UPDATED ABUNDANCE ESTIMATES FOR BLUE AND HUMPBACK WHALES ALONG THE U.S. WEST COAST USING DATA THROUGH 2018

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Updated abundance estimates for blue and humpback whales along the U.S. West Coast using data through 2018

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Introduction

This report provides updated West-Coast abundance estimates for blue and humpback whales from mark-recapture estimates based on photo-identifications work conducted by Cascadia Research Collective (CRC) and collaborators through 2018. A new analysis of the photo-identification data is underway using Bayesian models and will be available in the future. The purpose of this report is to provide updated estimates through 2018 using approaches that have been used previously (Calambokidis and Barlow 2004, 2013, 2017, Calambokidis et al. 2017).

During 2018, CRC worked closely with SWFSC and during the NOAA California Current Ecosystem Survey by conducting supplementary small boat operations to obtain photo-identifications and collect biopsy samples. This effort was combined with data from other projects as well as contributions from collaborators available through our collaboration with *Happywhale.com* (a web-based citizen science project that provides automated matching of humpback fluke identification photographs).

Methods

Small boat survey effort in 2018 that contributed data on sightings, photo-identifications, and sometimes tissue samples fell into three categories:

1) There were 65 vessel/days of effort from June through November 2018 by Cascadia where the primary mission was obtaining photo-identifications of humpback and other large whales along the US West Coast for this project. This is the dedicated survey effort mostly conducted in conjunction and following the NOAA ship survey and covered areas where humpback and other whales had been sighted. The number of survey days exceeded the number of survey days called for in the proposal. Almost all this effort was conducted with Cascadia RHIBs but in a few cases involved other vessels. For example there were a few days of effort conducted by Jeff Jacobson arranged and funded through this project out of Eureka, Crescent City, and Fort Bragg, areas where due to weather and low sightings not much effort was conducted during Cascadia' period in the area.
2) There were an additional 44 vessel/days of effort by Cascadia and collaborators primarily for other research (tagging, entanglement response, and ship strike research) but where photo-identification and sampling was a secondary goal. These efforts contributed to our overall effort including photographic identifications and sample collection. A primary example of this was a collaborative effort by Cascadia (with Stanford and others) in August in Monterey Bay to deploy multi-sensor video tags on humpback, blue, and fin whale in conjunction with aerial drone images. During that project we were able to obtain large numbers of photographic identifications and skin samples that are included here.
3) There were 86 other days with effort during 2018 not counted in above that were either earlier in the season prior to the CCES effort, were more opportunistic data by Cascadia personnel from whale watch vessels (in the Strait of Juan de Fuca), or more exclusively for other projects where there was more limited dedicated photographic identification. Some elements of this, for example, opportunistic data and photographs collected from whale watch boats by Cascadia personnel, still contributed to photo-ID sample size.

Overall, the above efforts resulted in an unprecedented number of photographic identifications and tissue sample collections in 2018 (Table 1, Figure 1). There were 821 sightings of an estimated 2,603 humpback whales during the surveys and obtained almost 1,400 good photographic quality identifications which yielded just under 900 unique individuals (after accounting for resightings of the same whale). The small boat sightings covered the whole US West Coast (Figure 1). More than 300 humpback tissue samples were collected were collected. Sightings, photo-identifications, and samples covered most of the US West Coast (Table 1). The only region underrepresented in the data set for humpback whales was Southern California due to the low number of sightings during the latter portion of the survey (from both the NOAA ship and the small boat effort).

Supplemental identifications were gleaned from opportunistic sources including historical contributors Monterey Bay Whale Watch (Nancy Black), Peggy Stapp, Channel Islands Naturalist Corps, Aquarium of the Pacific and other sources. Finally, over 5,000 identifications were provided by contributions made to Happywhale from along the US West Coast in 2018 - primarily from Monterey Bay, the Southern California Bight, and the Salish Sea.

Table 1. Sightings, animals, estimated photo-IDs, and tissue samples collected during small boat effort by Cascadia and collaborators from June to November 2018 on the US West Coast. See text above for clarification on terminology.

Species/Region	Washing.	Oregon	N Calif.	Gulf of Faral.	Mont. Bay	S Calif.	Total
Humpback whales							
Sightings	179	109	97	207	214	15	821
Animals	578	614	263	438	682	28	2603
Good Quality IDs	218	426	226	205	296	26	1397
Unique IDs (minus dupl.)	174	242	177	186	134	0	895
Unique with all sources	476	261	178	257	874	180	2042
Samples	68	78	20	68	48	22	304
Blue whales							
Sightings		25	2	25	111	8	171
Animals		42	4	42	219	16	323
Estimated IDs		30	4	28	129	14	205
Samples		4		7	28		39
Gray whales							
Sightings	9	1					10
Animals	12	1					13
Estimated IDs	10	1					11
Samples	5						5
Fin whales							
Sightings	1	5			16	2	24
Animals	1	7			17	2	27
Estimated IDs	1	7			12	2	22
Samples		1			3	4	8

Figure 1. Tracks of survey effort and humpback whale sightings (circles) and tissue samples collected (squares) during small boat effort in 2018.

