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Sightings of southern resident killer whales in the Salish Sea 1976–2014: the importance of a long-term opportunistic dataset

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ABSTRACT: Southern resident killer whales (SRKWs) *Orcinus orca* may be present year round in the Salish Sea, i.e. the inland waterways of Washington State (USA) and southern British Columbia (Canada). SRKWs were listed as endangered in 2005 under the US Endangered Species Act. The Whale Museum (Washington, USA) has been collecting opportunistic sightings reports on SRKWs since 1976 with a goal of providing managers and regulatory agencies with reliable spatial and temporal data on this population. Information in this dataset comes from 5 classes of killer whale sighting sources and is systematically evaluated for accuracy before integration into the dataset. From 1976 to 2014, The Whale Museum's Orca Master dataset documented a total of 82 447 SRKW sightings in the Salish Sea. Sightings were concentrated in a few key hot spots, with an overall pattern of consistent presence in the Central Salish Sea during the summer months and a presence in Puget Sound proper during the fall and early winter months. A shift in SRKW presence in Puget Sound was documented in the late 1990s, possibly driven by increased foraging on fall chum salmon *Oncorhynchus keta* by 2 pods ('K' and 'L'), and is consistent with the hypothesis that the movement patterns of these whales may be driven by prey availability. The Whale Museum's dataset highlights the importance of long-term monitoring to document shifts that may take decades, and shows how opportunistic datasets can be valuable tools for illuminating spatial and temporal trends.

KEY WORDS: Orca · *Orcinus orca* · Endangered species · Sightings database · Occurrence · Puget Sound

INTRODUCTION

Killer whales (or orcas) *Orcinus orca* are among the most widely distributed marine mammals and can be found in every ocean (Leatherwood & Dahlheim 1978, Heyning & Dahlheim 1988, Ford 2014). They are most abundant in nearshore temperate waters but also occur, at lower densities, in tropical, subtropical, and offshore waters (Mead & Brownell 2005, Ford 2014). Eastern North Pacific stocks of killer whales tend to be highly social animals that occur primarily in stable matriarchal social groups or pods that range in size from 2 to dozens of animals (Bigg et al. 1990, Parsons et al. 2009). Temporary groups as large as several hundred individuals, called superpods, form occasionally (Bigg et al. 1990, Parsons et al. 2009, Ford 2014). In the Northeast Pacific, 3 distinct ecotypes of killer whales are recognized: resident, tran-

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sient, and offshore. These types differ in morphology, ecology, behavior, and genetics (Baird & Stacey 1988, Hoelzel & Dover 1991, Barrett-Lennard 2000, Morin et al. 2006, 2010, De Bruyn et al. 2013). All 3 types may be found in the same area at the same time and may have partially overlapping home ranges, but they are not known to interbreed and seem to avoid interaction (Morin et al. 2006, De Bruyn et al. 2013). Transient and offshore orcas are thought to have a diverse diet including marine mammals, sharks, squid, other whales, and fish, while the Northeast Pacific resident orca diet consists primarily of fish, mostly Chinook salmon *Oncorhynchus tshawytscha* (Baird et al. 2005, Hanson et al. 2010a, Hanson & Walker 2014). The name resident killer whales reflects their summer behavior, when they may spend days or weeks in the same area, yet they are known to travel seasonally between summer and winter core areas sometimes separated by thousands of kilometers (Balcomb & Bigg 1986, Krahn et al. 2004).

The most studied resident killer whale population is the southern resident killer whale (SRKW) (Krahn et al. 2004, NOAA 2005). SRKWs comprise 3 maternal lineages or pods: J, K, and L (Balcomb et al. 1980, Balcomb & Bigg 1986, Bigg et al. 1990, Hoelzel & Dover 1991). They are considered 1 'stock' under the US Marine Mammal Protection Act (MMPA) and 1 'distinct population segment' under the US Endangered Species Act (ESA) (Krahn et al. 2004, NOAA 2005). The SRKW population is currently estimated to consist of approximately 76 whales (Center for Whale Research 2017). The lowest recorded level was 67 whales in 1971 and was thought to be due to the live-capture of SRKWs for oceanarium display beginning in the late 1960s, which caused an estimated 30% decrease in the local population (Bigg & Wolman 1975). In the 1980s, the population showed signs of recovery from the captures but then decreased again by 20% in the 1990s (Krahn et al. 2004). Due to its small population size, distinct population segment status, declining prey, exposure to pollutants, vulnerability to oil spills, and increased exposure to vessel traffic and associated noise, the SRKWs were listed as endangered under the ESA in 2005 (Krahn et al. 2004, NOAA 2005).

Opportunistically collected 'presence-only' data from wildlife sightings databases and natural history collections are a valuable tool for monitoring species distribution and movement patterns (Kaschner et al. 2006, Richardson et al. 2012, Esteban et al. 2014), especially when systematic surveys are not possible because of costs and/or logistical challenges. Sightings databases are also helpful in determining critical habitat or hot spots, i.e. those areas that contain essential physical and biological features that a species uses for foraging, resting, and other activities. In an effort to adequately establish and manage conservation measures, for example, opportunistic sightings records were used to identify key habitat of an endangered subpopulation of killer whales in the Strait of Gibraltar and were used to link their distribution to that of a primary prey source (Esteban et al. 2014). Opportunistic datasets frequently take advantage of citizen scientists to increase the scope and broaden the geographic range of a study (Dickinson et al. 2010). While datasets incorporating citizen data may often have less consistent data collection protocols than those of systematic surveys, they can still be used to create reliable estimates of population trends and distribution if the potential for error and bias is taken into consideration (van Strien et al. 2013).

The Whale Museum (TWM), whose mission is to promote stewardship of whales and the Salish Sea ecosystem through education and research, has curated a marine mammal sightings database since its inception in 1976. The Orca Master dataset, a subset of the marine mammal sightings database that is specifically focused on SRKWs, is arguably one of the most comprehensive long-term datasets of killer whale distribution in the world. It was established with the goal of providing scientists and managers with a reliable, up-to-date spatial and temporal dataset on the locations of SRKWs that is uniform between studies, and it has been frequently applied toward mitigation efforts (Osborne et al. 2004, Traxler 2013, Olson et al. 2014). For example, the Orca Master dataset has been used to help determine if the SRKWs should receive federal protection and to help identify their critical habitat in the Salish Sea (Osborne et al. 2002, Krahn et al. 2004, NOAA 2005). Here, we report data on SRKW sightings in the Salish Sea from 1976 to 2014 to illuminate long-term spatial and temporal patterns in habitat use for this endangered population and to highlight the value of long-term opportunistic monitoring.

