Testing the Gray Whale *SLA*: allowing environmental variability to influence population dynamics

JOHN R. BRANDON AND ANDRÉ E. PUNT

School of Aquatic and Fisheries Sciences, Box 35020, University of Washington, Seattle, WA 98195-5020, USA
Contact e-mail: jbrandon@u.washington.edu

ABSTRACT

The performance of the gray whale *SLA* was evaluated based on an operating model which was conditioned on available information, including survey estimates of 1+ abundance, calf counts, strandings data, and the extent of sea-ice in the early season feeding grounds in the Bering Sea. The scenarios considered in the analyses explore the impact of different sources of environmental variation, including scenarios in which future environmental forcing and episodic events are driven by the relationship between extent of sea-ice and reproductive success and survival. A variety of sources of uncertainty are considered, including parameter uncertainty, the uncertainty about the relationship between the extent of sea-ice and population dynamics, and observation error. The impact of these sources of uncertainty on the performance of the *Gray Whale SLA* appears small.

KEYWORDS: BIRTH RATE; GRAY WHALE; ICE; MANAGEMENT PROCEDURE; MODELLING; NORTHERN HEMISPHERE; WHALING – ABORIGINAL

INTRODUCTION

The eastern North Pacific (ENP) stock of gray whales is currently subject to aboriginal hunting, with recommended strike limits based on the *Gray Whale Strike Limit Algorithm* (*SLA*) under the Aboriginal Subsistence Whaling Management Procedure (AWMP) of the IWC (IWC, 2003). *Implementation Reviews* are scheduled under the AWMP every five years, and that for the gray whale *SLA* is currently due. The goal of *Implementation Reviews* is to evaluate new information that has become available since the last *Implementation Review* (or the original *Implementation*) and to determine whether the current state of nature is not outside the realm of plausibility envisioned during the testing of the original *SLA*. If this is the case, additional simulation trials may be conducted to assess whether the performance of the adopted *SLA* remains reasonable, and if not, what changes to the *SLA* are needed.

New or updated sources of information pertaining to the population dynamics of ENP gray whales have become available in recent years and need to be considered during this *Implementation Review*, including: (1) new abundance estimates (Rugh *et al.*, 2008); (2) new estimates of calf production during 1994-2008 from the northbound migration at Point Piedras Blancas, California (Perryman *et al.*, 2002; Perryman, *unpublished data*), and; (3) the number of stranded animals on the coasts of California, Oregon and Washington states, for which a combined annual count is available for 1975-2006 (Brownell Jr. *et al.*, 2007). The latter potentially contains information on the magnitude of the mortality event during 1999/2000 (Gulland *et al.*, 2005). In addition to these data sets, it has been hypothesized that observed variability in the calf counts is a function of the amount of sea-ice covering the early season feeding grounds (Perryman *et al*., 2002).

Therefore, in this paper we test the performance of the *SLA* given scenarios for which future population dynamics are subject to environmental forcing and episodic events, using an operating model that integrates these sources of new information and the hypothesis of environmental forcing on the population dynamics (Brandon and Punt, 2009). A forecast of relevant sea-ice conditions based on global climate model output (Overland and Wang, 2007) is used to modify the future stochastic birth and survival rates when testing the *SLA*, given the estimated relationship between observed variations in recent sea-ice (Rayner *et al.*, 2003) and calf and strandings data. This approach involves the incorporation of climate-model based forecasts into the operating model; the same basic approach is also is being used to test the performance of alternative management strategies in other fisheries (e.g., Gulf of Alaska walleye Pollock, *Theragra chalcogramma*; A'mar *et al.*, *In Press*).

Standard summary statistics are provided for the trials investigated here, and these are compared to recent results from the *Evaluation Trials* provided by Punt and Breiwick (2008) to the extent possible. The analyses presented here should help to ensure that the performance of the current *SLA* remains satisfactory (or else provide insight into potential weaknesses), given the new information that has become available since the previous phase of testing and adoption (IWC, 2005).

METHODS

Operating Model

The population dynamics model developed by Brandon and Punt (2009) (corresponding with their 'Full' scenario) was used as the operating model. This model is sex- and age-based, with an annual time-step. The dynamics includes stochastic birth and survival rates, and explicitly considers the transition between receptive and calving stages for mature females (Fig. 1). For consistency, the notation of Brandon and Punt (2009) is adopted below.

Density dependence was assumed to act through the birth rate according to a Pella-Tomlinson function of 1+ depletion:

$$b_t = \max\left\{0,\ b_{\text{eq}} + (b_{\max} - b_{\text{eq}})\left[1 - \left(\frac{N_{1+,t}}{K_{1+}}\right)^z\right]\right\} \tag{1}$$

where:

$b_{\max}$ is the maximum birth rate (in the limit of zero population size);

K_{1+} is the carrying capacity of the 1+ component of the population (all animals aged 1 yr and older);

b_{eq} is the equilibrium birth rate at carrying capacity;

z is the degree of density-dependent compensation (assumed to equal 2.39, which implies maximum sustainable yield at a population size approximately 60% of K_{1+}), and;

$N_{1+,t}$ is the size of the 1+ component of the population (both sexes combined) in year *t*.

