Abundance estimates of humpback and blue whales off the US West Coast based on mark-recapture of photo-identified individuals through 2008

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INTRODUCTION

Humpback and blue whales are considered endangered and their populations were depleted by whaling throughout most of their range. Both species make seasonal migrations between low latitude areas in winter and high latitude areas in summer. Blue whales feed off California from May through November (Dohl *et al.* 1983) and migrate to waters off Mexico and Central America in winter and spring (Calambokidis *et al.* 1990, Stafford *et al.* 1999, Mate *et al.* 1999, Chandler *et al.* 1999). Photographic identification of blue whales has revealed that animals identified off California are part of an eastern North Pacific population of blue whales that ranges as far north as the Queen Charlotte Islands and the Gulf of Alaska (Calambokidis et al. 2009) and as far south as the Costa Rica Dome (Chandler *et al.* 1999).

Recent studies of humpback whales in the entire North Pacific conducted under the SPLASH project have revealed a complex population structure with high degree of site fidelity to specific feeding and wintering areas but without a one to one association between these areas (Calambokidis et al. 2008). Overall abundance of humpback whales in the North Pacific was growing at 4-7% per year and through 2006 numbered about 20,000 (Calambokidis et al. 2008, Barlow et al. Submitted).

Starting in the early 1990s, photo-ID of humpback and blue whales along the US West Coast has provided accurate estimates of abundance using capture-recapture methods (Calambokidis et al. 1990a, 1990b, Calambokidis and Barlow 2004). These have complimented density-based abundance estimates available from line-transect surveys conducted by SWFSC (Barlow 2009, Barlow and Forney 2007, Forney 2007, Calambokidis and Barlow 2004). While annual estimates of humpback whales have been obtained from mark-recapture, blue whale abundance has only been primarily possible when at least one representative sample was obtained from the periodic surveys by SWFSC systematically covering both inshore and offshore waters (Calambokidis and Barlow 2004).

The primary objectives of the research reported here was to obtain new estimates of humpback and blue whale abundance along the US west coast based on mark-recapture of photographically identified individuals and examine trends in abundance.

METHODS

In 2008 we sought to:

1. Obtain a large and representative sample of humpback and blue whale identifications from coastal waters and, where possible, offshore waters of the West Coast in 2008 to supplement that already available for past years. This included dedicated photo-effort, opportunistic identifications obtained as part of other research, and identifications provided opportunistically by collaborators.
2. Compare identification photographs obtained during the SWFSC systematic surveys conducted in 2005 and 2008 with those available from our other surveys.
3. Generate new abundance estimates of humpback and blue whales through 2008 using mark-recapture.
4. Compare these estimates with those obtained during the last 17 years to evaluate potential trends in abundance.

Survey effort

A major focus of our field effort was to obtain as large a sample of photographic identifications as possible with broad geographic and temporal coverage. Strategies for achieving this included: 1) conduct small boat operations in many different areas, 2) cover large areas both offshore and inshore, 3) effectively sample large concentrations of whales, and 4) achieve broad temporal coverage. We achieved these objectives with a combination of dedicated small boats surveys, opportunistic identifications during our other field research, and identifications from other opportunistic sources.

Cascadia conducted 66 days of dedicated and opportunistic photo-identification surveys off California, Oregon, and Washington in the summer and fall of 2008 (Table 1). These were primarily conducted between June and November. Timing and exact locations of these surveys were based on weather patterns and anticipated whale abundance based on sighting reports and historical data. The primary vessels employed in these dedicated photo-identification surveys were three 5.3-5.9m rigid-hull inflatables equipped with outboard engines operated by Cascadia Research and used extensively in our past photo-identification research. Vessels covered up to 200 nmi/day and operated up to 50 nmi offshore. The boats were transported from one region to another by trailer. Additional opportunities to obtain identification photographs occurred during efforts to tag and track humpback and blue whales, monitoring of marine mammals of areas in conjunction with acoustic monitoring especially off central Washington, and surveys conducted as part of collaborations with Channel Islands and Olympic Coast National Marine Sanctuaries.

A number of collaborators provided additional identification photographs obtained more opportunistically. The most extensive contribution of opportunistic photographs came from our collaboration with the Channel Islands Naturalist Corps as well as whale watch operations out of Monterey Bay and San Francisco Bay.

