The Relationship between Continuous Sighting of Southern Resident Killer Whale (*Orcinus orca*) and Fraser Chinook Salmon (*Oncorhynchus tshawytscha*) Abundance in the San Juan Archipelago

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Abstract

Studies by Ford et al. in 2010 have shown that Southern Resident Killer Whale (SRKW) survival rates are strongly correlated with Chinook salmon (FCS) availability. During the summer months of June, July and August, SRKW are sighted nearly every day in the San Juan Archipelago (SJA). It is hypothesized that, if the continuous sighting of Southern Resident killer whales in the San Juan Archipelago is a foraging pattern related to the abundance of Fraser Chinook salmon, continuous sightings of SRKW should correlate with Fraser Chinook abundance with a consistent prey abundance threshold. Continuous sighting of SRKW in SJA is found to be positively correlated with Chinook abundance. The optimal lag between Chinook catch per unit effort (CPUE) at Albion, 50km upstream of Fraser River and SRKW presence in SJA is found to be 37 days. Chinook CPUE threshold for continuous sighting is found to be 0.830 with a minimum of 0.131. Sightings are more common in the San Juan Island area, in particular off the west coast of San Juan Island. Proportions of sightings in the Gulf Islands, San Juan Island area, and Strait of Juan de Fuca are not statistically different before, during and after period of continuous sighting. SRKW presence is positively correlated with sea surface temperature (SST) in Friday Harbor. The minimum SST for first whale day is 7.59˚C with an average of 8.46˚C. On-site Fraser Chinook salmon sampling at SJA for future studies is essential as abundance pattern may not be consistent with what inferred from Albion CPUE no matter the time lag. Further analysis of more years of data, and incorporation of data for all days of year is recommended.

Introduction

Southern Resident killer whales (*Orcinus orca*), henceforth referred to as SRKW, are a population of killer whales native to the Pacific coast of North America. This distinct population segment of killer whales has been listed under Endangered Species Act by National Oceanic and Atmospheric Administration (NOAA) in November 2005, and has remained so as of today (NOAA 2011). Extensive studies by Ford and Ellis (2006) and Hanson et al. (2010) have shown that SRKW selectively prey on Chinook salmon (*Oncorhynchus tshawytscha*), particularly of the Fraser river stock. Fraser River Chinook salmon (FCS) is a sensitive stock that is being managed and protected under Canada's Policy for Conservation of Wild Pacific Salmon by the Canadian Department of Fisheries and Oceans (DFO 2011).

Ford and Ellis (2006) suggested that SRKW's preference for Chinook salmon is most likely due to the salmon's relatively large size, high energy content and perennial presence in SRKW's coastal range. SRKW is the apex predator of the Salish Sea. In the attempt to examine the link between SRKW survival and prey abundance, Ford et al. (2010) discovered that SRKW survival rates are strongly correlated with availability of Chinook salmon. They have hence hypothesized that SRKW are dependent on Chinook salmon as their primary food source. They have also suggested that SRKW's specialization in Chinook salmon is a form of "fixed behavioural tradition" that has been inherited from generation to generation by learning. In a more recent study, Hanson et al. (2010) discovered, by examining kill remains and genetic material in SRKW feces, that during the summer months, around 80% of the Chinook prey originated from the Fraser River, in particular the Upper Fraser.

During the summer months of June, July and August each year, SRKW are known by local whale watchers to travel along the west coast of San Juan Island. Alternatively, they may also travel around the San Juan Island via Boundary Pass or Active Pass, through Rosario Strait and return to Haro Strait. During this time, SRKW are sighted nearly every day in the San Juan Archipelago. It has been suggested that this phenomena is related to Fraser Chinook salmon abundance in the area.

FCS return to their natal stream to spawn between April and September, with one subpopulation – the Harrison River Chinook returning during September to November. FCS has been categorized by the DFO into three seasonal runs. The spring run migrates through lower Fraser River before July 15; the summer run does so between July 15 and September 1; while the fall run enter the lower Fraser after September 1 (DFO 1999). This information suggests that the timing of continuous sighting of SRKW seems to coincide with upriver migration of adult FCS.

It is therefore hypothesized that, if the continuous sighting of Southern Resident killer whales in the San Juan Archipelago is a foraging pattern related to the abundance of Fraser Chinook salmon, continuous sightings of SRKW should correlate with Fraser Chinook abundance with a consistent prey abundance threshold.

Previous Studies

Ashe et al. (2010) mapped SRKW sightings from an independent data collection effort between May to August 2006 in the Salish Sea area using the geographic information system (GIS). For each sighting, it was determined by observation if the killer whales were foraging or feeding. They discovered that SRKW were more likely to be foraging or feeding along the south-west coast of San Juan Island than at other adjacent locations.

