Stock Assessment of Blue Marlin (*Makaira nigricans*) in the Pacific with MULTIFAN-CL

External Peer Review

Prepared for the University of Miami Independent System for Peer Review

By

John Hampton

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Executive summary

I have conducted a review of a blue marlin stock assessment prepared by scientists from the National Marine Fisheries Service Honolulu Laboratory, the Inter-American Tropical Tuna Commission and the Japan National Research Institute of Far Seas Fisheries. A Statement of Work and the assessment report under review are attached as Appendices I and II, respectively. The review methodology was primarily a desk study of the assessment report and available literature, as well as a series of independent analyses carried out by the reviewer.

Blue marlin are captured throughout the tropical and sub-tropical Pacific Ocean, largely as incidental catch in tuna longline operations. Small numbers of blue marlin are also caught incidentally by purse seiners. In several Pacific locations, blue marlin are targeted by recreational tournament and charter-boat fisheries. Available catch, effort and length-frequency data for longline and eastern Pacific purse seine fisheries were compiled for the assessment. A length-based, age-structured, spatially explicit population model (known as MULTIFAN-CL) was used. The review made the following findings and recommendations:

(i) This assessment would be classified as relatively data-poor. Length-frequency data are entirely missing for some fisheries and not available for some periods in the other fisheries. The absence of small juvenile blue marlin from the catch and the biological characteristics of reproduction and recruitment make the length-frequency data fairly uninformative regarding growth rates and recruitment variability. Also, tagging data, which are often a critical source of semi-fishery-independent data in pelagic fisheries assessments, were not available for the assessment. These deficiencies required a number of simplifying assumptions to be made in the assessment, including: fixing the von Bertalanffy *K* parameter to a specific value (0.2); fixing movement rates to a specific, uniform value (0.1); assuming a uniform distribution of recruitment among the regions; assuming no age-dependency in natural mortality; and assuming common selectivity for JPN and TKP longline fisheries in the same region. For the most part, these assumptions seem reasonable under the circumstances. The advantage of using methodology like MULTIFAN-CL in such a case is that these assumptions are forced to be explicit, rather than being hidden in the structure of the model. Therefore, I find that the methodology used was appropriate for the blue marlin assessment.

(ii) The absence of large-scale tagging data is an important limitation in any stock assessment where fishery-independent surveys are infeasible. Tagging data potentially offer a direct link to absolute population size because the experimental, tagged population is known and therefore exploitation rates, if they can be reasonably extrapolated to the population in general, may be much better determined.

Recommendation 1: For future assessments, efforts should be made to incorporate all available blue marlin tagging data for the Pacific.

Recommendation 2: Carefully designed tagging experiments should be a fundamental part of any strategic research plan for blue marlin.

(iii) A shortcoming of the assessment is the lack of any rigorous sensitivity analyses for simplifying assumptions noted above. As demonstrated by some of the additional analyses that I have undertaken, different (but plausible) assumptions, or relaxation of assumptions, can produce somewhat different stock assessment interpretations. It is therefore recommended that:

Recommendation 3: Sensitivity analysis with respect to simplifying assumptions be carried out to determine their effects on the stock assessment results.

(iv) The available biological information on blue marlin suggests that there is profound sexual dimorphism in growth and perhaps in natural mortality. Neither the available data nor the population model were sex specific, which necessitated assumptions that all biological and exploitation processes are non-sex-specific. The effect that failure of this assumption has on the stock assessment results is unknown. Regarding historical data, there is probably little that can be done. However future catch sampling programs should, where possible, record the sex of blue marline sampled. In the short-term, it would be desirable to extend the MULTIFAN-CL model to provide sex-specific dynamics, even if most of the available data are, and will continue to be, grouped for sex. This would allow, for example, sex-specific growth and natural mortality parameters to be specified. If sex-ratio data are available for any fisheries, then these data could also be included in the estimation. At the very least, a sex-specific model would allow some investigation of the likely effects of sexually-dimorphic processes on stock assessment results. It is therefore recommended that:

Recommendation 4: Catch sampling programs record the sex of sampled blue marlin wherever possible.

Recommendation 5: The MULTIFAN-CL model be extended to provide sex-specific population dynamics.

Recommendation 6: Available data on the sex ratio of blue marlin catches be compiled and included in the model estimation in an appropriate form.

(v) The use of a habitat model to provide estimates of effective longline effort for the JPN fisheries allows spatial and temporal variability in the fishing depth of the gear and in the depth distribution of variables believed to constitute blue marlin habitat to be accounted for in the measure of fishing effort. This is a powerful tool in stock assessment of pelagic species. In some cases, such a procedure may allow simplifying assumptions to be made concerning the spatial and temporal variability in catchability and selectivity for fisheries so treated.

Recommendation 7: Simplification of assumptions concerning selectivity (constant among regions) and catchability (constant among regions and over time) for the JPN longline fisheries be investigated and incorporated into the stock assessment model as appropriate.

(vi) The presentation of the assessment report needs some modification to enhance readability and information content. Some suggestions include:

- Separate sections on data treatment for the habitat model and for MULTIFAN-CL;
- A complete table of parameter estimates, including information on constraints applied to each;
- Organize results in terms of a base-case analysis, with other sections dealing with sensitivity analyses in which important assumptions or fixed parameters are varied over reasonable ranges.

(vii) The assessment report concluded, on the basis of the analyses undertaken, that blue marlin were currently being fished at near their MSY. However, the assessment gave no information concerning the current or historical state of the stock. I provided some additional analyses (for which the MULTIFAN-CL software needed to be extended) to show ratios of fishing mortality and adult biomass to their estimated MSY levels. For the model used in the assessment report, I found that fishing mortality was beneath the MSY level only

for the most recent two years of most of the time series. If the data for 1996 and 1997 used in the analysis are complete and this level of fishing mortality has been maintained in subsequent years, then the fishery would likely be operating within the MSY guideline. However, the estimated adult biomass was found to be significantly below the equivalent adult biomass at MSY during the previous 25 years indicating that the stock has been in an overfished state (according to the MSY criterion) during this time.

Recommendation 8: Future assessments include estimates of the ratios of annual fishing mortality to the fishing mortality at MSY and adult biomass at the beginning of each year to adult biomass at MSY.

(viii) I conducted two additional analyses to test the 'stock structure' assumptions made in the assessment report. These included a model in which very low movement among regions (akin to four essentially separate stocks) was assumed and a model in which the movement rates and average recruitment distribution among the regions were estimated. For the low-movement model, somewhat more optimistic stock assessment conclusions are drawn. This model fit the data and prior assumptions slightly better than the high-movement model. The model with movement rates and recruitment distribution estimated appeared to provide biologically reasonable results (although this should be checked by an expert in blue marlin biology) with a significantly better fit to the data and prior assumptions. The stock assessment results for this model were intermediate to those of the high- and low-movement models, but more similar to the high-movement results. This suggests that it may be feasible to estimate 'stock structure' parameters within the model itself.

Recommendation 9: Future assessments attempt to estimate movement rates and recruitment distribution as part of the model estimation process. Careful attention should be paid to whether or not such estimates produce biologically reasonable results.

1. Introduction

Blue marlin (*Makaira nigricans*) is a large pelagic species that occupies tropical and sub-tropical waters of the Pacific, Atlantic and Indian Oceans. A population assessment for the Pacific stock has been prepared by scientists from the National Marine Fisheries Service Honolulu Laboratory, the Inter-American Tropical Tuna Commission and the Japan National Research Institute of Far Seas Fisheries. This assessment is the subject of the present independent peer review, which was solicited by the University of Miami Independent System for Peer Review.

The terms of reference of the review were to examine:

(i) Assumptions in defining the stock structures based on genetic or other information;

(ii) Application of the most recent biological life-history data and long-term catch and effort data;

(iii) Underlying dynamics of the population model; and

(iv) Applicability of the population model to fisheries management.

The detailed Statement of Work is provided in Appendix I.

The review methodology consisted of a desk study that focused on the assessment document (Abstract provided in Appendix II). Copies of the data files and details of the implementation of the MULTIFAN-CL model were requested from the senior author of the assessment (P. Kleiber). The requested files were provided by email. Access to this information allowed me to conduct several independent model runs using the MULTIFAN-CL software to explore certain aspects of the assessment. These analyses are described in detail in section 4 of this review.

The structure of the review was designed in line with the terms of reference, with some slight modifications for reasons of clarity. In section 2, I briefly review information on the biology and fisheries for blue marlin in the Pacific. This is not meant to be exhaustive but is intended to cover the points of most relevance to the assessment. Section 3 focuses in detail on the assessment methodology, including the population dynamics model (TOR iii), the data analysed (TOR ii), the assumptions (mainly concerning biology) of the analysis (TORs i and ii), and the assessment results and conclusions (TOR iv). In section 4 the results of independent analyses conducted during the course of this review are described. Finally, I provide a summary of findings and recommendations in section 5.

