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Incorporating the dynamics of marine systems into the stock assessment and management of sablefish

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Abstract

Progress in ecosystem management requires the characterisation of the dynamics of a species's ecosystem and the influences of climatic oscillations on those dynamics. Within the North Pacific, ecosystem dynamics have been described on decadal-scales (regimes) and have been shown to shift abruptly (regime shifts). The year class success of sablefish (*Anoplopoma fimbria*) exhibit decadal-scale patterns that relate to decadal-scale patterns in North Pacific climate–ocean conditions. As an example, and a step towards, incorporating the dynamics of marine systems into the stock assessment and management of sablefish, we produce a 'report card' that characterises the species's ecosystem on decadal-scales. This report card consists of a matrix of climatological and oceanographic indices for the North Pacific, and regional environmental and biological indices. It indicates that both Pacific-wide and regionally, conditions were generally good for sablefish year class strength during the 1977–1988 regime, but these favourable conditions did not persist into the 1990s. Exploitation scenarios can be developed around the decadal-scale dynamics in sablefish year class success and their life history, in particular longevity. Fisheries managers can begin to develop exploitation strategies that acknowledge these changes in the sablefish ecosystem. The report card presents an aggregation of parameters that, on average, gives an impression of productivity during a specific regime and can be used to augment present stock assessment and management efforts. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

1.1. Ecosystem and precautionary approaches to management

There has been a recognition that fisheries management requires an ecosystem-based approach (see for example FRCC, 1998; NRC, 1999; NMFS, 1999). Common to reviews on the principles of ecosystem management is that ecosystems change with time. However, the change need not be oscillatory and several alternative stable states are possible (Isaacs, 1975). One of the first steps to ecosystem management, as suggested by the Ecosystem Principles Advisory Panel (United States), is to characterise the biological, chemical and physical dynamics of an ecosystem with specific consideration of climate influences (NMFS, 1999). In Canada, the Canadian Oceans Act, passed in 1997 requires that, along with consideration of ecosystem features, a precautionary approach to management must be applied. This management objective requires a more holistic perspective that uses information on the biotic and abiotic factors that determine trophic level interactions (predation, competition), carrying capacity changes (food availability), and habitat suitability.

1.2. Ecosystem dynamics

In the North Pacific, many studies have shown that neither climate nor ocean systems fluctuate around a stable mean, but experience rapid shifts from one state (regime) to another (Ebbesmeyer et al., 1991; Polovina et al., 1994; Mantua, Hare, Zhang, Wallace, & Francis, 1997; Beamish et al., 1999; Watanabe & Nitta, 1999; Overland, Adams, & Bond, 1999). Within the last 100 years, at least four regime shifts have occurred, around 1925 (Minobe, 1997), 1947 (Francis & Hare, 1994), 1977 (Ebbesmeyer et al., 1991; Beamish & Bouillon, 1993) and 1989 (Beamish et al., 1999; Watanabe & Nitta, 1999), and there is the suggestion that a fifth regime shift occurred around 1997, manifested in the winter of 1998 (McFarlane, King, & Beamish, 2000). Responses to rapid shifts in Pacific-wide and regional-scale parameters have been detected in pelagic and demersal fish species (Kawasaki & Omori, 1986; Beamish & Bouillon, 1993; Hare & Francis, 1995; Polovina, 1996; Beamish et al., 1999; Clark, Hare, Parma, Sullivan, & Trumble, 1999; McFarlane et al., 2000). These shifts imply that decadal-scale dynamics need to be addressed in stock assessment and fisheries management.

1.3. The fishery for sablefish

Sablefish (*Anoplopoma fimbria*) is an economically important groundfish species off the west coast of Canada. In 1998, the value of the fish landed in the commercial fishery was $41 million (Canadian). The commercial fishery has operated since the late 19th century; the initial annual landings were as high as 5956 tonnes during the 1910s, but were modest from 1920–1965 (210 to 1895 tonnes). Following the declaration of the Canadian Fishing Zone in 1977, the landings by the Canadian commercial fleet has varied from a low of 830 tonnes in 1978 to a high of 5381 tonnes in 1989. In recent years (1996-1998), the landings have averaged 4016 tonnes. Since 1973 the dominant fishing gear used by the fishery has been Korean conical traps (73% of the annual landings). In 1990, the fishery switched to an Individual Vessel Quota in an attempt to stabilise the length of the fishing season, to improve the management, to optimise the landed value and to reduce quota overruns.

1.4. Sablefish biology and population dynamics

Sablefish can live $>$100 years (Beamish & McFarlane, 2000). They occur along the continental shelf and slope from Baja California to northern Japan (McFarlane & Beamish, 1983). Growth is rapid until age 5 when fish begin to mature. After maturity the growth of males is greatly reduced and they rarely exceed lengths of 70 cm. Females, however, continue to grow slowly and can reach lengths of 90–100 cm. Sablefish have high fecundity; an average sized spawning female in the fishery (65–75 cm) annually produces 180–280 thousand eggs, and larger females (90–100 cm in length) can produce up to one million.

In Canadian waters, spawning takes place from January to March at the midwater depths (~300–500 m) over bathymetric depths $>$1000 m (Mason, Beamish, & McFarlane, 1980; McFarlane & Nagata, 1988). The specific gravity of the eggs increases, and it is estimated that they sink to depths of ~1000m, within 18 days of spawning (McFarlane & Beamish, 1992). Hatching begins about 12 days after fertilisation. The larval fish ascend back up the water column and begin feeding on calanoid copepods while the yolk sac is still being absorbed. When in early April, the larval sablefish arrive in near surface-waters their yolk has been fully utilised (McFarlane & Beamish, 1992). Within British Columbia waters, most juvenile sablefish inhabit shallower waters (up to 200 m) in Hecate Strait and off the west coast of Vancouver Island prior to their recruitment to slope waters off northern and southern British Columbia (Beamish & McFarlane, 1983). Sablefish begin to migrate offshore at age 3, and recruit into the fishery when they are approximately 5 years old.