Results and Discussion

We calculated updated estimates of abundance for humpback whales using photographic identifications collected through 2018. Capture-recapture estimates of humpback whales for California-Oregon using three closed-population models as has been applied in the past[1] (Calambokidis and Barlow 2004, 2013, 2017), showed a dramatic increase in recent years (Figure 2, Table 2). These estimates will further be evaluated and tested in the future including in comparison with results from planned Bayesian models and from analysis of the 2018 sighting survey.

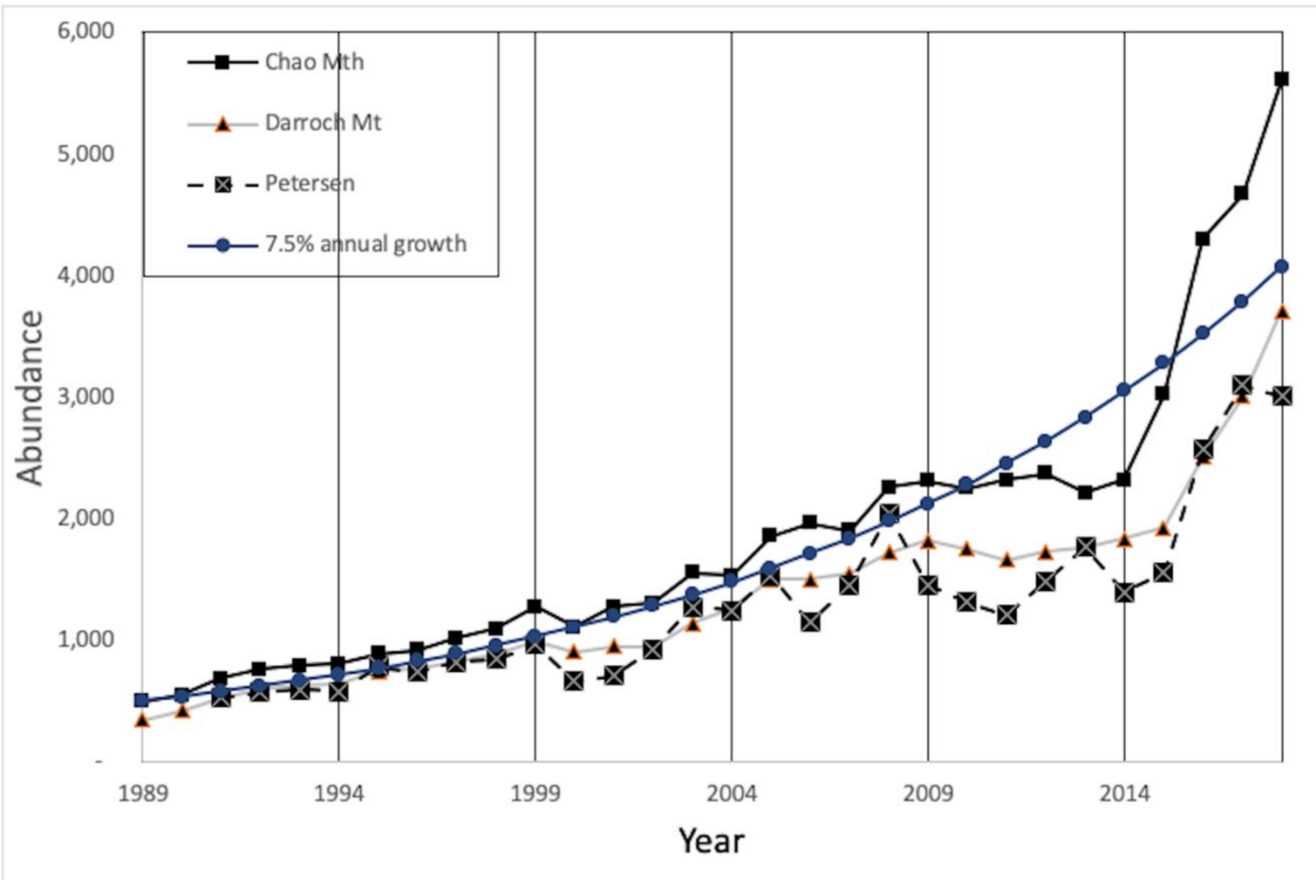

Figure 2. Estimated abundance of humpback whales off California and Oregon based on three models. Chao Mth model using rolling 4-year periods and accounting for heterogeneity of capture probability, Darroch Mt model using rolling 4-year periods without correction of heterogeneity, and inter-year Petersen mark-recapture models using adjacent years. Estimates are plotted against final year of series used. Also shown is trend for a population starting at 500 and increasing at 7.5% per year (the rate at which estimates were increasing through the late 2000s). See Table 2 for details on estimates including standard errors.