E. Ashe, D. P. Noren and R. Williams   Animal behaviour and marine protected areas

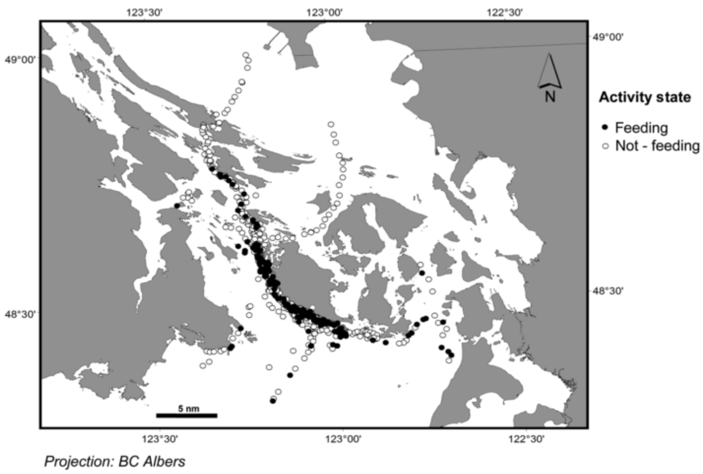
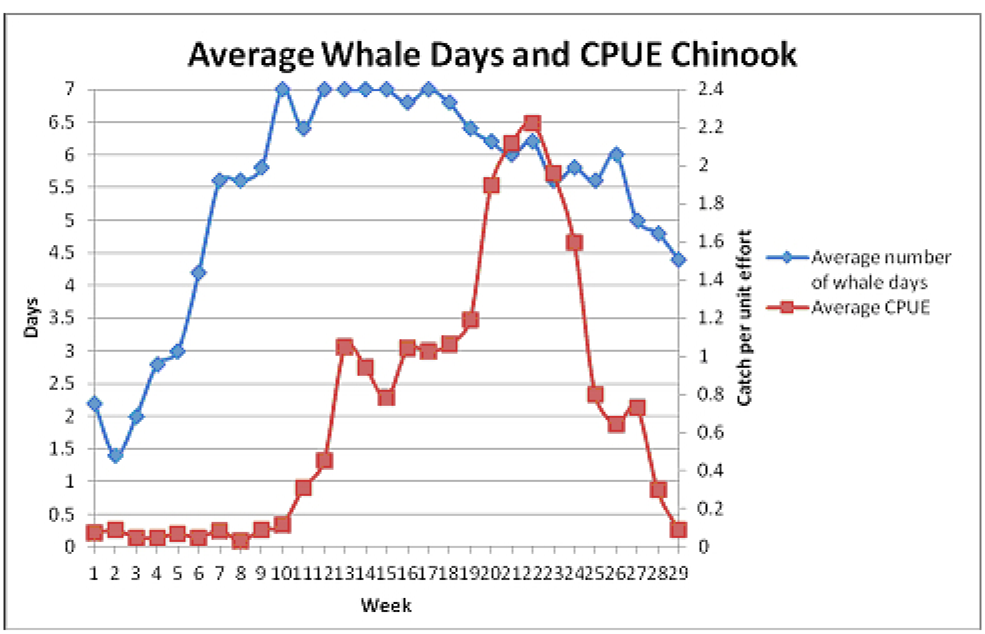


Figure 2 Map of locations for all feeding (closed circles) and non-feeding (open circles) activity observations ($n=764$) in the study area.

©Ashe et al. 2010

Charla Basran, a Beam Reach student from 2011, inferred from Ashe's study that Chinook density may be relatively high in the south-west coast of San Juan Island. She discovered that the number of whale days (days where killer whale sightings occur) per week in the Salish Sea had a significant positive correlation (Pearson's correlation r = 0.492, p<0.05) with FCS density which was inferred from catch per unit effort of FCS at Albion test fishery.



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Basran averaged “whale days” at San Juan Islands per week from 2006 to 2010. She then applied a similar method to obtain a time series of weekly catch per unit effort of FCS from 2006 to 2010, at Albion Test Fishery at Albion, BC, Canada, a test fishery 50km upstream of Fraser River. Basran discovered a lag of approximately one to two weeks between the peak in number of killer whale sightings per week, often occurring in late July or August, and the peak of CPUE of FCS, often occurring in early September.

Methods

<u>Study Area</u>

For this study, the study area is trimmed from the expanse of SRKW range in the Salish Sea to include only the San Juan Archipelago (Figure 1). The northern boundary is defined to be below or equal latitude 48.96°, approximately the latitude of Active Pass. The southern boundary is defined as above or equal latitude 48.18°, approximately the latitude of Admiralty Inlet. The Eastern boundary is defined to be below or equal to latitude -122.63, approximately the longitude East of Vendovi Island. The western boundary is defined to be above or equal to longitude -123.83, approximately the longitude of Sooke. SRKW sightings outside of the study area are omitted.

