Supplemental materials for 'Shifting phenology of an endangered apex predator tracks changes in its favored prey'

March 10, 2020

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Effects of changes in effort on estimated phenological change (simulations)

To better understand how increased effort across the time-series (i.e., increased numbers of sightings over time) may affect estimates of trends in phenology, we simulated data sets of whale presence during two seasons equivalent to those in our data set (spring/summer, which was 1 May through 31 Sept, or 153 days, and fall/winter, which was 1 October through 1 Feb, or 123 days). We used whale presence probabilities that matched the mean observed probabilities for the Central Salish Sea and Puget Sound regions, separately, from 1978-2017 (Table S1). We kept them constant over 40 simulated years, respectively. We then created an observation data set, in which effort (the number of observations) varied. During the low effort time period (years 1-20), the number of observations had a mean of 15 per year for Puget Sound and 104 per year in the Central Salish Sea (matching the means for these regions from 1978-1997 in the OrcaMaster database). During the high effort time period (years 21-40 in our simulated data set), the number of annual observations had a mean of 39 for Puget Sound and 133 for the Central Salish Sea (matching those in the OrcaMaster database from 1998-2017). We then calculated first- and last- observations dates for each simulated year. We ran these simulations 100 times and calculated the difference between the low effort and high effort time periods. We compared these to the mean differences in first- and last-observation dates across time periods in the OrcaMaster database, for each region, to understand whether observed changes may be due to changes in effort over time, rather than changes in killer whale activity.

Our simulations indicate that, if SRKW activity did not change and only effort changed across the two time-periods, the first observation would be expected to shift earlier from 1978-2017, especially in Puget Sound (Figure S1). Thus, the large increase in effort across this time period may have affected trends in phenological shifts. However, the expected change due to increased effort opposes the patterns we observed in for the Central Salish Sea (i.e., we would expect earlier arrival, later departure, and increased occurrence probability). Further, focusing on 2001-2017 only, effects of changes in effort are likely to be minimal (Figure S2).

Southern Resident Killer Whales and their prey at Lime Killn Point State Park

Using a threshold probability lower than 0.5 did not quanliatatively alter results

Changing the breakpoint to 2007 or 2008 did not qualitatively alter results

Supplemental Tables

Table S1: **Salmon runs in Central Salish Sea and Puget Sound Proper** included in our analyses.

Region	Location	Species	Origin	Latitude	Longitude
Central Salish Sea	ALBION TEST FISHERY	Chinook	wild/hatchery	49.2104	-122.6228
Puget Sound Proper	CEDAR RIVER HATCHERY	Chinook	wild	47.3761	-121.9625
Puget Sound Proper	CEDAR RIVER HATCHERY	coho	wild	47.3761	-121.9625
Puget Sound Proper	GARRISON HATCHERY	chum	wild	47.1915	-122.5741
Puget Sound Proper	GEORGE ADAMS HATCHERY	chum	hatchery	47.3013	-123.1818
Puget Sound Proper	GEORGE ADAMS HATCHERY	Chinook	hatchery	47.3013	-123.1818
Puget Sound Proper	HOODSPORT HATCHERY	chum	hatchery	47.407	-123.1399
Puget Sound Proper	HOODSPORT HATCHERY	Chinook	hatchery	47.407	-123.1399
Puget Sound Proper	MCKERNAN HATCHERY	chum	hatchery	47.3066	-123.203
Puget Sound Proper	MINTER CR HATCHERY	chum	hatchery	47.3726	-122.7026
Puget Sound Proper	MINTER CR HATCHERY	Chinook	hatchery	47.3726	-122.7026
Puget Sound Proper	MINTER CR HATCHERY	coho	wild	47.3726	-122.7026
Puget Sound Proper	MINTER CR HATCHERY	coho	hatchery	47.3726	-122.7026
Puget Sound Proper	SOOS CREEK HATCHERY	chum	wild	47.3093	-122.1688

Table S2: **Salmon phenology has shifted earlier in Puget Sound Proper**, from 1997-2017, as quantified in the 13 runs included in our hierarchical model across coho, chum, and Chinook adult return data (see Table S1).

