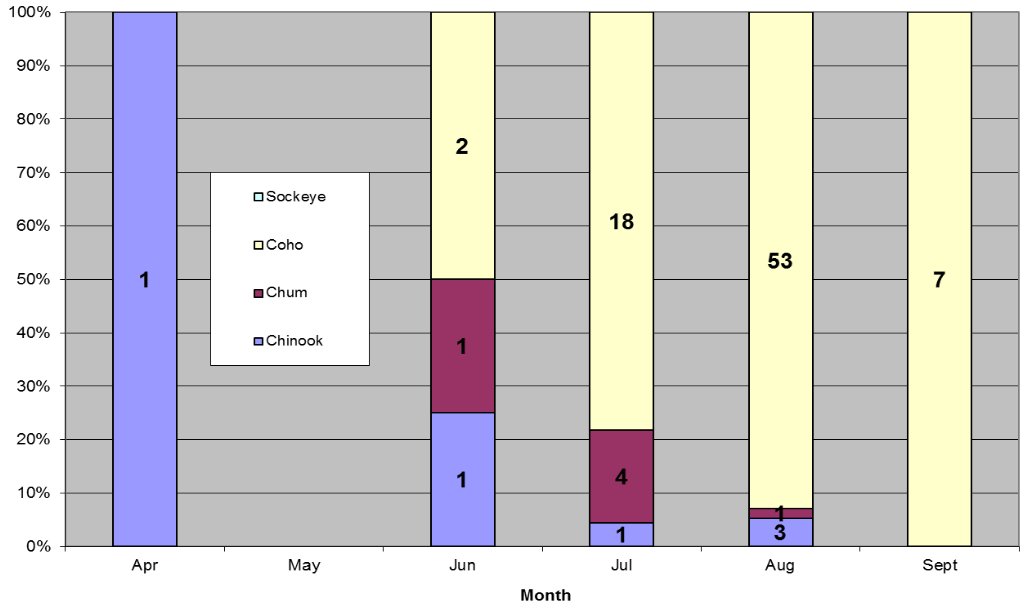
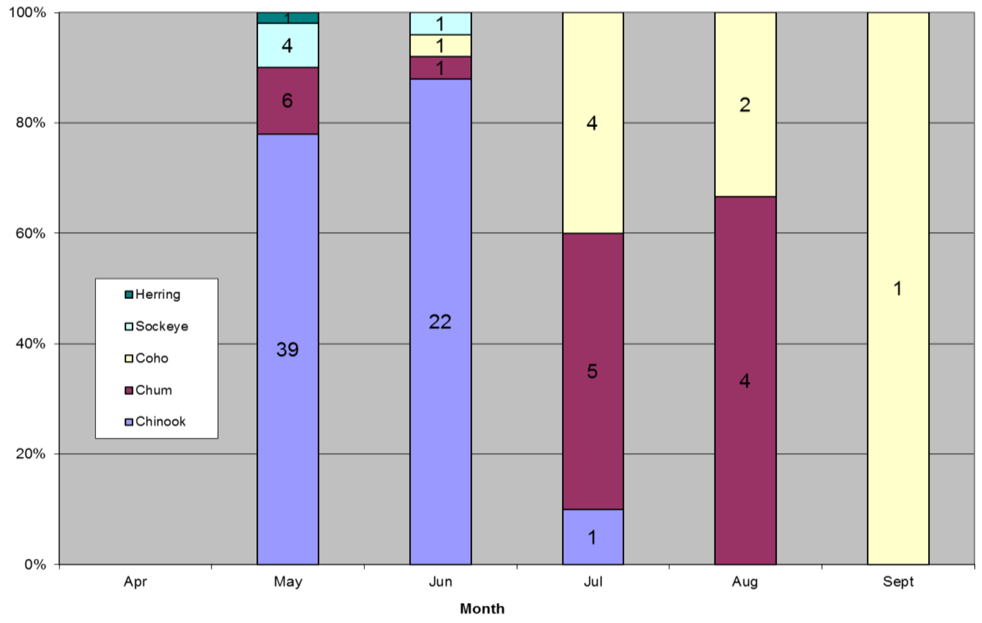


Figure 21. Species distribution of scale samples collected during southern Alaska resident killer whale predation events in Kenai Fjords, Alaska 1991-2012



Most of the Chinook predation events occurred in May or early June in Kenai Fjords. Unfortunately there is limited data from this period from Prince William Sound, although, the one late April sample from the Sound was a Chinook (Fig 13,14). Although sample size is small, in Kenai Fjords in July-September it appears chum and Coho salmon are predominant prey. In Prince William Sound there is some predation on Chinook and chum in June, July, and August, however; predation is primarily on Coho after June and Coho was the only prey species recorded in September (n= 7). The five sockeye predation events occurred in Kenai Fjords in May and June.

Observation of kills and harassments (transient killer whales)

During the entire course of our study, 1984-2009 a total of 66 predation events and 91 harassment (no kill observed) events by transient killer whales were observed. These were split between the Gulf of Alaska (GOA) transient population and the depleted AT1 transient population (Table 11).

The AT1 transients preyed almost exclusively upon harbor seals and Dall's porpoise consistently throughout the study period, although two harbor porpoise and one northern fur seal were also documented prey (this study). Most of the unidentified prey items were thought to have been harbor seals although some may have been harbor porpoise. The Gulf of Alaska transients were rarely observed preying on Dalls porpoise (twice) or harbor seals (twice), but seemed to focus on Steller's sea lions in both Prince William Sound and Kenai Fjords, at least during our inshore biased observations. In our Maniscalco et al (2007) paper, Steller sea lions were determined primary prey for groups of GOA transients that visited Kenai Fjords, however, the rate of predation was not thought to have caused the decline of Steller sea lions, nor did it appear large enough to prevent recovery.

Table 11. Summary of predation and harassment events for Gulf of Alaska and AT1 transient killer whales.

Gulf of Alaska (GOA) Transients 1984-2012

	Kill	Harass	Total
Steller sea lions	13	29	42
Dall's porpoise	3	3	6
Sea Otter	1	5	5
Harbor seal	2	0	2
Birds	9	6	15
Humpback	0	2	2
Harbor porpoise	2	0	2
UnID	2	0	2
TOTAL	**30**	**43**	**71**

Note: Three Steller sea lion kills were observed in Kodiak I. waters

1 harbor seal and 2 harbor porpoise kills were in Kachemak Bay.

AT1 transients 1984-2012

	Kill	Harass	Total
Harbor seal	15	13	28
Dalls Porpoise	13	8	20
Steller Sea Lion	0	14	14
Harbor porpoise	2	0	2
Northern Fur Seal	1	0	1
UnID Marine Mammal	9	3	12
Humpback Whale	0	8	8
Sea Otter	0	3	3
River Otter	0	1	1
Salmon	0	1	1
TOTAL	**39**	**48**	**85**

Most harbor seal kills (n = 15) occurred beneath the water's surface and were detected by the appearance of blubber fragments, hair, and oil on the surface. When prey was uncertain we attempted to identify it genetic analysis of tissue. Seabirds often investigated the kill sites and sometimes alerted us to their presence. In contrast, Dall's porpoises kills (n=13) involved highly visible surface chases. All but three harbor seal kills occurred during near-shore foraging, and all Dall's porpoise kills occurred during offshore foraging. Transients spent 21.5% of their time near-shore foraging and 23.8% of their time offshore foraging, suggesting they spent nearly an equal amount of time hunting for seals as for porpoises.

