 Fish. Oceanogr. 5(Suppl. 1), 189–203, 1996

Contributions of FOCI research to forecasts of year-class strength of walleye pollock in Shelikof Strait, Alaska

BERNARD A. MEGREY,[1] ANNE B. HOLLOWED,[1] STEVEN R. HARE,[2] S. ALLEN MACKLIN,[3] AND PHYLLIS J. STABENO[3]

[1]*NOAA, Alaska Fisheries Science Center, Seattle, WA 98115, USA*
[2]*School of Fisheries, University of Washington, Seattle, WA 98195, USA*
[3]*NOAA, Pacific Marine Environmental Laboratory, Seattle, WA 98115, USA*

ABSTRACT

NOAA's Fisheries Oceanography Coordinated Investigations (FOCI) contributes information to help forecast year-class strength of walleye pollock (*Theragra chalcogramma*) in the Gulf of Alaska. Quantitative estimates of recruitment are obtained from models of stock assessment and stock projection employing information supplied by FOCI. To generate its information, FOCI convenes specialists in marine biology, physical and fisheries oceanography, meteorology, and statistics to assemble and analyse relevant biological and physical time series with respect to recruitment and processes hypothesized to influence fish survival. Statistical methods encompass linear and nonlinear regression, stochastic simulation modelling, transfer function time series modelling, and tree-modelling regression. The current database consists of 31 years of data, and analyses have identified factors that affect ocean stratification and circulation during spring and summer of the fish's birth year as being important to recruitment. A conceptual model of the recruitment process serves as the framework for a recruitment forecast scheme. A stochastic mathematical simulation model of the conceptual model produces similarities between simulated and observed recruitment time series. FOCI has successfully forecast recruitment observed over the past several years.

Key words: forecast, recruitment, stock assessment, walleye pollock, year-class strength

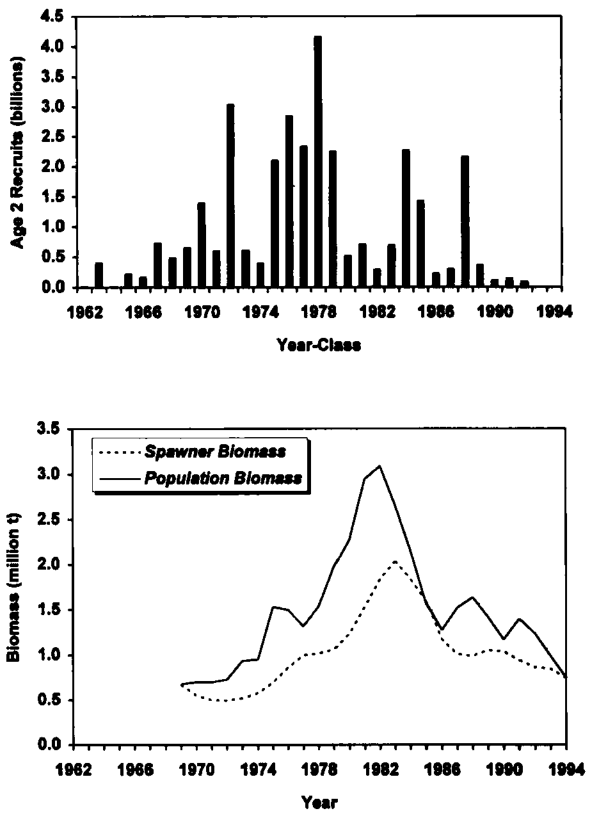
Received for publication 25 July 1995
Accepted for publication 6 October 1995

INTRODUCTION

An increasing number of fisheries oceanography research programmes have flourished during the last 50 years. Some are multi-national, multi-regional, or multi-species focused, e.g., California Cooperative Oceanic Fisheries Investigations (CalCOFI, Hewitt, 1988), NOAA Coastal Ocean Program (COP, Wenzel and Scavia, 1993), and Global Ocean Ecosystems Dynamics (GLOBEC, Eckman, 1994). Other programmes such as the Fisheries Ecology Program (FEP, Smith *et al.*, 1989), Fisheries Oceanography Coordinated Investigations (FOCI, Kendall *et al.*, 1996, pp. 4–18 in this supplement), Ocean Production Enhancement Network (OPEN, e.g. Goddard *et al.*, 1994), and Association of Primary Production and Recruitment in a Subarctic Ecosystem (APPRISE, Bienfang and Ziemann, 1995) focus on specific regions, species, or processes. Much of this research seeks to contribute critical information to fisheries science by providing a fundamental understanding of relationships between the physical and biological environments that account for variation in recruitment success. This aspect of fisheries oceanography is especially relevant to stock assessment, because it is year-class variation that largely determines annual abundance levels of commercially exploited fish stocks (Rothschild, 1986).

Of the programmes mentioned above, FOCI is one of the longest continuing studies, conducting its research on walleye pollock, *Theragra chalcogramma* (hereafter called pollock), in Shelikof Strait since 1985. FOCI's research, which covers every major life stage of Gulf of Alaska pollock, has established a sufficient knowledge-base to support an examination of the relationship between environmental variability and year-class strength. This body of work includes studies that enumerate abundance trends (Hinckley *et al.*, 1991; Kim and Gunderson, 1989; Megrey, 1990; Picquelle and Megrey, 1991, 1993); examine processes affecting life stages (Bailey and Macklin, 1994; Brodeur *et al.*, 1991; Canino *et al.*, 1991; Hinckley *et al.*, 1990; Hinckley *et al.*, 1991; Kendall *et al.*, 1987; Kendall and Kim, 1989; Kim and Bang, 1990; Schumacher and Kendall, 1991; Yamashita and Bailey, 1989; Yoklavich and Bailey, 1989, 1990); investigate fish behaviour (Olla *et al.*, 1996, see pp. 167–178 in this supplement); map hori-

Figure 1. Time series of age-2 walleye pollock recruitment (top panel) and spawner and population biomass (bottom panel) derived from application of fisheries-dependent and fishing-independent data to a stock assessment model.



zontal, vertical, and temporal distributions (Kendall *et al.*, 1987, 1994; Kendall and Picquelle, 1990; Kim and Kendall, 1989; Kim and Gunderson, 1989; Kim and Nunnallee, 1991; Rugen, 1990); describe the oceanic and atmospheric environment (Bond and Macklin, 1993; Macklin *et al.*, 1993; Ortner *et al.*, 1990; Reed *et al.*, 1987; Reed and Schumacher, 1989a,b; Schumacher *et al.*, 1990); and develop techniques to examine recruitment-process hypotheses (Megrey *et al.*, 1995; Stabeno and Megrey, 1991). This collected knowledge has enabled FOCI to develop a conceptual model of pollock survival that is useful in selecting variables to forecast recruitment. FOCI is the only marine fisheries oceanography research programme in the United States to attempt to guide management by forecasting year-class strength.

FOCI forecasts abundance of Shelikof Strait, Gulf of Alaska pollock, a stock that undergoes order-of-magnitude recruitment variability (Fig. 1). Alaska pollock is one of the most valuable commercial marine fish species in the world. In the decade of the 1980s, pollock was the single most important species by weight in the world fish catch (Bakkala *et al.*, 1987). Since the mid-1980s, pollock catches in Alaskan waters have averaged between 1 and 1.5 million tonnes annually (Kinoshita *et al.*, 1995). For 1993, about 70% of the total Alaska groundfish catch was pollock valued at about $1bn, and the pollock harvest constituted nearly a third of the total 1993 fish harvest in the Exclusive Economic Zone (EEZ) of the United States (Kinoshita *et al.*, 1995). The Gulf of Alaska contributed 7% of the total Alaska catch from 1991 through 1994. The economic value of the fishery and the inherent population variability underscores the importance of prudent management (Hollowed and Megrey, 1993; Megrey *et al.*, 1994). One need look no further than the Georges Bank fishery closure (Kunzig, 1995; Sinclair and Page, 1995) to see the impact of population variability in an ecosystem.

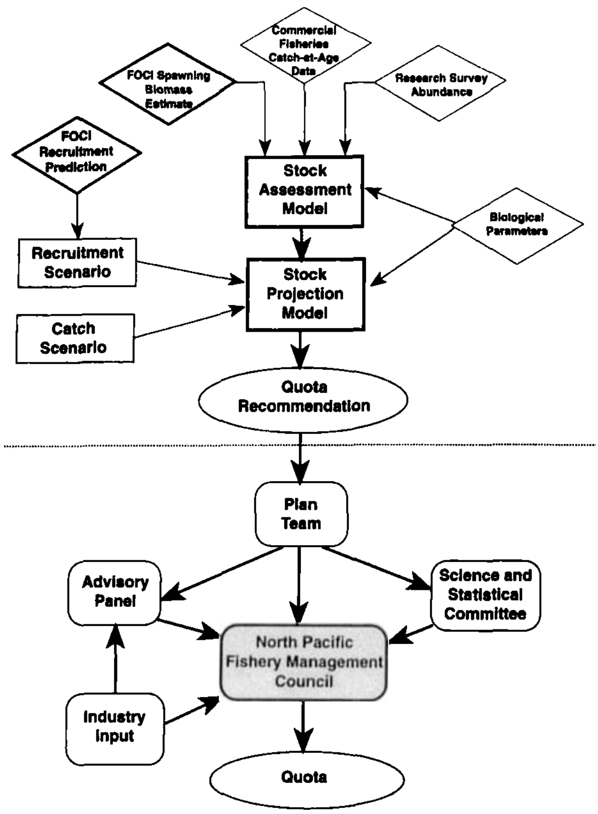
As with most marine species, the annual fishable pollock population varies depending on biotic and abiotic processes occurring on differing time and space scales. Figure 1 illustrates the variability in year-class strength from 1962 through 1992 for the Shelikof Strait, Gulf of Alaska pollock population. Over the 31-year period, recruitment has varied by an order and a half in magnitude and experienced one episode of peak recruitment success in the late 1970s. The spawning biomass and population biomass time series (Fig. 1) also show high variability characteristic of exploited gadid populations.

