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ABSTRACT

Abundance of North Pacific sei whales (*Balaenoptera borealis*) was estimated using sighting data obtained during the 2010-2012 International Whaling Commission-Pacific Ocean Whale and Ecosystem Research (IWC-POWER) Cruise, taking into account of comments at last IWC Scientific Committee (IWC/SC) meeting. Sensitivity analyses were also conducted to investigate the robustness of the abundance estimate to alternative detection functions. The abundance in the central and eastern North Pacific (north of 40°N, south of the Alaskan coast including both the US and Canadian EEZs between 170°E-135°W), from July to August was estimated as 27,197 (CV=0.236) for the base case scenario. In the sensitivity analysis using alternative detection function, the abundance estimates is 33,725 (CV=0.281) when Hazard rate model with no covariates was used. The abundance estimate would not be substantially changed by covariate used in the detection function. Abundance information of sei whales based on IWC-POWER cruise data will be useful for the in-depth assessment of this species in the North Pacific that is planned to start this year by the IWC/SC.

INTRODUCTION

Commercial whaling of sei whale (*Balaenoptera borealis*) was conducted in the North Pacific until 1976 when the commercial take of this species was banned by the International Whaling Committee (IWC). The population size of the North Pacific sei whale after the exploitation period was estimated at 9,000 whales (or 21% of the initial size) (IWC, 1977).

In recent years sighting data of sei whales have been collected in the western North Pacific through dedicated Japanese whale sighting surveys, and the sighting component of the Japanese Whale Research Program under Special Permit in the western North Pacific and its second phase (JARPN and JARPN II). Distribution of sei whales based on Japanese Scouting Vessels (JSV), JARPN and JARPN II sighting data was summarized by Miyashita *et al*., (1995), Matsuoka *et al*. (2000; 2009). Sei whale abundance in the western North Pacific (east of Japanese coast, west of 170ºE, north of 35ºN, south of Russian EEZ) based on JARPN II sighting data was estimated at 5,406 whales (CV=0.300) in July and August (Hakamada *et al*., 2009).

The IWC Pacific Ocean Whale Ecosystem Research (IWC-POWER) surveys started in 2010 and have been conducted every year (Matsuoka *et al*., 2011; 2012; 2013; 2014; 2015). Preliminary abundance estimates for sei whales were calculated for each IWC-POWER survey in the period 2010-2012 (Hakamada *et al*., 2011; 2012; Hakamada and Matsuoka, 2013; 2014). There were no primary sightings of sei whales in the 2013 survey and only one primary sighting in the 2014 survey (Matsuoka *et al*., 2014; 2015).

This paper presents the results of abundance estimates of sei whales for the combined data of the period 2010-2012, considering some comments on previous analyses (Hakamada and Matsuoka, 2014) at the IWC/SC meeting last year.

MATERIALS AND METHODS

Survey area

Survey areas for the 2010-2012 IWC-POWER surveys are shown in Figure 1. In 2010, the central North Pacific (north of 40°N, south of Aleutian Islands, between 170°E and 170°W) was surveyed, and the survey area was divided into two strata by the latitudinal line of 47°N. Track line within The US EEZ were surveyed first and then track lines in high sea area were surveyed (Figure 2). In 2011, the eastern North Pacific north of 40°N, south of Alaskan Peninsula, and between 170°W and 150°W was surveyed. The survey area was divided into northern and southern strata by the EEZ line of the USA. In 2012, the eastern North Pacific north of 40°N, south of the Alaskan coast including both the US and Canadian EEZs, between 150°W and 135°W was surveyed. The survey area was divided into northern and southern strata by the EEZ line of the USA and Canada.

Research vessel

The sighting survey was conducted by the research vessel *Kaiko-Maru* (*KK1*) in 2010 and *Yushin-Maru No.3* (*YS3*) in 2011 and 2012. Specifications of *KK1* and *YS3* are provided in Matsuoka *et al*. (2011) and Matsuoka *et al*. (2013), respectively.

Survey design

Cruise tracks were designed using the program DISTANCE (Thomas *et al*., 2010) following the principles outlined in the IWC Scientific Committee's Requirements and Guidelines for Surveys (IWC, 2012). Planned cruise tracks and survey order for 2010-2012 IWC-POWER are shown in Figure 2. Observed distance and angles were corrected using data obtained from the Angle and Distance Experiment.

