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Status and Management of the Pacific Hake (*Merluccius productus*) Resource and Fishery off The West Coast of The United States and Canada

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STATUS AND MANAGEMENT OF THE PACIFIC HAKE (*Merluccius productus*) RESOURCE AND FISHERY OFF THE WEST COAST OF THE UNITED STATES AND CANADA

by

R.C. Francis[1/], G.A. McFarlane[2/], A.B. Hollowed[1/], G.L. Swartzman[3/], W.M. Getz[4/]

Resource Ecology and Fisheries Management Division
Northwest and Alaska Fisheries Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration
2725 Montlake Boulevard East
Seattle, WA 98112

1/ Northwest and Alaska Fisheries Center
Resource Ecology and Fisheries Management Division
2725 Montlake Boulevard East
Seattle, WA 98112

2/ Department of Fisheries and Oceans
Fisheries Research Branch
Pacific Biological Station
Nanaimo, B.C. V9R 5K6
Canada

3/ Center for Quantitative Science HR-20
University of Washington
Seattle, WA 98195

4/ Division of Biological Control
University of California
1050 San Pablo Ave.
Albany, CA 94706

ABSTRACT

This paper attempts to describe the history and condition of the offshore Pacific hake (*Merlucius productus*) resource and fishery, as well as to use a modified version of a model developed by Getz and Swartzman (1981) and Swartzman et al. (1983) to explore the likely limits and consequences of joint U.S./Canada management of the resource. The work of Bailey (1980, 1981, 1982) serves to establish a statistical link between year-class strength and environmental conditions at the time of spawning. Thus, environmental driving variables are used to establish bounds for long-term management of the resource. Finally, the most current information on the condition of the resource is used in conjunction with several management policy algorithms to examine current annual fishery management.

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INTRODUCTION

Commercially and ecologically, the Pacific hake (also called Pacific whiting, Fig. 1), *Merluccius productus*, is one of the most important fish species on the west coast of North America. The offshore stock of Pacific hake (life history represented in Fig. 2) supports the largest single species fishery on the coast and is an important trophic link in the California Current ecosystem.

Since 1966, this stock has been the target of a large fishery off the west coast of the United States and Canada. The fishery, which runs from April to October, is managed separately in U.S. and Canadian waters. Presently, the stock appears to be significantly underexpolited in U.S. waters due to a lack of North American markets and the exclusion of Soviet and Polish national fleets. The main reason for the low market value appears to be the existence of a myxosporean parasite (*Kudoa paniformes*) which leads to serious degredation of the flesh after death through proteolytic activity in the muscle tissue. In January 1982, a U.S./Canada working group on Pacific hake viewed the parasite problem as the most serious barrier to full development of domestic markets for its fishery. Even with poor markets and a low present value, the Pacific hake fishery is important to both the United States and Canada in the form of joint ventures with other countries. It is a sure source of revenue which serves to annually remove some of the pressure of over-exploitation from other groundfish fisheries (rockfish, flatfish).

Not only is the fishery for Pacific hake highly variable (estimated catches have ranged from 91,000 to 236,000 metric tons (t)), but the resource itself exhibits extreme variations in abundance as a result of variation in year-class strength. The work of Bailey (1980, 1981, 1982), most recently summarized by Bailey and Francis (1983), serves to establish a statistical link between year-class strength and environmental conditions at the time of spawning. The relationships were quantified and merged into an age-structured management model by Swartzman et al. (1983). As a result of this work, the U.S./Canada International Groundfish Committee pointed out that although the fishery is presently underutilizing the resource, a cooperative (U.S./Canada) effort should be directed towards joint research programs which examine the relationships between the U.S. and Canadian fisheries for hake. They emphasized that the results of these studies should be used to develop an array of joint management alternatives. This paper reports the results of such an effort.

First we attempt to describe the condition of the resource and the fishery; we then use the model developed by Getz and Swartzman (1981) and refined by Swartzman et al. (1983) to explore the likely limits of a joint U.S./Canada management policy. Environmental driving variables are used to study the bounds of long term management of the resource. Finally the most current information on the condition of the resource is used in conjunction with several management policy algorithms to examine current annual fishery management. Our ultimate goal as fisheries biologists is to describe to the manager the likely effects of different contemplated actions and, in particular, to give advice in light of uncertainty about the resource. We hope that this paper provides U.S. and Canadian fisheries managers with information they need to begin to develop a rational, cooperative management strategy.

CONDITION OF STOCK

The Fishery and the Population

Pacific hake has been the target of a large foreign fishery off the west coast of the United States and Canada (Table 1, Fig. 3). A Soviet fishery began in 1966 with a catch of 137,000 t. Between 1973 and 1976 Poland, the Federal Republic of Germany, the German Democratic Republic, and Bulgaria joined the fishery. Reported catches peaked in 1976 at 237,000 t. Reductions in catch in recent years in U.S. waters have been primarily due to severe political restrictions on foreign effort subsequent to the implementation of the Magnuson Fisheries Conservation and Management Act (MFCMA) of 1977.

A small domestic fishery for hake has existed in U.S. waters since least 1879 (Jow 1973). The fishery has been rather insignificant, with catches in the range of 200 to 500 t/yr. However, in recent years joint venture fisheries for hake have become important in both U.S. and Canadian waters.

The fishery for hake is closely tied to the migratory movements of the population. Historically the fishery has begun in waters off northern California and southern Oregon in April and moved northward as schools migrated in a northerly direction during the summer (Bailey et al. 1982). The fishery in Canadian waters generally starts in July or early August (Beamish and McFarlane 1983). In all areas the fishery usually ends in mid- to late October with the offshore and southerly movement of the fish back to the winter spawning grounds.

The distribution of catch by International North Pacific Fisheries Commission (INPFC) area for 1977-82 is presented in Fig. 4. Recently the largest removal has been from the INPFC Columbia Area (with the exception of 1982 when the fishery was forced north due to a preponderance of small unmarketable fish south of the INPFC Vancouver Area).

Age Structure

The age at which most fish are recruited to the U.S. fishery is 2 or 3 years, whereas most fish are recruited at age 5 or 6 to the Canadian fishery. Figures 5 and 6 give the relative age frequencies of catches in U.S. (1973-82) and Canadian (1976,1978-82) waters respectively. Table 2 gives the estimated total (U.S. and Canada) catch at age for 1977 through 1982. Strong year-classes clearly dominate the fisheries in both U.S. and Canadian waters (Table 3). Currently the 1970, 1973, and 1977 year-classes are dominant in the fishery. In 1982 these three year-classes accounted for 59% and 76% of the estimated catches by age in the U.S. and Canadian zones, respectively. Indications are that the 1980 year-class (T. Dark, Northwest and Alaska Fisheries Center (NWAFC), pers. commun.), not yet fully recruited to either the U.S. or Canadian fisheries, may be one of the strongest year-classes ever observed in the fishery. During the history of the fishery it is apparent that strong year-classes have occurred in 1980, 1977, 1973, 1970, 1967 or 1968, 1964, and 1961 (Beamish and McFarlane 1983).

Bailey (1981,1982) and Bailey and Francis (1983) document the current state of knowledge of the early life history and its effects on subsequent recruitment in Pacific hake. Their studies point to conditions during the first few months of life as being critical in determining year-class strength. This work and its management implications are summarized in a later section.

Mean Length at Age

A comparison of the mean size of males and females from the 1970 year-class sampled in the U.S. and Canadian commercial fisheries from 1976 through 1982 (Fig. 7) shows that not only do larger older fish tend to occur in the Canadian fishery, but the individuals of any particular year-class tend to stratify on a north-south gradient by size, with the larger fish tending to occur farther north. In addition, Beamish and McFarlane (1983) indicate that females dominate the catch in the Canadian zone, ranging from 60% to 82% of the catch since 1977.

Estimates of Biomass

Numerous direct estimates of the biomass of the coastal stock of Pacific hake have been made and are reviewed by Bailey et al. (1982). The most reliable estimates of stock biomass are obtained in the triennial National Marine Fisheries Service (NMFS) trawl/hydroacoustic groundfish survey of the west coast region (Dark et al. 1980, Nelson and Dark 1983). Table 4 gives estimates of stock biomass by INPFC statistical area for comprehensive surveys conducted in 1977 and 1980, and Fig. 8 gives the estimates of relative age-frequency (ages 3+) by INPFC area for the 1980 survey. Fig. 9 gives estimates of the fraction of the stock by age in the INPFC Vancouver Area from the 1977 and 1980 surveys (roughly equal to the fraction of the exploitable stock in Canadian waters). All of these demonstrate the size and age stratification of Pacific hake on a north-south gradient.

Recent indications (M. Nelson, NWAFC, pers. commun.) are that the estimates of biomass from the hydroacoustic surveys (Nelson and Dark

1983) may be too high and should be reduced by as much as 37%. This is due to the estimation of target strength used to scale the echo integrator data (Williamson and Traynor in press). For the development of management policy options reported in this paper, parameters are estimated assuming an average target strength of -35dB for hake (Dark et al. 1980). The implications of a possible change of target strength on the estimates of stock production and fishery management are discussed in later sections.

The most common indirect method for estimating available stock biomass is cohort analysis which uses a time series of catch at age data. Francis (1983) describes a weighted cohort analysis procedure used for hake. He reports markedly different results, especially in terms of estimates of stock biomass, between estimates made under the assumption of constant age-specific natural mortality (M) and those made under the assumption of variable age-specific natural mortality. Using the 1977 and 1980 NWAFC trawl-hydroacoustic survey estimates of stock biomass as validation criteria, indications are that a variable age-specific representation of M is more realistic. Table 5 gives the results of a similar cohort analysis updated to include catch at age data through 1982 (Table 2). This provides the basic parameters for the age-structured management model results reported in the next section.

A MANAGEMENT MODEL

The History of Management

Prior to the implementation of the Magnuson Fisheries Conservation and Management Act (MFCMA) in 1977, management of foreign fisheries off the west coast was by bilateral agreements. In the United States from 1977-82, management was directed by a Preliminary Management Plan (PMP) for groundfish prepared by the Department of Commerce. Subsequently, the Pacific Fisheries Management Council (PFMC) prepared a fisheries management plan (FMP) for groundfish, including hake, which was implemented in September 1982. Under the plan, the hake resource in the U.S. zone is managed under the assumption that

1) Estimated maximum sustainable yield (MSY) is attainable,

2) For the entire resource (U.S. and Canada), MSY ranges from 120,000-270,000 mt with a mean value of 195,000 mt,

3) 90% of the fishable resource is available to the U.S. fishery and 10% to the Canadian fishery.

The implication from the plan is that MSY in the U.S. zone ranges from 108,000 to 243,000 t with a mean value of 175,500 t.

The plan noted that following years where the all-nation removal of hake exceeded 200,000 t, several indicators were observed which suggested that the population was reduced substantially from what it had been at the onset of the fishery. These indicators included changes in fishing patterns, juvenation of the catch, and decreased catch per unit of effort (CPUE). Therefore, 200,000 t seems to be a directly observable, as well as analytical, upper limit of annual catch from the total resource.

Canadian management of hake (Stocker 1981) is presently based on the triennial U.S. biomass estimate and an estimate of the proportion of the stock that occupies the Canadian zone. The recommended allowable catch for hake in the Canadian zone is 35,000 t.

Fisheries management authorities use a variety of quantitative tools to help evaluate the status of stocks and make management decisions. These models are often based on assumptions which cannot be easily supported. For example, in classical age-structured Beverton and Holt analysis, recruitment is assumed to be constant, independent of stock. Alternatively, deterministic stock-recruit models (Beverton and Holt 1957, Walters 1969, and Ricker 1975) and stock production models (Gulland 1983) fail to incorporate environmental parameters which often play an important role in determining year-class strength (Sissenwine 1977, Van Winkle et al. 1979, Lett and Kohler 1976, Nelson et al. 1977). With this in mind, Getz and Swartzman (1981) developed a stochastic model which combines the elements of a discrete time age structured Leslie matrix population model, a Beverton and Holt continuous time age-structured harvest model, and a Markov probability transition matrix stock-recruit model. This model was modified and applied to the Pacific hake offshore fishery (Swartzman et al. 1983). Modifications included

1) Incorporation of environmental effects on recruitment, and

2) Development of a management policy algorithm which sets quotas in such a way as to use strong year-classes in a practical and efficient manner while protecting the stock when it is depressed and environmental conditions do not appear to be conducive to stock improvement in the immediate future.

The algorithm's performance was compared with constant effort and constant catch alternatives and was found to be superior in terms of protecting the stock against collapse and maintaining higher long-term average CPUEs.

Both the population/fishery model and the management policy algorithm have subsequently been refined. The model described in Swartzman et al. (1983) has been modified to

1) Divide the fishable stock into separate substocks available to fishing in U.S. and Canadian waters,

2) Allow effort to be divided between U.S. and Canadian waters,

3) Increase the number of age classes from 8 to 13 in order to include fish older than age 11,

4) Incorporate information on egg production as a function of individual fish weight to produce an egg index to replace fecund stock biomass in the recruitment functions,

5) Replace the stock-recruit probability transition matrix with means and variances of recruitment for given levels of egg production, and

6) Redefine the state of the system from a probability vector of numbers at age to a mean and variance of numbers at age.

The management algorithm has been modified to include an objective function which is to be maximized, and to protect both the older (mostly Canadian) stock and the stock as a whole from collapse in the event of a sequence of low recruitment years. This new algorithm has the option of either dual control by U.S. and Canadian fisheries managers or simultaneous control as before. A detailed description of these modifications is given by Swartzman et al. (in prep.).

Application of the Getz-Swartzman model to the Pacific hake fishery can be separated into four modes: historical, equilibrium, management, and stock projection. In the historical mode, long-term runs of the model are made over a historical time series of environmental conditions at the time of spawning and under various values of model parameters. Simulated and observed time series of both catch and stock biomass are compared, enabling us to choose the most realistic parameter values and model configurations. In the equilibrium mode, runs are made under long-term constant environmental conditions. Both equilibrium yields and stock biomasses are estimated. In the management mode, attempts are made to systematically vary effort over the same environmental time series used in the historical runs to maximize long-term yield or CPUE while minimizing annual variations in stock, yield, and effort. In the projection mode, model estimates of the condition of the stock are replaced by the current best estimate of the stock to enable evaluation of short term future management stratagies.

