PHENOLOGICAL EFFECTS ON SOUTHERN RESIDENT KILLER WHALE
POPULATION DYNAMICS

By

MIKA KENIN HALLÉ OGILVIE

B.Sc., University of Victoria, 2004

A thesis submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

in

ENVIRONMENT AND MANAGEMENT

We accept this thesis as conforming
to the required standard

....
Dr. Anna Hall, Thesis Supervisor
Royal Roads University (Adjunct Professor)

....
Dr. Matt Dodd, Thesis Coordinator
School of Environment and Sustainability

....
Dr. Ann Dale, Director
School of Environment and Sustainability

ROYAL ROADS UNIVERSITY

July 2019

Abstract

Southern resident killer whale survival is threatened by a variety of known risk factors, but more likely exist. As this population lives entirely within the coastal Pacific waters of North America, the ocean environment may play a role in their survival. Killer whale life history population dynamics, reproductive success and neonate survival were evaluated for links to five physical oceanographic parameters: salinity, sea surface temperature, air pressure, wave height and wave period. This phenological study was conducted within the Canadian waters of the Salish Sea in the federally identified critical habitat. The timings of physical changes were analysed annually and seasonally over temporal periods of positive and negative population trajectories. Significant relationships were found in all cases, most notably with ocean salinity and air pressure. These findings shed light on the biophysical phenological relationships in killer whale survival and should be incorporated into future recovery actions.

Table of Contents

List of Figures

List of Tables

List of Appendices

Acknowledgements

The completion of this thesis is due in no small part to the support of family, friends and co-workers. Thank you to Jane Cogan, Lisa Moorby and Ken Balcomb from the Center for Whale Research and Dr. Richard Thomson from the Institute of Ocean Sciences for providing the data sets that form the basis of this thesis. Much appreciation to Fisheries and Oceans Canada and Michelle Bigg for filling in the gaps. Thank you to Royal Roads University and to Chris Ling for the understanding and accommodations that allowed me to persevere. I am very grateful to Eagle Wing Whale and Wildlife Watching Tours and the Wild 4 Whales Foundation for supporting me, my co-workers (especially Valerie Shore) for picking up the slack, and Brett Soberg for always making sure I had everything I needed to keep going these past few years.

Thank you to my family for bearing with me through this journey. The support and encouragement of my grandparents, Irene and Keith, paved the way for success. Thank you to Casey Ogilvie, Reagan Sutherland and Jean Ogilvie for understanding when I was not as present as I should have been. I am so grateful to my parents, Francine Hallé and Keith Ogilvie, for playing such active roles as grandparents while I was working on my thesis, and to the love of my life, my daughter Lily, in whose debt I will forever remain, for her understanding, patience and maturity as I worked through this process during the first five years of her life. She is my joy and I am so proud of her.

Perhaps most importantly, a heartfelt thank you to my supervisor, co-worker and friend, Dr. Anna Hall. It has been a long journey, but her unwavering support and encouragement never waned. She has gone above and beyond to help me down this path from the moment we first met, and I will be forever grateful for her support as both a friend and mentor over the years. Thank you for believing in me.

Introduction

The Earth's climate and physical processes have a powerful effect on the organisms that have evolved in a delicate balance with their environment. Environmental change can have profound effects on biological systems and tip the balance in favour of one species over another. Some species thrive, while others do not. This process was described over a century ago as the Theory of Evolution by Natural Selection by Charles Darwin (1859). Species survival depends on the synchrony between adaptation and the rate of change.

The effects of contemporary climate change are becoming increasingly evident as marine species are occurring outside their usual ranges. In 2016, a Guadalupe fur seal (*Arctocephalus townsendi,*) and a green sea turtle (*Chelonia mydas*) were each rescued off Vancouver Island, British Columbia (BC) far beyond their regular south Pacific range, both suffering the effects of their extralimital excursions (Vancouver Aquarium, 2016a; Vancouver Aqurium 2016b). Similarly, a Humboldt squid (*Dosidicus gigas*) was found by BC fishermen, having strayed from its usual California habitat (Hume, 2018), and reviews of shark species present in BC waters suggest that these anomalies may become increasingly more common (Brown, 2018). While the stimuli remain unknown, the results are clear—individuals and species being found far beyond their usual range limits in physical conditions to which they are not adapted. Improving our understanding of the biophysical relationships between marine species and their ocean environment may provide insight into why these types of events happen, and the potential future effects of a changing ocean climate on species distribution and survival.

This understanding is particularly important for species that occur at the edges of their ranges or those with precarious conservation statuses. Biophysical evaluations should not only include the effects at the species or population level, but also on species life cycles. For species

or populations that are already reduced in numbers, this is even more crucial to effect meaningful

conservation actions.

Phenology

Phenology is the study of the cyclic events that occur during the life histories of plant and

animal species and encompasses a wide range of events including migration, mating, parturition,

and foraging. Walther et al. (2002) defines phenology as "the timing of seasonal activities of

animals and plants". These events can often be very closely linked to physical factors such as

temperature, water availability and photoperiod length (Badeck et al., 2004). Recognising such

connections and the timing of these events can be subtle, such as phytoplankton growth and

invertebrate larval development (Poloczanska et al., 2016), or can be conspicuous, such as the

seasonal migrations of birds and butterflies (Cotton, 2003; Diamond, Frame, Martin, & Buckley,

2011). As our collective knowledge of natural and physical phenomena increases, so too does

our awareness of the cycles that may be affected. This includes the potential exacerbation by

anthropogenic contributions that are now recognised by most scientists and referred to as climate

change.

Tracking species phenology is essential to conservation biology and management

(Badeck et al., 2004), and is especially important to evaluate the biological and ecological effects

of climate change. Impacts can be both far-reaching and indirect and may occur throughout

different trophic levels (Lusseau et al., 2004). With this, there is the potential for a cascade

effect throughout the food web as the timing of life history events may no longer coincide with

the physical conditions that are suitable for particular species. Without research or monitoring,

the effects of contemporary climate change on individual species or populations are at risk of

occurring unnoticed and undocumented.

Globally, temperatures are shifting from their traditional norms and the timing of ecological and biological processes are being affected (Walther et al., 2002; Cotton, 2003; Crozier et al., 2008). "Anthropogenically induced global climate change has profound implications for marine ecosystems and the economic and social systems that depend on them." (Harley et al., 2006). However, temporal events such as the El Nino Southern Oscillation (ENSO) can complicate detection of true shifts in long-scale patterns (Badeck et al., 2004). The contributions each makes to the ocean environment can be difficult to determine, but the magnitude and timing of water temperature changes have been found to be important indicators of climate change in marine ecosystems (Bailleul, Lesage, Power, Doidge, & Hammill, 2012; Bograd et al., 2009). This highlights the importance of long-term research and the resulting data sets in characterising cyclic and non-cyclic events and consequences, particularly for species that occupy expansive ecosystems that span geopolitical boundaries.

Phenology plays a particularly critical role in boundary ecosystems such as the California Current Large Marine Ecosystem (CCLME) that spans from BC, Canada to Mexico (Bograd et al., 2009). The productivity of this system is largely governed by seasonal cycle of coastal upwelling (Bograd et al., 2009). Understanding phenological relationships for ocean animals, including marine mammals, could provide valuable information and aid in the early detection of potential biological changes in relation to climatic events, allowing for better planning in conservation biology and management actions. An interdisciplinary, integrated approach is necessary to ensure a comprehensive understanding of these relationships (Visser & Both, 2005). This approach was not historically used, but its importance is now becoming more evident, at least with regard to one highly public species of marine mammal that inhabits the CCLME—the killer whale (*Orcinus orca*).

Killer Whales

Killer whales, one of the top marine predators, are found in all of the world's oceans (Forney & Wade, 2006). Taxonomists currently classify all killer whales as belonging to the same genus and species, despite the recognised disparities between different groups. Killer whales are found in separate, genetically distinct populations made up of stable pods or communities with different dialects, diets, and population dynamics. Photo-identification (photo-ID) of killer whales, pioneered by Dr. Michael Bigg, has facilitated study by allowing easy recognition of individuals by the unique shapes, nicks and scars on the dorsal fin and saddle patch (Ford, Ellis & Balcomb, 2000). Killer whale photo-ID studies along the northwest coast of North America have identified three separate "ecotypes": resident, transient (also known as Bigg's), and offshore communities (de Bruyn, Tosh, & Terauds, 2013). These different ecotypes have unique prey specialisations that can be generalised to three taxonomic groups: teleost fish, mammals, and chondrichthyan fishes, respectively (Ford, Ellis, & Balcomb, 2000). Within the group that feeds on the teleost fish, the southern resident killer whale (SRKW) population has become one of the most intensely studied and publicly favoured populations of cetaceans in the world.

The southern resident population has been monitored since 1976 by the Center for Whale Research (CWR) using photo-ID techniques (Ford et al., 1998; CWR, 2018). From this, it is known that there are three pods within this small breeding group, referred to as J, K and L pods. These whales live in a matrilineal society, and individuals remain with their maternal families for life. They are sexually dimorphic from birth with different ventral pigmentation patterns, but it can take researchers time to be able to determine the gender based on these markings. Thus, as

whales age, and the more encounters that occur with scientists and other observers, the more likely it is to be able to determine whether a calf is male or female.

Dedicated research has continued in BC and Washington since the early 1970s (Ford et al., 1998) and has explored killer whale acoustics (Ford, 1991; Deecke, Ford & Spong, 2000), physiology (Noren, 2011), social structure (Parsons, Balcomb, Ford & Durban, 2009), feeding behaviour (Ford *et al*, 1998; Ford & Ellis, 2006; Hanson, Emmons, Ward, Nystuen, & Lammers, 2010), and anthropogenic effects including pollution (Ross, 2006), noise (Holt, Noren, Veirs, Emmons, & Veirs, 2009), boat traffic (Noren, Johnson, Rehder, & Larson, 2009; Williams, Trites, & Bain, 2002; Williams, Bain, Smith, & Lusseau, 2009), and pathogens (Schroeder et al., 2009). All of these are currently considered important risk factors to the survival of southern resident killer whales (Fisheries and Oceans, 2018).

This population is currently listed as *Endangered* under the Canadian Species at Risk Act (SARA, 2002) and the U. S. Endangered Species Act (ESA, 1973), and has a total population of 74 individuals (as of thesis submission July 2019). Their regular summer range comprises the nearshore waters of BC and Washington (Olesiuk, Bigg, & Ellis, 1990), but their annual distribution extends as far south as California. Within the regular summer range (often referred to as the Salish Sea; Hauser, Logsdon & Holmes, 2007) there is a growing and relatively new-found public and governmental concern for this population, but it was not always this way.

BC killer whales have had a tumultuous relationship with humans. Once considered a nuisance by fishermen, these animals were targeted and shot through unregulated predator control (Colby, 2018). This persecution shifted in the mid to late 1960s as curiosity overtook fear, and attentions turned to live captures for the global aquarium trade (Colby, 2018). During this time, 47 individuals from the southern resident population were captured—many of which

were juveniles that were easier to transport, train, house and feed—were sold to sea parks and aquaria around the world (Colby 2018). These captures removed an entire generation from this small population. There was a profound and lingering effect on the social dynamics of the southern resident killer whale population, and recovery continues today.

Recovery is dependent on a number of factors, but phenological life history events such as mating and parturition with viable neonates is crucial. As killer whales do not become reproductively able until an average 12 years of age (Robeck, Willis, Scarpuzzi, & O'Brien, 2015) and then only produce one calf every 5.3 years (on average) until reproductive senescence around age 40 (Olesiuk et al., 1990), and that up to 69% of pregnancies are unsuccessful (Wasser *et al*., 2017), the southern resident killer whale population is at an even greater survival risk despite their proximity to the human populations of southern BC and northwestern Washington.

Today, killer whales are now both culturally and economically important icons of the BC and Washington coasts. Southern resident killer whales form the foundation of a multimillion-dollar ecotourism industry that since the early 1990s, has traversed the waters of the Salish Sea in search of whales that were historically predictable during the summer and fall months. This predictability was a direct result of their phenological relationship with their primary prey.

Southern residents are not migratory but do exhibit seasonal distributional shifts that are correlated with the phenological patterns of their preferred prey—Chinook salmon (*Oncorhynchus tshawytscha*; Heimlich-Boran, 1988; Ford & Ellis, 2006). These anadromous fish have specific migration cycles (Crozier et al., 2008), and the whales' location can be predicted based on the strength and timing of the salmon runs (Shields et al., 2018). "Salmon life histories are finely tuned to local environmental conditions, which are intimately linked to climate... [This] suggests that climate change will profoundly affect salmon life histories"

(Crozier et al., 2008, p. 252–3). Since the southern resident population is food-limited

(Fearnback, Durban, Ellifrit, & Balcomb, 2011), any changes to the availability and location of

their prey are likely to affect both their distribution and population dynamics.

While southern resident killer whales used to regularly occur in the Salish Sea during the

summer months, their historic predictability has changed in recent years (Olson, Wood, Osborne,

Barrett-Lennard & Larson, 2018; Shields, Lindell & Woodruff, 2018). Since 2005 there has

been a new trend in their life history patterns marked more by their absence than presence, most

notably from April to June. These absences coincide with a decline in the Fraser River Chinook

salmon escapements, further strengthening the theory that prey (in this case, specifically spring

Chinook salmon) are an important indicator of killer whale habitat use (Shields et al., 2018).

From this, it is clear that the relationships between the physical ocean environment and the

dependent biological species must be understood to better effect conservation measures.

Research Questions and Objectives

Southern resident killer whales are listed as *Endangered* (Fisheries and Oceans Canada,

2018) due to their small population size and the number of known risk factors affecting their

survival. While much scientific effort has been expended, the phenological relationship between

the southern resident killer whale population dynamics and the ocean environment has been

largely overlooked. My M.Sc. thesis research evaluated the phenological relationships between

the population size, population trajectory, reproductive success and neonate survival with five

physical factors: ocean salinity, sea surface temperature, air pressure, wave height and wave

period.

My specific research questions were:

1. What is the relationship between the annual and seasonal levels of salinity, sea surface temperature, air pressure, wave height and wave period on southern resident killer whale population dynamics?

2. How do these physical factors relate to reproductive success?

3. Do these physical factors correlate with neonate survival?

It is my hope that the results of this study will contribute to the conservation and management of the southern resident killer whales and provide new insights into the factors affecting their long-term survival.

Methods

Study Area

The study area was within the Canadian southern resident killer whale critical habitat (Fisheries and Oceans Canada, 2018; Figure 1). Though the killer whale range also includes U.S. waters, the restriction to Canadian waters was considered representative given the oceanography of southern BC and northwestern Washington, that marine wildlife does not recognise political borders, and the large-scale influence of the CCLME on the entire Salish Sea ecosystem.
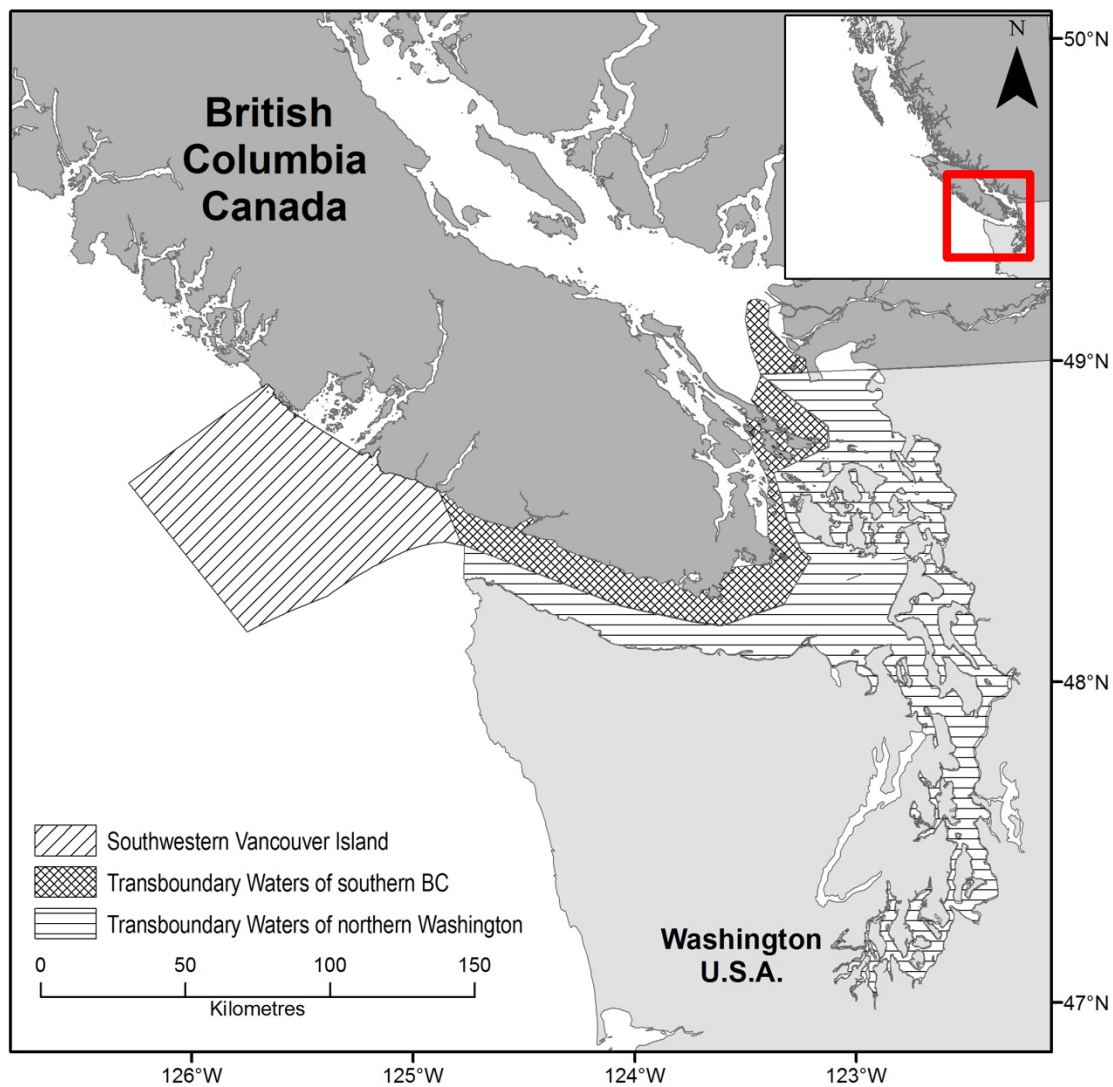
Figure 1. Critical habitat areas identified for southern resident killer whales (Fisheries and Oceans Canada, 2018).

Southern Resident Killer Whale Population Data

The CWR provided the killer whale population data (1975–2018) with each whale identified with an alpha-numeric code indicating pod membership (J, K, or L) and a chronological number within that pod (i.e., the Southern Resident Orca Survey; CWR, 2018). These data were provided in two formats:

1) the population census as of July 1 annually.

2) the total population size including all births and deaths per calendar year.

Population dynamics were extracted directly from these data with reproductive success defined as a documented live birth, and neonate survival defined as the survival of a calf past one year.

Matriline data were extracted from the Orca Survey Naturalist Guide and were based on known relationships (CWR, 2012). Individual whales were classified according to pod and matriline (Table 1).

Table 1.

Classification of individual southern resident killer whales into pod and matriline membership.

Pod	Matriline	Individual Killer Whale Alphanumeric Code
J	J8	J6 J8
	J11	J11 J25 J27 J31 J39
	J14	J1 J2 J12 J14 J23 J24 J30 J37 J40 J43 J45 J49 J55
	J16	J3 J7 J16 J26 J33 J36 J42 J48 J50 J52
	J17	J5 J13 J17 J28 J35 J44 J46 J47 J53 J54
	J19	J4 J15 J19 J21 J29 J41 J51
	J22	J9 J10 J18 J20 J22 J32 J34 J38
K	K7	K1 K2 K7
	K8	K3 K5 K8 K14 K15 K16 K23 K24 K26 K29 K32 K35 K36 K42
	K12	K4 K12 K22 K28 K31 K33 K37 K39 K41 K43
	K13	K11 K13 K20 K25 K27 K34 K38 K44
	K18	K17 K18 K21 K40 K46
	K30	K19 K30
L	L22	L22 L28 L32 L38 L44 L56 L63 L69 L75 L79 L85 L87 L89
	L11	L10 L11 L12 L41 L42 L64 L77 L94 L113 L114 L119 L121
	L25	L14 L23 L25 L49
	L2	L2 L6 L39 L67 L78 L88 L98 L101
	L26	L26 L52 L60 L71 L81 L90 L92
	L72	L7 L16 L37 L43 L53 L72 L76 L95 L104 L105
	L4	L4 L27 L55 L61 L62 L68 L80 L82 L86 L93 L96 L103 L106 L109 L112 L116 L118 L120 L123
	L15	L13 L15 L20
	L66	L8 L36 L45 L57 L66
	L47	L21 L47 L48 L83 L91 L99 L102 L107 L110 L111 L115 L122
	L9	L3 L5 L9 L33 L51 L58 L59 L73 L74 L84 L97
	L54	L1 L35 L50 L54 L65 L100 L108 L117

The life history of each killer whale was described by year of birth, year of death, maternal identification (ID), maternal year of birth, maternal year of death, maternal age at birth, maternal group, pod membership, and information on group members living at the time of the birth (Appendix A, Table A1).

Only known maternal connections (not implied/assumed) were examined. Several assumptions and modifications were required for the killer whale life history evaluation and social structure. These included:

- all birth dates prior to 1975 were all assumed to be estimates;

- estimated date of birth was considered to be actual date of birth;

- J50's death was known to occur 2018 but was not in the 2018 CWR Census data as it occurred after July 1. The 2018 data were amended such that the analytical data set was as accurate and up to date as possible.

- The following births/deaths were mentioned, but not included in the CWR data. These were assigned IDs for the purposes of this study and included in the analysis.

  o 2010 calf of L72; assigned ID of L72A

  o 2013 calf with (probable) mother J28; assigned ID of J28A

  o 2016 calf of J31; assigned ID of J31A

  o 2016 calf of K27; assigned ID of K27A

  o 2018 calf of J35; assigned ID of J35A.

- A second 2016 calf, of unknown pod/mother, was excluded due to a lack of information.

- J55, of the J14 matriline, was removed from the maternal age at birth analysis, as the mother was not identified with certainty due to the death of the neonate shortly after parturition.

The final analytical killer whale data set was evaluated with respect to population and social dynamics. Age at death (AAD) was examined between pods, by gender, and between matrilines. Maternal age at birth (AAB) and age at first calf (AFC) were examined within the population, between pods, and between matrilines. The total number of calves that reproduced,

as well as the total number of known calves per female, were also analyzed. Familial influence on AAB was examined with regard to the presence of an older female relative, an older female relative with a calf, the presence of mother and grandmother, and the number of female "helpers": females within the matriline over ten years old, as well as those who were outside the direct matriline but who have been known to closely associate with that matriline for the past four decades.

Maternal and familial influence on calf survival (AAD) were analyzed for all calves born since 1975. Intra-matriline relationships were also examined by evaluating the presence of an older female, whether that older female had a living calf at the time of the birth, whether the previous generations were still alive (i.e., if a calf had a grandmother and great-grandmother alive at the time of birth), as well as the number of adult female helpers available to the mother and neonate.

Oceanographic Data

A request for physical oceanographic data was made to the Institute of Ocean Sciences, Sidney, BC. Salinity, sea surface temperature (SST), air pressure, wave height and wave period data were provided from six locations in the study area. These oceanographic data collection sites were Race Rocks and Entrance Island coastal lighthouses and four at-sea meteorological buoys (MB): MB 46087 (Neah Bay), MB 46088 (New Dungeness), MB 46146 (Halibut Bank) and MB 46206 (La Perouse Bank; Figure 2).

Entrance Island lighthouse is located off the northeastern tip of Gabriola Island, in the Strait of Georgia (49°12'32.8" N 123°48'31.0" W; Figure 2). Race Rocks lighthouse is located on a small rocky island at the southernmost tip of western Canada, southwest of Victoria (48°17′52.9″ N 123°31′53.1″ W; Figure 2). Meteorological buoy 46087 (Neah Bay) is at the

entrance to Juan de Fuca Strait on the traffic separation lighted buoy JA (48°29'35" N 124°43'35"

W) in 260.6 m of water (Figure 2). MB 46088 (New Dungeness) is located 17 nautical miles

(nm) northeast of Port Angeles, Washington, in 114.3 m of water (48°20'1" N 123°9'53" W;

Figure 2). MB 46146 (Halibut Bank) is located northeast of Nanaimo, in the middle of the Strait

of Georgia, in 42 m of water (49°20'24" N 123°43'48" W; Figure 2). MB 46206 (La Perouse

Bank) is located southwest of Ucluelet off the west coast of Vancouver Island, in 72 m of water

(48°50'24" N 126°0'0" W; Figure 2).