phenophase	parameter	mean	25%	75%	2.5%	97.5%
first	intercept	1724.86	1442.52	2007.22	900.37	2549.48
	year	-0.73	-0.87	-0.59	-1.14	-0.32
peak	intercept	932.39	735.04	1129.77	356.14	1508.88
	year	-0.32	-0.42	-0.22	-0.61	-0.03
last	intercept	1640.82	1447.50	1834.16	1076.32	2205.48
	year	-0.66	-0.75	-0.56	-0.94	-0.38

Table S3: **Estimated shifts with varying breakpoints and threshold probabilities for estimating phenology**

Phenophase	error	threshold
first		
last peak		

Pod-specific shifts at lime kiln

Supplemental Figures

raw data summaries: caption The shift toward later arrival in the central Salish Sea is evident in the number of whale days, averaged across the most recent portion of the time series (2009-2017) compared to the average of the earlier half of the timeseries we analyzed A,B). Shading around lines represents standard deviation for left panels, Gray shading in left panels shows the time year during which regional models were fit.

Figure with Changing the breakpoint of 2006 in Figure 3to 2007 or 2008 did not qualitatively alter results (Fig. SX) Coincident with these phenological trends, the number of whale days has also changed across the time-series (Fig. SX). Since 2001, the number of whale days has decreased in the Central Salish Sea, across all pods, whereas in Puget Sound proper the number of whale days did not show a consistent trend (Fig. SX). From 1978 to 2017, the number of whale days increased in both regions (and for all pods).

To Do Add to supplemental Materials:

(d) show relationship between lime kiln, and central salish sea phenology

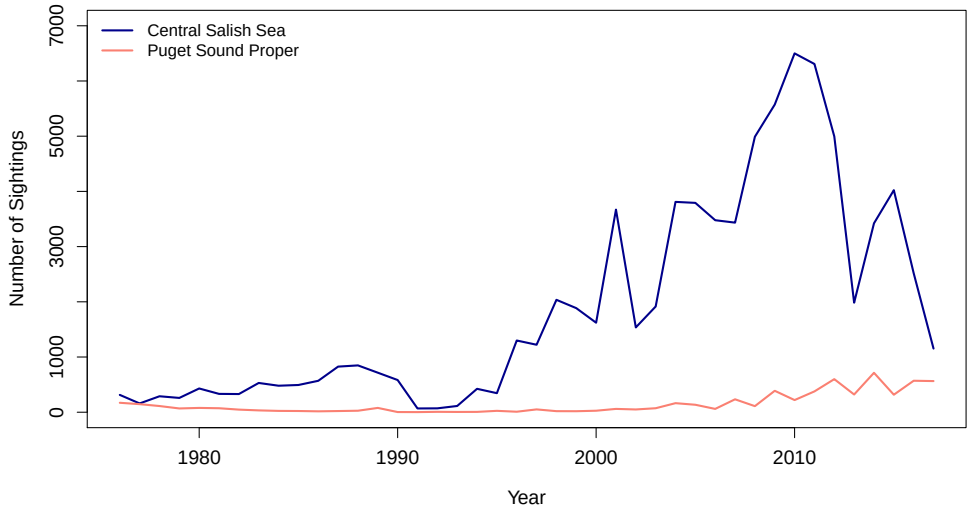

Figure S1: **Sightings of SRKWs from the OrcaMaster Database**, from 1978-2017.

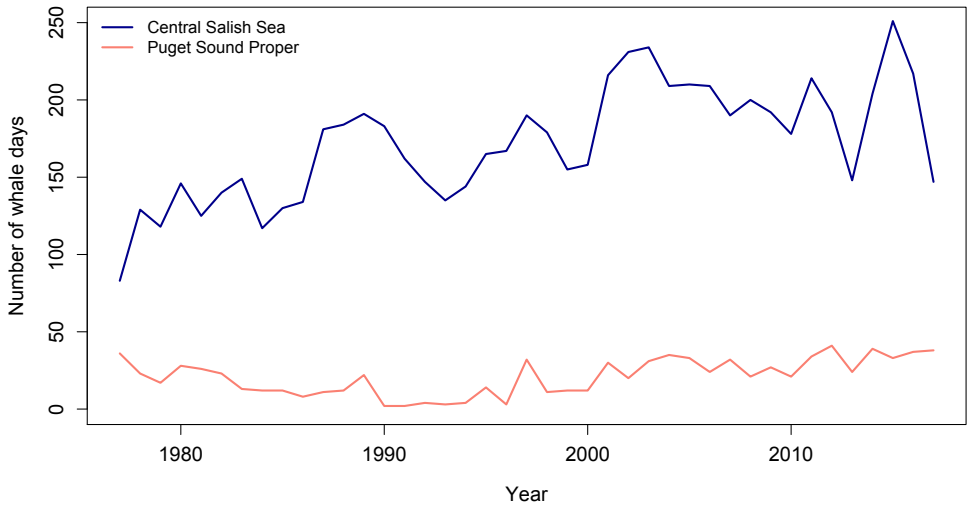

Figure S2: **Number of whale days from the OrcaMaster Database**, from 1978-2017.