A Management Model; Description and Modifications

What follows is a brief description of the modified Getz-Swartzman model used in this analysis. A detailed description of the analytic formulation is given by Swartzman et al. (in prep.).

The numbers of individuals and their standard deviations in each of n=13 age classes (ages 3,4,...15+) at time t are given by $[\mu_i(t), \sigma_i(t); i=1,...,13]$. Prior to each fishing season, each $\mu_i(t)$ can be split into

U.S. and Canadian substocks $(\mu_i^{U.S.}(t), \ \mu_i^{Can.}(t))$, where

$$\mu_i^{U.S.}(t) = \mu_i(t) \, [\, 1 - \theta\,(\overline{w}_i)]$$

$$\mu_i^{Can.}(t) = \mu_i(t) \, \theta\,(\overline{w}_i)$$

and

$\overline{w}_i$ = average weight of an individual in age class i prior to the fishing season.

The function $\theta\,(\overline{w}_i)$ (Fig. 10) is estimated from results obtained in the 1980 NWAFC trawl/hydroacoustic survey. These results were derived from data in Table 6. Several important factors which are taken into consideration in the splitting of the stock include:

1) At any given age, fish in Canadian waters are larger than those in U.S. waters,

2) The average weight at age of the stock at the end of the fishing season will be affected by relative levels of harvest in U.S. and Canadian waters,

3) The fraction of a year-class available to the Canadian fishery will be affected by the average weight at age prior to the fishing season,

4) Growth occurs only after the fishing season and growth rates are different for fish in U.S. and Canadian waters.

Thus if the stock is split prior to the 5-month fishing season, it is recombined for the 7-month spawning season.

Recruitment is assumed to be a function of 1) environmental conditions at the time of spawning, and 2) an index of egg production. Bailey (1981) showed hake recruitment to be inversely correlated to wind driven Ekman transport on the spawning grounds at the time of spawning. Fig. 11 (from Bailey and Francis 1983) shows that between 1966 and 1977 all strong year-classes appeared in years of lower than average upwelling at the time of spawning, although not all low-upwelling years produced strong year-classes. On the other hand, high-upwelling years produced weak year-classes in seven out of seven cases. Swartzman et al. (1983) further reasoned that offshore transport is positively correlated with the level of upwelling which, in turn, is negatively correlated with sea surface temperature. Therefore, years of "cold" water temperatures on the spawning grounds are assumed to be years of high offshore transport and low larval survival, and years of "warm" water temperatures on the spawning grounds are assumed to be years of low offshore transport and higher, although more variable, larval survival (Fig. 11).

The average January-March sea-surface temperature in the Los Angeles Bight (Marsden Square 120-2, D. McLain, Pacific Environmental Group, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Southwest Fisheries Center, Monterey, California. pers. commun.) is used as our reference temperature. This data, refined from that reported in Swartzman et al. (1983), is available from 1931-82 and is plotted in Fig. 12. The data were divided into warm (>15°C) and cold (<15°C) based on examination of the frequency histogram of these temperatures.

Table 7 gives the data and estimates upon which the various stock-environment-recruit relationships are built. The first column gives the analog of Bailey's (1981) year-class index (YCI = mean percent contribution of a cohort at ages 4,5,6), except that it is derived from commercial catch-at-age data from the entire fishery. The second column gives estimates of recruitment at age 3 (R_3) from the cohort analysis of the previous section for the 1970-79 year-classes and predicted from a linear regression of YCI on R_3 (1970-79 year-classes) for the 1960-69 year-classes. The third column gives estimates of egg production as a function of spawning biomass from work of McFarlane and Beamish (1983) on the Strait of Georgia hake stock. These estimates are considered to be more realistic than those of McGregor (1966) for the offshore stock. The last two columns give the temperature conditions which produced those year-classes. Warm years have a mean R_3 of 1.063 billion individuals (coefficient of variation (CV) = 93%) and cold years have a mean R_3 of 0.260 billion individuals (CV = 74%). It should be noted that this compares with mean R_3's of 1.198 billion individuals (CV = 51%) and 0.442 billion individuals (CV = 28%) for warm and cold years, respectively, based on the 1973-80 cohort analysis used as a basis for parameter estimates in Swartzman et al. (1983).

For the model used in this analysis, recruitment statistics (mean and variance) must be estimated at eight discrete egg number levels (states) for both warm and cold year conditions. As before, the assumption was made that over the observed range of egg production (Table 7), there is no discernable effect of egg production on recruitment. In order to incorporate possible density dependent effects at low (unobserved) levels of egg production, two sets (warm, cold) of egg-recruit functions were estimated. The first uses the method developed by Shepherd (1982) for situations where small amounts of data are available. The equation

$$R_3 = aE/\left[1 + \left(\frac{E}{k}\right)^{\beta}\right]$$

where R_3 is recruitment numbers at age 3 and E is egg numbers, was fit by Shepherd's (1982) method to the data of Table 7 with $\beta = 1$. The second pair of curves uses negative exponential egg-recruit curves similar to those reported in Swartzman et al. (1983) of the form

$$R_3 = a\left(1 - e^{-kE}\right)$$

The parameters of both are given below.

		a	K
Shepherd	Warm	1.045×10^{-5}	1.991×10^{14}
	Cold	0.125×10^{-5}	6.032×10^{14}
Neg. Exp.	Warm	1.070×10^{9}	0.3571×10^{-13}
	Cold	0.262×10^{9}	0.3571×10^{-13}

The means of R_3 for the eight levels of egg production used in the model are given in Table 8 and the curves are plotted in Fig. 13. The variances were estimated by assuming that the observed coefficients of variation of recruitment (93% and 74% for warm and cold years respectively) remained constant over the range of egg numbers used in the model.

Historical Runs

Historical runs of the model were made over a 50-year period (1933-82) for which sea-surface temperature at the time of spawning were available. Driving variables for the population and yield model were 1) effort levels in thousands of standard vessel days for 1966-82, the years of the fishery, and 2) classification of environmental conditions on the hake spawning ground into "warm" and "cold" for 1931-82 (Fig. 12). Historical runs were made for four sets of model parameters and configurations:

1) OLD - single stock, parameters as in Swartzman et al. (1983) based on 1973-80 cohort analyis.

2) 83/MOD1 - single stock, parameters based on most recent 1973-82 cohort analysis, negative exponential stock-recruit functions.

3) 83/MOD2 - single stock, parameters based on 1973-82 cohort analysis, Shepherd stock-recruit functions.

4) SPLIT - split stock (prior to each fishing season the total stock is split into U.S. and Canadian substocks), parameters based on 1973-82 cohort analysis, negative exponential stock-recruit functions.

Summarized results of the runs in terms of mean percent error [MPE = (observed - simulated)/observed] *100 and correlation for catch (1966-82) and stock biomass (1973-82, observed biomass from cohort analysis) are presented in Table 9. The mean annual values of catch (thousand t) and biomass (million t) are also given for comparative purposes. The OLD version was run only through 1981 and so a separate set of comparisons are made for it. It is quite clear that 83/MOD1 with the negative exponential stock-recruit functions gives the best fit to both catch and stock biomass. This pair of stock-recruit functions was therefore used in all subsequent runs of the model. The SPLIT version, although somewhat less accurate, seems to behave similarly to 83/MOD1. Figures 14 and 15 give the observed, 83/MOD1, and SPLIT values for stock biomass (1940-82) and catch (1966-82) respectively. As was the case earlier (Swartzman et al. 1983), expected fishery yields agree quite well with observed yields for 1970-82, whereas for 1966-69 the yields calculated by the model are consistently higher than those reported for the fishery. Three factors could be responsible:

1) Incorrect standardization of effort in early years,

2) Underreporting of early catches,

3) Our criterion for initializing the state of the fishery may have overestimated the biomass of the fishable stock at that time.

Equilibrium Yield Analysis

In this analysis, long-term runs of the model were made under 1) constant environmental conditions, and 2) constant levels of fishing effort. These sets of runs were made for warm, cold, and average temperature conditions. For the average condition, means and variances of recruits against egg numbers were taken as a composite of warm and cold year values weighted by the average 40-year probabilities of warm (0.503) and cold (0.497) temperatures. A running 40-year average of warm and cold years for 1931-82 was chosen since environmental conditions (Fig. 12) appear to run in approximately 20-year cycles. The resultant estimates of MSY under constant environmental conditions are presented in Table 10. In addition to the values of yield and effort (f) associated with MSY, for 83/MOD1 and SPLIT we give (in parenthesis - Table 10) the values of yield and effort corresponding to the point where marginal yield-per-recruit from an additional unit of effort is 0.1 times the marginal yield-per-recruit at very low levels of fishing. According to Gulland (1983), this is the point beyond which there is very little reward from increased fishing. The two levels of effort given in Table 10 will be referred to as f_{max} and $f_{0.1}$. Both sets of values are used in subsequent management algorithm runs of the model.

In the case of the OLD composite, separate sets of equilibrium runs were made for the split of 38% and 62% between warm and cold years, respectively, as was reported in Swartzman et al. (1983) and the 50% split based on running 40 year averages. This serves to link the old estimates of stock production (both parameters and model form) to the new ones developed for this analysis. It is obvious that the estimates of composite production are very sensitive to the relative frequencies of warm and cold years.

Figs. 16 and 17 give the corresponding expected sustained yield and effort curves for 83/MOD1 and SPLIT. The results demonstrate the large variability in stock production as a function of environmental conditions. In addition, parameters from the new cohort analysis (1973-82) result in significantly lower estimates of production in cold years than those from the old cohort analysis (1973-80) used in Swartzman et al. (1983). This is due to lower estimates of average cold year recruitment (0.260 billion in the new runs and 0.442 billion in the old runs) in the more recent cohort analysis.

The Management Algorithm

In management applications of the modified Getz-Swartzman model, parameters were developed for both the single stock and the split stock options. The original objective was to apply the single stock option to isolate the management scheme(s) which maximized yield and/or CPUE, while minimizing annual variation in stock, yield and effort levels. The split stock option was then applied to evaluate various methods of allocating U.S. and Canadian catches. (The split stock option subsequently turned out to have more power than this, however.) The long-term performance of the fishery under the management algorithm was compared with its performance under a series of constant effort scenarios.

The management algorithm combines an objective function related to yield with boundary constraints which operate over a planning horizon (5 years in this case). A complete discussion of these options is available in Swartzman et al. (in prep.). In general terms, the management algorithm provides a simulation of fishing scenarios at various levels of effort. The number of different effort combinations is limited by boundary constraints established by the user. For the purpose of this evaluation, the constraints include minimum reproductive stock levels, minimum level(s) of CPUE, and upper and lower limits on effort. For a given year of a simulation, effort is initiated at the level which produced MSY under composite equilibrium conditions and then systematically increased or decreased to isolate that value of total effort (or combination of U.S. and Canadian effort) which maximizes the objective function without violating any of the boundary constraints. The manner in which effort is increased or decreased over the 5-year planning horizon depends on whether effort is above or below some critical level determined from the equilibrium yield analysis. In this evaluation, the objective function maximizes yield in the next simulated year subject to the boundary constraints holding for 5 years into the future (e.g. set effort to maximize 1984 yield, subject to the stock and CPUE remaining greater than minimum levels and effort remaining below a maximum for 1984-88). In the case of the split stock runs, U.S. and Canadian stocks are weighted equally.

Definition of management objectives in a multinational fishery can take many forms and must be set by fisheries managers themselves. We have therefore tried to present our results from a variety of perspectives. In essence we are attempting to provide insight to U.S. and Canadian fisheries managers as to the likely consequences of contemplated management decisions. In order to evaluate these possibilities, we examine model estimates of yield, effort, CPUE and average and minimum stock biomasses, along with their corresponding variances, under a variety of possible management strategies. Runs are made using both single and split stock forms of the model and by both holding effort constant and varying annual effort by employing the management policy algorithm.

In the single stock applications, only one value for critical effort is used (15,100 vessel days (d)) corresponding to effort at which the increase in composite equilibrium yield per additional unit of effort was less than 10% of the initial rate of increase ($f_{0.1}$) (Gulland 1983).

Minimum egg numbers were represented by two limits based on equilibrium yield analysis: the first being egg numbers at cold year MSY and the second egg numbers at composite year MSY. During the first 4 years of a 5-year planning horizon, the probability of simulated egg numbers falling into the lowest egg category (less than = 0.4×10^{14} eggs) was not allowed to exceed that observed in the cold year equilibrium runs (0.184).

Similarly, in the fifth year of a 5-year planning horizon, the probability of the simulated egg numbers falling into the lowest egg category was not allowed to exceed that observed in the composite year equlibrium runs (0.001). Thus the algorithm was designed to reduce the risk of very low egg production over the short term while trying to bring the reproductive stock to composite MSY levels by the end of the 5-year planning horizon.

In single stock runs three minimum levels of CPUE were explored (20, 15, and 10 t/d). The lowest value (10 t/d) is 10% less than the minimum CPUE observed from the historical catch series (10.8 t/d, Table 1). The highest value (20 t/d) is 10% less than the minimum CPUE observed in historical runs of the model using 83/MOD1 recruitment parameters (22.3 t/d). The value of 15 t/d was inserted as a compromise between the two. The upper limit of effort was set at 20,000 d. This represents the maximum effort at which MSY was observed in the 83 MOD1 (50/50) composite equilibrium runs (MSY was achieved at both 18,500 and 20,100 d).

Preliminary split stock analyses were made using critical levels of U.S. and Canadian effort which totaled the 15,100 d used in the single stock runs. The split stock (50/50) composite equilibrium run demonstrated that MSY at a combined effort of 15,100 d was observed at 11,800 d in United States and 3,400 d in Canadian (Table 10). This combination was therefore selected as critical effort to control the behavior of the algorithm. The probability of the egg numbers falling into the lowest egg category during the first four years of the planning horizon and on the last year of the planning horizon was prevented from falling below that observed under split stock cold (0.155) and composite (0.005) equilibrium at MSY. Three minimum levels of U.S. and Canadian CPUE were studied; a) 15 t/d, b) 10 t/d, and c) unconstrained. Two combinations of U.S. and

Canadian upper effort limits were explored primarily to investigate the effect of limiting U.S. fishing. These combinations restricted respective U.S. and Canadian efforts to; a) 15,100 and 8,400 d, and b) 6,300 and 6,300 d.