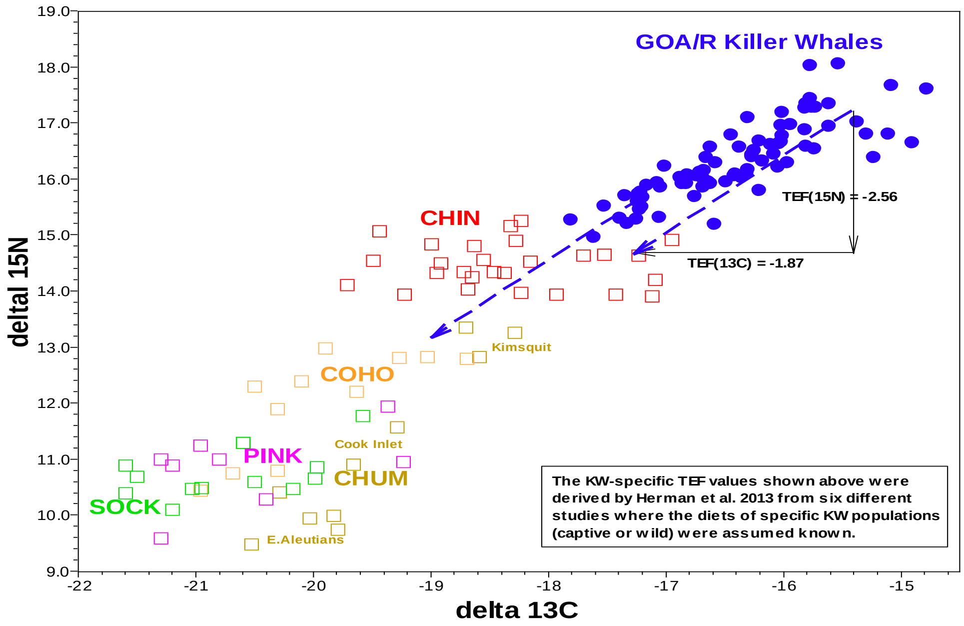
Chemical analysis of killer whale blubber and skin

A total of 134 biopsy samples were collected in Prince William Sound/Kenai Fjords from 2003 to 2012 for chemical analysis (34 of them during the 2010-2012 study period). Of these, 110 samples had a sufficient amount of skin and/or blubber tissue available for the complete suite of chemical analyses presented here. All chemical analyses and subsequent statistical anlaysis were completed at the Northwest Fisheries Science Center (Environmental Assessment Program).

The southern Alaska resident killer whales exhibit a wide range of stable isotope values with 15N values ranging from 15.0 – 18.1‰, This indicates that they forage on a mix of prey occupying widely differing trophic positions (ΔTL = 1.2, Figure 22.).

If we assume that the prey (at least in spring, summer and fall) is primarily salmonids as suggested by our sampling of scales from predation sites, then animals exhibiting high 15N values are consistent with predation on predominantly Chinook salmon; animals having low 15N values are consistent with predation on a mix of chinook and some lower trophic level prey such as coho and/or chum salmon.

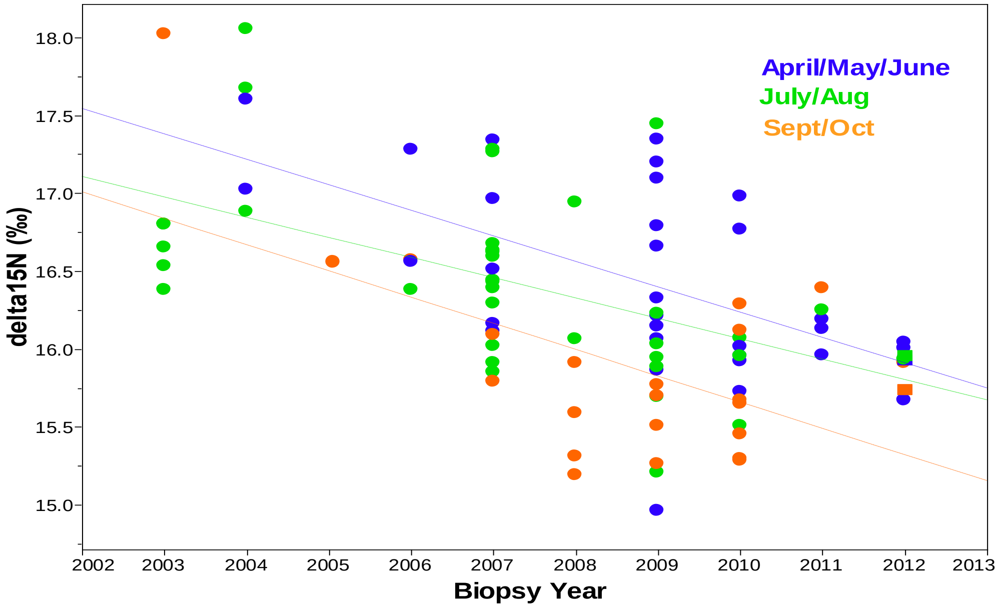
Figure 22. Stable Isotopes in Southern Alaska Resident killer whales relative to putative salmon prey



The KW-specific TEF values shown above were derived by Herman et al. 2013 from six different studies where the diets of specific KW populations (captive or wild) were assumed known.

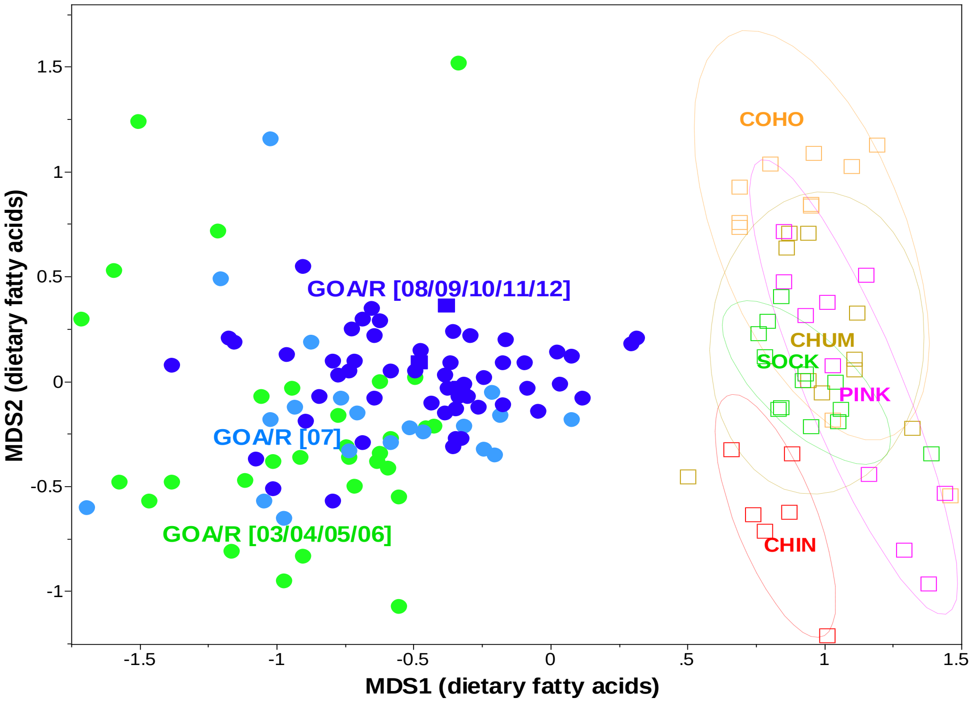
On average, the trend in 15N stable isotope values has been one of decline over the past decade (Figure 23) This is suggestive of either a shift in prey consumed with time (e.g., less chinook, more coho/chum) and/or a lowering in 15N isotopes at the base of the food-chain in the Gulf of Alaska.