Selectivity was assumed to be knife-edged and uniform on ages 5+, and the population trajectories were initialized in 1930 (Brandon and Punt, 2009).

The operating model was conditioned on available data, including: (1) estimates of population size during 1967-2006 (starting year of survey) from the southbound migration at Granite Canyon, California (Rugh *et al.*, 2005, 2008); (2) estimates of calf production during 1994-2008[1] from the northbound migration at Point Piedras Blancas, California (Perryman *et al.*, 2002; Perryman, *unpublished data*), (3) the number of stranded animals on the coasts of California, Oregon and Washington states, for which a combined annual count is available for 1975-2006 (Brownell Jr. *et al.*, 2007)[2], and; (4) estimated sea-ice area covering the Bering Sea, averaged over March and April during 1953-2008, as calculated by the Hadley Center for their sea ice and sea surface temperature data set version 1 ('HadSST') (Rayner *et al.*, 2003) (Fig. 2, left panel).

Deviations from expected birth and survival rates were allowed to be a function of sea-ice variability in the Bering Sea. Thus, the model is an adaptation of the hypothesis that the amount of sea-ice in the Bering Sea early during the feeding season may be related to variability in calf production the following year (Perryman *et al.*, 2002).

Future Projections

The population was projected forward from the start of 2009. Values for the environmental index were based on an ensemble mean forecast of future sea-ice in the Bering Sea (March-April average) (Overland and Wang, 2007). The trials were based on a 92-year time horizon (T=92), because the time series of forecasted sea-ice was only available through 2098. Each simulated trajectory was based on a set of parameter values $\underline{\theta}_i$ (e.g., K_{1+}, $b_{\max}$ etc…) sampled from the joint Bayesian posterior distribution constructed using the MCMC algorithm (Brandon and Punt, 2009). In a given year, the process error residuals about the expected birth and survival rates were:

$$\varepsilon_t = \left(I_t^{obs} / \beta\right) - \gamma_t \tag{2}$$

where:

I_t^{obs} is the forecasted value of the environmental index for year t (Fig. 2, left panel);

β is a scaling parameter that accounts for the influence of the environment on the process error residuals (sampled from the joint posterior);

γ_t is a generated normal random deviate reflecting error about the sea-ice – process error relationship, such that $\gamma_t \sim N(0;\sigma_I^2)$, and;

σ_I is the standard deviation of the residual error for the environmental index:

$$\sigma_I = |\beta|\,\sigma_I^* \tag{3}$$

This formulation takes a fixed input value for σ_I^* (assumed to be 0.30 for these analyses, corresponding with the 'Full' model of Brandon and Punt (2009)) and scales the

[1] The two early estimates of calf production during 1980-1981 (Poole, 1984) were not used in these analyses.

[2] Data on strandings are collected in other locations (e.g. Mexico and Alaska), but the stranding network effort in California, Oregon and Washington has been more consistent through the years.

expected standard deviation of the fits to the environmental index by the absolute value sampled from the posterior distribution for *β*.

Stochastic birth and survival rates

The stochastic survival and birth rates were calculated given the generated process errors for each year. Birth rates were assumed to vary annually about the deterministic value given by Eqn. 1. Since this rate must lie between zero and one, its realization in any one year was calculated using a logistic transformation:

$$b_t^* = \left[1 + \exp(-(\Phi^{-1}\left(b_t\right)\sqrt{2.76 + \sigma_\varepsilon^2} + \varepsilon_t + \varepsilon_{\text{add-1},t}))\right]^{-1} \tag{4}$$

where:

Φ^{-1} is the inverse standard normal cumulative distribution function;

ε_t is the process error deviation for year *t*, and;

$\varepsilon_{add-1,t}$ allows for additional process error in the birth rate during years with extraordinary dynamics, such as 1999 and 2000 (in other years, this parameter was set equal to zero).

This formulation of stochastic birth rates ensured that the expected birth rate in a given year was equal to the deterministic value from Eqn. 1.

Survival rates were also allowed to vary annually with the same process error residuals as birth rates. It was assumed that these rates were independent of sex and perfectly correlated between ages in a given year, so that:

$$S_{a,t}^* = \left[1 + \exp(-(\Phi^{-1}\left(S_a\right)\sqrt{2.76 + \sigma_\varepsilon^2} + \varepsilon_t + \varepsilon_{add-2,t}))\right]^{-1} \tag{5}$$

where:

$S_{a,t}^*$ is the realized age-specific survival rate during year *t*;

S_a is the expected survival rate from age *a* to age *a*+1; and

$\varepsilon_{add-2,t}$ is a parameter which allows for additional process error in survival rates during years with extraordinary dynamics, such as 1999 and 2000 (in other years, this parameter was set equal to zero).