Figure S3: **Number of whale days at Lime Kiln State Park** has declined since 1994, across all pods (A), J pod (B), K pod (C), and L pod (D).

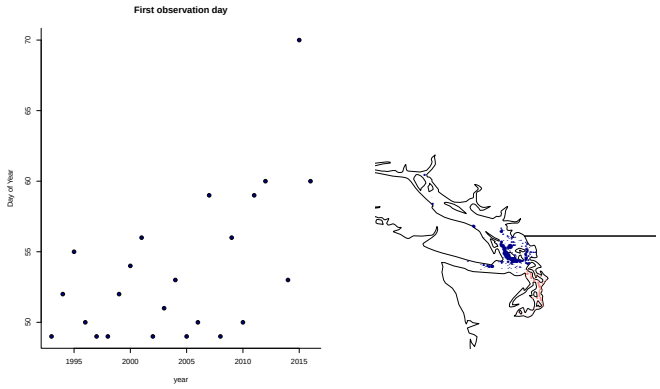

Figure S4: **SRKW phenology at Lime Kiln State Park is shifting**, which the day of year of first sighting getting later (A) and the day of year of last sighting getting earlier frmo 1994-2017. These trends are associated with a decrease in the amount of time SRKWs are spending near Lime Kiln: the number of days on which SRKWs were observed ("whale days") has declined since 1994.