MATERIALS AND METHODS

The majority of the Orca Master dataset is focused on the inland waters of Washington State (WA), USA, and British Columbia (BC), Canada, a trans-boundary fjord-like marine ecosystem known as the Salish Sea, which is home to over 8 million people and 2 major metropolitan areas: Vancouver, BC, and Seattle, WA (Fraser et al. 2006, Gaydos et al. 2008)

(Fig. 1). The complete Orca Master dataset incorporates records dating back to 1948 (Traxler & Osborne 2013). Prior to 1976, however, there was no dedicated effort to record SRKW presence in the Salish Sea. Historical records prior to 1976 include only 46 anecdotal observations in the TWM archives (Traxler & Osborne 2013). The comprehensive marine mammal sightings database (incorporating all marine mammal species) was formalized in 1976 with the initiation of TWM's public reporting system and the onset of systematic photo-identification surveys (Balcomb & Goebel 1976). The marine mammal sightings database was expanded in the early 1980s by incorporating data from the commercial whale watch industry as well as other reliable data sources such as independent researchers and trained naturalists (Osborne 1991, 1999, Hauser et al. 2006, 2007). Given the onset of systematic photo-identification surveys

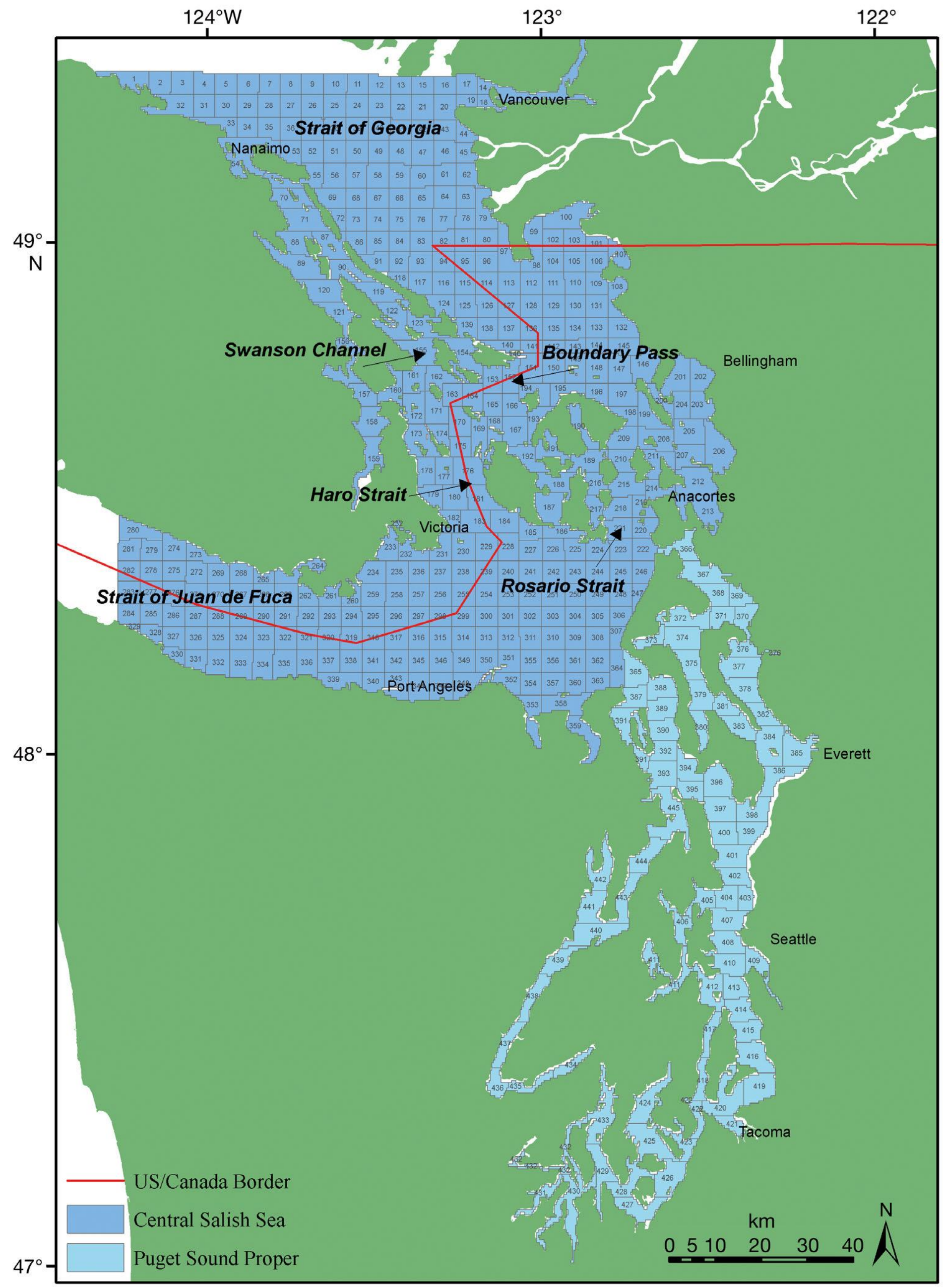

Fig. 1. Salish Sea, with customized quadrant system for quantifying southern resident killer whale sighting reports

and the initiation of the public hotline in 1976, only data from 1976–2014 are reported here.

The Orca Master dataset includes 5 different data sources which are tracked by specific codes (Table 1). The largest and first data source for the Orca Master dataset was TWM's public sightings archives (1976–present) reported year-round to TWM through several different channels (Balcomb et al. 1980, Heimlich-Boran 1988, Felleman et al. 1991, Osborne 1991, 1999, Olson 1998, Olson et al. 2014). These channels include the Whale Hotline (a phone reporting system for public sightings); online reports through TWM's website (http://hotline.whalemuseum.org); eyewitness sighting compilations from affiliated naturalists, scientists, and commercial whale-watch vessels; e-mail postings from other non-profit sighting networks (e.g. Orca Network); and hydrophone detections from listeners to the Salish Sea Hydrophone Network (http://seasound.org; Osborne 1999, Osborne et al. 2002, 2004, Traxler & Osborne 2013, Olson et al. 2014). The marine mammal sightings archives provide the only year-round source for the Orca Master dataset and are primarily composed of opportunistic reports. Records are identified as 'from a public source' if the observer is not known to TWM staff, or as 'reliable' if the observer is known to TWM staff to be experienced in marine mammal sightings or is a marine mammal professional. A consensus of 2 public reports or 1 reliable report was required to determine pod presence in a given month in the Salish Sea (Table 2).