While Entrance Island lighthouse and meteorological buoys 46146 and 46206 were just

beyond the perimeter of the critical habitat study area (Fisheries and Oceans Canada, 2018), they

were included to increase the physical oceanographic data set and better characterise the physical

oceanographic system of southern resident killer whale critical habitat.
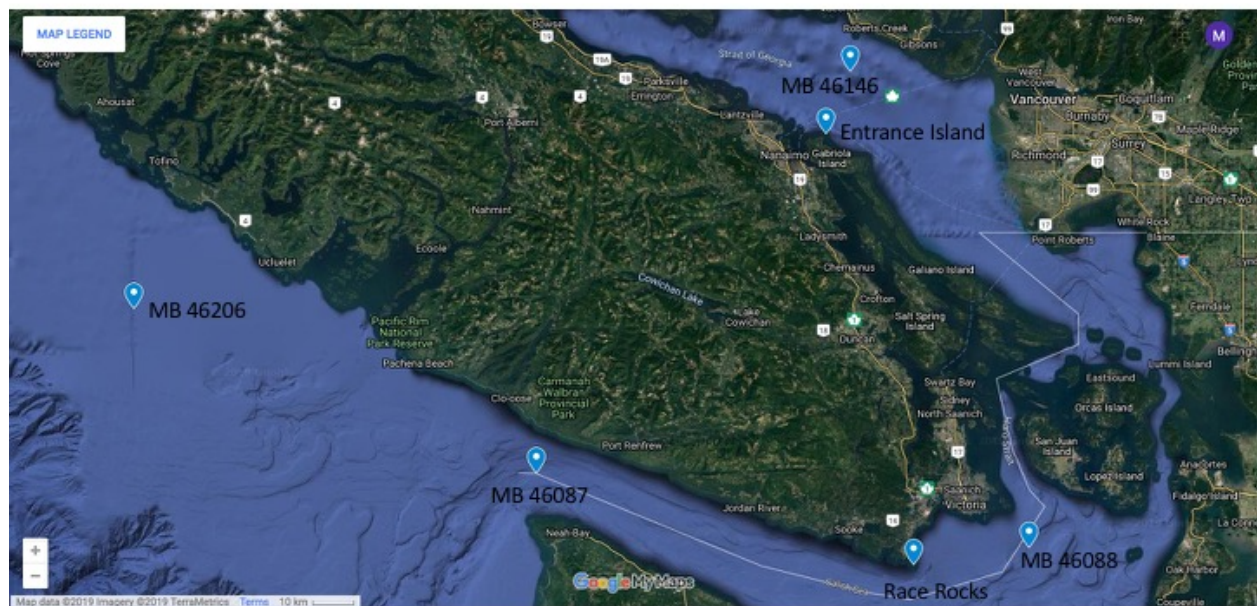
Figure 2. Satellite image with physical oceanographic data station locations (image courtesy:
Google Maps).

The physical data availability varied spatially and temporally as follows (Appendix B,

Table B1):

- Entrance Island: monthly means and standard deviations (May 1936–August 2016) for

  salinity ($n = 28913$) and SST ($n = 29099$; Table B1);

- Race Rocks: monthly means and standard deviations (February 1921–August 2016) for

  salinity ($n = 28423$) and SST ($n = 34136$);

- MB 46087: monthly means and standard deviations (July 2004–July 2017) for air

  pressure ($n = 3992$), SST ($n = 3958$), wave height ($n = 3821$) and wave period ($n = 3821$);

- MB 46088: monthly means and standard deviations (July 2004–July 2017) for air

  pressure ($n = 4374$), SST ($n = 4109$), wave height ($n = 4348$) and wave period ($n = 3963$);

- MB 46146: monthly means and standard deviations (March 1992–September 2015) for

  air pressure ($n = 7986$), SST ($n = 8146$), wave height ($n = 8075$) and wave period ($n =$

  8030);

- MB 46206: monthly means and standard deviations (December 1988–September 2016)

  for air pressure ($n = 9238$), SST ($n = 9312$), wave height ($n = 9324$) and wave period ($n =$

  8920).

These data were temporally filtered to 1975–2018. All physical data were classified by

year, month and season. Year and month were chronologically ordered. Season was classified

as winter (December–May) and summer (June–November).

Statistical Analyses

The killer whale and oceanographic data were synthesized and formatted for analyses in

Microsoft Excel software. Statistical analyses were conducted using NCSS Statistical Software

2018 (Hintze, 1998).

The killer whale population data were tested for normality and statistically examined for annual population totals and means, annual birth and death totals and means, age at death, maternal age at birth, maternal age at first known calf, number of female calves that reproduced (per female), number of calves (per female), familial influence on maternal age at birth and familial influence on maternal age at first calf. The killer whale population data were coded for years when the population was below or above the population mean (coded as 0 and 1, respectively), and when the population was decreasing or increasing (0 and 1, respectively).

Oceanographic data at Entrance Island, Race Rocks, and meteorological buoys 46087, 46088, 46146 and 46206 were examined separately for each physical variable (salinity, sea surface temperature, air pressure, wave height and wave period) to determine whether there was a statistically significant difference between seasons and over time. Study sites were then compared to determine if there were differences in each physical variable between sites annually and seasonally.

The entire study area—the Salish Sea—was then analyzed as a whole with relation to killer whale population dynamics. Monthly means for each physical variable were examined for periods when the killer whale population was below or above the mean, and when the population was decreasing or increasing, in order to identify any relevant correlations between the physical and biological processes.

Results

Killer Whale Population Dynamics

The southern resident killer whale population was at 71 individuals in 1976, reached a maximum of 98 animals in 1995, and by 2018 had declined to 75 whales. Over the 43 years (1975–2018), the average population size was 84 individuals, with considerable variability

between pods (Table 2). On average, L Pod was more than twice as large as either J or K (Table

2). The population as a whole had an average of three births and deaths per year, with L pod

having higher average rates than either J or K pods (Table 2). Interestingly, L pod was the only

pod with the average birth rate lower than the average death rate (Table 2). The population

median was 84.00 animals, with a population size of 82.00 and 85.00 most common (i.e. mode;

Table 2). The population median (and most common number) for births was 3.00, and

population median for deaths was 3.00, with 1.00 and 3.00 the most common (Table 2).

Table 2

Summary statistics based on the southern resident orca census (1976–2018): mean, median and mode for population total, births and deaths.

	Population			Births			Deaths		
	Mean	Median	Mode	Mean	Median	Mode	Mean	Median	Mode
SRKW	84.07	84.00	82.00, 85.00	3.14	3.00	3.00	3.07	3.00	1.00, 3.00
J pod	21.35	20.00	19.00	0.91	1.00	0.00	0.72	0.00	0.00
K pod	17.56	18.00	19.00	0.58	0.50	0.00	0.54	0.00	0.00
L pod	45.16	45.0	41.00	1.65	1.50	0.00	1.81	2.00	1.00

Visual inspection of the population data indicated that overall trends in numerical

abundances exhibited temporal variability both in the population and between pods. The

southern resident killer whale population experienced four periods of increase: 1976–1980,

1984–1995, 2001–2006, and 2014–2016 (Figure 3). These were all followed by periods of

decrease: 1980–1984, 1995–2001, 2006–2014 and 2016–2018 (Figure 3). The longest period of

consistent long-term growth occurred from 1984–1995, when the population peaked at 98

animals (Figure 3). From this maximum, a decline occurred until 2001 (Figure 3). There was a

subsequent short increase in population size until 2006 followed by a slight decline that

continued to 2018 (Figure 3).

In contrast to L pod's fluctuating population dynamics, both J and K pods experienced only minor changes (Figure 3). J pod experienced a gradual population increase until 2010, then a slight decrease until 2014, followed by two years of growth and two years of loss (Figure 3). K pod, however, remained fairly stable, with a slight increase over the 43-year study period (Figure 3). Neither of these pods experienced the large declines that have been documented in L Pod. The overall population fluctuation pattern most closely resembled the fluctuations of L pod (Figure 3).
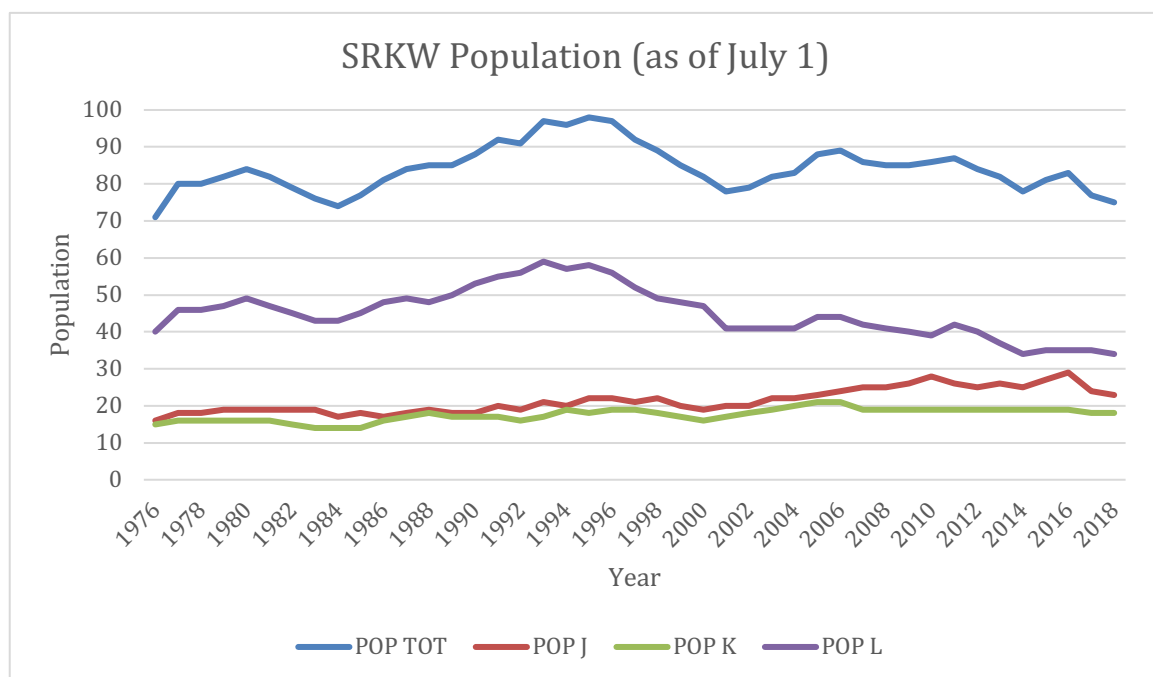
Figure 3. Southern resident population according to July 1 yearly census, 1976–2018.

Examination of the annual percentage population change indicated that the positive changes became smaller and fewer over time, while the negative population changes have become larger and more frequent (Figure 4).
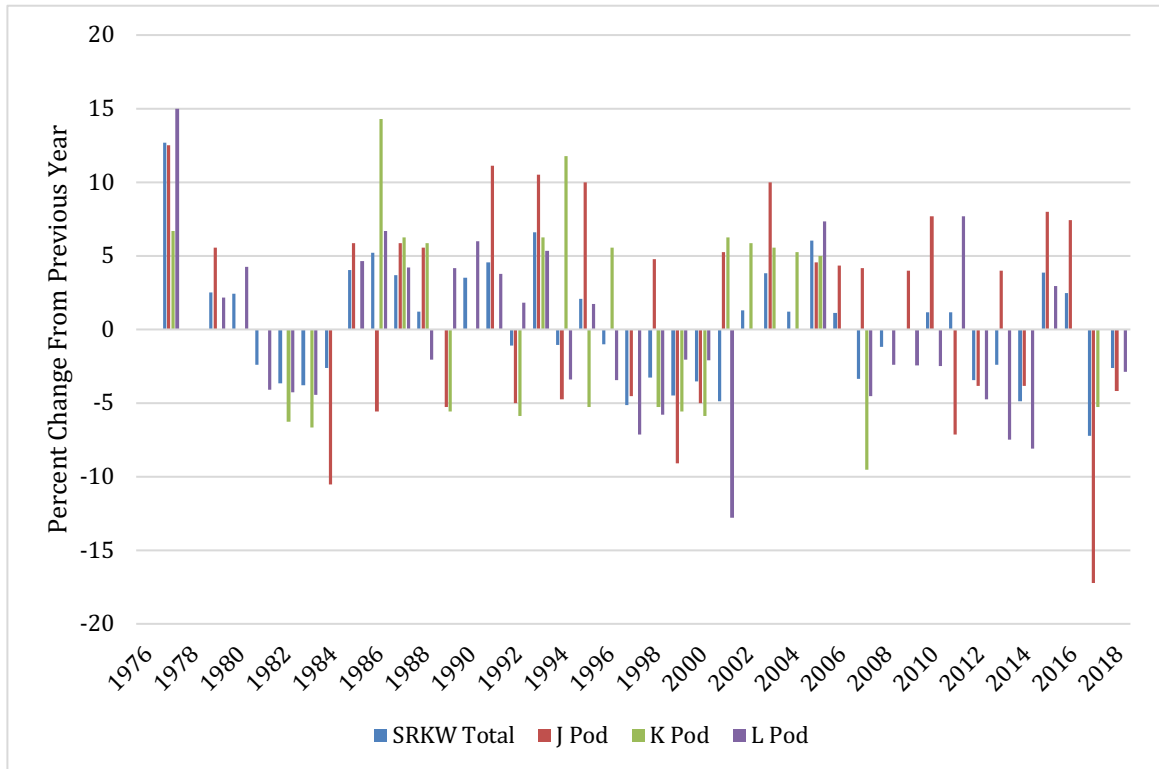
Figure 4. Southern resident killer whale percentage population change by year.

The total number of births in the southern resident killer whale population ranged from

lows of zero (1983, 1997, 2013 and 2017) to a high of nine in 1977 (Table 2; Figure 5). The

average number of births was 3.14 per year (Table 2, Figure 5). The most recent "baby boom"

occurred between 2014 and 2016 with the births of 10 live calves, with three more that were

either stillborn or survived only a very short time and thus were not included in the official

population census (CWR, 2018).
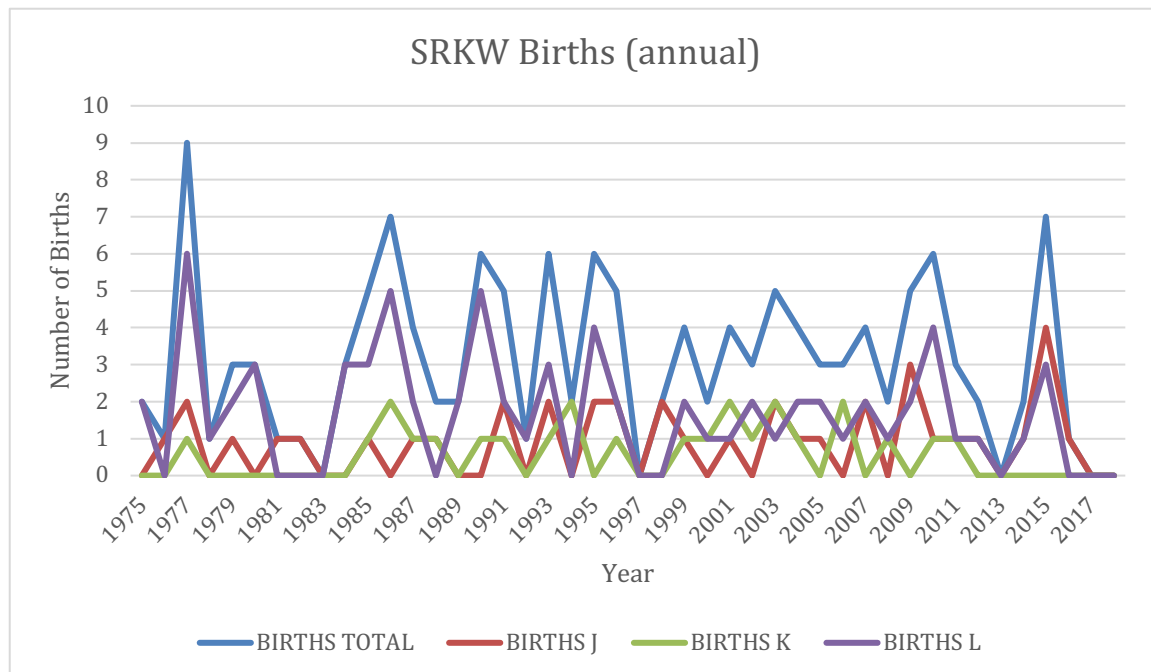
Figure 5. Southern resident killer whale annual births.

Killer whale deaths ranged from zero (in 1976, 1992, 2001 and 2003) to seven (in 1998, 2000, 2006 and 2008), with an average of 3.07 per year for the entire population (Table 2, Figure 6).
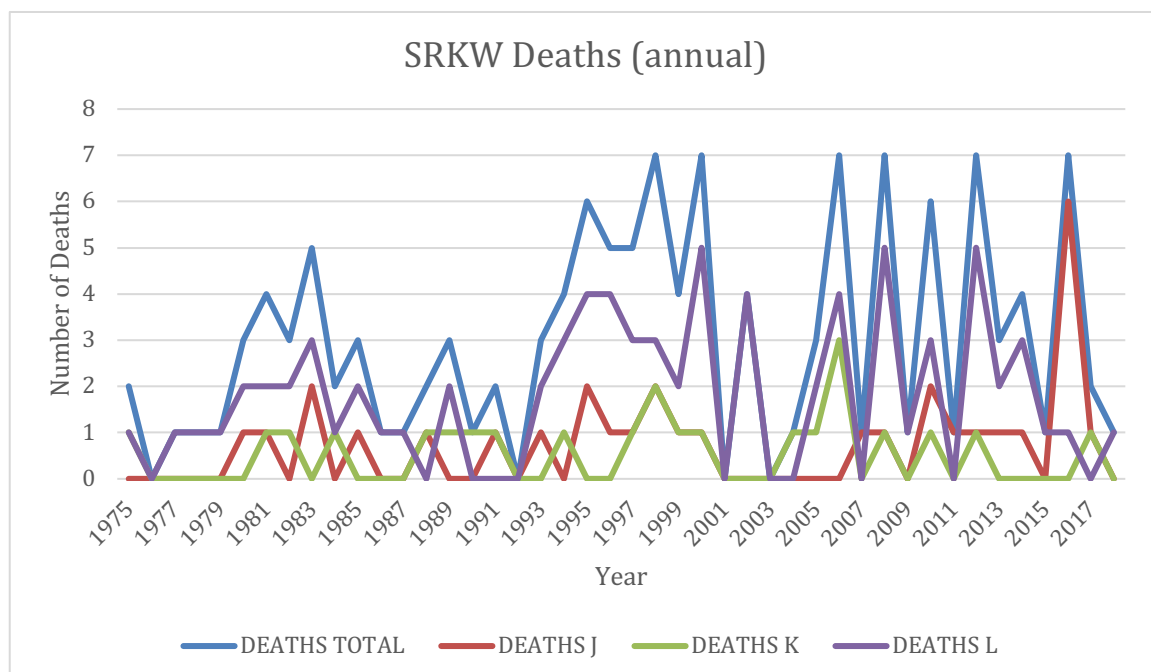
Figure 6. Southern resident killer whale annual deaths.

Age at death (AAD).

Age at death (AAD) was examined for the southern resident population, between pods, and according to gender (F = female, M = male, NA = unknown). AAD ranged from zero (neonates who did not survive their first year) to 105 years (J2, who is estimated to have been born in 1911 and died in 2016; Table 3). On average, female southern resident killer whales lived longer than males by approximately two decades, with the average life span in K pod being longer than either J or K (Table 3). Individuals of unknown gender lived on average less than a year (Table 3).

Table 3

Age at death average, standard deviation, median and mode for the southern resident population and individual pods.

	Population	Females	Males	Unknown
SRKW Population				
Average	25.04	42.36	20.29	0.97
Standard Deviation	23.75	23.42	13.29	1.88
Median	21.50	46.00	21.00	0.00
Mode	0.00	0.00	23.00	0.00
Total	138.00	56.00	52.00	30.00
J Pod				
Average	24.83	40.06	17.46	0.17
Standard Deviation	27.18	29.01	19.21	0.41
Median	17.00	37.5	14.00	0.00
Mode	0.00	--	0.00	0.00
Total	35.00	16.00	13.00	6.00
K Pod				
Average	29.75	55.60	24.50	1.38
Standard Deviation	29.03	22.74	16.68	2.67
Median	29.50	54.50	29.50	0.00
Mode	0.00	--	--	0.00
Total	24.00	10.00	6.00	8.00
L Pod				
Average	23.71	39.17	20.64	1.06
Standard Deviation	20.28	21.48	9.63	1.77
Median	23.00	47.50	22.00	0.00
Mode	0.00	3.00	23.00	0.00
Total	79.00	30.00	33.00	16.00

Note. (--) indicates data not available (no duplicate data points).

AAD data were not normally distributed (Shapiro-Wilk Normality Test, $W = 0.90$, $p < .001$). There was a statistically significant difference in AAD within the population as a whole, including neonates that did not survive their first year (AAD ≥ 0; Wilcoxon Signed-Rank Test, $Z = 9.85$, $p < .001$), rejecting the null hypothesis that there is no difference in AAD within the southern resident population. Removing the neonate mortality data (i.e., using only AAD ≥ 1), data were again not normally distributed (Shapiro-Wilk Normality Test, $W = 0.94$, $p < .001$), and

resulted in a statistically significant relationship (Wilcoxon Signed-Rank Test, $Z = 9.19$, $p < .001$), indicating that AAD varied throughout the population.

Age at death between pods.

The median AAD in J, K and L pods was 17.00, 29.50 and 23.00, respectively, while median AAD in the population as a whole was 21.50 (Table 3). Although there appears to be some variation between pods, AAD of killer whales did not differ based on pod membership (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties*, $H = 0.51$, *d.f.* = 2, $p = .775$). Neonates that did not survive their first year were again removed (i.e., AAD ≥ 1), and the analysis re-run, but there was again no statistical significance in AAD based on pod membership (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties*, $H = 2.75$, *d.f.* = 2, $p = .253$).

The pods were examined individually as well as being compared to the rest of the population to determine whether AAD of any one pod was significantly different from the others. J and K pods were grouped together and compared to L pod with no statistically significant difference for AAD ≥ 0 (Mann-Whitney U Test *corrected for ties*, $U_{JK} = 2321.5$, $U_L = 2339.5$, *d.f.* = 1, $Z = -0.04$, $p = .971$) and for AAD ≥ 1 (Mann-Whitney U Test *corrected for ties*, $U_{JK} = 1697.5$, $U_{KL} = 1317.5$, *d.f.* = 1, $Z = 1.13$, $p = .261$).

There was also no statistically significant difference in AAD between J and KL pods for AAD ≥ 0 (Mann-Whitney U Test *corrected for ties*, $U_J = 1690$, $U_{KL} = 1915$, *d.f.* = 1, $Z = -0.55$, $p = .582$) or AAD ≥ 1 (Mann-Whitney U Test *corrected for ties*, $U_J = 1132$, $U_{KL} = 1163$, *d.f.* = 1, $Z = -0.10$, $p = .919$).

There was also no statistically significant difference in JL vs K pods for AAD ≥ 0 (Mann-Whitney U Test *corrected for ties*, $U_{JL} = 1224$, $U_K = 1512$, *d.f.* = 1, $Z = 0.81$, $p = .419$) or AAD ≥ 1 (Mann-Whitney U Test *corrected for ties*, $U_{JL} = 600$, $U_K = 1092$, *d.f.* = 1, $Z = 1.95$, $p = .052$).

Age at death by gender.

Age at death data were sorted by gender, and there was a statistically significant difference in the AAD of females (F), males (M) and unknown (NA) animals (for AAD ≥ 0) (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H = 73.44, d.f. = 2, p < .001*; Figure 7). Neonates that did not survive their first year were then excluded (i.e. AAD ≥ 1). Results were similar, as there was a statistically significant difference in AAD between the three groups (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H = 45.61, d.f. = 2, p < .001*; Figure 8).
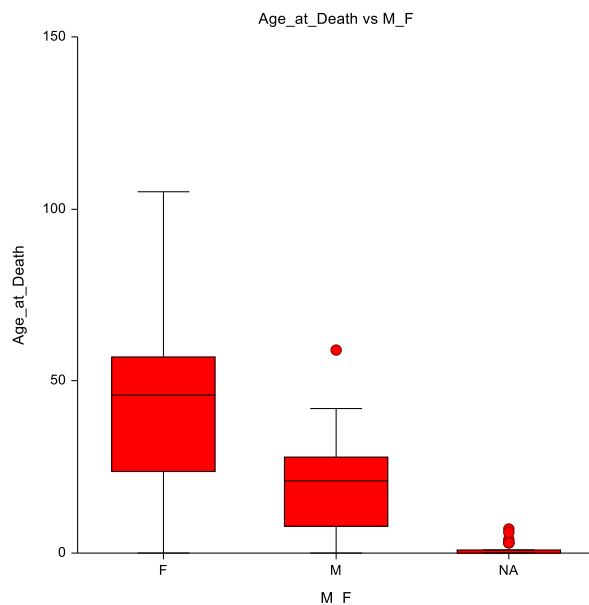
Figure 7. Age at death between F, M and NA (AAD ≥ 0).
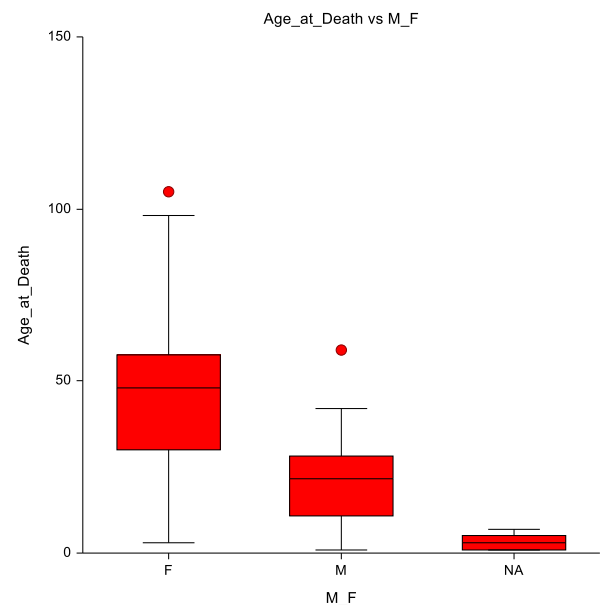
Figure 8. Age at death between F, M and NA (AAD ≥ 1).