Sablefish exhibit decadal-scale patterns in their relative year class success, with periods of weaker or stronger year classes (Fig. 1, King, McFarlane, & Beamish, 2000). The shifts between one period of similar year class success to another correspond to the regime shifts in Pacific-wide climate and ocean indices (King et al., 2000). Presently, Canadian sablefish quotas are based on

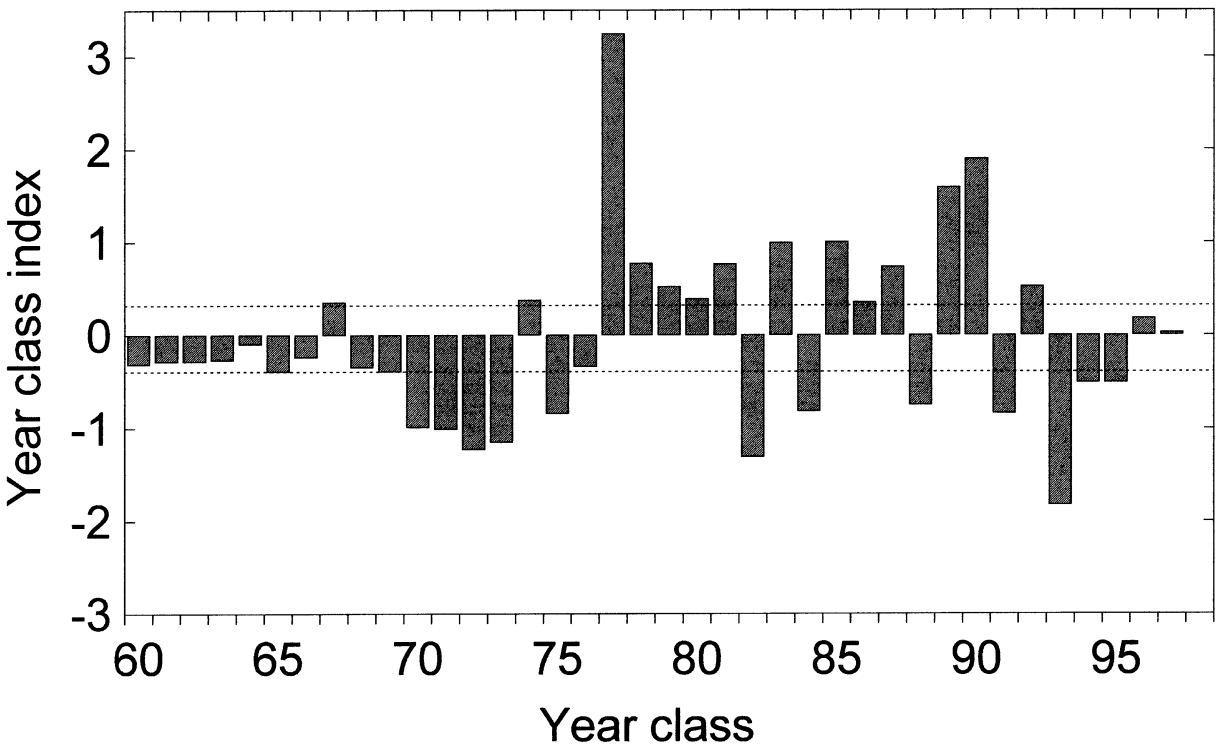

Fig. 1. The sablefish year class index for sablefish (from King et al., 2000).

yield recommendations produced from an integrated mark-recapture and catch-age analysis (Haist, Saunders, & Hilborn, 1999). The decadal-scale dynamics observed in North Pacific climate–ocean conditions and sablefish year class success have not been incorporated into the stock assessment process. Since the first step towards a holistic perspective is characterising the biological, chemical and physical dynamics of an ecosystem, we present a method of providing such information to fisheries managers.

We begin by presenting climate-ocean indices previously observed to reflect regime shifts in the North Pacific. McFarlane and Beamish (1992) hypothesised that year class strength is determined during the larval stages, so we have selected regional environmental and biological time series that seem likely to affect larval survival. As with many species, sablefish pre-recruitment indices such as estimates of larval or juvenile abundance are only intermittently available, but they can be of some use as indicators of change in year class success. We use pre-recruitment and fishery indices for sablefish throughout British Columbia waters to make inference for year class success for all sablefish irrespective of stock structure. Canadian tagging data (McFarlane & Beamish, 1988) and U.S. tagging data (Kimura, Shimada, & Shaw, 1998) imply that there is sufficient migration between Alaskan, Canadian and west coast US sablefish populations to consider sablefish stocks a single biological population throughout the species's range in the northeast Pacific. In addition, McFarlane and Beamish (1992) noted that strong year classes are concurrent in sablefish throughout the northeast Pacific, indicating there are similar year class responses to climate–ocean conditions. We construct a 'sablefish report card' of North Pacific climate–ocean indices, regional physical and biological oceanographic variables and pre-recruitment indices to show how recent conditions can be considered in stock assessment and fisheries management efforts.

2. Methods

2.1. Selecting variables

The North Pacific, regional, pre-recruitment and fishery indices selected for inclusion in the report card are listed in Table 1.

The Aleutian Low Pressure Index (ALPI), the Pacific Circulation Index (PCI), and the Pacific Decadal Oscillation Index (PDO) were selected to represent the decadal-scale regime dynamics of the north Pacific. McFarlane, Saunders, Thomson and Perry (1997) concluded that once sablefish larvae reach the surface waters, their distribution is influenced by both the outer shelf-break current and the inner coastal current. The outer current switches its direction of flow in spring and fall; upwelling in summer results southward flow, and winter downwelling in northward flow (Thomson, Hicky, & LeBlond, 1989). The inner coastal current flows northward and in summer is driven by Fraser River flow through the Juan de Fuca and is augmented by south-westerly winds along the coast (Thomson et al., 1989). McFarlane and Beamish (1992) noted that sablefish larvae feed exclusively on the nauplii and adults of calanoid copepods. The sub-arctic and boreal copepods have a peak in their breeding during springtime (Mackas, 1995), and since larval sablefish feed exclusively on copepods in spring, they are likely to benefit most from a copepod community dominated by spring breeders.