The second data source was commercial whale watch pager data from 1997 to 2007 initially collected by Sea Coast Expeditions and later by Orca Spirit Adventures Group of Victoria, BC. Observations of whale movements were systematically collected by members of these organizations who were searching from both land and water for SRKWs. Electronic pages containing information on whale location and pod identity were sent out to a closed network and recorded by TWM staff and volunteers, or the whale watch operators themselves. Pager data were available during the whale watch season, May through October; however, this data source was discontinued after the 2007 season with the increased use of cell phones.

The third data source was provided by Soundwatch vessels from 1998 to 2014 (Seely et al. 2017). TWM runs the Soundwatch Boater Education and Monitoring program whose primary goal is to distribute educational literature to private whale watch boats and collect data on vessel traffic around the whales (Seely 2016, Seely et al. 2017). Every half hour, Soundwatch personnel count boats around SRKWs, noting the time, GPS location, pod, and direction of the orcas. Similar sighting information obtained from the Cetus Society's Straitwatch Boater Education program was also included with the Soundwatch data. Soundwatch data were only available during the regular whale watch season (May–September).

The fourth source of data was a longitudinal dataset collected from Lime Kiln Point State Park. From 1990 to 2014, from late May until early August, Dr. Robert Otis recorded data about the whales as they passed by the park in the hours between 09:00 and 17:00 h. This represents a very important summertime control dataset and dedicated sighting effort

Table 1. Description and total number of southern resident killer whale sighting records for the 5 main sources of the Orca Master database. TWM: The Whale Museum

Source	Years	Description	Location record	No. of records
TWM sighting archive	1948–2014 (year-round)	Sighting records reported by public and reliable observers to TWM	Locations given in descriptive terms and matched to TWM Quadrants	41054
Pager	1997–2007 (summer)	Whale watch pager system	Pager coordinates matched to TWM Quadrants	18893
Soundwatch	1998–2014 (summer)	Sightings observed by Soundwatch personnel recorded every half hour on the water	TWM Quadrant	13179
Lime Kiln Station	1991, 1994–2014 (summer)	Sightings observed from Lighthouse research station	Lime Kiln study area is 1 TWM Quadrant 18	1881
SPOT data	2008–2014 (summer)	Satellite GPS tracking units used by various researchers	Actual latitude/longitude tracks of boats following whales	8467

Table 2. Monthly southern resident killer whale pod occurrence in the Salish Sea (1976–2014). Sightings without positive identification are indicated by a question mark. Sightings where only some members of a pod were identified are *italicized*. Yellow: J pod; dark blue: K pod; light blue: J and K pod; light green: J and L pod; dark green: J, K, and L pod

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1976	?	?	?	J, K	J			J, K, L			?	J
1977	?	?	?	?	?	?		J, K, L				
1978	J		J, K		J			J, K, L			J	
1979			J					J, K, L			J, K	J
1980			J					J, K, L			J	
1981			J	J, K	J			J, K, L				J
1982			J			J, K		J, K, L		J, K	J	
1983			J					J, K, L			J, K	J
1984			J			J, K		J, K, L			J	
1985			J			J, K		J, K, L			J	
1986			J		J, K			J, K, L			J	
1987			J					J, K, L			J, K	
1988			J		J, K			J, K, L			J	
1989	J		J, K	J				J, K, L			J, K	
1990			J					J, K, L			J	
1991			J		J, K			J, K, L		J, K	J	
1992			J					J, K, L				
1993			J		J, K			J, K, L			J	
1994			J					J, K, L		J, L	J	
1995			J					J, K, L			J	
1996			J					J, K, L			J, K	J
1997			J					J, K, L		Dyes Inlet	J, L	J, K
1998			J					J, K, L			J, K	J
1999			J					J, K, L				
2000	J, K, L		J					J, K, L				
2001	J, K, L		J					J, K, L				
2002	J, K, L	J	J, K, L ?	J				J, K, L				
2003	J, K, L		J					J, K, L				J, K
2004	J, K, L		J		J, L			J, K, L				
2005	J, K, L	J ?	J		J, L			J, K, L				J, K
2006	J ?	J	J, K, L	J				J, K, L				
2007	J ?		J			J, L		J, K, L			J	J, K, L
2008	J, K, L	J, L	J					J, K, L				J, K, *L*
2009	J ?	J, K, L	J	NONE	J, K			J, K, L				J, K
2010	J	J, K, L	J		J, L			J, K, L				
2011	J, K, *L*	J, K	J		J, *L*	J, K, *L*		J, K, L				J, K
2012	J, K	J, K	J					J, K, L				
2013	J	J, L	J, K, L	NONE	J	J, L		J, K, L				J, K
2014	J, K, *L*	J	J, K	K	J	J, L		J, K, L				

that establishes a uniform observer effort and helps identify detailed pod movements in a portion of Haro Strait (Osborne et al. 2004, Koski & Osborne 2005).

The fifth data source was the SPOT satellite GPS messengers from 2008 to 2014, from May until October. In most years, 2 SPOT devices were used: 1 by a commercial whale watch operator and 1 by a non-government organization (NGO) research group on San Juan Island. The SPOT devices record a position every 10 min when the appropriate button is pushed. Boat logs from the reporting party were reviewed to ensure that any coordinates incorporated into the Orca Master dataset occurred when whales were present. Location data were sent via satellite link to the SPOT website from which it was downloaded. The SPOT recorders generate accurate latitude/longitude coordinates and have proven to be a useful source for tracking movement patterns of boats following the whales.

Information incorporated into the Orca Master dataset includes date, time, pod, location, and direction of travel. Known sightings of transient orcas, offshore orcas, northern resident orcas, and other whale species were removed. When information about pod identity was not reported, additional information was often added by a TWM staff member based on records coded as 'reliable' indicating which pod(s) was (were) in the area at that time. This 'likely pod' was assigned as a new field in an attempt to improve accuracy without altering the original report. All sightings that were suspected to be transient orcas, offshore orcas, or northern resident orcas under 'likely pod' were still included in the dataset but were not used in figures or habitat use analyses. In spite of this effort to assign sightings to pods and exclude other ecotypes, there are likely some sightings in the dataset that are not SRKWs.