[1] The program CAPTURE (White et al. 1982) was used in this and previous analyses for the Darroch Mt and Chao Mth models, but in prior years, the programs RMark and Mark were used in intermediate steps to access CAPTURE. Here we used an R script to format capture-recapture data for direct analysis by CAPTURE.

The increase in humpback whale abundance since 2014 exceeds what is biologically plausible and could be the result of several factors potentially operating in combination:

1. The apparent stabilization of population growth starting in the late 2000s was not real and the population in fact continued to grow. As shown in Figure 2, a continued 7.5% annual increase in the population (assuming a starting population of 500 in 1989) would lead to an abundance of just over 4,000 by 2018, a number relatively consistent with the mix of abundance estimates for 2018 from the three models. A downward bias in abundance for the late 2000s to mid 2010s is consistent with a period of less representative coverage of the US West Coast and although the Chao Mth method should correct the negative bias in abundance estimates caused by heterogeneity in sampling probability among individuals, preliminary simulations show that this bias-correction is less effective when the sampled proportion of the population is low.
2. The added contribution of data from Happywhale especially starting in 2016, dramatically increased sample size and temporal coverage with most of these contributions from whale watching in a few areas like Monterey Bay. This could have either created greater bias in the estimates due to uneven coverage or through sheer sample size that helped negate biases.
3. There has been an influx of animals into this region from neighboring areas as populations have grown throughout the North Pacific. Some feeding areas including SE Alaska have reported recent dramatic declines in occurrence of humpback whales. While we do not have evidence this has directly contributed to an increase in whales off California-Oregon, this is being further explored.
4. One potential source of upward bias is the potential that the inclusion of more publicly submitted photographs (mostly through Happywhale) has increased the submission of images of the dorsal surface of flukes that could add new false unmatched identifications.

To test the potential that the added contributions from Happywhale and wider seasonal coverage were not the source of the recent increase, we also conducted the same abundance estimates using a dataset that only included effort from June to October (to reduce the potential that animals enroute to or from other feeding areas early or late in the season were being sampled) and excluded the Happywhale contributions (Figure 3, Table 3). These changes showed a similar increasing trend in abundance as the complete dataset but reduced the magnitude of the increase in recent years somewhat. This assessment indicated that while the Happywhale contribution and the greater seasonal coverage might be a contributor to the dramatic increase in recent years but that they are certainly not the primary factor.