Survey mode

Closing mode and IO mode were conducted in the 2010 survey. Passing with abeam closing mode was used during the survey in 2011 and the 2012 survey. More details of closing and IO modes are provided in Matsuoka *et al*. (2011), and more details of passing with abeam closing mode are provided in Matsuoka *et al* (2012; 2013). Because the use of passing mode in the IWC-POWER would result in very high proportions of unidentified cetaceans, the POWER technical advisory group (TAG) recommended that Passing with abeam closing mode (NSP) is the most appropriate survey mode, both with respect to confirming species identity and school size (IWC, 2013). Sighting and effort data in both survey modes were pooled for abundance estimation because of the limited sample size as in the case of IDCR/SOWER based abundance estimation for large baleen whales (Branch and Butterworth, 2001; Branch, 2011). Duplicate sightings in IO mode are excluded from the analysis.

Data used

Analyses in this paper are based on sighting data obtained during the POWER surveys during 2010-2012. Data validation by the IWC Secretariat was completed for the data obtained in 2010 and 2011 but the validation work has not been completed for the 2012 data. In this analysis, data that were not validated by IWC Secretariat was used.

Analytical procedure

For this analysis it is assumed that g(0)=1. Detections are truncated at 3.0 n.miles. Abundance and its CV were estimated based on a Horvitz-Thompson like estimator of abundance expressed by formula (1) and (2), respectively.

$$
\begin{aligned}
P &= \frac{A}{2WL}\sum_{i=1}^{n}\frac{s_i}{p_i(z_i)} \\
&= \frac{A}{2L}\sum_{i=1}^{n} s_i \hat{f}(0 \mid \mathbf{z}_i) \qquad (1)
\end{aligned}
$$

where P is abundance estimate, A is area size of the surveyed area, W is truncation distance (3.0 n.miles), L is searching effort, n is the number of schools detected within perpendicular distance of W, s_i is school size of ith detection, $p_i(z_i)$ is the probability that school i is detected given that it is within the perpendicular distance W and given the covariate z_i. $f(0|z_i)$ is conditional probability density function of distance 0 given covariates z_i

$$\mathrm{var}(P) = \left(\frac{A}{2WL}\right)^2 \left\{ \frac{1}{L(K-1)} \sum_{k=1}^{K} l_k \left(\frac{P_{Ck}}{l_k} - \frac{P_C}{L} \right)^2 + \sum_{j=1}^{r} \sum_{m=1}^{r} \frac{\partial P_C}{\partial \theta_j} \frac{\partial P_C}{\partial \theta_m} H_{jm}^{-1}(\theta) \right\} \quad (2)$$

where K is the number of transect, l_k is searching distance in kth transect, P_{Ck} is abundance estimate in covered region (within 3 n.miles from track line surveyed) in kth transect, P_C is abundance estimate in the covered region, $H_{jm}^{-1}(\theta)$ is the jmth element of inverse of Hessian matrix of detection function for covariate θ.

Multiple Covariate Distance Sampling (MCDS) Engine in DISTANCE program was used (Thomas *et al.*, 2010). Given discussions at the IA sub-committee on detection function (IWC, 2015), we reconsider and refit Half Normal and Hazard Rate models as candidate models for the detection function. Full model of the detection function was provided by

$$g(x) = 1 - \exp\left\{ -\left(x \big/ a\exp(Size + Beaufort + Year) \right)^{-b} \right\} \quad (3)$$

$$g(x) = \exp\left[-x^2 \big/ 2a^2 \exp\{2(Size + Beaufort + Year)\} \right] \quad (4)$$

where x is perpendicular distance, a and b ($b \geqq 1$) are parameter, *Size* is observed school size, *Beaufort* is categorical variable for Beaufort sea state (good: 0-3, bad: 4-5) and *Year* is categorical variable for year.

AIC was used to select the best model to estimate detection probability of $1/Wf(0|z_i)$.

Smearing was not conducted on running MCDS because MCDS doesn't deal with smearing. Perpendicular distance was not binned on fitting detection function because selection of cut point could affect results of model selection and coefficient estimates of detection function different from previous analysis.

Mean school size is estimated from the primary sightings whose school size was confirmed.

Sensitivity Analysis
How the selection of detection function affects the abundance estimate was examined. Abundance estimates were compared among the detection function examined in this analysis.