Constant Effort Runs

Historical runs of the single and split stock models were executed holding effort constant at each of the three levels used subsequently to control the algorithm. The maximum value, 15,100 d, corresponds to $f_{0.1}$ for the composite equilibrium run. The minimum value, 10,100 d, is the minimum effort which maintained composite equilibrium CPUE greater than the 1966-82 average in the historical run. The third, 12,600 d, is the mean of the previous two.

The model was run for 50 years (our present time series of environmental data). Average annual stock biomass, yield, effort, and CPUE were calculated over a 40-year period (1943-82) to eliminate from the results of this analysis the effect of the high yields observed during the first 10 years of simulated fishing due to the high arbitrary initial conditions. Table 11 shows 40-year average annual yield and CPUE for each of the single and split stock constant effort runs.

Single stock constant effort runs produced similar levels of total yield (183,000-187,000 t) for each of the three effort levels corresponding to critical effort levels used in the subsequent management runs (15,100, 12,600, 10,100 d). As expected, these runs show that maximum yield (187,000 t) is obtained at some intermediate effort level, while the maximum CPUE (18.1 t/d) is observed at a lower effort level. The similarity of total yield estimates illustrates that an average yield of approximately 180,000 t could be maintained over a wide range of constant effort values.

Split-stock constant effort runs were made at two levels of total effort (12,600 and 15,100 d). At 12,600 d, total yield, as well as minimum and mean stock biomasses, was very similar to that produced in the single stock runs. These two runs indicate that the heavier the distribution of effort is towards the U.S. fishery, the greater the chance of driving the stock to dangerously low levels. At a higher level of total effort (15,100 d) the split stock model produces significantly lower yields, and lower average stock levels, than the single stock model. We feel that this reflects the point that the U.S. fishery impacts both the health of the stock and its potential yield more significantly than the Canadian fishery. And the only way this impact can be studied is by separating the two fisheries in the model.

Management Algorithm Runs

As was the case with the constant effort runs, the management algorithm was run for both the single and the split stock versions of the model. Table 12 presents those single stock runs which maximized yield (MY) and CPUE (MC) as well as a corresponding run with no constraints on CPUE. Although yields are slightly lower than the constant effort analogs, both efficiency (CPUE) and stock protection (minimum and average stock biomasses) are significantly larger under the algorithm than under the constant effort scenario.

The split stock management algorithm analog to the (6.3,6.3) constant effort run (first split stock run of Table 11) behaves in a similar fashion, although the margin of improved performance (CPUE, minimum and average stock biomasses) is not as great as in the single stock case. This appears to be due to the fact that the efficiency of the Canadian fishery decreases very rapidly relative to increased effort in the U.S. fishery, although increased yield from the Canadian fishery does not put the stock in great jeopardy. Therefore with no constraints on CPUE, the algorithm allows the Canadian fishery to operate, on the average, at a relatively high but inefficient level. This is borne out by the second and third split stock runs of Table 12. The second split stock run illustrates that increased U.S. and total yield is obtained by relaxing the effort constraints. This results in a decrease in Canadian yield (the Canadian fishery is shut down during 5 years), and the efficiency and stability of both the U.S. and Canadian fisheries is diminished. The third run shows that if effort is relatively unconstrained while a lower CPUE limit of 10 t/d is imposed on both fisheries, most of the catch is taken by the U.S. fishery (the Canadian fishery does not operate in 29 out of the 40 simulated years due to its inability to satisfy the minimum CPUE constraints), and the same total catch as the first run is removed more efficiently. However, in this case the stock is placed in substantially greater jeopardy.

When running the management algorithm, the reason for the higher average yield in the split stock case is due to the manner in which stock protection constraints are applied in the two models. In the single stock situation, effort is applied uniformly across the population age structure. Therefore, total effort will be significantly reduced if a series of weak year-classes are just entering the fishery although the older stock may be in relatively good condition. On the other hand, in the split stock model, U.S. effort is applied fairly uniformly across the population age structure but Canadian effort is applied disproportionately to the older age classes. Thus the split stock model will allow for a continuation of Canadian fishing when the older stock is in good condition but the younger stock is in poor condition. This result is particularily apparent between 1951 and 1953 when the U.S. annual allowable catch began to decrease while the Canadian yields remained relatively high (Fig. 18). This appears to be the primary reason for differences in average yield between the two models under the management algorithm. Therefore, if the assumptions underlying the split stock model are valid, its extra dimensionality adds significant insight to studying the management process.

Discussion

Although the form of the modified Getz-Swartzman model along with the results of the historical, equilibrium and management algorithm runs do not present a complete picture of the dynamics of the offshore hake stock and fishery, they do reveal several fundamental properties concerning stock and U.S./Canada fishery production. Essentially, they serve to characterize both the long-term limits and short term fluctuations of total fishery production, as well as the expected tradeoffs between fisheries of the U.S. and Canadian zones. These results can be summarized as follows.

1) There is a large amount of variability in hake production, a good deal of which seems to be a function of environmental conditions acting on early life history stages of the animal. Our best estimates (Figures 12, 15, and 16) indicate a 4 to 8-fold difference in production between favorable and unfavorable environmental conditions.

2) The concept of equilibrium yield is rather meaningless for this stock of Pacfic hake. Over the last 50 years, the largest run of cold years (Fig. 11) was seven (1946-52) and of warm years six (1940-45). Attempts at estimating equilibrium yield by making long runs of the model under "constant average" environmental conditions (Table 10) appear to significantly overshoot the mark in terms of estimating long-term average potential fishery production.

3) Due to a short time series of reliable catch-at-age data (Table 2) available for cohort analysis (Table 5), estimates of critical model parameters vary considerably every time another year of data is added. This becomes most apparent on comparison of estimates of production presented in this paper with those in Swartzman et al. (1983). In addition, the estimate of target strength for hydroacoustic estimates of stock biomass are somewhat uncertain and the value used could have overestimated stock biomass by as much as 37%. This reduction in the estimate of stock biomass from the 1977 and 1980 NWAFC surveys could reduce estimates of absolute fishery production by as much as 25%. As a result, caution should be exercised in making estimates of absolute stock production until a) the annual revisions of the cohort analysis begin to settle down, and b) the estimate of target strength used to scale the echo integrator data is refined.

4) In spite of the preceding point, 200,000 t appears, in fact, to be an upper limit to the long-term average catch from the offshore hake resource. This maximum could only be attained by varying catch from year to year, taking advantage of strong year-classes when they appear by increasing yields to levels substantially greater than 200,000 t and, similarly, reducing yields to levels significantly below 200,000 t at

times when the stock is in poor condition. Under the management algorithm policy which produced maximum average catches (Table 12), the coefficients of variation of annual catch, effort and stock biomass were 48%, 63%, and 26% respectively for the single stock version of the model.

5) Under split stock conditions restricting U.S. and Canadian effort to 6,300 days rather than 15,100 (U.S.) and 8,400 (Canadian) would result in a 5% decrease in total yield and an increase in average CPUE of 17% (Table 12). Furthermore, the management policy which attained this would decrease the coefficient of variation of annual catch from 35% to 30% and of annual effort from 32% to 19%. This illustrates the long-term benefit of restricting yield to enhance the overall efficiency of both fisheries.

6) Split stock constant effort runs (summarized in Swartzman et al. in prep.) demonstrate that a 40-year average yield of 180,000 t could not be maintained when total U.S. effort was increased above 10,000 d. Apparently, under constant effort conditions the stock is reduced to a point from which it cannot recover during a series of poor recruitment years. This illustrates the advantage of adopting a flexible management policy for Pacific hake to take full advantage of strong year-classes and to provide protection for poor year-classes.

7) Studying output from split stock runs of the management algorithm (Swartzman et al. in prep., summarized in Table 12) it seems clear that in order for the Canadian fishery to maintain itself at average annual catch levels greater than 30,000 t, the U.S. fishery cannot maintain average annual catch levels greater than 160,000 t. Runs presented in Table 12 indicate that if the U.S. fishery harvested at average annual catch levels equal to the present U.S. MSY (175,500 t), the Canadian

fishery would be driven to virtual economic extinction due to significant reductions in CPUE. This also seems to be borne out on examination of the historical catch statistics (Table 1, Fig. 3). In years when the harvest in Canadian waters exceeded 30,000 t the catch in U.S. waters averaged 91,000 t, whereas in years when the catch in U.S. water exceeded 175,000 t the catch in Canadian waters averaged 14,000 t. It is not known, however, if this is a reflection of stock availability or the distribution of the Soviet fishing fleet.

8) The low CPUE (Table 12) in the Canadian zone under heavy exploitation is, possibly, an artifact of the way the stock was split in the model. The model assigns a constant fraction of each weight class (Fig. 10) to the U.S. and Canada zones, no matter what the underlying stock biomass is. One might support this assumption by speculating that the Canadian zone, being the northerly migratory bound for the stock, has a fixed carrying capacity. On the other hand, there is evidence that the northerly extent of stock migration is a function of stock density. For example, only large year-classes seem to occupy the waters off Canada at ages 3 or 4. At any rate, only observation through surveys and the monitoring of relative catch rates and biological structure in the two fisheries will provide insight to this mechanism.

9) In the long run, the stock seems to suffer more from heavy exploitation in the U.S. zone, resulting from increased fishing pressure on the younger stock, than that in the Canadian zone. This is reflected in the higher average stock biomass in the first split stock run (1.08 million t) than the second (0.91 million t) in Table 12.

CURRENT STATUS OF THE STOCK

The modified Getz-Swartzman model provides an option to predict the performance of future fishing seasons based on selected management scenarios. In the projection mode, the most recent available information on year-class strength replaces model estimates based on the historical temperature time series. This aspect of the model is particularly useful because it enables evaluation of annual management policies based on the best available data. The management runs of the previous section have the resolution necessary to predict long-term fluctuations in the fishery. However, in order to examine policy for a particular year, the best current information on the status of the resource must be used.

Projections of the 1984 fishing season were determined based on our best estimate of the status of the hake stock prior to the 1983 fishing season from the most recent cohort analysis. This evaluation of the stock did not provide any estimates of year-class strength after the 1979 year-class. Preliminary estimates indicate that the 1980 year-class is extremely strong (Bailey and Francis 1983, T. Dark, NWAFC, 2725 Montlake Blvd. E., Seattle, WA 98112. pers. commun.). Therefore 1984 projections were evaluated assuming both optimistic (OR) and average (AR) warm 1980 year-class recruitment. Optimistic 1980 recruitment (3.030 billion fish) was determined as the average of the three strongest recruitment years observed in the historical time series (1961, 1970, and 1977). Average warm year recruitment (1.074 billion fish) was based on an estimate of warm year recruitment from the status of the adult stock in 1980 using the 83/MOD1 recruitment curve.

The observed temperature pattern for 1981, 1982, and 1983 was warm, cold, warm (WCW). California Cooperative Oceanic Fisheries Investigations, (CalCOFI) egg and larval surveys (G. Stauffer, NWAFC, pers. commun.) as well as preliminary results from the 1983 NWAFC west coast groundfish survey (M. Nelson, NWAFC, pers. commun.) indicate that recruitment in all three of these years was very low. Therefore, projections were examined assuming cold years (poor recruitment) for 1981-83. Finally, the management algorithm was run for 1984 assuming both warm and cold year recruitment for the 1984 year-class. The expression CCCW and CCCC refer to these scenarios for the 1981-84 year classes.

Using the 1983 initial conditions described above, single stock harvest was imposed throughout the duration of the 1983 fishing season to provide 1984 initial conditions. Effort was restricted to produce a yield similar to that observed in 1983 (114,000 t). Using the model estimate of age composition after harvest, 1984 projection runs were made for the single stock management option which maximized yield in the previous section.

In a similar manner, split stock estimates of the 1984 age composition (initial conditions) were produced by assuming 1983 initial conditions and imposing effort restrictions to achieve U.S. and Canadian yields which approximated those observed in 1983 (73,000 t and 43,000 t respectively). Based on the projected age composition of the stock, 1984 management algorithm runs were made under the first split stock case presented in Table 12. This case was chosen because it promoted continuation of Canadian fishing while maintaining an average total yield of around 180,000 t.

In addition to the 1984 projections based on observed catch and effort levels for 1980-83, single stock projections were examined assuming that the management algorithm had been employed and fully adhered to since 1980. To examine this fished stock scenario, initial conditions in 1980 were determined from cohort analysis. Annual harvest was then imposed using the single stock algorithm mentioned above for each fishing season. After each annual run, the stock was updated by replacing the model estimate for age 3 recruitment with the value predicted from the cohort analysis. As was stated earlier, only those temperature patterns which were most representative of observed recruitment patterns were tested (CCCC and CCCW).

Table 14 presents estimates of initial conditions prior to fishing in 1983 from both the cohort analysis and the historical run of the model. Comparisons of the two reveal the utility of the projection mode to improve estimates. Although historical runs are an adequate measure of long-term behavior of the fishery, their use for short term projections are inadequate as exemplified by the poor correlation between cohort and historical run estimates. Although the overall estimate of stock was similar to the observed level, the historical run of the model fails to accurately represent the age distribution of the stock. Historical runs of the model overestimated the size of the 1978 year class and underestimated the size of the 1977 year-class.

Results of the 1984 single stock projections are presented in Table 15. Surprisingly, the average projected 1984 allowable catch assuming 1984 was a warm year (243,000 t) is approximately the same as that assuming 1984 was a cold year (232,000 t). These, in turn, are very close to the highest yields observed in the historical data (230,000 t). This is due to the fact that although mean recruitment in a warm year is much higher than that in a cold year, the large variance around warm year recruitment makes the risk of falling into the lowest stock category greater for a warm year preceded by three years of poor recruitment than a cold year preceded by three years of poor recruitment. We feel that, from the standpoint of management, it is important to attempt to represent the risks to the stock under various time series of recruitment conditions in order to provide adequate protection for the stock.