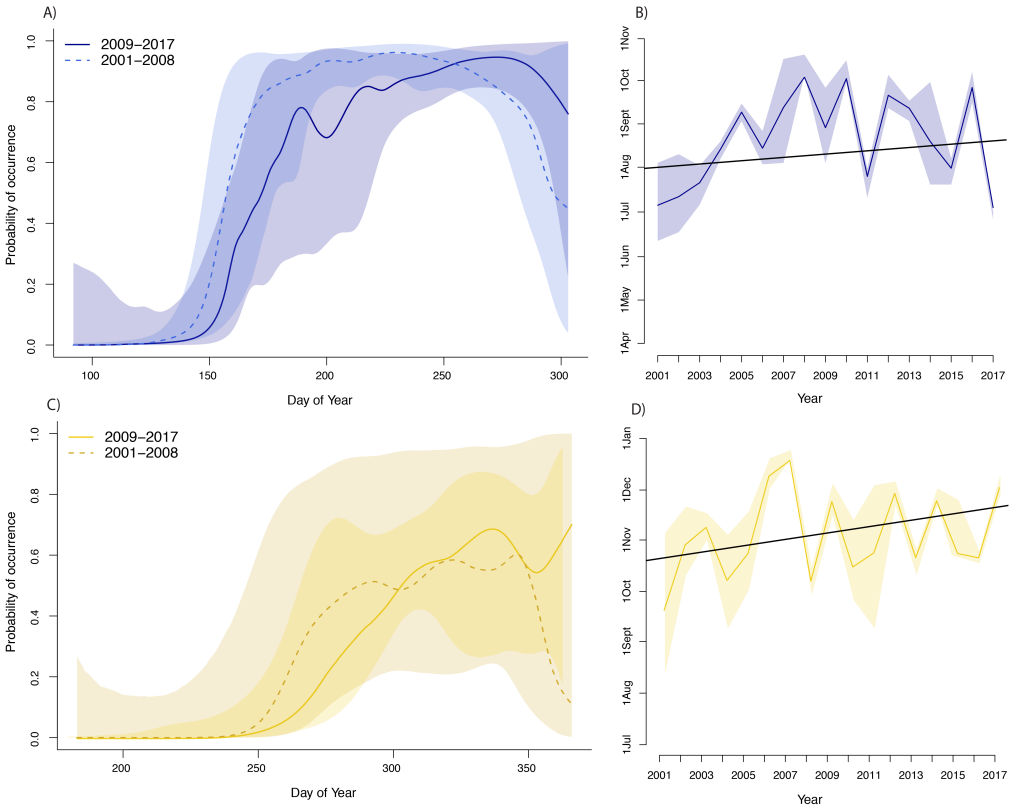

Figure S5: **K-pod activity varies seasonally in the Central Salish Sea (A) and Puget Sound proper (C).** This phenology has shifted later in recent years in the Central Salish Sea (B) and in Puget Sound (D). The shift toward later arrival in the central Salish Sea is evident the estimated probabilities of occurrence from the occupancy models for K-pod (A,C) as well as the linear trends in peak occurrence probability from 2001-2017 (B,D). Shading around lines represents 50% credible intervals (95% credible intervals in Table SX).

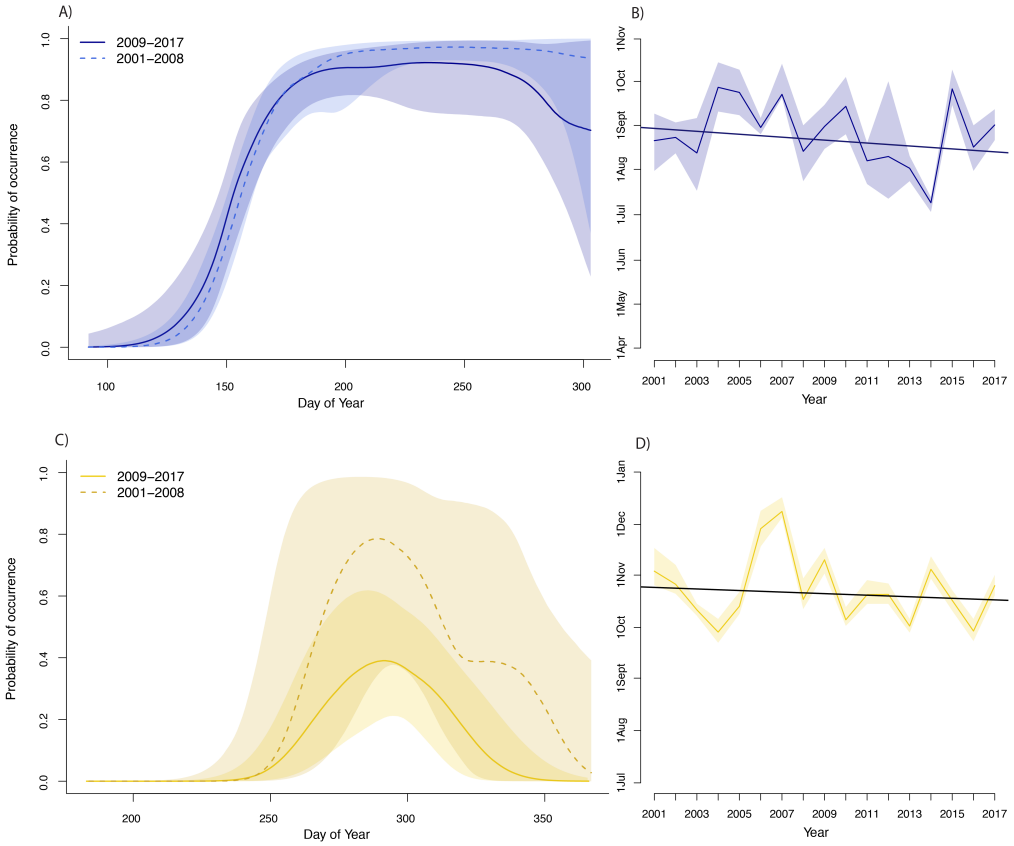

Figure S6: **L-pod activity varies seasonally in the Central Salish Sea (A) and Puget Sound proper (C)**. This phenology has shifted later in recent years in the Central Salish Sea (B) and in Puget Sound (D). The shift toward later arrival in the central Salish Sea is evident the estimated probabilities of occurrence from the occupancy models for K-pod (A,C) as well as the linear trends in peak occurrence probability from 2001-2017 (B,D). Shading around lines represents 50% credible intervals (95% credible intervals in Table SX).