For these analyses, the additional process error in survival rates was assumed to be equal to that for birth rates (i.e., $\varepsilon_{add-1,t} = \varepsilon_{add-2,t} = \varepsilon_{add,t}$)

Data Generation

Future abundance estimates were assumed to become available every 10 years. Observation error was assumed to be log-normal:

$$N_{1+,t}^{\text{obs}} = N_{1+,t}\, e^{\phi_t} \tag{6}$$

where:

$N^{\text{obs}}_{1+,t}$ is the survey estimate of 1+ abundance for year t;

$N_{1+,t}$ is the 'true' 1+ abundance at the start of year t;

ϕ_t is a normal random deviate ~N(0, σ^2); where $\sigma = \sqrt{\overline{CV}^2_{est} + CV^2_{\text{add-1}}}$;

$CV_{\text{add-1}}$ is the extent of additional error about the abundance estimates (sampled from the joint posterior), and;

$\overline{CV}_{est}$ is the expected (sampling) standard deviation of the logarithm of $N^{\text{obs}}_{1+,t}$:

$$\overline{CV}_{est} = \sqrt{\frac{1}{Y}\sum_{y=1}^{Y} CV^2_{\text{y}}}, \tag{7}$$

where:

y indexes years for which there are survey data up to 2008, and;

Y is the total number of such years.

The estimates of abundance and $\overline{CV}_{est}$ (as opposed to σ) were passed to the *SLA*. No attempt was made to account for further estimation error in the abundance estimates (i.e., mean school size estimation error calculations were ignored).

Need

The annual need Q_t for year t was calculated according to the 'need envelope':

$$Q_t = Q_{2009} + \frac{t-2009}{91}\left(Q_{2098} - Q_{2009}\right) \tag{8}$$

where:

Q_{2009} (=150) is the present need, and;

Q_{2098} is the final need (in year 2098).

The level of need supplied to the *SLA* was the total (block) need for the 5-year period for which the strike limits were to be set. Two values were assumed for final need (in yr. 2098), corresponding with the 'base case' (Q_{2098}=340) and 'high need' (Q_{2098}=530) trial levels used in previous testing of the *SLA* (IWC, 2003).

Trials

The set of trials is listed in Table 1. In addition to the two levels of final need, six scenarios were explored with respect to the future probability (if any) of catastrophic (otherwise known as 'episodic') events and the nature of stochastic (or deterministic) population dynamics: (H0) Deterministic population dynamics with no future catastrophic events[3]; (H1) Environmental stochasticity (as a function of sea-ice) with no future catastrophic events; (H2) Environmental stochasticity (as a function of sea-ice)

[3] The two deterministic trials are most comparable with the base-case operating models in IWC (2004).

with probability of future catastrophic events conditioned on the stranding index (corresponding to the percentage of catastrophic years[4] during the time series of stranding counts); (H3) Environmental stochasticity (as a function of sea-ice) with the probability of future catastrophic events p^* conditioned on the percentage of times they occurred during the fitting process when 1+ depletion was greater than 0.40 (Eqn. 9; Fig. 2 right); (H4) As for H3, but the environmental stochasticity was independent of the sea-ice index, i.e. simply $\varepsilon_t \sim N\left(0,\sigma_\varepsilon^2\right)$, and; (H5) As per H4 but with no future catastrophes.

A depletion of 0.4 represents a level which encompasses the full range of trajectories from the posterior (i.e., a small number of those trajectories were estimated to have never recovered to more than 50% of carrying capacity, when carrying capacity was estimated to have been around 50,000 individuals). The probability of future catastrophes p^* conditioned on the percentage of times they occurred during the fitting process when 1+ depletion was greater than 0.40 was then:

$$p^* = 2\left[\left(\sum_{t=1930}^{2008} I(N_{1+,t} / K > 0)\right)^{-1}\right] \qquad (9)$$

where:
$I()$ is the indicator function.

Performance Statistics
The performance statistics were calculated based on future block quotas returned from the standalone version of the 'GUP2' *SLA* (Punt and Breiwick, 2008). All performance statistics were computed in terms of the 1+ component of the population following the standard methods and notation of the AWMP (IWC, 2003). Specifically, four performance statistics were calculated:

1. (D1) Final depletion: $N_{1+,2098}/K_{1+}$;
2. (D8) Rescaled final population size: $N_{1+,2098}/N^*_{1+,2098}$;

where:
$N^*_{1+,2098}$ is the 1+ population size in the final year *T*, under a scenario of zero future catches.

3. (D10) Relative increase: $N_{1+,2098}/N_{1+,2009}$, and;
4. (N9) Average need satisfaction: $\frac{1}{T}\sum_{t=2009}^{2098}\frac{C_t}{Q_t}$.

where:
C_t is the catch during year *t*, which is determined by the *SLA* through the 5-year block quota system.

[4] The 2 years (1999 and 2000) during the unusual mortality event were considered to be catastrophic.

