# ASSESSMENT OF THE WEST AND EAST AUSTRALIAN BREEDING POPULATIONS OF SOUTHERN HEMISPHERE HUMPBACK WHALES USING A MODEL THAT ALLOWS FOR MIXING ON THE FEEDING GROUNDS AND TAKING ACCOUNT OF THE MOST RECENT ABUNDANCE ESTIMATES FROM JARPA

**S.J. Johnston and D.S. Butterworth**

MARAM (Marine Resource Assessment and Management Group)
Department of Mathematics and Applied Mathematics
University of Cape Town
Rondebosch, 7701
South Africa

## ABSTRACT

The most recent JARPA survey estimates of abundance are used to update the dynamic production model analyses of West and East Australian humpback breeding populations (Johnston and Butterworth 2002). These analyses take account of the results of both these surveys on the feeding grounds and of breeding area surveys, by applying a model that incorporates mixing of the two breeding populations on the feeding grounds of Areas IV and V. Results are quite precisely determined, with the available data providing a self-consistent picture of population recoveries well above their minima of the 1960's. Best estimates are projected under continuing zero harvest, and show approaches to pristine levels in some 10 years for the western and 15-20 years for the more depleted eastern breeding population.

## INTRODUCTION

Initial assessments of breeding population of Southern Hemisphere humpback whales were presented at the 2000 IWC Scientific Committee meeting (Findlay *et al.* 2000; Findlay and Johnston 2001). These assessments were updated the following year (Johnston *et al.* 2001), and covered seven distinct Southern Hemisphere breeding populations, coupled with three sets of hypotheses as to how historic catches from mixtures of these breeding populations on the high latitude feeding grounds are to be allocated to such breeding populations; results were shown to be relatively insensitive across these hypotheses. Johnston *et al.* (2001) further reported results for models for two of the breeding populations for which the models were fitted to CPUE trends as well as to relative abundance indices. Johnston and Butterworth (2002) presented a model which was an extension of these previous assessments, in that links between feeding grounds and breeding grounds were explored. An age-aggregated production model approach continued to form the basis of these assessments.

As in Johnston and Butterworth (2002), here we examine two breeding populations: breeding population W (West Australia, which has previously been denoted as stock “D”), and breeding population E (East Australia, which has previously been denoted as stock “E”). The models are fit not only to CPUE (though heavily down-weighted) and relative abundance data from the breeding grounds, but also to the recently updated JARPA abundance estimates from feeding Areas IV and V (kindly provided by K. Matsuoka, pers. commn). Comparisons are made with IWC/IDCR SOWER-survey abundance estimates from these two feeding Areas.

## DATA

In this document the year, say 1950, refers to the austral summer season 1950/51. The following data are taken into account in the population model developed.

### The catch series

The catch series for both breeding populations W and E and Antarctic feeding Areas IV and V, and the bases for their development, are reported in the Appendix.

### Relative abundance trends (breeding grounds)

Data for breeding population E are from Brown *et al.* (1997) and cover surveys spanning the period 1981-1996. Data for breeding population W are from IWC (1996) cover five surveys spanning the period 1982-1994. These data are reproduced here in Table 1.

### CPUE data (breeding grounds)

These data are from Chittleborough (1965) and span the period 1950-1962 (breeding spopulation W) and 1953-1962 (breeding population E). They are reproduced here in Table 2.

### JARPA estimates of abundance (feeding Areas)

Updated JARPA estimates of humpback whale abundance in feeding Areas IV and V (Matsuoka, K. pers. commn) are reported in Table 3. These data are available for every second year from 1989-2003 (Area IV) and 1990-2002 (Area V).

### Recent estimates of absolute abundance - “targets” (breeding grounds)

Recent estimates of abundance of humpback whales from the breeding grounds for stocks W (Bannister and Hedley 2001) and E (Brown *et al.* 1997) are reported in Table 4.

### IWC/IDCR-SOWER estimates of abundance (feeding Areas)

Estimates of abundance south of $60^o$ S from the IWC/IDCR-SOWER sighting surveys were provided by T.A.Branch (pers. commn). These are the Area specific estimates that are summed to give the corresponding circumpolar abundance estimates reported in Branch and Butterworth (2002). These data are available for two years for Area IV (1978 and 1988) and three years for Area V (1980, 1985 and 1991) – see Table 5.

These data are not used in the model fitting procedure, but instead for subsequent comparative purposes.

## METHODS

The West (W) and East (E) Australian breeding populations are assumed to feed exclusively in both Antarctic feeding Areas IV (70°E-130°E) and V (130°E-170°E), with no humpback whales from other breeding populations in those Areas.

The catch records for the two feeding grounds (reported in Table I in the Appendix) correspond to 70°E-120°E (most of Area IV) and 120°E-170°E (mainly Area V). An *ad hoc* adjustment is made to these catches to make allowance for the extra 10 degrees of the latter set of catches which should correspond to the Area IV catch. This *ad hoc* adjustment simple removes 20% of the recorded latter set of catches and adds them to the former set. [Data are available to make this adjustment exactly, but it was not possible to pursue this in the time available.]

The population model described here allows for mixing of the two breeding populations in the feeding Areas. Catches taken in the feeding Areas are apportioned to each breeding population relative to the numbers present in that feeding Area.

## The Base Case population model

Breeding stock population dynamics

$$N_{y+1}^{B,W} = N_y^{B,W} + r^W N_y^{B,W}\left(1-\left(\frac{N_y^{B,W}}{K^w}\right)^{\mu}\right) - C_y^W \tag{1}$$

$$N_{y+1}^{B,E} = N_y^{B,E} + r^E N_y^{B,E}\left(1-\left(\frac{N_y^{B,E}}{K^E}\right)^{\mu}\right) - C_y^E \tag{2}$$

where

| | |
|---|---|
| $N_y^{B,W}$ | is the number of whales in the breeding population W at the start of year *y*, |
| $N_y^{B,E}$ | is the number of whales in the breeding population E at the start of year *y*, |
| $r^W$ | is the intrinsic growth rate (the maximum per capita the population can achieve, when its size is very low) for breeding population W, |
| $r^E$ | is the intrinsic growth rate for breeding population E, |
| $K^W$ | is the carrying capacity of breeding population W, |
| $K^E$ | is the carrying capacity of breeding population E, |
| $\mu$ | is the "degree of compensation" parameter; this is set at 2.39, which fixes the MSY level to MSYL = 0.6K, as conventionally assumed by the IWC Scientific Committee, |
| $C_y^W$ | is the total catch (in terms of animals) in year *y* from breeding population W, and |

$C_y^E$ is the total catch (in terms of animals) in year $y$ from breeding population E.

Feeding stocks

Mixing of the breeding populations in the feeding Areas is described by:

$$N_y^{F,IV} = \alpha N_y^{B,W} + (1-\beta) N_y^{B,E} \qquad (3)$$

$$N_y^{F,V} = (1-\alpha) N_y^{B,W} + \beta N_y^{B,E} \qquad (4)$$

where

$N_y^{B,IV}$ is the number of whales in feeding Area IV at the start of year $y$,

$N_y^{B,V}$ is the number of whales in feeding Area V at the start of year $y$,

$\alpha$ is the proportion of breeding population W which feeds in feeding Area IV, and

$\beta$ is the proportion of breeding population E which feeds in feeding Area V.

Thus it follows that:

$1-\alpha$ is the proportion of breeding population W which feeds in feeding Area V, and

$1-\beta$ is the proportion of breeding population E which feeds in feeding Area IV.

Catches

$$C_y^W = C_y^{W,IV} + C_y^{W,V} + C_y^{W,BW} \qquad (5)$$

$$C_y^E = C_y^{E,IV} + C_y^{E,V} + C_y^{E,BE} \qquad (6)$$

where

$C_y^{W,IV}$ are the catches of animals in year $y$ in the western feeding Area (Area IV) which come from the breeding population W,

$C_y^{W,V}$ are the catches of animals in year $y$ in the eastern feeding Area (Area V) which come from the breeding population W,

$C_y^{W,BW}$ are the catches of animals in year $y$ taken from breeding population W, either in the breeding area or on the migration route,

$C_y^{E,IV}$ are the catches of animals in year $y$ in the western feeding Area (Area IV) which come from the breeding population E,

$C_y^{E,V}$ are the catches of animals in year $y$ in the eastern feeding Area (Area V) which come from the breeding population E, and

$C_y^{W,BE}$ are the catches of animals in year *y* taken from breeding population E, either in the breeding Area or on the migration route.