The 1984 split stock allowable catch projections (Table 15) show similar patterns relative to 1984 spawning conditions but, on the average, estimate substantially higher allowable catches (327,000 and 313,000 t average allowable catches for warm and cold year 1984 spawning conditions respectively) than the single stock case. This again illustrates the added dimensionality of the split stock option (if the assumptions under which it operates are correct). Whereas in the single stock case effort is applied uniformly across the entire population age structure, in the split stock case U.S. effort is applied fairly uniformly across the population age structure and Canadian effort is applied disproportionately to the older age classes. Thus this difference in allowable catch between the single and split-stock modes reflects the fact that the older stock appears to be in relatively good condition due to the recent history of underexploitation in the U.S. fishery while the younger stock (with the exception of the incoming strong 1980 year-class) requires protection due to the apparent recent sequence of poor recruitment. Under the single stock option, the total fishery is restricted to protect the younger stock, whereas under the split stock option only U.S. fishing is so-restricted. As a result, average projected allowable 1984 U.S. (238,000 t) and Canadian (82,000 t) catches are 48% and 280%, respectively, above the 1966-82 historical averages (Table 13).

Comparison of single stock projections based on observed efforts (Best Current Estimates) to fished stock projections (Fished Stock Scenario) reveals advantages of year to year management of fisheries, such as hake, with highly variable year-classes. Table 16 presents a comparison of observed and fished stock projected annual yields for 1980-83. It is apparent that the catch in fished stock scenarios would have been greater in 1980, less in 1981 and 1982, and greater in 1983 than the observed pattern. The algorithm would have allowed an increase in fishing in 1980 to take advantage of the incoming strong 1977 year class. The observed fishing pattern indicates that the 1977 year-class was not heavily exploited until 1981. This comparison indicates that the observed pattern of fishing for 1980-83 resulted in a net loss in total yield of around 220,000 t. This could be partially offset in 1984 by an average increase in allowable catch of around 33,000 t (Table 15) due to the fact that the stock was not heavily fished between 1980 and 1983.

ADVICE TO THE MANAGER

We believe that this paper provides a significant rationale and basis for joint U.S./Canada management of the offshore Pacific hake stock. Once fisheries managers decide on an acceptable balance between hake catches in the U.S. and Canadian zones, the management policy algorithm discussed earlier can provide insight into how that balance might be struck on a year to year basis.

If one combines present U.S. and Canadian management of the stock, one concludes that MSY is attainable and is around 210,000 t (175,000 t U.S., 35,000 t Canada). Our analysis, along with that of Swartzman et al (1982), indicates that a policy of constant annual removal of 210,000 t would be disastrous to both the stock and the fishery. At the present time, we recommend a combined stock optimum yield of no more than 190,000 t (maximum of single and split stock options explored in Table 12). As our analysis points out this could only be attained under a policy of varying catch from year to year, taking advantage of strong year-classes when they appear by increasing yields over optimum yield (OY), and protecting the stock by reducing yields below OY when the stock is in poor condition. As Swartzmen et al. (1982) indicated, managing the total hake fishery according to MSY under a constant annual yield quota would allow at most 175,000 t to be harvested annually. We still feel this is a valid number.

Finally, our analysis indicates that the current (prior to fishing in 1984) status of the older stock is very good due to a recent history of relatively low exploitation in the U.S. fishery, whereas the present younger stock may require protection in the immediate future. Indications are that the 1980 year-class is very large, but that the 1981-83 year-classes may be very small. If one assumes that a poor year class was produced in 1984 (this scenario must be considered in current management analysis), then the two versions of the model estimate (Table 15) an average total allowable catch for 1984 of around 270,000 t.

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Table 1.--Annual catches of Pacific hake (1000 t) in U.S. and Canadian waters by foreign (F), joint venture (JV), and domestic (D) fleets and estimates of effort (1000 standard days) for total fishery.

	U.S.				Canada						
Year	F	JV	D	Total[b]	F	JV	D	Total[a]	Total	CPUE[c]	Effort[d]
1966	137.0			137.0	0.7			0.7	137.7	19.2	7.171
1967	195.1			195.1	1.3			1.3	196.4	33.0	5.951
1968	68.0			68.0	44.3			44.3	112.3	10.8	10.397
1969	109.1			109.1	65.0			65.0	174.1	17.9	9.726
1970	202.2			202.2	26.4			26.4	228.6	24.9	9.180
1971	147.5			147.5	26.7			26.7	174.2	19.7	8.842
1972	111.6			111.6	43.4			43.4	155.0	21.0	7.381
1973	144.8			144.8	15.7			15.7	160.5	23.9	6.752
1974	209.3			209.3	17.9			17.9	227.2	26.1	8.705
1975	201.9			201.9	18.2			18.2	220.1	18.9	11.646
1976	230.8			230.8	6.7			6.7	237.5	25.7	9.242
1977	127.2			127.2	5.2			5.2	132.4	31.2	4.244
1978	96.8	0.9		97.7	4.5	1.8		6.3	104.0	34.9	2.980
1979	114.9	8.8		123.7	7.9	4.2	0.3	12.4	136.1	25.8	5.276
1980	44.0	27.6		71.6	0.0	17.5	0.1	17.6	89.2	28.3	3.152
1981	70.4	43.6	0.0	114.1	3.1	17.5	4.4	25.0	139.1	28.3	4.915
1982	7.1	67.5	1.0	75.6	11.3	20.9	0.0	32.2	107.8	30.9	3.489
Mean				139.2				21.5	160.7		7.003

[a] Reported by G.A. McFarlane (6-9-83)

[b] 1966-80 from Bailey et al. (1982)
1981-82 from PMFC PacFIN data base

[c] 1966-81 from Bailey et al. (1982) for U.S. fishery
1982 estimated from Bulgarian fleet in U.S. waters.

[d] Estimated assuming CPUE (Canada) = CPUE (U.S.).

Table 2.--Catch in numbers (millions) of Pacific hake off the west coast of U.S. and Canada, 1973-82.

Age	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
1	-	31.517	-	-	-	-	-	-	7.769	-
2	-	1.401	87.127	0.329	1.812	-	6.232	-	1.107	27.438
3	55.891	1.051	2.650	36.822	3.805	4.124	8.986	14.825	1.769	1.941
4	9.673	161.438	3.644	29.260	54.469	8.038	14.560	8.721	106.910	2.069
5	21.711	22.062	126.219	29.589	11.297	48.228	8.731	8.897	10.389	71.525
6	40.198	38.171	21.533	185.097	20.180	9.320	44.775	9.920	12.165	5.785
7	25.151	47.626	23.190	27.617	69.779	20.185	16.502	22.612	6.498	7.549
8	23.001	27.665	37.435	13.808	11.551	37.187	29.058	10.415	27.807	6.752
9	21.497	12.257	16.895	4.932	6.281	6.274	19.684	15.711	7.521	16.975
10	10.318	3.852	7.288	0.986	3.127	2.862	3.704	14.199	6.522	3.426
11	4.514	1.751	3.644	0.329	1.842	1.527	2.242	3.398	14.508	3.491
12	1.935	1.051	1.325	-	1.076	0.605	0.659	1.878	3.091	11.039
13	1.075	0.350	0.331	-	0.340	0.310	0.681	1.199	1.112	0.800
14	-	-	-	-	-	0.086	0.168	0.196	1.028	0.541
15	-	-	-	-	-	-	0.123	-	0.245	-

1973-76 - from reported Polish age composition (Jackowski 1980)
1977-82 - U.S. and Canadian observer samples

Table 3.--Contribution (% catch by number) of the strong 1970, 1973, and 1977 year-classes to the Pacific hake fisheries in the U.S. and Canadian zones.

	Year Class	1976	1977	1978	1979	1980	1981	1982
U.S.	1970	57	38	27	12	8	4	4
	1973	10	30	36	30	21	13	10
	1977	-	-	-	4	16	56	45
	Total	67	68	63	46	45	73	59
Canada	1970	36	-	22	26	44	29	19
	1973	3	-	6	11	16	21	14
	1977	-	-	-	-	-	5	43
	Total	39	-	28	37	60	55	76

Table 4.--Distribution of Pacific hake biomass (1000 t) from two Northwest and Alaska Fisheries Center trawl-hydroacoustic surveys from International North Pacific Fisheries Commission (INPFC) Monterey area north.

		INPFC Area				
Year	Source	Vancouver	Columbia	Eureka	Monterey	Total
1977	Midwater	343.821	316.440	360.944	108.087	1129.292
	Bottom	6.560	32.917	9.501	18.266	67.244
	Total	350.381	349.357	370.445	126.353	1196.536
1980	Midwater	322.335	260.477	182.783	578.841	1344.436
	Bottom	17.286	20.156	11.481	143.824	192.747
	Total	339.621	280.633	194.264	722.665	1537.183

Target Strength = -35dB

Table 5.--Input data and summarized results of Pacific hake cohort analysis.

Year	Recruitment at age 3 (billions)	Effort (10^3 days)	Age	Total q	M
1973	2.350	6.752	3	0.00184	0.278
1974	0.717	8.705	4	0.00932	0.210
1975	0.344	11.646	5	0.01501	0.195
1976	0.936	9.242	6	0.03108	0.257
1977	0.184	4.244	7	0.04343	0.357
1978	0.221	2.980	8	0.08482	0.457
1979	0.156	5.276	9	0.09132	0.557
1980	2.374	3.152	10	0.14954	0.657
1981	0.081	4.915	11	0.14954	0.757
1982	0.212	3.489			
Mean	0.758				
CV	117%				

q = annual catchability coefficient

M = annual instantaneous natural mortality rate

Table 6.--Average weights at age and observed proportions at age in U.S. and Canadian fishery zones - 1980 Northwest and Alaska Fisheries Center survey.

Age i	$\bar{w}$ (kg)[a] U.S.	Canada	Combined	$\theta(\bar{w})$[b]
3	0.443	-	0.443	0.000
4	0.545	-	0.545	0.000
5	0.644	0.791	0.663	0.107
6	0.729	0.904	0.769	0.076
7	0.798	0.977	0.855	0.248
8	0.853	1.095	0.947	0.145
9	0.898	1.183	1.023	0.370
10	0.933	1.228	1.078	0.616
11	0.962	1.286	1.134	0.537
12	0.985	1.377	1.205	0.543
13	1.000	1.377	1.219	0.651
14	1.007	1.377	1.233	0.397
15+	1.007	1.377	1.236	0.605

[a] Estimated from observed average length at age and weight-length relationship

$$w = 0.001815\ l^{2.73}$$

[b] $\theta(\bar{w})$ = fraction of animals of average weight $\bar{w}$ in Canada.

Table 7.--Observed and predicted values for Pacific hake recruitment.

Year Class	Year Class Index[a]	R_3[b] (10^9ind.)	E(10^{14} ind.)[c]	Temp (°C)	Class[d]
60	0.716	(1.082)		15.38	W
61	1.833	(2.815)		15.61	W
62	0.128	(0.170)		14.70	C
63	0.201	(0.283)		15.08	W
64	0.216	(0.307)		15.64	W
65	0.040	(0.034)		14.78	C
66	0.216	(0.302)		14.88	C
67	0.513	(0.767)		15.53	W
68	0.313	(0.457)		15.56	W
69	0.173	(0.240)		15.11	W
70	1.405	2.350		15.32	W
71	0.210	0.717		13.93	C
72	0.217	0.344		13.60	C
73	0.929	0.936	1.967	15.12	W
74	0.203	0.185	2.283	13.87	C
75	0.230	0.221	2.501	13.89	C
76	0.164	1.156	2.612	14.51	C
77	1.496	2.374	2.279	15.32	W
78	0.059	0.082	2.028	15.80	W
79		0.212	1.636	14.59	C
80			1.976	15.71	W
81			2.001	15.58	W
82			2.085	14.95	C

[a] Derived by Francis from commercial catch-at-age

[b] Recruitment at age 3
Observed values obtained from 73-82 cohort analysis
Predicted values from equation R = -0.03 + 1.55 YCI in parenthesis.

[c] $E = \#\text{ eggs} = \sum_i N_i \, C_i \;\; 1.8934 \times 10^5 \, \overline{w}_i^{\,1.25}$

i = Age class.
c_i = Fraction of age class; Mature.
$\overline{w}_i$ = Average weight (kg) of an individual in age age class i.

[d] W = Warm year
C = Cold year

Table 8.--Parameters used for environment-egg-recruit relationships in model

Egg Mark 10^{14} ind	Shepherd[a] Warm 10^9ind	Shepherd[a] Cold 10^9ind	Neg. Exp.[b] Warm 10^9ind	Neg. Exp.[b] Cold 10^9ind
0.2	0.190	0.024	0.101	0.100
0.6	0.482	0.068	0.843	0.223
1.0	0.696	0.107	1.020	0.253
1.4	0.859	0.142	1.063	0.260
1.8	0.988	0.173	1.073	0.262
2.2	1.090	0.202	1.076	0.262
2.6	1.180	0.227	1.076	0.262
3.0	1.250	0.250	1.076	0.262
CV	93%	74%	93%	74%

[a] From Shepherd (1982)

[b] From Swartzman et al. (1983)

Table 9.--Summary of 50-year historical runs.

			OLD	83/MOD1	83/MOD2	SPLIT	Observed
Yield	73-81	MPE	21.8	17.6	25.5	23.6	
		r	0.93	0.92	0.92	0.91	
		Mean		171	145	169	161
	73-82	MPE	-	17.8	27.2	23.0	
		r	-	0.93	0.93	0.92	
		Mean		162	137	161	155
	66-82	MPE	-	47.0	41.1	48.0	
		r	-	0.40	0.48	0.43	
		Mean		214	180	211	161
Biomass	73-81	MPE	23.1	16.1	21.6	16.3	
		r	0.48	0.52	0.51	0.51	
		Mean	1.39	1.18	0.97	1.10	1.25
	73-82	MPE	25.5	17.0	20.8	16.7	
		r	0.40	0.46	0.50	0.44	
		Mean	1.41	1.19	0.97	1.12	1.23
Yield + Biomass Combined	73-81	MPE	22.5	16.8	23.6	20.3	
	3-82	MPE	-	17.3	24.0	19.9	

r = correlation coefficient

MPE = Mean percent error

Mean yield in thousand t

Mean biomass in million t

Table 10.--Results of equilibrium yield analysis.