RESULTS

Searching effort and primary sightings
Searching effort and primary sightings for each stratum are summarized in Table 1. Searching effort was 1816.2, 2397.8 and 2126.1 in 2010, 2011 and 2012, respectively. Survey coverage for each stratum during the 2010-2012 IWC-POWER surveys is shown in Table 2. Coverage is lower in the northern strata in 2010 and 2011 due to poor weather conditions in those years (Matsuoka *et al.*, 2011; 2012). In the southern strata, coverage is good due to good weather conditions (Matsuoka *et al.*, 2011; 2012; 2013). The truncated numbers of sightings are 49, 37 and 76 in 2010, 2011 and 2012, respectively. Figure 3 shows the plot of track lines actually surveyed and the position of sei whale primary sightings during the 2010- 2012 IWC-POWER surveys. Most of the primary sightings occurred in the southern strata.

Model selection of detection function
Table 3 gives AIC for each candidate model. Among the models, the Half normal model with no covariates was selected to estimate the detection probability for the base case in this study. Table 4 shows estimate of

coefficient for detection function selected by AIC. Table 5 shows that the averaged detection probability was 0.633 (CV=0.067). Figure 4 shows the detection function and observed frequency of detection. The Chi-square statistic is 17.534 with 11 degrees of freedom (*p*=0.093). Figure 5 shows QQ plot of the detection function that suggests that the residuals are almost normally distributed.

Abundance estimate
Table 1 shows abundance estimates in each stratum for the base case. Correlation among abundance estimates by strata are shown Table 6. The total abundance estimate was 27,197 (CV=0.236) for the base case.

Sensitivity analysis
Table 7 compares abundance estimates and their CVs for each detection function examined. This table suggests that the abundance estimate is not substantially different due to the selection of covariates. The abundance estimate would be different depending on the model used (Hazard rate model or Half normal model).

Table 8 shows parameters estimated for Hazard rate with no covariates. Shape parameter *b* was estimated at the lower bound of the range for the parameter. This probably causes lower precision in the abundance estimate based on the Hazard rate model than that based on the Half normal model. Table 9 shows that the estimated average detection probability was 0.511 with CV=0.166. The estimate is lower and precision is worse than the base case. Chi-square statistic is 14.194 with 10 degrees of freedom (*p*=0.164) and the fit is similar to the base case. Figure 5 shows QQ plot of the detection function that suggests that the residuals are almost normally distributed.

Total abundance estimate is 33,725 with CV=0.281 (Table 10). Abundance estimate is larger than the base case and its CV is higher than the base case.

DISCUSSIONS

Distribution of sei whale
There were few sightings in the northern strata during the 2010-2012 surveys. This may be similar to the case of few sightings of the sei whales in the coastal area of the USA and Canada recently (Barlow and Forney, 2007; Zerbini *et al*., 2006; Williams and Thomas, 2007). Commercial catch of sei whales were distributed the coastal areas (Kanda *et al*., 2015). The reason for the apparent change in distribution should be investigated in the future.

Covariates of detection function
It was discussed that the weather conditions were more favourable on average in 2012 than in the previous surveys (waters in the Gulf of Alaska tend to be calmer than the waters to the west) which might be a factor influencing the differences in the shapes of the annual detection functions (IWC, 2015) at the IWC/SC meeting last year. Taking this into account, it was investigated whether detection function could be different among the year. Table 2 suggests that detection functions that allows detectability could different among years were not the best model by AIC. Using detection function with year as a covariate, abundance estimates were not substantially different from that using detection function with no covariate (Table 6).

Averaged abundance
Difference in AIC estimate is about 1 between Hazard rate model with no covariates and Half normal model with no covariates (i.e. the best model). This suggests that the Hazard rate model with no covariates is also a good model, though it is not the best model. The fit of both detection functions is similar from the Chi-square statistics. Average of the two abundance estimate could be used alternative scenario for abundance estimation in in-depth assessment of this species. The average of the two abundance estimates by Akaike weights (Buckland et al., 1997; Burnham and Anderson, 2002) is 29,632 and its CV is 0.242.

Abundance estimate for North Pacific sei whales incluing outside of POWER research area.
The abundance estimate in the IWC-POWER research area was 27,197 (CV=0.236). Sei whale abundance estimate in the western North Pacific (east of Japanese coast, west of 170°E, north of 35°N, south of Russian

EEZ) based on JARPN II data was 5,406 (CV=0.300) in July and August (Hakamada *et al*., 2009). The abundance estimate for sei whales will be updated using data obtained during 2008-2013 JARPN II surveys.

