Taking Stock: An Inventory and Review of World Herring Stocks in 2000

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Abstract
This paper provides an overview of the biology, catch history, and current biomass status of the world’s major herring stocks. Herring occur throughout the northern coastal marine areas of the Atlantic and Pacific oceans and parts of the Arctic Ocean. Throughout their entire range, they have been used for food and commerce for millennia. Although several herring stocks have been fished commercially for more than 1,500 years, it is only within the last 100 years that nearly all stocks have been subjected to intense fisheries. During the last century, many stocks “collapsed” but most subsequently “recovered.” A few experienced several collapses. Currently, some stocks are thriving but the present state of others is worrisome. This review provides a brief history and review of the present state of each stock provided by the biologists who are familiar with them. In most cases the stocks described in this paper represent aggregations of different biological subpopulations existing within “major stocks.” In some instances, especially from multinational fisheries, contributions from different authors were integrated to describe certain stocks. Although our objective was not to explain the causes of variation in abundance, the effect of climatic variation on herring abundance is repeatedly mentioned by various contributors. The effect of climate on Baltic, North Sea, and Norwegian herring has been known for a long time but the effects of climate are reinforced in this report for other stocks. We also see that some changes appear to be synchronous among stocks within the same general areas of the Atlantic and Pacific. In particular, we see a pattern of increases in herring stocks in the southwest Atlantic (Georges Bank, Maine) but a decrease in some in the northwest Atlantic (Newfoundland). Another clear observation is that while there are many biological differences among herring stocks, almost all are subject to substantial fluctuations in abundance and the most severe declines are preceded or accompanied by intense fishing. The temporal duration of periods of crash and recovery vary, but in general it is about a decade or longer. This would be expected given the life span of herring, which ranges from about 6 or 7 years in extreme southern populations to 20 years or more in northern populations. In most instances, when fishing decreases the stocks “recover” but this has not occurred in the Hokkaido-Sakhalin stock, which was once one of the world’s largest, with nearly 1 million t landed annually. There is no clear explanation for the failure of this stock to recover after all fishing has stopped, unless the population has been depleted beyond a point of no return. Although there is still hope that this stock may recover some day, after a decline of 50 years perhaps a “recovery” is not possible. There still are herring in the area but it is not clear if the small local stocks that still occupy those areas are part of the same biological entity that was once the great migratory Hokkaido-Sakhalin herring stock. The virtual disappearance of the Hokkaido-Sakhalin herring, when considered relative to the last century of herring fisheries in other areas of the world, indicates that herring stocks are remarkably resilient, but perhaps not indestructible.
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Introduction

Throughout coastal regions of the Northern Hemisphere, herring (*Clupea pallasii* and *Clupea harengus*) have been fished for millennia as food. Herring have supported commercial fisheries in Europe for at least 1,500 years (Hodgson 1957). In the last 500 years, following technological advances in salt preservation, herring have guided the economies and politics of northern Europe, especially through policies of the Hanseatic League (Mollat du Jourdin 1993). In the western Atlantic, herring supported commercial fisheries when Europeans regularly fished in the Bay of Fundy about 500 years ago (Tibbo 1966). Pacific herring have been harvested commercially for over 500 years in northern Japan (Morita 1985) and during the last century, herring have supported intense Japanese and Russian fisheries (Motoda and Hirano 1963, Tyurnin 1973). On the Pacific coast of North America herring were widely used by indigenous peoples (Drucker 1955) and commercial herring fisheries began in California in the mid-1800s (Suer 1987), in British Columbia in the late 1870s (Taylor 1964), and in Alaska in the 1880s (Grosse and Hay 1988). This paper, prepared for an international symposium on herring at the end of the millennium, provides an inventory and brief review of the world’s major herring stocks.

The basic question addressed in the paper is: How have the world’s herring fared after the last 100 years of commercial fisheries? The answers we provide are based on collaborative contributions from biologists representing nearly all major herring stocks of the world. Each provided a brief biological description of their stocks and, if available, time series data on spawning stock biomass and annual catches.

Although the objective of this paper may appear to be simple, in practice it is complex. Throughout the world, there are different types of agencies that assess and review herring. Some are multinational, such as the International Council for the Exploration of the Sea (ICES), others are managed by national governments, and still others by regional governments within countries. Among these different jurisdictions there are different practices for recording catch, with some included within calendar years and others within seasons. Further, there were several instances where there were minor discrepancies in estimates of catch when there was more than one person reporting on the same stocks. Aging conventions vary slightly among institutions so that the understanding of the real age of “age-1 herring” varies, by up to 1 year. This confounds comparisons of cohorts among different stocks. A difficult task was compiling historical catch data, because some regional catch data are regarded as confidential in some jurisdictions, including one in North America. Summaries of annual catch data, however, are usually published in one or more informal sources and large geographical summaries are presented in documents prepared by the Food and Agriculture Organization of the United Nations (FAO). In a few instances where unpublished data were not available we used published sources, some of which may have been slightly incomplete.
This paper represents a second attempt at such a global description of herring. The first was by Fedorov (1968), which is actually a small book (in Russian). Fedorov also presented biological summaries including maps showing migratory patterns and comments on different life history stages of major stocks. Although we had originally attempted to include about the same amount of detail as Fedorov, the resulting compilation was too long for these proceedings. Further, the inclusion of too much detail might detract from the main purpose of this paper, which is a commentary on the status of the world’s herring stocks. Consequently, our comments on biological attributes of various herring stocks are brief.

The paper is organized into seven sections. Part 1 is a short description of the biology of herring with some comments on the significance of herring fisheries and research to the development of fisheries science. This is followed by five sections that describe the status of herring stocks in each of five regions: the eastern and western Atlantic, the eastern and western Pacific, and the Arctic. Part 2 describes the eastern Atlantic and adjacent seas including Iceland and the western Atlantic. Parts 3a and 3b describe stocks from Newfoundland to the Gulf of Maine. Part 4 describes the eastern Pacific from California to the eastern Bering Sea. Parts 5a and 5b describe the western Pacific from the western Bering Sea to the Yellow Sea. Part 6 briefly reviews herring in the Arctic Ocean and adjacent seas. The organization of each subsection, including headings, varies slightly, and reflects the emphases of the contributing authors. For the sake of brevity we did not attempt to provide maps showing all of the geographic names mentioned in the text. The paper concludes with Part 7, which provides some brief synthesis and summary comments for the whole paper.

Part 1. Brief Overview of Herring Distribution and Biology

Herring are members of the clupeid family. The family Clupeidae consists of about 330 species (Whitehead 1985), including Pacific and Atlantic herring. In the last century clupeids composed about one-third of total world catches (Blaxter and Hunter 1982), although this varies annually according to fluctuations of some of the largest stocks. Most clupeids are tropical, or subtropical, but Pacific and Atlantic herring are the most northern of clupeids, and the only ones in Arctic waters. The taxonomic usage has varied with time and location. Much of the literature has recognized Pacific and Atlantic herring and Baltic herring as separate subspecies: *Clupea harengus harengus* (Atlantic), *C. h. pallasii* (Pacific), and *C. h. membras* (Baltic). Baltic herring are coastal spawners living under conditions of reduced salinity. Recently usage has tended to favor recognition of Atlantic and Pacific herring as species (*C. harengus* and *C. pallasii*). Probably the most conspicuous difference is the occurrence of “fall-spawning” herring in the Atlantic, whereas Pacific herring are mainly late winter and spring
spawners. Also, in general, Pacific herring tend to spawn closer to shore and often in intertidal waters, whereas Atlantic herring tend to spawn in deeper water, although some spring-spawning Atlantic herring also spawn in shallow water. For convenience, this report follows that practice of recognizing Atlantic and Pacific herring as species although we are uncertain about the best nomenclature for Arctic herring.

Herring spawn only once a year. All of the eggs are released within a single spawning period. The number of eggs increases with female size, with the smallest herring (~150 mm) having perhaps $10^4$ eggs and the largest (~400 mm) having more (~$10^5$). The eggs are adhesive and deposited on gravel bottoms (particularly in Atlantic herring), or on vegetative substrate (Pacific herring and some spring-spawning Atlantic herring). Mean length and longevity vary with latitude, with smaller, shorter-lived herring (~5-6 years) in the south and larger, longer-lived populations in the north. Table 1 shows the age of maturity, age determination method (scales or otoliths), $L_\text{m}$, approximate temperature at spawning, and maximal age for a number of different stocks. Tables 2 and 3 show the approximate age-specific length (centimeters) and weight (grams) from various stocks. In general, the northern herring grow larger and sometimes faster, in both the Atlantic and the Pacific. This simple generalization, however, is complicated by the observation that in some northern areas (such as some Icelandic populations) the larval stage may be prolonged and extend over the first winter, so age-specific growth rates during the early years may appear to be slower in such populations.

Most herring tend to migrate between summer feeding areas on shelf waters, to overwintering areas, which may be in nearshore protected waters, and then to spawning locations. In general, herring schools consist of individuals of similar size and/or age. Juveniles do not mix in their first year (often called age 0+). They school together and do not associate with older, larger juveniles (age 1+) or adult schools and in some areas may stay nearer to inside or sheltered waters. Herring are noted for their extensive vertical migrations, being deeper in the water by day and shallower at night. Herring are not herbivorous, but eat mainly zooplankton. Larvae consume copepod eggs and nauplii, plus young stages of other organisms, whereas juveniles tend to eat copepods and other zooplankton. Adults consume many different items but in many areas copepods and euphausiids dominate. Herring are both particulate feeders and filter feeders.

As a prey species, herring are consumed by nearly all animals large enough to eat them, and in some areas cod (Gadus) populations appear to rely on herring as a principal prey species. In the northern Pacific and other areas, herring populations support piscivorous salmonids as well as many marine bird and mammal species.

Herring have been the subject of biological investigations for several hundred years (Whitehead 1985) and information from herring has served
Table 1. Comparison of biological characteristics among herring stocks.

<table>
<thead>
<tr>
<th>Location</th>
<th>Age at first maturity</th>
<th>Age determination method</th>
<th>Age units</th>
<th>L&lt;sub&gt;c&lt;/sub&gt; (cm)</th>
<th>Spawning temp. (ºC)</th>
<th>T (years)</th>
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<td>Ring</td>
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<td>Ring</td>
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<td>8</td>
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These estimates are approximate and do not describe temporal or spatial variation. Fall and spring refer to fall and spring spawning stocks.

as a basis for investigations of other clupeids. Investigations on herring have influenced other aspects of fisheries science in most countries that have a history of herring fisheries. Russian fisheries literature, even back to the mid-nineteenth century, makes frequent reference to studies of Baltic and White Sea herring. Early research on herring has generated some of the most profound and enduring hypotheses in fisheries science, which have been applied to many other species. This includes the famous “Hjort” or “critical period” hypothesis (Hjort 1914) that attempts to explain the reason for strong year classes according to the survival of young herring at the larval period. Variation among herring populations within the Baltic and White Sea prompted much of what we know about marine fish physiology and much is derived from pioneering work by Hempel and Blaxter; e.g., see reviews by Blaxter and Holliday (1963) and Blaxter and Hunter (1982). Research on herring has provided the basis for several major developments in fisheries science and management (Stephenson 2001, this
Table 2. Comparison of length-at-age (centimeters) among stocks. The estimates are approximate and do not account for spatial or temporal variation.

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Table 2. (Continued.) Comparison of length-at-age (centimeters) among stocks. The estimates are approximate and do not account for spatial or temporal variation.

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Some measurements are in total length (TL) or fork length (FL). All others are assumed to be standard length (SL). The age of "0+" indicates fish in the first year of life but this varies according to stock, especially with some that overwinter as larvae (see Table 1). Several independent estimates are shown for some stocks. Fall and spring refer to fall- and spring-spawning stocks. The Lake Furen stock is from eastern Hokkaido (see Kobayashi 2001, this volume).
Table 3. Weight (grams) at age compared among different herring stocks.

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Table 3. (Continued.) Weight (grams) at age compared among different herring stocks.

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</table>

The estimates are approximate and do not account for spatial or temporal variation. The age of “0+” indicates fish in the first year of life but this varies according to stock, especially with some that overwinter as larvae (see Table 1). Several independent estimates are shown for some stocks, including 3 for the Hokkaido-Sakhalin stock. Fall and spring refer to fall and spring spawning stocks.
volume) including the early polar migration theory; development of the population/stock concept and contributions to the modern view of fish stock structure; tracking and quantification of year classes; and explanations for fluctuations in finfish abundance in the influential hypotheses of Hjort (1914) (“critical period”), Cushing (1972) (“match-mismatch”), and Iles and Sinclair (“larval retention”). Herring research also has served as the impetus for more recent development of hydroacoustic methods; explorations of the linkages between fisheries dynamics and hydrography (Heath 1989); new applications of theory to stock structure and metapopulations (McQuinn 1997b); and innovative approaches to fisheries regulation and management.

Part 2. Eastern Atlantic and Adjacent Seas
The section on the eastern Atlantic includes summaries from the Baltic Sea, North Sea, Celtic Sea, the Norwegian spring-spawning herring, and the Icelandic herring (Fig. 1). Probably several stocks, such as the Norwegian spring-spawning herring, or Icelandic herring, that we have called “Atlantic” herring, might also have been described as occurring in Arctic waters. It is customary, however, to view such stocks as “Atlantic” herring, and we follow that convention. Herring of the White Sea might also have been included here but we chose to include them as populations associated with the Arctic Ocean.

Baltic Herring
Herring are distributed throughout the Baltic Sea, including the Gulf of Bothnia where salinity is low (< 5 ppt). Herring spawn is patchy along the coast of the Baltic Sea in shallow water (depth usually 1-10 m). Most spawning is from April to June, but ranges from March to August. The preferred spawning substrate is vegetation. Small stocks of autumn-spawning herring spawn in deeper banks (10-20 m) offshore. Herring larvae and young herring are mainly found in shallow water close to the coast.

Adult herring conduct regular migrations from their spawning grounds to feeding areas in the open sea, mainly to the south (Aro 1989), and most are believed to return to the same spawning places. Herring spawning in the northern Baltic Sea, in the Gulf of Bothnia, stay mainly in that area also during feeding. Part of the herring spawning population in the southern Baltic Sea migrates to Skagerrak, northeastern North Sea, for feeding (Jönsson and Biester 1981).

Stock Structure
The intraspecific grouping of Baltic herring has been studied since the days of Heincke, who in 1882 described meristic variation in Clupea harengus and interpreted it as racial characteristics. He defined spring- and autumn-spawning races, based mainly on differences in number of vertebrae and seasonal development of gonads. Many others have continued to define a large number of intraspecific groups: races, stocks, and
Figure 1. The eastern North Atlantic showing the major herring stocks. For most stocks, dark areas indicate spawning grounds (S) and shaded areas indicate either juvenile rearing areas (J), feeding areas (F), or overwintering areas.