Photographic identification from ship surveys

A critical part of the mark-recapture estimates for blue whales was the systematic identifications obtained in conjunction with broad-scale SWFSC marine mammal ship surveys. Key samples for the current study were the identifications obtained during the 2005 and 2008 SWFSC surveys covering waters out to 300 nmi off California, Oregon, and Washington. Additional fine-scale survey effort was completed during CSCAPE 2005 in waters of four West Coast National Marine Sanctuaries, providing additional blue whale identifications in nearshore waters.

Data analyses

All photographs were judged using a three-tier quality criterion. This score, along with associated sighting information (date, latitude, longitude), was entered into the identification database for analysis. Identification photographs of suitable quality were internally compared to identify resightings (and remove duplicates) of animals for each year. Each individual was then compared to Cascadia's historical catalog (archived photographs) of all blue whales identified off northern Baja, California, Oregon and Washington. Individual whales identified each year that did not match past years and which were of suitable quality were assigned a new unique identification number and added to the catalog annually.

Estimates of humpback and blue whale abundance were made using several capture-recapture methods (Calambokidis and Barlow 2004). The primary methods were two-sample Petersen capture-recapture estimates (Chapman modification for sampling without replacement) conducted using the identifications obtained in different pairs of samples including: 1) pairs of adjacent years as the two samples, and 2) identifications from the systematic broad-scale and fine-scale ship surveys as one sample and the second sample from the coastal surveys for the same time period. An unbiased estimate of blue whale abundance using the two-sample Petersen estimate requires that all animals in the population have an equal probability of being photographed in at least one of the samples. The second sample does not have to meet this criterion as long as it is independent of the first sample. This approach of using the identifications from the systematic ship surveys as the one representative sample provided reliable estimates of blue whale abundance for similar surveys in the past (Calambokidis and Barlow 2004).

We also conducted the first estimates of blue whale abundance using mark-recapture between feeding and wintering areas. This types of approach has been found to be the least biased method of estimating humpback whale abundance because it allows for more complete mixing of animals and avoids problems with heterogeneity of capture probability that often results from sampling biases in a particular region (Barlow et al. submitted, Calambokidis et al. 2008).

Table 1. Summary of effort conducted by Cascadia Research in 2008 for photo-ID.