2. Blue marlin biology and fisheries in the Pacific

Blue marlin are circumtropically distributed in the world's oceans, inhabiting mainly the upper mixed layer where surface temperatures exceed 24ºC (Nakamura 1985; Hinton and Nakano 1996). In the Pacific, longline catches are concentrated between about 20ºN and 20ºS in a more or less continuous basin-scale band (Figure 1). Larvae occur in the same general area, but with higher concentration in the western Pacific (Nishikawa et al. 1985). No evidence for genetically distinct sub-populations in the Pacific has been found (Graves and McDowell 1995; Buonaccorsi et al. 1999), but the degree of basin-scale population mixing remains largely unknown due to a paucity of tagging data for this species. However, the tagging data that are available, including recent electronic pop-up tagging, have

demonstrated the potential for long-distance movement, with a number of observed tagged-fish movements on scales of thousands of miles over time frames of several months (www.tagagiant.com/tagamarlin).

Growth and/or mortality of blue marlin are thought to be highly sex-specific, as female blue marlin reach much greater sizes than males (Nakamura 1985). This sexual dimorphism may have implications for stock assessment. Estimates of growth rates have been reported by Skillman and Yong (1976), and this information has been incorporated into the assessment. Estimates of natural mortality are not available, although reported longevity of >10 years would provide an upper limit on natural mortality of about 0.4 yr^{-1}.

Blue marlin are captured primarily by longliners targeting bigeye and yellowfin tuna. Annual catches peaked in the early 1960s at around 20,000 t, declined to around half that level during the 1970s, and then increased during the 1980s and 1990s to average about 15,000 t annually (Figure 2). Significant incidental catches of blue marlin are also taken by purse seiners, mainly in sets on floating objects. In the eastern Pacific, these catches have been in the vicinity of 1,000 t in recent years (Figure 1a, Appendix II). In the western Pacific, recent annual purse seine catches are estimated to be on the order of hundreds of tonnes (Lawson 1997). Small catches of blue marlin are also taken in recreational fisheries in various locations around the Pacific. While catches are small, these fisheries may be quite significant to local economies.

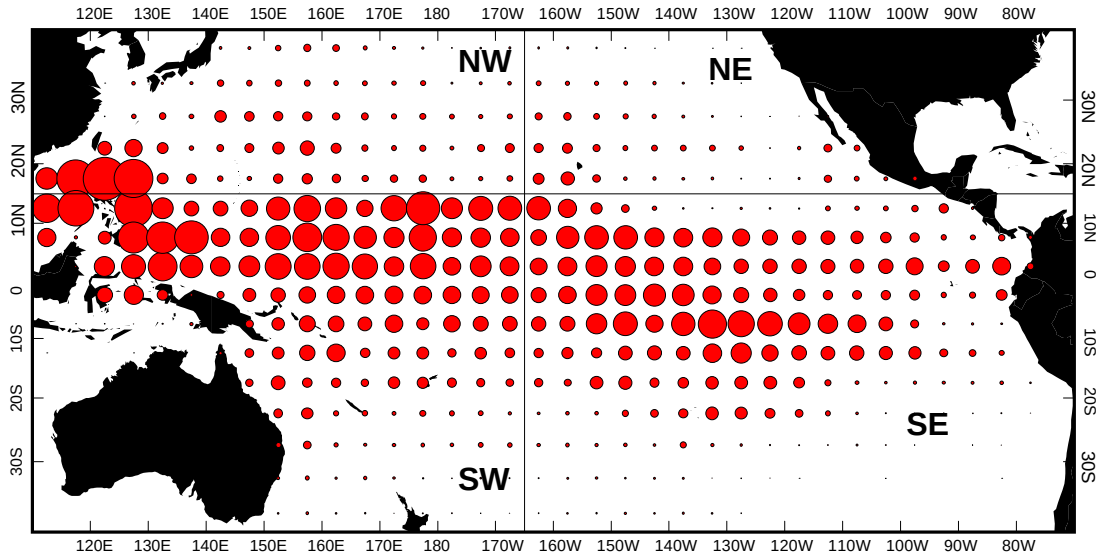

Figure 1. Distribution of blue marlin longline catch in the Pacific Ocean, 1962-1999. The definition of regions used in the assessment is shown. *Source: Standing Committee on Tuna and Billfish Public Domain Data.*

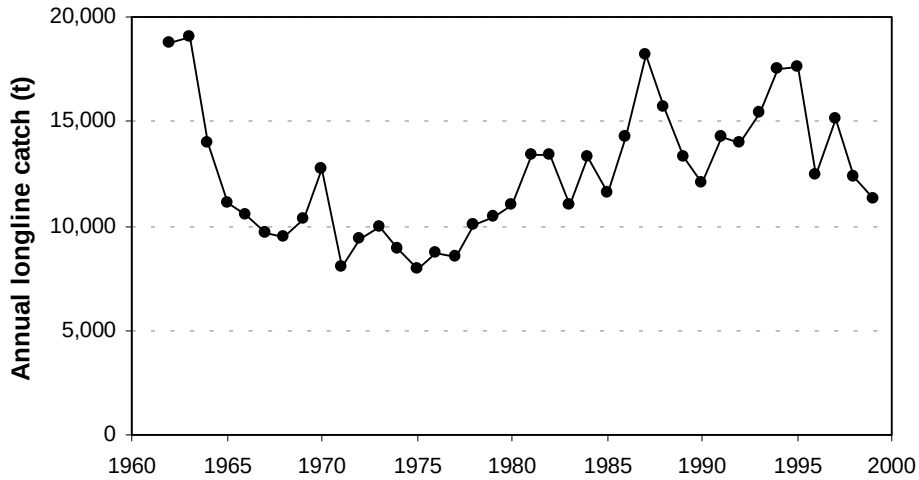

Figure 2. Estimated Pacific-wide blue marlin longline catch. *Source: Standing Committee on Tuna and Billfish Public Domain Data.*

3. Assessment methodology

3.1. MULTIFAN-CL

The methodology that has been applied to blue marlin stock assessment is known as MULTIFAN-CL (Fournier et al. 1998; Hampton and Fournier 2001). MULTIFAN-CL is a length-based, age structured model that uses statistical theory to fit the model to observed data. With the advent of faster computers, the application to stock assessment of complex (though more realistic) models of this class is becoming more widespread. Some of the features of this approach to stock assessment modeling, and of the MULTIFAN-CL software in particular, that have particular relevance to the blue marlin assessment are as follows:

- The statistical foundation of the model, which is fundamentally Bayesian, allows a structured approach to model development, i.e. statistical theory can be applied to determining the level of model complexity most appropriate to the available data, the biological characteristics of the stock, and the nature of the fisheries.
- The model can accommodate spatial heterogeneity, through the incorporation of spatial structure in the population and fisheries and fish movement. This is important for blue marlin assessment where there is uncertainty in the rate of basin-scale population mixing – a spatially explicit model offers the potential to estimate movement (mixing) rates, or if estimation is infeasible, to examine the sensitivity of the results to different mixing assumptions.
- The model employs a structural time series approach to estimating catchability for each fishery defined in the model. This allows the usual and often unrealistic assumption of constant catchability over time to be relaxed.
- The model allows the definition of multiple fisheries, each of which may have its own exploitation characteristics (selectivity and catchability coefficients).

- As a consequence of the statistical fitting procedure employed by the model, a certain amount of missing effort and size composition data can be accommodated. It is therefore unnecessary to use arbitrary but often complicated schemes to 'substitute' length-frequency data (in particular) into strata where no observations exist. The likelihood function consists only of contributions from data that were actually observed. This is of particular importance to the blue marlin assessment, where length-frequency data are not available for every fishery for all time periods.
- Information obtained from the fitting procedure can be used to compute approximate posterior probability distributions for model parameters and other quantities of interest. This procedure is amenable to comparison of current estimated stock status in relation to particular biological reference points and to assessment of future harvest strategies using risk analysis.

For these reasons, I believe that MULTIFAN-CL is an appropriate framework in which to conduct blue marlin stock assessment. In addition to the points made above, the model is implemented in optimized C++ computer code using advanced numerical features, such as computation of exact derivatives using automatic differentiation. These and other features allow highly efficient parameter estimation, which is essential for stock assessment using large, complex models in situations where, as always, time is limited.

3.2. Definition of fisheries

MULTIFAN-CL requires the definition of "fisheries" that consist of relatively homogeneous fishing units. Ideally, the fisheries so defined will have selectivity and catchability characteristics that do not vary greatly over time (although in the case of catchability, some allowance can be made for time-series variation). However, it is seldom practicable or even necessary to stratify the data into a large number of fisheries so as to isolate all variability in these parameters. More fisheries means more parameter complexity, so a parsimonious approach is required. For most pelagic fisheries assessments, fisheries defined according to gear type, fishing method and region will usually suffice.