Location of whales was described in 3 distinct ways: TWM Quadrants, Washington Department of Fish and Wildlife (WDFW)/Department of Fisheries and Oceans Canada (DFO) Fishery Areas, and latitude/longitude. In an effort to quantify anecdotal descriptions of the areas where animals were reported prior to the widespread availability of GPS units and mobile apps, TWM developed a quadrant system that is still used today (Heimlich-Boran 1988, Olson 1998, Osborne 1999, Olson et al. 2014). All anecdotal location data were matched from the original description, often referring to a point on land, to the TWM quadrant that was adjacent to the land-based sighting (Fig. 1). The quadrants only extend about two-thirds of the way out the Strait of Juan de Fuca and as far north as Burrard Inlet, so the whale sightings outside of these areas will have a fish area but not a quadrant assigned to them. There are 445 TWM quadrants that are approximately 4.6 km by 4.6 km each. Hydrophone detections were ascribed to the quadrant containing the hydrophone. Locations from the pager data were initially reported on a separate grid system created by the whale watch operators. Later, the pager data were transformed into quadrants as well as latitude and longitude by digitizing the quadrant map and developing computer code to perform the needed interpolations and transformations. The quadrant results were checked against the earlier work to ensure accuracy. With expanding spatial technology and improved accessibility to devices with GPS, an increasing number of sightings are now being reported with latitude/longitude coordinates. All reports with accurate latitude/longitude (including data from Soundwatch or SPOT devices) were assigned a quadrant and fish area in addition to their more precise location coordinates. All sightings from 1976–2014 were tallied for each quadrant, with the frequency depicted on the map at the centroid of each quadrant (Fig. 2).

TWM's marine mammal sightings data were collected in a fashion that is not subject to a uniform test of reliability due to the large variety of sighting platforms, observers, and the variation in their qualifications (Heimlich-Boran 1988, Osborne 1991, 1999, Olson 1998, Hauser 2006, Hauser et al. 2006). Sampling biases result from variation in: (1) number of observers, (2) number of observers actively searching for whales, (3) period of daylight, and (4) visibility in terms of sea surface and atmospheric conditions. It is also important to note that TWM has increased its efforts to collect sightings data over the years by recruiting new sources, many of which overlap in coverage area (Fig. S1 in the Supplement at www.int-res.com/articles/suppl/n037p105_supp.pdf). In addition, newer internet-based sightings platforms (e.g. Orca Network) have greatly increased the sightings reported each year. To reduce the effect of effort when looking at SRKW presence over time, the metric 'whale day' was calculated by eliminating multi-

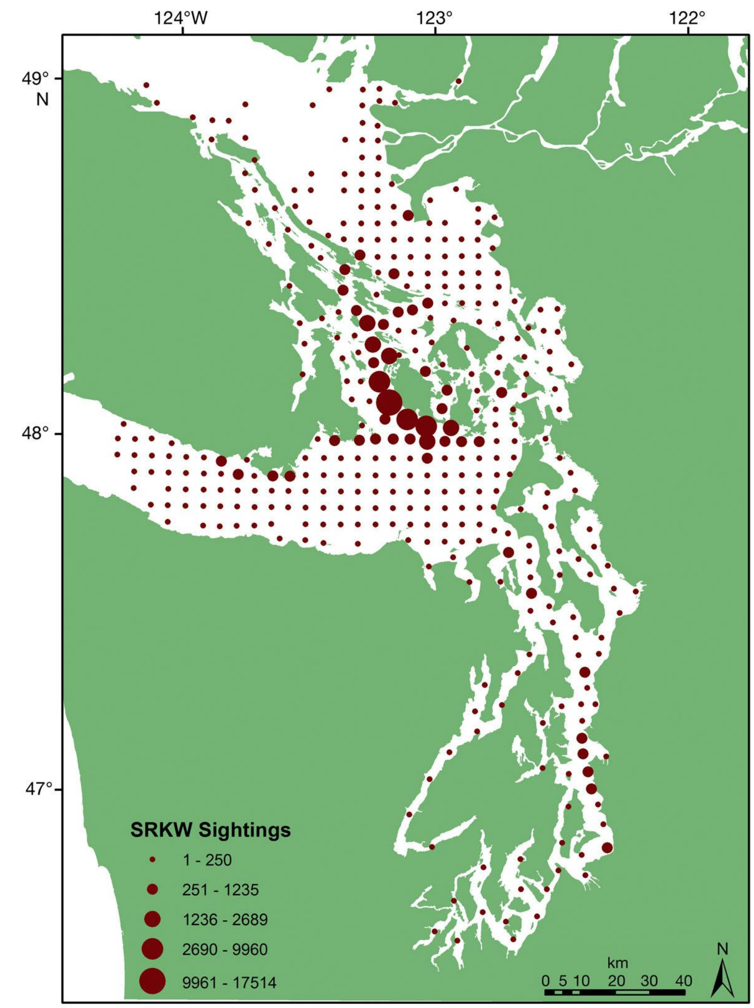

Fig. 2. Southern resident killer whale (SRKW) sightings from 1976–2014 (n = 82 447). Density of sightings quadrant^{-1} is represented by circle size. All suspected sightings of other killer whale ecotypes have been removed

ple sightings of whales on the same day. A whale day is any day on which SRKWs were reported in a given area regardless of the number of times they were reported on that day. To further minimize the effect of effort, whale days were only analyzed on a large regional scale (e.g. Central Salish Sea [Quadrants 1–364], which includes the Haro Strait Region and the Strait of Juan de Fuca, and Puget Sound proper [Quadrants 365–445], the area south of Admiralty Inlet). To even further reduce temporal bias, we also examined a subset of our data using a single consistent source: non-whale watch related reports to the public sightings archives (Table 1).

To further reduce geographical bias, we followed a 4-step process to effort-correct the sightings data and create a relative density estimate in the Salish Sea. This process was based on an effort-correction model created by the Coastal Ocean Research Institute (Rechsteiner et al. 2013) which we adapted for the Orca Master dataset. The 4 steps were (1) removing duplicate sightings, (2) assigning the number of whales to that sighting, (3) creating a spatial map of relative sighting effort based on the distribution of sources and their effectiveness at making and reporting sightings and, (4) generating a relative effort-corrected density estimate.

(1) Removing duplicates: Sightings within 1 h of each other and within 2 nautical miles (3704 m) of each other were considered duplicates. These duplicates were removed by preferentially keeping higher quality sightings (i.e. the more reliable data source).