Date	Vessel	Locality	Start Time	End Time	Total Effort (Hrs)	Distance (nm)	Objective
Surveys-California							
5/18/2008	N1	San Diego- Ensenada	8:40	16:58	8:18	120	General Photo ID
5/20/2008	N1	Ensenada-San Diego	13:30	18:48	5:18	75	General Photo ID
6/9/2008	N1	Mission Bay	7:50	17:41	9:51		Photo-ID/Tagging
6/9/2008	N2	Mission Bay	8:02	17:30	9:28	80	Bm Filming
6/10/2008	N1	Mission Bay	7:30	23:59	16:29	80	Photo-ID/Tagging
6/10/2008	N2	Mission Bay	7:42	17:40	9:58	75.2	Photo-ID/Nat Geo Filming
6/11/2008	N2	Mission Bay	10:10	17:51	7:41	84.4	Photo-ID/Nat Geo Filming
6/11/2008	N1	Mission Bay	10:30	17:45	7:15	68	Photo-ID/Tagging
6/12/2008	N2	San Diego	7:48	15:36	7:48	91.7	Photo-ID/Nat Geo Filming
6/12/2008	N1	San Diego to Ensenada	7:45	19:26	11:41	173	General Photo ID
6/13/2008	N1	San Diego into Mexico	7:50	19:30	11:40	121	Photo-ID/Tagging
6/13/2008	N2	San Diego into Mexico	7:51	19:00	11:09	79.4	Photo-ID/Nat Geo Filming
6/14/2008	N1	San Diego	8:08	18:30	10:22	63	Photo-ID/Tagging
6/14/2008	N2	San Diego	8:01	14:45	6:44	53.1	Photo-ID/Nat Geo Filming
6/15/2008	N1	Mission Bay	8:30	18:05	9:35	70	Photo-ID/Tagging
6/15/2008	N2	Mission Bay	8:40	17:21	8:41	85.3	Photo-ID/Nat Geo Filming
6/16/2008	N1	Mission Bay	8:20	16:48	8:28	75	Photo-ID/Tagging
6/17/2008	N1	San Diego to Ensenada	8:20	18:55	10:35		Photo-ID/Tagging
6/18/2008	N1	Ensenada to San Diego	9:35	16:45	7:10	91	Photo-ID/Tagging
8/14/2008	ZIP	Port San Luis	7:50	15:38	7:48	68.7	General Photo ID
8/14/2008	N2	Santa Barbara Channel	10:51	18:40	7:49		Tagging
8/15/2008	ZIP	Port San Luis	7:48	15:52	8:04	104	General Photo ID
8/15/2008	N2	Santa Barbara Channel	8:45	19:57	11:12	120	Tagging
8/16/2008	ZIP	Morro Bay	8:32	19:13	10:41	73.9	General Photo ID
8/16/2008	N2	Santa Barbara Channel	9:20	20:20	11:00	67	Tagging
8/17/2008	ZIP	Santa Barbara	9:30	19:10	8:41	83.6	Discovery Filming
8/17/2008	N2	Santa Barbara Channel	9:25	19:15	9:50	105	Tagging
8/18/2008	N2	Ventura	8:05	17:37	9:32		General Photo ID
8/18/2008	ZIP	Ventura	8:15	17:35	9:20	92.7	Bm Fliming
8/19/2008	N2	Ventura	8:15	16:10	7:55		Tagging
8/19/2008	ZIP	Ventura	8:16	16:04	7:48	77.3	Tagging
8/31/2008	N2	Long Beach	10:19	16:28	6:09	64.9	General Photo ID
9/7/2008	N2	Santa Monica Bay	13:40	19:56	6:16	79	General Photo ID
9/8/2008	N2	Santa Barbara Channel	8:40	19:40	11:00	120	Tagging
9/9/2008	N2	Santa Barbara Channel	9:12	18:30	9:18	170	Tagging
9/10/2008	N2	Santa Barbara Channel	9:40	19:00	9:20	67	Tagging
9/11/2008	N2	Santa Barbara	8:30	17:37	9:07	80	Tagging
9/12/2008	N2	Santa Barbara Channel	7:55	19:25	11:30	118	Tagging
9/13/2008	N2	Santa Barbara Channel	8:25	18:35	10:10	91	Tagging
9/14/2008	N2	Monterey Bay	9:45	14:55	5:10		General Photo ID
9/16/2008	N2	Half Moon Bay	13:55	19:15	5:20	46.5	General Photo ID
9/17/2008	N2	Bodega Bay	9:58	19:03	9:05	97.5	General Photo ID
9/18/2008	N2	Bodega Bay	9:17	18:52	9:35	96.6	General Photo ID
9/19/2008	N2	Half Moon Bay	9:38	15:34	5:56	62.2	General Photo ID
10/20/2008	ZIP	Pt St George	10:45	18:50	8:05	100	General Photo ID
10/21/2008	ZIP	Pt St George	9:20	16:00	6:40	61	General Photo ID
10/22/2008	ZIP	Bodega Bay	8:45	18:53	10:08	118	General Photo ID
10/23/2008	ZIP	Bodega/Cordell	8:45	18:40	9:55	92	General Photo ID
10/24/2008	ZIP	Pt St George	12:20	14:20	2:00	18	General Photo ID
11/2/2008	N2	Marina del Rey	8:09	15:27	7:18	69.2	General Photo ID
11/3/2008	N2	Santa Barbara Channel	9:37	12:35	2:58	36.3	General Photo ID
11/5/2008	N2	Half Moon Bay	7:05	17:04	9:59	109	General Photo ID
11/6/2008	N2	Half Moon Bay	7:20	14:36	7:16	76.3	General Photo ID
Surveys-Washigton and Oregon							
1/23/2008	ZIP	Westport	8:30	16:33	8:03	111	
3/5/2008	N1	Westport	11:15	13:35	2:20		
4/1/2008	ZIP	Westport	8:31	16:38	8:07	147	
5/29/2008	N2	Westport	7:39	18:00	11:01	134	
7/2/2008	ZIP	Westport	8:46	18:44	9:30	158	
7/5/2008	ZIP	Sekiu	18:08	22:00	3:52		Humpback entanglement
7/6/2008	ZIP	Sekiu	6:15	11:45	5:30		Humpback entanglement
7/10/2008	ZIP	Sekiu	17:30	21:45	4:15		Humpback entanglement
7/15/2008	Wind Song	Neah Bay	7:30	16:56	9:26		General Photo ID
8/10/2008	ZIP	Westport	7:50	19:40	11:20	133	
9/2/2008	ZIP	Westport	7:55	16:25	8:30	140	
10/15/2008	ZIP	Westport	8:15	16:30	8:15	105	
10/19/2008	ZIP	Depoe Bay	11:45	18:24	6:39	110	General Photo ID