Figure 23. Decline in 15N stable isotopes with time (*inter-annual*) for all southern Alaska resident killer whales analyzed to date.



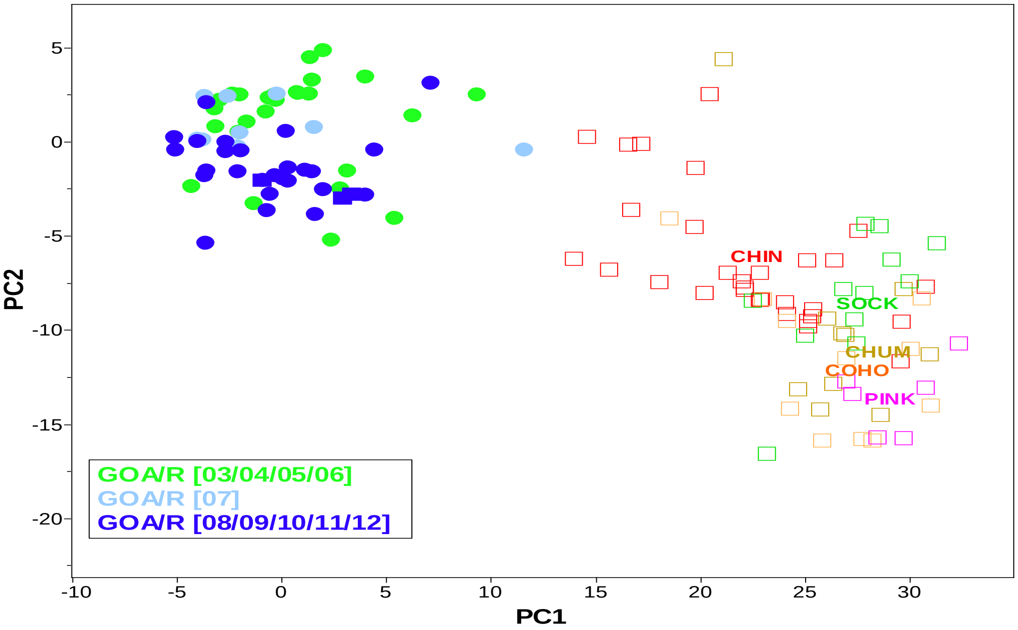
The composition of dietary fatty acids measured in the blubber of these whales have also shifted over the last decade and are consistent with consumption of a greater amount of coho and/or chum salmon (less chinook) in recent years (Figure 24).

Figure 24. Multidimensional Analysis of the pattern of dietary Fatty Acids measured in GOA/R killer whales relative to their putative salmonid prey *(killer whales color-coded by biopsy year)*



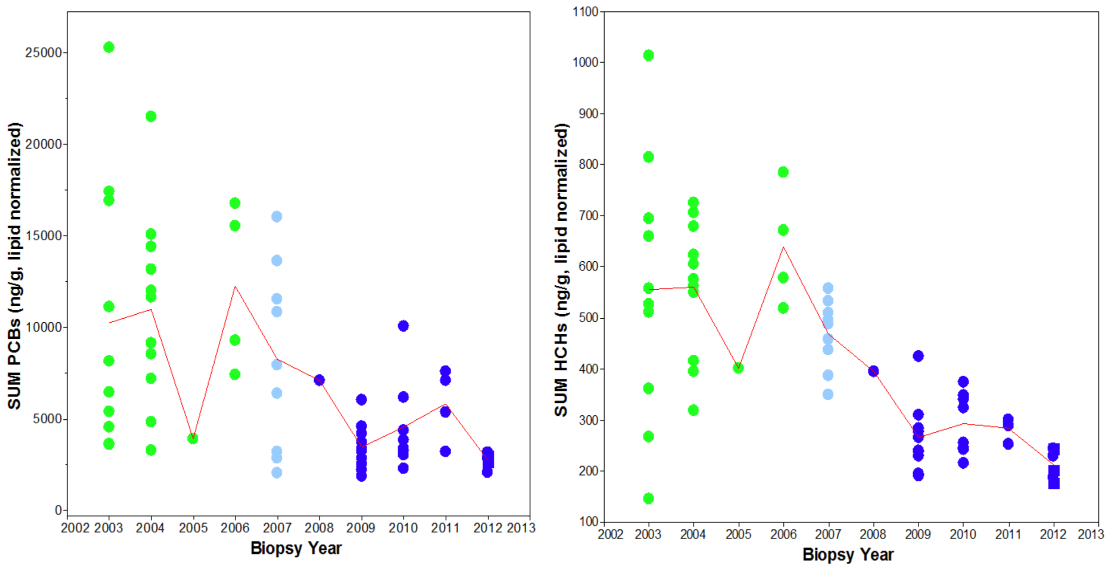
Similar to both stable isotopes and dietary fatty acids, patterns in contaminant data (Figure 25) supports the hypothesis prey of southern Alaska resident killer whales has shifted over the past decade in a manner qualitatively consistent with a transition from predominantly Chinook to increasing amounts of coho, chum, or other salmonid.

Figure 25 Principal Component Analysis depicting inter-annual changes in PCB congener levels measured in the blubber of Gulf of Alaska resident killer whales relative to putative salmonid prey *(Males Age<10yrs excluded from this analysis)*