Environmental conditions	Model	MSY (thousand t)	Effort (thousand d)
Cold	OLD	151	18.9
	83/MOD1	49 (49)	5.0 (5.0)
	SPLIT		
	U.S.	21 (35)	3.4 (3.4)
	Canada	28 (13)	8.4 (3.4)
	Total	49 (48)	11.8 (6.7)
Warm	OLD	368	18.9
	83/MOD1	378 (365)	21.9 (16.8)
	SPLIT		
	U.S.	337 (332)	15.1 (11.8)
	Canada	39 (29)	8.4 (3.4)
	Total	376 (361)	23.5 (15.1)
Composite	OLD(38/62)	209	14.7
	OLD(50/50)	237	13.4
	83/MOD1(50/50)	218 (214)	18.5 (15.1)
	SPLIT(50/50)		
	U.S.	179 (198)	10.1 (11.8)
	Canada	34 (10)	8.4 (3.4)
	Total	213 (211)	18.5 (15.1)

$SY_{0.1}$ in parenthesis under MSY

$f_{0.1}$ parenthesis under effort

Table 11.--Summary of 40 year stock, yield, effort, and catch per unit of effort (CPUE) for single and split stock constant effort runs.

I. SINGLE STOCK

Effort (1000 d)	Min stock (million t)	Mean stock (CV) (million t)	Yield (CV) (1000 t)	CPUE (t/d)
15.1	0.347	0.787 (33)	183 (30)	12.1
12.6	0.380	0.894 (33)	187 (31)	14.8
10.1	0.418	1.000 (33)	183 (31)	18.1

II. SPLIT STOCK

	Effort (1000 d)	Min stock (million t)	Mean stock (CV) (million t)	Yield (CV) (1000 t)	CPUE (t/d)
Tot.	12.6	0.402	0.962 (32)	185 (29)	14.7
U.S.	6.3			145 (29)	23.0
Can.	6.3			40 (32)	6.3
Tot.	12.6	0.341	0.778 (32)	182 (29)	14.5
U.S.	9.8			166 (29)	17.0
Can.	2.8			16 (30)	5.7
Tot.	15.1	0.270	0.603 (33)	161 (29)	12.6
U.S.	11.8			148 (30)	10.6
Can.	3.4			13 (30)	3.8

Table 12.--Summary of management runs.

I. SINGLE STOCK

Target	Constraints: Min. CPUE (t/d)	Min. stock (million t)	40 Year Averages: Stock (CV) (million t)	Yield (CV) (1000 t)	Effort (CV) (1000 d)	CPUE (t/d)
MY	15	0.58	1.14 (26)	177 (48)	8.5 (63)	24.0
MC	20	0.67	1.21 (26)	168 (60)	6.7 (68)	26.0
-	0	0.58	1.12 (26)	174 (44)	9.2 (66)	23.3

II. SPLIT STOCK

Constraints: Min. CPUE (t/d)	Max. effort (1000 d)		Min. stock (million t)	40 Year Averages: Stock (CV) (million t)	Yield (CV) (1000 t)	Effort (CV) (1000 d)	CPUE (t/d)
0	(6.3,6.3)	Tot.	0.56	1.08 (26)	181 (30)	10.5 (19)	17.2
		U.S.			137 (39)	5.0 (31)	27.1
		Can.			44 (36)	5.5 (22)	8.1
0	(15.1,8.4)	Tot.	0.49	0.91 (25)	191 (35)	14.3 (32)	13.8
		U.S.			155 (51)	7.9 (51)	21.5
		Can.			36 (64)	6.4 (53)	6.5[a]
10	(15.1,8.4)	Tot.	0.48	0.93 (25)	185 (34)	23.7 (41)	19.5
		U.S.			174 (44)	21.2 (52)	21.3
		Can.			11(216)	2.5(218)	10.0[b]

[a] Canadian fishery shut down for 5 out of 40 years
[b] Canadian fishery shut down for 29 out of 40 years

MY = Maximum total yield

MC = Maximum total catch per unit of effort (CPUE)

Table 13.--Mean historical annual yield, estimated effort and catch per unit of effort (CPUE), 1966-82.

	U.S.	Canada	Total
Yield (thousand t)	139.2	21.5	160.7
Effort (thousand d)	-	-	7.0
CPUE (t/d)	-	-	24.7

Table 14.--Estimated numbers (million fish) by age prior to the 1983 fishery.

Year-class	Age	Historical model run	Cohort analysis
1980	3	993.0	-
1979	4	190.0	159.0
1978	5	604.0	47.5
1977	6	471.0	1059.0
1976	7	80.1	40.2
1975	8	47.3	39.7
1974	9	21.9	14.3
1973	10	33.6	31.4
1972	11	2.3	3.2
1971	12	0.5	3.1
1970	13	0.4	2.0
1969	14	0.1	0.2
1968	15+	0.0	0.0
1968-1979	Total	1451.3	1399.7

r = correlation coefficient = 0.59

Table 15.--Results of single and split stock allowable catch projections for 1984.

I. SINGLE STOCK

R80	T84	Best Current Estimate Yield (1000 t)	Effort (1000 d)	CPUE (t/d)	Fished Stock Scenario Yield (1000 t)	Effort (1000 d)	CPUE (t/d)
XWR	W	329	8.6	38.3	282	8.6	32.7
XWR	C	295	7.6	39.0	245	7.4	33.3
AWR	W	156	4.6	33.8	142	4.8	29.5
AWR	C	169	5.0	33.5	148	5.0	29.4
Mean		237	6.5	-	204	6.5	-

II. SPLIT STOCK

R80	T84		Yield (1000 t)	Effort (1000 d)	CPUE (t/d)
XWR	W	Tot.	393	12.6	41.7
		U.S.	311	6.3	49.3
		Can.	83	6.3	13.1
XWR	C	Tot.	393	12.6	41.7
		U.S.	311	6.3	49.3
		Can.	83	6.3	13.1
AWR	W	Tot.	260	11.3	28.5
		U.S.	179	5.0	35.5
		Can.	81	12.9	12.9
AWR	C	Tot.	233	10.3	28.1
		U.S.	152	4.2	36.2
		Can.	81	6.3	12.9
Mean		Tot.	320	11.8	-
		U.S.	238	5.5	-
		Can.	82	6.3	-

R80 = Recruitment conditions in 1980
XWR = Exceptionally warm year
AWR = Average warm year
T84 = Recruitment conditions in 1984

Table 16.--1980-83 yield (1000 t) under fished-stock scenario, single stock model.

Year	Observed	Fished
1980	90	300
1981	139	114
1982	168	112
1983	114	207[a]
Total	511	733

[a] Average of yield produced under exceptionally warm (XWR) and average warm (AWR) recruitment for 1980 year-class.

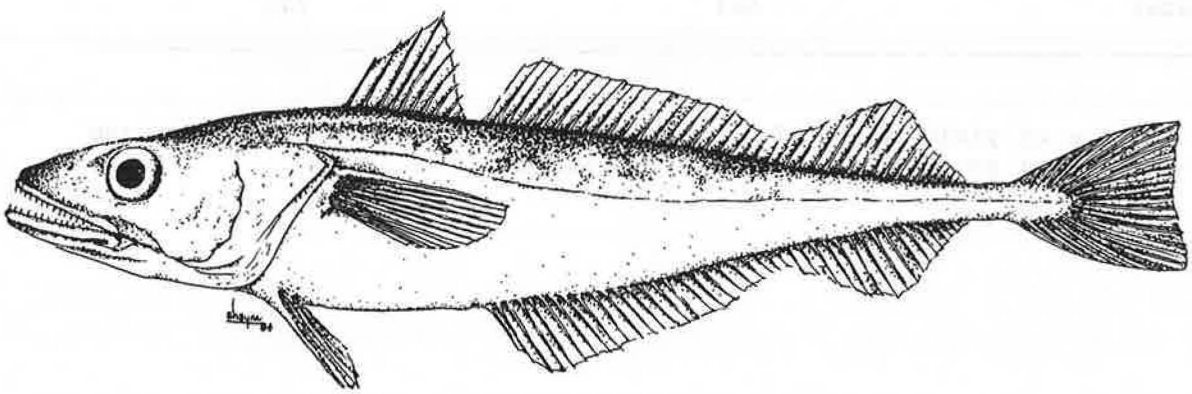


Figure 1.--Pacific hake (<u>Merrluccius Productus</u>).

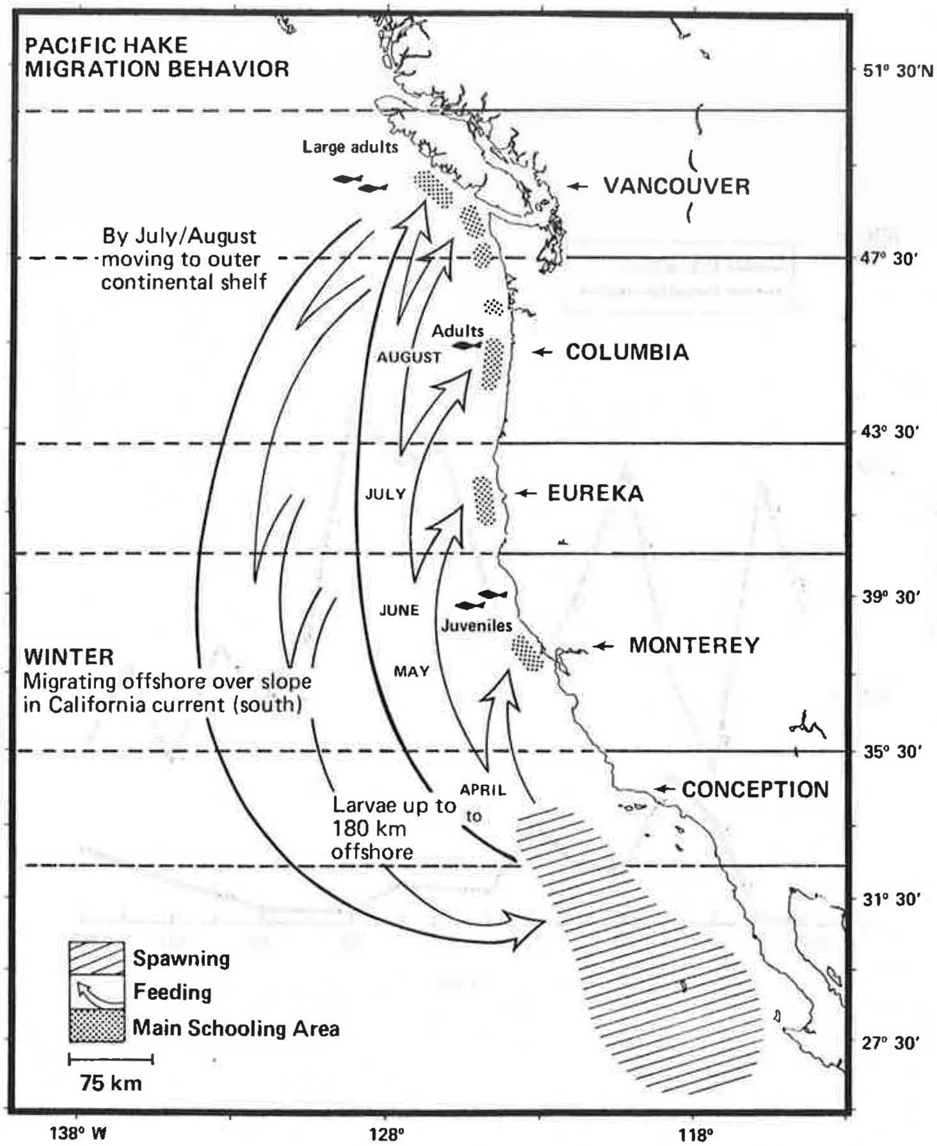


Figure 2.--Migratory patterns of Pacific hake.

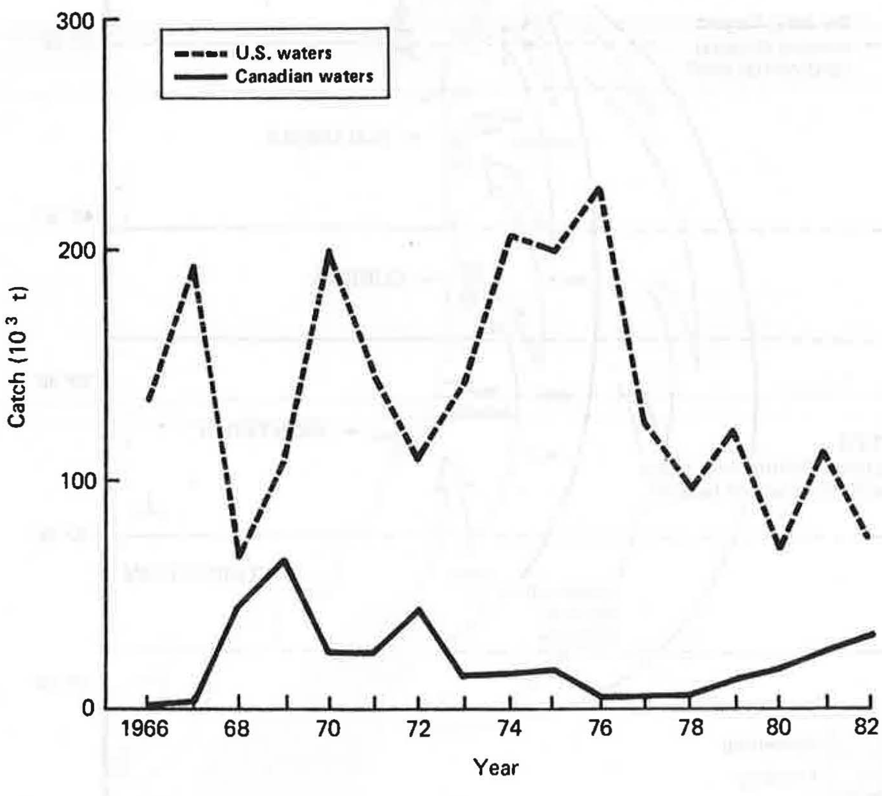


Figure 3.--Annual catches of Pacific hake in United States and Canadian waters.