RESULTS

Overall 2008 provided relatively large number of photographic identifications of humpback and blue whales. For humpback whales, 438 unique individuals were identified off California and Oregon, the highest number obtained in any of effort to date (Table 2). An additional 59 animals were identified off Washington but are not included in the abundance estimates since these potentially represent a different feeding area (Calambokidis et al. 1996, 2001, 2004, 2008). A total of 216 unique blue whales were identified along the West Coast from the west coast of Baja to Washington. While this represents a fairly typical year for obtaining blue whale identifications it as well below the record 353 blue whales identified in 2007 when large concentrations occurred both off San Diego early in the summer and in the Santa Barbara Channel in late summer and fall.

Humpback whales

The data from 2008 was used to generate updated mark-recapture estimates of humpback whale abundance off California and Oregon (Table 2). These yielded estimates for 2007-2008 of 2,043 humpback whales, the largest we have obtained to date. While the overall rate of increase since 1991 has generally been around 8% and not unreasonable, the trend just for the last 10 years has both been more erratic and after an apparent drop after 1998 more rapid (Figure 1). Several factors appear to be at work. Even though the population has increased, our sample size each year has remained fairly constant; this has resulted in lower numbers of recaptures between years (lower recapture rates reflect higher abundance estimates) and higher CVs which are largely driven by numbers of recaptures. As the proportion of the population sampled has decreased and resulted in lower recapture rates, the potential influence of biasing factors to the abundance estimates has increased.

One possibility considered was whether any of the high rate of increase in abundance in the last 10 years could be the result of immigration from other areas. This might be expected especially if humpback whale abundances in different regions reach carrying capacity at different times and thereby prompting movement of animals among regions beyond what had been occurring. There was no indication of this movement in the SPLASH inter-regional matches which showed very low rates of interchange between California-Oregon and other feeding areas (Calambokidis et al. 2008). Additionally, we examined the distribution of mtDNA haplotypes by latitude for evidence of animals coming from other areas. Past studies showed a dramatic difference in mtDNA haplotypes between humpback whales that feed off California, dominated by E and F2 haplotypes, and those from SE Alaska which are primarily A- and A+ haplotypes (Baker et al. 1990, 1994, 1998). Much more extensive analyses conducted in recent years especially the SPLASH years of 2004 to 2006 reveal a dramatic latitudinal gradient in the proportions of these haplotypes and still very few animals off California with the haplotype patterns that dominate Northern British Columbia and SE Alaska (Figure 2).

Table 2. Summary of identifications in pairs of adjacent years (n1 and n2) and matches (m) off California and Oregon along with Petersen mark-recapture estimates of abundance and CV.

Year	n1	n2	m	Pop	CV
1990-91	206	269	105	**526**	0.05
1991-92	269	397	188	**568**	0.03
1992-93	397	253	173	**580**	0.03
1993-94	253	244	108	**570**	0.05
1994-95	244	329	100	**799**	0.06
1995-96	329	332	146	**747**	0.05
1996-97	332	268	106	**836**	0.06
1997-98	268	386	120	**859**	0.06
1998-99	386	329	129	**981**	0.06
1999-2000	329	228	108	**692**	0.06
2000-01	228	266	81	**745**	0.07
2001-02	266	313	85	**974**	0.08
2002-03	313	386	92	**1,306**	0.08
2003-04	386	280	79	**1,358**	0.08
2004-05	280	366	67	**1,516**	0.09
2005-06	366	292	88	**1,207**	0.08
2006-07	292	297	54	**1,587**	0.11
2007-08	297	438	63	**2,043**	0.10