Because FOCI's goal is to understand how the environment affects recruitment (Kendall *et al.*, 1996), it follows that FOCI will use that understanding to provide forecasts of recruitment used in the fishery management process. In this paper we describe the ways in which FOCI research is used to provide critical information to the fisheries management process. First, we describe a conceptual model of the recruitment process for this stock, and then we provide a stochastic simulation model representation of the conceptual model and compare the two. Our evolving approach to forecasting recruitment for 1991–1994 is then discussed.

THE MANAGEMENT PROCESS

When FOCI began, a system already existed for the transfer of information to fisheries management (Fig. 2). Guidance is passed to the North Pacific Fishery Management Council (NPFMC) and its Plan Teams, Advisory Panel, and Science and Statistical Committee. This body makes recommendations for the management of all groundfish stocks off the coast of Alaska, including the Gulf of Alaska pollock fishery. NPFMC's recommendations are forwarded to the Secre-

Figure 2. Schematic representation of information flow in the Gulf of Alaska walleye pollock management process. Scientific activity aimed at generating management advice is described above the dotted line. FOCI's contribution to this process is indicated in shaded diamonds. The allocation process by the North Pacific Fishery Management Council (shaded) is described below the dotted line.



tary of Commerce for final approval. The NPFMC regulates the catch of pollock in the Alaska EEZ by establishing annual quotas on commercially harvested fish and shellfish. Lowe and Baldwin (1992) provide a more detailed description of the fishery management system.

Guidance for NPFMC, including quota recommendations, is supplied by NMFS based on two processes. A retrospective assessment of past and current stock abundance (the stock assessment analysis) uses a combination of commercial fisheries catch-at-age data and research survey abundance estimates. A separable age-structured stock assessment model is used in this step. Currently trawl and hydroacoustic techniques are used to survey the pollock populations and to help calibrate estimates of absolute population abundance. The FOCI's Fishery-independent spawning biomass estimates and variances derived from the annual egg production method (Picquelle and Megrey, 1991, 1993) have been used in the assessment model in addition to hydroacoustic and bottom trawl survey results.

Once the current condition of the stock is estimated, the likely impacts and risks associated with proposed management actions are examined within the framework of a population dynamics stock projection model. This exercise evaluates the effects of alternative harvest strategies and recruitment scenarios on future abundance of the pollock stock. In this important step information on the natural variability of the fishery resource is provided in addition to a determination of how exploitation affects the natural biological processes. Previous research (Hollowed and Megrey, 1993; Megrey *et al.*, 1994) has shown that the status of the future stock from the projection model is extremely sensitive to the recruitment assumption. FOCI contributes to this exercise by providing formal recruitment forecasts. FOCI's recruitment forecasts significantly simplify the stock projection analysis by limiting the number of simulations to include only those recruitment scenarios that are most possible based on the quantitative and qualitative information at hand. Results of this model are used to establish a quota recommendation for consideration by the management council and its three subcommittees.

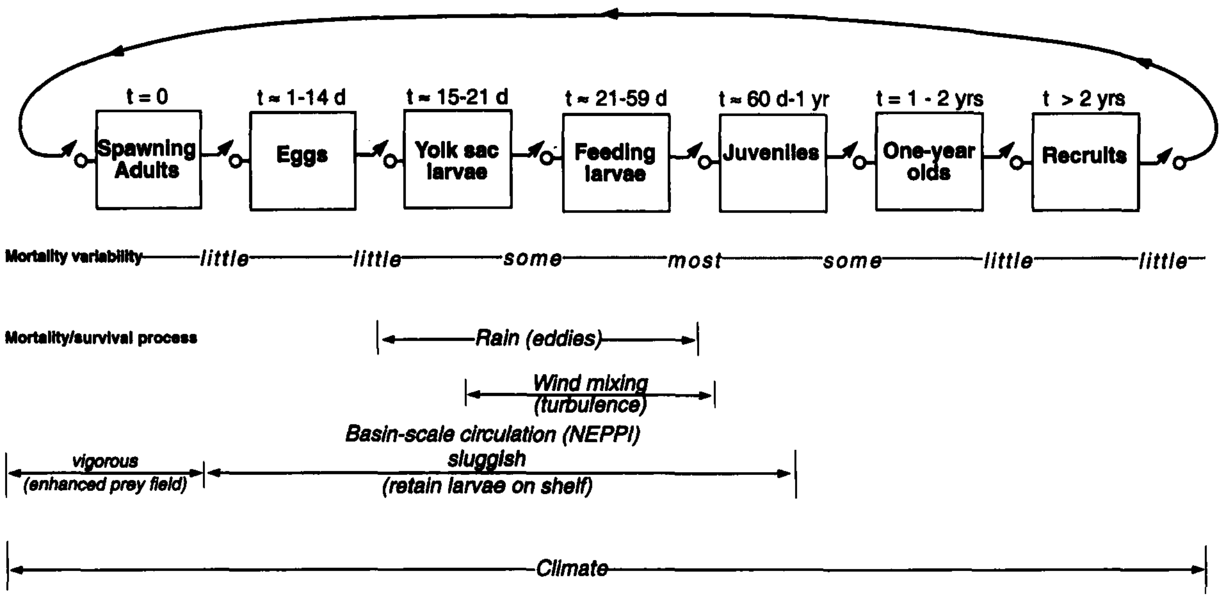
CONCEPTUAL MODEL AND MATHEMATICAL REPRESENTATIONS

Conceptual model

Pollock of the western Gulf of Alaska exploit Shelikof Strait as a major spawning ground. Presumably there are characteristics of the location that promote survival of the stock, and returning to that location is part of its evolved reproductive strategy. FOCI scientists have developed a conceptual model of conditions necessary for enhanced survival of pollock that leads to successful recruitment to the fishery (Fig. 3). The model can be termed a switch or survival gauntlet model in that it represents successive conditions or switches that must be realized for the fish to survive. Each switch has a conditional probability of being set for survival or mortality. The probability is subject to spatial and temporal variability, e.g., a 'hatch' switch could be dependent on water temperature that varies in space and time. Switches can act on individuals, cohorts or populations.

FOCI's conceptual model is based on 10 years of research on life stages and distribution of pollock, their behaviour, and the physical and biological processes that influence them. For pollock in the western Gulf of

Figure 3. Conceptual model of Gulf of Alaska walleye pollock survival at different life stages. Relative mortality, important environmental processes and the life stages that they affect are indicated.



Alaska, we believe the major components to be the climate, the preconditioning of the environment prior to spawning, the ability of the physical environment to retain the planktonic life stages of pollock on the continental shelf, and the abundance and distribution of prey and predators on the shelf. These elements span several spatial and temporal scales. The greatest threat to survival occurs during the early stages of life. Year-class abundance is generally established within 90 days of hatching (Bailey *et al.*, 1996, see pp. 124–136 in this supplement).

On the climate scale a change in the character of North Pacific fisheries occurred during the late 1970s. This has been termed a 'regime shift' by Hollowed and Wooster (1992) and corresponds with observed changes in the physical climate (Trenberth and Hurrell, 1995). For pollock in the Gulf of Alaska, peak recruitment during the late 1970s (Fig. 1) was associated with the regime shift. Pollock recruitment returned to lower values after 1979. Because the pollock recruitment time series spans only one regime shift, a significant argument about climate processes and survival cannot be made. However, we believe that long-term averages of appropriate basin or global-scale environmental indices may be good indicators of regime shifts.

On the basin scale, there are necessary biotic and abiotic conditions for successful spawning, hatching and first feeding. These are established annually on the shelf prior to spawning. We believe that these conditions are associated with a vigorous circulation in the Gulf of Alaska during late winter. Recently, pollock that were spawned in years when the spring circulation was sluggish have recruited with above-average abundance (Hermann *et al.*, 1996, see pp. 39–57 in this supplement). This suggests that after the vigorous Gulf circulation has replenished nutrients on the shelf, pollock survival is improved if the circulation relaxes to a sluggish state. This may promote retention of larvae on the continental shelf. Much of the variability in the circulation of the Gulf of Alaska is due to large-scale atmospheric forcing (Stabeno *et al.*, 1995). The Aleutian Low dominates the variability of the atmospheric circulation over the Gulf of Alaska and plays a crucial role in the hydrological cycle (Niebauer, 1988). A basin-scale index such as the North-east Pacific Pressure Index (NEPPI, Emery and Hamilton, 1985) could qualify as a probability parameter for these 'preconditioning' and 'relaxation' switches.