There was no difference in the females' AAD between pods for AAD ≥ 0 (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H = 3.61, d.f. = 2, p = .165*) or AAD ≥ 1 (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H = 2.83, d.f. = 2, p = .243*).

There was also no statistically significant difference in the males' AAD between J, K, and L pods, both including neonates under a year (AAD ≥ 0; Kruskal-Wallis One-Way ANOVA

on Ranks, *corrected for ties, H = 3.00, d.f. = 2, p = .223*) and excluding them (AAD ≥ 1;

Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H = 1.25, d.f. = 2, p = .535*).

Data were then examined for unknown gender and results again showed no statistically

significant difference in AAD between pods for both AAD ≥ 0 (Kruskal-Wallis One-Way

ANOVA on Ranks, *corrected for ties, H = 1.02, d.f. = 2, p = .602*) and AAD ≥ 1 (Kruskal-Wallis

One-Way ANOVA on Ranks, *corrected for ties, H = 4.07, d.f. = 2, p = .131*).

The AAD between females, males and individuals of unknown gender was also analysed

within each pod. There was a statistically significant difference in J pod, for both AAD ≥ 0

(Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H = 15.00, d.f. = 2, p < .001*;

Figure 9) and AAD ≥ 1 (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H =*

6.86, *d.f. = 2, p = .032*; Figure 10).
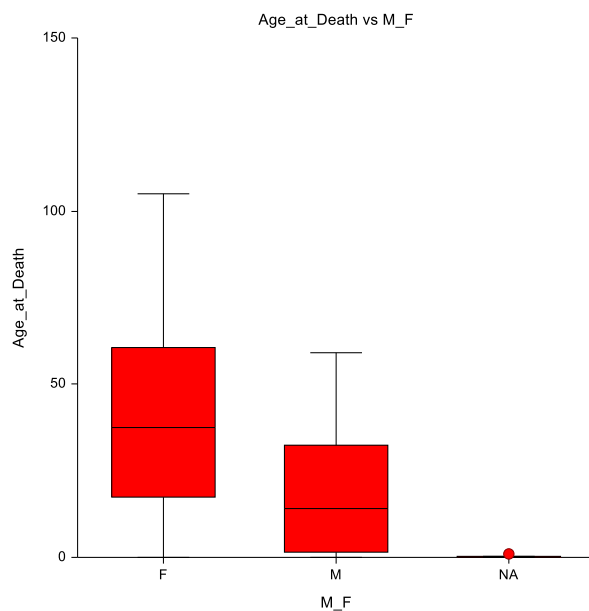
Figure 9. Age at death between F, M and
NA in J pod (AAD ≥ 0).
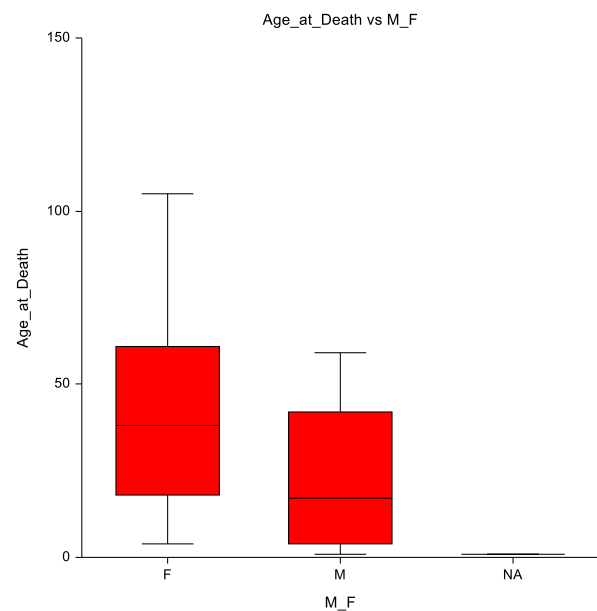
Figure 10. Age at death between F, M and
NA in J pod (AAD ≥ 1).

There was also a statistically significant difference between females, males and unknown

gender in K pod for both AAD ≥ 0 (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for*

ties, H = 18.08, *d.f.* = 2, *p* < .001; Figure 11) and AAD ≥ 1 (Kruskal-Wallis One-Way ANOVA

on Ranks*, H* = 10.09, *d.f.* = 2, *p* = .006; Figure 12).
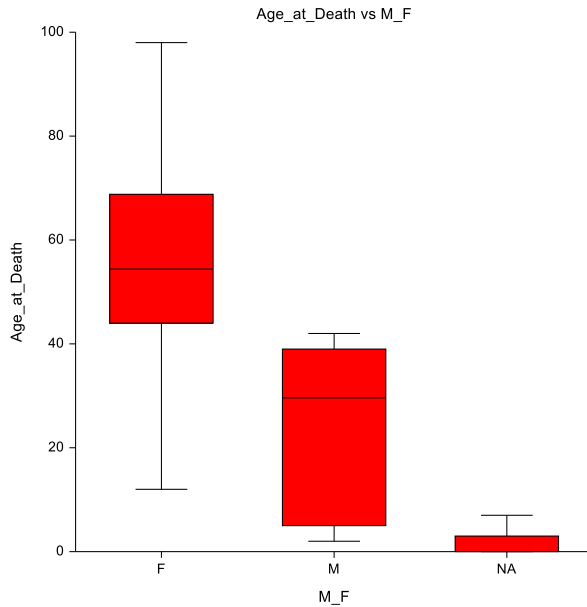
Figure 11. Age at death between F, M and NA in K pod (AAD ≥ 0).
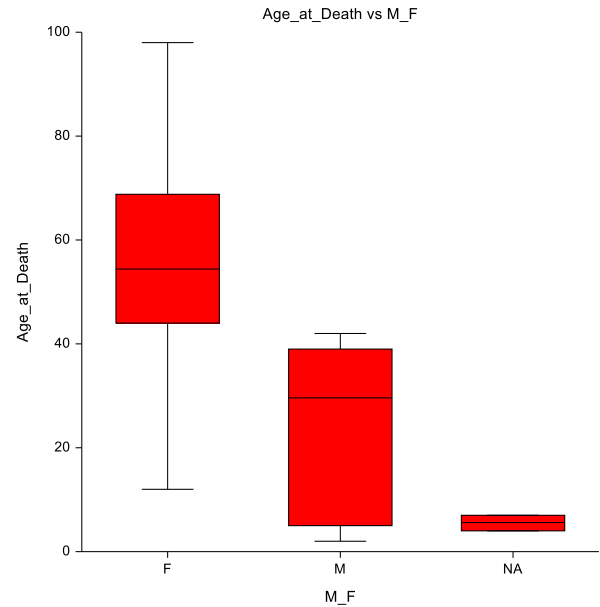
Figure 12. Age at death between F, M and NA in K pod (AAD ≥ 1).

As with J and K pods, L pod also demonstrated a statistically significant difference in the

longevity of females, males and individuals of unknown gender for both AAD ≥ 0 (Kruskal-

Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 41.18, *d.f.* = 2, *p* < .001; Figure 13)

and AAD ≥ 1 (Kruskal-Wallis One-Way ANOVA on Ranks*, H* = 30.35, *d.f.* = 2, *p* < .001; Figure

14).
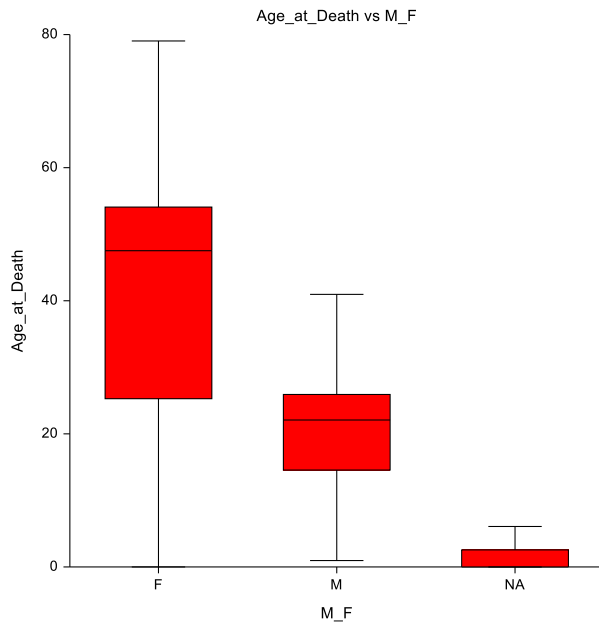
Figure 13. Age at death between F, M and NA in L pod (AAD ≥ 0).
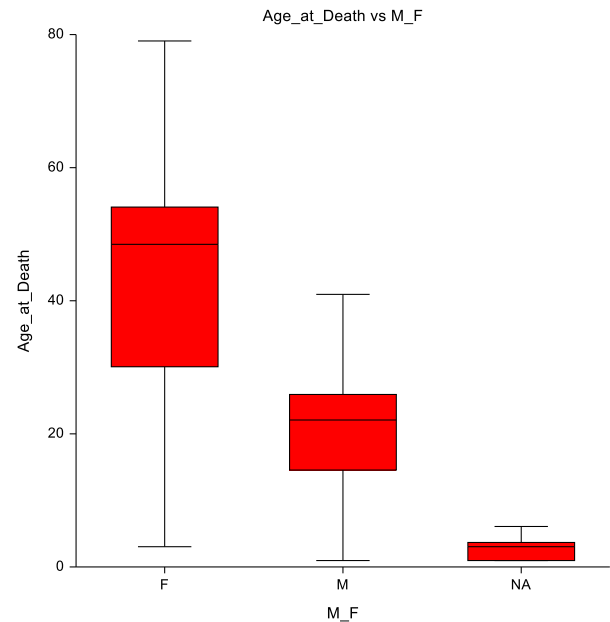
Figure 14. Age at death between F, M and NA in L pod (AAD ≥ 1).

All individuals with unknown gender (NA) were then removed to compare AAD of only females (F) and males (M) in the southern resident population. Results were statistically significant between F and M for both AAD ≥ 0 (Mann-Whitney U Test *corrected for ties*, $U_F =$ 2263.5, $U_M =$ 648.5, *d.f.* = 1, $Z =$ -4.96, *p* < .001) and AAD ≥ 1 (Mann-Whitney U Test *corrected for ties*, $U_F =$ 2154.5, $U_M =$ 495.5, *d.f.* = 1, *p* < .001).

Examination of the ages at death of males and females within pods also showed significant differences. In J pod, females and males had different life spans for both AAD ≥ 0 (Mann-Whitney U Test *corrected for ties*, $U_F =$ 154.5, $U_M =$ 53.5, *d.f.* = 1, $Z =$ -2.20, *p* = .028) and AAD ≥ 1 (Mann-Whitney U Test *corrected for ties*, $U_F =$ 123.5, $U_M =$ 41.5, *d.f.* = 1, $Z =$ -2.11, *p* = .035).

In K pod, females and males also had different life spans (Mann-Whitney U Test *corrected for ties*, $U_F =$ 55, $U_M =$ 5, *d.f.* = 1, $Z =$ -2.66, *p* = .008). All individuals had an AAD of at least 1 or more so no additional tests were required for AAD ≥ 0 and AAD ≥ 1.

The previous findings were consistent in L pod, where females and males had different lifespans for both AAD $\geq$ 0 (Mann-Whitney U Test *corrected for ties*, U_F = 1088.5, U_M = 321.5, *d.f.* = 1, *Z* = 4.00, *p* < .001) and AAD $\geq$ 1 (Mann-Whitney U Test *corrected for ties*, U_F = 1088.5, U_M = 227.5, *d.f.* = 1, *Z* = 4.71, *p* < .001).

Age at death between matrilines.

There was no difference in the life spans between matrilines for both AAD $\geq$ 0 (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 28.98, *d.f.* = 26, *p* = .312) and AAD $\geq$ 1 (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 26.51, *d.f.* = 24, *p* = .328).

Lifespan was then examined separately across the matrilines for females, males and unknown individuals. There was no difference in lifespan of females between matrilines for both AAD $\geq$ 0 (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 23.81, *d.f.* = 24, *p* = .472) and AAD $\geq$ 1 (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 24.21, *d.f.* = 24, *p* = .449). There was no difference in lifespan of males between matrilines for both AAD $\geq$ 0 (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 7.36, *d.f.* = 7, *p* = .393) and AAD $\geq$ 1 (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 17.65, *d.f.* = 16, *p* = .345). There was also no difference in lifespan of individuals with unknown gender between matrilines for both AAD $\geq$ 0 (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 18.64, *d.f.* = 22, *p* = .668) and AAD $\geq$ 1 (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 22.90, *d.f.* = 23, *p* = .466).

Reproductive success

Maternal age at birth.

Visual data inspection of histogram and test indicated that maternal age at birth (AAB)

data (Table 5) did not follow a normal distribution (Shapiro-Wilk Normality Test, $W = 0.96$, $p <$

.001). A statistically significant difference was found in AAB within the southern resident

population (Wilcoxon Signed-Rank Test, $Z = 10.30$, $p < .001$).

Table 4.

Maternal age at birth average, standard deviation, median, mode and number of calves, for total
southern resident population and individual pods.

	SRKW	J Pod	K Pod	L Pod
Average	24.28	23.56	22.04	25.51
Standard deviation	8.42	8.90	8.35	8.04
Median	23.00	21.00	19.50	25.00
Mode	20.00	19.00	22.00	20.00
Number of calves	140.00	44.00	26.00	72.00

No statistical difference in maternal AAB was found between pods (Kruskal-Wallis One-

Way ANOVA on Ranks, *corrected for ties*, $H = 4.30$, *d.f. = 2, p = .117*). Each pod was then

separately compared individually to the rest of the population. There was a statistical difference

in maternal AAB between JK and L pods (Mann-Whitney U Test *corrected for ties*, $U_{JK} =$

1882.5, $U_L = 2941.5$, *d.f. = 1, $Z = -2.23$, p = .026*), but not between J and KL pods (Mann-

Whitney U Test *corrected for ties*, $U_J = 1756$, $U_{KL} = 2262$, *d.f. = 1, $Z = -1.17$, p = .243*), or JL

and K pods (Mann-Whitney U Test *corrected for ties*, $U_{JL} = 1745.5$, $U_K = 1192.5$, *d.f. = 1, $Z = -$*

1.49, p = .136).

There was no statistically significant difference in maternal AAB between matrilines

(Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties*, $H = 27.02$, *d.f. = 21, p = .170*).

Maternal age at first known calf (AFC).

Visual data inspection of histogram and test indicated that data were not normal (Shapiro-Wilk Normality Test, $W = 0.83$ $p < .001$*).* There was a statistically significant difference in AFC within the whole population (Wilcoxon Signed-Rank Test, $Z = 6.51$*, $p < .001$*).

There was no statistical difference in maternal AFC between pods (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, $H = 4.48$, d.f. $= 2$, $p = .107$*), but there was a statistically significant difference between JK and L pods (Mann-Whitney U Test *corrected for ties*, $U_{JK} = 263$, $U_L = 520$, *d.f. $= 1$, $Z = -2.11$, $p = .035$*). This difference was not found between J and KL pods (Mann-Whitney U Test *corrected for ties*, $U_J = 255$, $U_{KL} = 408$, *d.f. $= 1$, $Z = -1.36$, $p = .174$*), or JL and K pods (Mann-Whitney U Test *corrected for ties*, $U_{JL} = 282$, $U_K = 178$, *d.f. $=$ 1, $Z = -1.11$, $p = .269$*).

There was no statistically significant difference in maternal AFC between matrilines (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, $H = 23.37$, d.f. $= 21$, $p = .324$*).

Number of female calves that reproduced per female.

The number of female offspring produced by each individual female was examined to determine how many of these offspring had reproduced, per female. There was no statistically significant difference based on pod membership (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, $H = 1.75$, d.f. $= 2$, $p = .416$*) or maternal age at first calf (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, $H = 20.86$, d.f. $= 20$, $p = .406$*).

Total number of calves per female.

There was also no difference in the number of known calves per female either based on pod membership (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, $H = 0.28$, d.f.*

= 2, *p* = .871) or maternal age at first known calf (Kruskal-Wallis One-Way ANOVA on Ranks,

corrected for ties, H = 23.67, *d.f.* = 20, *p* = .257).

Familial influence on maternal age at birth (AAB).

There was a statistical difference in maternal age at birth (AAB) based on the presence

of an older female relative (Mann-Whitney U Test *corrected for ties*, U_0 = 390, U_1 = 90, *d.f.* = 1,

Z = 3.45, *p* < .001) as well as an older female relative with a living calf (Mann-Whitney U Test

corrected for ties, U_0 = 393.5, U_1 = 110.5, *d.f.* = 1, *Z* = 3.18, *p* = .002).

The CWR identifies four different relationships within the southern resident killer whale

community: direct, probable, possible, and none. These were split into three for analytical

purposes: direct (Y), probable/possible (P) and none (N), showing a statistically significant

difference in AAB (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 37.15,

d.f. = 2, *p* < .001; Figure 15).
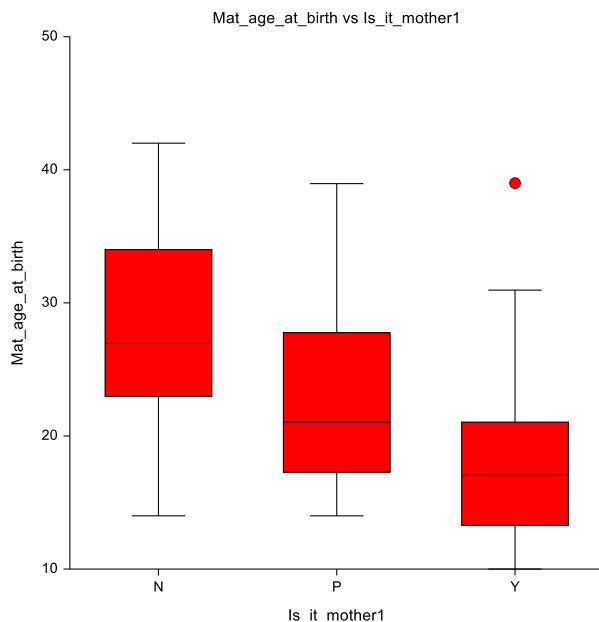
Figure 15. Maternal age at birth based on presence of mother's mother (N/Y/P). N.= mother not
present; P = female present may be mother; Y = female present is confirmed mother.

Data were also analyzed assuming P = Y, with a statistically significant difference in maternal age at birth (Mann-Whitney U Test *corrected for ties*, U_N = 414.5, U_Y = 110.5, *d.f.* = 1, Z = 3.35, *p* < .001). Analyses determined no difference in maternal age at birth with the presence of both the mother and grandmother (Mann-Whitney U Test *corrected for ties*, U_N = 69.5, U_Y = 18.5, *d.f.* = 1, Z = -1.35, *p* = .177) or the number of female helpers present (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 6.81, *d.f.* = 4, *p* = .146).

The number of female helpers was then divided into two categories: A (number of helpers ≤ 1) and B (number of helpers ≥ 2), with no statistical difference (Mann-Whitney U Test *corrected for ties*, U_A = 340, U_B = 189, *d.f.* = 1, Z = 1.65, *p* = .099). This was then re-examined for categories A ≤ 2 and B ≥ 3, with no significant difference (Mann-Whitney U Test *corrected for ties*, U_A = 194, U_B = 166, *d.f.* = 1, Z = -0.36, *p* = .719).

Familial influence on maternal age at first calf (AFC).

There was a statistically significant difference in maternal age at first calf (AFC) in relation to the presence of an older female relative (Mann-Whitney U Test *corrected for ties*, U_0 = 383.5, U_1 = 76.5, *d.f.* = 1, Z = 3.28, *p* = .001). A difference was also found for AFC with the presence of an older female relative with a living calf (Mann-Whitney U Test *corrected for ties*, U_0 = 423, U_1 = 165, *d.f.* = 1, Z = 2.44, *p* = .015).

When examining the effect of the presence of a living mother, data were classified as direct relation (Y), probable/possible relation (P) and no relation (N). The presence of the mother was examined and found to be statistically significant in relation to maternal AFC (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 10.87, *d.f.* = 2, *p* = .004; Figure 16). Data were then analyzed again with the assumption that probable/possible relations were in fact direct relations (P = Y) since any family member this close would likely provide

similar support, but no statistical significance was found (Mann-Whitney U Test *corrected for ties*, $U_N = 446$, $U_Y = 178$, *d.f.* $= 1$, $Z = 2.48$, $p = .013$).
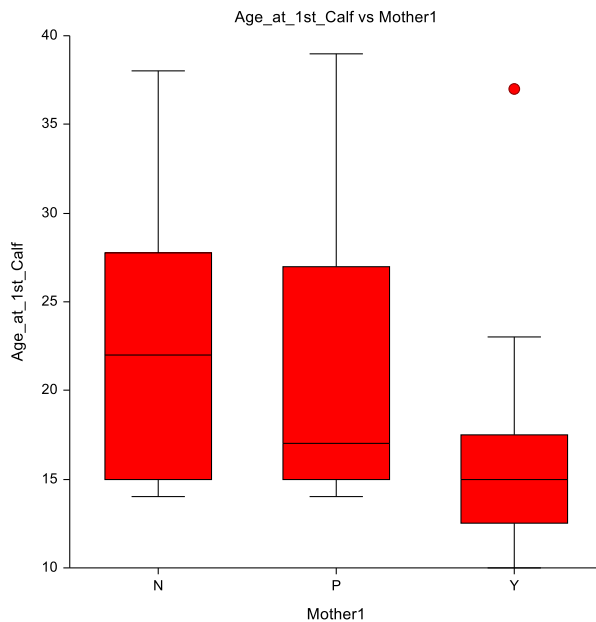
Figure 16. Maternal age at first calf in relation to presence of mother.

There was no statistically significant difference in maternal AFC with the presence of both mother and grandmother (Mann-Whitney U Test *corrected for ties*, $U_N = 158.5$, $U_Y = 91.5$, *d.f.* $= 1$, $Z = -0.97$, $p = .332$) or the number of female helpers (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* $= 5.65$*, d.f.* $= 4$*, p* $= .227$).

The number of female helpers was then divided into two categories (as above): A (number of helpers ≤ 1) and B (number of helpers ≥ 2), with no significant difference (Mann-Whitney U Test *corrected for ties*, $U_A = 500$, $U_B = 275$, *d.f.* $= 1$, $Z = 1.85$, $p = .064$). This was then re-examined for categories A ≤ 2 and B ≥ 3, with no significant difference (Mann-Whitney U Test *corrected for ties*, $U_A = 325$, $U_B = 263$, *d.f.* $= 1$, $Z = -0.58$, $p = .563$).

Neonate survival

Individual females were identified and the number of calves that survived their first year per female was determined. There was no statistically significant difference between pods (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 0.39, *d.f.* = 2, *p* = .822). Calf survival past one year (per female) was also examined based on maternal AFC, with no statistically significant difference detected (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 27.70, *d.f.* = 20, *p* = .117).

When taking into account all births since 2000, 38.6% of known calves did not survive past one year; 52.5% did not survive past two years; and 60.5% did not survive past 5 years (Table A1).

Maternal and familial influence on calf survival.

There was no statistically significant difference in AAD of calf based on maternal ID (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 50.74, *d.f.* = 42, *p* = .167) or maternal AAB (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 29.47, *d.f.* = 28, *p* = .389). There was also no difference in AAD of calf based on pod membership (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 6.05, *d.f.* = 2, *p* = .049). There was no statistically significant difference in AAD of calf when an older female relative was present for either AAD $\geq$ 0 (Mann-Whitney U Test *corrected for ties*, U_0 = 587, U_1 = 349, *d.f.* = 1, *Z* = 1.63, *p* = .104) or AAD $\geq$ 1 (Mann-Whitney U Test *corrected for ties*, U_0 = 213, U_1 = 267, *d.f.* = 1, *Z* = -0.61, *p* = .540).