We can calculate the breakdown by breeding population of the catches in a feeding Area, *viz.* $C_y^{W,IV}, C_y^{W,V}, C_y^{E,IV}$ and $C_y^{E,V}$, from the assumption that catches by stock are in the same ratio as the numbers of each breeding population present:

$$\frac{C_y^{W,IV}}{\left[C_y^{W,IV} + C_y^{E,IV}\right]} = \frac{\alpha N_y^{B,W}}{N_y^{F,IV}} \tag{7}$$

$$\frac{C_y^{E,IV}}{\left[C_y^{W,IV} + C_y^{E,IV}\right]} = \frac{(1-\beta) N_y^{B,E}}{N_y^{F,IV}} \tag{8}$$

$$\frac{C_y^{W,V}}{\left[C_y^{W,V} + C_y^{E,V}\right]} = \frac{(1-\alpha) N_y^{B,W}}{N_y^{F,V}} \quad \text{and} \tag{9}$$

$$\frac{C_y^{E,V}}{\left[C_y^{W,V} + C_y^{E,V}\right]} = \frac{\beta N_y^{B,E}}{N_y^{F,V}} \tag{10}$$

where we know

$[C_y^{W,IV} + C_y^{E,IV}]$ = Area IV catches recorded for year *y*, and

$[C_y^{W,V} + C_y^{E,V}]$ = Area V catches recorded for year *y*.

The likelihood function

The estimable parameters of the model are: $r^W, r^E, K^W, K^E, \alpha$ and $\beta$. The *r* parameters are constrained to be less than or equal to 0.126. This constraint is to force the model to respect demographically plausible bounds, as evaluated by Clapham *et al.* (2001) during the 2000 IWC Scientific Committee meeting.

The population model is fit to the following data:

i) relative abundance data from breeding ground/migration route surveys (see Table 1),
ii) CPUE data from breeding grounds (see Table 2),
iii) updated JARPA abundance estimates from feeding Areas IV and V (see Table 3), and
iv) absolute abundance estimates (treated as target population sizes) from the breeding grounds (for particular years) reported in Table 4.

Certain of the sensitivity tests conducted omit some of these data. Abundance estimates from the IWC/IDCR-SOWER sighting surveys (Branch and Butterworth (2002) are reported in Table 5. These data are not included in the likelihood, but comparisons between the model estimated numbers in the feeding grounds and these abundance estimates are shown.

The Base Case model is fit to the relative abundances from the breeding ground surveys and CPUE trends as follows. It is assumed that the observed abundance index is log-normally distributed about its expected value:

$$I_y^A = q^A \hat{N}_y^{B,A} e^{\varepsilon_y} \tag{11}$$

where

| | |
|---|---|
| $I_y^A$ | is either the survey-based relative abundance or CPUE index for year *y* for breeding population *A* (either W or E), |
| $q^A$ | is the multiplicative bias/catchability coefficient for that index for breeding population *A*, |
| $\hat{N}_y^{B,A}$ | is the model estimate of population size at the start of year *y* for breeding population *A*, and |
| $\varepsilon_y$ | is from $N(0,\sigma_{B,A}^2)$. |

The Base Case model treats the JARPA abundance estimates as relative indices as follows. It is assumed that the observed abundance index is log-normally distributed about its expected value:

$$I_y^A = q_{JARPA}^A \hat{N}_y^{F,A} e^{\varepsilon_y} \tag{12}$$

where

| | |
|---|---|
| $I_y^A$ | is the JARPA abundance estimate for year *y* and feeding stock *A* (either IV or V), |
| $q_{JARPA}^A$ | it the multiplicative bias of the JARPA abundance estimate for feeding stock *A*, which is set equal to 1 when this is treated as an index of absolute abundance, |
| $\hat{N}_y^{F,A}$ | is the model estimate of population size at the start of year *y* for feeding stock *A*, and |
| $\varepsilon_y$ | is from $N(0,(\sigma_{JARPA}^A)^2)$. |

The contribution of the various data to the negative of the log-likelihood function is given by:

$$\begin{aligned}
-\ln L = {} & w_1 \sum_A \Big(n_B^A \ln\sigma_B^A + \frac{1}{2{\sigma_B^A}^2} \sum_y \left(\ln I_y^A - \ln q_B^A - \ln \hat{N}_y^{B,A}\right)^2\Big) + \\
& w_2 \sum_A \Big[n_{CPUE}^A \ln\sigma_{CPUE}^A + \frac{1}{2\sigma_{CPUE}^{A\ 2}} \sum_y \left(\ln I_{CPUE,y}^A - \ln q_{CPUE}^A - \ln \hat{N}_y^{B,A}\right)^2\Big] + \\
& w_3 \sum_A \Big[n_{JARPA}^A \ln\sigma_{JARPA}^A + \frac{1}{2\sigma_{JARPA}^{A\ 2}} \sum_y \left(\ln I_{JARPA,y}^A - \ln q_{JARPA}^A - \ln \hat{N}_y^{F,A}\right)^2\Big] + \\
& w_4 \sum_A \left(N_Y^{A,obs} - \hat{N}_Y^{B,A}\right)^2
\end{aligned} \tag{13}$$

where

$w_1$ is the weight given to the breeding ground survey-based relative abundance data ($w_1 = 1$ for the Base Case),

$w_2$ is the weight given to the CPUE data, which are heavily downweighted for the Base Case with a value of $w_2 = 0.0001$ (due to the fact that the CPUE data are considered to be less reliable than the survey-based relative abundance data – effectively this means that these CPUE data do not influence the fit itself, but their inclusion in the likelihood serves to provide an estimate of the associated catchability coefficient $q$),

$w_3$ is the weight given to the JARPA absolute abundance data, ($w_3 = 1$ for the Base Case) and

$w_4$ is the weight given to the population target size - a value of $w_4 = \dfrac{1}{2\tilde{\sigma}^2}$ is used, where $\tilde{\sigma}$=1000, so that the estimated population trajectory may not hit the target level exactly.

The $\sigma$ parameters are the residual standard deviations which are estimated in the fitting procedure by their maximum likelihood values:

$$\hat{\sigma}^A = \sqrt{1/n\sum_y \left(\ln I_y^A - \ln q^A - \ln \hat{N}_y^{B,A}\right)^2} \quad \text{for breeding survey/CPUE data} \quad (14)$$

and

$$\hat{\sigma}^A_{JARPA} = \sqrt{1/n\sum_y \left(\ln I^A_{JARPA,y} - \ln q^A_{JARPA} - \ln \hat{N}_y^F\right)^2} \quad \text{for feeding ground} \quad (15)$$

JARPA survey data

where

$n$ is the number of data points in the abundance index or CPUE series, and
$q$ is the multiplicative bias/catchability coefficient, estimated by its maximum likelihood value:

$$\ln \hat{q}^A = 1/n\sum_y \left(\ln I_y^A - \ln \hat{N}_y^{B/F,A}\right) \quad (16)$$

## Sensitivity tests

Four sensitivity tests of the Base Case assumptions are considered and reported:

Sensitivity 1: JARPA estimates of abundance (Table 3) are treated as absolute rather than as relative indices of feeding stock numbers.

Sensitivity 2: As for Sensitivity 1, but exclude information on target abundances (i.e. $w_4 = 0$).

Sensitivity 3: Information from the JARPA surveys is excluded (i.e. $w_3 = 0$).

Sensitivity 4: The target abundance estimates are increased from 8000 to 13640 for breeding population W (this being the upper 95% confidence limit reported by Bannister and Hedley, 2001), and from 3200 to 6000 for breeding population E (a somewhat arbitrary increase, being the same as used to reflect sensitivity in Johnston *et al.*, 2001).

A further sensitivity test was carried out in which no target abundance information was provided and the JARPA estimates of abundance were treated as relative indices. The results that followed were clearly unrealistic, suggesting an extremely small breeding population W (numbers an order of magnitude less than suggested by Bannister and Hedley, 2001), so that this approach was not pursued further.

## Confidence Intervals

A bootstrapping approach is used to calculate confidence intervals for the various population model estimates.

Details of the approach used to generate replicate data sets are as follows:

Replace $I_y^A$ with $I_y^{A,u} = \hat{q}\hat{N}_y e^{\varepsilon^u}$, with $\varepsilon^u$ from $N(0,\sigma{*}^2)$, for the CPUE data, the relative abundance data from the feeding ground surveys and the JARPA estimates, and where $\sigma{*} = \sqrt{\frac{n}{n-2}}\sigma$, *n* is the number of data points, and $\sigma$ is as estimated in the original fit for the series concerned.

The bootstrap procedure also replaces the "targets" $N_y^{A,obs}$ with $N_{\text{y}}^{A,u} = \hat{N}_y^{B,A} + \eta^u$ where $\eta^u$ from $N(0{,}1000^2)$ (as $\tilde{\sigma}$ = 1000 – see $w_4$).

Estimation is conducted from one hundred bootstrap replicates (*u*), with the results ordered to provide distributions.

The 5th and 95th percentiles (as estimated by the 5th and 96th values in the ordered sequences) for various model estimates are reported in Table 6.