(2) Number of whales: Not all Orca Master sightings have the number of whales reported. We thus used those sightings which did include counts to estimate median numbers of animals in each pod assemblage (J, K, L, JK, JL, KL, JKL, SRKW) and used these to estimate the number of animals present during each sighting.

(3) Effort: We created an effort layer in a GIS framework based on a cost–distance analysis from the home ports of whale watch operators as well as population centers where recreational boaters are based, in a manner similar to Rechsteiner et al. (2013) (Fig. S2). This effort layer was normalized between 0 and 1 and then converted to 5 effort classes by rounding the effort up to the highest value in that class (classes: 0.2, 0.25, 0.33, 0.5, 1). This was done to simplify the model and avoid overcorrection of sightings in areas with low effort. A spatial overlap in GIS was used to assign these effort classes to each sighting.

(4) Relative density: The number of animals in each sighting report was divided by the effort assigned to the location where the sighting was made to estimate the number of whales per unit effort for each sighting. These were then used as inputs into a GIS kernel density estimate (with 1 km grid cell outputs and a 4 km search radius) to estimate the number of whales km^{-2} during the combined period of 1976–2014.

Despite the biases of the Orca Master dataset, sighting reports for SRKWs within the inland waters are thought to be robust due to continuous search efforts and public awareness of the importance of the species. In other words, the whales were unlikely to be missed if they were present in the overall study area (Hauser et al. 2006). Although all of the data have been reported with some kind of location detail, SRKW movements cover large areas, and the original location sources are often approximate. Statistical differences between sightings and whale days $decade^{-1}$ were determined with a Kruskal-Wallis test using the RealStats add-on in Microsoft Excel.

RESULTS

Raw sightings

The total number of documented SRKW sightings from all data sources in TWM's Orca Master dataset from 1976–2014 was 83 474 (Table 1), of which 82 447 sightings remained after suspected sightings of other killer whale ecotypes were removed (Fig. 2). Of these sightings, 75 374 were in the Central Salish Sea; 6670 were in Puget Sound proper; and 398 were outside the defined quadrant area. Of those, 16 856 had latitude/longitude coordinates associated with them. The mean ± SE number of sightings yr^{-1} was 2114 ± 291.5 (n = 39 yr). The mean number of whale days yr^{-1} was 193.1 ± 5.4 (n = 39 yr). SRKW presence ranged from a low of 139 whale days in 1977 to a high of 266 whale days in 2001. The mean number of sightings yr^{-1} between the 4 decades of data has changed significantly (Kruskal-Wallis test [K-W], H = 33.29, df = 3, $p < 0.001$; Fig. 3a) and the number of mean whale days yr^{-1} between the 4 decades of data has also changed significantly (K-W, H = 21.75, df = 3, $p < 0.001$; Fig. 3b), with an increasing shift for both occurring in the mid-1990s.

When using a subset of the Orca Master dataset coming from a single consistent source, we see different patterns in the Central Salish Sea and Puget Sound proper. In the Central Salish Sea, there was an overall increasing trend from 1976–1989, a decreasing trend from 1990–1999, an increasing trend from 2000–2003, and a decreasing trend from 2004–2014. In Puget Sound proper, there was an overall decreas-