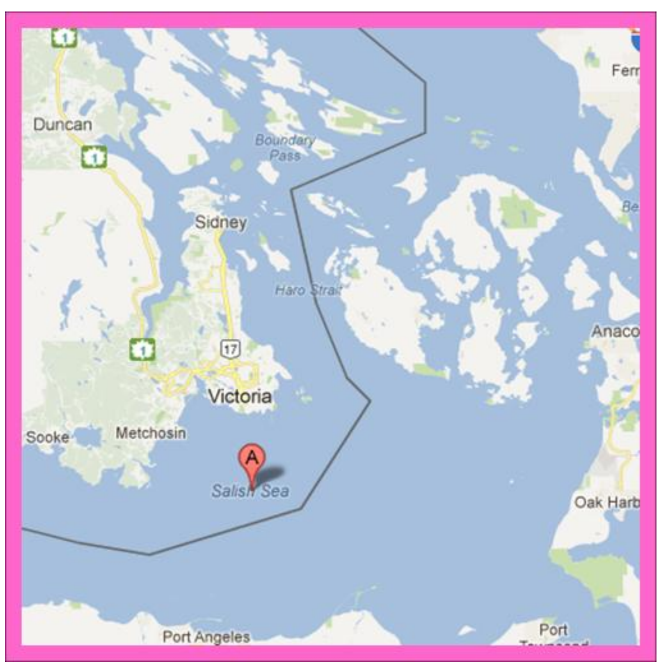

Figure 1. Map of study area.

Study Period

Study period is April 1 to October 31 of the year 2006-2010. This is the approximate period of Fraser River Chinook upriver migration, and the period where SRKW sightings are most common in the San Juan Archipelago. Furthermore, only data within the study period has been considered due to lack of Albion Chinook CPUE data outside this time period. Julian day is assigned to each day of year for April 1 to October 31 – a total of 214 Julian days.

Archived Data Obtained

Date, time and gridded GPS location of Southern Resident Killer Whale Sightings through 2006-2010, were obtained from the Killer Whale Sightings Database "Orcamaster", maintained by the Whale Museum of San Juan Island. One or more report of SRKW sighting on a single day is used as a binary index of presence of whale on that day, where 0 = "present" and 1 = "absent". SRKW sightings from the database were scanned to eliminate sightings of transient killer whales, sightings with unspecified ecotype, and reports without GPS location. GPS location from the database represents the location of the observer and is therefore used only as a rough estimation of the whales' exact location.

Chinook Salmon Catch per Unit Effort per day from April 1 to October 20 each year was obtained from the Albion Test Fishery (ATF) maintained by Fisheries and Oceans Canada. ATF is located approximately 50km up Fraser River. ATF deploys their fishing vessel twice a day to coincide with the daily high tide (ATF 2010). During flood tide, ocean currents travel from south to north from Haro Strait to Fraser River. Adult Chinook salmon from British Columbia coastal waters tend to move with tidal currents (Candy and Quinn 1999). It is therefore inferred that flood tide facilitates upriver migration of adult FCS from Salish Sea through Haro Strait, and that CPUE can be representative of FCS abundance in the San Juan Archipelago. It could therefore be inferred that the presence of FCS at San Juan Archipelago precedes an increase in CPUE at Albion. Chinook CPUE at Albion test fisheries is used as an index to represent

Chinook abundance in the Salish Sea.

Archived historic sea surface temperature and tidal height data measured at Friday Harbor, WA, from 2006-2010 were obtained from NOAA website <http://tidesandcurrents.noaa.gov>. Daily averages were calculated for sea surface temperature from hourly measurments, and average tidal exchange per day was calculated from tidal height measurements during each low, low-low, high, and high-high tide. In this study, tidal height is considered to be an index of current strength.

Determination of Optimal Time Lag

An arbitrary minimum lag of 10 days between assumed Chinook presence in San Juan Archipelago and Albion Chinook count was assigned based on known minimum Chinook salmon swim speed of 0.7km/h (Candy and Quinn 1999). The optimal time lag between continuous presence of SRKW at San Juan Archipelago and CPUE taken at Albion Test Fisheries and was determined by regressing 5-year average whale days per seven days (as a moving sum), against 5-year average CPUE per seven days (as a moving average). In order for these two variables to be paired for each Julian day, moving sum of whale days was taken due to the binary nature of whale presence/absence data, and moving average CPUE was taken as CPUE data is only available every other day in the months of September and October. Optimal time lag was tested for by applying a variety of time lag to the regression, and choosing time lag with the highest R^2 value for the best-fit line.