Table S4: **Estimated linear trends in peak-, start-of-, and end-of-season SRKW phenology** in Puget Sound proper and the central Salish Sea, from occupancy model estimates of presence probabilites. 'Peak' is the day of year with the maximum probability of presence (or the mean across day of year, if there are multiple days with the peak probability of presence). To estimate the start of the season, we identified the earliest day of year with an estimated presence probility greater than 0.5. To estimate the end of the season, we identified the latest day of year with an estimated presence probility greater than 0.5. 50 percent and 95 percent uncertainty intervals are shown.

				1978-2017 trend			2002-2017 trend		
Pod	Region	Season	Phase	mean	25%	75%	mean	25%	75%
J	Puget Sound	Fall	peak	1.17	0.93	1.44	0.81	-0.37	1.94
J	Puget Sound	Fall	first	0.54	0.10	0.97	2.68	1.66	3.71
J	Puget Sound	Fall	last	0.87	0.43	1.31	-1.07	-2.00	-0.15
J	Puget Sound	Fall	peak	1.14	0.87	1.41	0.74	-0.42	1.86
J	Puget Sound	Fall	first	0.54	0.08	0.99	2.67	1.60	3.77
J	Puget Sound	Fall	last	0.97	0.52	1.40	-0.95	-1.91	-0.03
J	Central Salish Sea	Summer	peak	1.04	0.65	1.44	5.78	3.73	8.19
J	Central Salish Sea	Summer	first	-0.74	-0.88	-0.58	1.11	0.93	1.20
J	Central Salish Sea	Summer	last	1.12	0.96	1.28	0.48	0.31	0.67
J	Central Salish Sea	Summer	peak	1.13	0.74	1.53	5.16	2.14	8.47
J	Central Salish Sea	Summer	first	-0.75	-0.90	-0.61	1.11	0.94	1.20
J	Central Salish Sea	Summer	last	1.12	0.95	1.27	0.47	0.29	0.65
K	Puget Sound	Fall	peak	1.80	1.51	2.11	1.82	0.59	2.96
K	Puget Sound	Fall	first	1.70	1.14	2.27	2.73	1.55	3.90
K	Puget Sound	Fall	last	2.76	2.24	3.30	1.62	0.88	2.33
K	Puget Sound	Fall	peak	1.77	1.48	2.07	1.92	0.67	3.08
K	Puget Sound	Fall	first	1.67	1.14	2.23	2.27	1.01	3.62
K	Puget Sound	Fall	last	2.75	2.20	3.32	1.50	0.89	2.11
K	Central Salish Sea	Summer	peak	0.90	0.59	1.22	1.11	0.15	2.08
K	Central Salish Sea	Summer	first	-0.34	-0.61	-0.09	0.87	0.34	1.62
K	Central Salish Sea	Summer	last	0.65	0.42	0.84	-0.81	-1.42	-0.25
K	Central Salish Sea	Summer	peak	0.90	0.60	1.20	1.14	0.26	2.04
K	Central Salish Sea	Summer	first	-0.36	-0.62	-0.10	0.83	0.30	1.60
K	Central Salish Sea	Summer	last	0.69	0.46	0.89	-0.79	-1.44	-0.20
L	Puget Sound	Fall	peak	1.09	0.90	1.27	-0.21	-0.73	0.25
L	Puget Sound	Fall	first	1.87	1.22	2.57	1.84	0.84	2.92
L	Puget Sound	Fall	last	1.06	0.32	1.82	-1.76	-2.29	-1.23
L	Puget Sound	Fall	peak	1.09	0.63	1.55	-0.21	-1.44	1.17
L	Puget Sound	Fall	first	1.83	-1.70	4.68	1.13	-11.14	11.44
L	Puget Sound	Fall	last	1.97	-1.91	5.76	-0.15	-6.22	9.94
L	Central Salish Sea	Summer	peak	0.23	-0.02	0.50	-1.05	-1.98	-0.09
L	Central Salish Sea	Summer	first	-1.81	-2.10	-1.52	0.53	0.23	0.87
L	Central Salish Sea	Summer	last	1.07	0.83	1.30	-0.18	-0.39	0.05
L	Central Salish Sea	Summer	peak	0.23	-0.41	0.86	-1.05	-3.37	1.23
L	Central Salish Sea	Summer	first	-1.20	-2.87	1.10	1.02	-1.13	3.36
L	Central Salish Sea	Summer	last	-0.09	-1.14	1.33	-1.01	-2.93	0.72

Table S5: **Estimated linear trends in peak-, start-of-, and end-of-season SRKW phenology** in Puget Sound proper and the central Salish Sea, from occupancy model estimates of presence probabilites. 'Peak' is the day of year with the maximum probability of presence (or the mean across day of year, if there are multiple days with the peak probability of presence). To estimate the start of the season, we identified the earliest day of year with an estimated presence probility greater than 0.5. To estimate the end of the season, we identified the latest day of year with an estimated presence probility greater than 0.5. 5 percent and 95 percent uncertainty intervals are shown.