## RESULTS AND DISCUSSION

The results of the Base Case model fit to the data and the associated sensitivities are detailed in Table 6. Comparative results for the Base Case using instead the 2002 JARPA estimates of abundance are also reported. The estimates of $\alpha$ are generally close to 1, whereas those of $\beta$ are somewhat lower. This suggests that few animals from breeding population W feed in Area V, but a rather greater proportion of breeding population E feed in Area IV.

Figs 1-4 show how well the model results fit the available abundance-related information. The breeding ground survey trends are reflected closely (Fig. 1). The fits to the JARPA feeding ground trends show greater variability – for feeding Area IV, the model is unable to reproduce the two high most recent estimates (Fig. 2). This greater variability is, however, not unexpected, as unlike for the breeding grounds, numbers in feeding grounds from year to year would be expected to change to a greater extent as food distribution patterns change. In qualitative terms, the CPUE trends over the 1950's and early 1960's (Fig. 3) are also reasonably reflected. Agreement is not exact however, which is why these data are under-weighted in the model fit, as they cannot in any case be considered comparatively as reliable as the later scientific survey results as indices of population abundance. The IDCR-SOWER abundance estimates, although not used in the model fitting procedure, appear quite consistent with the model estimates given their large variances [1](Fig. 4).

Trends in the estimated breeding and feeding stocks for the Base Case model fit are shown in Fig. 5. In terms of best estimates, near complete recoveries to pristine levels under zero harvest are suggested in some 10 years for stock W, and some 15-20 years for the currently more depleted (relative to pristine) stock E.

Comparison with the Base Case results with those prior to the availability of the updated JARPA estimates of abundance show little change (Table 6c). Breeding population W is now estimated to be marginally less productive (lower $r$) and less recovered than previously thought.

Treating JARPA abundance estimates as reflecting absolute abundances increases the extent to which both W and E breeding populations are estimated to have recovered (Sensitivities 1 and 2, Table 6b). Similar results follow if the target abundance estimates for the breeding populations are increased (Sensitivity 4, Table 6c). Evidently (Table 6b, Sensitivity 2) the absolute estimates provided by the JARPA surveys suggest that the estimates of absolute abundance for the breeding grounds given in Table 4 are negatively biased estimates of overall abundance, more so for East Australia. Breeding ground population projections for Sensitivities 2 and 4 are compared to the Base Case in Figure 6, again indicating that approaches to pristine levels will occur earlier in the future.

However, if no account is taken of the JARPA abundance estimates (Sensitivity 3, Table 6c), the productivity ($r$) for population W is notable less, as is the extent of recovery (there is little difference for population E). Bootstrap confidence intervals also generally show an increase (though only slight) compared to the Base Case; the reason the JARPA estimates have this relatively small impact on the model results is their greater variability, which leads to less weight placed upon them in the fitting procedure (note the $\sigma_{JARPA}$ is typically 3-6 times larger than the $\sigma_B$ for the abundance estimates from the feeding ground surveys).

## CONCLUDING REMARKS

The available data continue to give a self consistent picture of breeding populations to the west and east of Australia that are recovering well from their minima in the 1960's, with the recovery of the western stock likely the further advanced.

---

[1] CV estimates are not immediately available for the Area-specific estimates given in Table 5. However, given that the associated circumpolar estimates have CVs of about 0.3 (Branch and Butterworth 2002), these Area-specific estimates will have CVs that are somewhat larger than this.

## REFERENCES

Bannister, J.L. 1994. Continued increase in humpback whales off Western Australia. *Rep. int. Whal. Commn* 44:309-310.

Bannister, J.L. and Hedley, S.L. 2001. Southern Hemisphere Group IV humpback whales: their status from recent aerial surveys. Memoirs of the Queensland Museum 47(2):587-598.

Branch, T.A. and D.S. Butterworth. 2002. Estimates of abundance south of 60°S for cetacean species sighted frequently on the 1978/79 to 1997/98 IWC/IDCR-SOWER sightings surveys. *J. Cet. Res. Manage.*3:251-270.

Brown, M.R., Field, M.S., Clarke, E.D., Butterworth, D.S. and M.M. Bryden. 1997. Estimates of abundance and rate of increase for East Australian humpback whales from the 1996 Land-based survey at Point Lookout, North Stradbroke Island, Queensland. Document SC/49/SH35 submitted to the IWC Scientific Committee, 15pp.

Chittleborough, R.G. 1965. Dynamics of two populations of the humpback whale, *Megaptera Novaeangliae* (Borowski). *Aust. J. Mar. Freshw. Res.* 16: 33-128.

Clapham, P., Robbins, J., Brown, M., Wade, P. and K. Findlay. 2001. A note on plausible rates of population growth in humpback whales. Appendix 5, Report of the Sub-Committee on the Comprehensive Assessment of Whale Stocks – In-depth Assessments. *J. Cet. Res. Manage.* 3 (Suppl):196-197.

Findlay, K.P., Cunningham, C.L. and D.S. Butterworth. 2000. A first step towards a preliminary assessment of Southern Hemisphere Humpback whales. Document SC/52/IA5 submitted to the IWC Scientific Committee, 23pp.

Findlay, K.P. and S.J. Johnston. 2001. Further steps towards a preliminary assessment of Southern Hemisphere humpback whales (breeding populations A and G). J. Cetacean Res. Manage. 3(Suppl.) 193-194.

IWC. 1996. Report of the international Whaling Commission, Annex E, Report of the Sub-Committee on Southern Hemisphere Baleen whales, Annex E. *Rep. Int. Whal. Commn* 46: 117-138.

Johnston, S.J., Butterworth, D.S. and K.P. Findlay. 2001. Further results from a prelimary assessment of Southern Hemisphere Humpback whales. Document SC/53/IA20 submitted to the IWC Scientific Committee, 31pp.

Johnston, S.J. and D.S. Butterworth. 2002. An assessment of the west and east Australian breeding stocks of Southern Hemisphere humpback whales using a model that allows for mixing in the feeding grounds. Document SC/54/H17 submitted to the IWC Scientific Committee, 27pp.

Matsuoka, K., Hakamada, T., Murase, H. and S. Nishiwaki. 2001. Current abundance and density trend of humpback and fin whales in the Antarctic Areas IV and V using JARPA data. IWC document SC/53/IA18 submitted to the IWC Scientific Committee.

## ACKNOWLEDGEMENTS

We thank K. Matsuoka for providing the most recent JARPA-based estimates of humpback abundance that were used in these analyses.

Table 1: Relative abundance estimates for breeding populations W (IWC 1996) and E (Brown *et al.* 1997).

| **Year** | **Area W (West Australia)** |
|---|---|
| 1982 | 10.2 |
| 1986 | 16.2 |
| 1988 | 12.7 |
| 1991 | 23.6 |
| 1994 | 36.0 |
|  | **Area E (East Australia)** |
| 1981 | 381 |
| 1982 | 493 |
| 1986 | 1008 |
| 1987 | 879 |
| 1991 | 1533 |
| 1993 | 1807 |
| 1996 | 2872 |

Table 2: CPUE data off the west and east coasts of Australia (breeding populations W and E respectively) (from Chittleborough 1965).

| **Year** | **Area W (West Australia)** | **Area E (East Australia)** |
|---|---|---|
| 1950 | 0.475 |  |
| 1951 | 0.424 |  |
| 1952 | 0.347 |  |
| 1953 | 0.353 | 0.972 |
| 1954 | 0.351 | 0.755 |
| 1955 | 0.244 | 0.779 |
| 1956 | 0.178 | 0.704 |
| 1957 | 0.146 | 0.714 |
| 1958 | 0.123 | 0.750 |
| 1959 | 0.090 | 0.740 |
| 1960 | 0.062 | 0.522 |
| 1961 | 0.055 | 0.230 |
| 1962 | 0.051 | 0.069 |

Table 3: Updated JARPA estimates of abundance of humpback whales in feeding Areas IV and V (K. Matsuoka pers. commn).

| **Year** | **Area IV** |
|---|---|
| 1989 | 3873 |
| 1991 | 5203 |
| 1993 | 2740 |
| 1995 | 8850 |
| 1997 | 10874 |
| 1999 | 16211 |
| 2001 | 33010 |
| 2003 | 31750 |
| | **Area V** |
| 1990 | 767 |
| 1992 | 3837 |
| 1994 | 3567 |
| 1996 | 1543 |
| 1998 | 8301 |
| 2000 | 4720 |
| 2002 | 2735 |

Table 4: Estimates of breeding ground abundance of humpback whales used in the model ("targets"), together with the year to which they are taken to correspond.

| **Breeding population** | **Abundance** | **Year** | **Source** |
|---|---|---|---|
| W (West Australia) | 8000 | 1999 | Bannister and Hedley (2001) |
| E (East Australia) | 3200 | 1996 | Brown *et al.* (1997) |

Table 5: Estimates of abundance of humpback whales south of $60^{O}$S from the IWC/IDCR-SOWER sighting surveys (T.A. Branch pers. commn).