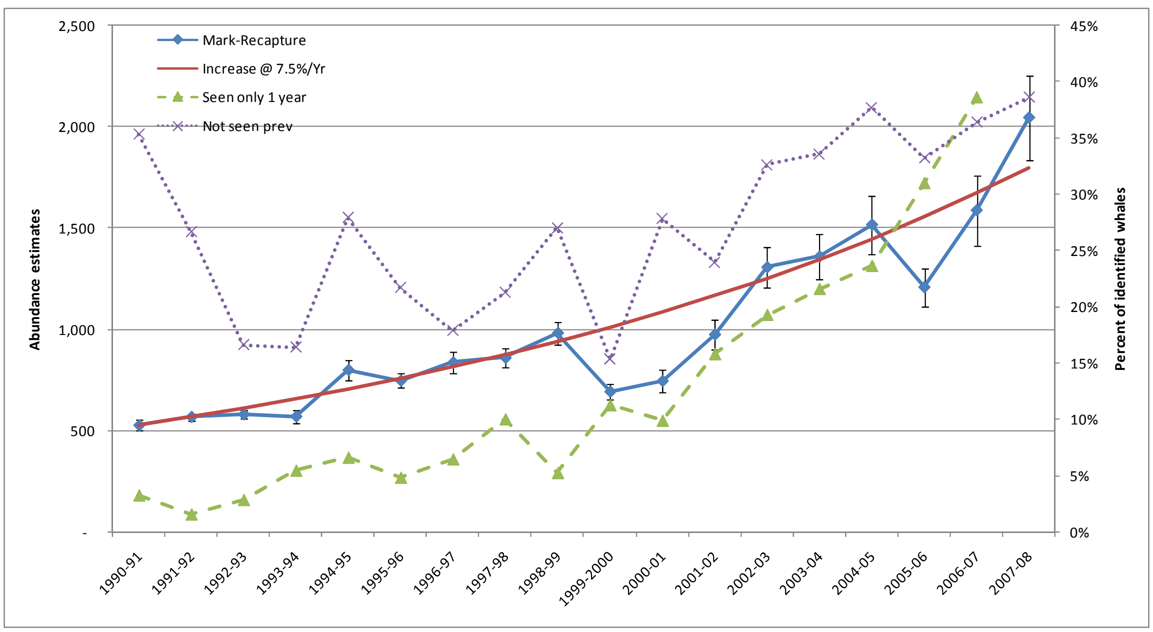

Figure 1. Abundance estimates of humpback whales from mark-recapture off California and Oregon through 2008.