Chinook Salmon Abundance and Continuous Sightings of SRKW

To investigate if Chinook salmon abundance is related to continuous sightings of SRKW in the San Juan Archipelago, moving sum of whale days per seven days was regressed against moving average CPUE per seven days for each Julian year. A regression was also performed with 5-year average whale days per seven days against 5-year average CPUE per seven days. The optimal lag previously obtained was applied to all regressions. With the assumption that a non-linear relationship exists between these two variables, Spearman's rank correlation test was performed using R statistical software (R Developmental Core Team 2010) for each regression to determine the correlation coefficient and p-value.

Spatial Differentiation of SRKW Sightings Before, During and After Continuous Sighting

To minimize the human error of missed sightings, period of continuous SRKW sighting is defined as a period with no more than 2 days' absence. The study area is divided into a further three sub-regions (Figure 2): Strait of Juan de Fuca – latitude between 48.19 ~ 48.37, San Juan Islands – latitude between 48.40 ~ 48.77, Gulf Islands – latitude between 48.78 ~ 48.93.

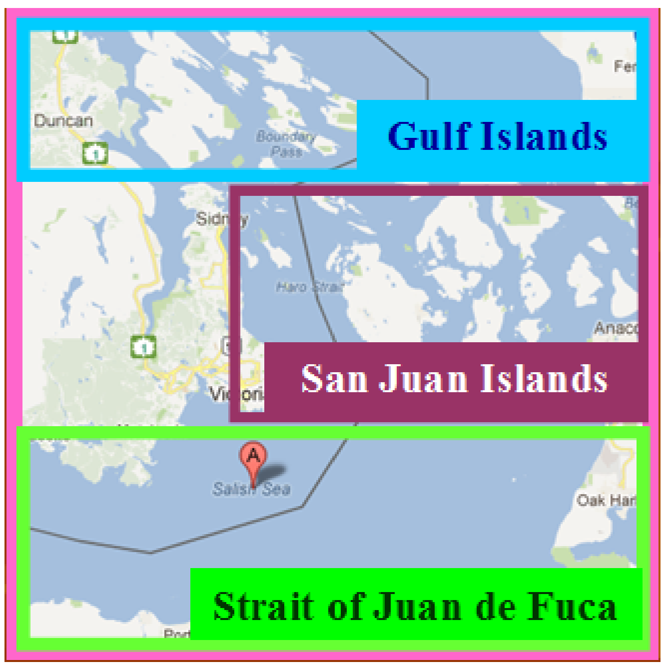

Figure 2. Map of sub-regions.

To determine if there is a sub-region within the study area where SRKW presence is more common, incidences of sighting in each sub-region were first counted and calculated as a proportion of total incidences in the study area for each Julian year. Individual sightings were not counted cumulatively. For each whale day, any number of sightings in a single sub-region is considered one incidence for such sub-region. If change of sub-region occurs within a single day, it is considered a separate incidence. The number of separate incidences serves as an index to estimate the amount of time spent in each sub-region. A proportion for each of the three sub-regions was obtained out of total number of incidences in each Julian year. For each year, the same is done for three time bins of before, during, and after each year's defined period of continuous sightings. 3*3=9 proportions were obtained for each Julian year. Each proportion is out of total number of incident in each sub-region in each Julian year.

A non-parametric ANOVA, the Kruskal-Wallis test was performed using R statistical software (R Developmental Core Team 2010) to assess if there is a difference in proportion among three sub-regions in general, among sub-regions within each time bin, and within each sub-region between three time bins. Each Julian year is treated as a replicate.

Environmental Factors and Continuous SRKW Presence

To investigate if there are other factors than prey abundance that affect continuous presence of SRKW in the San Juan Archipelago, 5-year average whale days per seven days was regressed against 5-year average daily sea surface temperature and 5-year average daily change in tidal height. Furthermore, moving sum of whale days per seven days was regressed against average daily sea surface temperature and average daily change in tidal height for each Julian year. Spearman's rank correlation test was performed using R statistical software (R Developmental Core Team 2010) for each regression to determine the correlation coefficient and p-value.