| **YEAR** | **Circumpolar Survey** | **Area IV** | **Area V** |
|---|---|---|---|
| 1978 | I | 1039 | - |
| 1980 | I | - | 966 |
| 1985 | II | - | 568 |
| 1988 | II | 3375 | - |
| 1991 | III | - | 2066 |

Table 6a: Base Case and 2002 (before JARPA update) results (the JARPA values are treated as relative indices and the model includes fitting to target abundance data). Note that the *–lnL* contributions listed exclude the weighting factors $w_1$ to $w_4$ (see equation 13). Note also that the values in round brackets are the bootstrap medians, and the values in square brackets the 5th and 95th percentiles. Note that $\sigma_{JARPA}$ values apply respectively to Area IV and V rather than breeding populations W and E respectively.

| | **Base Case** | | **2002 (before JARPA update)** | |
|---|---|---|---|---|
| | **Stock W** | **Stock E** | **Stock W** | **Stock E** |
| $\alpha$ | 0.944 (0.898)<br>[0.810; 0.999] | | 0.959 | |
| $\beta$ | 0.671 (0.696)<br>[0.622; 0.790] | | 0.667 | |
| $r$ | 0.122 (0.121)<br>[0.090; 0.126] | 0.126 (0.123)<br>[0.109; 0.126] | 0.124 | 0.126 |
| $K$ | 16879 (18212)<br>[16109; 21316] | 33857 (33072)<br>[30842; 34939] | 16365 | 34235 |
| $q_{JARPA}$ | 1.56 (1.64)<br>[1.10; 2.40] | 1.18 (1.07)<br>[0.54; 2.17] | 1.20 | 1.41 |
| $N_{\text{lowest}}$ | 236 (233)<br>[169; 645] | 114 (124)<br>[64; 223] | 225 | 116 |
| $N_{\text{target}}$ * | 7803 (7748)<br>[6222; 3717] | 3183 (3247)<br>[1419; 4825] | 7958 | 3213 |
| $N_{2000}$ | 8601 (8548)<br>[6893; 10139] | 5104 (5039)<br>[2192; 7703] | 8771 | 5153 |
| $N_{2003}$ | 11166 (11090)<br>[9216; 12754] | 7250 (6974)<br>[3085; 10852] | - | - |
| $N_{2000}/K$ | 0.51 (0.46)<br>[0.36; 0.57] | 0.15 (0.15)<br>[0.07; 0.23] | 0.54 | 0.15 |
| $N_{2003}/K$ | 0.66 (0.60)<br>[0.47; 0.72] | 0.21 (0.22)<br>[0.09; 0.32] | - | - |
| $N_{\text{lowest}}/K$ | 0.014 (0.014)<br>[0.009; 0.029] | 0.003 (0.004)<br>[0.002; 0.007] | 0.014 | 0.003 |
| $\sigma_{CPUE}$ (breeding) | 0.378 | 0.343 | 0.376 | 0.336 |
| $\sigma_B$ (relative abundance - breeding) | 0.173 | 0.109 | 0.177 | 0.109 |
| $\sigma_{JARPA}$ (feeding) | 0.455 | 0.630 | 0.352 | 0.371 |
| *-lnL* CPUE (breeding) | -6.14 | -5.70 | -6.21 | -5.90 |
| *-lnL (* relative abundance - breeding) | -6.26 | -12.00 | -6.16 | -12.00 |
| *-lnL JARPA* (feeding) | -2.30 | 0.267 | -3.25 | -2.95 |
| *-lnL "targets"* (breeding) | 38774 | 281.9 | 1748 | 191 |
| *-lnL (total) (includes weights)* | -20.27 | | -24.37 | |

* the abundance "targets" of 8000 (W) and 3200 (E) – see Table 4 - are not hit exactly (as the fitting procedure assigns standard errors to each of 1000).

Table 6b: Base Case (JARPA treated as relative indices), Sensitivity 1 (JARPA treated as absolute indices) and Sensitivity 2 (target abundance data excluded in model fit; JARPA treated as absolute indices) results. Note that the –*lnL* contributions listed exclude the weighting factors $w_1$ to $w_4$.

| | **Base Case** | | **Sensitivity 1 (JARPA absolute)** | | **Sensitivity 2 (JARPA absolute, but exclude target abundance data)** | |
|---|---|---|---|---|---|---|
| | **Stock W** | **Stock E** | **Stock W** | **Stock E** | **Stock W** | **Stock E** |
| $\alpha$ | 0.944 | | 0.950 | | 0.990 | |
| $\beta$ | 0.671 | | 0.735 | | 0.628 | |
| $r$ | 0.122 | 0.126 | 0.124 | 0.126 | 0.126 | 0.126 |
| $K$ | 16879 | 33857 | 17332 | 33298 | 15363 | 35352 |
| $q_{JARPA}$ | 1.56 | 1.18 | 1.0 | 1.0 | 1.0 | 1.0 |
| $N_{\text{lowest}}$ | 236 | 114 | 254 | 127 | 276 | 217 |
| $N_{\text{target}}$ * | 7803 | 3183 | 8786 | 3539 | 9575 | 5934 |
| $N_{2000}$ | 8601 | 5104 | 9659 | 5670 | 10392 | 9428 |
| $N_{2003}$ | 11166 | 7250 | 12356 | 8041 | 12617 | 13188 |
| $N_{2000}/K$ | 0.51 | 0.15 | 0.56 | 0.17 | 0.68 | 0.27 |
| $N_{2003}/K$ | 0.66 | 0.21 | 0.71 | 0.24 | 0.82 | 0.37 |
| $N_{\text{lowest}}/K$ | 0.014 | 0.003 | 0.015 | 0.004 | 0.018 | 0.006 |
| $\sigma_{CPUE}$ (breeding) | 0.378 | 0.343 | 0.378 | 0.350 | 0.370 | 0.307 |
| $\sigma_B$ (relative abundance - breeding) | 0.173 | 0.109 | 0.176 | 0.109 | 0.178 | 0.110 |
| $\sigma_{JARPA}$ (feeding) | 0.455 | 0.630 | 0.582 | 0.630 | 0.483 | 0.683 |
| -*lnL* CPUE (breeding) | -6.14 | -5.70 | -6.15 | -5.51 | -6.42 | -6.82 |
| -*lnL (* relative abundance - breeding) | -6.26 | -12.00 | -6.19 | -12.00 | -6.11 | -11.93 |
| -*lnL JARPA* (feeding) | -2.30 | 0.267 | -0.32 | 0.26 | -1.82 | -2.67 |
| -*lnL “targets”* (breeding) | 38774 | 281.9 | 618361 | 115324 | - | - |
| -*lnL (total) (includes weights)* | -20.27 | | -17.88 | | -22.54 | |

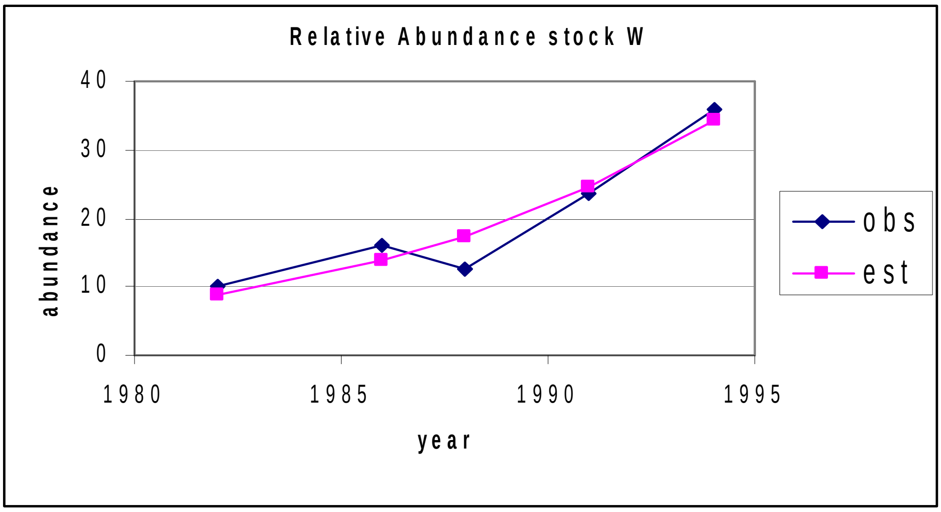
* the abundance “targets” of 8000 (W) and 3200 (E) – see Table 4 - are not hit exactly (as the fitting procedure assigns standard errors to each of 1000).