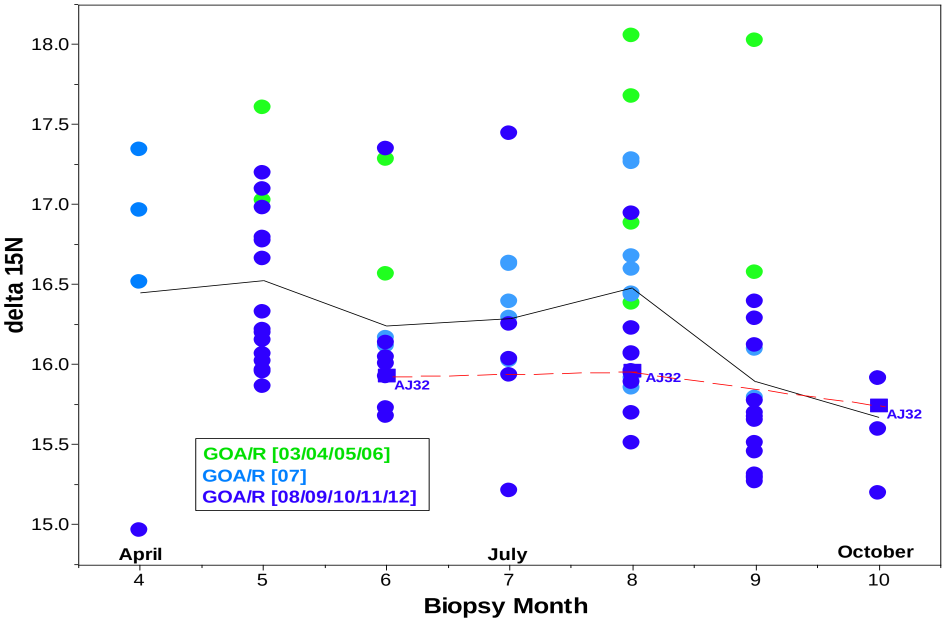
Contaminant analysis also supports a change in diet from more contaminated to less contaminated prey over the last decade. Lipid normalized PCBs have decreased in concentration by about a factor of 4 over the decade (Figure 26) consistent with transition from more highly contaminated Chinook to less contaminated chum, coho, or other prey. Lipid normalized HCHs have decreased in concentration by about a factor of 3 over the decade. Sum DDTs and Sum CHLRs (not plotted) exhibit very similar annual trends to the Sum PCBs shown here. Although part of this decrease is likely due to the slow decline in PCB and other contaminant concentrations throughout the entire ecosystem over time, the changes are far beyond the bounds of natural decline. Because of this sharp decline, since about 2006 all sampled males age>10 have demonstrated SUM PCB concentrations below the ~17,000ng/g toxic effects threshold for PCBs in marine mammal blubber.

Figure 26. Change in concentrations of selected contaminants with time (*inter-annual*) for GOA/R killer whales *(Males Age<10yrs excluded in this analysis)*



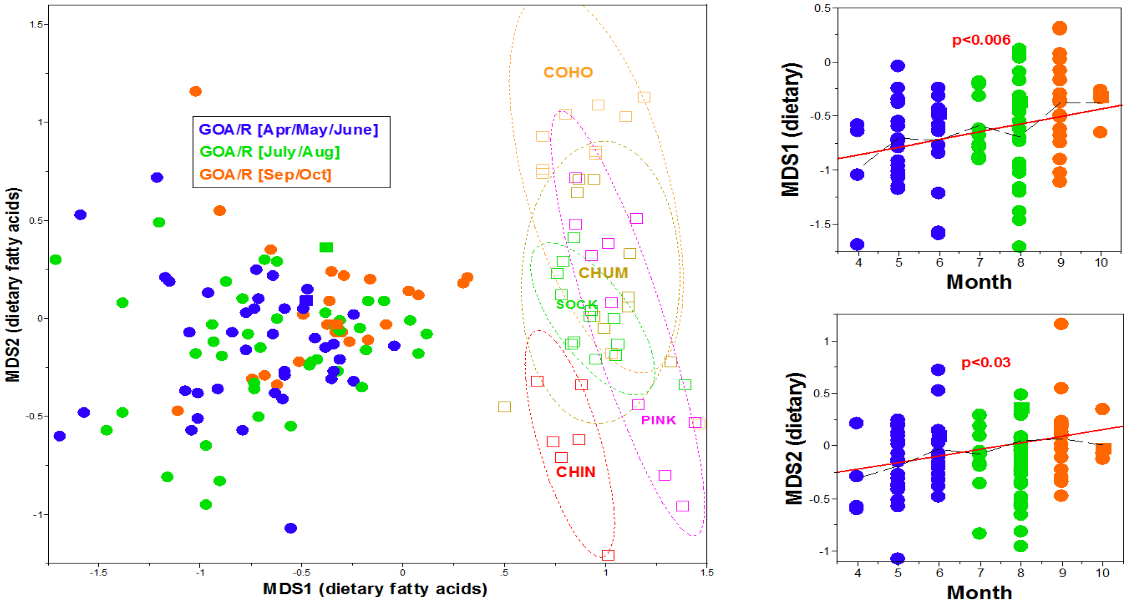
Southern Alaska resident killer whale 15N values are observed to decline slightly from spring to fall which is consistent with a shift from predominantly chinook in the spring to a diet that includes increasing quantities of coho and/or chum salmon as the year progresses. The levels for AJ32 were projected (SI machine unavailable) from fatty acid data and shows the decline in 15N over the season, although initial sample may not reflect true 15N level due to low fatty acid content (Figure 27).

Figure 27. Change in 15N stable isotopes with time (*seasonal*) for all GOA/R killer whales analyzed to date *(killer whales color-coded by collection years)*



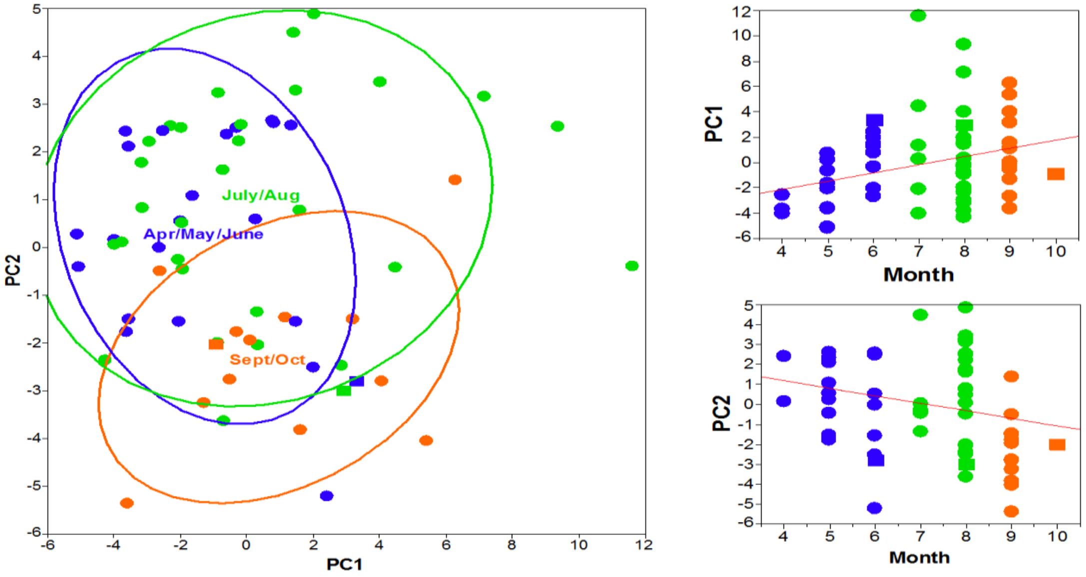
The patterns of dietary fatty acids measured in GOA/R killer whales also change throughout the year (seasons) and are consistent with a shift from predominantly chinook salmon in the spring to increasing amounts of coho/chum in the late summer and early fall months (Figure 28).