Biology and Stock Assessment
The data used in the assessments (ICES 1999a, 2000) include catch statistics as officially reported, and, when necessary, supplemented by ICES working group estimates and biological data (age, weight, maturity) obtained by sampling the landings by national fisheries research institutes in all nine Baltic countries (Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Russia, Sweden). The Baltic Fisheries Assessment Working Group has, since 1990, chosen to assess Baltic herring as four stocks (for units used earlier see Sjöstrand [1989]). Stock estimates from hydroacoustic surveys are used in tuning the sequential catch analysis (VPA). Surveys have been carried out in the Baltic since 1978 (Håkansson et al. 1979, ICES 1999b) in September and October, when the herring are dispersed in the Baltic proper on their feeding grounds. The youngest age groups stay closer to the coast and inside the archipelagos and are not properly covered.

Fishery and Management
The herring fishery remained a coastal fishery with nets, seines, and traps until the 1950s. The drastic increase of the fishery since then was made possible by the development of the trawl fishery and the practically unlimited market for fish in the eastern countries. The fear of continued increase in the catch capacity that could cause overexploitation and threaten the sustainability of the fishery led to the agreement of the Gdansk convention (Convention on Fishing and Conservation of the Living Resources in the Baltic Sea and the Belts). It was signed in 1973 by all countries around the Baltic and entered into force in 1974. Its aims, to achieve greater and closer cooperation between the parties in order to maintain the maximum stable productivity of the living resources of the region, are implemented by the International Baltic Sea Fishery Commission (IBSFC). The commission yearly requests advice on stock status and catch options from the ICES. There are no explicit management objectives agreed for the herring fisheries in the Baltic Sea. The IBSFC manages the fisheries through yearly catch limitations, total allowable catch (TAC), split into national quotas. Technical measures are applied additionally. Herring is managed in two units (subdivisions 22-29S, 32 and 29N-31) with separate TACs. Unfavorable market conditions for herring have been reflected in decreased landings for human consumption whereas the landings for industrial purposes have increased during the last few years.
Status by Stock (Assessment Unit)

In subdivisions 22-24 (western Baltic) and in division IIIa (Kattegat and Skagerrak) the spring-spawning stock spawns at several places in the Kattegat and southwest Baltic with its major spawning sites around the island of Rügen. The stock is migratory and mixes with the North Sea autumn-spawning herring in northeastern North Sea and Skagerrak during the feeding period. Landings increased from about 100,000 t in the late 1970s to around 200,000 t in the 1980s but have decreased since the 1980s. The state of the stock is uncertain due to problems in identifying spring and autumn spawners during the nonspawning time in the historical catch data and the lack of a coordinated comprehensive survey. In subdivisions 25-29 and 32 (central Baltic) herring are of a heterogeneous nature with a number of different spawning populations along the coasts. After spawning these are mixed in the open sea. Pronounced differences in size at age between herring from the southern and northeastern parts of the area contribute to the variability in stock estimates. Landings fluctuated around 300,000 t from the beginning of the 1970s to 1989 but have since decreased to around 200,000-250,000 t mainly due to a declining market for herring (Fig. 2a). Although the stock size is uncertain, it appears certain that the biomass is decreasing as fishing mortality is increasing, and the stock is considered to be outside safe biological limits. A marked decrease in mean weight at age for the herring has been registered since the beginning of the 1980s (Sparholt et al. 1994). Thus the spawning stock in numbers has, in contrast to the biomass development, been stable since the beginning of the 1980s or even increased. Simultaneously, the biomass of cod, the major herring predator, has decreased drastically and the frequency of influxes of saline water from the North Sea has been low. In subdivision 30 (Bothnian Sea) landings increased during the last decade from about 20,000 t to 60,000 t. The present state is difficult to judge due to low precision of assessment. There as an increased effort in the 1990s, believed to have increased fishing mortality. The spawning stock has declined after the peak in 1994. In subdivision 31 (Bothnian Bay) landings have never exceeded 10,000 t and have been around 5,000 t the last 5 years. Exploitation of the stock is considered to be within safe biological limits. The actual spawning-stock biomass (SSB) and fishing mortality are, however, not known. Production models do not indicate major changes in SSB and age compositions of catches are consistent with a lightly exploited stock.

Species Interaction–Multispecies Assessment

Interaction between the major species in the Baltic (cod, herring, and sprat) is important. Multispecies VPA (Helgason and Gislason 1979, Pope 1979) has been used to estimate total number of prey and predation mortalities. Data on food consumption and consumption rations of predators are needed in addition to data for the single species VPA. Results from multispecies assessments are presented (ICES 1999c) and summarized by Sparholt (1994), who also gives a comprehensive overview.
Figure 2. Catch (solid dark line) and spawning stock biomass (SSB, dashed line) for eastern North Atlantic herring stocks.
**Norwegian Spring-Spawning Herring**

**Fishery**

Annual catch statistics have been gathered by national authorities and reported to the ICES. These annual statistics have been published in Bulletin Statistique from the first edition in 1903 to the present. Also, fishing statistics are published in ICES reports (working group reports, and annual reports of the Advisory Committee for Fishery Management, ICES).

**Biological Data and Assessments**

Biological data are sampled by national fishery research institutes (in Norway, Iceland, and Russia). These are long-term data series. (In Bergen, there are records of biological data and age readings from 1907 to 1999.) Analytical assessments (VPAs) have been carried out annually since about 1980. These are based on catch statistics and abundance estimates of the stock. The abundance estimates are based on acoustic abundance estimation with echo sounders and tagging experiments (ICES 1999d). Published assessments (ICES 1999d) reports show that the stock fluctuated from high levels just after the Second World War to a stock collapse in the late 1960s. The stock has recovered again and is assessed to be at high levels again in recent years.

**Biology of the Stock**

The Norwegian spring-spawning herring is one of the stocks in the so-called Atlanto-Scandian group of herring stocks (Johansen 1919). The other two are the spring spawners and summer spawners in Iceland. These three stocks have certain similarities: they dwell in high latitudes, around Iceland and in the Norwegian Sea; grow to a large maximum size of about 40 cm; and the two spring spawners have the ability to migrate over large distances (Devold 1963).

The Norwegian spring spawners spawn in early spring (February-March) off the Norwegian coast in an area ranging from approximately 59º00’N to about 69º00’N (Devold 1963). The most important spawning grounds are found close to the coast at about 63º00’N. The larvae drift northward with the Norwegian coastal current and end up in the Barents Sea or in the fjords in northern Norway (Dragesund 1970a,b). By the end of summer, the larvae metamorphose and start shoaling. They remain in this nursery region until the spring in their third year of life and then migrate southward along the Norwegian coast where they mix with older age groups. At the age of 5-8 years (depending on growth), they mature and spawn (ICES 1999d). After spawning, the adult stock migrates from the Norwegian coast, in northwesterly direction, into the Norwegian Sea (Devold 1963). Here they feed during summer in May to September. Prior to the collapse of the stock in the late 1960s the feeding migration extended to the north coast of Iceland whence the herring migrated to the overwintering area east of Iceland and returned to the spawning grounds in January/February. How-
ever, presently the stock (then) migrates back to the Norwegian coast in September where it concentrates close to shore, in a smaller region in northern Norway (Slotte and Johannessen 1997). Here the spawning stock and young prespawning age groups overwinter in dense concentrations. In January, prior to spawning, the stock begins to migrate southward along the Norwegian coast as they complete the final stages of sexual matura-

**Fishery and Management**

Historically, the stock was exploited at all stages: as juveniles, young, and adults. The record of fishery statistics, which is believed to be reliable, shows that there used to be a heavy exploitation of young individuals in the 1950s and early 1960s (Dragesund and Ulltang 1978). In the early 1960s, the total landings were about 2 million t of which three-quarters were juveniles. However, after the collapse of the stock, a minimum size regulation was enforced and after 1970 it has been illegal to catch small herring from this stock.

The fishery is carried out in spring, at the spawning grounds, and in the Norwegian Sea. Some fishing also takes place after the stock has returned to the Norwegian coast. The exploitation is shared in agreement between five parties: the European Union (EU), Iceland, the Faroe Islands, Russia, and Norway. On the basis of scientific advice from the ICES, the parties negotiate annually and agree on a total allowable catch and a share between them. Currently, Norway has a share of 57%, Iceland 16%, Russia 14%, EU 8%, and the Faroe Islands 5%. During the rebuilding phase of the stock, the landings have been restricted and it was a goal to keep the instantaneous fishing mortality rate below 0.05.

**Historical Development and Status of the Stock**

Assessment of the stock is based on annual landings statistics which are split by age groups based on age readings from samples of the catches. In addition, the abundance of the stock is estimated by acoustic abundance estimation and by tagging (ICES 1999d). In recent years the acoustic survey, covering the stock while it feeds in the Norwegian Sea, is done with participation of research vessels from several countries (Holst et al. 1998). The survey is coordinated by a planning group in the ICES. On the basis of the time series of the catch statistics, abundance estimates, and biological samples, an analytical assessment is carried out annually by an ICES working group (ICES 1999d). The assessments have been made annually since the mid-1970s, and recently a long-term VPA, from 1907 to 1998, was made for the stock (Toresen and Østvedt 2000). The assessments show that the spawning stock has probably fluctuated substantially through the last 50 years. In the early 1950s the spawning stock biomass was estimated to be about 10 million t (Fig. 2b). The biomass decreased drastically in the 1950s and 1960s and the stock collapsed in the late 1960s. In the early 1970s, the spawning stock was not detectable. Following strict
regulations (i.e., minimum size regulations of 20 cm and moratorium on exploitation of adults in the years 1974-1977) the stock slowly recovered. In 1983, a very strong year class developed and matured in the late 1980s when the spawning stock increased to a level of about 4 million t. In the early 1990s several strong year classes emerged and by the late 1990s, the stock grew to a level of about 10 million t. However, recent assessments show that the stock probably will decrease in abundance in the near future because the most recent year classes (~1993) are poor. The current exploitation, with a total allowable catch of 1.3 million t, is estimated to be in excess of what will be produced, either as recruitment or individual growth, in the near future. In recent scientific advice, it is stressed that when a rich year class appears, it will still take at least 5 years before it matures to spawn. It was therefore agreed that the long-term management for the stock will be to limit the exploitation to avoid having the stock reduced to less than 2.5 million t. Historical data shows that below this level there is a lower probability of good recruitment.

**North Sea Herring**

According to Parrish and Saville (1965) three main centers and spawning times can be identified for herring in the North Sea: (1) the northwestern North Sea, from the Shetlands to the east coast of Scotland (Buchan), spawning from July to mid-September; (2) the English northeast coast and Dogger Bank, spawning from September to November; and (3) the southern Bight and eastern English Channel, spawning from November to January. Early investigations from these main spawning centers revealed consistent differences between them, especially between the northwestern and central North Sea spawners and those spawning in the southern North Sea and eastern English Channel. However, while feeding and overwintering, herring from the different spawning components mix. During the feeding period in summer (April-July) the major fisheries for adult herring takes place. Even though there are some morphological differences among stocks, the variance within each is substantial, and it is therefore not possible to tell the one from the others in catches. Because of the difficulties in allocating the amount of catch to the right stock component, it was decided in 1987 to pool the data for the different stocks together and make a common assessment of the three stock components.

Annually, landing statistics are reported to the ICES. On the basis of samples from the fishery, the catch is split in numbers per age group. In addition, various abundance estimates are carried out by North Sea coastal states. These estimates are based on different methods, as bottom trawl surveys, acoustic surveys, and larvae surveys. All surveys are coordinated by ICES planning groups. The time series of the estimates are of different length, but there are available abundance estimates based on each of the three methods, annually since 1979. The North Sea herring are assessed annually by the ICES. The current assessment is done by the integrated catch analysis (ICA) method. This method has been evolved from the theory
described by Fournier and Archibald (1982) to the practical applications described by Deriso et al. (1985), and to new applications by Patterson in recent herring assessments (Patterson and Melvin 1996). The approach is fundamentally to build a model to describe the data. The intent of these integrated catch-at-age analyses is to provide the flexibility to incorporate all available types of information—ranging from catch-at-age data, acoustic survey, egg or larvae survey, catch-per-effort, length frequency distributions, stock recruitment relationships, to migration patterns—within one statistical framework that allows for parameter estimation by simultaneous fitting of the model to all data sources.

**Biology**

North Sea herring spawn in the western parts of the North Sea during late summer and autumn. The larvae drift southeastward into the German Bight and thereafter spread northward along the west coast of Denmark. Depending on the force of the currents and wind, various portions of the year class spread into the Skagerrak (which is the bight surrounded by Norway, Denmark, and Sweden). Skagerrak and the region off the west coast of Denmark are important nursery grounds for North Sea herring. The herring spend about 3 years in these eastern parts of the North Sea after which they migrate westward to join the spawning stock. After spawning, the adult stock concentrates in an area outside the southwest coast of Norway, and spends the winter in somewhat deeper waters there. In early spring, the herring spread, moving westward again, and start feeding in central parts of the North Sea.

**Fishery**

Historically, the herring in the North Sea have been exploited by several countries and herring fisheries have been especially important for the Netherlands, Scotland, Denmark, and Norway. The annual yield (Fig. 2c) has for many years been about 300,000 t of adult herring and some 100,000-200,000 t of small and juvenile herring (ICES 1999e). This exploitation, especially the part aiming for small fish, has not been sustainable. There has therefore been an international pressure to decrease the take of small herring, and in 1996 the managers in the EU and Norway agreed on a management policy to reduce that part substantially. Managers also agreed to regulating the fishery to keep fishing mortalities on adult herring at levels below 0.25.

**Historical Development and Status of the Stock**

The time series of the spawning stock biomass from 1960 to 1998, as estimated by the ICES Herring Assessment Working Group for the Area South of 62°N (ICES 1999e) shows that the SSB was probably at a level around 2 million t in the early 1960s. The spawning stock decreased steadily, and by the late 1960s it was estimated to be below 500,000 t. The stock continued to decrease, and by the mid-1970s the stock was at a level
less than 100,000 t. From the late 1970s and on, the stock started to recover, and during the 1980s, increased to a high level of about 1.3 million t in 1989. **In the 1990s the stock decreased again, probably due to unsustainable exploitation, and reached a low level of less than 500,000 t in 1993. The stock remained at these low levels for several years before increasing again probably as a result of strict regulations limiting exploitation both of juveniles and adults. The SSB was estimated to be 870,000 t in 1998 and is expected to increase in the coming years if the managers agree to control exploitation.**

**Celtic Sea Herring**

The herring fishery in the Celtic Sea and ICES division VIIj is located off the south coast of Ireland, and covers ICES divisions VIIa South, VIIg, j, h, and k. The main fisheries now take place in the inshore waters along the Irish coast. The main spawning areas are located along the south and southwest coasts of Ireland. Within the spawning areas the main spawning grounds are well known and defined and individual spawning beds have been mapped. The main juvenile nursery areas are located in the northern part of the Irish Sea (division VIIa North) and in bays and estuaries along the south and southwest coast. In the winter, shoals congregate for spawning in inshore waters along the coastline and after spawning appear to migrate out to deeper water, although shoals of spent fish are also located in inshore waters but may not remain there for prolonged periods. The summer feeding areas are located in offshore waters (e.g., Labadie and Jones banks and the “Smalls” area). Adult migrations take place to and from the spawning and feeding grounds during spring and autumn. Juvenile migrations take place from the nursery areas when fish are in their second and third years to the spawning grounds for first-time spawning.