Table 6c: Base Case results compared to sensitivity results for which the JARPA abundance estimates are excluded from the model fitting procedure (Sensitivity 3) and for where the target abundance values are increased (to 13640 for stock W and 6000 for stock E) (Sensitivity 4). Note that the *–lnL* contributions listed exclude the weighting factors $w_1$ to $w_4$.

| | **Base Case** | | **Sensitivity 3 (Exclude JARPA abundance estimates)** | | **Sensitivity 4 (Increase target abundances)** | |
|---|---|---|---|---|---|---|
| | **Stock W** | **Stock E** | **Stock W** | **Stock E** | **Stock W** | **Stock E** |
| $\alpha$ | 0.944 (0.898)<br>[0.810; 0.999] | | 0.941 (0.897)<br>[0.830; 0.999] | | 0.784 | |
| $\beta$ | 0.671 (0.696)<br>[0.622; 0.790] | | 0.662 (0.708)<br>[0.573; 0.798] | | 0.718 | |
| $r$ | 0.122 (0.121)<br>[0.090; 0.126] | 0.126 (0.123)<br>[0.109; 0.126] | 0.107 (0.110)<br>[0.084; 0.126] | 0.126 (0.124)<br>[0.107; 0.126] | 0.120 | 0.126 |
| $K$ | 16879 (18212)<br>[16109; 21316] | 33857 (33072)<br>[30842; 34939] | 18145 (19017)<br>[16791; 22668] | 33613 (32900)<br>[30340; 34061] | 20783 | 29707 |
| $q_{JARPA}$ | 1.56 (1.64)<br>[1.10; 2.40] | 1.18 (1.07)<br>[0.54; 2.17] | - | - | 1.05 | 0.45 |
| $N_{\text{lowest}}$ | 236 (233)<br>[169; 645] | 114 (124)<br>[64; 223] | 357 (312)<br>[182;729] | 115 (122)<br>[68; 230] | 455 | 218 |
| $N_{\text{target}}$ * | 7803 (7748)<br>[6222; 3717] | 3183 (3247)<br>[1419; 4825] | 7987 (7965)<br>[6457; 9516] | 3199 (3218)<br>[1471; 4818] | 13389 | 6023 |
| $N_{2000}$ | 8601 (8548)<br>[6893; 10139] | 5104 (5039)<br>[2192; 7703] | 8723 (8685)<br>[7067; 10430] | 5129 (5077)<br>[2294; 7688] | 14439 | 9531 |
| $N_{2003}$ | 11166 (11090)<br>[9216; 12754] | 7250 (6974)<br>[3085; 10852] | 11119 (11204)<br>[9360; 13168] | 7285 (7084)<br>[3174; 10818] | 17251 | 13209 |
| $N_{2000}/K$ | 0.51 (0.46)<br>[0.36; 0.57] | 0.15 (0.15)<br>[0.07; 0.23] | 0.48 (0.45)<br>[0.34; 0.57] | 0.15 (0.16)<br>[0.07; 0.23] | 0.69 | 0.32 |
| $N_{2003}/K$ | 0.66 (0.60)<br>[0.47; 0.72] | 0.21 (0.22)<br>[0.09; 0.32] | 0.61 (0.58)<br>[0.44; 0.73] | 0.22 (0.22)<br>[0.10; 0.33] | 0.83 | 0.44 |
| $N_{\text{lowest}}/K$ | 0.014 (0.014)<br>[0.009; 0.029] | 0.003 (0.004)<br>[0.002; 0.007] | 0.020 (0.017)<br>[0.010; 0.033] | 0.003 (0.004)<br>[0.002; 0.007] | 0.022 | 0.007 |
| $\sigma_{CPUE}$ (breeding) | 0.378 | 0.343 | 0.378 | 0.353 | 0.399 | 0.372 |
| $\sigma_B$ (relative abundance - breeding) | 0.173 | 0.109 | 0.166 | 0.109 | 0.173 | 0.110 |
| $\sigma_{JARPA}$ (feeding) | 0.455 | 0.630 | - | - | 0.496 | 0.620 |
| *-lnL* CPUE (breeding) | -6.14 | -5.70 | -6.14 | -5.40 | -5.45 | -4.88 |
| *-lnL (* relative abundance - breeding) | -6.26 | -12.00 | -6.47 | -12.00 | -6.28 | -11/97 |
| *-lnL JARPA* (feeding) | -2.30 | 0.267 | - | - | -1.60 | 0.154 |
| *-lnL "targets"* (breeding) | 38774 | 281.9 | 159 | 0.9 | 62789 | 555 |
| *-lnL (total) (includes weights)* | -20.27 | | -18.48 | | -19.67 | |

* the abundance "targets" are not hit exactly (as the fitting procedure assigns standard errors to each of 1000).

Figure 1: Base Case model fits to the relative abundance trends on the breeding grounds.



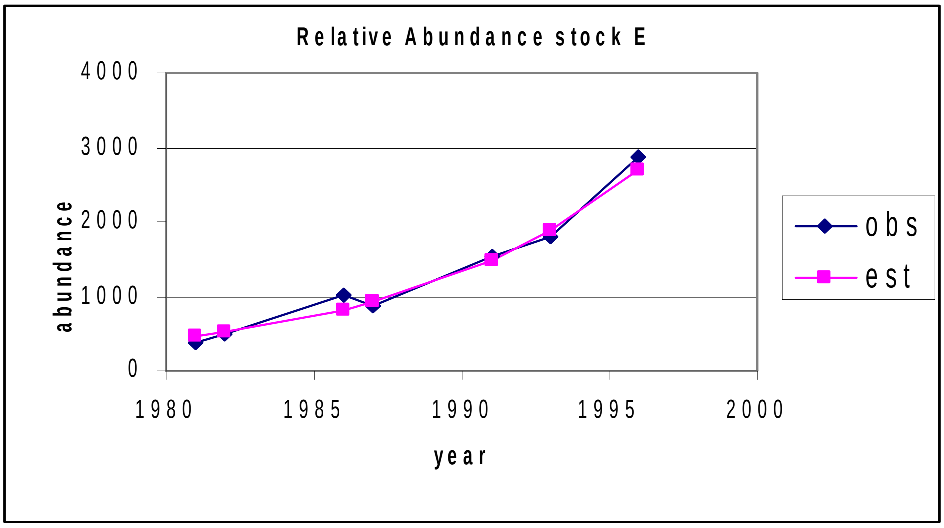
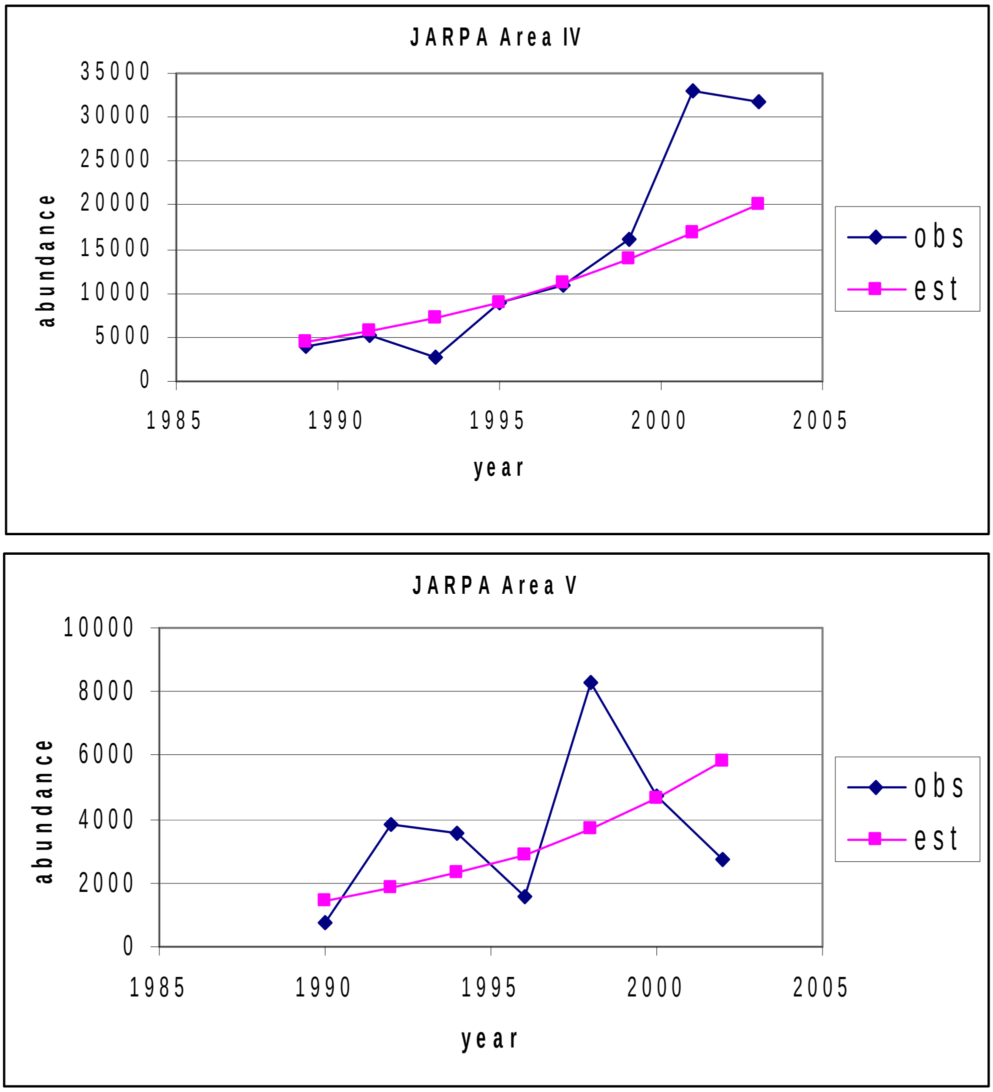
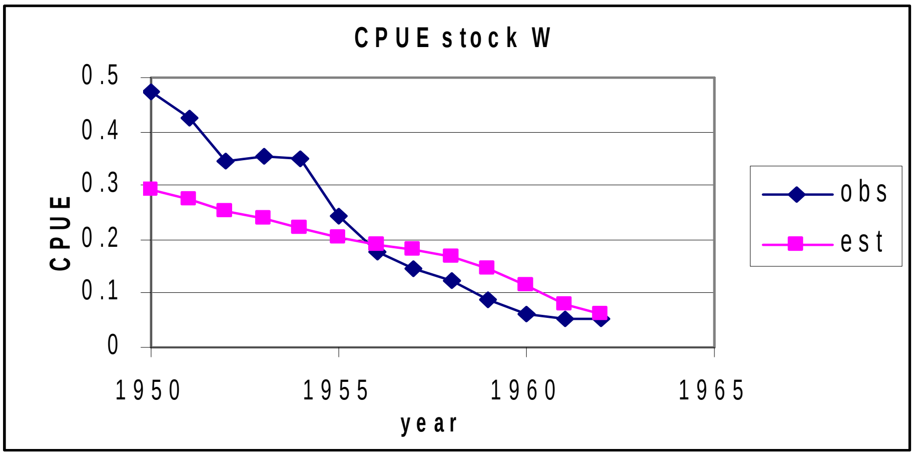