For the blue marlin assessment, 14 fisheries were defined:

1–4 Japan and Mexico longline, regions 1–4

5–8 Other nationalities longline, regions 1–4

9–10 Purse seine dolphin sets, regions 1–2

11–12 Purse seine floating object sets, regions 1–2

13–14 Purse seine unassociated sets, regions 1–2

The classification of the longline fisheries by nationality was on the basis of the availability of set configuration data. Such data were available for the Japan and Mexico fleets (denoted JPN), which allowed the application of a habitat model (Hinton and Nakano 1996) to estimate effective longline effort. This allows the number of longline hooks fishing in defined blue marlin habitat (the surface mixed layer) to be estimated accounting for spatial and temporal variability in mixed layer depth and the depth distribution of the fishing gear. In principle, this procedure would remove environmental and operational variability in catchability and thus the CPUE data would better reflect the exploitable abundance of the

population. The habitat model could not be applied to the longline fleets of other nationalities (denoted TKP), and it is therefore reasonable to expect that the CPUE data would not be as informative regarding trends in exploitable abundance. Such variable 'quality' of effort data for the different fisheries is recognized in the model by assigning different prior variances to the effort deviations (or residuals). In the blue marlin assessment, the prior variance of effort deviations for the JPN fisheries was equivalent to a CV of approximately 0.2, whereas for the TKP fisheries, it was set to approximately 0.7. This appears to be a reasonable weighting for these fisheries. Surprisingly, however, the purse seine fisheries were accorded a similar prior variance to the JPN fisheries. Consideration could be given to down-weighting the purse seine effort data to an intermediate prior variance to reflect the greater intrinsic variability of purse seine effort and CPUE with respect to a non-target species such as blue marlin.

3.3. Model assumptions

As with any model, various structural assumptions have been made in the blue marlin model. Such assumptions are always a trade-off to some extent between the need, on the one hand, to keep the parameterization as simple as possible, and on the other, to allow sufficient flexibility so that important characteristics of the fisheries and population are captured in the model. The main structural assumptions made in the blue marlin assessment are discussed below, with my own comments on their appropriateness.

3.3.1. Spatial structure and movement

As noted earlier, there is considerable uncertainty regarding blue marlin stock structure in the Pacific. Analyses of genetic material have been unable to demonstrate the existence of distinct genetic stocks of blue marlin in the Pacific found (Graves and McDowell 1995; Buonaccorsi et al. 1999). Also, limited tagging data have demonstrated that individual blue marlin are able to undertake movements on the scale of thousands of miles within a time frame of months (www.tagagiant.com/tagamarlin). Nevertheless, it is still possible that overall basin-scale movement may be restricted to the extent that local exploitation effects are not immediately 'smeared' over the entire stock range. There is therefore a need in blue marlin assessment to at least be able to consider alternative hypotheses regarding movement rates. For this reason, I would strongly support the decision of the investigators to use a model with spatial structure. While the spatial configuration is rudimentary (4 regions, as shown in Figure 1), this is probably sufficient to examine different hypotheses. Also, a more complex spatial disaggregation would not be warranted given the lack of explicit data on movement (e.g., as would be available from large-scale tagging data).

While the modelling framework used has the flexibility to allow different movement hypotheses to be examined, the present assessment fails to do this. Rather, it makes the assumption that movement rates are high (annual coefficients of 0.1 between all regions) and that recruitment is uniformly distributed among the regions. As the authors point out, this is not much different to carrying out a spatially-aggregated analysis. Presumably, lack of time precluded different hypotheses being examined. This is an obvious limitation of the present assessment that should be addressed in due course. I examined two different alternatives to the model structure presented – (i) movement coefficients of 0.01 (equivalent to

four almost independent stocks in the Pacific); and (ii) movement coefficients and recruitment distribution estimated within the model. The results of these model runs are described in section 4.

3.3.2. Age and growth

Growth of blue marlin is modeled using a von Bertalanffy growth equation. The MULTIFAN-CL model normally obtains information on growth from the length-frequency data, which in turn provides a basis for catch-at-age estimation. However, in the case of blue marlin, recruitment to all fisheries occurs at a relatively large size, >100 cm eye-FL. Also, larval sampling data (Nishikawa et al. 1985) suggest that spawning (and therefore subsequent recruitment of juveniles to the population) occurs year-round in tropical waters. These features of the fisheries and biology mean that clear age-class modes would not be expected to be apparent in the length-frequency samples. The data would therefore be fairly uninformative regarding growth and age structure. An added complication is that blue marlin are suspected of being strongly sexually dimorphic with regards to growth. As sex-specific length-frequency data are not available, any growth signal that might be present in male and female length frequencies separately would obviously be smeared in composite male-female samples. For the present assessment, the authors have taken what appears to be the only feasible option, that is, to fix the von Bertalanffy K parameter at an average value indicated by the literature. However, the effect that this assumption has on the assessment results is unknown and is a source of uncertainty in the results.

For age-structured models in general, it is necessary to specify the number of significant age classes in the population, with typically the last age class being defined as a 'plus group', i.e. consisting of fish that age and older. In the current assessment, twenty age classes have been used, but alternatives are yet to be tried. It would be useful to try alternative models with different numbers of age classes to see if the fit to the data could be improved (or not significantly degraded in the case of fewer age classes).

3.3.3. Recruitment

'Recruitment' in terms of the MULTIFAN-CL model is the appearance of age-class 1 fish in the population. In this assessment, it was assumed that recruitment is equally distributed among the model regions, which in combination with high assumed movement rates made for a fairly homogeneous population. However, it seems to me that more realistic hypotheses could be posed regarding the distribution of recruitment. The fact that so little of the catch occurs in the two northern regions would suggest that more recruitment occurs in the southern regions. Also, the greater area of warm-water habitat in the western Pacific might similarly suggest that recruitment would be higher in the west. In one of the independent analyses described in section 4, I have allowed the distribution of recruitment to be independently estimated, with not unreasonable results. Consideration could be given to this approach in future assessments.

Recruitment was assumed to occur as an instantaneous annual event at the start of each year. This assumption is largely forced by the need to keep the recruitment parameterization as simple as possible in the context of the present options available in the MULTIFAN-CL software. Perhaps an assumption more consistent with the life history of blue marlin (more or less continuous spawning and recruitment) would

be to retain an annual recruitment parameter, but to distribute it evenly across the months within each year. This would require some software development but would not be particularly difficult.

3.3.4. Catchability and selectivity

Selectivity is fishery-specific and was assumed to be time-invariant. Selectivity coefficients have a range of 0–1. In one model run, the coefficients for all fisheries were assumed to be non-decreasing with age. However, when this constraint was removed, the estimated selectivities tended to decline for the older age classes, and the stock size estimates were deemed to be impossibly large. The approach taken by the authors, with which I concur, was to consider the non-decreasing selectivity model as providing minimum estimates of stock size, while noting that some degree of selectivity decline and higher stock sizes were valid possibilities.

Selectivity parameters were constrained to be equal for the JPN and TKP longline fisheries fishing in each region, mainly because no length-frequency data were available for the TKP fleets. Longline fisheries fishing in different regions were allowed separate selectivity parameters. These assumptions are quite reasonable for a preliminary analysis. However, I wonder whether or not more selectivity parameter sharing among fisheries would significantly degrade the model fit. For example, would it be reasonable to constrain <u>all</u> longline fisheries to have the same selectivity, thus attributing differences in length-frequency distributions among the regions to the underlying sub-populations? This may be an area where some parameter 'savings' can be made at little 'cost' to the fit, and I would recommend that this be investigated.

Catchability was allowed to vary slowly over time (akin to a random walk) for all fisheries using a structural time-series approach. Random walk steps were taken annually, but the variance of the catchability deviations was constrained to enhance the stability of the model. Seasonal variation in catchability was also modeled in order to explain the strong seasonal variability in CPUE for most of the fisheries. As with selectivity, it may be possible to constrain, in particular, the catchability coefficients of the four JPN fisheries to be the same. This would 'save' a large number of parameters and may be justifiable given the common standardization of fishing effort (habitat model) applied to these fisheries. If this were done, particular attention would need to be paid to defining the effective relative size of each region, so that the population size estimates were correctly scaled to the common catchability parameters.

3.3.5. Natural mortality

Natural mortality was an estimated parameter, but was assumed to be invariant over time, age and region. This is an assumption made for most stock assessments. Estimation of age-specific natural mortality rate was not attempted, but there appeared to be little information in the data to support this more complex model – experience with MULTIFAN-CL and similar models suggests that age-specific natural mortality estimation is generally only possible when extensive tagging data are incorporated into the estimation. That said, it might be interesting to see if selectivity decline for older age classes persisted in the unconstrained selectivity model if *M*-at-age were allowed (or assumed) to increase for the older age classes.