Further analyses showed no statistically significant difference in the presence of an older female with a living calf for either AAD $\geq$ 0 (Mann-Whitney U Test *corrected for ties*, U_0 = 604,

PHENOLOGY AND SOUTHERN RESIDENT KILLER WHALES   43

$U_1 = 452$, $d.f. = 1$, $Z = 0.98$, $p = .329$) or AAD ≥ 1 (Mann-Whitney U Test *corrected for ties*, $U_0 = 204$, $U_1 = 300$, $d.f. = 1$, $Z = -1.07$, $p = .283$).

There was however a statistically significant difference in AAD of calf when the grandmother was present using data classified as direct relation (Y), probable/possible relation (P) and no relation (N) for both AAD ≥ 0 (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H = 6.19, d.f. = 2, p = .045*; Figure 17) and AAD ≥ 1 (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H = 1.85, d.f. = 2, p = .396*; Figure 18).
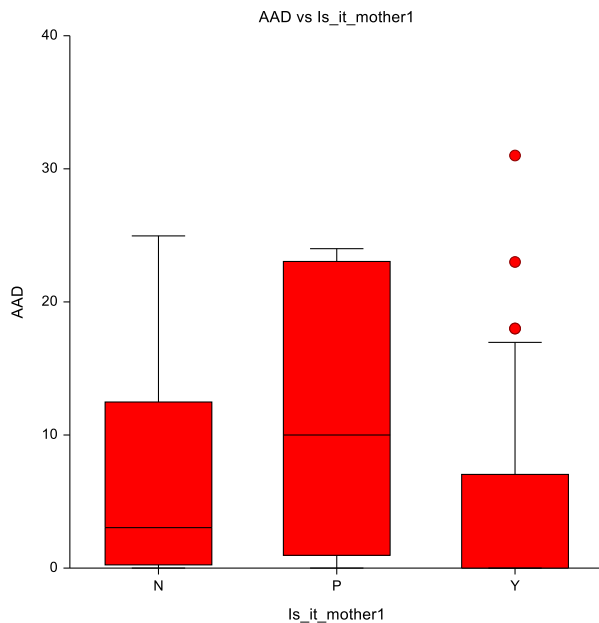
Figure 17. Age at death of calf based on presence of mother's mother (Y/P/N) where AAD ≥ 0.
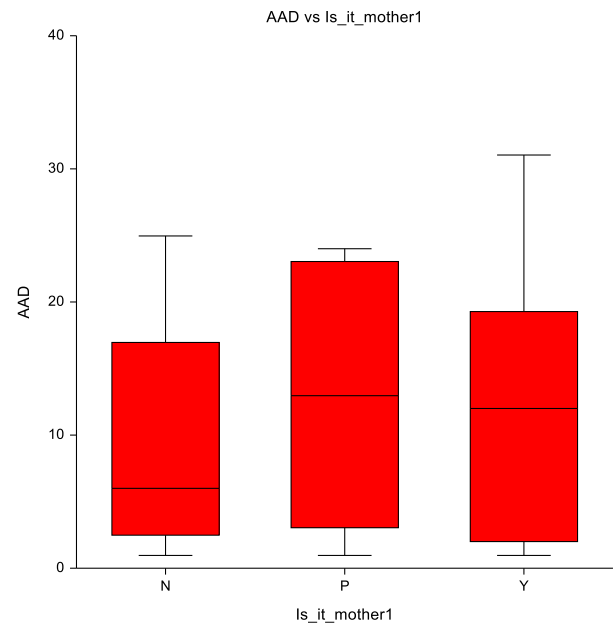
Figure 18. Age at death of calf based on presence of mother's mother (Y/P/N) where AAD ≥ 1.

When using the assumption that probable/possible relations were direct relations (P = Y), there was no statistically significant difference in AAD of calf when grandmother was present (Y/N, as above) for either AAD ≥ 0 (Mann-Whitney U Test *corrected for ties*, $U_N = 624$, $U_Y = 552$, $d.f. = 1$, $Z = 0.43$, $p = .664$) or AAD ≥ 1 (Mann-Whitney U Test *corrected for ties*, $U_N = 207.5$, $U_Y = 317.5$, $d.f. = 1$, $Z = -1.21$, $p = .228$).

No statistically significant difference in AAD of calf was found based on the presence of both the grandmother and great-grandmother for either AAD $\geq$ 0 (Mann-Whitney U Test *corrected for ties*, U_N = 100, U_Y = 101, *d.f.* = 1, Z = 0.00, p = 1.000) or AAD $\geq$ 1 (Mann-Whitney U Test *corrected for ties*, U_N = 44.5, U_Y = 43.5, *d.f.* = 1, Z = 1.00, p = 1.000).

There was also no difference in AAD of calf based on the number of female helpers for either AAD $\geq$ 0 (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 4.98, *d.f.* = 4, *p* = .289) or AAD $\geq$ 1 (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 3.19, *d.f.* = 4, *p* = .526). The number of female helpers was divided into two categories: A $\leq$ 1 and B $\geq$ 2, with no significant difference (Mann-Whitney U Test *corrected for ties*, U_A = 268.5, U_B = 260.5, *d.f.* = 1, Z = 0.08, p = .939). There was also no significant difference when this was then re-examined for A $\leq$ 2 and B $\geq$ 3 (Mann-Whitney U Test *corrected for ties*, U_A = 198.5, U_B = 161.5, *d.f.* = 1, Z = -0.48, p = .631).

Oceanographic Data

Annual and seasonal variation.

All physical data sets were tested for normality using the Shapiro-Wilk Normality Test (Table B3). Only salinity monthly mean (Race Rocks) and wave height monthly mean (MB 46088) were normally distributed—the remainder were not. Parametric and non-parametric tests were used accordingly. Data were classified and coded into winter (December–May) and summer (June–November) to examine seasonal changes over time.

Salinity.

Visual inspection of the data (Table 5; Figure 19) showed minimal variation in both summer and winter salinity average monthly means at either Entrance Island or Race Rocks. Salinity was low at Race Rocks in 1976–78, 1982–84, 1991–93, 1995–1999, and 2011–14 (Table

5; Figure 19), with the 2012 summer having lower than average salinity monthly means at both

locations (Table 5; Figure 19). Ocean salinity at Entrance Island decreased in the summer, but

remained fairly constant at Race Rocks, and was consistently higher at Race Rocks than

Entrance Island (Table 5).

Table 5

Descriptive statistics (mean, median mode, minimum and maximum) for salinity monthly means at Entrance Island and Race Rocks).

Location	Mean (psu)	Median (psu)	Mode (psu)	Minimum (psu)	Maximum (psu)	Years
			Winter			
Entrance Island	27.91	27.93	--	25.39	29.55	1974–2015
Race Rocks	31.07	31.03	31.38	30.43	31.82	1974–2015
			Summer			
Entrance Island	26.08	26.24	--	23.00	27.50	1975–2016
Race Rocks	31.24	31.22	--	30.44	32.04	1975–2016

Note. (--) indicates data not available (no duplicate data points).
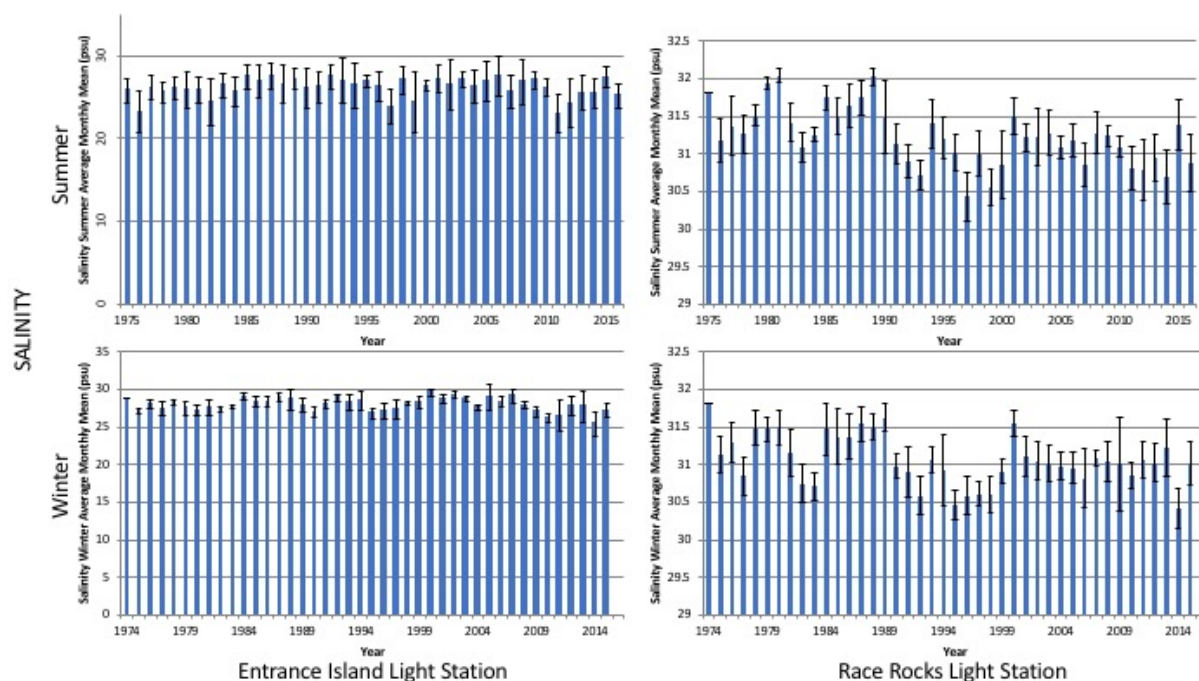
Figure 19. Seasonal salinity average monthly means at Entrance Island and Race Rocks lighthouses.

There was a statistically significant difference between winter and summer salinity monthly means at Entrance Island (Mann-Whitney U Test *corrected for ties*, U_{summer} = 140.5, U_{winter} = 1623.5, d.f. = 1, Z = -6.63, p < .001) and Race Rocks (Two Sample t-Test, t = 2.10, d.f. = 82, p = .039), with overall salinity being higher at Race Rocks.

Salinity monthly means had significant variation over time both on an annual basis and a seasonal basis. Entrance Island: annually (Wilcoxon Signed-Rank Test, Z = 19.32, p < .001), in winter (Wilcoxon Signed-Rank Test, Z = 13.68 p < .001), and in summer (Wilcoxon Signed-Rank Test, Z = 13.65, p < .001). Race Rocks: annually (One Sample t-Test, t = 1576.83, d.f. = 499, p < .001), in winter (One Sample t-Test, t = 1196.93, d.f. = 250, p < .001) and in summer (One Sample t-Test, t = 1084.72, d.f. = 248, p < .001).

Salinity monthly means were also significantly different at both lighthouses annually (Mann-Whitney U Test *corrected for ties*, $U_{Entrance}$ = 21, $U_{RaceRock}$ = 248479, d.f. = 1, Z = -27.33, p < .001) and seasonally: winter (Mann-Whitney U Test *corrected for ties*, $U_{Entrance}$ = 5, $U_{RaceRock}$ = 62494, d.f. = 1, Z = -19.3420, p < .001) and summer (Mann-Whitney U Test *corrected for ties*, $U_{Entrance}$ = 4, U_K = 61748, d.f. = 1, Z = -19.29, p < .001).

Sea Surface Temperature (SST).

Summer SST average monthly means showed much more variability over time throughout the study area than winter temperatures (Figures 20 and 21). The waters around Entrance Island and MB 46146 had the highest monthly mean SST in the summer, while the more southerly waters of the study area near Victoria (Race Rocks and MB 46088) were the coldest of all sites during the winter (Table 6).

Table 6

Descriptive statistics (mean, median mode, minimum and maximum) for sea surface temperature monthly means at lighthouses and meteorological buoys.

Location	Mean (deg C)	Median (deg C)	Mode (deg C)	Minimum (deg C)	Maximum (deg C)	Years
			Winter			
Entrance Island	8.76	8.74	8.77	7.70	10.33	1975–2016
Race Rocks	8.52	8.42	7.69	7.57	11.15	1974–2015
MB46087	9.04	8.93	--	7.78	10.33	2004–2018, 20010–2016
MB46088	8.34	8.13	--	7.38	9.40	2004–2016
MB46146	9.03	8.71	--	7.97	14.26	1991–2014
MB46206	9.51	9.56	--	8.30	10.91	1988–2015
			Summer			
Entrance Island	14.67	14.70	--	13.24	17.53	1975–2016
Race Rocks	10.62	10.60	--	9.65	11.86	1975–2016
MB46087	11.47	11.25	--	10.69	12.33	2004–2009, 2011–2017
MB46088	10.68	10.87	--	9.77	11.46	2004–2017
MB46146	14.70	14.63	--	13.66	16.72	1992–2015
MB46206	12.73	12.71	--	11.49	14.81	1989–2016

Note. (--) indicates data not available (no duplicate data points).

Visual inspection of the data indicated elevated SST average monthly means at Race Rocks in the winters of 1983 and 1987, and at MB 46146 in the winter of 1999 (Figures 20 and 21). There was also an increasing trend in SST from 1975 to 2015 which is more apparent when looking at larger temporal scales (Figures 20 and 21).
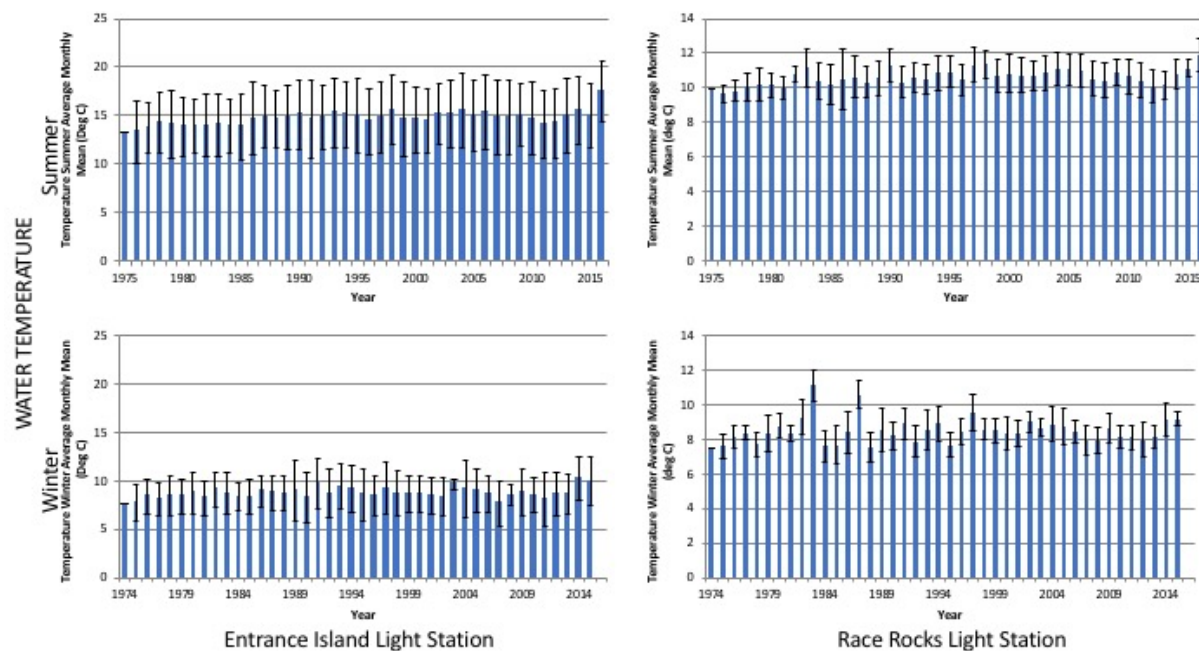
Figure 20. Seasonal sea surface temperature average monthly means in winter and summer at Race Rocks and Entrance Island lighthouses.
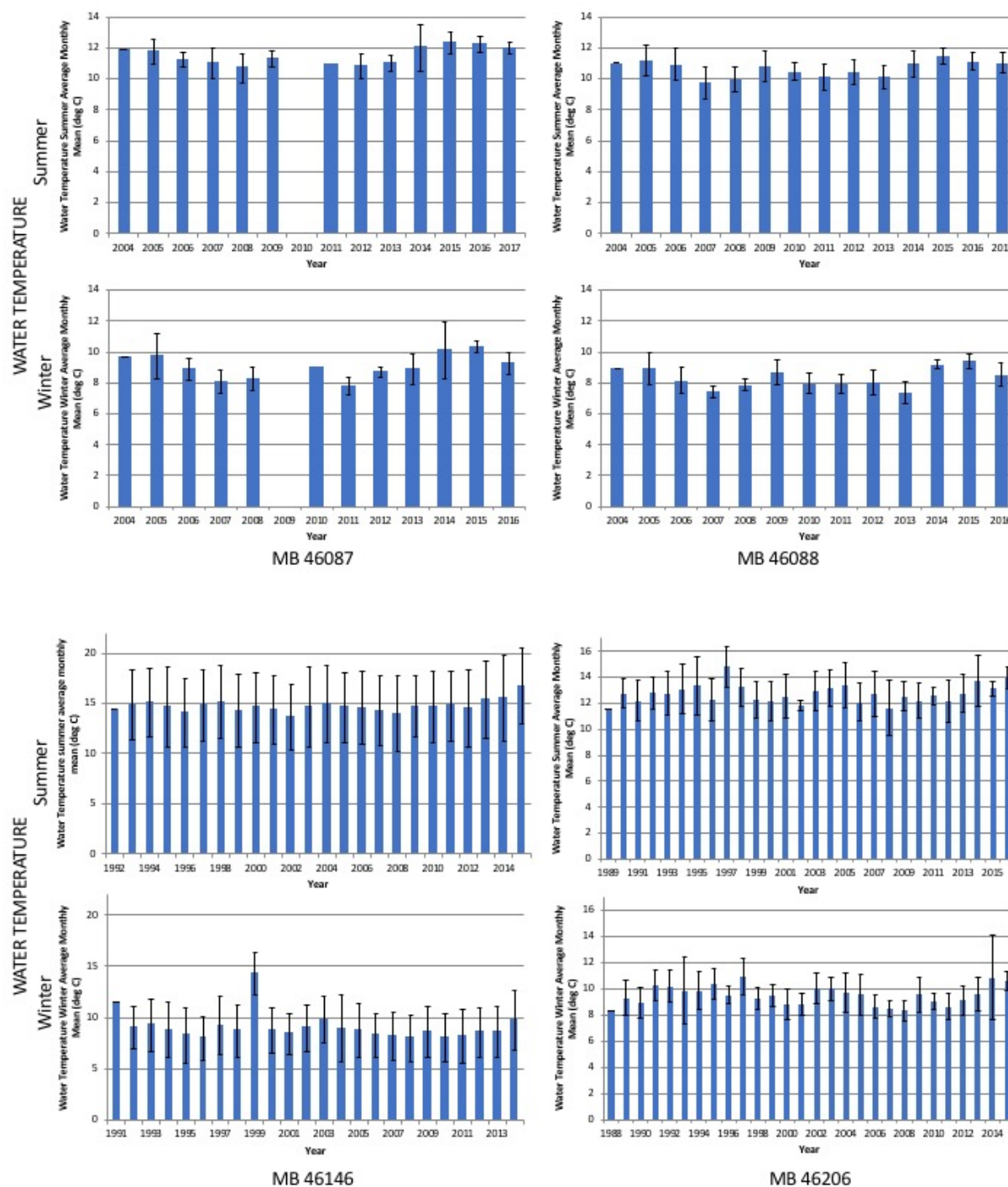
Figure 21. Seasonal sea surface temperature average monthly means in winter and summer at all four meteorological buoys.

A significant difference in SST monthly means was found between seasons at all locations (Table 7).

Table 7

Results of Mann-Whitney U Tests. There is a statistically significant difference in SST monthly means between winter and summer at all locations.

Location	U_{summer}	U_{winter}	d.f.	Z	p
Entrance Island	1764	0	1	7.89	< .001
Race Rocks	1705	59	1	7.36	< .001
MB 46087	156	0	1	-4.22	< .001
MB 46088	182	0	1	-4.39	< .001
MB 46146	547.5	4.5	1	-5.77	< .001
MB 46206	784	0	1	6.42	< .001

Similarly, a significant difference in SST monthly means both annually and seasonally

was found at all locations (Table 8).

Table 8

Results of Wilcoxon Signed-Rank Tests showing there is a statistically significant difference in SST monthly means over time annually and seasonally.

Location	Annual		Winter		Summer	
	Z	P	Z	P	Z	P
Entrance Island	19.34	< .001	13.68	< .001	13.68	< .001
Race Rocks	19.37	< .001	13.73	< .001	13.68	< .001
MB 46087	10.01	< .001	6.84	< .001	7.32	< .001
MB 46088	10.19	< .001	7.11	< .001	7.32	< .001
MB 46146	14.32	< .001	10.08	< .001	10.19	< .001
MB 46206	15.33	< .001	10.76	< .001	10.94	< .001

There was a statistically significant difference in SST monthly means between all

oceanographic data collection sites annually (Kruskal-Wallis One-Way ANOVA on Ranks,

corrected for ties, H = 109.79*, d.f.* = 5*, p* < .001; Figure 22), in winter (Kruskal-Wallis One-Way

ANOVA on Ranks, *corrected for ties, H* = 81.10*, d.f.* = 5*, p* < .001) and in summer (Kruskal-

Wallis One-Way ANOVA on Ranks, *corrected for ties, H* = 321.63*, d.f.* = 5*, p* < .001).
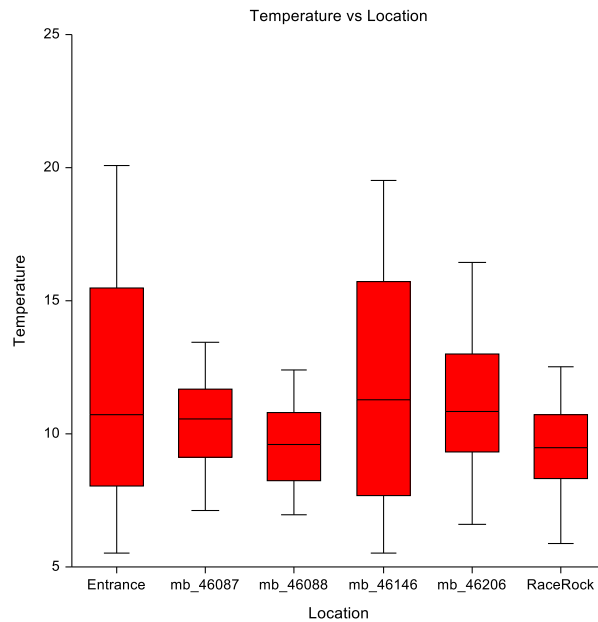
Figure 22. Annual sea surface temperature monthly mean at each study site.

Air Pressure.

There was more variability in air pressure average monthly means in the winter than in the summer, with lows occurring in 1994, 1997, 2005 and 2009 (Table 9; Figure 23). Air pressure in 1997 in particular was lower than usual, and the winter of 1991 was quite low at MB 46206 (Table 9; Figure 23).

Table 9.

Descriptive statistics (mean, median mode, minimum and maximum) for air pressure monthly mean at all four meteorological buoys.

Location	Mean (millibars)	Median (millibars)	Mode (millibars)	Minimum (millibars)	Maximum (millibars)	Years
			Winter			
MB 46087	1016.76	1017.31	--	1014.20	1018.32	2004–2008, 2010–2016
MB 46088	1016.16	1016.90	--	1012.52	1019.23	2004–2016
MB 46146	1016.65	1016.81	--	1013.36	1018.57	1991–2014
MB 46206	1015.46	1015.43	--	1009.15	1021.51	1988–2015
			Summer			
MB 46087	1016.66	1016.55	--	1015.46	1018.55	2004–2009, 2011–2017
MB 46088	1016.26	1016.10	--	1014.89	1017.88	2004–2017
MB 46146	1016.31	1016.20	--	1014.76	1018.20	1992–2015
MB 46206	1016.83	1016.80	--	1014.10	1018.52	1989–2016

Note. (--) indicates data not available (no duplicate data points).

However, there was only a significant difference in air pressure monthly mean between winter and summer at MB 46206 (La Perouse Bank; Mann-Whitney U Test *corrected for ties*, $U_{summer} = 544$, $U_{winter} = 240$, *d.f.* $= 1$, $Z = 2.48$, $p = .013$). All other meteorological buoys had no statistically significant difference between winter and summer: MB 46087 (Mann-Whitney U Test, $U_{summer} = 73$, $U_{winter} = 83$, *d.f.* $= 1$, $Z = 0.25$, $p = .807$), MB 46088 (Mann-Whitney U Test, $U_{summer} = 88$, $U_{winter} = 94$, *d.f.* $= 1$, $Z = 0.12$, $p = .903$), MB 46146 (Mann-Whitney U Test, $U_{summer} = 202$, $U_{winter} = 350$, *d.f.* $= 1$, $Z = 1.56$, $p = .118$).