**Fisheries Data**

The assessment of this stock is now based on age analyses of the catches using a conventional integrated catch at age (ICA) model in which acoustic surveys are used as a tuning index. Two surveys are carried out each spawning season and data are available from 1990. Catches per effort of paired midwater trawlers were also successfully used from 1966 to 1979 and subsequently larval surveys were also successfully used as an index of spawning stock.

The Irish fleet now takes over 95% of the total catch, using paired midwater trawls. Most of the catch is taken by “dry hold” boats but some catches are also taken by vessels with refrigerated seawater tanks. Since the mid-1980s the fishery has been mainly dependent on the Japanese “roe” market. Catch-at-age data are available from 1958 and analytical assessments were carried out from 1958 to 1999. Data on total catch are available for the fishery since 1905 (Fig. 2d).
Annual catches prior to 1916 were less than 5,000 t. Subsequently they increased to about 10,000 t for a short time in the 1920s before decreasing again until the late 1950s. Catches increased rapidly in the 1960s and reached a peak of over 45,000 t in 1969. The fishery then collapsed and was closed for 5 years from 1977 to 1982. Following the reopening, catches have been stable at around 20,000 t, which is approximately the same as the TAC.

**Status of Stock**

*The state of this stock at present is believed to be high. Recruitment has been good in the last number of years and fishing mortality has decreased to the lowest observed since the mid-1960s.* Landings have been stable for a number of years at around the TAC of 20,000 t. The stock collapsed in the 1970s because of decreased recruitment and a high fishing mortality and the fishery was closed for 5 years. There are concerns for the stock because the historical data show that it is very sensitive to increased mortality. It is also clear that over the time period there have been two different periods of recruitment: a high and a low period. At present there is no method of estimating recruitment and it is therefore not known when recruitment may decrease and produce a decline in stock size. There are also concerns that because the market is highly dependent on the Japanese “roe” market there has been widespread discarding of herring unsuitable for roe production. These discards are difficult to estimate and may result in an underestimate of fishing mortality. Further concerns arise because of the proposals to remove gravel from some of the more important spawning grounds.

**West of Scotland Herring**

The West of Scotland herring is found distributed widely over the shelf area to the west and north of Scotland. The West of Scotland herring are assessed annually by ICES. However, because of the uncertainty in the total catch and the age structure the assessments have not been accepted. The assessment model used is the integrated catch analysis (ICA) method. This method has been evolved from the theory described by Fournier and Archibald (1982) to the practical applications described by Deriso et al. (1985), and to new applications by Patterson in recent herring assessments (Patterson and Melvin 1996). On the basis of samples from the fishery, the catch is split in numbers per age group. Samples are supplied from an international fishery with Scottish, Dutch, German, and English vessels. Currently sampling information is poor and there is uncertainty about the landings and the age distribution. In addition, abundance indices of 2-9+ herring are obtained by a Scottish acoustic survey. This survey is coordinated by an ICES planning group and carried out at the same time as the North Sea survey with overlapping boundaries. The time series for this survey, which is carried out in July, is from 1991 to 2000, excluding 1997 when it was conducted in June. From 1972 to 1991 a larvae abun-
dance survey was conducted and used to provide an SSB index. This survey was halted in 1991 as the acoustic surveys provided age-disaggregated data and more precise indices. These assessment model outputs provide a guide for stock management. Currently the stock is regarded as lightly exploited and recommended catches are set to the mean of the last 5 years.

**Biology**

The West of Scotland herring stock is composed of two groups: spring and autumn spawners. Currently most of the population is made up of the latter group. Some herring mature and spawn with an age of “two winter rings” (wr) but most herring reach maturity by around 3 years (wr). Autumn spawning occurs from late August to October around the northwest of Ireland and to the west and north of the Outer Hebrides and off Cape Wrath, in depths up to 100 m (Rankine 1986). The spring-spawning component is currently of unknown extent, with spawning sites inshore particularly on Balantrae Bank and south of Arran on the Clyde (Parrish et al. 1959, Bailey et al. 1986). The period of incubation is temperature-dependent and about 3 weeks at ambient temperatures. Newly hatched larvae follow the current systems and drift to the north and east and then west across the north of Scotland (Dooley and McKay 1975, Heath and MachLachlan 1985). Some are retained on the west of Scotland but a large proportion, particularly those from the Hebrides and Cape Wrath spawning sites, are carried through the Fair Isle channel and travel well into the North Sea. In spring the larvae reach the nursery areas where they develop into juveniles. Young herring spend some time in the inshore areas and sea lochs and the Moray Firth in the North Sea before migrating offshore to join the adult population. There is some evidence to suggest, from tagging experiments and from using biological markers, that as herring mature, some of those that moved as juveniles to the east coast population make the return journey back to the West of Scotland spawning areas (MacKenzie 1985).

**Fishery**

Historically, several countries have exploited the herring in the West of Scotland and herring fisheries have been especially important for the Netherlands, Scotland, and Germany. Before 1970 the fishery was predominantly taken in the North Minch, yielding between 25,000 and 40,000 t annually (Baxter 1958, ICES 1979). In the 1950s these were driftnet and ring-net fisheries, converting to pair-trawlers and purse-seiners in the late 1960s. An offshore fishery by Dutch, German, and French trawlers started in the late 1960s, and for protection against overexploitation several spawning grounds were closed in September and October. Currently the bulk of the catch is taken by three main fleets: a Scottish inshore pair-trawl fleet which works around Barra and in the Minch; a Scottish purse-seine fleet
which operates in the northern part of the area; and an offshore fleet, mainly Dutch and German freezer trawlers, which fish in the deeper waters at around 150 m depth near the edge of the continental shelf. Annual landings statistics are reported to ICES. The estimated SSB and catch are shown in Fig. 2e. The annual yield has for many years been about 40,000 t of adult herring age 2 wr and older (ICES 2001).

**Historical Development and Status of the Stock**

The time series of the spawning stock biomass from 1976 to 2000 as estimated by the ICES Herring Assessment Working Group for the Area South of 62ºN (ICES 2001) and shows that the SSB was probably at a level around 120,000 t in the early 1980s. The stock may have been higher in the early 1970s but when the North Sea fishery was closed, fishing on the western stock increased. The western fishery was closed in 1979 and reopened along with the North Sea in the 1980s. Since then the fishery has been at around 30,000 t. The TAC from this area has been taken in the North Sea over the last 10 years. Recent changes in regulation have reduced this area misreporting and catches are thought to have been reduced. Currently catch advice is for the status quo catch, the average of the last 5 years.

**Icelandic Summer-Spawning Herring**

**Fishery Data Records**

Annual catch statistics on herring have been collected by national authorities and reported to the ICES since 1903 and subsequently published in Bulletin Statistique. However, it was not fully realized until about the middle of the twentieth century that the herring catches at Iceland consisted of three stocks; i.e., Icelandic summer and spring spawners as well as the Norwegian spring spawners all belonging to the Atlanto-Scandian herring (Fridriksson and Aasen 1950). When this was realized the herring catches in Iceland were split on the basis of intensive biological sampling. Therefore, reliable catch statistics on the Icelandic summer-spawning herring is available from 1948. In more recent years fishery statistics are also available in other ICES reports.

**Biology**

Biological data are collected by the Marine Research Institute in Reykjavik and are available since the late 1940s on this stock. Published assessment (e.g., ICES 1999f) reports show that the stock collapsed in the late 1960s. Since 1975 there has been a gradual recovery.

Summer-spawning herring off Iceland spawn in July, mainly south and southwest of the country. The larvae usually hatch in August, and they remain as larvae throughout the winter. They metamorphose the following spring. The nursery grounds are mainly in the fjords of north and northwest Iceland, and there the juveniles stay until they are about 2 years old. The adult component has two distinct feeding seasons: in the periods
April-June, i.e., prior to the spawning season; and August-October, i.e., following the spawning season (Jakobsson et al. 1969). The feeding areas are off the west and east coasts of Iceland, and the wintering areas of the adult stock have been variable in recent years. The adult herring overwintered in the east coast fjords in the 10 years from 1980 to 1989, but more recently most of the adults have overwintered off the east coast of Iceland, while the recruiting year classes have overwintered off southwest Iceland.

**Development of the Fisheries, Exploitation, Management, and Stock Status**

During the 1950s the fishery was exclusively made with driftnets and the catches varied from 15,000 t to 35,000 t (Fig. 2f). Sonar guided purse-seining started in 1960 and the catches increased to about 130,000 t in 1963. This was followed by a sharp decline and a fishing ban at the end of 1971. Since 1975 the catches increased gradually to about 100,000 t during the 1990s (Jakobsson 1980).

The fishing mortality was at a low level during the driftnet fishery in the 1950s but increased sharply during the purse-seine period in the 1960s. The SSB reached about 300,000 t in the beginning of the 1960s, fell to less than 20,000 t in the period 1968-1973, then gradually increased to about 500,000 t in the 1990s. During the recovery of the stock average recruitment increased with larger spawning stock (Jakobsson et al. 1993).

During the moratorium on fishing a new policy for future harvesting of the stock was formulated which included seasonal restrictions: (a) limiting the fishing season to the last 4 months of the year when the annual weight at age was at maximum; (b) minimum landing size of 27 cm and compulsory release of purse-seine catches that obviously consisted of small immature herring; and (c) acting on recommendations from the ICES, the target fishing mortality rate was set at $F_{0.1} = 0.22$ for this stock (Jakobsson 1973). **This policy has proved to be very successful and the SSB has been increased to about 500,000 t, which is almost twice as big as observed prior to the collapse during the 1960s.** Similarly, recruitment has been on a much higher level than previously observed. Since 1975 the fishery management has been based on individual quotas that have been freely transferable since 1990 (Jakobsson and Stefansson 1999). This ITQ system appears to work very well and is highly economical. Based on the experience of managing this stock during the period 1971-1999 the future prospects are optimistic as long as no unexpected environmental change takes place.

**Part 3. Western North Atlantic**

The western Atlantic includes summaries from two areas on the shores of Newfoundland, of which one (western Newfoundland) includes spring and fall spawners; the Gulf of St. Lawrence (with spring and fall spawners); the eastern shores of Nova Scotia and the Bay of Fundy; and the Gulf of Maine
and Georges Bank (Fig. 3). The western Atlantic herring are divided into Part 3a (northwestern North Atlantic) and Part 3b (southwestern North Atlantic) because there is some overlap of stock configurations between the Bay of Fundy, Georges Bank, and the Gulf of Maine. This is explained briefly following the subheading “Southwestern North Atlantic.”

**Part 3a. Northwestern North Atlantic**

*East and Southeast Newfoundland*

*Biology and Migrations*

East and southeast Newfoundland herring overwinter in deep waters within the coastal bays around the island. Spring spawners, which constitute the vast majority of the stocks, then migrate into shallow coastal waters (normally <10 m) where they spawn, normally from late April to early June. Subsequent to spawning, mature herring tend to disperse throughout the bays during the summer as they begin to actively feed. Along the northeast coast, the summer feeding migration tends to be northward of the overwintering grounds. During the fall, herring form schooling aggregations and begin their migration back into the bays.

*Fisheries Data*

For management purposes east and southeast Newfoundland herring comprise five stock complexes. The majority of fish in each of these stocks are spring spawners. Although the stocks are discrete during spawning, there is some overlap during the migratory phase (Wheeler and Winters 1984). Herring are harvested primarily by a fleet of small purse-seine vessels (< 20 m); they are also caught by fixed-gear fishers for lobster bait.

Prior to the 1970s, the fishery was executed by fixed-gear fishers and annual landings averaged less than 10,000 t (Fig. 4a). With the introduction of the mobile purse-seine fleet in the mid-1970s and the recruitment of two large year classes in the late 1960s, annual landings increased to a peak of approximately 30,000 t in the late 1970s. Quotas were first introduced in 1977 and were exceeded by approximately 50% from 1977 to 1979. This, combined with poor recruitment through the 1970s, led to the collapse of stocks. Consequently, the fishery was closed in most areas during the early 1980s. It reopened during the mid-1980s with the recruitment of a moderate-size year class in 1982. Landings peaked at approximately 20,000 during the 1980s and averaged approximately 6,000 t through the 1990s.

Analytical assessments are completed biannually for four of the five east and southeast Newfoundland herring stocks. Population sizes of spring spawners only are estimated for each stock using an integrated catch-at-age (ICA) analysis (Wheeler et al. 1999). Catch and weight-at-age matrices, by stock area, are available from 1970 to the present. Five series of abundance estimates were available for the most recent assessment, research
gillnet catch rates (from index fishermen) and acoustic biomass estimates extending back to the 1980s, and commercial gillnet catch rates, gillnet fisher observations, and purse-seine fisher observations commencing in 1996. The status of each stock is defined by a stock status classification system based upon environmentally dependent stock-recruit relationships.

Commentary

Newfoundland herring stocks are at the northernmost range of herring in the northwest Atlantic. Strong recruitment of year classes tends to be very sporadic and is influenced by environmental conditions (Winters and Wheeler 1987). Below-normal water temperatures experienced during the early to mid-1990s were not conducive to strong recruitment. Consequently, even with modest fisheries, most stocks have declined but stabilized at low levels compared to the 1970s. Although there are not yet any indications, warming trends in water temperatures within the last few years may lead to increased recruitment.
Figure 4. Catch (solid dark line) and spawning stock biomass (SSB, dashed line) for western North Atlantic herring stocks.
**West Coast of Newfoundland (4R) Herring**

**Biology and Migrations**

Within most of the geographic range of northwest Atlantic herring (*Clupea harengus* L.), including the west coast of Newfoundland (NAFO division 4R), some herring populations spawn in the spring (April to June) and others in the summer or autumn (July to October). Within each seasonal-spawning population (or stock), there are local spawning populations (or components) associated with specific spawning areas. Examples of spring-spawning components can be found in St. George’s Bay, Port-au-Port Bay, and St. John Bay. These local components intermix throughout the range of the population, although most evidence suggests that once an individual fish spawns with a given local spawning component, it will return to spawn with that component year after year (Blaxter 1985). A local spawning component can therefore be considered as the basic biological unit to be protected from overexploitation. Local spawning components are, however, not independent of each other, as recruiting individuals may not spawn with their parental spawning component, but may be adopted by another local component, either with the same or a different spawning season (McQuinn 1997a). All the local components which together occupy a common geographic range, as delimited by their annual migration patterns, constitute the overall population (or metapopulation) which in turn defines the management area (McQuinn 1997b).

In the NAFO division 4R management area, individual fish cannot be attributed to their local population component if they are caught outside of the spawning season. Therefore the basic management unit has been defined as the seasonal-spawning stock, which can be determined from the stage of gonad development. The major spawning areas for the spring-spawning stock are located at the southern end of the coast in and around St. George’s Bay and Port-au-Port Bay although several other spawning sites are known along the coast toward the north. Mature herring arrive and spawn in these areas from the end of April to the middle of June before dispersing. Autumn spawning is concentrated mainly north of Point Riche from mid-July to mid-September. At other times of the year, these two spawning stocks are mostly found in mixed schools in either feeding or overwintering areas. The major feeding areas, i.e., off St. George’s Bay in the spring, north of Point Riche and in the Strait of Belle Isle in the summer, and off Bonne Bay in the fall, are associated with concentrations of copepods (red-feed) and/or euphausiids (krill) which are their main food items. Based on winter research survey data (McQuinn and Lefebvre 1995), they are believed to overwinter in the deeper waters of the Esquiman Channel.