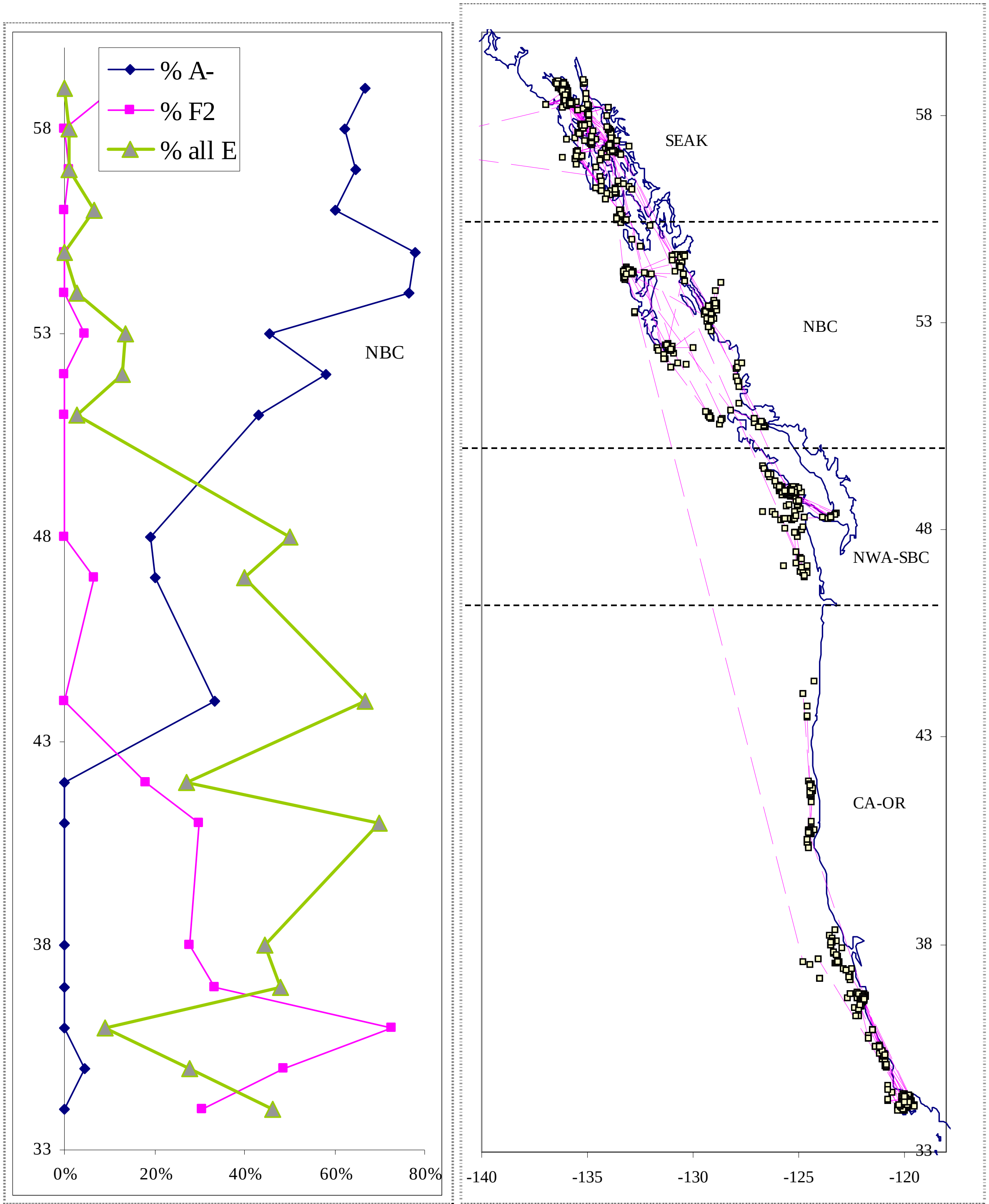

Figure 2. Humpback whale mtDNA haplotype proportions by latitude from California to SE Alaska (data from Baker et al.1990, 1998, unpublished data).

Blue whales

Estimates of blue whales were generated for 2005 to 2008 (Table 3). It was not possible to estimate blue whale abundance from the 2008 systematic surveys alone because of the small sample size obtained in those surveys (15 left side images and 10 right sides). This was due primarily to the relatively low rate of blue whale sightings in the 2008 survey (Barlow 2009).

Blue whale photographic identifications from 2008 including those from systematic surveys were used to improve the most recent abundance estimates that had been based on data through 2006 (including the 2005 CSCAPE surveys) (Calambokidis et al. 2007). The 2005 to 2008 period allowed pooling both the 2005 CSCAPE and 2008 SWFSC surveys for the systematic surveys and the 2005-2008 period for the comparison sample from all other effort (Table 3). This pooled sample yielded a slightly lower estimate (2,497 versus 2,842) with a tighter CV and was more in line with the past estimates than the one based on just IDs from the 2005 CSCAPE surveys (Calambokidis et al 2007). The most recent estimates were still higher than those from 1991 to 2002, suggesting a possible increase in abundance in recent years.

Table 3. Blue whale abundance estimates incorporating the 2008 identifications

Samples	**Left sides**					**Right sides**					**Mean**
	n1	**n2**	**m**	**Est.**	**CV1**	**n1**	**n2**	**m**	**Est.**	**CV1**	
Past estimates											
1991-93	61	293	8	**2,024**	0.29	74	289	10	**1,976**	0.26	**2,000**
1995-97	43	350	7	**1,930**	0.30	34	361	7	**1,583**	0.29	**1,756**
2000-2002	20	452	5	**1,585**	0.32	24	474	5	**1,978**	0.33	**1,781**
2004-2006	35	352	5	**2,117**	0.34	38	365	3	**3,568**	0.42	**2,842**
New estimates using 2005 to 2008											
2005-2008 All Qual	50	548	9	**2,799**	0.27	47	548	11	**2,195**	0.24	**2,497**
2005-2008 Gd Qual Non-Syst	50	264	4	**2,702**	0.38	47	246	4	**2,370**	0.38	**2,536**
2005-2008 Gd Qual Syst	39	548	7	**2,744**	0.30	37	548	6	**2,979**	0.32	**2,862**
2005-2008 only Gd Qual	39	264	3	**2,649**	0.42	37	246	3	**2,346**	0.42	**2,497**

This larger sample size also allowed alternate estimates to be made based only on higher quality photo-IDs to test whether the poorer quality IDs were biasing the estimate by creating missed matches. While estimates using only the higher quality IDs were more variable due to the smaller sample size they were in the same range as the estimates using all photographs indicating there did not appear to be a bias using all photographs (Table 3).