Figure 23. Seasonal air pressure average monthly mean at all four meteorological buoys within the Salish Sea.

There was a statistically significant difference in air pressure monthly mean over time, both annually and seasonally, at all locations (Table 10).

Table 10

Results of Wilcoxon Signed-Rank Tests showing there is a statistically significant difference in air pressure monthly mean over time annually and seasonally.

Location	Annual		Winter		Summer	
	Z	*P*	*Z*	*P*	*Z*	*P*
MB 46087	10.04	< .001	6.90	< .001	7.32	< .001
MB 46088	10.48	< .001	7.27	< .001	7.57	< .001
MB 46146	14.19	< .001	9.89	< .001	10.19	< .001
MB 46206	15.26	< .001	10.76	< .001	10.83	< .001

When comparing air pressure monthly mean between the different study sites, no statistically significant difference was found annually (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H = 2.50, d.f. = 3, p = .475*) or in winter (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H = 6.31, d.f. = 3, p = .097*), however there was a difference in summer between locations (Kruskal-Wallis One-Way ANOVA on Ranks, *corrected for ties, H = 11.78, d.f. = 3, p = .008; Figure 24*).
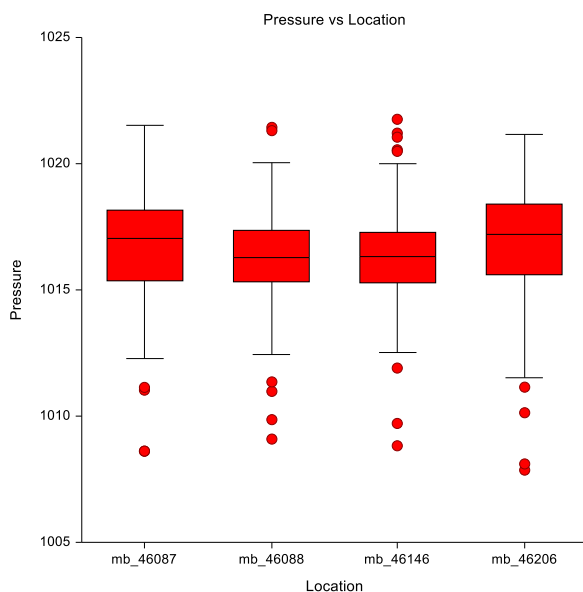
Figure 24. Summer air pressure monthly mean for all four meteorological buoys.

Wave Height.

Visual inspection of the wave height at the four meteorological buoys indicated that the two furthest from the open ocean, MB 46088 (New Dungeness) and MB 46146 (Halibut Bank), had lower wave height average monthly means in both summer and winter (Table 11; Figure 25).

MB 46087 experienced the lowest winter wave height monthly mean in 2010, followed by the highest in 2011 (Table 11; Figure 25). The lowest summer wave height monthly mean occurred in 2017 (Table 11). There is less variability at MB 46088, with a winter high in 2007 and a low in 2014, and summer lows in 2007, 2013 and 2015, and a high in 2017 (Table 11; Figure 25). MB 46146 shows an unusual high in the winter of 1993, and periods of lows in the winters of 1991–1992, 2002–2004, and 2012–2014 (Table 11; Figure 25). Summer wave height monthly means were relatively steady, with a low in 2013 (Table 11). MB 46206 showed winter lows in 1993, 2001, 2004 and 2013, with highs in 1997–1998 and 2015 (Table 11; Figure 25). The summer showed unusual lows in 1993, 2001 and 2016 (Table 11; Figure 25).

Table 11

Descriptive statistics (mean, median mode, minimum and maximum) for wave height monthly means at all four meteorological buoys.

Location	Mean (metres)	Median (metres)	Mode (metres)	Minimum (metres)	Maximum (metres)	Years
			Winter			
MB 46087	2.12	2.04	--	1.64	2.64	2004–2008, 2010–2016
MB 46088	0.44	0.45	--	0.36	0.52	2004–2016
MB 46146	0.40	0.40	--	0.30	0.54	1991–2014
MB 46206	2.58	2.53	--	2.03	3.03	1988–2015
			Summer			
MB 46087	1.66	1.69	--	1.34	1.82	2004–2009, 2010–2017
MB 46088	0.39	0.38	--	0.33	0.47	2004–2017
MB 46146	0.37	0.37	--	0.28	0.42	1992–2015
MB 46206	1.85	1.91	--	1.28	2.10	1989–2016

Note. (--) indicates data not available (no duplicate data points).

There were statistically significant differences in wave height monthly means between seasons at all locations: MB 46087 (Mann-Whitney U Test, $U_{summer} = 9$, $U_{winter} = 147$, $d.f. = 1$, $Z = 3.73$, $p < .001$), MB 46088 (Two Sample t-Test, $t = -3.82$, $d.f. = 25$, $p < .001$), MB 46146 (Mann-Whitney U Test, $U_{summer} = 157$, $U_{winter} = 395$, $d.f. = 1$, $Z = 2.52$, $p = .012$), and MB 46206 (Mann-Whitney U Test, $U_{summer} = 3$, $U_{winter} = 781$, $d.f. = 1$, $Z = -6.37$, $p < .001$).
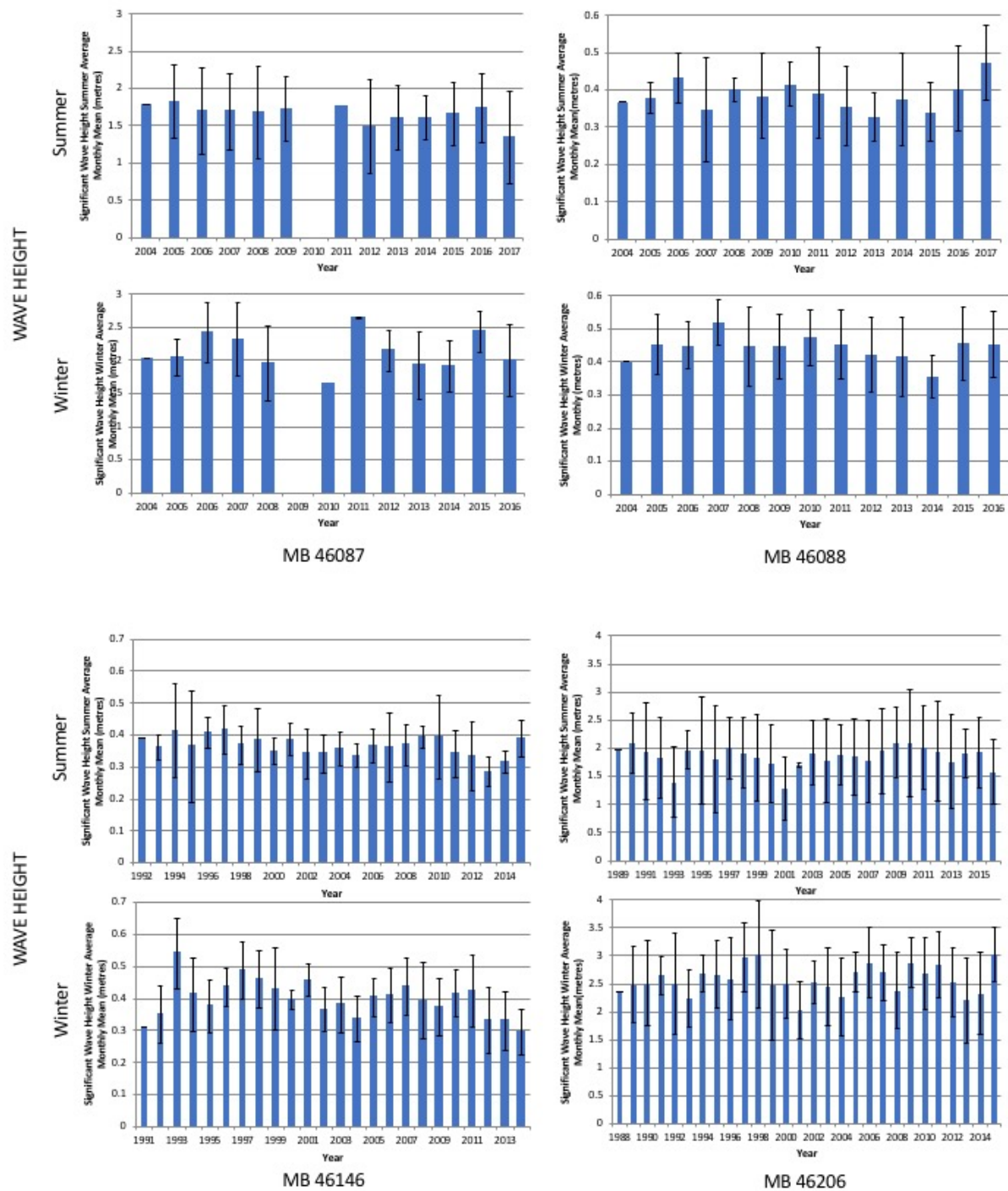
Figure 25. Seasonal wave height average monthly means at all the four meteorological buoys.

Wave height monthly means differed significantly over time at all four meteorological buoys:

- MB 46087 annually (Wilcoxon Signed-Rank Test, $Z = 9.85$, $p < .001$), in winter (Wilcoxon Signed-Rank Test, $Z = 6.79$, $p < .001$), and in summer (Wilcoxon Signed-Rank Test, $Z = 7.16$, $p < .001$);

- MB 46088 annually (One Sample t-Test, $t = 49.44$, $d.f. = 144$, $p < .001$), in winter (One Sample t-Test, $t = 37.92$, $d.f. = 68$, $p < .001$) and in summer (One Sample t-Test, $t = 35.23$, $d.f. = 75$, $p < .001$);

- MB 46146 annually (Wilcoxon Signed-Rank Test, $Z = 14.32$, $p < .001$), in winter (Wilcoxon Signed-Rank Test, $Z = 10.08$, $p < .001$) and in summer (Wilcoxon Signed-Rank Test, $Z = 10.19$, $p < .001$);

- MB 46206 annually (Wilcoxon Signed-Rank Test, $Z = 15.36$, $p < .001$), in winter (Wilcoxon Signed-Rank Test, $Z = 10.83$, $p < .001$) and in summer (Wilcoxon Signed-Rank Test, $Z = 10.90$, $p < .001$).

Wave height monthly means also varied significantly between locations, annually (Kruskal-Wallis One-Way ANOVA on Ranks, $H = 651.70$, $d.f. = 3$, $p < .001$; Figure 26), in winter (Kruskal-Wallis One-Way ANOVA on Ranks, $H = 323.11$, $d.f. = 3$, $p < .001$) and in summer (Kruskal-Wallis One-Way ANOVA on Ranks, $H = 340.64$, $d.f. = 3$, $p < .001$).
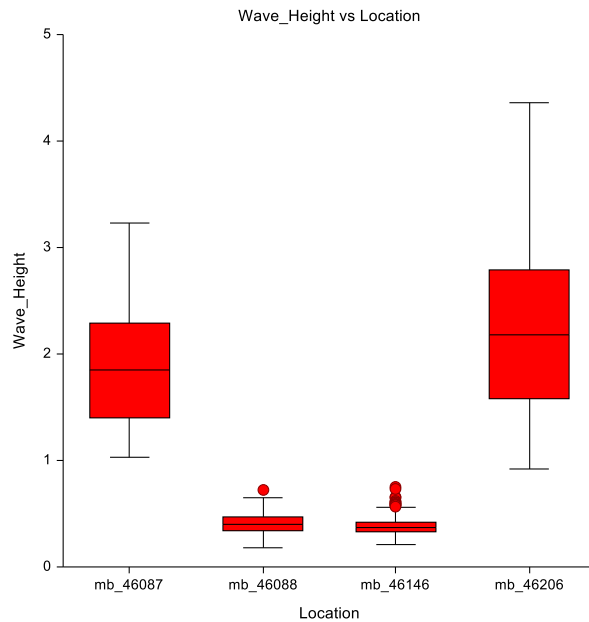
*Figure 26.* Annual wave height average monthly mean

Wave Period.

The meteorological buoys furthest inshore (MB 46088 and 46146) had lower wave period average monthly means than those in the southern and western regions of the critical habitat (MB 46087 and MB 46206; Table 12; Figure 27). The latter two also showed greater variability between summer and winter, with higher values in winter months (Table 12, Figure 27). The wave period average monthly means at MB 46087 and 46088 were less variable over time, with relative lows in the winters of 2010 and 2017 (Table 12; Figure 27). The wave period average monthly means at MB46146 peaked in 1999 with overall slightly lower values in recent years (Table 12; Figure 27). The wave period average monthly means at MB 46206 were lowest in the summer 2001 (Table 12; Figure 27).

Table 12

Descriptive statistics (mean, median mode, minimum and maximum) for wave period monthly means at all four meteorological buoys.

Location	Mean (seconds)	Median (seconds)	Mode (seconds)	Minimum (seconds)	Maximum (seconds)	Years
			Winter			
MB46087	11.35	11.32	--	10.30	12.55	2004–2008, 2010–2016
MB46088	5.23	5.13	--	4.78	5.89	2004–2016
MB46146	3.71	3.68	--	3.33	4.78	1991–2014
MB46206	11.68	11.66	--	10.85	12.39	1988–2000, 2002–2014
			Summer			
MB46087	9.75	9.73	--	8.43	10.69	2004–2009, 2011–2017
MB46088	5.20	5.25	--	4.55	5.75	2004–2017
MB46146	3.77	3.77	--	3.30	4.60	1992–2015
MB46206	10.33	10.30	--	8.97	11.34	1989–2016

Note. (--) indicates data not available (no duplicate data points).

Winter and summer wave period monthly means differed for the two locations closest to the open ocean : MB 46087 (Mann-Whitney U Test, $U_{summer} = 1$, $U_{winter} = 155$, *d.f.* $= 1$, $Z = 4.16$, $p < .001$), and MB 46206 (Mann-Whitney U Test *corrected for ties*, $U_{summer} = 8$, $U_{winter} = 720$, *d.f.* $= 1$, $Z = 6.15$, $p < .001$). However, no difference was found at the inshore locations: MB 46088 (Mann-Whitney U Test, $U_{summer} = 90$, $U_{winter} = 92$, *d.f.* $= 1$, $Z = 0.02$, $p = .981$) and MB 46146 (Mann-Whitney U Test, $U_{summer} = 321$, $U_{winter} = 231$, *d.f.* $= 1$, $Z = -0.95$, $p = .344$).
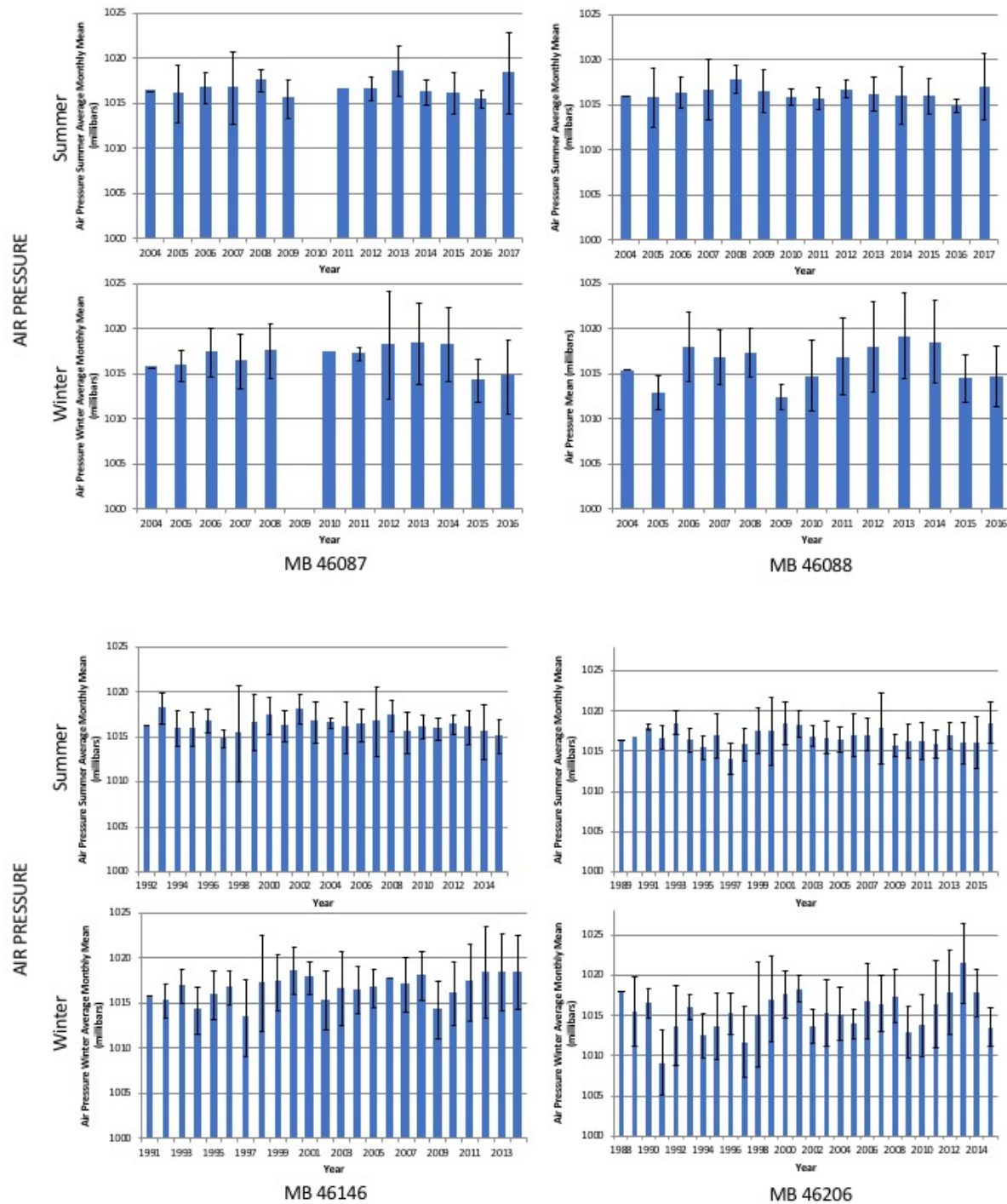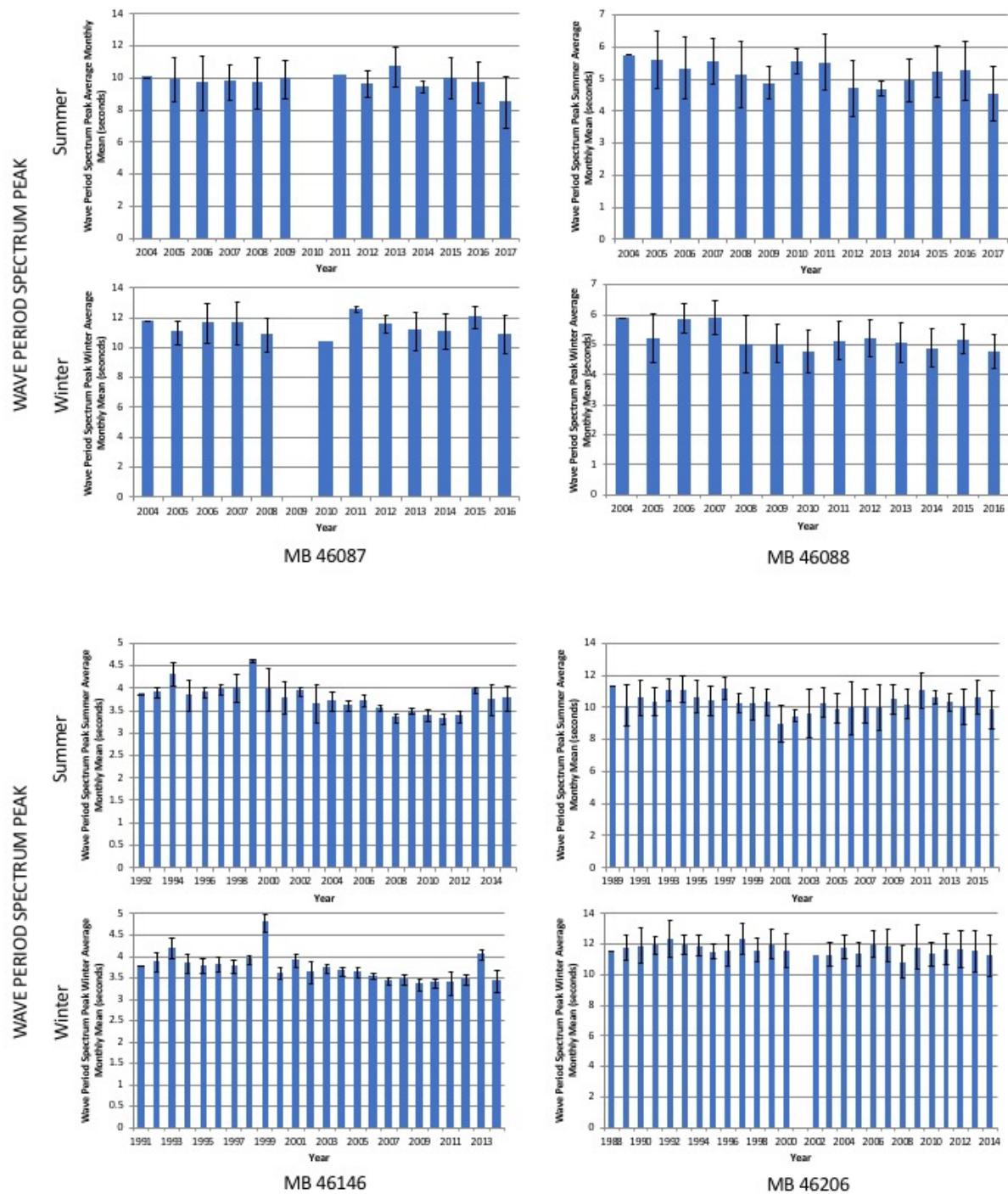
Figure 27. Seasonal wave period average monthly means at the four meteorological buoys.

There was a statistically significant difference in wave period monthly means over time, annually and seasonally, at all locations (Table 13).

Table 13

Results of Wilcoxon Signed-Rank Tests showing there is a statistically significant difference in wave period monthly means over time annually and seasonally.

	Annual		Winter		Summer	
Location	Z	P	Z	P	Z	P
MB 46087	9.85	< .001	6.79	< .001	7.16	< .001
MB 46088	10.30	< .001	7.16	< .001	7.42	< .001
MB 46146	14.27	< .001	10.01	< .001	10.19	< .001
MB 46206	15.06	< .001	10.62	< .001	10.69	< .001

Comparing the wave period monthly means between locations, a difference was found annually (Kruskal-Wallis One-Way ANOVA on Ranks, $H = 695.29$, d.f. = 3, $p < .001$; Figure 28), in winter (Kruskal-Wallis One-Way ANOVA on Ranks, $H = 338.86$, d.f. = 3, $p < .001$) and in summer (Kruskal-Wallis One-Way ANOVA on Ranks, $H = 356.76$, d.f. = 3, $p < .001$).
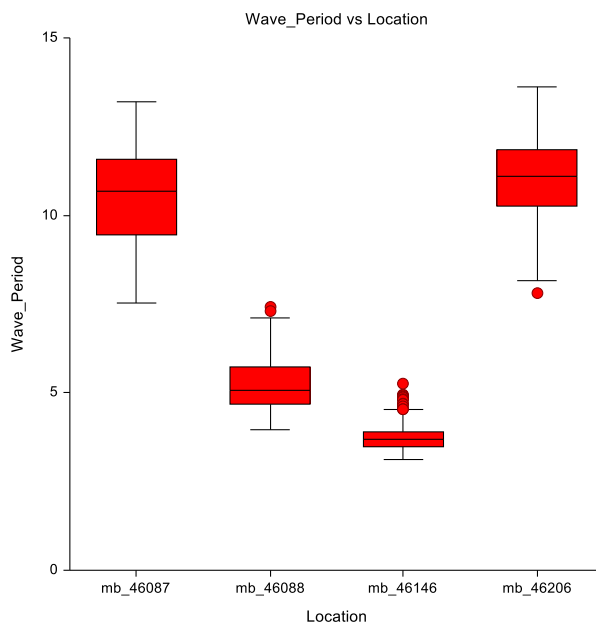
Figure 28. Annual wave period monthly means.

Biophysical Relationships—Regional.

Salinity.

Entrance Island.