**Fisheries Data**

Herring in western Newfoundland are exploited mainly from April to December by large (>25 m) and small (<20 m) purse-seiners and to a much lesser extent by fixed gillnetters. Since 1986, total herring landings from
the west coast of Newfoundland have averaged 17,300 t (from 12,400 t to 26,400 t) as compared to an average of 14,100 t for the previous decade. The 1999 stock-status assessment (McQuinn et al. 1999) indicated that the spring-spawning stock is in danger of collapse. The autumn-spawning stock is declining gradually, while the exploitation rate has been slowly increasing. Apart from the 1990 year class, recruitment to the spring-spawning stock has been below average since the 1987 year class recruited. The spring-spawner spawning-stock biomass (SSB) declined to a historical low of 14,000 t in 1999 (Fig. 4b). Recruitment to the autumn-spawning stock has been above average since the large 1979 year class, which has kept this stock at an intermediate level. The autumn-spawner SSB has been declining slowly, from 80,000 t in 1984 to 42,000 t in 1998 (Fig. 4c).

The latest assessment indicated that fishing mortality on these stocks has been increasing over the past 12-15 years and had been around $F_{0.1}$ for the spring spawners between 1991 and 1997. The closure of St. George's Bay and Port-au-Port Bay in 1995 had the desired effect of slowing the decline of this stock by concentrating fishing on the autumn spawners, of decreasing the quantity of spring spawners in the total catch, and of allowing these fish to spawn undisturbed. However, analyses have shown that the resumption of fishing in these southern bays in 1998 was premature, and that the concentrated harvesting of spring spawners in the spring fishery resulted in a sharp increase in fishing mortality, well above $F_{0.1}$. This is in agreement with comments received from inshore fishermen as well as the index-fisherman catch rates which suggest that the stock has continued to decline since 1997 and has now reached a historical low.

Commentary

These herring stocks, located near the northern end of the species distribution in the western Atlantic, are characterized by the occasional influx of very large year classes, up to 4 times the size of the standing stock which produced them, on roughly a 10- to 12-year cycle. For the spring-spawning stock, recruitment has been below average since the 1987 year class, and over 15 years have passed since the last large recruitment pulse (1980 and 1982 year classes). The production schedule of this stock over the past 30 years (McQuinn et al. 1999) shows that between 1987 and 1997, annual surplus production (recruitment + growth – natural mortality) rarely was positive, and annual net production (surplus production – fishing mortality) consistently was negative. This is mainly due to reduced average recruitment over this 11-year period, brought about by either reduced survival of young herring with less favorable environmental conditions, reduced spawning efficiency due to increased fishing pressure on spawning concentrations, and/or a possible increase in seal predation (although the consumption estimates are subject to large uncertainties). Regardless of the cause, the production of this stock (growth and recruitment) has not kept up with
removals (catches and natural mortality), resulting in a declining SSB even though catches have been in line with the $F_{0.1}$ management strategy.

**Gulf of St. Lawrence**

*Fisheries Data*

Southern Gulf of St. Lawrence herring are harvested primarily by an inshore gillnet fleet fishing in 4T and a fleet of small purse-seine vessels (<20 m) in 4T and 4Vn. Two stocks of herring are harvested in these fisheries. The spring-spawning stock spawns before July 1 and the fall-spawning stock after July 1. During the spring and fall fishing seasons, larger seiners (>20 m) are prohibited from fishing in several areas set aside for exclusive fishing by the inshore fleet.

Prior to 1967, southern Gulf of St. Lawrence herring were exploited mainly by gillnets and average landings from 1935 to 1966 were 34,000 t. In the mid-1960s, a purse-seine fishery was introduced and average landings were 166,000 t from 1967 to 1972. Quotas were introduced in 1972 at 166,000 t and reduced to 40,000 t in 1973. Separate quotas for spring and fall spawners began in 1985. Catches of spring and fall spawners combined have been below the TAC since 1988. In the late 1970s and early 1980s spring and fall spawning stocks were about 10% of current stock sizes (Figs. 4d-e). The spring-spawner TAC was exceeded from 1994 to 1996 and was nearly caught in 1997 and 1998. The fall-spawner TAC has not been exceeded since 1986. Since 1981, the inshore fixed-gear component has had the majority of the catch of spring and fall spawners.

An ADAPT-VPA is the main assessment method. Separate assessments are provided for spring and fall spawners (Claytor et al. 1998, Claytor and LeBlanc 1999). Catch and weight-at-age matrices from 1978 to the present are estimated for each spawning group. Gillnet catch rates (1978-present) are the main abundance indices used to calibrate the VPA. For the spring spawners catch rates from the Escuminac, New Brunswick, and southeast New Brunswick fisheries are used. For the fall spawners, catch rates from all areas are used but the time series is split into two sections corresponding to the year in which there was a major shift in mesh size used in the gillnet fishery. The first is from 1978 to 1991, when 2 5/8" was the predominant mesh size (75-91%), and the second, after 1992 when the percentage using 2 5/8" dropped (54-67%) in favor of larger mesh sizes of 2 3/4" to 2 7/8". Most recently, biomass estimates from an annual acoustic survey (1994-present) have been used as auxiliary indices. It is expected that in time, the indices from the acoustic survey will become the main abundance index for spring and fall spawners. Current stock levels estimated from the VPA for fall spawners are among the highest observed since 1978. Uncertainties resulting from difficulties in estimating incoming recruitment and low abundance indices in the acoustic survey moderate this view. The abundance of fall spawners remains above those observed when the stock was very low in the early 1970s and late 1980s. Current
stock levels estimated from the VPA for spring spawners indicate a stock size that has been about average since 1985 but above the low levels observed in the late 1970s and early 1980s.

Commentary
Estimates of 4+ spring spawner biomass peaked in 1995, when the 1991 year class, which was the largest on record, entered the fishery. This year class has been supporting the fishery since it first appeared in 1995. The 1992 year class was among the lowest since 1978 but the two most recently estimated year classes, 1993 and 1994, were above average. The result of these trends in year-class strength are that the biomass levels were relatively stable for the past 4 years. The $F_{0.1}$ fishing levels were between 16,000 t and 18,500 t from 1996 to 1999.

The history of recruitment since the spring-spawning stock started to rebuild in 1983 is that incoming 4-year-olds have ranged from 50 million to 150 million individuals. Two very strong year classes, 1988 and 1991, consisted of greater than 300 million individuals. It is only the influence of these year classes that increased 4+ biomass levels to above 80,000 t, and, unless year classes of this size appear again, no major increases in biomass or $F_{0.1}$ levels can be expected.

Prior to 1998, estimates of 4+ fall spawner biomass peaked in 1991, when the very large 1987 year class appeared in the fishery. The population declined until 1996, when the large 1992 year class appeared in the fishery. Since then, year classes have been above average and the population is growing. The $F_{0.1}$ fishing levels were between 50,000 t and 60,000 t from 1996 to 1999. The assessment of spring and fall spawning stocks is being improved by the development of an acoustic research survey that covers the majority of the stock area just after the gillnet fishery, and by increased involvement of fishing boats to collect acoustic data during surveys and regular fishing activity. These projects build on telephone surveys of the fleet which began in 1986 and workshops which began in 1994 to incorporate local fishers’ knowledge as part of the assessment of these stocks.

Part 3b. Southwestern Atlantic
A Note on Herring Stock Definitions in the Southern North Atlantic
Atlantic herring from the eastern shore of Nova Scotia, the Bay of Fundy, and Gulf of Maine region are divided into three major spawning stocks: (1) a large-size stock that spawns in U.S. and Canadian waters on Georges Bank and in U.S. waters southeast of Cape Cod; (2) an intermediate-size stock that spawns in Canadian waters south of Nova Scotia; and (3) a smaller-size stock that spawns in U.S. coastal waters of the Gulf of Maine (Iles and Sinclair 1982). Each of these three stock complexes consists of several major and many minor spawning components. Prior to 1993 all three stock
complexes were assessed separately. In 1993 the United States began using a spring bottom trawl survey as an index of abundance to tune VPA stock abundance models. Because adult herring from both the Georges Bank (5Z) and Gulf of Maine (5Y) spawning stocks occupy continental shelf waters south of Cape Cod in the spring and cannot be distinguished from each other, this resulted in the creation of the coastal stock “complex,” an arbitrary assessment unit. On the other hand, since 1988 Canada has assessed and reported only on that part of 5Z which is east of the Great South Channel (longitude 69.0ºW), thereby excluding a large segment (5Z west) of the stock complex.

**Scotia-Fundy**

**Fisheries Data**

Fisheries in recent years have been dominated by purse seine, weir, and gillnet with relatively minor landings by shutoff, trap, and midwater trawl. Most fishing takes place on dense summer feeding, spawning, and overwintering aggregations. Landings occur throughout the year, but occur mainly from July to October. In recent years landings have been measured (volumetric determination) by an independent dock-side monitoring program. Extensive biological sampling has been undertaken since 1986 (Power and Iles 2001, this volume). In recent years there has been considerable involvement by the fishing industry in recording size information and collecting biological samples in support of fishery evaluation.

Landings and biological information series are available for years since 1965 (Fig. 4f). Surveys of the abundance of distribution of herring larvae were undertaken annually from 1972 to 1998. Acoustic surveys of major overwintering aggregations were undertaken in the 1980s and early 1990s. Since 1997 there have been acoustic surveys of major aggregations and of spawning areas using commercial vessels (Melvin et al., 2001, this volume). Annual landings have ranged from 30,000 t to 200,000 t and averaged 120,000 t for the period 1963-1999. The assessment indicates that the SSB fluctuated between 85,000 t and almost 600,000 t during the same period. The last decade saw a substantial drop in SSB (until 1996), followed by a substantial recent increase.

**Commentary**

The 4VWX management unit contains a number of spawning areas separated by various degrees of space and time. Spawning units that are in close proximity, with similar spawning times, and which share a larval distribution area (e.g., Trinity Ledge and German Bank in southwestern Nova Scotia) are considered part of the same complex, and undoubtedly have much closer affinity than spawning units which are widely separated in space or time, and do not share a common larval distribution. Some spawning areas are large and offshore, whereas others are small, and more localized, sometimes very near shore or in small embayments. The situa-
tion is complicated further by the fact that some of these herring tend to migrate long distances, and to mix outside of the spawning period with members of other spawning groups. Some spawning areas are known from fishery sampling, tagging, etc. to have formed the basis for major historical fisheries, while others have not. For the purposes of evaluation and management, the 4VWX herring fisheries are divided into four components: (1) southwestern Nova Scotia/Bay of Fundy spawning component, (2) offshore Scotian Shelf Banks spawning component, (3) coastal Nova Scotia spawning component, and (4) southwestern New Brunswick migrant juveniles. Recognizing that each component has several spawning areas, and that mixing of fish occurs among components, industry and management have explored means of managing the complexity within each component (such as distributing fishing effort among spawning areas according to their relative size) and of taking appropriate account of interaction among components (such as restrictions on some areas of mixing).

Specific conservation objectives were reviewed and developed further during 1997. Three objectives and a number of targets within these objectives were defined as follows: Objective 1: Maintain reproductive capacity of herring in each management unit by (i) ensuring persistence of all spawning components in the management unit; (ii) maintaining biomass of each spawning component above a minimum threshold; (iii) maintaining a broad age composition for each spawning component; and (iv) maintaining a long spawning period for each spawning component. Objective 2: Prevent growth overfishing by continuing to strive for fishing mortality ($F$) below 0.1. Objective 3: Maintain ecosystem integrity (“ecosystem balance”) or ecological relationships by implementation of a precautionary approach that requires further definition of target and limit reference points associated with these three objectives.

An “in-season” management process was implemented in the southwest Nova Scotia fishery during 1995 and has been extended to other areas and fisheries (Stephenson et al. 1999). This approach encourages surveying using the fishing fleet under scientific direction and control prior to fishing to ensure that fishing is distributed appropriately among various components of the stock (particularly among spawning components) according to the relative size and current state of each component (Melvin et al. 2001, this volume). It has improved data collection and enabled modifications to management decisions to be made with the involvement of participants and on the basis of up-to-date information.

**Atlantic Coastal Stock Complex: Gulf of Maine and Georges Bank**

**Biology**

Spawning occurs at more or less discrete locations on the northern edge and northeast peak of Georges Bank, on Nantucket Shoals, in the vicinity of Jeffreys Ledge, along the eastern Maine coast, and at several other poorly
known sites along the Maine coast in the summer and fall (July-December). Eggs are deposited primarily on gravel substrate at water depths of 25-75 m. Larvae that hatch along the coast are transported in a southwesterly direction by the coastal Gulf of Maine current (Graham 1982, Chenoweth et al. 1989, Townsend 1992) and in a clockwise direction on Georges Bank. Larvae metamorphose into juveniles the following spring and remain in coastal waters in the Gulf of Maine, southern New England, and the mid-Atlantic states until the fall of their third year. Adults (age 3+) that spawn in the Gulf of Maine migrate south in the fall and mix with adults from Georges Bank and Nantucket Shoals to overwinter in southern New England and mid-Atlantic continental shelf waters, then return north in the spring and, following a summer feeding migration into the Gulf of Maine, reoccupy their respective spawning grounds in the late summer and fall.

History of Stock Assessments

Early assessments on Georges Bank and western Gulf of Maine herring were tuned using the catch of juvenile herring in the Maine fixed-gear fishery as an index of recruitment. These assessments did not rely on trawl survey data for tuning purposes and were applied to single stock components (ICNAF Redbook 1976; Anthony and Waring 1980a,b). Following the introduction of trawl survey abundance indices for VPA tuning purposes in the early 1990s, there were concerns about patchy spatial distribution of prespawning and spawning aggregations of adult herring in fall surveys. On the other hand, the use of spring survey data, collected when most of the adults from the two spawning stocks occupy shelf waters south of Cape Cod and cannot be differentiated, required the combination of the two stocks for assessment purposes. The most recent of these assessments, performed by the U.S. National Marine Fisheries Service in collaboration with state fishery scientists, was reviewed by the 27th Stock Assessment Review Committee in 1997 (NOAA 1998). Preliminary assessment information for the Gulf of Maine stock was also included in the 1998 stock assessment report. Additional information on the Gulf of Maine stock was presented at this meeting by D.K. Stevenson.

Georges Bank

Fisheries Data

Georges Bank once supported the largest herring fishery in the western Atlantic. The fishery began in 1961 when the former U.S.S.R. harvested 68,000 t of herring (Fig. 4g). From 1961 to 1965 the U.S.S.R. dominated the fishery with annual reported catches ranging between 38,000 and 151,000 t. The fishery expanded rapidly when Poland and the German Democratic Republic entered the fishery in the mid-1960s. Catches peaked at 374,000 t in 1968. Between 1967 and 1976 vessels from 12 countries, including Canada and the United States, participated in the fishery. The fishery col-
lapsed in 1977 and between 1978 and 1993 there was no directed fishery for herring on the bank. The fishery reopened in 1994, when several Canadian herring vessels traveled to Georges Bank. Harvests were minimal until 1997 when 6,262 t were taken by U.S. vessels. Fishing activity by the U.S. fleet recently increased, with reported catches of 17,342 in 1998 and approximately 10,000 t in 1999.