Figure 2: Base Case model fits to JARPA abundance estimates (for the feeding grounds).



Note: As the JARPA estimates are treated as indices of relative abundance, the model trajectory shown above is the true abundance multiplied by the estimated bias factor ($q_{JARPA}$ - respectively 1.56 and 1.18 for Area IV and V).

Figure 3: Base Case model fits to breeding ground CPUE trends.



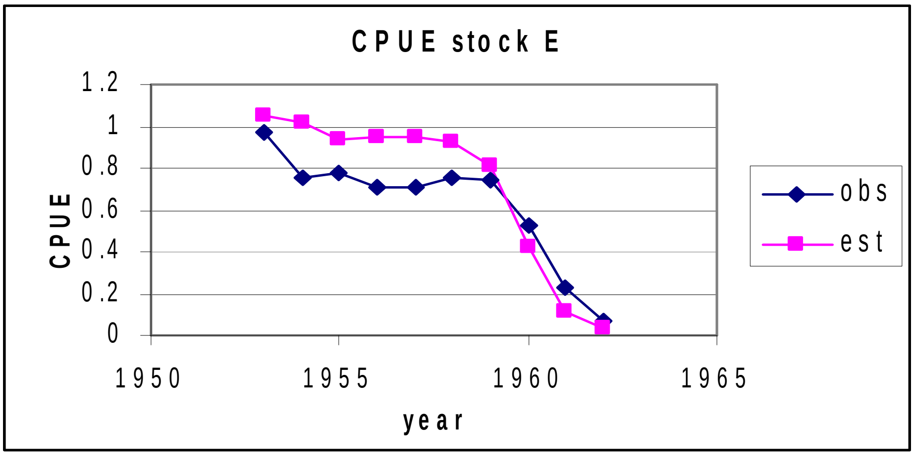
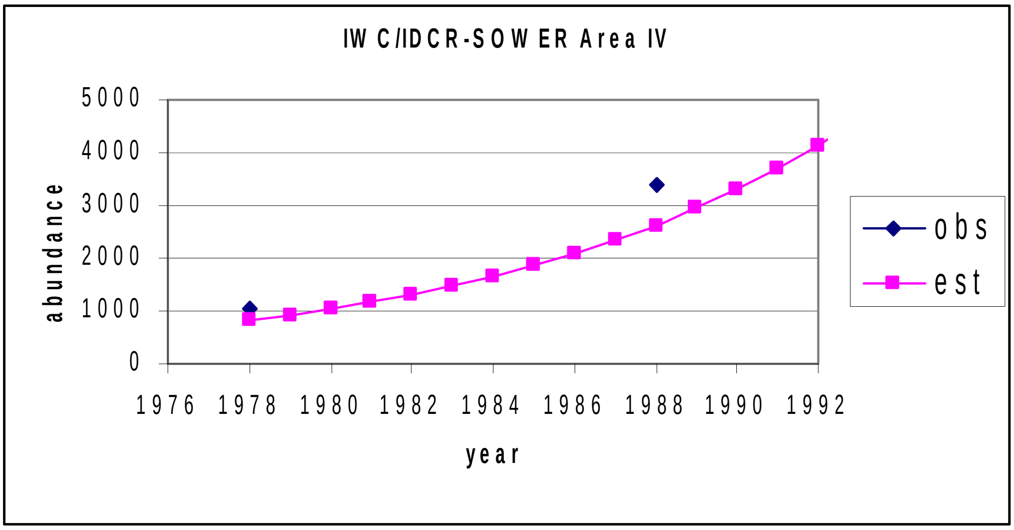


Figure 4: Comparisons between the IWC/IDCR-SOWER survey and Base Case model estimates of abundance in the feeding Areas.



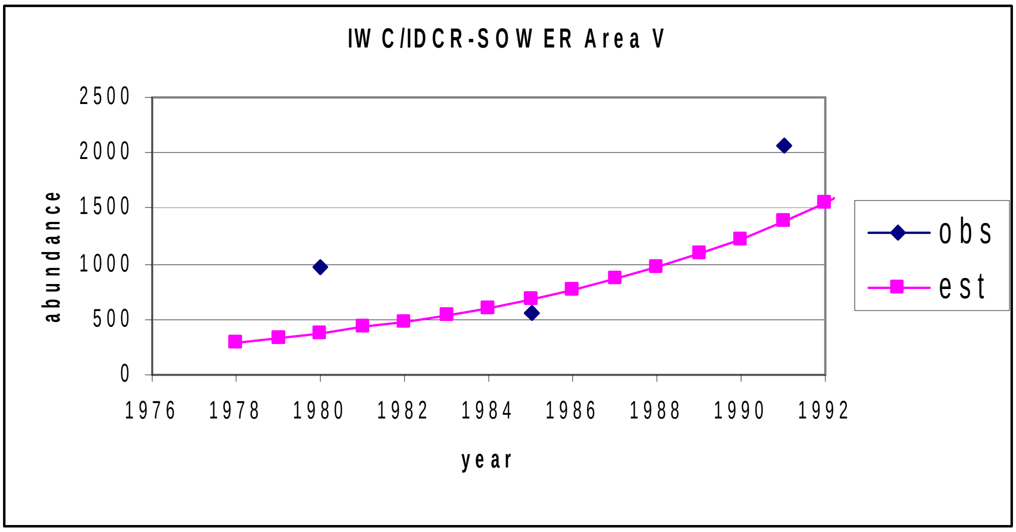
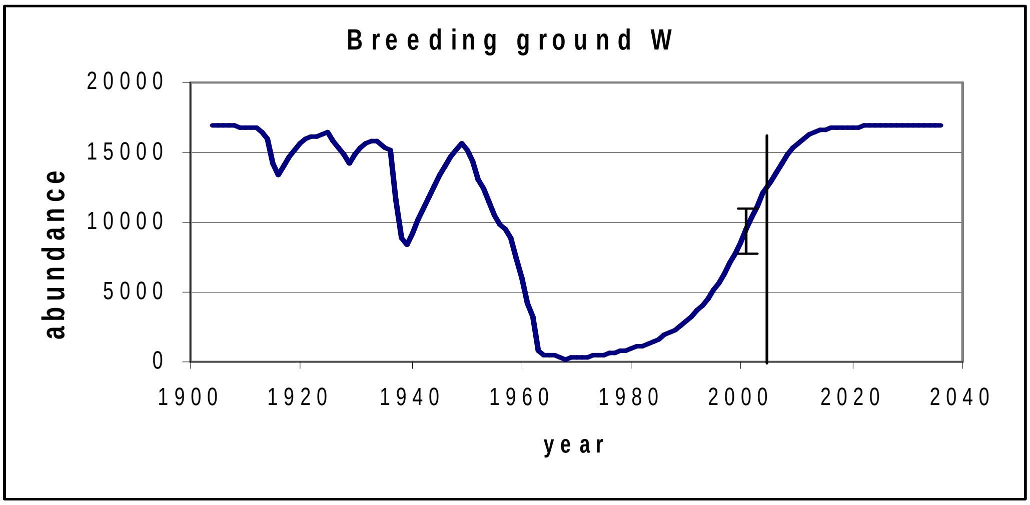


Figure 5a: Base Case estimated breeding population trends, with projected trajectories assuming a continued zero harvesting strategy. The vertical line indicates the start of the projection. The error bars denote a 90% bootstrap-based confidence interval for the 2000 population size (time precluded estimates of these intervals for other years).