Blue whale identifications from 2008 allowed estimates of overall blue whale abundance from mark-recapture estimates using identifications on wintering areas compared to identifications on summer feeding areas. An expedition to the Costa Rica Dome in January 2008 conducted by Cascadia Research, Oregon State University, and Scripps and sponsored by National Geographic obtained identifications of 65 blue whales on the Costa Rica Dome (Cascadia Research unpublished data). Suction cup tag deployments and observations revealed this area was being used as a feeding area (as well as a winter calving and mating area). Mark-recapture estimates based on one sample from the 2008 Dome expedition and the other sample from West Coast identification in summer and fall 2007 and 2008 yielded much higher abundance estimates than those obtained comparing feeding area samples (Table 4). These results are also higher than those based on identifications from a previous fall/winter expeditions to the Dome in 1999-2000 which yielded estimates much closer to those obtained with the feeding area samples. The high estimates based on the 2008 sample suggests the Dome is used by some blue whales that do not feed off California and the abundance estimate using the Dome is not just for the portion of the population that feeds off the US West Coast.

Table 4. Estimates of blue whale abundance based on Petersen mark-recapture estimates using one sample from the Fall/winter near the Costa Rica Dome and another sample from summer/fall feeding areas off West Baja and California.

Samples	**Left sides**					**Right sides**					**Mean**
	n1	**n2**	**m**	**Est.**	**CV1**	**n1**	**n2**	**m**	**Est.**	**CV1**	
2008 Dome - 2007-2008 West Coast	57	401	2	**7,771**	0.49	62	383	5	**4,031**	0.36	**5,901**
1998-2001 Dome vs West Coast	20	521	3	**2,740**	0.40	20	508	3	**2,671**	0.40	**2,705**

In order to examine trends in abundance of blue whales with larger more consistent samples we conducted inter-year Petersen mark-recapture estimates based on adjacent years samples since 1992 similar to what was conducted with humpback whales (Figure 4). These abundance estimates while useful for examining trends in abundance underestimate true abundance because of heterogeneity of capture probabilities from the coastal bias of these samples making some animals more likely to be consistently recaptured. These estimates do indicate a significant upward trend in abundance of blue whales (linear regression, r^2=.035, p=0.012) although at a rate of under 3% per year. This increase could also be partly or entirely the result of shifts in other factors that might alter the degree of bias in these estimates. Blue whales appear to have shifted aspects of their distribution in the eastern North Pacific in the last 10 years (Calambokidis et al. 2009) and this has resulted in changes in estimated densities of blue whales from line-transect surveys (Barlow 2009, Barlow and Forney 2007, Forney 2007).

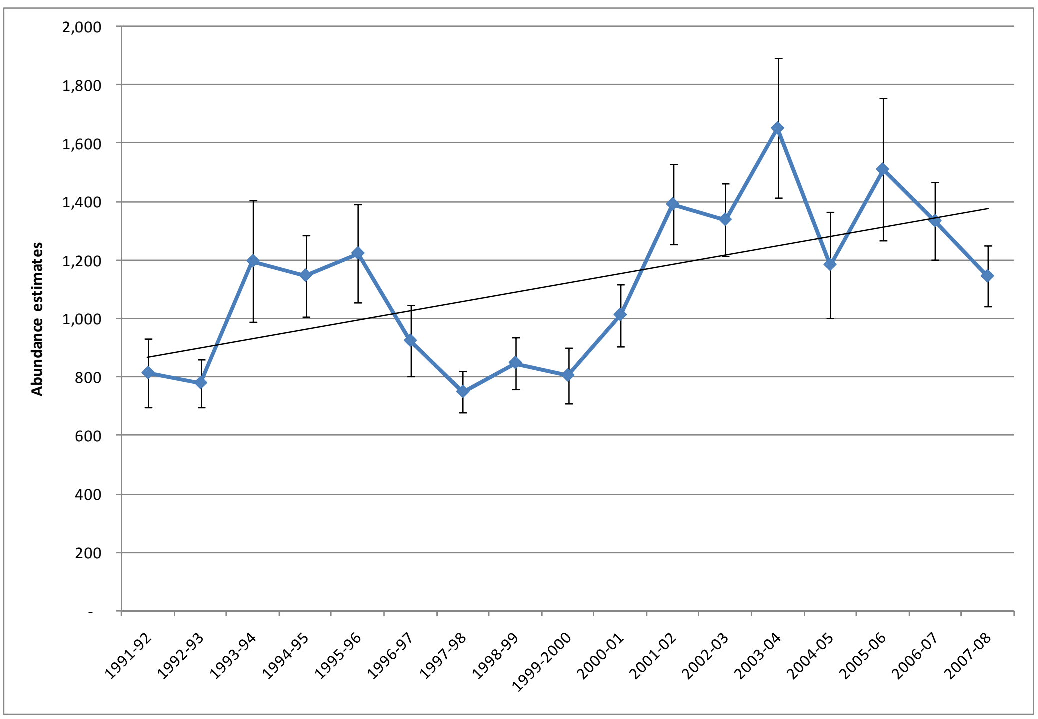

Figure 3. Estimates of blue abundance based on Petersen mark-recapture estimates of photographically identified individuals in adjacent years for west Baja to Washington.