**Data Sources**

There are several survey databases available in both Canada and the United States that can be, or have been, used to assess the status of Georges Bank herring. Repositories for the following survey data are the National Marine Fisheries Service (NMFS), Woods Hole, Massachusetts, and the Canadian Department of Fisheries and Oceans (DFO), St. Andrews, New Brunswick. The surveys include:

<table>
<thead>
<tr>
<th>Survey Type</th>
<th>Period</th>
<th>Repository</th>
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<tbody>
<tr>
<td>U.S. fall bottom trawl survey</td>
<td>1963-2000</td>
<td>NMFS</td>
</tr>
<tr>
<td>U.S. spring bottom trawl survey</td>
<td>1968-2000</td>
<td>NMFS</td>
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<tr>
<td>U.S. winter bottom trawl survey</td>
<td>1992-2000</td>
<td>NMFS</td>
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<tr>
<td>U.S. fall acoustic survey</td>
<td>1998-2000</td>
<td>NMFS</td>
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<tr>
<td>U.S. fall larval surveys</td>
<td>1971-1994</td>
<td>NMFS</td>
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<td>(ICNAF, MARMAP, etc.)</td>
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<tr>
<td>Canadian spring groundfish survey</td>
<td>1987-2000</td>
<td>DFO</td>
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<tr>
<td>Canadian adult/larval herring survey</td>
<td>1986-1995</td>
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**Stock Assessment and Trends in Abundance**

Since 1993 the United States has assessed Georges Bank herring as part of the coastal stock complex. Several of the databases listed above have been evaluated as possible tuning indices for VPAs. In the most recent U.S. assessment (June 1998), the spring bottom trawl and winter bottom trawl indices (number per tow for ages 2-8) were used to tune the VPA. In recent years Canada has not used a VPA to assess the status of Georges Bank herring. Instead, assessment advice has been based on biological characteristics, changes in spatial distribution, and comparisons of current larval abundance estimates with estimates from the early 1970s, prior to the collapse of the stock when SSB estimates for the Georges Bank stock were available (Melvin et al. 1996).

In its relatively short history, the Georges Bank herring stock has gone from one of the largest populations on the east coast of North America to virtually zero and back again. The extent of the decline in the 1970s was remarkable. Between 1979 and 1981 only 2 of more than 500 fishing sets in the fall bottom trawl survey produced any herring. The first signs of recovery occurred in 1984, when a large number of juveniles from the 1983 year class were captured. Between 1986 and 1993 there was a general increase in abundance, a protraction of spawning distribution, and positive signs of recruitment. In 1992, the spawning distribution (determined from the occurrence of larvae <10 mm) had returned to historical
areas and included the northeast peak of the bank. Since 1993, the abundance of herring on Georges Bank may have reached, or exceeded, precollapse levels. In 1995 the U.S. estimate of SSB for the coastal stock complex was 787,000 t (of which approximately 80% was estimated to originate from Georges Bank). Canada estimated 100,000-200,000 t for Georges Bank east of the Great South Channel. Biomass estimates derived from the most recent U.S. assessment (NOAA 1998) indicate a substantial increase in total stock size during the past few years, reaching about 3.5 million t in 1997. The U.S. assessments are heavily influenced by spring trawl survey abundance indices, which increased significantly in recent years in southern New England and mid-Atlantic waters. Current stock size estimates are 3 times higher than estimates from the late 1960s when the fishery peaked on Georges Bank. Retrospective analysis has revealed that current stock sizes are overestimated in this assessment. However, preliminary biomass estimates obtained from prespawning aggregations of herring along the northern edge of Georges Bank in the fall of 1999 were similar to the VPA biomass estimates (William Overholtz, U.S. Department of Commerce, National Marine Fisheries Service, pers. comm.). A conditioned surplus production model produced a much more conservative stock size estimate of 1 million t and a maximum sustainable yield of 317,000 t (Stevenson et al. 1997, NOAA 1998).

Commentary
The Georges Bank herring stock provides a prime example of the detrimental effects of poor recruitment and overfishing. So effective were the combined effects of these two factors that the stock collapsed in 1977, just 15 years after fishing first started on the bank. From 1978 to 1984 there were so few herring on Georges Bank that many researchers, resource managers, and industry members believed the stock to be lost forever. Slowly during the mid-1980s research surveys began to document signs of recovery. However, it was not until 1992, when spawning was documented in most of the known historical areas, that investigators monitoring the stock’s progress believed the stock could reach or exceed precollapse biomass levels. Details of the early stages (1983-1990) of recovery were documented by Stephenson and Power (1989), Smith and Morse (1990), and Stephenson and Kornfield (1990). The middle and late stages of the recovery were documented by Melvin et al. (1996) and most recently by NOAA (1998).

The future outlook for Georges Bank herring is very positive. The most recent U.S. trawl survey (fall 1999) confirmed the continued expansion of the stock. Fishing mortality is at an extremely low level. However, as the fishery expands care must be taken to avoid a repeated overexploitation of the stock. Managers must consider the effects of rapid or large-scale expansion on the long-term sustainability of the stock. Geographical boundaries and the seasonal movement of this transboundary stock also need to be determined. Because of the
transboundary nature of the stock, Canada and the United States have collaborated on recent assessments and are now planning to conduct a joint assessment of Georges Bank herring.

Finally we point out that in recent years, with the recovery of the Georges Bank stock, the abundance of herring on overwintering grounds in southern New England and the mid-Atlantic states also has increased dramatically, as have catches in the commercial fishery (Fig. 4h).

**Gulf of Maine Stock**

A fishery for juvenile herring developed in Maine and New Brunswick in the latter part of the nineteenth century, stimulated by the development of canning techniques. The last 15 years have seen the demise, in U.S. waters, of the nearshore fixed-gear juvenile fishery and a rise in importance of the offshore mobile gear (purse seines and midwater trawls) adult fishery. There is still a fixed-gear fishery in New Brunswick that harvests 15,000-20,000 t annually. The Gulf of Maine catch exceeded 75,000 t a year during the first decade of this century and again in the 1950s. The catch remained fairly steady at 80,000-100,000 t a year during the past 10 years as the fishery became less vulnerable to annual variations in juvenile abundance (Fig. 4i).

Biomass estimates are derived from a virtual population analysis of Gulf of Maine catch-at-age data (which include the New Brunswick fixed-gear fishery) and terminal fishing mortality estimates for individual year classes based on numbers caught at age (NOAA 1998, Stevenson 1998). The results indicate that the Gulf of Maine stock doubled in size in a 3-year period during the mid-1980s, remained stable at 350,000-400,000 t between 1986 and 1994, then increased to about 500,000 t in 1996 and 1997 (Fig. 4g). A more recent VPA for this stock based on 1976-1998 catch-at-age data indicates that stock biomass in January 1998 declined to about 350,000 t (presented at the Herring 2000: Expectations for a New Millennium symposium by D.K. Stevenson). The sharp increase in stock size that occurred between 1983 and 1986 was due to the recruitment of the large 1983 year class which, unlike previous year classes, was exploited very minimally at age 2. The development of the mobile gear fishery during the 1980s was based on the increased biomass of adults, in particular adults belonging to the 1983 year class.

**Part 4. Eastern Pacific**

In contrast to other parts of the world, herring populations in the eastern Pacific, from California to the Bering Sea, consist of a relatively large number (>20) of relatively small populations (most < 100,000 t) (Fig. 5). Most have limited migrations, with spawning and juvenile rearing areas in nearshore areas and summer feeding limited to the relatively narrow continental shelf.
Virtually all eastern Pacific herring stocks use assessment methods that require some quantitative assessment of spawning. Pacific herring spawn mainly in nearshore, shallow inter- and subtidal waters. Over the years various techniques have developed to quantify herring spawning. This includes visual estimates from aerial surveys in remote areas of Alaska to detailed surveys using scuba divers, to make explicit counts of the total numbers of eggs on spawning grounds in California, Washington, and British Columbia.

**Alaska**

**Biology**

Within Alaskan waters Pacific herring spawn at discrete locations from Dixon Entrance in southeastern Alaska to Norton Sound. Like herring in other parts of the eastern Pacific, spawning occurs on intertidal and subtidal vegetation in spring. The timing of spawning is related to temperature, and progresses around the Alaska coast from March in southeastern Alaska, to June in Norton Sound. In warmer years, herring spawning occurs earlier
throughout Alaska. However, there are some patterns in the time series of herring spawning that do not appear to be explained just by temperature variability. For example, since 1993 in Sitka Sound, spawning has occurred 3 weeks earlier than in all previous records. The changes in spawn timing can be biologically significant, affecting seabirds, shorebirds, marine mammals, and piscivores that are focused on herring spawning in the spring.

The life history strategy of herring in the Bering Sea is distinctly different from populations in the Gulf of Alaska and more southern regions in the eastern Pacific. Bering Sea herring attain large body size (to 500 g), whereas Gulf of Alaska herring reach only half that size. The eastern Bering Sea herring are long-distance migrants. The largest population spawns along the north shore of Bristol Bay, near the village of Togiak. Following spawning, these herring migrate in a clockwise direction down along the Alaska Peninsula, reaching the Unimak Pass area in early July (Funk 1990). They feed along the continental shelf edge, slowly moving northward to overwinter near the Pribilof Islands. The Bering Sea herring life history strategy appears to be an adaptation to take advantage of the distant rich feeding grounds and mild overwintering areas on the continental shelf edge while utilizing the protected inshore bays for summer larval nurseries. In contrast, Gulf of Alaska herring are smaller, have shorter life-spans, have more frequent recruitment events, and do not undergo long-distance migrations. In the Gulf of Alaska, recruitment events tend to occur synchronously over fairly broad areas that contain otherwise discrete spawning aggregations. Gulf of Alaska herring have some genetic distinction from Bering Sea herring (Grant and Utter 1984).

There appear to be strong, autocorrelated, and almost cyclic changes in size-at-age time series that date back to the reduction fisheries of the early 1920s. The cause of these apparent cycles in body size is not known, but the anomalies have been correlated to a time series of zooplankton abundance measured at Prince William Sound salmon hatcheries, and also to the Pacific Decadal Oscillation (Evelyn Brown, University of Alaska Fairbanks, pers. comm.). Only a mild effect of density dependence is seen in adult herring at studied locations in Alaska, such as Prince William Sound. However, density dependence could be an important mechanism affecting larval and juvenile herring growth, for which little time series data exist.

Recruitment also shows signs of periodic autocorrelated anomalies. In the Gulf of Alaska recruitment time series a 4-year cycle of strong year classes is apparent, although that pattern has changed recently. Recruitment events occur more frequently in the Gulf of Alaska (typically averaging every fourth year), whereas in the Bering Sea, strong recruitment events occur much less frequently, typically averaging every tenth year. Most areas experienced a positive response in recruitment associated with the 1977 regime shift. These recruitment indices were derived from routine agency stock assessments in support of fishery management.
Year-class abundance is quantified at a recruiting age of 3 in the Gulf of Alaska, and age 4 in the Bering Sea. Adult survival rate is usually treated as constant for stock assessment purposes. When this holds, the recruitment time series provide an excellent measure of abundance for comparison to long-term climate indices, particularly because herring early life history is fine-tuned to ocean processes with low tolerance for changing conditions. However, occasional adult herring epizootics have been observed in Prince William Sound, which can drastically alter adult survival rates. When adult survival rate changes substantially, the recruitment time series will not provide a good measure of adult abundance. Thus far, substantial changes in adult survival appear to be relatively rare, so that the recruitment indices typically provide a reliable index of abundance for both juveniles and adults.

Based on patterns in size at age and recruitment, Williams (1999) grouped Alaska herring into three categories: Bering Sea, Outer Gulf of Alaska, and Inner Gulf of Alaska. The spatial scale of these groupings reflects the spatial scale of oceanographic processes underlying herring productivity, as well as the different Bering Sea and Gulf of Alaska life history strategies. Fishery managers need to understand finer spatial scales of herring stock structure than these large groupings based on coherence in growth and recruitment anomalies. Because herring milt can be readily observed from aircraft and precisely defines spawning locations, fishery managers use maps of herring milt locations to define discrete groups of herring appropriately sized for management units.

**Trends in Herring Abundance and Historical Catch in Alaska**

In Alaska subsistence fisheries for Pacific herring predate recorded history. Traditional dried herring remains a major staple of the diet in Bering Sea villages near Nelson Island (Pete 1990), where salmon are not readily available. Alaska’s commercial herring industry began in 1878 when 30,000 pounds of salt-cured product were prepared for human consumption. By 1882, a reduction plant at Killisnoo in Chatham Strait was producing 30,000 gallons of herring oil annually. The herring reduction industry expanded slowly through the early twentieth century, reaching a peak harvest of 142,000 t in 1934. Exploitation rates were quite high during the reduction fishery era, with large fluctuations in stock levels and annual harvests. As Peruvian anchovetta reduction fisheries developed, Alaska herring reduction fisheries declined, so that by 1967 herring were no longer harvested for reduction products in Alaska.

A Japanese and Russian trawl fishery for herring began in the central and eastern Bering Sea in the late 1950s, reaching a peak harvest of 146,000 t in 1970 (Fig. 6a). Substantial catches of herring for sac roe began throughout Alaska in the 1970s as market demand increased in Japan (Fig. 6b). Presently, herring are harvested primarily for sac roe destined for Japanese markets. Statewide herring harvests have averaged approximately 45,000 t in recent years. Much of the herring taken in these fisheries were
from western Alaska coastal spawning stocks in the Bering Sea, which are the largest of Alaskan stocks (Fig. 6c).

Approximately 25 distinct fisheries for Pacific herring occur in Alaskan waters. Almost all of these herring fisheries are closely linked to a specific spawning population of herring. Most of the herring harvest currently occurs during sac roe fisheries, which harvest herring just before their spring spawning period. Both males and females are harvested, although the sac roe fisheries target the much higher-valued roe-bearing females. Alaska statutes require that the males also be retained and processed and not discarded as bycatch. Most sac roe fisheries occur during a series of short openings of a few hours each, spanning approximately 1 week. Fishing is not allowed between these short openings, to allow processors time to process the catch, and for managers to locate additional herring of marketable quality.

The present abundance in the Bering Sea, based mainly on the SSB estimates of the Togiak region, is much lower (~140,000 t) than the highest estimate of nearly 500,000 t in 1985. The abundances of the many smaller stocks in the same region show no clear trends in time.

Spawn-on-kelp fisheries harvest intertidal and subtidal macroalgae containing freshly deposited herring eggs. Both of these fisheries produce products for consumption primarily in Japanese domestic markets. Smaller amounts of herring are harvested from late July through February in herring food/bait fisheries. Most of the herring harvested in these fisheries are used for bait in Alaskan longline and pot fisheries for groundfish and shellfish. Smaller amounts are used for bait in salmon troll fisheries, with occasional utilization for human or zoo food.