				1978-2017 trend			2002-2017 trend		
Pod	Region	Season	Phase	mean	25%	75%	mean	25%	75%
J	Puget Sound	Fall	peak	1.17	0.93	1.44	0.81	-0.37	1.94
J	Puget Sound	Fall	first	0.54	0.10	0.97	2.68	1.66	3.71
J	Puget Sound	Fall	last	0.87	0.43	1.31	-1.07	-2.00	-0.15
J	Puget Sound	Fall	peak	1.14	0.87	1.41	0.74	-0.42	1.86
J	Puget Sound	Fall	first	0.54	0.08	0.99	2.67	1.60	3.77
J	Puget Sound	Fall	last	0.97	0.52	1.40	-0.95	-1.91	-0.03
J	Central Salish Sea	Summer	peak	1.04	0.65	1.44	5.78	3.73	8.19
J	Central Salish Sea	Summer	first	-0.74	-0.88	-0.58	1.11	0.93	1.20
J	Central Salish Sea	Summer	last	1.12	0.96	1.28	0.48	0.31	0.67
J	Central Salish Sea	Summer	peak	1.13	0.74	1.53	5.16	2.14	8.47
J	Central Salish Sea	Summer	first	-0.75	-0.90	-0.61	1.11	0.94	1.20
J	Central Salish Sea	Summer	last	1.12	0.95	1.27	0.47	0.29	0.65
K	Puget Sound	Fall	peak	1.80	1.51	2.11	1.82	0.59	2.96
K	Puget Sound	Fall	first	1.70	1.14	2.27	2.73	1.55	3.90
K	Puget Sound	Fall	last	2.76	2.24	3.30	1.62	0.88	2.33
K	Puget Sound	Fall	peak	1.77	1.48	2.07	1.92	0.67	3.08
K	Puget Sound	Fall	first	1.67	1.14	2.23	2.27	1.01	3.62
K	Puget Sound	Fall	last	2.75	2.20	3.32	1.50	0.89	2.11
K	Central Salish Sea	Summer	peak	0.90	0.59	1.22	1.11	0.15	2.08
K	Central Salish Sea	Summer	first	-0.34	-0.61	-0.09	0.87	0.34	1.62
K	Central Salish Sea	Summer	last	0.65	0.42	0.84	-0.81	-1.42	-0.25
K	Central Salish Sea	Summer	peak	0.90	0.60	1.20	1.14	0.26	2.04
K	Central Salish Sea	Summer	first	-0.36	-0.62	-0.10	0.83	0.30	1.60
K	Central Salish Sea	Summer	last	0.69	0.46	0.89	-0.79	-1.44	-0.20
L	Puget Sound	Fall	peak	1.09	0.90	1.27	-0.21	-0.73	0.25
L	Puget Sound	Fall	first	1.87	1.22	2.57	1.84	0.84	2.92
L	Puget Sound	Fall	last	1.06	0.32	1.82	-1.76	-2.29	-1.23
L	Puget Sound	Fall	peak	1.09	0.63	1.55	-0.21	-1.44	1.17
L	Puget Sound	Fall	first	1.83	-1.70	4.68	1.13	-11.14	11.44
L	Puget Sound	Fall	last	1.97	-1.91	5.76	-0.15	-6.22	9.94
L	Central Salish Sea	Summer	peak	0.23	-0.02	0.50	-1.05	-1.98	-0.09
L	Central Salish Sea	Summer	first	-1.81	-2.10	-1.52	0.53	0.23	0.87
L	Central Salish Sea	Summer	last	1.07	0.83	1.30	-0.18	-0.39	0.05
L	Central Salish Sea	Summer	peak	0.23	-0.41	0.86	-1.05	-3.37	1.23
L	Central Salish Sea	Summer	first	-1.20	-2.87	1.10	1.02	-1.13	3.36
L	Central Salish Sea	Summer	last	-0.09	-1.14	1.33	-1.01	-2.93	0.72