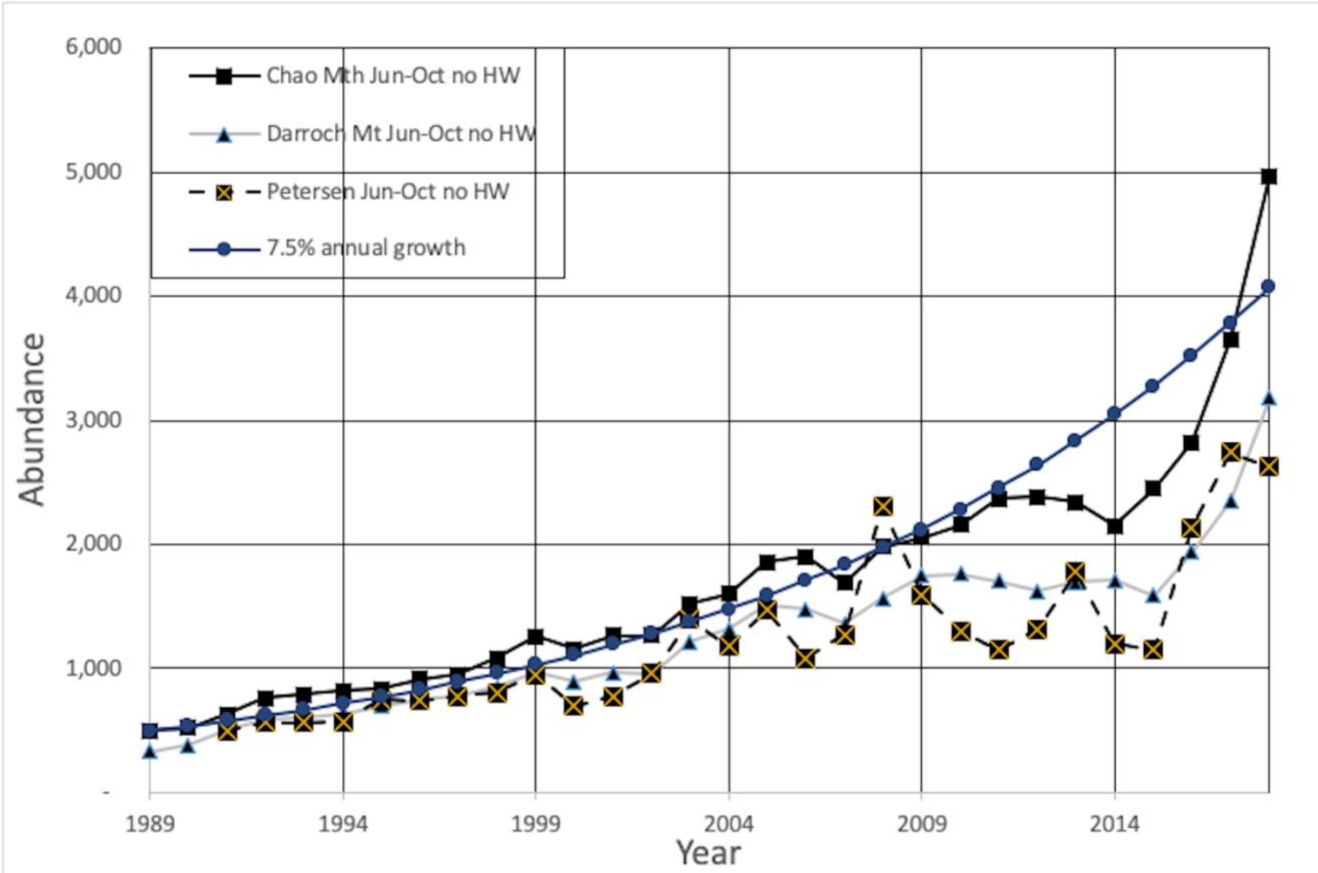

Figure 3. Estimated abundance of humpback whales off California and Oregon based on three models as shown in Figure 2, but using only identifications from June to October of each year and excluding contributions through Happywhale. Estimates are plotted against final year of series used. Trend for a population starting at 500 and increasing at 7.5% per year is shown (the rate at which estimates were increasing through the late 2000s). See Table 3 for details on estimates including standard errors.

Table 2. Unique photographic identifications, recaptures by year, estimated abundance (N) and standard errors (SE) for humpback whales off California and Oregon based on three models. Chao Mth model using rolling 4-year periods and accounting for heterogeneity of capture probability, Darroch Mt model using rolling 4-year periods without correction of heterogeneity, and inter-year Petersen mark-recapture models using adjacent years. Estimates are shown on row for final year of series used (with 2nd year of Petersen and end of 4 year period used for Chao and Darroch).

Year	Unique IDs	Recaptures to Prev Year	N Petersen	SE Petersen	N Darroch Mt	SE Darroch Mt	N Chao Mth	SE Chao Mth
1986	91							
1987	149	61						
1988	210	91						
1989	108	68			344	83	499	38
1990	205	62			418	97	552	36
1991	270	105	526	28	526	123	682	41
1992	400	190	568	16	593	100	759	38
1993	261	175	596	19	624	89	793	34
1994	244	110	577	31	644	91	804	33
1995	330	102	786	49	742	122	892	37
1996	331	148	737	33	770	152	919	42
1997	267	107	823	50	820	175	1,016	50
1998	384	121	845	47	883	168	1,090	50
1999	329	131	962	52	991	221	1,276	65
2000	229	113	665	36	905	206	1,112	57
2001	266	86	705	49	952	231	1,276	72
2002	313	89	931	67	939	249	1,304	79
2003	386	94	1,278	95	1,142	346	1,553	100
2004	305	94	1,246	92	1,261	385	1,535	91
2005	379	75	1,529	135	1,498	477	1,860	113
2006	294	97	1,143	81	1,500	488	1,964	124
2007	296	59	1,459	149	1,546	568	1,901	127
2008	445	64	2,037	205	1,720	601	2,255	148
2009	483	147	1,458	81	1,823	577	2,308	139
2010	498	183	1,312	60	1,751	470	2,254	120
2011	401	165	1,207	59	1,663	389	2,320	117
2012	529	142	1,489	85	1,727	392	2,373	116
2013	603	180	1,768	89	1,759	369	2,210	97
2014	653	282	1,395	45	1,835	358	2,322	97
2015	722	303	1,554	50	1,926	317	3,021	127
2016	1,209	340	2,564	85	2,508	371	4,303	172
2017	1,254	489	3,098	84	3,010	405	4,674	161
2018	1,568	654	3,005	62	3,713	448	5,612	170

Table 3. Unique photographic identifications, recaptures by year, estimated abundance (N) and standard errors (SE) for humpback whales off California and Oregon as in Table 2 but only using photographic identifications from June to October and not including those from Happywhale. Chao Mth model using rolling 4-year periods and accounting for heterogeneity of capture probability, Darroch Mt model using rolling 4-year periods without correction of heterogeneity, and inter-year Petersen mark-recapture models using adjacent years. Estimates are shown on row for final year of series used (with 2nd year of Petersen and end of 4 year period used for Chao and Darroch).