RESULTS

1601 simulations were run for each scenario, corresponding to the number of samples from the posterior provided by Brandon and Punt (2009). In general, the gray whale *SLA* was able to satisfy need and maintain a population size near carrying capacity for each of scenarios examined in these analyses. For example, all of the scenarios with base need had an average need satisfaction of 100% and the lowest median final 1+ depletion was 0.874 (Table 2). Not surprisingly, those scenarios with higher final need resulted in lower final depletion levels and lower average need satisfaction. However, the differences were not very large (e.g., the lowest median 1+ depletion for the high need scenarios was 0.817). Moreover, none of the scenarios resulted in a lower 5th percentile for the final 1+ depletion less than 0.60. The relative increase statistic (D10) was close to 1 for all scenarios, which indicates stability in the population dynamics. This is, however, not unexpected given the results of Brandon and Punt (2009) which suggest that this population is close to carrying capacity at present.

The annual probability of future catastrophes for the two 'H2' scenarios was 0.0625, as determined by the number of years for which an episodic event was observed, divided by the total number of years in the strandings index (2yrs/32yrs)(Brownell *et al.*, 2007). The distribution of probabilities of future catastrophes for the 'H3' and 'H4' scenarios is shown in Fig. 2 (right panel). The probability of future catastrophe ranged between 0.025 and 0.222 for those scenarios, with a median of 0.043, which was less than that when conditioned on the stranding index. However, the average difference between these two approaches was relatively small, as evidenced by the nearly identical results between these two assumptions (Table 2; Fig. 3).

The predicted area of sea-ice on the Bering Sea feeding grounds is forecasted to decrease dramatically, with less than 50% of the average observed area of sea-ice in March-April during future decades (Fig. 2, left panel) (Overland and Wang, 2007). The scenarios (H1, H2, and H3) with population dynamics that were a function of this environmental index resulted in the most optimistic outcomes (Table 2), with some final depletion levels which were slightly greater than 1.0. On the other hand, the two scenarios that modeled generic environmental stochasticity independent of sea-ice (H4 and H5), resulted in the most pessimistic final depletion levels of any of the scenarios investigated (Table 2). Likewise, the trend in process error residuals was very different between these two sets of scenarios. Those scenarios which modeled process error as a function of future sea-ice resulted in an increasing trend in process error deviations, while those scenarios which modeled environmental stochasticity as an independent process resulted in no such trend (Fig. 4). However, in terms of the median average need satisfaction, there was essentially no difference between any of the scenarios (Table 2).

The results of the "deterministic" trials (H0) were more optimistic than those of the corresponding trials on which the *Gray Whale SLA* was based (GE01 and GE14) (compare table 2 of Breiwick and Punt (2009) with the results for the two H0 trials in table 2 of this paper). However, the differences in the values for the performance statistics are slight, and qualitatively the results of trial H0 and GE01 are identical. The differences in results are attributable to a variety of causes, including differences in the population dynamics models, in the data used to condition the operating model, and in the priors for the parameters of the model.

DISCUSSION

The analyses incorporated an index of sea-ice variability into an operating model which was used to test the gray whale *SLA*, given forecasts for future climate change and a hypothesis regarding the interaction between sea-ice and population dynamics. The trials presented here differ from the standard set designed by the Standing Working Group of the AWMP, in that they were explicitly conditioned on the most recently available data and a hypothesis regarding environmental forcing. For example, deviations in the survival rates during the 1999/2000 mortality event (and resulting population sizes at the start of the future trajectories) were conditioned on observed variability in the strandings data. A set of several alternative trials was also preformed, to compare the results of the environmental forcing scenario to those for which future population dynamics were assumed to be deterministic, or to be subject to random environmental stochasticity (i.e., ignoring sea-ice). For all of the scenarios considered here, the gray whale *SLA* was able to maintain stock size and satisfy need at very high levels. Therefore, there is no indication from these analyses that any revisions to the *SLA* are necessary at this time.

It is interesting to note that the assumption that the population dynamics were related to sea-ice led to more optimistic results. This was essentially the result of extrapolating (based on those years for which calf production and strandings data exist) a recent relationship between the environment and population dynamics into the future, under the assumption that such an effect (if it exists) would be constant with respect to time and population density (among other factors). While this is obviously an oversimplification, the framework used here could be modified during the next *Implementation Review* in order to take into account alternative hypotheses with respect to predicted changes in the effect of future environmental variability on population dynamics (e.g., by modifying σ_I^* as a function of depletion).

REFERENCES

A'mar, Z.T., Punt, A.E. and M.W. Dorn. *In press*. The evaluation of two management strategies for the Gulf of Alaska walleye Pollock under climate change. *ICES J.Mar.Sci.* XX: XXX.

Brandon, J.R. and Punt, A.E. 2009. Assessment of the eastern stock of North Pacific gray whales: incorporating calf production, sea-ice and strandings data. Paper SC/61/AWMP2

Brownell, Jr., R.L., Claudia A.F. Makeyev, and Rowles, T.K. 2007. Stranding Trends for Eastern Gray Whales, *Eschrichtius robustus*: 1975-2006. SC/59/BRG40 presented to the IWC Scientific Committee, May 2007, Anchorage, U.S.A. (unpublished).