3.4. Data used to fit the model

The data used to fit the model are described in the assessment report. I found this section of the report to be a little confusing. In places, it is difficult to know if the procedures being described relate to the data being analysed by the habitat model to derive estimates of effective longline effort, or to the data being input to MULTIFAN-CL. For example on p. 5 of the report it is stated that "Catch data in weight by area were required for the analyses" and considerable detail is devoted to describing the estimation of average weights. However, it is clear from the MULTIFAN-CL data file that catches in number are being analysed. Perhaps breaking this section into two parts would help clarify matters.

Overall, I would classify the assessment as relatively 'data poor' for this type of model. Considerable compromise in terms of constraining or fixing parameters was required because of this. In my view, this is not a weakness of the assessment given the data available – I believe that it is better to accommodate 'data poor' situations in this manner than to use simpler and possibly unrealistic models where the assumptions are structural (implicit) rather than parameterized (explicit). The approach that has been taken at least allows the effects of the various assumptions to be tested by changing the assumed parameter values. This is not possible where the assumptions are implicit.

The length-frequency data available for the assessment is by no means complete. No data at all were available for the TKP longline fleets, while 39% of JPN longline strata and 17% of purse seine strata were not covered by length-frequency samples. Fortunately, the assessment methodology used can allow for a certain amount of missing data without the need to generate artificial data through elaborate data substitution schemes. In the case of the TKP longline fishery, an assumption that the selectivity coefficients were the same as those for the Japan/Mexico fishery was required. This is a reasonable assumption to make under the circumstances. However, it would be highly desirable that future longline catch sampling programs include adequate coverage of the TKP fleets.

The absence of large-scale tagging data is an important limitation in any stock assessment where fishery-independent surveys are infeasible. Tagging data potentially offer a direct link to absolute population size because the experimental, tagged population is known and therefore exploitation rates, if they can be reasonably extrapolated to the population in general, may be much better determined. For future assessments, efforts should be made to incorporate all available blue marlin tagging data for the Pacific. Additionally, carefully designed tagging experiments should be a fundamental part of any strategic research plan for blue marlin.

3.5. Assessment results

The results of the assessment may be summarized as follows:

- The fitted population model was able to provide a reasonably accurate representation of the observed catch and length-frequency data.
- The habitat-model standardized effort for the JPN longline fisheries and the nominal effort for the purse seine fisheries suggested reasonably constant catchability over time (apart from seasonal patterns). Nominal effort for the TKP longline fisheries suggested a recent decline in catchability in three of the four regions.

- The assessment results were very sensitive to the non-decreasing selectivity constraint (NDSC). Removal of the constraint resulted in a better nominal fit to the data, but the overall results, particularly for absolute population size, were implausible. Fits without NDSC were therefore not considered for stock assessment purposes.
- Total recruitment shows a sharp decline during the 1960s and is relatively stable thereafter. The estimated biomass decline is largely driven by the recruitment pattern, although there is also a significant impact of fishing – recent biomass is approximately 30% lower than it would have been in the absence of fishing. Note that this fishery impact assumes that there has been no effect of fishing on recruitment, i.e. that the recruitments estimated to have occurred under the observed fishing regime would also have occurred if no fishing had ever taken place. However, the estimated stock-recruitment relationship suggests that recruitment has shown some sensitivity to adult biomass decline, so this estimate of fishery impact may be under-estimated.
- Estimated fishing mortality (expressed as total annual catch divided by estimated abundance at the start of each year) increases to approximately 0.15 in the mid-1980s, after which it falls to about half that level in the last couple of years of the assessment period. By comparison, the natural mortality rate was estimated at 0.38 yr^{-1}.
- Two yield analyses were undertaken in order to estimate maximum sustainable yield (MSY) and related quantities. The yield analyses were based on the model with the NDSC assumption, and they differed only in the average fishing-mortality-at-age assumed for the base *F* in the analysis. In case 1, base *F*-at-age was calculated as the average over the last 5 years of the assessment; in case 2 an average over the last 2 years was used. The *F*-at age multiplier associated with MSY in case 1 was approximately 0.7, implying that the 1993–1997 average *F*-at-age was higher that that producing MSY. For case 2, the *F*-at-age multiplier associated with MSY was approximately 1.3, implying that the 1996–1997 average *F*-at-age was lower than that producing MSY. This difference is simply due to the reduction in estimated *F* for the last two years of the analysis rather than any change in the age-specific pattern of exploitation.

3.6. Assessment conclusions

Under the current paradigm of reference-point-based assessment, it is necessary to assess the current level of exploitation in relation to some pre-defined reference point(s). The authors have essentially completed this task in the current assessment by estimating multipliers of recent *F*-at-age that correspond to MSY. On this basis they concluded that the current fishing effort is close to that which produces the MSY. Ideally, some notion of uncertainty should be built in to this comparison. While the yield curves themselves have associated confidence intervals, it is not straightforward to provide equivalent confidence intervals on the ratio F/F_{MSY} . I extended the MULTIFAN-CL model to provide estimates of F_y/F_{MSY} for each year as well as their 95% confidence intervals. In this case, I have used the same simplified definition of *F* as proposed by the authors, i.e. total annual catch divided by the population at the start of the year. I expressed both quantities in terms of biomass, consistent with the rest

of the yield analysis. One advantage of estimating F_y / F_{MSY} internally in the model is that the confidence intervals of the ratio are likely to be smaller than those of either component of the ratio alone.

The estimation of F/F_{MSY} is one means of establishing if *overfishing* is currently occurring or if it has occurred in the past. The other issue that must be addressed in an assessment is whether or not the current status of the stock is *overfished*. This has not been formally dealt with in the assessment. The usual way that this is done is to estimate the time series of B_y / B_{MSY}, where biomass (*B*) may be either total or adult biomass. In this instance, adult biomass is probably more meaningful as it corresponds more closely to the exploited portion of the population. I have also extended the MULTIFAN-CL software to provide estimates of B_y / B_{MSY} and their 95% confidence intervals. Time series of both F_y / F_{MSY} and B_y / B_{MSY} are provided in the next section for the yield analyses presented in the assessment report.

Because of data limitations, a variety of assumptions were imposed on the assessment, including fixing the von Bertalanffy *K* parameter at 0.2 yr^{-1}, assuming no age-dependency in natural mortality, assuming a uniform distribution of recruitment among the regions and fixing movement rates to relatively high values. Alternatives to these assumptions, which could have profound effects on the assessment results, have not yet been explored. In data-limited cases where parameters must be fixed, thorough sensitivity analyses take on even greater importance. This is a shortcoming of the present assessment that needs to be addressed. As examples, some alternative hypotheses with respect to movement and recruitment distribution are examined in the next section.

4. Independent analyses

Some independent analyses have been undertaken using the data and model configuration files provided by the senior author. The objectives of these analyses were to:

(i) Provide times series of F_y / F_{MSY} and B_y / B_{MSY} for the analyses provided in the assessment report and for the other independent analyses; and

(ii) Investigate the effects on the assessment results of the following alternative hypotheses regarding movement rates and the distribution of recruitment: A. movement among regions is relatively low (coefficients of 0.01 cf. 0.10 per year assumed in the assessment report); and B. movement among regions and the distribution of recruitment among regions are estimated parameters of the model.

4.1. F- and B-ratios for the existing analyses

The time series of F_y / F_{MSY} and B_y / B_{MSY} for the yield analyses presented in the assessment report are shown in Figure 3 (the two yield analyses produced essentially identical results in terms of these ratios). It is evident that the *F*-ratio exceeded 1.0 for much of the time series and that it is only in the most recent two years that fishing mortality has been within the F_{MSY} reference point. Under the B_{MSY} reference point, the population would be classified as overfished since the early 1970s. The fact that the stock appears to have been sustainably fished at this level for nearly 30 years may say something about the MSY reference point paradigm!