We use abundance estimates from sablefish larval surveys as a pre-recruitment index. In addition, we use the occurrence of juvenile sablefish in catches from bottom-trawl research surveys conducted periodically throughout Hecate Strait. Tagging studies indicate that in Hecate Strait juvenile sablefish migrate into slope waters throughout British Columbia (McFarlane & Saunders, 1997). Aside from an exceptional year class of 1977, approximately 65–80% of the tagged juveniles from Hecate Strait move to the west coasts of Queen Charlotte Islands, Vancouver Island and to a greater extent just off Queen Charlotte Sound (McFarlane & Saunders, 1997).

We selected two fishery indicators to include in the report card. Saunders and McFarlane (1992) suggested that whenever the commercial trawl fleet discarded sablefish over a widespread by area, this was indicative of a strong year class in that year. Length frequencies of recent discards indicate the discarded fish are younger than 2 years old (Fig. 2). The younger sablefish tend to inhabit shallow depths, while older sablefish are found at deeper depths (Saunders, Leaman, & McFarlane, 1997). Presumably, when a strong year classes is initially entering the fishery, it inhabits shallow depths. Thus an abundant year class will be evident as a higher catches per unit effort in the shallow depths by the sablefish trap fishery.

2.2. Building the report card

We wanted to quantify the state of each index value for a given year in order to 'grade' each regime period. We used the 33 and 66 percentiles of each time series' distribution to assign an

Table 1
Time series used to build the report card

Time series	Period	Description	Source of data	Reference
North Pacific climate–ocean indices				
Aleutian Low Pressure Index (ALPI)	1900–2000	The mean area (10^6 km^2) in the north Pacific in winter (December–March) $\leq$100.5 kPa. ALPI is the anomaly from a long-term (1950–1997) mean area. A positive value reflects an intense Aleutian Low.	University Cooperation for Atmospheric Research, National Centre for Atmospheric Research, Boulder, Colorado, USA.	Beamish & Bouillon (1993); Beamish, Neville, & Cass (1997).
Pacific Circulation Index (PCI)	1900–1999	The dominant winter (December–March) atmospheric circulation patterns in the north Pacific expressed as frequency anomalies from a long-term (1900–1966) mean. A positive value reflects above average zonal and meridional circulation that translates into westerly and south-westerly transfer of air masses off the west coast of Canada.	Long-Term Meteorological Forecasts Department, Arctic and Antarctic Research Institute, St. Petersburg, Russia.	King, Ivanov, Kurashov, Beamish, & McFarlane (1998); Beamish, McFarlane, & King (2000).
Pacific Decadal Oscillation index (PDO)	1900–1999	This index is based on the EOF scores on gridded sea surface temperature in the north Pacific and reflects spatial patterns. We used the winter (November–December) averaged values. The positive phase reflects warmer surface waters in the central and western north Pacific and cooler waters along the eastern north Pacific. A negative phase is characterised by cooler central-western waters and warmer surface waters in the eastern portion.	N. Mantua pers. comm. Joint Institute for the Study of the Atmosphere and Oceans, Department of Atmospheric Sciences, University of Washington, Seattle, Washington, USA.	Zhang (1996); Mantua et al. (1997)

Table 1 (*continued*)

Time series	Period	Description	Source of data	Reference
Regional indices				
Bakun index of winter downwelling and summer upwelling	1946–1999	The Bakun index measures the intensity of downwelling and upwelling and is derived from surface wind vectors. Monthly mean index values for an area south-west of Vancouver Island (48°N 125°W) were expressed as anomalies from the long-term (1946–1999) mean. Anomalies were averaged for winter (October–March) downwelling and summer (April–September) upwelling periods.	Pacific Fisheries Environmental Laboratory, National Fisheries Marine Service, Southwest Fisheries Science Centre, Seattle, Washington.	Bakun (1973); Schwing, O'Farrell, Steger, & Baltz (1996).
Fraser River discharge	1912–1999	Mean summer (April–September) discharge rate (cubic meters per second) measured at Hope, British Columbia.	Water Survey of Canada, Environment Canada, Regina, Saskatchewan, Canada.	Environment Canada (1990).
British Columbia atmospheric circulation patterns	1958–1998	Daily gridded sea level pressure data (2.5°×2.5° resolution) for the coastal and inland region of British Columbia (40°N to 62.5°N and 115°W to 140°2) were used in an eigenvector-based synoptic map classification (Yarnal, 1993) using the three dominant synoptic types identified by McKendry (1994). A principal components analysis on the spring and summer (April–September) frequencies was used to produce standardised scores, where a positive score reflects above average south-westerly and westerly circulation processes (loading coefficients 0.38 and 0.32 respectively) and below average north-westerly processes (−0.53).	Climate Diagnostic Centre, NOAA, Boulder, Colorado, USA	Beamish et al. (2000).

(continued on next page)

Table 1 (*continued*)

Time series	Period	Description	Source of data	Reference
Copepod abundance	1979–1981; 1983; 1985–1999	The mean anomalies of sub-arctic copepods (*Neocalanus cristatus*, *N. plumchrus* and *Eucalanus bungus*) and boreal continental shelf copepods (*Ctenocalanus vanus*, *Clausocalanus* spp. and *Paracalaus parvus*) along the slope off the west coast of Vancouver Island. Anomalies were estimated as per Mackas (1995).	D. Mackas, pers. comm., Institute of Oceanographic Sciences, Fisheries and Oceans Canada, Sydney, British Columbia, Canada	Mackas (1992); Mackas (1995).
Pre-recruitment indicators				
Larval surveys	1984–1989; 1992; 1999	Neuston larval surveys were conducted in April at 56 stations along 8 transects off the west coast of Vancouver Island. The mean number per cubic meter for stations sampled along the continental slope were used as an index of annual relative larval abundance.	G. McFarlane, pers. comm., Pacific Biological Station, Fisheries and Oceans Canada, Nanaimo, British Columbia, Canada	McFarlane et al. (1997); King et al. (2000).
Juvenile abundance	1984; 1986–1987; 1989; 1991; 1993; 1995–1997	Bottom-trawl research surveys are conducted in the early summers (May–June) throughout Hecate Strait. Length frequencies using a von Bertalanffy growth equation for juveniles was used to estimate the numbers of sablefish aged 1 and 2 in the catches. Relative abundance for year classes were estimated by standardising the sample size to 1000 individuals and assuming a mortality rate of 0.1.	J. King, pers. comm., Pacific Biological Station, Fisheries and Oceans Canada, Nanaimo, British Columbia, Canada.	Saunders & McFarlane (1992); King et al. (2000).