FOCI studies have also noted a propensity for the coincidence of larval patches and mesoscale eddies (Schumacher *et al.*, 1993), and determined that for early larvae, presence within an eddy improved survival (Bograd *et al.*, 1994). Baroclinic instabilities in the Alaska Coastal Current are a source of eddies for Shelikof Strait. Runoff or rainfall is a useful index for an 'eddy' switch as the baroclinity of this current fluctuates with the amount of freshwater discharged along the coast (Royer, 1982). Stronger discharge promotes an increased density gradient across the current, providing more energy for development of instabilities.

Another switch relates to first-feeding larvae. Exhaustion of the yolk sac results in the need to capture food, primarily copepod nauplii (Napp *et al.*, 1996, see pp. 19–38 in this supplement), and this is a critical stage for larval survival. Bailey and Macklin (1994), surmising that increased turbulence interfered with the ability of a larva to feed, found that strong wind events during the first-feeding period were detrimental to survival of pollock larvae. An index of wind mixing for Shelikof Strait provides information for the first-feeding switch. Although it may quantify the ability of larvae to feed, it needs to be coupled with a term describing the availability of food. Larval condition and the amount of nauplii in the guts correlate with microzooplankton abundance, indicating that in some cases food may limit growth and, potentially, survival (Canino, 1994; Theilacker *et al.*, 1996, see pp. 112–113 in this supplement). FOCI has not developed an index of available prey, although considerable understanding of copepod dynamics has been gained (Napp *et al.*, 1996).

Stochastic switch model

The stochastic switch model, a mathematical representation of the conceptual model described above, is a numerical simulation model of the recruitment process that has three switch levels. Each level, which is specified with an individual statistical description of survival, determines the overall mortality experienced by the recruits. Although the stochastic switch model has not been incorporated into FOCI's formal prediction scheme, we plan to use it to explore long-term variability of recruitment.

Recruitment The switch model is run for 32 years. In each year the first 90 days after hatching are simulated. The model is seeded with larvae during the first 30 days. The larvae are divided into 10 cohorts using a 3-day hatch interval. The first cohort are those hatched on days 1–3, the second days 4–6, etc. (Fig. 4).

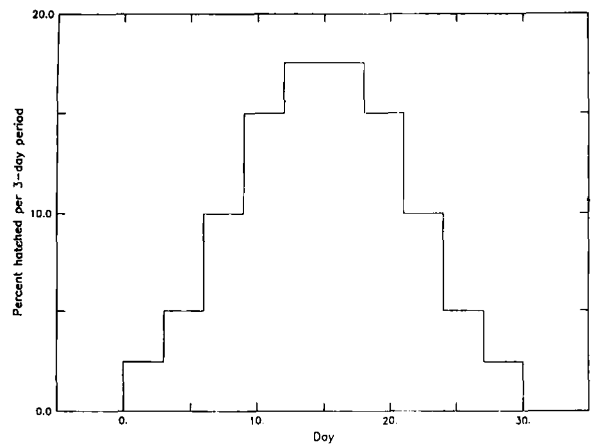
In each year (n) and for each cohort (j), the number of larvae alive at the end of 90 days is calculated as

$$R_{jn} = \prod_{i=3j-2}^{90} [1 - \Lambda_i(n)] R_j$$

where R_{jn} is the number of recruits in year n of cohort j, $\Lambda_i(n)$ is the daily mortality (% day^{-1}) in year n, and R_j is the number of larvae hatched (5×10^{12}) and partitioned as in Fig. 4. The total number of larvae (R_n) alive at 90 days in year n is calculated by summing over each of the 10 cohorts

$$R_n = \sum_{j=1}^{10} R_{jn}$$

Figure 4. Assumed hatch date distribution used in the stochastic switch model to generate recruitment values.



Generalized mortality Generalized mortality consists of a base daily mortality rate modified by an additive and multiplicative effect for each of the three stochastic mortality components. These are: random mortality that is unprescribed to any process or cause, mortality induced by wind mixing , and mortality due to eddy events. The generalized daily mortality model for these three switches can be written

$$\Lambda_i(n) = \left(Z + \sum_{s=1}^{3} \phi^s\right) \prod_{s=1}^{3} \lambda^s$$

where $\Lambda_i(n)$ is the generalized mortality experienced by the cohort, Z is the base level mortality (0.01% day^{-1}), and ϕ^s and λ^s are the additive and multiplicative mortality adjustments, and s indexes the three mortality switches. The base mortality was estimated from field data (unpublished). The three mortality switches are indicated with superscripts to represent the random (s = 1, ϕ^r, λ^r), wind mixing (s = 2, ϕ^w, λ^w), and eddy mortality (s = 3, ϕ^e, λ^e) components, respectively. These are described in more detail below.

Random mortality Each year is defined with a base mortality (Z = 0.01% day^{-1}). The mortality component random variable (χ^r) is uniformly distributed on the interval [0, 1], and the random mortality adjustment parameters are determined by the following decision rules

If $\chi^r \leq 0.05$ then $\phi(n)^r = 0.0$ and $\lambda^r = 1.0$,
If $\chi^r > 0.05$ then $\phi(n)^r = 0.04$ and $\lambda^r = 1.0$,

where $\phi(n)^r$ is the additive random mortality adjustment for year n. This formulation specifies that in 5% of the years this random mortality is equal to the base mortality. In 95% of the years this random mortality is 0.05. The integral time scale (Stabeno and Smith, 1987) for the recruitment time series is 1.2 years. If no memory of previous years is included in the switch model the integral time scale of the switch recruitment series is 1.0. To incorporate memory, random mortality is calculated as

$$\phi^r = (\phi(n)^r + \phi(n-1)^r)/2,$$

where $\phi(n)^r$ *and* $\phi(n-1)^r$ are defined in the decision rule above. We ascribe to random mortality the cumulative mortality due to unmodelled processes such as climate.

Wind mixing mortality First-feeding larvae are particularly sensitive to wind mixing (Bailey and Macklin, 1994). The random wind mixing mortality component random variable (χ^w) for the three first-feeding days for each cohort is uniformly distributed on the interval [0, 1], and the random wind mixing mortality adjustment parameters are determined by the following decision rules

If $\chi^w < 0.50$ (winds weak to moderate) then $\phi^w = 0.0$ and $\lambda^w = 1.0$,
If $0.5 \le \chi^w < 0.75$ (winds strong) then $\phi^w = 0.49$ and $\lambda^w = 1.0$,
If $\chi^w \ge 0.75$ (winds extreme) then $\phi^w = 0.99$ and $\lambda^w = 1.0$.

If winds are weak or moderate, there is no effect on mortality. If the winds are strong then half the cohort dies. If winds are extreme, then essentially all of the cohort dies. Additionally, if 9 of the 10 hatch periods have 'weak winds' ($\chi^w < 0.30$), then 25% of each cohort dies due to an assumed inability to encounter food.

Eddy mortality The eddy mortality component is consistent with evidence that larval mortality in an eddy is reduced. We assume that about 40% of the larvae end up in an eddy (Stabeno *et al.*, 1996, see pp. 81–91 in this supplement), that eddies last for about 21 days, and that once a larva becomes entrained in an eddy it does not escape until the eddy spins down.

The random eddy mortality component random variable (χ^e) is uniformly distributed on the interval [0, 1], and the random eddy mortality adjustment parameters are determined by the following decision rules

If $\chi^e \le 0.4$ (larvae in an eddy) then $\phi^e = 0.0$ and $\lambda^e = 0.5$
If $\chi^e > 0.4$ (larvae not in an eddy) $\phi^e = 0.0$ and $\lambda^e = 1.0$

If larvae are in an eddy, the reduced mortality is applied for 21 days. Mortality then returns to the original base rate for the remainder of the 90 days.

There is a conditional dependency between the wind mixing and eddy mortality components. If winds are weak then the presence of eddies controls mortality. If the winds are strong to extreme, then all larvae die and eddies have no effect on mortality.

Stochastic switch model results

Each 32-year simulation was replicated 30 times to provide summary statistics to compare against the observed recruitment time series. The switch simulation model did a reasonable job of producing a recruitment time series that had similar statistical characteristics as the observed time series. Samples from three simulations (Fig. 5A) show occasional years with high recruitment and runs of average and low recruitment. Statistical properties of the simulated recruitment series show similarities with respect to the range of recruitment values. These were expressed as a comparison of the first and fourth quartiles of recruitment, mean recruitment compared against recruitment variance, and a measure of the recruitment integral time scale which is a measure of autocorrelation in the recruitment time series.