While there was no statistically significant difference between ocean salinity and the killer whale population mean anomaly annually (Mann-Whitney U Test *corrected for ties*, $U_0 = 27704.5$, $U_1 = 302895$, $d.f. = 1$, $Z = 0.84$, $p = .399$), in winter (Mann-Whitney U Test *corrected for ties*, $U_0 = 7535$, $U_1 = 7017$, $d.f. = 1$, $Z = -0.48$, $p = .635$) or in summer (Mann-Whitney U Test *corrected for ties*, $U_0 = 6537.5$, $U_1 = 7907.5$, $d.f. = 1$, $Z = 1.2656$, $p = .206$), a difference was found between salinity and the killer whale population trajectory annually (Mann-Whitney U Test *corrected for ties*, $U_0 = 24030$, $U_1 = 30780$, $d.f. = 1$, $Z = -2.29$, $p = .022$) and in summer (Mann-Whitney U Test *corrected for ties*, $U_0 = 5592$, $U_K = 8076$, $d.f. = 1$, $Z = -2.39$, $p = .017$). Winter was not significant (Mann-Whitney U Test *corrected for ties*, $U_0 = 6141$, $U_1 = 7595$, $d.f. = 1$, $Z = -1.39$, $p = .164$).

Race Rocks.

Interestingly at Race Rocks, a statistically significant difference in salinity and killer whale population mean anomaly was found for all three time periods: annually (Mann-Whitney U Test *corrected for ties*, $U_0 = 35931.5$, $U_1 = 22820.5$, $d.f. = 1$, $Z = -4.24$, $p < .001$), winter (Mann-Whitney U Test *corrected for ties*, $U_0 = 9228.5$, $U_1 = 5567.5$, $d.f. = 1$, $Z = -3.32$, $p < .001$) and summer (Mann-Whitney U Test *corrected for ties*, $U_0 = 8912.5$, $U_1 = 5667.5$, $d.f. = 1$, $Z = -2.98$, $p = .003$).

The same was true for the comparison between salinity and the killer whale population trajectory: annually (Mann-Whitney U Test *corrected for ties*, $U_0 = 18863.5$, $U_1 = 36624.5$, $d.f. = 1$, $Z = -5.98$, $p < .001$), winter (Mann-Whitney U Test *corrected for ties*, $U_0 = 4984.5$, $U_1 = $

8989.5, *d.f.* = 1, *Z* = -3.79, *p* < .001) and summer (Mann-Whitney U Test *corrected for ties*, U_0 = 4353.5, U_1 = 9416.5, *d.f.* = 1, *Z* = -4.84, *p* < .001).

Sea surface temperature (SST).

Entrance Island.

There was no statistical difference in SST and killer whale population mean anomaly annually (Mann-Whitney U Test *corrected for ties*, U_0 = 28195, U_1 = 30070, *d.f.* = 1, *Z* = 0.61, *p* = .542), in winter (Mann-Whitney U Test *corrected for ties*, U_0 = 7231.5, U_1 = 7320.5, *d.f.* = 1, *Z* = 0.08, *p* = .936) or in summer (Mann-Whitney U Test *corrected for ties*, U_0 = 6653.5, U_1 = 7926.5, *d.f.* = 1, *Z* = 1.17, *p* = .243).

There was also no statistical difference in SST and killer whale population trajectory annually (Mann-Whitney U Test *corrected for ties*, U_0 = 27094, U_1 = 27919, *d.f.* = 1, *Z* = -0.28, *p* = .780), in winter (Mann-Whitney U Test *corrected for ties*, U_0 = 6683, U_1 = 7053, *d.f.* = 1, *Z* = -0.35, *p* = .724) or in summer (Mann-Whitney U Test *corrected for ties*, U_0 = 6643, U_1 = 7127, *d.f.* = 1, *Z* = -0.46, *p* = .644).

Race Rocks.

No statistical difference was found between SST and the killer whale population mean anomaly annually (Mann-Whitney U Test *corrected for ties*, U_0 = 27221.5, U_1 = 31530.5, *d.f.* = 1, *Z* = 1.39, *p* = .164) or in winter (Mann-Whitney U Test *corrected for ties*, U_0 = 6998, U_1 = 7798, *d.f.* = 1, *Z* = 0.73, *p* = .468), however summer was significant (Mann-Whitney U Test *corrected for ties*, U_0 = 61105, U_1 = 8469.5, *d.f.* = 1, *Z* = 2.17, *p* = .030).

No statistically significant difference was found between SST and the killer whale population trajectory annually (Mann-Whitney U Test *corrected for ties*, U_0 = 28595, U_1 = 26893, *d.f.* = 1, *Z* = 0.57, *p* = .567), in winter (Mann-Whitney U Test *corrected for ties*, U_0 =

7375, $U_1 = 6599$, $d.f. = 1$, $Z = 0.73$, $p = .464$) or in summer (Mann-Whitney U Test *corrected for*

ties, $U_0 = 6901.5$, $U_1 = 6868.5$, $d.f. = 1$, $Z = 0.03$, $p = .976$).

Meteorological Buoy 46087 (Neah Bay).

There was no statistically significant difference in SST and the killer whale population

mean anomaly either annually (Mann-Whitney U Test, $U_0 = 2390$, $U_1 = 1850$, $d.f. = 1$, $Z = -1.24$,

$p = .216$) or in winter (Mann-Whitney U Test, $U_0 = 550$, $U_1 = 347$, $d.f. = 1$, $Z = -1.47$, $p = .141$),

however summer was again significant (Mann-Whitney U Test, $U_0 = 839$, $U_1 = 391$, $d.f. = 1$, $Z =$

-2.60, $p = .009$).

There was a statistically significant difference in SST and the killer whale population

trajectory annually (Mann-Whitney U Test, $U_0 = 1536$, $U_1 = 2866$, $d.f. = 1$, $Z = -3.00$, $p = .003$),

in winter (Mann-Whitney U Test, $U_0 = 287$, $U_1 = 673$, $d.f. = 1$, $Z = 2.71$, $p = .007$) and in summer

(Mann-Whitney U Test, $U_0 = 409$, $U_1 = 821$, $d.f. = 1$, $Z = -2.39$, $p = .017$).

Meteorological Buoy 46088 (New Dungeness).

No statistical difference was found between SST and the killer whale population mean

anomaly annually (Mann-Whitney U Test, $U_0 = 2430$, $U_1 = 2267$, $d.f. = 1$, $Z = -0.35$, $p = .728$), in

winter (Mann-Whitney U Test, $U_0 = 607$, $U_1 = 495$, $d.f. = 1$, $Z = -0.70$, $p = .483$) or in summer

(Mann-Whitney U Test, $U_0 = 669$, $U_1 = 579$, $d.f. = 1$, $Z = -0.51$, $p = .607$) at MB 46088.

However, the relationship between SST and the killer whale population trajectory was

significant for all three time periods: annually (Mann-Whitney U Test, $U_0 = 1585$, $U_1 = 2980$, *d.f.*

$= 1$, $Z = -3.03$, $p = .002$), in winter (Mann-Whitney U Test, $U_0 = 271$, $U_1 = 831$, $d.f. = 1$, $Z = -$

3.54, $p < .001$) and in summer (Mann-Whitney U Test, $U_0 = 398$, $U_1 = 772$, $d.f. = 1$, $Z = -2.23$, p

$= .026$).

Meteorological Buoy 46146 (Halibut Bank).

At MB 46146, the relationship between SST and the killer whale population mean anomaly annually was not significant (Mann-Whitney U Test, $U_0 = 8985$, $U_1 = 9047$, *d.f.* $= 1$, $Z = -0.05$, $p = .962$) , in winter (Mann-Whitney U Test, $U_0 = 2353$, $U_1 = 2113$, *d.f.* $= 1$, $Z = 0.53$, $p = .595$) or in summer (Mann-Whitney U Test, $U_0 = 2380$, $U_1 = 2156$, *d.f.* $= 1$, $Z = 0.49$, $p = .627$).

There was also no difference in SST and killer whale population trajectory annually (Mann-Whitney U Test, $U_0 = 8989$, $U_1 = 9433$, *d.f.* $= 1$, $Z = 0.34$, $p = .733$), in winter (Mann-Whitney U Test, $U_0 = 2179$, $U_1 = 2321$, *d.f.* $= 1$, $Z = 0.31$, $p = .755$) or in summer (Mann-Whitney U Test, $U_0 = 2277$, $U_1 = 2435$, *d.f.* $= 1$, $Z = 0.34$, $p = .737$).

Meteorological Buoy 46206 (La Perouse Bank).

There was no difference at MB 46206 between SST and the killer whale population mean anomaly annually (Mann-Whitney U Test, $U_0 = 11734$, $U_1 = 11352$, *d.f.* $= 1$, $Z = 0.25$, $p = .806$), in winter (Mann-Whitney U Test, $U_0 = 2783$, $U_1 = 2822$, *d.f.* $= 1$, $Z = -0.07$, $p = .944$) or in summer (Mann-Whitney U Test, $U_0 = 3149$, $U_1 = 2791$, *d.f.* $= 1$, $Z = 0.63$, $p = .526$).

Results were similar between the SST and the killer whale population trajectory annually (Mann-Whitney U Test, $U_0 = 12013$, $U_1 = 12347$, *d.f.* $= 1$, $Z = -0.21$, $p = .835$), in winter (Mann-Whitney U Test, $U_0 = 2697$, $U_1 = 3196$, *d.f.* $= 1$, $Z = -0.90$, $p = .367$) and in summer (Mann-Whitney U Test, $U_0 = 3225$, $U_1 = 3065$, *d.f.* $= 1$, $Z = 0.28$, $p = .784$).

Air pressure.

Meteorological Buoy 46087 (Neah Bay).

At MB 46087, no statistically significant difference was found when comparing air pressure and the killer whale population mean anomaly either annually (Mann-Whitney U Test *corrected for ties*, $U_0 = 2177.5$, $U_1 = 2115.5$, *d.f.* $= 1$, $Z = -0.14$, $p = .890$), in winter (Mann-

Whitney U Test, $U_0 = 458$, $U_1 = 462$, $d.f. = 1$, $Z = 0.02$, $p = .983$) or in summer (Mann-Whitney U Test, $U_0 = 609$, $U_1 = 621$, $d.f. = 1$, $Z = 0.06$, $p = .949$).

Similar results were found when comparing air pressure with the killer whale population trajectory annually (Mann-Whitney U Test *corrected for ties*, $U_0 = 2424$, $U_1 = 2049$, $d.f. = 1$, $Z = 0.83$, $p = .405$), in winter (Mann-Whitney U Test, $U_0 = 473$, $U_1 = 517$, $d.f. = 1$, $Z = 0.30$, $p = .767$) and in summer (Mann-Whitney U Test, $U_0 = 750$, $U_1 = 480$, $d.f. = 1$, $Z = 1.57$, $p = .117$).

Meteorological Buoy 46088 (New Dungeness).

No significant difference was found at MB 46088 when comparing air pressure and the killer whale population mean anomaly: annually (Mann-Whitney U Test *corrected for ties*, $U_0 = 2801.5$, $U_1 = 2478.5$, $d.f. = 1$, $Z = -0.63$, $p = .527$), in winter (Mann-Whitney U Test *corrected for ties*, $U_0 = 710.5$, $U_1 = 498.5$, $d.f. = 1$, $Z = -1.25$, $p = .212$) and in summer (Mann-Whitney U Test, $U_0 = 846$, $U_1 = 549$, $d.f. = 1$, $Z = 1.56$, $p = .118$).

Results were similar when comparing air pressure and the killer whale population trajectory: annually (Mann-Whitney U Test *corrected for ties*, $U_0 = 3047.5$, $U_1 = 2181.5$, $d.f. = 1$, $Z = 1.71$, $p = .086$), in winter (Mann-Whitney U Test *corrected for ties*, $U_0 = 685.5$, $U_1 = 530.5$, $d.f. = 1$, $Z = 0.91$, $p = .364$) and in summer (Mann-Whitney U Test, $U_0 = 846$, $U_1 = 549$, $d.f. = 1$, $Z = 1.56$, $p = .118$).

Meteorological Buoy 46146 (Halibut Bank).

A significant difference in air pressure and the killer whale population mean anomaly was found at MB 46146 both annually (Mann-Whitney U Test *corrected for ties*, $U_0 = 10104.5$, $U_1 = 7367.5$, $d.f. = 1$, $Z = 2.19$, $p = .029$) and in winter (Mann-Whitney U Test *corrected for ties*, $U_0 = 2589$, $U_1 = 1587$, $d.f. = 1$, $Z = 2.34$, $p = .019$), but not in summer (Mann-Whitney U Test *corrected for ties*, $U_0 = 2348.5$, $U_1 = 2187.5$, $d.f. = 1$, $Z = 0.35$, $p = .727$).

No difference was found between air pressure and the killer whale population trajectory: annually (Mann-Whitney U Test *corrected for ties*, $U_0 = 8978.5$, $U_1 = 8688.5$, *d.f.* $= 1$, $Z = -0.23$, $p = .818$), in winter (Mann-Whitney U Test *corrected for ties*, $U_0 = 2144$, $U_1 = 1981$, *d.f.* $= 1$, $Z = -0.38$, $p = .703$) or in summer (Mann-Whitney U Test *corrected for ties*, $U_0 = 2317$, $U_1 = 2395$, *d.f.* $= 1$, $Z = 0.17$, $p = .869$).

Meteorological Buoy 46206 (La Perouse Bank).

At MB 46206 there was a significant difference in air pressure and the killer whale population mean anomaly both annually (Mann-Whitney U Test *corrected for ties*, $U_0 = 13254.5$, $U_1 = 9474.5$, *d.f.* $= 1$, $Z = 2.46$, $p = .014$) and in winter (Mann-Whitney U Test *corrected for ties*, $U_0 = 3437.5$, $U_1 = 21675$, *d.f.* $= 1$, $Z = 2.36$, $p = .018$), but not in summer (Mann-Whitney U Test *corrected for ties*, $U_0 = 3141$, $U_1 = 2619$, *d.f.* $= 1$, $Z = 0.95$, $p = .343$).

However, no difference was found between air pressure and the killer whale population trajectory: annually (Mann-Whitney U Test *corrected for ties*, $U_0 = 12538.5$, $U_1 = 11342.5$, *d.f.* $= 1$, $Z = 0.76$, $p = .448$), in winter (Mann-Whitney U Test *corrected for ties*, $U_0 = 3151.5$, $U_1 = 2713.5$, *d.f.* $= 1$, $Z = 0.79$, $p = .427$) or in summer (Mann-Whitney U Test *corrected for ties*, $U_0 = 3037$, $U_1 = 3031$, *d.f.* $= 1$, $Z = 0.01$, $p = .993$).

Wave height.

Meteorological Buoy 46087 (Neah Bay).

There was no significant difference at MB 46087 between wave height and the killer whale population mean anomaly: annually (Mann-Whitney U Test, $U_0 = 3082$, $U_1 = 1946$, *d.f.* $= 1$, $Z = -0.32$, $p = .747$), in winter (Mann-Whitney U Test, $U_0 = 499$, $U_1 = 375$, *d.f.* $= 1$, $Z = -0.92$, $p = .360$) or in summer (Mann-Whitney U Test, $U_0 = 515$, $U_1 = 625$, *d.f.* $= 1$, $Z = 0.67$, $p = .501$).

Results were similar between wave height and the killer whale population trajectory: annually (Mann-Whitney U Test, $U_0 = 2129$, $U_1 = 1989$, $d.f. = 1$, $Z = 0.33$, $p = .742$), in winter (Mann-Whitney U Test, $U_0 = 521$, $U_1 = 409$, $d.f. = 1$, $Z = -0.80$, $p = .423$) and in summer (Mann-Whitney U Test, $U_0 = 479$, $U_1 = 628$, $d.f. = 1$, $Z = -0.93$, $p = .354$).

Meteorological Buoy 46088 (New Dungeness).

At MB 46088, no difference was found between wave height and the killer whale population mean anomaly: annually (Mann-Whitney U Test, $U_0 = 2275$, $U_1 = 2925$, $d.f. = 1$, $Z = 1.29$, $p = .197$), in winter (Mann-Whitney U Test, $U_0 = 542$, $U_1 = 628$, $d.f. = 1$, $Z = 0.51$, $p = .607$) or in summer (Mann-Whitney U Test, $U_0 = 587$, $U_K = 848$, $d.f. = 1$, $Z = 1.36$, $p = .1756$).

There was also no difference in wave height and the killer whale population trajectory: annually (Mann-Whitney U Test, $U_0 = 2644$, $U_1 = 2522$, $d.f. = 1$, $Z = 0.24$, $p = .809$), in winter (Mann-Whitney U Test, $U_0 = 676$, $U_1 = 508$, $d.f. = 1$, $Z = 1.01$, $p = .315$) or in summer (Mann-Whitney U Test, $U_0 = 585$, $U_1 = 810$, $d.f. = 1$, $Z = -1.18$, $p = .237$).

Meteorological Buoy 46146 (Halibut Bank).

A statistically significant difference in wave height and the killer whale population mean anomaly was found annually (Mann-Whitney U Test, $U_0 = 7624$, $U_1 = 10408$, $d.f. = 1$, $Z = -2.17$, $p = .030$), but not in winter (Mann-Whitney U Test, $U_0 = 1900$, $U_1 = 2566$, $d.f. = 1$, $Z = -1.48$, $p = .139$) or in summer (Mann-Whitney U Test, $U_0 = 1850$, $U_1 = 2686$, $d.f. = 1$, $Z = -1.82$, $p = .069$) at MB 46146.

There was also difference in wave height and killer whale population trajectory annually (Mann-Whitney U Test, $U_0 = 10844$, $U_1 = 7578$, $d.f. = 1$, $Z = -2.52$, $p = .012$) and in winter (Mann-Whitney U Test, $U_0 = 2841$, $U_1 = 1659$, $d.f. = 1$, $Z = -2.62$, $p = .009$), but not in summer (Mann-Whitney U Test, $U_0 = 2602$, $U_1 = 2110$, $d.f. = 1$, $Z = -1.05$, $p = .293$).

Meteorological Buoy 46206 (La Perouse Bank).

No difference was found at MB 46206 between wave height and the killer whale population mean anomaly: annually (Mann-Whitney U Test, $U_0 = 10619$, $U_1 = 12586$, $d.f. = 1$, $Z = -1.26$, $p = .208$), in winter (Mann-Whitney U Test, $U_0 = 2699$, $U_1 = 3024$, $d.f. = 1$, $Z = -0.59$, $p = .554$), or in summer (Mann-Whitney U Test, $U_0 = 2620$, $U_1 = 3260$, $d.f. = 1$, $Z = -1.15$, $p = .252$).

Results were similar for wave height and the killer whale population trajectory: annually (Mann-Whitney U Test, $U_0 = 12234$, $U_1 = 12246$, $d.f. = 1$, $Z = -0.01$, $p = .995$), in winter (Mann-Whitney U Test, $U_0 = 3194$, $U_1 = 2841$, $d.f. = 1$, $Z = 0.63$, $p = .531$) and in summer (Mann-Whitney U Test, $U_0 = 2936$, $U_1 = 3269$, $d.f. = 1$, $Z = -0.58$, $p = .563$).

Wave period.

Meteorological Buoy 46087 (Neah Bay).

No difference was found at MB 46087 for wave period and the killer whale population mean anomaly: annually (Mann-Whitney U Test, $U_0 = 2105$, $U_1 = 1923$, $d.f. = 1$, $Z = -0.43$, $p = .665$), in winter (Mann-Whitney U Test, $U_0 = 462$, $U_1 = 412$, $d.f. = 1$, $Z = -0.37$, $p = .715$) or in summer (Mann-Whitney U Test, $U_0 = 531$, $U_1 = 609$, $d.f. = 1$, $Z = 0.48$, $p = .634$).

Results were similar for wave period and the killer whale population trajectory: annually (Mann-Whitney U Test, $U_0 = 2092$, $U_1 = 2026$, $d.f. = 1$, $Z = 0.15$, $p = .878$), in winter (Mann-Whitney U Test, $U_0 = 460$, $U_1 = 470$, $d.f. = 1$, $Z = 0.07$, $p = .948$) and in summer (Mann-Whitney U Test, $U_0 = 480$, $U_1 = 627$, $d.f. = 1$, $Z = -0.92$, $p = .360$).

Meteorological Buoy 46088 (New Dungeness).

No difference was found at MB 46088 between wave period and the killer whale population mean anomaly: annually (Mann-Whitney U Test, $U_0 = 2060$, $U_1 = 2880$, $d.f. = 1$, $Z =$

1.69, $p = .090$), in winter (Mann-Whitney U Test, $U_0 = 491$, $U_1 = 649$, $d.f. = 1$, $Z = 0.97$, $p = .332$) or in summer (Mann-Whitney U Test, $U_0 = 524$, $U_1 = 806$, $d.f. = 1$, $Z = 1.55$, $p = .121$).

Results were similar between wave period and the killer whale population trajectory annually (Mann-Whitney U Test, $U_0 = 2144$, $U_1 = 2716$, $d.f. = 1$, $Z = -1.19$, $p = .234$) or in winter (Mann-Whitney U Test, $U_0 = 609$, $U_1 = 543$, $d.f. = 1$, $Z = 0.40$, $p = .690$), however a difference was found in the summer (Mann-Whitney U Test, $U_0 = 446$, $U_1 = 814$, $d.f. = 1$, $Z = -2.08$, $p = .037$).

Meteorological Buoy 46146 (Halibut Bank).

At MB 46146, a statistically significant difference was found between wave period and the killer whale population mean anomaly both annually (Mann-Whitney U Test, $U_0 = 8383$, $U_1 = 9425$, $d.f. = 1$, $Z = -0.82$, $p = .413$) and in winter (Mann-Whitney U Test, $U_0 = 2066$, $U_1 = 2284$, $d.f. = 1$, $Z = -0.49$, $p = .623$), but not in summer (Mann-Whitney U Test, $U_0 = 2089$, $U_1 = 2447$, $d.f. = 1$, $Z = -0.78$, $p = .436$).

There was a also a difference in wave period and the killer whale population trajectory: annually (Mann-Whitney U Test, $U_0 = 11644$, $U_1 = 6534$, $d.f. = 1$, $Z = -3.98$, $p < .001$), in winter (Mann-Whitney U Test, $U_0 = 2696$, $U_1 = 1684$, $d.f. = 1$, $Z = -2.29$, $p = .022$) and in summer (Mann-Whitney U Test, $U_0 = 3175$, $U_1 = 1537$, $d.f. = 1$, $Z = -3.50$, $p < .001$).

Meteorological Buoy 46206 (La Perouse Bank).

A difference was found at MB 46026 between wave period and the killer whale population mean anomaly both annually (Mann-Whitney U Test, $U_0 = 8945$, $U_1 = 11920$, $d.f. = 1$, $Z = -2.05$, $p = .041$) and in summer (Mann-Whitney U Test, $U_0 = 2006$, $U_1 = 3286$, $d.f. = 1$, $Z = -2.46$, $p = .014$), but not in winter (Mann-Whitney U Test, $U_0 = 2262$, $U_1 = 2879$, $d.f. = 1$, $Z = -1.21$, $p = .226$).

No difference was found between wave period and killer whale population trajectory: annually (Mann-Whitney U Test, $U_0 = 11105$, $U_1 = 11647$, $d.f. = 1$, $Z = -0.36$, $p = .721$), in winter (Mann-Whitney U Test, $U_0 = 2833$, $U_1 = 2776$, $d.f. = 1$, $Z = 0.11$, $p = .916$) or in summer (Mann-Whitney U Test, $U_0 = 2778$, $U_1 = 2989$, $d.f. = 1$, $Z = -0.39$, $p = .699$).

Biophysical Interactions—Salish Sea.

The Salish Sea was examined as a whole system to determine whether there was a statistically significant difference between the physical variables and killer whale population mean anomaly and trajectory, both annually and seasonally. Each physical variable (salinity, sea surface temperature, air pressure, wave height and wave period) was tested separately, and the majority were not statistically significant (Table B3). The only statistically significant results were:

- Salinity and killer whale population trajectory annually (Mann-Whitney U Test *corrected for ties*, $U_0 = 97981.5$, $U_1 = 122612.5$, $d.f. = 1$, $Z = -2.95$, $p = .003$);

- Salinity and killer whale population trajectory in summer (Mann-Whitney U Test *corrected for ties*, $U_0 = 23614.5$, $U_1 = 31261.5$, $d.f. = 1$, $Z = -2.60$, $p = .009$);

- Air pressure and killer whale population mean anomaly annually (Mann-Whitney U Test *corrected for ties*, $U_0 = 102605.5$, $U_1 = 80066.5$, $d.f. = 1$, $Z = 3.12$, $p = .002$); and

- Air pressure and killer whale population mean anomaly in winter (Mann-Whitney U Test *corrected for ties*, $U_0 = 25957.5$, $U_1 = 17358.5$, $d.f. = 1$, $Z = 3.50$, $p < .001$).

Discussion

It is ultimately the number of births and deaths of a species that drives population dynamics. For most populations this cannot be assessed with certainty. The southern resident killer whale community is unique amongst many large mammal populations in that the entire

population size is known with individuals and their life histories recorded since 1976.

Evaluation of the population dynamics of this community revealed that both J and K pods have

remained relatively stable over the 43-year study period, with the most significant fluctuations

occurring in L pod.