Estimation of stock abundance requires information on stock structure and distribution. Kanda *et al*. (2009; 2011; 2013) suggested that the open water area of the North Pacific was mainly occupied by individuals from a single stock of sei whales. Murase *et al*. (2009; 2013) suggested that distribution of the sei whales predicted by a generalized additive model (GAM) is continuous in the southern part of the survey area during 2010-2012 IWC-POWER.

Under these assumptions and the assumption that there are no correlations among the estimates, the combined abundance estimates for the JARPN II and IWC-POWER research areas in July-August was 32,603 (CV=0.203).

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Table 1. Abundance estimates for the sei whales and their CV's for each stratum based on 2010-2012 IWC-POWER cruises from July to August for base case. A is area size of the surveyed area, n_s and n_w are the number of schools detected and the number of individuals detected within perpendicular distance of 3.0 n.miles, l is searching distance, P is abundance estimate and CI is abbreviation for confidence interval.

Year	Stratum	Period	A	L	n_s	n_w	n_w/L	CV(n_w/L)	***P***	CV(P)	95%LL	95%UL
2010	Northern	7/8-16, 8/1-3,20	238,627	490.5	4	4	0.008	0.502	**512**	0.507	185	1,415
	Southern	7/18-8/1, 8/3-25	365,244	1,325.7	45	84	0.063	0.441	**6,093**	0.446	2,520	14,733
2011	Northern	7/22-8/1	193,560	723.8	0	0	-	-	**0**	-	-	-
	Southern	8/2-8/31	569,167	1,674.0	37	72	0.043	0.452	**6,445**	0.457	1,066	38,985
2012	Northern	7/24-8/3	142,427	767.5	2	4	0.005	0.751	**195**	0.754	45	853
	Southern	8/3-8/30	529,362	1,358.6	74	136	0.100	0.337	**13,952**	0.343	6,927	28,099
Total	-	-	2,038,387	6,340.0	162	300	0.047	0.230	**27,197**	0.236	16,841	43,923

Table 2. Survey coverage for each stratum during the 2010-2012 IWC-POWER surveys.

Survey year	Northern	Southern
2010	34%	70%
2011	58%	78%
2012	80%	85%

Table 3. AIC estimate for each model of detection functions for base case. For selected model, AIC is indicated by bold letters. HR: Hazard Rate and HN: Half Normal.

Model	HR	HN
School size+Beaufort+Year	327.7	326.9
School size+Beaufort	327.8	327.5
School size+Year	328.1	327.4
Beaufort+Year	327.7	326.5
School size	327.5	326.7
Beaufort	327.6	327.2
Year	327.7	326.5
No covariate	326.9	**325.9**

Table 4. Parameter estimate for detection function selected by AIC.

Parameter	Estimate	SE
a	1.619	0.152

Table 5. Estimate of average p_i=1/W $\hat{f}(0\,|\,\mathbf{z}_i)$, its standard error (SE) and its CV.

	Estimate	SE	CV
Average p	0.633	0.043	0.067

Table 6. Correlation matrix for abundance estimates by strata.

	2010N	2010S	2011S	2012N	2012S
2010N	1.000	0.020	0.020	0.012	0.026
2010S	0.020	1.000	0.022	0.014	0.030
2011S	0.020	0.022	1.000	0.013	0.029
2012N	0.012	0.014	0.013	1.000	0.018
2012S	0.026	0.030	0.029	0.018	1.000

Table 7. Sensitivity of abundance estimate for sei whales applying different detection functions

Model	Covariates	P	CV(P)	Model	Covariates	P	CV(P)
Hazard Rate	S+B+Y	**32,264**	0.262	Half Normal	S+B+Y	**26,145**	0.225
	S+B	**31,471**	0.265		S+B	**25,921**	0.229
	S+Y	**30,652**	0.262		S+Y	**25,907**	0.230
	B+Y	**35,647**	0.287		B+Y	**27,287**	0.230
	S	**31,146**	0.266		S	**25,943**	0.234
	B	**34,878**	0.282		B	**27,381**	0.234
	Y	**33,454**	0.283		Y	**27,024**	0.234
	None	**33,725**	0.281		None	**27,197**	0.236

Table 8. Parameter estimate for detection function of Hazard rate model with no covariates. Parameter *b* estimate is at the lower bound of the range for *b*.