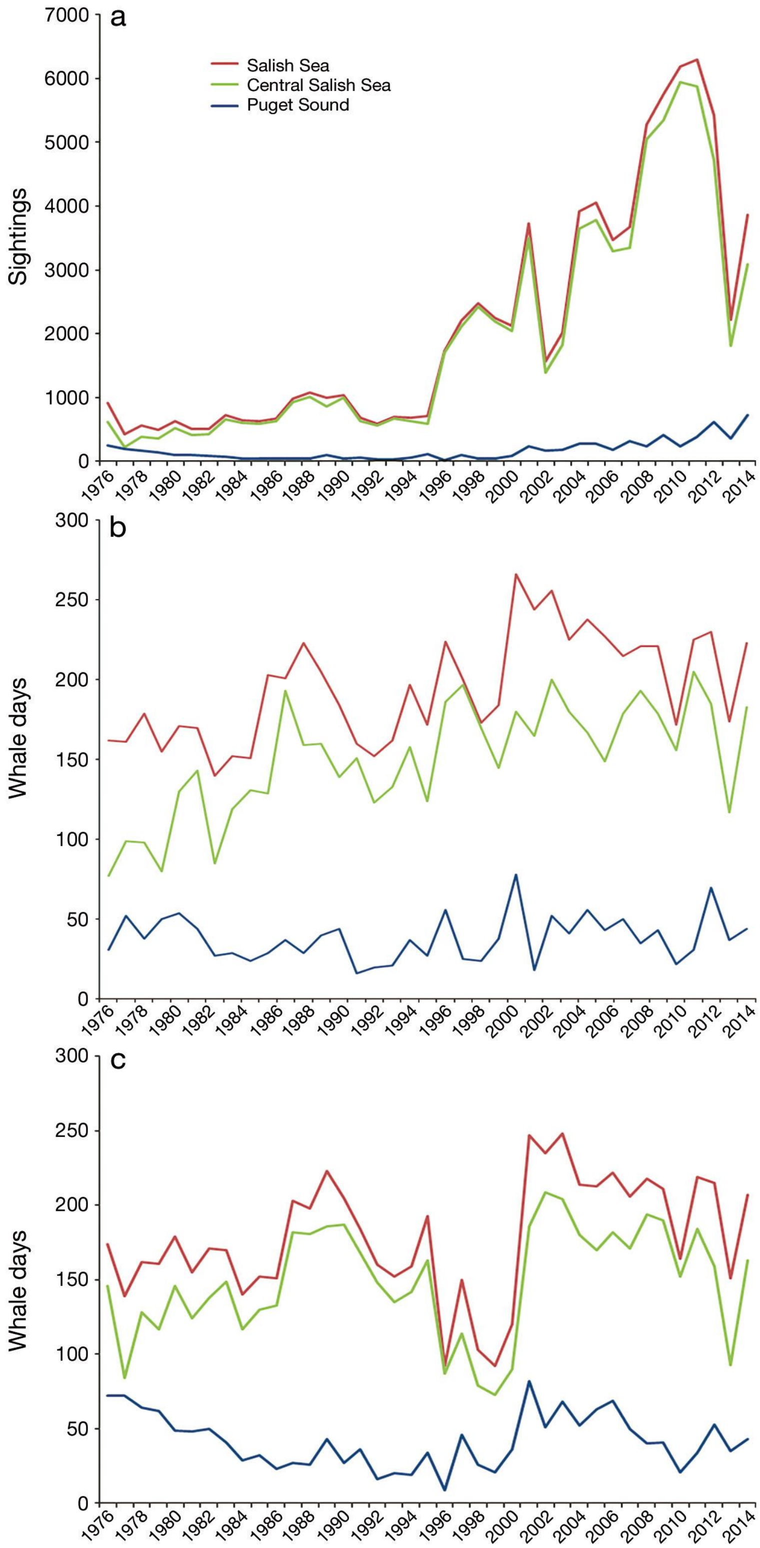

Fig. 3. (a) Sightings yr^{-1} and (b) whale days yr^{-1} of southern resident killer whale (SRKWs) in the Salish Sea, Central Salish Sea, and Puget Sound proper from 1976–2014. (c) As in panel (b), but using only records from the public sightings archives of the Orca Master dataset

ing trend from 1976–1996, an increasing trend from 1997–2001, and a decreasing trend from 2002–2014 (Fig. 3c). There was still a significant difference in the mid-1990s for whale days in Puget Sound between decades (K-W, H = 11.822, df = 3, p = 0.007), which was also significant when just the data from 1986–1995 and 1996–2005 were compared (K-W, H = 3.86, df = 1, p = 0.049). However, there was no difference between decades for the Central Salish Sea (K-W, H = 0.516, df = 3, p = 0.473).

Presence/absence

The most basic underlying pattern established was SRKW presence or (presumed) absence from the inland waters of the Salish Sea (Table 2). From 1976–2014, J pod was present nearly year-round, and all 3 pods (J, K, and L) were present continuously during summer and fall months. The trend in this pattern since the winter of 1999–2000 is for K and L pods to increase the number of months they are detected in the inland waters by staying in the Salish Sea through the fall and into the early winter, before completely exiting the inland waters for months at a time in late winter. In recent years (2009 and 2013–2014), there have been some noted anomalies, with the absence of J pod from the Salish Sea in April for the first time since the onset of the TWM database in 1976.

Distribution

SRKWs have been reported in nearly every quadrant in the Salish Sea (Fig. 2); however, certain geographical areas were used notably more frequently than others. These hot spots (as indicated by the largest circles in Fig. 2) include Haro Strait along the west side of San Juan Island (Quadrants 176, 181, 184–185) as well as Boundary Pass and Swanson Channel (Quadrants 151–153, 155, 162–164). Overall, 38 089 sightings (45.6 %) were represented by Haro Strait. SRKWs were recorded in this hot spot at least once on 58.46% of the total whale days yr^{-1}. A total of 4368 sightings (5.2%) were represented by the Boundary Pass/Swanson Channel hot spot, with SRKWs sighted in this hot spot at least once on 22.94% of the total whale days yr^{-1}. A third and less dominant area of interest lies along the major waterways of Puget Sound proper, south of Admiralty Inlet and north of Vashon Island (Quadrants 407–408, 410, 413–415). Overall, 1810 sightings (2.2%) were represented by this hot spot in Puget Sound proper. SRKWs were recorded in this hot spot at least once on 3.89% of the total whale days yr^{-1} and on 11.7% of whale days during the months of October through January.

Similar spatial patterns were evident after effort correction but with added spatial resolution (Fig. 4). The core areas in Haro Strait, Boundary Pass, and Swanson Channel had density estimates 1 or 2 orders of magnitude higher than adjacent areas in the Salish Sea. Other areas with lowerdensities, but still clear concentrations of SRKW habitat use, included the north side of the Strait of Juan de Fuca (presumably from animals entering and exiting the Salish Sea), Rosario Strait, and the approaches to the mouth of the Fraser River, as well as into Puget Sound proper.

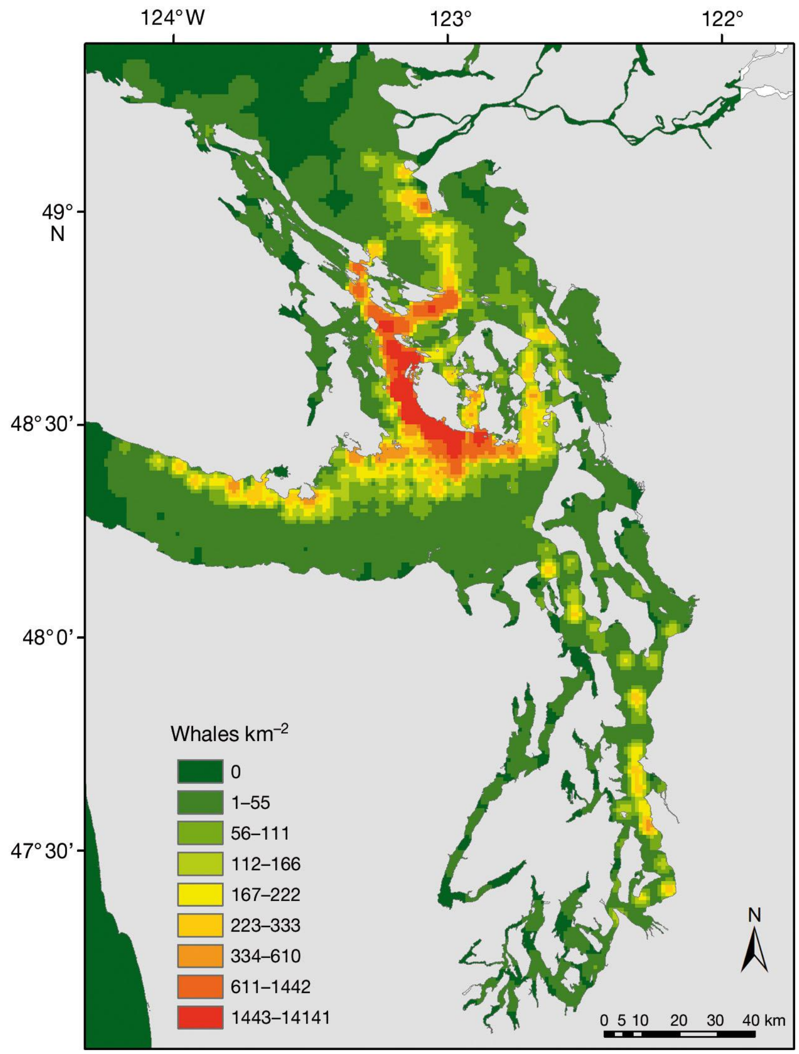

Fig. 4. Southern resident killer whale density (number of whales km^{-2}) based on effort-corrected data in the Salish Sea from 1976–2014

Seasonality

SRKW occurrence in the Salish Sea showed strong seasonal trends. In the Central Salish Sea, an overall pattern of increased occurrence during the summer months was consistent across the decades with 71.7% (n = 5567) of whale days occurring between May and September (Fig. 5a; Fig. S3). In Puget Sound proper, there was limited SRKW occurrence in the spring and summer and an increased occurrence in the late fall and early winter, with 60.3% (n = 1412) of whale days occurring between the months of October and January. This seasonal pattern has increased within the past 2 decades starting in the late 1990s (K-W, $H = 29.99$, df = 3, $p < 0.001$; Fig. 5b; Fig. S4).