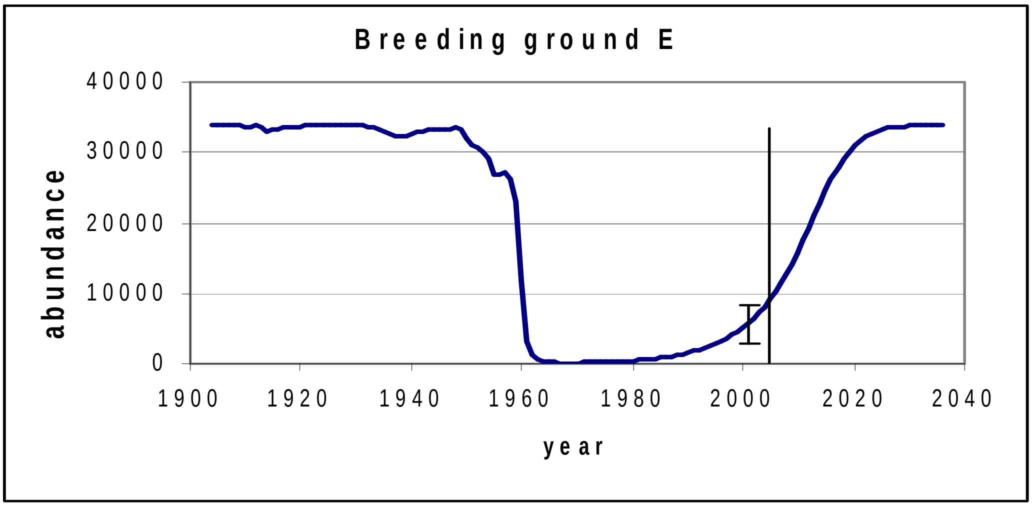
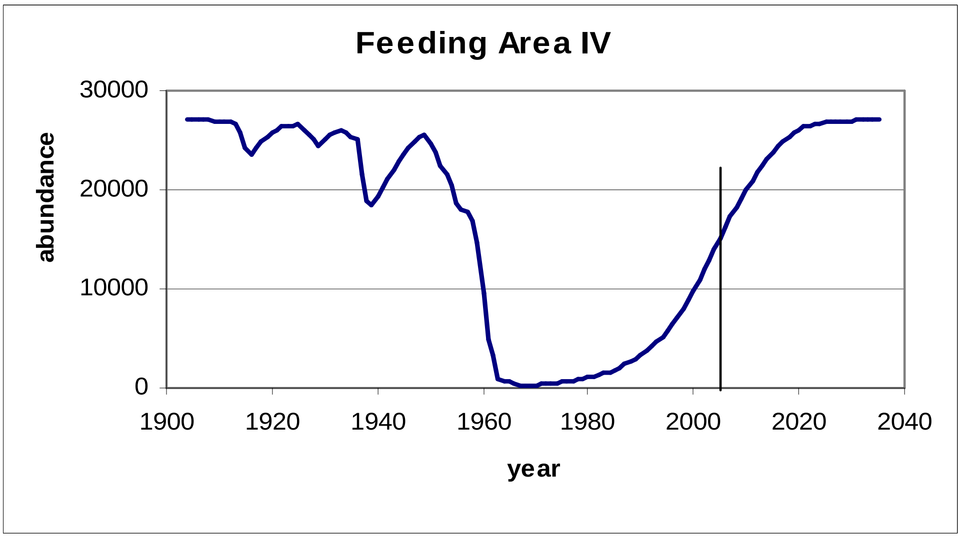


Figure 5b: Base Case estimated feeding stock trends, with projected trajectories assuming a continued zero harvesting strategy. The vertical line indicates the start of the projection.



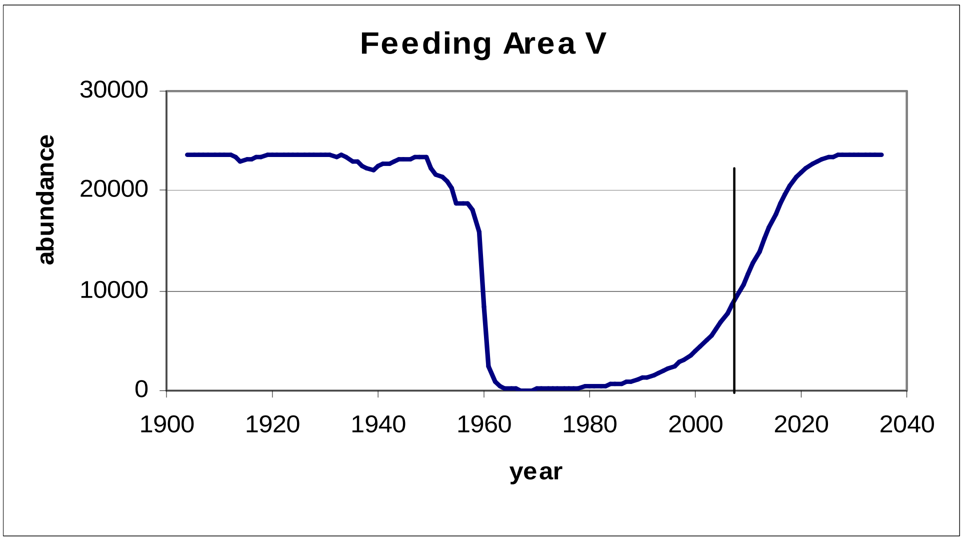
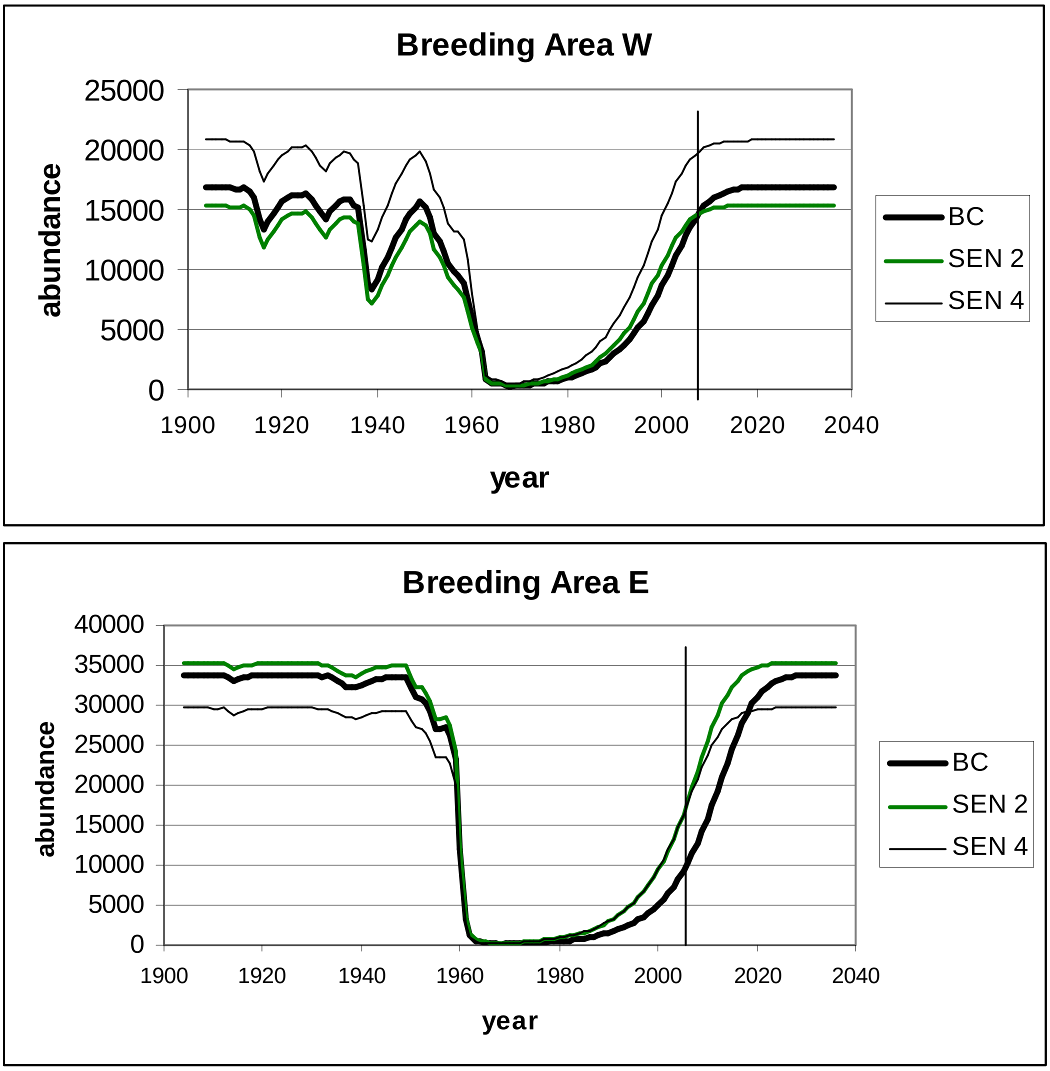


Figure 6a: Comparison between Base Case, Sensitivity 2 (excludes target abundance data and treats JARPA estimates as absolute) and Sensitivity 4 (target abundance data values increased) estimated breeding population trends, with projected trajectories assuming a continued zero harvesting strategy. The vertical line indicates the start of the projection.