Table 1 (*continued*)

Time series	Period	Description	Source of data	Reference
Fishery indicators				
Commercial trawl fishery discards	1996–1999	The mean coastwide discard rate (tonnes per thousand hours effort) of non-marketable sablefish ($\leq$55 cm in length) in the commercial trawl fishery. Each year was expressed as an anomaly from the four year mean.	J. King, pers. comm., Pacific Biological Station, Fisheries and Oceans Canada, Nanaimo, British Columbia, Canada.	Saunders & McFarlane (1992).
Sablefish trap fishery effort	1982–1998	When strong year classes are entering the fishery (i.e. fully recruited at age 7), they initially inhabit shallow depths. We use the proportion of the coastwide sablefish trap fishery with effort directed to shallow depths ($<$750 m) to estimate the relative abundance of year classes 1975–1991.	M. Saunders, pers. comm., Pacific Biological Station, Fisheries and Oceans Canada, Nanaimo, British Columbia, Canada.	Saunders et al. (1997).

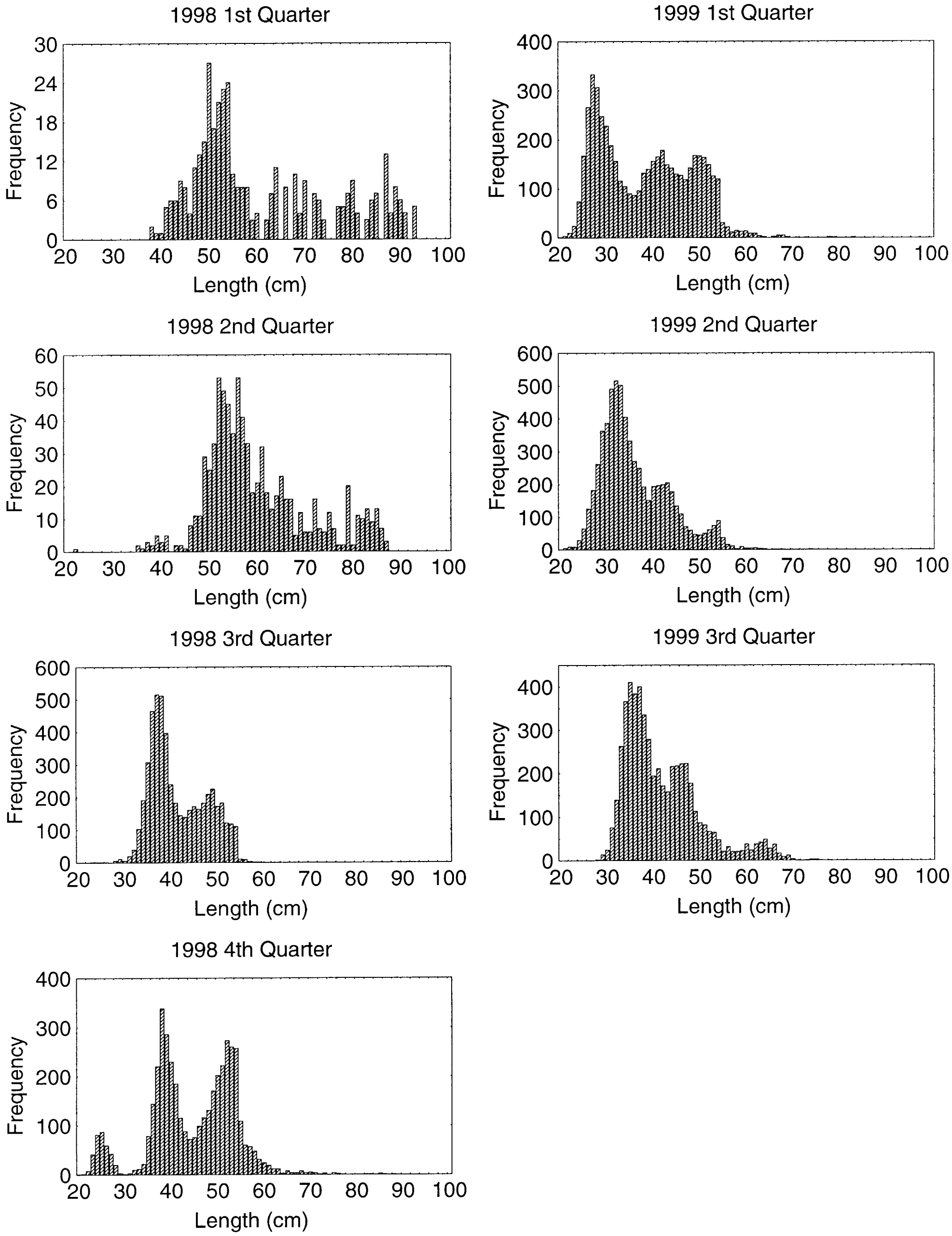

Fig. 2. Length frequencies of non-marketable sablefish caught in the commercial trawl fishery for each quarter in 1998 and 1999. Fish less than 20 cm are assumed to be age 0 fish, those with lengths 20–40 cm are assumed to be age 1 fish, and fish greater than 40 cm are assigned age 2.

index value of ‘good’, ‘average’ (between the 33 and 66 percentile value) and ‘poor’. Admittedly this is arbitrary, but we needed a systematic and comparable approach for the grading each index. Within each regime period (1947–1976; 1977–1988; 1989–1997) we counted the number of years that each index was graded good, average or poor, and the most frequent grade was considered the characteristic state for the index during that regime. If the frequency of two or three grades were similar, then a mixed grade was assigned. It is important to note that the grade labels correspond to expected year class strength of sablefish, not necessarily above or below average values for any given index. For example, it is likely that weak winter downwelling (negative values) are favourable for larval dispersion onto the shelf, so weak downwelling would be graded good. When available, indices were graded for 1998 and 1999.