L pod has gone from a total of 40 animals in 1976, to 59 in 1993, and then slowly

decreased to a low of 34 individuals in 2018 (CWR, 2018). These fluctuation in L pod drive the

overall population dynamics of the southern resident population as the two trajectory patterns are

nearly identical. In comparison, J pod has increased slightly from 1976 until 2016, when there

was a sharp decline (following the "baby boom"), going from a high of 29 animals back down to

23 in only two years (CWR, 2018). Surprisingly, K pod has exhibited a slight increase (15 to 18

animals) over the 43-year period with no marked declines. Within the southern resident killer

population, it is K pod that is doing the best overall, with fewer deaths occurring than either of

the other pods. While the analysis of age at death did not find a significant relationship between

pod membership and longevity, it appears that K pod may experience longer life spans than

individuals in either J or L pods. Future analyses with longer time periods may resolve this.

As a population, the southern residents have experienced a dynamic population trajectory

over the past 43 years. Just over four decades ago, there were 71 individuals, by 1995 the

population peaked at a high of 98, and then dropped to 75 animals in recent years (CWR, 2018).

Whilst the population has experienced periods of increase and decrease, there has been a general

continuing decline since 2006, notwithstanding the "baby boom" of 2014–16 with the addition of

10 calves that exhibited 50% mortality within a few years of birth (CWR, 2018). Analysis of the

annual percent change in the killer whale population found that the temporal increases have

become smaller and fewer over time, while the negative population changes have become larger

and more frequent in recent decades.

In addition to this numerical downward trend, there are also changes in the spatial

distribution and habitat use of the southern resident community. During the summer and fall, all

three pods have historically been present—indeed, predictable—within the Salish Sea. During

the winter months, increased habitat segregation is observed, with J pod favouring the NE part of

Washington and K and L pods favouring the southern part, as shown by Hanson et al. (2013)

using passive acoustic recorders. On a range-wide scale, Olson et al. (2018) also found clear

distributional patterns with K and L pods favouring habitats beyond the Salish Sea particularly

during the late winter and early spring months (e.g., February–May). This finding is of

significance since the majority of the current southern resident killer whale conservation efforts

are focused entirely within the Salish Sea, yet L pod, which has suffered the greatest numerical

losses, spends the least amount of time in this area, especially in the late winter months (Olson et

al., 2018).

These killer whales have been recognised for their historical site fidelity to the waters of

the Salish Sea, but a recent shift in spatial distribution has provided support to the theory that

prey availability determines southern resident killer whale movements (Olson et al., 2018). This

suggests that if the habitat quality declines with regard to prey, the importance of that habitat

may also decline for the killer whales. The whales' presence in the Salish Sea and critical habitat

has recently been correlated with the strength of the Fraser River Chinook salmon run (Shields et

al., 2018), further supporting the notion that habitat quality is directly related to prey and that a

decline in prey precipitated the reduced use of this critical habitat.

Examination of the relationship between longevity and gender found that females live longer on average, with an average lifespan of 42.36 years old for females (Table A3). Male southern residents died much earlier at an average of only 20.29 years old (Table A3). Statistically the pod or matriline membership did not affect the age at death, but qualitatively it appears that individuals belonging to K pod live longer (Table A3). As research continues on the population dynamics of these three pods, this should be re-examined.

In addition to the different trajectories of J, K and L pods, analyses of differences in the maternal age at birth and maternal age at first known calf identified that L pod was significantly different from the rest of the southern resident population (Table A4). The average maternal age at birth for L pod females was three years older ($\mu=25.51$ years) than the rest of the population ($\mu= 22.54$). This is of particular interest considering that prey abundance has been identified as a biological correlation to both killer whale survival and reproduction (Ward, Holmes & Balcomb, 2009), and L pod often disperses to the more southerly regions of the range. This may then result in a greater cost to individuals during the winter months when the energetic demands may be exacerbated by sea conditions generated by Pacific winter storms.

Neither pod membership nor the mother's age at her first calf were found to relate to the number of calves produced per female, or to the total number of female calves that reproduced (per female; Table A4). However, familial influence did have an effect on the reproductive success of southern resident killer whales. Maternal age at birth was 7–10 years younger in the presence of the females' mother, an older female, or an older female with a living calf within the matriline (Table A4). While this may be because a younger female is more likely to have living older relatives, it may also indicate that reproductive success is influenced by the presence of older and reproductively active related females. However, it appears that a direct genetic relation

is not necessarily a factor as the presence of both the grandmother and great-grandmother, or the number of female helpers was not significantly related to reproductive success (Table A4).

The effect of familial influence on maternal age at first known calf yielded similar results (Table A4). Maternal age at first calf was 5–9 years younger in the presence of the females' mother, an older female, or an older female with a living calf (Table A4). However, as above, there was no correlation with the presence of both the grandmother and great-grandmother, or the number of female helpers (Table A4).

Lending to the importance of family relationships within killer whale pods, a significant difference was found with calf survival when the grandmother was alive (Table A5). Analyses examining differential success of females' calf production (i.e. age at death of calf and maternal ID), the mother's age at the time of a calf's birth, pod membership, the presence of an older female, the presence of both grandmother and great-grandmother, or the number of female helpers were not statistically significant in terms of the reproductive success (Table A5). This may demonstrate the importance of inter-generational impacts on neonate survival. The live captures and subsequent removals which occurred from 1964 to 1976 may have had a cascading effect well beyond the time periods of the captures. Individuals taken during that time would have been in their fifties now and may have influenced population dynamics not only with the births of their own calves but with the supporting roles they would have played with calves born throughout their lives.

Examination of the physical oceanographic variables found seasonal differences between the winter and the summer in all cases at all locations except air pressure and wave period. No difference was found in air pressure at MB 46087, MB 46088 and MB 46146, and in wave period at MB 46088 and MB 46146, all of which are inshore locations. Ocean salinity, sea

surface temperature, air pressure, wave height and wave period all exhibited changes over time at all six oceanographic data collection locations. There were also significant differences between locations both annually and seasonally for all physical parameters except annual and winter air pressure.

Salinity was related to killer whale population dynamics in almost all analyses (Table 14). At Race Rocks, the mean salinity was lower when the killer whale population size was above the population mean both annually and seasonally (Table 14). Additionally, the salinity was higher when the population was increasing, at both Race Rocks and Entrance Island, annually and during the summer (Table 14).

Winter analyses at Race Rocks also identified a significant relationship between higher mean salinity and time periods when the population was increasing (Table 14). Spatial variation was found with salinity levels consistently higher at Race Rocks than Entrance Island. However, this is unsurprising given the proximity of the latter to several streams and rivers including the Fraser River across the Strait of Georgia. Lower salinity may indicate higher rainfall which would create better spawning habitat. In order to explore these trends further, time lags should be examined to take into consideration prey life cycles and their effects on killer whale foraging success.

SST was found to be related to the killer whale population at the oceanographic sites closest to the Juan de Fuca Strait. SST was found to be significantly related to years when the killer whale population was above the mean at Race Rocks during the summer (Table 14). At the entrance to Juan de Fuca Strait at MB 46087 (Neah Bay), SST was lower when the population was above the mean (Table 14). At both MB 46087 and MB 46088 higher SST was found annually and seasonally during years when the population was increasing (Table 14). This

relationship with SST and the killer whale population positive trajectories may indicate a spatial importance of this region which is also an important passageway for migratory Chinook salmon.

Examination of air pressure throughout the Salish Sea was used as a proxy for storm activity. At MB 46146 (Halibut Bank) and MB 46206 (La Perouse Bank) lower air pressure was found to be correlated with the years that the killer whale population was above the mean both annually and during the winter (Table 14). It is interesting to note that these are the two buoys furthest from the Juan de Fuca Strait. Storm activity may cause increased upwelling and nutrient cycling, as well as increased rainfall, resulting in more favourable conditions for returning salmon.

At MB 46146 (Halibut Bank), higher annual wave heights also occurred during years when the population was above the mean, and lower annual and winter wave heights occurred during years the population was increasing (Table 14). Wave period at MB 46146 was also lower during years when the population was increasing, both annually and seasonally (Table 14). At MB 46206 (La Perouse Bank), wave period was higher when the population was above the mean (Table 14). Both wave height and period were only correlated at locations furthest from the Juan de Fuca Strait.

Fewer correlations were found with physical variables in the Salish Sea in the winter months, possibly due to the fact that the whales spend less time in this area, however sea conditions elsewhere may be statistically significant. The cyclic events that occur each year when L pod is present in the Salish Sea, as well as the physical conditions (and their effects on prey availability) present in the winter habitats, require further study.

Table 14

Summary of statistical analyses comparing physical data at each location to killer whale population mean anomaly and trajectory. Is there a statistically significant difference between the physical variable and killer whale mean anomaly and trajectory? N = No, Y = Yes.

Location	Physical Variable	Annual Mean Anomaly	Annual Trajectory	Summer Mean Anomaly	Summer Trajectory	Winter Mean Anomaly	Winter Trajectory
Entrance Island	Salinity	N	Y	N	Y	N	N
	Temperature	N	N	N	N	N	N
Race Rocks	Salinity	Y	Y	Y	Y	Y	Y
	Temperature	N	N	Y	N	N	N
MB 46087	Pressure	N	N	N	N	N	N
	Temperature	N	Y	Y	Y	N	Y
	Wave Height	N	N	N	N	N	N
	Wave Period	N	N	N	N	N	N
MB 46088	Pressure	N	N	N	N	N	N
	Temperature	N	Y	N	Y	N	Y
	Wave Height	N	N	N	N	N	N
	Wave Period	N	N	N	Y	N	N
MB 46146	Pressure	Y	N	N	N	Y	N
	Temperature	N	N	N	N	N	N
	Wave Height	Y	Y	N	N	N	Y
	Wave Period	N	Y	N	Y	N	Y
MB 46206	Pressure	Y	N	N	N	Y	N
	Temperature	N	N	N	N	N	N
	Wave Height	N	N	N	N	N	N
	Wave Period	Y	N	Y	N	N	N

When looking at the Salish Sea as a whole system, there were only two physical variables that were significantly related to the killer whale population. When the population trajectory was increasing, mean salinity was slightly higher, particularly in the summer months (Table 15).

During years when the population was above the mean, air pressure was lower, most notably

during the winter months (Table 15). This may have indicated more winter storms and

subsequent rainfall, creating better salmon spawning areas.

Table 15

*Summary of statistical analyses comparing physical data throughout the Salish Sea as a whole to
killer whale population mean anomaly and trajectory (Y = Yes, N = No).*

Physical Variable	Annual		Summer		Winter	
	Mean Anomaly	Trajectory	Mean Anomaly	Trajectory	Mean Anomaly	Trajectory
Salinity	N	Y	N	Y	N	N
Temperature	N	N	N	N	N	N
Pressure	Y	N	N	N	Y	N
Wave Height	N	N	N	N	N	N
Wave Period	N	N	N	N	N	N

     Several limitations were unavoidable in this study. Fewer sightings of both K and L

pods in the winter may compromise the detection of neonates who only survive a short time,

influencing these data and analyses. While five physical factors were examined in relation to the

killer whale population dynamics, reproductive success and neonate survival, there may be

others that are important. That significant relationships were found should serve as a basis for

more in-depth study of the biophysical interactions in the killer whale ecosystem. Further to this,

the physical data were not consistent and exhibited spatial and temporal variability and were

limited to a small portion of the entire range of this highly mobile population. While this study

focused on the measured values, another way of looking at the relationship between the physical

and the biological data would be to examine the mean anomalies at each study site in comparison

to killer whale population dynamics.

     The southern residents make use of the entire range of the CCLME, and any changes

within it must be considered to affect not only the whales themselves but their prey species and

forage fish further down the food chain. Habitat use and prey availability in winter feeding

grounds (traditionally Oregon and California) have changed a great deal yet recent conservation

efforts focused entirely in politically active hot spots like the Salish Sea do not recognize these

factors. If current trends continue, the southern residents can be expected to spend less time in

the Salish Sea and their historic feeding grounds. New laws regulating management of small

vessels on the water and distance from whales, allocation of arbitrary sanctuaries and "no-go"

zones will not help the southern residents if they have moved to other regions within their range

beyond the Salish Sea. A more integrative and holistic conservation approach which includes

the whole of the population's range is necessary to identify relevant cycles and anomalies that

might help predict in advance when the southern resident killer whales might require a greater

proportion of natural resources set aside for their survival.

In summary, the specific research questions examined the biological relationships within

the southern resident killer whale population and the effects of physical oceanographic factors on

the population dynamics, reproductive success and neonate survival. The research conducted for

this thesis found significant relationships in all cases, with salinity showing a particularly strong

correlation at almost every individual study site. Looking at the Salish Sea as a whole, salinity

and atmospheric pressure exhibited the most significant correlations to killer whale life history

and population dynamics. These phenological relationships indicate that changing physical

factors are relevant to southern resident killer whale foraging habitat use, reproduction and

population dynamics, and should be considered when determining future recovery strategies.

Conclusions and Recommendations

Southern resident killer whale habitat use within the Salish Sea is seasonal, and this is the

northern limit of their range—a part which is being used less and less every year (Shields et al.,

2018). As a result, ongoing conservation efforts should not only be focused on the historic

summer habitat of this population of whales but should be expanded to encompass their winter

range as well as more recent habitat preferences. This is particularly relevant for the survival of

L pod, historically the largest pod that has experienced the greatest declines and spends the least

amount of time within the Salish Sea. Within the Salish Sea, physical oceanographic properties

affect the population dynamics, reproductive success and subsequent neonate survival of this

population. An examination of the physical properties of the range as a whole is recommended

in order to better understand how population dynamics are being affected. Further analyses

should consider time lags to take into account length of gestation and lactation on killer whale

fecundity and relate these phenological events to the physical oceanographic environment.

Effect of physical variables on the different life stages of salmon as well as smaller forage fish,

and relevant time lags, should also be considered. The effects of physical oceanographic

variables should be examined separately for each pod and throughout their habitat to determine

whether their dispersal in winter months affects their population dynamics and survival.

Ecological relationships are complex, and more research is needed to determine the

extent of each possible influence into killer whale population dynamics. In the meantime, a

precautionary approach is suggested, which should include first and foremost a concerted cross-

boundary effort to restore historic Chinook salmon runs around southern BC and Washington

waters.

References

Badeck, F.–W., Bondeau, A., Bottcher, K., Doktor, D., Lucht, W., Schaber, J. & Sitch, S. (2004).

Responses of spring phenology to climate change. *New Phytologist, 162,* 295–309.

doi:10.1111/j.1469-8137.2004.01059.x

Bailleul, F., Lesage, V., Power, M., Doidge, D. W. & Hammill, M. (2012). Migration

phenology of beluga whales in a changing Arctic. *Climate Research (53),* 169-178.

doi:10.3354/cr01104

Bograd, S. J., Schroeder, I., Sarkar, N., Qiu, X., Sydeman, W. J. & Schwing, F. B. (2009).

Phenology of coastal upwelling in the California Current. *Geophysical Research Letters

(36),* L01602. doi:10.1029/2008GL035933

Brown, S. (2018, July 18). Shark week: 14 sharks, including the great white, swim in B.C. waters

and more are coming. *Vancouver Sun.* Retrieved from

https://vancouversun.com/news/staff-blogs/shark-week-14-sharks-including-the-great-

white-swim-in-b-c-waters

Center for Whale Research. Official Orca Survey: Naturalist's Family Tree Guide to Orca

Whales of the Southern Resident Community. (Center for Whale Research, Friday

Harbor, Washington, 2012).

Center for Whale Research. *Southern Resident Orca Survey*. (Center for Whale Research, Friday

Harbor, Washington, 2018).

Colby, Jason M. *Orca: How We Came to Know and Love the Ocean's Greatest Predator*. New

York: Oxford University Press, 2018.

Cotton, P. A. (2003). Avian migration phenology and global climate change. *Proceedings of the

National Academy of Sciences, 100*(21), 12219-12222. doi:10.1073/pnas.1930548100

Crozier, L. G., Hendry, A. P., Lawson, P. W., Quinn, T. P., Mantua, N. J., Battin, J. . . Huey, R.

    B. (2008). Potential responses to climate change in organisms with complex life

    histories: evolution and plasticity in Pacific salmon. *Evolutionary Applications, 1*(2),

    252-270. doi:10.1111/j.1752-4571.2008.00033.x

Darwin, C. (1859). *On The Origin of Species by Means of Natural Selection, or Preservation of*

    Favoured Races in the Struggle for Life. Retrieved from http://darwin-

    online.org.uk/content/frameset?itemID=F373&viewtype=text&pageseq=1

de Bruyn, P. N., Tosh, C. A., & Terauds, A. (2013). Killer whale ecotypes: is there a global

    model? *Biological Reviews*, *88*(1), 62-80. doi:10.1111/j.1469-185X.2012.00239.x

Deecke, V. B., Ford, J. K. B. & Spong, P. (2000). Dialect change in resident killer whales

    (Orcinus orca): implications for vocal learning and cultural transmission. *Animal*

    Behaviour , 60 (5), 629-638. doi:10.1006/anbe.2000.1454

Diamond, S. E., Frame, A. M., Martin, R. A., & Buckley, L. B. (2011). Species' traits predict

    phenological responses to climate change in butterflies. *Ecology*, *92*(5), 1005-1012.

    doi:10.1890/10-1594.1

Fearnback, H., Durban, J. W., Ellifrit, D. K. & Balcomb, K. C., III. (2011). Size and long-term

    growth trends of Endangered fish-eating killer whales. *Endangered Species Research,*

    13, 173-180. doi:10.3354/esr00330

Fisheries and Oceans Canada (2018). Recovery strategy for the northern and southern resident

    killer whales (*Orcinus orca*) in Canada. *Species at Risk Act* Recovery Strategy Series,

    Fisheries and Oceans Canada, Ottawa.

Ford, J. K. B. (1991). Vocal traditions among resident killer whales (*Orcinus orca*) in coastal

    waters of British Columbia. *Canadian Journal of Zoology, 69*(6), 1454-1483.

    doi:10.1139/z91-206.

Ford, J. K. B., & Ellis, G. M. (2006). Selective foraging by fish-eating killer whales *Orcinus*

    orca in British Columbia. *Marine Ecology Progress Series, 316*, 185-199.

    doi:10.3354/meps316185

Ford, J. K., Ellis, G. M., & Balcomb, K. C. (2000). *Killer whales: the natural history and*

    genealogy of Orcinus orca in British Columbia and Washington. UBC Press.

Ford, J. K. B., Ellis, G. M., Barrett-Lennard, L. G., Morton, A. B., Palm, R. S. & Balcomb, K.

    C., 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(8), 1456-1471. doi: 10.1139/z98-089

Ford, J. K., Ellis, G. M., & Balcomb, K. C. (2000). *Killer whales: the natural history and*

    genealogy of Orcinus orca in British Columbia and Washington. UBC Press.

Forney, K. A., & Wade, P. R. (2006). Worldwide distribution and abundance of killer whales.

    Whales, whaling and ocean ecosystems, 145-162.

Hanson, M. B., Emmons, C. K., Ward, E. J., Nystuen, J. A., & Lammers, M. O. (2013).

    Assessing the coastal occurrence of endangered killer whales using autonomous passive

    acoustic recorders. *The Journal of the Acoustical Society of America, 134*, 3486-3495.

    doi:10.1121/1.4821206

Harley, C. D. G., Hughes, A. R., Hultgren, K. M., Miner, B. G., Sorte, C. J. B., Thorneber, C. S.

    . . . Williams, S. L. (2006). The impacts of climate change in coastal marine systems.

    Ecology Letters, 9, 228-241. doi:10.1111/j.1461-0248.2005.00871.x

Hauser, D. D., Logsdon, M. G. & Holmes, E. E. (2007). Summer distribution patterns of

    Southern Resident killer whales (Orcinus orca): core areas and spatial segregation of

    social groups. *Marine Ecology Progress Series , 351*, 301-310. doi: 10.3354/meps07117

Heimlich-Boran, J. R. (1988). Behavioral ecology of killer whales (Orcinus orca) in the Pacific

    Northwest. *Canadian Journal of Zoology, 66*(3), 565-578. doi:10.1139/z88-084

Hintze, J. L. (1998) NCSS 2018. Kaysville, Utah: Number Crunching Statistical Software.

Holt, M. M., Noren, D. P., Veirs, V., Emmons, C. K., & Veirs, S. (2009). Speaking up: Killer

    whales (Orcinus orca) increase their call amplitude in response to vessel noise. *The

    Journal of the Acoustical Society of America*, *125*(1), EL27-EL32.

    doi:10.1121/1.3040028

Hoyt, E. (1990). *Orca: the whale called killer*. Firefly Books. (Original work published 1981)

Hume, M. (2018, May 2). Squid sightings show species' unusual trek. *The Globe and

    Mail*. Retrieved from https://www.theglobeandmail.com

Lusseau, D., Williams, R., Wilson, B., Grellier, K., Barton, T. R., Hammond, P. S. &

    Thompson, P. M. (2004). Parallel influence of climate on the behaviour of Pacific killer

    whales and Atlantic bottlenose dolphins. *Ecology Letters, 7*, 1068-1076.

    doi:10.1111/j.1461-0248.2004.00669.x

Noren, D. P., Johnson, A. H., Rehder, D. & Larson, A. (2009). Close approaches by vessels

    elicit surface active behaviors by southern resident killer whales. *Endangered Species

    Research, 8*, 179-192. doi: 10.3354/esr00205

Noren, D. P. (2011). Estimated field metabolic rates and prey requirements of resident killer

    whales. *Marine Mammal Science, 27*(1), 60-77. DOI: 10.1111/j.1748-

    7692.2010.00386.x

Olesiuk, P. F., Bigg, M. A., & Ellis, G. M. (1990). Life history and population dynamics of

    resident killer whales (Orcinus orca) in the coastal waters of British Columbia and

    Washington State. *Report of the International Whaling Commission, Special*, (12), 209-

    243.

Olson, J. K., Wood, J., Osborne, R. W., Barrett-Lennard, L. & Larson, S. (2018). Sightings of

    southern resident killer whales in the Salish Sea 1976-2014: the importance of a long-

    term opportunistic dataset. *Endangered Species Research, 37*, 105-118.

    Doi:10.3354/esr00918

Parsons, K. M., Balcomb, K. C., III, Ford, J. K. B. & Durban, J. W. (2009). The social dynamics

    of southern resident killer whales and conservation implications for this endangered

    population. *Animal Behaviour , 77* (4), 963-971. doi:10.1016/j.anbehav.2009.01.018

Poloczanska, E. S., Burrows, M. T., Brown, C. J., Molinos, J. G., Halpern, B. S., Hoegh-

    Guldberg, O., . . . Sydeman, W. J. (2016). Responses of marine organisms to climate

    change acoss oceans. *Frontiers in Marine Science, 3*(62). doi:10.3389/fmars.2016.00062

Robeck, T. R., Willis, K., Scarpuzzi, M. R. and O'Brien, J. K. (2015). Comparisons of life-

    history parameters between free-ranging and captive killer whale (*Orcinus orca*)

    populations for application toward species management. *Journal of Mammology, 96* (5),

    1055-1070.

Ross, P. S. (2006). Fireproof killer whales (Orcinus orca): Flame-retardant chemicals and the

    conservation imperative in the charismatic icon of British Columbia, Canada. *Canadian*

    Journal of Fisheries and Aquatic Sciences, 63(1), 224. doi:10.1139/f05-244

Schroeder, P., Raverty, S., Cameron, C., Zabek, E. Eshghi, A., Bain, D., . . . Hanson, B. (2009).

    Investigation into the microbial culture and molecular screening of exhaled breaths of

endangered southern resident killer whales (SRKW) and pathogen screening of the sea-

surface microlayer (SML) in Puget Sound. Report to the Northwest Fisheries Science

Center, National Oceanic and Atmospheric Administration, Seattle, WA, USA.

Retrieved from University of Washington website:

http://depts.washington.edu/uwconf/psgb/proceedings/papers/SRKW_paper_Schroeder_

et_al.pdf.

Shields, M. W., Lindell, J., & Woodruff, J. 2018. Declining spring usage of core habitat by

endangered fish-eating killer whales reflects decreased availability of their primary prey.

Pacific Conservation Biology, 24, 189-193.

doi:10.1071/PC17041

SARA (Species at Risk Act). 2002. Bill C-5. An act respecting the protection of wildlife species

at risk in Canada. Available from http://laws.justice.gc.ca/en/frame/cs/S-15.3///en

(accessed October 2015).

U.S. ESA (Endangered Species Act of 1973). 1973. Available from

http://www.fws.gov/endangered/pdfs/esaall.pdf (accessed October 2015)

Vancouver Aquarium. (2016, January 26). Rescued sea turtle found far from home (Web log

post). Retrieved from http://www.aquablog.ca/2016/01/rescued-sea-turtle-found-far-

from-home/

Vancouver Aquarium. (2016, January 22). Rare Guadalupe fur seal saved in joint rescue (Web

log post). Retrieved from http://www.aquablog.ca/2016/01/rare-guadalupe-fur-seal-

saved-in-joint-rescue/

Visser, M. E. & Both, C. (2005). Shifts in phenology due to global climate change: the need for

a yardstick. *Proceedings of the Royal Society B, 272*, 2561-2569.

doi:10.1098/rspb.2005.3356

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J. C. . . Bairlein, F.