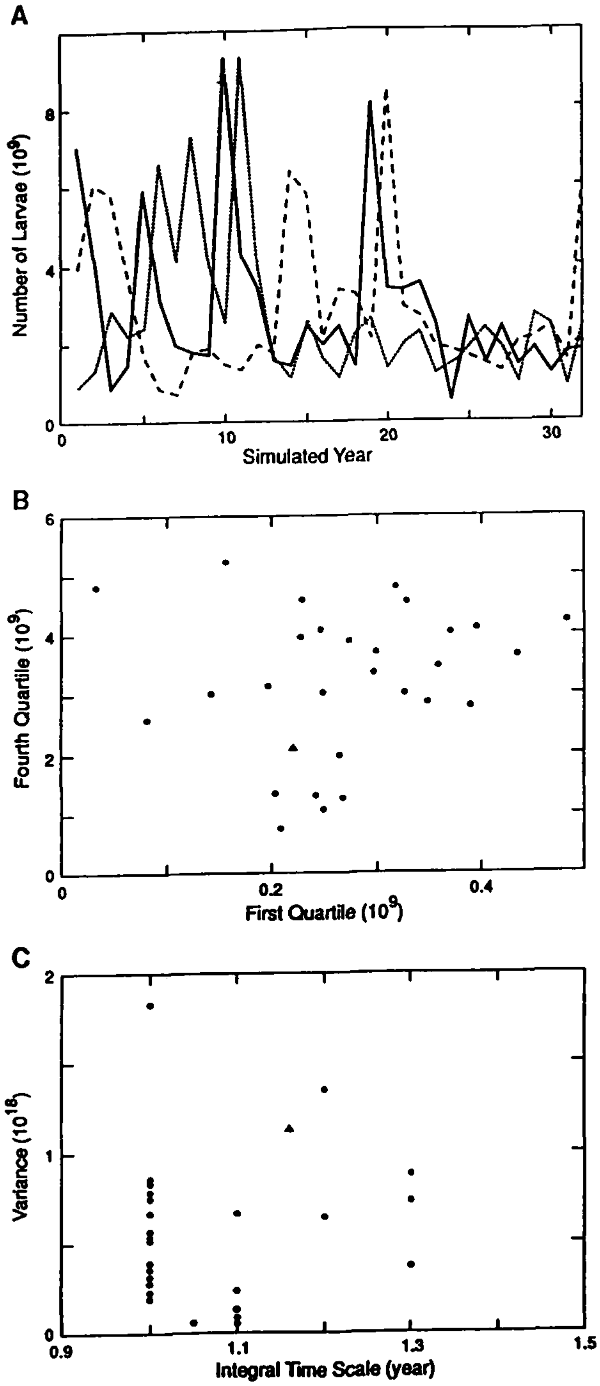
Plotting the first and fourth quartiles of the recruitment time series (Fig. 5B) shows that the observed series fall approximately in the middle of the simulated data. The mean of the 32-year simulation was set to the mean of the observed recruitment time series. The observed variability is higher than that simulated (Fig. 5B), indicating that the switch model underestimates the variability of the observed time series. The integral time scale of the simulated series is consistent with the observed value that falls approximately in the middle of the plot (Fig. 5C). In each of these comparisons the switch model generated statistical characteristics consistent with the observed recruitment time series.

Other environment-recruitment models

FOCI's task is to understand processes that lead to pollock survival, quantify each process by establishing relationships between abundance and environmental variables, and then combine the relationship into numerical techniques that relate to assessment and projection. The inverse process is also useful, i.e. using statistical techniques to discover relationships between the environment and abundance that guide understanding. In this regard, FOCI employs a number of models that, although not part of the formal forecast method, aid in the process.

These models are exercised cautiously as there are acknowledged difficulties in understanding how changes in the environment relate to recruitment. First,

Figure 5. Summary results from the stochastic switch model (see text). (A) Three recruitment time series realizations from the simulation model. (B) First and fourth quartiles of simulated recruitment (circles) compared to observed recruitment (triangle). (C) Integral time scale from simulated recruitment compared to observed.

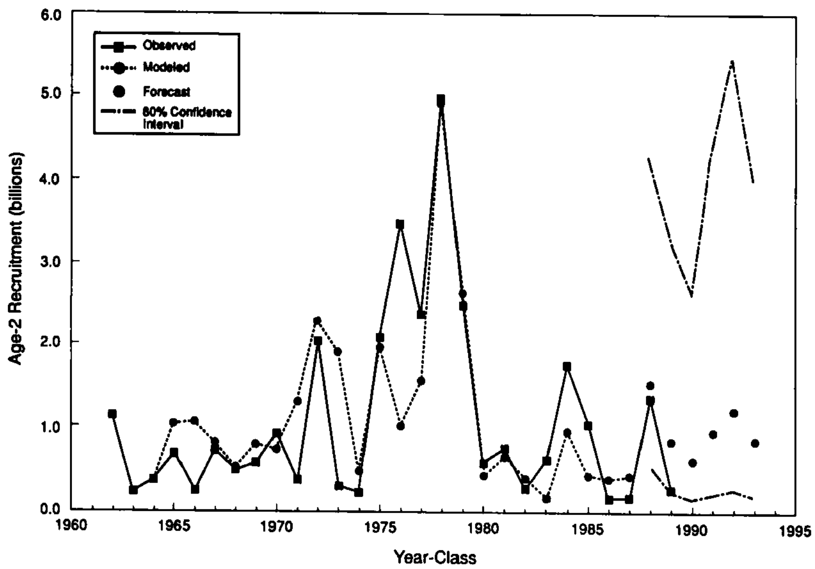


the physical environment is influenced by nonlinear dynamics and varies over wide temporal and spatial scales (Wooster and Bailey, 1989). Further, Walters and Ludwig (1981) showed that inaccuracies in measuring environmental variability and biotic response compound the difficulty. Additional complications develop from fluctuating mortality rates and their causes as fish mature. Nevertheless, investigators have researched causes of recruitment fluctuations in fish and related these to environmental determinants: Hollowed (1992) lists studies for stocks along the North-east Pacific coast; additional examples are Nelson *et al.* (1977), Leggett (1977), Chadwick *et al.* (1977), Bailey (1981), Leggett *et al.* (1984), and Parker (1989). Some studies failed to establish strong environmental links to recruitment, while others identified important potential determinants of year-class strength in fish.

Currently, there are contrasting philosophies regarding the utility of cause and effect environment-recruitment models. Because of the mixed success in establishing clear connections between variability in the environment and recruitment, two attitudes flourish regarding the utility of environment-recruitment studies. Walters and Collie (1988) criticized correlative environment-recruitment studies as futile because of biases, measurement error, and the near certainty of spurious correlations. Others are optimistic—Kope and Botsford (1990) claim that correlative studies provide information on patterns that lead to the formulation of testable hypotheses. Hollowed (1992) and Tyler (1992) advocate correlative studies that are approached with caution. A sound conceptual framework and judicious use of statistical methods can reduce the likelihood of spurious correlations. FOCI addresses forecasting by following the three-stage approach recommended by Hollowed (1992) and Tyler (1992): (i) Begin with an examination of temporal and spatial distributions of various life stages of pollock, then relate these to postulated key events in the life history that may influence survival. This important step is intended to reduce the environmental variables to a manageable subset and identify when they might affect survival. (ii) Examine spatial and temporal characteristics of biological distributions and relate them to potential environmental influences. (iii) Compare time series of selected environmental variables with the time series of recruitment using a suite of statistical methods.

Other modelling approaches that follow the philosophy described above have been investigated. Megrey *et al.* (1995) examined associations between recruitment and the environment using linear modelling techniques. Their findings indicated that rainfall in January

Figure 6. Comparison of observed recruitment to that predicted from the nonlinear transfer function model fit to Gulf of Alaska walleye pollock recruitment time series. June NEPPI and Kodiak rainfall in January and February were the independent variables. The model explained 69% of the variation in recruitment and supplied actual recruitment forecast for years 1988–1993.



and February and NEPPI in June in the birth year were significantly related to age-2 recruitment. Also a nonlinear time series transfer function model (B. Megrey, unpubl. data), after Box *et al.* (1994), has been applied in 1993 and 1994 and used to forecast recruitment. Methods used to fit the time series model are described in Hare and Francis (1995). Recruitment forecasts from this model are possible by reserving a segment of the time series from the segment used to fit the parameters. The analysis performed in 1993 (Fig. 6) explained 69% of the variation in recruitment, forecast recruitment for 1989–1993, and included June NEPPI and Kodiak rainfall as independent variables.

Recently, nonparametric tree regression and general additive modelling (Hastie and Tibshirani, 1990) techniques have been applied to fisheries problems (Jacobson and MacCall, 1995; Swartzman *et al.*, 1992). The pollock information base has been investigated with these new techniques (B. Megrey,unpubl. data) but the results were not consistent with each other or FOCI's conceptual model.