Results

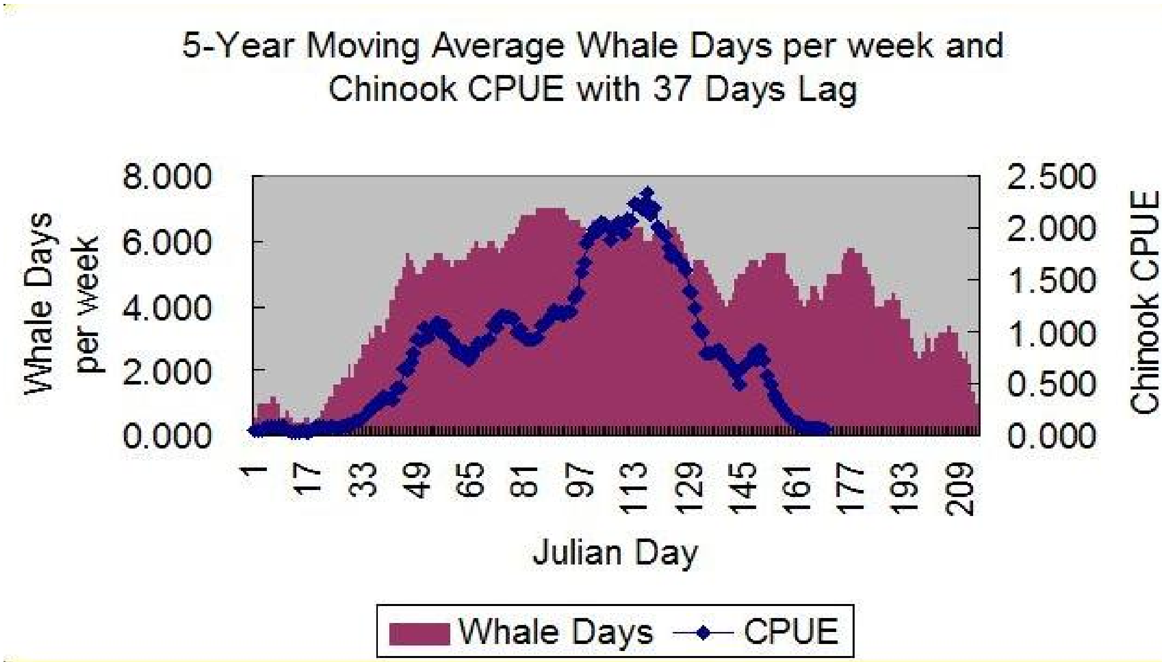

Figure 3. Time series of 5-Year Average Whale Days per 7 Days against 5-Year Average Chinook CPUE per 7 Days with 37 Days Lag.

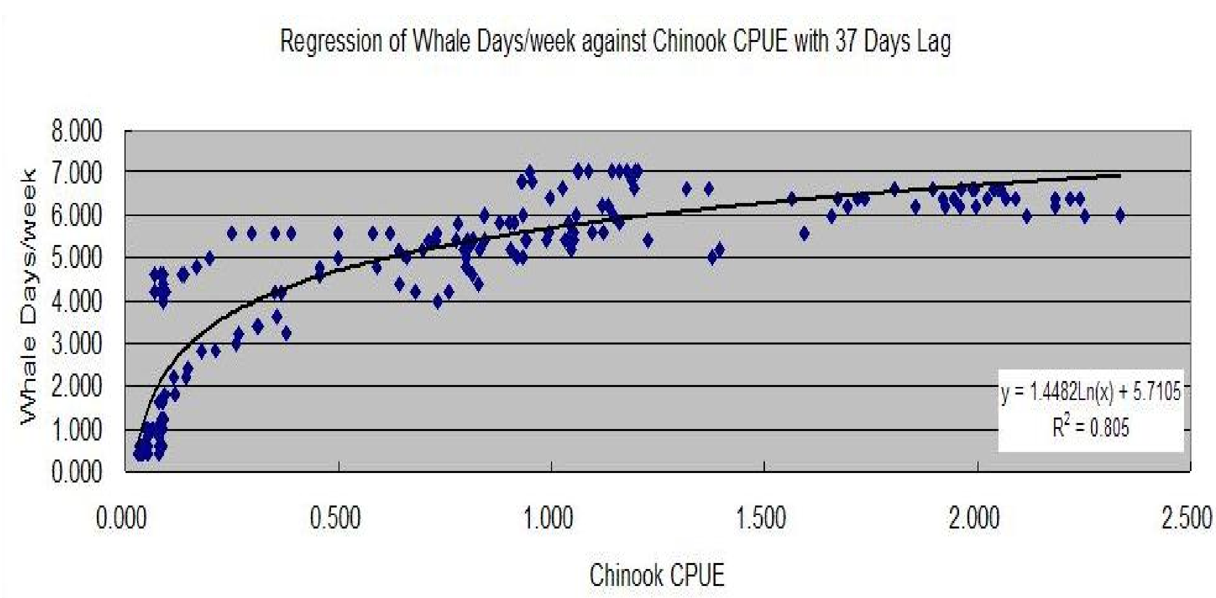

Figure 4. Regression of 5-Year Average Whale Days per 7 Days against 5-Year Average Chinook CPUE per 7 Days with 37 Days Lag. R^2=0.805. Spearman's rank correlation ρ =0.866, p-value<2.2e^-16.

Optimal Time Lag

With reference to Figure 4, optimal time lag between Continuous Presence of SRKW at San Juan Archipelago and Albion CPUE was determined to be 37 days with an R^2 value of 0.805 from the regression curve. The relationship appears to be logarithmic.