Figure 28. Multidimensional Analysis of the pattern of dietary fatty acids measured in GOA/R killer whales relative to their putative salmonid prey *(killer whales color-coded by season)*



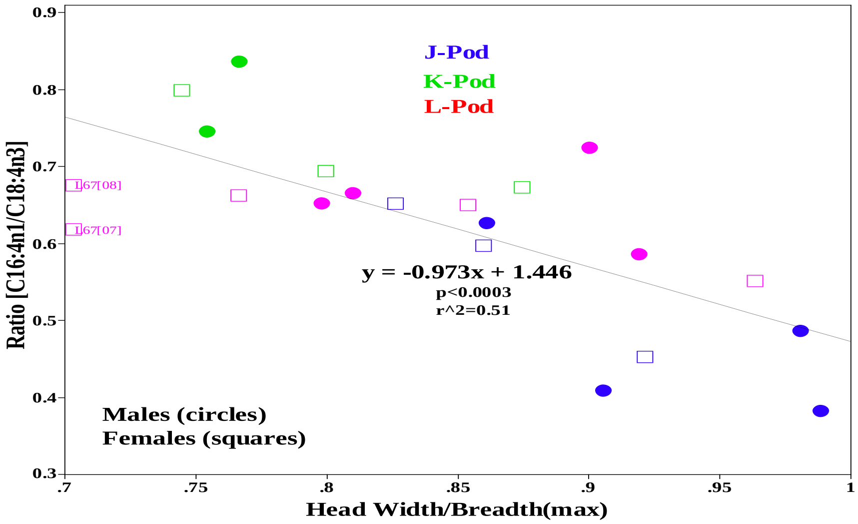
The principal component analysis of PCB congeners also supports the hypothesis developed from scale sampling at kill sites, that there is a change in diet for southern Alaskan resident killer whales over the course of the season (Figure 29). It is a decrease in PC2 that has made the major contribution to this change and since the PC2 levels in Chinook salmon are higher than all other species of salmonid prey it suggests a decrease in Chinook consumption and increase in consumption of other salmonids (chum, coho)

Figure 29 . Principal Component Analysis depicting how the pattern of PCB congeners measured in the blubber of Gulf of Alaska resident killer whales change over the season *(Males Age<10yrs excluded from this analysis)*



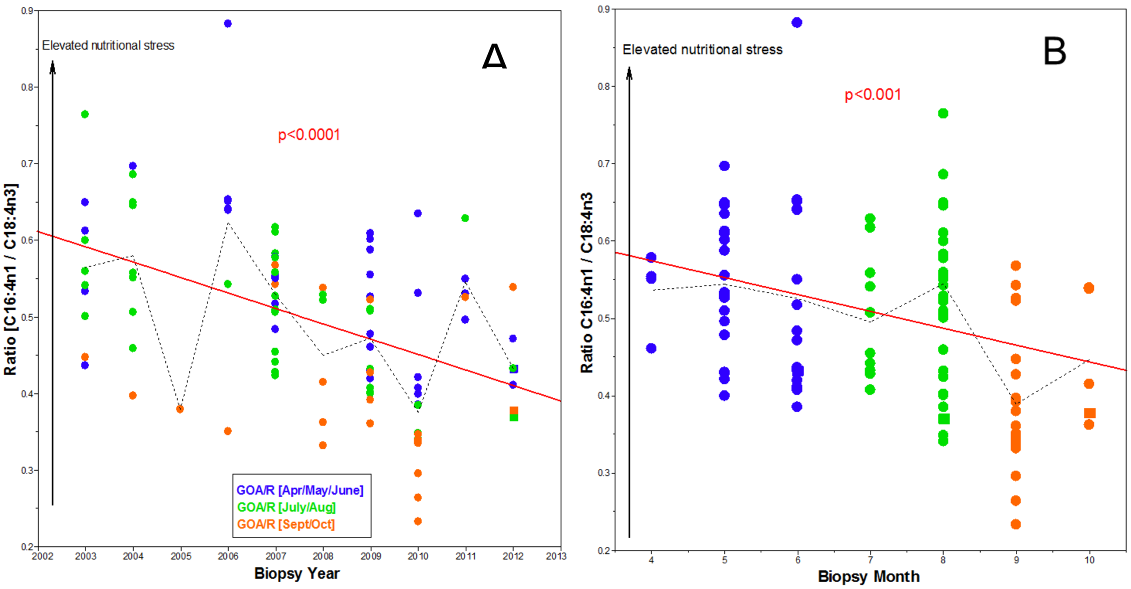
In the Puget Sound Southern Resident killer whale population, photogrammetrically measured small neck width to body breadth ratios have been thought to indicate nutritional stress. The relationship of this indicator corrleates with the fatty acid ratio C16:4n1/C18:4n3 which may serve as a biomarker of nutritional stress in resident killer whales (Figure 30).

Figure 30. Blubber fatty acid ratio exhibiting the highest correlation with SRKW "peanut-head" head/neck width to girth ratios



We observed that our hypothesized C16:4n1/C8:4n3 nutritional stress indicator decreases with time (both annually & seasonally) suggesting that: (1) there appears to have been an overall slight improvement in nutritional status in more recent years with 2010 being a particular good feeding year (this year had above average recruitment as well that extended into 2011), (2) the nutritional status of these whales appears to be poorest in the early spring months but improves somewhat throughout the year (spring to fall) (Figure 31).

Figure 31. Change in nutritional stress with time (*inter-annual & seasonal*) for GOA resident killer whales as indicated by the SRKW peanut-head fatty acid biomarker [C16:4n1/C18:4n3]



Discussion

Sampling of prey of offshore killer whales suggests that the movement of this unique population of killer whales northward into the Gulf of Alaska is related to predation on Pacific sleeper sharks. Although these whales do not prey only on sharks (Dahlheim et al 2008), it is apparent that sharks are a major component of the diet and may result in the excessive tooth wear found exhibited by these whales; the denticles in shark skin wearing away the teeth (Ford et al 2011). Shark livers are large and lipid rich and are apparently sought by the killer whales. The whales appear to dive deep to find the sharks, but we have not yet attached a depth recording tag to an offshore killer whale.

Observation of predation by transient killer whales on marine mammals has followed the basic pattern observed in recent decades, although we have not made as many observations in recent years as emphasis of the study has shifted. AT1 whales were focused on harbor seals and Dalls porpoise and the Gulf of Alaska transients exhibited a broader diet that dominated by Steller sea lions in summer. Although predation on humpback whales has been observed and may be increasing in the Cook Inlet and Kodiak regions (Matkin, unpublished data) , we have not seen this in the Kenai Fjords/Prince William Sound region.