Gulland, F.M.D., H. Pérez-Cortés M., J. Urbán R., L. Rojas-Bracho, G. Ylitalo, J. Weir, S.A. Norman, M.M. Muto, D.J. Rugh, C. Kreuder, and T. Rowles. 2005. Eastern North Pacific gray whale (*Eschrichtius robustus*) unusual mortality event, 1999-2000. In NOAA Technical Memorandum NMFS-AFSC-150. [www.afsc.noaa.gov/Publications/AFSC-TM/NOAA-TM-AFSC-150.pdf]

International Whaling Commission (IWC). 2003. Report of the Scientific Committee, Annex E. Report of the Standing Working Group on the Development of an Aboriginal Subsistence Whaling Management Procedure (AWMP). *J. Cetacean Res. Manage.* (Suppl.) 5: 154–255.

International Whaling Commission (IWC). 2004. Chair's Report of the Fifty-Sixth Annual Meeting. Annual Report of the International Whaling Commission, *J. Cetacean Res. Manage.* (Suppl.) 4: 1–58.

International Whaling Commission (IWC). 2005. Report of the Scientific Committee. Annex E. Report of the Standing Working Group (SWG) on the development of an Aboriginal Subsistence Whaling Management Procedure (AWMP). Appendix 3. Fishery Type 2: Implementation for Eastern North Pacific Gray Whales *J. Cetacean Res. Manage.* (Suppl.) 5:127-40

Overland, J. and Wang, M. 2007. Future regional Arctic sea ice declines. *Geophys. Res. Lett.* 34: L17705.

Perryman, W.L., Donahue, M.A., Perkins, P.C. and Reilly, S.B. 2002. Gray whale calf production 1994-2000: are observed fluctuations related to changes in seasonal ice cover? *Mar. Mammal Sci.* 18:121-44.

Poole, M.M. 1984. Preliminary assessment of annual calf production in the gray whale, *Eschrichtius robustus*, from Pt Piedras Blancas, California. *Rep. int. Whal. Commn* (special issue) 6:223-31.

Punt, A.E. and Breiwick, J.M. 2008. On standalone versions of the Bowhead and Gray Whale SLAs. Paper SC/M08/AWMP1 presented to the Workshop on Developing Assessment Methods and a Management Procedure for Greenlandic Fisheries, 26-29 March 2008, Copenhagen (unpublished). 11pp. [Paper available from the IWC Secretariat].

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan. 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.* 108, No. D14, 4407.

Rugh, D.J., Hobbs, R.C., Lerczak, J.A. and Breiwick, J.M. 2005. Estimates of abundance of the eastern North Pacific stock of gray whales (*Eschrichtius robustus*) 1997-2002. *J. Cetacean Res. Manage.* 7:1-12.

Rugh, D., Breiwick, J., Hobbs, R., Shelden, K., and Muto, M. 2008. Eastern North Pacific gray whale abundance in the winter 2006-2007. SC/60/BRG6. Presented to the IWC Scientific Committee, June 2005. Santiago, Chile. (unpublished). [Paper available from the IWC Secretariat]

ACKNOWLEDGEMENTS

Support for JB was provided by a grant from the IWC. Travel support for JB was provided by the IWC and a UW student travel grant. Wayne Perryman (SWFSC), Cherry Allison (IWC), Muyin Wang (NOAA/PMEL), and Robert Brownell Jr. (SWFSC) kindly provided (respectively) unpublished estimates of calf production, the most recent catch history records, global climate model forecasts of sea-ice and the stranding data. Finally, we acknowledge the many people who have been responsible for collecting the data analyzed here.

Table 1.
The scenarios considered. The trials are denoted by an 'H' followed with the trial number and then 'BN' or 'HN' for base or high final need. Descriptions are given for each scenario in terms of the stochastic or deterministic nature of the population dynamics and the probability of future catastrophes. The extent of future stochasticity σ_{ε} is equal to 0.50 (for consistency with the 'Full' analyses of Brandon and Punt (2009)) for all except the deterministic scenario.

Trial	Description	σ_{ε}	Final need	Probability of future catastrophe	Future stochasticity
H0 : BN	Deterministic + no future catastrophes	NA	340	0	None (Deterministic)
H1 : BN	Environmental stochasticity + no future catastrophes	0.5	340	0	Environmental
H2 : BN	Environmental stochasticity + p(future catastrophe)= 0.0625	0.5	340	0.0625	Environmental
H3 : BN	Environmental stochasticity + p(future catastrophe)= *p**	0.5	340	*p** (Eqn. 9)	Environmental
H4 : BN	Stochasticity (no sea-ice) + p(future catastrophe)=*p**	0.5	340	*p** (Eqn. 9)	Environmental (no sea-ice)
H5 : BN	Stochasticity (no sea-ice) + no future catastrophes	0.5	340	0	Environmental (no sea-ice)
H0 : HN	Deterministic + no future catastrophes	NA	530	0	None (Deterministic)
H1 : HN	Environmental stochasticity + no future catastrophes	0.5	530	0	Environmental
H2 : HN	Environmental stochasticity + p(future catastrophe)= 0.0625	0.5	530	0.0625	Environmental
H3 : HN	Environmental stochasticity + p(future catastrophe)= *p**	0.5	530	*p** (Eqn. 9)	Environmental
H4 : HN	Stochasticity (no sea-ice) + p(future catastrophe)= *p**	0.5	530	*p** (Eqn. 9)	Environmental (no sea-ice)
H5 : HN	Stochasticity (no sea-ice) + no future catastrophes	0.5	530	0	Environmental (no sea-ice)