Harvest policies used for herring in Alaska set the maximum exploitation rate at 20% of the exploitable or mature biomass, consistent with other herring fisheries on the west coast of North America. The 20% exploitation rate is lower than commonly used biological reference points (Funk 1991) for species with similar life history characteristics. In some areas, such as southeastern Alaska, a formal policy exists for reducing the exploitation rate as the biomass drops to low levels. In other areas, managers similarly reduce the exploitation rate as abundance drops, without the more formal exploitation rate framework. In addition to exploitation rate constraints, minimum threshold biomass levels are set for most Alaskan herring fisheries. If the spawning biomass is estimated to be below the threshold level, no commercial fishing is allowed. Threshold levels are generally set at 25% of the long-term average of unfished biomass (Funk and Rowell 1995).

**British Columbia Herring**

*Stock Structure and Migrations*

The herring population that occurs in British Columbia is believed to consist of five major migratory stocks as well as a large number of smaller...
Figure 6. Catch (solid dark line) and spawning stock biomass (SSB, dashed line) for eastern North Pacific herring stocks. Figure 6b shows the sum of all Alaska stocks and Fig. 6c shows the SSB for each of the main subareas. Figure 6d shows the sum of all British Columbia stocks and Fig. 6e shows the SSB for northern and southern areas separately.
localized stocks (Hay and McCarter 1997, Schweigert et al. 1999). Based on their geographical spawning locations the five major stocks occur along the southeastern coast of the Queen Charlotte Islands, the north coast of British Columbia, the central coast of British Columbia, the west coast of Vancouver Island, and the Strait of Georgia. The localized stocks occur at the heads of many of the long inlets or fjords of the central and north coasts as well as in Johnstone Strait, the Strait of Georgia, and the west coast of the Queen Charlotte Islands. The spawning period for the major stocks begins in late February or early March in the south and progresses through mid-April as one moves northward (Haegele and Schweigert 1985). The spawning times for the localized stocks also occur in this period although there are some interesting exceptions from as early as late December or January in the Queen Charlotte Islands to as late as June or early July in the central coast. After spawning, the major migratory populations move offshore to the summer feeding areas, which are believed to be within Hecate Strait for the Queen Charlotte Islands and north coast stocks and likely some of the central coast stock. Fish that spawn within the Strait of Georgia migrate offshore through both the Strait of Juan de Fuca in the south and mix with west coast Vancouver Island fish on La Perouse Bank, as well as through Johnstone Strait into Queen Charlotte Sound or off the northwest coast of Vancouver Island where they could mix with either central coast or west coast of Vancouver Island stocks. Larval and juvenile distributions are not well known for other areas outside of the Strait of Georgia where they are ubiquitous (Haegele 1997, Hay and McCarter 1997). In general, surveys in all areas indicate diffusion of larvae away from the major spawning areas with time. Subsequently, juveniles appear to be found almost everywhere along the available shorelines.

Indications are that some juveniles begin to migrate offshore in the fall of their first year (Taylor 1964), although recent studies within the Strait of Georgia suggest that many juvenile herring overwinter there in their first year and do not migrate offshore until the following June-July, possibly following the adults as they return to offshore feeding grounds following spawning.

The Fishery

The first documented records of Pacific herring catches occurred in 1877 although herring were taken historically by aboriginal peoples. The earliest commercial fishery was for domestic consumption but larger quantities were exported to China as a salted product beginning in the early 1900s (Taylor 1964). The market for this product appears to have disappeared by the late 1920s, and in the early 1930s a reduction fishery began and expanded throughout the coast in the 1940s and 1950s as the sardine stocks collapsed off of California. By the early 1960s all herring stocks in British Columbia were being heavily exploited by this fishery, which collapsed and was closed in 1968 (Fig. 6d). The fisheries during this period
were prosecuted initially with drag or beach seines and later with purse seines. The fishery occurred during the fall inshore migration of maturing stocks primarily from October through January. A limited amount of gillnetting occurred in the summer in the Strait of Georgia in the 1950s. After a 3-year closure an experimental roe herring fishery was opened in 1971 and it expanded rapidly through this decade. The roe fishery occurs on or near the spawning grounds during early March to early April. The roe fishery uses a combination of gillnets (45%) and seines (55%) to catch the quota. Concerns about collapsing stocks in the early 1980s led to the introduction of the currently used 20% fixed harvest rate policy to set quotas preseason. This policy was augmented with a fishing threshold or “cutoff” level in 1985 to ensure a spawning reserve for stock rebuilding in periods of natural stock decline (Stocker 1993). The harvesting policy has resulted in annual harvests of 30,000-40,000 t of herring coastwide during the past two decades although there have been fishing closures in each of the five stock areas during this period. In addition, there are small food and bait fisheries which harvest approximately 2,000 t annually. Another fishery that occurs in some localized areas of the coast is the spawn-on-kelp fishery, which is primarily undertaken by Native groups and lands about 360 t of product which includes the kelp and attached eggs.

**Fisheries Data and Stock Assessment**

Annual estimates of total landings have been collected since the early 1930s on a coastwide basis and since 1917 on a localized scale. These data are available in unpublished manuscripts at the Pacific Biological Station. Beginning in 1950, individual fishing companies were required to submit sales slips of their landings to the B.C. Department of Fisheries and these have been maintained in an electronic database to present. Similarly, much of the early data that was collected on the annual deposition of herring spawn and biological samples of the spawning runs is presented in summarized form in the annual B.C. Department of Fisheries reports. All available raw data for spawn deposition and biological sampling data such as length, weight, sex, and age are available in electronic form to present in a database. Other assorted biological data such as tagging and recovery information are also available in electronic databases.

The annual assessments of stock abundance rely on estimates from two analytical models. The first is a modification of the escapement model described by Schweigert and Stocker (1988) and relies on the data collected on spawn deposition. The second is a catch-age or age-structured model which is a modification of the model described by Fournier and Archibald (1982). Both models reconstruct mature stock abundance for the period since 1951 and forecast prespawning abundance for the next season. Forecasts of upcoming run size are based on the combination of estimates of surviving repeat spawners and newly recruited spawners which are presented as poor, average, and good, based on historical recruitment levels. The biological data required to annually monitor and assess stock abundance
levels is obtained through a test fishing program which collects samples of herring from all the major spawning stocks and as many of the minor stocks as possible. In addition, scuba diver teams make annual surveys of the approximately 500 km or more of shoreline to assess herring spawn.

**Biology**

The age at first maturity appears to be the third year for most areas of British Columbia (Hay and McCarter 1999). A small proportion of the population in the southern stocks matures in the second year and in the northern areas in the fourth year. Maximal gonad weight at maturity is a function of fecundity and egg size but has been found to be about 25-30% of total body weight in B.C. stocks (Ware 1985). Similarly to gonad weight, fecundity is a conservative function of body weight and has been found to be constant at 200 eggs per gram of female weight (Hay 1985). Age determination is routinely done by scales although some trials with otoliths suggest that the oldest fish may be aged conservatively with scales. The largest herring observed in British Columbia was 310 mm long (SL), weighed 340 g, and was about 15 years old. Available data indicates that herring in British Columbia spawn at about 8ºC (Hay 1985). Larval herring feed primarily on copepod nauplii as do juveniles which subsequently switch to euphausiids which are the major prey item for adult herring (Wailes 1936).

**Stock Status**

Pacific herring in British Columbia are short-lived, generally less than 8 years of age, which makes the stocks very dynamic and subject to marked fluctuations in abundance depending on environmental conditions during the prerecruit life stage. Indications for the west coast of Vancouver Island are that survival is inversely related to water temperature (Ware 1991), which has resulted in decreased survival in recent years as water temperatures have increased due to recurring El Niño events and possible global warming. However, all B.C. herring stocks have experienced marked fluctuations in abundance during the past century. Abundance declined for most stocks following the strong El Niños of 1940-1941 and 1958-1959 (Taylor 1964). Abundance of all stocks collapsed in the late 1960s following the large fisheries of the early 1960s combined with poor conditions for survival at this time. All stocks recovered rapidly in the early 1970s (Fig. 6e) following the reduction fishery closure. The two southern stocks declined in the mid-1980s following poor year classes in the early 1980s. Northern stocks were buoyed by a very strong 1977 year class. **Subsequently, strong 1985, 1989, and 1994 or 1995 year classes have maintained most stocks at healthy levels. The exception has been the west coast of Vancouver Island, which appears to have been adversely affected by warm water conditions since about 1976** (Schweigert et al. 1999). Prospects for the future of B.C. herring stocks will depend to a significant degree on the oceanic conditions over the next few decades. Should warm
water continue to dominate the marine environment one may expect that survival for west coast of Vancouver Island and Queen Charlotte Islands stocks will continue to be poor. In addition, the impact of a rapidly increasing Pacific sardine stock on B.C. herring stock productivity is unknown.

**California**

**Fishery Data**

Commercial landings data dating back to 1916 are available in California Department of Fish and Game bulletins. The data are recorded by fish dealers and processors, who are required to fill out receipts for each landing and submit copies to the department. Landings statistics and other aspects of herring fisheries in California are also published in Department administrative reports and the journal, *California Fish and Game* (Watters and Oda 1997, State of California 2000).

**Biology**

Biological data are available from the California Department of Fish and Game and are published in administrative reports, a fishery bulletin, and the journal, *California Fish and Game* (e.g., Sprat 1981, 1987, 1992). Spawning population surveys were first conducted in California during 1954-1955 using acoustic and egg deposition surveys. Time series data exist from 1973 to the present for the San Francisco Bay and Tomales Bay spawning populations. These data include spawning biomass estimates, age composition, lengths, and weights. San Francisco Bay biomass estimates are derived from acoustic and egg deposition surveys, and fishery-independent samples of herring are collected from each school with midwater trawl gear for age determination. Tomales Bay biomass estimates are derived from egg deposition surveys and fishery-independent samples of herring are collected using variable-mesh gillnets.

California herring are at the southern end of the range for *Clupea pallasii* in the eastern North Pacific Ocean (Miller and Schmidkte 1956). Spawning occurs as far south as San Diego Bay but the largest spawning population utilizes San Francisco Bay, which is at 37°50'N. Spawning occurs from November through March in nearshore and estuarine environments. Most spawning areas are characterized as having reduced salinity, calm and protected waters, and spawning substrate such as marine vegetation or rocky intertidal areas; however, man-made structures such as pier pilings and rip rap are also frequently used spawning substrates in San Francisco Bay.

Throughout the spawning season, schools of herring enter bays and estuaries, where they may remain up to 3 weeks before spawning. School size varies but can be as large as tens of thousands of metric tons and kilometers in length in San Francisco Bay. Spawn depth distribution generally is shallower than 9 m, but has been found to a depth of 18 m in San
Francisco Bay. A large spawning run may last a week and can result in 30 km of shoreline covered by a 9-m-wide band of herring eggs.

Young-of-the-year herring remain in the bay until summer or early fall, when they migrate to the open ocean. Some herring reach sexual maturity at age 2 when they are about 155 mm (standard length) and all are sexually mature at age 3. California herring may live to be 9 years old and reach a maximum length of about 230 mm body length, although fish older than 7 are rare. Adults leave the bay immediately after spawning. Little is known about the distribution of herring in the open ocean (Reilly 1988).

Fishery and Management

In California, the Pacific herring (Clupea pallasii) fishery peaked three times during the past century in response to demand for herring. During the intervening years herring catches were low, when most herring were used as pet food, bait, or animal food at zoos. The herring reduction fishery peaked in 1918 at 3,630 t, but this fishery ended in 1919 when reduction of whole fish into fish meal was prohibited. From 1947 to 1954 herring were canned to supplement the declining supply of Pacific sardines; landings peaked in 1952 at 4,310 t. Canned herring, however, proved to be a poor substitute for sardines and limited demand led to the demise of this fishery by 1954.

In 1973, sac-roe fisheries developed in California and elsewhere along the west coast of North America to supply the demands of the Japanese market. Since then, the majority of herring landed in California have been for the roe market, with small amounts of whole herring marketed for human consumption, aquarium food, and bait. Herring sac roe from San Francisco Bay is typically smaller than sac roe from British Columbia and Alaska, but is highly valued for its unique golden coloration. California sac-roe herring landings peaked twice, at 10,433 t in 1982 and 10,705 t in 1997 (Fig. 6f). The lowest landings have occurred either during or just after El Niño events and corresponded with reduced population size.

The sac-roe fishery is limited to California’s four largest herring spawning areas: San Francisco Bay, Tomales Bay, Humboldt Bay, and Crescent City Harbor. There also exists a small open-pound herring eggs-on-kelp fishery in San Francisco Bay. San Francisco Bay has the largest spawning population of herring and produces more than 90% of the state’s herring catch. The four spawning areas are managed separately by the California Department of Fish and Game although it is not known whether adjacent spawning populations, such as San Francisco Bay and Tomales Bay, are the same stock.

For San Francisco and Tomales bays, catch quotas are based on the latest population estimates from acoustic surveys and spawning-ground surveys. Quotas are adjusted annually and are generally set at about 15% of the previous season’s spawning biomass estimates. This percentage is adjusted lower if the population is at a low level and/or unfavorable conditions such as El Niño exist.
Since 1973, the herring fishery has been managed through a limited-entry system that has been carefully controlled. Until the 1997-1998 season, both round haul gear (purse seines and lampara nets) and set gillnet gear were allowed in the sac-roe fishery; since then only set gillnet gear is allowed in all of the sac-roe fisheries. The set gillnet gear has a minimum mesh size requirement, the purpose of which is to target age 4 and older herring.

**Status of the Stock**

Assessments are limited to the spawning portions of the San Francisco Bay and Tomales Bay stocks (the two largest in the state), and include fishery-independent estimates of biomass and age composition. *Since 1979, California's spawning biomass estimates ranged from a high of 96,841 t to a low of 18,675 t, with peaks occurring in 1982 (96,841 t), 1988 (64,375 t), and 1996 (91,725 t).* The lowest biomass estimates have occurred during or just after El Niño events: 38,174 t in 1984; 23,204 t in 1993; and 18,675 t in 1998. The lack of upwelling and associated warm water conditions that occur during El Niño events reduce the production of food for herring, which can affect their condition and survival. It also may displace herring to areas of colder water. *San Francisco Bay's population has not yet recovered from the effects of the 1997-1978 El Niño; spawning biomass was estimated at 24,853 t in 2000.*

**Part 5. Western North Pacific**

This section is divided into two subsections. The first is the northwestern North Pacific herring, which includes five major stocks in Russian waters (Fig. 7). The biological descriptions and explanations of trends in these five stocks are presented as a unit, so their presentation here under a single subheading was for convenience. The southwestern North Pacific includes the Hokkaido-Sakhalin herring and the presentation here represents an integration of information provided by several contributors. This section concludes with a description of Yellow Sea herring.