Year	Unique IDs	Recaptures to Prev Year	N Petersen	SE Petersen	N Darroch Mt	SE Darroch Mt	N Chao Mth	SE Chao Mth
1986	91							
1987	149	61						
1988	208	91						
1989	93	62			334	8.2	502	40
1990	148	42			382	9.7	521	37
1991	252	74	502	34	497	13.5	629	42
1992	359	160	565	20	584	13.0	759	45
1993	254	161	566	20	609	10.8	794	40
1994	241	107	570	31	638	10.3	819	38
1995	266	85	750	53	698	12.8	837	38
1996	291	104	742	45	754	17.5	917	48
1997	197	73	780	62	783	21.0	956	55
1998	358	87	807	55	848	20.6	1,083	60
1999	309	116	950	57	968	25.8	1,261	74
2000	179	79	697	50	892	25.5	1,154	72
2001	240	55	774	75	969	28.5	1,267	80
2002	279	69	963	83	958	31.4	1,264	86
2003	348	69	1,395	128	1,213	47.2	1,522	111
2004	269	79	1,177	96	1,315	49.0	1,602	110
2005	321	58	1,473	152	1,508	57.7	1,860	128
2006	252	74	1,085	92	1,477	57.2	1,904	136
2007	160	31	1,272	185	1,359	61.9	1,688	135
2008	343	23	2,307	411	1,567	73.0	1,982	160
2009	365	78	1,593	138	1,747	84.3	2,059	162
2010	362	101	1,302	92	1,765	76.0	2,161	159
2011	328	103	1,147	78	1,703	59.9	2,366	160
2012	413	102	1,321	93	1,628	51.4	2,382	153
2013	484	112	1,776	124	1,701	50.1	2,343	139
2014	506	203	1,204	50	1,713	44.6	2,152	111
2015	409	180	1,147	51	1,591	35.9	2,450	128
2016	640	122	2,136	144	1,936	44.6	2,819	142
2017	714	166	2,743	159	2,347	55.7	3,645	187
2018	1,068	290	2,626	101	3,180	73.1	4,973	239

Similar to California-Oregon, estimates of humpback whale abundance for Washington/Southern British Columbia showed increases especially in recent years (Figure 4, Table 4). While overall numbers are much lower than for California-Oregon, the rate of increase is actually higher given the very low numbers estimates in early years (consistent photo-ID effort for this region only started in about 1994 with earlier samples sizes not adequate for estimating abundance). Overall there was a greater degree of inter-annual variability in estimates for this region likely reflecting the still more limited sample size. This region has also experienced a significant expansion in the areas used by humpback whales, especially extending into the Salish Sea starting in the mid-2000s. In recent years this increase has also resulted in increased whale watch effort for humpback whales which has also increased the level of citizen science contributions of photographic identifications.