3. Results

The North Pacific climate-ocean indices (Fig. 3), regional indices (Fig. 4), the pre-recruitment indices (Fig. 5) and fishery indices (Fig. 6 and Table 2) are plotted as deviations from their long-term means. The 33 and 66 percentiles are indicated for each time series and the frequency of occurrence for annual values below and between these threshold values were used to assign the grades in the report card (Table 3). For the 1947–1976 regime period, all available indices were graded poor, except regional downwelling, which was graded as intermediate between poor and average. Year class success was graded average for this regime period, though it should be noted that index values were estimated for the 1960–1976 year classes only. The 1977–1988 regime period generally was characterised by good grades for the majority of indices. The exceptions were summer upwelling, juvenile abundance and commercial fishing effort in shallow depths, all of which received intermediate grades between average and good. The larval abundance, however, received a poor/average grade for this period. The corresponding grade for year class success was good. The following regime period, 1989–1997, was more varied in the grades assigned to the indices, but predominantly the grades were poor. The corresponding grade assigned to year class success was also poor.

3.1. Recruitment to future fishing years

Since sablefish begin to recruit to the fishery at approximately age five, the year classes from 1995–1997 will begin to be harvested in 2000–2002. Though the grades for the 1989–1997 regime period were variable, the predominant grade is poor so the outlook for the upcoming year classes is poor.

4. Discussion

The sablefish report card informs the fishery managers that the strong year classes of 1977 through 1988 were produced during a regime that was characterised by strong Aleutian Lows, above average south-westerly and westerly winter atmospheric circulation patterns, cooling in the central sub-arctic Pacific and warming along the coast (as is characteristic of a positive phase in

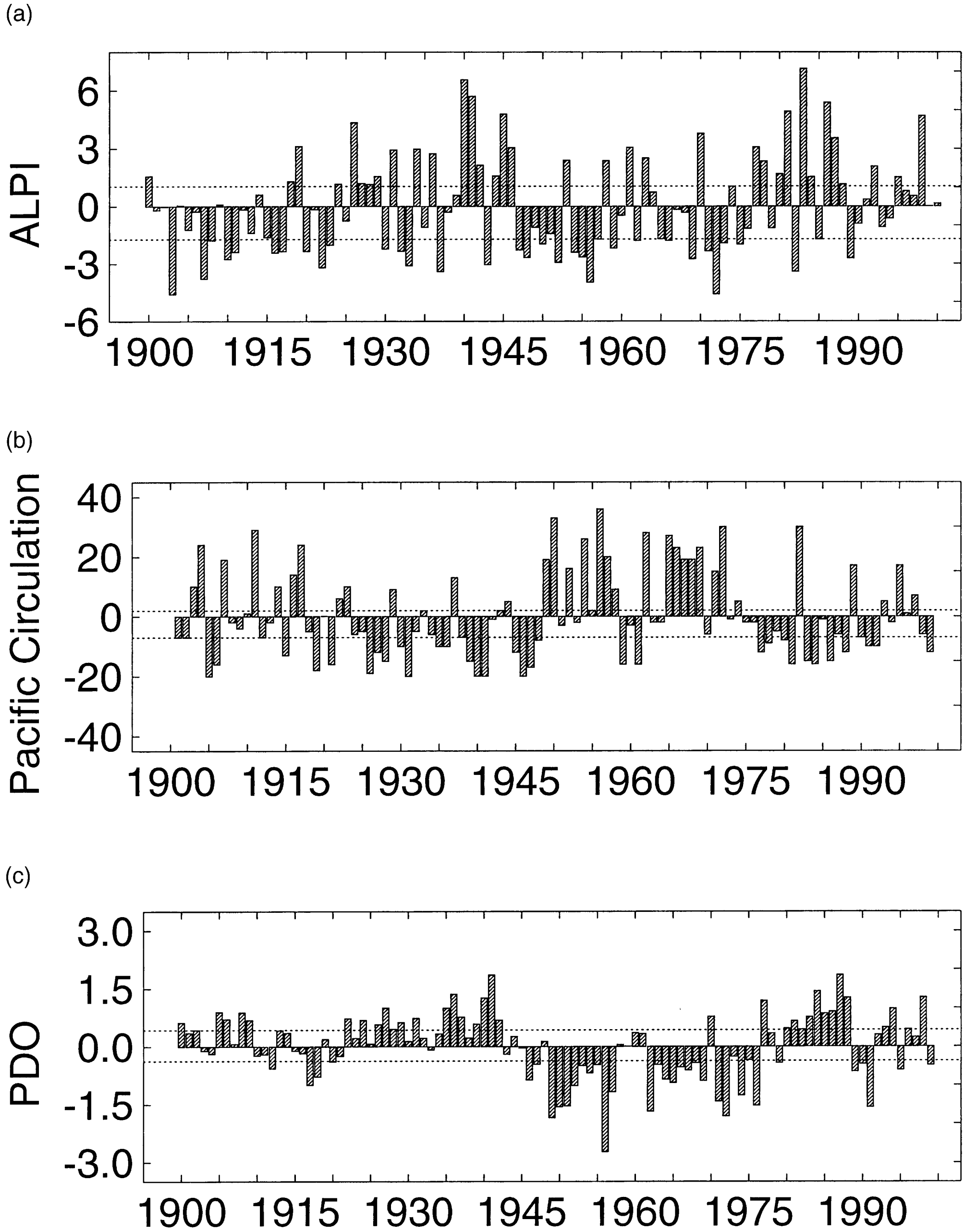

Fig. 3. North-Pacific climate ocean indices. a) the Aleutian Low Pressure Index (Beamish et al., 1997). The 2000 ALPI value (open bar) is preliminary, based on December and January values only b) the frequency anomalies of the meridional atmospheric processes from the Pacific Circulation Index (King et al., 1998). c) the Pacific Decadal Oscillation index (Mantua et al., 1997). Dashed lines denote the 33 and 66 percentile values used to assign grades (see text for explanation).