DISCUSSION

The SRKW-focused Orca Master dataset is one of the largest, longest-running, and most comprehensive sightings datasets for any species in the Salish Sea and for any orca population in the world. With 82 447 total sightings from 1976–2014, these data have been used to help determine if the SRKWs should receive federal protection and to help establish the central portion of the Salish Sea and Puget Sound as critical habitat for southern residents (Osborne et al. 2002, Krahn et al. 2004, NOAA 2005).

The number of SRKW sightings and whale days was relatively stable during the first 2 decades of data collection until 1995, when a shift resulted in an

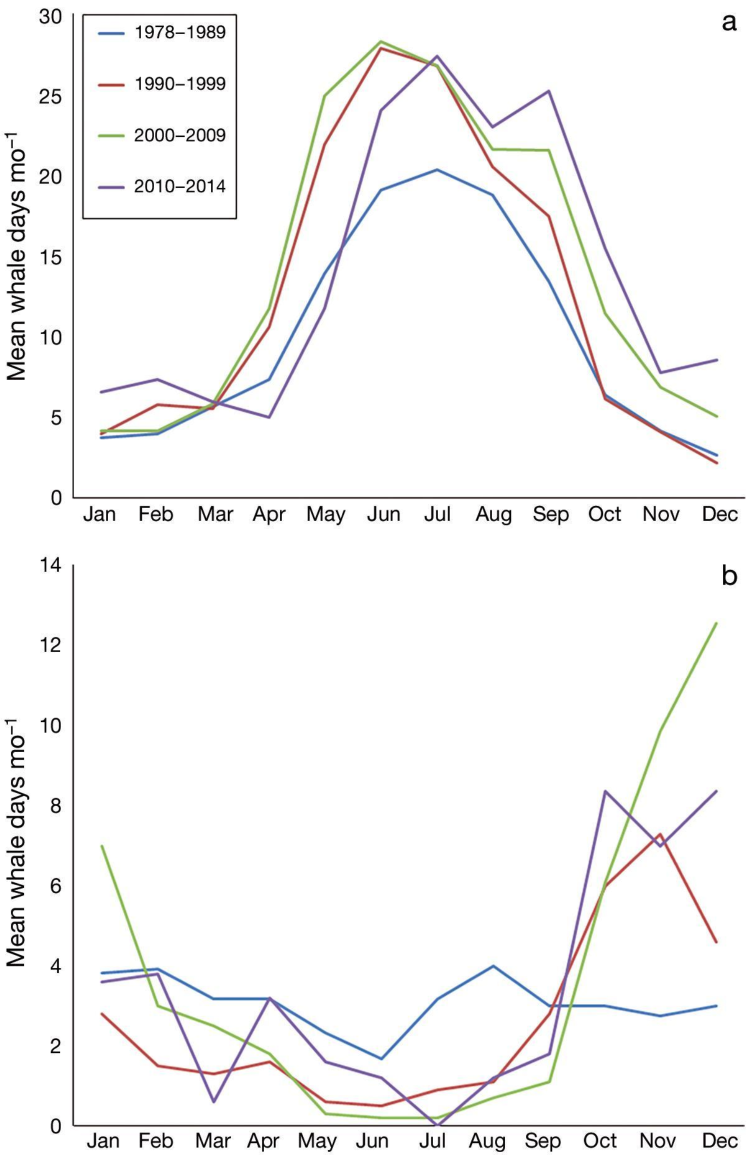

Fig. 6. Comparison of decadal means for southern resident killer whale (SRKW) whale days in (a) the Central Salish Sea and (b) Puget Sound proper

almost 3-fold increase in total sightings yr^{-1} that remained sustained over the following 2 decades. Much of this shift was due to an increased effort by TWM and an increased number of sources. A similar increasing pattern was found using the metric whale days, which is less sensitive to effort bias, with a doubling of whale days in the decades following 1995. A more complex pattern emerged when using a subset of the Orca Master dataset coming from a single consistent source with temporal trends varying by region. Further work is needed to investigate the driving factors of these shifting patterns. A consistent trend across all 3 metrics included a sharp increase in 2001, which was likely influenced by the onset of internet-based sightings platforms beginning in the same year. Another consistent pattern for the Central Salish Sea was a sharp decrease in 2013, possibly influenced by the low returns of Chinook salmon to the Fraser River (DFO 2016).

A notable pattern of increased SRKW presence in Puget Sound in the fall and winter months may have stemmed from a time when a sub-group of L pod was trapped in Dyes Inlet near Bremerton, WA, in 1997 after apparently following strong salmon returns in the area (see List Ln Monthly Edition Number 45 at https://rosap.ntl.bts.gov/view/dot/13132). Since that event, all 3 pods (J, K, and L) have been sighted in the Salish Sea and Puget Sound throughout the fall and into January and February; prior to 1997, typically only J pod remained (Table 2). This shift is supported by the observed sharp increase in whale days for K and L pods in Puget Sound proper from October to January using a subset of data from a single source (Fig. S5). Despite the increase in internet-based reports possibly influencing trends observed after the early 2000s, the increase in whale days for K and L pods appears to have occurred prior to that time period, and thus cannot be solely explained by an increase in reporting effort. We propose that this pattern of increased occurrence was due to an increase in the strength of fall chum salmon *Oncorhynchus keta* runs in southwest Puget Sound since the 1990s. Dyes Inlet is known to have significant chum runs that typically make up 50–70% of the chum salmon to the area (Fresh et al. 2006). Average chum run returns in this area for 1990–1999 were 63 100 for even years and 37 700 for odd years. In 1998, however, over 130 000 chum salmon were documented returning to East Kitsap streams (Fresh et al. 2006).