## Appendix I. Allocation of Catches to Breeding Population and Feeding Stocks

All catches to the north of 40°S were allocated to breeding populations while all catches to the south of 40°S were allocated to feeding stocks. Tables I and II show the resulting catch series for the breeding grounds and for the feeding grounds respectively. Note that the feeding ground catches correspond to the catches for what has been previously described as the Naïve model (Findlay *et al.* 2000).

### Breeding Populations

Catches were allocated to breeding populations as follows (see Table I).

West: Land, floating factory and low latitude pelagic catches from the Australian West Coast, Soviet catches apportioned to Area IV (north of 40°S).

East: Land and floating factory catches from the Australian East Coast, New Zealand and Tonga, Soviet catches apportioned to Area V (north of 40°S).

### Feeding stocks

Catches were allocated to feeding stocks under the Naïve model. Catches are allocated to the two feeding Areas (IV and V) by year (see Table II).

Area IV: 60ºE - 120ºE : the 60ºE - 120ºE BIWS catches, Soviet catches apportioned to Area IV (south of 40°S), early Kerguelen Island catches, and the *Olympic Challenger* catches for 60ºE - 120ºE.

Area V: 120ºE - 170ºW : the 120ºE - 170ºW BIWS catches, Soviet catches apportioned to Area V (south of 40°S), the early Ross Sea catches, and the *Olympic Challenger* catches for 120ºE - 170ºW.

Table I. Southern Hemisphere humpback whale catches to the north of 40° S apportioned to breeding populations west and east of Australia. [Note that the year 1904, for example, represents the 1904/05 austral summer.]

| Year | West | East |
|---|---|---|
| 1904 | 0 | 0 |
| 1905 | 0 | 0 |
| 1906 | 0 | 0 |
| 1907 | 0 | 0 |
| 1908 | 0 | 0 |
| 1909 | 0 | 0 |
| 1910 | 0 | 0 |
| 1911 | 0 | 0 |
| 1912 | 296.0 | 296.0 |
| 1913 | 670.5 | 670.5 |
| 1914 | 1968.0 | 0 |
| 1915 | 1430.0 | 0 |
| 1916 | 0 | 0 |
| 1917 | 0 | 0 |
| 1918 | 0 | 0 |
| 1919 | 0 | 0 |
| 1920 | 0 | 0 |
| 1921 | 0 | 0 |
| 1922 | 155.0 | 0 |
| 1923 | 166.0 | 0 |
| 1924 | 0 | 0 |
| 1925 | 669.0 | 0 |
| 1926 | 735.0 | 0 |
| 1927 | 996.0 | 0 |
| 1928 | 1033.0 | 0 |
| 1929 | 0 | 0 |
| 1930 | 0 | 78.0 |
| 1931 | 0 | 110.0 |
| 1932 | 0 | 18.0 |
| 1933 | 0 | 44.0 |
| 1934 | 0 | 52.0 |
| 1935 | 0 | 57.0 |
| 1936 | 3072.0 | 69.0 |
| 1937 | 3242.0 | 55.0 |
| 1938 | 917.0 | 75.0 |
| 1939 | 0 | 80.0 |
| 1940 | 0 | 107.0 |
| 1941 | 0 | 86.0 |
| 1942 | 0 | 71.0 |
| 1943 | 0 | 90.0 |
| 1944 | 0 | 88.0 |
| 1945 | 0 | 107.0 |
| 1946 | 0 | 110.0 |
| 1947 | 2.0 | 101.0 |
| 1948 | 4.0 | 92.0 |
| 1949 | 193.0 | 141.0 |
| 1950 | 388.0 | 79.0 |
| 1951 | 1224.0 | 111.0 |
| 1952 | 1187.0 | 721.0 |
| 1953 | 1300.0 | 809.0 |
| 1954 | 1320.0 | 898.0 |
| 1955 | 1126.0 | 832.0 |
| 1956 | 1119.0 | 1013.0 |
| 1957 | 1120.0 | 1025.0 |
| 1958 | 967.0 | 1023.0 |
| 1959 | 737.0 | 1278.0 |
| 1960 | 573.0 | 1341.0 |
| 1961 | 587.0 | 981.0 |
| 1962 | 548.0 | 209.0 |
| 1963 | 87.0 | 0 |
| 1964 | 1.0 | 0 |
| 1965 | 5.0 | 0 |
| 1966 | 28.0 | 0 |
| 1967 | 12.0 | 0 |
| 1968 | 0 | 0 |
| 1969 | 0 | 0 |
| 1970 | 0 | 0 |
| 1971 | 0 | 0 |
| 1972 | 0 | 0 |
| 1973 | 0 | 0 |
| 1974-2003 | 0 | 0 |

Table II. Southern Hemisphere humpback whale catches to the south of 40° S apportioned to the two feeding Areas IV and V. [Note that the year 1904, for example, represents the 1904/05 austral summer.]

| **Year** | **IV** | **V** |
|---|---|---|
| | 60-120E | 120E-170W |
| 1904 | 0 | 0 |
| 1905 | 0 | 0 |
| 1906 | 0 | 0 |
| 1907 | 0 | 0 |
| 1908 | 217.0 | 0 |
| 1909 | 118.0 | 0 |
| 1910 | 83.0 | 0 |
| 1911 | 0 | 0 |
| 1912 | 0 | 0 |
| 1913 | 0 | 0 |
| 1914 | 0 | 0 |
| 1915 | 0 | 0 |
| 1916 | 0 | 0 |
| 1917 | 0 | 0 |
| 1918 | 0 | 0 |
| 1919 | 0 | 0 |
| 1920 | 0 | 0 |
| 1921 | 0 | 0 |
| 1922 | 0 | 0 |
| 1923 | 0 | 0 |
| 1924 | 0 | 0 |
| 1925 | 0 | 0 |
| 1926 | 0 | 0 |
| 1927 | 0 | 0 |
| 1928 | 11.0 | 0 |
| 1929 | 0 | 0 |
| 1930 | 0 | 0 |
| 1931 | 159.0 | 0 |
| 1932 | 82.0 | 0 |
| 1933 | 593.0 | 0 |
| 1934 | 1340.0 | 0 |
| 1935 | 938.0 | 4.0 |
| 1936 | 1435.0 | 0 |
| 1937 | 832.0 | 0 |
| 1938 | 835.0 | 24.0 |
| 1939 | 0 | 0 |
| 1940 | 0 | 0 |
| 1941 | 0 | 0 |
| 1942 | 0 | 0 |
| 1943 | 0 | 0 |
| 1944 | 0 | 0 |
| 1945 | 0 | 0 |
| 1946 | 0 | 0 |
| 1947 | 1.0 | 0 |
| 1948 | 11.0 | 74.3 |
| 1949 | 725.2 | 1308.1 |
| 1950 | 1207.9 | 998.1 |
| 1951 | 958.5 | 486.8 |
| 1952 | 223.6 | 723.4 |
| 1953 | 309.9 | 1120.9 |
| 1954 | 379.5 | 2614.5 |
| 1955 | 844.2 | 156.6 |
| 1956 | 27.0 | 182.5 |
| 1957 | 544.8 | 1158.7 |
| 1958 | 1661.1 | 3182.1 |
| 1959 | 66.0 | 13159.0 |
| 1960 | 779.3 | 9846.7 |
| 1961 | 468.0 | 1936.0 |
| 1962 | 2352.0 | 290.6 |
| 1963 | 288.8 | 321.7 |
| 1964 | 91.5 | 70.7 |
| 1965 | 76.3 | 265.8 |
| 1966 | 172.0 | 112.0 |
| 1967 | 98.0 | 27.0 |
| 1968 | 0 | 0 |
| 1969 | 0 | 0 |
| 1970 | 0 | 0 |
| 1971 | 0 | 0 |
| 1972 | 0 | 0 |
| 1973 | 0 | 0 |
| 1974-2003 | 0 | 0 |