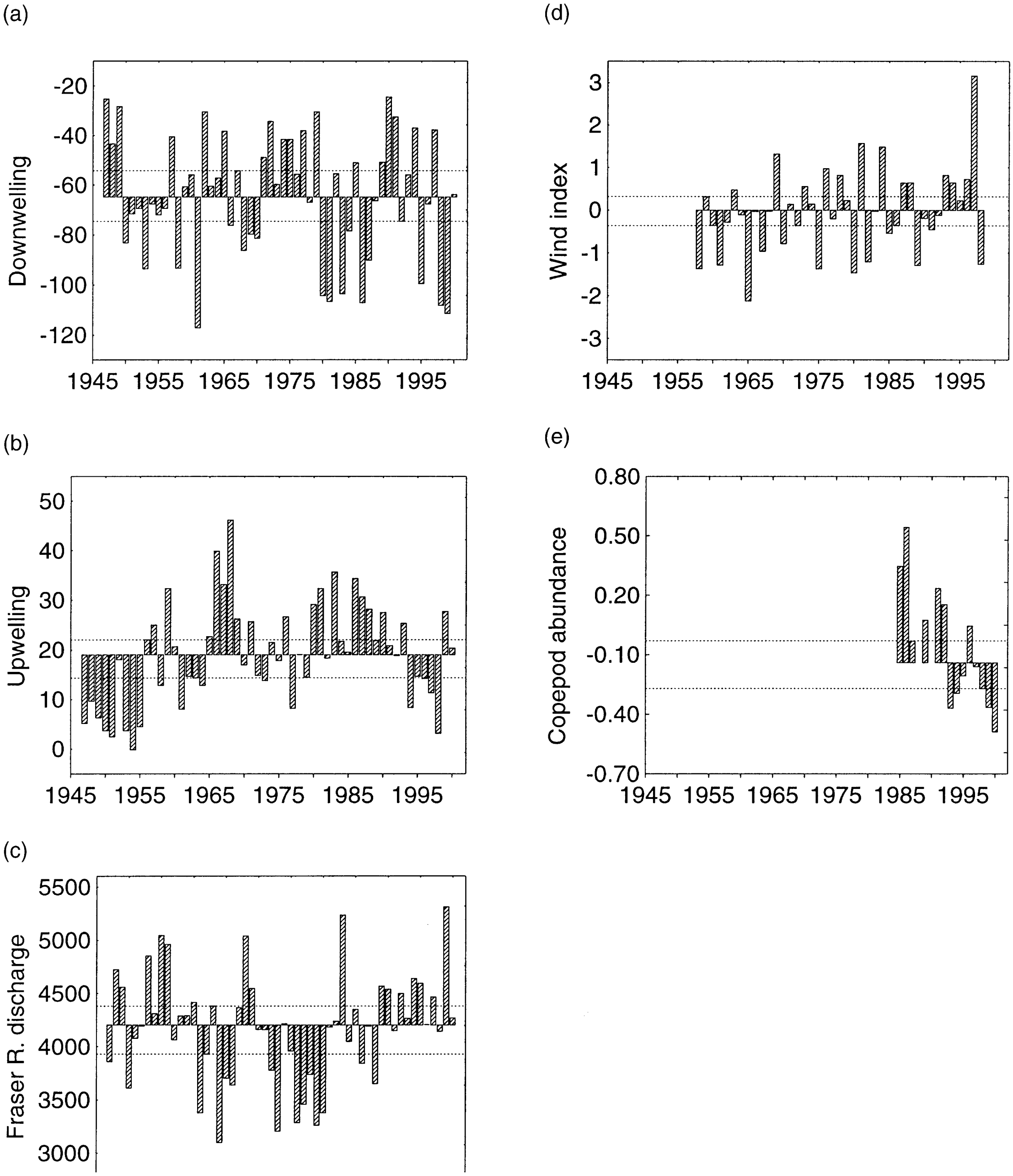

Fig. 4. Regional indices expressed as deviations from the series' mean. a) Mean winter (October–March) Bakun downwelling and b) mean summer (April–September) upwelling indices for 48°N and 125°W. c) Mean spring and summer Fraser River discharge ($m^3 \cdot s^{-1}$). d) Multivariate index of spring and summer British Columbia atmospheric circulation patterns. A positive value denotes above average westerly and south-westerly winds and below average north-westerly winds. e) Mean abundance of subarctic and boreal copepods along the continental slope. Dashed lines denote 33 and 66 percentile values used to assign grades (see text for explanation).