The most consistent hot spot or region for SRKWs to be sighted is in the Haro Strait region of the Central Salish Sea. This is the area where they are most likely to be noticed and reported because most of the

5 primary sources of the Orca Master dataset are located in the Haro Strait region or adjacent to it. However, this is also the region with the greatest relative density of SRKWs, as indicated by the effort-corrected data. The Haro Strait hot spot is considered to be core summer habitat for SRKWs. The topography is believed to be conducive to efficient foraging for SRKWs due to its high relief bathymetry with deep nearshore areas associated with adjacent shallower reefs and strong tidal currents that tend to attract and trap SRKW prey (Groot et al. 1984, Heimlich-Boran 1988, Hauser et al. 2007). Furthermore, fecal sampling studies have confirmed that SRKWs forage on Fraser River Chinook salmon in this core area (Hanson et al. 2010a). The extensive occupancy of SRKWs shown by our sighting records supports Haro Strait as being important habitat for SRKWs.

Although no other areas are comparable to Haro Strait for frequency of SRKW sightings, there are other areas where they are commonly documented. For example, the SRKWs may be frequently found in the routes to the mouth of the Fraser River, including Swanson Channel and Boundary Pass. While not as much information is available regarding SRKW behavior in this area, past studies have shown that the 3 pods spend time traveling through these areas, with J pod most likely to use Swanson Channel and Active Pass, L pod preferring Boundary Pass, and K pod showing an intermediate pattern (Heimlich-Boran 1988, Hauser et al. 2007). Although this area might not be ideal for feeding, due to its deep waters and lack of high relief bathymetry for the whales to use as barriers for trapping prey, it may serve as a key pathway between the Haro Strait hot spot up to the mouth of the Fraser River (Heimlich-Boran 1988). Another area where SRKWs may often be found seasonally is in the Puget Sound corridor south of Admiralty Inlet and north of Vashon Island that parallels Dyes Inlet. This is likely driven by late fall/early winter excursions by the SRKW into Puget Sound that have occurred with more frequency in the past 2 decades, particularly for K and L pods, mostly likely in order to feed on chum salmon runs (Simenstad et al. 1982, Helle & Hoffman 1998, Osborne 1999).

Annually, SRKWs exhibit 3 primary distribution patterns: (1) summer (June–August) primarily centered in the straits around the San Juan Islands; (2) fall/winter (September–January), a variation on summer with extended excursions into Puget Sound and short trips outside the Salish Sea; and (3) winter/spring (February–May) with extended excursions outside the Salish Sea, particularly for K and L pods. The summer and fall patterns highlighted by the Orca Master dataset have also been supported by other studies (Heimlich-Boran 1988, Osborne 1999, Hauser 2006). The reduced occurrence of SRKW in the winter months shown by the Orca Master dataset suggests a coastal distribution in winter (Krahn et al. 2004); however, use of coastal habitat in the winter is most strongly supported by hydrophone detections, dedicated coastal surveys, and satellite tagging efforts (Hanson et al. 2010b, 2013, 2017). The 3 pods exhibit slightly different seasonal patterns, with J pod typically sighted in the Salish Sea every month of the year. Since the late 1990s, K and L pods have increased the number of months in which they are detected in the inland waters by staying through the fall and into the early winter before completely dispersing from the Salish Sea for months at a time in late winter. There have been exceptions to this pattern in recent years, with J pod sometimes absent in April, such as in 2009, 2013, and 2014.

Although the decadal means highlight the overall seasonal patterns in SRKW presence in the Salish Sea, there are several anomalous years. For example, whale days in the Central Salish Sea were well below the decadal mean of the previous decade for the months of April–August 2013 (Fig. S3). One possible explanation for this reduced spring/summer presence in 2013 is the low returns of Chinook salmon to the Fraser River (DFO 2016). There is also variation from the decadal means in the Puget Sound area, with increased whale days in the winter months following the Dyes Inlet event of 1997 (Fig. S4). These departures from the decadal trends may indicate the changing distribution patterns of SRKWs, thought to be due to changes in prey availability.

The value of a long-term dataset such as Orca Master is the power to determine significant changes or shifts that would not be noticeable during shorter intervals. The pattern of SRKW sightings over the past 40 yr has been that all 3 resident pods, J, K, and L, are most often sighted in the Salish Sea in the summer months from May–September, with the majority of the SRKWs leaving in the winter months. The summer occupancy of the SRKWs coincides with the time when most of the ocean-going salmon return to the inland waters of the Salish Sea to their natal rivers and streams to spawn (Groot et al. 1984, Healey & Groot 1987). This has been the stable pattern over many decades. In the late 1990s, however, there was a significant shift in the SRKW distribution, with an increased presence of K and L pods in Puget Sound Proper following the Dyes Inlet event. Had the Orca Master dataset started after 1997, this temporal shift would have gone unnoticed. Having all 3 pods in the

Salish Sea for 8 to 9 mo would have been considered the norm rather than a shift from a previous pattern of the pods being present for only about 5 mo. This shift gives us important insight into what drives SRKW presence in the Salish Sea. It supports the hypothesis that the movement patterns of these whales are primarily driven by prey availability and implies that SRKWs may change their distribution patterns with shifting prey resources.

This shift in SRKW distribution is an example of shifting baselines, a phenomenon in ecosystem monitoring where it is difficult to evaluate the importance of individual ecosystem stressors and associated changes without a measure or baseline of the pre-impacted ecosystem (Pauly 1995). For example, short-term measurements or studies of ecosystems may show increases in species occurrence and habitat use, while the overall long-term trend may still be a decrease in species occurrence and range (Pinnegar & Engelhard 2008, Lotze & Worm 2009). In other words, the point of reference has moved, thus making the longer trend of the species and the ecosystem difficult to document. Because species distribution patterns and ecosystems are complex and may change slowly over time, it is critically important to establish baseline measures and commit to long-term monitoring.

While it is important to recognize the inherent bias associated with opportunistic data collections, robust sightings records like Orca Master can be invaluable tools for illuminating long-term spatial and temporal patterns that targeted research projects might not be able to detect. These long-term datasets may also prove to be critical for assessing deviations from baseline trends in light of recent climatic and oceanographic changes. Future studies may benefit from generating predictive models and linking patterns with other types of environmental data.

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