(2002). Ecological responses to recent climate change. *Nature, 416*, 389-395.

doi:10.1038/416389a

Ward, E. J., Holmes, E. E., & Balcomb, K. C. (2009). Quantifying te effects of prey abundance

on killer whale reproduction. *Journal of Applied Ecology, 46*: 632-640.

doi:10.1111/j.1365-2664.2009.01647.x

Wasser, S. K., Lundin, J. I., Ayres, K., Seely, E., Giles, D., Balcomb, K., … Booth, R. (2017).

Population growth is limited by nutritional impacts on pregnancy success in endangered

Southern Resident killer whales (*Orcinus orca). PLoS One, 12*(6): e0179824.

doi:10.1371/journal.pone.0179824

Williams, R., Bain, D. E., Smith, J. C., & Lusseau, D. (2009). Effects of vessels on behaviour

patterns of individual southern resident killer whales Orcinus orca. *Endangered Species

Research*, *6*(3), 199-209. doi:10.3354/esr00150

Williams, R. T., Trites, A. W., & Bain, D. E. (2002). Behavioural responses of killer whales

(Orcinus orca) to whale-watching boats: opportunistic observations and experimental

approaches. *Journal of Zoology , 256*, 255-270. doi:10.1017/S0952836902000298

Appendix A

Table A1

Individual killer whale data summarized based on year of birth, year of death, maternal identification (ID), maternal year of birth, maternal year of death, maternal age at birth, maternal group, pod membership, and information on group members living at the time of birth.

ID	M/F	Age at Death	Year of Birth	Year of Death	Pod	Maternal ID	Maternal Year of Birth	Maternal Year of Death	Maternal Age at Birth	Matriline
J20	F	17	1981	1998	J	J10	1962	1999	19	J22
J28	F	23	1993	2016	J	J17	1977		16	J17
J32	F	18	1996	2014	J	J20	1981	1998	15	J22
J10	F	37	1962	1999	J	NA				J22
J11	F	36	1972	2008	J	NA				J19
J12	F	61	1935	1996	J	NA				J14
J13	F	9	1971	1980	J	NA				J17
J14	F	42	1974	2016	J	J12	1935	1996	39	J14
J2	F	105	1911	2016	J	NA				J14
J4	F	38	1957	1995	J	NA				J19
J5	F	59	1938	1997	J	NA				J17
J7	F	44	1939	1983	J	NA				J16
J8	F	80	1933	2013	J	NA				J8
J9	F	68	1917	1985	J	NA				J22
J35A	F	0	2018	2018	J	J35	1998		20	J17
J50	F	4	2014	2018	J	J16	1972		42	J16
J15	M	5	1976	1981	J	J4	1957	1995	19	J19
J18	M	23	1977	2000	J	J10	1962	1999	15	J22

ID	M/F	Age at Death	Year of Birth	Year of Death	Pod	Maternal ID	Maternal Year of Birth	Maternal Year of Death	Maternal Age at Birth	Matriline
J23	M	4	1987	1991	J	J14	1974	2016	13	J14
J29	M	0	1993	1993	J	J19	1979		14	J4
J30	M	17	1995	2012	J	J14	1974	2016	21	J14
J33	M	14	1996	2010	J	J16	1972		24	J16
J34	M	18	1998	2016	J	J22	1985		13	J22
J1	M	59	1951	2010	J	NA				J14
J3	M	42	1953	1995	J	NA				J16
J52	M	2	2015	2017	J	J36	1999		16	J16
J54	M	1	2015	2016	J	J28	1993	2016	22	J17
J6	M	42	1956	1998	J	NA				J8
J28A	M	0	2013	2013	J	J28	1993	2016	20	J17
J21	NA	1	1982	1983	J	J4	1957	1995	25	J19
J25	NA	0	1988	1988	J	J11	1972	2008	16	J11
J43	NA	0	2007	2007	J	J14	1974	2016	33	J14
J48	NA	0	2011	2011	J	J16	1972		39	J16
J55	NA	0	2016	2016	J	NA				J14
J31A	NA	0	2016	2016	J	J31	1995		21	J19
K28	F	12	1994	2006	K	K12	1972		22	K12
K11	F	77	1933	2010	K	NA				K13
K13	F	45	1972	2017	K					
K18	F	56	1948	2004	K	NA				K18
K3	F	41	1957	1998	K	NA				K8
K30	F	53	1929	1982	K	NA				K30
K4	F	66	1933	1999	K	NA				K12

ID	M/F	Age at Death	Year of Birth	Year of Death	Pod	Maternal ID	Maternal Year of Birth	Maternal Year of Death	Maternal Age at Birth	Matriline
K40	F	49	1963	2012	K	NA				K18
K7	F	98	1910	2008	K	NA				K7
K8	F	59	1930	1989	K	NA				K8
K29	M	2	1996	1998	K	K3	1957	1998	39	K8
K31	M	6	1999	2005	K	K12	1972		27	K12
K1	M	42	1955	1997	K	NA				K7
K17	M	28	1966	1994	K	NA				K18
K19	M	31	1953	1984	K	NA				K30
K5	M	38	1953	1991	K	NA				K8
K23	NA	0	1988	1988	K	K14	1977		11	K8
K24	NA	0	1990	1990	K	K14	1977		13	K8
K32	NA	0	2000	2000	K	K16	1985		15	K8
K15	NA	4	1971	1975	K	NA				K8
K39	NA	0	2006	2006	K	K28	1994	2006	12	K12
K41	NA	0	2006	2006	K	K22	1987		19	K12
K46	NA	7	1974	1981	K	K18	1948	2004	26	K18
K27A	NA	0	2016	2016	K	K27	1994		22	K13
L53	F	37	1977	2014	L	NA				L72
L65	F	10	1984	1994	L	L35	1942	1996	42	L35
L67	F	23	1985	2008	L	L2	1960	2012	25	L2
L75	F	7	1986	1993	L	L22	1971		15	L22
L93	F	3	1995	1998	L	L27	1965	2015	30	L4
L11	F	43	1957	2000	L	NA				K12
L111	F	0	2008	2008	L	L47	1974		34	L47

ID	M/F	Age at Death	Year of Birth	Year of Death	Pod	Maternal ID	Maternal Year of Birth	Maternal Year of Death	Maternal Age at Birth	Matriline
L112	F	3	2009	2012	L	L86	1991		18	L4
L12	F	79	1933	2012	L	NA				L11
L15	F	51	1930	1981	L	NA				L15
L2	F	52	1960	2012	L	NA				L2
L21	F	58	1950	2008	L	NA				L47
L23	F	30	1952	1982	L	NA				L25
L26	F	57	1956	2013	L	NA				L26
L27	F	50	1965	2015	L	NA				L4
L28	F	45	1949	1994	L	NA				L22
L3	F	54	1948	2002	L	NA				L9
L32	F	50	1955	2005	L	NA				L22
L35	F	54	1942	1996	L	NA				L35
L37	F	51	1933	1984	L	NA				L72
L4	F	47	1949	1996	L	NA				L4
L43	F	34	1972	2006	L	NA				L72
L45	F	57	1938	1995	L	NA				L66
L5	F	48	1964	2012	L	NA				L9
L51	F	26	1973	1999	L	NA				L9
L60	F	30	1972	2002	L	NA				L26
L66	F	62	1924	1986	L	NA				L66
L7	F	49	1961	2010	L	NA				L72
L9	F	65	1931	1996	L	NA				L9
L72A	F	0	2010	2010	L	L72	1986		24	L72
L100	M	13	2001	2014	L	L54	1977		24	L54

ID	M/F	Age at Death	Year of Birth	Year of Death	Pod	Maternal ID	Maternal Year of Birth	Maternal Year of Death	Maternal Age at Birth	Matriline
L57	M	31	1977	2008	L	L45	1938	1995	39	L66
L58	M	22	1980	2002	L	L5	1964	2012	16	L9
L62	M	20	1980	2000	L	L27	1965	2015	15	L4
L63	M	11	1984	1995	L	L32	1955	2005	29	L22
L68	M	10	1985	1995	L	L27	1965	2015	20	L4
L71	M	20	1986	2006	L	L26	1956	2013	30	L26
L73	M	24	1986	2010	L	L5	1964	2012	22	L9
L74	M	23	1986	2009	L	L3	1948	2002	38	L9
L78	M	23	1989	2012	L	L2	1960	2012	29	L2
L79	M	24	1989	2013	L	L22	1971		18	L22
L81	M	7	1990	1997	L	L60	1972	2002	18	L26
L95	M	20	1996	2016	L	L43	1972	2006	24	L72
L96	M	1	1996	1997	L	L55	1977		19	L4
L98	M	7	1999	2006	L	L67	1985	2008	14	L2
L1	M	41	1959	2000	L	NA				L35
L10	M	38	1959	1997	L	NA				L2
L101	M	6	2002	2008	L	L67	1985	2008	17	L2
L104	M	2	2004	2006	L	L43	1972	2006	32	L72
L13	M	28	1952	1980	L	NA				L15
L14	M	17	1972	1989	L	NA				L25
L16	M	29	1949	1978	L	NA				L72
L20	M	27	1955	1982	L	NA				L15
L33	M	32	1963	1995	L	NA				L9
L38	M	33	1965	1998	L	NA				L22

ID	M/F	Age at Death	Year of Birth	Year of Death	Pod	Maternal ID	Maternal Year of Birth	Maternal Year of Death	Maternal Age at Birth	Matriline
L39	M	25	1975	2000	L	L2	1960	2012	15	L2
L42	M	21	1973	1994	L	NA				L11
L44	M	24	1974	1998	L	L32	1955	2005	19	L22
L50	M	16	1973	1989	L	NA				L35
L6	M	21	1962	1983	L	NA				L2
L61	M	23	1973	1996	L	NA				L4
L8	M	19	1958	1977	L	NA				L66
L92	M	23	1995	2018	L	L60	1972	2002	23	L26
L102	NA	0	2002	2002	L	L47	1974		28	L47
L48	NA	6	1977	1983	L	L21	1950	2008	27	L47
L49	NA	1	1979	1980	L	L23	1952	1982	27	L25
L52	NA	3	1980	1983	L	L26	1956	2013	24	L26
L56	NA	3	1978	1981	L	L32	1955	2005	23	L22
L59	NA	0	1979	1979	L	L3	1948	2002	31	L9
L64	NA	0	1985	1985	L	L11	1957	2000	28	L11
L69	NA	1	1984	1985	L	L28	1949	1994	35	L22
L76	NA	0	1987	1987	L	NA				L72
L80	NA	3	1990	1993	L	L27	1965	2015	25	L4
L97	NA	0	1999	1999	L	L51	1973	1999	26	L9
L99	NA	0	2000	2000	L	L47	1974		26	L47
L107	NA	0	2005	2005	L	L47	1974		31	L47
L114	NA	0	2010	2010	L	L77	1987		23	L11
L120	NA	0	2014	2014	L	L86	1991		23	L4
L36	NA	0	1975	1975	L	L45	1938	1995	37	L66

Table A2

Coding for southern resident killer whale population mean anomaly and trajectory.

Year	KW pop size	KW pop mean anomaly	KW anomaly code	KW pop yearly change	KW trajectory code
1976	71.00	-13.07	0		
1977	80.00	-4.07	0	12.67	1
1978	80.00	-4.07	0	0.00	1
1979	82.00	-2.07	0	2.50	1
1980	84.00	-0.07	0	2.44	1
1981	82.00	-2.07	0	-2.38	0
1982	79.00	-5.07	0	-3.66	0
1983	76.00	-8.07	0	-3.80	0
1984	74.00	-10.07	0	-2.63	0
1985	77.00	-7.07	0	4.05	1
1986	81	-3.07	0	5.19	1
1987	84	-0.07	0	3.70	1
1988	85	0.93	1	1.19	1
1989	85	0.93	1	0.00	1
1990	88	3.93	1	3.53	1
1991	92	7.93	1	4.55	1
1992	91	6.93	1	-1.09	0
1993	97	12.93	1	6.59	1
1994	96	11.93	1	-1.03	0
1995	98	13.93	1	2.08	1
1996	97	12.93	1	-1.02	0
1997	92	7.93	1	-5.15	0
1998	89	4.93	1	-3.26	0
1999	85	0.93	1	-4.49	0
2000	82	-2.07	0	-3.53	0
2001	78	-6.07	0	-4.88	0
2002	79	-5.07	0	1.28	1
2003	82	-2.07	0	3.80	1
2004	83	-1.07	0	1.22	1
2005	88	3.93	1	6.02	1
2006	89	4.93	1	1.14	1
2007	86	-13.07	0	-3.37	0
2008	85	0.93	1	-1.16	0
2009	85	0.93	1	0.00	1
2010	86	1.93	1	1.18	1

Year					
2011	87	2.93	1	1.16	1
2012	84	-0.07	0	-3.45	0
2013	82	-2.07	0	-2.38	0
2014	78	-6.07	0	-4.88	0
2015	81	-3.07	0	3.85	1
2016	83	-1.07	0	2.47	1
2017	77	-7.07	0	-7.22	0
2018	75	-9.07	0	-2.60	0

Table A3

Population dynamics statistical summary.

Analysis	AAD≥0	AAD≥1
Is there a difference in AAD within the SRKW pop?	Yes	Yes
Is there a difference in AAD between pods J, K and L?	No	No
Is there a difference in AAD between JK and L pods?	No	No
Is there a difference in AAD between J and KL pods?	No	No
Is there a difference in AAD between JL and K pods?	No	No
Is there a difference in AAD between F, M and NA in SRKW pop?	Yes	Yes
Is there a difference in AAD in F between pods?	No	No
Is there a difference in AAD in M between pods?	No	No
Is there a difference in AAD in NA between pods?	No	No
Is there a difference in AAD between F, M and NA in J pod?	Yes	Yes
Is there a difference in AAD between F, M and NA in K pod?	Yes	Yes
Is there a difference in AAD between F, M and NA in L pod?	Yes	Yes
Is there a difference in AAD between M and F (no NA) in SRKW pop?	Yes	Yes
Is there a difference in AAD between F and M (no NA) in J pod?	Yes	Yes
Is there a difference in AAD between F and M (no NA) in K pod?	Yes	Yes
Is there a difference in AAD between F and M (no NA) in L pod?	Yes	Yes
Is there a difference in AAD between matrilines?	No	No
Is there a difference in AAD of F between matrilines?	No	No
Is there a difference in AAD of M between matrilines?	No	No
Is there a difference in AAD of NA between matrilines?	No	No

Table A4

Reproductive success statistical summary.

Is there a difference in maternal AAB between pods?	No
Is there a difference in maternal AAB between JK and L pods?	Yes
Is there a difference in maternal AAB between J and KL pods?	No
Is there a difference in maternal AAB between JL and K pods?	No
Is there a difference in maternal AAB between matrilines?	No
Is there a difference in maternal AFC between pods?	No
Is there a difference in maternal AFC between JK and L pods?	Yes
Is there a difference in maternal AFC between J and KL pods?	No
Is there a difference in maternal AFC between JL and K pods?	No
Is there a difference in maternal AFC between matrilines?	No
Is there a difference in the number of female calves that reproduced (per female) between pods?	No
Is there a difference in the number of female calves that reproduced (per female) based on age at first calf?	No
Is there a difference in total number of calves per female between pods?	No
Is there a difference in total number of calves per female based on AFC?	No
Is there a difference in maternal AAB based on presence of older female	Yes
Is there a difference in maternal AAB based on presence of older female with living calf?	Yes
Is there a difference in maternal AAB based on presence of mother's mother (Y/N/P)?	Yes
Is there a difference in maternal AAB based on presence of mother's mother (Y/N; assume P=Y)?	Yes
Is there a difference in maternal AAB based on presence of mother's mother and grandmother?	Yes
Is there a difference in maternal AAB based on presence of number of female helpers?	No
Is there a difference in maternal age at first calf (AFC) based on presence of older female?	Yes
Is there a difference in maternal AFC based on presence of older female with living calf?	Yes
Is there a difference in maternal AFC based on presence of mother (Y/N/P)?	Yes
Is there a difference in maternal AFC based on presence of mother (Y/N; assume P=Y)?	Yes
Is there a difference in maternal AFC based on presence of mother and grandmother?	No
Is there a difference in maternal AAB based on number of adult female helpers?	No

Table A5

Neonate survival statistical summary.

Is there a difference in calf survival past one year per female based on pod membership?	No
Is there a difference in calf survival past one year per female based on age at first calf?	No
Is there a difference in AAD of calf based on maternal ID?	No
Is there a difference in AAD of calf based on maternal age at birth?	No
Is there a difference in AAD of calf based on pod membership?	No
Is there a difference in AAD of calf based on presence of older female?	No
Is there a difference in AAD of calf based on presence of older female with living calf?	No
Is there a difference in AAD of calf based on presence of mother's mother (Y/N/P)?	Yes
Is there a difference in AAD of calf based on presence of mother's mother (Y/N; assume P=Y)?	No
Is there a difference in AAD of calf based on presence of mother's mother and grandmother?	No
Is there a difference in AAD of calf based on presence of number of female helpers?	No

Appendix B

Table B1

Physical data received from Institute of Ocean Sciences.

Source	Temporal Frame	Physical Data Type	Sample Size
Entrance Island	May 1936-August 2016	Salinity Monthly Mean (psu)	28913
	May 1936-August 2016	Salinity Standard Deviation (psu)	28913
	May 1936-August 2016	Temperature Monthly Mean ('deg C')	29099
	May 1936-August 2016	Temperature Standard Deviation ('deg C')	29099
Race Rocks	Feb 1921-August 2016	Salinity Monthly Mean (psu)	28423
	Feb 1921-August 2016	Salinity Standard Deviation (psu)	28423
	Feb 1921-August 2016	Temperature Monthly Mean ('deg C')	34136
	Feb 1921-August 2016	Temperature Standard Deviation ('deg C')	34136
MB46087	July 2004-July2017	Pressure:Air:Sea_level Monthly Mean' (millibars)	3992
	July 2004-July2017	Pressure:Air:Sea_level Standard Deviation' (millibars)	3992
	July 2004-July2017	Temperature:Water Monthly Mean' ('deg C')	3958
	July 2004-July2017	Temperature:Water Standard Deviation' ('deg C')	3958
	July 2004-July2017	Height:Wave:Significant Monthly Mean' (metres)	3821
	July 2004-July2017	Height:Wave:Significant Standard Deviation' (metres)	3821
	July 2004-July2017	Period:Wave:Spectrum_peak Monthly Mean' (seconds)	3821
	July 2004-July2017	Period:Wave:Spectrum_peak Standard Deviation' (seconds)	3821
MB46088	July 2004-July2017	Pressure:Air:Sea_level Monthly Mean' (millibars)	4374
	July 2004-July2017	Pressure:Air:Sea_level Standard Deviation' (millibars)	4374
	July 2004-July2017	Temperature:Water Monthly Mean' ('deg C')	4109

Source	Temporal Frame	Physical Data Type	Sample Size
	July 2004-July2017	Temperature:Water Standard Deviation' ('deg C')	4109
	July 2004-July2017	Height:Wave:Significant Monthly Mean' (metres)	4348
	July 2004-July2017	Height:Wave:Significant Standard Deviation' (metres)	4348
	July 2004-July2017	Period:Wave:Spectrum_peak Monthly Mean' (seconds)	3963
	July 2004-July2017	Period:Wave:Spectrum_peak Standard Deviation' (seconds)	3963
MB46146	March 1992-Sept 2015	Pressure:Air:Sea_level Monthly Mean' (millibars)	7986
	March 1992-Sept 2015	Pressure:Air:Sea_level Standard Deviation' (millibars)	7986
	March 1992-Sept 2015	Temperature:Water Monthly Mean' ('deg C')	8146
	March 1992-Sept 2015	Temperature:Water Standard Deviation' ('deg C')	8146
	March 1992-Sept 2015	Height:Wave:Significant Monthly Mean' (metres)	8075
	March 1992-Sept 2015	Height:Wave:Significant Standard Deviation' (metres)	8075
	March 1992-Sept 2015	Period:Wave:Spectrum_peak Monthly Mean' (seconds)	8030
	March 1992-Sept 2015	Period:Wave:Spectrum_peak Standard Deviation' (seconds)	8030
MB46206	Dec 1988-Sept 2016	Pressure:Air:Sea_level Monthly Mean' millibars	9238
	Dec 1988-Sept 2016	Pressure:Air:Sea_level Standard Deviation' millibars	9238
	Dec 1988-Sept 2016	Temperature:Water Monthly Mean' 'deg C'	9312
	Dec 1988-Sept 2016	Temperature:Water Standard Deviation' 'deg C'	9312
	Dec 1988-Sept 2016	Height:Wave:Significant Monthly Mean' metres	9324
	Dec 1988-Sept 2016	Height:Wave:Significant Standard Deviation' metres	9324
	Dec 1988-Sept 2016	Period:Wave:Spectrum_peak Monthly Mean' seconds	8920
	Dec 1988-Sept 2016	Period:Wave:Spectrum_peak Standard Deviation' seconds	8920

Table B2

Results of Shapiro-Wilk Normality tests for physical data sets.

Parameter	Location	W	P	Reject Normality?
Salinity	Entrance Island	0.93	0.0000	Yes
	Race Rocks	1.00	0.9340	No
Temperature	Entrance Island	0.91	0.0000	Yes
	Race Rocks	0.97	0.0000	Yes
	MB 46087	0.96	0.0002	Yes
	MB 46088	0.96	0.0003	Yes
	MB 46146	0.91	0.0000	Yes
	MB 46206	0.97	0.0000	Yes
Pressure	MB 46087	0.97	0.0017	Yes
	MB 46088	0.97	0.0014	Yes
	MB 46146	0.97	0.0000	Yes
	MB 46206	0.93	0.0000	Yes
Wave Height	MB 46087	0.96	0.0004	Yes
	MB 46088	0.99	0.4448	No
	MB 46146	0.94	0.0000	Yes
	MB 46206	0.96	0.0000	Yes
Wave Period	MB 46087	0.97	0.0110	Yes
	MB 46088	0.94	0.0000	Yes
	MB 46146	0.92	0.0000	Yes
	MB 46206	0.99	0.0246	Yes

Table B3

Biophysical interaction—Salish Sea. Summary of Mann-Whitney U Test to determine whether there was a statistically significant difference between each physical variable and killer whale population mean anomaly and trajectory, annually and seasonally.

Season	U_0	U_1	d.f.	Z	P	Significant difference?
			Salinity			
		Killer whale population mean anomaly				
Annual	121854	111636	1	-1.2	0.2406	No
Winter	31426.5	27268.5	1	-1.3	0.179	No
Summer	29895	28155	1	-0.6	0.5707	No
		Killer whale population trajectory				
Annual	97981.5	122612.5	1	-3	0.0032	Yes
Winter	25000.5	30418.5	1	-1.8	0.0680	No
Summer	23614.5	31261.5	1	-2.60	0.0094	Yes

Sea surface temperature						
Killer whale population mean anomaly						
Annual	402032.5	435867.5	1	1.50	0.1347	No
Winter	100541.5	104471.5	1	0.50	0.6177	No
Summer	100897	113007	1	1.49	0.1362	No
Killer whale population trajectory						
Annual	393857	415483	1	-0.98	0.3275	No
Winter	93006	105434	1	-1.62	0.1063	No
Summer	102727	103503	1	-0.10	0.9221	No
Air pressure						
Killer whale population mean anomaly						
Annual	102605.5	80066.5	1	3.12	0.0018	Yes
Winter	25957.5	17358.5	1	3.50	0.0005	Yes
Summer	24669	23351	1	0.50	0.6205	No
Killer whale population trajectory						
Annual	98038.5	85921.5	1	1.67	0.0950	No
Winter	23306	20166	1	-1.28	0.2022	No
Summer	25812.5	22717.5	1	1.16	0.2472	No
Wave height						
Killer whale population mean anomaly						
Annual	85338	98100	1	-1.76	0.0788	No
Winter	20410	23628	1	-1.29	0.1962	No
Summer	21921	25750	1	-1.45	0.1482	No
Killer whale population trajectory						
Annual	89760	95360	1	-0.77	0.4427	No
Winter	22265	22043	1	0.09	0.9295	No
Summer	22206	26025	1	-1.43	0.1516	No
Wave period						
Killer whale population mean anomaly						
Annual	83535	91577	1	-1.15	0.2520	No
Winter	19925	22150	1	-0.92	0.3555	No
Summer	21229	24219	1	-1.17	0.2427	No
Killer whale population trajectory						
Annual	85444	92108	1	-0.94	0.3458	No
Winter	20608	21827	1	0.50	0.6143	No
Summer	21910	24398	1	-0.96	0.3355	No