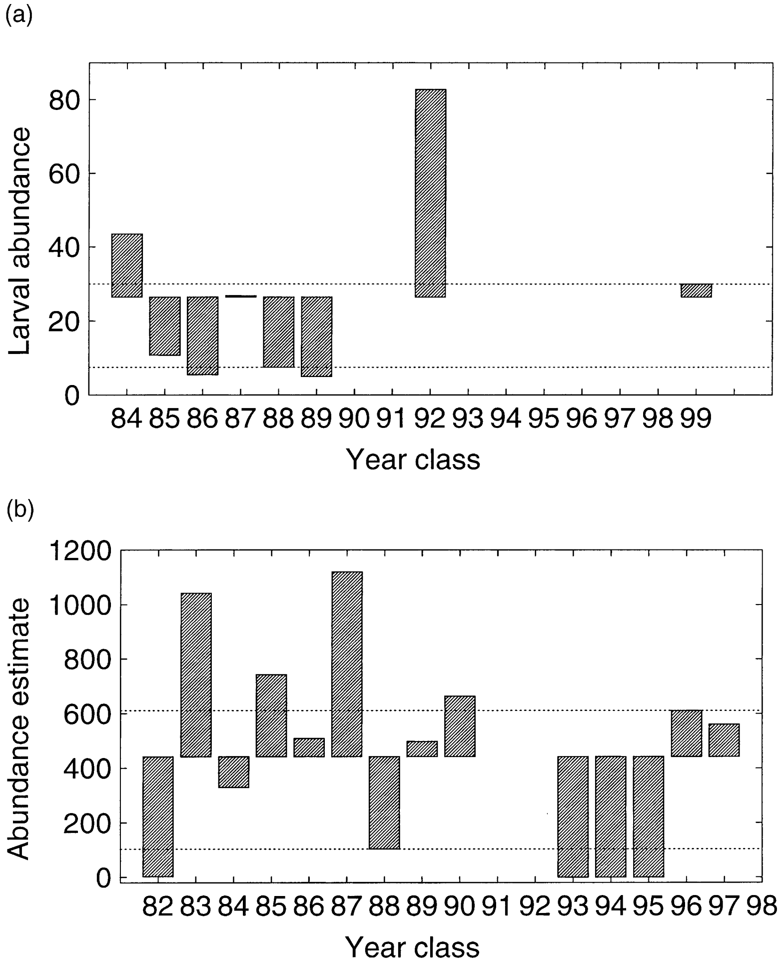

Fig. 5. Pre-recruitment indices. a) Mean larval abundance (#/m^3) measured at standard stations along the continental slope. b) Relative abundance of year classes (standardised to 1000 and assuming an annual mortality rate of 0.1) based on research survey catches of juveniles (age 1–2) in Hecate Strait.

the PDO index). These Pacific-wide conditions were coupled with above average abundances of sub-arctic and boreal copepods, relatively weak winter downwelling and strong summer upwelling conditions along the continental slope off British Columbia. The spring and summer discharges from the Fraser River were generally low. British Columbian regional spring and summer atmospheric circulation patterns were characterised by above average incidence of south-westerly and westerly winds.

These Pacific-wide and regional conditions did not continue into the 1990s, and since 1991 the year class success of sablefish has been poor. The pre-recruitment indices also suggest that the year classes from 1989 to 1997 would predominantly be poor. From this it seems highly likely that the year classes recruiting to the fishery within the next couple of years (i.e. fishing years 2000–2003) will continue to be poor. The report card suggests that conditions in 1998 were similar to conditions when strong year classes were produced, apart from copepod abundance being below

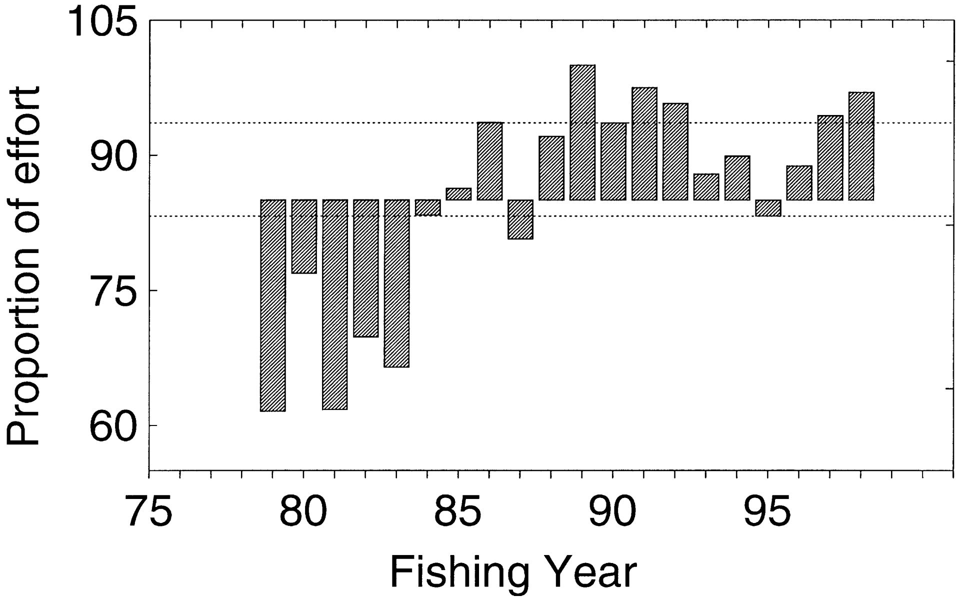

Fig. 6. Percent of effort of the sablefish trap fishery directed to shallower waters (<750 m).

Table 2
Catch per unit effort (pieces per thousand hours) of non-marketable juvenile sablefish by the Canadian commercial trawl fleet

Year	CPUE
1996	0.48
1997	0.73
1998	0.58
1999	0.56

average and the average Fraser River flows continued to be above average. In 1999, most indices in the report card suggested average year class success, while copepod abundance, winter downwelling and north Pacific atmospheric circulation patterns suggested above average success.

The sablefish report card is a first attempt at characterising the state of the fish's ecosystem for observed regime periods. The intent is to apply a holistic assessment of climate and ecosystem states in order to augment sablefish management efforts. Though this first attempt is qualitative, it does use a systematic approach to the grading of the state of specific environmental variables, and it offers an simple approach to providing effective advice to fisheries managers. Successful management agencies such as the International Pacific Halibut Commission combine information from knowledgeable fishermen, experienced managers and stock assessment models to create an evaluation process that optimises the chances of making good decisions (McCaughran, 1997).