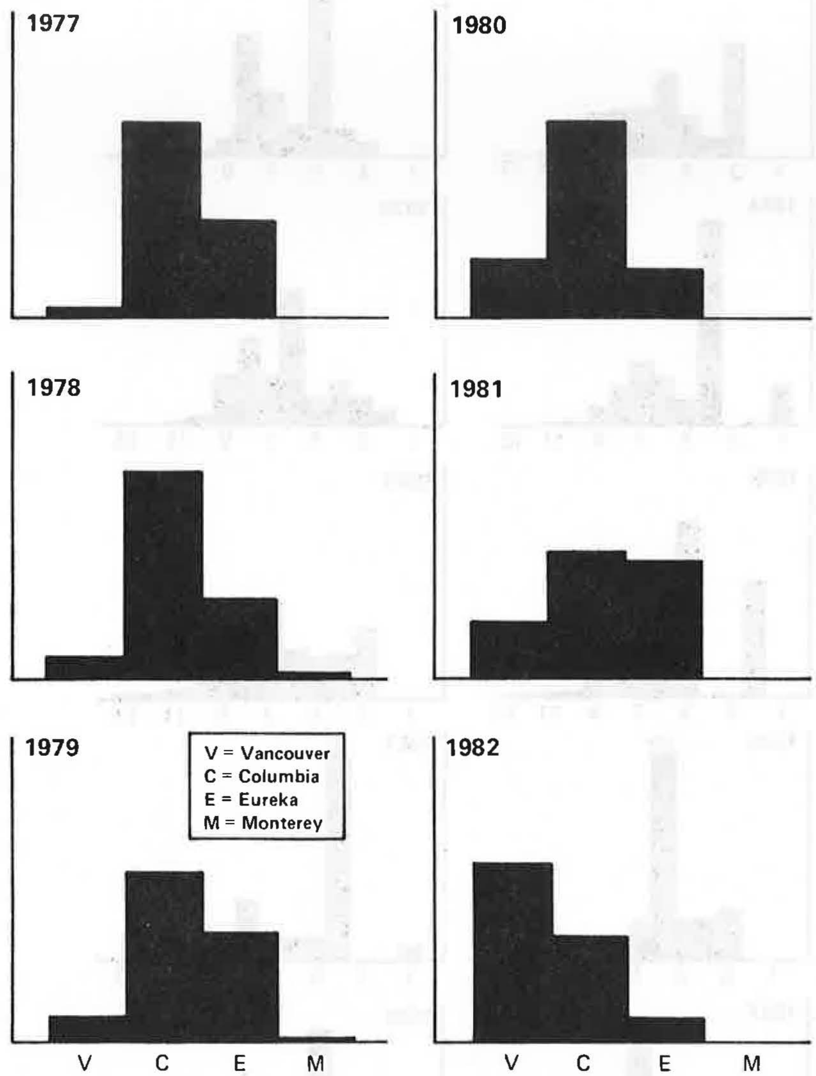


Figure 4.--Relative distribution Pacific hake catch by weight in International North Pacific Fisheries Commission areas.

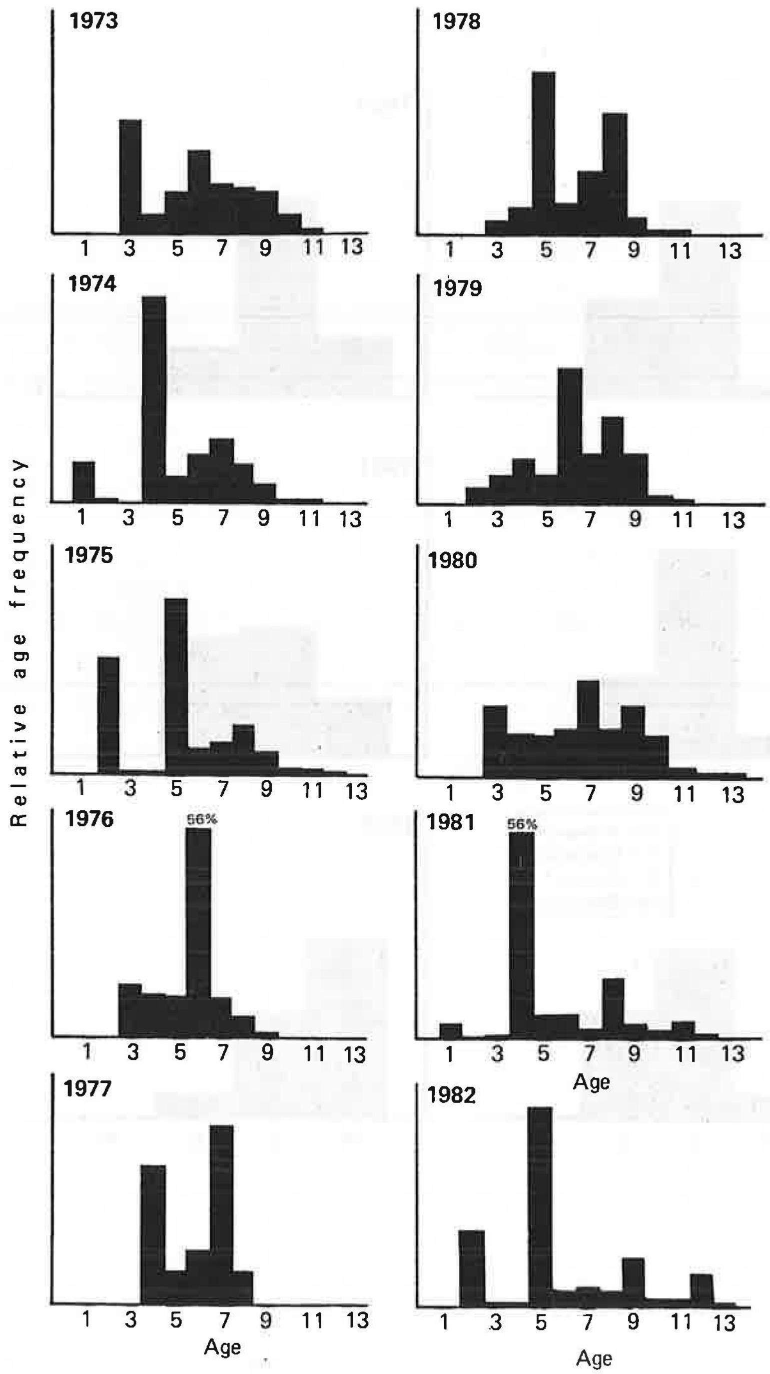


Figure 5.--Relative age-frequency of Pacific hake catch in United States waters, 1973-82.

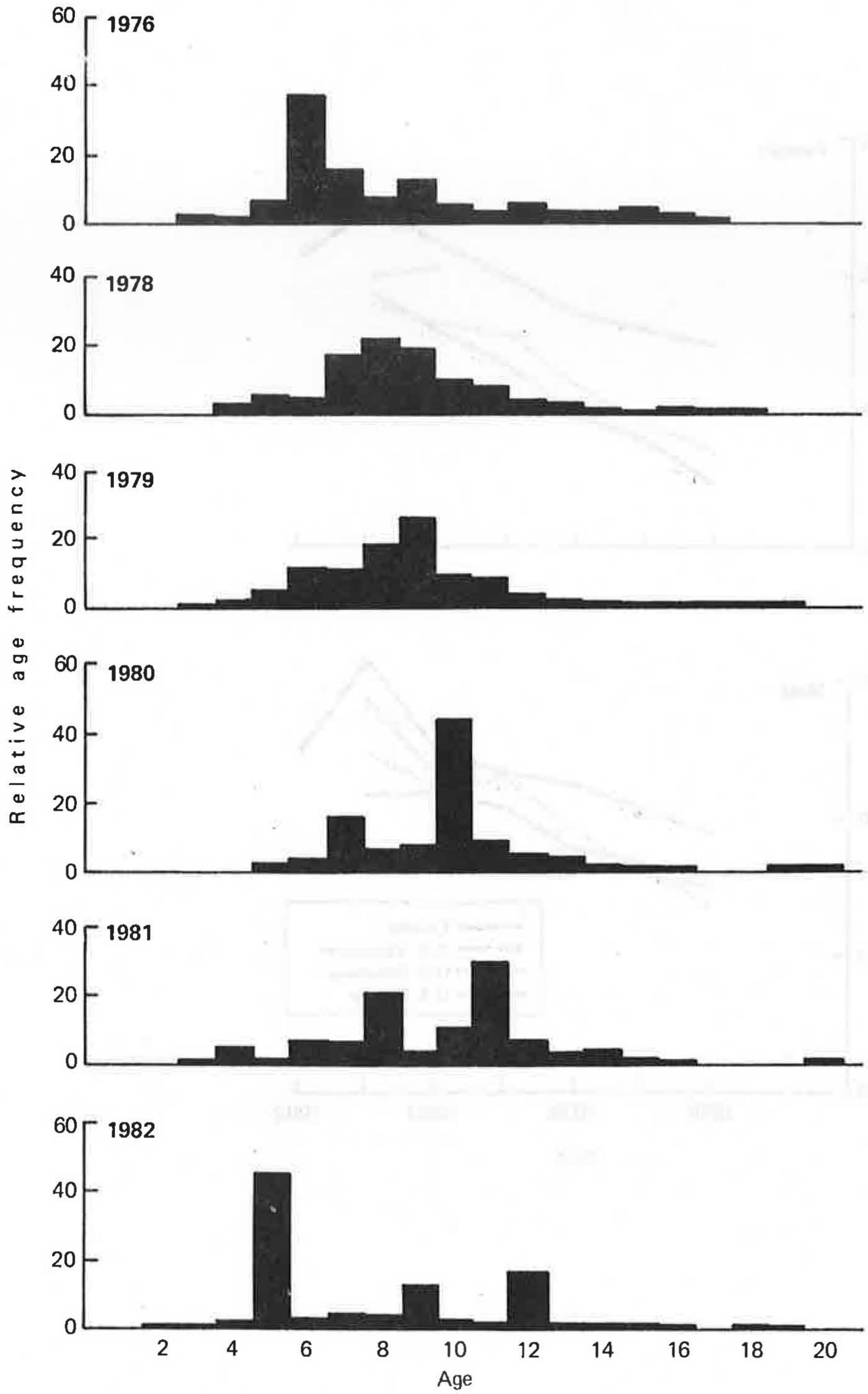


Figure 6.--Relative age-frequency of Pacific hake catch in Canadian waters, 1976, 1978-82.

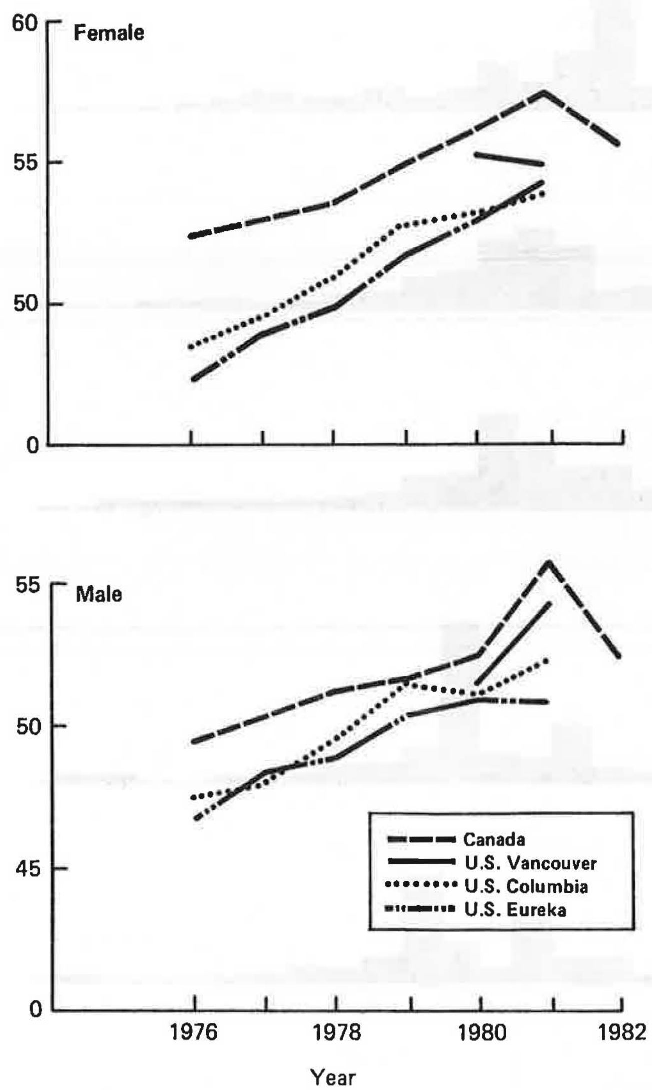


Figure 7.--Mean size of female and male Pacific hake from 1970 year-class in United States and Canadian fisheries from 1976-82.

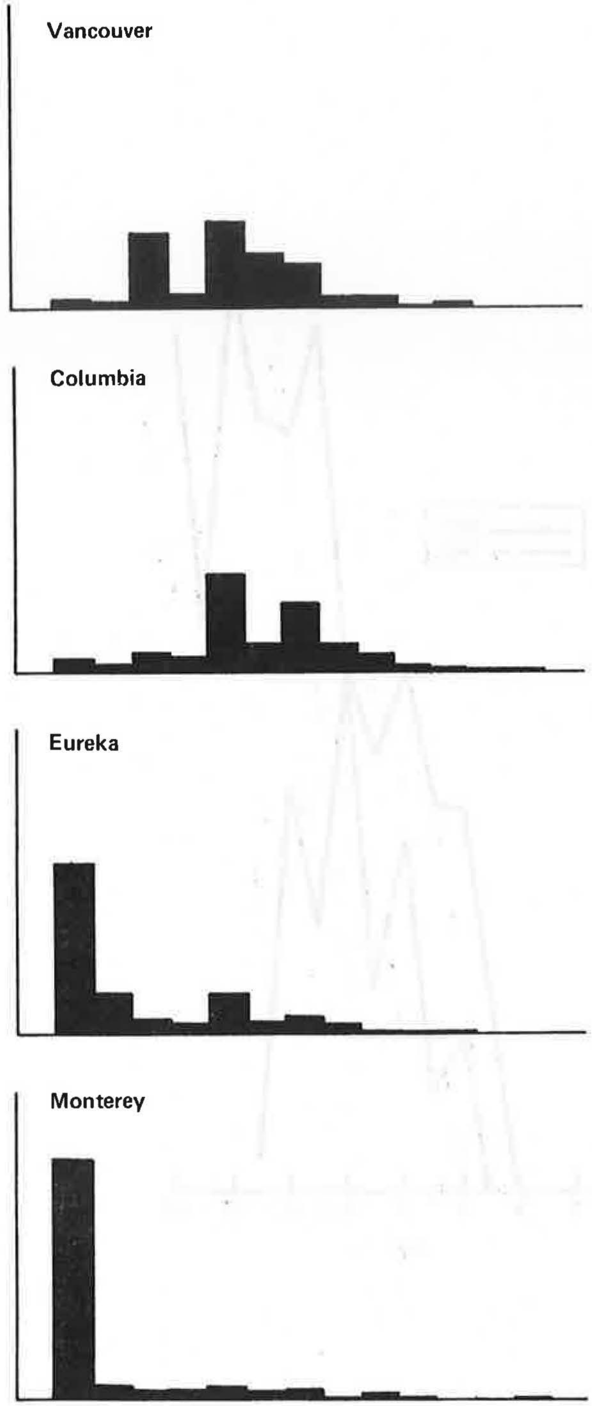


Figure 8.--Relative age-frequency of Pacific hake in 1980 Northwest and Alaska Fisheries Center trawl/hydroacoustic survey.