Table 2.
The medians, and upper and lower 5th percentiles of the performance statistics for each scenario. See text for the definitions for each of the performance statistics

		D1: Final 1+ Depletion			D8: Rescaled 1+ Depletion			D10: 1+ Relative Increase			N9: Avg. Need Satisfaction		
Trial	Description	5%	Median	95%	5%	Median	95%	5%	Median	95%	5%	Median	95%
H0 : BN	Deterministic + no future catastrophes	0.908	0.933	0.950	0.875	0.918	0.948	0.947	0.986	1.095	1.000	1.000	1.000
H1 : BN	Environmental stochasticity + no future catastrophes	0.940	0.981	1.030	0.910	0.965	1.019	0.973	1.041	1.179	1.000	1.000	1.000
H2 : BN	Environmental stochasticity + p(future catastrophe)= 0.0625	0.914	0.974	1.026	0.886	0.959	1.016	0.954	1.032	1.158	1.000	1.000	1.000
H3 : BN	Environmental stochasticity + p(future catastrophe) = p^*	0.922	0.976	1.027	0.896	0.961	1.017	0.960	1.034	1.167	1.000	1.000	1.000
H4 : BN	Stochasticity (no sea-ice) + P(future catastrophe) = p^*	0.745	0.874	0.953	0.731	0.861	0.945	0.807	0.932	1.050	1.000	1.000	1.000
H5 : BN	Stochasticity (no sea-ice) + no future catastrophes	0.802	0.897	0.960	0.775	0.883	0.954	0.846	0.952	1.066	1.000	1.000	1.000
H0 : HN	Deterministic + no future catastrophes	0.855	0.899	0.927	0.833	0.884	0.921	0.913	0.950	1.038	0.971	0.980	0.988
H1 : HN	Environmental stochasticity + no future catastrophes	0.913	0.963	1.017	0.889	0.946	1.006	0.951	1.022	1.156	0.974	0.981	0.988
H2 : HN	Environmental stochasticity + p(future catastrophe)= 0.0625	0.880	0.954	1.011	0.858	0.937	1.001	0.927	1.011	1.132	0.973	0.981	0.988
H3 : HN	Environmental stochasticity + p(future catastrophe) = p^*	0.894	0.957	1.013	0.868	0.941	1.002	0.932	1.015	1.138	0.973	0.981	0.988
H4 : HN	Stochasticity (no sea-ice) + p(future catastrophe) = p^*	0.657	0.817	0.917	0.649	0.805	0.909	0.725	0.873	0.989	0.959	0.979	0.987
H5 : HN	Stochasticity (no sea-ice) + no future catastrophes	0.722	0.847	0.927	0.707	0.834	0.921	0.776	0.901	1.013	0.964	0.980	0.988

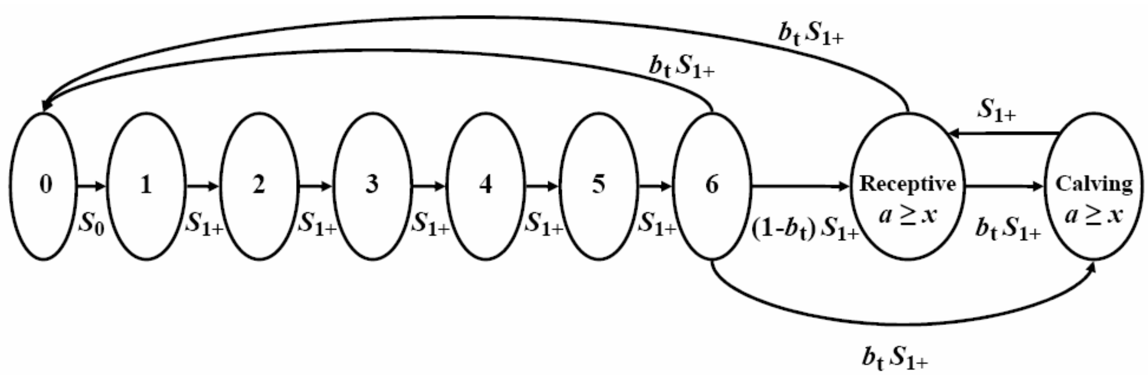

Figure 1. Life cycle graph of the model used to track the number of females in each reproductive stage though time. This life cycle refers to the underlying deterministic model, with transition probabilities shown as functions of life history parameters. However, it should be noted that the survival and birth rates were modified to be stochastic in the all analyses except for ‘H0’. The arrow from immature to calf arises because some juveniles may mature and give birth (i.e. become pregnant at first estrous) during the projection interval from time t to t+1.