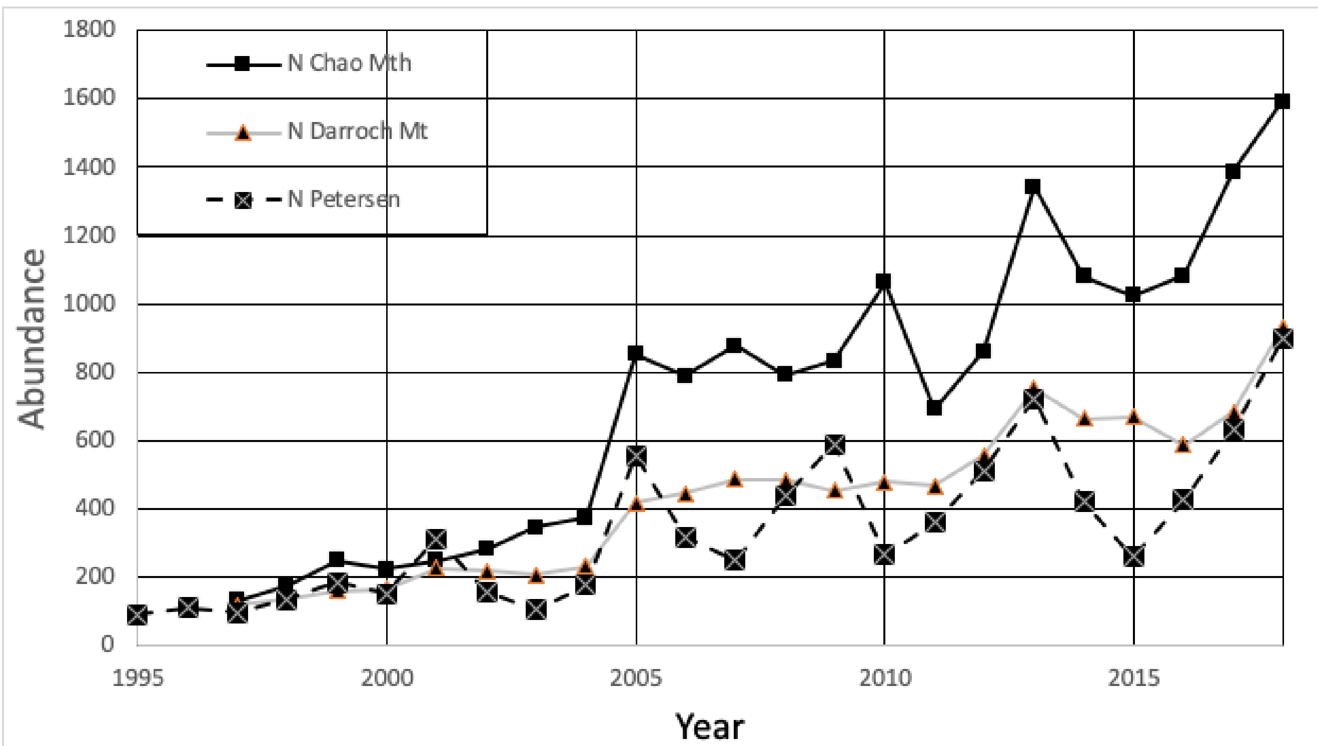

Figure 4. Estimated abundance of humpback whales off Washington/S British Columbia based on three models. Chao Mth model using rolling 4-year periods and accounting for heterogeneity of capture probability, Darroch Mt model using rolling 4-year periods without correction of heterogeneity, and inter-year Petersen mark-recapture models using adjacent years. Estimates are plotted against final year of series used. See Table 4 for details on estimates including standard errors.

Table 4. Unique photographic identifications, recaptures by year, estimated abundance (N) and standard errors (SE) for humpback whales off Washington/S British Columbia based on three models. Chao Mth model using rolling 4-year periods and accounting for heterogeneity of capture probability, Darroch Mt model using rolling 4-year periods without correction of heterogeneity, and inter-year Petersen mark-recapture models using adjacent years. Estimates are shown on row for final year of series used (with 2nd year of Petersen and end of 4 year period used for Chao and Darroch).

Year	Unique IDs	Recaptures to Prev Year	N Petersen	SE Petersen	N Darroch Mt	SE Darroch Mt	N Chao Mth	SE Chao Mth
1994	17							
1995	35	6	92	23				
1996	36	11	110	21				
1997	23	8	98	21	120	13.2	132	26
1998	50	8	135	31	138	11.9	174	31
1999	57	15	184	32	159	12.7	250	46
2000	41	15	151	25	166	13.3	223	38
2001	44	5	314	103	228	21.1	249	39
2002	48	13	157	29	218	19.6	281	48
2003	23	10	106	20	207	23.2	345	78
2004	88	11	177	32	232	20.1	375	70
2005	187	29	557	75	419	29.6	853	142
2006	45	26	319	36	446	34.0	790	126
2007	91	16	248	42	487	30.8	879	122
2008	85	17	439	80	484	30.8	792	106
2009	102	14	590	124	453	37.2	832	137
2010	61	23	265	36	478	38.5	1064	179
2011	63	10	360	86	469	41.6	692	113
2012	135	16	511	97	557	46.9	861	135
2013	132	24	723	116	753	72.0	1344	231
2014	56	17	420	74	664	58.8	1079	173
2015	132	28	260	30	669	48.1	1025	139
2016	220	68	425	29	588	29.8	1082	125
2017	314	109	632	34	683	25.6	1387	134
2018	478	167	897	38	929	23.3	1593	108

In addition to updated humpback estimates, we also estimated blue whale abundance using the data through 2018. Blue whale abundance estimates conducted in the past have generally relied on Petersen estimates with one sample being identifications from the systematic SWFSC surveys since these systematically sample both inshore and offshore waters as well as the entire coast (Calambokidis and Barlow 2004, 2013). There has not been a new set of systematically gathered photo-identifications of blue whales, but we can use the Chao estimate as a way to address the potential bias from heterogeneity in the more coastal small boat work. Another change in our identification records was our work with Azucena de la Cruz, a highly skilled matcher of blue whales who identified several internal matches within our catalog (which lowered estimates of abundance relative to previous analyses).