**Part 5a. Northwestern North Pacific**

*Notes on Different Forms of Herring in the Western North Pacific*

Several contributors to this symposium, and elsewhere, comment on different ecological forms of herring. Earlier it was noted that Bering Sea herring have different life history characteristics than more southerly herring in the eastern North Pacific. Similarly, in the northwestern Pacific there appear to be three distinct forms of herring: (1) a migratory “sea” herring, which is relatively long-lived and which undergoes considerable migrations; (2) a similar coastal form, which consists of a number of smaller populations and which spends most of its life close to shore with little or
no migrations; and (3) a unique “lagoon” form whose life history is connected with low-salinity lagoons or embayments. In general the marine forms comprise the largest populations and have supported commercial fisheries in the northwestern Pacific.

Much of the available review literature on the Russian Far East herring populations deals with several of the major populations in the same articles. For this reason, the following brief discussion of biology and fisheries also covers all of these groups, although we try to make clear any differences between the populations, from the western Bering Sea in the north to the Sea of Japan in the south. Two stocks, the Dekastri herring and Peter the Great Bay herring, might have been included with the next group (Part 5b, southwestern North Pacific herring) because they occur at the same latitudes as the Hokkaido-Sakhalin stock but their inclusion here is mainly for convenience. Because of their significance, the Hokkaido-Sakhalin stocks are described separately.

**Russian Herring: Korf-Karagin, Gizhiga-Kamchatka, Okhotsk, Dekastri, and Peter the Great Bay Herring**

Aside from the Hokkaido-Sakhalin herring (sometimes called the Sakhalin-Hokkaido herring) there are several major stocks in Russian waters of the western Pacific including the Korf-Karagin herring, Gizhiga-Kamchatka herring, Okhotsk herring, Dekastri herring, and Peter the Great Bay herring. (See Smirnov 2001 [this volume] for more detail on Gizhiga-Kamchatka stock.) These five stocks, as well as the Hokkaido-Sakhalin herring, consti-
tute the “sea” form of western Pacific herring. In addition, Russian biologists recognize 20 or more smaller populations known as “coastal” or “lagoon” herring. These latter groups are not described in this review but we will point out that the “lagoon” form, which inhabits fresh and brackish water for part of its life cycle, may be unique to the western Pacific, and such forms have not been described for the eastern Pacific. There are a number of papers describing the genetics and biology of these lagoon herring (see Kobayashi 2001, this volume). In general it seems that lagoon herring (sometimes called “lake” herring) mature early (2-3 years) and grow rapidly, but have a short life-span with few older than 5 years of age (Ayushin 1963).

**Biology**

A small proportion of herring in the Peter the Great Bay population mature at age 1, although most mature at age 2 and 3 (Ayushin 1963). In most other populations sexual maturity and spawning begin at age 2 or 3. Okhotsk herring spawn from mid-May to Mid-June, with sea temperatures mainly between 2 and 8ºC (Ayushin 1947, cited in Galkina 1961). Spawning grounds are mainly in the northwestern area of the Sea of Okhotsk between Tauiskaya Bay and Cape Ukoi. Spawning substrates include *Laminaria, Lessonia, Alaria, Cystoseira*, and red algae (Benko et al. 1987). The egg densities described for this area are extraordinarily high. In 1982 the average density was 10.9 million eggs/m² with some areas having more than 117 million eggs/m². This was substantially higher than the norms in other years in the same area, with means of 2-4 million/m². This density still is substantially higher than in most other parts of the world, by a factor of 3 or more (see list in Hay 1985 for interpopulation comparison).

Korf-Karagin herring spawn mainly in May in shallow bays and lagoons of Karagin and Korf bays (Naumenko 1996), mainly on eelgrass (*Zostera*) as the main substrate. These herring leave the area immediately after spawning and return to foraging areas. The range of foraging area inhabited depends on stock size and extends eastward during periods of high abundance, reaching longitude 178ºE. During years of low abundance, foraging appears to be confined to Olyutorsk Bay (northeastern part of the Kamchatka Peninsula). Early winter migrations bring herring back to Olyutorsk Bay, where fish reside in moderately shallow depths (20-50 m) before moving to deeper depths, and continue moving westward in late November and December reaching traditional overwintering areas around Cape Goven (Naumenko 1996). Juvenile herring reside within Karagin Bay for the first 2 years of life and do not mix with adult schools. They move to Olyutorsk Bay in their third year. Herring appear to be fully recruited by age 4, at which time they are about 24 cm in length.

In general, the relative scale of variation in year-class strength differs between northern and southern populations: the difference between strong and weak year classes is less in the south and the frequency of stronger year classes is higher, with strong year classes appearing once every 3-6 years. In
contrast, in northern populations strong year classes occur about once every 5 years. The causes of the variation in year-class strength have prompted much debate and research but without firm answers. It is clear, however, that there are some complex biotic interactions between some key species, and, in particular, it appears that in the western Bering Sea, herring abundance appears to be inversely related to pollock (*Theragra chalcogramma*).

**Fishery Data and Stock Status**

Catches for Russian stocks are indicated in Figs. 8a-e. Aside from the Hokkaido-Sakhalin herring, the commercial fisheries for Peter the Great Bay and Dekastri herring (Fig. 8a-b) were the earliest, with catches greater than 20,000 t made in the 1920s. Substantial commercial fisheries started in other stocks in later years: Korf-Karagin in 1939 (Fig. 8c) and Okhotsk (Fig. 8d) and Gihiga-Kamchatka (Fig. 8e) in the mid- to late 1940s. Early fishing gear was passive, consisting of weirs set in the vicinity of spawning areas. In more recent years, catches were made with gillnets, trawls, and purse seines. Catch records of all of these stocks are characterized by substantial variation in annual catch, reflecting fluctuations in the availability of herring. In all stocks, the declines in catch rates and assessed biomass have led to prohibition of commercial fishing. The three northern populations supported large catches which began to increase rapidly in the late 1950s, with maximal total catches exceeding 500,000 t in the late 1960s. This was followed by a rapid decline in all of the “marine” herring stocks, and a period of low abundance persisted until the late 1990s, when there were some indications of recovery of the Okhotsk and Korf-Karagin herring. The southern stocks, Dekastri and Peter the Great Bay herring, however, remain in a state of severe depression.

**Part 5b. Southwestern North Pacific**

**Hokkaido-Sakhalin Herring**

**Geography**

Hokkaido-Sakhalin herring were the most abundant of all western Pacific herring populations. In the first half of this century, which seems to have been a favorable time for this population, this stock was very widely distributed and formed an industrially fished stock in the northern part of the Sea of Japan, the Sea of Okhotsk (along the shores of eastern Sakhalin to the Island of Iona, and along the Kuril Islands to the Island of Paramushir), and the Pacific Ocean (along the southern Kurils). Larval and juvenile herring inhabit the areas near south and southeastern Sakhalin and northwestern Hokkaido. After spawning, herring migrate farther to the marine sites which, at the present time, are mainly in the Tatar Strait (Sea of Japan). Herring spend the winter above 200-400 m depths, in water layers of 100-200 m in Tatar Strait (Sea of Japan) (Druzhinin 1963). Spawning occurs in
Figure 8. Catches of western North Pacific herring stocks.
May, although at the present time the distribution is very limited, mainly to a few sites on the western Sakhalin coast (Sea of Japan) at depths to 10 m. There are a number of small local stocks distributed throughout this area, but their relationship to the once-large Hokkaido-Sakhalin stock is unclear.

Annual catch statistics for northern Japan and southern Sakhalin have been gathered by national and provincial authorities in Japan and Russia since 1887 until the present time (Fig. 8f). These long-term series of catch and biological data have been recorded by staff of fisheries research institutes in Russia and Japan, including the national fisheries institutes and provincial fisheries experimental stations. Data on catch at age and body length composition at each age recorded from 1910 to 1954 for northern Japan are published in the reports of the Hokkaido Regional Fisheries Research Laboratory. Annual catch has been reported to the Russian-Japanese Fishery Commission. Various assessment methods include virtual population analyses and cohort analysis.

The historical peak in catch was recorded in 1897 as 973,000 t. After this period, total landing decreased annually and fishing grounds started moving north along the western coast of Hokkaido from the late nineteenth century. Since that time annual catch had gradually declined with continual fluctuation and the spawning herring had disappeared since 1955 from the Hokkaido coast. In those days herring was mainly caught by gillnet and set net. At present the Hokkaido-Sakhalin herring stock is at the lowest level of abundance for the whole history of the population’s commercial exploitation (Motoda and Hirano 1963, Pushnikova 1996)

There appears to be three distinct periods of abundance in the last century, which can be appreciated by comparing estimated numbers of individuals:

Period 1: Late 1800s to 1950, period of high abundance. The stock varied annually from 15.2 billion (1948) to 228.2 billion (1940), and averaged 67.2 billion fish. The numbers of recruits for each generation in this period varied from 1.8 billion (1949) to 201.5 billion (1939), averaging 28.3 billion fish in each generation.

Period 2: From 1951 to 1960, period of population decline. The stock varied from 1.7 billion (1960) to 13.4 billion (1951), averaging 5.8 billion fish. Recruitment varied from 0.3 billion (1960) to 5.4 billion (1953), averaging 1.9 billion fish.

Period 3: 1961 to the present, period of population depression. The stock varied from 0.4 billion (1988) to 5.6 billion (1974), averaging 1.6 billion fish. Recruitment varied from 0.14 billion (1986) to 4.7 billion (1973), averaging 0.8 billion fish.
Commentary

After the collapse of this stock, only small fisheries have continued. These consist of gillnet fisheries in spring, near the spawning ground targeting small local populations, and trawl-net fisheries in the spring-autumn season in the feeding area that again target some small local populations in the Hokkaido-Sakhalin areas. The overall stock condition has been at quite a low level since 1955 and, except 1986, the annual catch has been less than 50,000 t. The 1983 year class, however, appeared to be an abundant year (from ages 2-5) and the 1988 year class also was noticeable, but much less than the 1983 year class. Year-class strength since then has been poor.

The reason that the stock has not recovered is not clear. One explanation is that oceanographic conditions have changed. Since late in the 1940s the sea-surface temperatures on the western coast of Hokkaido have been warmer during the winter-spring seasons but colder in the summer seasons. These oceanographic changes may affect the regional environment and the mechanism of recruitment of the Hokkaido-Sakhalin population. The major decline, however, coincided with the development of more intensive searching and fishing. This included the use of acoustic sounders to find fish and, in Russian waters, the use of airplanes for spotting their feeding areas. In the 1950s, trap nets continued to be used during the spawning period, but the industry also began using trawling nets to capture fish in the feeding areas. Immature and young fish were caught. The industrial pressure on young fish increased and this intense fishing pressure coincided with a period of natural decline in abundance.

Therefore, it is probable that the existing depression in abundance is caused for the most part by excessive fishing, which restricts recruitment. Historically, Russia and Japan both have harvested the same population of Hokkaido-Sakhalin herring. The result of an irrational fishing intensity during a period of natural decline has been a steady, long-term depression, to the point where some researchers have declared that in Japanese waters this population has disappeared in recent years (Kobayashi 1983).

Trend in Hokkaido-Sakhalin Herring Population

There are no indications of change in the extremely depressed status of Hokkaido-Sakhalin herring. This statement is based on the following observations: a trend toward decreasing productivity over successive generations; very infrequent formation of strong cohorts during the last 20 years; the absolute absence of spawning among the Hokkaido-Sakhalin herring in the coastal areas where they historically have spawned; the huge area of potential but currently empty spawning grounds; and the extraordinarily low numbers of reproductive fish.
**Yellow Sea Herring**

**Biology**

Yellow Sea herring mature early, with 99% mature at age 2. Minimum fork length and body weight of mature fish was 200 mm and 80 g for females and 168 mm and 46 g for males. Absolute fecundity ranged between 19,300 and 78,100 eggs and relative fecundity (number of eggs per gram) of net body weight was between 210 and 379 eggs. The estimate of eggs per unit length (E/L, or eggs per centimeter of fork length) was 93-269 eggs. Both E and E/L increased linearly with net body weight, exponentially with fork length, and with age. Relative fecundity did not vary with body weight, fork length, or age and was quite stable over time.

The growth rate of Yellow Sea herring varies seasonally, with rapid growth in summer and the period from late winter to the prespawning stage, but it is slow in the autumn and early winter. Growth rates were lowest during the spawning and postspawning period, but even then growth did not stop. This growth aspect was connected with seasonal variation of feeding. Growth rates varied with age and were greatest in young herring less than 3 years old, and slower at ages of 4 or more. There was no apparent relationship between rate of growth and population abundance.

Pacific herring in the Yellow Sea migrate between inshore and deeper water in response to seasonal changes. Yellow Sea herring have never been found in the area south of 34°N, and there are significant differences in the number of vertebrae, dorsal rays, anal rays, and scutes between Yellow Sea herring and Hokkaido herring in the Sea of Japan (Tang 1991). Therefore, the Yellow Sea herring is considered as a distinct population of Pacific herring.

The Yellow Sea herring has a long exploitation history. Its importance is demonstrated by the existence of villages and localities named for their association with it. In the last century, the commercial fishery for this species experienced three peaks (in about 1900, 1938, and 1972), each followed by a period of little or no catch (Fig. 8g). In 1967, a large number of 1-year-old herring appeared in bottom trawl catches. In 1972 a very strong 1970 year class was recruited to the fishery, and the stock reached its historical maximum abundance biomass, estimated at 200,000 t or $26.8 \times 10^8$ fish. **Since 1982, the stock has declined substantially because of a series of weak year classes. The catch decreased to below 1,000 t in 1989-1990, and there is no fishing today.**

Yellow Sea herring undergo rapid and extreme fluctuations in abundance. Tang (1981, 1987) reported that environmental conditions such as rainfall, wind, and daylight could strongly affect fluctuations in recruitment. Further, the long-term changes in biomass of Yellow Sea herring may be correlated with a 36-year cycle of dryness/wetness oscillation in eastern China (Fig. 9).
Part 6. Arctic Populations

Arctic populations of herring have not had a long history of exploitation, and therefore are literally and figuratively peripheral to one of the main objectives of this review, which is to review the status of herring stocks after a century of fishing. On the other hand, the review also is an “inventory,” so for that reason we include some brief comments on Arctic herring populations. In general, the biological literature on Arctic herring populations, which is relatively sparse compared to more southern populations, tends to be associated with individual seas. We follow that approach.

There are a number of coastal seas within the Arctic Ocean (Fig. 10), and most have some records of herring. The Greenland Sea lies between northeastern Greenland and Spitsbergen. To the east of the Greenland Sea is the Barents Sea, on the north coast of Norway and northeastern Russia. The coastal seas on the north coast of Russia, from west to east, consist of four large seas: the Barents, Kara, Laptev, and East Siberian seas. The White Sea, in northeastern Russia, opens to the Barents Sea between the Kola and Kanin peninsulas. On the extreme northeastern coast of Russia, the Chukchi Sea separates western Alaska and the Chukchi Peninsula of Russia. On the north coast of North America, the Beaufort Sea spreads from northeastern Alaska to the western Canadian Arctic. The northeastern Canadian coast also includes the large Hudson Bay (mainly south of 65ºN)
Figure 10. The Arctic Ocean and adjacent seas showing approximate herring distribution. Herring occur in each of the seas or estuaries of rivers with underlined names. The dashed line shows the distribution of the Cheshapchora herring, in the southern Barents and Kara seas. The dark circles indicate reports of herring found in river estuaries. The large semicircle indicates, figuratively, the zone across the North Atlantic and parts of the Arctic Ocean where herring distribution is nearly continuous. The dark area in the eastern Canadian Arctic indicates areas where herring do not occur, with the limits of their ranges being approximately the Coppermine River and Ungava Bay. [Author’s note: subsequent to the preparation of this report, we have learned that there are indeed herring in parts of Hudson Bay. (J. Dodson, Biology Dept., Univ. of Laval, Québec, pers. comm.)]
as well as Baffin Bay (between Baffin Island and western Greenland). The large Davis Strait separates the Arctic Ocean and the Labrador Sea (part of the northwestern Atlantic Ocean).