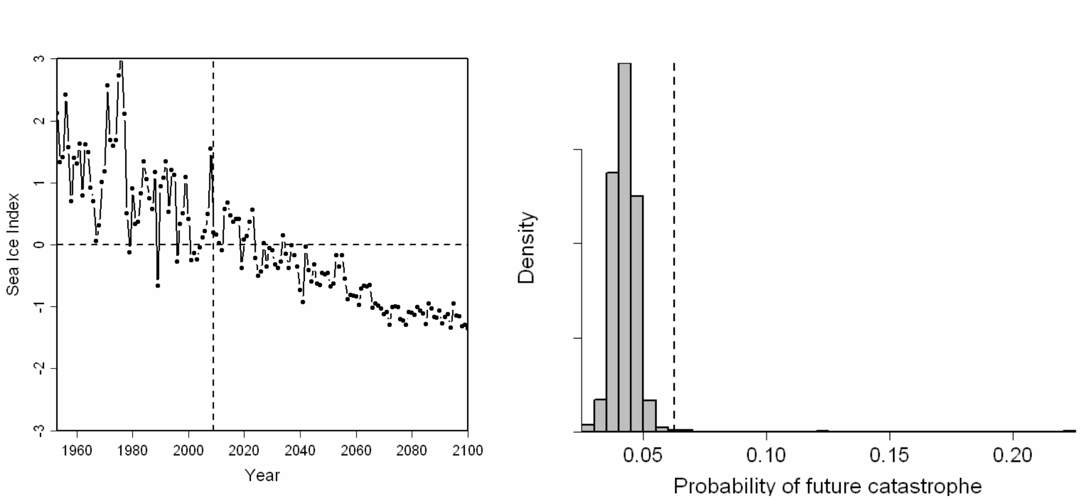

Figure 2. (Left panel) The standardized index for the March-April average sea-ice area covering the Bering Sea. The vertical dashed line denotes 2009 and the start of that portion of the time series which is based on the ensemble global climate model mean predictions provided by Overland and Wang (2007). Prior to 2009, the time series is based on the HadSST observations of sea-ice (Rayner *et al*., 2003). The horizontal dashed line at zero is shown for reference; positive values indicate years with greater than average sea-ice over the entire time period and vice-versa. (Right panel) The distribution for the probability of future catastrophe. This distribution is conditioned on the number of years for which the depletion of each trajectory is greater 0.40 during 1930-2008, divided by 2 (the number of years with observed catastrophes, corresponding to 1999 and 2000) (Brandon and Punt, 2009). The dashed vertical line denotes the probability as calculated from the strandings index (Brownell *et al.*, 2007)