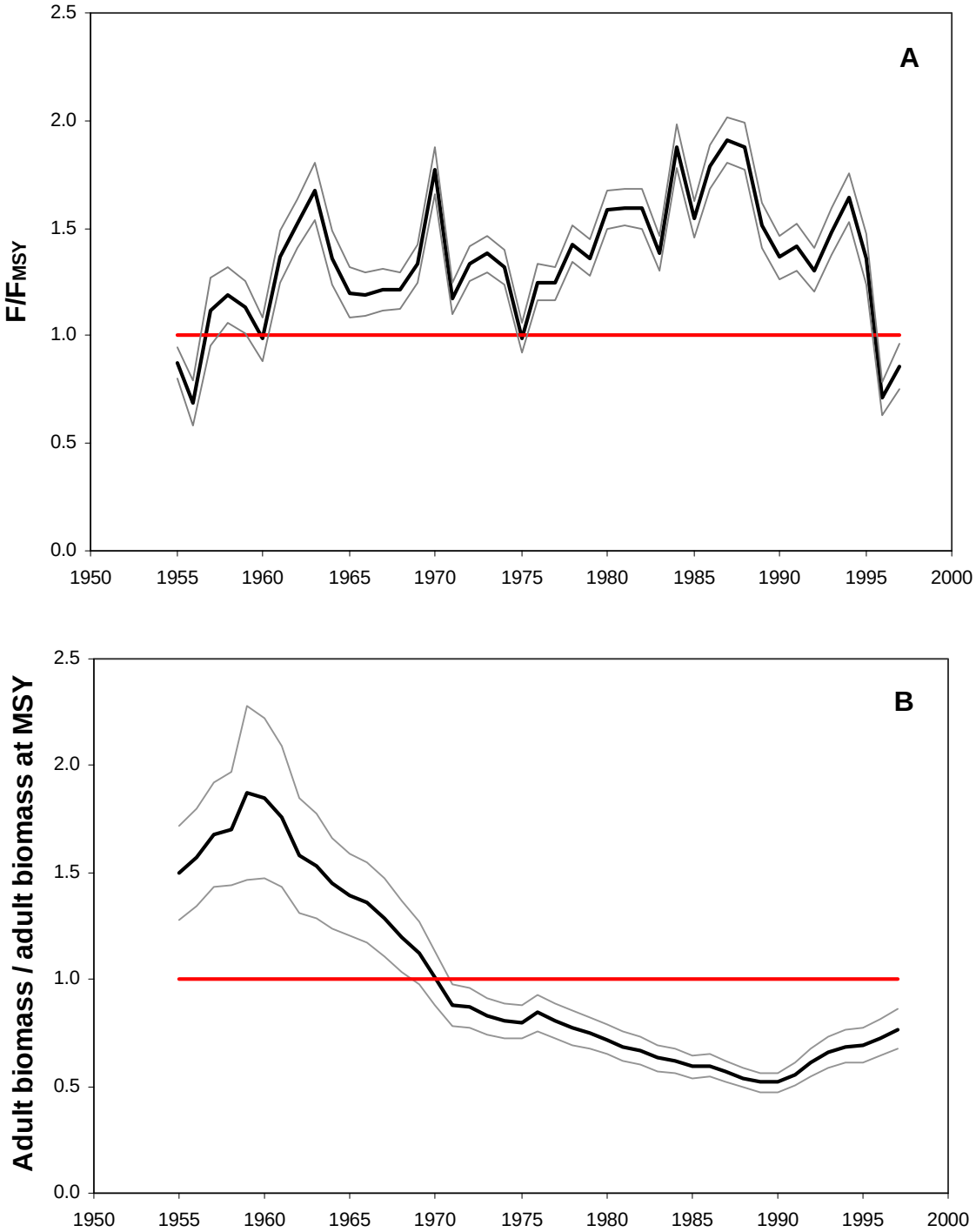

Figure 3. Assessment report yield analysis results: time series of (A) the ratio of *F* (calculated as total annual catch divided by total biomass at the start of each year) to *F* at MSY and (B) B_{adult} to B_{adult} at MSY, with 95% confidence intervals. Points above the horizontal line in (A) are indicative of overfishing. Points below the horizontal line in (B) are indicative of the population being in an overfished state.

4.2. Analysis with low movement rates assumed

This analysis was identical to that presented in the assessment report, with the exception that the assumed movement coefficients were 0.01 rather than 0.1 per year among all regions. This would represent a situation where the blue marlin stock was partitioned into four components represented by the four model regions with relatively little exchange.

The estimates of *F*-ratios and *B*-ratios are shown in Figure 4. This analysis presents a somewhat more optimistic picture of level of exploitation and status of the stock. Fishing mortality exceeded the MSY level less frequently than under the high movement assumption, and the level of adult biomass has been near the MSY level since about 1980. This model resulted in a slightly better fit to the data and prior assumptions than the high-movement model (log-likelihood value of 92,407.6 cf. 92,403.5).

4.3. Analysis with estimated movement rates and recruitment distribution

In this analysis the 12 movement coefficients linking the 4 regions were estimated, along with the distribution of recruitment among the regions. The recruitment distribution was assumed to remain constant over time. Full documentation of the model configuration is provided in Appendix III, which lists the shell script that I used to run MULTIFAN-CL for this analysis.

The growth, selectivity and catchability trend results obtained with this model are similar to those in the assessment report. The natural mortality rate is estimated to be lower, 0.18 yr^{-1}, but still within reasonable bounds. Average catchability coefficients, and hence fishing mortalities, are somewhat higher. The matrix of estimated annual movement rates is as follows:

	To NE	To SE	To SW	To NW
From NE	–	0.67	0.66	0.00
From SE	0.39	–	0.00	0.06
From SW	0.17	0.00	–	0.13
From NW	0.00	0.00	0.14	–

The estimated movement rates, which are based on differences in estimated age structure among the regions, are very heterogeneous, with generally higher movement rates estimated in the N↔S directions than in the E↔W directions. The log-likelihood function value obtained for the model was 92,589.1, which compared to the value obtained for the low-movement, uniform-recruitment model of 92,407.6, the latter model involving 15 fewer estimated parameters. This difference in log-likelihood is highly significant under any model selection criteria. Whether or not the results are biologically reasonable would be best considered by experts in blue marlin biology.

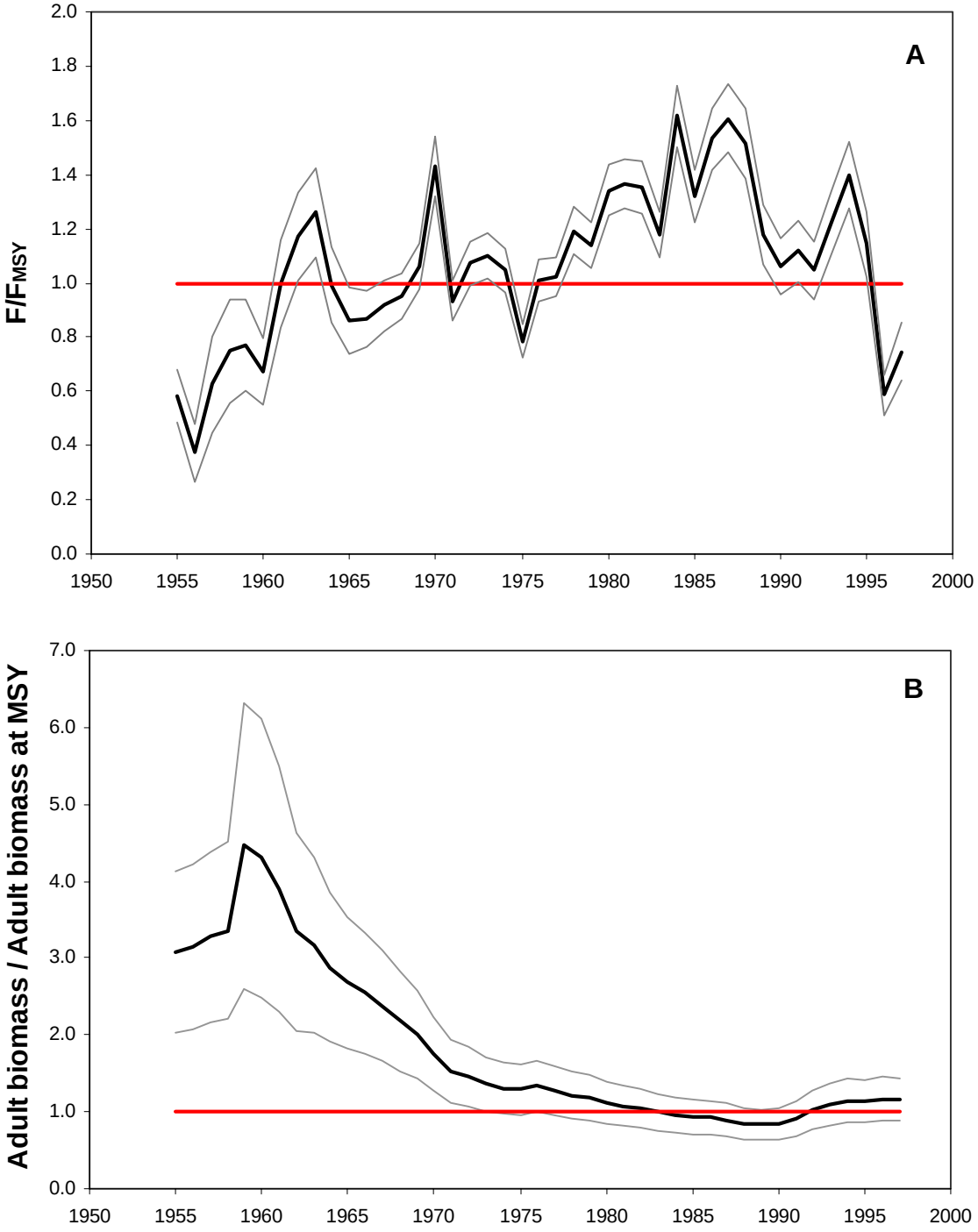

Figure 4. Low movement rate results: time series of (A) the ratio of F (calculated as total annual catch divided by total biomass at the start of each year) to F at MSY and (B) B_{adult} to B_{adult} at MSY, with 95% confidence intervals. Points above the horizontal line in (A) are indicative of overfishing. Points below the horizontal line in (B) are indicative of the population being in an overfished state.