FOCI RECRUITMENT FORECAST

Common recruitment forecasting techniques include use of quantiles, stock-recruitment relationships, time series methods, and qualitative decision analysis techniques such as the Delphi Method (Zuboy, 1981). The FOCI scheme is based on the simple conceptual model described above and employs several of these techniques. The current approach provides forecasts in categories of below average, average, and above average recruitment.

Forecast strategy

Information for the recruitment forecast may include qualitative as well as quantitative information. Although quantitative data are preferred and may often be available from field sampling, scientists also develop an intuitive sense of how conditions in the current year compare to previous situations. These valuable 'anecdotal' observations and 'subjective impressions' are combined with quantitative estimates to make a forecast of year-class strength.

Our information sources cover the first three months of the first year of life through the first two years of life. In the early years of FOCI, research emphasis was on the egg and larval stages, and information sources from those stages constitutes the bulk of our database. In recent years, we have begun to explore the influence of the juvenile life stage on recruitment (Brodeur and Wilson, 1996, see pp. 148–166 in this supplement), but results are not yet available for incorporation into our forecast models. Variables that influence survival during the first year of life include: (i) rainfall, i.e. increased freshwater input, that is likely to be beneficial to recruitment because baroclinic instabilities arising from the addition of freshwater promote the formation

Table 1. Comparison of FOCI recruitment forecast to actual recruitment for the years 1989–1994. Recruitment strength forecasts are indicated as weak (W), average (A), or strong (S). Data sources are listed at the bottom.

Type of forecast	Year class 1989	1990	1991	1992	1993	1994	Year prediction made	Method
Quantitative 1992[a]	W	W	W–A	S			1992	Spawner-recruit data, time sequence of data
Quantitative[b]			A	A	A		1993	Non-linear transfer function time series model
Qualitative[c]			W	W	A		1993	Subjective observations
Combined 1993			W	W	A		1993	
Quantitative[d]			S	A	A	A	1994	Non-linear transfer function time series model
Quantitative[e]			W	W	A		1994	Hydroacoustic length composition
Qualitative[f]			A–S	A	A	A–S	1994	Rain
Qualitative[g]			W	A	A	A–S	1994	Wind mixing
Qualitative[h]			W	A	A	A–S	1994	Advection
Qualitative[i]			W	A–S	W–A	A	1994	Index of larval abundance
Combined 1994			W	W	A	A	1994	
Actual Recruitment	W	W	W	W	W–A	A–S		

[a]Used recruitment time series 1962–1989 and spawner-recruit data 1969–1989; no environmental data.
[b]Used recruitment time series 1962–1989 as well as environmental data.
[c]Used NMFS survey data.
[d]Used recruitment time series 1962–1991 as well as environmental data in refit of transfer function model.
[e]Hydroacoustic length composition from Shelikof Strait 1991–1993 (C. Wilson, pers. comm.).
[f]Average Kodiak rainfall during January and February for 1991–1994 (A. Macklin, pers. comm.).
[g]Wind mixing energy at 55°N 156°W during April, May and June 1991–1994 (A. Macklin, pers. comm.).
[h]Advection from moored current meters (P. Stabeno, pers. comm.).
[i]Larval counts from ichthyoplankton tows in Shelikof Strait (K. Bailey, pers. comm.).

of eddies; (ii) low to moderate winds associated with weak oceanic mixing that are assumed to be good for recruitment because they appear to be related to successful first feeding; and (iii) vigorous advection after spawning that is presumed to reduce recruitment because it transports larval pollock off the continental shelf into areas of low productivity. In addition, the abundance of larvae in ichthyoplankton tows in late May provides an annual index of larval abundance. Information sources that cover the first two years of life include length composition estimates from the spring hydroacoustic survey. A hydroacoustic survey has been conducted in Shelikof Strait during the spawning period since 1981, and the length composition information can identify strong incoming year classes in the population. Finally, recruitment forecasts are available from the non-linear transfer function time series model discussed earlier.

Information sources and forecast methods have evolved in each of the three years that FOCI has supplied a recruitment forecast. During this evolution the conceptual model provided the direction for incorporation of variables and mechanisms. When qualitative information was used, each component of the suite of qualitative information was considered separately as if that particular variable were the only one affecting recruitment. In 1992, only spawner and recruit data were used in the forecast (Table 1). No apparent relationship existed between spawning abundance and recruitment. The forecast scheme in 1992 was cast in a probabilistic framework. Plotting the recruitment time series according to year class showed autocorrelated regularities. The regularities provided an opportunity to calculate probabilities of a strong recruitment year following a poor year, or a strong following a strong. In addition, recruitment vs. spawning biomass plots provide data with which to calculate empirical probabilities associated with various scenarios—for example, the probability of a strong year class resulting from a small spawning biomass. This follows the nonparametric classification scheme described by Rothschild and Mullen (1985) and Getz and Swartzman (1981). Partitions based on percentiles were used to assign a recruitment or spawner value to a qualitative class. The 33rd and 66th percentiles were used to define three recruitment states (weak, average, strong).

Previous correlative modelling of pollock recruitment (Megrey *et al.*, 1995) indicated that rainfall and NEPPI explained a significant portion of the variation in recruitment. The simple linear model however did not address the autocorrelated nature of the recruitment data. Therefore, in 1993 a recruitment transfer function time series model (Fig. 6) was developed following Hare and Francis (1995). An advantage of the time series model over the more traditional linear regression approach is that the time series model acknowledges the autocorrelated nature of the recruitment values and provides a mechanism for generating recruitment forecasts. In 1993, the transfer function model and objective observations from NMFS research surveys were used to generate recruitment scenario candidates for the stock projection model.

In 1994, the non-linear transfer function time series model was refit by adding 1990 and 1991 data to the recruitment and environmental time series. We assumed that the same variables were important, and we withheld the last two data points to use in the forecast as a means of evaluating the model. Length composition information from the 1993 spring hydroacoustic survey of Shelikof Strait was considered quantitative as it reflects direct observations from trawl survey samples. The composition shows the almost 1-year-olds of the previous year class as pollock in the length interval 8–15 cm. In 1992–1994 these percentages were approximately 4%, 3% and 8%, respectively. This suggests that 1991 is weak, 1992 is weak, and 1993 is average. Larval survival appears to be greater in eddies. The number of eddies appears to be a function of freshwater runoff (Hermann and Stabeno, 1996; Stabeno and Hermann, 1996). Data show that rainfall, assumed to be beneficial to recruitment, was above average in 1991, average in 1992, average in 1993 and above average in 1994. Wind mixing, low levels of which are assumed to be good for recruitment, was high in 1991, average in 1992 and 1993, and low in 1994. Vigorous advection after spawning is presumed to contribute to poor recruitment. Information from moored current meters and satellite-tracked drifters in Shelikof Strait shows that advection was high in 1991, average in 1992 and 1993, and low in 1994. Analysis of the abundance of larvae appearing in ichthyoplankton tows shows that in 1991 there was a high incidence of tows with no larval pollock and few tows with high abundance levels. In 1992 and 1993 larval rough counts were higher than in 1991. Although the 1992 and 1993 means were similar, there were more occurrences of high abundance tows (>100) in 1992. The highest frequency of tows with 1–20 larvae occurred during 1994 which also had the second lowest number of tows with no larval pollock. There were no tows with very high abundance levels (>100/tow) during 1994. These patterns of larval abundance suggest that the 1991 year class is weak, 1992 is average to strong, 1993 is weak to average, and 1994 is average.

Forecast results

The recruitment forecasts in 1992 using the non-parametric spawner recruit data (summarized in Table 1) indicated that 1989 and 1990 were weak, 1991 was weak to average and 1992 was strong. The recruitment forecast in 1993 using the time series model suggested that year classes 1991, 1992 and 1993 were average in abundance. However, we know from FOCI ichthyoplankton survey work conducted in 1991 and 1992 as well as preliminary information from the 1991 and 1992 NMFS hydroacoustic survey of spawning aggregations in Shelikof Strait that these year classes appeared to be below average. Thus the combined FOCI recruitment forecast in 1993 was that 1991 and 1992 were below average and that 1993 was average.