Parameter	Estimate	SE
a	0.835	0.342
*b**	1.000	0.312

Table 9. Estimate of average p_i=1/W $\hat{f}(0 \mid \mathbf{z}_i)$, its standard error (SE) and its CV for Hazard rate with no covariate.

	Estimate	SE	CV
Average *p*	0.511	0.085	0.166

Table 10. The abundance estimates for the sei whales and their CV's for using Hazard rate detection function with no covariate. The Notations are as for Table 1.

Year	Stratum	Period	A	L	n_s	n_w	n_w/L	CV(n_w/L)	P	CV(P)	95%LL	95%UL
2010	Northern	7/8-16, 8/1-3,20	238,627	490.5	4	4	0.008	0.502	**635**	0.529	224	1,801
	Southern	7/18-8/1, 8/3-25	365,244	1,325.7	45	84	0.063	0.441	**7,555**	0.471	3,018	18,915
2011	Northern	7/22-8/1	193,560	723.8	0	0	-	-	**0**	-	-	-
	Southern	8/2-8/31	569,167	1,674.0	37	72	0.043	0.452	**7,992**	0.482	1,613	39,589
2012	Northern	7/24-8/3	142,427	767.5	2	4	0.005	0.751	**242**	0.769	55	1,069
	Southern	8/3-8/30	529,362	1,358.6	74	136	0.100	0.337	**17,300**	0.375	8,205	36,477
Total	-	-	2,038,387	6,340.0	162	300	0.047	0.230	**33,725**	0.281	19,395	58,644

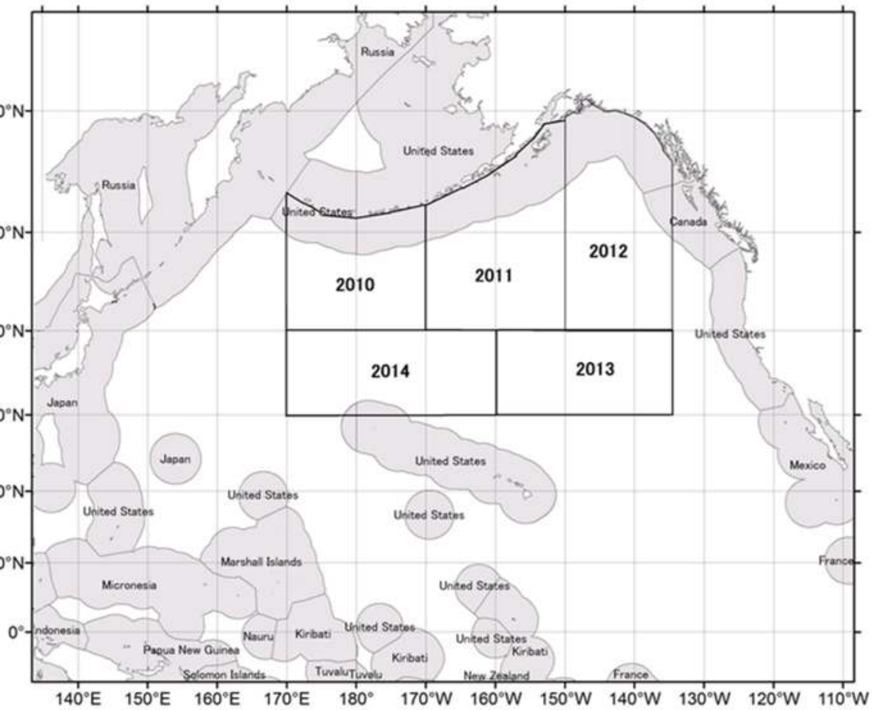

Figure 1. Survey area for 2010-2014 IWC-POWER surveys. Data for 2010-2012 IWC-POWER surveys were analyzed because there were no primary sightings of sei whales in the 2013 survey and only one primary sighting of the sei whales in the 2014 survey.