The estimated distribution of recruitment among the regions, which was assumed to be uniform in the other analyses, is NE: 0.00, SE: 0.33, SW: 0.39, NW: 0.27. On face value, this distribution would not seem unreasonable given the distribution of the fisheries (Figure 1), larval distribution (Nishikawa et al. 1985) and distribution of blue marlin habitat. The estimated movement rates and recruitment distribution give rise to a population biomass distribution as shown in Figure 5. The regional distribution of the population biomass seems reasonable, and perhaps more in accordance with blue marlin biology than that obtained in the other analyses (where, because of uniform movement and recruitment, the population would be equally distributed among the regions).

The estimated impact of the fisheries on the population is considerably higher than for the fixed-movement/recruitment distribution models, as indicated by the red area in Figure 5. This is a function of the lower estimate of *M* and higher estimates of *F* in this analysis.

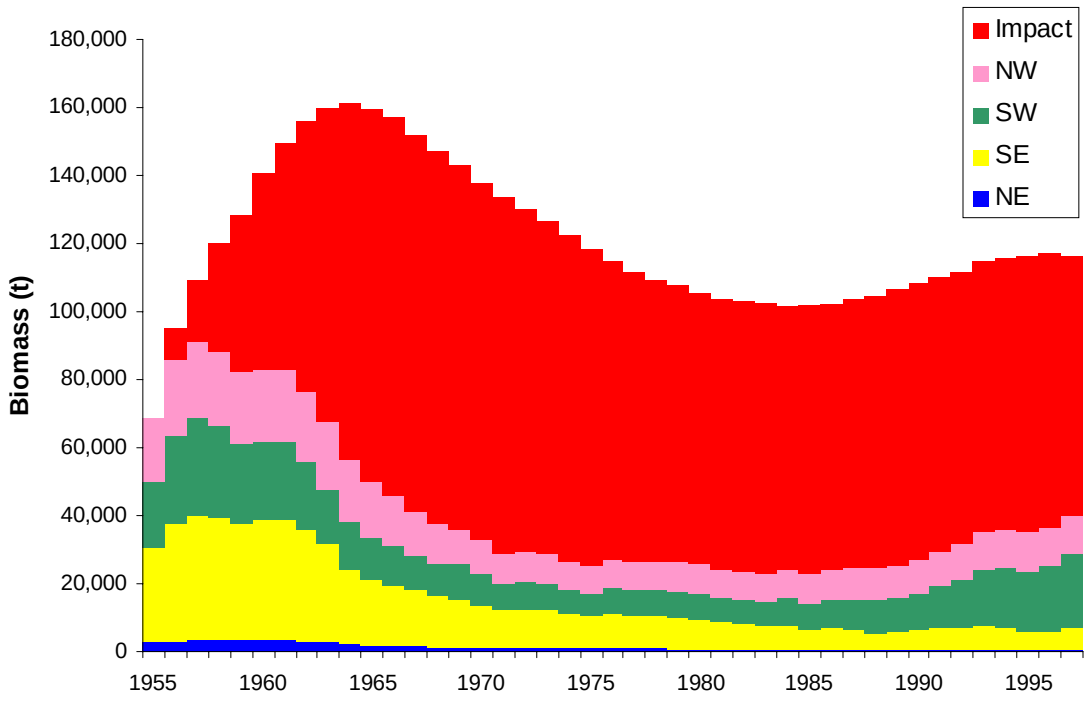

Figure 5. Estimated total biomass by region from the model with estimated movement rates and recruitment distribution. The upper red portion represents the hypothetical additional biomass (over all regions) if there had never been any fishing and the estimated recruitments had occurred.

The estimated *F*- and *B*-ratios associated with this analysis are shown in Figure 6. They are intermediate between the high- and low-movement results, but leaning more towards the high movement situation. Recent *F* is below the F_{MSY} reference point, but has exceeded it for most of the earlier time series. Similarly, recent levels of B_{adult} are just above the MSY-based reference point, but were more depressed in the previous 20 years or so.

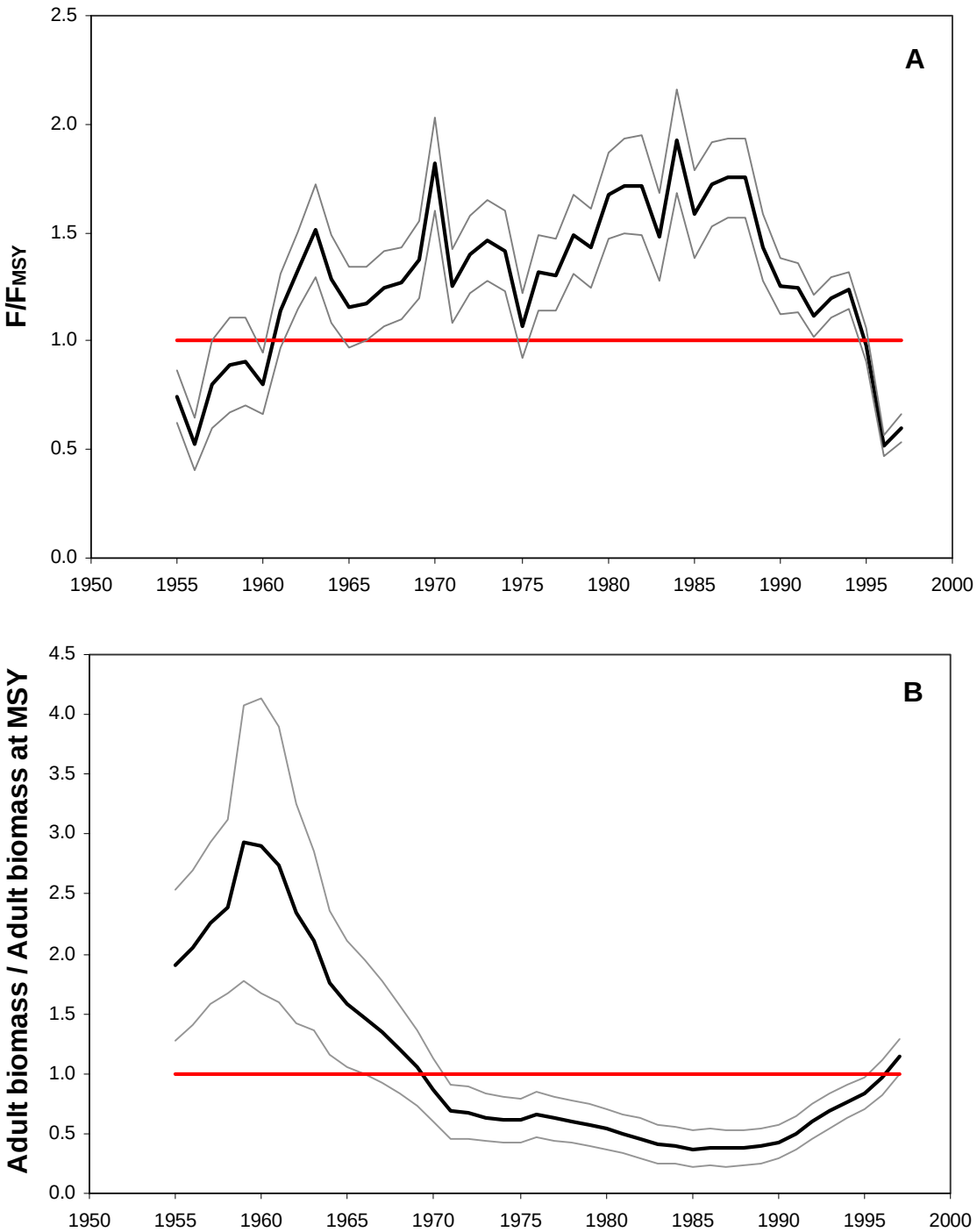

Figure 6. Estimated movement rate and recruitment distribution results: time series of (A) the ratio of F (calculated as total annual catch divided by total biomass at the start of each year) to F at MSY and (B) B_{adult} to B_{adult} at MSY, with 95% confidence intervals. Points above the horizontal line in (A) are indicative of overfishing. Points below the horizontal line in (B) are indicative of the population being in an overfished state.