Chinook Salmon Abundance and Continuous Sightings of SRKW

With a 37-day lag applied, regression of 5-year average whale days per seven days against 5-year average CPUE per seven days yielded a Spearman's ρ of 0.866 and p-value$<2.2e^{-16}$, implicating a significant positive correlation. Each with 37-day lag applied, regression of moving sum of whale days per seven days against moving average CPUE per seven days for each Julian year yielded $0.346<\rho<0.753$ and $2.2e^{-16}<p<0.010$. A significant positive correlation is implicated for each year as well, though the strength of relationship differs each year. Regression for the year 2007 was disregarded due to insufficient CPUE data.

Chinook Abundance Threshold for Continuous SRKW Sighting

Chinook abundance threshold for SRKW to be continuously sighted was at first visually observed from the inflection point of the regression curve in Figure 4. CPUE value corresponding to 5 and above whale days was determined from table of data to be 0.830. Portion of the curve with the greatest slope was found to correspond to an increase of 0 to 4 whale days, implicating the highest rate of increase in number of whale days per seven days. For an increase of 0 to 4 whale days, CPUE increases from 0 to 0.181, approximating 0.0453 CPUE per additional whale day. For an increase of 4 whale days to 5 whale days per seven days, CPUE increases from 0.181 to 0.830, a 450% increase.

SRKW Presence in Sub-regions

Across five years, 54.8% of the sighting incidences occur in the San Juan Islands, while 20.8% and 24.4% of the incidences occur in the Gulf Islands and Strait of Juan de Fuca respectively. These percentages remain relatively similar before, during and after continuous sightings, except for a slight increase in percentage in incidences at

Strait of Juan de Fuca after continuous sightings (Appendix A). However, Kruskal-Wallis tests yielded no significant difference in proportion neither among three sub-regions in general, nor among sub-regions within each time bin, nor within each sub-region between three time bins. p-values range between 0.406-0.284.

Environmental Factors and Continuous SRKW Presence

Regression of 5-year average whale days per seven days against 5-year average daily sea surface temperature yielded a Spearman's ρ of 0.547 and p-value<2.2e^-16, implicating a significant positive correlation. Regression of moving sum of whale days per seven days against average daily sea surface temperature for each Julian year yielded $0.273<\rho<0.816$ and $2.2e^{-16}<p<0.0354$. A significant positive correlation is implicated for each year, though the strength of relationship differs quite considerably among years.

Regression of 5-year average whale days per seven days against 5-year average daily tidal exchange yielded a Spearman's ρ of -0.132 and p-value=0.0544, implicating no significant correlation. Regression of moving sum of whale days per seven days against average daily tidal exchange for each Julian year yielded $-0.0190<\rho<0.0596$ and $p>0.388$. No significant correlation is implicated for each year. An exception is year 2010, where $\rho=-0.190$ and $p=0.00565$, but this alone is inconclusive, in light of results for other years. The relationship between whale presence and tidal exchange appears unclear.

Discussion

Optimal Time Lag

Given that the optimal time lag was calculated from 5-year averages, it is probable that optimal time lag of highest R^2 value for best-fit curve is different for each year. To visualize the 37-day time lag for each year, Southern Resident Killer Whale presence/ absence, as a binary representation where 0 = "present" and 1 = "absent" for each Julian day, is superimposed over the corresponding year's moving average of Chinook CPUE as a continuous time series. In general, with application of 37-day lag, peaks of

Chinook CPUE, whose number and magnitude differ each year, tend to fall within period of continuous sighting.

In a 2012 study by Ayres et al., Chinook CPUE at Albion and SRKW glucocorticoid level were temporally superimposed with a 10-day lag. The nadir of glucocorticoid, indicating the lowest level of nutritional and physiological stress, occurs approximately 10 days before the highest peak of Chinook CPUE at Albion Test Fisheries. However, with a 10-day lag, the highest peak of Chinook CPUE falls late in the period of continuous sighting in the San Juan Island and sometimes outside of it, whereas this highest peak falls consistently within the period of continuous sighting with a 37-day lag (Appendix B). Nonetheless, the 37-day lag remains a rough estimation. For future studies, it would be far more effective to determine adult Fraser Chinook abundance in the San Juan Archipelago by sampling on-site, as Chinook abundance pattern in the San Juan Archipelago may not be consistent with what inferred from Albion CPUE.

<u>Chinook Abundance Threshold for Each Year</u>

For each year, the estimated CPUE threshold for more than four whale days per seven days was determined from the data table with variables paired by Julian day. Threshold for four whale days was chosen instead of that for five days due to better consistency. Chinook abundance for the beginning of continuous sightings was determined from where the period-7 moving average of CPUE intercepts the first day of continuous presence. A range of CPUE values were obtained, with a minimum of 0.131 and maximum 2.081. Average CPUE for more than four whale days per seven days was 0.680, and 1.063 for beginning of continuous sighting (Table 1). These average values are somewhat consistent with those calculated from the 5-year average regression, but the range is considerable across years and probably confounded by the aforementioned factors.