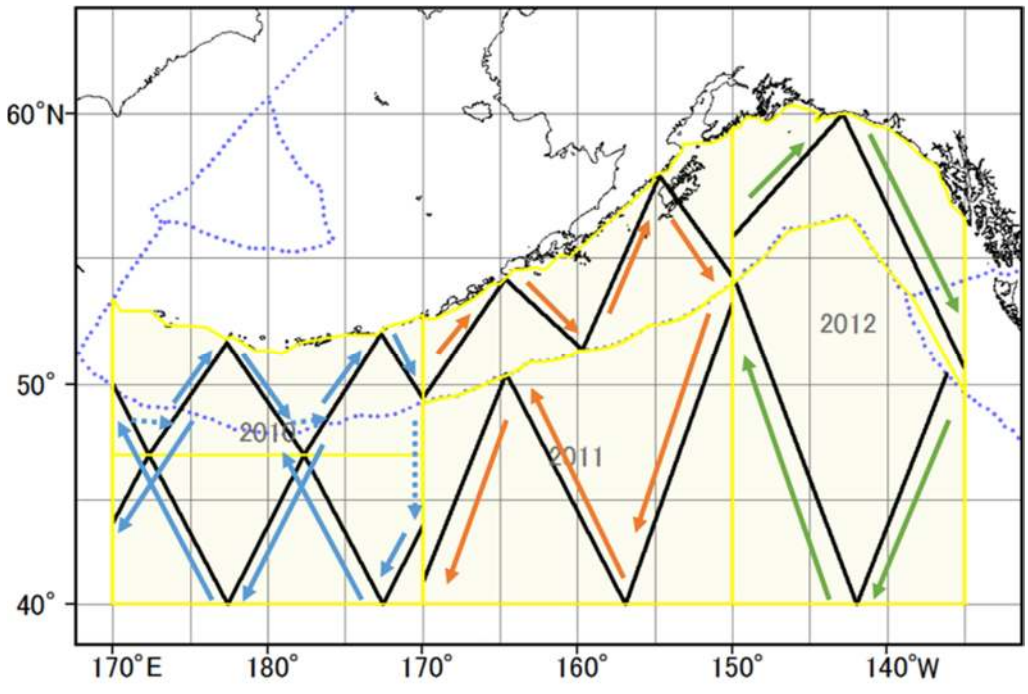

Figure2. Planned track line for 2010-2012 IWC-POWER surveys (bold black lines). Arrows show survey order in 2010 (light blue), 2011 (orange) and 2012 (yellow green), respectively. Yellow lines represent boundary for survey strata. Areas in EEZs were surveyed first then areas in high seas were surveyed. Dotted light blue arrow indicates transit. Blue dotted lines indicate boundary for Foreign Economic Exclusive Zones (EEZs). Yellow zone indicate survey areas.

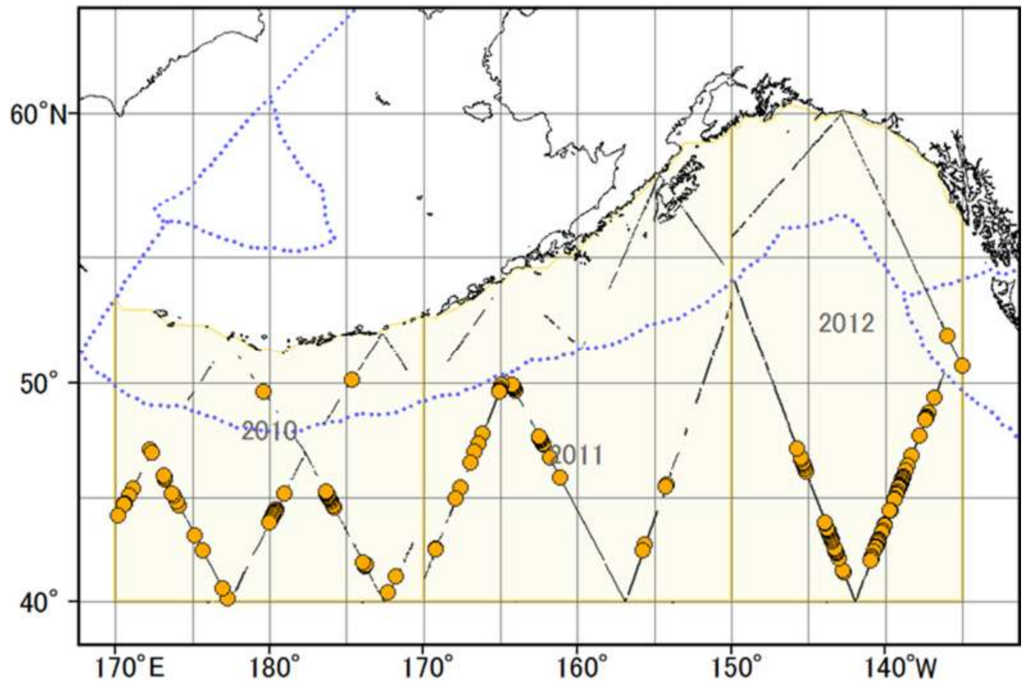

Figure 3. Plot of actually surveyed track line (black lines) and position of primary sightings of the sei whales (orange circles) during 2010-2012 IWC-POWER surveys.