The results of our chemical analysis of southern Alaska resident killer whales remain consistent with our field sampling observations of fish remains and fish scales suggesting a greater dependence on Chinook salmon in the early season and a shift to lower trophic level salmonids (chum, coho) in later season. We use a three pronged analytical approach with stable isotopes, fatty acids, and contaminant levels all supporting this hypothesized shift. Over the past decade there has been a shift toward lower 15N levels and fatty acid ratios in SAR killer whales that reflect either changes in food chain and tropic dynamics and/or a change in killer whale feeding habits. Changes in contaminant levels also support this supposition. From data supplied by Tom Kline, Prince William Sound Science Center (personal communication) it appears there has been a slight downward shift in 15N levels in prey, but not enough to explain our observations. The primary driver in trophic change in resident killer whale is likely a change in feeding habits such as the reduction of the higher trophic king salmon in the diet. King salmon stocks have declined in most Alaskan regions (including the Gulf of Alaska) and are a major conservation concern. Ironically, the condition of SAR killer whales has improved from what we see in lipid ratios and also in recent recruitment rates. This may be a food quality as well as food quantity issue. Although king salmon are the largest salmonids with the highest oil content, coho and chum have fewer saturates and high levels of omega 3 type fatty acids and in this sense may provide a higher quality food, albeit due to their smaller size, capture may require additional effort to secure adequate caloric intake. The quantity of coho salmon available going into the winter months, may have significant impact on the ability to recruit calves which are generally born during these months. Better condition may reflect fall feeding conditions. This does not suggest that king salmon are not an important prey component that might have serious consequences for killer whales if significantly reduced in number. They are the only salmonid available nearshore in late winter and early spring. In any event, SAR killer whales do not appear under nutritional stress at this time. They are a comparative healthy population of resident killer whales in contrast to the endangered Southern resident population of Washington State/British Columbia. In that population food stress is suspected of playing a major role in the lack of recovery. The inadequate protection and decline of salmon stocks and habitat has apparently contributed to a serious decline in that population. Healthy salmon stocks are no doubt essential for southern Alaska killer whale population as well.

(Note: it was necessary at this point to project SI levels for 2011-12 due to non –availabilty of SI analytical equipment. The actual levels will be obtained upon equipment repair/replacement.)

PUBLIC OUTREACH

An integral part of our research on killer whales has involved public outreach. The North Gulf Oceanic maintains a website www.whalesalaska.org that contains links to oil spill related materials as well as updated information on field activities and findings. This website has been completely revamped in Fall 2012 although updating of materials is an ongoing process. Scientific publications as well as identification catalogues are available on the site. To provide a more immediate and interactive contact and outlet for information from recent activities, NGOS initiated a Facebook site in late 2012. This site receives regular postings regarding whale sightings and events. Both sites provide a method of contact for scientists as well as a draw for the public to learn more about and appreciate the whales. In addition, we have maintained close contact with schools, giving regular talks and presentations. We have made presentations in venues as varied as the Alaska Marine Science Symposium, Maui Whale Fest, and Pratt Museum. We work annually with tourboat operators to improve their educational programs and update their catalogues (for both killer whales and humpback whales), as well as refresh them on viewing guidelines methods to prevent harassment of whales. We have maintained another website www.alaskawhalesightings.com that permits individuals to submit photographs that can be used by researchers to identify individual whales. The site provides clear guidelines to avoid harassment of whales and provides a running summary of the whales that have been identified over the season on a near daily basis. We have published several journal articles and other popular articles during the period of this study (see STUDY HISTORY).

ACKNOWLEDGMENTS

The *Exxon Valdez* Oil Spill Trustee Council provided the bulk of the funding for this project from 2010-2012 via the National Marine Fisheries Service. Shayne MacLellan and her team at the Pacific Biological Station in Nanaimo, B.C. Canada provided identification and aging of fish scales from predation studies. Dan Olsen, Cy St Amand, L.A. Holmes, and Olga von Ziegesar made invaluable field contributions to the project. Several scientists at the NMFS Environmental Contaminant Laboratory in Seattle, WA made analytical contributions including D.G. Burrows and R.H. Boyer. Gerry Sanger provided valuable sighting information in Prince William Sound. Without the assistance of the tour boat industry and the many skilled skippers based in Seward, Alaska the success we enjoyed in the field would not have been possible. We look forward to continuing our cooperative effort in the future. To the numerous individuals that have aided in field data collection and data input over the years, we offer our sincere thanks.

LITERATURE CITED

Allen, B. M., and R. P. Angliss. 2010. Alaska marine mammal stock assessments, 2009. U.S. Department of Commerce., NOAA Technical Memorandum NMFS-AFSC-206, 276 p.

Andrews, R.D., R.T. Pitman, and L.T. Balance. 2008. Satellite tracking reveals distinct movement patterns for Type B and Type C killer whales in the southern Ross Sea, Antarctica. Polar Biol. 31:1461-1468

Baird, R.W., & Whitehead, H. (2000). Social organization of mammal-eating killer whales: group stability and dispersal patterns. Canadian Journal of Zoology, 78, 2096-2105.

Balcomb, K.C., J.R. Boran and S.J. Heimlich. 1982. Killer whales in greater Puget Sound. Reports of the International Whaling Commission. 32: 681-685.

Barrett-Lennard, L G , Ford, J K B, & Heise, K A (1996). The mixed blessing of echolocation: differences in sonar use by fish-eating and mammal-eating killer whales. Animal Behaviour, 51, 553-565.

Barrett-Lennard, L.G. 2000. Population structure and mating systems of northeastern Pacific killer whales. Ph.D. thesis, University of British Columbia, Vancouver.

Barrett-Lennard, L.G., and G.M. Ellis. 2001. Population structure and genetic variability in northeastern Pacific killer whales: toward an assessment of population viability. DFO Canadian. Science Advisory Secretariat Research Document 2001/065. 35 pp.

Bigg, M.A. 1982. An assessment of killer whale Orcinus orca. stocks off Vancouver Island, British Columbia. Reports of the International Whaling Commission 32: 655-666.

Bigg, M.A., P.F. Olesiuk, G.M. Ellis, J.K.B. Ford and K.C. Balcomb, III. 1990. Social organization and genealogy of resident killer whales Orcinus orca in the coastal waters of British Columbia and Washington State. Reports of the International Whaling Commission. Special Issue 12: 383-405.

Brault, S., and H. Caswell. 1993. Pod-specific demography of killer whales Orcinus orca. Ecology 74: 1444-1454.

Caughley, G. 1966. Mortality patterns in mammals. Ecology 47: 906-18.

Cole, L.C. 1954. The population consequences of life history phenomena. Quarterly Review of Biology 29: 103-137.

Dahlheim, M.E, A. Schulman-Janiger, N. Bla ck, R Ternullo,D. Ellifrit, K. Balcomb. 2008. Eatstern temperate North Pacific offshore killer whales (Orcinus orca): Occurance, movements and insights into feeding ecology. Marine Mammal Science 24(3): 719-729

Dahlheim, M.E., Ellifrit, D.K., and Swenson, J.D. 1997. Killer whales of southeast Alaska - a catalogue of photo-identified individuals. Day Moon Press, Seattle.

Dahlheim, M.E. 1997. A photographic catalog of killer whales , Orcinus orca, from the Central Gulf of Alaska to the Southeastern Bering Sea. U.S. Department of Commerce, NOAA Technical Report NMFS 131.

Dahlheim, M.E. and C.O. Matkin. 1994. Assessment of Injuries to Prince William Sound Killer Whales in: Thomas Loughlin, ed. Marine Mammals and the ExxonValdez, AcademicPress.