The quantitative recruitment forecast in 1994 using the refit model indicated that the 1991 year class was strong and the 1992–1994 year classes were average. These results are somewhat suspicious as the model did not fit as well ($R^2 = 0.49$) as it did in the 1993 fitting ($R^2 = 0.69$). Also, most other information sources suggest that 1991 is not a strong year class. Accordingly, a different procedure for a combined recruitment forecast was adopted. Each piece of information was classified as to whether it directly estimated a strong, average, or weak year class or whether it suggested the strength of the year class because of a presumed effect and mechanism as described above. A definitive forecast of strong was given a score of 3, average a 2, and weak a 1. In some ambiguous cases non-integer scores were used based on the following intervals: 1.00–1.66 (weak), 1.67–2.33 (average), and 2.34–3.00 (strong). To arrive at the combined forecast for each year, a weighted average of all information sources for that year was calculated by multiplying the information source weight by the score of the forecast from the information source, then summing the totals over all information sources available for that year. The combined forecast depended on the interval (described above) occupied by the weighted total. Weighting factors differed for each year as all information sources were not available for every year. The sum of the weights for all available information sources in any year was 1. The combined weights for the quantitative information sources were set to 0.5. These were distributed over the time series

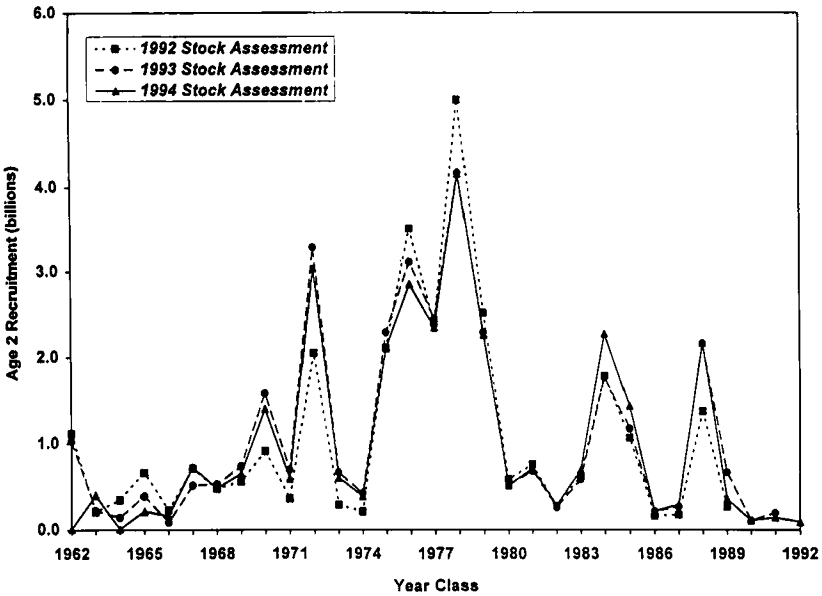


Figure 7. Comparison of the recruitment time series resulting from application of the 1992, 1993, and 1994 stock assessment model.

model and hydroacoustic length composition information sources as 0.2 and 0.3 respectively. Weights for the remaining qualitative information sources (rain, wind, advection, and larval index) collectively summed to the remaining 0.5, thus they each received a weight of 0.125. In years when information sources were missing the weighting factors for the hydroacoustic and/or the time series model index were increased to keep the sum of the weights to 1.0. By following this procedure, the combined forecast conducted in 1994 was: the 1991 year class is weak, 1992 is weak, 1993 is average, and 1994 is average.

There are six years of corresponding observed and forecast recruitment values (Table 1). Analysis of commercial catch data and fishery-independent hydroacoustic surveys has shown the 1989–1992 year classes to be weak. The 1993 year class appears to be weak to average and the 1994 year class average to strong. Except for the estimate of the 1992 year-class made in 1992, the observed year-class strengths have agreed with the forecasts.

DISCUSSION

The simple random switch model reproduced recruitment time series that were statistically similar to the observed recruitment time series. It is striking that a simple model of three stochastic processes replicates the statistical properties of the observed time series so well, but note the large variation in these statistical properties (Fig. 5). This holds hope for other fisheries-oceanography programmes because it shows that it is not necessary to measure everything if a sound conceptual framework and judicious use of statistical methods are used.

A major problem with recruitment studies and forecasting schemes is that the recruitment time series is not stationary. In each fishing year a new set of catch-at-age data is collected from the cohorts that make up the exploitable population. A slightly different picture of the recruitment trend emerges when these new data are merged with the old data and the stock assessment model rerun (Fig. 7). This pattern can be seen by comparing the 1984 and 1988 year-class estimates from the 1992, 1993 and 1994 stock assessments. As a new year of catch data from these cohorts is added to the assessment, the recruitment estimate increases. Contrarily, the 1978 year-class estimate decreases. Another problematic characteristic of the recruitment time series is that the greatest amount of uncertainty is associated with the magnitude of the incoming year class. Unfortunately, this is the year class for which managers urgently require accurate information.

For Gulf of Alaska pollock, the identification of a strong year class is not dependent on the assessment year (Fig. 7). However, the absolute magnitude of the recruitment estimate does fluctuate considerably. For instance, the estimate of the 1972 year class differs by about 48% between the 1992 and 1994 stock assessments. This complicates attempts to identify associations with environmental and biological covariates.

FOCI is the only marine fisheries oceanography research programme in the United States, and one of the few in the world, to attempt to guide management by forecasting year-class strength. We believe FOCI's success with recruitment forecasting is attributable to three things. First, and most important, FOCI has a good conceptual model. It is interesting to note that originally the FOCI hypothesis of mechanisms that influenced recruitment variability involved temperature, transport and turbulence. After many years of research, transport and turbulence remain in the hypothesis, and these have been augmented by the importance of eddies. Second, FOCI solicits information from a wide variety of sources and utilizes a full suite of qualitative and quantitative information in making its forecast. Third, the forecast attempts to identify the recruitment condition in the most general sense. Instead of forecasting recruitment in precise absolute terms (e.g. 4.3 billion fish) FOCI uses generalized recruitment classifications (e.g. weak, average and strong) that are sufficient for management needs.

Empirical recruitment models that are typically used in forecasting may have predictive utility, but they do not provide information on the underlying processes that affect recruitment abundance. This is a serious shortcoming. In order to advance our knowledge, modelling must accompany research directed at understanding the processes leading to variations in recruitment. Additionally, process models may suggest changing environmental conditions that could erode the predictive capacity of correlative models. Furthermore, most recruitment time series are too short to resolve the long term variability that is observed in nature. This situation underscores the value of comparative studies as they preclude the need to wait patiently for more data to be accumulated.

Process-orientated fisheries-oceanography programems like FOCI have long-term benefits to fisheries assessment. Process-orientated research allows for improved long-range forecasts of stock behaviour under a variety of fisheries management options. This mechanistic understanding assists scientists in evaluating the potential impact of management decisions on future stock production. Research on potential density-dependent responses to high or low stock conditions are also crucial for making prudent scientific advice on the amount of the resource to remove. Finally, mechanistic research is useful in establishing threshold biomass levels where the potential for accelerated declines in abundance or sharp changes in the ecosystem would be expected to occur. Identifying these types of processes will ensure the continued long-term health of both the fishing industry and the pollock resource.

ACKNOWLEDGEMENTS

This research was conducted as part of NOAA's Fisheries Oceanography Coordinated Investigations (FOCI), contribution no. FOCI-0239, US Department of Commerce, Seattle, Washington.

REFERENCES

Bailey, K.M. (1981) Larval transport and recruitment of Pacific hake *Merluccius productus*. *Mar. Ecol. Prog. Ser.* **6**:1–9.

Bailey, K.M., and Macklin, S.A. (1994) Analysis of patterns in larval walleye pollock (*Theragra chalcogramma*) survival and wind mixing events in Shelikof Strait, Gulf of Alaska. *Mar. Ecol. Prog. Ser.* **113**:1–12.

Bailey, K.M., Picquelle, S., and Spring, S. (1996) Mortality of larval walleye pollock *Theragra chalcogramma* in the western Gulf of Alaska, 1988–91. *Fish. Oceanogr.* **5**(Suppl. 1):124–136.

Bakkala, R.G., Wespestad, V.G., and. Low, L.L. (1987) Historical trends in abundance and current condition of walleye pollock in the eastern Bering Sea. *Fish. Res.* **5**:199–216.

Bienfang, P.K., and Ziemann, D.A. (1995) APPRISE: A multiyear investigation of environmental variation and its effects on larval recruitment. *Can. Spec. Pub. Fish. Aquat. Sci.* **121**:483–487.

Bograd, S.J., Stabeno, P.J., and Schumacher, J.D. (1994) A census of mesoscale eddies in Shelikof Strait, Alaska, during 1991. *Geophys. Res.* **99**:18243–18254.

Bond, N.A., and Macklin, S.A. (1993) Research aircraft observations of offshore directed flow near Wide Bay of the Alaska Peninsula. *Mon. Weather Rev.* **121**:150–161.

Box, G.E.P., Jenkins, G.M., and Reinsel, G.C. (1994) *Time Series Analysis: Forecasting and Control*. 3rd edn. Englewood Cliffs, NJ: Prentice-Hall, 598 pp.

Brodeur, R.D., Bailey, K.M., and Kim, S. (1991) Cannibalism on eggs by walleye pollock (*Theragra chalcogramma*) in Shelikof Strait, Gulf of Alaska. *Mar. Ecol. Prog. Ser.* **71**:207–218.

Brodeur, R.D., and Wilson, M.T. (1996) A review of the distribution, ecology and population dynamics of age-0 walleye pollock in the Gulf of Alaska. *Fish. Oceanogr.* **5**(Suppl. 1):148–166.

Canino, M.F. (1994) Effects of temperature and food availability on growth and RNA/DNA ratios of walleye pollock *Theragra chalcogramma* (Pallas) eggs and larvae. *J. Exp. Mar. Biol. Ecol.* **175**:1–16.