	Julian Day			
Year	Beginning of Continuous Sighting	End of Cont. Sighting	Duration of Cont. Sighting	First Whale Day (Julian Day)
2006	23	128	105	19
2007	24	130	106	3
2008	43	136	93	1
2009	77	193	116	34
2010	55	192	137	30
			Average Duration	
			111.4	

Year	Estimated CPUE Threshold >4 Whale Days per week	CPUE beginning Cont. Sighting	Sea Surface Temperature begin Cont. Sightings	CPUE first consecutive Whale Days	SST first consecutive Whale Days	SST first Whale Day
2006	0.435	0.131 (minimum)	8.804	n/a	n/a	8.652
2007	no information	no information	8.688	n/a	n/a	8.163
2008	0.744	0.537	8.657	n/a	n/a	7.587
2009	0.179	1.504	9.963	0.191	8.533	8.533
2010	1.363	2.081	9.713	0.28	9.37	9.37
Average	**0.680**	Average	9.165		Average	8.461
Average	**1.063**	Min	8.657		Min	7.587
(begin Cont. Sighting)		Max	9.963		Max	9.37

Table 1. Average CPUE for more than four whale days per seven days is 0.680, and 1.063 for beginning of continuous sighting. Minimum Sea Surface Temperature for beginning of continuous sighting is 8.657 degrees Celsius and for first whale day 7.587 degrees Celsius. Annual shifts in beginning of continuous sighting and first whale day are observed, generally occurring later in the year as compared to earlier years. Duration of continuous sighting remains relatively constant, with an average of 111.4 days.

Environmental Factors and Continuous SRKW Presence

The relationship between whale presence and sea surface temperature (SST) is generally positive. A minimum sea surface temperature is observed for the beginning of each year’s continuous sighting and first whale day, to be 8.657°C and 7.587°C respectively. The average SST for beginning of continuous sighting is 9.165°C (Table 1). The average SST for first whale day is 8.461°C, approximately 0.5°C less than the when continuous sighting begins. There seems to be an increase in the minimum

SST for beginning of continuous sighting through five years. However, annual shifts in beginning of continuous sighting and first whale day have been observed, generally occurring later in the year as compared to earlier years. In every year, SST increases relatively consistently for the first 90 Julian days. First whale day and beginning of continuous sighing has occurred considerably later in the year in 2009 and 2010, corresponding to a higher SST than the previous years. From these data alone, a conclusion to whether the beginning of continuous sighting or first whale day is influenced by a minimum SST value cannot be drawn. It seems more so that they are independent of one another. Analysis of more years of historical data, and incorporation of data from 2011 and 2012 is necessary to further investigate the minimum SST for continuous sighting and first whale day. Moreover, incorporation of data for all days of the year would provide better insight.

Sightings at West side of San Juan Island

With reference to the 2010 study by, Ashe et al, a further analysis is done to investigate the proportion of sightings off the west coast of San Juan Island. Similar to aforementioned methods, sightings corresponding to five specific GPS points on the grid off the west coast of San Juan Island were identified, and incidence was assigned to each Julian day as a binary index. It was found that on average, 48.8% of total sightings in the Julian year occur off the west coast of San Juan Island, and within the year, 89.3% of sightings within the sub-region San Juan Islands occur off the west-coast of San Juan Island (Table 2).

Year	**Westside Incidences**	Proportion out of annual total	Proportion out of SJI
2006	111	0.470	0.835
2007	115	0.509	0.885
2008	106	0.493	0.876
2009	116	0.470	0.906
2010	126	0.500	0.962
	Average	**0.488**	**0.893**

Table 2. On average, 48.8% of total sighting incidences in the year occur off the west coast of San Juan Island. 89.3% of sightings within the sub-region San Juan Islands occur off the west coast of San Juan Island.

Conclusion

Continuous sighting of SRKW in the San Juan Archipelago is found to be positively correlated with Chinook abundance, with optimal lag between Chinook CPUE at Albion and SRKW presence in SJA of 37 days. Chinook CPUE threshold for continuous sighting is found to be 0.830 with a minimum of 0.131. Sightings are more common in the San Juan Island area, in particular off the west coast of San Juan Island. Proportions of sightings in the Gulf Islands, San Juan Island area, and Strait of Juan de Fuca are not statistically different before, during and after period of continuous sighting. SRKW presence is positively correlated with sea surface temperature in Friday Harbor. The minimum SST for first whale day is 7.59˚C with an average of 8.46˚C.