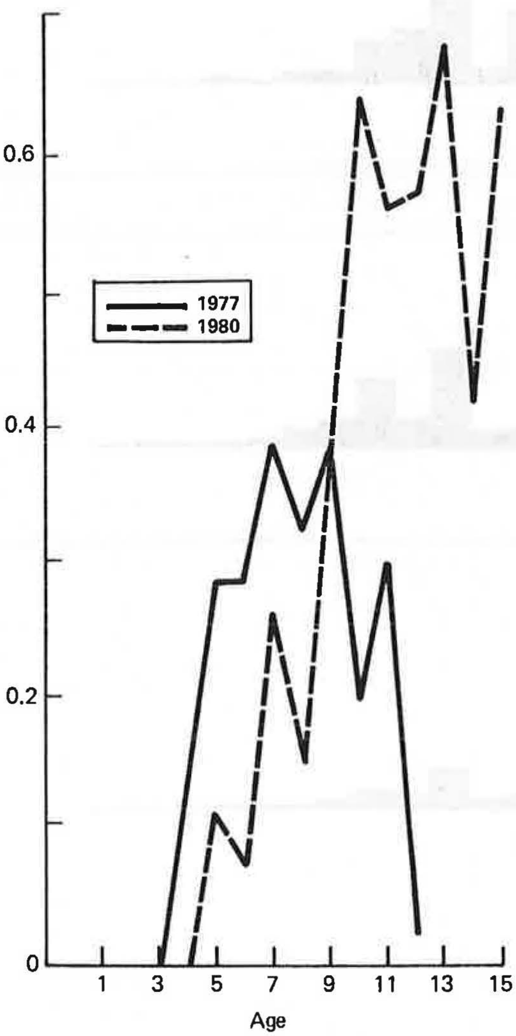


Figure 9.--Fraction of Pacific hake stock in International North Pacific Fisheries Commission, Vancouver area by age, 1977 and 1980, Northwest and Alaska Fisheries Center trawl/hydroacoustic survey.

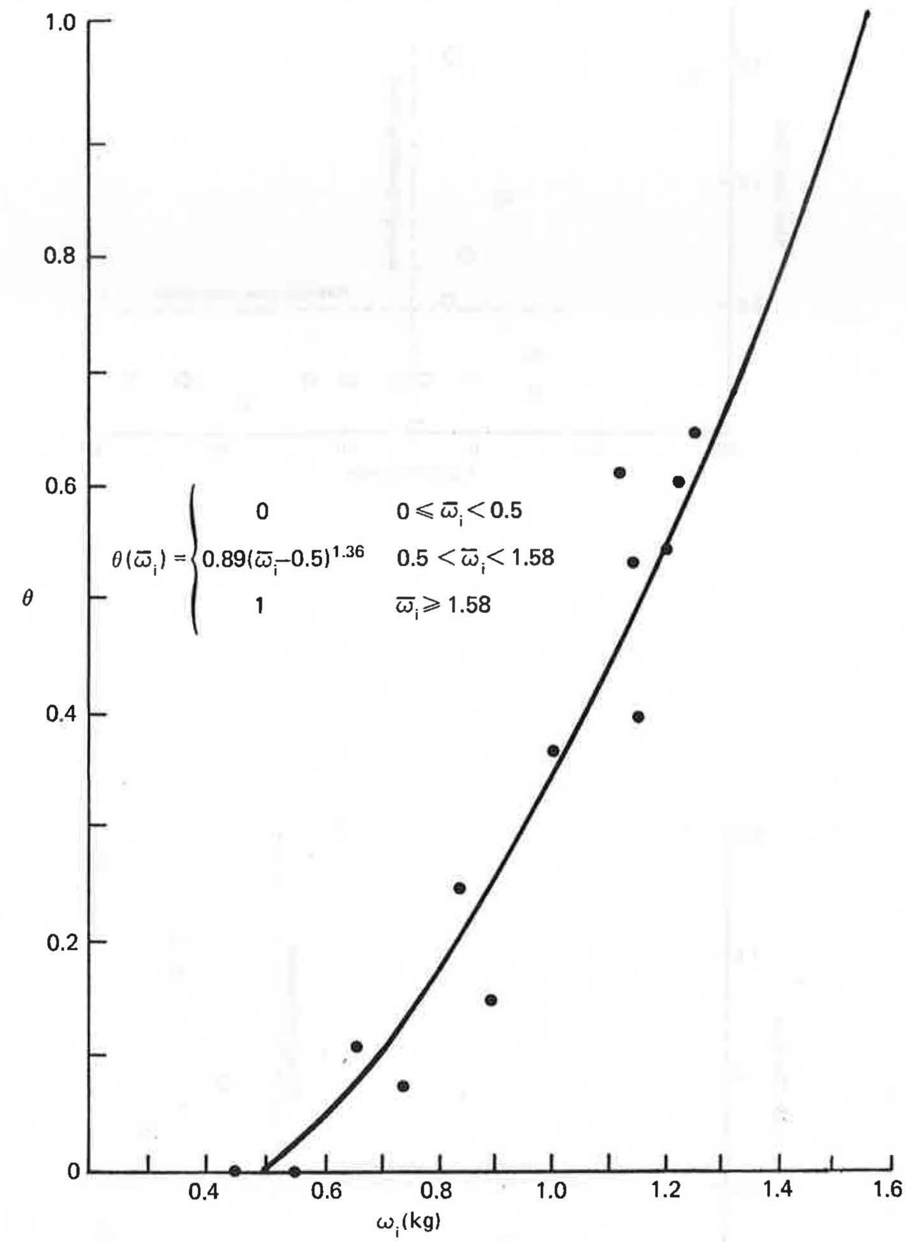
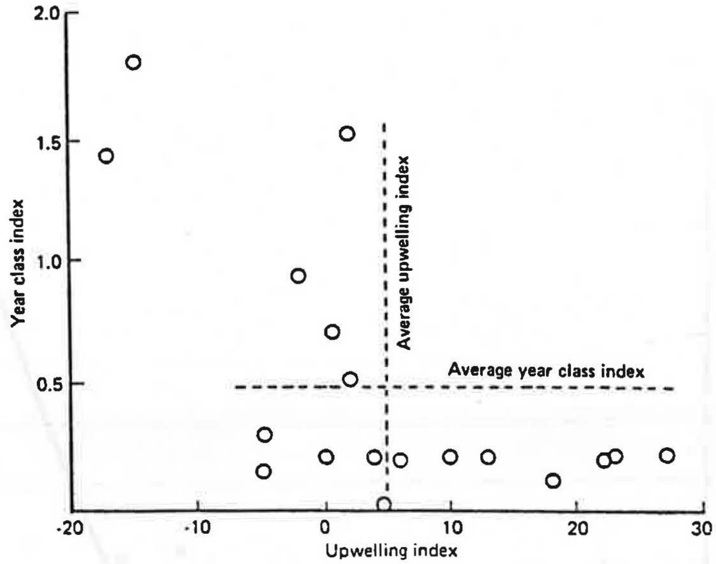


Figure 10.--Observed (1980 Northwest and Alaska Fisheries Center Survey) and expected fraction of a weight class entering Canadian fishery.



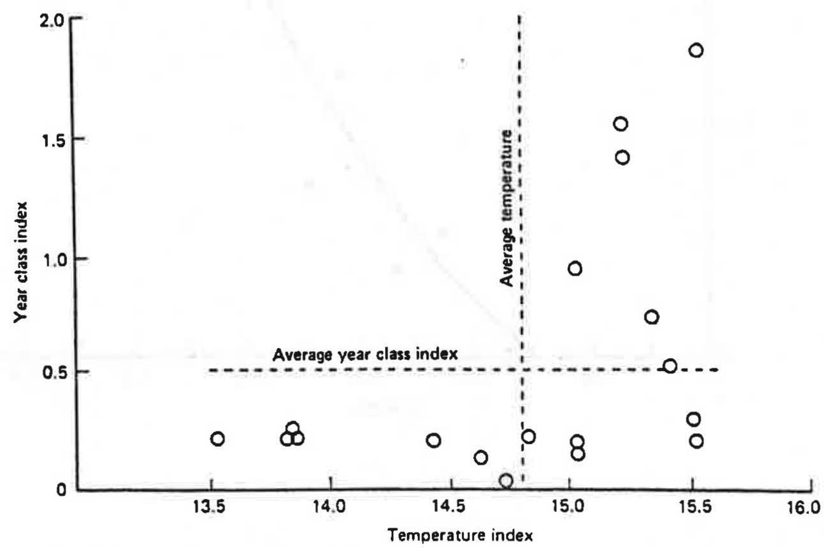


Figure 11.--Pacific hake year-class index (1960-77) as related to upwelling and temperature indices at time of spawning (36° N latitude, January).

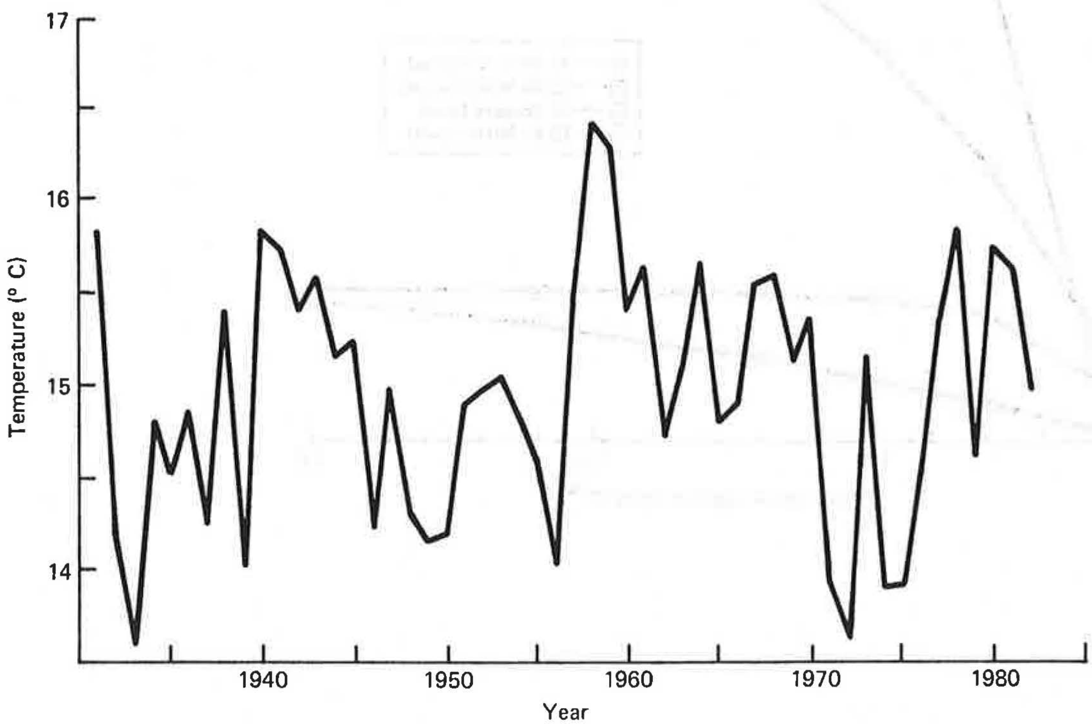


Figure 12.--1931-82 mean January - March Sea surface temperature (°C) in Los Angeles Bight.

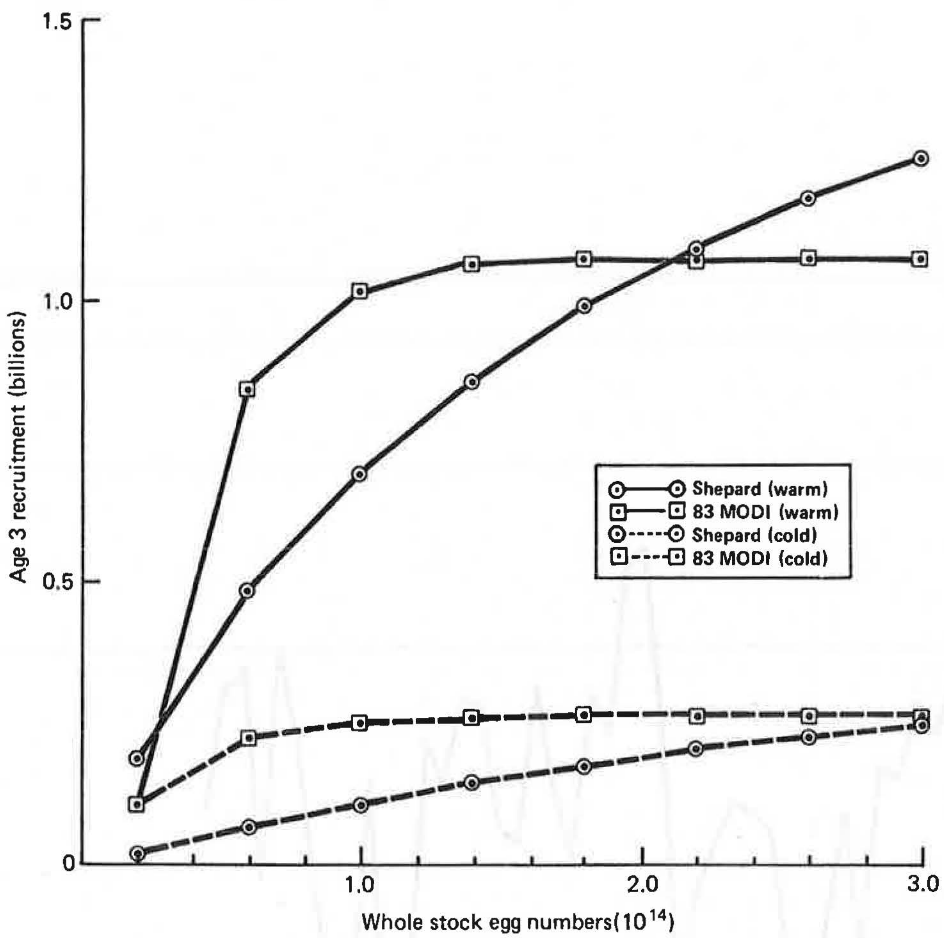


Figure 13.--Cold and warm year stock-recruit relationship.