**Greenland Sea**

The Greenland Sea is not documented as a spawning area for herring but some areas are occupied during summer feeding migrations of Norwegian spring-spawning herring. Also, juveniles from the Norwegian coast can extend to the southeastern areas of Spitsbergen.

**Barents and Kara Seas**

The Barents Sea has a long history of fisheries for herring, cod, and capelin (see Orlova et al. 2001, this volume). The main fisheries are on Norwegian spring-spawning herring as they are either feeding or overwintering. In addition, parts of the southern Barents Sea are occupied by a different form of herring, called by Svetovidov (1952) the “Chesha-Pechora” (low vertebral number herring). This form of herring extends from Mezan Bay, which separates the White Sea from the Barents Sea, to the Ob Inlet estuary, on the southwestern shores of the Kara Sea.

**White Sea**

The White Sea is an inlet of the Barents Sea (~95,000 km²) in northwestern Russia opening into the Barents Sea between the Kola and Kanin peninsulas. Kandalashka Bay, in the southern section, is the deepest part of the sea (340 m). The Mezen, the Northern Dvina, and the Onega rivers empty into large bays of the White Sea. There are at least three distinct herring populations in the White Sea, each associated with different bays: the Onega Bay, Kandalaksha Bay, and Dvina Bay herring. They are exclusively spring spawners and there are a number of biological differences between these populations. Because of their nearshore spawning on macrophytes in the spring, as well as biological characteristics (especially vertebral number), Russian biologists have recognized White Sea herring as the same subspecies as Pacific herring (Clupea harengus pallasii). We mention this here, not as an endorsement or refutation of this taxonomic usage, but to point out that the White Sea herring are quite different from their neighboring Norwegian spring spawners. Commercial fisheries are small, landing about 1,200 t annually (Krixunov 1990). Each of the three populations in the White Sea declined in the early to mid-1960s, recovered in the 1970s, and then declined again (Krixunov 1990).

**Laptev and East Siberian Seas**

There is very little available information on herring in these areas. Svetovidov (1952) reported on herring taken in the delta of the Lena River, a large Siberian river that drains into the Laptev Sea. Spawning is reported to occur in Tiksi Cove. Less clear are reports of herring in the Indigirka
River estuary, which drains into the East Siberian Sea (Svetovidov 1952). Accounts of herring occurring (and spawning) in brackish estuarine Arctic waters is consistent, however, with reports from the North American Arctic (see below).

Chukchi Sea
Kotzebue Sound is on the extreme eastern part of the Chukchi Sea. The locations and dates of herring spawning in Kotzebue Sound (see Hay 2001, this volume). This area supports local subsistence fisheries and limited commercial fisheries. Although this area is part of the Chukchi Sea, it also can be viewed as the northern edge of the eastern Bering Sea, which supports large herring fisheries.

Beaufort Sea
The first record of Pacific herring (Clupea pallasii) caught in the Canadian Beaufort Sea was reported by Richardson (1823, cited in Riske 1960) in his description of fishes captured during Sir John Franklin’s expeditions to the Polar Sea between 1819 and 1822. Riske (1960) lists several other early instances of herring being captured along the Beaufort Sea coast between the Mackenzie River Delta and Cape Bathurst. He collected 248 fish in 1958 to compare life history and morphometric and meristic characters with those of fish from the southern British Columbian coast. He concluded that Arctic and British Columbian herring constitute one taxonomic unit, Clupea harengus pallasii.

Recent collections of Pacific herring from the Beaufort Sea were made to address potential impacts of hydrocarbon exploration at Tuktoyaktuk and to evaluate the feasibility of a commercial roe fishery. Gillman and Kristofferson (1984) listed the sampling events that included catches of Pacific herring. These studies focused in the Mackenzie River Delta and adjacent areas. Sampling programs concentrated in the nearshore area. A perusal of published reports shows that all information on Pacific herring is based on about 2,300 fish, the vast majority being collected between 1981 and 1983 during the roe fishery feasibility study (Gillman and Kristofferson 1984).

Biology
According to Bond (1982), herring have been collected along the Arctic coast of North America eastward to the Yukon but appear to be more abundant east of the Mackenzie River Delta. No animals have been collected recently east of Paulatuk (Riske 1960). Seasonal variation in catch per unit of effort (Bond 1982, Lawrence et al. 1984) suggests that fish migrate from the shallow inshore spawning areas in June to offshore feeding areas and then return in August to overwinter and then spawn in the next spring. Beaufort Sea herring appear to tolerate low salinities. They have been reported as far as 100 km upstream from the Beaufort Sea, in the Mackenzie
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River Delta (Hunter 1975). Lawrence et al. (1984) reported collecting herring from waters with salinities ranging between 13 and 30 ppt. Herring are also exposed to wide ranges in temperature. Lawrence et al. (1984) reported temperature ranges of 1.9-14.0, 7.3-13.9, and 2.1-8.5°C for June/July, August, and September, respectively. Gillman and Kristofferson (1984) measured sea surface temperatures ranging between 2.5 and 3.5°C during the spawning season. Nearshore waters warm rapidly. Tanasichuk et al. (1993) estimated that sea temperatures during the larval phase would be about 12.5°C.

Most of the available data are for age composition and size-at-age. Bond (1982) showed age-length data for a number of studies. His figure indicated that fish captured were between 2 and 16 years old. Growth in length appears to be linear and relatively rapid to age 8 with an asymptotic length of about 310 mm fork length. Bond’s length-at-age estimates differ from those presented by Tanasichuk et al. (1993). It is not known whether this reflects a biological difference or differences in aging methods.

Tanasichuk et al. (1993) compared growth and reproductive characteristics of herring collected from the Beaufort Sea and British Columbia. Beaufort Sea herring became progressively longer-at-age after age 5 whereas mass-at-age was similar. Condition (length-specific mass) was greater for Strait of Georgia herring because size-specific ripe ovarian mass was 2.1 times heavier. These differences in growth may be related to differences in natural mortality which was almost twice as high for herring from British Columbia. Lawrence et al. (1984) and Bond (1982) reported that Beaufort Sea herring were not strict planktivores. Stomach contents included infaunal benthic organisms, epibenthos, and plankton. Stomach content weight of 0.12 and 0.62 g dry mass, respectively, suggests a very low daily ration.

Fisheries

Herring are not taken routinely and are only harvested domestically as incidental catch by gillnets. Attempts at developing commercial fisheries were unsuccessful, mainly because of high production and transportation costs (Corkum and McCart 1981, Gillman and Kristofferson 1984). Estimates of local spawning biomass are surprisingly low. Shields (1985) reported an estimated biomass of 8.2 t for one of the key spawning areas. His explanations for the low biomass estimates were that (1) the survey area might not be a major spawning location because of interannual variability in spawning locations, (2) a protracted spawning period meant that not all the spawn deposited in the study area would have been surveyed, and (3) it is uncertain if Beaufort Sea herring spawn every year.

Other Waters: Hudson Bay, Baffin Bay, Davis Strait

Although herring are known to occur in the southern Davis Strait area, along the coastal areas of Labrador and Greenland, there are no established spawning areas north of Newfoundland. Herring are documented
as occurring in Bathurst Inlet (Scattergood et al. 1959). Therefore there is a substantial geographical range where there are no records of herring occurrence (Fig. 10). This range extends from about Ungava Bay (adjacent to the Labrador Sea), as the approximate limit of their range to the west from the Atlantic, to Coppermine River (Riske 1960), as the approximate limit of their range to the east, from the Beaufort Sea, or Pacific Ocean.

The present herring distribution in the Arctic, even though not well known, probably represents remnants of a much more pronounced presence of herring in the Arctic when their distribution probably was circum-polar, probably during past periods of warmer climate. It will be interesting to see if climate changes forecasted for the remaining 99 years of this century will impact this herring distribution. One of the indicators could be the new presence of herring in new locations, such as Hudson Bay. Given the broad distribution of herring in other parts of the Arctic, the absence of herring in Hudson Bay is a puzzle.

Part 7. Synopsis, Summary, and Conclusions

What Have We Learned?

Has this inventory and review of herring stocks revealed anything that was previously unknown? From one perspective we suggest that the answer is no: the foregoing contributions have only served to amalgamate and assemble into a single document information that was well known for each stock. From another perspective we suggest that an inventory such as this does make some new contributions in the sense that the information derived from the “whole” may exceed the sum of the “parts.” In this regard, we suggest that there may indeed be some conclusions that, while perhaps not entirely original, may be drawn more forcefully from this review than from the component contributions, or from some of the previous contributions cited in the references. For instance, one clear observation is the relative magnitude of the Norwegian spring-spawning herring. This single stock, during periods of high biomass (> 10 million t), is the equivalent, or greater, than all of the other herring stocks in the world combined! Another observation is that if “large” herring stocks are defined as those of 1 million t or greater, there are not many in the world—probably less than 10 worldwide.

A clear conclusion is that in the year 2000 there were still many herring stocks, and that 100 years of fishing between 1900 and 2000 has not resulted in their demise. It is probable, however, that there has been an elimination of spawning components within some stocks and the long-term effects of this are not clear. An equally clear observation, however, is that virtually all herring stocks have undergone substantial change in abundance in the past, and during periods of active fishing most have declined to the point where the stock has been described as “collapsed.” From this we can make two other points. One is that we see that most stocks have
recovered to the point where present, or recent, abundance has equalled or exceeded historical estimates. The other is that there is (or was) a very large stock, the Hokkaido-Sakhalin stock, that is seriously depleted, perhaps to the point of functional extinction. Similarly, there are grounds for concern about the Yellow Sea herring, Baltic herring, and two of the southern populations in the western Pacific: the Dekastri and Peter the Great Bay herring.

**Elements Common to Different Contributions**

A common theme running through many of the descriptions of herring stocks is the effect of environment or long-term climate change on herring abundance and distribution. Remarkably, the general impact of climate on herring has been understood for a long time; see, for instance, Rachel Carson’s (1951) popularized discussion of climate and the changes on the Bohuslan herring of the middle ages in the Baltic, or more recent analyses of long-term climate change by Southward et al. (1988), Höglund (1978, and Øiestad (1994). The Russian scientific literature on herring makes frequent reference to effects of climate. Regardless, at the present time invoking climate change as an explanation for changes in fish stock abundance can be controversial. The controversy arises because it may be seen by some as a rationalization, or an excuse, to deflect criticism away from inadequate assessments or policies that resulted in the overfishing of herring.

There are grounds for scepticism about climate change as explanations for changes in stock abundance. As pointed out by Cushing (1971) 30 years ago, climate change is usually suggested as an explanation for most instances of collapse of fish stocks, but the arguments vary with the species and few explanations provide convincing biological mechanisms for the relationship between climate and fish abundance. In this review, many contributions point out that past fishing effort and practices were too high and not biologically sustainable but most also suggest that climate change is a very important factor affecting herring. There is now growing evidence that climate change is a key factor affecting abundance of many fish species; for instance, see Beamish (1995) and references therein. Therefore reference to climate as a factor affecting herring is not invoked here, or anywhere above, as an excuse for stock collapses. Rather, a useful observation from this review is that climate change was suggested by most contributors, independently, as an important factor affecting nearly all of the herring stocks described above. The problem is, however, that no one yet fully understands the biological mechanisms of climate change on herring abundance (Toresen and Østvedt 2000).

**Stocks of Concern**

We conclude by pointing out some of the most obvious and troubling observations in this review. One is that there has been a striking recovery
of herring on the Georges Bank, and this appears to coincide with remarkable increases in herring abundance in the southern range of the western Atlantic, with herring catch extending south to North Carolina. Concurrently, the most northern western Atlantic herring stocks are declining (Newfoundland east and west coast spring spawners). The Atlanto-Scandian herring (Norwegian spring-spawning herring and Icelandic herring) appear to be in a period of high abundance, while North Sea and Baltic herring are in decline. The geographic and temporal patterns of abundance of herring in the Pacific are less clear. First, however, it should be noted that most stocks in the eastern Pacific (North American coast) are relatively small, with few exceeding 100,000 t, except for the Bering Sea. For the purposes of brevity, in this review we were forced to pool the abundance estimates of a number of smaller stocks. Regardless, the abundance of herring, from California to the Gulf of Alaska, indicates a mixed pattern, but generally most stocks had a higher spawning biomass in the late 1990s than they did in the previous five decades. The exception to this is Prince William Sound, and as pointed out in other papers in the Herring 2000 symposium, spawning grounds in this area were contaminated with oil in 1989 and the impact of that event may be responsible.

The general patterns of herring abundance in the southwestern North Pacific are not encouraging in the year 2000. The once great Hokkaido-Sakhalin stock has not recovered after a collapse that occurred more than 50 years ago and this is the only major herring stock in the world that has not recovered. Also worrisome is the Yellow Sea herring stock, which has not been abundant since the mid-1970s. Similarly, two other stocks in the southwestern North Pacific, the Peter the Great Bay and Dekastri herring, are severely depressed. Also the Gizhiga-Kamchatka stock appears to be low. On the other hand, the largest stock in the northwestern Pacific, the Okhotsk Sea stock, appears to be abundant at the present time, and the Korf-Karagin stock, low until recently, appears to be increasing.

Probably it is too simplistic to limit the discussion of “concern” only to those stocks that currently are at low levels of abundance. It is well understood that abundances of all herring stocks undergo major fluctuations of their own accord but we also understand that rapid stock reductions have been made worse by aggressive fishing strategies. Therefore another perspective is that any stock is a potential stock of concern where fishing management policies do not recognize the inherent variability of herring. There is a need for further development of management approaches that consider multiple factors and that can react quickly to complex changing conditions.

Limitations of This Review

Probably the available data and other biological information about herring equal or exceed that of any other marine species (Whitehead 1985) and we acknowledge that this report may not be as thorough or complete
as we would have liked. The summary is incomplete on two counts. First, there was more information provided to us, or available, than we could include. Second, even with some deficiencies of data, more analyses would have been possible. From the perspective of understanding how fish stocks respond to fishing, and how climate affects fish and fisheries, it would appear to be wise to assemble the best information possible and make it as broadly available as possible.

Perhaps the greatest limitation of this review is the restricted description of the apparent complexity of stock structure of large herring stocks. The nature of the structure of marine fish stocks is the basis of active research and debate in the literature, and we could not do justice to this topic here. Similarly there is very little reference made in this review to the distribution and biology of the large number of “smaller stocks.” There are many throughout nearly all regions, and their ecological and genetic relationship to larger stocks is not well understood.

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