The optimal time lag and CPUE threshold values found for this study are merely rough estimates. In order to better assess Chinook abundance in the San Juan Archipelago and its relationship with continuous sightings of SRKW, Fraser Chinook salmon abundance should be determined on-site, in particular off the west coast of San Juan Island where proportion of sighting incidences is highest. In his 2012 presentation, Mike Ford of Northwest Fisheries Science Center mentioned that an adult Southern Resident Killer Whale requires 1,000 Chinook a day. Through on-site investigation of Chinook salmon abundance, it would be possible to estimate the prey abundance threshold using the number of Chinook available in San Juan Archipelago. This estimation should also take into consideration the population fluctuation of SRKW. SRKW presence can also be analyzed by pod to determine if a certain pod prefers a certain season run of Fraser Chinook. Annual shifts in beginning of continuous sighting and first whale day from now on can thereby also be investigated using threshold values obtained on-site.

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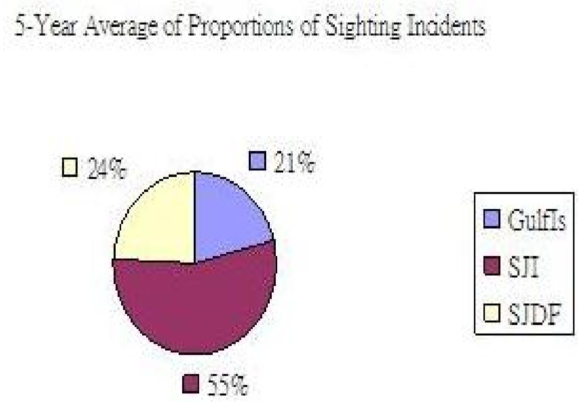
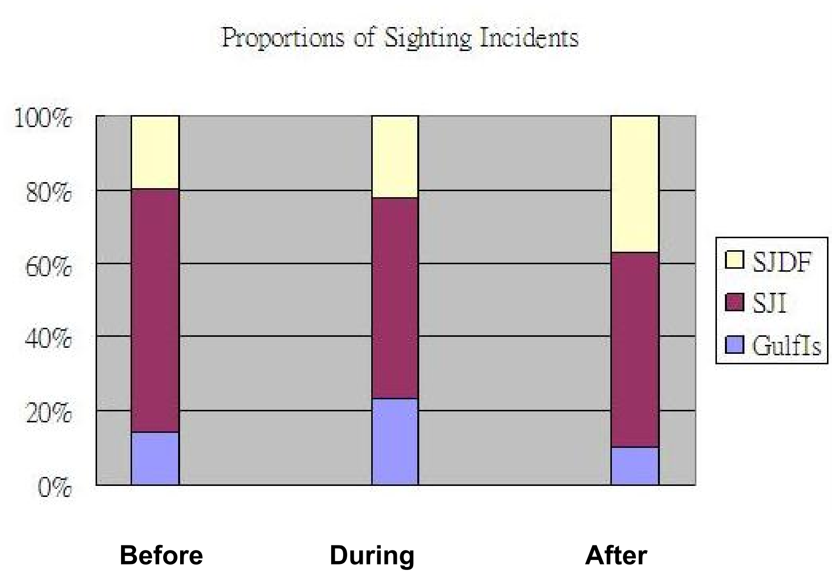
Appendix A

Pie chart, bar chart and table showing proportions of sighting incidences in three sub-regions as a whole, as well as before, during and after continuous sightings.





Proportions	Gulf Islands	San Juan Islands	Strait of Juan de Fuca
Average across 5 Years	0.208	0.548	0.244
Standard Deviation	0.039	0.027	0.030
Proportions	**Before Continuous Sighting**		
	Gulf Islands	**SJI**	**SJDF**
Average across 5 Years	0.143	0.659	0.198
Standard Deviation	0.093	0.135	0.187
	During Cont. Sight.		
	Gulf Islands	**SJI**	**SJDF**
Average across 5 Years	0.235	0.545	0.220
Standard Deviation	0.036	0.026	0.046
	After Cont. Sight.		
	Gulf Islands	**SJI**	**SJDF**
Average across 5 Years	0.102	0.526	0.373
Standard Deviation	0.033	0.055	0.047

Appendix B

Comparison of 10-day and 37-day lag. With 10-day lag, peak of CPUE falls later in the period of continuous sighting and in some cases outside of this period. With 37-day lag, peak of CPUE falls earlier in and consistently within period of continuous sighting.

	Julian Day			
Year	**Beginning Cont. Sighting**	**End Cont. Sighting**	**Duration Cont. Sighting**	**First Whale Day**
2006	23	128	105	19
2007	24	130	106	3
2008	43	136	93	1
2009	77	193	116	34
2010	55	192	137	30
			Average Duration: 111.4	
Year	**Peak CPUE**	**Julian Day of Peak CPUE**	**Peak CPUE Adjusted 10 days**	**Peak CPUE adjusted 37 days**
2006	3.42	113	**103**	**76**
2007	4.43	148	138	**111**
2008	7.54	151	141	**114**
2009	3.65	139	**129**	**102**
2010	3.78	95	**85**	**58**

Outside period of continuous sighting	**Within period of continuous sighting**