The additional years of data through 2018 along with the improved dataset allowed new estimates of blue whale abundance (Figure 5, Table 5). The Chao estimate of abundance for recent years was close to 2,000 consistent with some of our estimates we have reported previously, though with the new internal matches, these have resulted in lower estimates of abundances for the 1990s and 2000s (around 1,500) than the ~ 2,000 previously reported for that period (Calambokidis and Barlow 2004, 2013).

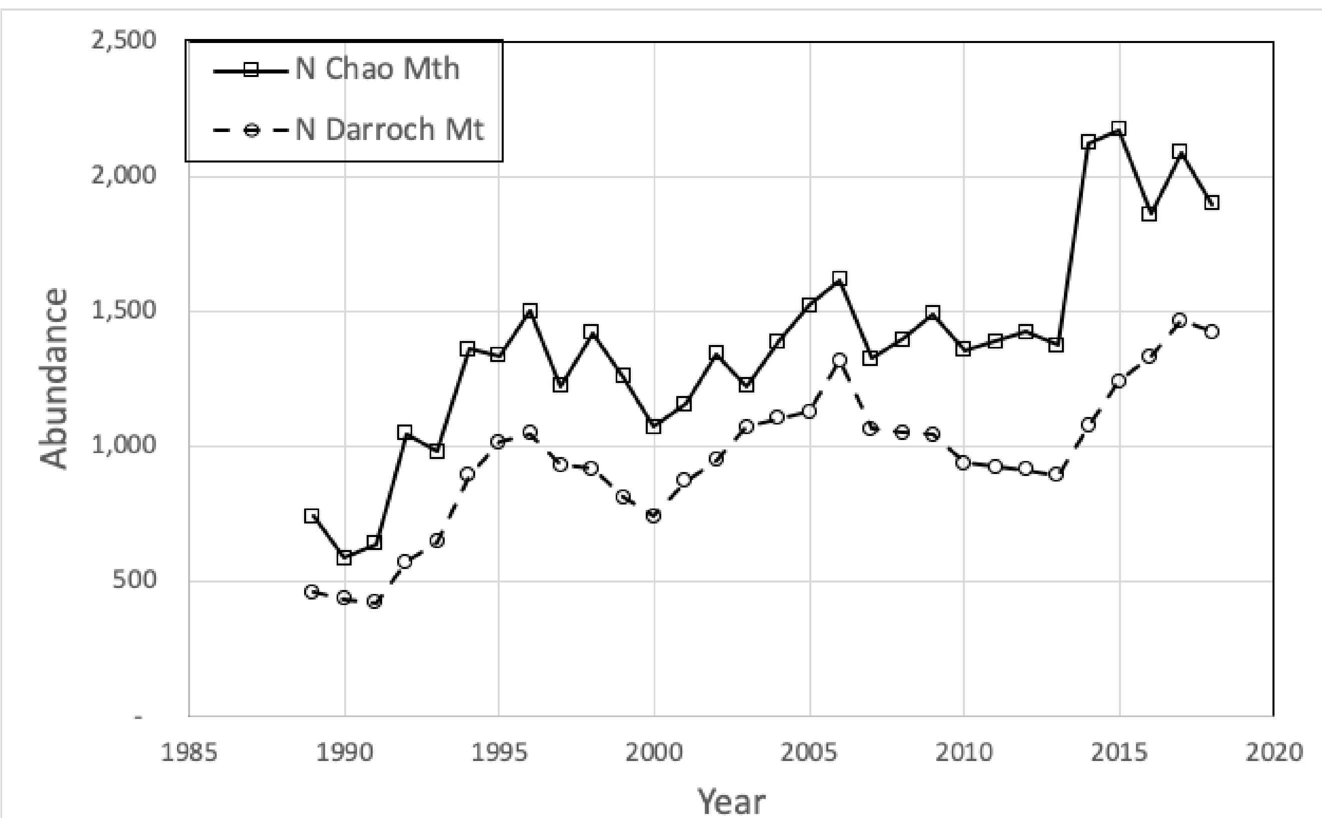

Figure 5. Estimated abundance of Blue Whales off the US West Coast based on two models. Chao Mth model using rolling 4-year periods and accounting for heterogeneity of capture probability, Darroch Mt model using rolling 4-year periods without correction of heterogeneity. Estimates are plotted on final year of series used (end of 4 year period). See Table 5 for details on estimates including standard errors.