5. Summary of findings and recommendations

The findings and associated recommendations of this review are as follows:

(i) This assessment would be classified as relatively data-poor. Length-frequency data are entirely missing for some fisheries and not available for some periods in the other fisheries. The absence of small juvenile blue marlin from the catch and the biological characteristics of reproduction and recruitment make the length-frequency data fairly uninformative regarding growth rates and recruitment variability. Also, tagging data, which are often a critical source of semi-fishery-independent data in pelagic fisheries assessments, were not available for the assessment. These deficiencies required a number of simplifying assumptions to be made in the assessment, including: fixing the von Bertalanffy *K* parameter to a specific value (0.2); fixing movement rates to a specific, uniform value (0.1); assuming a uniform distribution of recruitment among the regions; assuming no age-dependency in natural mortality; and assuming common selectivity for JPN and TKP longline fisheries in the same region. For the most part, these assumptions seem reasonable under the circumstances. The advantage of using methodology like MULTIFAN-CL in such a case is that these assumptions are forced to be explicit, rather than being hidden in the structure of the model. Therefore, I find that the methodology used was appropriate for the blue marlin assessment.

(ii) The absence of large-scale tagging data is an important limitation in any stock assessment where fishery-independent surveys are infeasible. Tagging data potentially offer a direct link to absolute population size because the experimental, tagged population is known and therefore exploitation rates, if they can be reasonably extrapolated to the population in general, may be much better determined.

Recommendation 1: For future assessments, efforts should be made to incorporate all available blue marlin tagging data for the Pacific.

Recommendation 2: Carefully designed tagging experiments should be a fundamental part of any strategic research plan for blue marlin.

(iii) A shortcoming of the assessment is the lack of any rigorous sensitivity analyses for simplifying assumptions noted above. As demonstrated by some of the additional analyses that I have undertaken, different (but plausible) assumptions, or relaxation of assumptions, can produce somewhat different stock assessment interpretations. It is therefore recommended that:

Recommendation 3: Sensitivity analysis with respect to simplifying assumptions be carried out to determine their effects on the stock assessment results.

(iv) The available biological information on blue marlin suggests that there is profound sexual dimorphism in growth and perhaps in natural mortality. Neither the available data nor the population model were sex specific, which necessitated assumptions that all biological and exploitation processes are non-sex-specific. The effect that failure of this assumption has on the stock assessment results is unknown. Regarding historical data, there is probably little that can be done. However future catch sampling programs should, where possible, record the sex of blue marline sampled. In the short-term, it would be desirable to extend the MULTIFAN-CL model to

provide sex-specific dynamics, even if most of the available data are, and will continue to be, grouped for sex. This would allow, for example, sex-specific growth and natural mortality parameters to be specified. If sex-ratio data are available for any fisheries, then these data could also be included in the estimation. At the very least, a sex-specific model would allow some investigation of the likely effects of sexually-dimorphic processes on stock assessment results. It is therefore recommended that:

Recommendation 4: Catch sampling programs record the sex of sampled blue marlin wherever possible.

Recommendation 5: The MULTIFAN-CL model be extended to provide sex-specific population dynamics, and that sensitivity tests regarding sex-specific growth and natural mortality be carried out.

Recommendation 6: Available data on the sex ratio of blue marlin catches be compiled and included in the model estimation in an appropriate form.

(v) The use of a habitat model to provide estimates of effective longline effort for the JPN fisheries allows spatial and temporal variability in the fishing depth of the gear and in the depth distribution of variables believed to constitute blue marlin habitat to be accounted for in the measure of fishing effort. This is a powerful tool in stock assessment of pelagic species. In some cases, such a procedure may allow simplifying assumptions to be made concerning the spatial and temporal variability in catchability and selectivity for fisheries so treated.

Recommendation 7: Simplification of assumptions concerning selectivity (constant among regions) and catchability (constant among regions and over time) for the JPN longline fisheries be investigated and incorporated into the stock assessment model as appropriate.

(vi) The presentation of the assessment report needs some modification to enhance readability and information content. Some suggestions include:

- Separate sections on data treatment for the habitat model and for MULTIFAN-CL;
- A complete table of parameter estimates, including information on constraints applied to each;
- Organize results in terms of a base-case analysis, with other sections dealing with sensitivity analyses in which important assumptions or fixed parameters are varied over reasonable ranges.

(vii) The assessment report concluded, on the basis of the analyses undertaken, that blue marlin were currently being fished at near their MSY. However, the assessment gave no information concerning the current or historical state of the stock. I provided some additional analyses (for which the MULTIFAN-CL software needed to be extended) to show ratios of fishing mortality and adult biomass to their estimated MSY levels. For the model used in the assessment report, I found that fishing mortality was beneath the MSY level only for the most recent two years of most of the time series. If the data for 1996 and 1997 used in the analysis are complete and this level of fishing mortality has been maintained in subsequent years, then the fishery would likely be operating within the MSY guideline. However, the estimated adult biomass was found to be significantly

below the equivalent adult biomass at MSY during the previous 25 years indicating that the stock has been in an overfished state (according to the MSY criterion) during this time.

Recommendation 8: Future assessments include estimates of the ratios of annual fishing mortality to the fishing mortality at MSY and adult biomass at the beginning of each year to adult biomass at MSY.

(viii) I conducted two additional analyses to test the 'stock structure' assumptions made in the assessment report. These included a model in which very low movement among regions (akin to four essentially separate stocks) was assumed and a model in which the movement rates and average recruitment distribution among the regions were estimated. For the low-movement model, somewhat more optimistic stock assessment conclusions are drawn. This model fit the data and prior assumptions slightly better than the high-movement model. The model with movement rates and recruitment distribution estimated appeared to provide biologically reasonable results (although this should be checked by an expert in blue marlin biology) with a significantly better fit to the data and prior assumptions. The stock assessment results for this model were intermediate to those of the high- and low-movement models, but more similar to the high-movement results. This suggests that it may be feasible to estimate 'stock structure' parameters within the model itself.

Recommendation 9: Future assessments attempt to estimate movement rates and recruitment distribution as part of the model estimation process. Careful attention should be paid to whether or not such estimates produce biologically reasonable results.

6. References

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Graves, J.E., and McDowell, J.R. 1995. Inter-ocean genetic divergence of istiophorid billfishes. *Marine Biology* **122**:193–203.

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Nishikawa, Y.S., Ueyanagi, S., and Kikawa, S. 1985. Average distribution of larvae of oceanic species of scombroid fishes 1956–1981. Far Seas Fisheries Research Laboratory, Japan. S Series 12, 93 p.

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Appendix I Statement of Work

STATEMENT OF WORK

Consulting Agreement Between the University of Miami and Dr. John Hampton

March 4, 2002

1. General

Blue marlin are an important recreational and sports fishing species to Hawaii and of importance commercially as well. Questions have been raised on the status of the blue marlin population in the central Pacific and the extent to which the Hawaii longline fishery might affect catchability of that species by the sports fishery. A population assessment for the Pacific blue marlin has been prepared based on information on the biological parameters of this species and historical catch and effort statistics by domestic and foreign fisheries. This assessment needs to be reviewed independently. These reviews should examine the assessment methods, models, and findings.

This assessment is expected to play an important role in allocation of blue marlin between commercial and recreational fishing fleets, both domestically and internationally. As a result, the review should consider not only the basic population science underlying this assessment, but also the applicability of the assessment model for determining the status of blue marlin stocks in the North Pacific, and how and whether the analyses used the best available information.

The reviewer shall analyze the blue marlin stock assessment, focusing on the following:

1. Assumptions in defining the stock structures based on genetic or other information;
2. Application of the most recent biological life-history data and long-term catch and effort data;
3. Underlying dynamics of the population model;
4. Applicability of the population model to fisheries management.

The reviewer shall conclude, in a written report, whether the analyses represent the best available information on which to proceed with fisheries management.

2. Specific

The reviewer's duties shall not exceed a maximum total of 10 days – several days to review the report and one week to produce a written report of the findings. No travel is necessary, and no consensus, pre-final review, or rejoinder comments are required.

The itemized tasks of the review include:

1. Analyzing in detail the blue marlin stock assessment by Dr. Pierre Kleiber, which will be provided by the NMFS Honolulu Laboratory;
2. Submitting a written report of findings, analyses, and conclusions concerning the blue marlin stock assessment. The report should include the following elements:
    a. Preface with an executive summary of findings and recommendations;
    b. Main body to consist of a background; description of review activities; summary of findings, conclusions, and recommendations;
    c. Status of Pacific blue marlin;
    d. Utility of the population assessment methodology to answer questions concerning fishery management issues;
    e. Separate appendixes the bibliography of all materials referenced in the review, including those documents provided by the Center for Independent Experts and the Southwest Fisheries Science Center; and a copy of the statement of work;
    f. Full photocopies (or PDF files) and citations of all papers, reports or other written materials cited by the review should be provided separately.
3. No later than March 31, 2002, submitting the final report addressed to the "University of Miami Independent System for Peer Review," and sent to Dr. David Die, UM/RSMAS, 4600 Rickenbacker Causeway, Miami, FL 33149 (via email to ddie@rsmas.miami.edu)

Signature: _____ Date: _____

Appendix II Abstract of assessment document

Stock Assessment of Blue Marlin *(Makaira nigricans)* in the Pacific with Multifan-CL

Pierre Kleiber, Michael G. Hinton, and Yuji Uozumi

ABSTRACT

In the Pacific blue marlin are an incidental catch of longline fisheries and an important resource for big game recreational fishing. Over the past two decades, blue marlin assessments by different techniques have yielded results ranging from an indication of declining stock to a state of sustained yield at approximately the maximum average level.