Table 3
The sablefish report card. When the length of the time series was intermittent or did not cover the complete regime, the actual timeframe is noted Indices for which below average values were assigned good grades are indicated

	Regime period					
	1947–1976	1977–1988	1989–1997	1998	1999	Comment
North Pacific indices						
ALPI	Poor	Good	Average	Good	Average	
PCI	Poor	Good	Poor	Average	Good	
PDO	Poor	Good	Poor	Good	Poor	
Regional indices						
Downwelling	Poor/average	Good	Poor	Good	Good	Weak downwelling is good grade
Upwelling	Poor		Poor	Good	Average	
Fraser River flows	Poor	Good	Poor/good	Good	Poor	Low flow is good grade
Wind direction	Poor	Good	Good			Good grade is above average sw and w winds, below average nw winds; 1958–1997 only
Copepod abundance	Poor	Good	Poor	Poor	Average	Begins in 1979
Pre-recruitment indices						
Larval survey		Poor/average	Poor/good		Good	Intermittent (see text for years)
Juvenile survey		Average/good	Poor			Intermittent (see text for years)
Fishery indices						
Discards			Average			For 1996–1997 year classes only
Shallow depth effort	Poor	Average/good	Good			For 1975–1991 year classes only
YCI	Average	Good	Poor			For 1960–1997 year classes only

4.1. Coupling regime and ecosystem dynamics with sablefish life history

Leaman and Beamish (1984) discussed the advantages of extreme longevity (life span greater than 50 years) as a life history characteristic and the implications it has for sustainable and rational management of the exploitation of stocks of long-lived fish, such as sablefish. One obvious advantage of longevity is that it allows a population to withstand prolonged periods (i.e. decadal-scales) of unfavourable environmental conditions. Leaman and Beamish (1984) noted that many species with extreme longevity live in deeper water (200–1000 m) where productivity is generally low. Thus longevity is a life history trait that allows species to inhabit deep water habitats, where energy resources may be low, but competition and predation pressure is low. The relatively high fecundity of sablefish probably enables them to take maximum advantage of any switch to favourable ocean conditions (McFarlane & Beamish 1986, 1992). Thus, the exceptional year class of 1977 and the strong year classes of the following years 1978–1982 were the products of a small spawning biomass that had survived at least 15 years of adverse conditions and poor recruitment.

Leaman and Beamish (1984) warned that exploitation strategies must take into account these life history traits that have allowed the species to withstand these changing environmental conditions. Consider two possible scenarios for sablefish productivity. The first is a productive regime during which reproduction tends to be successful and year classes to be strong. Saunders et al. (1997) reported that young sablefish (<5 years) occupy relatively shallow depths (<640 m) whereas the older fish (5–10 years) tend to occupy mid-depths (641–824 m). Sablefish older than 10 years dominate the population in even deeper water (>824 m). Since sablefish larvae require water depths of at least 1000m for their successful development (McFarlane & Beamish, 1992), the shallower habitats (<640 m) are likely to be better for growth but not for reproduction and so can be regarded as marginal. Fish in this marginal habitat do not contribute to reproduction, and may even delay their maturation until they can find suitable deep-water habitat. Such fish can be considered to be a surplus that is available to migrate and occupy the deeper water habitats when space becomes available.

Scenario two is when the prevailing regime is unproductive, larval mortality is high, and above average year classes are infrequent. Some fish may occupy the shallower, marginal habitats, depending on the length of the unfavourable conditions. Adults occupy the deep water and longevity ensures that an adequate spawning biomass is present when favourable environmental conditions return. The high fecundity ensures high reproductive success when the switch to favourable conditions occurs.

Management approaches to exploitation could be founded upon these two unexploited scenarios. Non-excessive fishing during a productive regime will not prevent the stock from replenishing itself as there are frequent strong year classes. The marginal habitat is occupied by young fish, and as fishing removes older fish from the preferred deep-water habitat, young adults can migrate to occupy this habitat, thus a large spawning biomass is maintained. Fishing during an unproductive regime requires a much more conservative approach. The biomass of mature fish declines both natural wastage and through fishing, and there are few young fish in the marginal habitat to replenish the breeding stock.

Fisheries managers could incorporate the sablefish life history traits using our report card approach to develop sustainable exploitation strategies that take into account the changes to the sablefish's ecosystem. For example, when indicators warn that the regime is unproductive (e.g.

fishing the 1991–97 year classes), then deep-water fishing effort has to be reduced to protect the spawning adult biomass in the preferred habitat. But when the indicators pointed towards a more productive regime, then deep-water fishing effort is less likely to reduce the spawning biomass significantly. Fishing strategies should be multifaceted, using a combination of spawning refugia (e.g. restricted fishing by area or depth to preserve age composition) to ensure the maintenance of a critical spawning biomass. Keeping in mind that sablefish begin to recruit to the fishery at age 5, at least five years of report card data are available on which to base management decisions.

Admittedly, it would be preferable to outline a stringent set of rules to evaluate grades on a year-to-year basis in order to forecast sablefish recruitment. This, however, requires a number of assumptions, which can not be made. First, that the indices here represent causal mechanisms regulating sablefish abundance and can be used on an annual basis to forecast recruitment. The annual grades assigned to the indices do not always match each other (or a particular pattern) or the grade assigned to the year class index. It would be unwise to assume that the ecosystem effects that influenced year class success during a previous regime will necessarily still apply during a future regime. Several attempts to forecast other species' abundance levels using ecosystem surrogates such as sea surface temperature have broken down in recent years. This does not indicate that there are no environmental effects. Rather, it reflects the difficulty of integrating a complex life history with the complexity of ecosystem changes. While we have tried to select appropriate variables based on our limited knowledge of sablefish life history, we acknowledge that new or more appropriate indices may become available, which can be included in the reporting. A second assumption of applying stringent rules is that the report card will succeed in detecting regime shifts. That ability will need to be developed and applied outside of this exercise.

The intent of the report card is to provide an approach to integrating parameters to yield an impression of sablefish productivity during a specific regime. The flexibility of its format allows for the inclusion of anecdotal and qualitative indices from fisheries managers and fishermen. It can be used to augment traditional stock assessment efforts, for example indicating probable changes in recruitment rates (and possibly mortality rates) to be included in a formal age-structured model. Finally, it is a simplified way to present to fisheries managers the complex information on climate influences, along with the physical and biological dynamics of the ecosystem that sablefish live in. It can be used to characterise an ecosystem for a previous or a current regime and it forces the inclusion of some consideration of ecosystem dynamics, along with life history characteristics, in stock assessment and management. Most importantly, our efforts here reflect the recent change in paradigms in fishery science: from assuming that environmental effects on fish populations will average out over a few years to acknowledging that environmental effects on fish stocks need to be taken seriously (Mann, 2000).

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