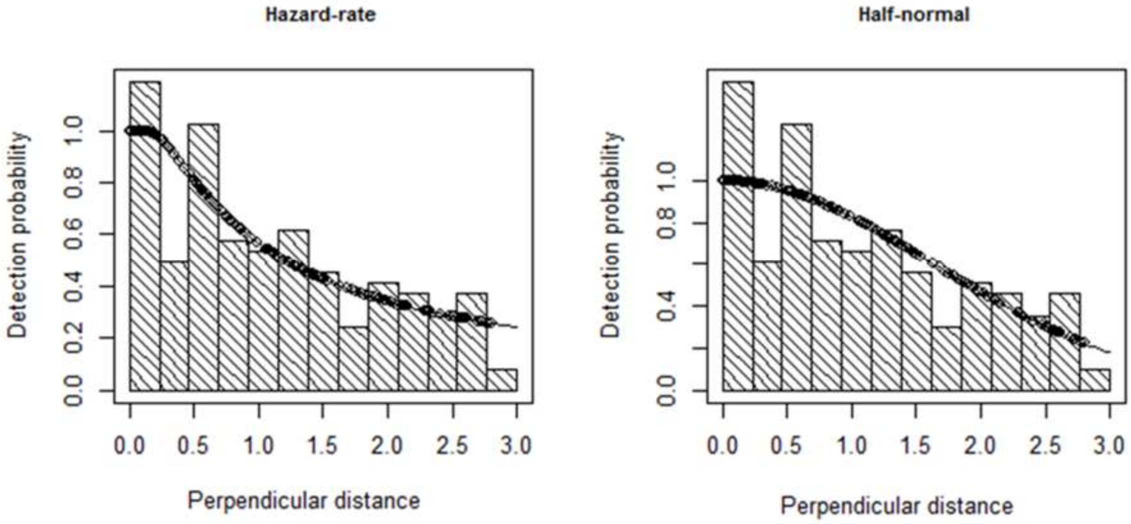

Figure 4. Plot of the estimated detection function fitted to the number of schools as a function of perpendicular distance (n. miles) from the track line for base case (left panel) and sensitivity (right panel).

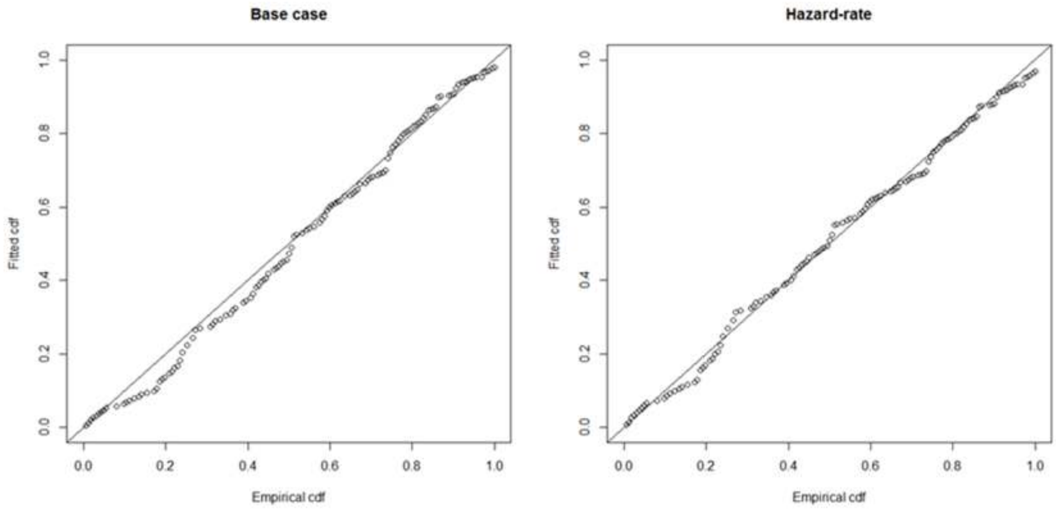

Figure 5. QQ plot of detection functions for the Half normal model with no covariates (Base case, left panel) and Hazard rate model with no covariates (right panel).