Longline fishing practices have changed over the years since the 1950s in response to changes in principal target species and to gear developments. Despite increasingly sophisticated attempts to standardize fishing effort to account for changing fishing practices, the stock assessments to date are likely confounded to greater or lesser degree by changes in catchability for blue marlin. Yet only data from commercial longline fisheries targeting tuna provide sufficient spatial and temporal coverage to allow assessment of this resource.

To re-assess the blue marlin stocks in the Pacific and also to assess the efficacy of a habitat-based standardization of longline effort, a collaborative analysis was conducted involving scientists at the National Research Institute of Far Seas Fisheries, Shimizu, Japan, the Inter-American Tropical Tuna Commission, La Jolla, California, and the NOAA Fisheries Honolulu Laboratory, Honolulu, Hawai'i. Using Multifan-CL as an assessment tool, we found considerable uncertainty in quantifying the fishing effort levels that would produce a maximum sustainable yield. However we found that at worst, blue marlin in the Pacific are close to a fully exploited state, i.e. the population and the fishery are somewhere near the top of the yield curve. We found furthermore that effort standardization using a habitat-based model allowed estimation of parameters within reasonable bounds and with reduced confidence intervals about those values.

Appendix III Model configuation file for estimated movement and recruitment distribution

```
#-----------------------------------------------------------------------------#
# Blue marlin analysis with estimated movement and recruitment distribution #
# Note: L-W coeff. in marlin.frq changed to 1.03E-05 to replicate av. wt.   #
#-----------------------------------------------------------------------------#
#  ------------------------
#  PHASE 0 - create initial par file
#  ------------------------
if [ ! -f 00.par ]; then
  gmult marlin.frq marlin.ini 00a.par -makepar
fi
#  ------------------------
#  PHASE 1 - initial par
#  ------------------------
#
if [ ! -f 01a.par ]; then
  nice gmult marlin.frq 00.par 01a.par -file - <<PHASE1
  1 32 2          # sets fast phase initial estimation
  1 141 3         # sets likelihood function for LF data to normal
  2 57 1          # sets no. of recruitments per year to 1
  2 93 1          # sets no. of recruitments per year to 1
  2 69 1          # sets generic movement option (now default)
  2 94 2 2 95 5   # initial age structure based on av. Z over 1st 5 periods
  -999 26 2       # sets length-dependent selectivity option
  -999 16 1       # sets non-decreasing selectivity for all fisheries
#Grouping:  selectivity    catchability
              -1 24  1         -1 29 1      # llJNE
              -2 24  2         -2 29 2      # llJNW
              -3 24  3         -3 29 3      # llJSE
              -4 24  4         -4 29 4      # llJSW
              -5 24  1         -5 29 5      # llONE
              -6 24  2         -6 29 6      # llONW
              -7 24  3         -7 29 7      # llOSE
              -8 24  4         -8 29 8      # llOSW
              -9 24  5         -9 29 9      # psDNE
             -10 24  6        -10 29 10     # psDSE
             -11 24  7        -11 29 11     # psFNE
             -12 24  8        -12 29 12     # psFSE
             -13 24  9        -13 29 13     # psSNE
             -14 24  10       -14 29 14     # psSSE
#effort dev penalties:
              -1 13 -10       # llJNE
              -2 13 -10       # llJNW
              -3 13 -10       # llJSE
              -4 13 -10       # llJSW
              -5 13  -1       # llONE
              -6 13  -1       # llONW
              -7 13  -1       # llOSE
              -8 13  -1       # llOSW
              -9 13 -10       # psDNE
             -10 13 -10       # psDSE
             -11 13 -10       # psFNE
             -12 13 -10       # psFSE
             -13 13 -10       # psSNE
             -14 13 -10       # psSSE
```

```
PHASE1
fi
#  ---------
#   PHASE 2
#  ---------
if [ ! -f 02a.par ]; then
  nice gmult marlin.frq 01a.par 02a.par -file - <<PHASE2
  1 1 1000        # set number of function evaluations per phase to 1000
#!!!
  1 149 10        # set penalty on recruitment devs to 100/10 (was 14/10)
  1 16 1          # estimate length dependent SD
  1 50 1          # set convergence criterion to 1E-01
  1 189 1         # write graph.frq (obs. and pred. LF data)
  1 190 1         # write plot.rep
# selectivity constraints:
#        age start const.    monotone       not needed?
              -1 3  10       -1 16  1         -1 21  4     # llJNE
              -2 3  10       -2 16  1         -2 21  4     # llJNW
              -3 3  10       -3 16  1         -3 21  4     # llJSE
              -4 3  10       -4 16  1         -4 21  4     # llJSW
              -5 3  10       -5 16  1         -5 21  4     # llONE
              -6 3  10       -6 16  1         -6 21  4     # llONW
              -7 3  10       -7 16  1         -7 21  4     # llOSE
              -8 3  10       -8 16  1         -8 21  4     # llOSW
              -9 3  10       -9 16  1         -9 21  4     # psDNE
             -10 3  10      -10 16  1        -10 21  4     # psDSE
             -11 3  10      -11 16  1        -11 21  4     # psFNE
             -12 3  10      -12 16  1        -12 21  4     # psFSE
             -13 3  10      -13 16  1        -13 21  4     # psSNE
             -14 3  10      -14 16  1        -14 21  4     # psSSE
PHASE2
fi
#  ---------
#   PHASE 3 - seasonal catchability
#  ---------
if [ ! -f 03a.par ]; then
  nice gmult marlin.frq 02a.par 03a.par -file - <<PHASE3
  -999 27 1       # estimate seasonal catchability for all fisheries
PHASE3
fi
#  ---------
#   PHASE 4 - time-series catchability
#  ---------
if [ ! -f 04a.par ]; then
  nice gmult marlin.frq 03a.par 04a.par -file - <<PHASE4
# estimate catchability time-series
#     enable     penalty   step interval
      -1 10 1   -1 15 50    -1 23 11       # llJNE
      -2 10 1   -2 15 50    -2 23 11       # llJNW
      -3 10 1   -3 15 50    -3 23 11       # llJSE
      -4 10 1   -4 15 50    -4 23 11       # llJSW
      -5 10 1   -5 15  1    -5 23 11       # llONE
      -6 10 1   -6 15  1    -6 23 11       # llONW
      -7 10 1   -7 15  1    -7 23 11       # llOSE
      -8 10 1   -8 15  1    -8 23 11       # llOSW
      -9 10 1   -9 15 50    -9 23 11       # psDNE
     -10 10 1  -10 15 50   -10 23 11       # psDSE
```

```
     -11 10 1  -11 15 50   -11 23 11       # psFNE
     -12 10 1  -12 15 50   -12 23 11       # psFSE
     -13 10 1  -13 15 50   -13 23 11       # psSNE
     -14 10 1  -14 15 50   -14 23 11       # psSSE
PHASE4
fi
#  ---------
#   PHASE 5 - movement coefficients
#  ---------
if [ ! -f 05a.par ]; then
  nice gmult marlin.frq 04a.par 05a.par -file - <<PHASE5
  2 68 1          # estimate movement coefficients
PHASE5
fi
#  ---------
#   PHASE 6 - natural mortality
#  ---------
if [ ! -f 06a.par ]; then
  nice gmult marlin.frq 05a.par 06a.par -file - <<PHASE6
  2 33 1          # estimate constant natural mortality rate
  2 82 30         # prior for M is 30/100
  2 84 2          # penalty for prior is 2 (CV=0.5)
PHASE6
fi
#  ---------
#   PHASE 7 - stock-recruitment and yield
#  ---------
if [ ! -f 07a.par ]; then
  nice gmult marlin.frq 06a.par 07a.par -file - <<PHASE7
    1 1 2500  # increase no. of function evaluations to 2500
    1 50 4    # set convergence to 1E-04
     2 145 5  # penalty for stock-rec parameters
     2 146 1  # activate stock-rec parameters
     2 147 2  # spawning to recruitment lag
     2 148 5  # no. yrs at end for avg. F
     2 149 0  # yield in wt (0) or numbers (1)
     1 149 0  # set recruit dev pen to 0 because it is now done by 2 145 5
PHASE7
fi
#  ---------
#   PHASE 8 - recruitment distribution
#  ---------
if [ ! -f 08a.par ]; then
  nice gmult marlin.frq 07a.par 08a.par -file - <<PHASE8
  -100000 1 1
  -100000 2 1
  -100000 3 1
  -100000 4 1
PHASE8
fi
```