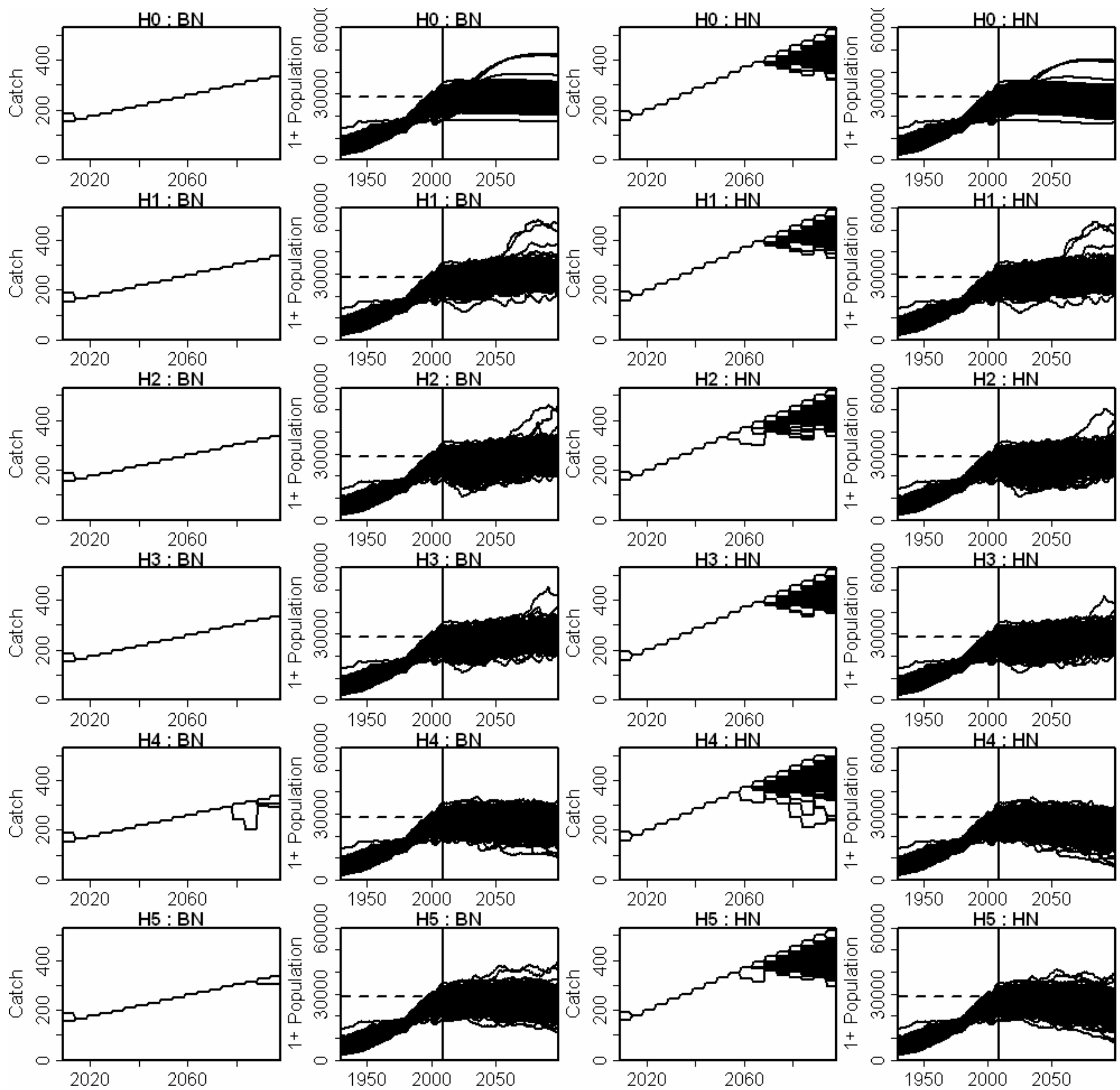

Figure 3. Time-trajectories of future catches (first and third columns) and population trajectories from 1930-2098 (second and fourth columns) for the twelve scenarios (Table 1). The left and right two columns are respectively for a final need levels of 340 and 530 whales per year. The results for each simulation are plotted as an individual line (e.g., a single visible line for catches represents a series of years where future catches were identical across scenarios).

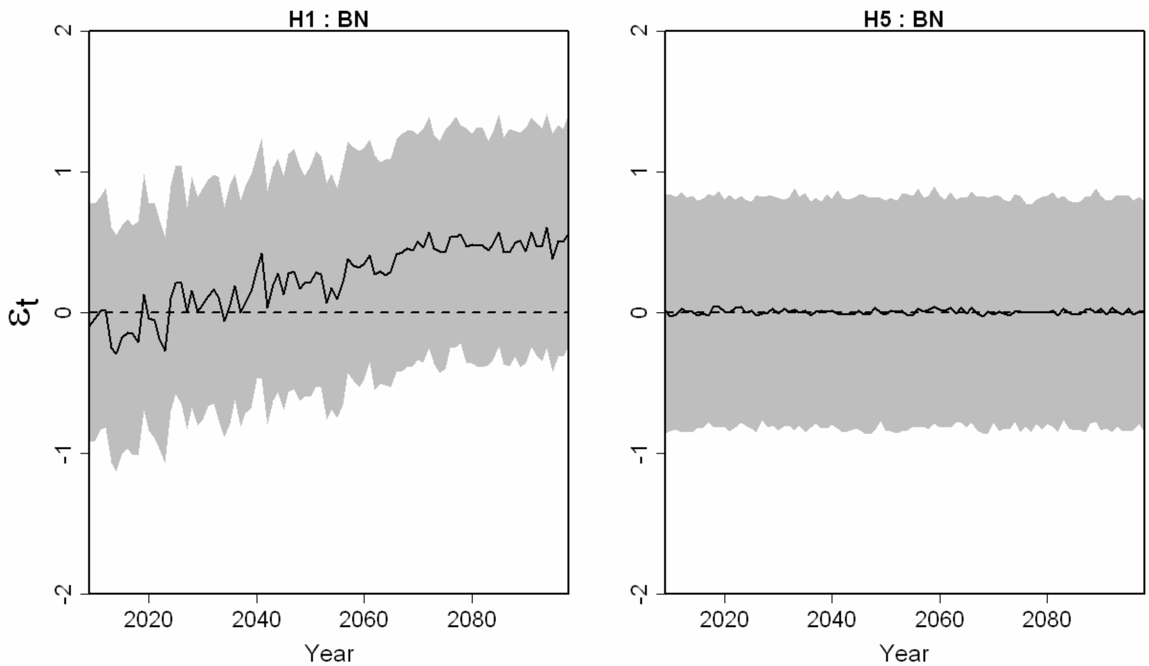

Figure 4. The time-trajectories of future process error residuals ε_t for a case where these residuals are a function of future sea-ice (H1:BN; left panel) and where they are independent of the sea-ice index (H5: BN; right panel). The annual median is plotted as the solid line, the 5th and 95th percentiles are shaded in gray and the horizontal dashed line at zero is shown for reference.