Canino, M.F., Bailey, K.M., and Incze, L.S. (1991) Temporal and geographic differences in feeding and nutritional condition of walleye pollock larvae, *Theragra chalcogramma*, in Shelikof Strait, Gulf of Alaska. *Mar. Ecol. Prog. Ser.* **79**:27–36.

Chadwick, H.K., Stevens, D.E., and Miller, L.W. (1977) Some factors regulating the striped bass population in the Sacramento-San Joaquin estuary, California, pp. 18–35. In: *Assessing the Effects of Power Plant-Induced Mortality on Fish Populations*. W. Van Winckle (ed.). New York: Pergamon Press, 388 pp.

Eckman, J.E. (1994) Modelling physical-biological coupling in the ocean: the U.S. GLOBEC program. *Deep-Sea Res. Part II* **41**:1–5.

Emery, W.J., and Hamilton, K. (1985) Atmospheric forcing of interannual variability in the northeast Pacific Ocean: Connections with El Niño. *J. Geophys. Res.* **90**:857–868.

Getz, W.M., and Swartzman, G.L. (1981) A probability transition matrix model for yield estimation in fisheries with highly variable recruitment. *Can. J. Fish. Aquat. Sci.* **38**:847–855.

Goddard, S.V., Wroblewski, J.S., Taggart, C.T., Howse, K.A., Bailey, W.L., Kao, M.H., and Fletcher, G.L. (1994) Overwintering of adult Northern Atlantic cod (*Gadus morhua*) in cold inshore waters as evidenced by plasma antifreeze glycoprotein levels. *Can. J. Fish. Aquat. Sci.* **51**:2834–2842.

Hare, S.R., and Francis, R.C. (1995) Climate change and salmon production in the Northeast Pacific Ocean. In: *Climate Change and Northern Fish Populations*. R.J. Beamish (ed.). *Can. Spec. Publ. Fish. Aquat. Sci.* **121**:357–372.

Hastie, T., and Tibshirani, R. (1990) *Generalized Additive Models*. New York: Chapman & Hall Inc., 335 pp.

Hermann, A.J., Hinckley, S., Megrey, B.A., and Stabeno, P.J. (1996) Interannual variability of the early life history of walleye pollock near Shelikof Strait as inferred from a spatially explicit, individual-based model. *Fish. Oceanogr.* **5**(Suppl. 1):39–57.

Hermann, A.J., and Stabeno, P.J. (1996) An eddy-resolving circulation model for the western Gulf of Alaska shelf: I. Model development and sensitivity. *J. Geophys. Res.*, in press.

Hewitt, R.P. (1988) Historical review of the oceanographic approach to fisheries research. *Calif. Coop. Oceanic Fish. Invest. Rep.* **29**:27–41.

Hinckley, S., Bailey, K.M., Picquelle, S.J., Stabeno, P.J., and Schumacher, J.D. (1990) Realistic estimation of mortality rates of larval walleye pollock in the Gulf of Alaska as determined from field sampling. *EOS, Trans. Am. Geophys. Union* **71**:93.

Hinckley, S., Bailey, K.M., Picquelle, S.J., Schumacher, J.D., and Stabeno, P.J. (1991) Transport, distribution, and abundance of larval and juvenile walleye pollock (*Theragra chalcogramma*) in the western Gulf of Alaska in 1987. *Can. J. Fish. Aquat. Sci.* **48**:91–98.

Hollowed, A.B. (1992) Spatial and temporal distributions of Pacific hake, *Merluccius productus*, larvae and estimates of survival during early life stages. *CalCOFI Rep.* **33**:100–123.

Hollowed, A.B., and Megrey, B.A. (1993) Evaluation of risks associated with application of alternative management strategies for Gulf of Alaska walleye pollock. In: *Proceedings of the International Symposium of Management Strategies for Exploited Fish Populations*. G. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke, and T.J. Quinn II (eds). Alaska Sea Grant Program Report No 93–02, University of Alaska, Fairbanks, Alaska, pp. 291–329.

Hollowed, A.B., and Wooster, W.S. (1992) Variability of winter ocean conditions and strong year classes of Northeast Pacific groundfish. *ICES Mar. Sci. Symp.* **195**:433–444.

Jacobson, L.D., and MacCall, A.D. (1995) Stock-recruitment models for Pacific sardine. *Can. J. Fish. Aquat. Sci.* **52**:566–577.

Kendall, A.W., Jr., Clarke, M.E., Yoklavich, M.M., and Boehlert, G.W. (1987) Distribution, feeding, and growth of larval walleye pollock, *Theragra chalcogramma*, in Shelikof Strait, Gulf of Alaska. *Fish. Bull. U.S.* **85**:499–521.

Kendall, A.W., Jr., Incze, L.S., Ortner, P.B., Cummings, S.R., and Brown, P.K. (1994) The vertical distribution of eggs and larvae of walleye pollock, *Theragra chalcogramma*, in Shelikof Strait, Gulf of Alaska. *Fish. Bull. U.S.* **92**:540–554.

Kendall, A.W., Jr., and Kim, S. (1989) Buoyancy of walleye pollock (*Theragra chalcogramma*) eggs in relation to water properties and movement in Shelikof Strait, Gulf of Alaska. In: *Effects of Ocean Variability on Recruitment and an Evaluation of Parameters Used in Stock Assessment Model.* R.J. Beamish and G.A. McFarlane (eds). *Can. Spec. Publ. Fish. Aquat. Sci.* **108**:169–180.

Kendall, A.W., Jr., and Picquelle, S.J. (1990) Egg and larval distributions of walleye pollock *Theragra chalcogramma* in Shelikof Strait, Gulf of Alaska. *Fish. Bull. U.S.* **88**:133–154.

Kendall, A.W., Jr., Schumacher, J.D., and Kim, S. (1996) Walleye pollock recruitment in Shelikof Strait: applied fisheries oceanography. *Fish. Oceanogr.* **5**(Suppl. 1):4–18.

Kim, S., and Bang, B. (1990) Oceanic dispersion of larval fish and its implication for mortality estimates: Case study of walleye pollock larvae in Shelikof Strait, Alaska. *Fish. Bull U.S.* **88**:303–311.

Kim, S., and Gunderson, D.R. (1989) Cohort dynamics of walleye pollock in Shelikof Strait, Gulf of Alaska, during the egg and larval period. *Trans. Amer. Fish. Soc.* **118**:264–273.

Kim, S., and Kendall, A.W., Jr. (1989) Distribution and transport of larval walleye pollock (*Theragra chalcogramma*) in Shelikof Strait, Gulf of Alaska, in relation to water movement. *Rapp. P.-v. Réun. Cons. int. Explor. Mer* **191**:127–136.

Kim, S., and Nunnallee, E.P. (1991) Distribution of walleye pollock, *Theragra chalcogramma*, spawning in Shelikof Strait, Gulf of Alaska, based on acoustic and ichthyoplankton surveys 1981, 1984 and 1985. *Bull. Korean Fish. Soc.* **23**:425–438.

Kinoshita, R.K., Greig, A., Hastie, J.D., and Terry, J.M. (1995, draft) *Economic Status of the Groundfish Fisheries off Alaska (1994) Socioeconomic Task*. Seattle, WA: Alaska Fisheries Science Center, 104 pp..

Kope, R., and Botsford, L.W. (1990) Determination of factors affecting recruitment of chinook salmon *Oncorhynchus tshawytscha* in central California. *Fish. Bull. U.S.* **88**:257–269.

Kunzig, R. (1995) Twilight of the cod. *Discover* **16**:44–60.

Leggett, W.C. (1977) Density dependence, density independence, and recruitment of American shad (*Alosa sapidissima*) population of the Connecticut River. In: *Assessing the Effects of Power Plant-Induced Mortality on Fish Populations*. W. Van Winckle (ed.). New York: Pergamon Press, pp. 3–17.

Leggett, W.C., Frank, K.T., and Carscadden, J.E. (1984) Meteorological and hydrographic regulation of year-class strength of capelin (*Mallotus villosus*). *Can J. Fish. Aquat. Sci.* **41**:1193–1201.

Lowe, S., and Baldwin, R.T. (1992) Science and fisheries: Alaskan waters. *Women Nat. Res.* **13**:17–20.

Macklin, S.A., Stabeno, P.J., and Schumacher, J.D. (1993) A comparison of gradient and observed over-the-water winds along a mountainous coast. *J. Geophys. Res.* **98**:16555–16569.

Megrey, B.A., Bograd, S.J., Rugen, W.C., Hollowed, A.B., Stabeno, P.J., Macklin, S.A., Schumacher, J.D., and Ingraham, W. J. Jr. (1995) An exploratory analysis of associations between biotic and abiotic factors and year-class strength of Gulf of Alaska walleye pollock. In: *Climate Change and Northern Fish Populations*. R.J. Beamish (ed.). *Can. Spec. Publ. Fish. Aquat. Sci.* **121**:227–243.

Megrey, B.A., Hollowed, A.B., and Baldwin, R.T. (1994) Sensitivity of optimum harvest strategy estimates to alternative definitions of risk. *Can. J. Fish. Aquat. Sci.* **51**:2695–2704.