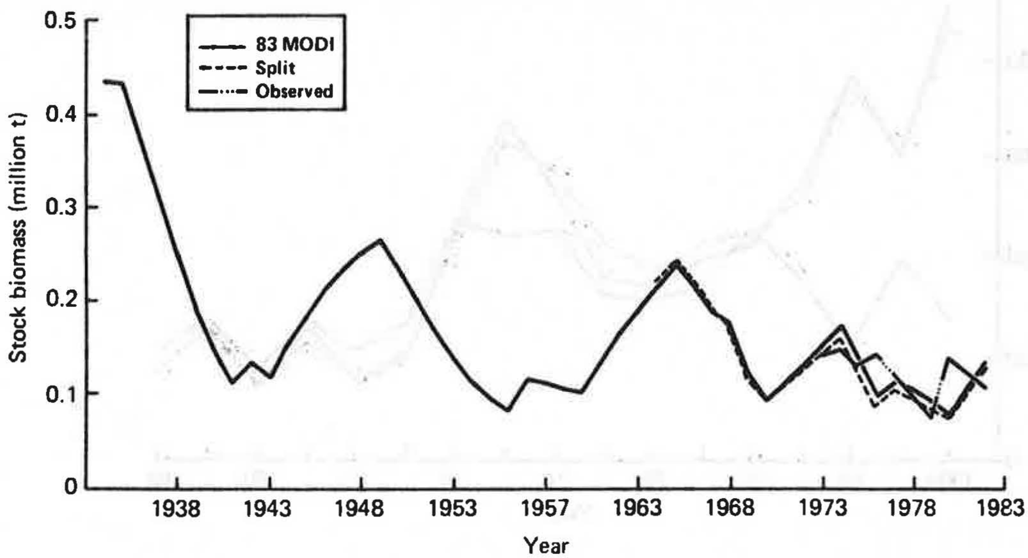


Figure 14.--Historical time series of observed (1973-82) and expected (1933-82) total stock biomass.

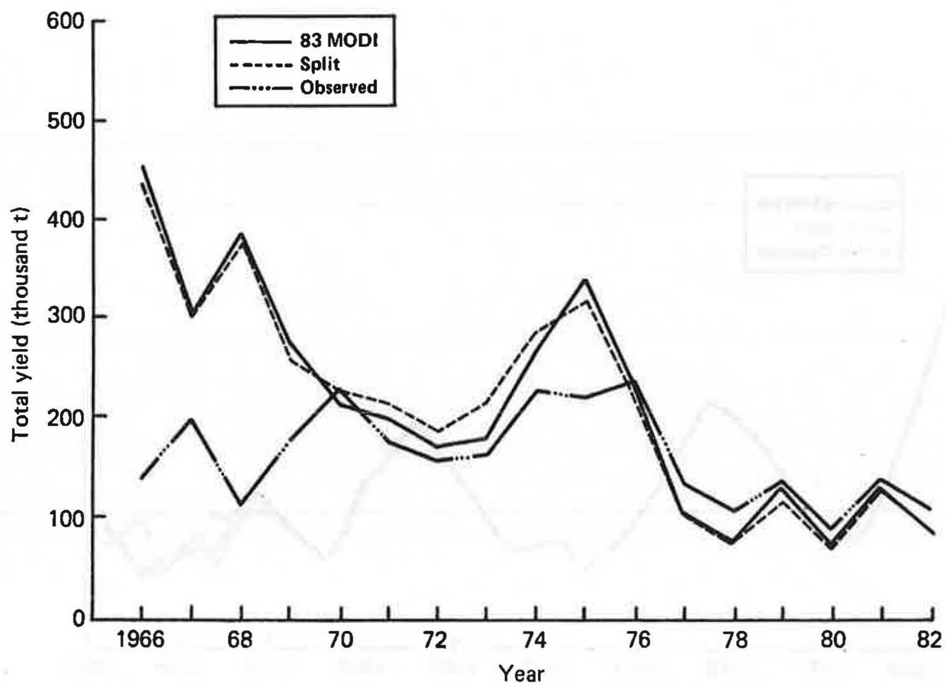


Figure 15.--Historical time series of observed and expected total yield (1966-82).

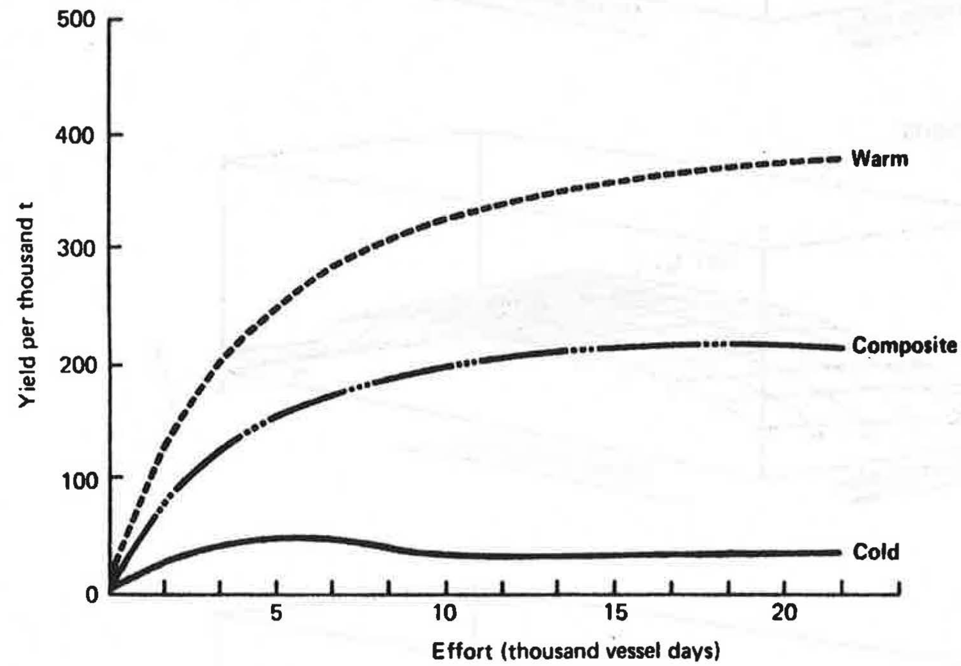


Figure 16.--Single stock 83MOD1 equilibrium yield.

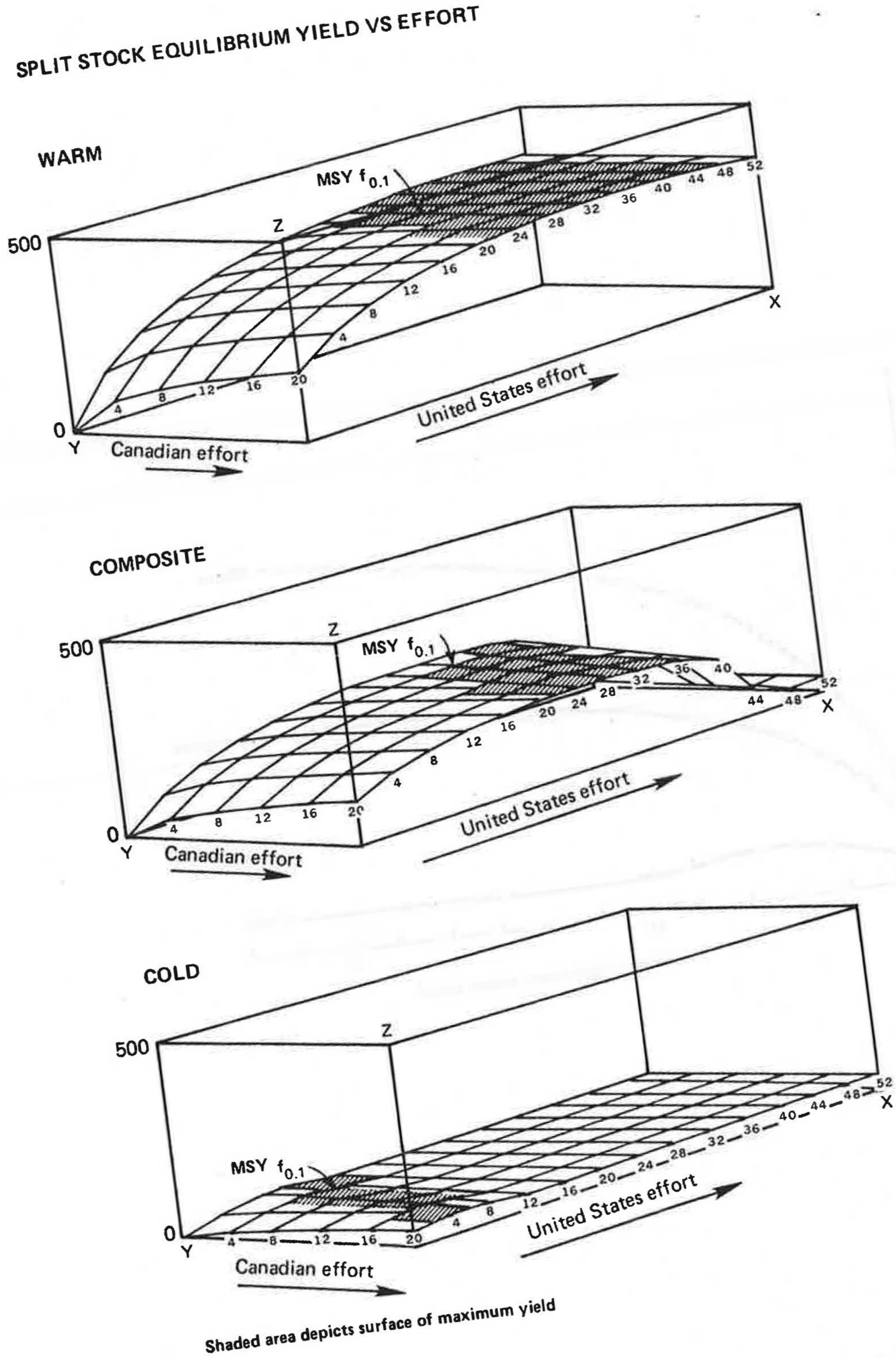


Figure 17.--Split stock equilibrium yield vs. effort.

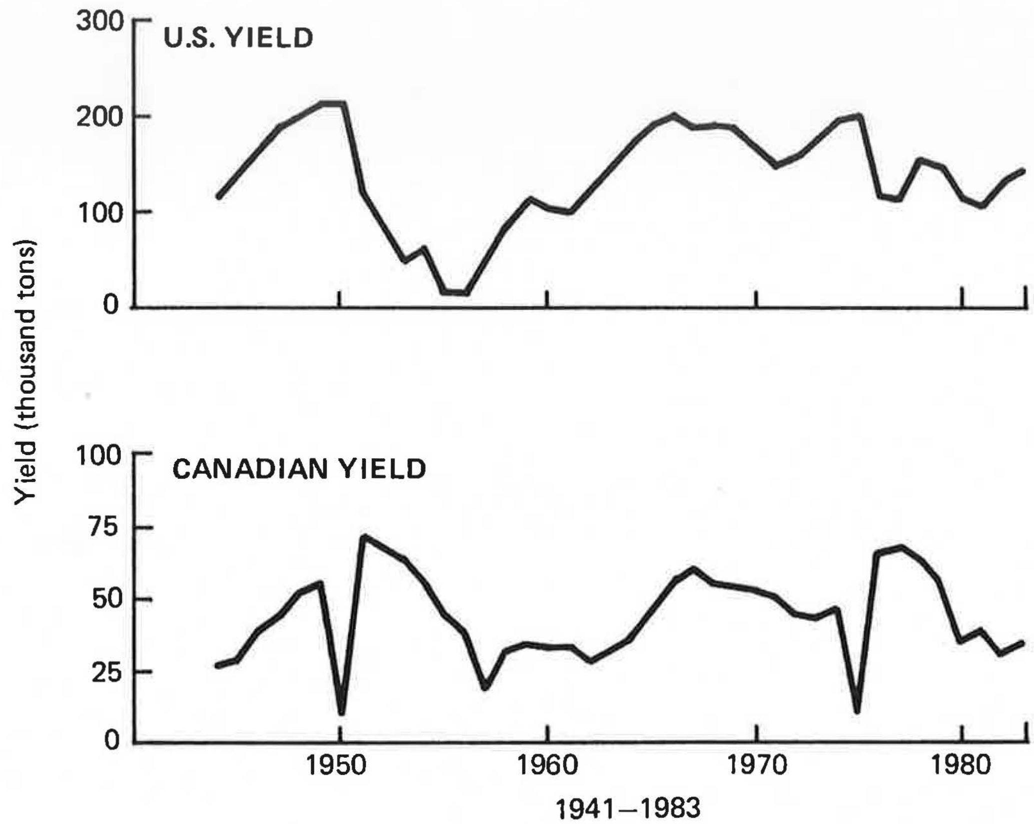


Figure 18.--Annual United States and Canadian yield (1943-83) for first split stock.