Table 5. Unique photographic identifications, recaptures by year, estimated abundance (N) and standard errors (SE) for blue whales off the US West Coast based on two models. Chao Mth model using rolling 4-year periods and accounting for heterogeneity of capture probability, Darroch Mt model using rolling 4-year periods without correction of heterogeneity. Estimates are shown on row for final year of series used (end of 4 year period).

Year	Unique IDs	N Darroch Mt	SE Darroch Mt	N Chao Mth	SE Chao Mth
1986	76				
1987	118				
1988	138				
1989	102	461	25.6	742	89.4
1990	106	438	21.0	588	59.1
1991	74	424	22.8	641	74.4
1992	269	573	27.4	1,050	120.1
1993	125	649	33.3	980	104.4
1994	188	895	50.8	1,361	147.1
1995	218	1,016	48.9	1,335	118.6
1996	174	1,048	61.2	1,502	159.3
1997	167	933	45.8	1,224	111.8
1998	219	918	42.0	1,422	132.0
1999	177	812	36.0	1,260	116.3
2000	174	742	30.1	1,072	91.9
2001	274	873	34.0	1,158	90.8
2002	286	949	35.8	1,343	105.3
2003	288	1,072	38.4	1,224	80.2
2004	182	1,105	40.3	1,391	97.6
2005	176	1,130	48.5	1,522	123.8
2006	250	1,318	67.7	1,619	142.1
2007	326	1,065	43.2	1,327	100.1
2008	207	1,051	40.5	1,397	105.4
2009	297	1,044	33.6	1,490	102.8
2010	263	938	26.5	1,358	87.9
2011	291	927	27.3	1,391	94.0
2012	210	915	26.4	1,426	97.1
2013	177	893	30.2	1,375	103.8
2014	260	1,076	43.8	2,123	191.6
2015	184	1,240	66.9	2,173	226.9
2016	264	1,332	70.1	1,860	175.2
2017	353	1,467	66.0	2,088	173.8
2018	195	1,426	68.2	1,898	161.3

Conclusions

We report multiple abundance estimates for humpback whales along the US West Coast based both on regions, capture-recapture models, years, and datasets. We conclude that the estimate of 4,973 (SE-239 and lower and upper 20th percentile values of 4,776 to 5,178) based on the Chao model for the last four most recent available years (2015-2018) for photo-IDs obtained from June to October and excluding Happywhale contributions is the best overall estimate of abundance of humpback whales along the US West Coast for the following reasons:

1. The Chao estimate is the only one that accounts for heterogeneity of capture probabilities which would be a biasing factor in the other models.
2. Inclusion of Happywhale further oversamples a few small areas of high whale-watch activity like Monterey Bay and is a new element that has increased contributions in most recent years.
3. While this estimate was calculated using identifications from California and Oregon, it likely incorporates the smaller number of Washington animals since there is some level of interchange with that area and adding our estimate for Washington-Southern British Columbia would likely be biased high both for that reason as well as because it would inappropriately (for purpose of calculating an Nmin for US waters) include whales outside US waters.
4. This estimate is somewhat in line with the just over 4,000 animals projected assuming the 7.5% annual growth rate (calculated previously) since the late 1980s and no pause in the early 2010s. The change from the late 1980s to the estimate we propose here would require an 8.2% annual growth rate, still well within plausible levels for the overall period if there had been no pause in growth.

While this estimate does represent a substantial increase from previous estimates, this seems reasonable given the much more complete coverage especially from 2018 which likely better sampled the whole coast and also captured the increase in humpback whale abundance.

Similarly, we conclude that for blue whales in the eastern North Pacific the best estimate of abundance is 1,898 (SE-161 and lower and upper 20th percentile values of 1,767 to 2,038) again based on the Chao model and most recent four years (2015-2018). This estimates is fairly consistent with some of the past estimates of blue whale abundance used in recent stock assessment reports (Carretta et al. 2020) from photo-identification (Calambokidis and Barlow 2004, 2013) and line transect ship surveys though these have ranged more widely over the years (Barlow 2016) possibly as a result of shifts in blue whale distribution and use of feeding areas (Calambokidis et al. 2009). Our revised estimates suggest a possible slight increase in abundance since the 1990s based on the Chao model and improved dataset. There has been concern about potential ship strike impacts on this population (Rockwood et al. 2017) though other work has indicated population abundance may be at or near pre-whaling numbers (Monnahan et al. 2014, 2015).

Our lower 20$_{th}$-percentile estimates of abundance (4,776 for humpback whales and 1,767 for blue whales) are calculated to be consistent with the minimum abundance estimates (Nmin) used to calculate potential biological removal (PBR) in NMFS stock assessment reports (Carretta et al. 2020).

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