Megrey, B.A. (1990) Population dynamics and management of walleye pollock stocks in the Gulf of Alaska, 1976–1986. *Fish. Res.* **11**:321–354.

Napp, J.M., Incze, L.S., Ortner, P.B., Siefert, D.L.W., and Britt, L. (1996) The plankton of Shelikof Strait: standing stock, production, mesoscale variability and their relevance to larval fish survival. *Fish. Oceanogr.* **5**(Suppl. 1):19–38.

Niebauer, H.J. (1988) Effects of El Niño-Southern Oscillation and North Pacific weather patterns on interannual variability in the subarctic Bering Sea. *J. Geophys. Res.* **93**:5051–5068.

Nelson, W.R., Ingraham, M.C., and Schaff, W.E. (1977) Larval transport and year-class strength of Atlantic menhaden (*Brevoortia tyrannus*). *Fish. Bull. U.S.* **75**:23–41.

Olla, B.L., Davis, M.W., Ryer, C.H., and Sogard, S.M. (1996). Behavioural determinants of distribution and survival in early stages of walleye pollock *Thesagra chalcogramma*: a synthesis of experimental studies. *Fish. Oceanogr.* **5**(Suppl. 1):167–178.

Ortner, P.B., Nieman, D.R., and Incze, L.S. (1990) Biological characterization of a coastal mesoscale eddy. *EOS, Trans. Am. Geophys. Union* **71**:177.

Parker, K.S. (1989) Influence of oceanographic and meteorological processes on the recruitment of Pacific halibut, *Hippoglossus stenolepis*, in the Gulf of Alaska. In: *Effects of Ocean Variability on Recruitment and an Evaluation of Parameters Used in Stock Assessment Models*. R.J. Beamish and G.A. McFarlane (eds). *Can. Spec. Pub. Fish. Aquat. Sci.* **108**:221–237.

Picquelle, S.J., and Megrey, B.A. (1991) A method of estimating spawning biomass from egg surveys with an application to walleye pollock, *Theragra chalcogramma*, in the Shelikof Strait, Alaska. AFSC Processed Rep. 93–04, 79 pp. Alaska Fish. Sci. Cent., Natl. Mar. Fish. Serv., NOAA, Seattle, WA.

Picquelle, S.J., and Megrey, B.A. (1993) A preliminary spawning biomass estimate of walleye pollock, *Theragra chalcogramma*, in the Shelikof Strait, Alaska, based on the annual egg production method. In: *Proceedings From the Symposium on the Advances in Estimating the Biomass of Marine Fish Stocks Using Ichthyoplankton, During the 15th Annual Early Life History Section of the American Fisheries Society*. J.R. Hunter and N.C.H. Lo (eds). *Bull. Mar. Sci.* **53**(2): 728–749.

Reed, R.K., and Schumacher, J.D. (1989a) Transport and physical properties in central Shelikof Strait, Alaska. *Cont. Shelf Res.* **9**:261–268.

Reed, R.K., and Schumacher, J.D. (1989b) Some mesoscale features of flow in Shelikof Strait, Alaska. *J. Geophys. Res.* **94**:12, 603–12, 606.

Reed, R.K., Schumacher, J.D., and Incze, L.S. (1987) Circulation in Shelikof Strait, Alaska. *J. Phys. Oceanogr.* **17**:1546–1554.

Rothschild, B.J. (1986) *Dynamics of Marine Fish Populations*. Cambridge, MA: Harvard University Press, pp. 277.

Rothschild, B.J., and Mullen, A.J. (1985) The information content of stock-and-recruitment data and its non-parametric classification. *J. Cons. Int. Explor. Mer.* **42**:116–124.

Royer, T.R. (1982) Coastal freshwater discharge in the northeast Pacific. *J. Geophys. Res.* **87**:2017–2021.

Rugen, W.C. (1990) Spatial and temporal distribution of larval fish in the western Gulf of Alaska, with emphasis on the period of peak abundance of walleye pollock (*Theragra chalcogramma*) larvae. NWAFC Processed Rep. 90–01, 162 pp. Alaska Fish. Sci. Cent. Natl Mar. Fish. Serv., NOAA, Seattle, WA.

Schumacher, J.D., and Kendall, A.W., Jr. (1991) Some interactions between young walleye pollock and their environment in the western Gulf of Alaska. *CalCOFI Rep.* **32**:22–40

Schumacher, J.D., Stabeno, P.J., and Bograd, S.J. (1993) Characteristics of an eddy over a continental shelf: Shelikof Strait, Alaska. *J. Geophys. Res.* **98**:8395–8404.

Schumacher, J.D., Stabeno, P.J., and Roach, A.T. (1990) Volume transport in the Alaska Coastal Current. *Cont. Shelf Res.* **12**:1071–1083.

Sinclair, M., and Page, F. (1995) Cod fishery collapse and North Atlantic GLOBEC. *U.S. GLOBEC News* **8**:1–5.

Smith, P.C., Frank, K.T., and Mahon, R. (1989) General introduction to southwest Nova Scotia Fisheries Ecology Program (FEP): 1982–89. *Can. J. Fish. Aquat. Sci.* **46** (Suppl. 1): 2–3.

Stabeno, P.J., and Hermann, A.J. (1996) An eddy-resolving circulation model for the western Gulf of Alaska shelf: II. Comparison of results to oceanographic observations. *J. Geophys. Res.*, in press.

Stabeno, P.J., and Megrey, B.A. (1991) Bio-physical models of the recruitment process in Gulf of Alaska walleye pollock. *Int. Counc. Explor. Sea CM 1991/Mini*: **4**.

Stabeno, P.J., Reed, R.K., and Schumacher, J.D. (1995) The Alaska Coastal Current: Continuity of transport and forcing. *J. Geophys. Res.* **100**:2477–2485.

Stabeno, P.J., Schumacher, J.D., Bailey, K.M., Brodeur, R.D., and Cokelet, E.D. (1996) Observed patches of walleye pollock eggs and larvae in Shelikof Strait, Alaska: their characteristics, formation and persistence. *Fish. Oceanogr.* **5**(Suppl. 1):81–91.

Stabeno, P.J., and Smith, R.L. (1987) Deep-sea currents off northern California. *J. Geophys. Res.* **92**:755–771.

Swartzman, G., Huang, C., and Kaluzny, S. (1992) Spatial analysis of Bering Sea groundfish survey data using generalized additive models. *Can. J. Fish. Aquat. Sci.* **47**:1366–1378.

Theilacker, G.H., Bailey, K.M., Canino, M.F., and Porter, S.M. (1996) Variations in larval walleye pollock feeding and condition: a synthesis. *Fish. Oceanogr.* **5**(Suppl. 1):112–123.

Trenberth, K.E., and Hurrell, J.W. (1995) Decadal coupled atmosphere-ocean variations in the North Pacific Ocean. In: *Climate Change and Northern Fish Populations*. R.J. Beamish (ed.). *Can. Spec. Publ. Fish. Aquat. Sci.* **121**:15–24.

Tyler, A.V. (1992) A context for recruitment correlations: Why marine fisheries biologists should still look for them. *Fish. Oceanogr.* **1**:97–107.

Walters, C.J., and Collie, J.S. (1988) Is research on environmental factors useful for fisheries management? *Can. J. Fish. Aquat. Sci.* **45**:1848–1854.

Walters, C.J., and Ludwig, D. (1981) Effects of measurement errors on the assessment of stock-recruitment relationships. *Can. J. Fish. Aquat. Sci.* **38**:704–710.

Wenzel, L., and Scavia, D. (1993) NOAA's Coastal Ocean Program: Science for solutions. Coastal Science and Policy I. *Oceanus* **36**:85–92.

Wooster, W.S., and Bailey, K.M. (1989) Recruitment of marine fishes revisited. In: *Effects of Ocean Variability on Recruitment and an Evaluation of Parameters Used in Stock Assessment Models*. R.J. Beamish and G.A. McFarlane (eds). *Can. Spec. Pub. Fish. Aquat. Sci.* **108**:153–159.

Yamashita, Y., and Bailey, K.M. (1989) A laboratory study of the bioenergetics of larval walleye pollock *Theragra chalcogramma*. *Fish. Bull. U.S.* **87**:525–536.

Yoklavich, M.M., and Bailey, K.M. (1989) Growth of larval and juvenile walleye pollock from Shelikof Strait, Gulf of Alaska, as determined from daily increments in otoliths. *Proc. of the Int. Symp. on the Biology and Management of Walleye Pollock, Anchorage, AK, November 14–16, 1988.* University of Alaska, Fairbanks, Sea Grant Report **89–1**:241–251.

Yoklavich, M.M., and Bailey, K.M. (1990) Hatching period, growth, and survival of young walleye pollock *Theragra chalcogramma* as determined from otolith analysis. *Mar. Ecol Prog. Ser.* **64**:13–22.

Zuboy, J. (1981) A new tool for fishery managers: The Delphi technique. *North Amer. J. Fish. Man.* **1**:55–59.