The abundance estimates of blue whales from mark-recapture are very different from those from density estimates based on line transect ship surveys (Forney 2007, Barlow 2009). While these two estimates of abundance showed good agreement with estimates of about 2,000 animals in the 1990s (Calambokidis and Barlow 2004), they now have diverged (Figure 4) with the line-transect estimates for the last three surveys all yielding abundance estimates of under 1,000 with the most recent estimate of 508 for 2008 (Barlow 2009). These methods measure different things and the agreement in the 1990s suggested that most of the population was present in the survey area during the line-transect surveys (Calambokidis and Barlow 2004) and the divergence in recent years appears to be the result of blue whales having shifted to a broader geographic distribution including into areas off British Columbia and in the Gulf of Alaska where they were common during commercial whaling (Calambokidis et al. 2009).

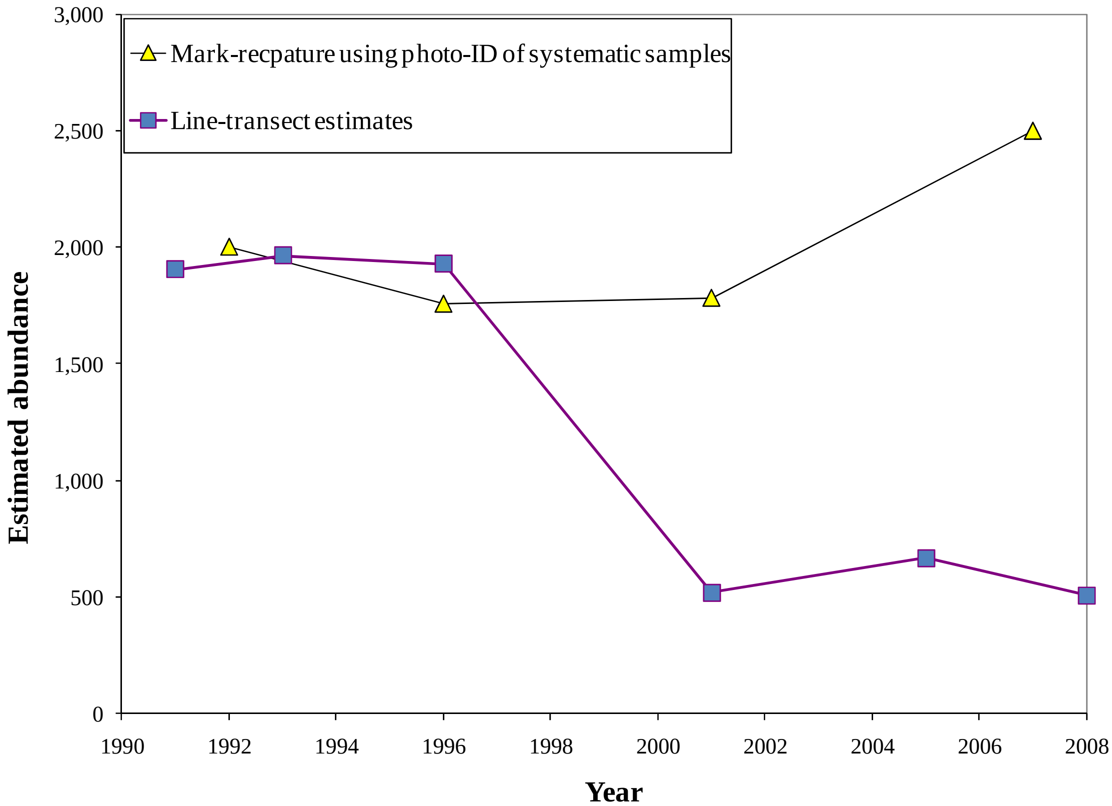

Figure 4. Comparison of abundance estimates from mark-recapture (including this study) and line transect from SWFSC cruises (Barlow and Forney 2007, Forney 2007, Barlow 2009).

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