Dahlheim, M.E. and J.M. Waite. 1992. Abundance and distribution of killer whales Orcinus orca. in Alaska in 1992 Annual report to the MMPA Assessment Program, Office of Protected Resources, NMFS,NOAA, 1335 East-West highway, Silver Spring MD 20910

DeMaster, D.P. 1978. Calculation of the average age of sexual maturity in marine mammals. Journal of the Fisheries Research Board of Canada. 35: 912-915.

Douglas, D. 2007. The Douglas Argos-Filter. Accessed 1 October 2007. http://alaska.usgs.gov/science/biology/spatial/manual.html

Durban, J., D. Ellifrit, M.Dahlheim, et al. 2010. Photographic mark-recapture analysis of clustered mammal-eating killer whales around the Aleutian Islands and Gulf of Alaska. Marine Biology 157: 591–1604.

Efron, B. 1982. The jackknife, the bootstrap, and other resampling plans. Society of Industrial and Applied Mathematics CBMS-NSF Monographs, 38.

Ellis, G.M., Towers, J.R., and Ford, J.K.B. 2011. Northern resident killer whales of British Columbia: Photo-identification catalogue and population status to 2010. Canadian Technical Reports of Fisheries and Aquatic Sciences 2942: v 71 p (available from http://www.dfo-mpo.gc.ca/Library/343923.pdf)

Ford, John K. B., Graeme M. Ellis, Craig O. Matkin, Michael H. Wetklo, Lance G. Barrett-Lennard, Ruth E. Withler. 2011. Shark predation and tooth wear in a population of northeastern Pacific killer whales. Aquat Biol 11:213-224

Ford, J.K.B, G.M. Ellis, P.F. Olesiuk, and K.C. Balcomb. 2010. Linking killer whale survival and prey abundance: food limitation in the oceans' apex predator? Biology Letters, 6:139-142.

Ford, J.K.B., G.M. Ellis and K.C. Balcomb. 2000. Killer Whales: the Natural History and Genealogy of Orcinus orca in the Waters of British Columbia and Washington. UBC Press and University of Washington Press, Vancouver, BC and Seattle, WA.

Ford, J.K.B., G.M. Ellis, L.G. Barrett-Lennard, A.B. Morton, R.S. Palm and K.C. Balcomb III. 1998. Dietary specialization in two sympatric populations of killer whales Orcinus orca in coastal British Columbia and adjacent waters. Canadian Journal of Zoology 76: 1456-1471.

Ford, J. K. B. (1991). Vocal traditions among resident killer whales (Orcinus orca) in coastal waters of British Columbia. Canadian Journal of Zoology, 69, 1454-1483.

Felleman, F.L., J.R. Heimlich-Boran, and R. Osborne 1991. The feeding ecology of killer whales (Orcinus orca) in the Pacific Northwest. Pages 113-147 in Pryor, K. and K. S. Norris, eds. Dolphin Societies: discoveries and puzzles. University of California Press, Berkeley, Ca.

Fuller, T. K. 1989. Population dynamics of wolves in North-Central Minnesota. Wildlife Monographs. 105.

Guinet, C., P. Domenici, R. de Stephanis, L. Barrett-Lennard, J. K. B. Ford, P. Verborgh. 2007. Killer whale predation on bluefin tuna: exploringthe hypothesis of the endurance-exhaustion technique. Mar Ecol Prog Ser 347: 111–119

Hanson MB, Baird RW, Ford JKB, Hempelmann-Halos J, Van Doornik DM, Candy JR, Emmons CK, Schorr GS, Gisborne B, Ayres KL, Wasser SK, Balcomb KC, Balcomb-Bartok K, Sneva JG, and Ford MJ (2010) Species and stock identification of prey consumed by endangered “southern resident” killer whales in their summer range. Endangered Species Research 11: 69–82.

Harvey JT, Dahlheim ME (1994) Cetaceans in oil. In: LoughlinTR (ed) Marine mammals and the ‘Exxon Valdez’.

Heise K, Barrett-Lennard LG, Saulitis EL, Matkin CO, Bain D (2003) Examining the evidence for killer whale predation on Steller sea lions in British Columbia and Alaska. Aquat Mamm 29:325–334

Herman DP, Burrows DG, Wade PR, Durban JW, Matkin CO, and others (2005) Feeding ecology of eastern North Pacific killer whales (Orcinus orca) from fatty acid, stable isotope, and organochlorine analyses of blubber biopsies. Mar. Ecol. Prog. Ser. 302:275-291.

Herman DP, Nowinski AK, Burrows DG, Tilbury KL, and Hobbs RC (2009) Assessing the feeding ecology of beluga whales in Cook Inlet Alaska using chemical tracers. 2nd biennial Northwest Fisheries Science Center Symposium, Seattle WA, February 2009 (poster presentation).

Hoelzel, A.R., and G.A. Dover. 1991. Genetic differentiation between sympatric killer whale populations . Heredity 66: 191-195.

Hoelzel, A.R., M. Dahlheim and S.J. Stern. 1998. Low genetic variation among killer whales Orcinus orca. in the eastern North Pacific and genetic differentiation between foraging specialists. Journal of Heredity 89: 121-128.

Hoelzel, A. R., J. Hey, M.E.Dahlheim, C. Nicholson, V.N. Burkanov, and N.A. Black 2007. Evolution of population structure in a highly social top predator, the killer whale. Molecular Biological Evolution 24: 1407–1415.

Hoyt, E. 1981. Orca, the whale called killer. E.P Dutton, New York, New York.

Iverson SJ, Field C Bowen WD, and Blanchard W (2004) Quantitative fatty acid signature analysis: a new method of estimating predator diets. Ecol. Monogr. 74:211-235.

Kaeriyama, M., H. Seo, and H. Kudo. 2009. Trends in run size and carrying capacity of Pacific salmon in the North Pacific ocean. North Pacific. Anadromous FisheriesCommission Bulletin No. 5:293-302.

Krahn MM, Herman DP, Ylitalo GM, Sloan CA, Burrows DG, and others (2004) Stratification of lipids, fatty acids and organochlorine contaminants in blubber of white whales and killer whales. J. Cetacean Res. Manage. 6:175-189.

Krahn MM, Herman DP, Matkin CO, Durban JW and others (2007) Use of chemical tracers in assessing the diet and foraging regions of eastern North Pacific killer whales. Mar. Environ. Res. 63:91-114.

Leatherwood, S., C.O. Matkin, J.D. Hall, and G.M. Ellis. 1990. Killer whales, Orcinus orca, photo-identified in Prince William Bound, Alaska, 1976 through 1987. Canadian Field Naturalist 1043: 362-37l.

Lotka, A.J. 1907. Relation between birth rates and death rates. Science 26: 21-22.

Loughlin TR (ed) 1994 Marine mammals and the 'ExxonValdez'. Academic Press, San Diego, CA

MacLellan, S. E. 2004. Guide for sampling structures used in age determination of Pacific salmon. Pacific Biological Station, Fisheries and Oceans Canada, Nanaimo, British Columbia V9T 6N7.

Marsh, H., and T. Kasuya. 1986. Evidence for reproductive senescence in female cetaceans. Reports of the International Whaling Commission Special Issue 8: 57-74.

Maniscalco, J.M., C.O. Matkin, D. Maldini, D.G. Calkins, S. Atkinson. 2007. Assessing Killer Whale predation on Steller sea lions from field observations in Kenai Fjords, Alaska. Marine Mammal Science 23(2): 306-321.

Matkin C.O., Saulitis E.L, Ellis G.M, Olesiuk P., & S.D., Rice (2008). Ongoing population level impacts on killer whales following the Exxon Valdez oil spill in Prince William Sound, Alaska. Marine Ecological Progress Series, 356, 269-281.

Matkin, C.O., Barrett-Lennard, . L.G., Yurk, H., Ellifrit, D., & Trites, A.W. 2007. Ecotypic variation and predatory behavior among killer whales (Orcinus orca) off the eastern Aleutian Islands, Alaska. Fishery Bulletin, 105, 74–87.

Matkin, C. O., Ellis, G. M. , Barrett-Lennard, L. G. , Yurk, H. , Saulitis, E. L. , Scheel, D. , et al. 2003. Photographic and acoustic monitoring of killer whales in Prince William Sound and Kenai Fjords, Exxon Valdez Oil Spill Restoration Project Final Report (No. Restoration Project 03012 Final Report). Homer, Alaska: North Gulf Oceanic Society.

Matkin C.O., G.M. Ellis, E.L. Saulitis, L. Barrett-Lennard and D.R.Matkin. 1999a. Killer whales of southern Alaska. North Gulf Oceanic Society, Homer, AK

Matkin, C.O., G. Ellis, P. Olesiuk and E. Saulitis. 1999b. Association patterns and inferred genealogies of resident killer whales, Orcinus orca, in Prince William Sound, Alaska. Fisheries Bulletin, U.S. 97: 900-919.

Matkin, C.O, L. Barrett-Lennard, H. Yurk, D. Ellifrit, and A. Trites. 2007. Ecotypic variation and predatory behavior of killer whales Orcinus orca. in the Eastern Aleutian Islands, Alaska. Fisheries Bulletin, U.S. 105:74-87.

Matkin, C.O., G.M. Ellis, E.L. Saulitis, P. Olesiuk, and S.D. Rice. 2008. Ongoing population-level impacts on killer whales Orcinus orca. following the Exxon Valdez oil spill in Prince William Sound, Alaska. Marine Ecological Progress Series 356:269–281.

Matkin, C.O., Graeme Ellis, David Herman, Eva Saulitis, Russel Andrews, Allison Gaylord, and Harald Yurk 2010. Monitoring, Tagging, Acoustics, Feeding Habits and Restoration of Killer Whales in Prince William Sound/Kenai Fjords 2003-2009. North Gulf Oceanic Society, Homer, Alaska

Matkin, C.O., Graeme Ellis, David Herman, Eva Saulitis, Russel Andrews, Allison Gaylord, and Harald Yurk 2010. Monitoring, Tagging, Acoustics, Feeding Habits and Restoration of Killer Whales in Prince William Sound/Kenai Fjords 2003-2009. North Gulf Oceanic Society, Homer, Alaska

Matkin, C.O., J.W. Durban, E.L. Saulitis, R. D. Andrews, J.M. Straley, D.R. Matkin, G.M. Ellis 2012. Contrasting abundance and residency patterns of two sympatric populations of transient killer whales (*Orcinus orca*) in the northern Gulf of Alaska. Fish. Bull. 110:143–155.

Matkin, C.O., G.W. Testa, G.M. Ellis, and E.L. Saulitis. In press. Life history and population dynamics of southern Alaska resident killer whales (*Orcinus orca*). Marine Mammal Science

Mech, L. D. 1970. The wolf, the ecology and behavior of an endangered species. Doubleday, New York, New York, USA.

Olesiuk, P.F., M.A. Bigg, and G.M. Ellis. 1990. Life history and population dynamics of resident killer whales Orcinus orca. in the coastal waters of British Columbia and Washington. Reports of the International Whaling Commission Special Issue 12: 209-242.

Olesiuk, P.F., G.M. Ellis, and J.K.B. Ford. 2005. Life history and population dynamics of resident killer whales Orcinus orca. in the coastal waters of British Columbia Research Document 2005/045. Fisheries and Oceans Canada, Nanaimo, B.C. Canada

Parsons, K., J. Durban, A. Burdin, et al. in press. Ecological specialization and the genetic structuring of killer whale populations in the northern North Pacific. Journal of Heredity.

Peterson CH, Rice SD, Short JW, Esler D, Bodkin JL, Ballachey,BE, Irons DB 2003 Long-term ecosystem responseto the ‘Exxon Valdez’ oil spill. Science 302:2082–2086

Peterson, R. O., J. D. Woolington, and T. N. Bailey. 1984. Wolves of the Kenai Peninsula, Alaska. Wildlife Monographs 88:1-52.

R Development Core Team. 2010. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3—900051-07-0, URL http://www.R-project.org.

Rice SD, Spies RB, Wolfe DA, Wright BA (eds) 1996 Proc Exxon Valdez Oil Spill Symp. Am Fish Soc, Bethesda, MD

Saulitis, E. L., C. O. Matkin, K. Heise, L. G. Barrett-Lennard, and G. M. Ellis. 2000. Foraging strategies of sympatric killer whale, Orcinus orca, populations in Prince William Sound, Alaska. Marine Mammal Science 16:94-109.

Seaman, D.E. and R.A. Powell. 1996. An evaluation of the accuracy of kernel density estimators for home range. Ecology. 77: 2075-2085.

Silverman, B. W. 1986. Density estimation for statistics and data analysis. Chapman and Hall, London, UK.

Scheel D., C.O. Matkin, and E.L. Saulitis. 2001. Distribution of killer whale pods in Prince William Sound, Alaska over a thirteen-year period, 1984–1996. Marine Mammal Science 17:555–569.

Schell DM, Barnett BA, and Vinette KA. (1998) Carbon and nitrogen isotope ratios in zooplankton of the Bering Shukchi and Beafort seas. Mar. Ecol. Prog. Ser. 162:11-23.

Sloan CA, Brown DW, Pearce RW, Boyer RH, Bolton JL, Burrows DG, Herman DP, Krahn MM
(2005) Determining aromatic hydrocarbons and chlorinated hydrocarbons in sediments and tissues using accelerated solvent extraction and gas chromatography/mass spectrometry. In Techniques in Aquatic Toxicology. CRC Press, Boca Raton, FL.

Testa J.W., K.J. Mock, C. Taylor, H. Koyuk, Coyle J and Waggoner R. 2012. Agent-based modeling of the dynamics of mammal-eating killer whales and their prey. Marine Ecological Progress Series 466: 275-291.

Yurk, H., L.G. Barrett-Lennard, J.K.B. Ford , and C.O. Matkin. 2002. Cultural transmission within maternal lineages: vocal clans in resident killer whales in southern Alaska. Animal Behaviour 63:1103–1119.

Yurk H 2005 Vocal culture and social stability in resident killer whales (*Orcinus orca*) of the Northeastern Pacific. PhD thesis, University of British Columbia, Vancouver